V_{tx}
— Status of V_{td}, V_{ts} and V_{tb}

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The Three Elusive Elements

three CKM elements V_{td}, V_{ts}, V_{tb}

- *not much* ’direct’ experimental knowledge
- *lot* of ’indirect’ information in the Standard Model
- *large* amount of precision studies
- *several* BSM Scenarios with non-standard CKM matrices
- *only* 25 minutes

I apologise for not covering your favourite topics!

Direct Measurements of $|V_{tb}|$ I

$t\bar{t}$ production allows simultaneous measurement of $\mathcal{R}_b$

$$\mathcal{R}_b = \frac{\mathcal{B}[t \to Wb]}{\mathcal{B}[t \to Wq]} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

and $\sigma_{t\bar{t}}$.
DØ 's result is: Phys.Rev.Lett.100:192003,2008

$$\mathcal{R}_b = 0.97^{+0.09}_{-0.08} \text{ (stat + syst)}$$

$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84} \pm 0.5 \text{ (lumi) pb}$$

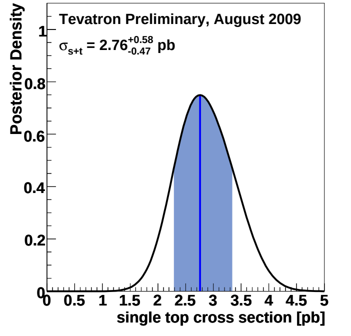
- the "model-independent" result is unfortunately only $|V_{tb}| \gg |V_{ts}|, |V_{td}|$

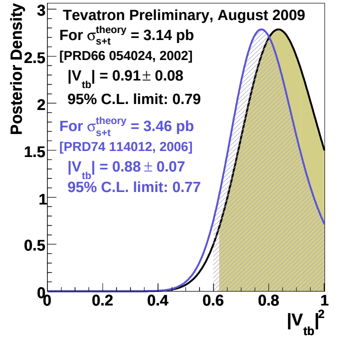
Direct Measurements of $|V_{tb}|$ II

single top production (at TeVatron & LHC) first observed in 1995

Production cross section directly proportional to $|V_{tb}|^2$

- combined CDF-DØ result ($m_t = 170$ GeV): CDF Note 9870, DØ Note 5973





$$|V_{tb}| = 0.88 \pm 0.07$$

SEE NEXT TALK FOR MORE!

Theory I: the Standard Model

easiest way: use unitarity of the CKM matrix (4 parameters)

- restore absolute values of unknown elements from known absolute values $|V_{ud}|$ from nuclear beta decay; $|V_{us}|$, $|V_{ub}|$, $|V_{cd}|$, $|V_{cb}|$, $|V_{cs}|$ from e.g. semileptonic meson decays
- add the measurement of the CKM angle γ to restore the CKM phase ($B \to D^{(*)}K$)
- one can strictly stay "tree-level"

Performing a fit one gets (for the Standard Representation) from UTfit

$$V_{CKM} = \begin{pmatrix} 0.9426 \pm 0.00015 & 0.22535 \pm 0.00065 & 0.00376 \pm 0.0002 \cdot e^{i(-73.8 \pm 9.4)^\circ} \\ -0.2252 \pm 0.00065 \cdot e^{i(-0.03656 \pm 0.0028)^\circ} & 0.97345 \pm 0.00015 & 0.04083 \pm 0.00045 \\ 0.00896 \ \& \ 0.01081 \pm 0.0006 \cdot e^{i(-22.9 \pm 1.4)^\circ} & -0.03979 \pm 0.00052 \cdot e^{i(-1.163 \pm 0.084)^\circ} & 0.99916 \pm 1.8 \times 10^{-05} \end{pmatrix}$$

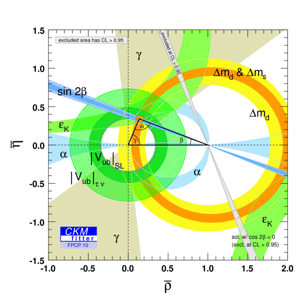
only larger uncertainty

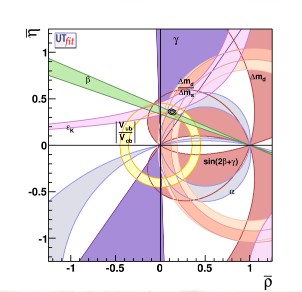
already quite precise

Theory I: the Standard Model

better: use all the information one can get

- plethora of precision measurements in flavour physics (meson mixing, $b \to s\gamma$ decays, $B \to J/\Psi K_s, \ldots$)
- powerful consistency check for unitarity (theory already makes use of this during the treatment of individual processes)





One finds:

$$|V_{td}| = 0.00865^{+0.00024}_{-0.00039} \qquad |V_{ts}| = 0.04072^{+0.00038}_{-0.00146} \qquad |V_{tb}| = 0.999133^{+0.000060}_{-0.000016}$$

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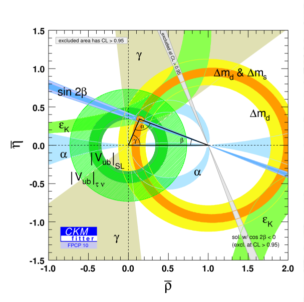

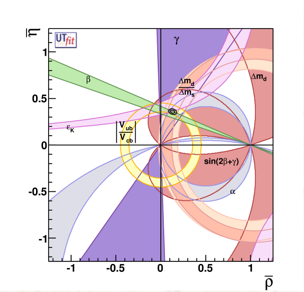

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As soon as unitarity is in the game there is almost no freedom for V_{tx}

Beyond Unitarity

- without unitarity the 3×3 CKM matrix would have 13 independent parameters

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{i\delta_{13}} \\ |V_{cd}| & |V_{cs}|e^{i\delta_{22}} & |V_{cb}| \\ |V_{td}|e^{i\delta_{31}} & |V_{ts}| & |V_{tb}|e^{i\delta_{33}} \end{pmatrix}$$

Kim & Yamamoto

Can one fit for that? — not really as non-unitarity must have a source

- SM CKM matrix is then typically a submatrix of a larger fermion mixing matrix
- three scenarios:
  - a sophisticated one: Randall-Sundrum
  - a minimal one: Vector-like Quarks
  - a simple one: extra SM-like generation

Additional Fermions

Simplest way for a non-unitary CKM matrix: adding fermions

- vector-like quarks
- more fermion generations ($\rightarrow$ non-unitarity of SM subblock)

Main concern:
reinterpret data from a non-unitary point of view

- Does the theory input rely e.g. on

$$V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} = 0$$

- Are relations that are necessary for data interpretation violated?

  e.g. high precision of measurement of $\sin(2\beta_s)$ via $B_s \rightarrow J/\Psi\Phi$ due to structure of decay
  $\rightarrow$ additional fermions may introduce a mismatch of penguin and tree decay

Additional Fermions: Vector-like Quarks

- make an appearance in many models: RS or E_6 GUTs
- one minimal scenario: one heavy $Q = +2/3$ vector-like singlet quark;

e.g. Kim & Dighe Int.J.Mod.Phys.E16,2007; Botella et al. Phys.Rev.D79:096009,2009; …

  - 4×3 CKM matrix; $V^\dagger V \neq 1$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \\ \hline V_{Td} & V_{Ts} & V_{Tb} \end{pmatrix}$$

  - Higgs interaction flavour changing
  - Z can induce FCNCs at tree-level $\propto$ to unitarity violation
    $\rightarrow$ detection via $t \rightarrow Zc$ @ LHC
  - very heavy vector quark will primarily mix with the t
    $\rightarrow$ (SM) unitarity constraints of first and second row within errors

Extra Generations

Conceptionally even simpler: see Tillman Heidsieck's talk

add a full SM-like generation (7 additional parameters in the quark sector)

- no tree-level FCNCs
- anomaly free but requires "unnaturally" heavy neutrino
- CKM & PMNS matrices have to be $4 \times 4 \rightarrow$ 4×4 unitarity constraints
- SM CKM matrix is again a sub-block

$$V_{CKM4} = \left(\begin{array}{ccc|c} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ \hline V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{array} \right)$$

constraints from unitarity

- limits on V_{td}, V_{ts}, V_{tb} have to come from $\Delta F = 1, 2$ processes

Bobrowsik et al. '09; Buras et al arXiv:1002.2126; Soni et al. PRD 82:033009,2010,

  - $b \rightarrow s\gamma$
  - B_d mixing gives stringent limits for $V^*_{td} V_{tb}$
  - rare Kaon and B decays

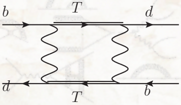
- electroweak observables play a more prominent rôle compared to vector quarks

J.Awall et al. EPJ '07 ; Erler & Langacker '10; Eberhardt et al. PRD '10; Chanowitz arXiv:1007.0043; …

Additional Fermions at work

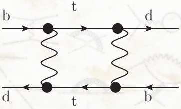
Both models (and to a much lesser extent RS) can allow for rather large modifications of $V_{td/s/b}$ (compare to the SM values) as they always introduce (at least) *two* corrections to a loop-induced process:

- new particles in the loop: T (vector) or t' (fourth) give an additional contribution



additional diagrams with one or both internal quarks of $T, t', \ldots$ type

- the change in the CKM elements modifies the SM part



modified SM couplings as CKM matrix is "thinned out"

- FCNCs @ tree may come into the game (not for 4G)

Only the sum of these contributions is bounded by data → cancellations are fairly natural

e.g. Hou et al PRD '07; Bobrowsik et al. PRD '09;

Numbers for the vector-like quarks

taking into account:

- tree-level bounds on CKM
- $B_d \to J/\Psi K_s$
- mass differences in the B_d and B_s system
- ϵ_K and ϵ'/ϵ_K
- rare K and B decays e.g. $K^+ \to \pi^+ \nu\bar{\nu}$, $B \to X_s \ell^+ \ell^-$
- electroweak oblique parameter T, R_b

J.Awall et al. (2007)

• Examples:

$m_T = 450$ GeV

$$|U_D| = \left(\begin{array}{ccc|c} 0.974179 & 0.225657 & 0.004031 & 0.006073 \\ 0.225619 & 0.972525 & 0.041766 & 0.039324 \\ 0.008330 & 0.047219 & 0.966377 & 0.252620 \\ 0.001136 & 0.032304 & 0.253683 & 0.966747 \end{array}\right)$$

$m_T = 300$ GeV

Botella et al. (2009)

$$|U_D| = \left(\begin{array}{ccc|c} 0.974195 & 0.225663 & 0.004137 & 0.002015 \\ 0.2254882 & 0.972938 & 0.041548 & 0.028688 \\ 0.009721 & 0.042034 & 0.945531 & 0.322660 \\ 0.002889 & 0.026471 & 0.322842 & 0.946078 \end{array}\right)$$

$\to O(5\%)$ effect in V_{tb}

$\to$ roughly the sensitivity of ATLAS + CMS

$\to$ large relative "corrections" to $V_{td/s}$

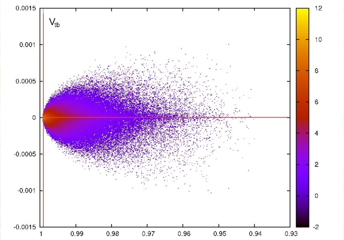
Numbers for the Fourth Generation

taking into account:

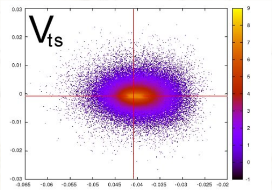
- tree-level bounds on CKM
- rough bound on $B_d \to J/\Psi K_s$ (danger of pollution due to a t' penguin)
- mass differences in the B_d and B_s system as well as ϵ_K
- rough bound from D^0 mixing
- some B decays e.g. $B \to \ell^+\ell^-$, $B \to X_s\gamma$
- electroweak oblique parameters T & S; R_b
- not including PMNS-related effects on G_F

Lacker & Menzel

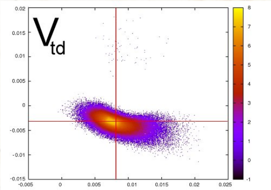
for V_{tb}



for V_{ts}



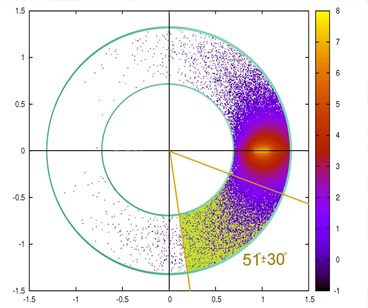
for V_{td}

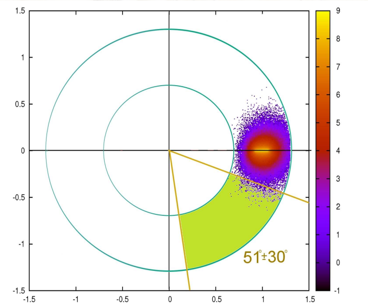


Eberhardt et al.

Sidenote: Φ_s

- already on the first day: hot topic Φ_s
- hot discussions
- Remark: both extensions (vector-like quarks and G4) potentially lead to large values of Φ_s
- how large the phase can be depends on how 'serious' one takes the electroweak sector





Warped Extra Dimensions and V_{tx}

Exploration of the flavour structure of models with a warped 5th dimension has intensified in the last few years:

- Huber & Shafi PLB 498:256-262,2001, Huber NPB 666:269-288,2003, Agashe et al. PRD 71:016002,2005, …
- Bauer et al. arXiv:0912.1625,PRD 79:076001,2009 ; Casagrande et al. JHEP 0810:094,2008; …
- Albrecht et al. JHEP 0909:064,2009, Blanke et al. JHEP 0903:108,2009,JHEP 0903:001,2009, Buras et al JHEP 0909:076,2009, Casagrande et al. arXiv:1005.4315,…

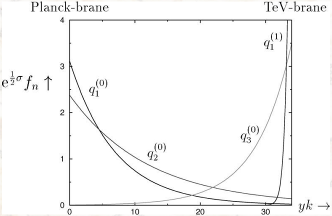
Relevant for the CKM matrix: it's no longer unitary
there are three potential sources:

- SM fermions can mix with their KK modes (SM CKM matrix is 3×3 sub-block)
- Effects of mixing of the W with its KK partners (non-universal coupling)
- KK modes of the W and their effect on G_F
  (V_{tx} is almost insensitive to this)

Warped Extra Dimensions

standard minimal set-up:

- fermions develop wave functions in the 5th dimension (Higgs confined to the IR brane)

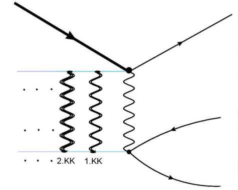


"hand-waving" argument:

- heavier quarks must have a larger wave function on the TeV brane
- those quarks will have large overlap with the KK modes
- the t and to lesser extent the b will mainly be affected by the mixing into KK modes

- during EWSB the W acquires a mass and receives admixtures of KK modes
  $\rightarrow$ general modification of CKM couplings
  $\rightarrow$ largest modifications for third row and column term

- direct effect of KK bosons (if CKM is defined via eff. 4-fermion vertex)



- as G_F and V_{Qq} always appear together
  $\rightarrow$ KK modes modify G_F obtained via μ lifetime
  $\rightarrow$ $G_F^{'true'} < G_F^{'observed'}$

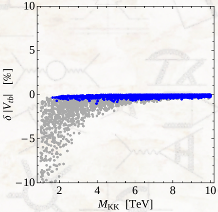
Warped Extra Dimensions: Numbers

- Unitarity violation in the minimal model:

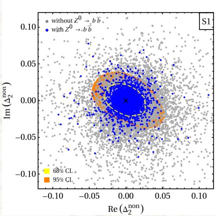
Bauer et al. arXiv:0912.1625

V_{tb}

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = \Delta_2$$



courtesy of U.Haisch



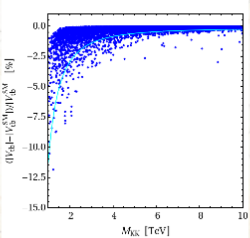
$\longrightarrow V_{tb}$ can be reduced by a only few percent

- Unitarity violation in custodially protected model:

involved analysis of unitarity in Buras et al. JHEP 0909:076,2009

$$1 - |V_{tb}|^2 - |V_{ts}|^2 - |V_{td}|^2 \leq \mathcal{O}(5\%)$$

$|V_{tb}|$ is main source



courtesy of S.Casagrande

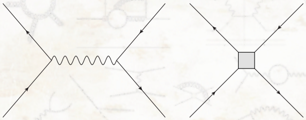
Summary

- unitarity is a very powerful constraint for the CKM matrix
  $\rightarrow$ fixes the matrix elements that cannot be accessed directly:
  V_{td}, V_{ts} and V_{tb}
- various BSM model do not feature a unitary CKM matrix
- once unitarity in no longer in place shifts in V_{tx} are possible
- prospects of direct measurement of non-unitarity via V_{tb}?
- all three models would be hard pressed if LHC would strengthen the current TeVatron central value of 0.88 for V_{tb}
- impact on G_F measurement may be relevant

Backup

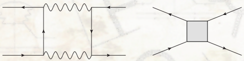
Interlude: "Definitions" for V_{CKM} elements

- using the SM Lagrangian: V_{td}, V_{ts} and V_{tb} tell us how the (weak) interaction eigenstate b has to be decomposed in mass eigenstates $\Rightarrow$ V_{CKM} give the "mass flavour" changing coupling of the W
- effective theory definition:
  - in experiment one observes e.g. $Q \to q\ell\nu$
  - so CKM comes in as part of the couplings of effective 4-fermion vertices



$\propto G_F V_{Qq}$

for the V_{tx} line one has



$\propto S_{IL}(x) G_F^2 V_{tq} V^*_{tq'}$

- for V_{tx} the effective picture is probably less natural as $m_t > m_W$

Additional Fermions — Nitpicking

As one adds a complete generation one cannot discard the effects of the lepton sector

- lepton flavour violation — Buras et al. arXiv:1006.5356
- potential modifications in some processes
- backreaction on the quark sector via the "electroweak"

One Example: — Lacker & Menzel JHEP 1007:006,2010

Measurement of G_F via μ lifetime — U is the PMNS matrix

$$\Gamma(\mu^- \to \text{all}) = \frac{G_F^2 m_\mu^5}{192\pi^3} \cdot PS(m_e, m_\mu) \cdot \left[(1 - \frac{\alpha(m_\mu^2)}{2\pi}(\pi^2 - \frac{25}{4}) + C_2 \frac{\alpha^2(m_\mu^2)}{\pi^2})(1 + \frac{3m_\mu^2}{5m_W^2}) \right] \cdot \sum_{i=1,2,3} |U_{ei}|^2 \sum_{j=1,2,3} |U_{\mu j}|^2$$

$\rightarrow$ extract a slightly too small G_F

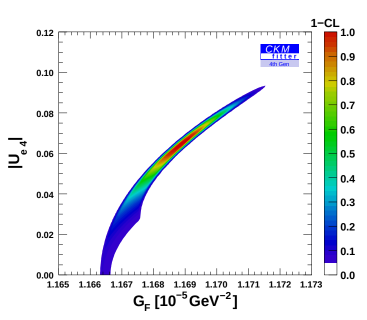
$\rightarrow$ increases uncertainty in G_F

$\rightarrow$ backreaction on precision fit of the electroweak observables

Additional Fermions — Nitpicking II

Included observables:

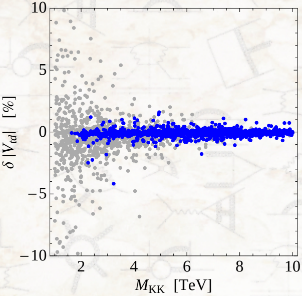
- muon lifetime
- partial rate from leptonic tau decays
- bounds on $\mu \to e\gamma$
- leptonic decays of $\pi^{\pm}$
- leptonic kaon decays

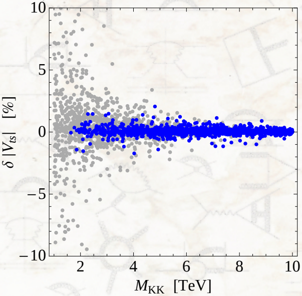


- "dependence" of the value of G_F on the PMNS element U_{e4}
- best fit for U_{e4} is tiny but non-zero
- slightly smaller value for $|V_{ud}|$ from superallowed β decays
- reduced precision in G_F
  $\rightarrow$ relaxes bounds on V_{tx} from T, R_b?

More from RS

Minimal:





Custodial: