How to really kill a new physics model

Alexander Lenz (CERN)

Bern, May 16th, 2012

Greek Mythology I

- Hydra: $\upsilon\delta\rho\alpha$
  - Snakelike monster with nine heads
  - Sister of Cerberos, Chimaira and Sphinx
  - **Bad for hunters:** When you cut off one head, two new ones grow...
- Common folklore: Hydra was killed by Herakles
- The painting:
  Antonio Pollaiuolo (1431-1498)
  Florence; 17.5 cm x 12 cm

Contents

- Hydra = SM4
- Herakles (Langacker,Erler; Peskin; ATLAS; CMS;...) claimed many times that he killed Hydra; e.g. 1110.3805
  First, the idea of a sequential fourth generation of quarks and leptons is in serious trouble. If there exist new heavy quarks U and D that couple to the Standard Model as a conventional quark doublet, the cross section for the production process gg $\rightarrow$ h is multiplied by a factor of 9. Given the fact that Higgs limits are now within a factor of a few of the Standard Model expectation, this excludes fourth generation models over the entire range of Higgs mass, excepting only high values above 550 GeV. It is important to note that other types of exotic fermions are still in play and are even interesting...
- But another head grew and Hydra is still alive
  Statements like: *m_H in the range of 120 to 550 GeV is excluded in the case of the SM4* **are not (yet) correct**
- Iolaos has to help

The SM4 - the simplest extension of the SM

Another sequential generation of fermions

Leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, \begin{pmatrix} \nu_4 \\ \ell_4 \end{pmatrix}$

Quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}, \begin{pmatrix} t' \\ b' \end{pmatrix}$

New parameters

- 4 Fermion masses
- 5 CKM parameters
- 5 PMNS parameters (Dirac neutrinos)

The deaths of Hydra

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  Electro-weak Observables do not exclude a fourth family!

$$m_{t'} - m_{b'} = \left(1 - \frac{1}{5} \ln \frac{m_H}{115\text{GeV}}\right) \cdot 50\,\text{GeV}$$

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  - Scans over the CKM4 parameter regions
    Bobrowski, A.L., Riedl, Rohrwild; Chanowitz; Soni,...; Buras et al.; Eberhardt, A.L., Rohrwild;...

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- **?Real Death or Resurrection?**

Main old arguments against the fourth family

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- 2002: "an extra generation of ordinary fermions is excluded at the 99.8% CL on the basis of the S parameter alone. [...] This result assumes [...] that any new families are degenerate. This restriction can be relaxed [...] to 95%."
- 2010: "an extra generation of ordinary fermions is excluded at the 6 σ level on the S parameter alone. This result assumes [...] that any new families are degenerate. [...] a fourth family is disfavored but not excluded by current data."

Erler/Langacker

Status of 2007

Kribs, Plehn, Tait, Spannowsky; PRD 2007

- SM4 is not excluded - in particular: δS vs. δT

$$m_{t'} - m_{b'} = \left(1 - \frac{1}{5} \ln \frac{m_H}{115\text{GeV}}\right) \cdot 50\,\text{GeV}$$

  CKM-mixing was neglected in electro-weak sector to obtain this result

- Triggered some activity: 305 citations $\approx$ 60 per year
- Several things were published before by Vysotsky, Rozanov, et al.; He, Polonsky, Su but widely ignored

Constraints on the SM4

Direct constraints

- Mass constraints (quarks, leptons)
- Direct measurements of CKM elements
- Phase constraints on the CKM matrix

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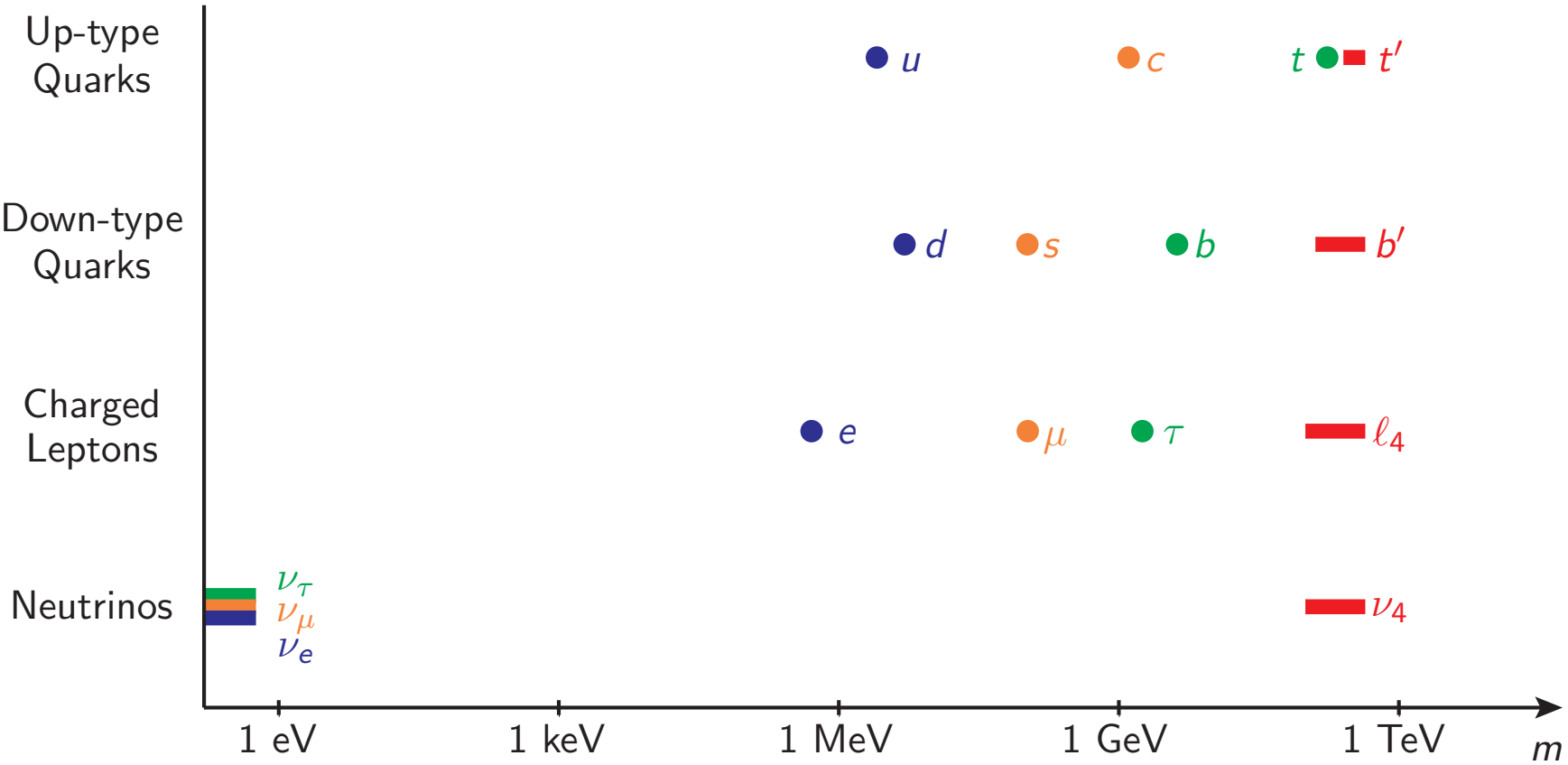
Indirect constraints

- FCNC
- Lepton observables
- Electro-weak precision observables
- Higgs-production

Direct mass limits: be careful, always assumptions...

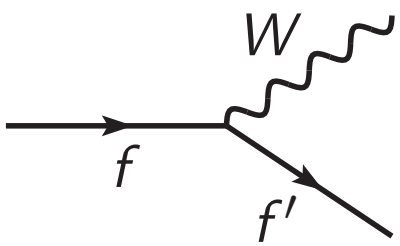


$m_{q'} > \mathcal{O}(550 - 100\text{GeV})$: ATLAS; CMS, D0, CDF:
e.g. Flacco et al. 2010

$m_{\nu_4} > \mathcal{O}(50\text{GeV})$: LEP $\qquad$ $m_{l_4} > \mathcal{O}(100\text{GeV})$: LEP

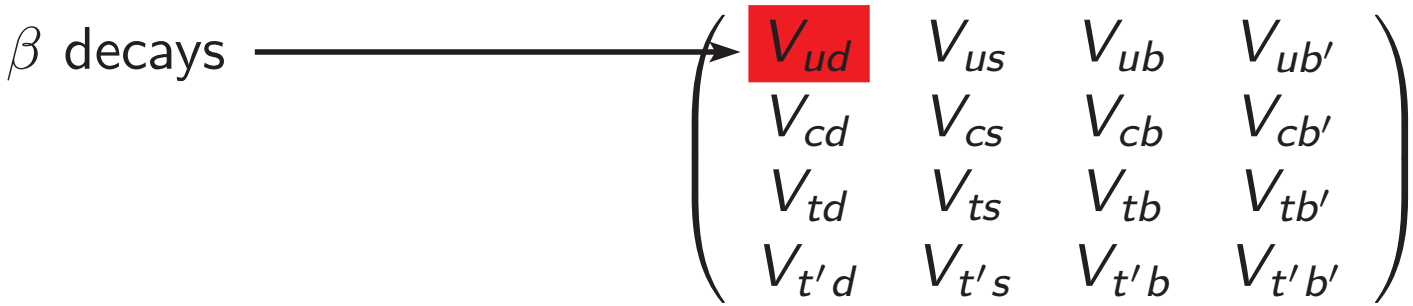
($m_H \notin [120\ \text{GeV}, 550\ \text{GeV}]$:ATLAS, CMS, CDF, D0)

Tree level constraints



$$V_{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

Tree level constraints



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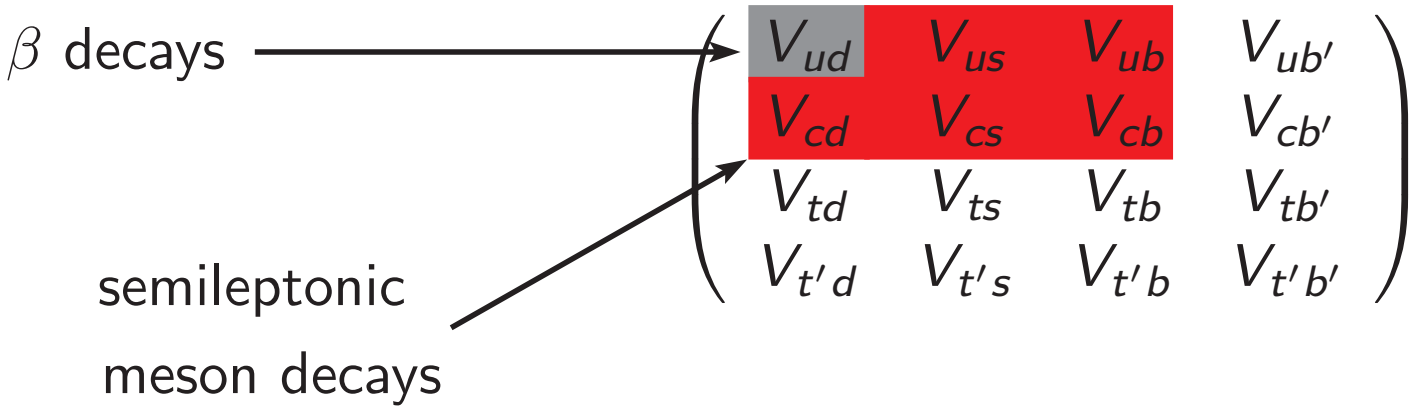

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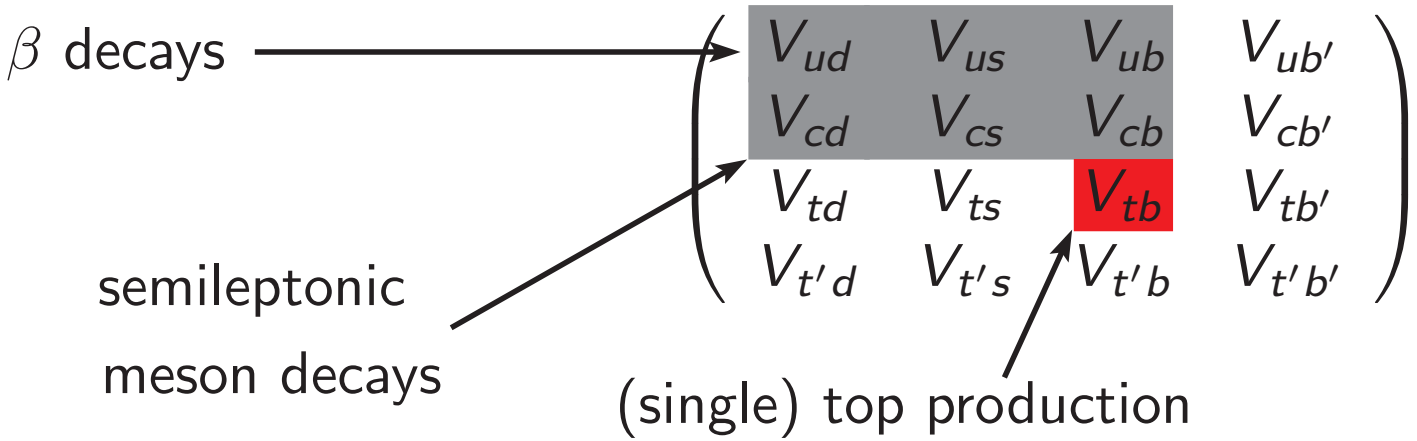

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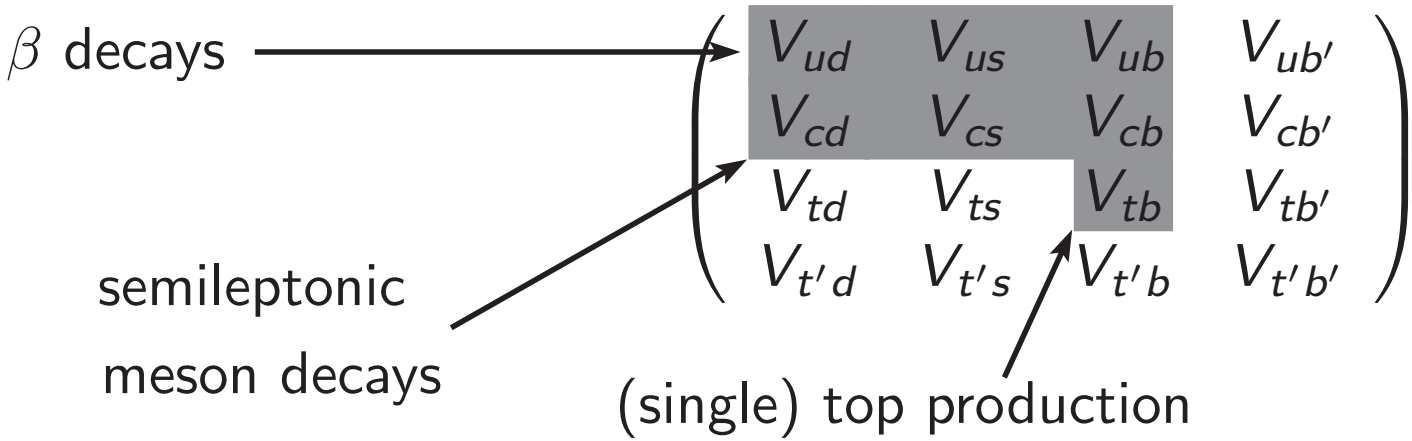
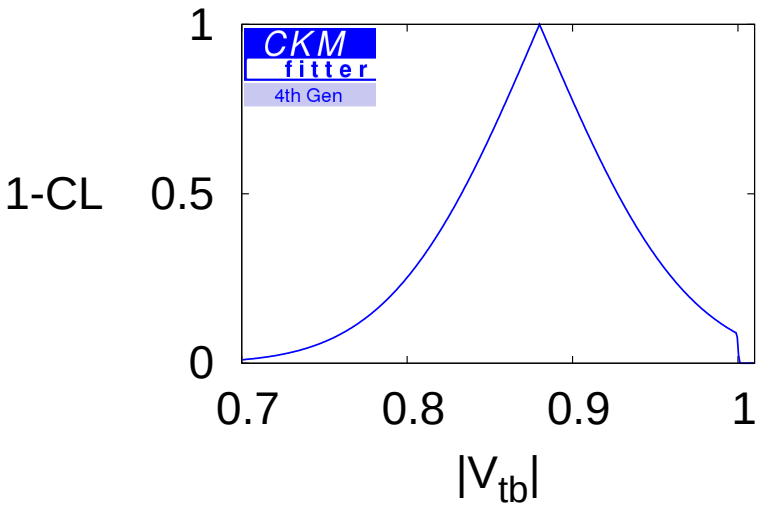
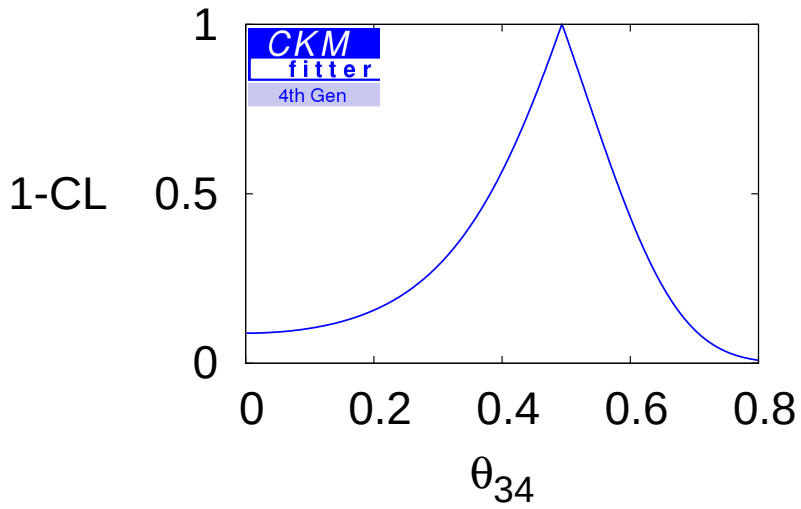


The latest PDG value for V_{tb} is 0.88 ± 0.07.

Tree level constraints alone



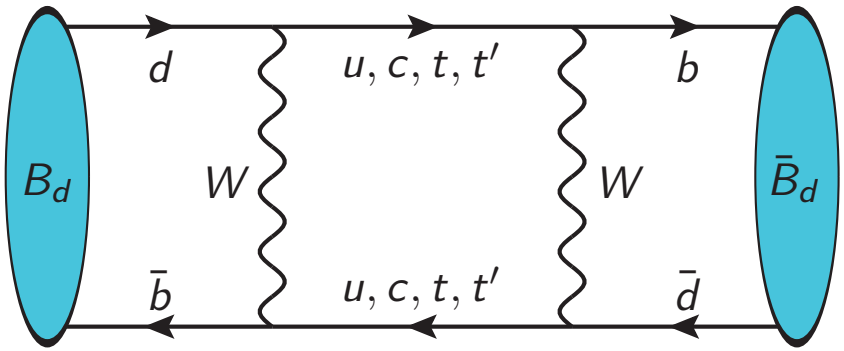


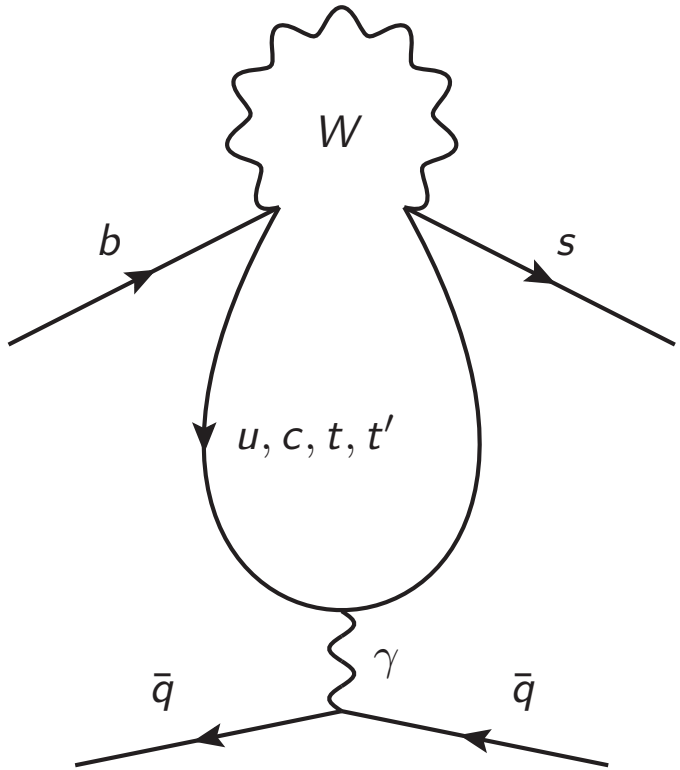
Still huge mixing with a fourth familiy possible!

$\Rightarrow$ include also loop observables!

Further constraints: FCNC

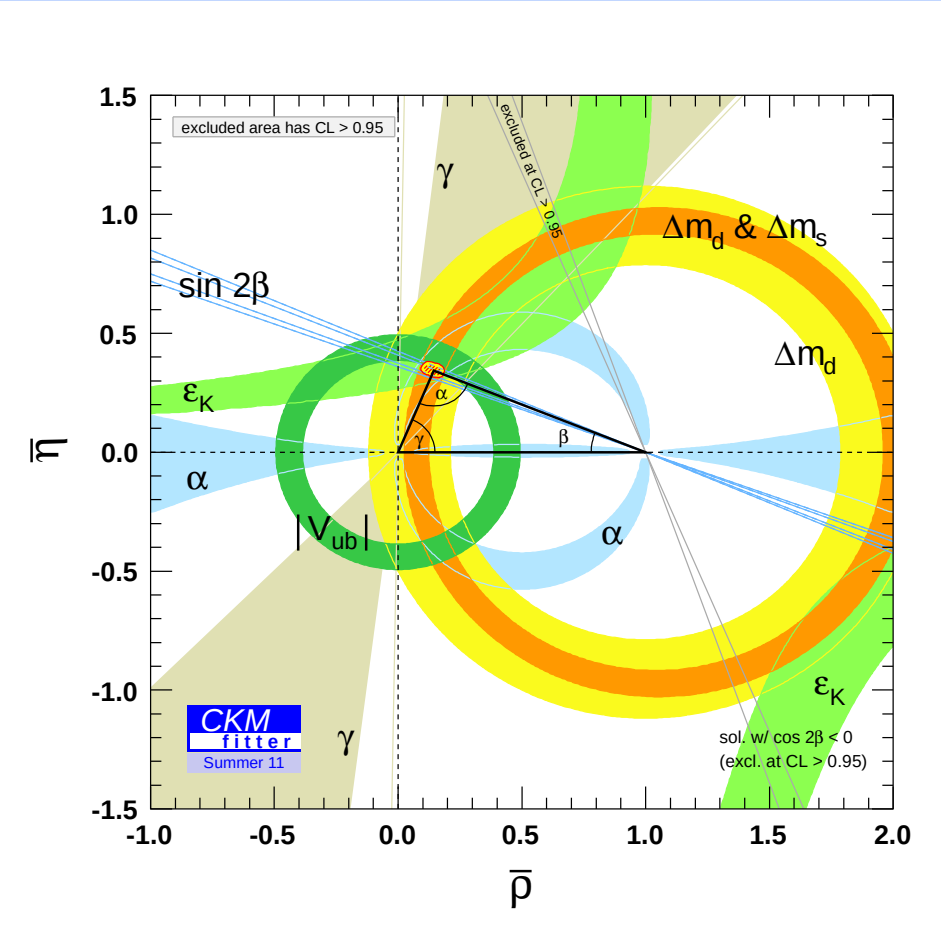
Flavour observables:





CKM Fits

CKM picture works very well ⇒ corrections should be small



Similar results from UTfit and Lunghi et al.

FCNC in the SM4

Analysis: still huge corrections possible!

There are two effects that change the value of M_{12} in the SM4

- t' running in the loop
- The t loop is also changed, because now the CKM elements from the 3x3 fit can not be use anymore!
  This was overseen many times!

Huge cancellations between these two effects are possible
0902.4883,1005.3505: Parameter sets with $\mathcal{O}(300\%)$ effects found
Similar results from Buras et al. '10; Chanowitz '09,'10; Soni et al. '09,'10,'11; Hou et al...

Bounds from FCNC

Observables used as bounds

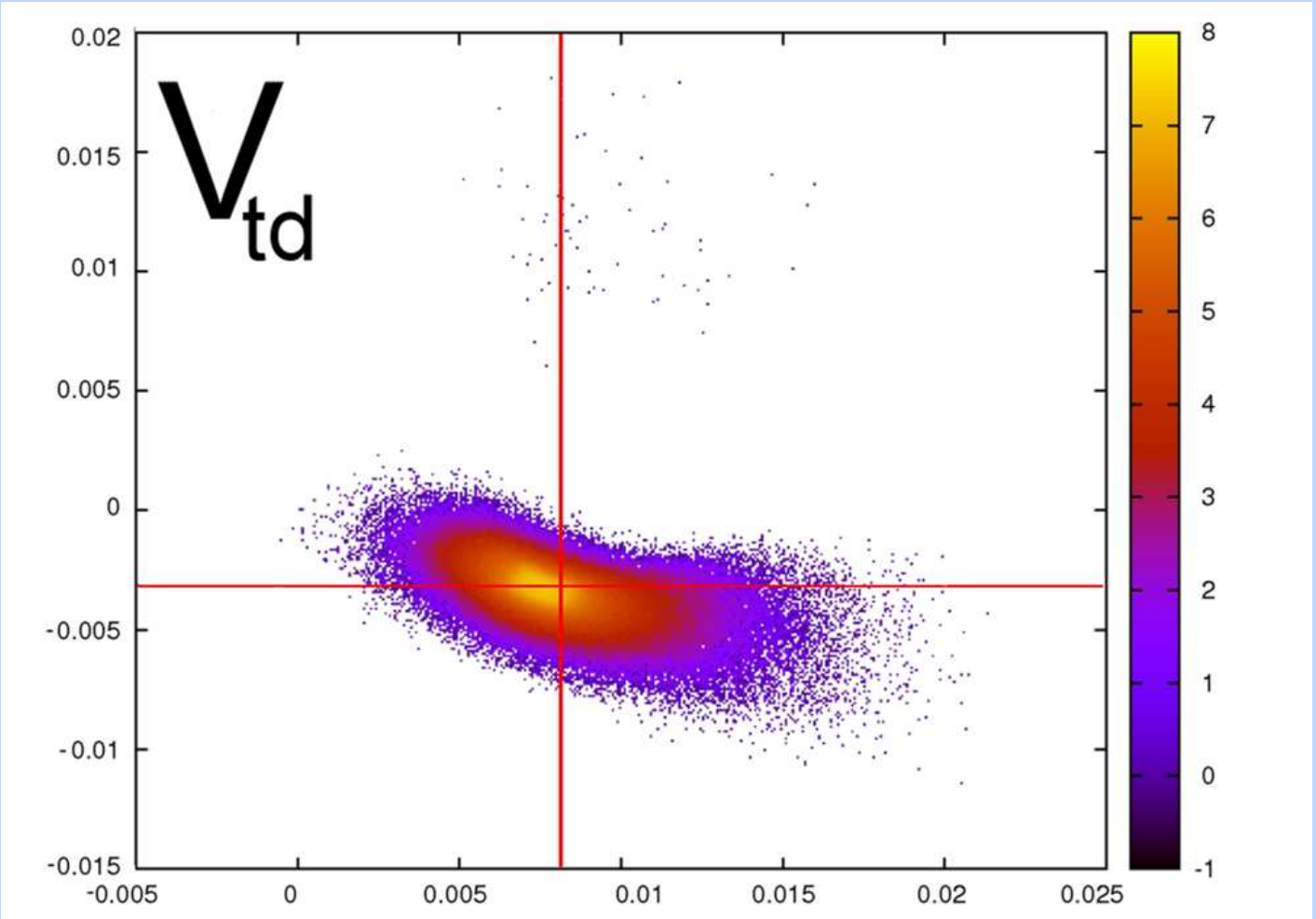
- ΔM_s, ΔM_d, ΔM_D
- ϵ_K: CP violation in K decays
- $b \to s\gamma$, $B_s \to \mu\mu$
- Semileptonic asymmetries, Dimuonasymmetry
- $sin2\beta$ from $B_d \to \psi K_s$
- $sin2\beta_s$ from $B_s \to \psi\phi$

Observables not yet used

- $B \to K^{(*)} ll$
- Rare K decays
- ΔA_{CP}
- ...

Bounds on the CKM element V_{td}

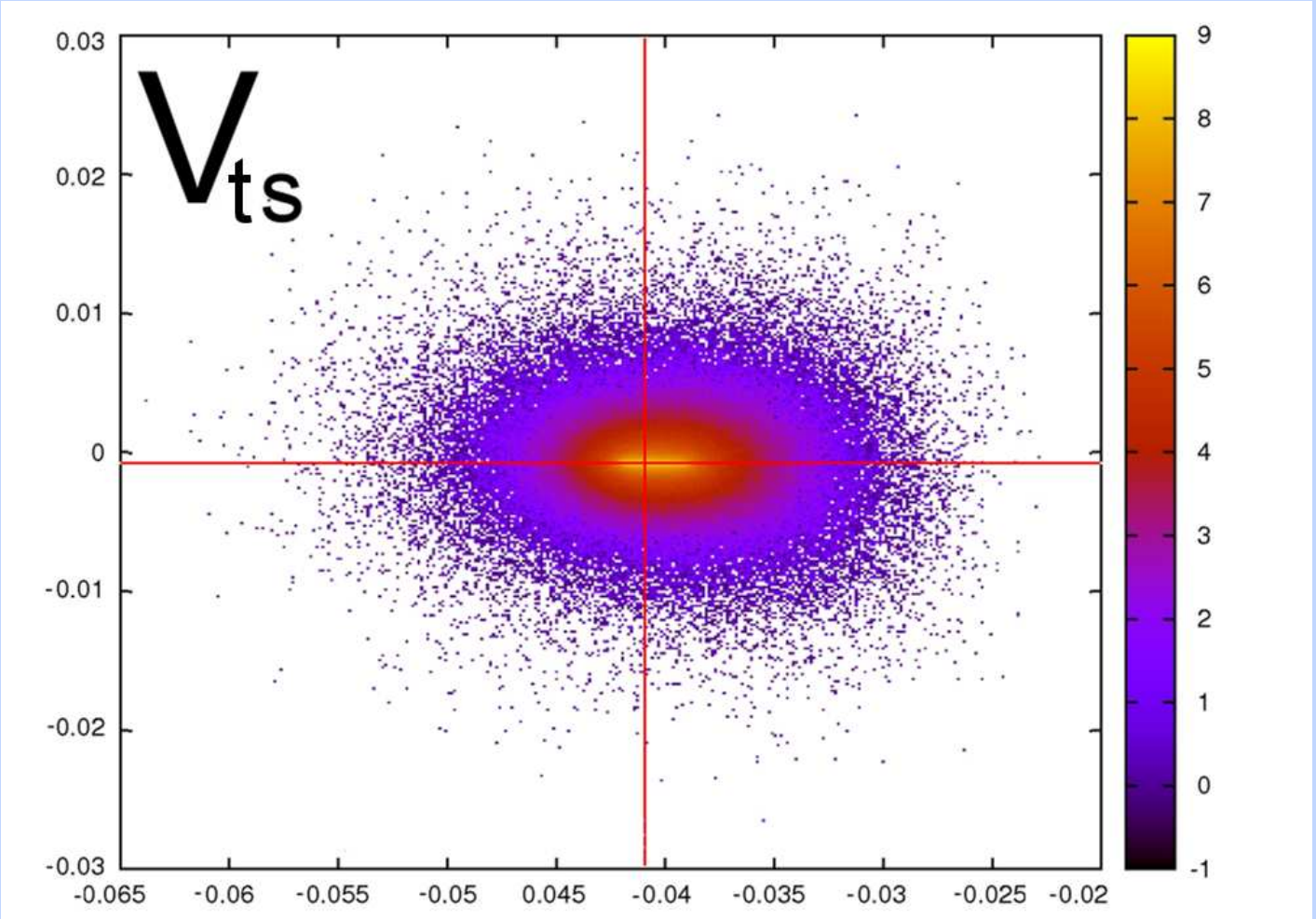
Im V_{td} vs. Re V_{td}



Eberhardt, A.L., Rohrwild: 1005.3505

Bounds on the CKM element V_{ts}

Im V_{ts} vs. Re V_{ts}



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Bounds on the CKM element V_{tb}

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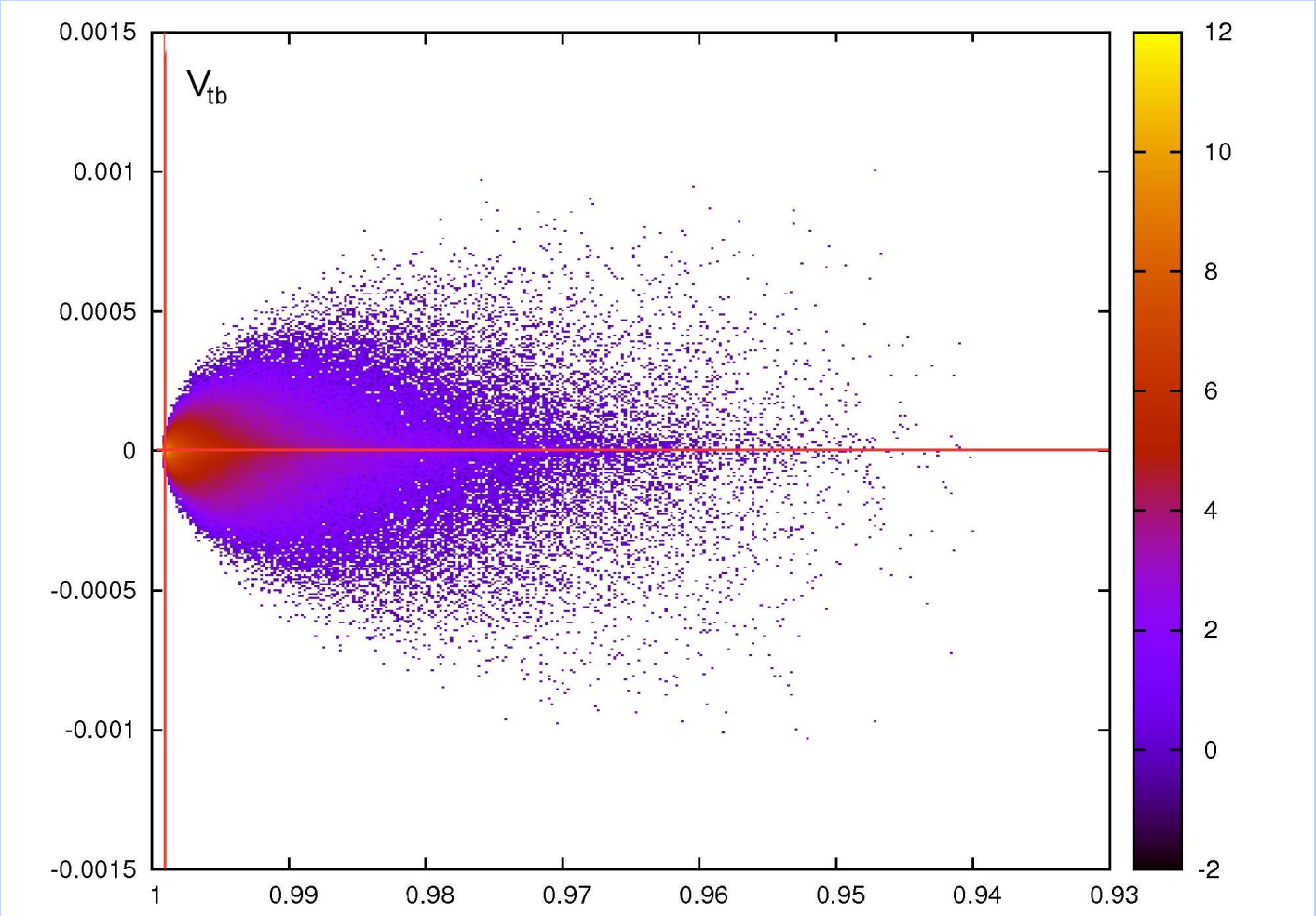

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— Lesson #1 —

Even if CKM looks perfect - huge effects possible

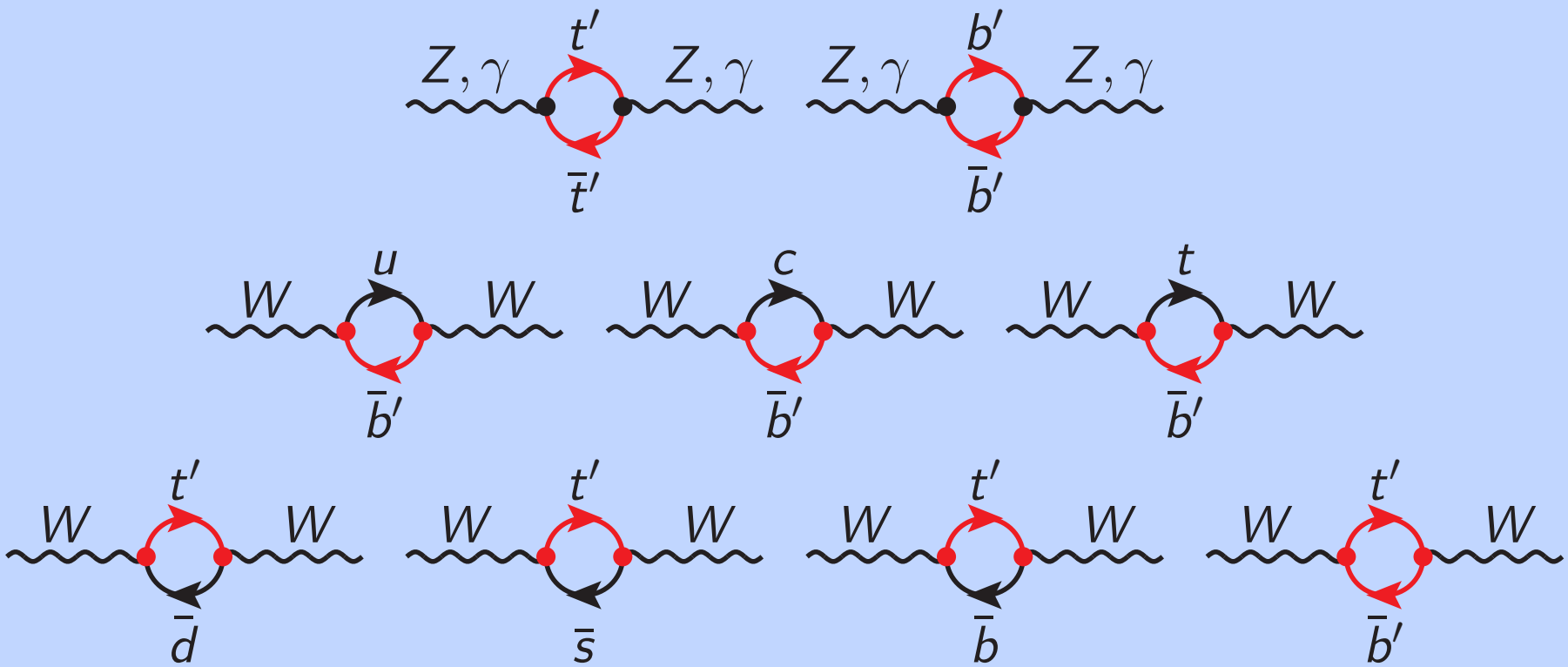
Cancellations

- If V_{CKM3} is not unitary, V_{tx} can differ sizeably from their SM3 values.
- Effects of a new particle (e.g. t') of **up to several hundred per cent** can be compensated by δV_{tx}

Keep this in mind, when discussing e.g. MFV or other models with non-unitary V_{CKM3}

What are S, T and U?

Self-energy contributions by the fourth family



Explicit expressions

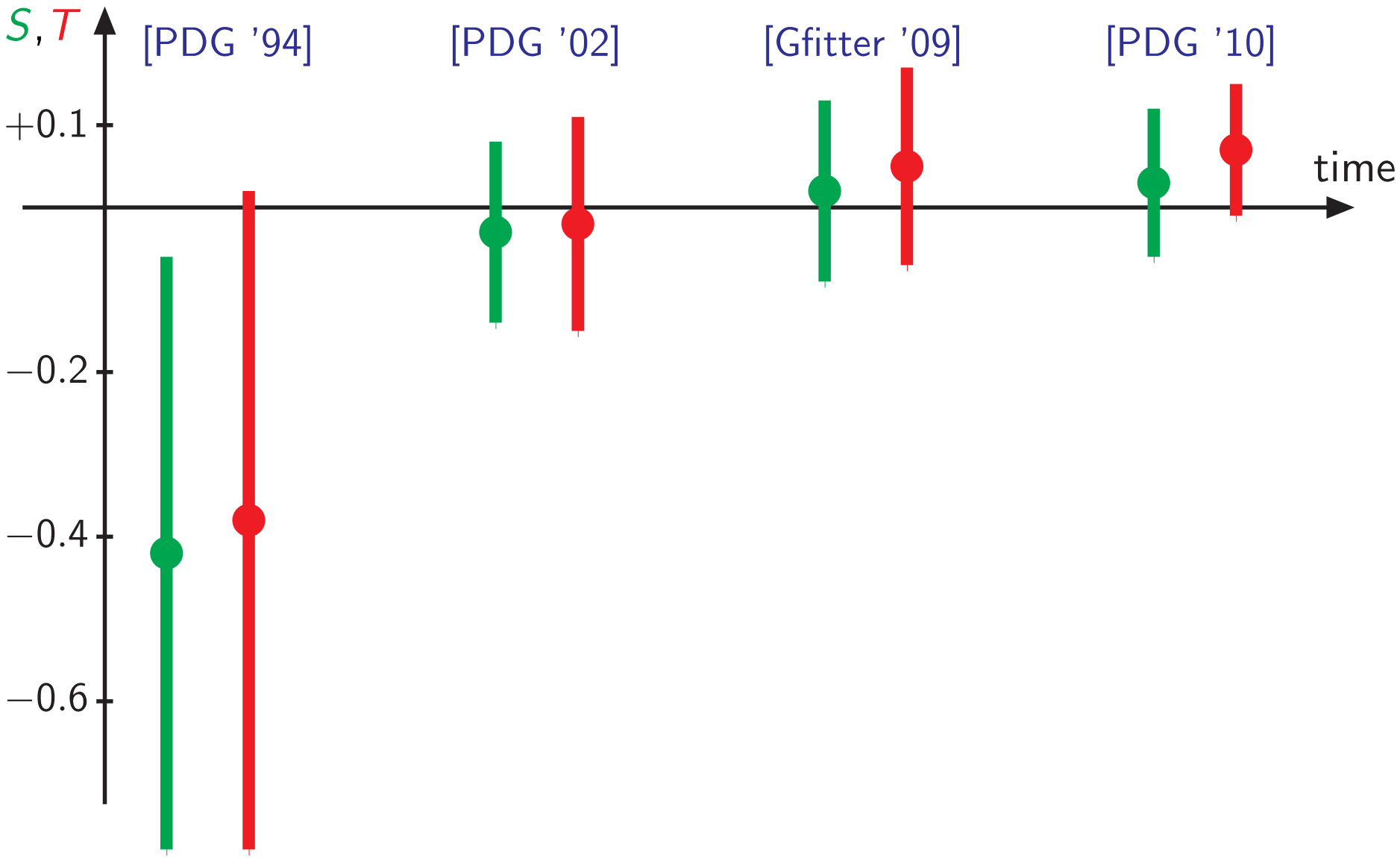
The exact formulae for S and T

$$S_{\text{ferm}} = \frac{N_c}{6\pi}\sum_{(U,D)}\left[1-\frac{2}{3}\ln\left(\frac{m_U}{m_D}\right)\right]+\frac{1}{6\pi}\sum_{(\nu,l)}\left[1+2\ln\left(\frac{m_\nu}{m_l}\right)\right]$$

$$T_{\text{ferm}} = \frac{N_c}{16\pi s^2 c^2 M_Z^2}\left[\sum_{i=U,D} m_i^2 - 4\sum_{U,D}\left|V_{UD}^{(\text{CKM})}\right|^2 \frac{m_U^2 m_D^2}{m_U^2-m_D^2}\ln\left(\frac{m_U}{m_D}\right)\right]$$

$$+\frac{1}{16\pi s^2 c^2 M_Z^2}\left[\sum_{i=\nu,l} m_i^2 - 4\sum_{\nu,l}\left|V_{\nu l}^{(\text{PMNS})}\right|^2 \frac{m_\nu^2 m_l^2}{m_\nu^2-m_l^2}\ln\left(\frac{m_\nu}{m_l}\right)\right] \geq 0$$

The S-T ellipse: Experimental values



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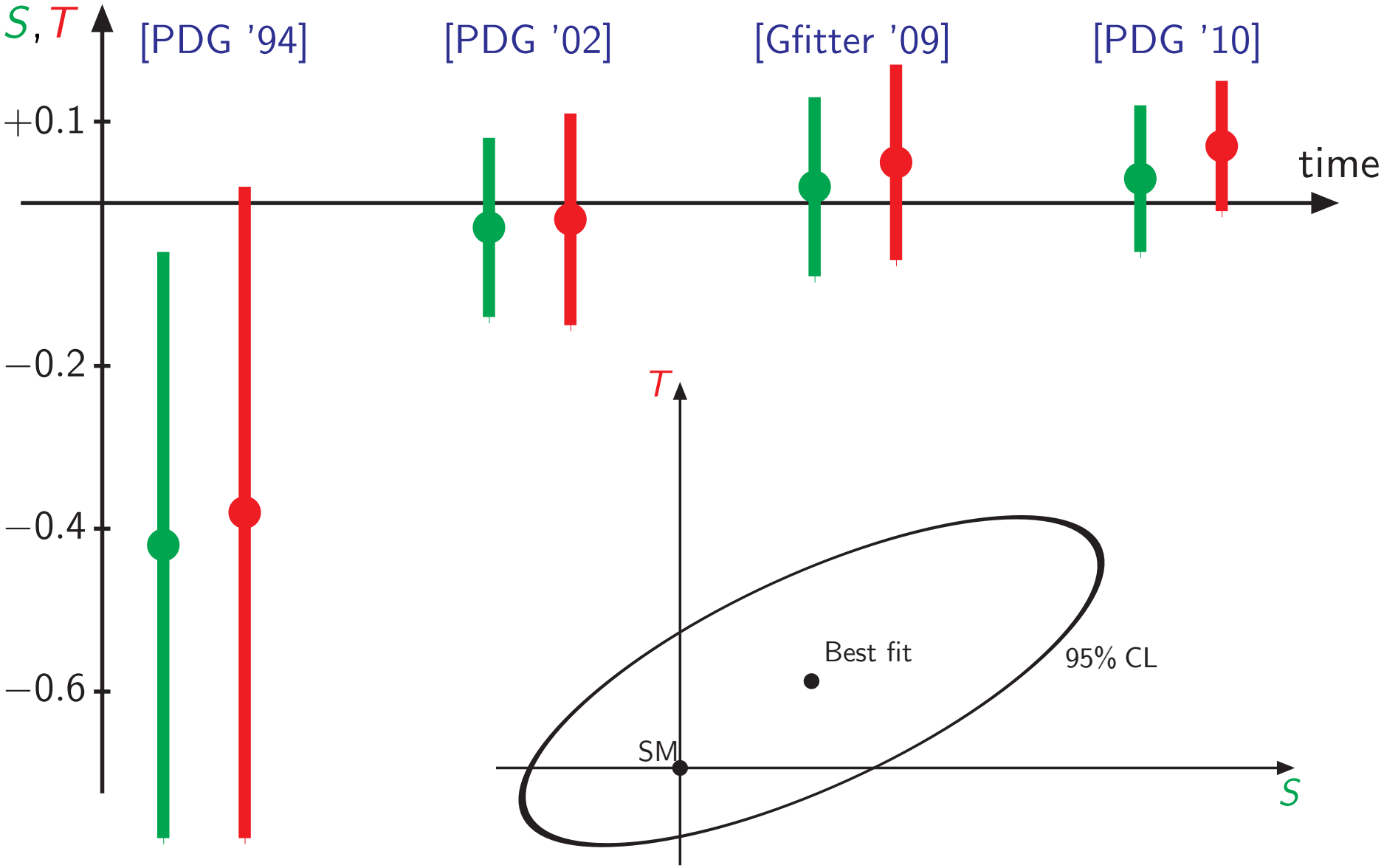
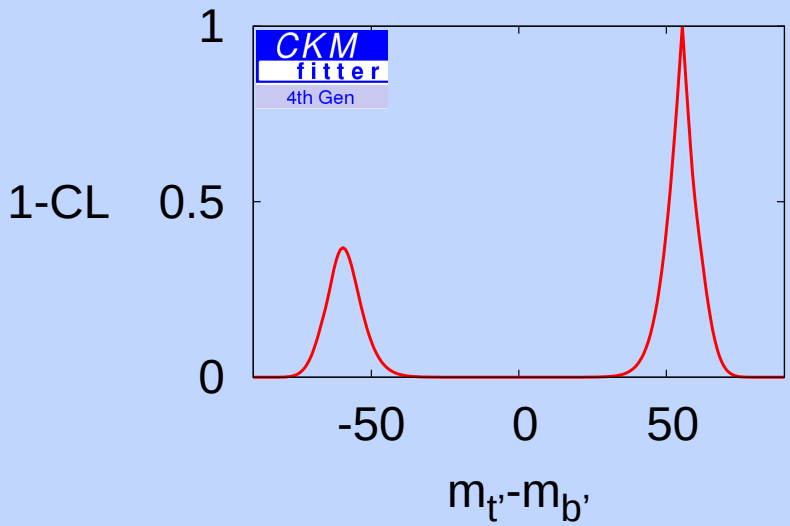


Fermion mass difference

Neglecting the leptons



$(V^{\mathrm{CKM}} = \mathbb{1})$

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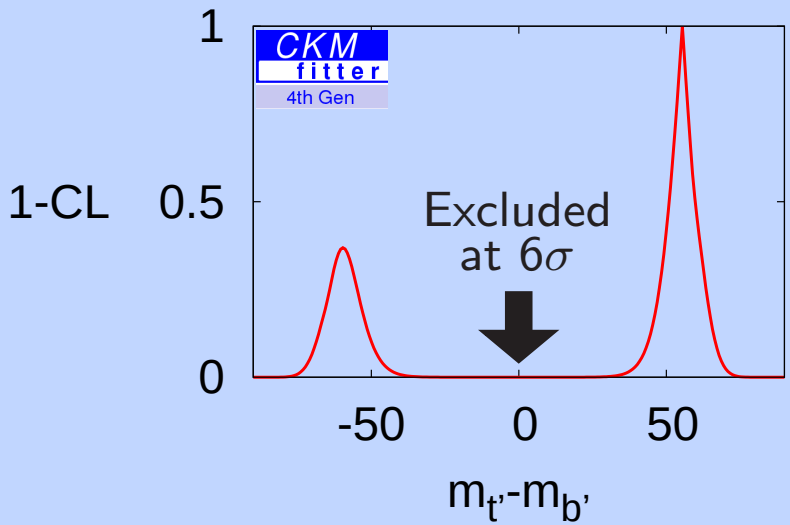

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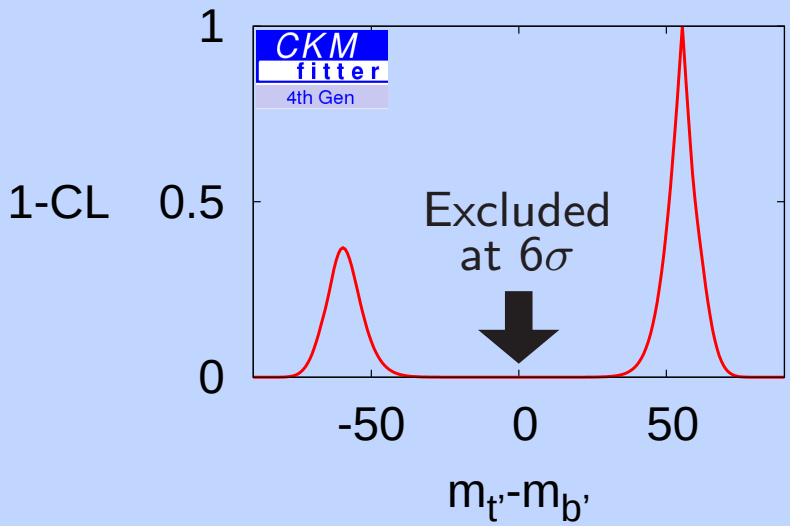

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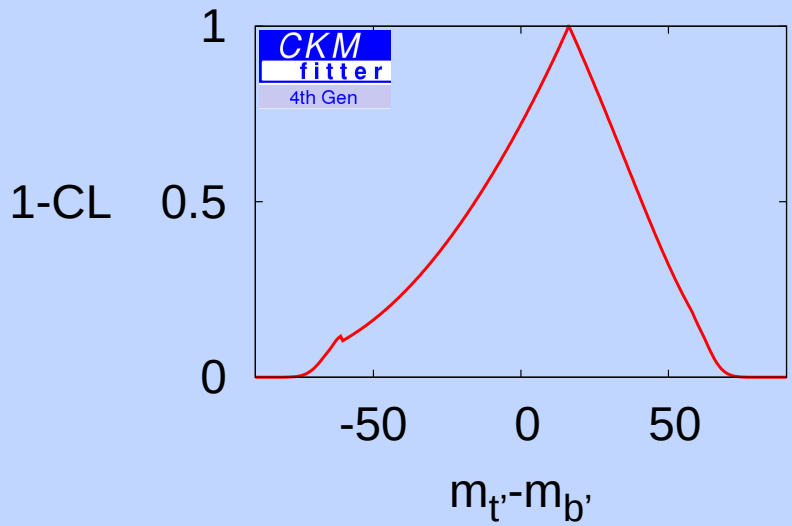

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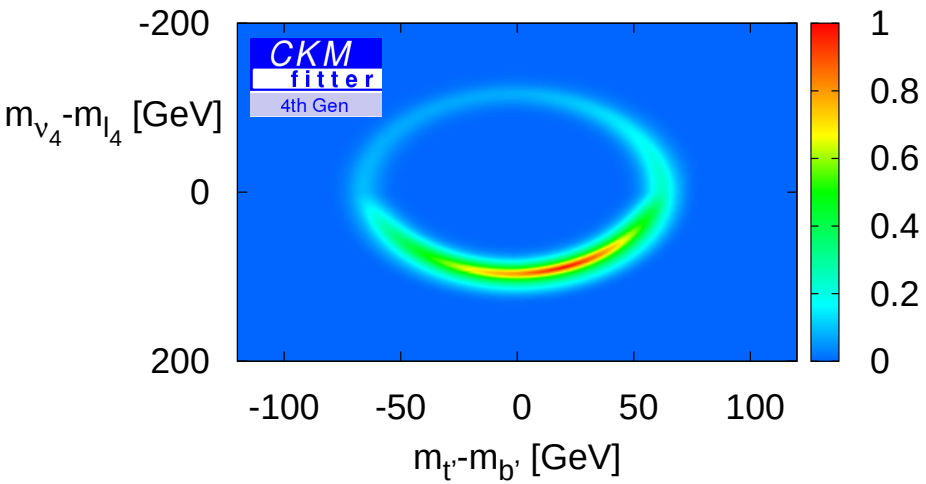
Fermion mass difference

Taking also the leptons into account:



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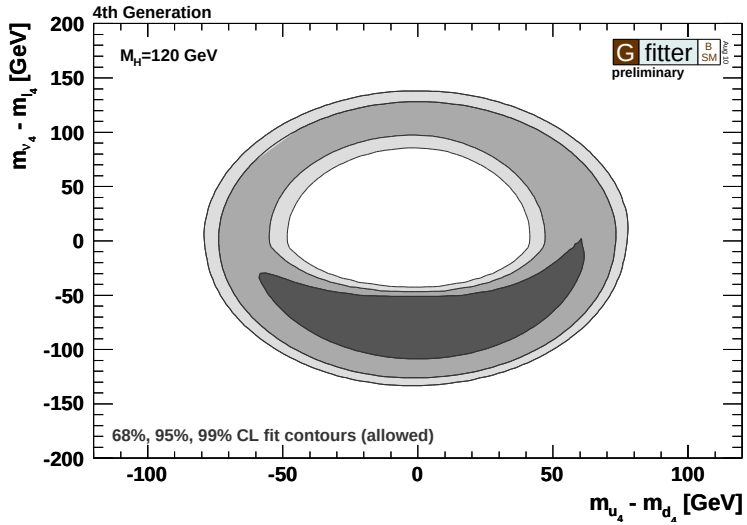

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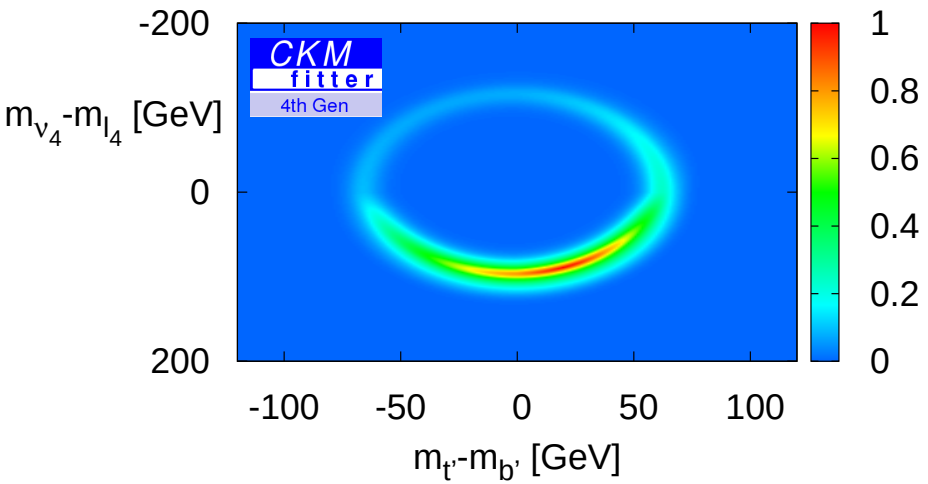

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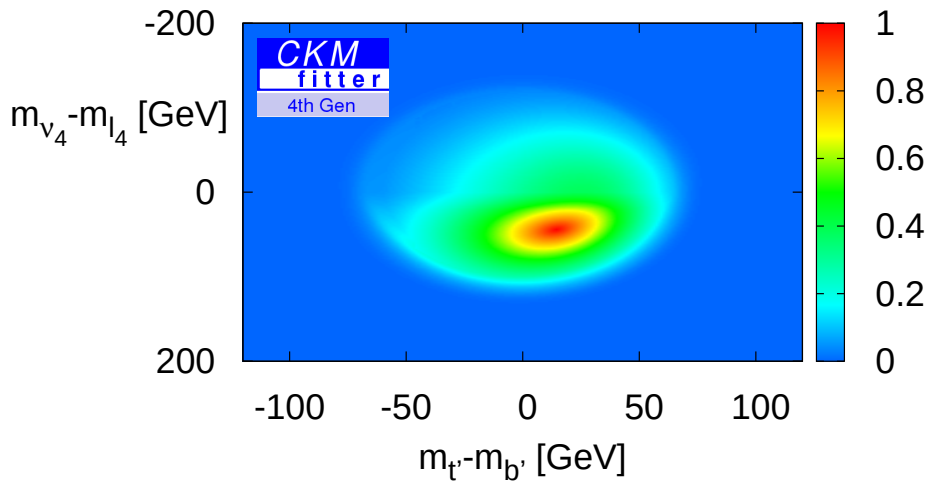

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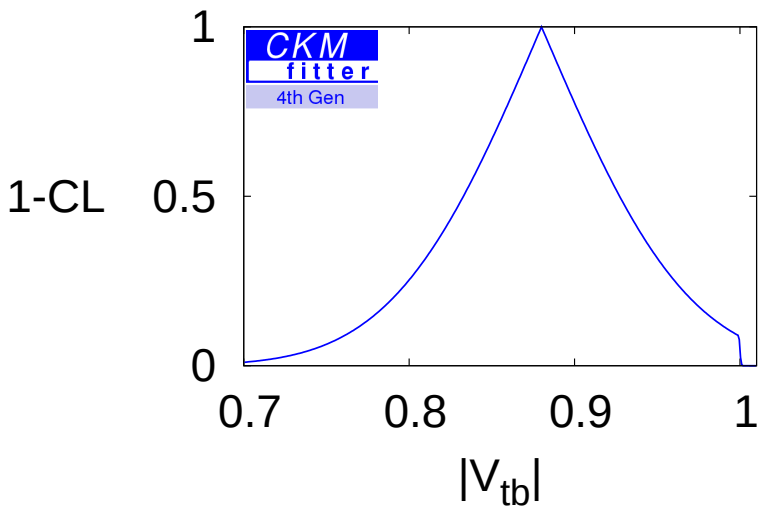
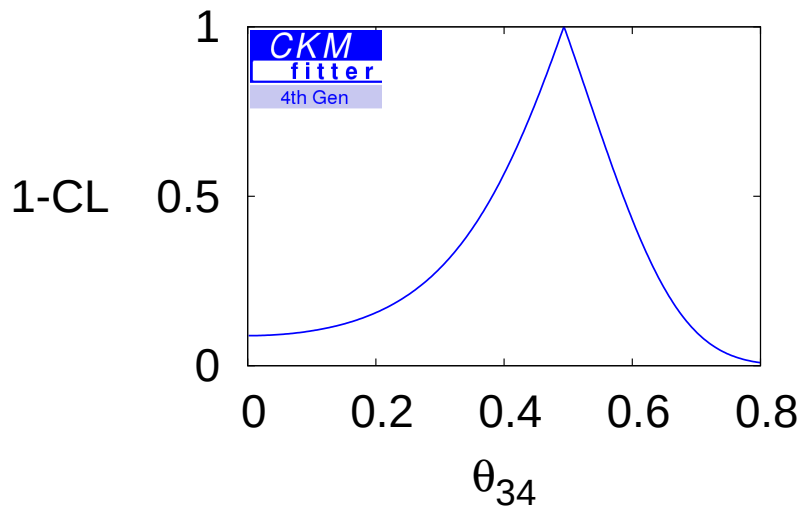
The impact of S and T

Tree-level

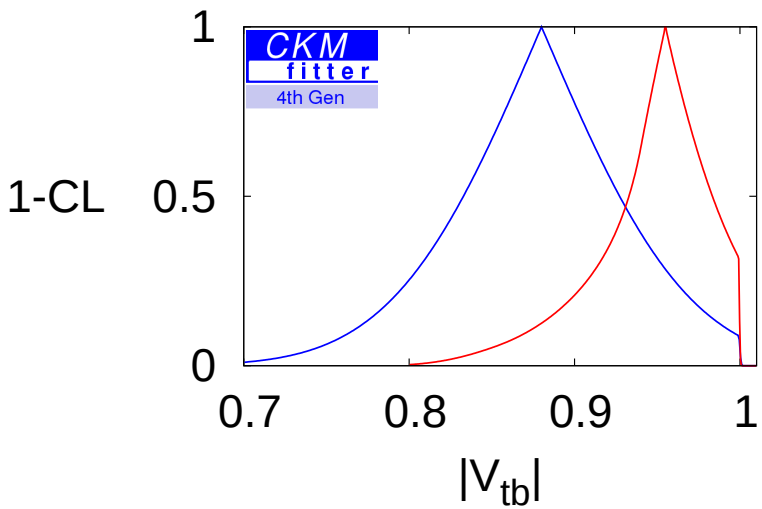


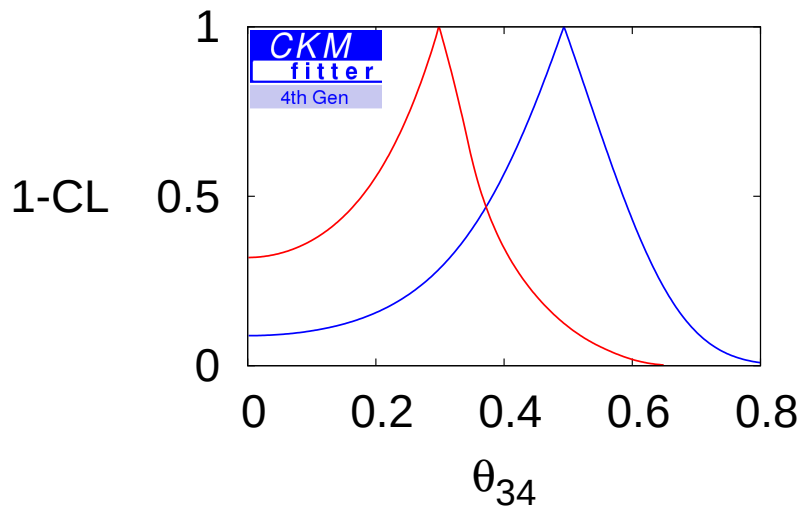


The impact of S and T

Tree-level

$+$ S and T





— Lesson #2 —

CKM4 dependence is essential for e-weak precision observables

- For the first time fully included in 1005.3505

  Eberhardt, A.L., Rohrwild

- Qualitative changes

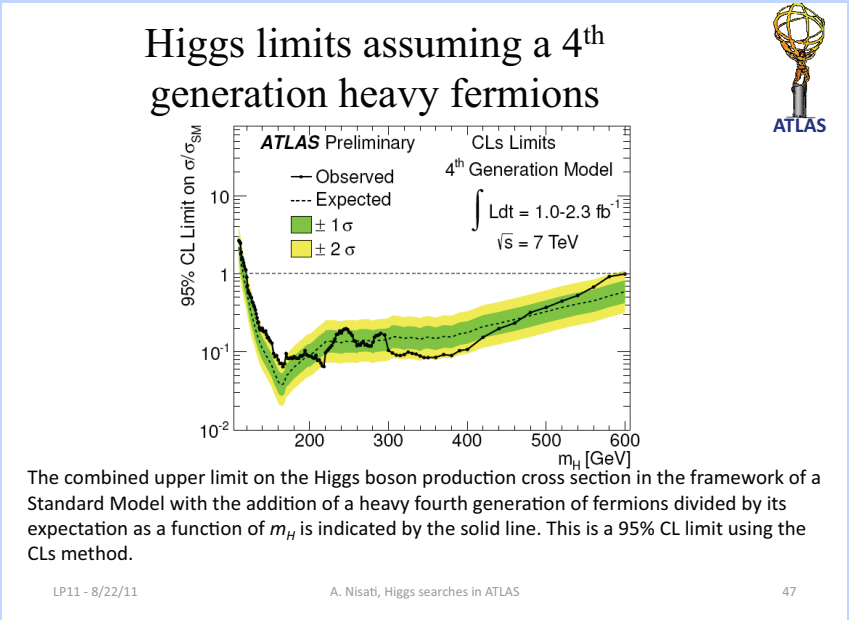
$$|m_{b'} - m_{t'}| < 80 \text{ GeV}$$
$$|m_{l_4} - m_{\nu_4}| < 140 \text{ GeV}$$

- Use full e-weak precision observables instead of S,T,U
  Implemenation of Zfitter in CKMfitter in progress
  - 1105.3434 Gonzales, Rohrwild, Wiebusch
  - Eberhardt, Herbert, Lacker, A.L., Menzel, Nierste, Wiebusch = CKM4Fitter 1204.3872

Higgs production and decay

Common folklore

- $$\sigma^{\mathrm{SM4}}(gg \to h) \approx 9\sigma^{\mathrm{SM3}}(gg \to h)$$
- NLO e-weak corrections to production and decay are dominated by light fermions, i.e. contribution of fourth family is negligible
- A large range of higgs mass values in the SM4 is already excluded by the non-observation of a higgs boson at LHC



Higgs production and decay

The facts

- The possibility $H \to \nu_4 \nu_4$ was not considered - Why?
- NLO e-weak corr. were reinvestigated and turned out to be huge

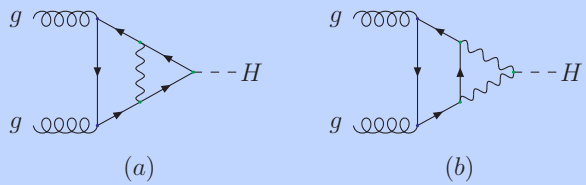


Figure 1: Examples of two-loop diagrams contributing to $gg \to H$.

G. Passarino, C. Sturm, S. Uccirati 1108.2025;

A. Denner, S. Dittmaier, A. Muck, G. Passarino, M. Spira, C. Sturm, S. Uccirati, M.M. Weber 1111.6395

Leading behaviour known since a long time - why negelcted?

Djouadi, Gambino 1994; Djouadi, Gambino, Kniehl 1997

This is currently implemented in the experimental search:

LHC Higgs Cross Section Working Group

Conclusions will change dramatically!

$H \to \nu_4 \nu_4$

- PDG bounds $m_{\nu_4} > 90$ GeV holds only for a unstable neutrino

	pure mass term	mixed mass term
unstable	80...90	62.1
stable ($\theta_{i4} < 3 \cdot 10^{-6}$)	45	33.5

Bulanov et al. 0301268; Carpenter, Rajamaran 1005.0628; Carpenter 1010.5502

- $H \to \nu_4 \nu_4$ will be one of the dominant channels!
  Khoze 0105069;
  Arik et al. 0203257;
  Belotsky et al. 0210153;
  ...

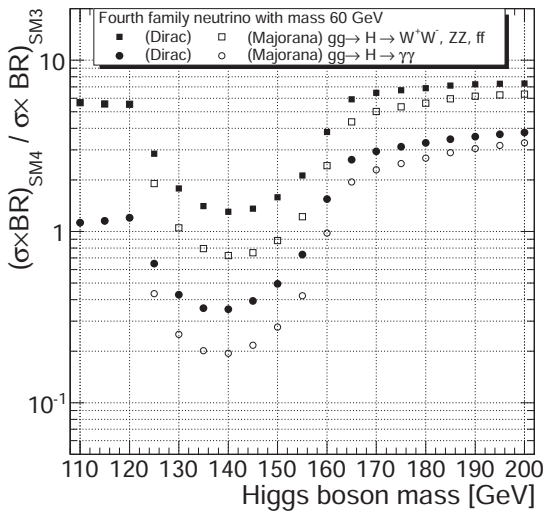


Figure 4: Same as Fig. 1 but for $m_{\nu_4} = 60$ GeV.

Cetin et al. 1108.4071; also Carpenter 1110.4895; Rozanov, Vysotsky 1012.1483

- Might be tested via heavy lepton searches and electro-weak precision observables

NLO e-weak corrections I

- Were not included in the LP2011 analyses
- Turned out to be huge: up to -60%!
- Are currently implemented in experimental analyses

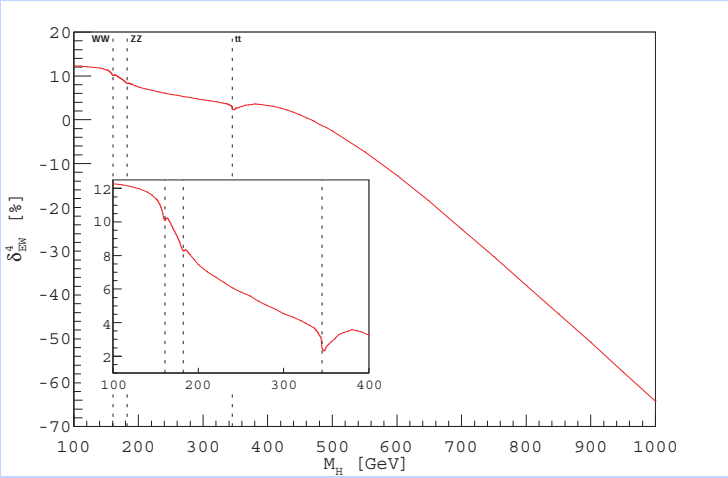


Figure 1: Relative corrections in SM4 ($t'-b'$ and $l'-\nu_{l'}$ doublets) due to two-loop EW corrections to $gg \to H$. The masses of the 4th-generation fermions are chosen according to Eq. (2.1). In the inset a blow-up of the small-M_H region is shown.

Table 7: Higgs branching fractions for the $\gamma\gamma$ decay channel without and with NLO EW corrections.

M_H [GeV]	w/o NLO EW	w/ NLO EW
100	$1.31 \cdot 10^{-4}$	$4.65 \cdot 10^{-5}$
110	$1.72 \cdot 10^{-4}$	$4.40 \cdot 10^{-5}$
120	$2.26 \cdot 10^{-4}$	$3.77 \cdot 10^{-5}$
130	$2.95 \cdot 10^{-4}$	$2.71 \cdot 10^{-5}$
140	$3.81 \cdot 10^{-4}$	$1.30 \cdot 10^{-5}$
150	$4.74 \cdot 10^{-4}$	$1.42 \cdot 10^{-6}$

Denner et al. 1111.6395

NLO e-weak corrections II

But!: Currently NLO e-weak corrections are only available for

$$\begin{aligned} m_{l4} = m_{\nu 4} = m_{b'} &= 600 \text{ GeV} \\ m_{t'} &= m_{b'} + 50 \text{ GeV}\,(1 - 0.2 ln M_H/115\ GeV) \\ V_{x4} &= 0 \end{aligned}$$

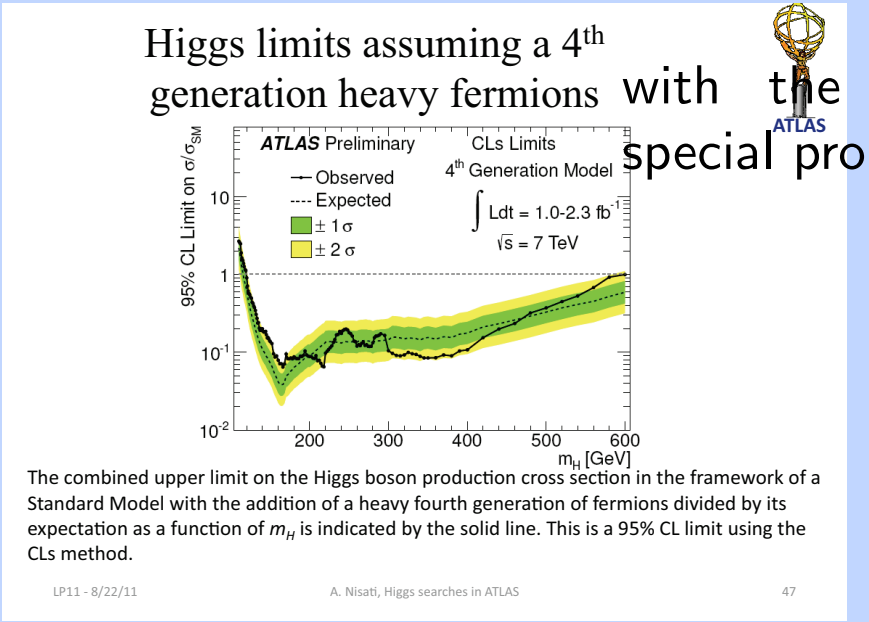
PROBLEMS:

- Cover the whole SM4 parameter space
  - also $M_H > 2m_{\nu_4}$
  - numerical integrations may take some time
  - Include CKM mixing in the corrections? This was crucial for S,T,U
- Corrections are huge $\rightarrow$ convergence is questionable

1111.6395v2 by A.Denner et al.

What does the Higgs search of LHC tell at LP2011?

Higgs limits assuming a 4th generation heavy fermions with the following special properties:



The combined upper limit on the Higgs boson production cross section in the framework of a Standard Model with the addition of a heavy fourth generation of fermions divided by its expectation as a function of m_H is indicated by the solid line. This is a 95% CL limit using the CLs method.

LP11 - 8/22/11 A. Nisati, Higgs searches in ATLAS 47

$$m_{l4} = m_{\nu 4} = m_{b'} = 600 \text{ GeV}$$

$$m_{t'} = m_{b'} + 50 \text{ GeV}\,(1 - 0.2 ln M_H/115\ GeV)$$

$$V_{x4} = 0$$

- NLO-eweak is negligible

Status: May 2012

Theory status:

- HDECAY includes now NLO-eweak corrections for general SM4 parameters - still no CKM4 mixing
- $H \to \nu_4 \nu_4$ taken into account
- S, T, U replaced by the explicit observables (Zfitter)

Michael Spira; A.L., Djouadi 1204.1252; Eberhardt et al. 1204.3872

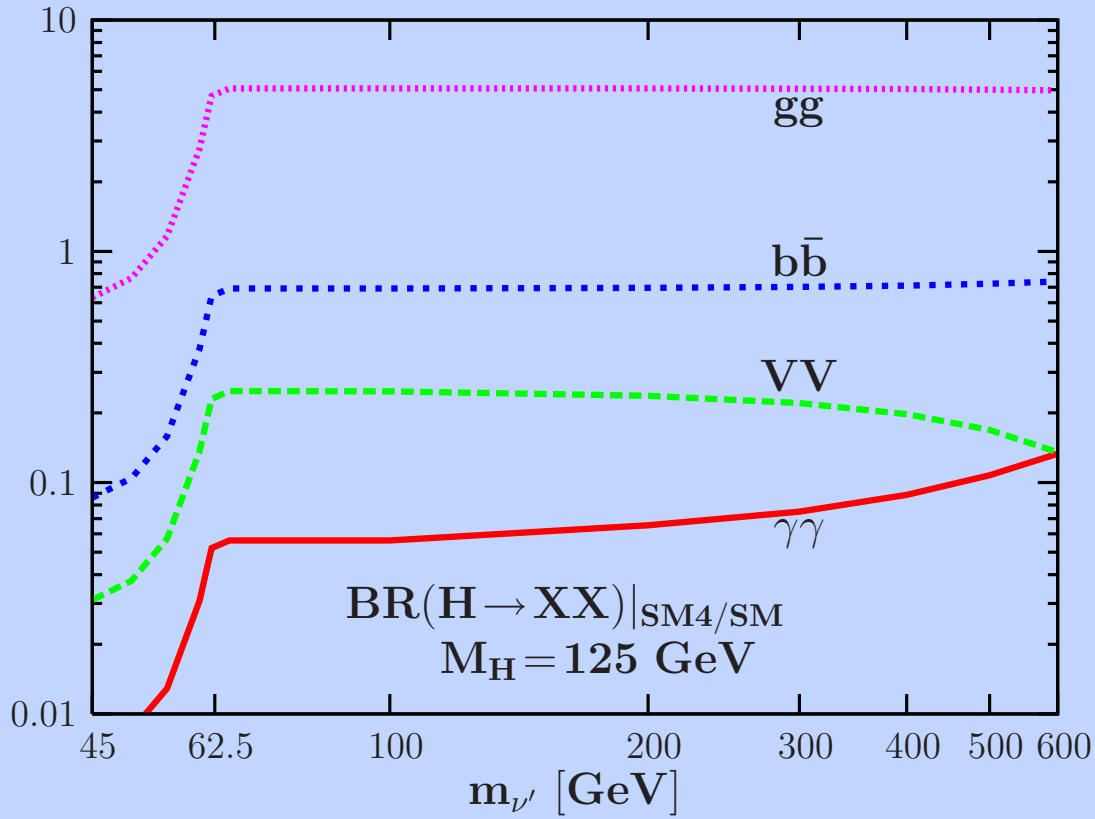
Experimental News:

- TeVatron sees hints for Higgs in associated Vector boson production and subsequent Higgs decay in $b\bar{b}$

Moriond 2012

Status: May 2012

Higgs Branching Ratios before full NLO-eweak for $H \to \gamma\gamma$



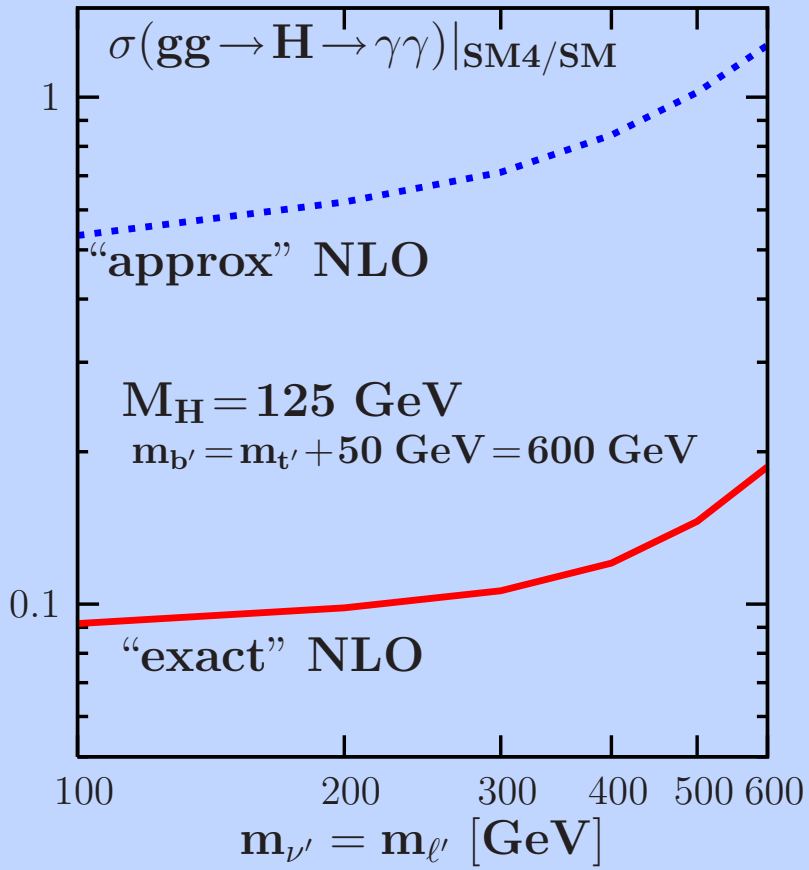
A.L., Djouadi 1204.1252

SM4 might be consistent with SM3, if

- Gluon fusion enhanced by a factor of 9
- Associated vector boson production not affected **BUT 1 & 2**

Status: May 2012

BUT 1: Full NLO-eweak for $H \to \gamma\gamma \Rightarrow$ SM4 is dead, if signal stays



A.L., Djouadi 1204.1252

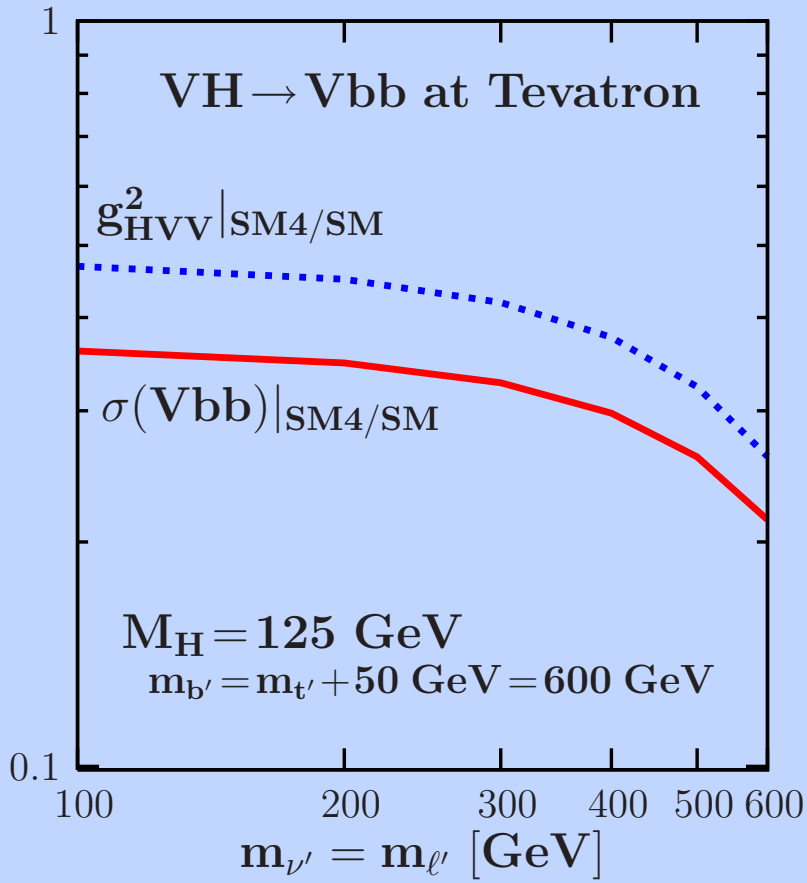
SM4 is in $H \to \gamma\gamma$ a factor of 10 **below** the SM3

Anti-BUT 1: HUGE NLO-eweak corrections!!

maybe not relieable and perturbativity is violated ???

Status: May 2012

BUT 2: The final Killer: The Tevatron signal, if it stays



A.L., Djouadi 1204.1252

Associated vector boson production is also reduced

$p + \bar{p} \to Hb\bar{b}$ is in the SM4 only about 20% – 35% of the SM3

thus invisible at Tevatron!

Status: May 2012

What did we learn so far?

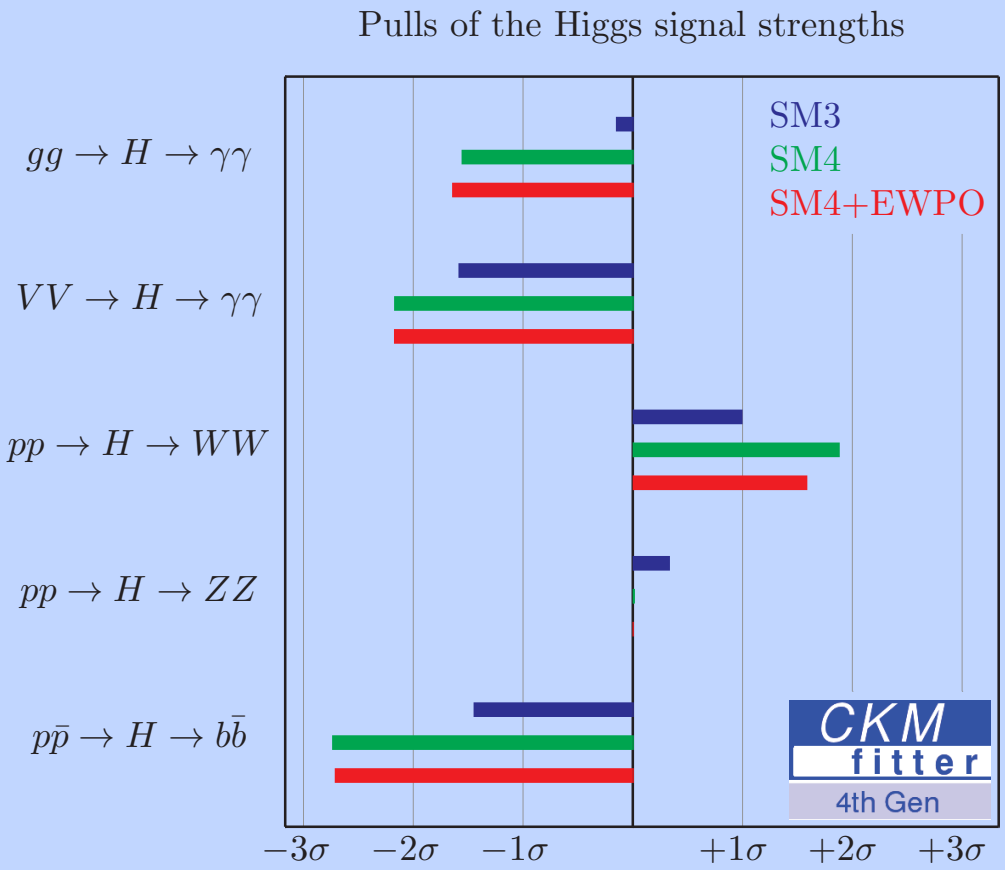
In ancient times it was believed that the SM4 leads to a significant enhancement of all Higgs decays, this could only be **compensated by the invisible decay** $H \to \nu_4 \nu_4$, which was neglected in many analyses.

News since about March 2012: Under-production might kill the SM4

- The numbers of $\gamma\gamma$ from a Higgs (for $m_H = 125$ GeV) is in the SM4 about a factor of 10 **below** the SM3
  This channel should be currently not detectable
  (Is perturbativity still valid?)
- The number of $b\bar{b}$ from associated Higgs-vector boson production (for $m_H = 125$ GeV) is in the SM4 only about $20\% - 35\%$ of the SM3
  This channel should be currently not detectable
- Higgs should actually be called **AEBHGHK**

Status: May 2012

Take the currently low significance of the Higgs signals into account

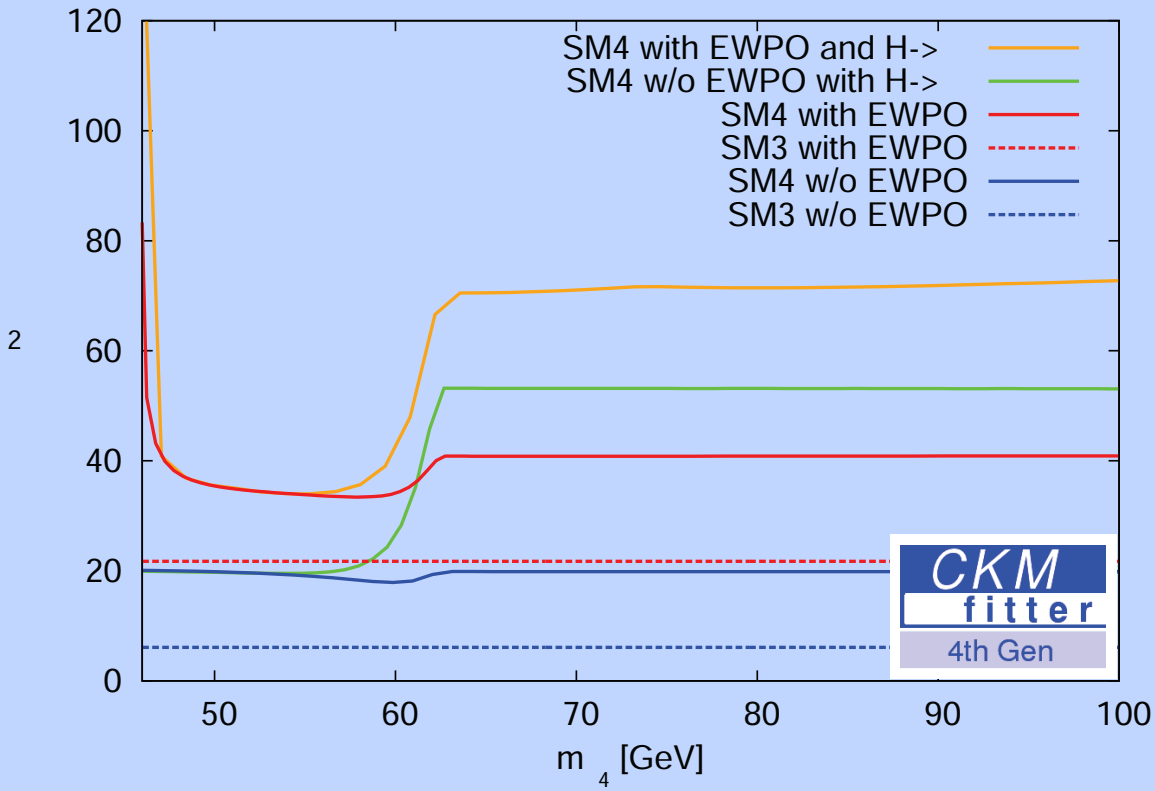


SM4 is disfavoured (SM3 also) but not yet ruled out

Eberhardt et al. 1204.3872

Status: May 2012

Take the currently low significance of the Higgs signals into account



SM4 is disfavoured (SM3 also) but not yet ruled out Eberhardt et al. 1204.3872

Conclusions

Interestings results from investigations of SM4

- Huge invisible effects in the flavor sector not excluded!
  Compare this with MFV-paradigm
- *Totgesagte leben länger* — It is difficult to rule out a model
  - CKM4 dependence turned out to be crucial
  - Higgs killing arguments turned around completely
    Over-production $\Rightarrow$ Under-production
- Current status of SM4:
  - $M_H \neq 125$ GeV
    $\Rightarrow$ SM4 viable
  - $M_H = 125$ GeV
    $\Rightarrow$ SM4 is disfavoured (SM3 also) for light ν_4, else stronger disfavoured
  - $M_H = 125$ GeV and central values of Higgs signal will stay in 2012
    $\Rightarrow$ ruled out

Conclusions

Next Steps

- Include flavor observables - in progress CKM4fitter,...
  There are some problem, which might be cured by the SM4
- LHC will tell this year, if $M_H = 125$ GeV is real

If LHC will not clearly rule out the SM4:

- Include flavor observables - in progress CKM4fitter,...
- Include lepton sector and CKM4 dependence of direct mass limits CKM4fitter,...
- all e-weak corrections at 2-loop order + full CKM4 dependence?

Greek Mythology II

- Herakles did not manage to kill Hydra, because whenever he cut off one head, two new ones grow...
- Iolaos the nephew of Herakles also joined this adventure
  Whenever Herakles cut off one head and the new ones started to grow, Iolaos burned them
- Hydra was killed - Herakles became famous for it - but he would not have managed without Iolaos help

Perturbative SM4 is not yet excluded by experimental data

How the story really will be :-)

ATLAS;
CMS Erler,
Langacker
Peskin,...

Cetin et al.; CKM4fitter,

Beham, (Hans) Sebald (1500-1550)

One head will always survive:

A non-perturbative fourth family

Work by

- K. Jansen et al. - Lattice
- P.Q. Hung et al.
- G. Hou et al.