Extended CKM fits

SM4 Workshop in Durham, 14 September 2011

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J. Rohrwild & M. Wiebusch, using CKMfitter

* KIT – Karlsruhe Institute of Technology (TTP)

Outline

- SM4 parameters
- "Direct" constraints
- Electroweak constraints
- Flavour constraints
- Outlook

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SM4 parameters

The "old" parameters

Quarks:	$m_u, m_d, m_s, m_c, m_b, m_t,$	$\theta_{12}, \theta_{13}, \theta_{23},$	φ_{13}
Leptons:	$m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau}, m_e, m_\mu, m_\tau,$	$\theta^\ell_{12}, \theta^\ell_{13}, \theta^\ell_{23},$	φ^ℓ_{13}
Higgs:	m_H		

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The new parameters

Quarks:	$m_{b'}, m_{t'},$	$\theta_{14}, \theta_{24}, \theta_{34},$	$\varphi_{14}, \varphi_{24}$
Leptons:	$m_{\nu_4}, m_{\ell_4},$	$\theta^\ell_{14}, \theta^\ell_{24}, \theta^\ell_{34},$	$\varphi^\ell_{14}, \varphi^\ell_{24}$

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14 free parameters

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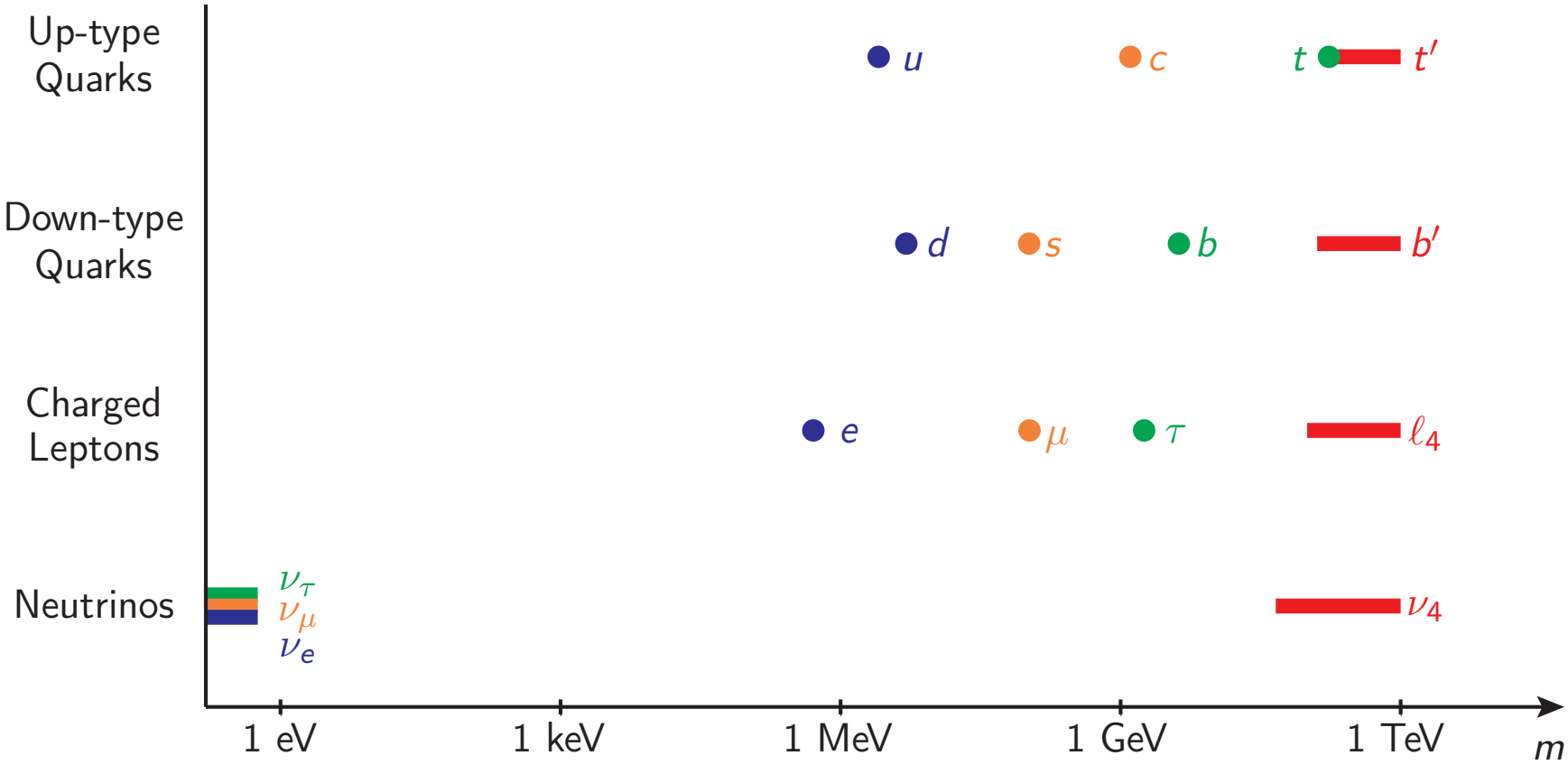
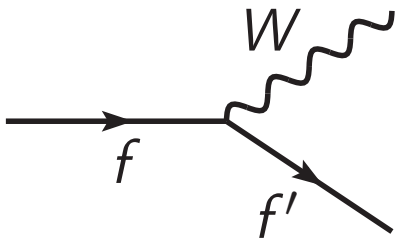
Direct mass limits



Tree level constraints



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

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Tree level constraints

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

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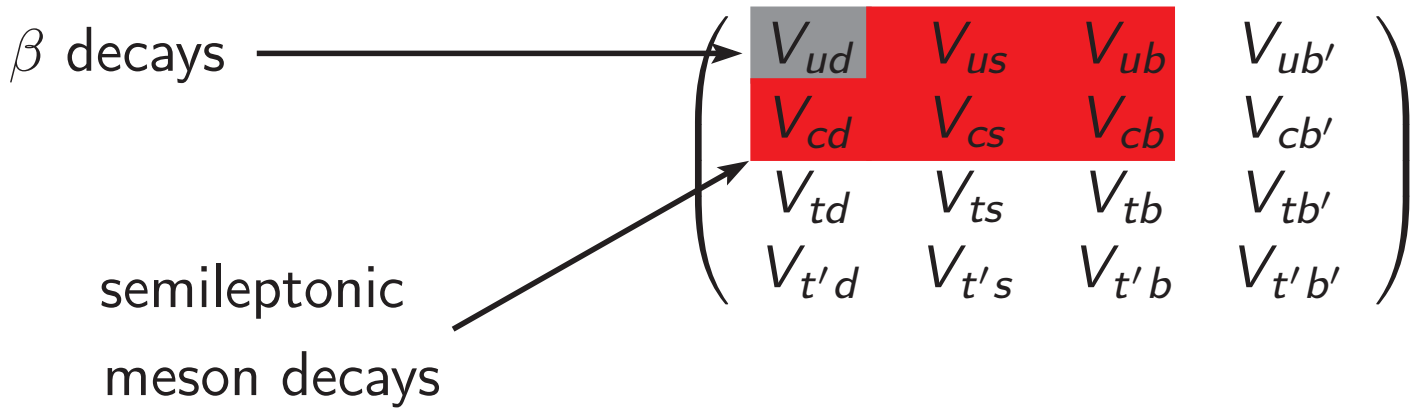
Tree level constraints



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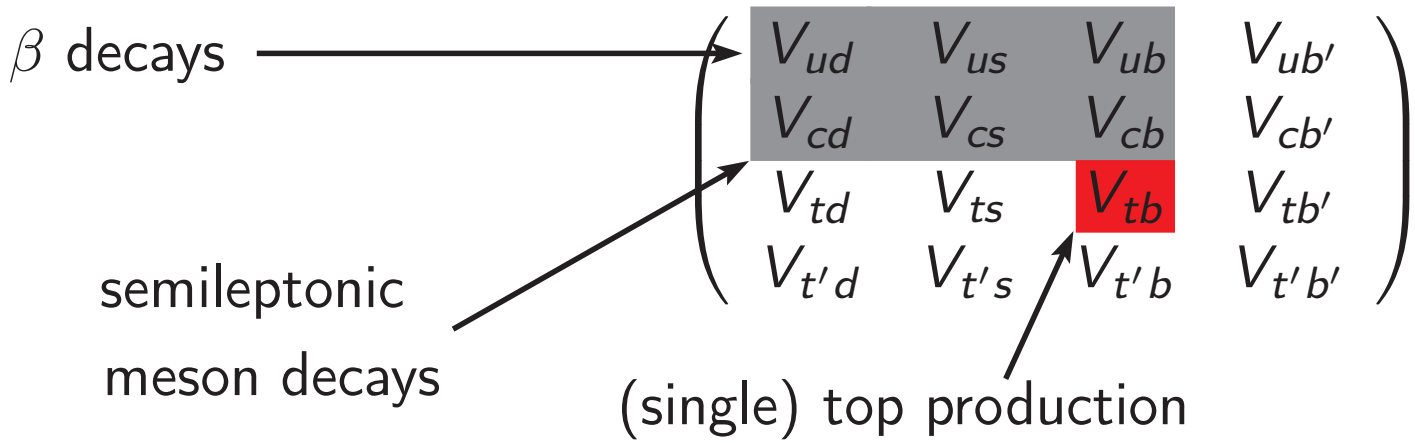
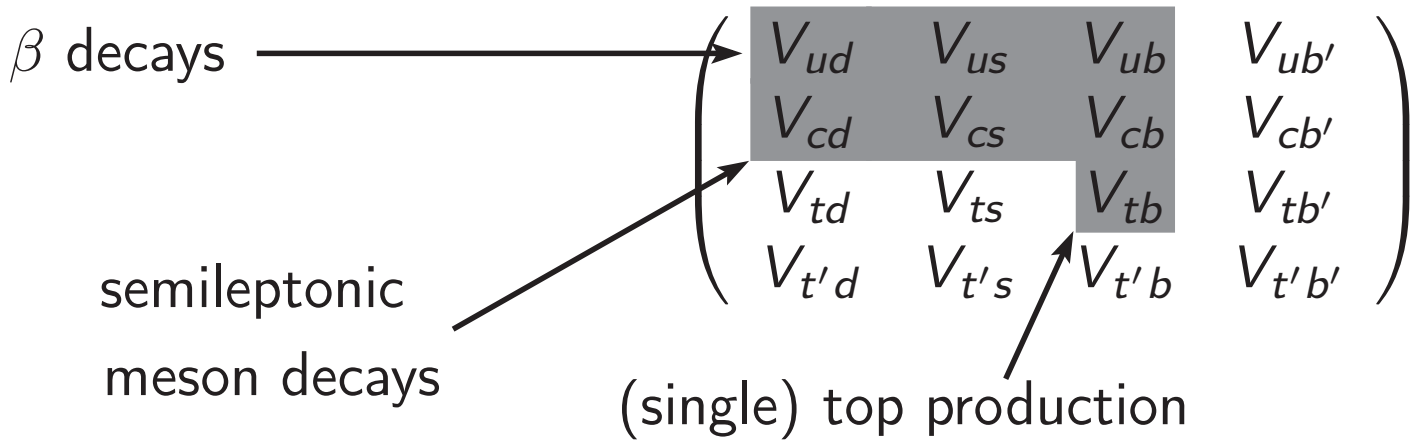


Tree level constraints



$\gamma \equiv \arg \dfrac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$ from CKMfitter fits

$W \to \ell\nu$ decays

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Electroweak constraints

Electroweak precision observables (LEP+TeVatron):

W and Z masses, total decay widths, partial widths, forward-backward asymmetries etc.

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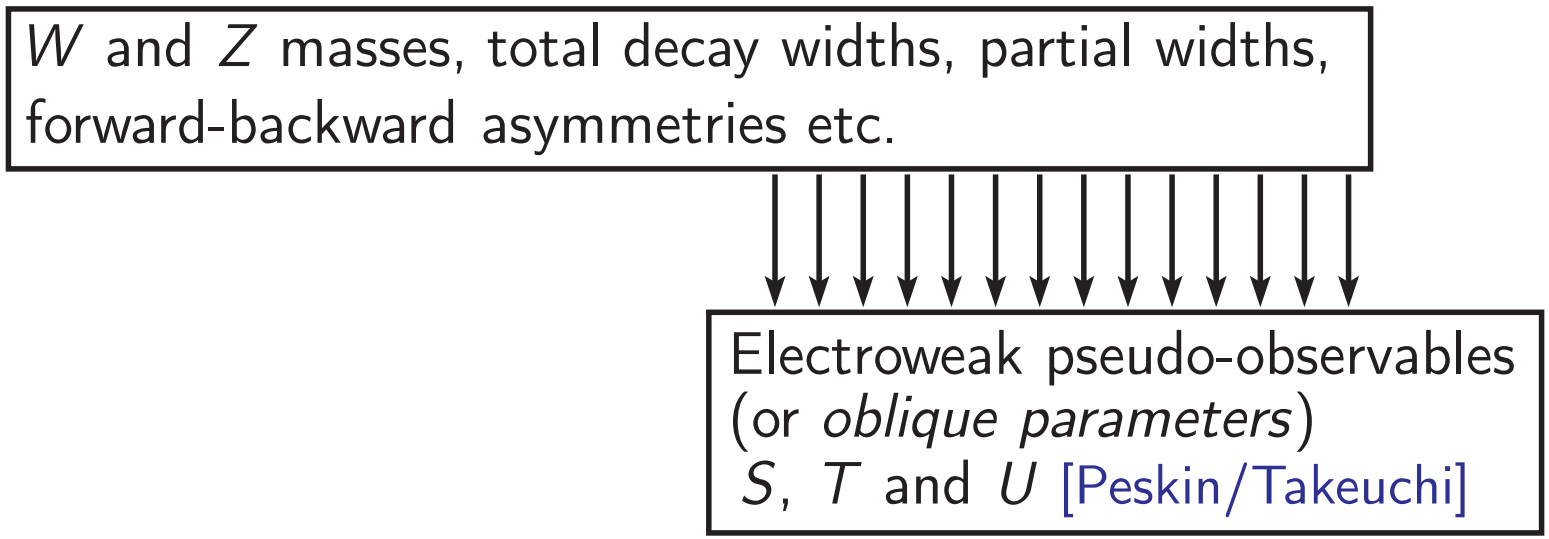
Electroweak constraints

Electroweak precision observables (LEP+TeVatron):



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Electroweak constraints

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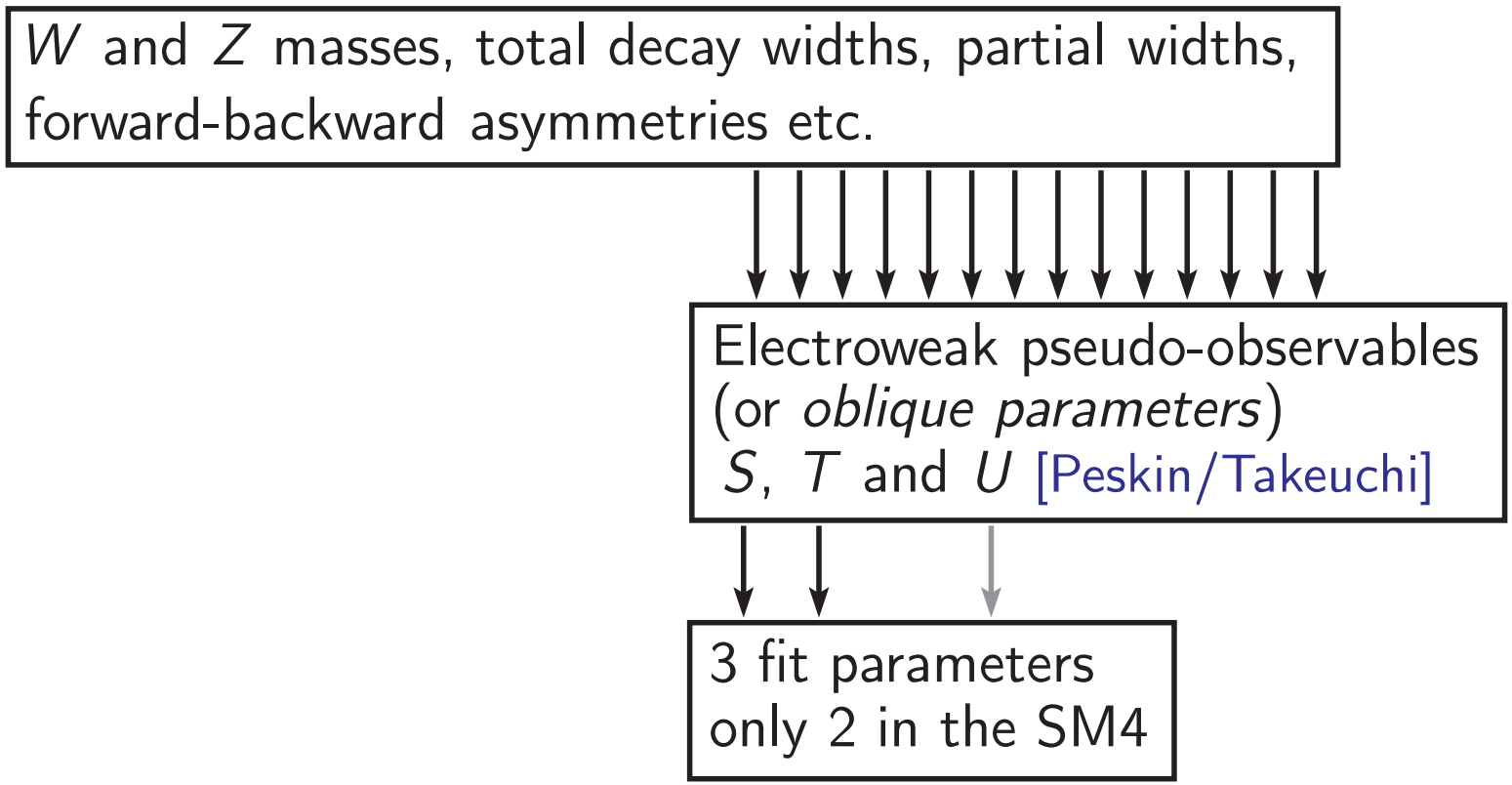
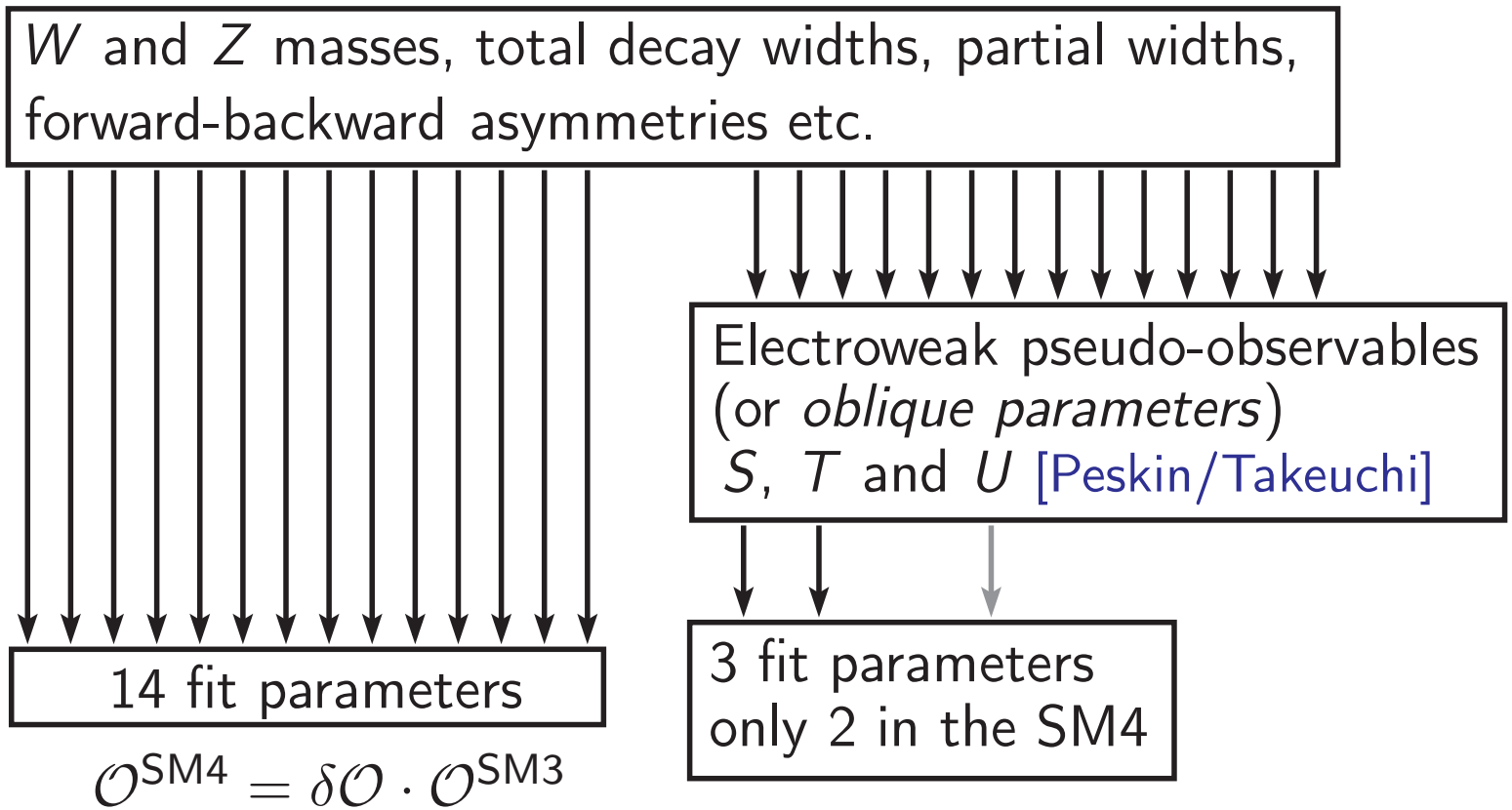


If we have $m_4 \gg m_Z$ and small couplings!

Electroweak constraints

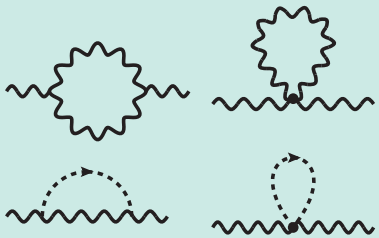
Electroweak precision observables (LEP+TeVatron):



Electroweak constraints

$$(S,T,U)_{\text{full}} = \underbrace{(S,T,U)^{\text{SM3}}_{\text{ferm}} + (S,T,U)^{\text{SM4}}_{\text{ferm}}}_{(S,T,U)_{\text{ferm}}} \leftarrow$$

$$+ \underbrace{(S,T,U)_{\text{gauge}} + (S,T,U)_{\text{Higgs}}}_{(S,T,U)_{\text{bos}}} \leftarrow$$



$$(S,T,U) = (S,T,U)^{\text{SM4}}_{\text{ferm}} + (S,T,U)^{\text{SM4}}_{\text{Higgs}}$$

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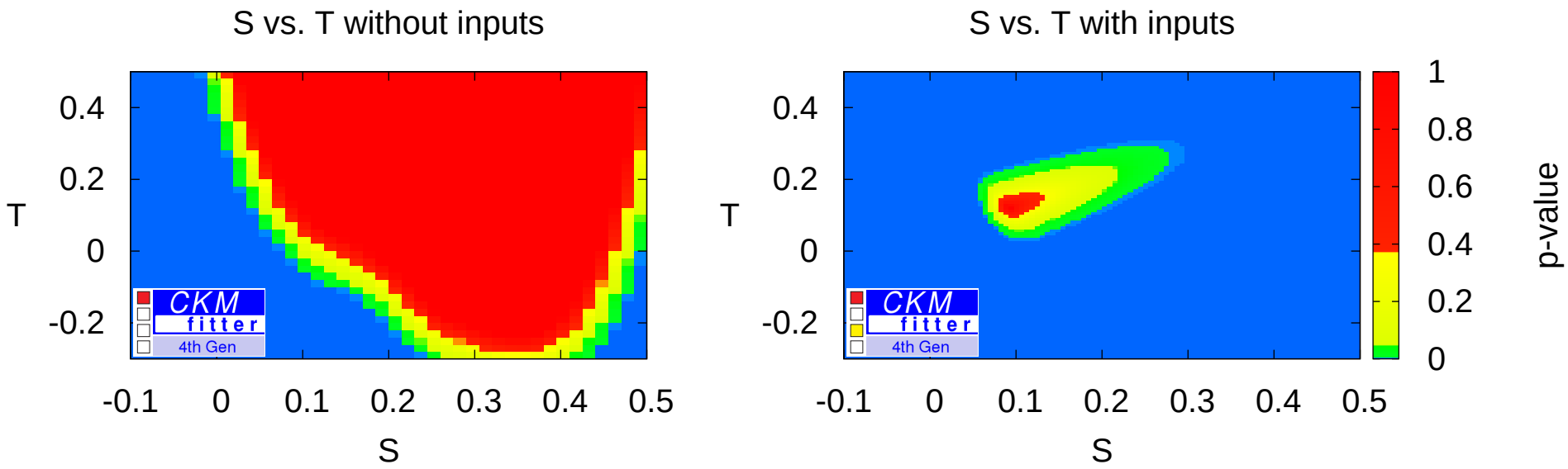
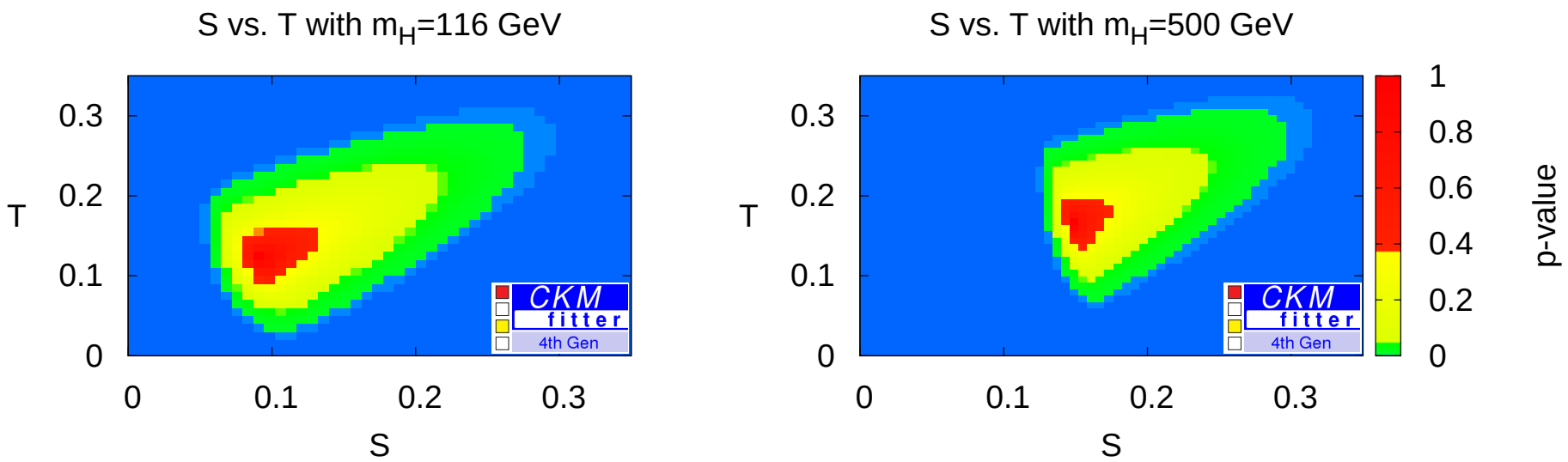
Electroweak constraints



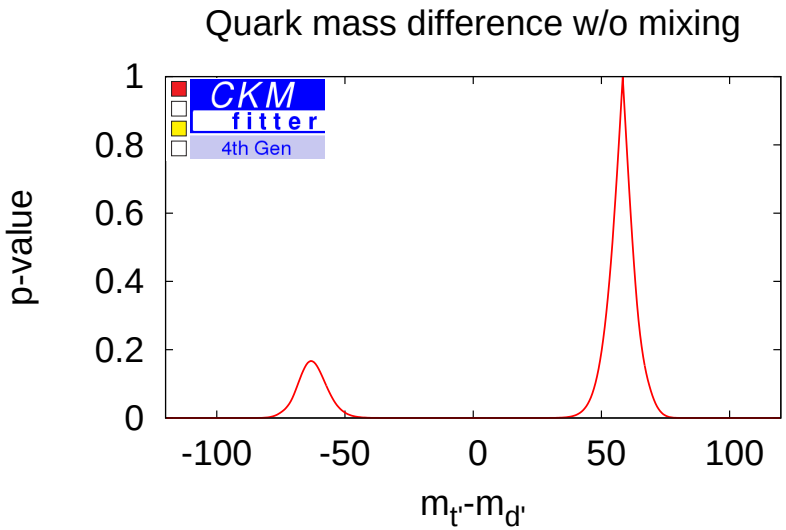
Electroweak constraints

With m_H fixed:



Electroweak constraints

Fermion mass difference
Neglecting the leptons:



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

Electroweak constraints

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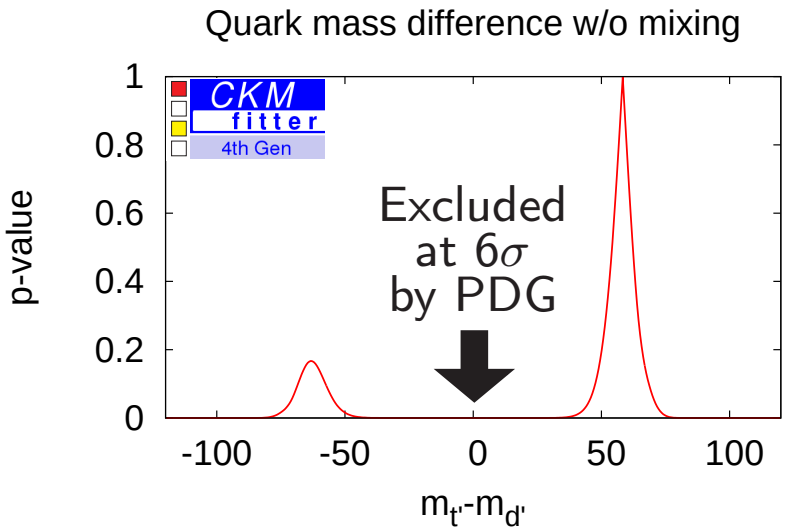

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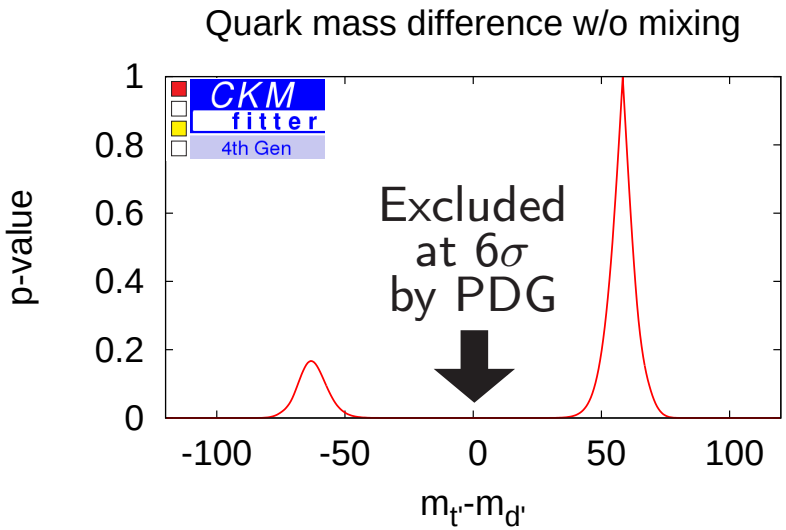

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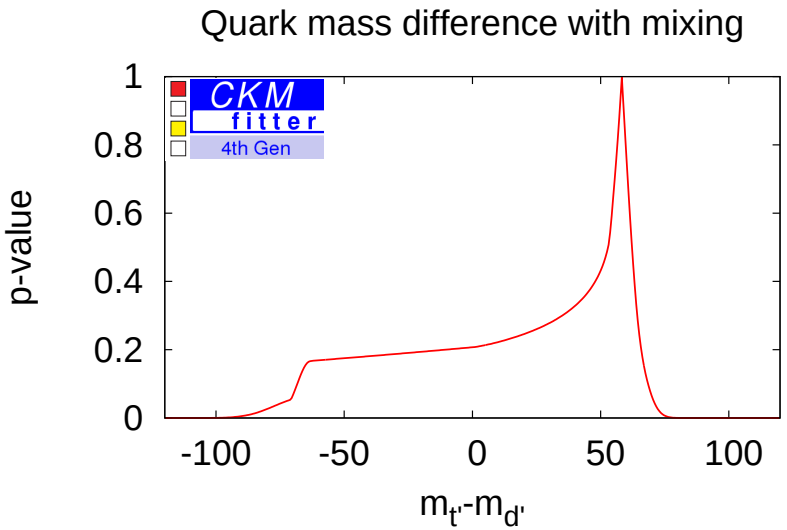

$(V^{\mathrm{CKM}} \neq \mathbb{1})$

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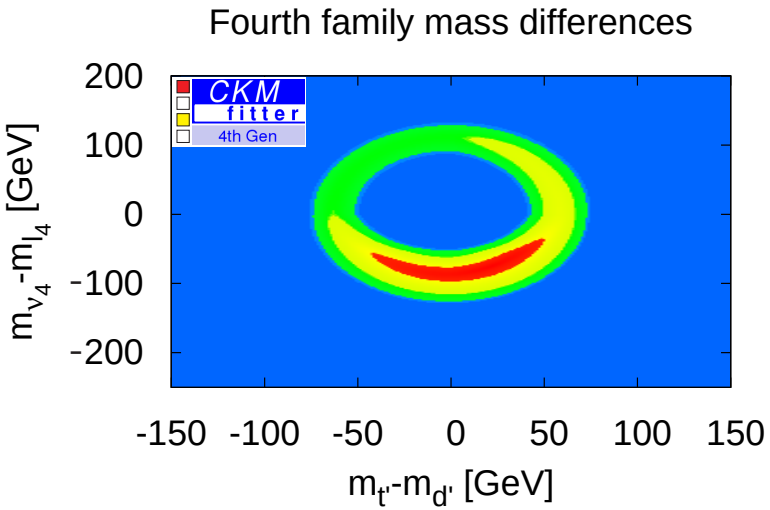
Electroweak constraints

Fermion mass differences taking also the leptons into account:



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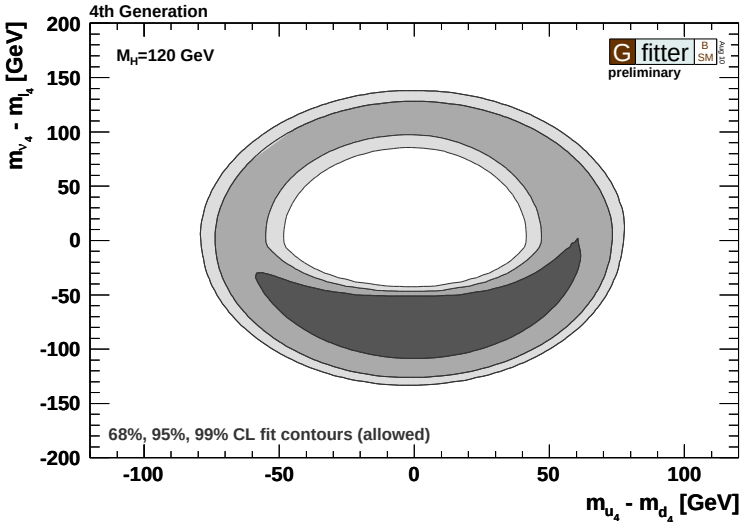

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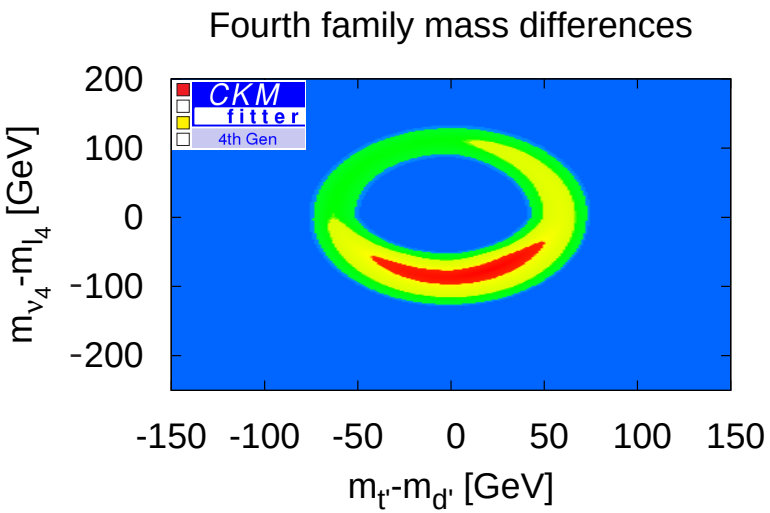

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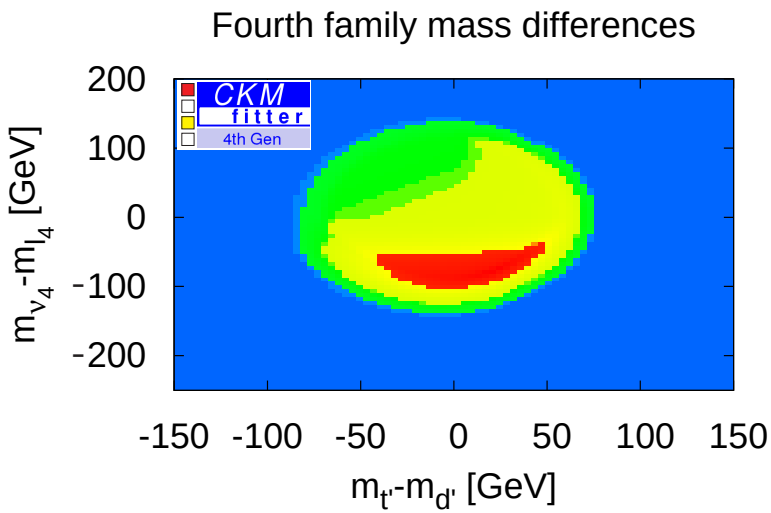

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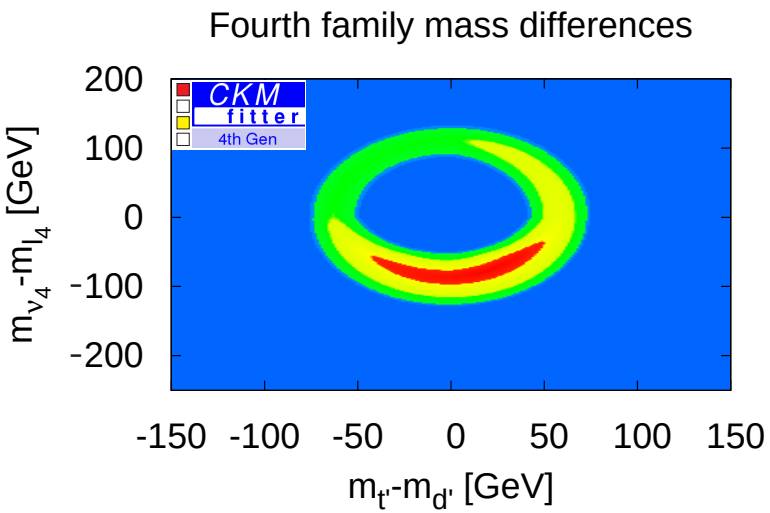

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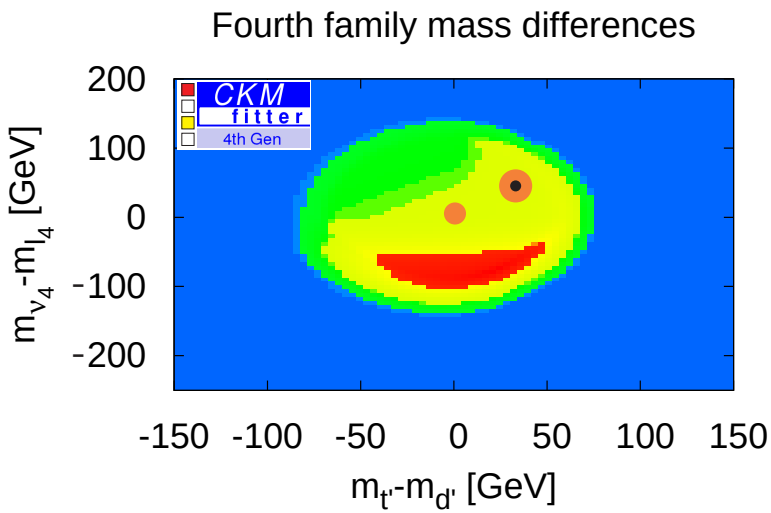

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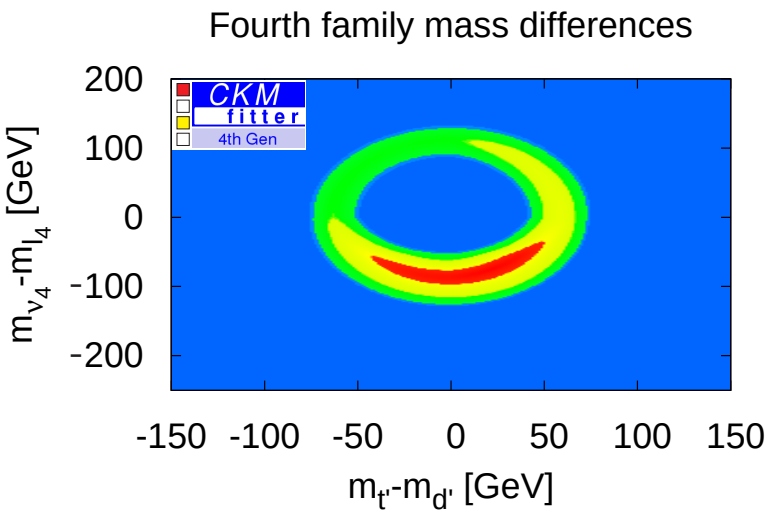

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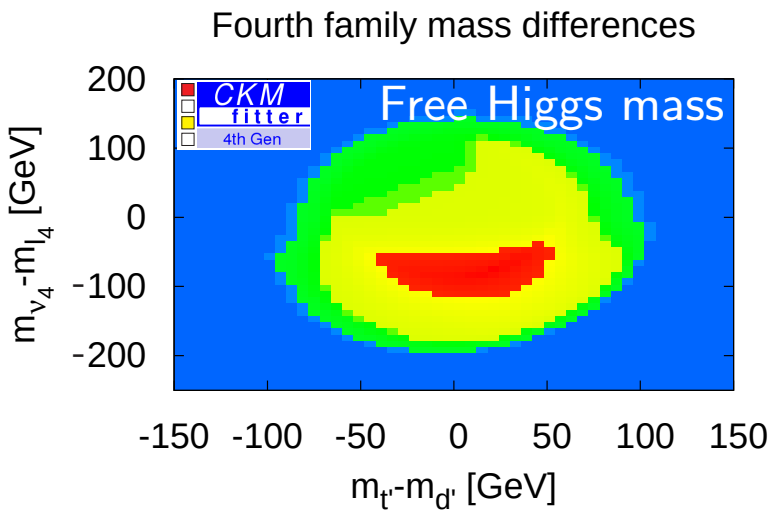

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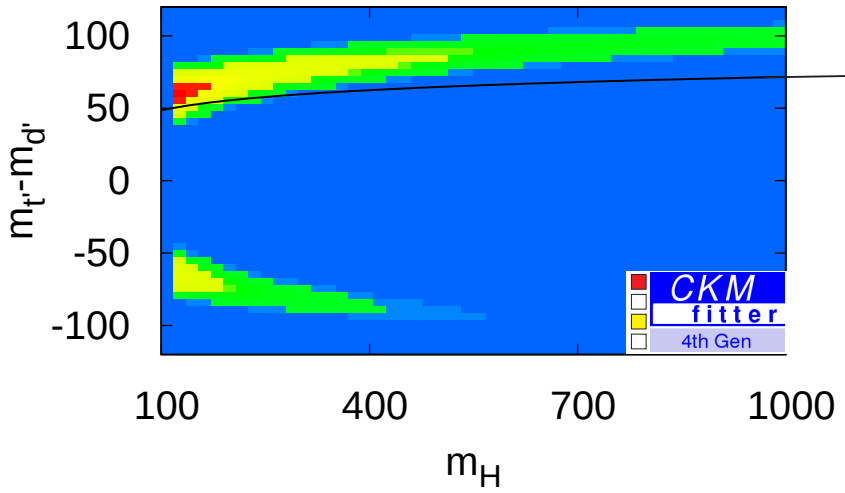
Electroweak constraints

Higgs mass vs. quark mass degeneration



$$m_{t'} - m_{b'} = (1 + \tfrac{1}{5} \ln \tfrac{m_H}{115\text{GeV}}) \cdot 50\text{GeV}$$

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Electroweak constraints

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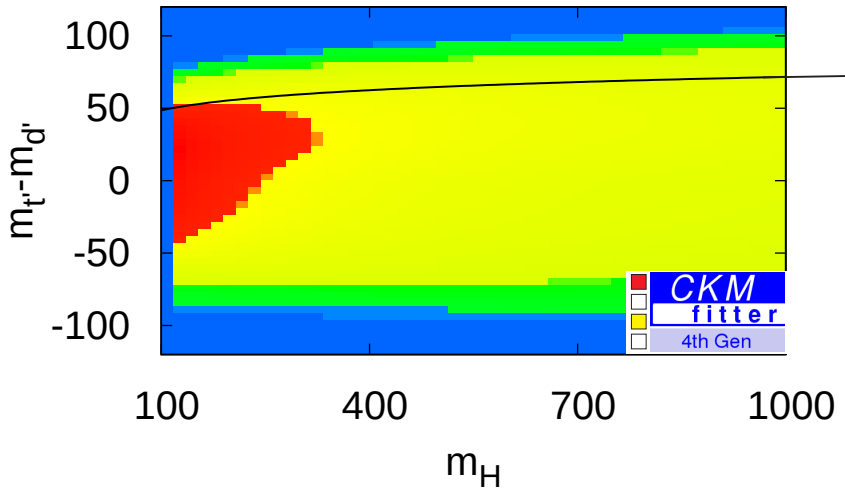

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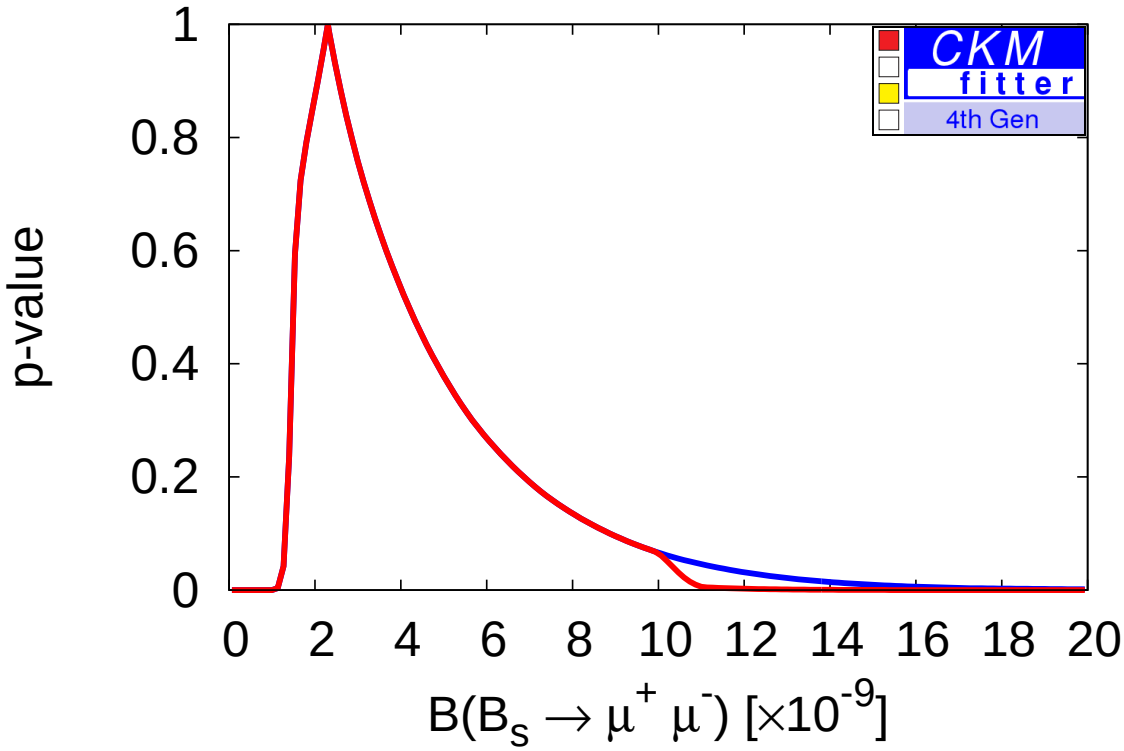
Flavour constraints

- $B_s \to \mu^+\mu^-$



Flavour constraints

- $B_s \to \mu^+\mu^-$
- ϵ_K
- A_{sl}, ΔM_{B_d}, ΔM_{B_s}
- Leptonic meson decays

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Outlook

- Grand unification with flavour observables
- Correct treatment of the EWPOs
- Non-trivial PMNS structure
- Waiting for new experimental results

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Outlook

- Grand unification with flavour observables
- Correct treatment of the EWPOs
- Non-trivial PMNS structure
- Waiting for new experimental results
- Dinner at El Coto

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Back-Ups

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Inputs I

$m_{t'} \in [150, 1000]$ GeV
$m_{b'} \in [128, 1000]$ GeV
$m_{\nu_4} \in [46, 1000]$ GeV
$m_{\ell_4} \in [100, 1000]$ GeV

$m_H \in [116, 1000]$ GeV

$|V_{ud}| = 0.97421^{+0.00034}_{-0.00029}$
$|V_{us}| = 0.2254 \pm 0.0013$
$|V_{ub}| = \left(3.92 \pm 0.09\ _{\text{(stat)}} \pm 0.45\ _{\text{(sys)}}\right) \cdot 10^{-3}$
$|V_{cd}| = 0.230 \pm 0.011$
$|V_{cs}| = 0.98 \pm 0.01\ _{\text{(stat)}} \pm 0.1\ _{\text{(sys)}}$
$|V_{cb}| = \left(40.89 \pm 0.37\ _{\text{(stat)}} \pm 0.59\ _{\text{(sys)}}\right) \cdot 10^{-3}$
$|V_{tb}| = 1.0 \pm 0.099$

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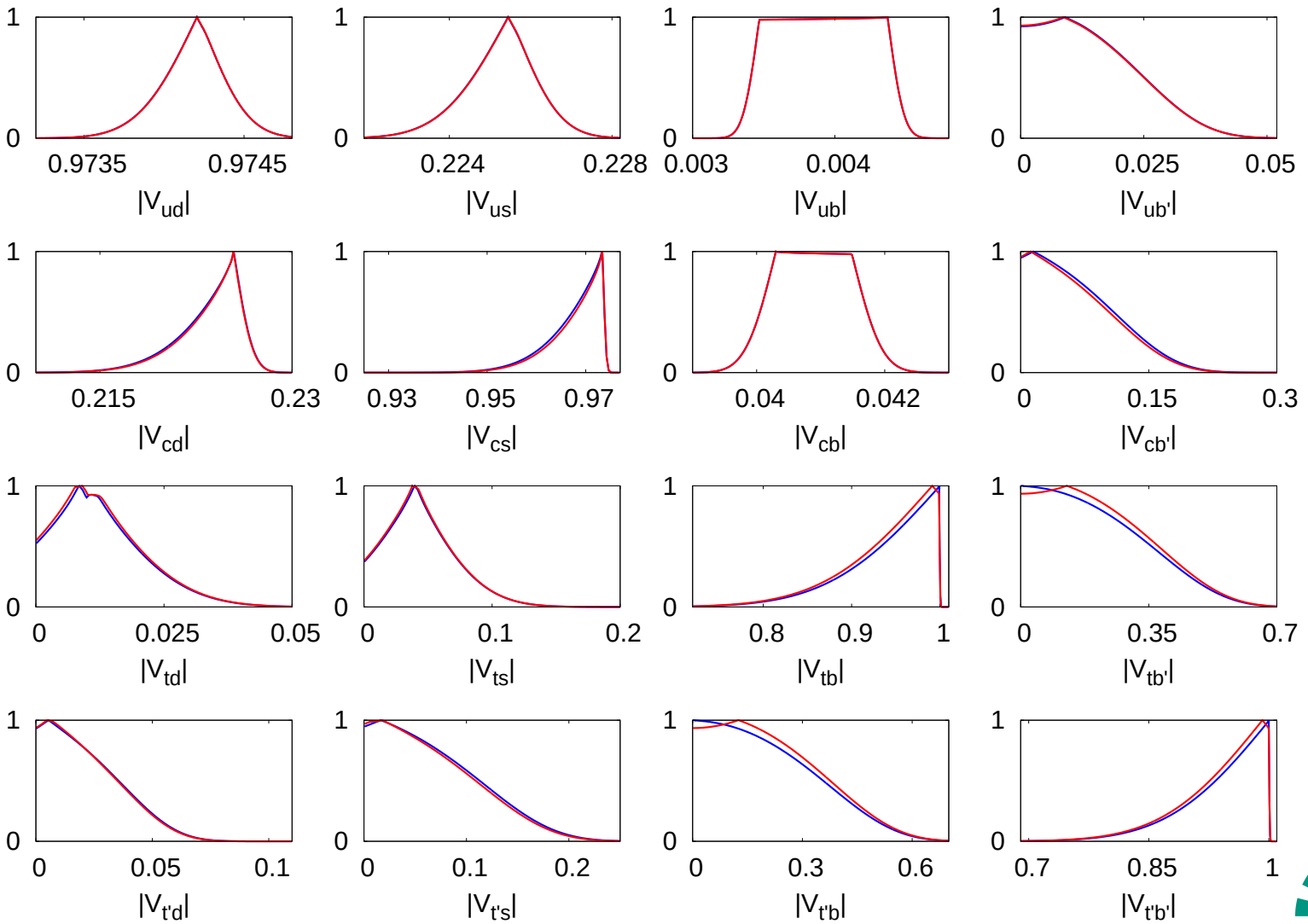
Inputs II

S	0.03 ± 0.09	0.867	
T		0.07 ± 0.08	
U			
$\mathcal{B}(W \to e\nu)$	0.1075 ± 0.0013	0.110	-0.195
$\mathcal{B}(W- > \mu\nu)$		0.1057 ± 0.0015	-0.132
$\mathcal{B}(W- > \tau\nu)$			0.1125 ± 0.0020

Electroweak constraints

Moduli of the CKM matrix without and with *ST* input:



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Explicit expressions

The exact formulae for S and T

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

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

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

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Explicit expressions

The exact formula for U

$$
\begin{aligned}
U_{\mathrm{ferm}} = & \frac{N_c}{3\pi} \sum_{U,D} \left| V_{UD}^{(\mathrm{CKM})} \right|^2 \left[\frac{2 m_U^2 m_D^2}{(m_U^2 - m_D^2)^2} + \left(\frac{m_U^2 + m_D^2}{m_U^2 - m_D^2} - \frac{2 m_U^2 m_D^2 (m_U^2 + m_D^2)}{(m_U^2 - m_D^2)^3} \right) \ln \left(\frac{m_U}{m_D} \right) \right] \\
& + \frac{1}{3\pi} \sum_{\nu,l} \left| V_{\nu l}^{(\mathrm{PMNS})} \right|^2 \left[\frac{2 m_\nu^2 m_l^2}{(m_\nu^2 - m_l^2)^2} + \left(\frac{m_\nu^2 + m_l^2}{m_\nu^2 - m_l^2} - \frac{2 m_\nu^2 m_l^2 (m_\nu^2 + m_l^2)}{(m_\nu^2 - m_l^2)^3} \right) \ln \left(\frac{m_\nu}{m_l} \right) \right] \\
& - \frac{5 N_c}{36\pi} \sum_{q} 1 - \frac{5}{36\pi} \sum_{\nu,l} 1
\end{aligned}
$$

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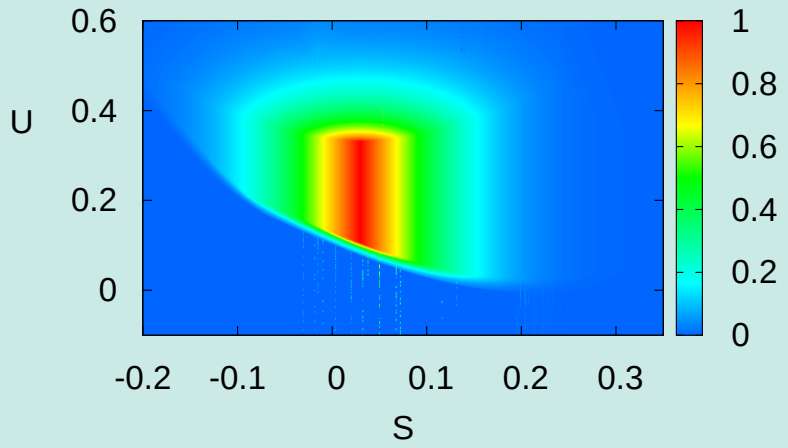
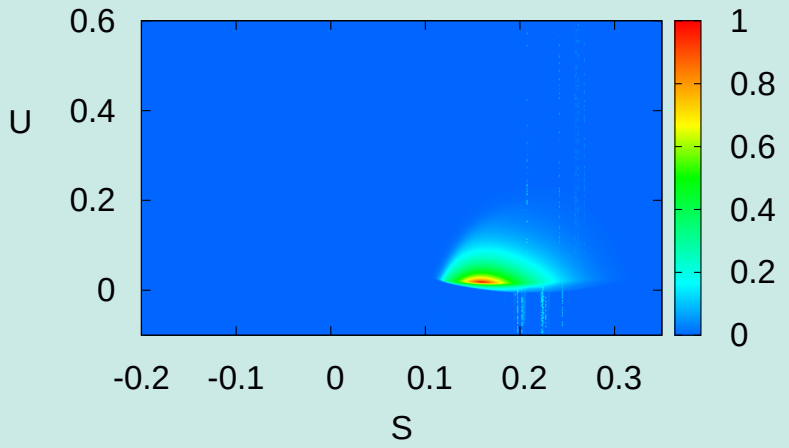
The S-T ellipse

The U parameter



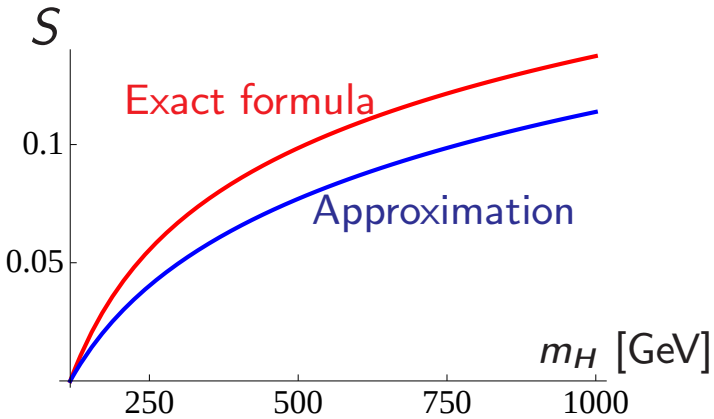
(without T)

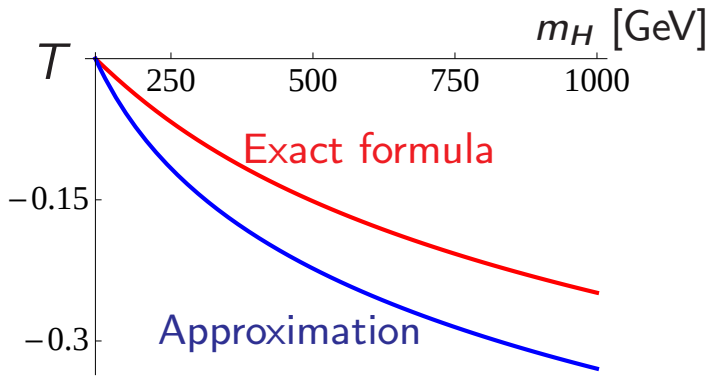


(with T)

The Higgs mass

The exact Higgs contributions:





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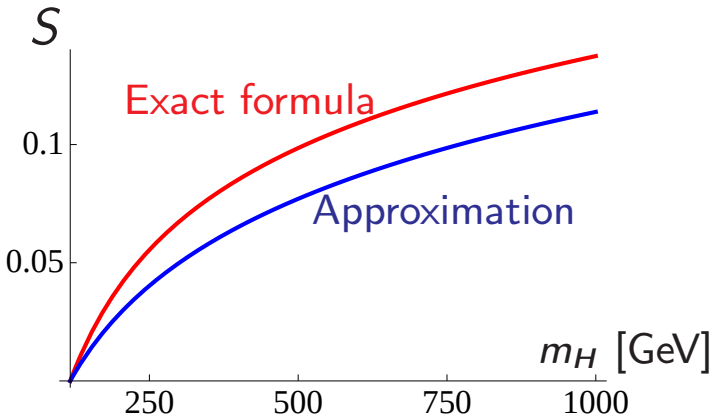

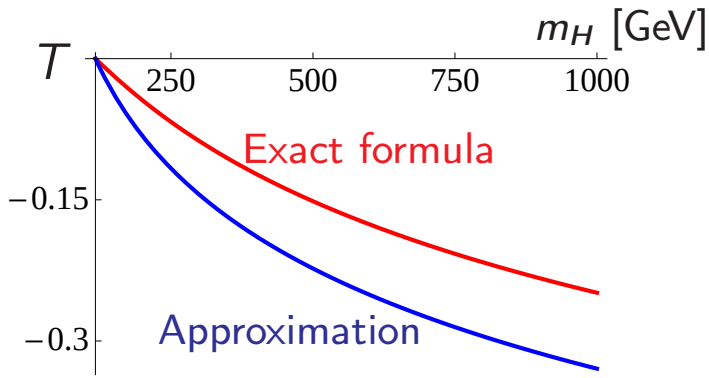

Relative errors: