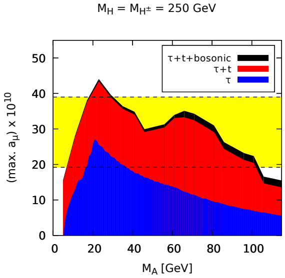
Muon $g-2$ in the 2HDM

Dominik Stöckinger, TU Dresden

SCALARS 2017, 3rd December 2017

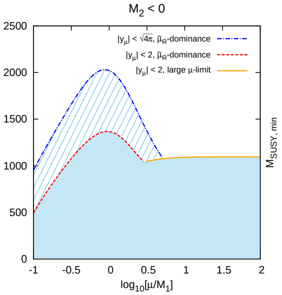


Collaboration with: A. Cherchiglia, H. Stöckinger-Kim

Motivation 1

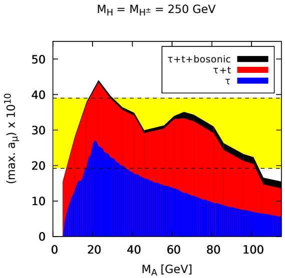
$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.1 \pm (6.3^{\rm Exp} \to 1.6^{\rm FUTURE}) \pm 3.6^{\rm Th(KNT)}) \times 10^{-10}$$

Keshavarzi,Nomura,Teubner'17; Jegerlehner'17:$\pm 4.4^{\rm Th}$



Largest SUSY ($\tan\beta \to \infty$)

[Bach,Park,DS,Stöckinger-Kim '15]

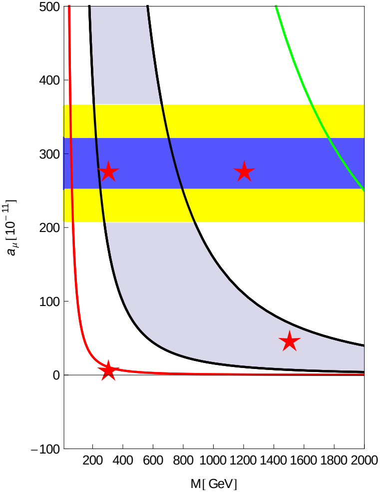


Largest THDM

[Cherchiglia,DS,Stöckinger-Kim '17]

Motivation 2: $g-2$ New Physics overview

Need $a_\mu^{\rm BSM} \sim 30 \times 10^{-10}$. BUT: $a_\mu^{\rm SM\ weak} \sim 15 \times 10^{-10}$ only!



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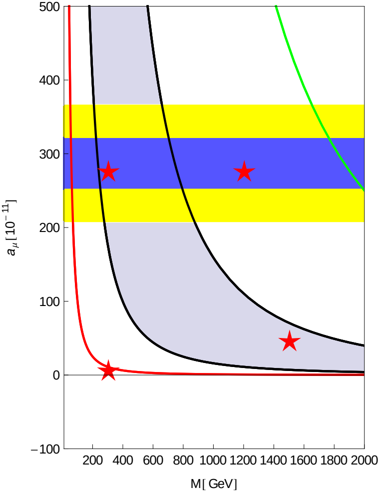
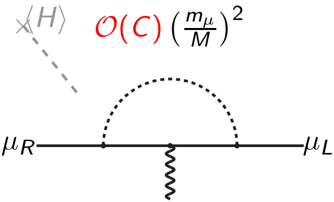
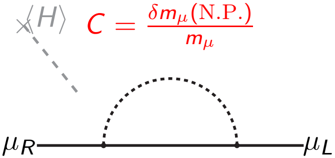






Outline

1. Two-Higgs doublet model
2. Parameter constraints
3. a_μ in the THDM
4. Conclusions

Two-Higgs Doublet Model

- $\rightsquigarrow h, H, H^{\pm}, A^0$
- Yukawas: type 1, 2 ($\leftarrow$ MSSM), X (lepton-specific), Y (flipped)
- consider general model without FCNC $\rightsquigarrow$ "aligned" [Pich, Tuzon]

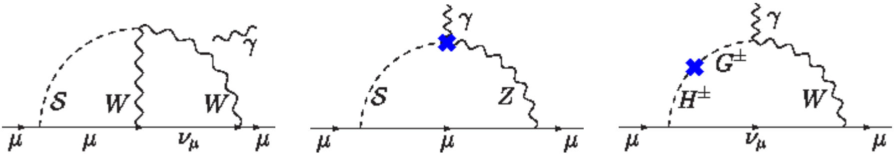
$$
\begin{aligned}
Y^A_{d,l;u} &= \mp\zeta_{d,l;u} \\
Y^h_f &= s_{\beta-\alpha} + c_{\beta-\alpha}\zeta_f \\
Y^H_f &= c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f
\end{aligned}
$$

MSSM/Type 2:	$\zeta_{d,l} = -\tan\beta,$	$\zeta_u = 1/\tan\beta$	
Type X (lepton-specific):	$\zeta_l = -\tan\beta,$	$\zeta_{d,u} = 1/\tan\beta$	
General: expect	$\zeta_l \sim 50,$	$\zeta_{d,u} \sim 1,$	$M_A < M_h$

Two-Higgs Doublet Model: full two-loop result

[Cherchiglia, Kneschke, DS, Stöckinger-Kim, 16]

$$a_\mu^{\text{2HDM,2}} = a_\mu^{\text{2HDM,1}} + a_\mu^{\text{B}} + a_\mu^{\text{F}} + a_\mu^{\Delta r\text{-shift}} \qquad \Rightarrow \Delta(a_\mu^{\text{2HDM,2}}) \lesssim 10^{-10}$$



- two-loop = leading
- one-loop $\propto$ $-$two-loop τ-contribution

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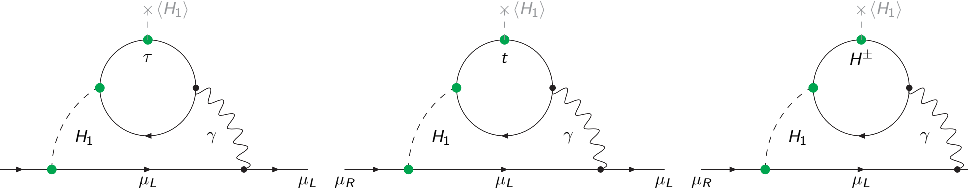

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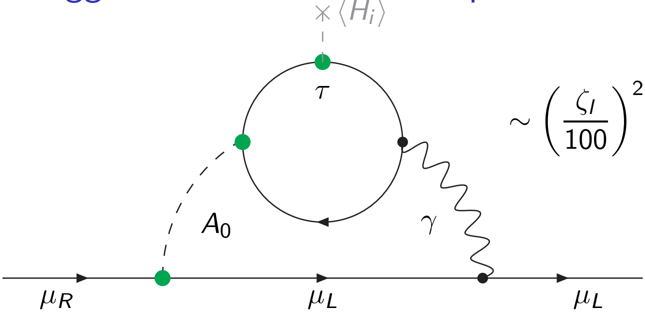
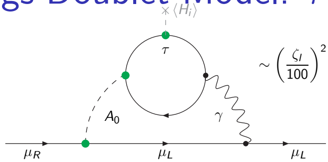
Two-Higgs Doublet Model: τ-loop



$$\sim \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8+\ldots}{(M_A/100\mathrm{GeV})^2}\right\}$$

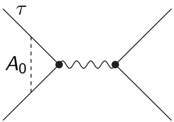
Two-Higgs Doublet Model: τ-loop



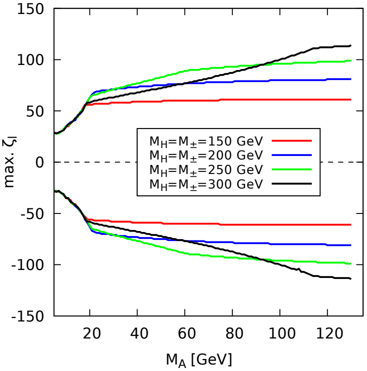
$$\sim \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8+\dots}{(M_A/100\text{GeV})^2}\right\} \times 10^{-10}$$

But: $Z \to \tau\tau$, τ-decay, LEP $e^+e^- \to 4\tau$ constraints on ζ_L!

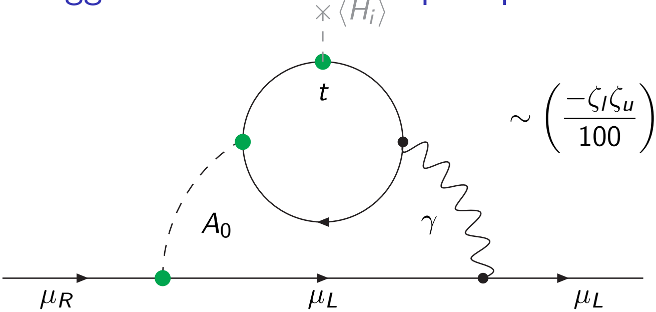
[also: Chun,Kim'16; Abe et al '15; Han et al '15]



$\Rightarrow$

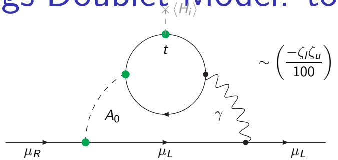


Two-Higgs Doublet Model: top-loop



$$\sim \left(\frac{-\zeta_l \zeta_u}{100}\right) \left\{22 + \ldots\right\} \times 10^{-}$$

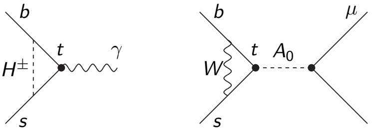
Two-Higgs Doublet Model: top-loop



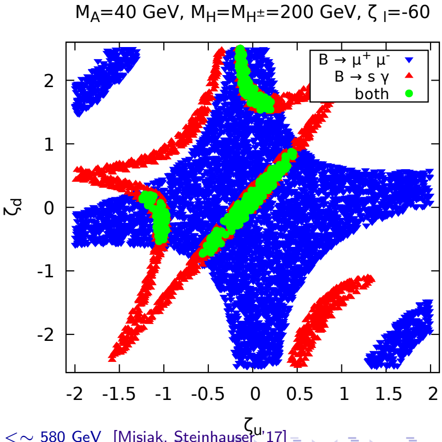
$$\sim \left(\frac{-\zeta_l \zeta_u}{100}\right) \left\{22 + \ldots\right\} \times 10^{-10}$$

But: $b \to s\gamma$ and $B_s \to \mu\mu$ constraints!

[also: Enomoto,Watanabe '15; Pich et al '14]



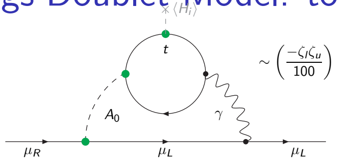
$\Rightarrow$



Note: type X: $\zeta_u = 1/\tan\beta \rightsquigarrow$ allowed

type 2: $\zeta_d = -\tan\beta$, $\zeta_u = 1/\tan\beta \rightsquigarrow$ excluded for $M_{H^\pm} \lesssim 580$ GeV [Misiak, Steinhauser '17]

Two-Higgs Doublet Model: top-loop

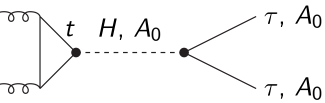


$$\sim \left(\frac{-\zeta_l \zeta_u}{100}\right) \left\{22 + \ldots\right\} \times 10^{-10}$$

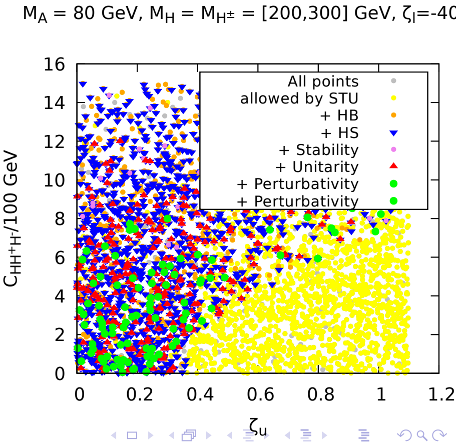
But: LHC constraints:

$gg \to A_0$, $A_0 \to \tau\tau$ decay high M_A

$gg \to H$, $H \to \tau\tau$ vs. $A_0 A_0$ decay

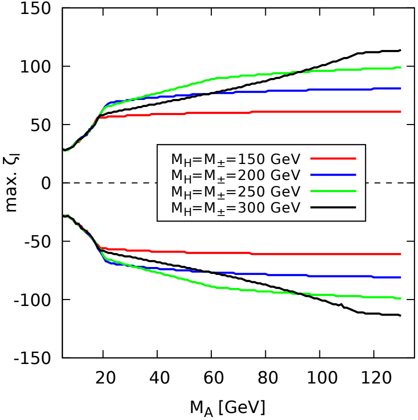


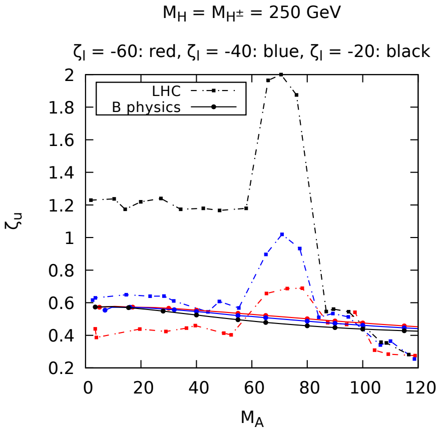
$\Rightarrow$



What are the constraints on the 2HDM parameters ?

Important: M_A ζ_l and ζ_u; less important: $M_{H,H^\pm}$, Higgs potential, ζ_d





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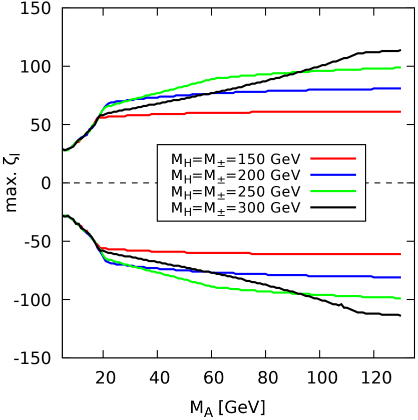
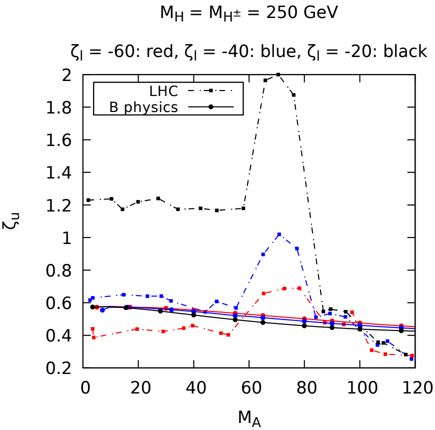
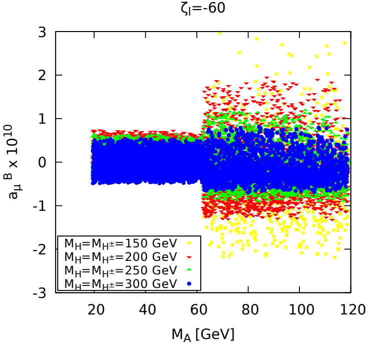




- lepton Yukawa $<\sim 100$ for $M_A > 20$ GeV
- quark Yukawas $<\sim 0.5$
- if $M_{H,H^\pm} > 250$ or < 200 GeV: bounds stronger

What are the constraints on the 2HDM parameters ?

Remaining, bosonic contributions $\propto C_{HH^+H^-}$ but small



useful approximation ($\times 10^{-10}$; $\hat{x} = \frac{m}{100\text{GeV}}$)

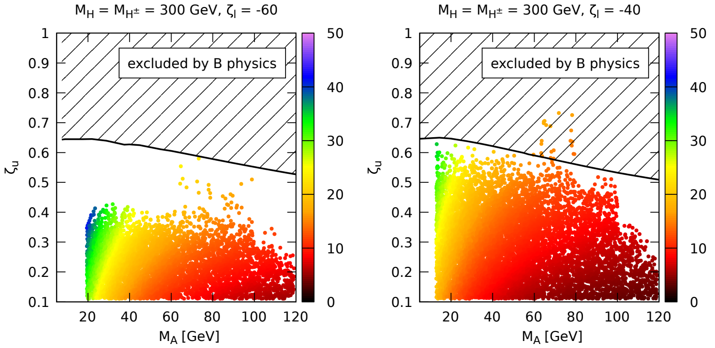
$$a_\mu^{2HDM,1} \simeq \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{-3 - 0.5\ln(\hat{x}_A)}{\hat{x}_A^2}\right\}$$

$$a_\mu{}^{F\tau} \simeq \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8 + 4\hat{x}_A^2 + 2\ln(\hat{x}_A)}{\hat{x}_A^2}\right\}$$

$$a_\mu{}^{Ft} \simeq \left(\frac{-\zeta_l\zeta_u}{100}\right) \left\{54 - 14\ln(\hat{x}_A) - 15\ln(\hat{x}_H)\right\}$$

$$|a_\mu^B| \simeq \rho |C_{HH^+H^-}/\text{GeV}|\,|\zeta_l| \times 10^{-15}$$

How does g-2 behave as function of parameters?

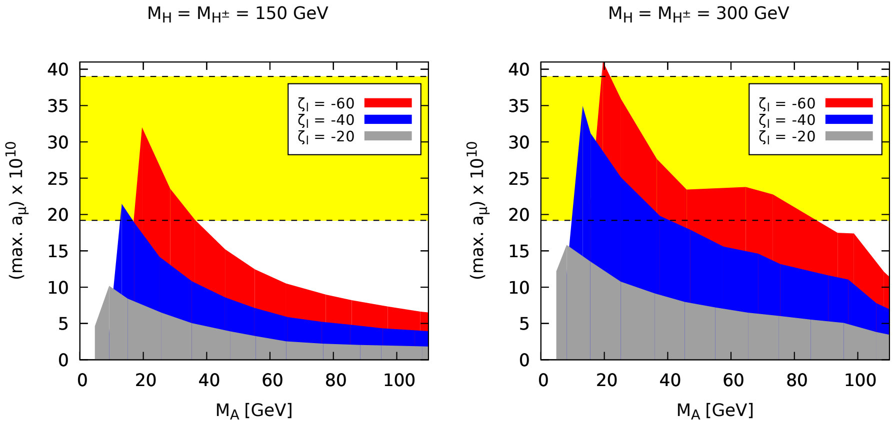


Important: M_A, ζ_l, ζ_u; less important: $M_{H,H\pm}$; only via bosonic contributions: $c_{\beta\alpha}, \lambda_{1,6,7}$, tan β

Type X: barely explain current deviation; Large ζ_u helps. For $|\zeta_l| < 20$: difficult, $a_\mu < 15 \times 10^{-10}$

What is the maximum possible a_μ in the 2HDM?

For fixed ζ_l

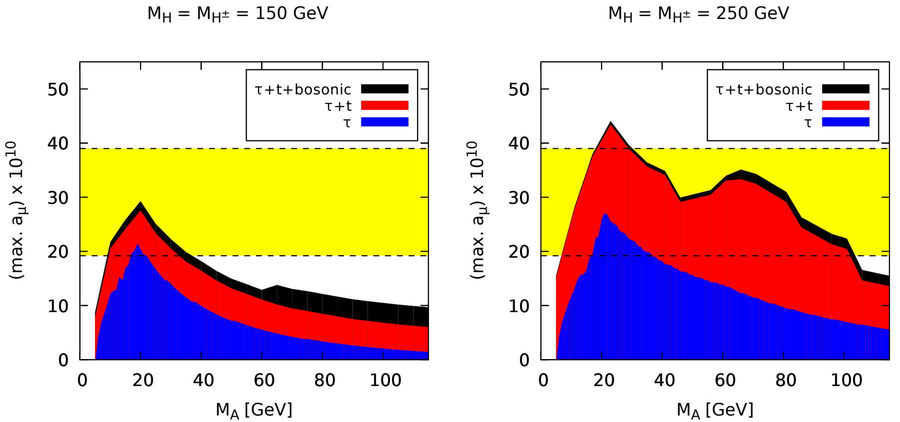


lowest M_A, weak suppression for higher M_A, 1σ explanation possible for $zeta_l = -40$.

Maximum for $zeta_l = -20$ and for $M_H = 150$: rather small

What is the maximum possible a_μ in the 2HDM?

Overall



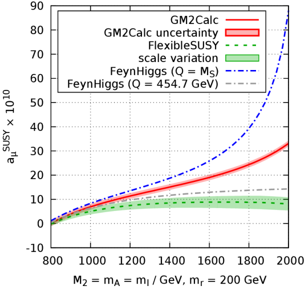
Type X maximum small; 1σ explanation only up to $M_A = 40$

beyond type X: top-loop, bosonic not suppressed for high M_A; peak at $M_A \sim 60 \ldots 80$, 1σ explanation possible up to $M_A = 100$.

Precision and reliability of BSM predictions

$$a_\mu(\text{Gm2Calc}) = 35 \times 10^{-10}, \; a_\mu(\text{SPheno}) = 61 \times 10^{-10}$$

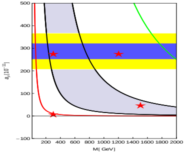
Shocking discrepancy for SUSY scenario with $m_{\tilde{q}} = 15\text{TeV}$!

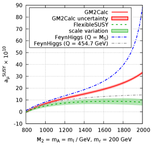


$\rightsquigarrow$ Include higher orders, use appropriate renormalization scheme, estimate theory uncertainty Available: 2HDM full two-loop; MSSM code Gm2Calc [Athron, JH Park, Voigt, Bach, Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim, Greifenhagen]

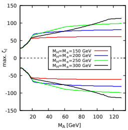
Conclusions

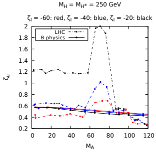
- $g-2$ and new physics:
  - Models with different properties
  - Precision important



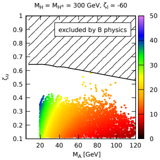


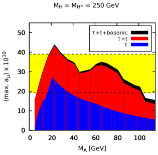
- THDM parameter constraints for $M_A < 100$ GeV:
  - Yukawa couplings $|\zeta_l| <\sim 50$, $\zeta_u <\sim 0.5$
  - large ζ_l only for $M_A > 20$ GeV
  - $M_{H,H^\pm} \sim 250$ GeV allow largest Yukawas





- THDM and a_μ
  - $\rightsquigarrow$ light A_0, large couplings to τ, t
  - Type X: barely explains deviation
  - beyond Z_2: $M_A = 20 \ldots 100$ GeV
  - Interesting for LHC: $pp \to A \to \tau\tau$



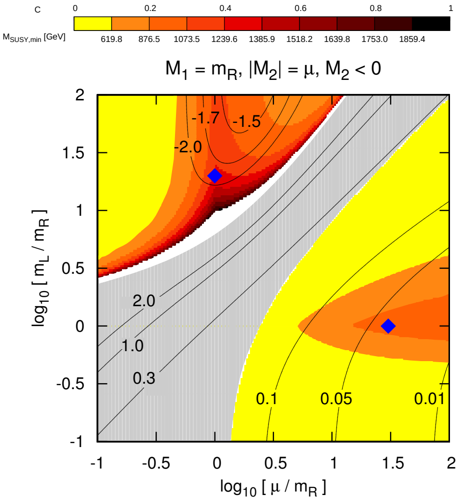


Large a_μ in MSSM for $\tan\beta \to \infty$,

[Bach,Park,DS,Stöckinger-Kim, '15]

$$a_\mu^{\rm SUSY} = \frac{y_\mu v_u \; a_\mu^{\rm red}}{m_\mu^{\rm pole}} + \ldots$$

$$m_\mu^{\rm pole} = \underbrace{y_\mu v_d}_{\text{usual approx.}} + \underbrace{y_\mu v_u \Delta_\mu^{\rm red}}_{\text{now important}} + \ldots$$



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