Karlsruher Institut für Technologie

# Production of CP violating NMSSM Higgs bosons

Matthias Weinreuter | 22.12.2012

INSTITUTE FOR THEORETICAL PHYSICS

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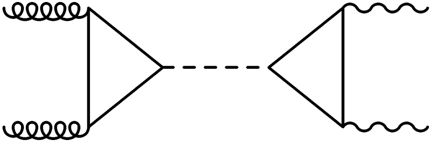
# Outline


1. Motivation
2. CP Violation
   - General remarks
   - CP violation in the NMSSM
3. The process $gg \to h_1 \to \gamma\gamma$
   - Example of a calculation
   - The parts and their assembling
   - Examplary view on complex MSSM results
4. Outlook & Conclusion

# Higgs production via gluonic fusion and photonic decay



- clean detection channel
- CP conserving and CP violating effects appear at the same coupling strength ("democratic") in $f, \tilde{f}$ loops
- observables in model with CP violating ($\not{C}\not{P}$) phases might differ from current expectations in significant orders of magnitude

# Two types of $\cancel{CP}$

- $M^2_{h^0} = \begin{pmatrix} M^2_S & M^2_{SP} \\ (M^2_{SP})^T & M^2_P \end{pmatrix} \leftarrow \begin{pmatrix} (3\times 3) & (3\times 2) \\ (2\times 3) & (2\times 2) \end{pmatrix}$
- $M^2_{SP} \neq 0 \Leftrightarrow \cancel{CP}$
- this can be realised by complex phases

1. Explicit $\cancel{CP}$
   - like $\delta_{13}$ in the SM CKM Matrix
   - Parameters of $\mathcal{L}$ like $\mu$ are allowed to be complex
2. Spontaneous $\cancel{CP}$
   - $\mathcal{L}$ is invariant under CP (all couplings $\in \mathbb{R}$ possible under suitable phase transformations)
   - but then $\langle H_k \rangle = \exp(i\varphi_k)\, v_k \quad (k = u, d, s)$ via spontaneous symmetry breaking (SSB)

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# Considering NMSSM

- In the MSSM spontaneous ~~CP~~ is impossible, if you demand flavour conservation[1]
- the NMSSM can indeed have complex phases in the vevs for each of the $H_u, H_d, S$
- physically relevant could be the combinations
  $\theta = \varphi_u + \varphi_d + \varphi_s$
  $\delta = 3\varphi_s$
- but no SSB can take place because $\frac{\partial V_{\text{Higgs}}}{\partial \theta}, \frac{\partial V_{\text{Higgs}}}{\partial \delta} = 0$ don't describe minima

[1] J.C. Romão, Phys.Lett. B 173 (1986)

# Explicit $\cancel{CP}$

- MSSM: Trilinear couplings $A$ from $\mathcal{L}_{\text{soft}}$:
  phases of 1st and 2nd generation $A$ heavily constrained
  from yet-not-measured EDMs of $e^-, \mu^-, n$
  What matters for leading order $\cancel{CP}$ is $\mathcal{I}m(\mu A_t)$
- NMSSM: $\mu$-replacing parameter $\kappa$ also allowed complex,
  so $\mathcal{I}m(\mu\kappa^*) = \mathcal{I}m(\lambda\langle S\rangle\kappa^*)$ is a measure for $\cancel{CP}$ .
- All in all we can have complex phases through $\mathcal{L}_{soft}$ by

  $\varphi_{A_e}, \varphi_{A_u}, \varphi_{A_d}, \varphi_{M_1}, \varphi_{M_2}, \varphi_{M_3}, \varphi_{\lambda}$, and $\varphi_{\kappa}$,

- on tree level $\varphi_{\kappa}, \varphi_{\lambda}$ matter, at one loop level also the neutralino/chargino $\varphi_{M_{1,2}}$ and sfermion $\varphi_{A_{u,d,e}}$ phases

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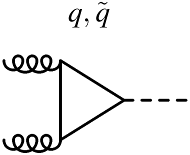
# Gluonic fusion $gg \to h_1$




- underlying algebra could be done using pen & paper
- Feynman rules, e.g.:

$$htt = e^{-i\varphi_u}\left(y_t \frac{(c_\beta R_{14} - iR_{12})}{\sqrt{2}}\right)P_L + e^{i\varphi_u}\left(y_t \frac{(-c_\beta R_{14} - iR_{12})}{\sqrt{2}}\right)P_R$$

- in comparison: real NMSSM
  letting $\varphi_u = 0, R_{14} = 0$ $(R_{14} \subset M^2_{SP})$

  $ht\bar{t}|_{\text{real}} \propto 1$, no $\gamma_5$ part

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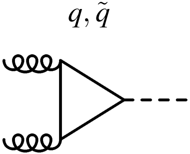


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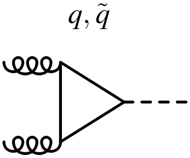


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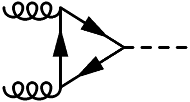
# Gluon Fusion, quark loop

$$\mathcal{M} = \varepsilon_1^\mu \varepsilon_2^\nu \mathcal{M}_{\mu\nu} \; ; \quad k_i^2 = 0 = \varepsilon_{i\mu} k_i^\mu$$



$$\mathcal{M}_{\mu\nu} \sim \int d^d q \frac{\mathrm{tr}((\not{q}+m)[gtt]_\mu(\not{q}-\not{k}_1+m)[gtt]_\nu(\not{q}-\not{k}_2+m)[htt])}{(q^2-m^2)((q-k_1)^2-m^2)((q-k_2)^2-m^2)}$$

- with $htt \sim S + P\gamma_5$ $(S, P \in \mathbb{C})$ the trace becomes

$$8mS \cdot \left((-(k_1 k_2) - q^2 + m^2) g_{\mu\nu} - k_{1\mu} k_{2\nu} + k_{1\nu} k_{2\mu} + 4 q_\mu q_\nu\right)$$
$$+ 8mP \cdot \left(-i\varepsilon_{\alpha\beta\mu\nu} k_1^\alpha k_2^\beta\right)$$

- pseudovector part due to the $\gamma_5$ structure of $htt$ absent in the real case

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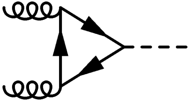

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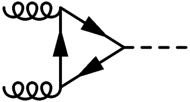

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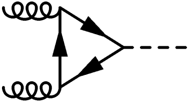
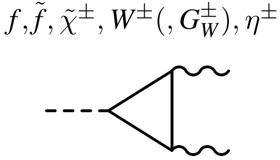


$$\mathcal{M}_{\mu\nu} \propto\ [\ldots]_S \left( \frac{m_h^2}{2} g_{\mu\nu} - k_1^\nu k_2^\mu \right) + [\ldots]_P \left( \epsilon_{\alpha\beta\mu\nu} k_1^\alpha k_2^\beta \right)$$

$$\sum_{\text{pol.}} \overline{|\mathcal{M}|^2} \propto |[\ldots]_S|^2 + |[\ldots]_P|^2$$

- no interference term between scalar and pseudoscalar part
- this allows to study both parts separately
- details on the $[\ldots]$ parts: not now (but all UV convergent)

# Photonic Decay $h_1 \to \gamma\gamma$




- in general similar structure than the gluon case (1 scalar, 2 vector bosons)

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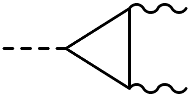
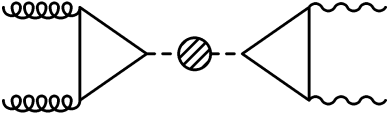



- BUT: calculation more cumbersome, up to not-anymore-possible-by-hand, e.g. W triangle

$$\mathcal{M}_{\mu\nu} \sim g_{\alpha\kappa}[\text{Prop}_{\alpha\beta}(q)][V_{\beta\mu\rho}(q,-k_1,-(q-k_1))][\text{Prop}_{\rho\sigma}(q-k_1)]\times$$
$$[V_{\sigma\nu\gamma}((q-k_1),-k_2,-(q-k_2-k_1))][\text{Prop}_{\gamma\kappa}(q-k_2-k_1)]$$

- $V_{\alpha\beta\gamma}(p_1,p_2,p_3) = \sum_{\text{Perm.}} g_{\beta\gamma}(p_2-p_3)_\alpha$
- $\text{Prop}_{\alpha\beta}(q) = \frac{g_{\alpha\beta}-\frac{q_\alpha q_\beta}{m^2}}{q^2-m^2}$ $\Rightarrow$ ugly $\Rightarrow$ FormCalc

# $\not{CP}$ in the Higgs propagator



- plus, there is mixing $\not{CP}$ in
  $gg \to H_i \to h_1 \to \gamma\gamma$
  $(gg \to h_1 \to H_i \to \gamma\gamma)$
  through $M_{SP}^2$ from the Higgs self-energy ($H_i$ labeling the Higgs CP eigenstates)
- sub-leading effect, enters in higher orders than $ggH/H\gamma\gamma$[1]
- it was shown[2] that $m_{h_1}$ can vary about $\pm 2$GeV with $\varphi_\mu$

[1] Moretti, Munir, Poulose, arXiv:hep-ph/0702242v1
[2] in the MSSM, Moretti, Munir, Poulouse, Phys.Lett.B 649, 206

# Assembling

- so: let FormCalc calculate everything
- in principle possible up to $\sum_{\text{pol.}} \overline{|\mathcal{M}|^2}$
- Why is this not done yet?
- because there are a lot of minor problems
  that are poorly documented, too.

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# Example: Observability of lightest Higgs boson in the complex MSSM[1]

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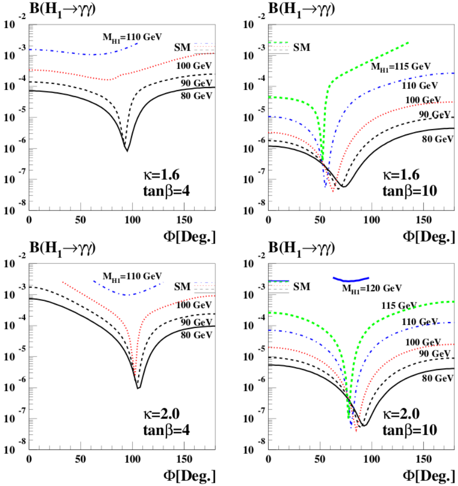


$h_1 \to \gamma\gamma$ branchings for various $\tan\beta$, $A_t \equiv K \times M_{\text{SUSY}}$

yields similar scenario (note SM in contrast)

[1] Choi,Hagiwara,Lee,arXiv:hep-ph/0110138v2 (2008)

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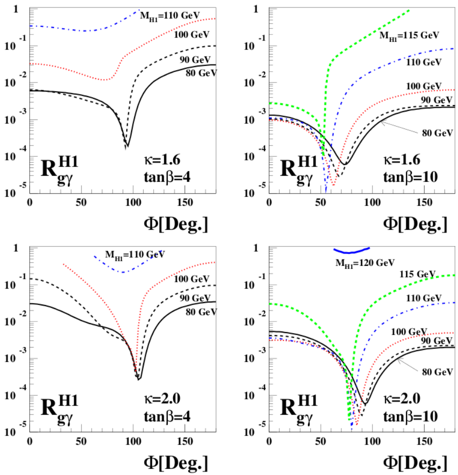


$gg \to h_1 \to \gamma\gamma$ (NWA)
composite process
relative to SM result

$$R^{h_1}_{g\gamma} \equiv \frac{[\sigma^{ggh_1}_{\text{LO}} \times \mathcal{B}^{h_1\gamma\gamma}]_{\text{MSSM}}}{[\sigma^{ggH}_{\text{LO}} \times \mathcal{B}^{H\gamma\gamma}]_{\text{SM}}}$$

$\Rightarrow$ indeed there can be massive cutbacks

[1] Choi,Hagiwara,Lee,arXiv:hep-ph/0110138v2 (2008)

# Outlook & Conclusion

- parameters could use more research ($m_{\tilde{t}_1}, A_t, \ldots$ also $\varphi_{M_i}$)
- when Higgs production is strongly supressed in some parameter region, then experimental exclusion limits could need some review
- possibility to get to know (measured and unmeasured) $\cancel{CP}$ better (cf. baryogenesis / Sacharov)

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Thank you for your time[1]!

[1] - me

# Soft SUSY-breaking Lagrangian[1]

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = & -m^2_{\tilde{Q}_L}\tilde{Q}^\dagger\tilde{Q} - m^2_{\tilde{L}_L}\tilde{L}^\dagger\tilde{L} - \sum_{f=u,d,e} m^2_{\tilde{f}_R}|\tilde{f}_R|^2 \\
& - \left(A_u\tilde{u}^*_R(\tilde{Q}^T\epsilon H_u) - A_d\tilde{d}^*_R(\tilde{Q}^T\epsilon H_d) - A_e\tilde{e}^*_R(\tilde{L}^T\epsilon H_d + c.c.)\right) \\
& - m^2_{H_u}H_u^\dagger H_u - m^2_{H_d}H_d^\dagger H_d - m^2_S|S|^2 \\
& - \left(A_\lambda(H_u^T\epsilon H_d)S + \frac{1}{3}A_\kappa S^3 + c.c.\right) \\
& - \frac{1}{2}\left(M_1\tilde{B}^0\tilde{B}^0 + M_2\tilde{W}^i\tilde{W}^i + M_3\tilde{g}\tilde{g} + c.c.\right)
\end{aligned}
$$

[1] thanks, Kathrin!