MSSM Higgs self-couplings at two-loop

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Discovery of a new boson

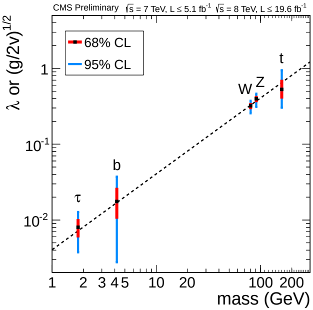
Observation of new boson ϕ by CMS and Atlas:

- mass: $m_\phi = 125 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
- spin-parity: $J_\phi^P = 0^+$
- couplings to other particles:
- self-couplings: $\lambda =???$

$\Rightarrow$ Compatible with SM Higgs boson

Also compatible with BSM Higgs Bosons?

Atlas



CMS

$m_\phi = 125$ GeV as an MSSM Higgs Boson

Assume ϕ is the light CP-even scalar MSSM Higgs boson

$$\phi = h$$

- moderate to heavy stops $m_{\tilde{t}_2} \gtrsim 300$ GeV
- large stop mixing $X_t \gtrsim \frac{1}{2}(m_{\tilde{t}_1} + m_{\tilde{t}_2})$
- decoupling limit: $m_A \gtrsim 250$ GeV for $\tan\beta \gtrsim 8$

  (or $m_A \gtrsim 350$ GeV for $\tan\beta \simeq 5$)

  $\rightarrow m_h = 125$ GeV ✓
- h becomes SM-like in the decoupling limit

  $\rightarrow BR(h \rightarrow WW, ZZ, \gamma\gamma)$ ✓

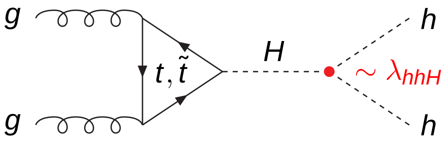
Ellis,··· (1991)
Haber,··· (1990)
Hempfling,Hoang (1994)
Heinemeyer,··· (1998)
Zhang (1999)
Slavich,··· (2001)
Espinosa, Zhang (2000)
Slavich,··· (2001)
Heynemeyer,··· (2005)
Martin (2007)
Harlander,··· (2010)
etc.

Motivation for Calculating Two-Loop Corrections to the Couplings

- Higgs self-couplings determine Higgs potential
- Higgs potential is responsible for EWSB

$\Rightarrow$ need to measure Higgs self-interactions to understand EWSB

- SM: λ_{hhh} difficult at LHC, e^+e^- collider might be needed
- MSSM: five Higgs bosons $\Rightarrow$ promising process at LHC:

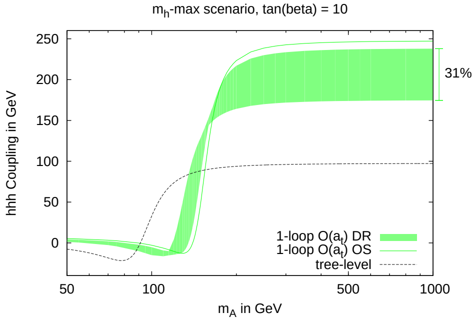


$\Rightarrow$ need high-precision predictions for trilinear couplings

Existing One-Loop Calculation

$$\lambda_{hhh}^{\mathcal{O}(\alpha_t)} = \frac{3m_Z^2}{v} + \frac{9m_t^4}{2\pi^2 v^3}\left[\log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right) - \frac{2}{3}\right], \quad \text{for} \begin{cases} \tan\beta \gg 1, \\ m_A \gg m_Z, \\ m_{\tilde{t}} \gg m_t \end{cases}$$

Barger, · · · (1992)



- large corrections
- sizable uncertainties

⇒ two-loop calculation needed.

Effective Potential Method

Effective Potential V^{eff}:

- Non-derivative part of the effective action
  $\rightarrow$ correct in the limit of vanishing external momenta
- Generating functional of 1PI Greens functions with no external legs (vacuum diagrams)
- n-th derivative of V^{eff}:
  sum of all 1PI diagrams with n external legs

$$\Rightarrow \lambda^{\mathcal{O}(x)}_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k} = \left.\frac{\partial^3 V^{\mathcal{O}(x)}}{\partial\mathcal{H}_i\partial\mathcal{H}_i\partial\mathcal{H}_i}\right|_{min} \quad \text{,where } \mathcal{H}_i = (h, H, A, G)$$

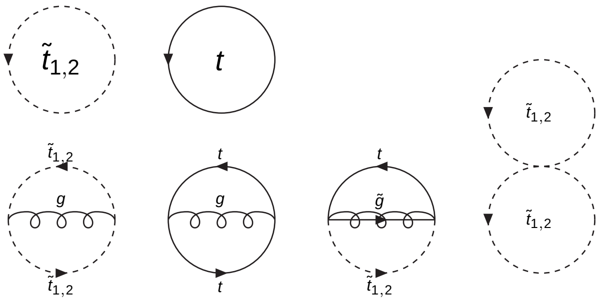
"effective coupling"

Computing the Effective Potential

First step: calculate δV^{α_t}, $\delta V^{\alpha_t \alpha_s}$ and $\delta V^{\alpha_t^2}$

1-loop:
$\mathcal{O}(\alpha_t)$

2-loop:
$\mathcal{O}(\alpha_t \alpha_s)$



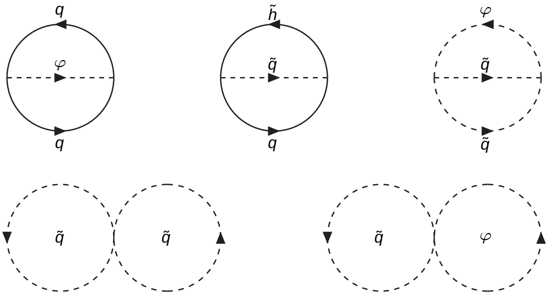
Zhang, · · · (1999)
Slavich, · · · (2001)

Computing the Effective Potential

First step: calculate δV^{α_t}, $\delta V^{\alpha_t \alpha_s}$ and $\delta V^{\alpha_t^2}$

2-loop:

$\mathcal{O}(\alpha_t^2)$



$q = (t, b)$

$\varphi = (H, h, G, A, H^{\pm}, G^{\pm})$

$\tilde{h} = (\tilde{h}^0_{1,2}, \tilde{h}^{\pm})$

$\tilde{q} = (\tilde{t}_1, \tilde{t}_2, \tilde{b}_L)$

Zhang,··· (1999)
Slavich,··· (2001)

Renormalization

The fully renormalized coupling can be calculated by

$$\lambda^{\mathcal{O}(\alpha_t+\alpha_t\alpha_s+\alpha_t^2)}_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k} = \left.\frac{\partial^3(V_0+\delta V^{\alpha_t}+\delta V^{\alpha_t\alpha_s}+\delta V^{\alpha_t^2})}{\partial\mathcal{H}_i\partial\mathcal{H}_j\partial\mathcal{H}_k}\right|_{min} + \delta\lambda^{CT}_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}.$$

The counterterm is obtained from derivatives

$$\delta\lambda^{CT}_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k} = \sum_i \frac{\partial\Delta\lambda^{\mathcal{O}(\alpha_t)}_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}}{\partial x_i}\delta^{\alpha_s+\alpha_t}x_i,$$

where $x_i = \left\{m_t^2, m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \sin 2\theta_{\tilde{t}}, A_t, \mu, v\right\}$ are all parameters of the one-loop couplings that are renormalized at $\mathcal{O}(\alpha_s+\alpha_t)$. Note that at $\mathcal{O}(\alpha_t)$ the wave function of the external states is also renormalized.

Cancellation of Divergences

For simplicity, start with $\overline{DR}$-scheme:

- $\overline{DR}$-counterterms $\delta^{\overline{DR}} x_i$ are $\frac{1}{\epsilon}$-divergences
- $\mathcal{O}(\epsilon)$-terms in δV^{α_t} give finite contributions
- $\mathcal{O}(\epsilon^0)$-terms in δV^{α_t} give $\frac{1}{\epsilon}$ poles

Non-trivial consistency check: All $\frac{1}{\epsilon^2}$ and $\frac{1}{\epsilon}$ poles cancel.

$$\Rightarrow \lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{\mathcal{O}(\alpha_t+\alpha_t\alpha_s+\alpha_t^2),\overline{DR}} \text{ is finite}$$

Renormalization Scheme

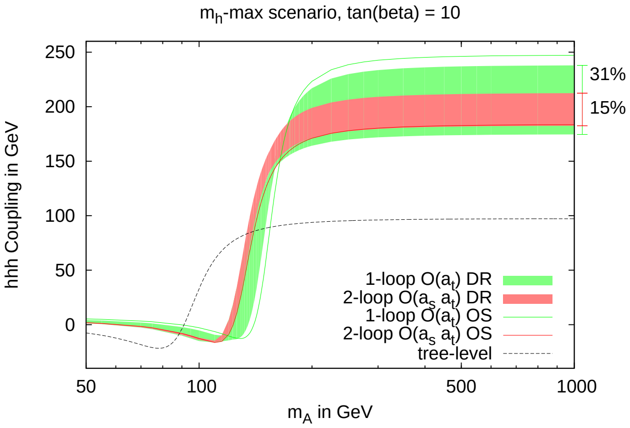
Can shift to any other scheme by adding finite counterterm.
e.g. on-shell-scheme:

$$\lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{\mathcal{O}(\alpha_t+\alpha_t\alpha_s+\alpha_t^2),OS} = \lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{\mathcal{O}(\alpha_t+\alpha_t\alpha_s+\alpha_t^2),\overline{DR}} + \Delta\lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{CT,OS}$$

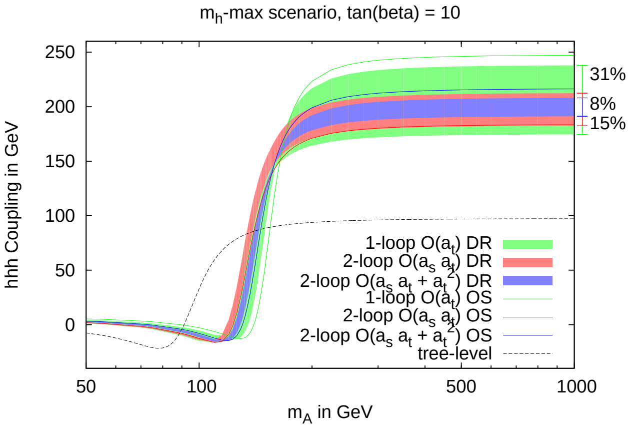
- $\Delta\lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{CT,OS} = \sum_i \frac{\partial\Delta\lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{\mathcal{O}(\alpha_t)}}{\partial x_i}\Delta^{\alpha_s+\alpha_t,OS}x_i$
- $\Delta^{\alpha_s+\alpha_t,OS}x_i$: finite part of on-shell counterterm

$\Rightarrow \lambda_{\mathcal{H}_i\mathcal{H}_j\mathcal{H}_k}^{\mathcal{O}(\alpha_t+\alpha_t\alpha_s+\alpha_t^2),OS}$ is independent of the 't Hooft scale Q.

Results: λ_{hhh}



Results: λ_{hhh}



Results: Other Self-couplings

In the same way we obtained

- $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ corrections for all other five trilinear neutral Higgs self-couplings: hhH, hHH, HHH, hAA, HAA
- $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ corrections for all nine quartic neutral Higgs self-couplings: $hhhh$, $hhhH$, $hhHH$, $hHHH$, $HHHH$, $hhAA$, $hHAA$, $HHAA$, $AAAA$

$\Rightarrow$ Uncertainties are well under control.

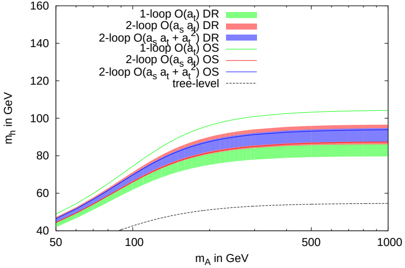
Summary

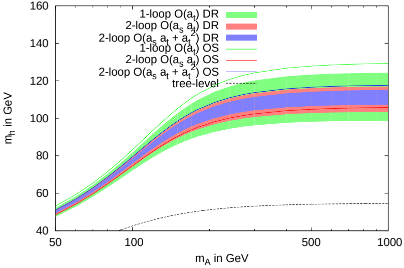
- The effective potential method provides an efficient way to calculate two-loop corrections to Higgs self-interactions.
- The $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ corrections to the hhh-coupling are small at the central scale $M_{SUSY}/2$ and the theoretical uncertainty is reduced from $\sim 31\%$ to $\sim 8\%$.

  $\Rightarrow$ stabilization

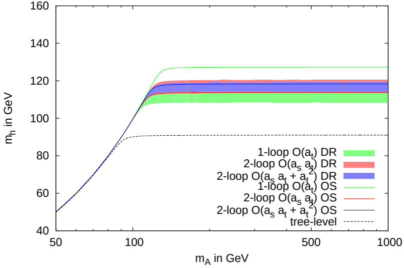
- Outlook:
  - analytic formulae $\rightarrow$ public code
  - use these effective couplings to calculate a collider process (supplemented by process dependent corrections)

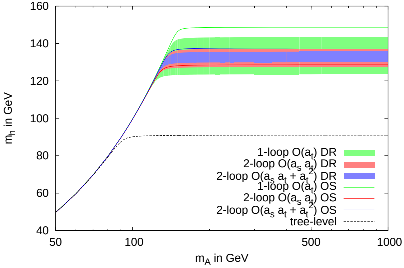
Backup: Mass $tb = 2$



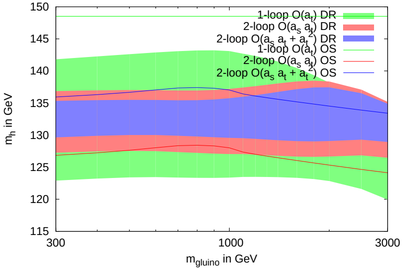


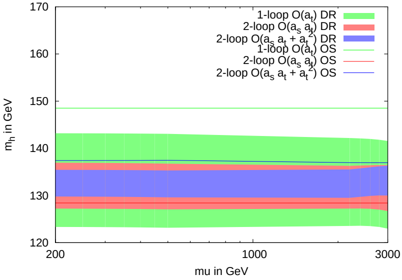
Backup: Mass $tb = 30$



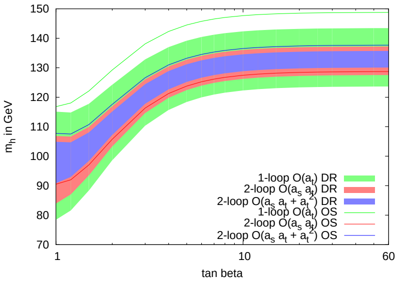


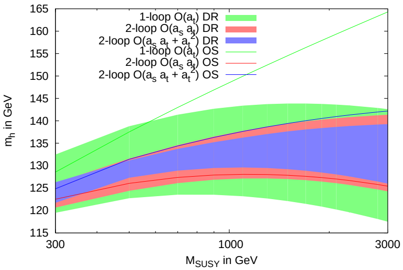
Backup: Mass (m_{gluino}, μ), $tb = 20$



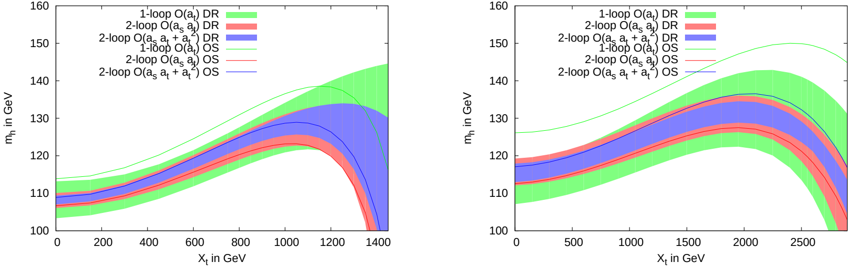


Backup: Mass (tb, M_{SUSY})

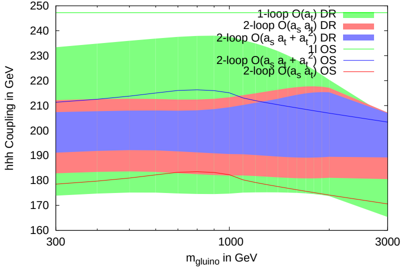


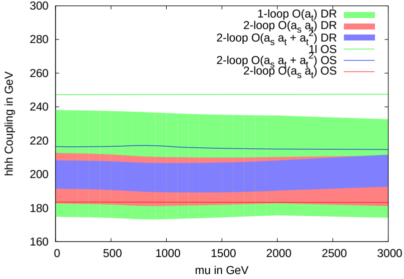


Backup: Mass (X_t), $tb = 10$

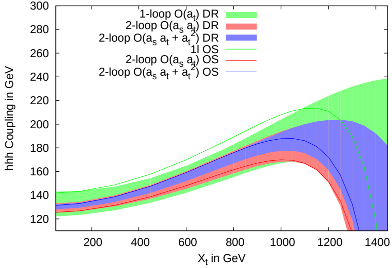


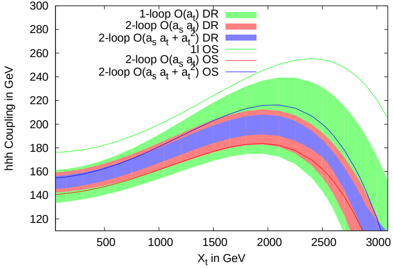
Backup: *hhh* Coupling (m_{gluino}, μ), *tb* $= 10$



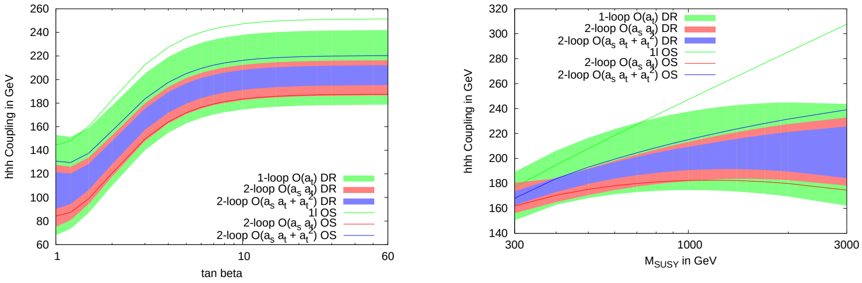


Backup: *hhh* Coupling (X_t), $tb = 10$

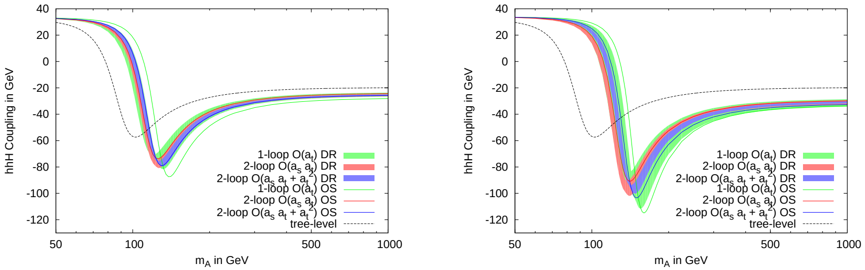




Backup: *hhh* Coupling (*tb*, M_{SUSY})



Backup: *hhH* Coupling $tb = 10$



Backup: *hhH* Coupling $tb = 2$