2-loop SUSY-EW corrections to Higgs production and decays

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in collaboration with

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Motivation

- $\mathrm{M_h}$: $125.5 \pm 0.2\ ^{+0.5}_{-0.6}$ GeV [ATLAS '13]
  $125.7 \pm 0.3 \pm 0.3$ GeV [CMS '13]
- Higs boson couples to
  - fermions: top-quarks, bottom-quarks, tau-leptons (LHC)
  - gauge bosons: W, Z, γ (LHC)
  - itself ??
- Exp. data in very good agreement with SM predictions !
- Phenom. interesting quantity:
  $\sigma \times BR$ (production rate $\times$ branching ratio)
  - New(BSM) physics through loop effects !
  - Precision measurements & calculations

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  - New(BSM) physics through loop effects !
  - Precision measurements & calculations
- This talk: top- and bottom-Yukawa corrections in the MSSM

Framework

- Effective field theory: $M_h \ll M_t \, , M_{susy}$

$$\mathcal{L} \longrightarrow \mathcal{L}_Y^{\rm eff} + \mathcal{L}_{\rm QCD}^{(5)} + \mathcal{O}(\frac{1}{M_{heavy}^2})$$

$$\mathcal{L}_Y^{\rm eff} = -\frac{h^{(0)}}{v^{(0)}} \left[C_1^0 \mathcal{O}_1^0 + \sum_q \left(C_{2q}^0 \mathcal{O}_{2q}^0 + C_{3q}^0 \mathcal{O}_{3q}^0 \right) \right] \, ,$$

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where

$$\begin{aligned}
\mathcal{O}_1^0 &= (G_{\mu,\nu}^{0,\prime,a})^2\,,\\
\mathcal{O}_{2q}^0 &= m_q^{0,\prime}\bar{q}^{0,\prime}q^{0,\prime}\,,\\
\mathcal{O}_{3q}^0 &= \bar{q}^{0,\prime}(i\not{D}^{0,\prime} - m_q^{0,\prime})q^{0,\prime}\,,
\end{aligned}$$

and the effects of heavy particles are contained in the coeff. $C_1, C_{2q}, \ldots$

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- "Matching" : low energy physics must be unchanged !!

$$\begin{aligned} \alpha_s^{(5)} &= \zeta_s\,\alpha_s^{(\rm full)} \\ m_{\rm top}^{(6)} &= \zeta_{m_{\rm top}} m_{\rm top}^{\rm full} \\ &\vdots \\ \zeta_s &= \zeta_s(\alpha_s, M_{\rm SUSY}, m_t, \mu) \\ \zeta_s, \zeta_{m_{\rm top}} &= \text{matching coefficient} \end{aligned}$$

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- Higgs decay width

$$\Gamma(h\to\bar{q}q) = \Gamma^{(0)}\left[(1+\Delta_q^{\rm SM})C_{2q}^2 + \Xi_q^{\rm SM}C_1C_{2q}\right]\,,$$

  - $\mathrm{M_h} \approx 126$ GeV: $h \to b\bar{b}$ dominant decay mode
  - $BR_i = \frac{\Gamma_i}{\sum_j \Gamma_j}$ sensitive to $\Gamma(h\to\bar{b}b)$

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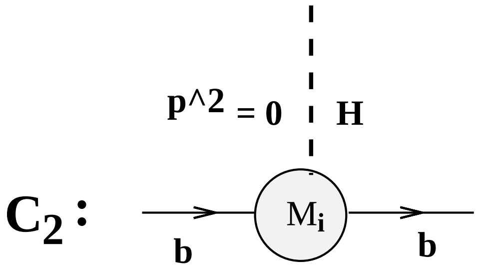
- Higgs production cross-section in gluon-fusion channel

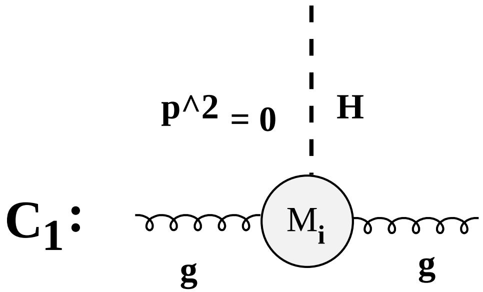
$$\sigma(pp \to h + X) = \sigma_0 \left[\left(\frac{C_1}{C_1^{\text{(1-loop)}}} \right)^2 \Sigma^{\rm SM} \right]$$

  - σ_0 contains full mass dependence at LO

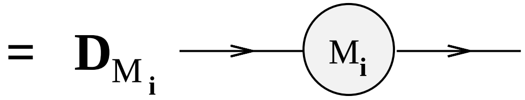
C_1 and C_2 at 2-loops in the MSSM

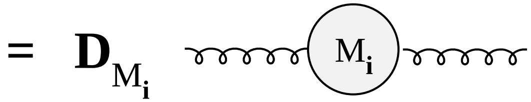
- direct calculation





- via LET





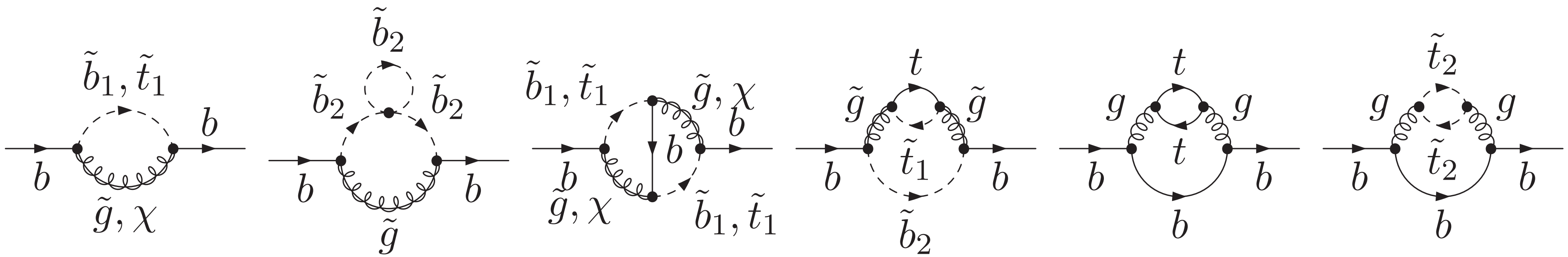
- LET in MSSM status

  SQCD: 3 loops [Kurz, Steinheuser, Zerf '12]

  SQCD+Yukawa: 2 loops [Noth and Spira '08,'10], [L.M. & Reisser '10], [Kunz and L.M. '13]

Calculation of C_{2b} at 2-loops in the MSSM

Feynman Diagrams



- Reduction to 2-loop tadpole MI [Davidichev and Tausk '93]
- Exact analytic results of $\mathcal{O}(\alpha_s^2, \alpha_s\alpha_t, \alpha_s\alpha_b)$ available

Calculation of C_{2b} at 2-loops in the MSSM

1-loop: [Hall, Rattazzi, Sarid '94], [Hempfling '94], ...,

- resummation of the $\tan\beta$-enhanced contributions ($\alpha_s^n \tan\beta$)
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$$C_2 = -\frac{-\sin\alpha}{\cos\beta} \frac{1}{1 + \alpha_s (A_b - \mu\tan\beta)\, m_{\tilde{g}}\, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) + \alpha_t A_t \mu \tan\beta\, I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)}$$

$$\times \left[1 + \alpha_s\, A_b\, m_{\tilde{g}}\, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) - \frac{1}{\tan\alpha\, \tan\beta}\, \alpha_s(-\mu\tan\beta)\, m_{\tilde{g}}\, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})\right]$$

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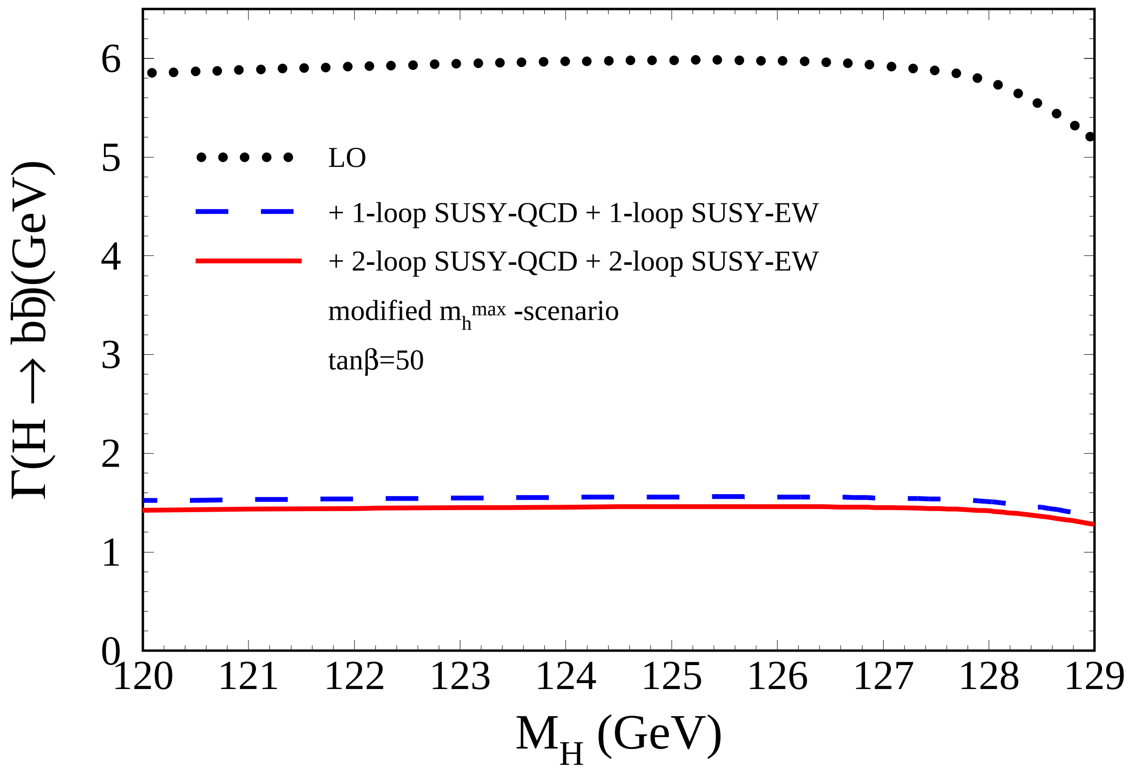
2-loops: [Noth and Spira '08, '10], [L.M. and Reisser '10], [Kunz and L.M. '13]

- residual theoretical uncertainty $\delta\Gamma(h \to b\bar b)|_{2-\text{loop}}$ up to 5%

$h \to b\bar{b}$ in the MSSM at 2-loops

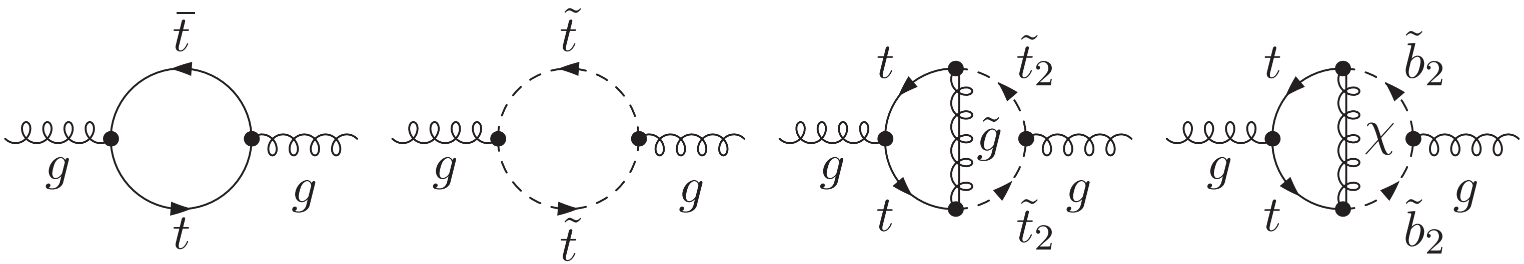


Modified $m_h^{\max}$ scenario:

$A_t = A_b = 1500$ GeV, $\tan\beta = 50$, $M_A = 1000$ GeV, $M_{\tilde{g}} = 860$ GeV, $\mu = 1000$ GeV, $M_{\tilde{q}_1} = M_{\tilde{q}_2} = 1040$ GeV, $M_{\tilde{t}_1} = 370$ GeV, $M_{\tilde{t}_2} = 1045$ GeV

Calculation of C_1 at $\mathcal{O}(\alpha_s\alpha_t)$ in the MSSM

Feynman Diagrams



- Exact analytic results of $\mathcal{O}(\alpha_s\alpha_t)$ available

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C_1 in SQCD

- LO[$\mathcal{O}(\alpha_s)$]: [Djouadi, Graudenz, Spira, Zerwas '95]
- NLO[$\mathcal{O}(\alpha_s^2)$] : [Dawson, Djouadi, Spira '96], [Harlander and Steinhauser '03, '04], [Bonciani, Degrassi, Vicini '07], [Muhlleitner and Spira '07], [Degrassi and Slavich '08], [Anastasiou, Beerli, Daleo'08], [Muhlleitner, Rzehak, Spira '08]
- NNLO[$\mathcal{O}(\alpha_s^3)$]: [Pak, Steinhauser, Zerf '10, 12]

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C_1 at ($\mathcal{O}(\alpha_s\alpha_t)$) [Kunz and L:M: '13] (preliminary!!)

- Modified $m_h^{\max}$ scenario: $< 1\%$ w.r.t. LO SQCD contribution
- Heavy SUSY spectrum: negligible

Top-Yukawa and $m_{\rm top}(\mu)$

- $\alpha_t(\mu) \sim m_{\rm top}(\mu)$ [Hempfling and Kniehl '94]
- Calculation of $m_{\rm top}^{\rm MSSM}(\mu \approx M_{\rm SUSY} > 1\ \text{TeV})$

Top-Yukawa and $m_{\mathrm{top}}(\mu)$

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- Calculation of $m_{\mathrm{top}}^{\mathrm{MSSM}}(\mu \approx M_{\mathrm{SUSY}} > 1$ TeV$)$
  - $m_{\mathrm{top}}^{\mathrm{MSSM}}(\mu)/M_{\mathrm{top}}^{\mathrm{OS}}$ [S. Martin '04] $\Rightarrow$ TSIL code [Martin and Robertson '05]

Large logs $\ln\left(\frac{\mu^2}{m_{\mathrm{top}}^2(\mu)}\right)$ for $\mu > 1$ TeV $\Rightarrow$ numerical instabilities

Δm_{top}	SM($\mu = M_{\mathrm{top}}^{\mathrm{OS}}$)	MSSM ($\mu = M_{\mathrm{SUSY}} = 6$ TeV)
1 loop	9.8 GeV	39.8 GeV
2 loops	1.7 GeV	5.3 GeV
3 loops	0.5 GeV	???

To be compared to $\Delta M_{\mathrm{top}}^{\mathrm{exp}} \approx 1$ GeV

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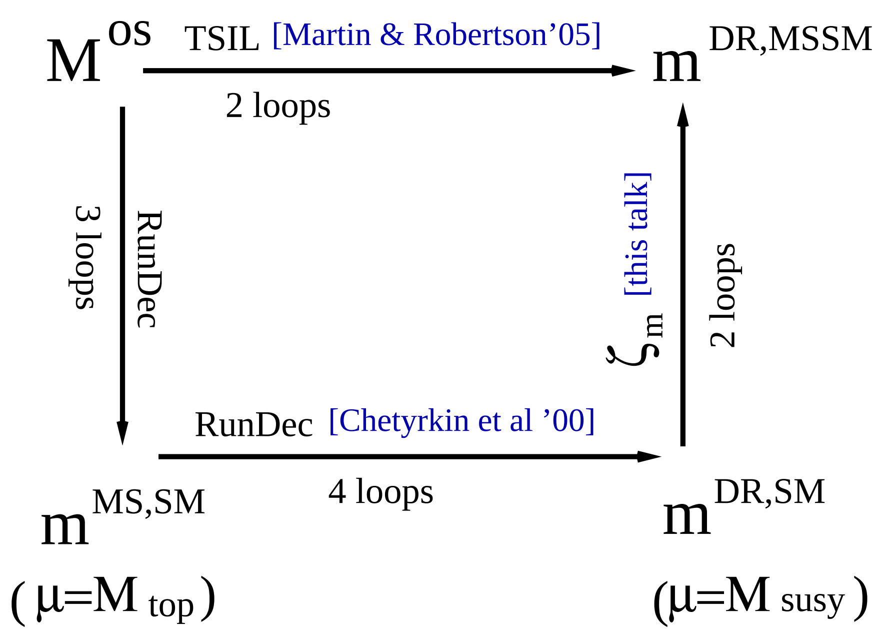
  - Resume the large logs

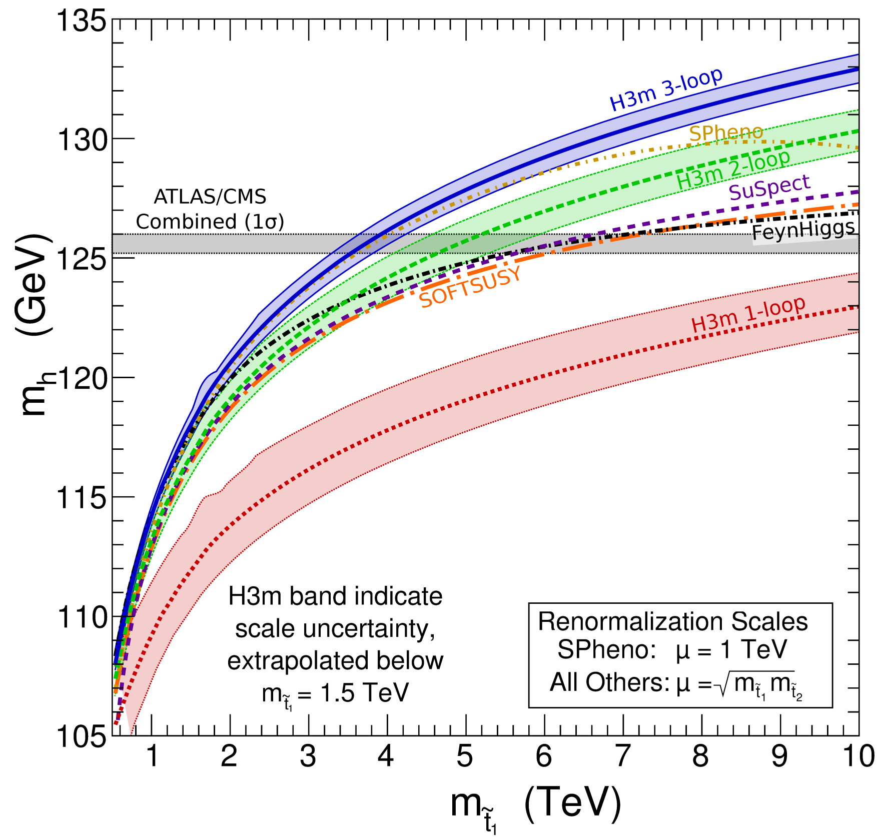


$\Delta m_{\rm top}^{\rm MSSM}(\mu = 6$ TeV$) = 0.75$ GeV

$m_{\rm top}(\mu)$ and $M_h^{\rm 3loops}$

- 2. method implemented in H3m [Kant, Harlander, L.M., Steinhauser '10]
- $M_h^{\rm 3loops}$ for heavy SUSY spectrum

[Feng, Kant, Profumo, Sanford '13]



Conclusions

- 2-loop top- and bottom-Yukawa corrections at most at the percent level w.r.t. LO contributions
- Resummation of large logs required for the calculation of top-Yukawa coupling at high energies