Higgs boson production in gluon fusion to NNLO in the MSSM

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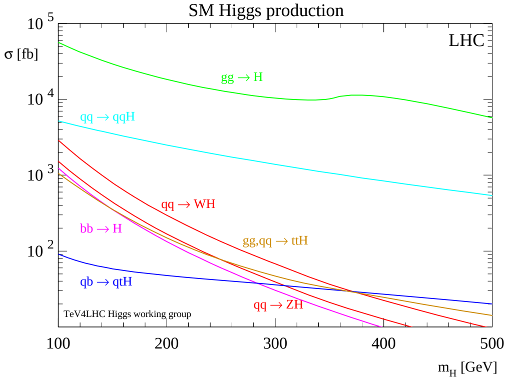
[arXiv:1012.0639 [hep-ph]]

Overview

1. $gg \to H$ (SM)
2. $gg \to h^0$(MSSM)
3. Calculation in SUSYQCD
4. Results
5. Summary and Outlook

Motivation

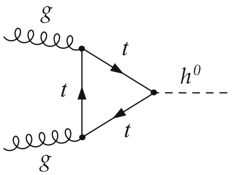
- Theoretical SM prediction of $\sigma_{gg\to H}$ [PDG 08]:



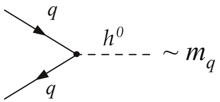
- What happens to the $gg \to H$ (gluon fusion) curve considering the MSSM as underlying theory?

$gg \to H$ at LO

- Calculation of $\sigma_{gg\to H}$ requires the matrix element $\mathcal{M}_{gg\to H}$:



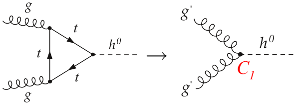
- Dominant contribution comes from heavy top quark loops (large Yukawa coupling):



$$m_t = 173.3 \text{ GeV}$$
$$\gg$$
$$m_q = \{m_u, m_d, m_s, m_c, m_b\} \approx 0$$

$gg \to H$ at higher loop-orders

- NLO result: [Dawson 91, Spira et al. 91, 95]
- NNLO result has been obtained in the framework of an effective field theory (EFT): [Harlander, Kilgore 02, Anastasiou, Melnikov 02, Ravindran .. 03]



- NNLO full theory calculation: [Harlander, Ozeren 09, Pak, Rogal, Steinhauser 09]
  $\to$ EFT predictions are reliable.
- Resummations [Actis, Catani, Grazzini, Moch, Neubert, Vogt ...]

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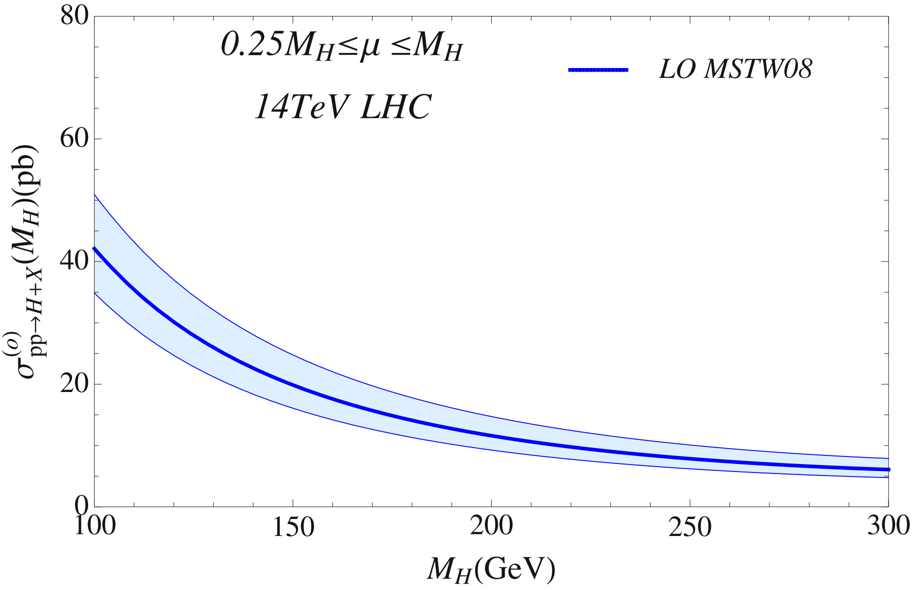

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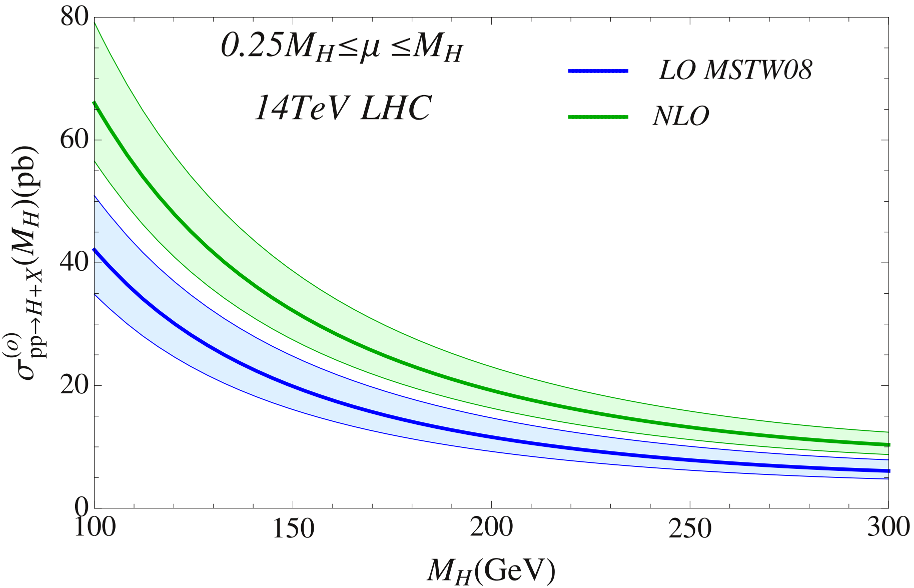

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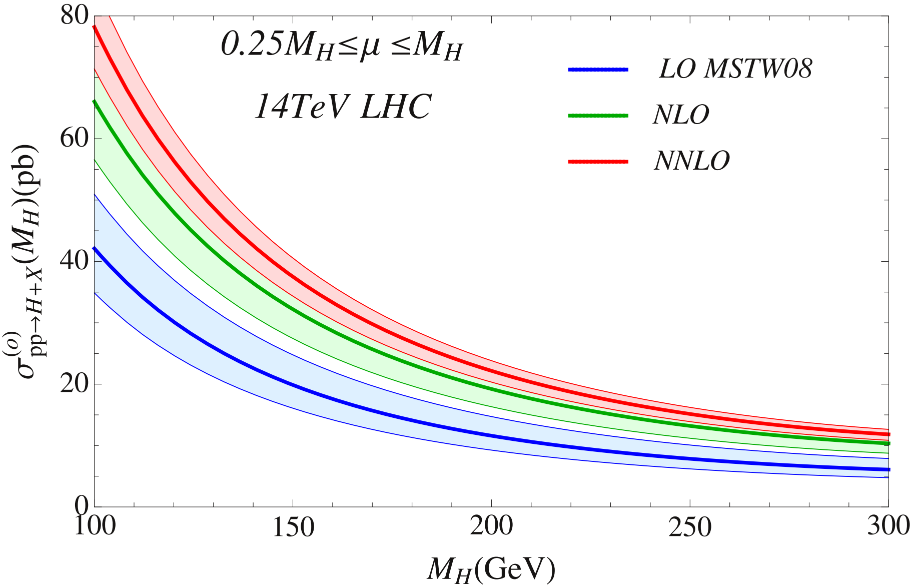
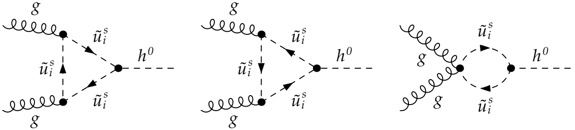
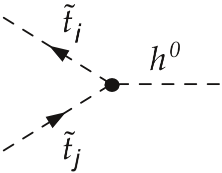


$gg \to h^0$ at LO

- QCD + additional squark diagrams:



- Feynman rule for $h_0\tilde{t}\tilde{t}$ vertex: $\quad I_3(\mathrm{SU}_2) = +\frac{1}{2} \quad \Omega^t_{i,j,k,l} = U^t_{i,j}U^t_{k,l}$



$$-i\sqrt{\sqrt{2}G_F s_\beta^{-1}}\times$$
$$\Big\{ + \left(2c_\alpha m_t^2 - \tfrac{4}{3}m_Z^2 s_\beta s_w^2 s_{\alpha+\beta}\right)\Omega^t_{i,2,j,2}$$
$$+ \left(2c_\alpha m_t^2 + \tfrac{1}{3}m_Z^2 s_\beta \left(4s_w^2 - 3\right) s_{\alpha+\beta}\right)\Omega^t_{i,1,j,1}$$
$$+ m_t\left(A_t c_\alpha + s_\alpha \mu_{\mathrm{SUSY}}\right)\left(\Omega^t_{i,1,j,2} + \Omega^t_{i,2,j,1}\right)\Big\}$$

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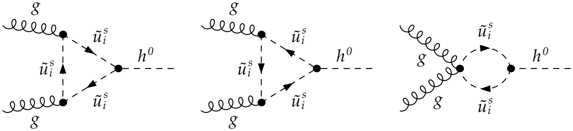
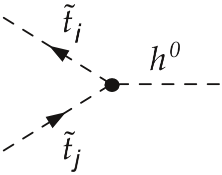


- Feynman rule for $h_0\tilde{t}\tilde{t}$ vertex:



$$\propto \Big\{ m_t^2(\dots) + m_t\left(A_t \cdots + \mu_{\text{SUSY}} \cdots\right) + m_Z^2(\dots) \Big\}$$

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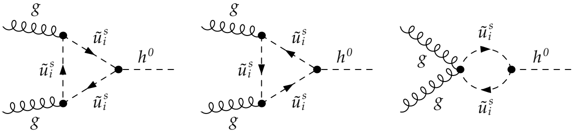

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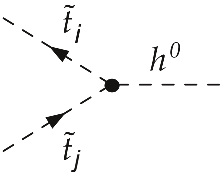


$$\propto \left\{ m_t^2 (\ldots) + m_t (A_t \cdots + \mu_{\mathrm{SUSY}} \cdots) + m_Z^2 (\ldots) \right\}$$

- No m_t terms in $h_0\tilde{b}\tilde{b}$ vertex:
  $\rightarrow$ neglecting this coupling (ok for small $\tan\beta$)

$gg \to h^0$ at higher loop-orders

- NLO SUSY-QCD:
  $\to$ up to 3 scales in one diagram!
  $\to$ no exact analytic results available.

- $\to$ First: EFT predictions where $m^2_{h^0} \ll \{m_t,\, m_{\tilde{t}_i},\, m_{\tilde{q}_i},\, m_{\tilde{g}}\}$ holds.
  [Harlander, Steinhauser 04]

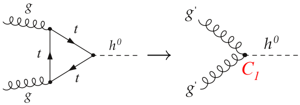
- NLO q & $\tilde{q}$ result: [Aglietti, Bonciani, Degrassi, Vicini 07, Mühlleitner,Spira 08]
- Numerical full theory analysis: [Anastasiou, Beerli, Daleo 07]
- Complete NLO analysis: [Harlander, Hofmann, Mantler 10]

- Estimation of NNLO contribution exists. [Harlander, Steinhauser 03]

- NNLO EFT calculation ?

Effective field theory and matching coefficient

- Integrate out all heavy masses:



$$\mathcal{L}_{\text{SUSY-QCD}} \rightarrow \mathcal{L}_{\text{EFT}} = \underbrace{-\frac{h^0}{v} C_1 \frac{1}{4} G_{a,\,\mu\nu} G_a^{\mu\nu}}_{C_1 \mathcal{O}_1} + \dots .$$

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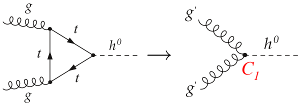

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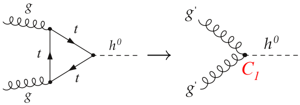

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EFT	MSSM
$h^0,\ g,\ q,\ c$	$h^0,\ c,\ g,\ \tilde{g},\ q,\ \tilde{q},\ t,\ \tilde{t},\ \epsilon$
$m_{h^0},\ m_q = 0$	$m_{h^0},\ m_t,\ m_{\tilde{g}},\ m_{\tilde{q}},\ m_{\tilde{t}},\ m_\epsilon$
DREG	DRED
$\alpha_s^{(5)\ \overline{\text{MS}}}$	$\alpha_s^{(6)\ \overline{\text{DR}}}$

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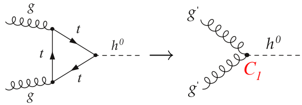

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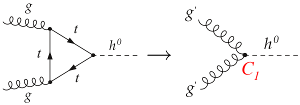

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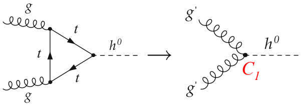

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$$\underset{④}{G^\mu} = \underset{ⓓ}{G^\mu} + \underset{2\epsilon}{\epsilon^\mu}$$

- $\rightarrow$ Require hierarchy: $m_{h^0} \ll \left(m_\epsilon \ll m_t,\ m_{\tilde{g}},\ m_{\tilde{q}},\ m_{\tilde{t}}\right)$

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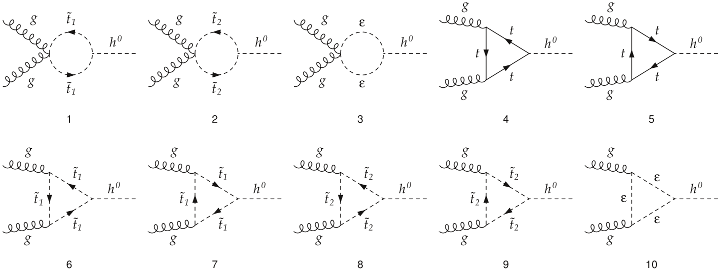
  - 

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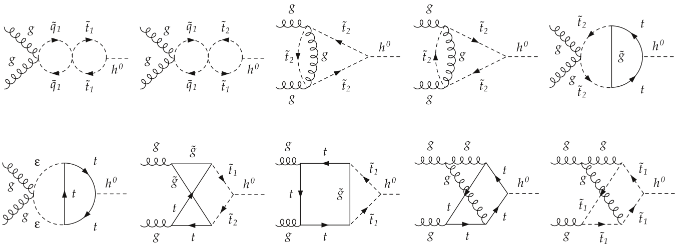
  - 

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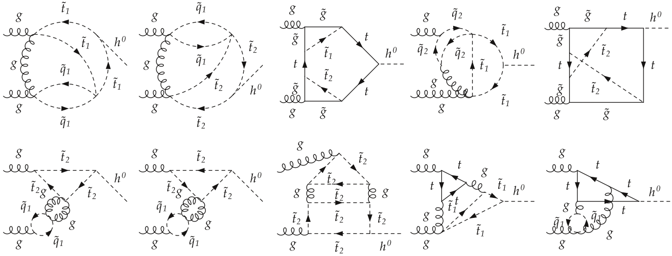
  - 

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- → fully automated algebraic calculation recommended!

  QGRAF [Nogueira]
  q2e [Seidensticker]
  exp [Seidensticker]
  MATAD [Steinhauser]
  FORM [Vermaseren]

Renormalization

- Counterterms and decoupling constants:

$$\left.\begin{array}{c} \delta\alpha_s^{\overline{\mathrm{DR}}} \\ \delta m_t^{\overline{\mathrm{DR}}} \\ \delta m_{\tilde{t}_i}^{\overline{\mathrm{DR}}} \\ \delta\theta_t^{\overline{\mathrm{DR}}} \\ \delta\Lambda_\epsilon^{\mathrm{NC}} \\ \zeta_3 \\ \zeta_g \end{array}\right\}\text{2-loop} \qquad \left.\begin{array}{c} \delta m_{\tilde{g}}^{\overline{\mathrm{DR}}} \\ \delta m_{\tilde{q}_i}^{\overline{\mathrm{DR}}} \\ \delta m_\epsilon^{\mathrm{OS}} \end{array}\right\}\text{1-loop}$$

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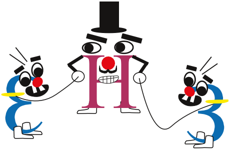

First approximation for C_1

- For the mass hierarchy $m_t \ll m_{\text{SUSY}} \stackrel{!}{=} m_{\tilde{t}_i} = m_{\tilde{q}_i} = m_{\tilde{g}}$ we obtain:

$$
\begin{aligned}
C_1^{\text{MSSM}} = & -\frac{\alpha_s^{(5)\,\overline{\text{MS}}}}{3\pi}\frac{c_\alpha}{s_\beta}\Bigg\{1+\frac{x_{ts}^2}{2}+\frac{\alpha_s^{(5)\,\overline{\text{MS}}}}{\pi}\left[\frac{11}{4}-\frac{1}{3}\left(t_\alpha+\frac{1}{t_\beta}\right)\frac{\mu_{\text{SUSY}}}{m_{\text{SUSY}}}+\left(\frac{23}{12}+\frac{5}{12}l_{\text{susy}}-\frac{5}{12}l_{\text{t}}\right)x_{ts}^2\right] \\
& +\left(\frac{\alpha_s^{(5)\,\overline{\text{MS}}}}{\pi}\right)^2\Bigg[\frac{2777}{288}+\frac{19}{16}l_{\text{t}}+\left(-\frac{67}{96}+\frac{1}{3}l_{\text{t}}\right)n_l \\
& +\left(-\frac{85}{54}-\frac{85}{108}l_{\text{susy}}-\frac{1}{18}l_{\text{t}}+\left(-\frac{1}{18}+\frac{1}{12}l_{\text{susy}}\right)n_l\right)\left(t_\alpha+\frac{1}{t_\beta}\right)\frac{\mu_{\text{SUSY}}}{m_{\text{SUSY}}} \\
& +\left(\frac{30779857}{648000}-\frac{2429}{10800}l_{\text{susy}}-\frac{475}{288}l_{\text{susy}}^2-\frac{24007}{10800}l_{\text{t}}+\frac{26}{45}l_{\text{susy}}l_{\text{t}}-\frac{377}{1440}l_{\text{t}}^2-\frac{15971}{576}\zeta_3\right. \\
& \left.+\left(-\frac{3910697}{216000}+\frac{63}{4}\zeta_3+\frac{4907}{4800}l_{\text{susy}}+\frac{131}{576}l_{\text{susy}}^2+\frac{313}{14400}l_{\text{t}}-\frac{101}{1440}l_{\text{susy}}l_{\text{t}}+\frac{3}{320}l_{\text{t}}^2\right)n_l\right)x_{ts}^2\Bigg]\Bigg\} \\
& +\mathcal{O}\left(x_{ts}^4\right)+\mathcal{O}\left(\frac{\mu_{\text{SUSY}}}{m_{\text{SUSY}}}x_{ts}^2\right). \qquad x_{ts}=\frac{m_t}{m_{\text{SUSY}}},\ l_{\text{susy}}=ln\left(\frac{\mu^2}{m_{\text{SUSY}}^2}\right),\ l_{\text{t}}=ln\left(\frac{\mu^2}{m_t^2}\right).
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\end{aligned}
$$

- $\lim_{m_{\mathrm{SUSY}}\to\infty} C_1^{\mathrm{MSSM}} = \frac{c_\alpha}{s_\beta} C_1^{\mathrm{SM}}$ ✓

First results

- Fix MSSM parameters:

$$M_{A^0} = 1000 GeV\,, \quad \tan\beta = 5\,, \quad \mu_{\mathrm{SUSY}} = 200\ \mathrm{GeV}\,.$$

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$$M_{h^0}(m_{\text{SUSY}})\,, \quad \sin\alpha(m_{\text{SUSY}})\,, \quad m_t^{\overline{DR}}(m_{\text{SUSY}})$$

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$$\rightarrow 89\text{ GeV} \leq M_{h^0} \leq 119\text{ GeV} \quad \text{for} \quad 200\text{ GeV} \leq m_{\text{SUSY}} \leq 2\text{ TeV}$$

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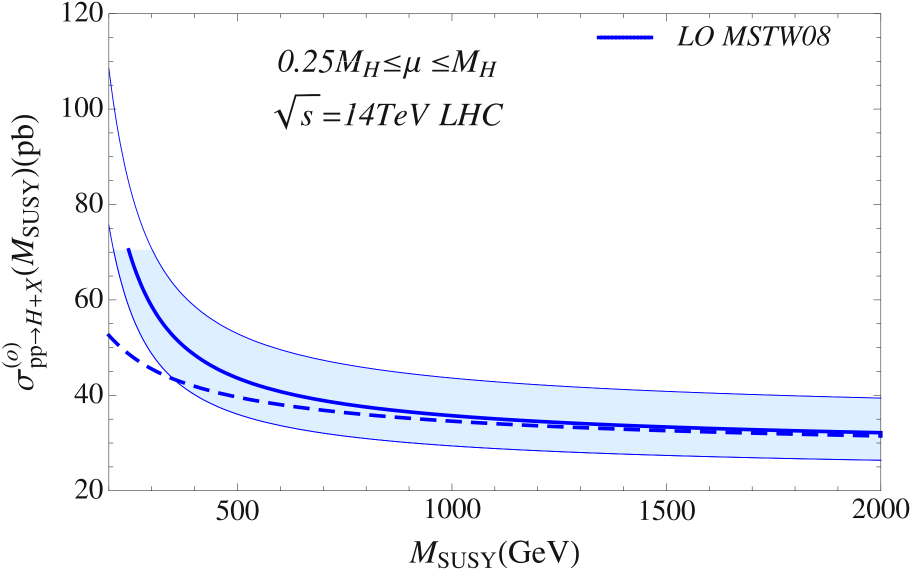
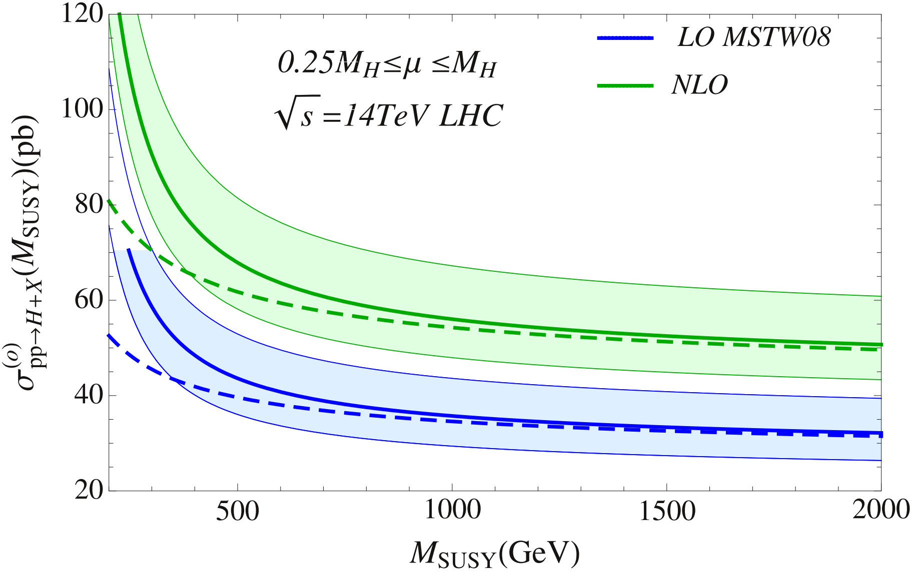
$\rightarrow$ 89 GeV $\leq M_{h^0} \leq$ 119 GeV for 200 GeV $\leq m_{\text{SUSY}} \leq$ 2 TeV
$\rightarrow \alpha \approx -0.2 \rightarrow \frac{\cos\alpha}{\sin\beta} \approx 0.99 \rightarrow$ SM like $h^0\,tt$-coupling

First results



First results



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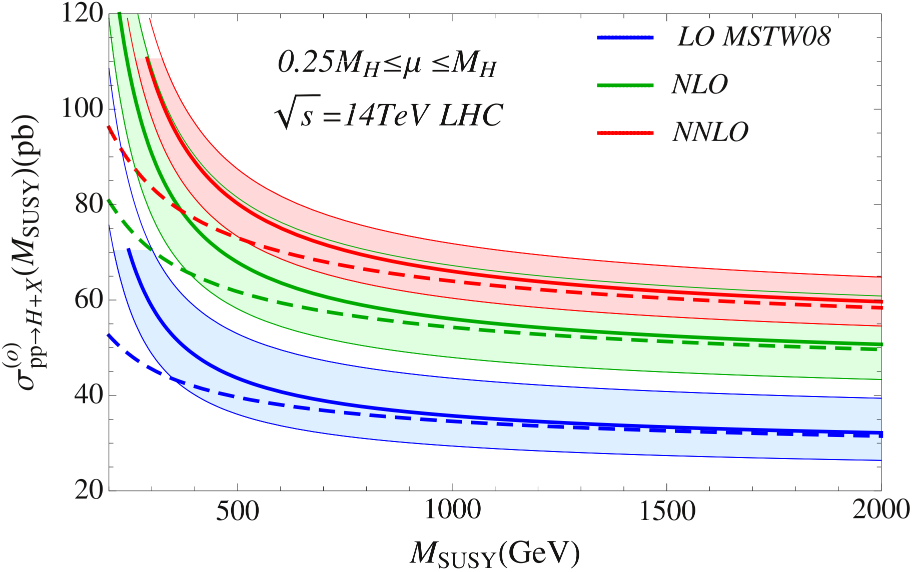

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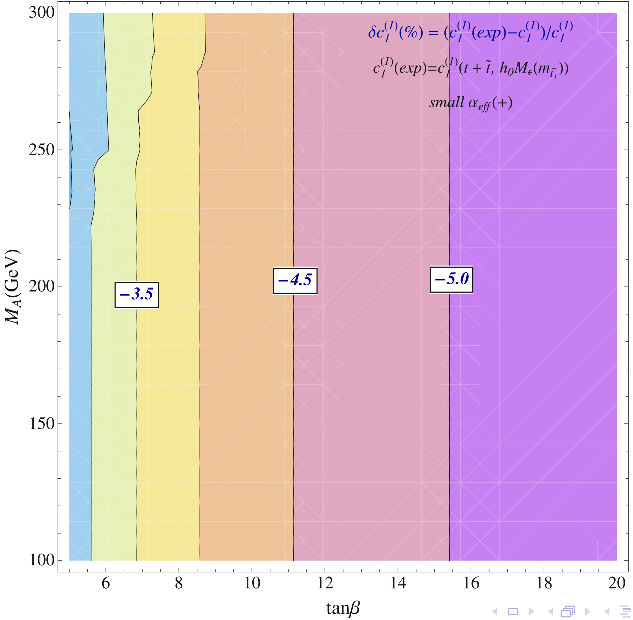
Results

PRELIMINARY



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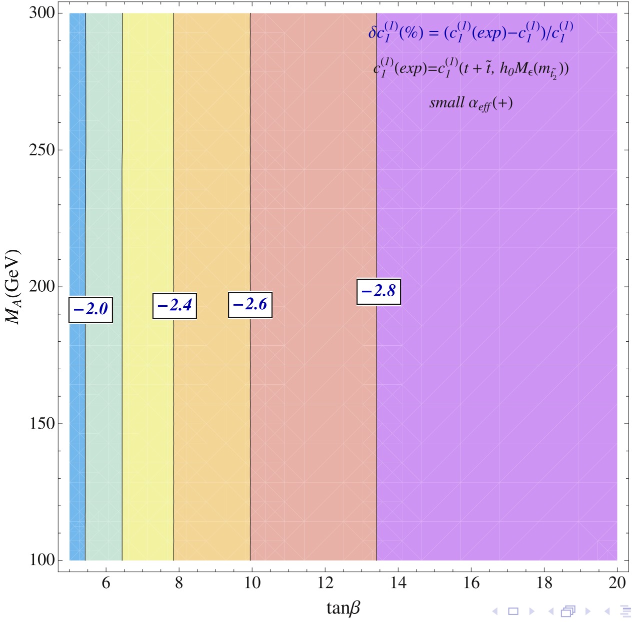

PRELIMINARY

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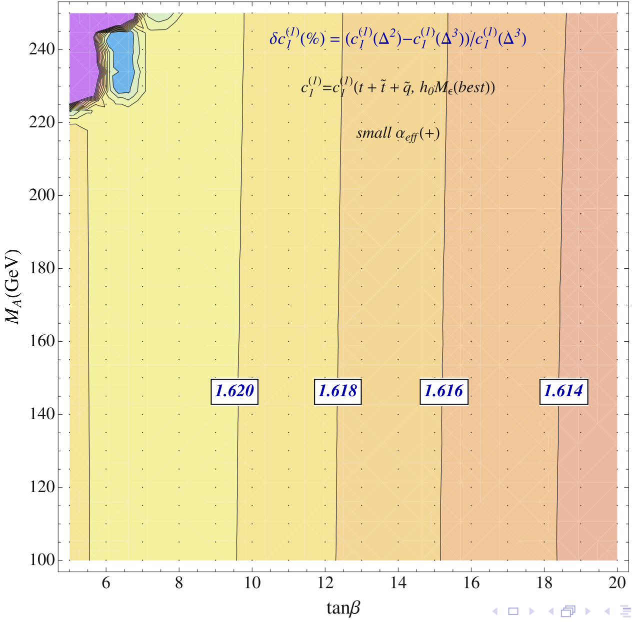

PRELIMINARY

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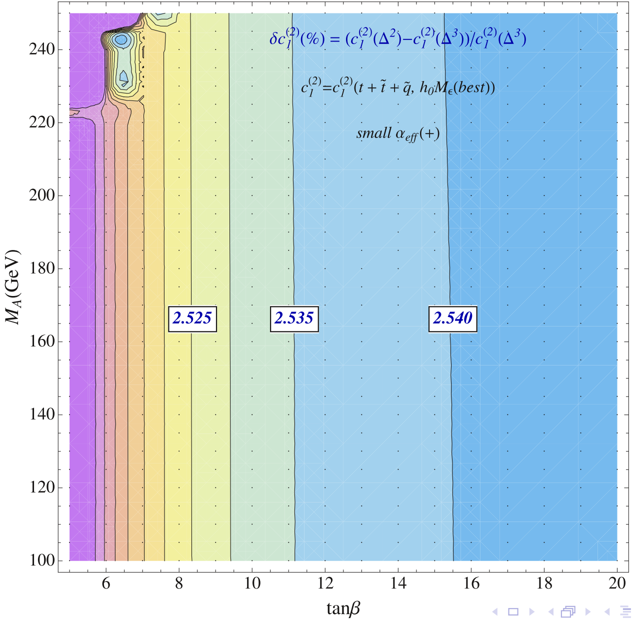

PRELIMINARY

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4 Summary and Outlook

- QCD scale dependence for $\sigma_{pp\to H+X}$ is large.
  $\to$ NNLO calculation required.
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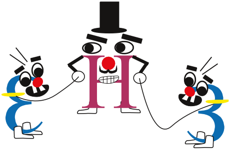
Thanks for your attention!

Excursion with ϵ-scalars



- ϵ-scalars induce additional terms in $\mathcal{L}$:

$$\mathcal{L}_\epsilon = -\frac{1}{2}\left(m_\epsilon^0\right)^2 \epsilon_\sigma^{0,\,a}\epsilon_\sigma^{0,\,a} - \frac{h^0}{v^0}\left(\Lambda_\epsilon^0\right)^2 \epsilon_\sigma^{0,\,a}\epsilon_\sigma^{0,\,a} + \dots .$$

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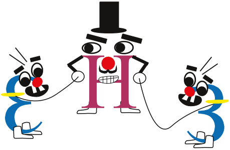

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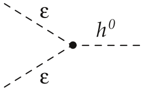
$\rightarrow$ 

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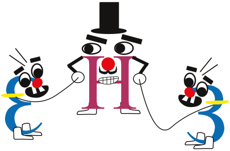

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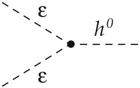

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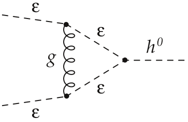

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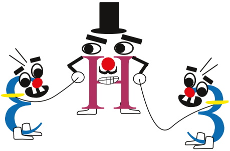

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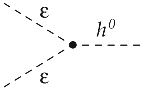
$\rightarrow$ 

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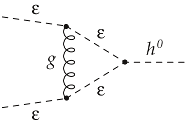

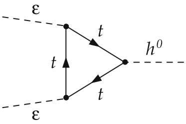

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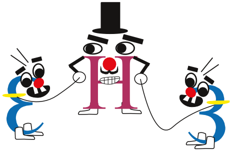

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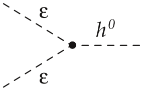
$\rightarrow$ 

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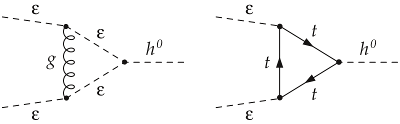

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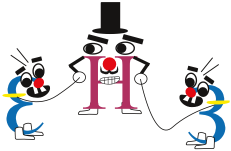

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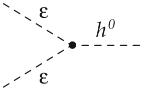
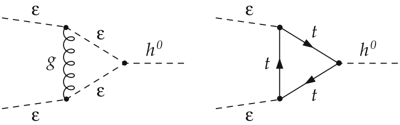
$\rightarrow$  $\sim \left(\Lambda_\epsilon^0\right)^2$



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- Check: $C_1^{\text{SM}}\left(\text{DRED}, \alpha_s^{(5)\,\overline{\text{MS}}}\right) = C_1^{\text{SM}}\left(\text{DREG}, \alpha_s^{(5)\,\overline{\text{MS}}}\right)$. ✓

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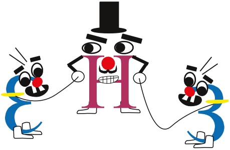

Calculating Cross Section

- Scale invariance: $\frac{d}{d\mu}\left(C_1(\mu)\mathcal{O}_1(\mu)\right) = 0 + \mathcal{O}(\alpha_s^4), \qquad \frac{d}{d\mu}C_1(\mu) \neq 0.$

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- Use scale invariant C_g and $\mathcal{O}_g$ [Chetyrkin, Kniehl, Steinhauser 97]:

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- Keep hard scale μ_h fixed, vary soft scale μ_s possible.