SUSY QCD corrections to Higgs boson production via gluon gluon fusion

M. Margarete Mühlleitner
(LAPTH Annecy-Le-Vieux)
Coll. with M. Spira

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Introduction

Gluon gluon fusion: dominant production process at existing and future hadron colliders.

QCD corrections have been calculated at

NLO (SM, MSSM): $K \approx 1.5 - 1.7$ — Spira, Djouadi, Graudenz, Zerwas; Dawson; Kauffman, Schaffer

NNLO (squarks, gluinos decoupled) — Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, vanNeerven

NLO SUSY QCD corrections: known so far in the heavy squark, gluino limit.

Dawson, Djouadi, Spira
Harlander, Steinhauser
Harlander, Hofmann

$\mathbf{m_{\tilde{Q}} < 400}$ **GeV:** squarks play a significant role $\rightsquigarrow$
calculation of the full squark mass dependence at NLO.

The MSSM Higgs sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\stackrel{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

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Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;...

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Modified couplings with respect to the SM: (decoupling limit) Gunion,Haber

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \longrightarrow 1$	$-s_\alpha/c_\beta \longrightarrow 1$	$s_{\beta-\alpha} \longrightarrow 1$
H	$s_\alpha/s_\beta \longrightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \longrightarrow \text{tg}\beta$	$c_{\beta-\alpha} \longrightarrow 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

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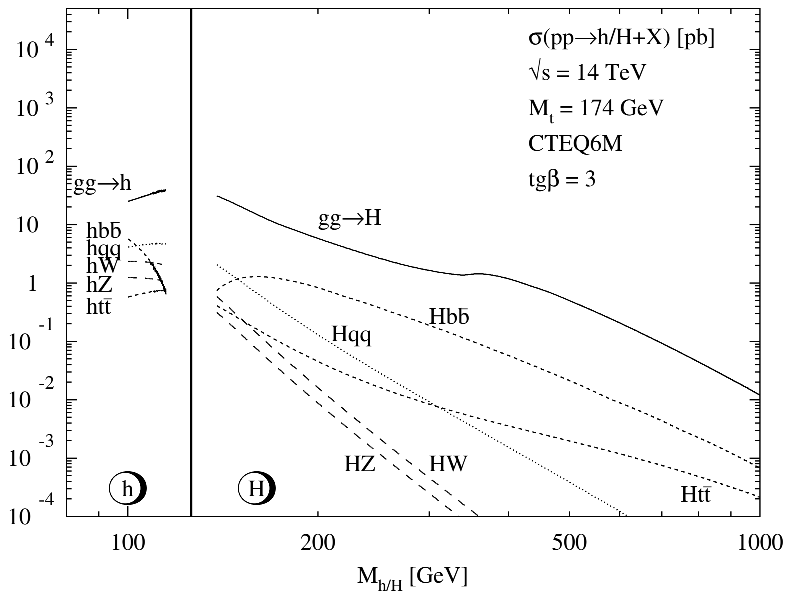
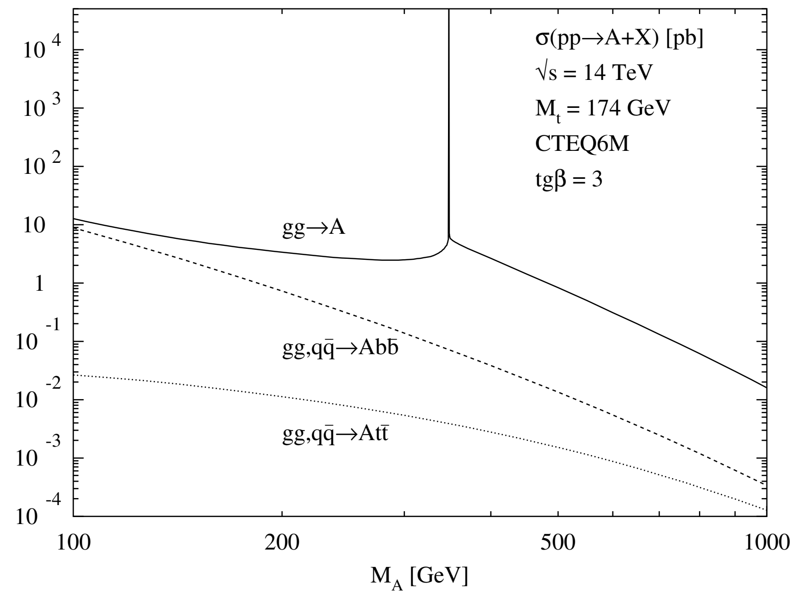
Dominant production mechanism at the LHC: $gg \rightarrow \Phi$

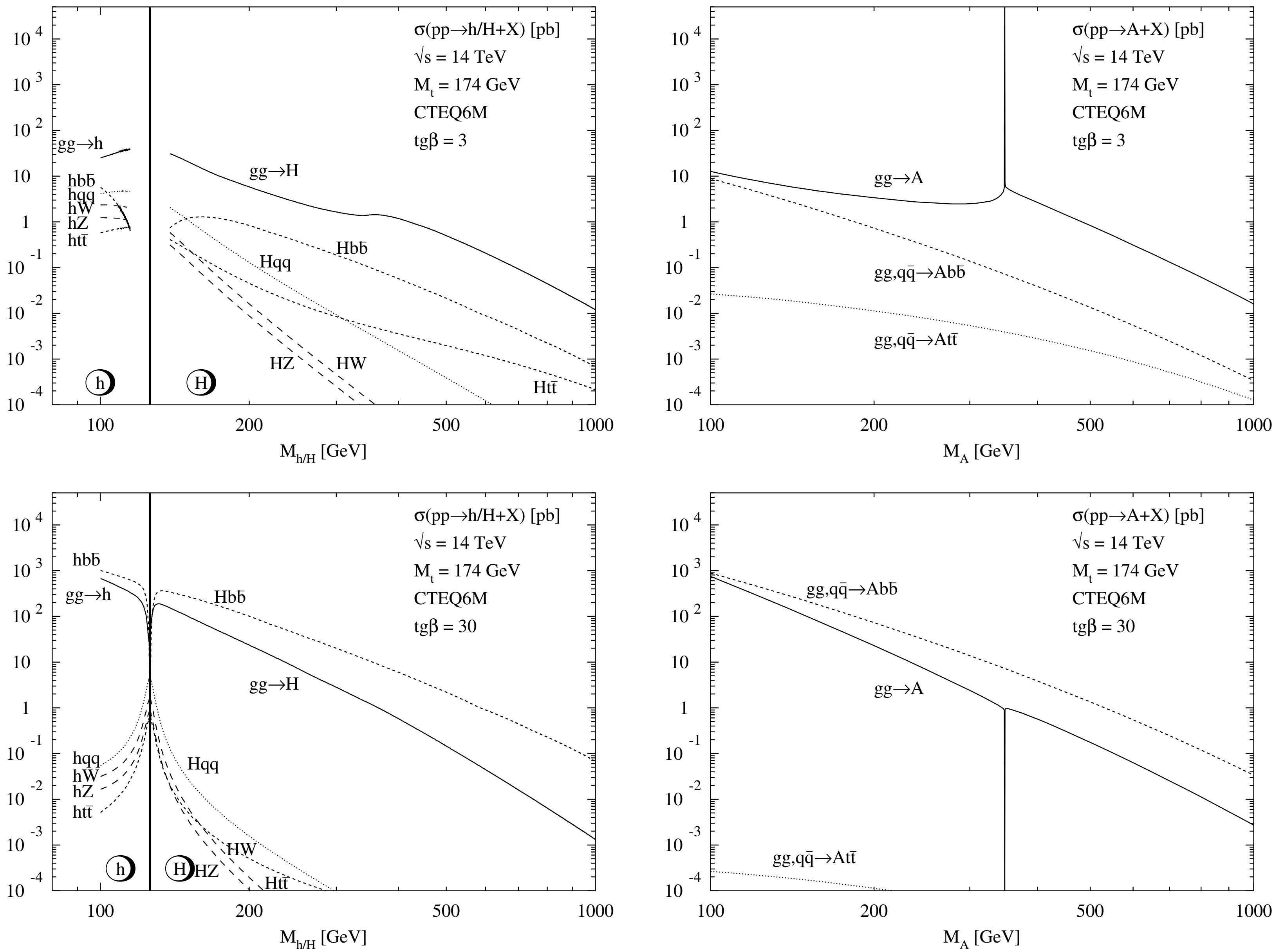
$\Phi b\bar{b}$ for $\tan\beta$ large

MSSM Higgs boson production at the LHC



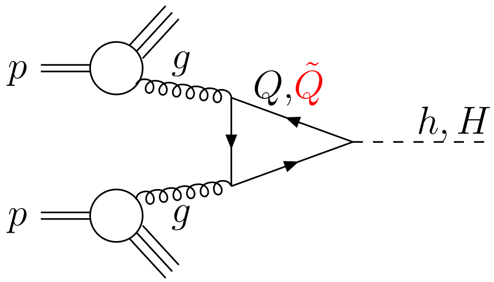


MSSM Higgs boson production at the LHC



$gg \to H, h$ at leading order

Lowest order - 1 loop



$$\sigma(pp \to \Phi + X) = \sigma_0 \tau_\Phi \frac{d\mathcal{L}^{gg}}{d\tau_\Phi} \qquad \tau_\Phi = \frac{M_\Phi^2}{s}$$

$$\sigma_0 = \frac{G_F \alpha_S^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^\Phi F(\tau_Q) - \sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}}) \right|^2 \qquad \tau_{Q,\tilde{Q}} = \frac{4m_{Q,\tilde{Q}}^2}{M_\Phi^2}$$

$$F(\tau_Q) = \frac{3}{2}\tau_Q \left[1 + (1-\tau_Q) f(\tau_Q)\right]$$

$$\tilde{F}(\tau_{\tilde{Q}}) = \frac{3}{4}\tau_{\tilde{Q}} \left[1 - \tau_{\tilde{Q}} f(\tau_{\tilde{Q}})\right]$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \end{cases}$$

Remarks:
- MSSM: $\tan\beta \uparrow \Rightarrow b/\tilde{b} \uparrow + t/\tilde{t} \downarrow$
- heavy quarks dominant
  $\Phi QQ \sim m_Q \rightsquigarrow t, b$
- $g_{\tilde{Q}}^\Phi \sim m_Q^2/m_{\tilde{Q}}^2 \rightsquigarrow \tilde{t}, \tilde{b}$
- $gg \to A$ no $\tilde{Q}$ contribution at LO

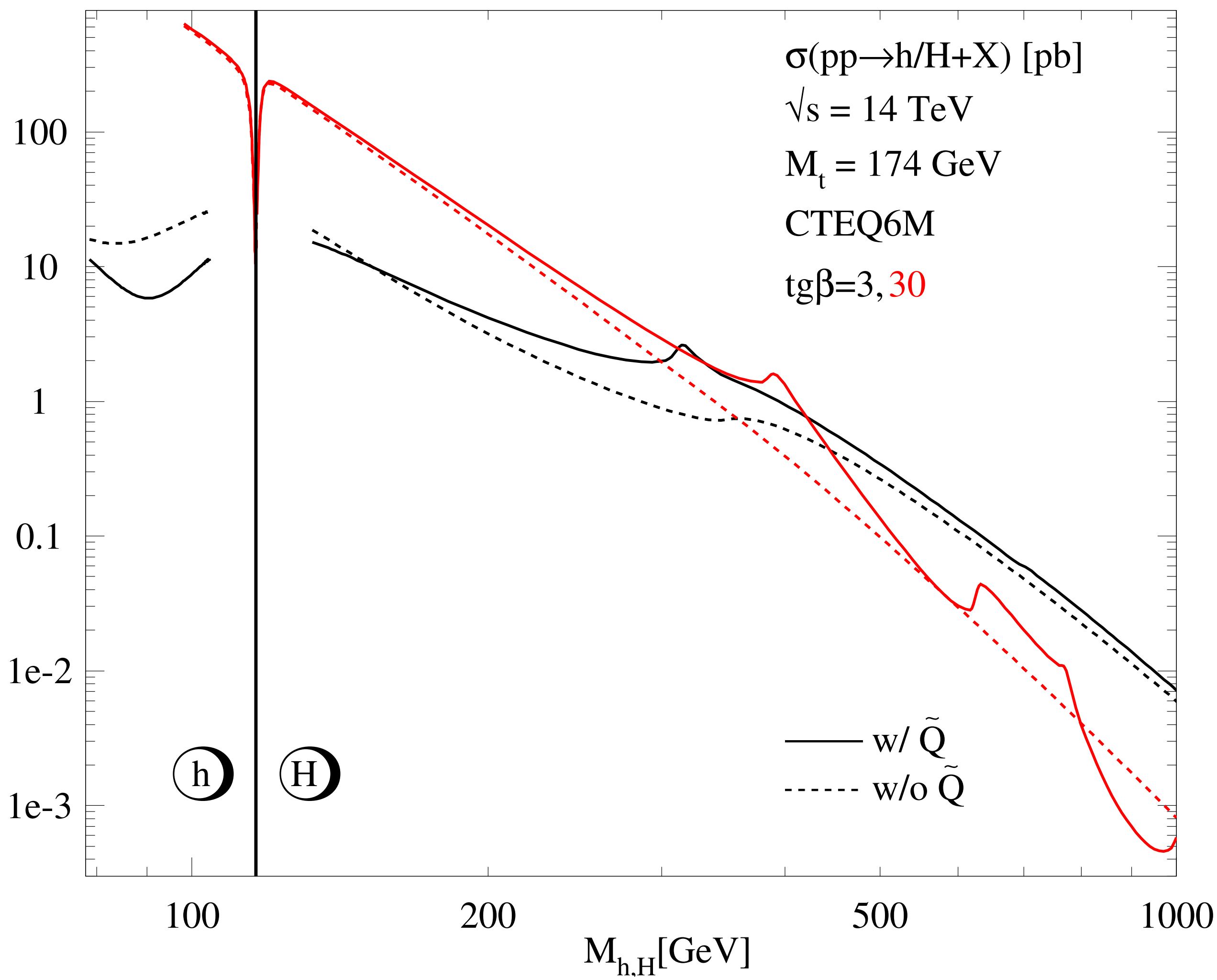
The scenario

The gluophic Higgs scenario Carena, Heinemeyer, Wagner, Weiglein

$m_t = 174$ GeV, $M_{SUSY} = 350$ GeV, $\mu = M_2 = 300$ GeV, $A_b = A_t = -670$ GeV

$\tan\beta = 3$		$\tan\beta = 30$	
$m_{\tilde{t}_1} = 156$ GeV	$m_{\tilde{t}_2} = 516$ GeV	$m_{\tilde{t}_1} = 200$ GeV	$m_{\tilde{t}_2} = 502$ GeV
$m_{\tilde{b}_1} = 346$ GeV	$m_{\tilde{b}_2} = 358$ GeV	$m_{\tilde{b}_1} = 315$ GeV	$m_{\tilde{b}_2} = 387$ GeV

The LO cross section w/ and w/o Squarks



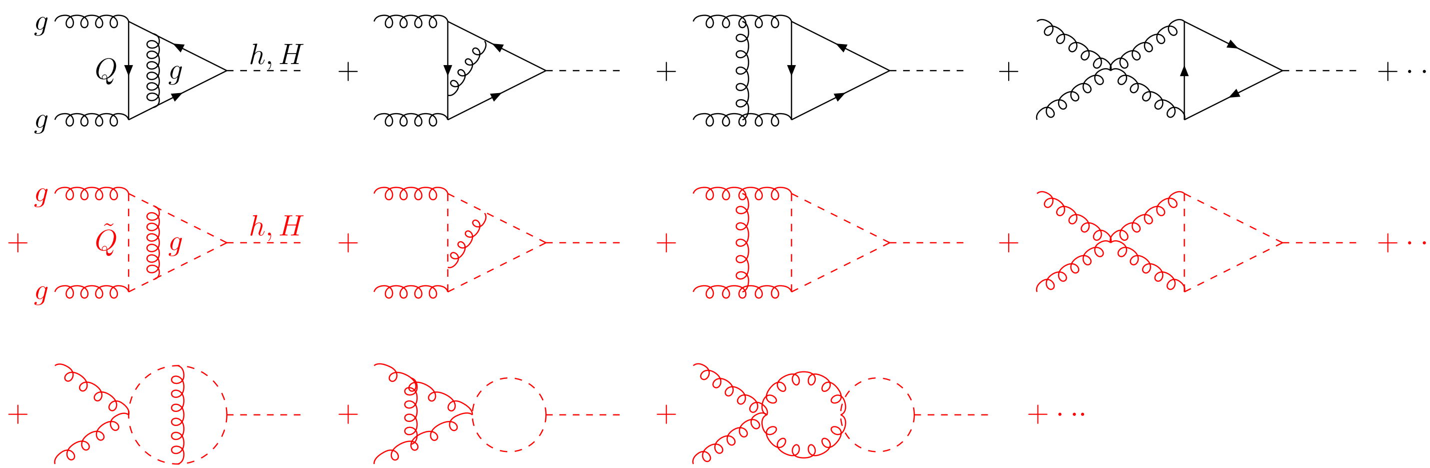
QCD corrections

$$\boxed{\Delta\hat{\sigma}_{ij} = \sigma_0 \Big\{ C_{ij}\delta(1-\hat{\tau}) + D_{ij}\Theta(1-\hat{\tau}) \Big\} \frac{\alpha_s}{\pi}} \qquad \hat{\tau} = \frac{M_\Phi^2}{\hat{s}}$$

↗ virtual+soft corrections

↑ real corrections

Virtual corrections [2 loops, no gluino contributions]



UV-,IR-,Coll-singularities in $n = 4 - 2\epsilon$ dimensions.

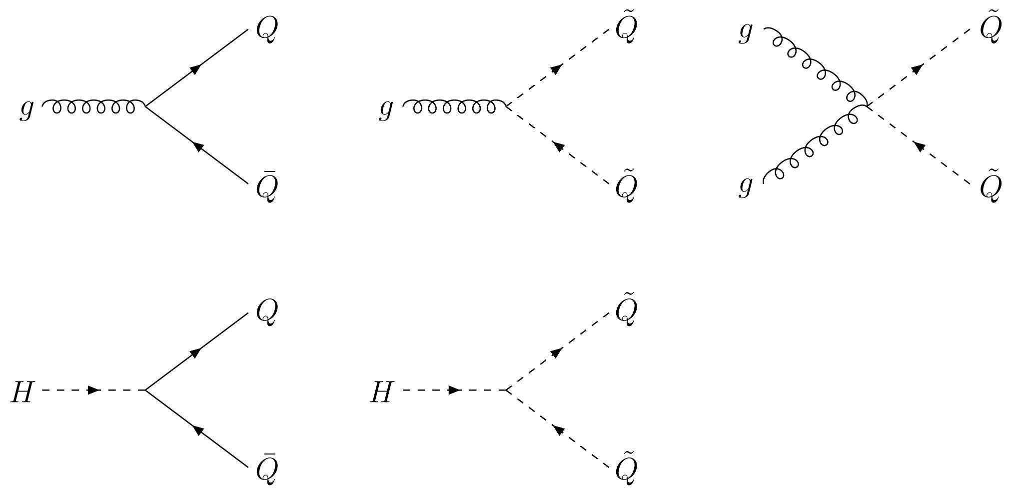
Renormalization

$\mathcal{L}$agrangian

$$\mathcal{L} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + \bar{Q}(i\not{D} - m_Q)Q + |D_\mu\tilde{Q}|^2 - m^2_{\tilde{Q}}|\tilde{Q}|^2$$
$$-g^H_Q \frac{m_Q}{v}\bar{Q}QH - g^H_{\tilde{Q}}\frac{m^2_{\tilde{Q}}}{v}|\tilde{Q}|^2 H + \frac{1}{2}(\partial_\mu H)^2 - \frac{M_H^2}{2}H^2$$

$$iD_\mu = i\partial_\mu - g_S G^a_\mu T^a$$

Interaction vertices:



Renormalization - Suite

- Quark/Squark mass $\mathbf{m_{Q,\tilde{Q}}}$: on-shell

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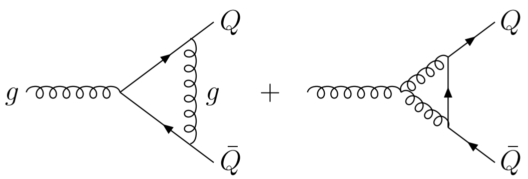

$Z_1 = Z_{\alpha_S}^{1/2} Z_3^{1/2} Z_2$

[Slavnov-Taylor identity]

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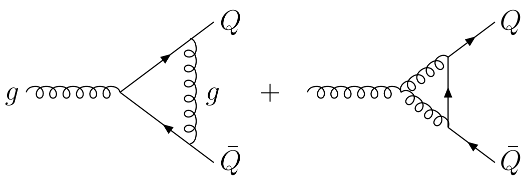

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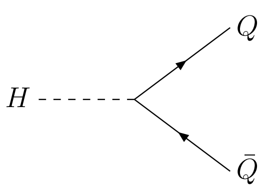
- **$HQ\bar{Q}$ vertex:**

$$\mathcal{L}_{\rm int} = -g_Q^H \frac{m_{Q_0}}{v} \bar{\Psi}_0 \Psi_0 H = -g_Q^H \frac{m_Q}{v} \bar{\Psi}\Psi H \underbrace{\left[Z_2 - \frac{\delta m_Q}{m_Q} \right]}_{Z_{HQQ}} + \mathcal{O}(\alpha_S^2)$$



$$\Gamma_{H\bar{Q}Q}(q^2 = 0) \neq Z_{HQQ}$$

Braaten,Leveille

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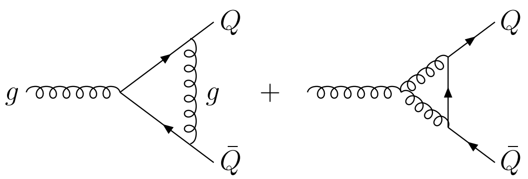

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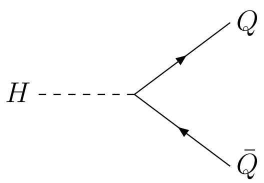

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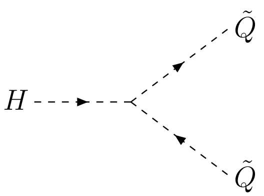
- **$\mathbf{H\tilde{Q}\tilde{Q}}$ vertex:**

$$\mathcal{L}_{\rm int} = -g_{\tilde{Q}}^H \frac{m^2_{\tilde{Q}_0}}{v} \tilde{Q}_0^* \tilde{Q}_0 H = -g_{\tilde{Q}}^H \frac{m^2_{\tilde{Q}}}{v} \tilde{Q}^* \tilde{Q} H \underbrace{\left[Z_2^{\tilde{Q}} - \frac{\delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \right]}_{Z_{H\tilde{Q}\tilde{Q}}} + \mathcal{O}(\alpha_S^2)$$



$$\Gamma_{H\tilde{Q}\tilde{Q}}(q^2 = 0) \neq Z_{H\tilde{Q}\tilde{Q}}$$

disregard renorm. of $g_{\tilde{Q}}^H$!

Virtual corrections - heavy squark limit

Total virtual correction [heavy squark limit, without b, t loops]:

$$C_{\text{virt}} = \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{M_H^2} \right)^{\epsilon} \left\{ -\frac{3}{\epsilon^2} - \frac{33-2N_F}{6\epsilon} \left(\frac{\mu^2}{M_H^2} \right)^{-\epsilon} + \pi^2 + \frac{23}{3} \right\}$$

$\uparrow$ IR $\quad$ $\uparrow$ Coll

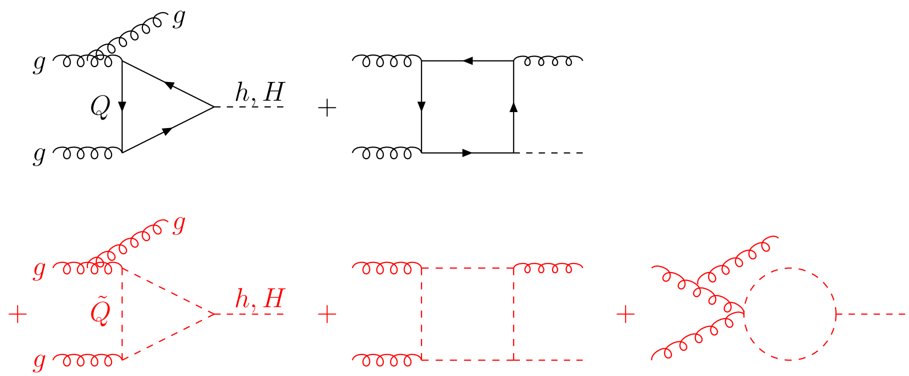
[$\frac{23}{3} \longrightarrow \frac{11}{2}$ in the heavy quark limit (without squark loops)]

To get a finite cross section the real corrections have to be added.

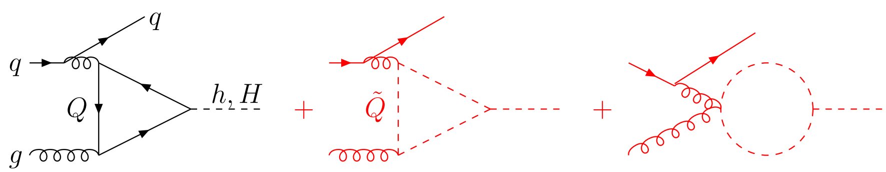
Real Corrections

3 incoherent processes:

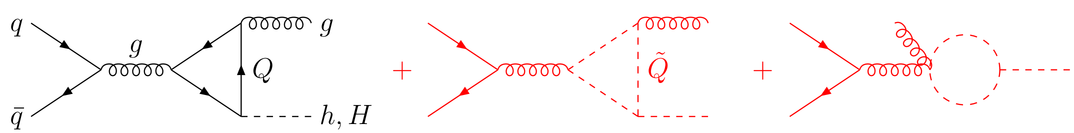
gg → Hg:



gq → Hq:



q$\bar{\text{q}}$ → Hg:



Phase space integration in $n = 4 - 2\epsilon$ dimensions $\rightsquigarrow$ IR, Coll. singularities: poles in ϵ

Real corrections - heavy squark limit

Total real corrections [heavy squark limit, without b, t loops]:

$$C_{\rm real} = \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{m_\Phi^2}\right)^\epsilon \left\{ \frac{3}{\epsilon^2} + \frac{33-2N_F}{6\epsilon} \right\}$$

$$D_{gg} = -\frac{\hat{\tau}}{\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{\hat{s}}\right)^\epsilon P_{gg}(\hat{\tau}) - \frac{11}{2}(1-\hat{\tau})^3 + 12\left\{ \left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}}\right)_+ - \hat{\tau}[2-\hat{\tau}(1-\hat{\tau})]\log(1-\hat{\tau}) \right\}$$

$$D_{gq} = -\left\{ \frac{1}{2\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{\hat{s}}\right)^\epsilon - \log(1-\hat{\tau}) \right\} \hat{\tau} P_{gq}(\hat{\tau}) - 1 + 2\hat{\tau} - \frac{\hat{\tau}^2}{3}$$

$$D_{q\bar{q}} = \frac{32}{27}(1-\hat{\tau})^3$$

- IR, Coll. poles in $C_{\rm real}$ subtract the corresponding ones of the virtual corrections.
- Coll. poles in the real corrections (Altarelli-Parisi kernels as coefficients) $\rightsquigarrow$ absorbed in NLO structure functions.

Result - heavy squark limit (without b, t loops)

$$
\begin{aligned}
\sigma(pp \to \Phi + X) &= \sigma_0 \left[1 + C \frac{\alpha_S}{\pi}\right] \tau_\Phi \frac{d\mathcal{L}^{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{qq} \\
C &= \pi^2 + \frac{23}{3} + \frac{33 - 2N_F}{6} \log \frac{\mu^2}{M_\Phi^2} \\
\Delta\sigma_{gg} &= \int_{\tau_\Phi}^1 d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Bigg\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} - \frac{11}{2}(1-\hat{\tau})^3 \\
&\quad + 12 \left[\left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \right)_+ - \hat{\tau}[2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \right] \Bigg\} \\
\Delta\sigma_{gq} &= \int_{\tau_\Phi}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Bigg\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \left[\log \frac{Q^2}{\hat{s}} - 2\log(1-\hat{\tau}) \right] \\
&\quad - 1 + 2\hat{\tau} - \frac{\hat{\tau}^2}{3} \Bigg\} \\
\Delta\sigma_{q\bar{q}} &= \int_{\tau_\Phi}^1 d\tau \sum_q \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \frac{32}{27}(1-\hat{\tau})^3
\end{aligned}
$$

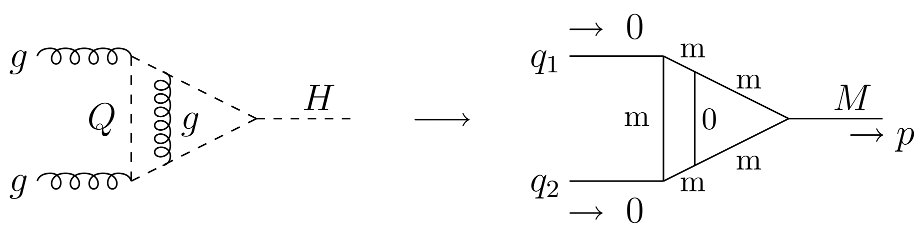
[μ=Ren. scale, Q=Fact. scale]

natural scales: $\mu^2 = Q^2 = M_\Phi^2$

General case (arbitrary $\mathrm{M}_\Phi, \mathrm{m}_\mathrm{Q}, \mathrm{m}_{\tilde{\mathrm{Q}}}$)

- Interference $b, t, \tilde{b}, \tilde{t}$
- 5-dim. Feynman integrals $\longrightarrow$ 1-dimensional [Trilogarithms]

Example:



$$S = \int \frac{d^n k d^n q}{(2\pi)^{2n}} \frac{1}{(k^2-m^2)[(k-q_1)^2-m^2][(k+q_2)^2-m^2][(k+q-q_1)^2-m^2][(k+q+q_2)^2-m^2]q^2}$$

$$= -\frac{\Gamma(2+2\epsilon)}{(4\pi)^4 m^4} \left(\frac{4\pi\mu^2}{m^2}\right)^{2\epsilon} \times I$$

$$I = \int_0^1 dx\, dy\, dz\, dr\, ds\, \frac{xz}{N^2} \qquad \rho = \frac{M_\Phi^2}{m_{\tilde{Q}}^2}(1+i0)$$

$$N = 1 + \rho\Big\{rx(1-x)(1-y-z)(1-y-zs) - [y+(1-y-z)x][1-y-x(1-y-zs)]\Big\}$$

Result

- α_S: $\overline{\rm MS}$ scheme, 5 active flavours
- $\lim_{m_{\tilde{Q}}\to\infty}$ recovered
- calculation analogous to $m_{\tilde{Q}} \to \infty$

$$\sigma(pp \to \Phi + X) = \sigma_0 [1 + C \frac{\alpha_S}{\pi}] \tau_\Phi \frac{d\mathcal{L}_{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{qq}$$

$$C = \pi^2 + C_1(\tau_Q, \tau_{\tilde{Q}}) + \frac{33-2N_F}{6} \log \frac{\mu^2}{M_\Phi^2}$$

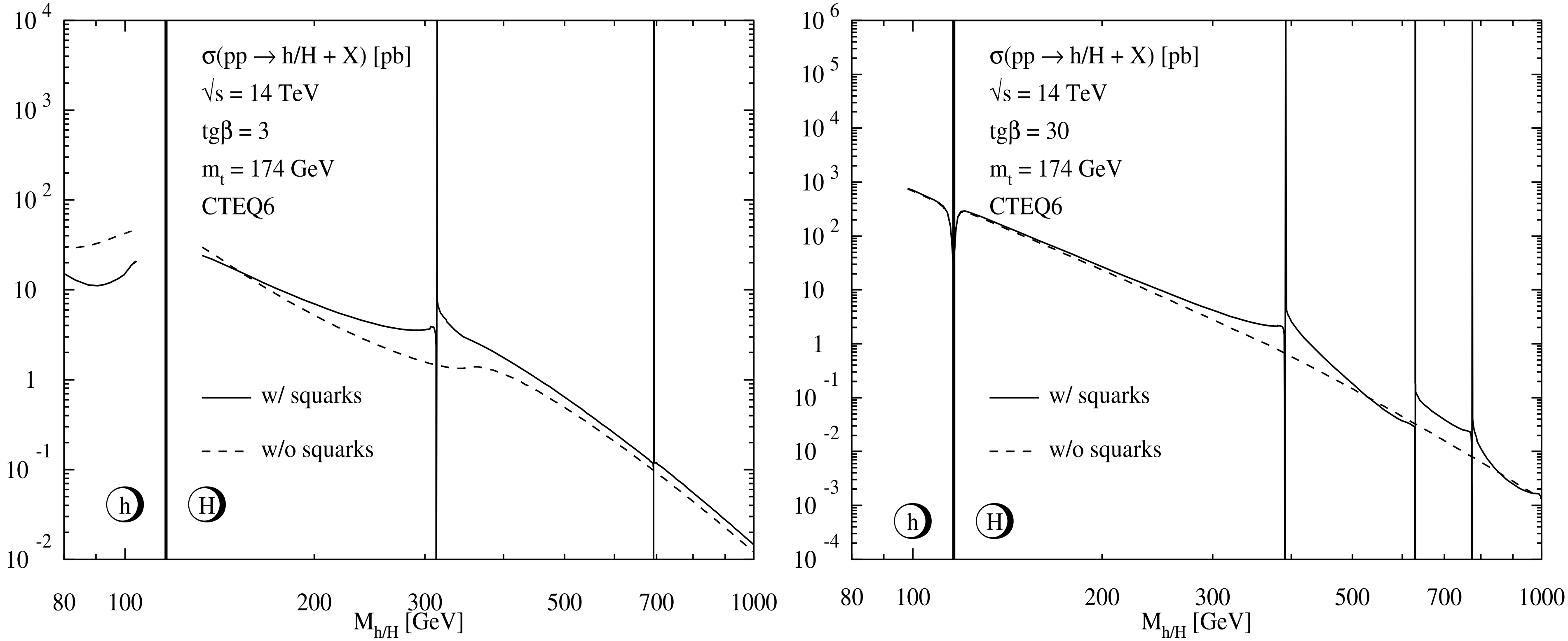
$$\Delta\sigma_{gg} = \int_{\tau_\Phi}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Big\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} + d_{gg}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) + 12 \Big[\Big(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \Big)_+ - \hat{\tau}[2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \Big] \Big\}$$

$$\Delta\sigma_{gq} = \int_{\tau_\Phi}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}_{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Big\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \Big[\log \frac{Q^2}{\hat{s}} - 2\log(1-\hat{\tau}) \Big] + d_{gq}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \Big\}$$

$$\Delta\sigma_{q\bar{q}} = \int_{\tau_\Phi}^1 d\tau \sum_q \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \, d_{q\bar{q}}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}})$$

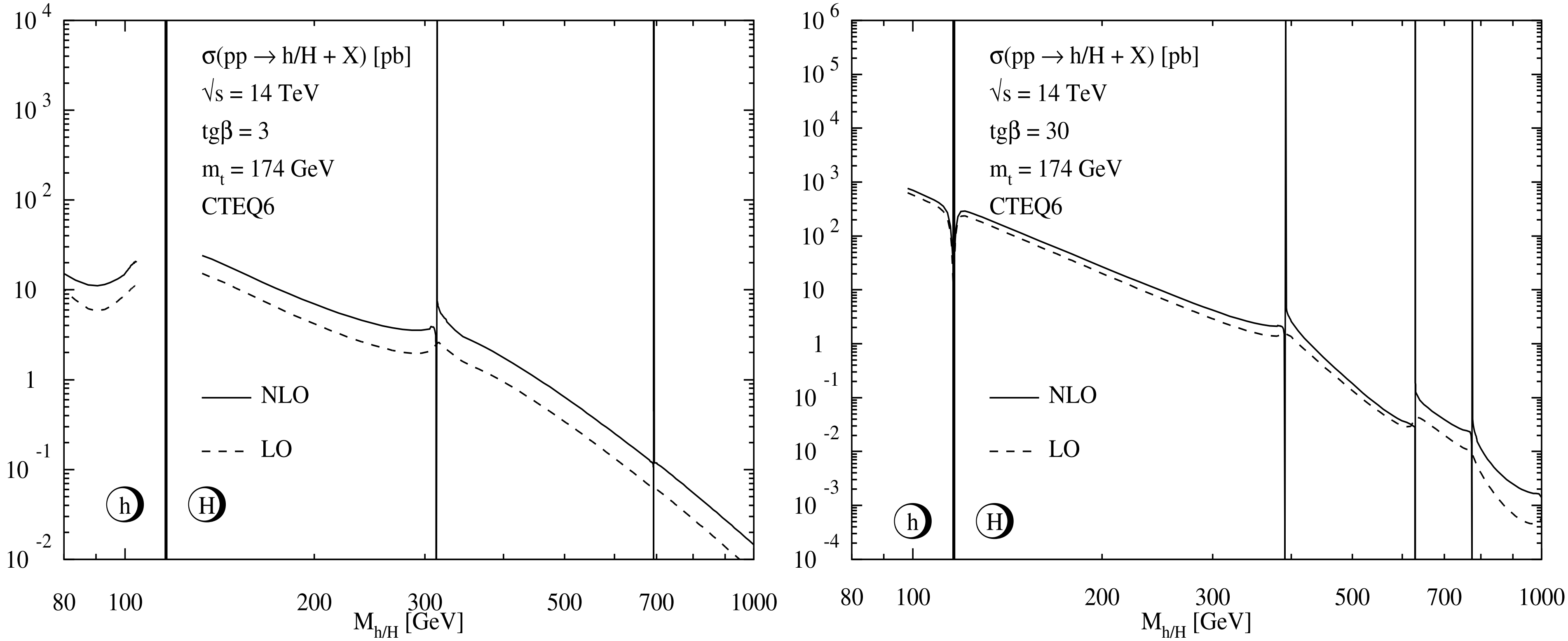
The NLO cross section w/ and w/o Squarks

PRELIMINARY



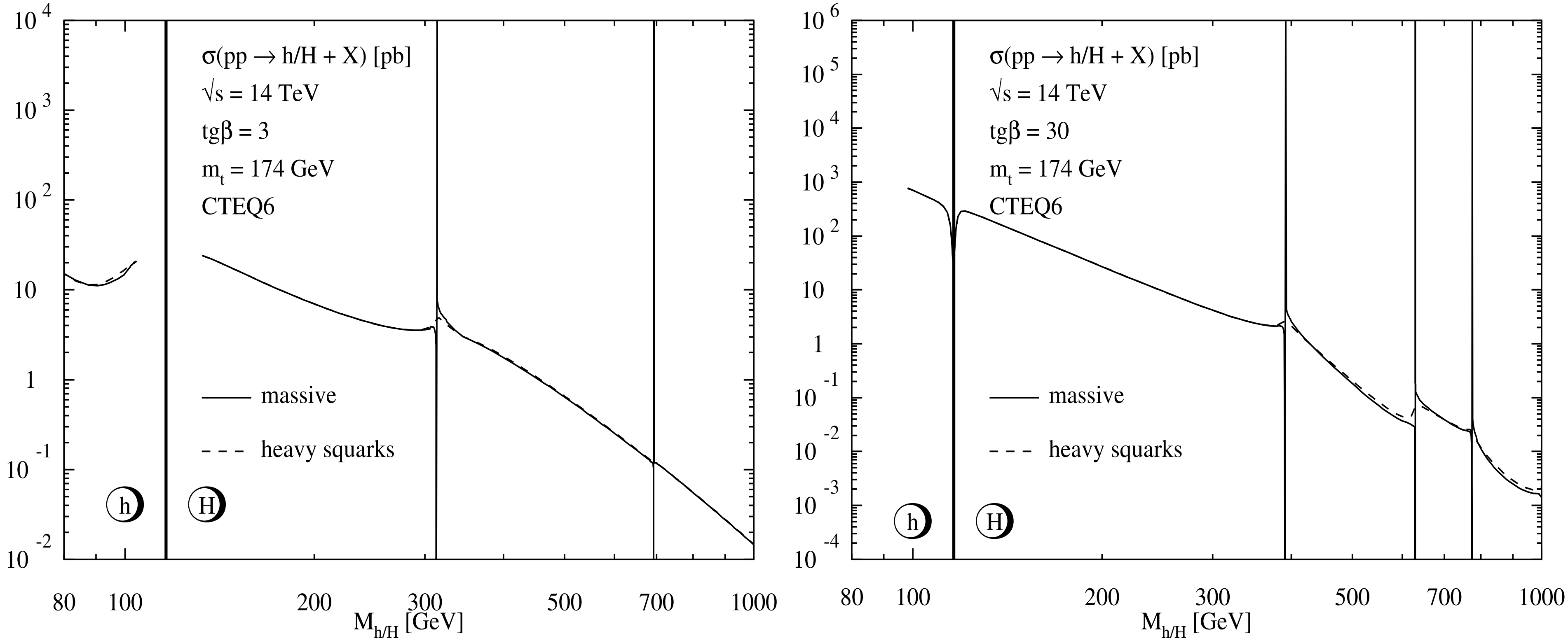
The LO and NLO cross section w/ Squarks

PRELIMINARY



The NLO cross section for massive squarks and in the heavy squark limit

PRELIMINARY



Conclusions

- Calculated NLO corrections to $gg \to h, H$ including the full squark mass dependence.

- K-factor due to squark inclusion is important: K $\lesssim 2$.

- K-factor very similar to the case of quark loops alone $\rightsquigarrow$ large corrections to squark loops, too.

- Inclusion of full squark mass dependence has significant effects on the K-factor compared to the heavy squark mass limit. The deviation can be as large as 10–20 %.