$\mathcal{S}$USY $\mathcal{Q}$CD $\mathcal{C}$orrections to $\mathcal{S}$quark $\mathcal{L}$oops in $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction via $\mathcal{G}$luon $\mathcal{G}$luon $\mathcal{F}$usion

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In coll. with M. Spira
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Outline of the talk

- $\mathcal{I}$ntroduction
- $\mathcal{Q}$CD corrections to squark loops in $gg \longrightarrow$ Higgs
- $\mathcal{C}$onclusions

Introduction

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

QCD corrections to top & bottom loops

NLO (SM, MSSM): increase σ by $\sim$ 10...100% Spira,Djouadi,Graudenz,Zerwas Dawson;Kauffman,Schaffer

SM; tg$\beta \lesssim 5$: limit $M_\Phi \ll m_t$ - approximation $\sim$ 20-30% Krämer,Laenen,Spira

NNLO @ $M_\Phi \ll m_t \Rightarrow$ further increase by 20-30%
scale dependence: $\Delta \lesssim 10 - 15\%$
Harlander,Kilgore
Anastasiou,Melnikov
Ravindran,Smith,van Neerven

Estimate of NNNLO effects $\rightsquigarrow$ improved perturbative convergence Moch,Vogt Ravindran

Soft gluon resummation: $\sim 10\%$ Catani,de Florian,Grazzini,Nason

NLO corrections: to squark loops

only in heavy squark limit Dawson,Djouadi,Spira

full SUSY-QCD corrections in heavy mass limit Harlander,Steinhauser Harlander,Hofmann

$\mathbf{m_{\tilde{Q}} \lesssim 400}$ **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

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

The MSSM Higgs sector

MSSM Higgs sector – supersymmetry & anomaly free theory ⇒ 2 complex Higgs doublets

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

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	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
H	$s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \rightarrow \text{tg}\beta$	$c_{\beta-\alpha} \rightarrow 0$
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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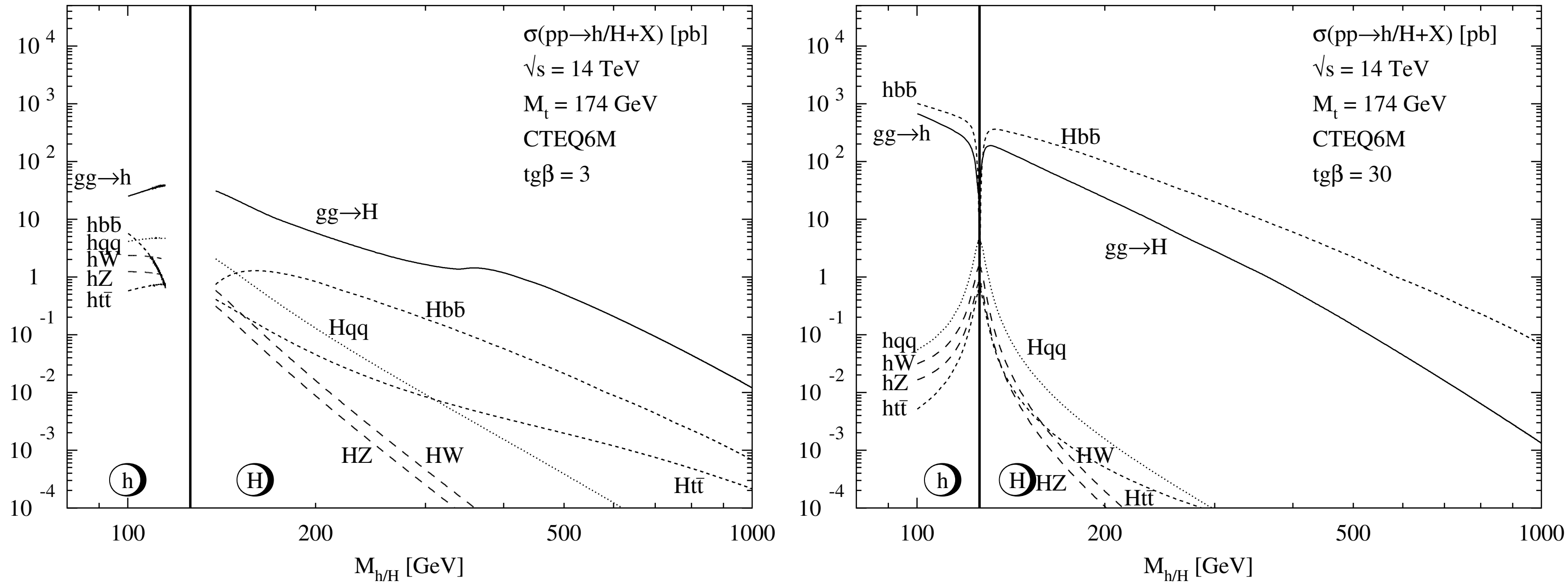
$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$
$g_{\Phi dd} \uparrow$
$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

Dominant production mechanism at the LHC: $gg \rightarrow \Phi$
$\Phi b\bar{b}$ for $\tan\beta$ large

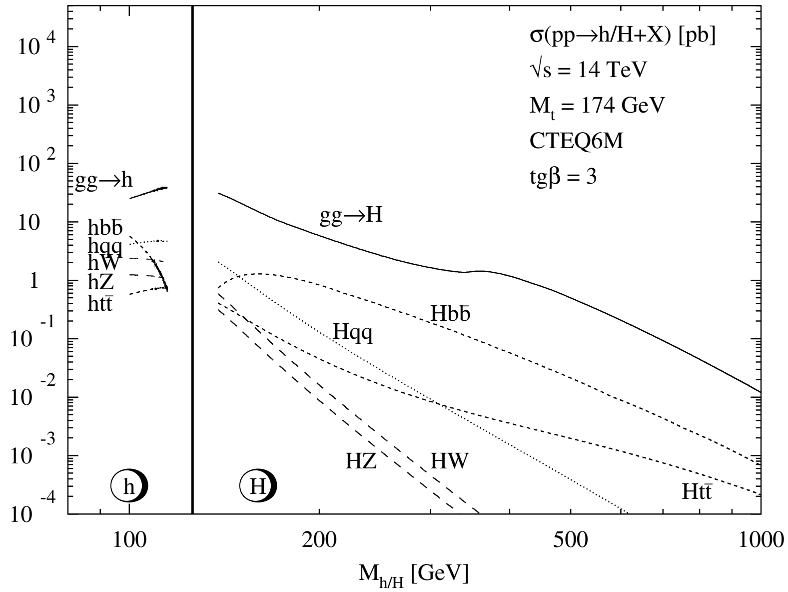
$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction at the LHC

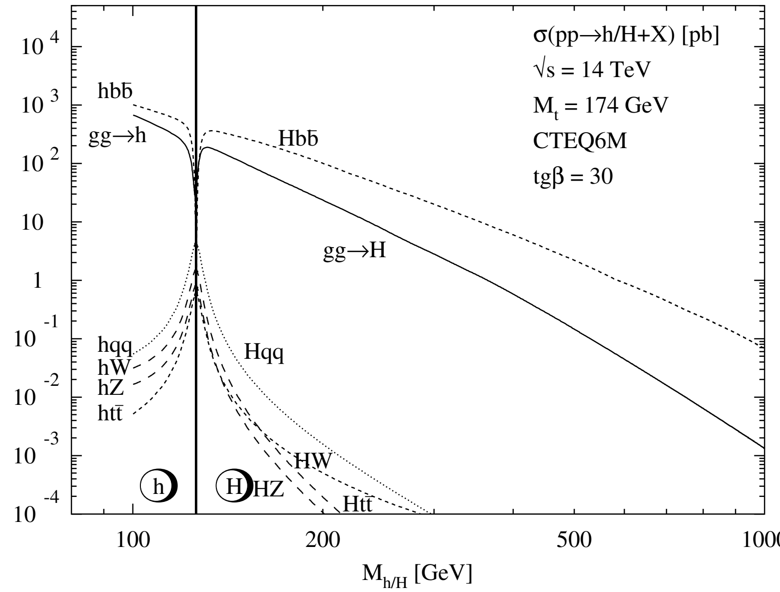
Spira



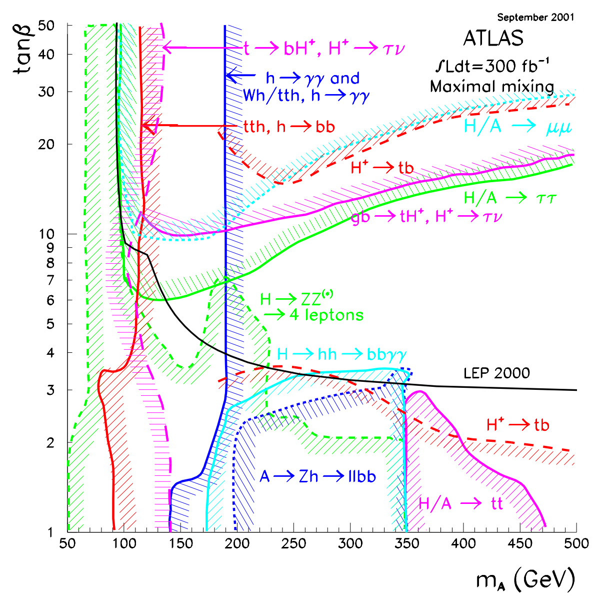
$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction at the LHC

Spira



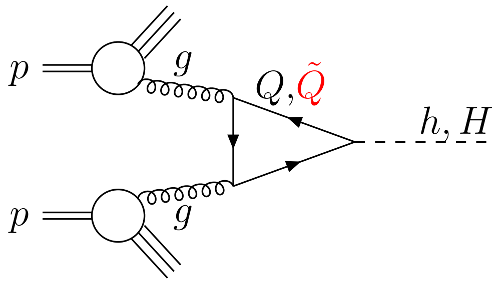


ATLAS



$gg \to H, h$ at leading order

Lowest order - 1 loop



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

$$\sigma_0 = \frac{G_F \alpha_S^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^\Phi F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}}) \right|^2$$

$\tau_\Phi = \frac{M_\Phi^2}{s}$, $\tau_{Q,\tilde{Q}} = \frac{4m_{Q,\tilde{Q}}^2}{M_\Phi^2}$

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

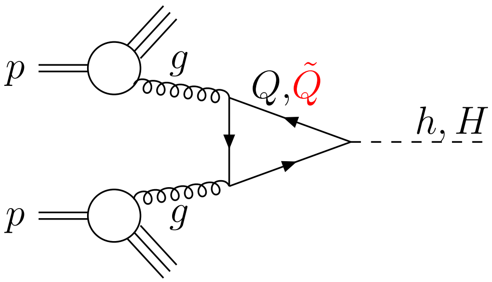
$$\tilde{F}(\tau_{\tilde{Q}}) = -\frac{3}{4}\tau_{\tilde{Q}} \Big[1 - \tau_{\tilde{Q}} f(\tau_{\tilde{Q}})\Big]$$

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

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x}\, g(x, \mu_F^2)\, g(\tau/x, \mu_F^2)$$

$gg \to H, h$ at leading order

Lowest order - 1 loop



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$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x}\, g(x,\mu_F^2)\, g(\tau/x,\mu_F^2)$$

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

$\mathcal{T}$he $\mathcal{S}$quark $\mathcal{L}$oops

Calculation of the QCD corrections to squark loops including the full mass dependence

Scenario:

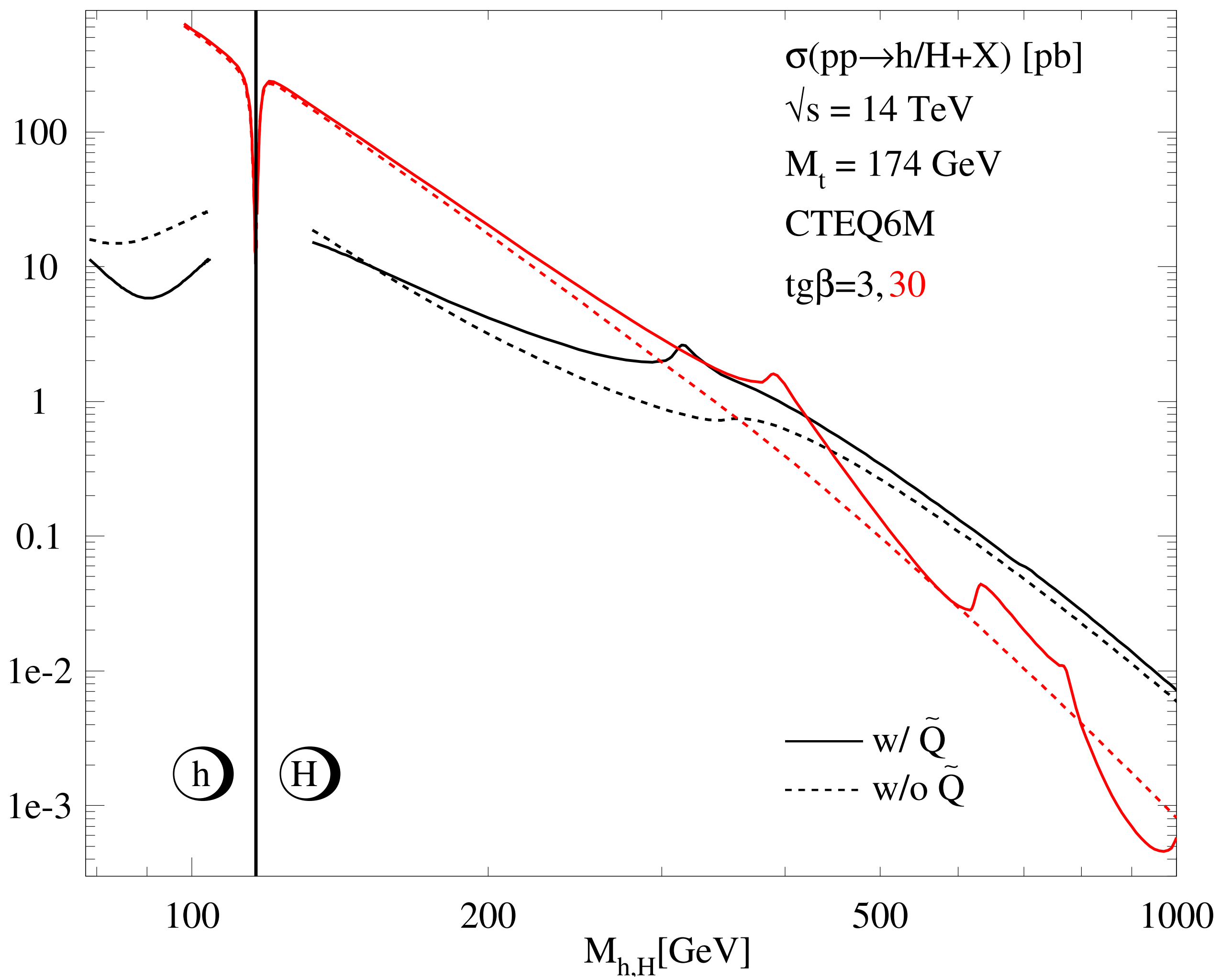
The gluophobic Higgs scenario [$m_t = 174.3$ GeV] Carena,Heinemeyer,Wagner,Weiglein

$$M_{SUSY} = 350 \text{ GeV}, \mu = M_2 = 300 \text{ GeV}, X_t = -770 \text{ GeV}, A_b = A_t, m_{\tilde{g}} = 500 \text{ GeV}$$

$\tan\beta = 3$		$\tan\beta = 30$	
$m_{\tilde{t}_1} = 156$ GeV	$m_{\tilde{t}_2} = 517$ GeV	$m_{\tilde{t}_1} = 155$ GeV	$m_{\tilde{t}_2} = 516$ GeV
$m_{\tilde{b}_1} = 346$ GeV	$m_{\tilde{b}_2} = 358$ GeV	$m_{\tilde{b}_1} = 314$ GeV	$m_{\tilde{b}_2} = 388$ GeV

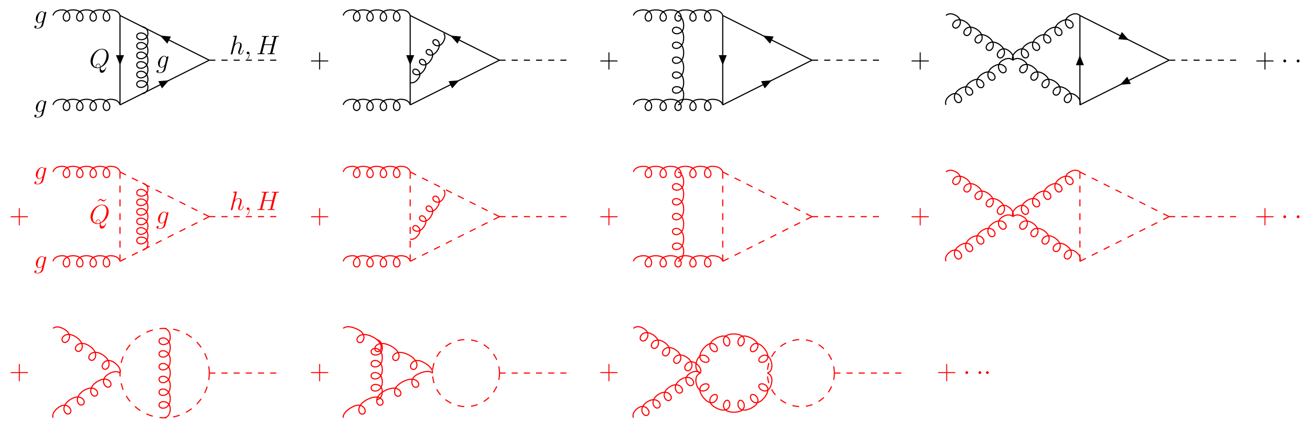
Squark contribution at leading order $\longrightarrow$

The $\mathcal{LO}$ $\mathcal{C}$ross $\mathcal{S}$ection w/ and w/o $\mathcal{S}$quarks



QCD corrections

Virtual corrections [2 loops, no gluino] $\rightsquigarrow$ UV-,IR-,Coll-singularities in $n = 4 - 2\epsilon$ dimensions.



General case (arbitrary $M_\Phi, m_Q, m_{\tilde{Q}}$)

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

(analytically: Harlander,Kant
Anastasiou,Beerli,Bucherer,Daleo,Kunszt
Aglietti,Bonciani,Degrassi,Vicini $\longrightarrow$ Comparison: full agreement)

QCD corrections - Suite

Lagrangian separates gluon and gluino exchange contributions in a renormalizable way

$$\mathcal{L} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{Q}(i\not{D} - m_Q)Q + |D_\mu\tilde{Q}|^2 - m^2_{\tilde{Q}}|\tilde{Q}|^2$$
$$-g^\Phi_Q\frac{m_Q}{v}\bar{Q}Q\Phi - g^\Phi_{\tilde{Q}}\frac{m^2_{\tilde{Q}}}{v}|\tilde{Q}|^2\Phi + \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{M^2_\Phi}{2}\Phi^2$$

$iD_\mu = i\partial_\mu - g_S G^a_\mu T^a + ieA_\mu\mathcal{Q}$

Renormalization: - $\mathbf{m_{Q,\tilde{Q}}}$: on-shell

- $\boldsymbol{\alpha_s}$: $\overline{\rm MS}$ scheme, 5 active flavours

Virtual correction:

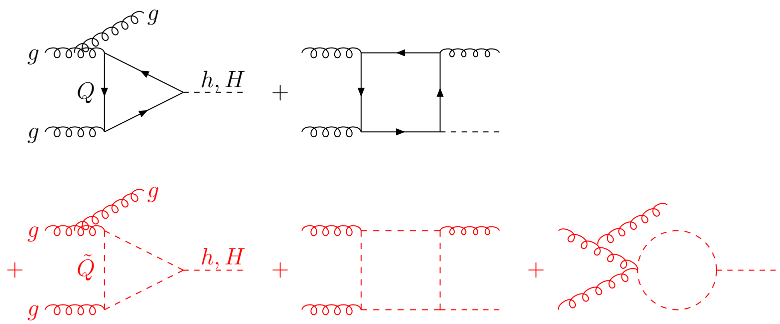
- Recovers heavy squark limit via effective Lagrangian Dawson,Djouadi,Spira
- After renormalization: IR & coll. singularities

$\rightsquigarrow$ Real corrections have to be added.

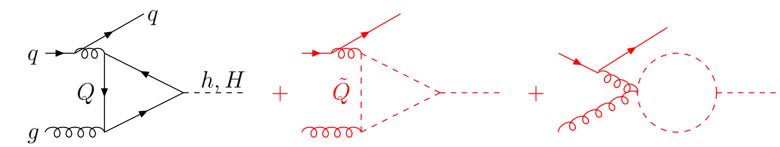
Real Corrections

Real corrections - 3 incoherent processes:

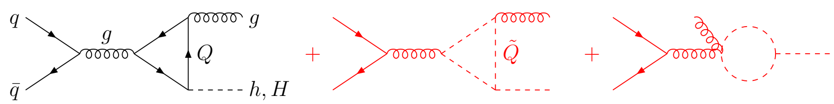
$\mathbf{gg \to Hg:}$



$\mathbf{gq \to Hq:}$



$\mathbf{q\bar{q} \to Hg:}$



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

- IR, Coll. poles in real corrections subtract the corresponding ones of the virtual corrections.
- Remaining coll. poles in the real corrections (Altarelli-Parisi kernels as coefficients) $\leadsto$ absorbed in NLO structure functions.

Result

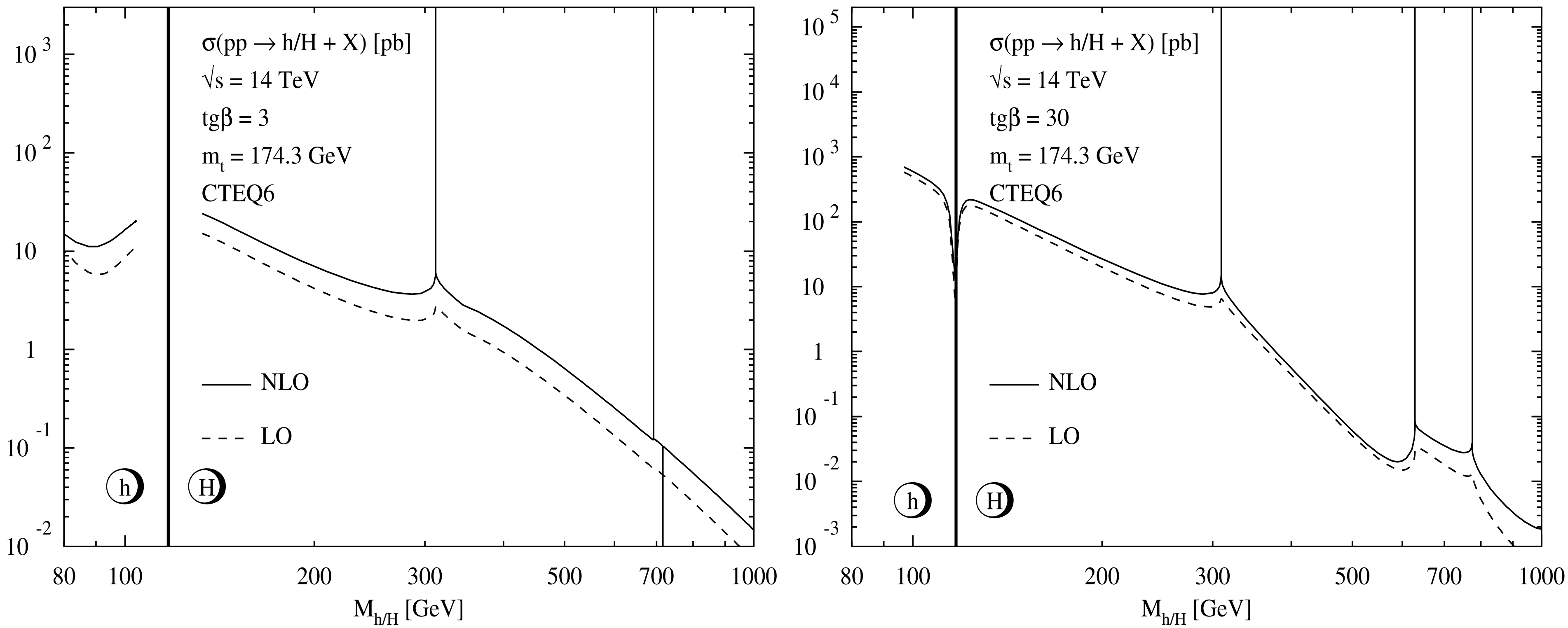
- μ=Ren. scale, Q=Fact. scale, $\mu^2 = Q^2 \approx M_\Phi^2$

$$\begin{aligned}
\sigma(pp \to \Phi + X) &= \sigma_0 [1 + C \tfrac{\alpha_S}{\pi}] \tau_\Phi \frac{d\mathcal{L}_{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{qq} \\
C &= \pi^2 + C_1(\tau_Q, \tau_{\tilde{Q}}) + \frac{33-2N_F}{6} \log \frac{\mu^2}{M_\Phi^2} \\
\Delta\sigma_{gg} &= \int_{\tau_\Phi}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Big\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} + d_{gg}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \\
&\quad + 12 \Big[\Big(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \Big)_+ - \hat{\tau}[2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \Big] \Big\} \\
\Delta\sigma_{gq} &= \int_{\tau_\Phi}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}_{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \Big\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \Big[\log \frac{Q^2}{\hat{s}} - 2\log(1-\hat{\tau}) \Big] \\
&\quad + d_{gq}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \Big\} \\
\Delta\sigma_{q\bar{q}} &= \int_{\tau_\Phi}^1 d\tau \sum_q \frac{d\mathcal{L}_{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0 \, d_{q\bar{q}}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}})
\end{aligned}$$

$$C_1(\tau_Q, \tau_{\tilde{Q}}) \to \frac{11}{2} + \frac{7}{2} \mathrm{Re} \left\{ \frac{\sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}})}{\sum_Q g_Q^\Phi F(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^\Phi \tilde{F}(\tau_{\tilde{Q}})} \right\} \qquad d_{gg}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \to -\frac{11}{2}(1-\hat{\tau})^3$$

$$d_{gq}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \to -1 + 2\hat{\tau} - \frac{\hat{\tau}^2}{3} \qquad d_{q\bar{q}}(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \to \frac{32}{27}(1-\hat{\tau})^3$$

The LO and NLO cross section w/ Squarks



$\Delta \sim 20 - 100\%$

Kinks, bumps, spikes: $\tilde{t}_1\bar{\tilde{t}}_1, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with rising Higgs mass.

Coulomb singularities

$\tilde{Q}\bar{\tilde{Q}}$ thresholds: Formation of 0^{++} states $\rightsquigarrow$ Coulomb singularities

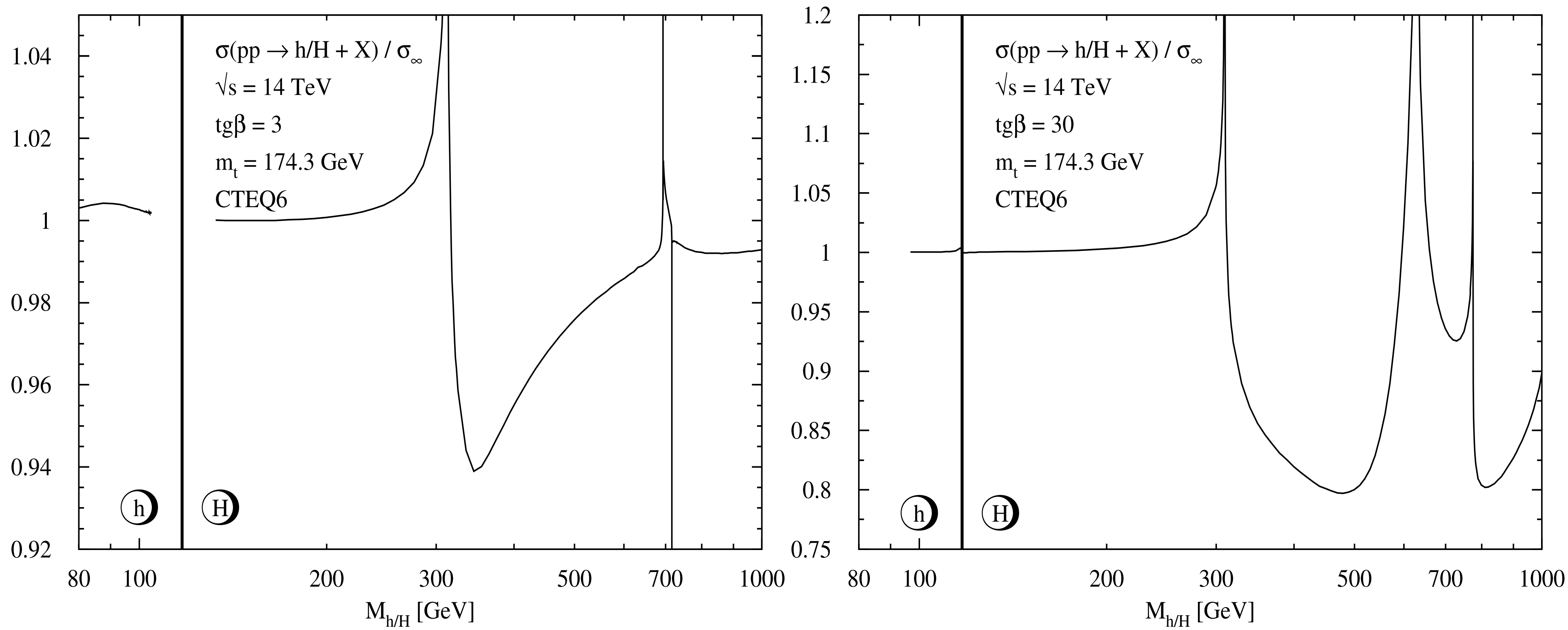
Singular behaviour can be derived from the Sommerfeld rescattering corrections $\rightsquigarrow$

At each specific $\tilde{Q}_0\bar{\tilde{Q}}_0$ threshold:

$$C_1(\tau_Q, \tau_{\tilde{Q}}) \to \text{Re}\left\{ \frac{g^{\Phi}_{\tilde{Q}_0} \tilde{F}(\tilde{Q}_0) \frac{16\pi^2}{3(\pi^2-4)} \left[-\ln\left(\tau^{-1}_{\tilde{Q}_0} - 1\right) + i\pi + const \right]}{\sum_Q g^{\Phi}_Q F(\tau_Q) + \sum_{\tilde{Q}} g^{\Phi}_{\tilde{Q}} \tilde{F}(\tau_{\tilde{Q}})} \right\}$$

Agrees quantitatively with numerical results.

σ_{NLO} w/ full squark mass dependence / σ_{NLO} in the heavy squark limit



$\sigma(pp \to h/H + X)/\sigma_\infty$ up to 20%

Kinks, bumps, spikes: $\tilde{t}_1\bar{\tilde{t}}_1, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with rising Higgs mass.

Scalar Higgs couplings to photons

LHC: $M_H \lesssim 140$ GeV – $H \to \gamma\gamma$ final state plays an important role for the Higgs boson search

Photon Collider: $\gamma\gamma \to h/H$ important role for the MSSM Higgs search at a PLC at high energies.

$$< \sigma(\gamma\gamma \to h/H) >= \frac{8\pi^2}{M^3_{h/H}} \Gamma(h/H \to \gamma\gamma) \frac{d\mathcal{L}^{\gamma\gamma}}{d\tau_{h/H}}$$

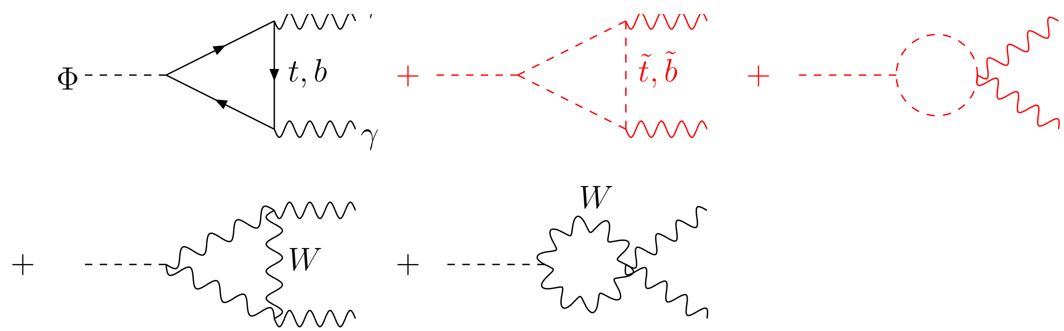
Relation $< \sigma(\gamma\gamma \to h/H) > \leftrightarrow \Gamma(h/H \to \gamma\gamma)$ holds also in NLO QCD:
Single gluon radiation vanishes due to color charge conservation as well as due to the Furry theorem.

Photon fusion cross section measureable with an accuracy of a few percent. Melles,Stirling,Khoze Krawzcyk,Niezurawski,Zarnecki Jikia,Söldner-Rembold

Precise knowledge of QCD corrections to $H \to \gamma\gamma$ important

$\mathrm{H, h} \to \gamma\gamma$ at leading order

Lowest order - 1 loop



$$\Gamma_{LO}(\Phi \to \gamma\gamma) = \frac{G_F \alpha^2 M_\Phi^3}{36\sqrt{2}\pi^3} \left| g_W^\Phi A_W^\Phi(\tau_W) + \sum_f N_{cf} e_f^2 g_f^\Phi A_f^\Phi(\tau_f) + \sum_{\tilde{f}} N_{c\tilde{f}} e_{\tilde{f}}^2 g_{\tilde{f}}^\Phi A_{\tilde{f}}^\Phi(\tau_{\tilde{f}}) \right|^2$$

$$A_W^\Phi(\tau) = -[2 + 3\tau + 3\tau(2-\tau)f(\tau) \qquad A_f^\Phi(\tau) = 2\tau[1 + (1-\tau)f(\tau)]$$

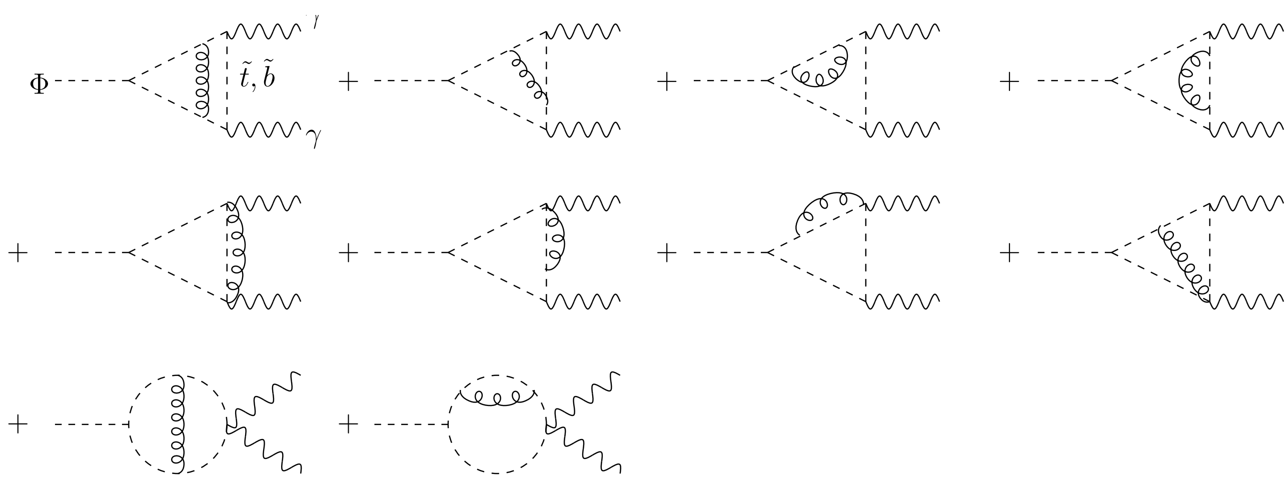
$$A_{\tilde{f}}^\Phi(\tau) = -\tau[1 - \tau f(\tau)] \qquad \tau_i = \frac{4m_i^2}{M_\Phi^2}$$

Remark: Chargino, $H^\pm$, charged $\tilde{l}$ contributions neglected here, however, included in our work/results.

QCD corrections

$$A_Q^\Phi(\tau_Q) \rightarrow A_Q^\Phi(\tau_Q)[1 + C_Q^\Phi(\tau_Q)\frac{\alpha_S}{\pi}]$$
$$A_{\tilde{Q}}^\Phi(\tau_{\tilde{Q}}) \rightarrow A_{\tilde{Q}}^\Phi(\tau_{\tilde{Q}})[1 + C_{\tilde{Q}}^\Phi(\tau_{\tilde{Q}})\frac{\alpha_S}{\pi}]$$

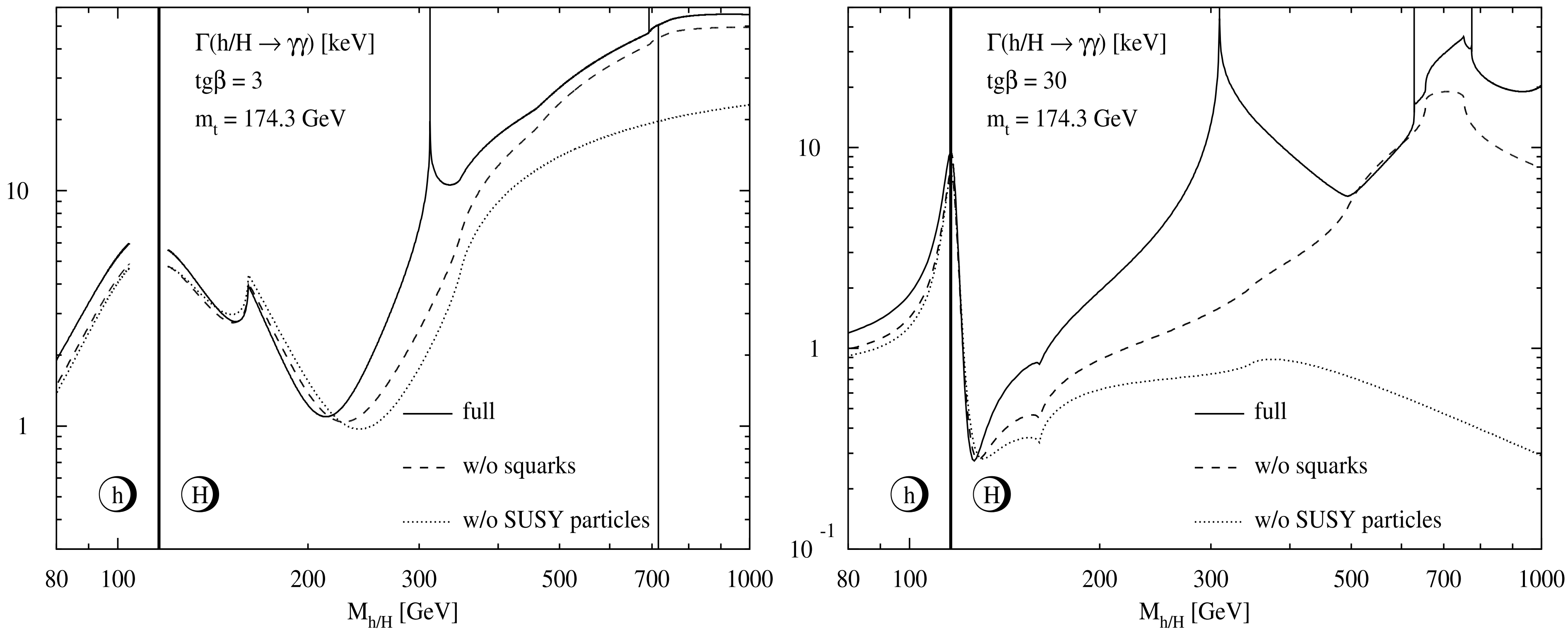
Virtual corrections [2 loops, no gluino contributions]



Remarks:

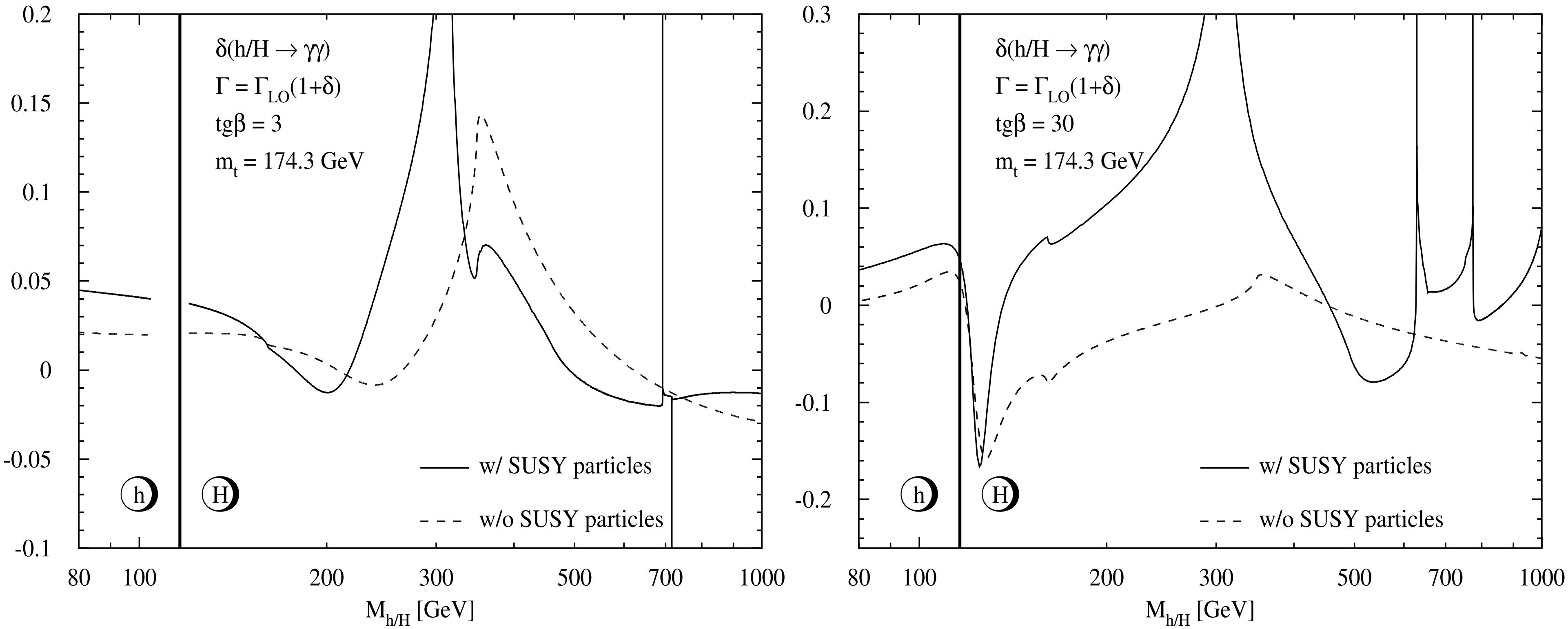
- Improve perturbative behaviour: squark loop contributions in terms of running squark masses $m_{\tilde{Q}}(\mu = M_\Phi/2)$, strong coupling $\alpha_S(\mu = M_\Phi)$.
- Massive QCD corrections to quark/squark loops implemented in HDECAY. Djouadi,Kalinowski, MMM,Spira

QCD corrected partial decay widths



Kinks, bumps, spikes: $WW, \tilde{t}_1\bar{\tilde{t}}_1, t\bar{t}, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{\tau}_1\bar{\tilde{\tau}}_1, \tilde{\tau}_2\bar{\tilde{\tau}}_2, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with rising Higgs mass.

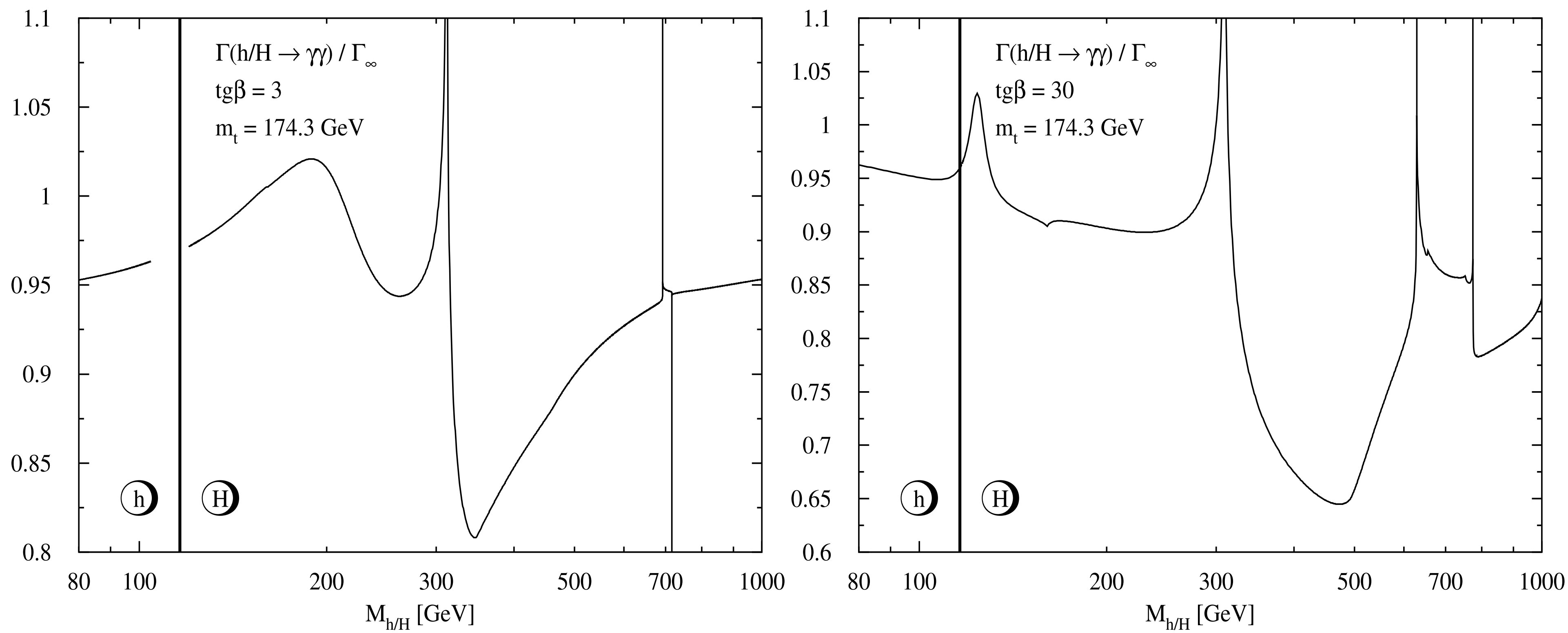
Relative QCD corrections to the partial decay widths



$\delta(h/H \to \gamma\gamma) \sim 10 - 20\%$

Kinks, bumps, spikes: $WW, \tilde{t}_1\bar{\tilde{t}}_1, t\bar{t}, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{\tau}_1\bar{\tilde{\tau}}_1, \tilde{\tau}_2\bar{\tilde{\tau}}_2, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with $M_{h/H} \uparrow$.

Γ_{NLO} w/ full squark mass dependence / Γ_{NLO} in the heavy squark limit



$\Gamma(h/H \to \gamma\gamma)/\Gamma_\infty$ up to $\sim 30\%$

Kinks, bumps, spikes: WW,$\tilde{t}_1\bar{\tilde{t}}_1, t\bar{t}, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{\tau}_1\bar{\tilde{\tau}}_1, \tilde{\tau}_2\bar{\tilde{\tau}}_2, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with $M_{h/H} \uparrow$.

Conclusions

- Calculated NLO corrections to $gg \to h/H$, $h/H \to \gamma\gamma$ including the full squark mass dependence. [Implemented in HIGLU.]

- K-factor with squarks included is large.

- 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 $\mathcal{O}(20\%)$ for $gg \to h/H$,
$\mathcal{O}(30\%)$ for $h/H \to \gamma\gamma$.

Note: 2 independent papers by Anastasiou,Beerli,Bucherer,Daleo,Kunszt / Aglietti,Bonciani,Degrassi,Vicini :
Virtual corrections to quark & squark loops in gg fusion derived analytically.
However, no full numerical analysis of the gluon fusion processes at NLO.
Comparison with second group: full agreement.

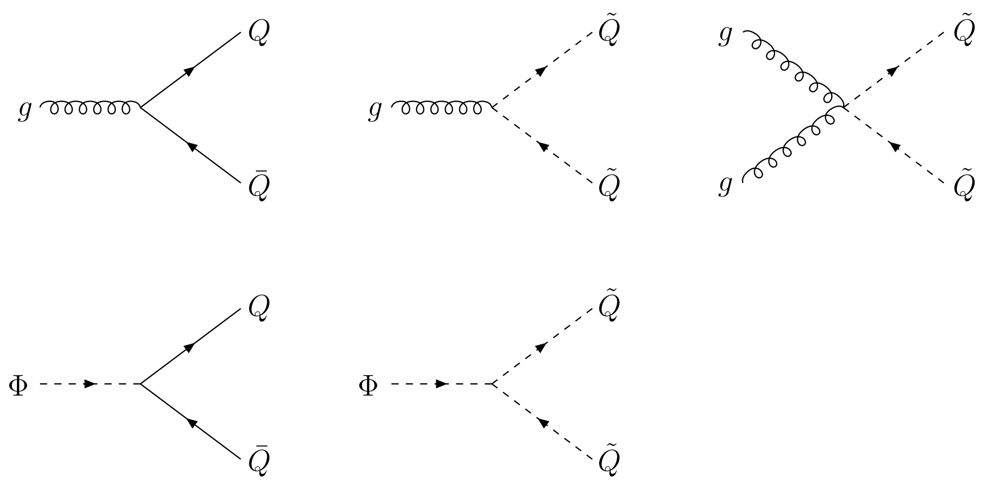
Renormalization

$\mathcal{L}$**agrangian** separates gluon and gluino exchange contributions in a renormalizable way

$$\mathcal{L} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{Q}(i\not{D} - m_Q)Q + |D_\mu \tilde{Q}|^2 - m^2_{\tilde{Q}}|\tilde{Q}|^2$$
$$-g^\Phi_Q \frac{m_Q}{v}\bar{Q}Q\Phi - g^\Phi_{\tilde{Q}}\frac{m^2_{\tilde{Q}}}{v}|\tilde{Q}|^2\Phi + \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{M^2_\Phi}{2}\Phi^2$$

$$iD_\mu = i\partial_\mu - g_S G^a_\mu T^a + ieA_\mu \mathcal{Q}$$

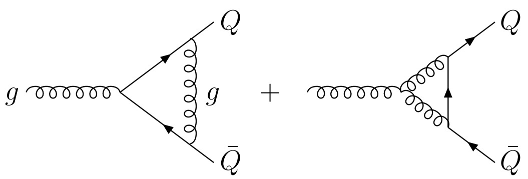
Gluon, $\Phi = \mathrm{H}/\mathrm{h}$ interaction vertices:



Renormalization - Suite

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

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

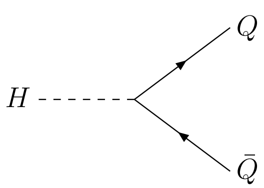


$$Z_1 = Z_{\alpha_S}^{1/2} Z_3^{1/2} Z_2$$

[Slavnov-Taylor identity]

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

$$\mathcal{L}_{\text{int}} = -g_Q^H \frac{m_{Q0}}{v} \bar{\Psi}_0 \Psi_0 H = -g_Q^H \frac{m_Q}{v} \bar{\Psi}\Psi H \underbrace{\left[Z_2 - \frac{\delta m_Q}{m_Q}\right]}_{Z_{HQQ}} + \mathcal{O}(\alpha_S^2)$$

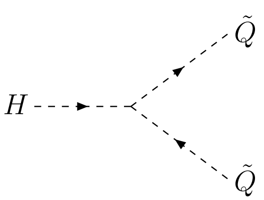


$$\Gamma_{H\bar{Q}Q}(q^2=0) \neq Z_{HQQ}$$

Braaten,Leveille

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

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



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

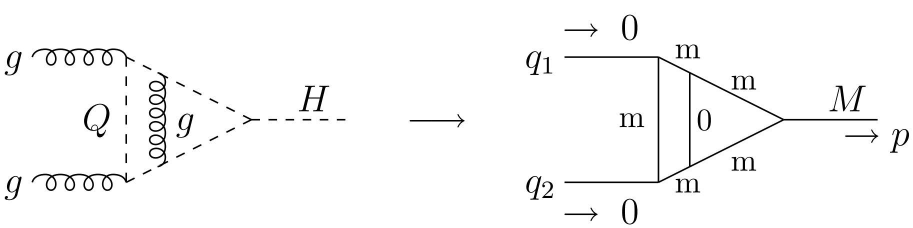
disregard renorm. of $g_{\tilde{Q}}^H$!

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] + purely numerical solution

(analytically: Harlander,Kant
Anastasiou,Beerli,Bucherer,Daleo,Kunszt
Aglietti,Bonciani,Degrassi,Vicini $\longrightarrow$ Comparison: full agreement)

Example:



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

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

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

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