Higgs Boson Production in Gluon Gluon and $\gamma\gamma$ Collisions

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(CERN/LAPTH)

Theory Seminar

Fermilab

March 16, 2006

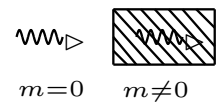
$\mathcal{H}$iggs $\mathcal{P}$hysics

Higgs physics at future colliders:
Establish experimentally the Higgs Mechanism

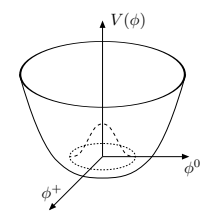
The Higgs mechanism:
Creation of particle masses in a gauge-invariant way

Test of the Higgs mechanism

- Discovery – m
- Spin and CP properties – J^{PC}
- Interaction with the scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X^{(2)}$



- EWSB requires Higgs potential $\leftrightarrow$ $\lambda_{HHH}, \lambda_{HHHH}$



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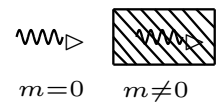

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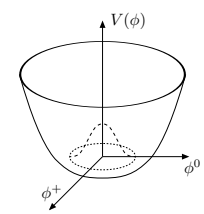

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Outline of the talk

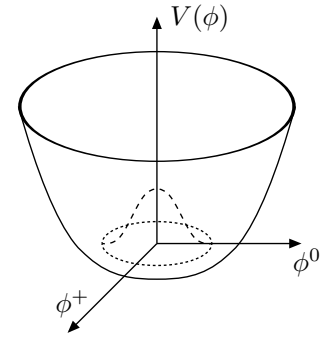
- $\mathcal{I}$ntroduction
- $\mathcal{Q}$CD corrections to squark loops in $gg \to$ Higgs
- $\tau\tau$ $\mathcal{F}$usion to SUSY Higgs bosons at a Photon Collider
- $\mathcal{C}$onclusions

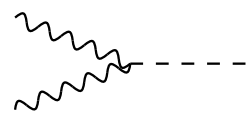
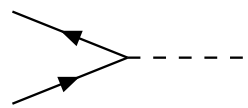
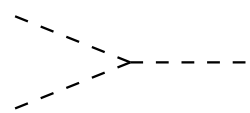
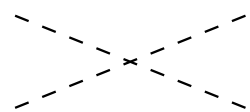
The SM Higgs Sector

The Higgs Potential: [$v = 246$ GeV]

$$V(\Phi) = \lambda[\Phi^\dagger\Phi - \tfrac{v^2}{2}]^2 \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightarrow$$

$$\boxed{V(H) = \tfrac{1}{2}M_H^2 H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4}$$



Higgs boson mass	$M_H = \sqrt{2\lambda}v$	
Gauge couplings	$g_{VVH} = \frac{2M_V^2}{v}$	
Yukawa couplings	$g_{ffH} = \frac{m_f}{v}$	
Trilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$	
Quartic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$	

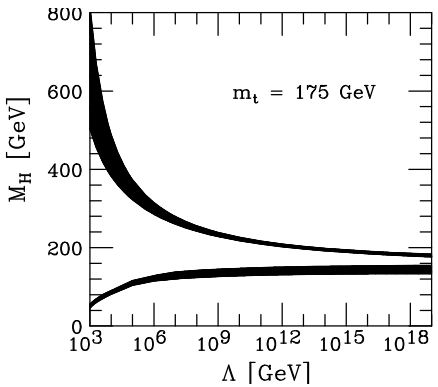
The only unknown parameter in the SM is the Higgs boson mass!

$\mathcal{SM}$ Higgs Sector - Mass Constraints

- Triviality $\longrightarrow$ upper bound
  Vacuum stability $\longrightarrow$ lower bound

Cabibbo,...;Sher;
Lindner;Hasenfratz,...;
Lüscher, Weisz;
Hambye,...;...

Hambye,Riesselmann



$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV

$\Lambda_{GUT} = 10^{16}$ GeV: 130 GeV $\lesssim M_H \lesssim$ 190 GeV

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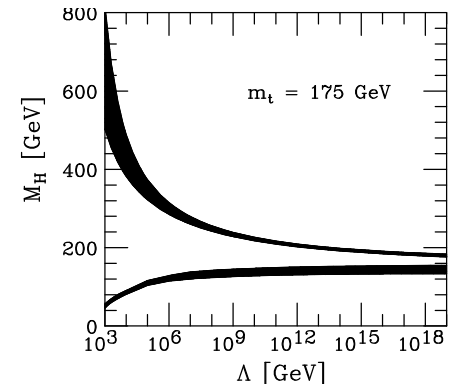

$$\Lambda = 1 \text{ TeV}: \quad 55 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$
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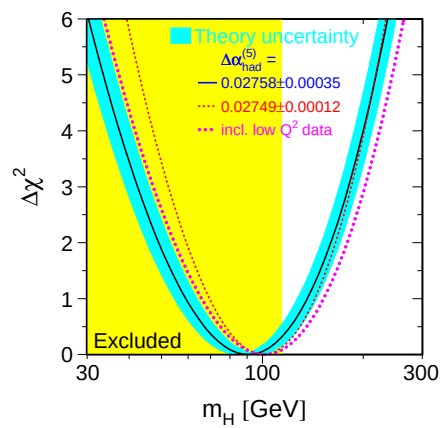
- Fits to electroweak precision data

EWWG

$$M_H = 91^{+45}_{-32} \text{ GeV}, \; M_H \lesssim 219 \text{ GeV @ } 95\% \text{ CL}$$



LEP Coll.

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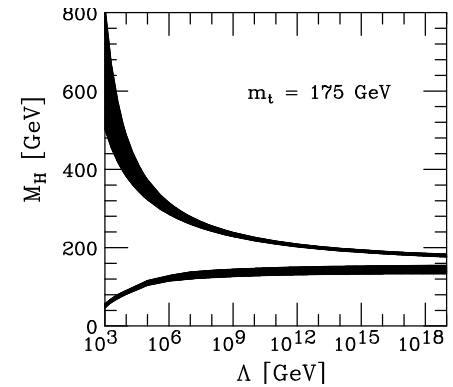

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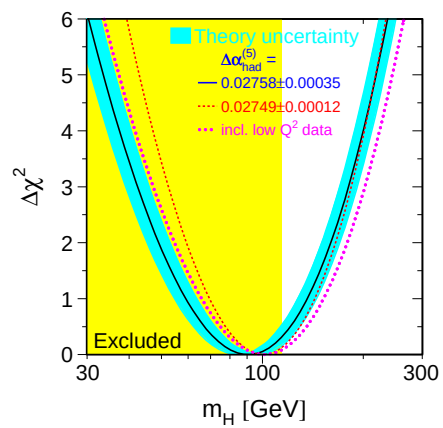
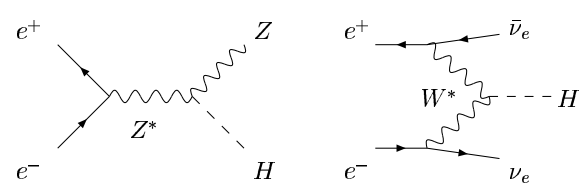


LEP Coll.

- Direct search @ LEP: $[M_H = 115.3 \text{ GeV}]$

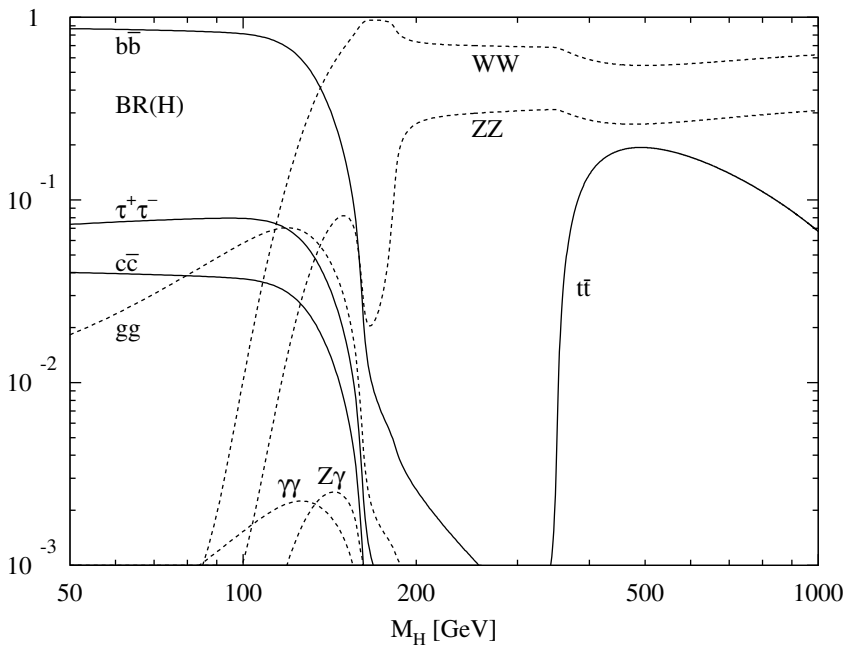
$$M_H > 114.4 \text{ GeV @ } 95\% \text{ CL}$$

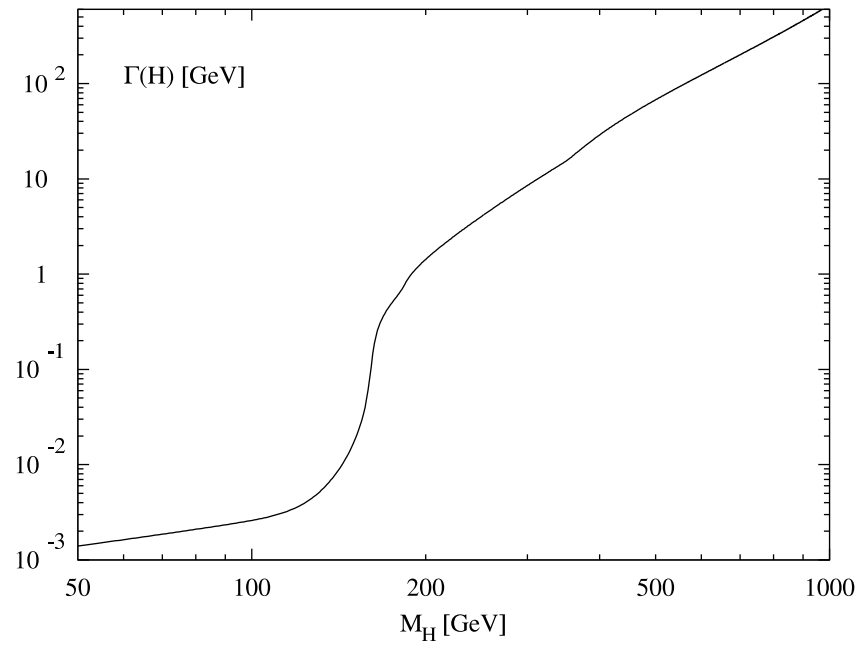
LEP Coll.



Higgs Boson Branching Ratios and Total Width

HDECAY

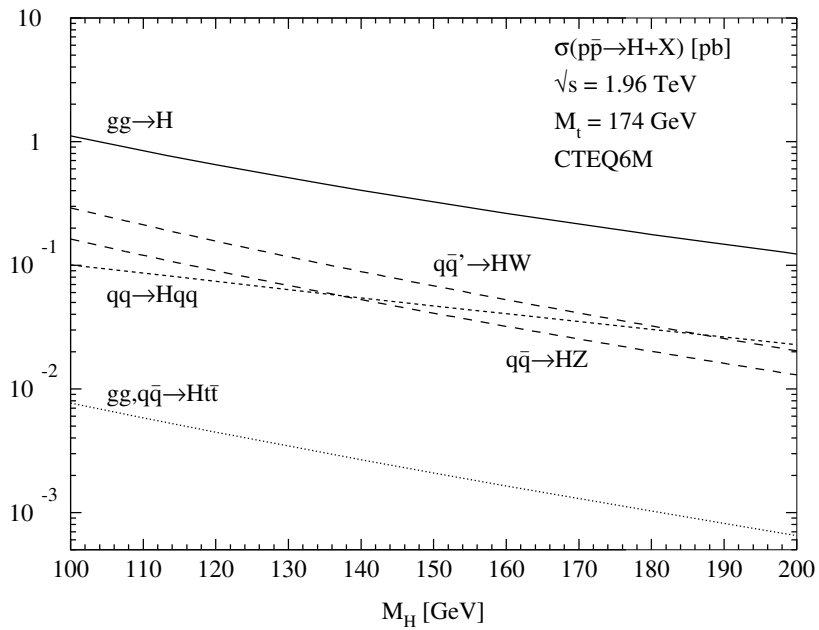




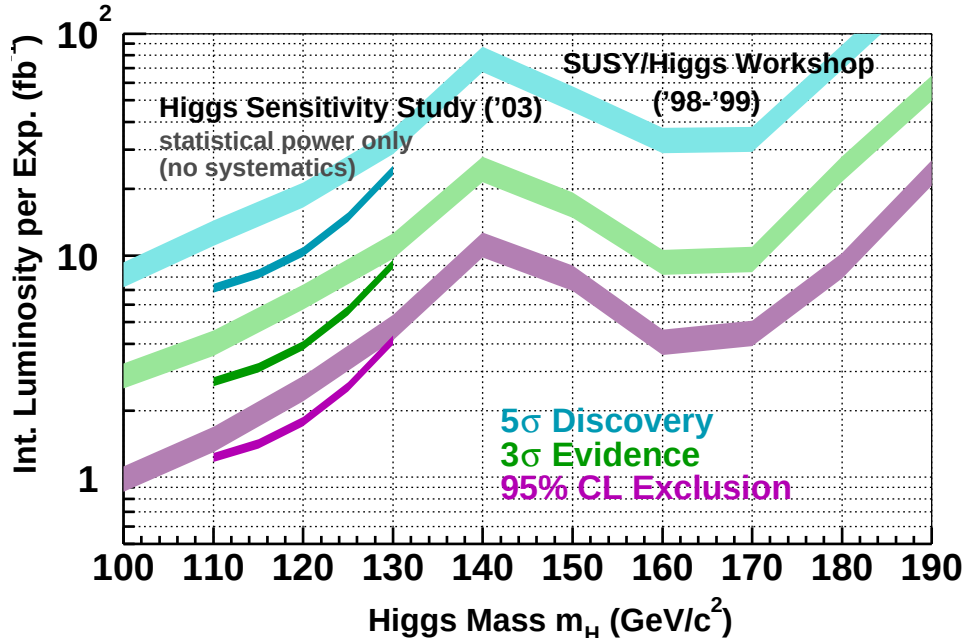
- $M_H \lesssim 140$ GeV: $H \to b\bar{b}$ dominant
- $M_H \gtrsim 140$ GeV: $H \to WW^*$, ZZ^*
- BR($H \to t\bar{t}$) up to 20 % above the $t\bar{t}$ threshold

Higgs Boson Search at the Tevatron

Spira



CDF,DO Colls.
Run II Higgs WG



- gg fusion dominant, problem large bkg
- Low Higgs mass (< 130 GeV): most promising WH, ZH production, $H \to b\bar{b}$, W, Z leptonically
- High Higgs mass: $WH \to WWW^*$, $ZH \to ZWW^*$, also $gg \to H \to WW^*$

Higgs Boson Search at the LHC

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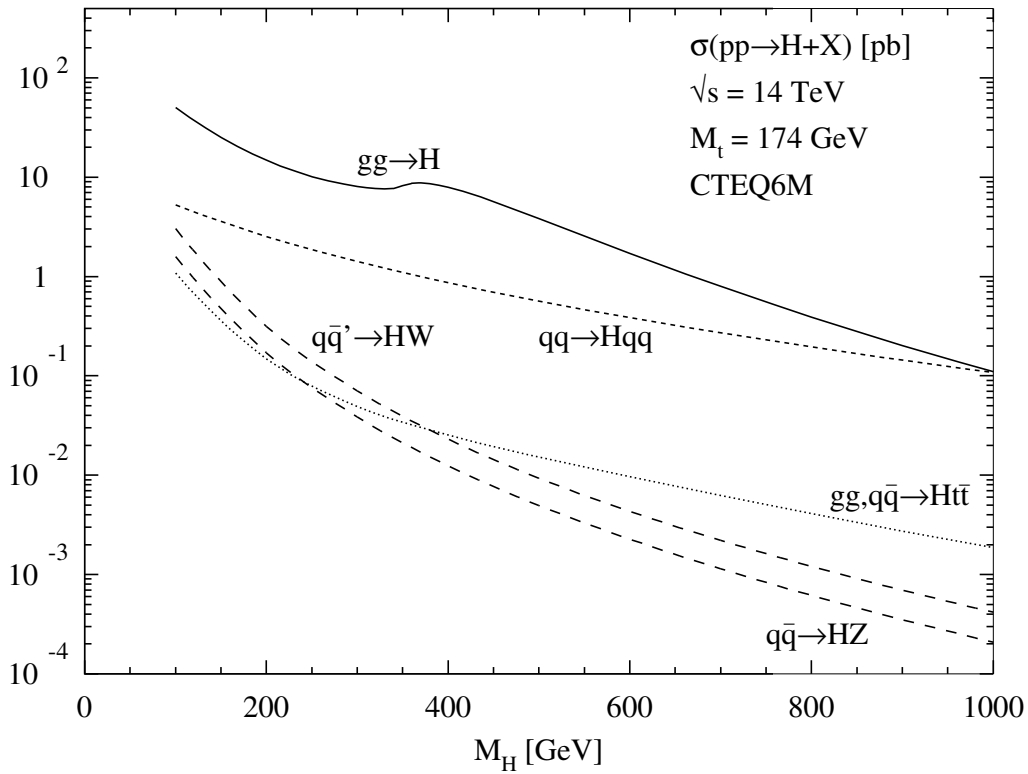
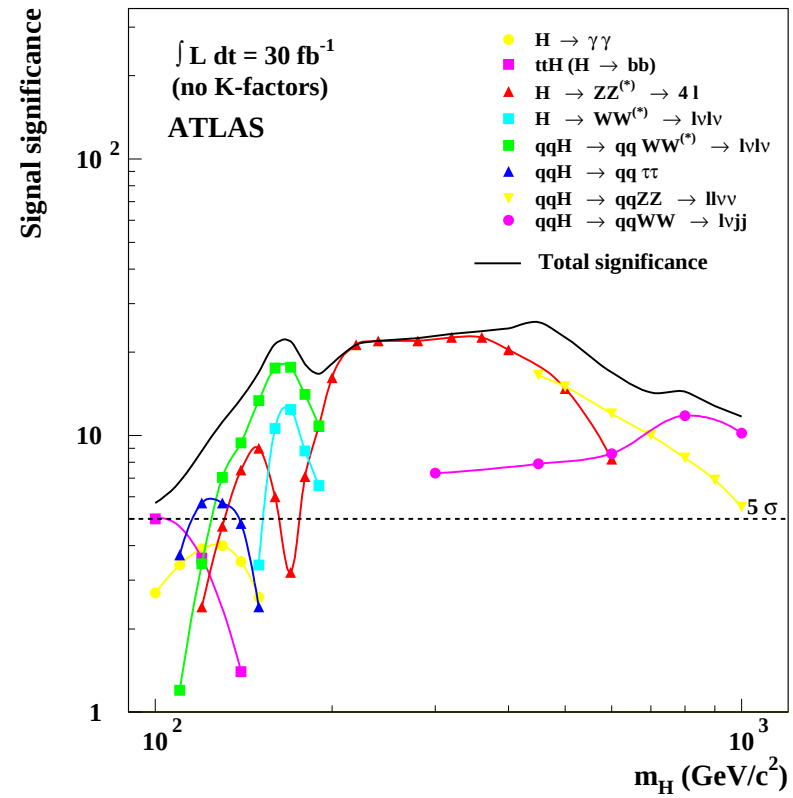


ATLAS Coll.



- gg fusion dominant, second largest vector boson fusion
- $M_H \lesssim 140$ GeV: $H \to \gamma\gamma$, $(b\bar{b})$
- 140 GeV $\lesssim M_H \lesssim$ 1 TeV: $H \to ZZ^{(*)} \to 4l^{\pm}$, $H \to WW, ZZ \to l$'s, jets

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^-

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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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Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gg v$

$M_h \rightarrow$ max. value, $\tan\beta$ fixed; h becomes SM-like

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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

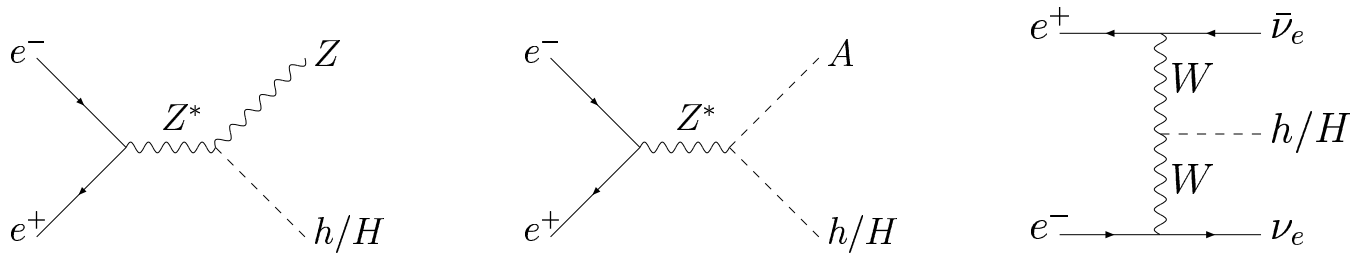
$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$

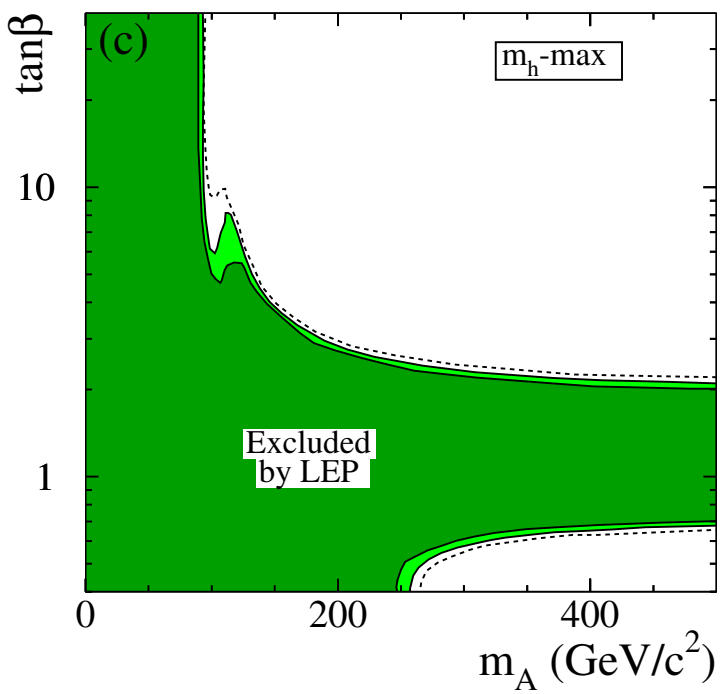
$g_{\Phi dd} \uparrow$

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

MSSM Higgs Mass Limits

▷ Direct Search at LEP: $e^+e^- \to Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$





$M_{h/H} \gtrsim 91$ GeV

$M_A \gtrsim 91.9$ GeV

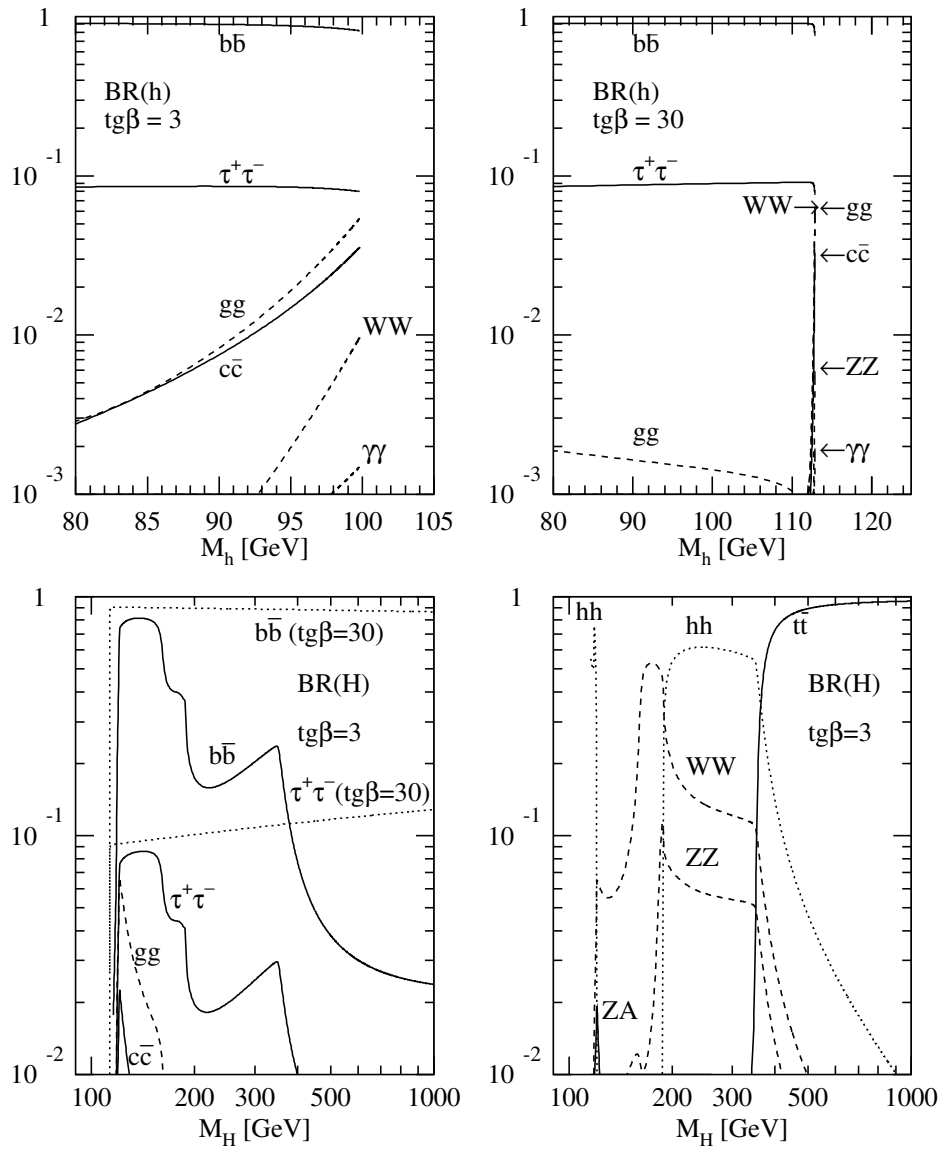
$M_{H^\pm} > 78.6$ GeV

$0.5 < \tan\beta < 2.4$ excluded

(only in this scenario, $m_t = 174.3$ GeV!)

MSSM Higgs Boson Branching Ratios

HDECAY



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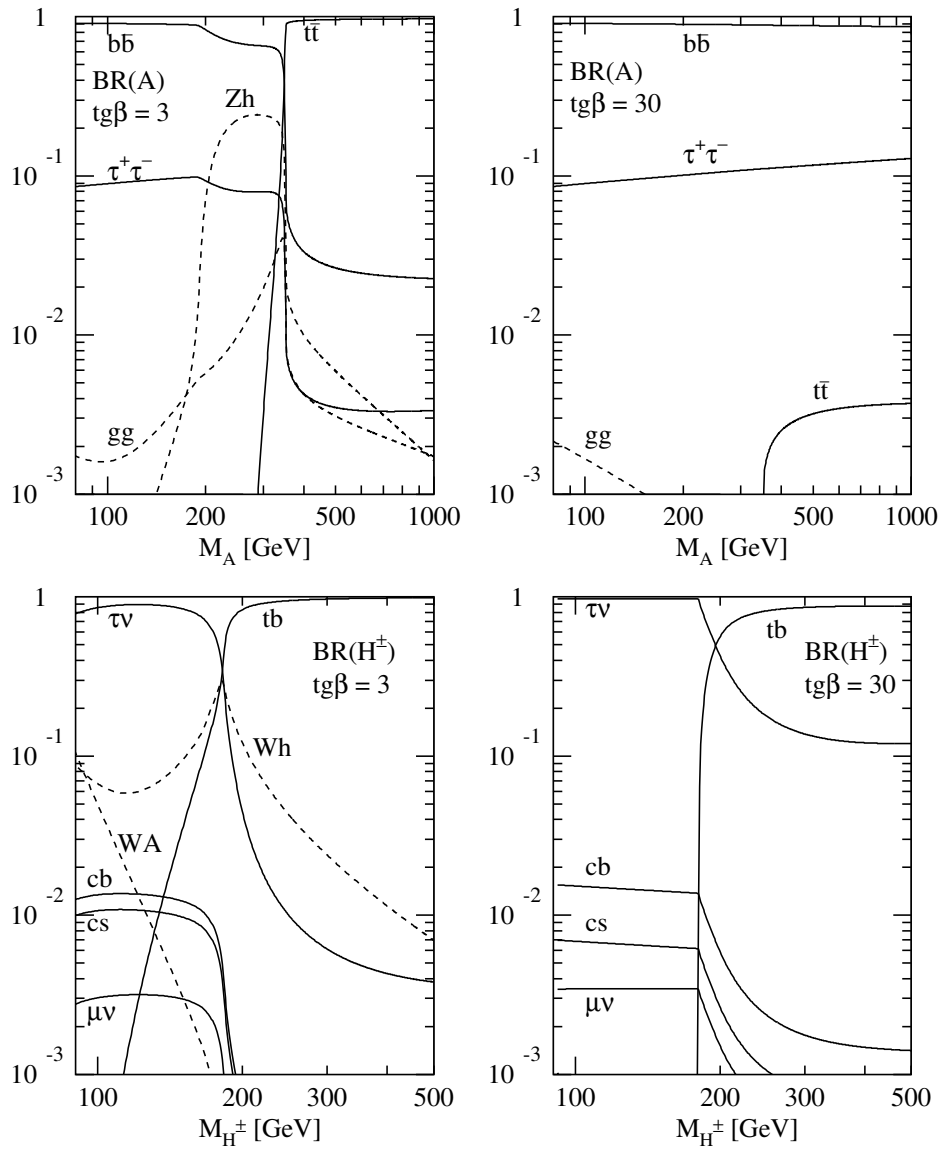
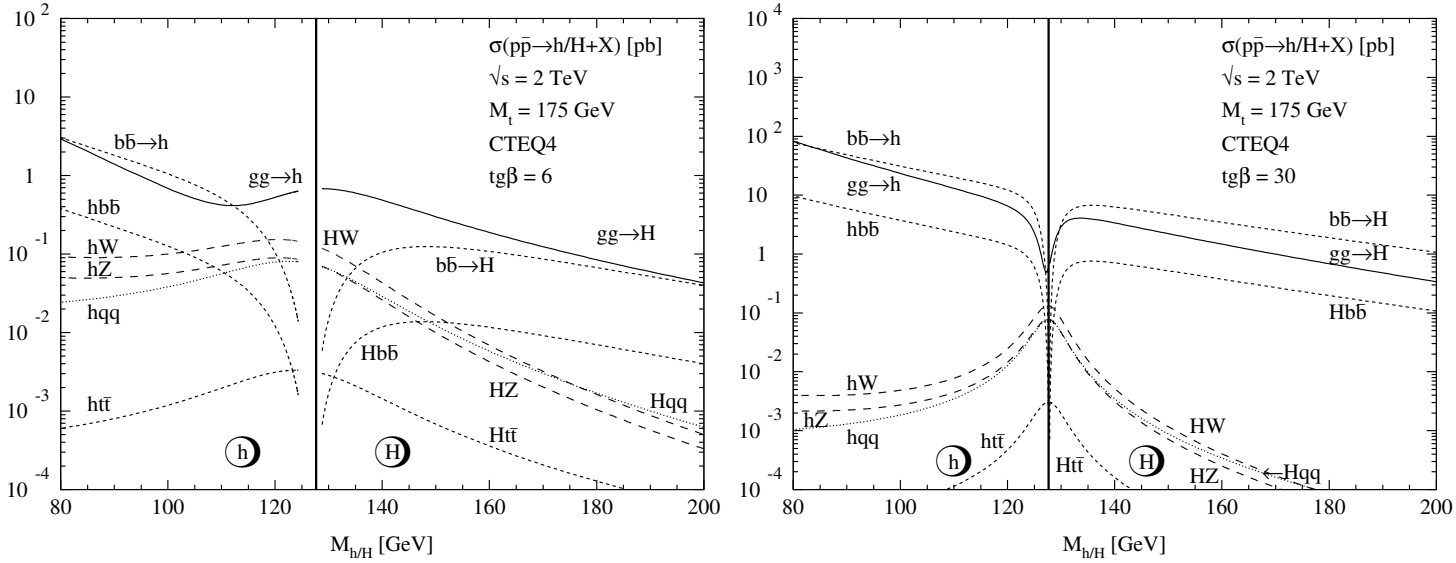


MSSM Higgs Boson Production at the Tevatron

Spira



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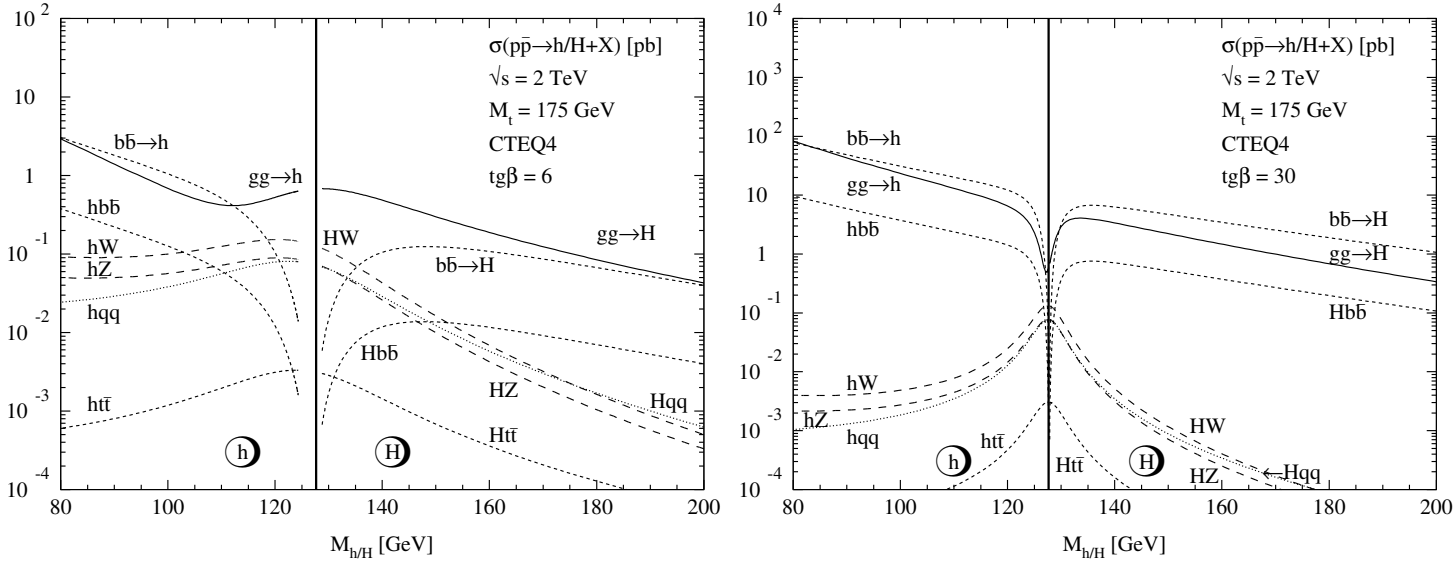
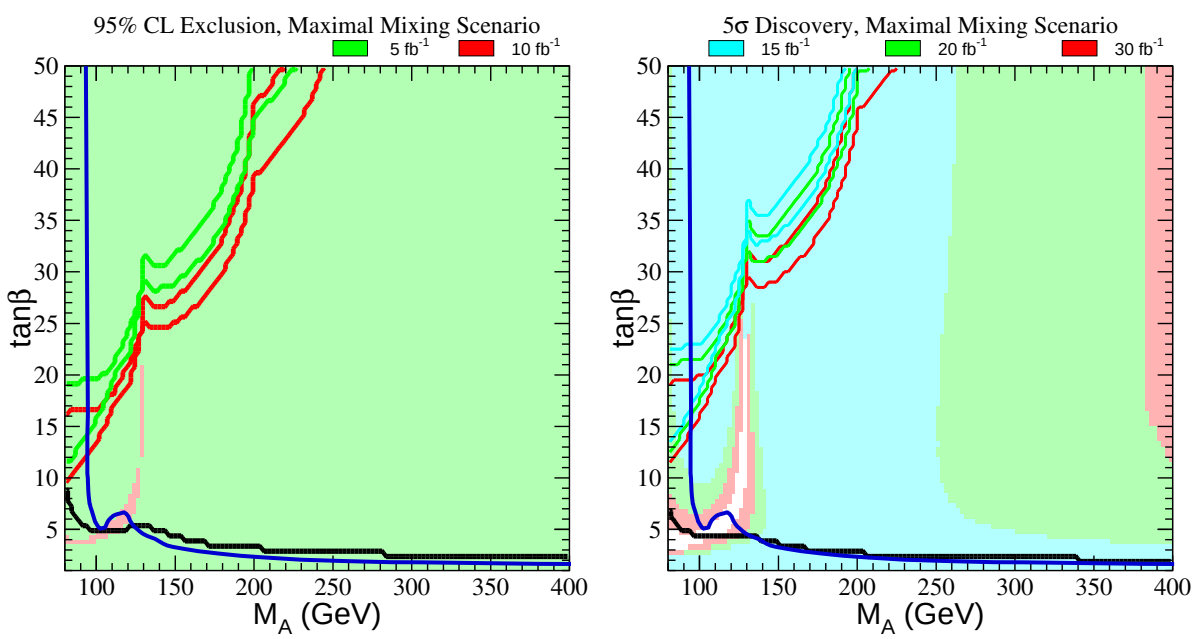


Carena et al.



MSSM Higgs Boson Production at the LHC

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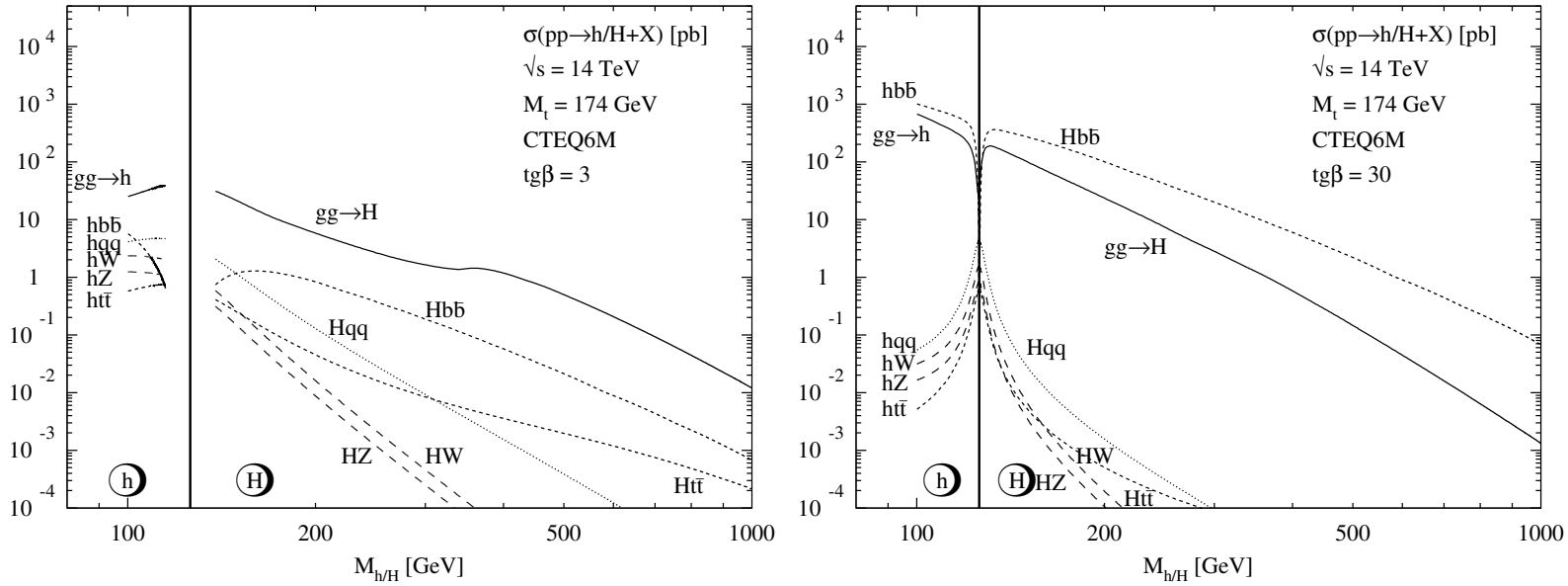

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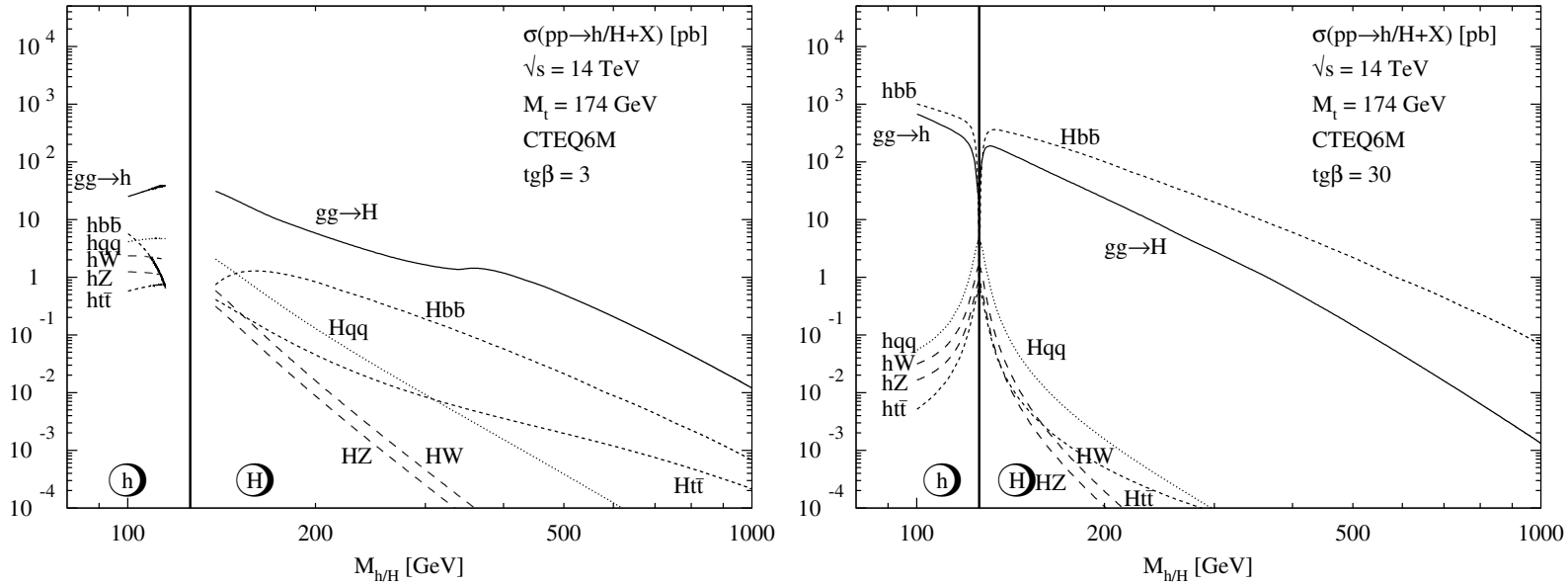
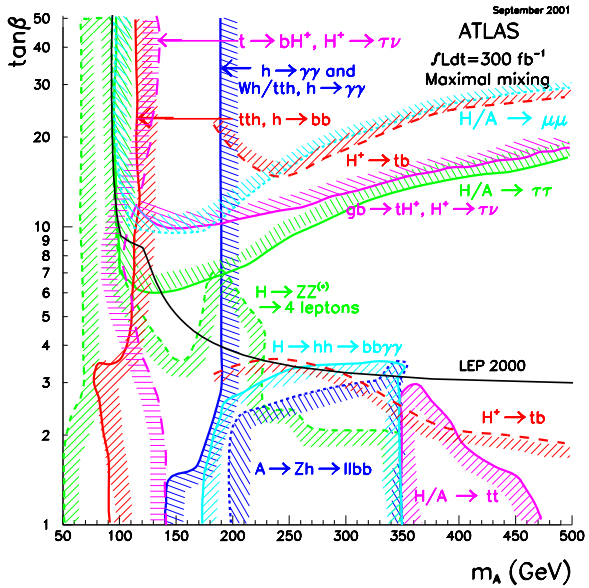


ATLAS



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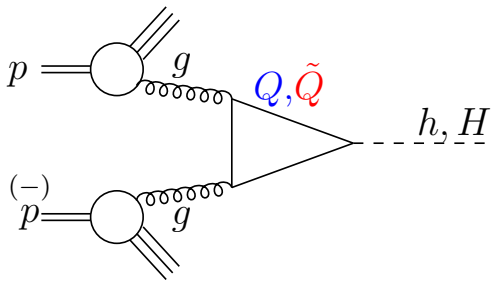
$\mathrm{gg} \to \mathrm{H}, \mathrm{h}$ at leading order

Lowest order - 1 loop

Georgi,...;Gamberini,...



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

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

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

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

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

$\mathcal{C}$omments

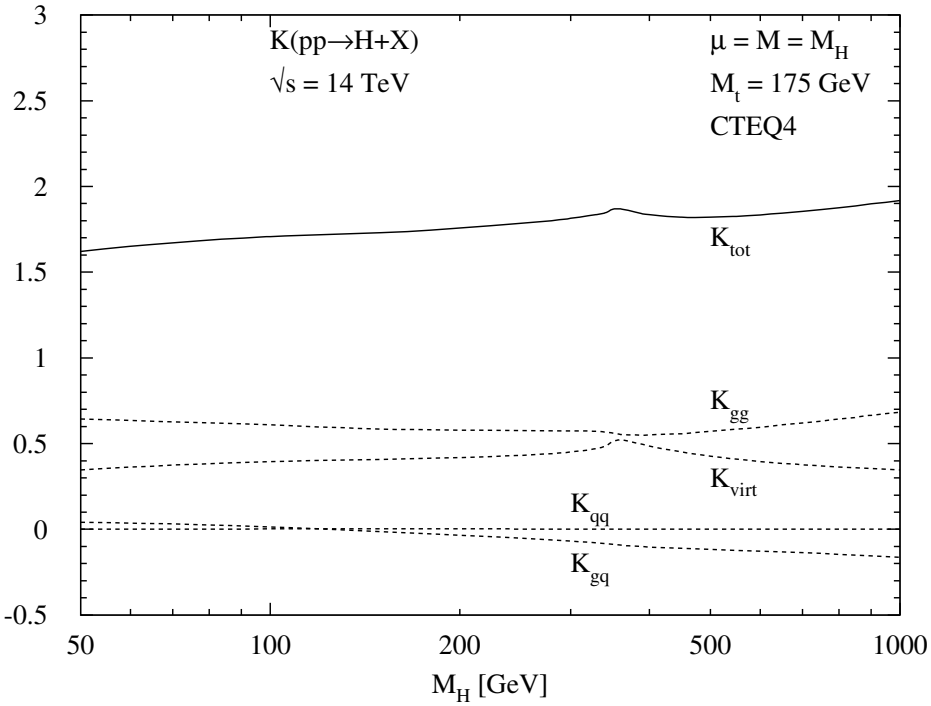
- ▷ Third generation dominant [$\tilde{t}, \tilde{b}$: $m_{\tilde{q}} \lesssim 400$ GeV, MSSM: $\tan\beta \uparrow \Rightarrow\ b/\tilde{b} \uparrow + t/\tilde{t} \downarrow$]

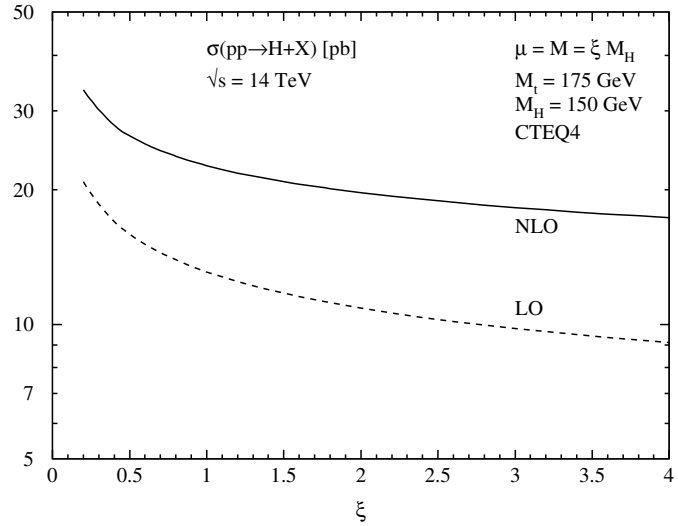
- ▷ Two-loop corrections: $\sim 10...100\%$
  [moderate for large $\tan\beta$ (b loop)]

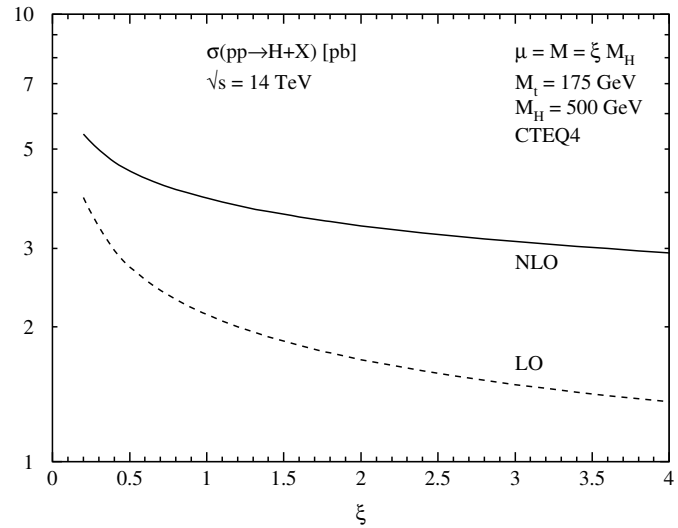
Spira,Djouadi,Graudenz,Zerwas
Dawson,Kauffmann

$gg \to H$ at NLO

Spira,Djouadi,Graudenz,Zerwas







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Spira,Djouadi,Graudenz,Zerwas
Dawson,Kauffmann

▷ SM, $\tan\beta \lesssim 5$: limit $M_\phi \ll m_t$ approximation for K-factor [$\Delta \lesssim 25\%$]

Comments

▷ Third generation dominant [$\tilde{t}, \tilde{b}$: $m_{\tilde{q}} \lesssim 400$ GeV, MSSM: $\tan\beta \uparrow \Rightarrow\ b/\tilde{b} \uparrow + t/\tilde{t} \downarrow$]

▷ Two-loop corrections: $\sim 10...100\%$
[moderate for large $\tan\beta$ (b loop)]

Spira,Djouadi,Graudenz,Zerwas
Dawson,Kauffmann

▷ SM, $\tan\beta \lesssim 5$: limit $M_\phi \ll m_t$ approximation for K-factor [$\Delta \lesssim 25\%$]

▷ NNLO calculated for $M_\Phi \ll m_t$
$\Rightarrow$ further increase by 20-30%
scale dependence: $\Delta \lesssim 10 - 15\%$

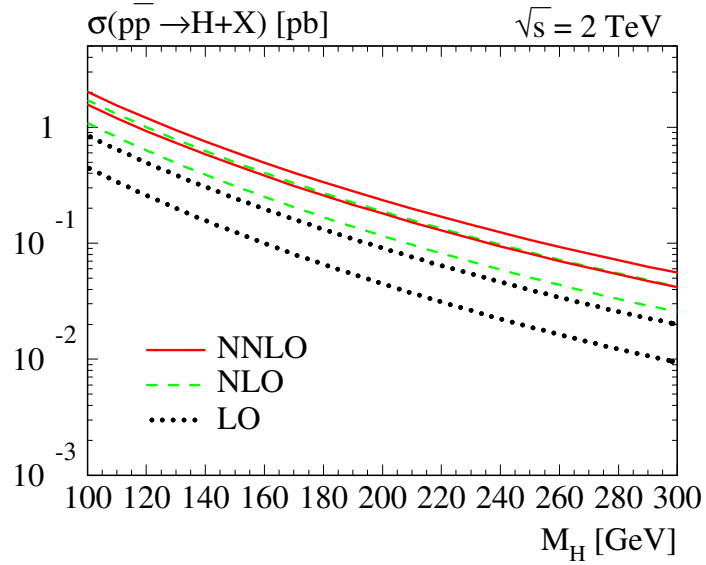
Harlander,Kilgore
Anastasiou,Melnikov
Ravindran,Smith,van Neerven

▷ Soft gluon resummation: $\sim 10\%$

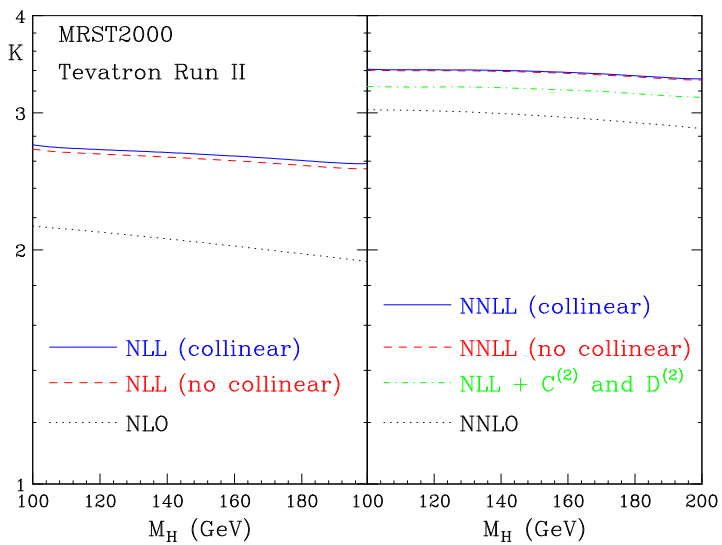
Catani,de Florian,Grazzini,Nason

$gg \to H$ at $\mathcal{NNLO}$ and beyond

Harlander,Kilgore



Catani,de Florian,Grazzini,Nason



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

QCD corrections to squark loops only known in the heavy squark limit

Squark contribution sizeable for $m_{\tilde{q}} \lesssim 400$ GeV $\Rightarrow$ (Coll. with M.Spira)

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

The Squark Loops

QCD corrections to squark loops only known in the heavy squark limit

Squark contribution sizeable for $m_{\tilde{q}} \lesssim 400$ GeV $\Rightarrow$ (Coll. with M.Spira)

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

Scenario:

The gluophobic Higgs scenario Carena,Heinemeyer,Wagner,Weiglein

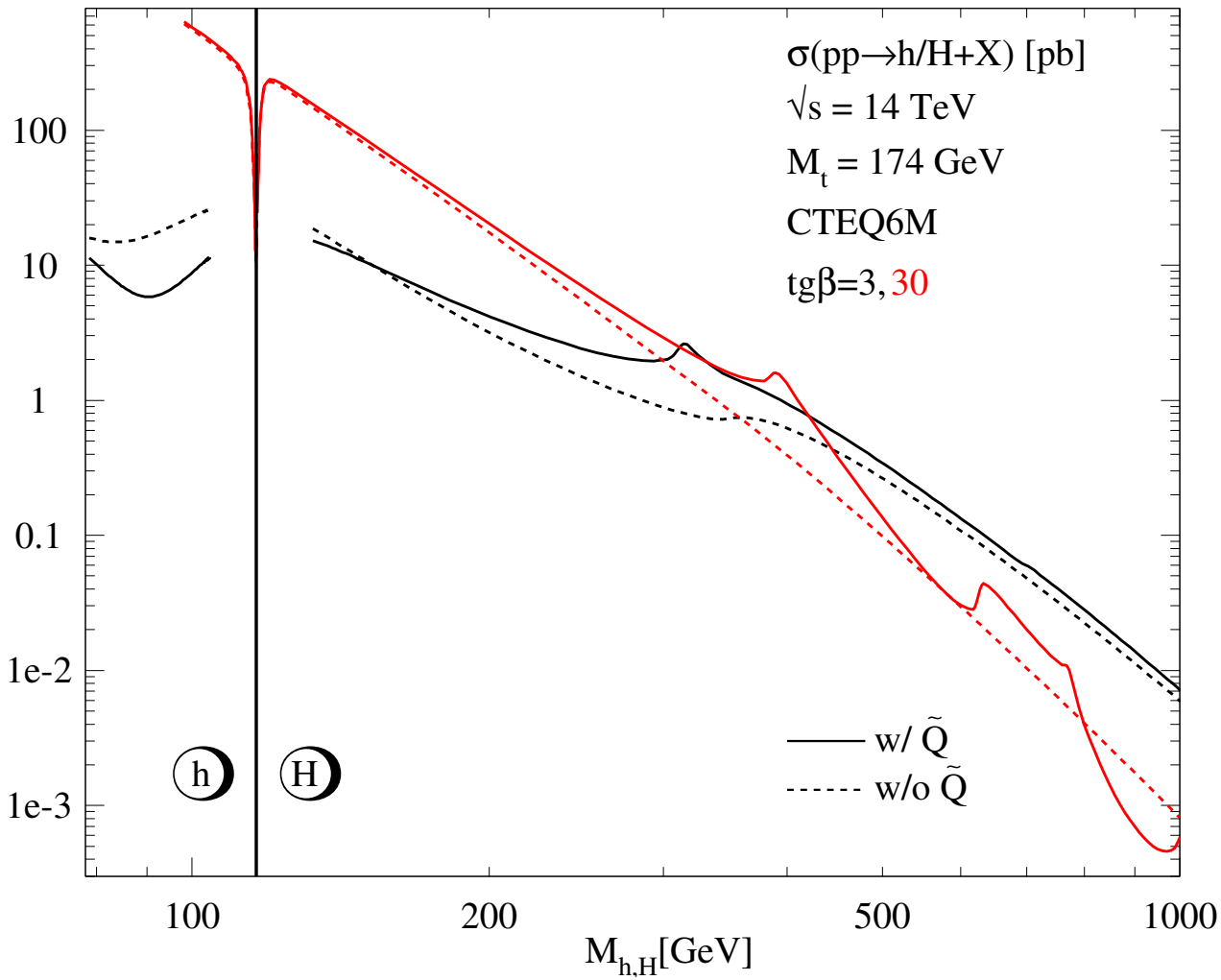
$$m_t = 174 \text{ GeV},\ M_{SUSY} = 350 \text{ GeV},\ \mu = M_2 = 300 \text{ GeV},\ A_b = A_t = -670 \text{ GeV}$$

$\tan\beta = 3$		$\tan\beta = 30$	
$m_{\tilde{t}_1} = 156$ GeV	$m_{\tilde{t}_2} = 516$ GeV	$m_{\tilde{t}_1} = 195$ 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

Squark contribution at leading order $\longrightarrow$

The $\mathcal{LO}$ Cross Section w/ and w/o Squarks

MMM,Spira



$\mathcal{QCD}$ Corrections to $\mathcal{S}$quark $\mathcal{L}$oops

First step: decouple gluino contributions $\rightsquigarrow$ adjust renormalization
(gluino contribution $\mathcal{O}(5\%)$)

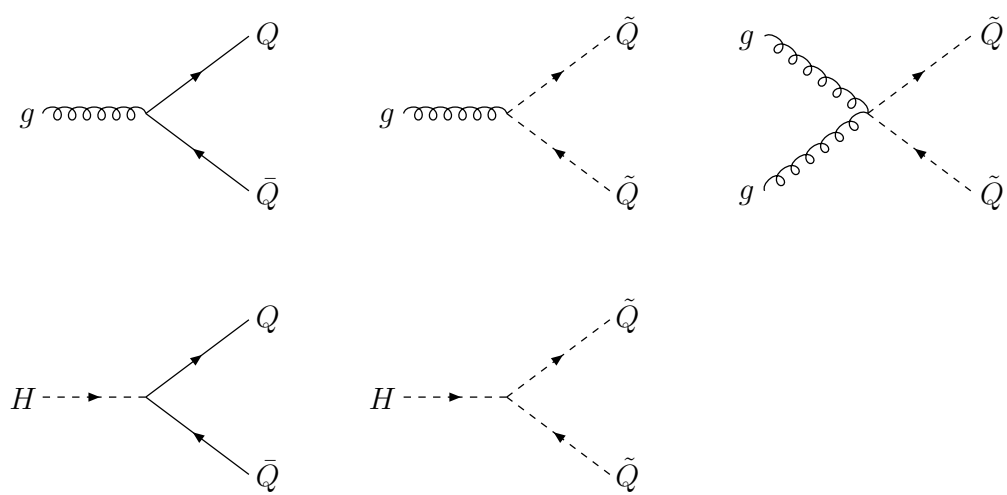
Harlander,Steinhauser,Hofmann

The Lagrangian

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

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

Interaction vertices:



$\mathcal{QCD}$ Corrections $\mathcal{O}(\alpha_S)$

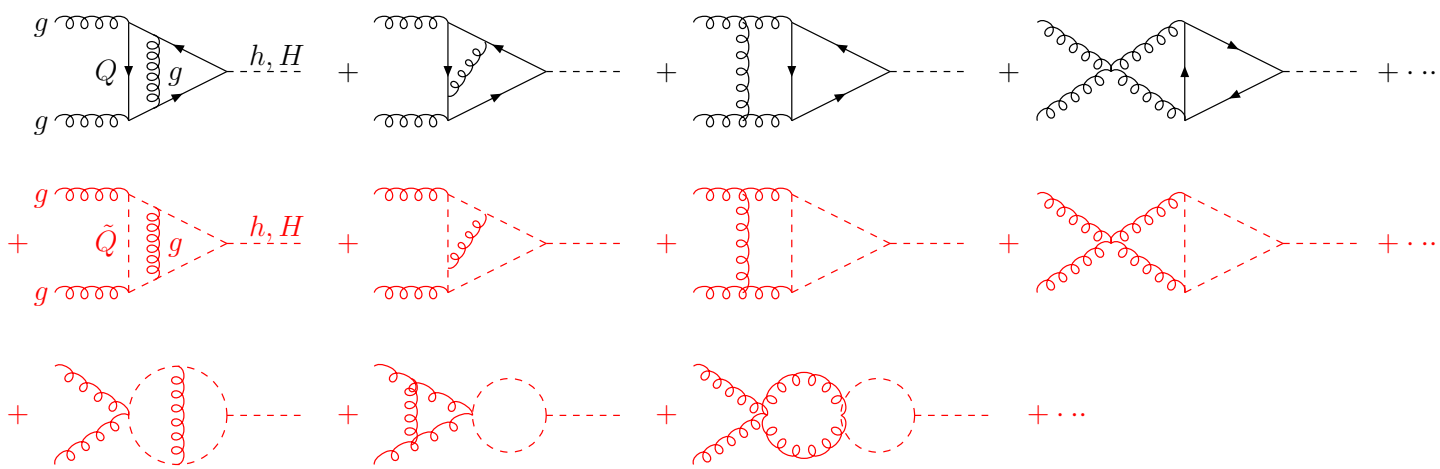
$$\Delta\hat{\sigma}_{ij} = \sigma_0 \Big\{ C_{ij}\delta(1-\hat{\tau}) + D_{ij}\Theta(1-\hat{\tau}) \Big\} \frac{\alpha_s}{\pi}$$

$$\hat{\tau} = \frac{M_\Phi^2}{\hat{s}}$$

virtual+soft corrections

real corrections

Virtual corrections [2 loops, no gluino contributions]



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

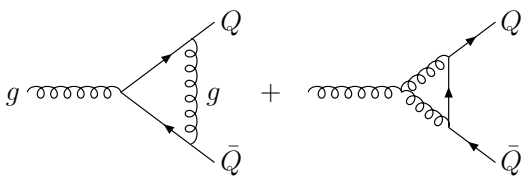
$\mathcal{UV}$-$\mathcal{S}$ingularities – $\mathcal{R}$enormalization

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

$\mathcal{UV}$-$\mathcal{S}$ingularities – $\mathcal{R}$enormalization

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

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



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

[Slavnov-Taylor identity]

$\mathcal{UV}$-$\mathcal{S}$ingularities – $\mathcal{R}$enormalization

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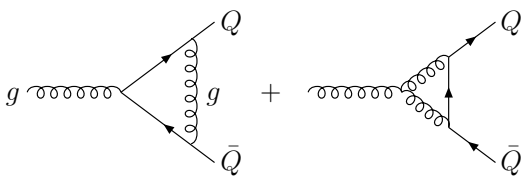

$$Z_1 = Z_{\alpha_S}^{1/2} Z_3^{1/2} Z_2$$

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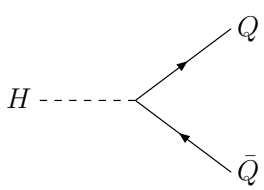
- **$\mathbf{HQ\bar{Q}}$ vertex:**

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



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

Braaten,Leveille

$\mathcal{UV}$-$\mathcal{S}$ingularities – $\mathcal{R}$enormalization

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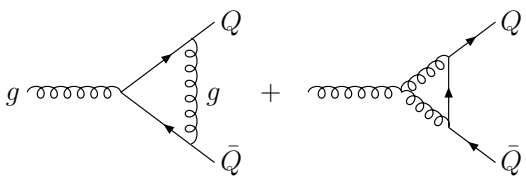

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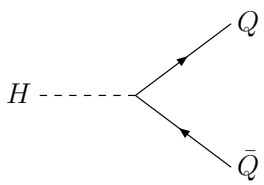
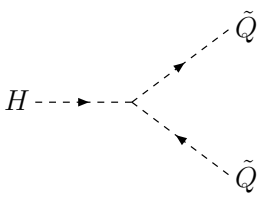


$$\Gamma_{H\bar{Q}Q}(q^2 = 0) \neq Z_{HQQ}$$

Braaten,Leveille

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

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



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

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

$\mathcal{V}$irtual $\mathcal{C}$orrections - $\mathcal{H}$eavy $\mathcal{S}$quark $\mathcal{L}$imit

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

$$C_{\rm virt} = \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \left(\frac{4\pi\mu^2}{M_H^2}\right)^{\epsilon} \left\{ -\frac{3}{\epsilon^2} - \frac{33-2N_F}{6\epsilon} \left(\frac{\mu^2}{M_H^2}\right)^{-\epsilon} + \pi^2 + 9 \right\}$$

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

[$9 \to \frac{11}{2}$ in the heavy quark limit (without squark loops)]

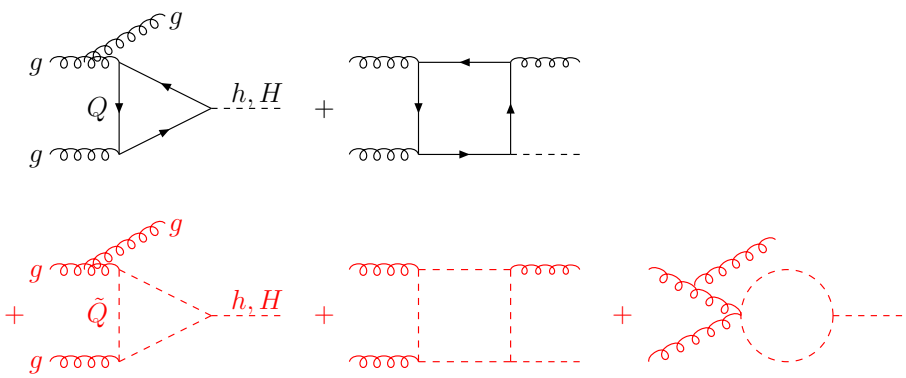
▷ Recovers heavy squark limit via effective Lagrangian — Dawson,Djouadi,Spira

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

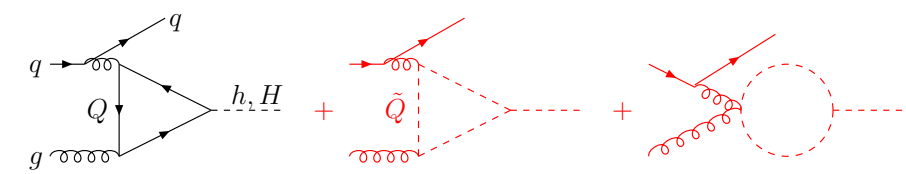
$\mathcal{R}$eal $\mathcal{C}$orrections

3 incoherent processes:

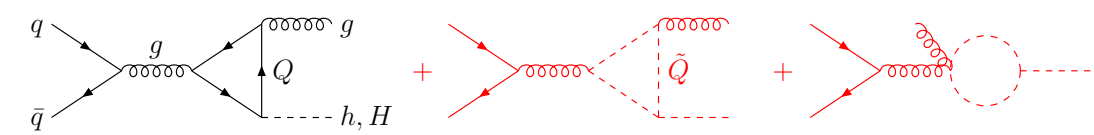
gg → Hg:



gq → Hq:



q$\bar{\text{q}}$ → Hg:



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

$\mathcal{R}$eal $\mathcal{C}$orrections - $\mathcal{H}$eavy $\mathcal{S}$quark $\mathcal{L}$imit

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

$$
\begin{aligned}
C_{\mathrm{real}} &= \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu^2}{m_\Phi^2}\Big)^\epsilon\Big\{\frac{3}{\epsilon^2}+\frac{33-2N_F}{6\epsilon}\Big\} \\
D_{gg} &= -\frac{\hat\tau}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu^2}{\hat s}\Big)^\epsilon P_{gg}(\hat\tau)-\frac{11}{2}(1-\hat\tau)^3 \\
&\quad +12\Big\{\Big(\frac{\log(1-\hat\tau)}{1-\hat\tau}\Big)_+ - \hat\tau[2-\hat\tau(1-\hat\tau)]\log(1-\hat\tau)\Big\} \\
D_{gq} &= -\Big\{\frac{1}{2\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\Big(\frac{4\pi\mu^2}{\hat s}\Big)^\epsilon-\log(1-\hat\tau)\Big\}\hat\tau P_{gq}(\hat\tau)-1+2\hat\tau-\frac{\hat\tau^2}{3} \\
D_{q\bar q} &= \frac{32}{27}(1-\hat\tau)^3
\end{aligned}
$$

- IR, Coll. poles in C_{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.

$\mathcal{R}$esult - $\mathcal{H}$eavy $\mathcal{S}$quark $\mathcal{L}$imit (without b, t loops)

$$
\begin{aligned}
\sigma(p \overset{(-)}{p} \to \Phi + X) &= \sigma_0[1 + C\tfrac{\alpha_S}{\pi}]\tau_\Phi \tfrac{d\mathcal{L}_{gg}}{d\tau_\Phi} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{qq} \\
C &= \pi^2 + 9 + \tfrac{33-2N_F}{6} \log \tfrac{\mu^2}{M_\Phi^2} \\
\Delta\sigma_{gg} &= \int_{\tau_\Phi}^1 d\tau \tfrac{d\mathcal{L}_{gg}}{d\tau} \tfrac{\alpha_S}{\pi} \sigma_0 \Big\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \tfrac{Q^2}{\hat{s}} - \tfrac{11}{2}(1-\hat{\tau})^3 \\
&\quad + 12 \Big[\Big(\tfrac{\log(1-\hat{\tau})}{1-\hat{\tau}} \Big)_+ - \hat{\tau}[2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \Big] \Big\} \\
\Delta\sigma_{gq} &= \int_{\tau_\Phi}^1 d\tau \sum_{q,\bar{q}} \tfrac{d\mathcal{L}_{gq}}{d\tau} \tfrac{\alpha_S}{\pi} \sigma_0 \Big\{ -\tfrac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \Big[\log \tfrac{Q^2}{\hat{s}} - 2\log(1-\hat{\tau}) \Big] \\
&\qquad\qquad -1 + 2\hat{\tau} - \tfrac{\hat{\tau}^2}{3} \Big\} \\
\Delta\sigma_{q\bar{q}} &= \int_{\tau_\Phi}^1 d\tau \sum_q \tfrac{d\mathcal{L}^{q\bar{q}}}{d\tau} \tfrac{\alpha_S}{\pi} \sigma_0 \tfrac{32}{27} (1-\hat{\tau})^3
\end{aligned}
$$

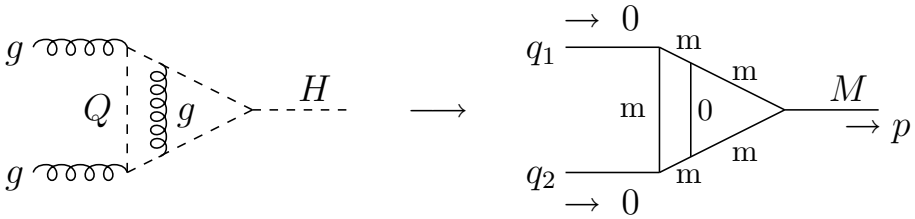
[μ=Ren. scale, Q=Fact. scale]

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

$\mathcal{G}$eneral $\mathcal{C}$ase (arbitrary $\mathrm{M_\Phi, m_Q, m_{\tilde{Q}}}$)

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

Example:



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

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

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

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

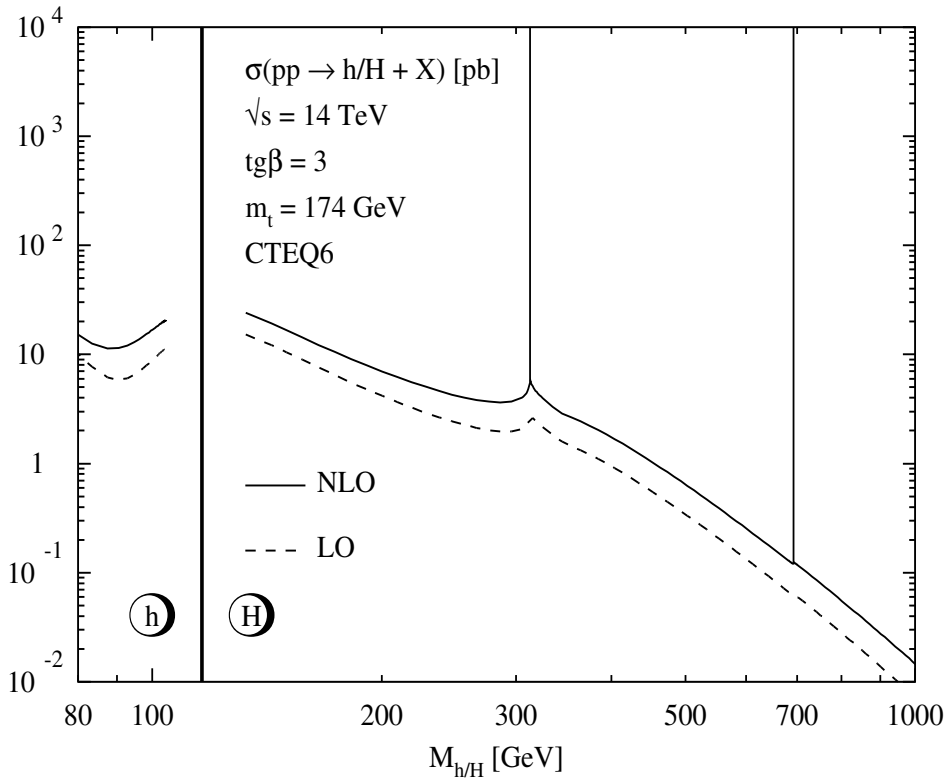
$\mathcal{R}$esult

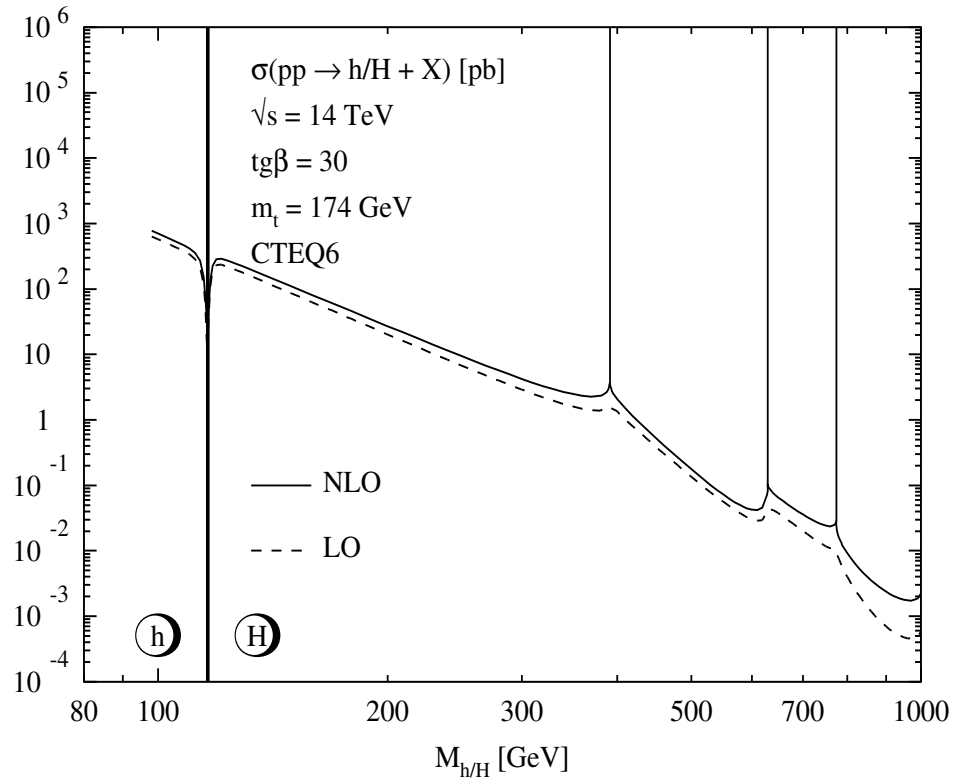
- α_S: $\overline{\mathrm{MS}}$ scheme, 5 active flavours
- $\lim_{m_{\tilde{Q}}\to\infty}$ recovered
- calculation analogous to $m_{\tilde{Q}} \to \infty$

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

The LO and NLO Cross Section w/ Squarks

MMM,Spira

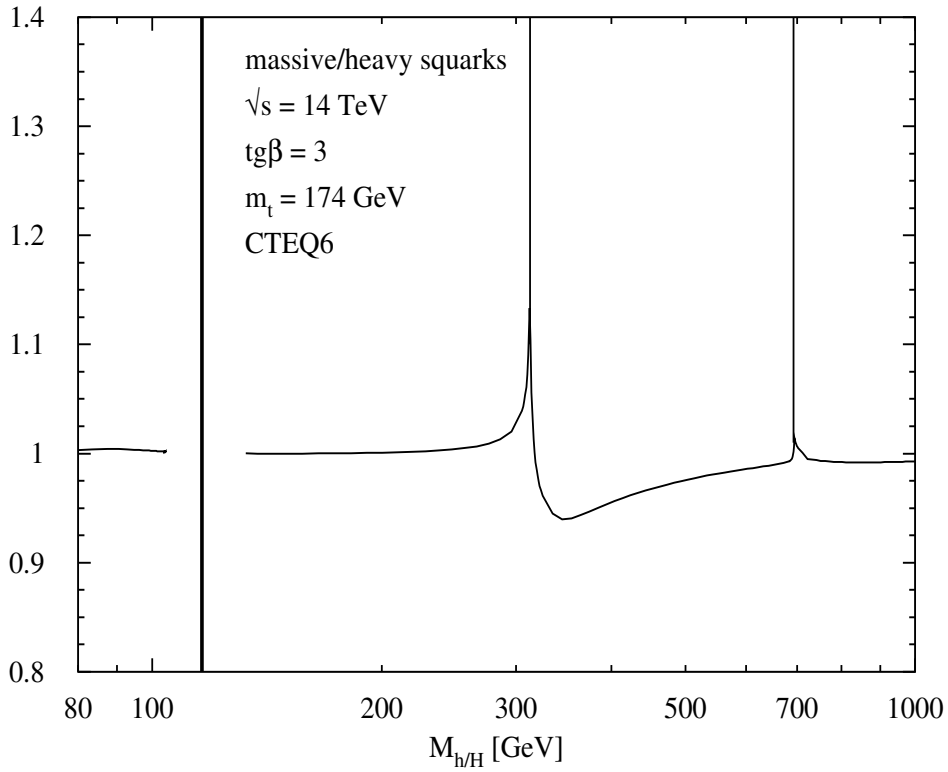


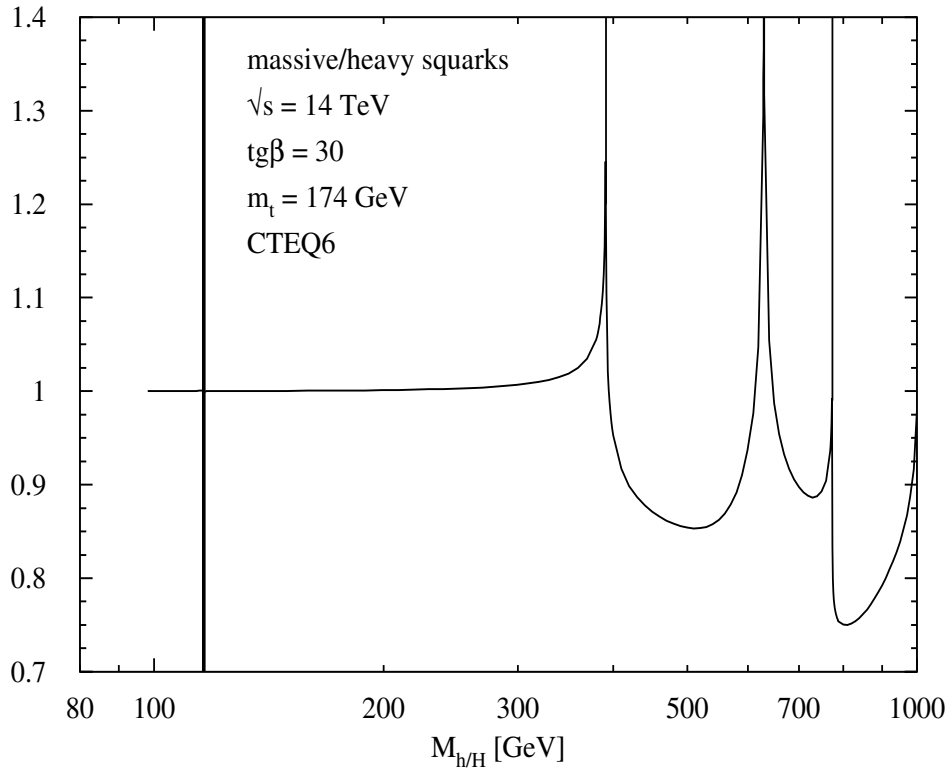


PRELIMINARY

$\mathcal{NLO}$ Cross Section for Massive Squarks and in the Heavy Squark Limit

MMM,Spira





PRELIMINARY

$\mathcal{H}$iggs $\mathcal{P}$hysics

Higgs physics at future colliders:
Establish experimentally the Higgs Mechanism

The Higgs mechanism:
Creation of particle masses in a gauge-invariant way

Outline of the talk

- $\mathcal{I}$ntroduction
- $\mathcal{Q}$CD corrections to squark loops in $gg \to$ Higgs
- $\tau\tau$ $\mathcal{F}$usion to SUSY Higgs bosons at a Photon Collider
- $\mathcal{C}$onclusions

$\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

- **MSSM Higgs Sector:** Central task - determination of $\tan\beta$, difficult for large values of $\tan\beta$ [ratio of the two VEVs of the two Higgs doublets introduced in the MSSM]

- **Precision:** $\delta\tan\beta/\tan\beta \sim 10\%$ at e^+e^-/pp colliders Choi et al.;Boos et al.;Gunion et al.;Kinnunen et al. Nieżurawski et al.;Velasco et al.

- **Alternative:** Determination of $\tan\beta$ in $\tau\tau$ fusion at a Photon Collider

- **Photon Collider: Option at a future ILC** Ginzburg,Kotkin,Panfil, Serbo,Telnov

  Photons via Compton back-scattering of laser light off the incoming $e^-e^\pm$ beams

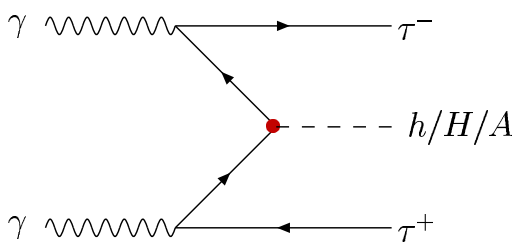
  high luminosity ($\int\mathcal{L} = 300$ fb^{-1} in 2 years)

  high energy, high degree of polarisation

$\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

- **$\tau\tau$ Fusion to h, H, A at a $\gamma\gamma$ Collider: Signal**



Couplings: for large $\tan\beta$

$A\tau\tau = \tan\beta$, $H\tau\tau \approx \tan\beta$ heavy H/A

$h\tau\tau \approx \tan\beta$ light A

Higgs decays: $h/H/A \to b\bar{b}$ at 90% (SPS1b)

$\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

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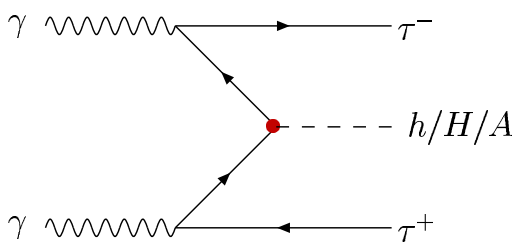

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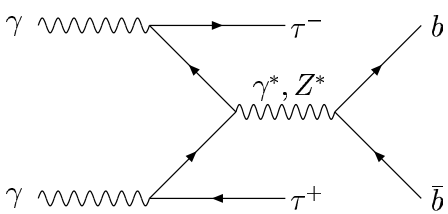
$h\tau\tau \approx \tan\beta$ light A

Higgs decays: $h/H/A \to b\bar{b}$ at 90% (SPS1b)

- **Bkg - Annihilation: $\tau^+\tau^- \to b\bar{b}$ and $b\bar{b} \to \tau^+\tau^-$ via γ, Z**

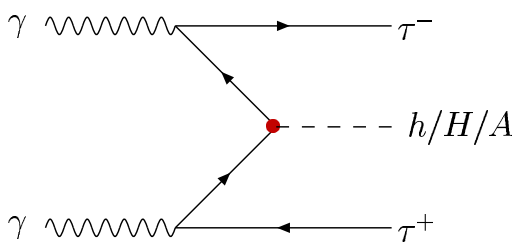


suppressed $\sim g^2$ except for $M_{bb} \sim M_Z$, $M_{\tau\tau} \sim M_Z$

$\tau\tau$ Fusion to SUSY Higgs Bosons at a Photon Collider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

- **$\tau\tau$ Fusion to h, H, A at a $\gamma\gamma$ Collider: Signal**



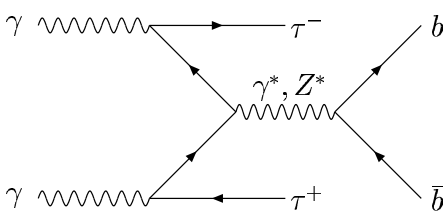
Couplings: for large $\tan\beta$

$A\tau\tau = \tan\beta$, $H\tau\tau \approx \tan\beta$ heavy H/A

$h\tau\tau \approx \tan\beta$ light A

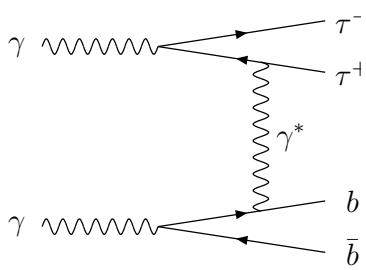
Higgs decays: $h/H/A \to b\bar{b}$ at 90% (SPS1b)

- **Bkg - Annihilation: $\tau^+\tau^- \to b\bar{b}$ and $b\bar{b} \to \tau^+\tau^-$ via γ, Z**



suppressed $\sim g^2$ except for $M_{bb} \sim M_Z$, $M_{\tau\tau} \sim M_Z$

- **Bkg - diffractive: $\gamma\gamma \to (\tau\tau)(bb)$**



suppressed by event topology:

$\tau\tau$ small invariant mass/same direction

bb dito/close to γ axes

$\mathcal{A}$nalysis

- **Signal:** complete set of signal diagrams

$$\gamma\gamma \to \tau\tau + h/H/A[\to b\bar{b}]$$

- **bkg's:** all 4 particle final states (without Higgs) of the process $\gamma\gamma \to (\tau\tau)(bb)$
  (calculated with CompHEP Boos,Dubinin,Ilyin,...)

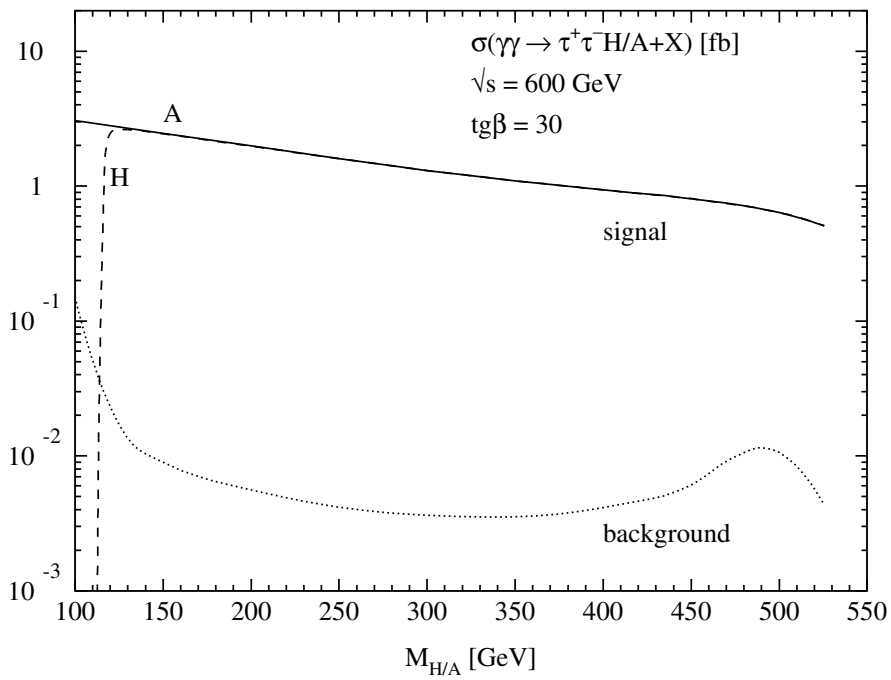
- **Cuts:** $M_{bb} = M_\Phi \pm \Delta$ with $\Delta = \max[\Gamma_\Phi/2, \Delta_{\rm ex}] \to \Delta_{\rm ex} = 0.05 M_\Phi$

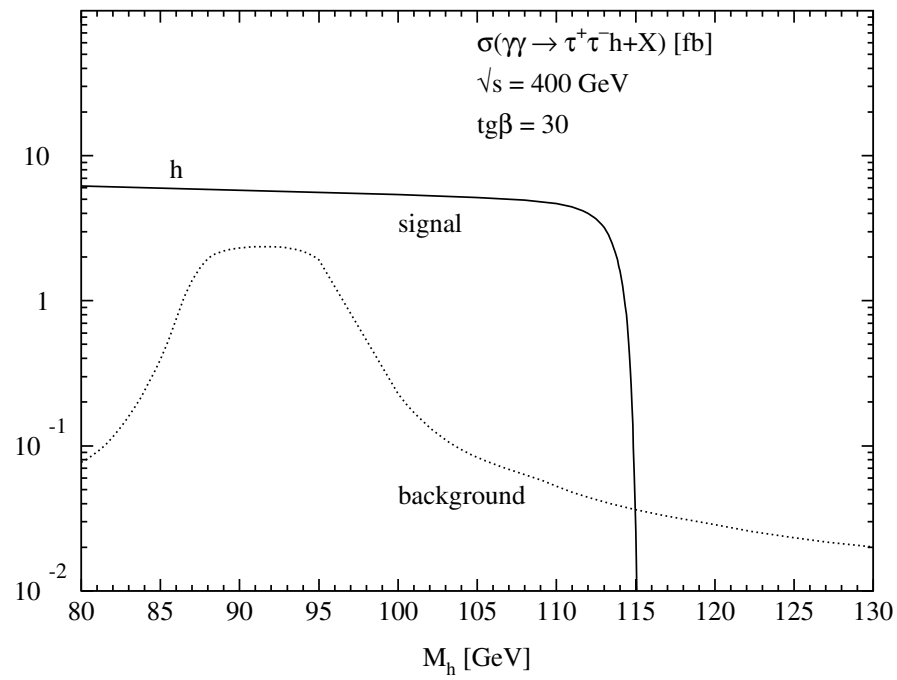
τ polar angle	≥ 130 mrad [shielding: dead mask]
τ energy	≥ 5 GeV
τ^+ and τ^-	assumed in opposite directions

- **Efficiencies:** $\epsilon_{bb} \sim 0.7$ and $\epsilon_{\tau\tau} \sim 0.5 \to \epsilon \sim 0.35$

$\mathcal{R}$esults

$E_{e^\pm e^-} = 800/500$ GeV $\Rightarrow E_{\gamma\gamma} = 600/400$ GeV, $\mathcal{L} = 200/100$ fb^{-1}





- $\sigma(H/A) = 3$ to 1 fb for $M_{A/H} = 100...500$ GeV and $\tan\beta = 30$
- $\sigma(h) = 5$ fb for $M_h = 110$ GeV and $\tan\beta = 30$

$\mathcal{A}$ccuracies

	$E_{\gamma\gamma} = 400$ GeV, $\mathcal{L} = 100$ fb^{-1}			$E_{\gamma\gamma} = 600$ GeV, $\mathcal{L} = 200$ fb^{-1}				
$M_{\rm Higgs}$ [GeV]	$A \oplus h$	$A \oplus H$		$A \oplus h$	$A \oplus H$			
	100	200	300	100	200	300	400	500
$\tan\beta$	I	II	III	IV	V	VI	VII	VIII
10	8.4%	10.7%	13.9%	8.0%	9.0%	11.2%	13.2%	16.5%
30	2.6%	3.5%	4.6%	2.4%	3.0%	3.7%	4.4%	5.3%
50	1.5%	2.1%	2.7%	1.5%	1.8%	2.2%	2.6%	3.2%

$\Delta \tan\beta \approx 0.9$ to 1.3 indep. of $\tan\beta$
for all M_A up to the kinematical limit

$\mathcal{T}$he results are encouraging enough to start experimental simulations including detector effects, overlaying events, optimized cuts, etc.

$\mathcal{C}$onclusions

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 $\rightsquigarrow$ also large corrections to squark loops
- 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 20 %.

Determination of $\tan\beta$ in $\tau\tau$ fusion

- $\tau\tau \to h/H/A$ at a future photon collider $\rightsquigarrow$ determination of $\tan\beta$ at $\mathcal{O}(10)\%$.
- Complements determination of $\tan\beta$ at pp/e^+e^- colliders.