# Probing The Higgs Boson Self-Coupling at Lepton and Hadron Colliders

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# 1 – Introduction

- If it exists, the Standard Model (SM) Higgs boson will be discovered at the LHC over the entire range $115\ \mathrm{GeV} < m_H < 1\ \mathrm{TeV}$
- can measure Higgs properties at LHC: (Dührssen)

  ☞ $M_H$ to 0.1%

  ☞ $\Gamma(H \to X)/\Gamma_H$ to $\mathcal{O}(10\%)$

  ☞ relative couplings to $\mathcal{O}(10\%)$
- at this point, what remains to be done: determine Higgs potential

$$V(\eta_H) = \frac{1}{2}\, m_H^2\, \eta_H^2 + \lambda\, v\, \eta_H^3 + \frac{1}{4}\, \tilde{\lambda}\, \eta_H^4,$$

$\eta_H$: physical Higgs field, $v = (\sqrt{2} G_F)^{-1/2}$,

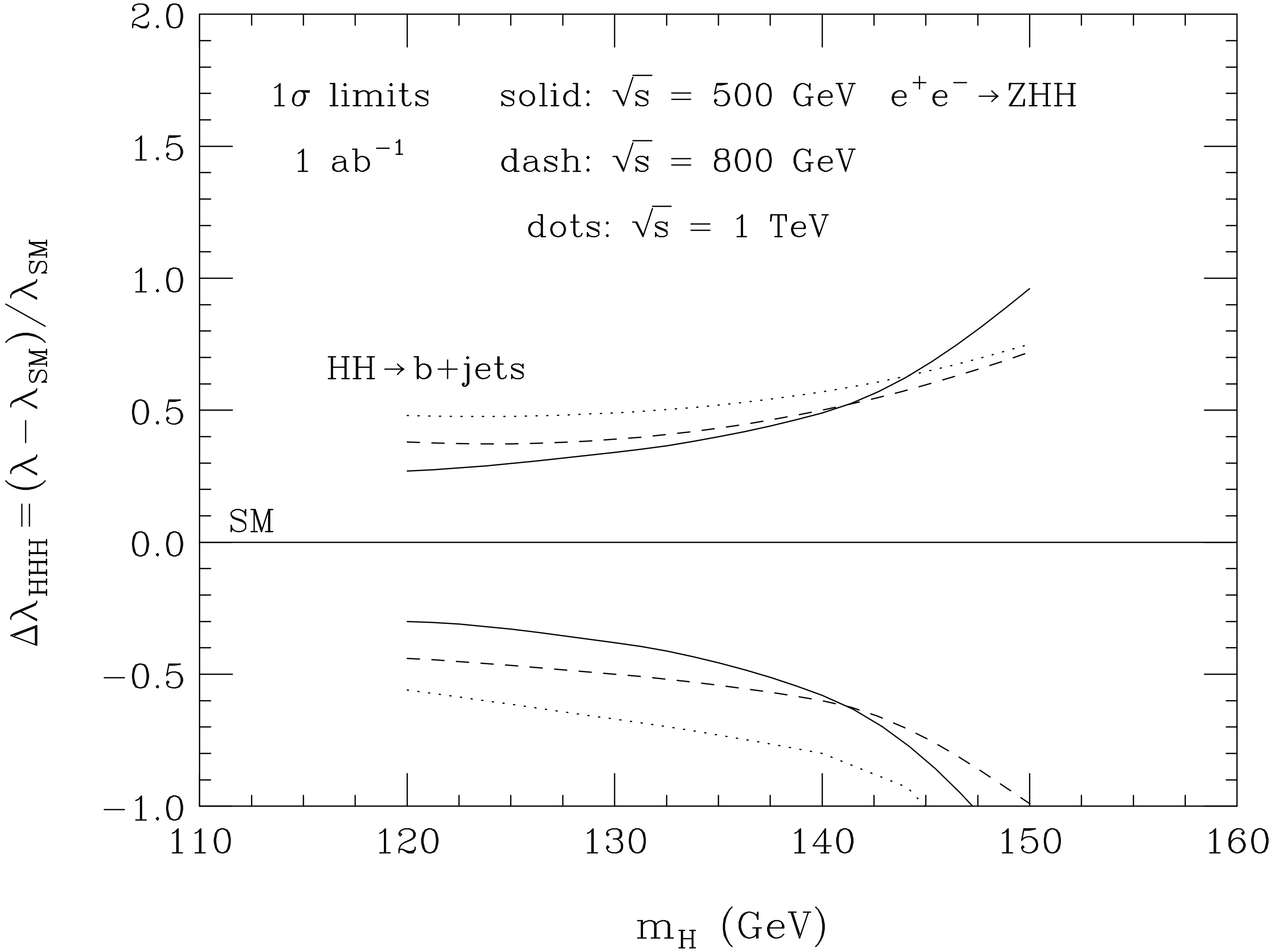
SM: $\tilde{\lambda} = \lambda = \lambda_{SM} = m_H^2/(2v^2)$

☞ $\lambda$ and $\tilde{\lambda}$ are *per se* free parameters

- to measure $\lambda$ ($\tilde{\lambda}$), experiments must observe $HH$ ($HHH$) production
  - ☞ $HHH$ cross sections too small to probe $\tilde{\lambda}$ at any machine considered so far
  - ☞ concentrate on $\lambda$ in the following
- radiative corrections to $HHH$ coupling:
  - ☞ SM: $-4\% \cdots - 11\%$ for 120 GeV $< M_H <$ 200 GeV (Yuan *et al.*)
  - ☞ can be up to 100% in general 2HDM
  - ☞ MSSM: up to 8% for light stop squarks (Hollik *et al.*)
- Higgs pair production at Linear Collider:
  - ☞ $e^+e^- \to ZHH$: dominates for $\sqrt{s} < 1$ TeV
  - ☞ $e^+e^- \to HH\nu\bar{\nu}$: dominates for $\sqrt{s} > 1.5$ TeV
- Higgs pair production at hadron colliders:
  - ☞ dominating mechanism: $gg \to HH$ (Glover, van der Bij)

## 2 – Higgs Pair Production at Linear Colliders

- case of a light Higgs boson with $HH \to b+$ jets ($e^+e^- \to ZHH$):
  - ☞ studied in detail for $m_H = 120$ GeV and $\sqrt{s} = 500$ GeV by Castanier et al.
    - ➞ can determine $HHH$ coupling with a precision of $\approx 20\%$ for 1 ab$^{-1}$
  - ☞ extrapolation to $m_H > 120$ GeV and $\sqrt{s} > 500$ GeV
    - ➞ limits degrade for larger $m_H$ ($Br(H \to b\bar{b})$, phase space)
    - ➞ and larger $\sqrt{s}$ ($\sigma(e^+e^- \to ZHH)$ falls)

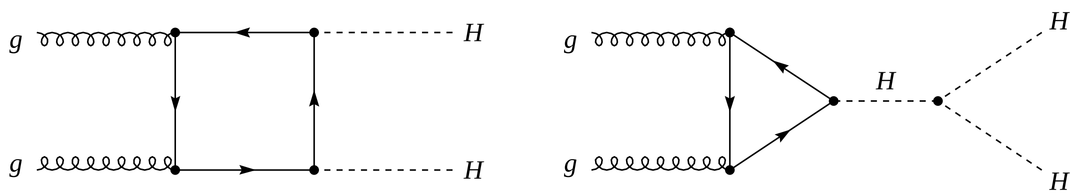

2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1σ limits
1 ab$^{-1}$
solid: $\sqrt{s}$ = 500 GeV
dash: $\sqrt{s}$ = 800 GeV
dots: $\sqrt{s}$ = 1 TeV
$e^+e^- \to ZHH$
$HH \to b$+jets
SM
$\Delta\lambda_{HHH} = (\lambda - \lambda_{SM})/\lambda_{SM}$
110
120
130
140
150
160
$m_H$ (GeV)

- what about a heavier Higgs boson with $HH \to 4W$, $WWZZ, 4Z$?
- no phase space for $m_H > 150$ GeV at a 500 GeV machine
  ☞ even for $\sqrt{s} = 1$ TeV, rates are very small
  ☞ almost no sensitivity to $\lambda$

# 3 – Higgs Pair Production at Hadron Colliders

- $HH$ production mechanism at hadron colliders:

☞ one-loop process $gg \to HH$ dominates




☞ cross section for $qq \to qqHH$ and $WHH$, $ZHH$ and $t\bar{t}HH$ production are a factor 10 – 30 smaller

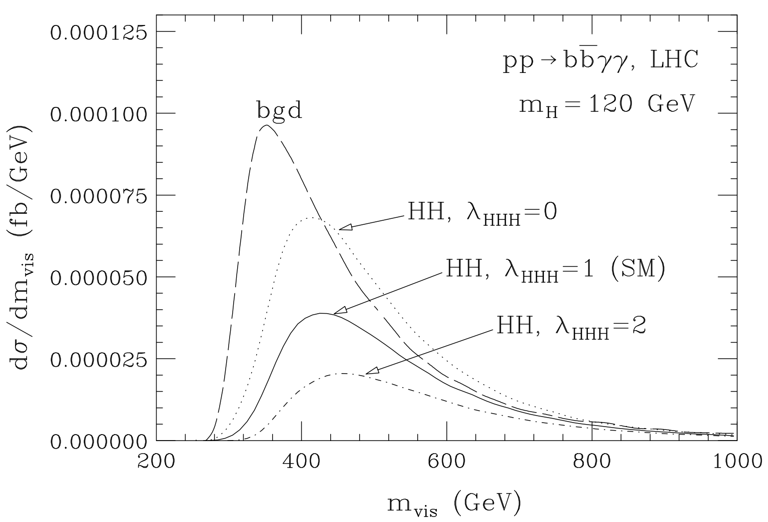
- for $m_H < 140$ GeV, $H \to b\bar{b}$ dominates
  - ☞ $HH \to 4b$ and $HH \to b\bar{b}\tau^+\tau^-$ are overwhelmed by background
  - ☞ so is $HH \to b\bar{b}\mu^+\mu^-$
- more promising for $m_H < 140$ GeV at hadron colliders:
  - ☞ $HH \to b\bar{b}\gamma\gamma$
- for $m_H > 140$ GeV, $H \to W^+W^-$ dominates
  - ☞ most channels swamped by background
  - ☞ most promising: $HH \to 4W \to (jj\ell^\pm\nu)(jj\ell'^\pm\nu)$

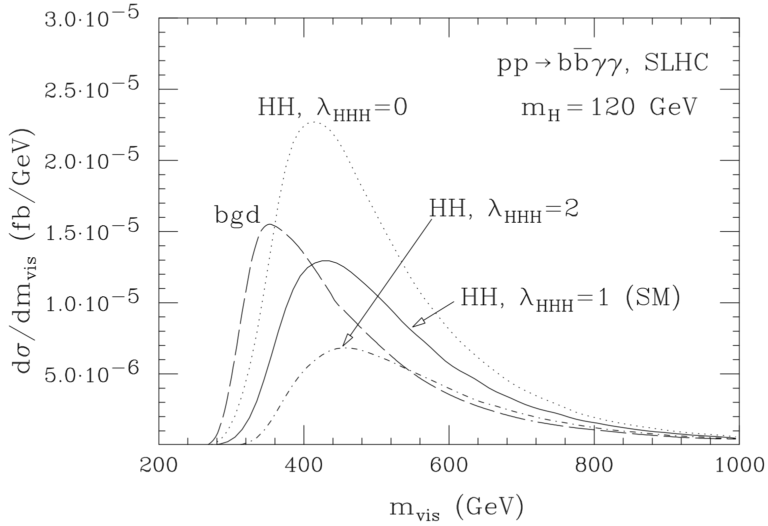
# $m_H < 140$ GeV: $HH \to b\bar{b}\gamma\gamma$

- calculation of the $HH$ signal:
  - ☞ use exact $gg \to HH$ one-loop matrix elements (Glover, van der Bij)
  - ☞ include QCD corrections in $m_t \to \infty$ limit: (Dawson et al.)
- backgrounds
  - ☞ irreducible: $b\bar{b}\gamma\gamma$, $H(\to \gamma\gamma)b\bar{b}$ and $H(\to b\bar{b})\gamma\gamma$
  - ☞ reducible: multi-jet and jet(s)+photon(s) production, $Hjj$ production, where jets are misidentified as $b$-quarks or photons
  - ☞ reducible backgrounds $\gg$ irreducible backgrounds

- can achieve $S/B \approx 1/2$ at LHC, and $S/B \approx 1/1$ at SLHC requiring $\Delta R(\gamma, b) > 1.0$, $\Delta R(\gamma, \gamma) < 2.0$
- use visible invariant mass to discriminate signal and bgd
- derive bounds on $HHH$ coupling from $\chi^2$ test of $m_{vis}$ distribution

☞ assume 10% normalization uncertainty of SM cross section



- 68.3% CL limits for $\Delta\lambda_{HHH} = \lambda/\lambda_{SM} - 1$ ("B sub" assumes reducible bgds can be subtracted)

| machine | $m_H = 120$ GeV | | $m_H = 140$ GeV | |
|---|---|---|---|---|
| $\int \mathcal{L} dt$ | norm | B sub | norm | B sub |
| LHC | $+1.6$ | $+0.94$ | – | – |
| 600 fb$^{-1}$ | $-1.1$ | $-0.74$ | – | – |
| SLHC | $+0.74$ | $+0.52$ | $+1.4$ | $+0.76$ |
| 6000 fb$^{-1}$ | $-0.62$ | $-0.46$ | $-0.8$ | $-0.58$ |

→ LHC will only be able to provide a first rough test for $m_H = 120$ GeV

→ SLHC will do better, but limits for $m_H = 120$ GeV ($m_H = 140$ GeV) will be a factor $2-4$ ($1.2-3$) weaker than those achievable at LC

→ still interesting if SLHC comes before LC

## $m_H > 140$ GeV: $HH \to 4W \to (jj\ell^\pm\nu)(jj\ell'^\pm\nu)$

- main background sources:
  $WWWjj$, $t\bar{t}W$ and $t\bar{t}j$ production
- other background sources:
  - ☞ $4W$ production
  - ☞ $t\bar{t}t\bar{t}$ production
  - ☞ $W^\pm W^\pm jjjj$ production
  - ☞ $t\bar{t}Z$ production (one-legged $Z$)
  - ☞ $WZjjjj$ production
  - ☞ $WWZjj$ production
  - ☞ overlapping events and double parton scattering: negligible at LHC, potentially important at SLHC and VLHC

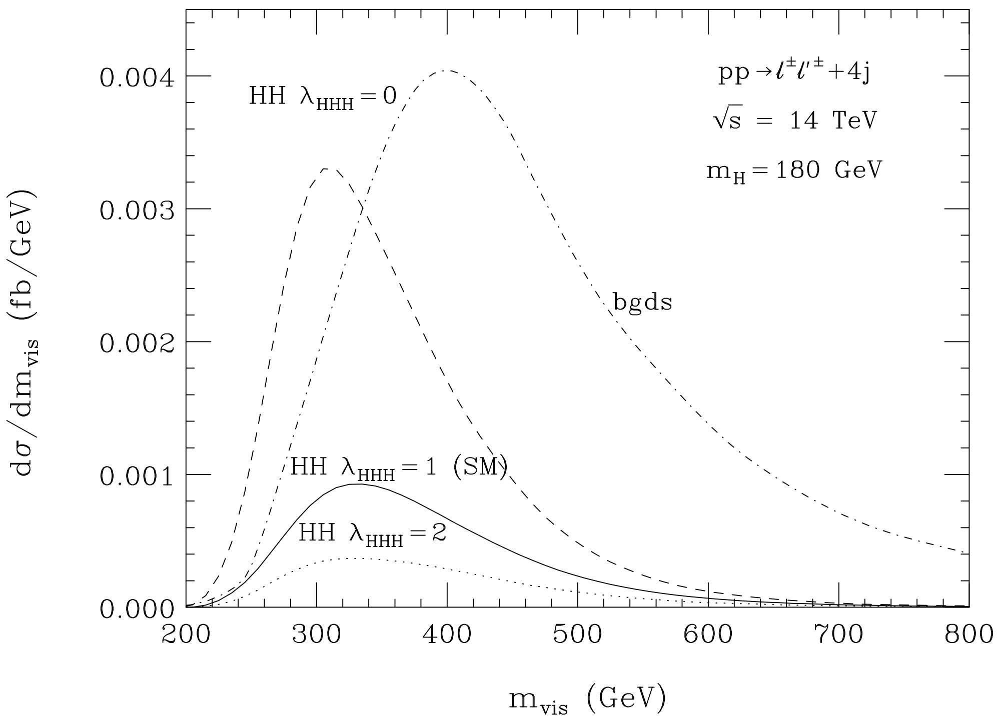
- $t\bar{t}j$ background
  - ☞ contributes to bgd if one of the $b$ quarks from $t \to Wb$ decays semi-leptonically
  - ☞ most of this bgd is removed by requiring isolated leptons
  - ☞ naively, $b \to c\ell\nu$ decays should dominate, because of CKM suppression of $b \to u\ell\nu$
  - ☞ phase space restricts lepton $p_T$ in $b \to c\ell\nu$ to

$$p_T(\ell) \leq \frac{m_B^2}{m_D^2}\, p_{T\,max}(c)$$

    $p_{T\,max}(c)$: max. $p_T$ of $c$-quark allowed in isolation cone (typically $1-3$ GeV) $m_{B,D}$: $B,\ D$-meson mass
  - ☞ for $b \to u\ell\nu$ replace $m_D$ by $\pi$- or $\rho$-mass
  - ☞ as a result, for $p_T(\ell) > 15$ GeV, which we require, most of the $t\bar{t}j$ background comes from $b \to u\ell\nu$, despite the suppression from $V_{ub}$

- LHC:
  - ☞ signal cross section 0.1 – 0.2 fb
  - ☞ total background: 0.8 – 1.0 fb
- use $m_{vis}$ to separate signal and bgd and determine limits on Higgs self-coupling

updated



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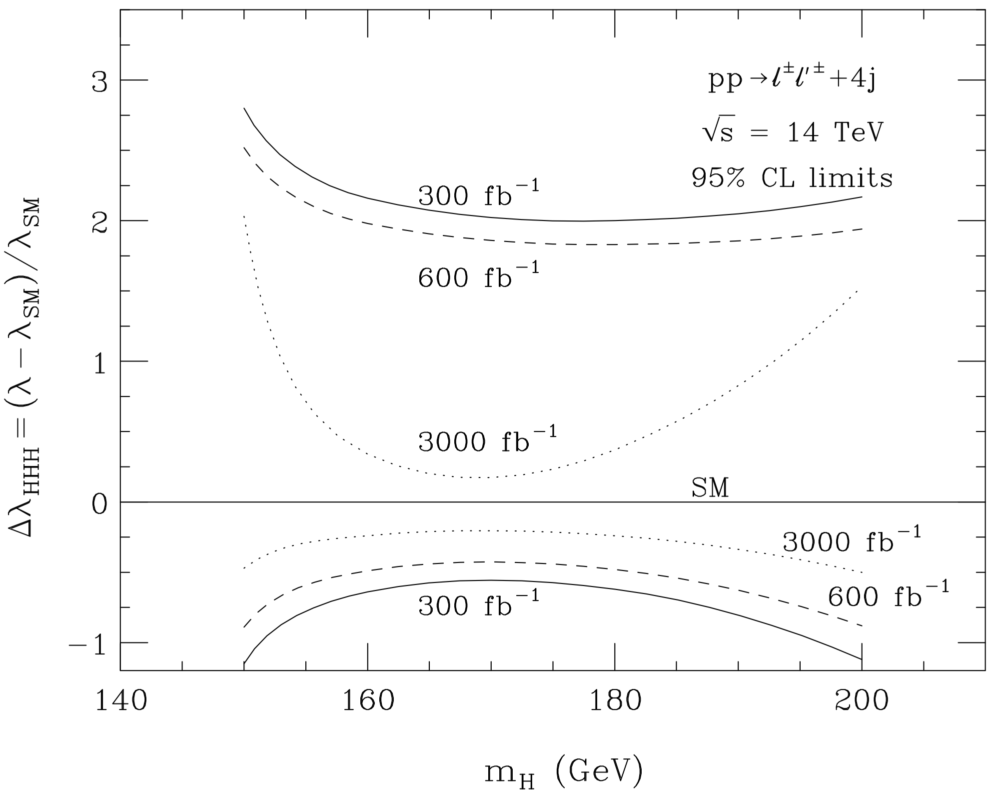


- for 300 fb$^{-1}$, $\lambda = 0$ is ruled out at 95% CL for 150 GeV $\leq m_H \leq$ 200 GeV
- for 3000 fb$^{-1}$, $\lambda$ can be determined with a precision of $20 - 30\%$ for 160 GeV $\leq m_H \leq$ 180 GeV

# 4 – Conclusions

- Higgs pair production makes it possible to directly probe the Higgs self-coupling
- We have carried out a detailed generator level investigation of Higgs pair production at hadron colliders
- We studied in detail signal and backgrounds for the $\ell^\pm \ell'^\pm + 4j$ and $b\bar{b}\gamma\gamma$ final states
- At the LHC, with 300 fb$^{-1}$, a vanishing Higgs boson self-coupling can be ruled out at 95% CL for 150 GeV $< m_H <$ 200 GeV
- To probe the Higgs boson self-coupling for $m_H < 150$ GeV via $HH \to b\bar{b}\gamma\gamma$ at the LHC, need luminosity upgrade
- LC and (S)LHC probe the Higgs potential for complementary mass ranges
- to probe radiative corrections, one needs CLIC and/or a VLHC