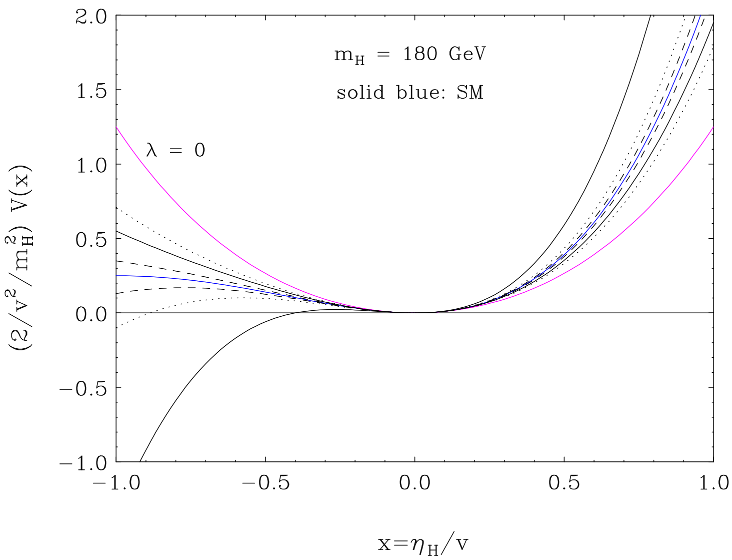
Probing The Higgs Boson Self-Coupling at Lepton and Hadron Colliders



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3. Higgs pair production at Linear Colliders
4. Conclusions

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1 – Introduction

- If it exists, the Standard Model (SM) Higgs boson will be discovered at the Tevatron or LHC

  ☞ at the Tevatron if $m_H < 180$ GeV and $> 15\ \mathrm{fb}^{-1}$ can be accumulated

  ☞ at the LHC over the entire range 115 GeV $< m_H < 1$ TeV

- The LHC promises complete coverage of Higgs decay scenarios

- Quantitatively at the LHC: measure

  ☞ M_H to 0.1%

  ☞ Γ_H to $\leq 10\%$

  ☞ $\sigma\times$ Br to 10%

- what remains to be done: determine Higgs potential

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

η_H: physical Higgs field, $v = (\sqrt{2}G_F)^{-1/2}$,
SM: $\tilde{\lambda} = \lambda = \lambda_{SM} = m_H^2/(2v^2)$
☞ λ and $\tilde{\lambda}$ are *per se* free parameters

- to measure λ ($\tilde{\lambda}$), experiments must observe HH (HHH) production
☞ HHH cross sections too small to probe $\tilde{\lambda}$ at any machine considered so far
☞ concentrate on λ 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.*)

- other studies of HH production at hadron colliders

  ☞ survey of HH production processes (including $t\bar{t}HH$) and backgrounds to $gg \to HH \to \ell^{\pm}\ell'^{\pm} + 4j$ in SLHC report (Gianotti et al.)

  ☞ PYTHIA based ATLAS study of several final states resulting from $HH \to (W^+W^-)(W^+W^-)$ and $HH \to (W^+W^-)(ZZ)$ (Blondel et al.)

- other studies of HH production in e^+e^- collisions:

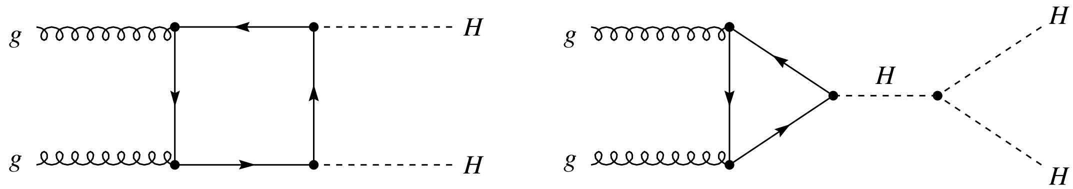
  ☞ ZHH production for $\sqrt{s} = 500$ GeV, 1 ab^{-1}, $m_H = 120$ GeV (Castanier, et al.)

  ☞ $HH\nu\bar{\nu}$ production for $\sqrt{s} = 3$ TeV, 5 ab^{-1} (CLIC), $m_H = 120$ GeV and $m_H = 180$ GeV (Battaglia et al.)

2 – 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

  ☞ consider $HH \to 4b$ and $HH \to b\bar{b}\tau^+\tau^-$

- for $m_H > 140$ GeV, $H \to W^+W^-$ dominates

  ☞ most channels swamped by background

  ☞ most promising:
  $HH \to 4W \to (jj\ell^{\pm}\nu)(jj\ell'^{\pm}\nu)$

- calculation of signal:

☞ use exact $gg \to HH$ one-loop matrix elements (matrix elements using the $m_t \to \infty$ limits are numerically much faster but yield completely wrong distributions)

☞ QCD corrections:

➞ known only in $m_t \to \infty$ limit

➞ and only for total cross section

➞ $k = 1.65$ at LHC, $k = 1.35$ at VLHC

➞ to approximately take into account QCD corrections we use these k-factors

➞ this significantly reduces the factorization and renormalization scale uncertainty (although $m_t \to \infty$ limit is used)

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

- cuts:

$$p_T(j) > 30,\,30,\,20,\,20 \text{ GeV}, \qquad p_T(\ell) > 15,\,15 \text{ GeV},$$
$$|\eta(j)| < 3.0, \qquad |\eta(\ell)| < 2.5,$$
$$\Delta R(jj) > 0.6, \qquad \Delta R(j\ell) > 0.4, \qquad \Delta R(\ell\ell) > 0.2,$$

☞ in addition require that the four jets form two pseudo-W's with

$$50 \text{ GeV} < m(jj) < 110 \text{ GeV}$$

☞ we assume this catches 100% of signal and backgrounds

☞ no $\not{p}_T$ cut

☞ no detector resolution effects are taken into account

☞ at LHC: tighten $\Delta R(jj)$ cut to $\Delta R(jj) > 1.0$

→ reduces background by $\approx 45\%$

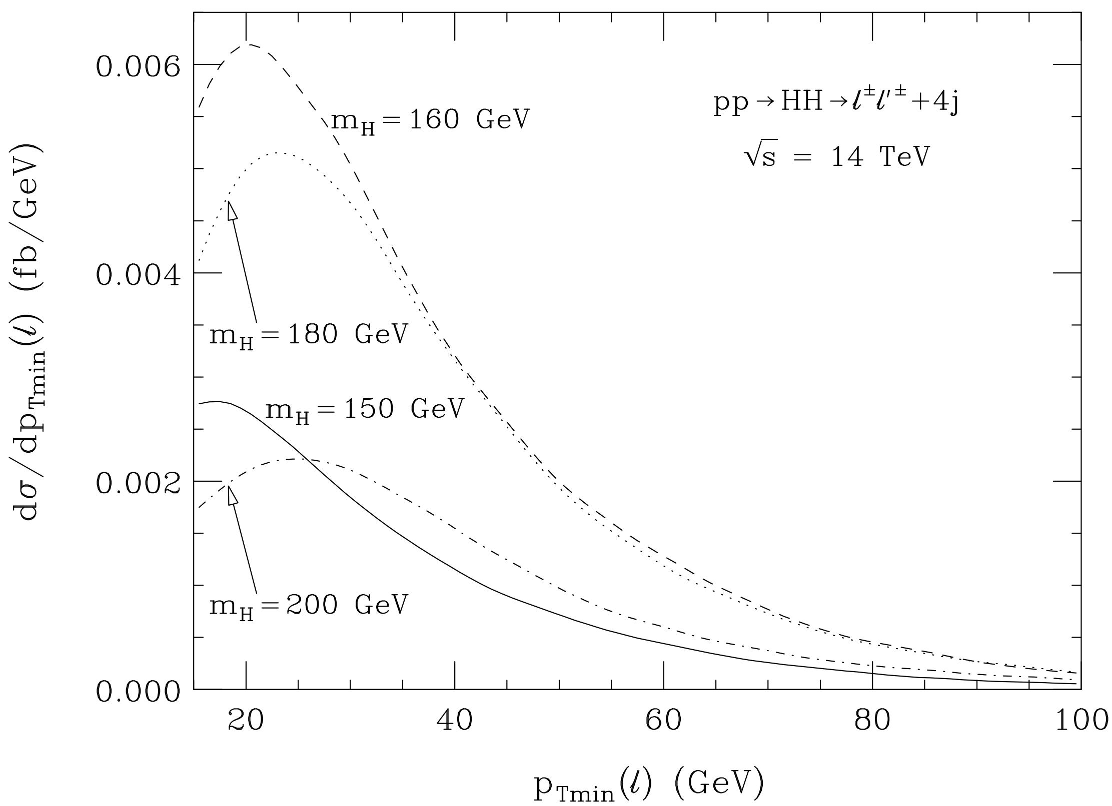
→ with little loss to signal $\approx 8\%$

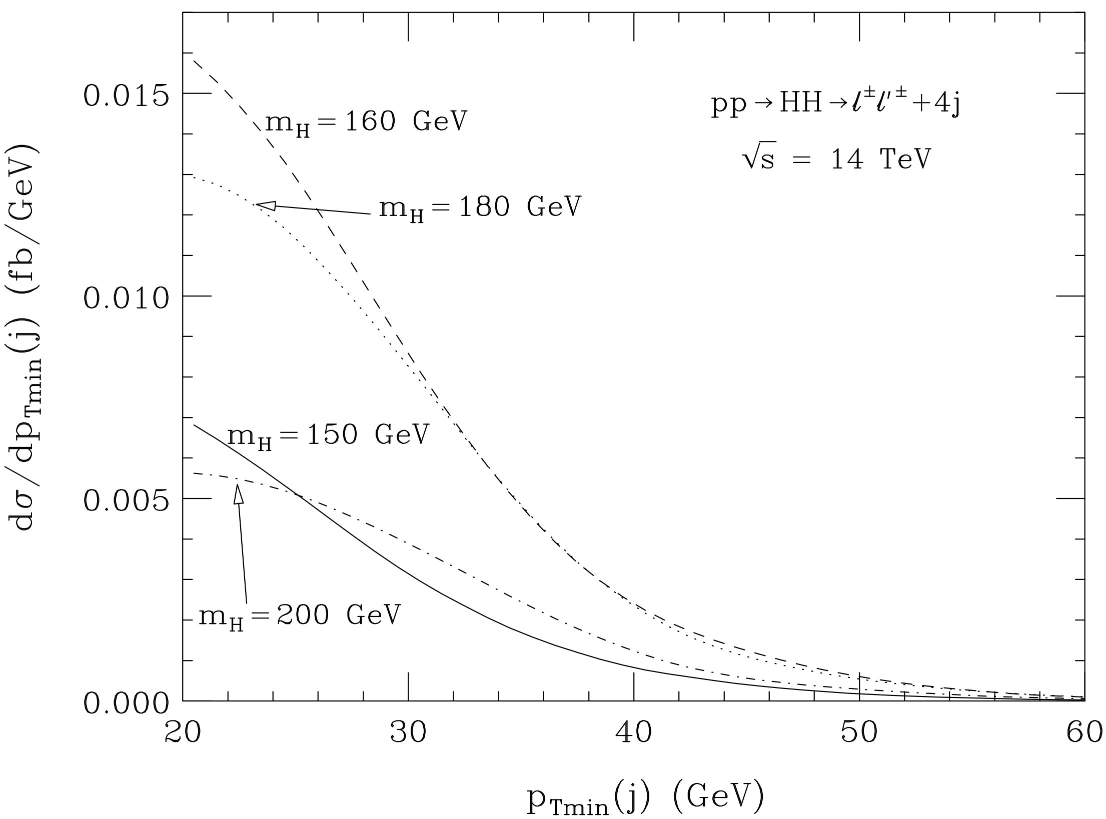
- comment:

  ☞ rates for HH production are very small

  ☞ need to retain as many signal events as possible

  ☞ $p_{Tmin}(\ell)$ and $p_{Tmin}(j)$ distributions peak at small values:





- ☞ qualitatively similar results at VLHC energies
- ☞ loose rate very quickly if p_T cuts are tightened
- ☞ very similar cuts used in SLHC study
- ☞ but choice is certainly challenging

- main background sources:
  $WWWjj$ and $t\bar{t}W$ 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

  ☞ $t\bar{t}j$ 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 semileptonically

  ☞ most of this bgd is removed by requiring isolated leptons

☞ $t\bar{t}$ PYTHIA calculation yields incorrect results: p_T distributions too hard

☞ we perform a parton level calculation which includes exact $b \to c\ell\nu$ matrix element

☞ to regularize the soft parton p_T distribution use truncated shower approximation:

➞ use $t\bar{t}j$ matrix elements

➞ multiply differential cross section with $1 - \exp(-p_T^2(\text{parton})/p_{TSA}^2)$

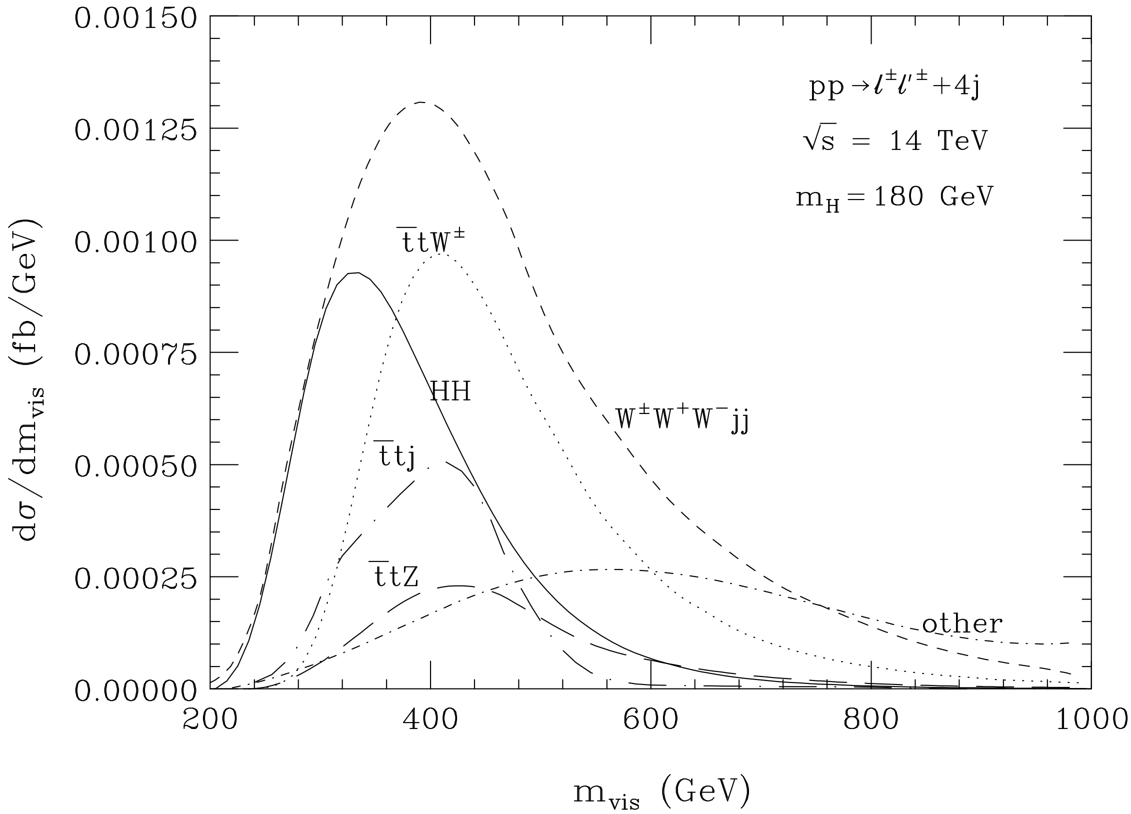
➞ choose p_{TSA} such that $\sigma_{t\bar{t}j} = \sigma_{t\bar{t}}$: $p_{TSA} = 15,\ 50$ GeV at LHC, VLHC

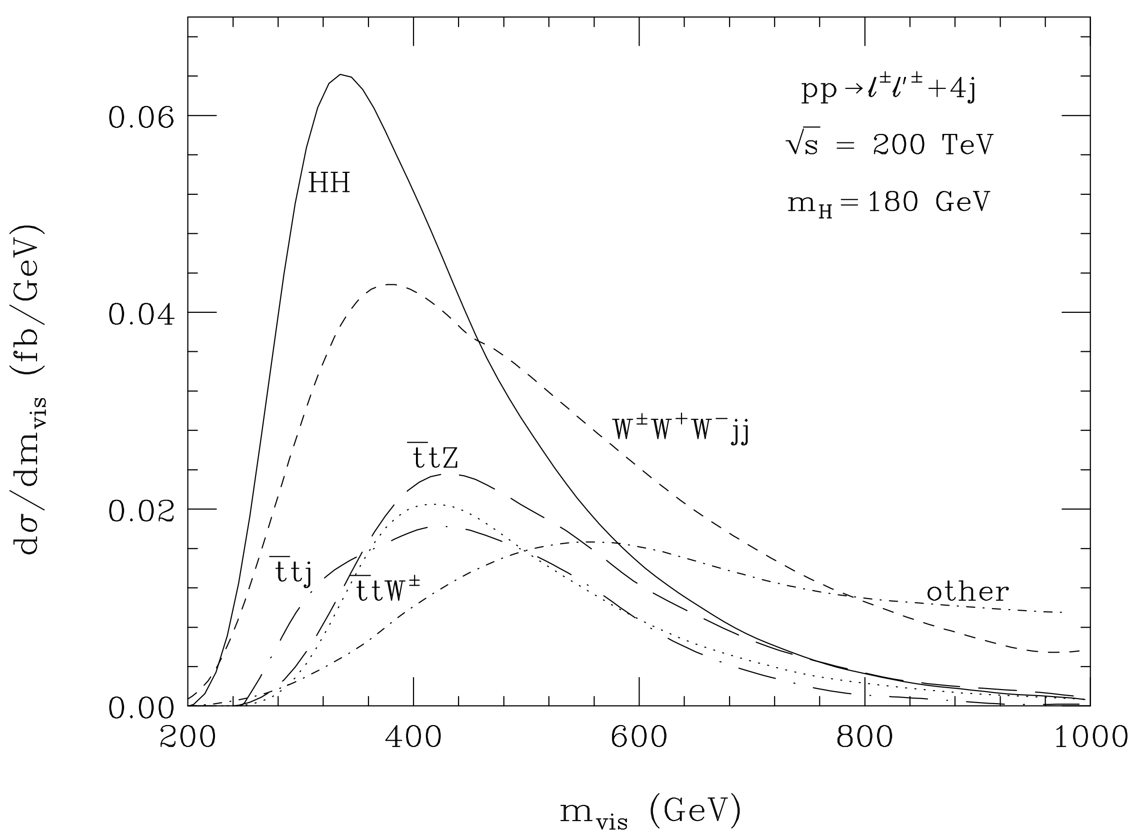
☞ $t\bar{t}j$ background very sensitive to $p_T(\ell)$ cut; ± 5 GeV changes bgd by factor $10^{\pm 1}$

☞ need more realistic calculation which includes detector effects

- LHC:
  - ☞ signal cross section $0.1 - 0.2$ fb
  - ☞ total background: $0.8 - 1.0$ fb
- VLHC:
  - ☞ signal cross section factor 100 larger than at LHC
  - ☞ S/B ratio a factor 2 improved w/r to LHC
- to improve signal to bgd ratio:
  - ☞ All background processes are multi body production processes
    → the invariant mass distribution $d\sigma/d\sqrt{\hat{s}}$ peaks at values significantly above threshold
  - ☞ in contrast:
    signal is a two-body production process
    → $d\sigma/d\sqrt{\hat{s}}$ sharply peaks at threshold
- however:
  with two neutrinos present, $\sqrt{\hat{s}}$ cannot be reconstructed

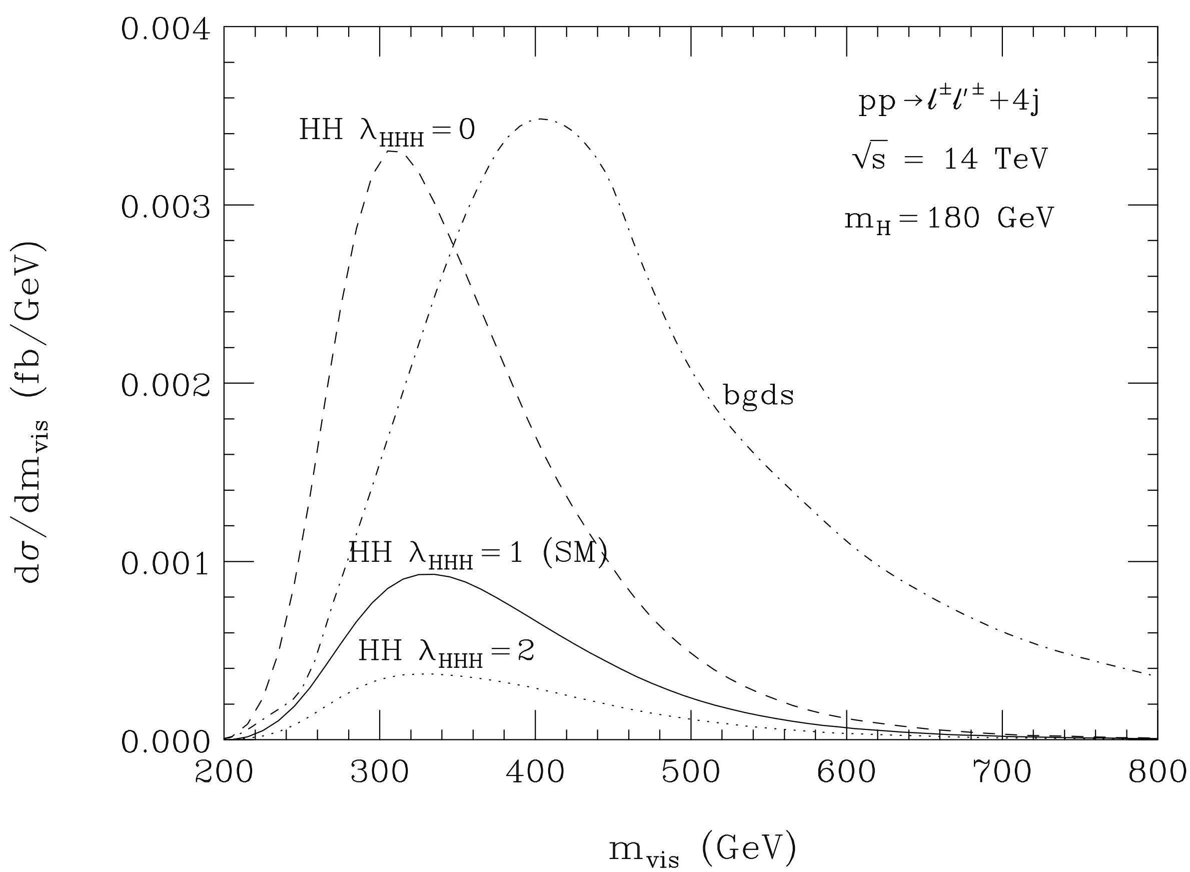
- use visible invariant mass, m_{vis}, instead: invariant mass of $2\ell + 4j$ system
- potential stumbling blocks:
  ☞ expect a significant fraction of $\ell^\pm \ell'^\pm + 4j$ events to have extra jets from QCD bremsstrahlung
  ➞ construct m_{vis} from 4 highest p_T jets
  ☞ extra jets could accidentally satisfy $m(jj)$ requirement
  ➞ limit number of possible jj pairs which satisfy $m(jj)$ requirement
  almost no signal events have > 2 $4j$ combinations in pseudo-W mass window
  (50 GeV $< m(jj) <$ 110 GeV)
  ☞ still need to worry about $2\ell + 4j$ events satisfying all cuts where one jet originates from QCD bremsstrahlung
  may be able to shrink $m(jj)$ range to $M_W \pm 20$ GeV
  ➞ need calculation of full QCD corrections to $gg \to HH$

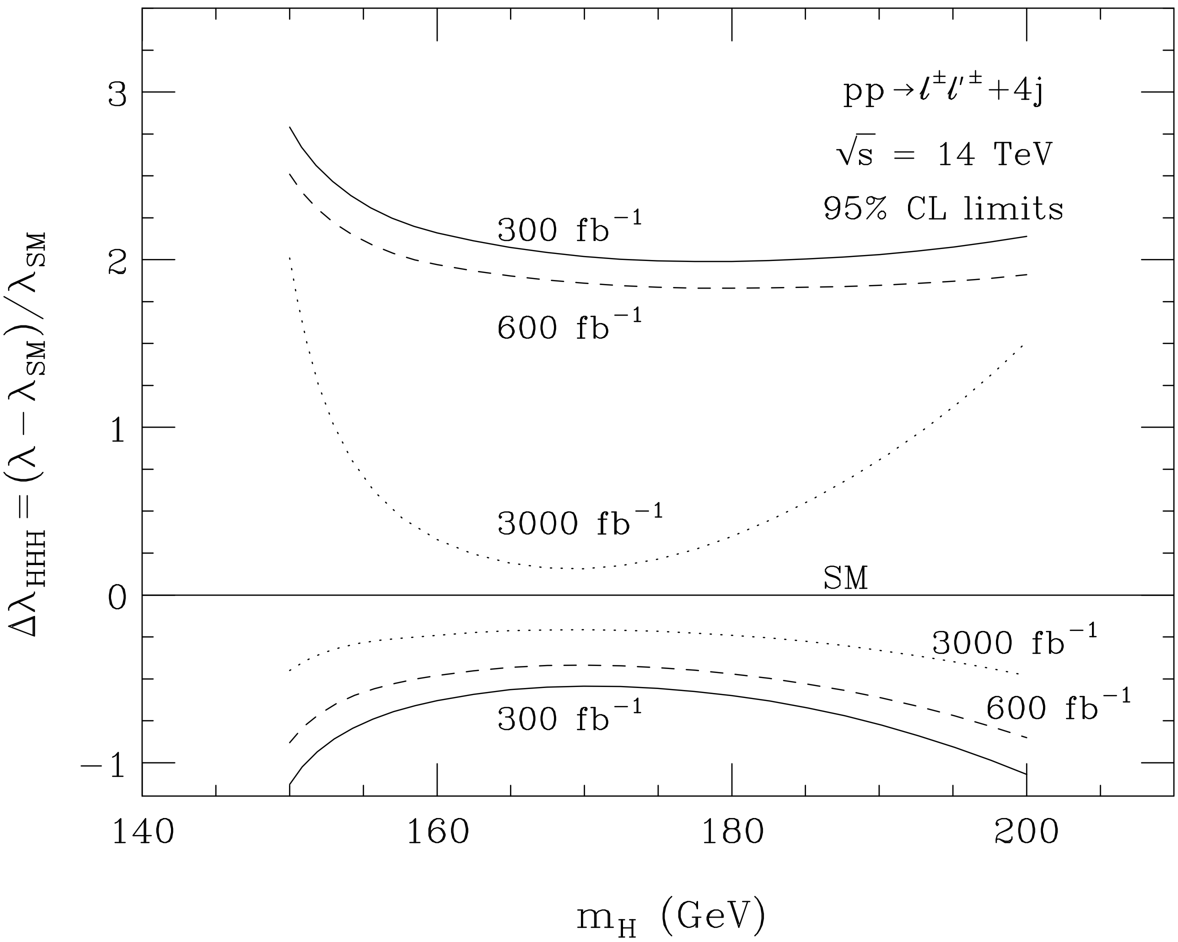

pp → ℓ±ℓ′± +4j
√s = 14 TeV
m_H = 180 GeV
t̄tW±
HH
W±W+W−jj
t̄tj
t̄tZ
other
dσ/dm_vis (fb/GeV)
m_vis (GeV)
0.00150
0.00125
0.00100
0.00075
0.00050
0.00025
0.00000
200
400
600
800
1000


pp → ℓ±ℓ′± +4j
√s = 200 TeV
m_H = 180 GeV
HH
W±W+W−jj
t̄tZ
t̄tj
t̄tW±
other
dσ/dm_vis (fb/GeV)
m_vis (GeV)
0.06
0.04
0.02
0.00
200
400
600
800
1000

Determining the Higgs Self-coupling

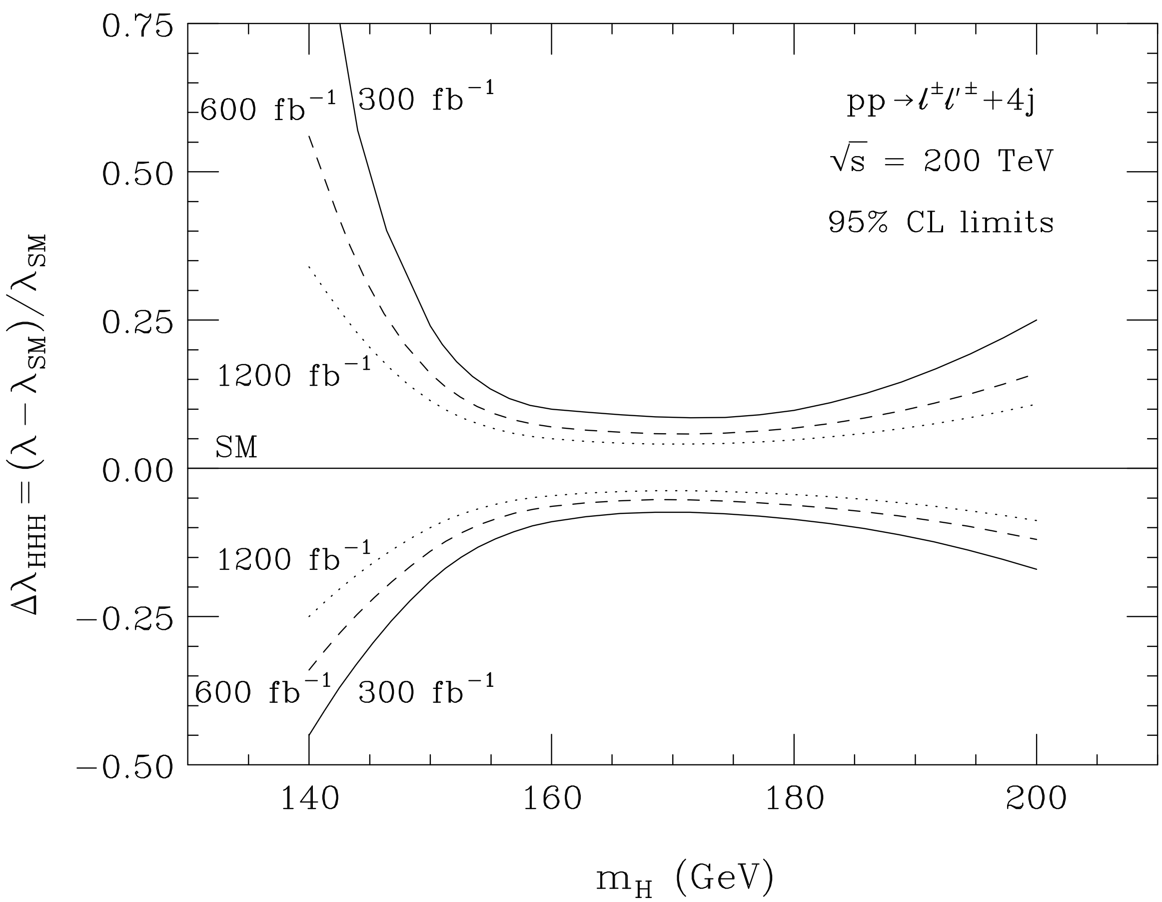
- Non-standard Higgs boson self-couplings only contribute to the $J = 0$ partial wave, and thus impact the m_{vis} distribution mostly at small values





- for 300 fb^{-1}, $\lambda = 0$ is ruled out at 95% CL for 150 GeV $\leq m_H \leq$ 200 GeV
- for 300 fb^{-1}, λ can be determined with a precision of up to 60% (95% CL)
- limits for 600 fb^{-1} improve by $10 - 25\%$
- for 3000 fb^{-1}, λ can be determined with a precision of $20 - 30\%$ for 160 GeV $\leq m_H \leq$ 180 GeV

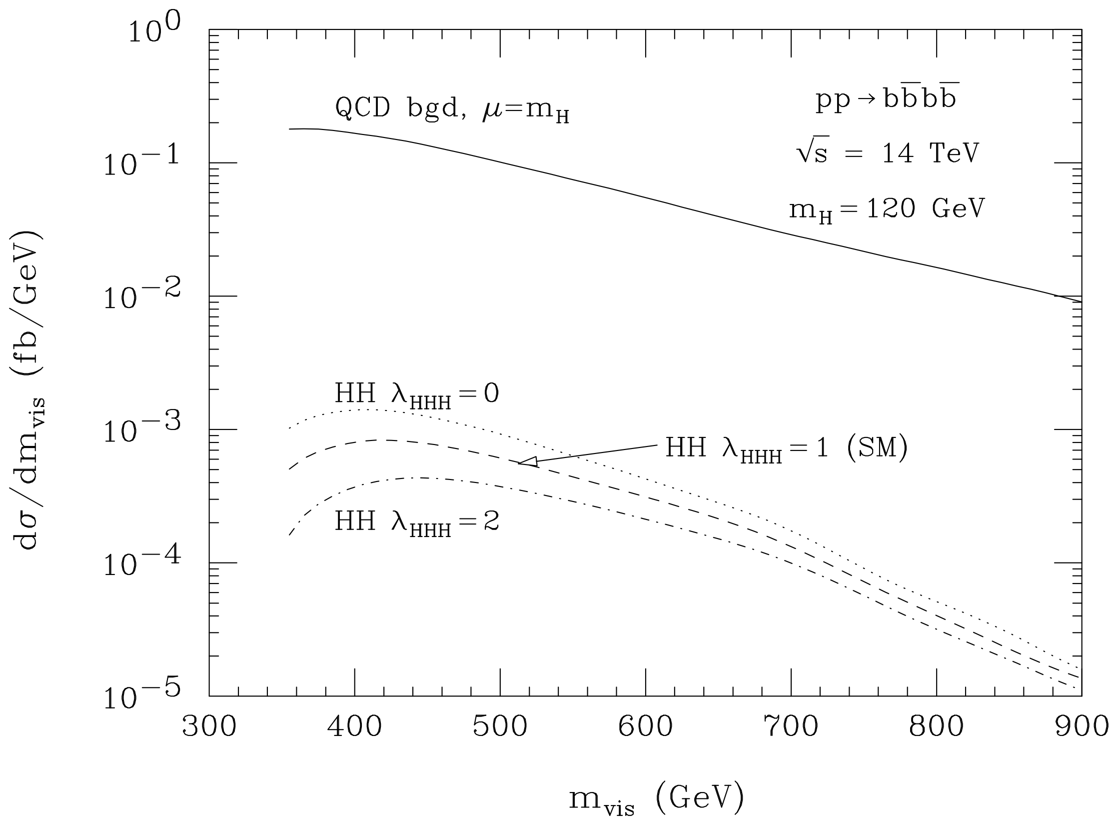
Limits at the VLHC



- at a 200 TeV collider one can measure λ with a precision of $8 - 25\%$ at 95% CL for 150 GeV $<$ $m_H <$ 200 GeV and 300 fb^{-1}

$m_H < 140$ GeV: $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}\tau^+\tau^-$

- $HH \to b\bar{b}b\bar{b}$:
  - ☞ QCD $b\bar{b}b\bar{b}$ production is main background



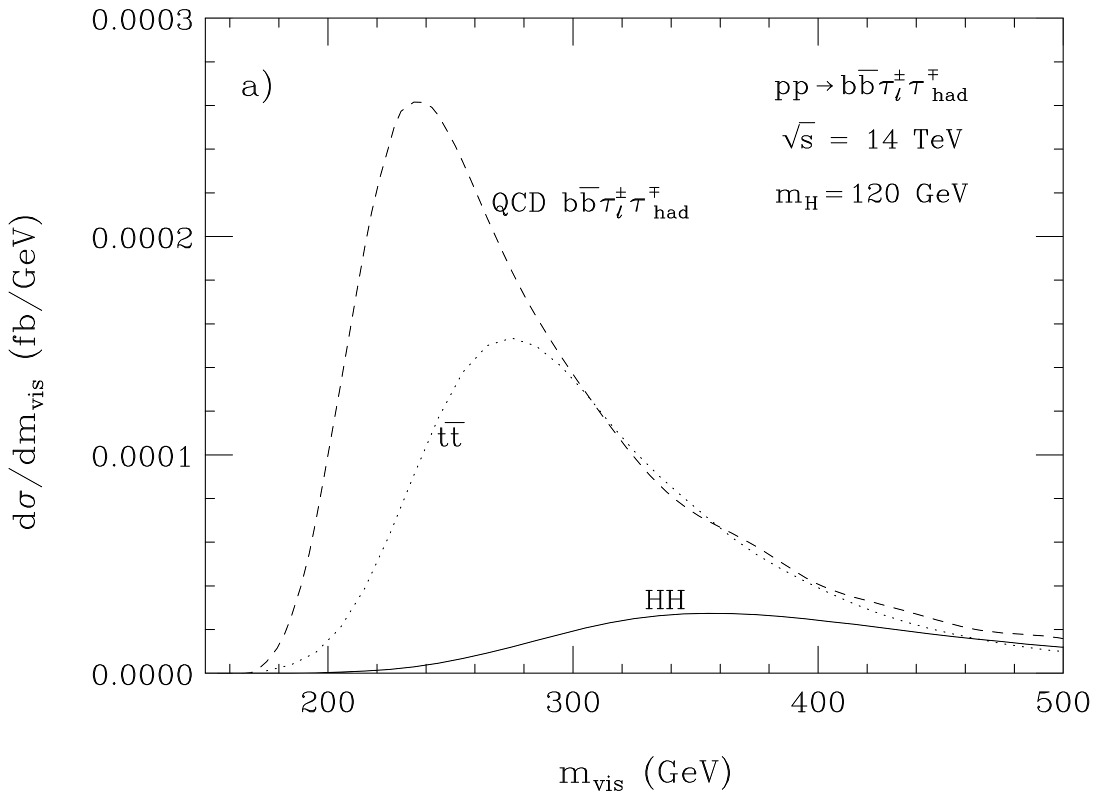
  - ☞ bgd more than 100 times larger than signal
  - ➞ no useful limits on Higgs boson self-coupling
  - ☞ similar result at VLHC energies

- $HH \to b\bar{b}\tau^+\tau^-$:

  ☞ main backgrounds:

  → QCD $b\bar{b}\tau^+\tau^-$ production

  → $t\bar{t} \to W^+bW^-\bar{b} \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau b\bar{b}$



→ 1σ bounds for $m_H = 120$ GeV [$\Delta\lambda_{HHH} = (\lambda/\lambda_{SM} - 1)$]:

$$\text{SLHC } (3000\text{ fb}^{-1}): \quad -1.6 < \Delta\lambda_{HHH} < 3.1$$

$$\text{VLHC } (300\text{ fb}^{-1}): \quad -0.84 < \Delta\lambda_{HHH} < 0.96$$

LC: $\Delta\lambda_{HHH} = \pm 0.20$ at 1σ

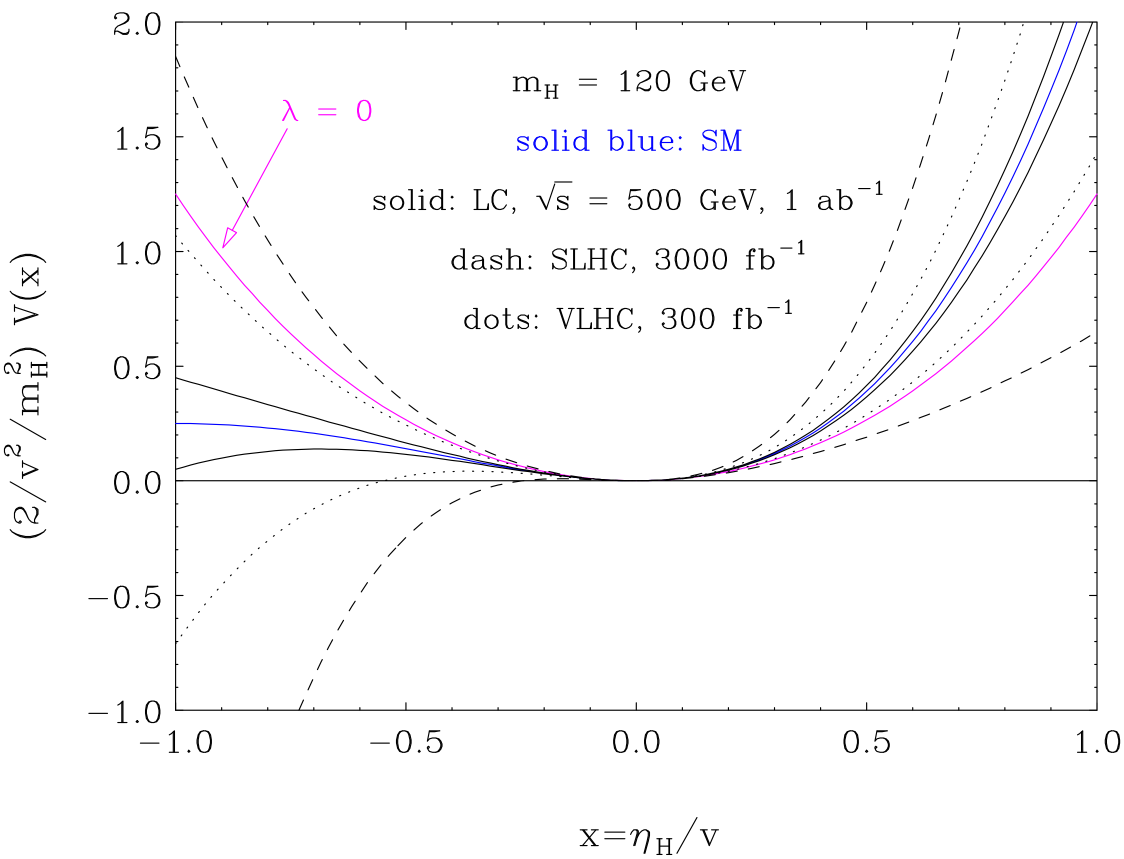
☞ limits worse for $m_H > 120$ GeV

- constraining the Higgs potential

☞ assuming a SM quartic Higgs coupling, one can write the Higgs potential as

$$\frac{2}{v^2 m_H^2} V(x) = x^2 + \lambda_{HHH}\, x^3 + \frac{1}{4}\, x^4$$

where $x = \eta_H / v$

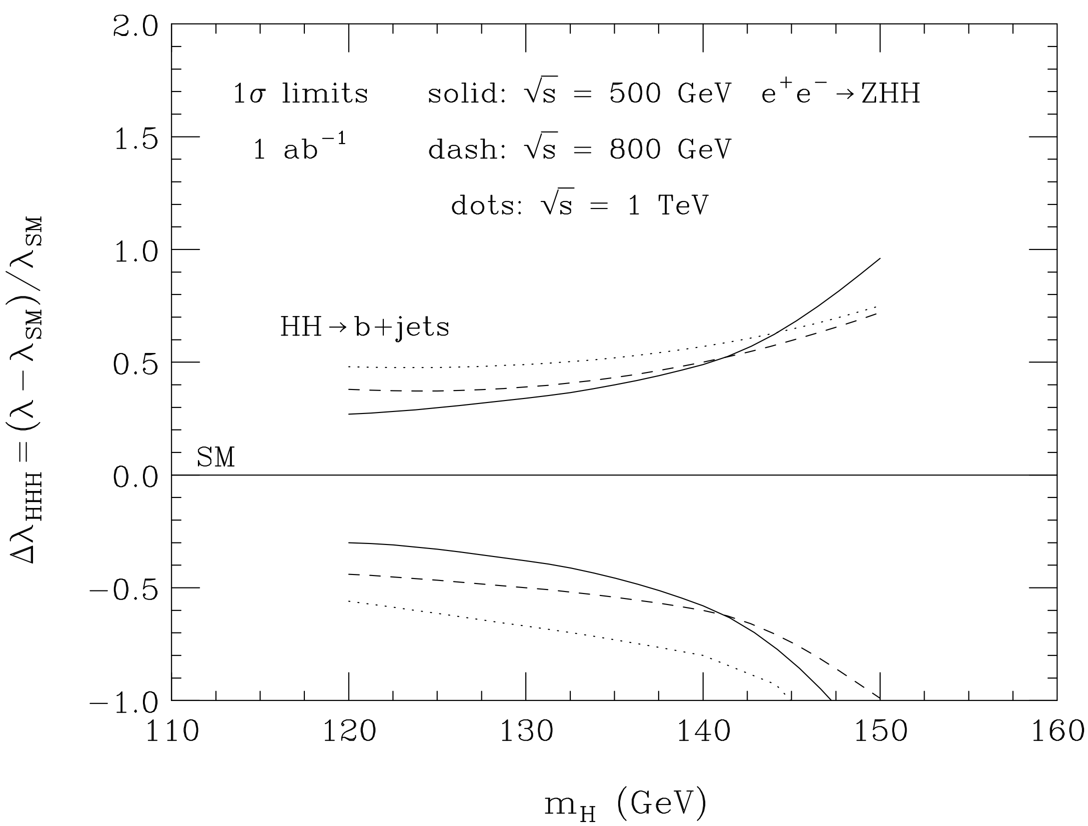


3 – Higgs Pair Production at Linear Colliders

- 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.

  ☞ extrapolation to $m_H > 120$ GeV and $\sqrt{s} > 500$ GeV



☞ good λ coverage for $m_H < 150$ GeV

- extrapolation:

  ☞ use number of signal and bgd. events for NN output parameter $N_N > 0.9$ from Castanier et al. analysis

  ☞ calulcalate number of signal events from ZHH cross section

  ☞ assuming the NN efficiency is independent of m_H and $\sqrt{s}$ in the ranges considered

  ☞ estimate number of bgd. events assuming that it scales with the top quark cross section vs. $\sqrt{s}$

- can do better by repeating the Castanier et al. analysis

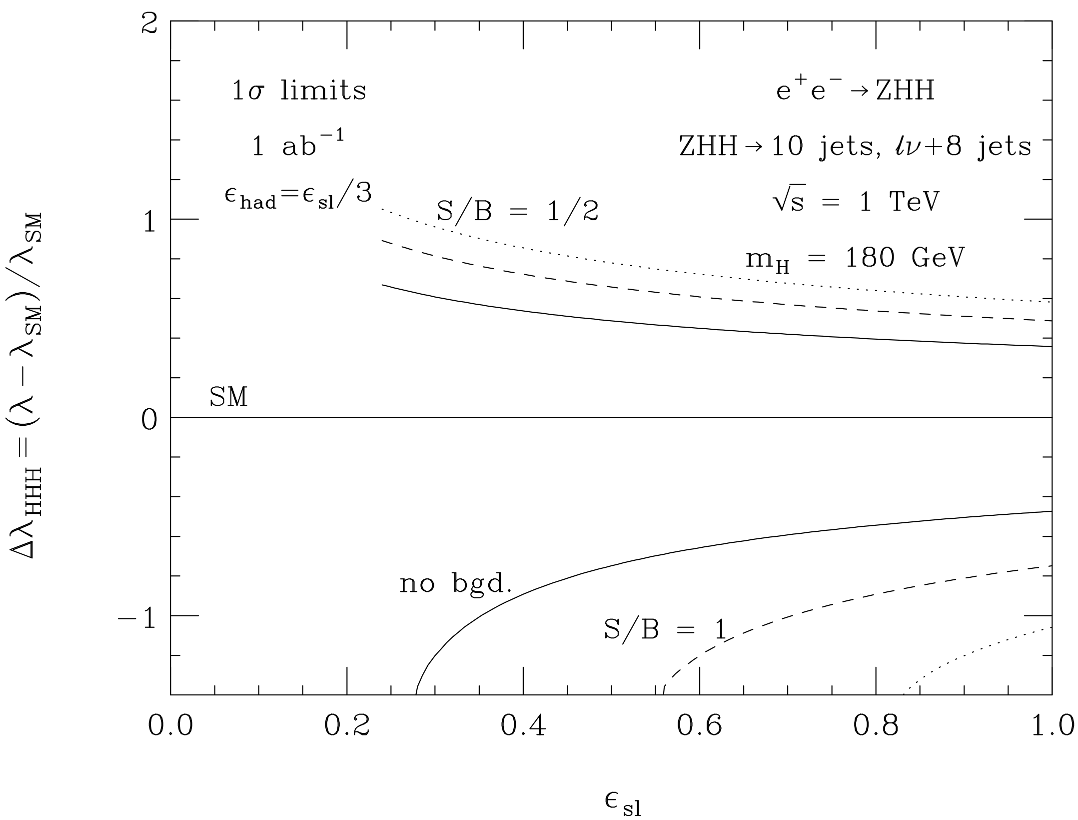
- what about a heavier Higgs boson with $HH \to 4W$, $WWZZ, 4Z$?
- no phase space for $m_H > 150$ GeV at a 500 GeV machine
  ☞ even for $\sqrt{s} = 1$ TeV, rates are very small
- largest branching fractions:
  ☞ $ZHH \to 10$ jets
  ☞ $ZHH \to \ell\nu + 8$ jets
- final states of similar or higher complexity as in $e^+e^- \to t\bar{t}H$
  ☞ large backgrounds: $t\bar{t}$, $W^+W^- +$ jets production
  ☞ strategy to reduce background:
  → impose preselection cuts to optimize S/B ratio
  → perform a neural net analysis
  → with detailed detector simulation

- since we don't have the tools to perform such an analysis:

☞ study sensitivity bounds on $\Delta\lambda_{HHH}$ as a function of efficiencies and S/B

☞ since event rates are small (≤ 7 events for $\sqrt{s} \leq$ 1 TeV and 1 ab^{-1}), use total cross section to derive bounds

☞ example: $\sqrt{s} = 1$ TeV and $m_H = 180$ GeV

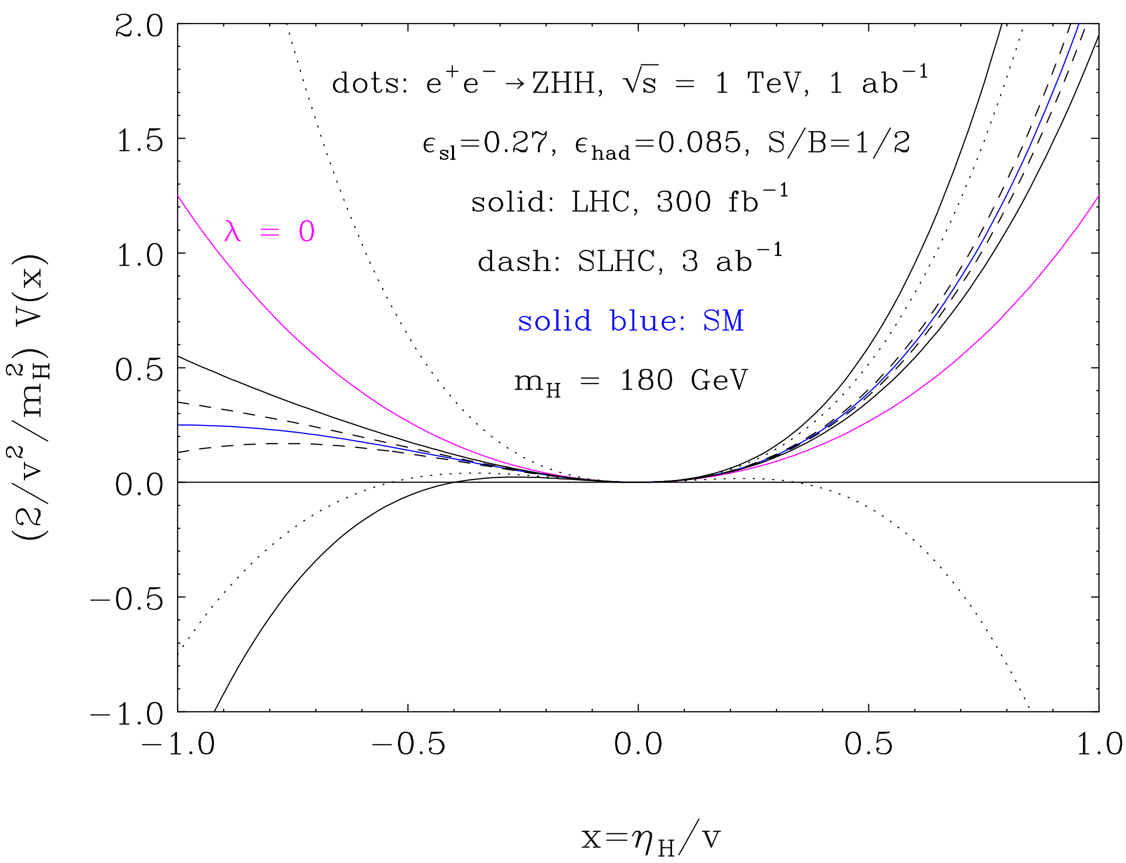


☞ almost no sensitivity to λ

- if one uses $t\bar{t}H$ efficiencies as guidelines ($m_H =$ 180 GeV, 1σ limits):

$$\begin{array}{rl} \text{LC } (1\text{ TeV}, 1\text{ ab}^{-1}) & -4.1 < \Delta\lambda_{HHH} < +1.0 \\ \text{LHC } (300\text{ fb}^{-1}) & -0.3 < \Delta\lambda_{HHH} < +1.6 \\ \text{SLHC } (3000\text{ fb}^{-1}) & -0.1 < \Delta\lambda_{HHH} < +0.1 \end{array}$$

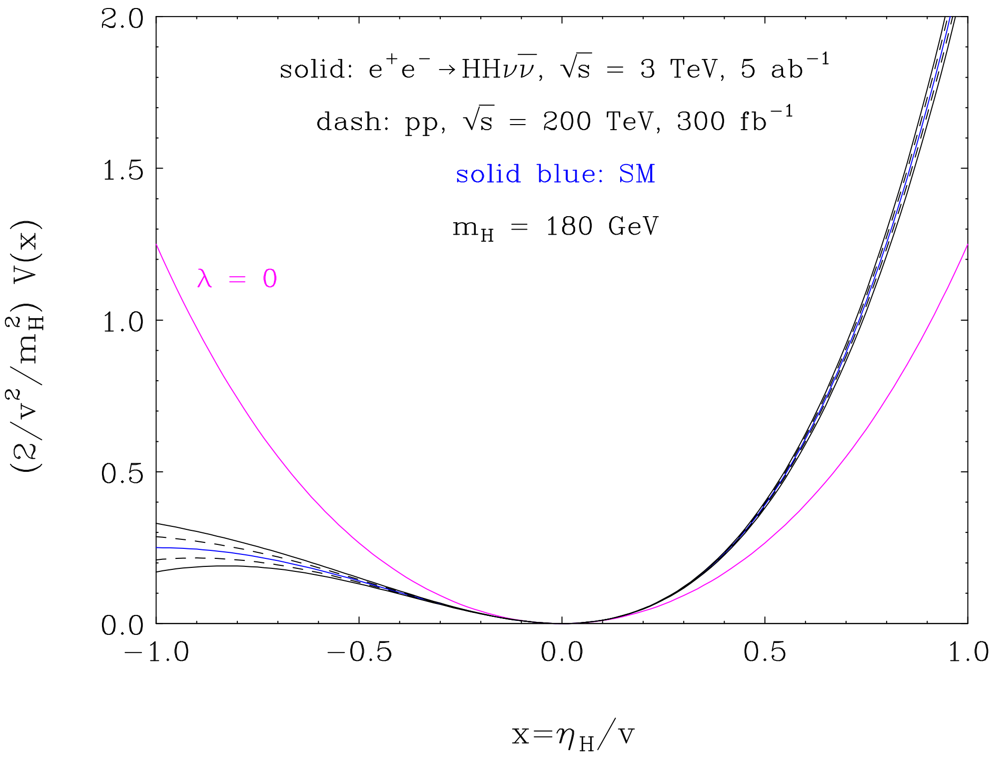
- conclusion needs to be confirmed by explicit NN analysis!



4 – Conclusions

LC and (S)LHC are complementary

- for $m_H < 140$ GeV a LC offers much better chances to probe the Higgs boson self-coupling
- for $m_H > 140$ GeV, the LHC – in particular if a luminosity upgrade can be realized – appears to have a clear advantage
- to probe SM or MSSM radiative corrections, need CLIC (e^+e^- collisions with $\sqrt{s} = 3-5$ TeV) with 5 ab^{-1} and/or VLHC (Battaglia et al.)



Les Houches Homework Assignment

(all homework due Friday, June 6, 2003)

- do more realistic study of $t\bar{t}j$ background for $HH \to 4W \to (jj\ell^{\pm}\nu)(jj\ell'^{\pm}\nu)$
- do calculation of $gg \to HHj$ with $HH \to 4W \to (jj\ell^{\pm}\nu)(jj\ell'^{\pm}\nu)$ and study effect of extra jet on m_{vis} distribution
- repeat Castanier et al. analysis for $m_H > 120$ GeV and $\sqrt{s} = 800 - 1000$ GeV
- perform NN analysis of $e^+e^- \to ZHH$ with $ZHH \to 10$ jets, $\ell\nu + 8$ jets