HIGGS POTENTIAL MEASUREMENT AT FUTURE COLLIDERS

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LHC/LC Study Group workshop
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What does it mean to find the Higgs?

Can we simply observe a bump in $m_T^{e\mu}$ or $m_{\tau\tau}$ and say we've found it? **HARDLY!**

Higgs has specific properties ($SU(2)$...) so a Higgs candidate must be investigated thoroughly to convince us of its nature: spin, gauge/Yukawa couplings, CP, and λ (the potential)

The Higgs potential in the SM is usually written as:

$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

λ fixed by unitarity: $\lambda_{SM} = M_H^2/(2v^2)$.

THE SM HIGGS POTENTIAL

Potential $\to$ Higgs 3,4-point self-couplings $-6v\lambda$, -6λ.

From a phenomenological point of view, experiment measures the coefficients of an effective potential

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

$\to$ λ, $\tilde{\lambda}$ now free parameters

To verify the Higgs mechanism, must measure λ, $\tilde{\lambda}$ by *direct observation of double and triple Higgs production*.

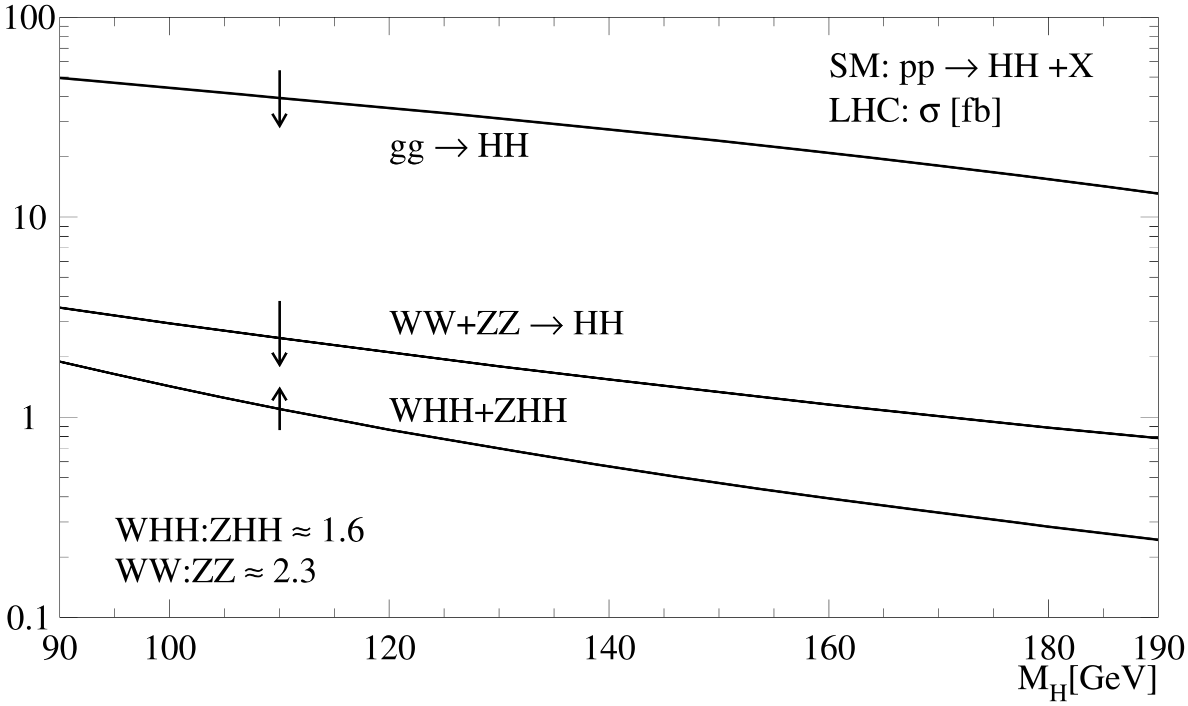
[$gg \to HHH$ @ VLHC: Plehn, Thomas, Zeppenfeld; in progress]

$gg \to HH$ is largest HH rate @ LHC
($\approx 40 - 20$ fb for $M_H \sim 100 - 200$ GeV
$\to$ 12k-6k events in 300 fb^{-1})

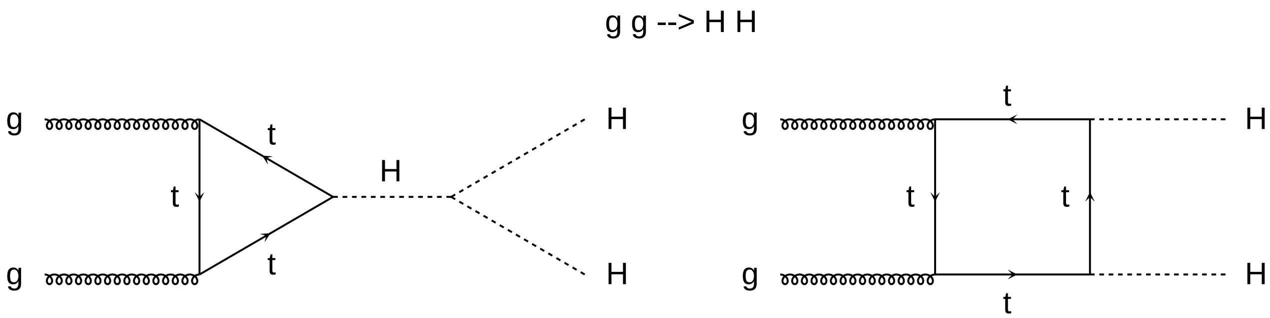
At TESLA-500, it is ZHH production
($\approx 0.25 - < 0.001$ fb for $M_H \sim 100 - 200$ GeV
$\to$ 250-10 events)

HH PRODUCTION AT LHC

[Djouadi, Kilian, Mühlleitner and Zerwas, 1999]



SM diagrams for the largest contribution are:



which interfere destructively.

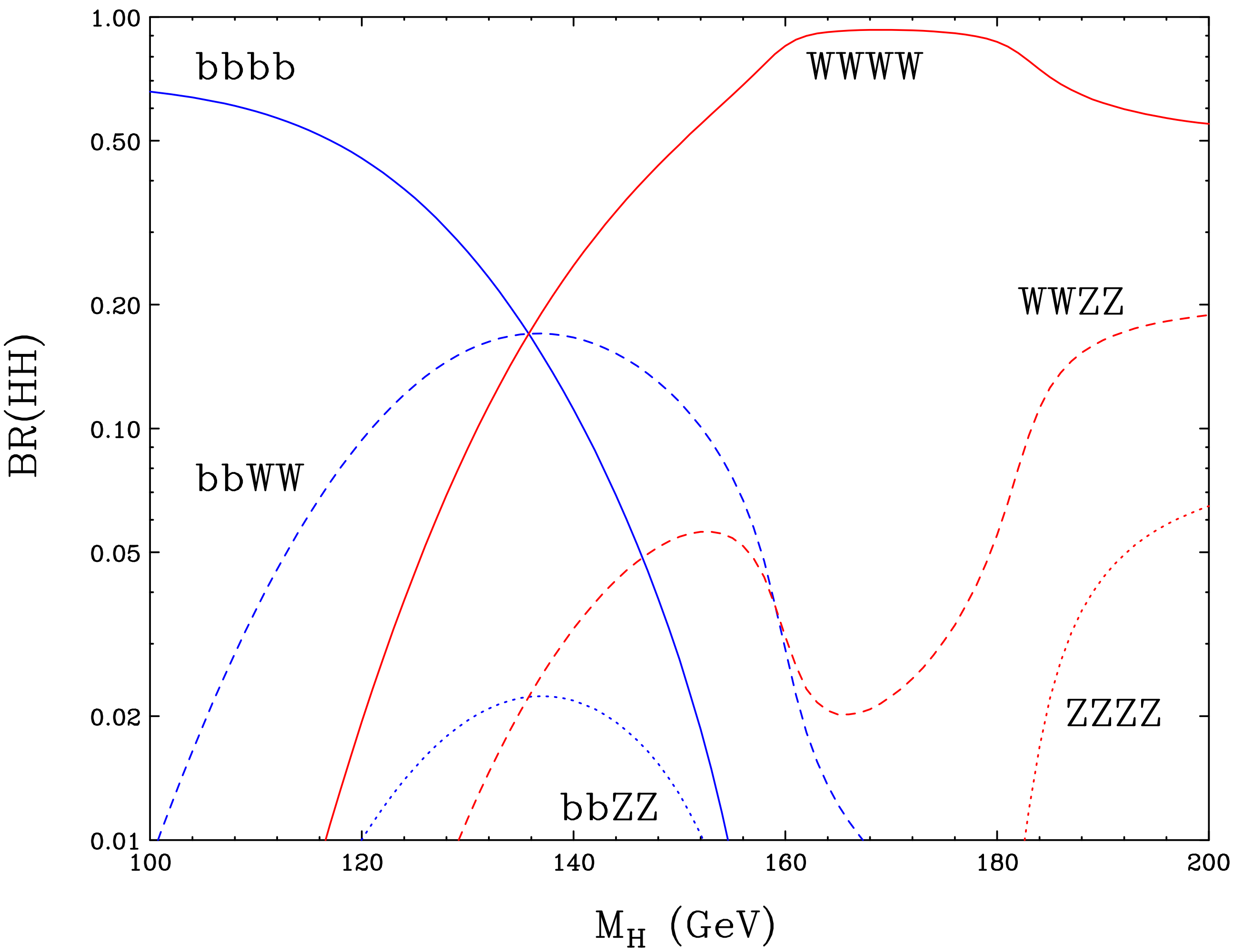
Only the triangle graph contains the relevant coupling, so extraction of λ is not simply a rate measurement.

Trick: measure (non-)existence of m_{vis} peak for $\lambda = 0$.

What to do with this?

Must consider a final state to observe HH production.

The Higgs decays to pairs of SM particles lighter than itself, or off-shell gauge bosons. Predominantly this is $b\bar{b}, W^+W^-, ZZ$.



log plot!

Consider $b\bar{b}b\bar{b}$ final states for small M_H, $W^+W^-W^+W^-$ for large M_H.

HH SIGNALS AT THE LHC

[Baur,Plehn,DR: PRL(89)151801, hep-ph/0211224 (PRD)]

For $M_H > 150$, examine $4W \longrightarrow$ multipleptons.

$$\ell^\pm \ell^\pm + 4j \quad , \qquad \ell^\pm \ell^\pm \ell^\mp + 2j$$

Many complex bkgds; considers NLO effects, min. detector effects and ϵ_{ID} for final states.

$\longrightarrow$ LHC can confirm $\lambda \neq 0$ (3-pt. Higgs coupling) for $150 < M_H < 200$ GeV.

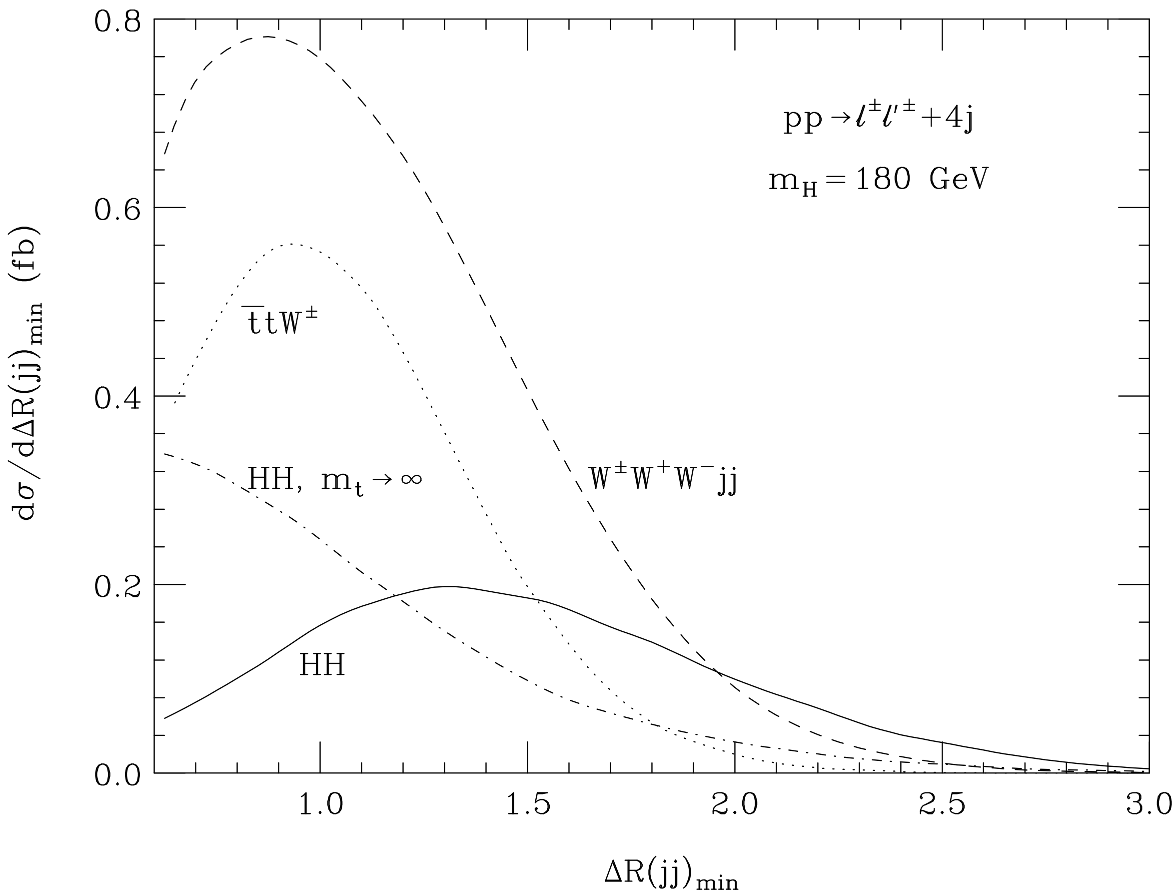
[Baur,Plehn,DR: in progress]

For $M_H < 150$, look for $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$.

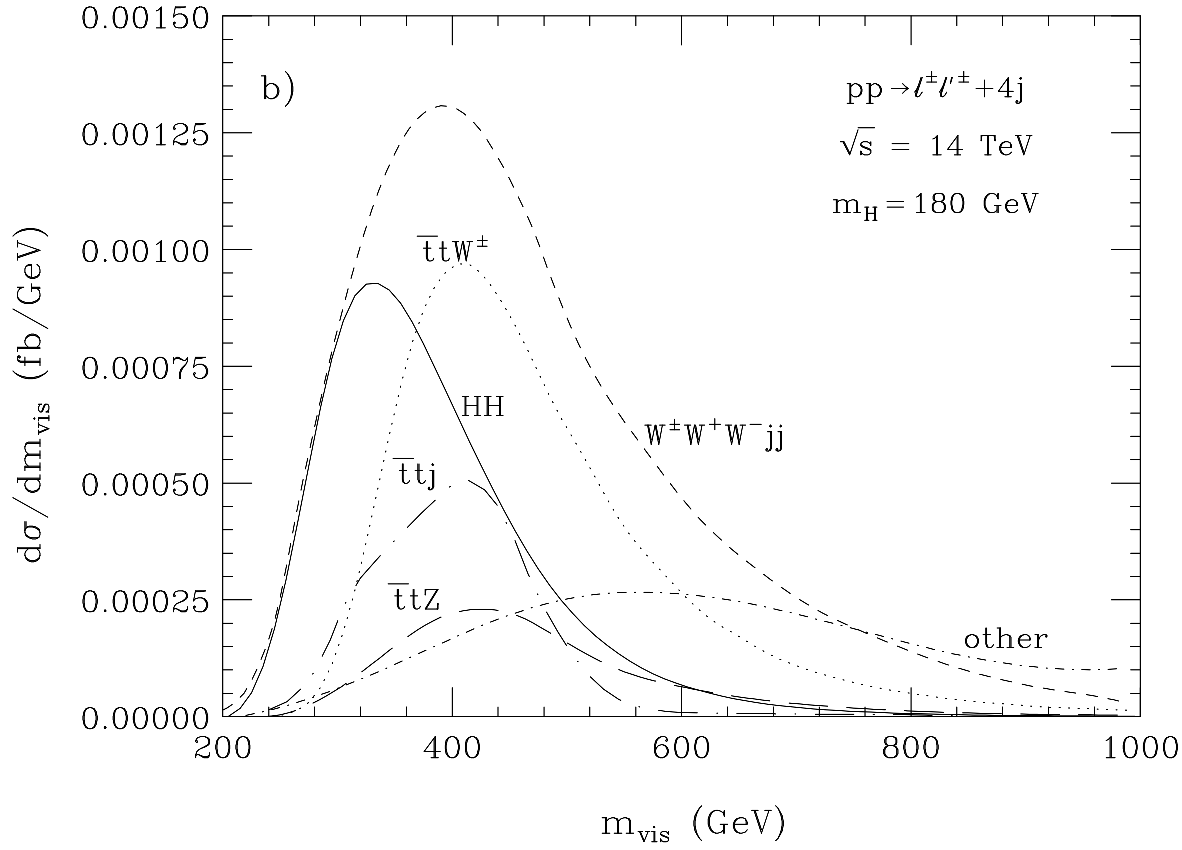
$\longrightarrow$ totally hopeless at LHC, SLHC, 1st measurement at VLHC if no TESLA.

SIGNAL CHARACTERISTICS

Jets typically much further apart in HH signal events:

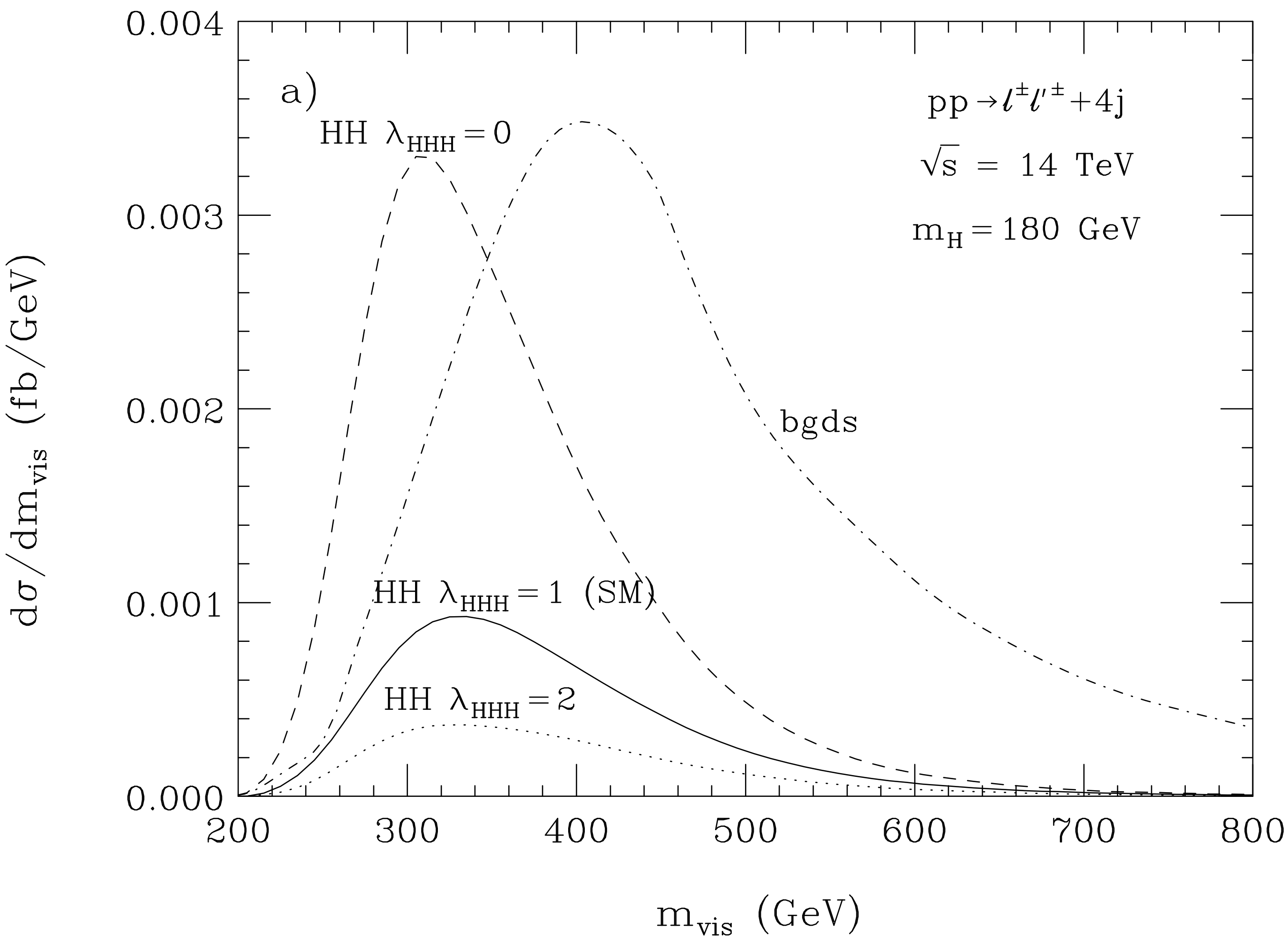


HH signal events exhibit m_{vis} peak much closer to threshold, as expected for 2-body production:



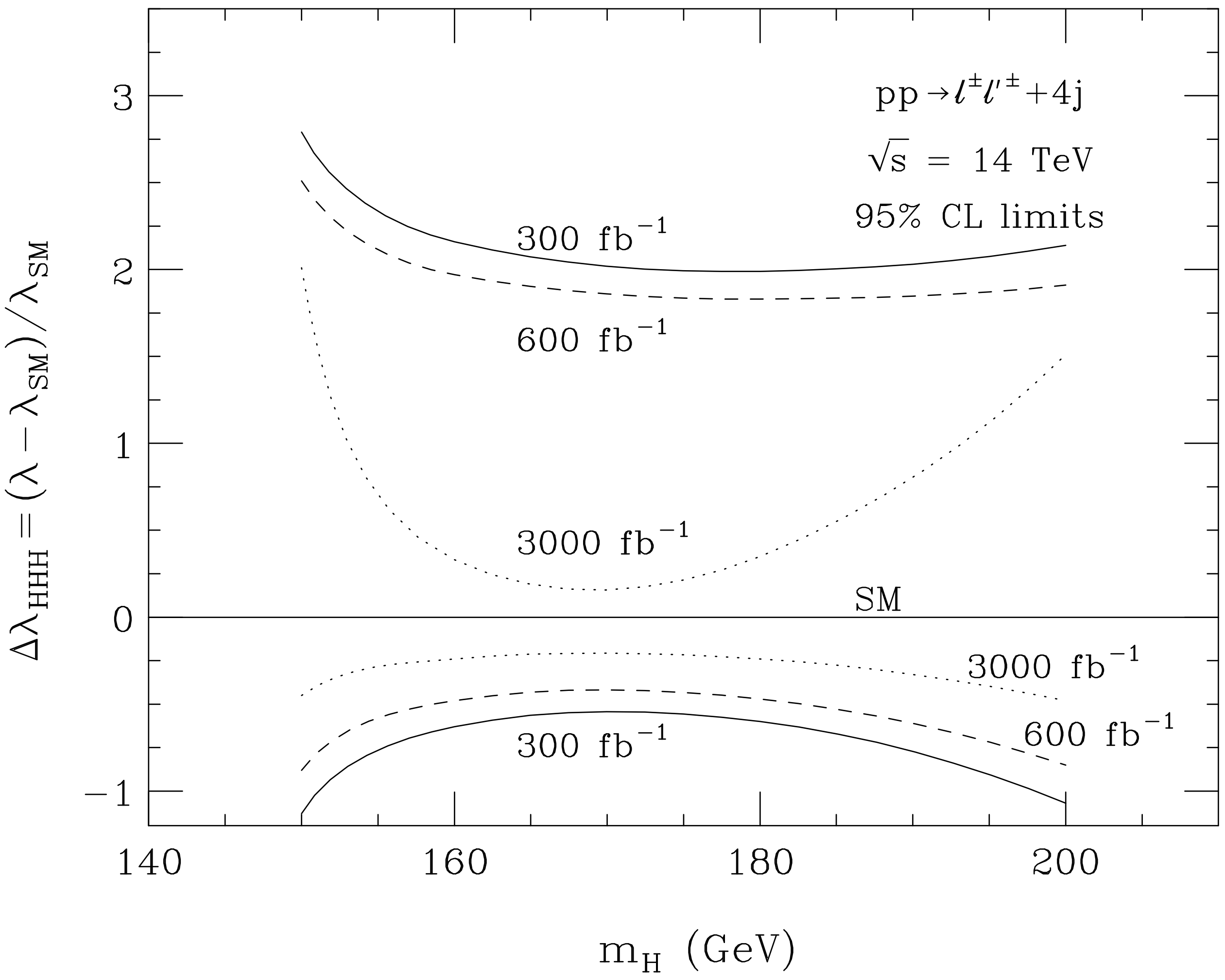
ATLAS study missed both of these physics effects: "black-box" approach to analyses demonstrates need for theory input.

VARIATION OF THE SELF COUPLING



$0 < \lambda < 2\lambda_{\rm SM}$: significant σ_{HH} change at low m_{vis}
$\rightarrow$ expected from phase space threshold behavior.

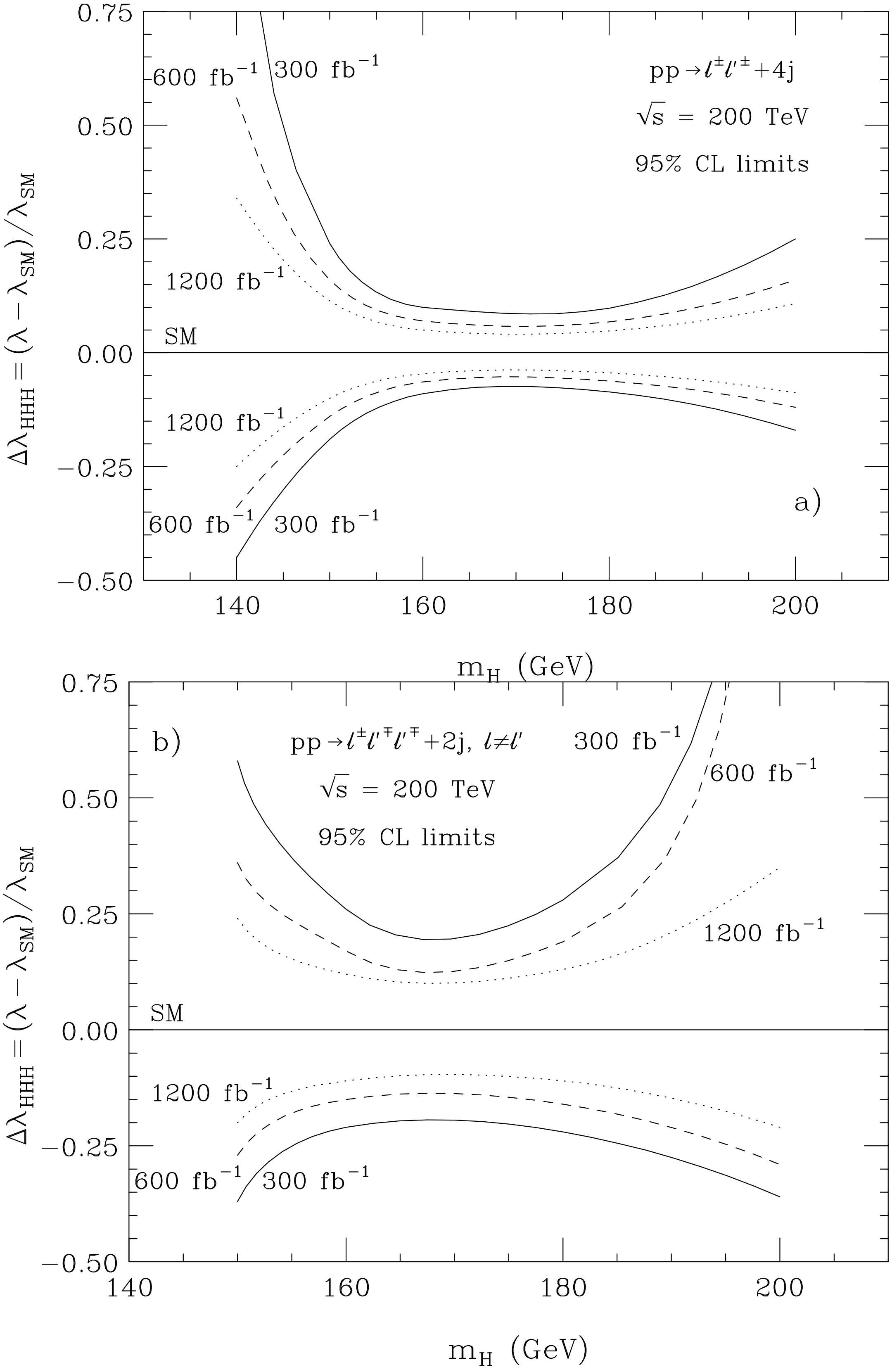
RESULTS FOR $HH \to 4W$ CHANNEL



1. $\lambda = 0$ excludable at $\geq 95\%$ c.l. (300 fb^{-1}) for $150 < M_H < 200$ GeV
2. $\times 2$ lumi improves bounds by $10 - 25\%$
3. λ determined at $20 - 30\%$ for 3000 fb^{-1} (recall: TESLA will compete with SLHC)

$HH \to 4W$ AT A VLHC

Prospects are phenomenal for a 200 TeV VLHC:



ATLAS STUDIES OF $HH \to 4W$

ATLAS study did not find this: "cannot do it".

Not unexpected, considering:

1. used finite m_t matrix elements, but missed the physics
   - $\to$ no $\triangle R$ cut
   - $\to$ no m_{vis} peak for χ^2 fit
2. did properly not take into account NLO effects
3. probable incorrect generation of $t\bar{t}j$ background
   - $\to$ huge effect on signal retention
4. no code for $WWWjj$ available ($WHjj$ wrong)

ATLAS now reinvestigating (K. Jakobs).

Issues to be resolved:

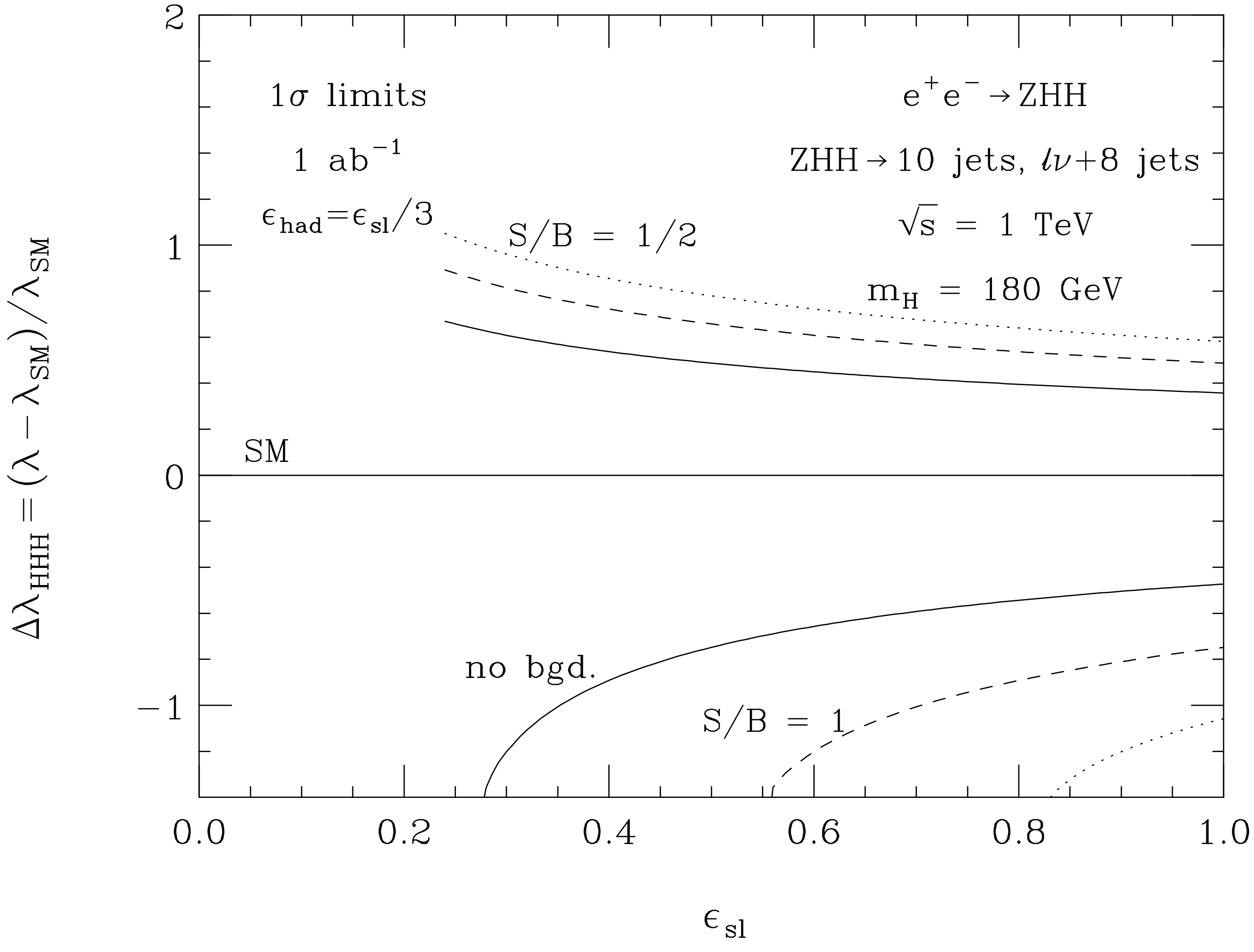
1. $t\bar{t}j$ lepton p_T distributions
2. ISF/FSR affecting m_{vis}
   - $\to$ degradation or overall shift?
3. fold in systematics from δY_t, $\delta\mathrm{BR}(WW)$, etc.

$HH \to 4W$ AT LC

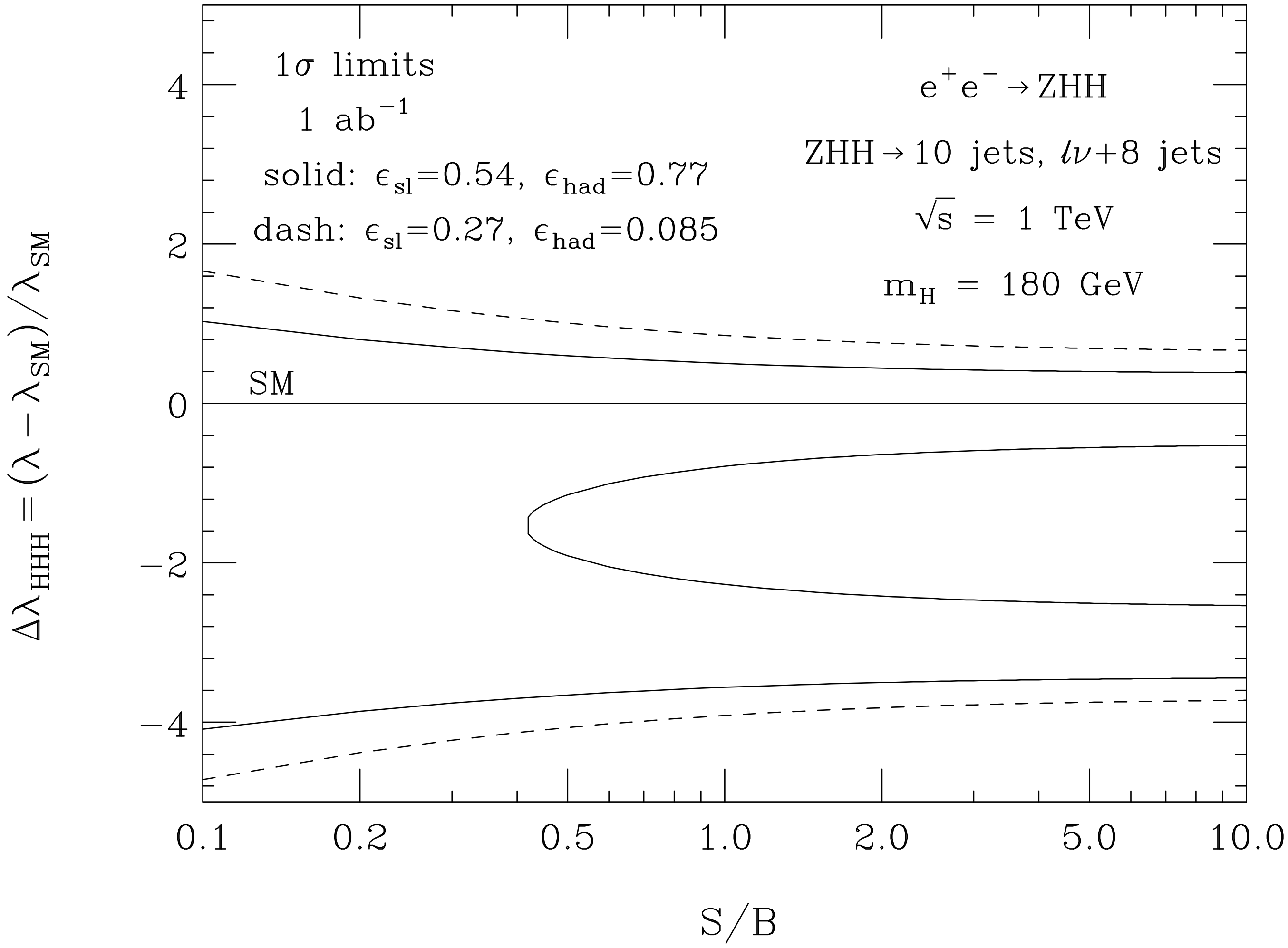
[Baur,Plehn,DR, in prep.]

$ZHH, \nu\bar{\nu}HH \to 0, 1, 2\ell + jets$ primitively:

$\sigma \cdot BR \cdot \epsilon_{\rm ID}$, *with varying ϵ_{ID} and background*



($\epsilon_{sl} = 0.54$ from Juste and Merino study)



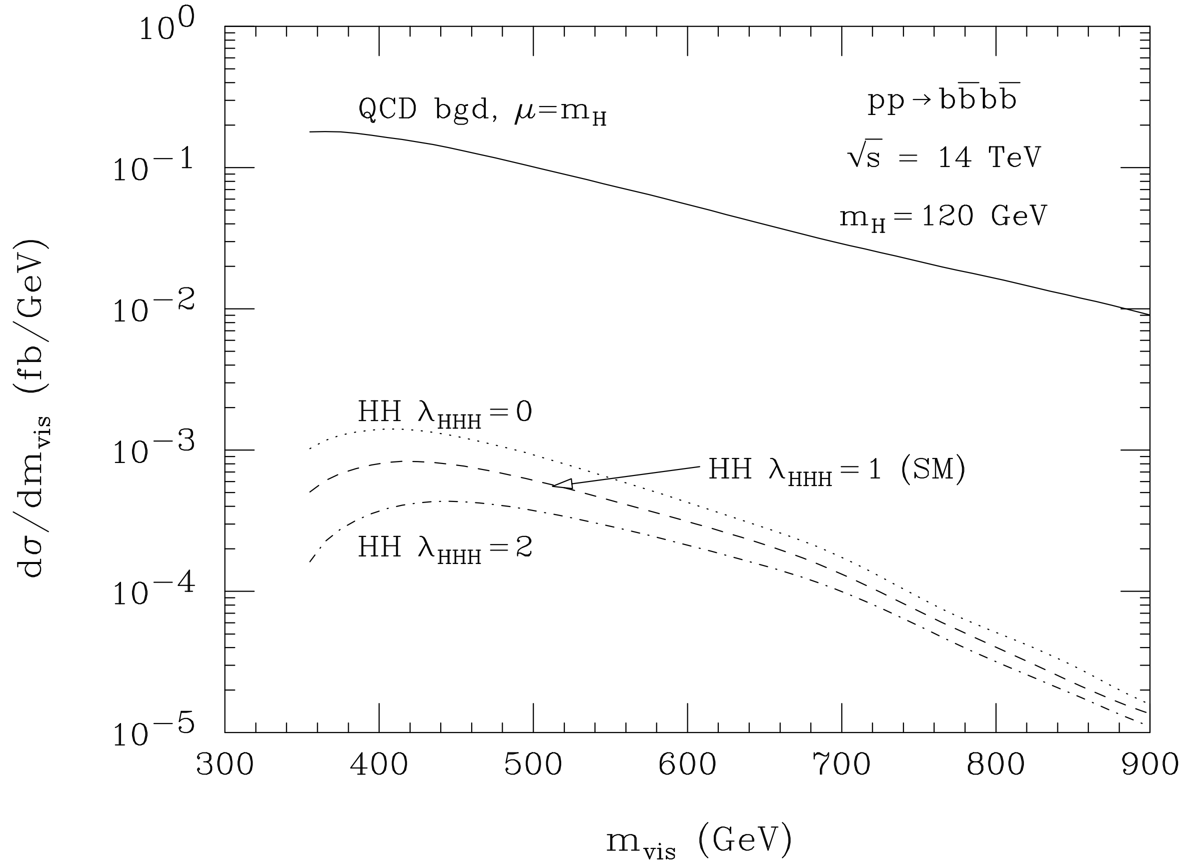
Needs complete study with detector simulation.

(but not at all promising)

$HH \to 4b$ AT LHC

What about $HH \to b\bar{b}b\bar{b}$ for lower M_H @ LHC?

Unfortunately, QCD $b\bar{b}b\bar{b}$ is factor 1000 larger...



$M_H = 120$ GeV, ϵ_{ID} and QCD bkg
(in terms of λ_{SM}):

lumi	1σ upper	1σ lower
LHC, 300 fb^{-1}	+10	-7
SLHC, 3000 fb^{-1}	+ 6	-3

Totally hopeless!

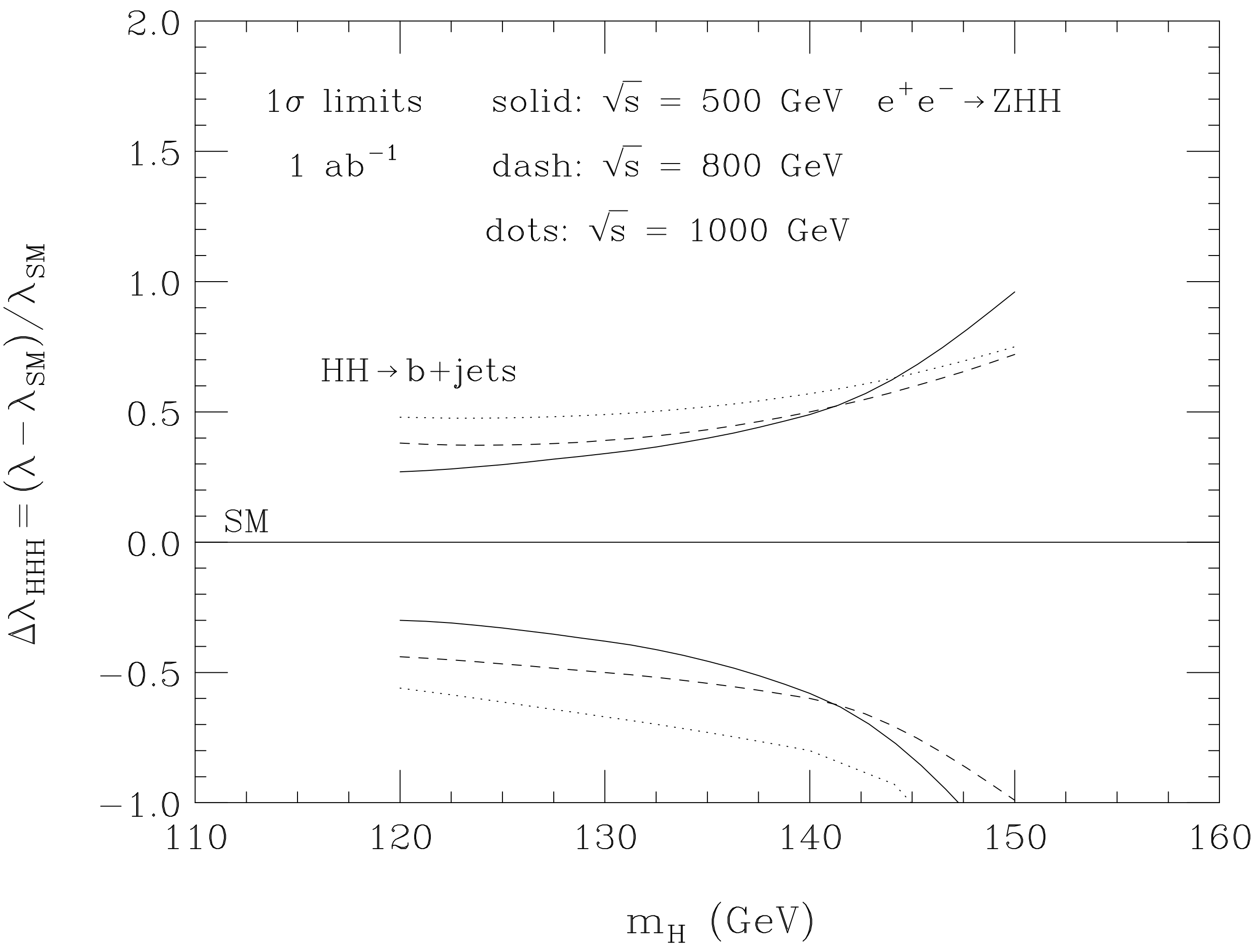
$HH \to b + jets$ AT LC

How good would λ measurement be at TESLA?

Note: couplings are much better measured!

(systematic uncertainties MUCH lower)

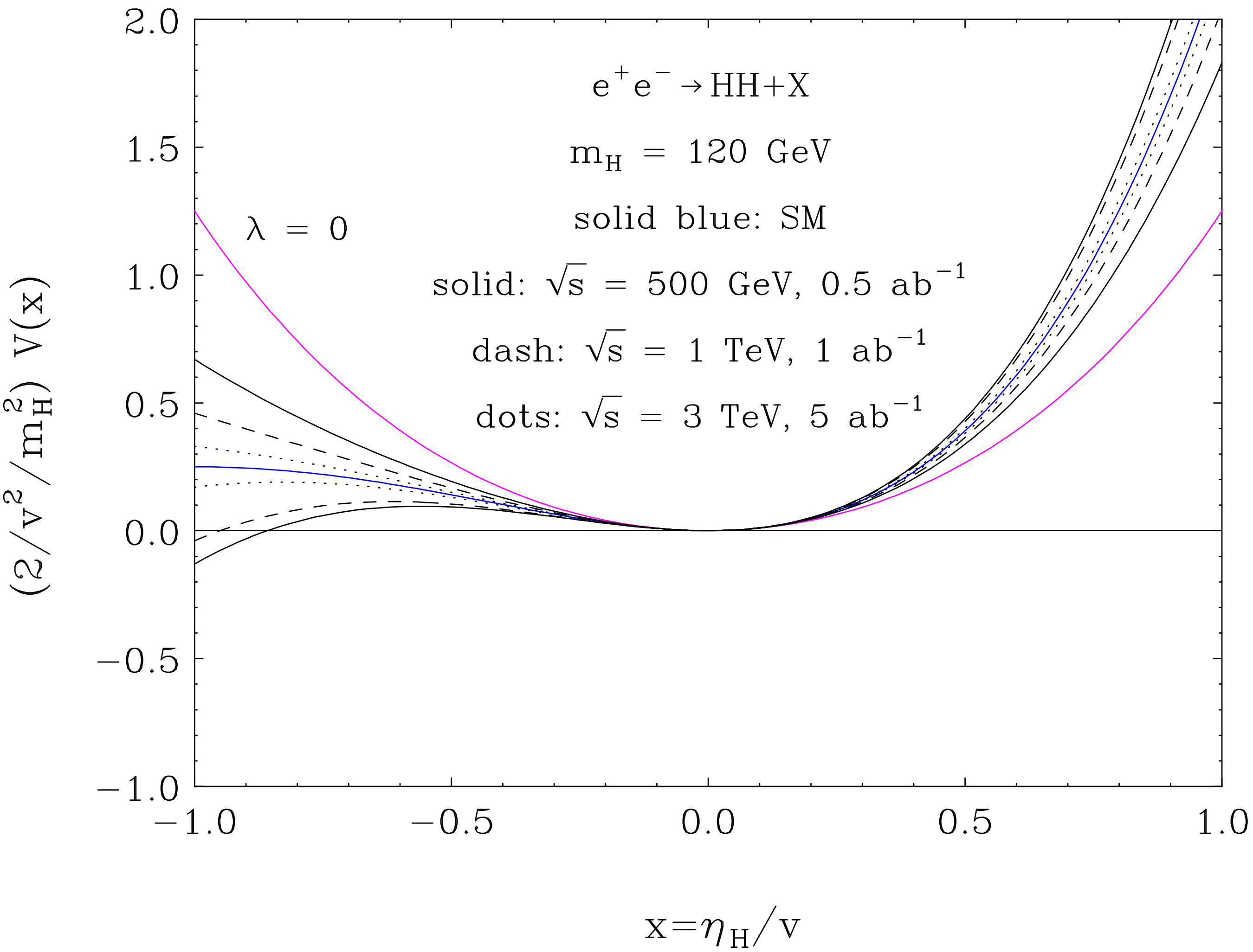
Also, no nasty QCD background.



[Castanier et al., hep-ex/0101028]

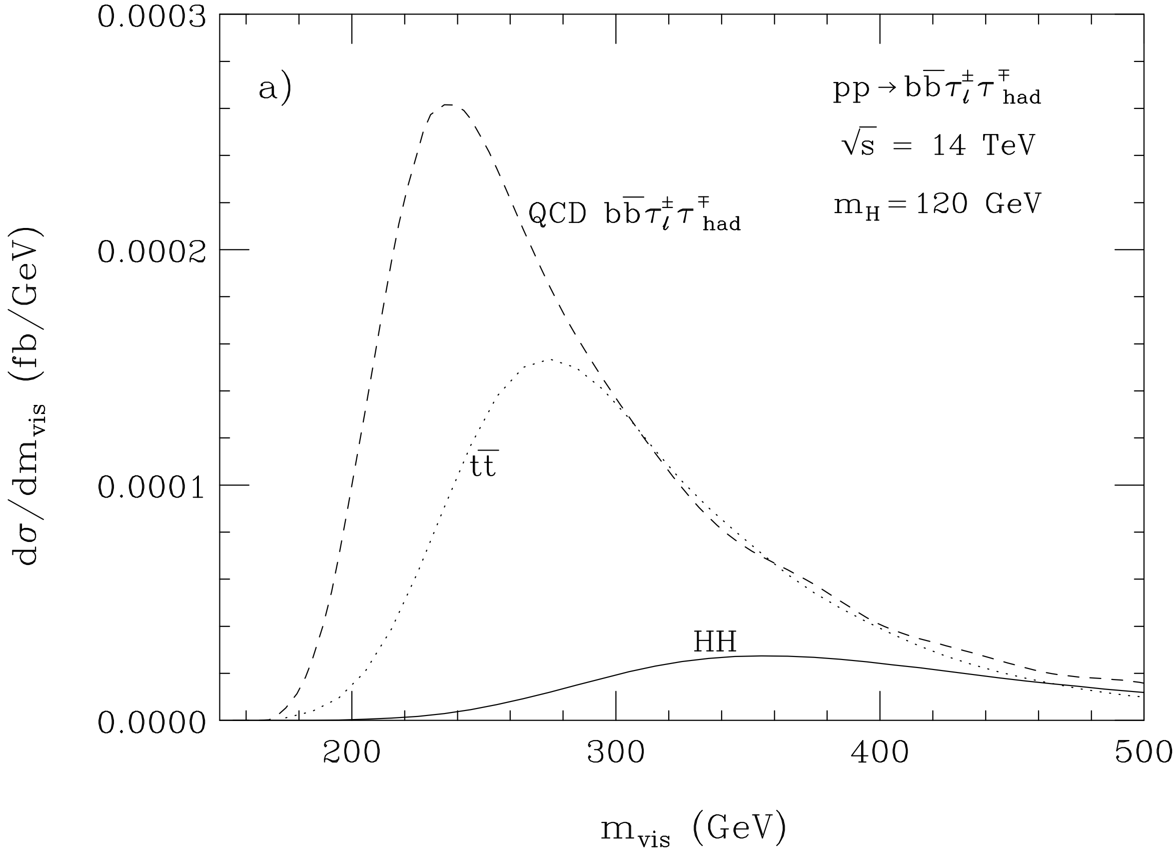
$HH \to b + jets$ AT LC

Shown another way...



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

What about $HH \to b\bar{b}\tau^+\tau^-$ @ LHC instead?



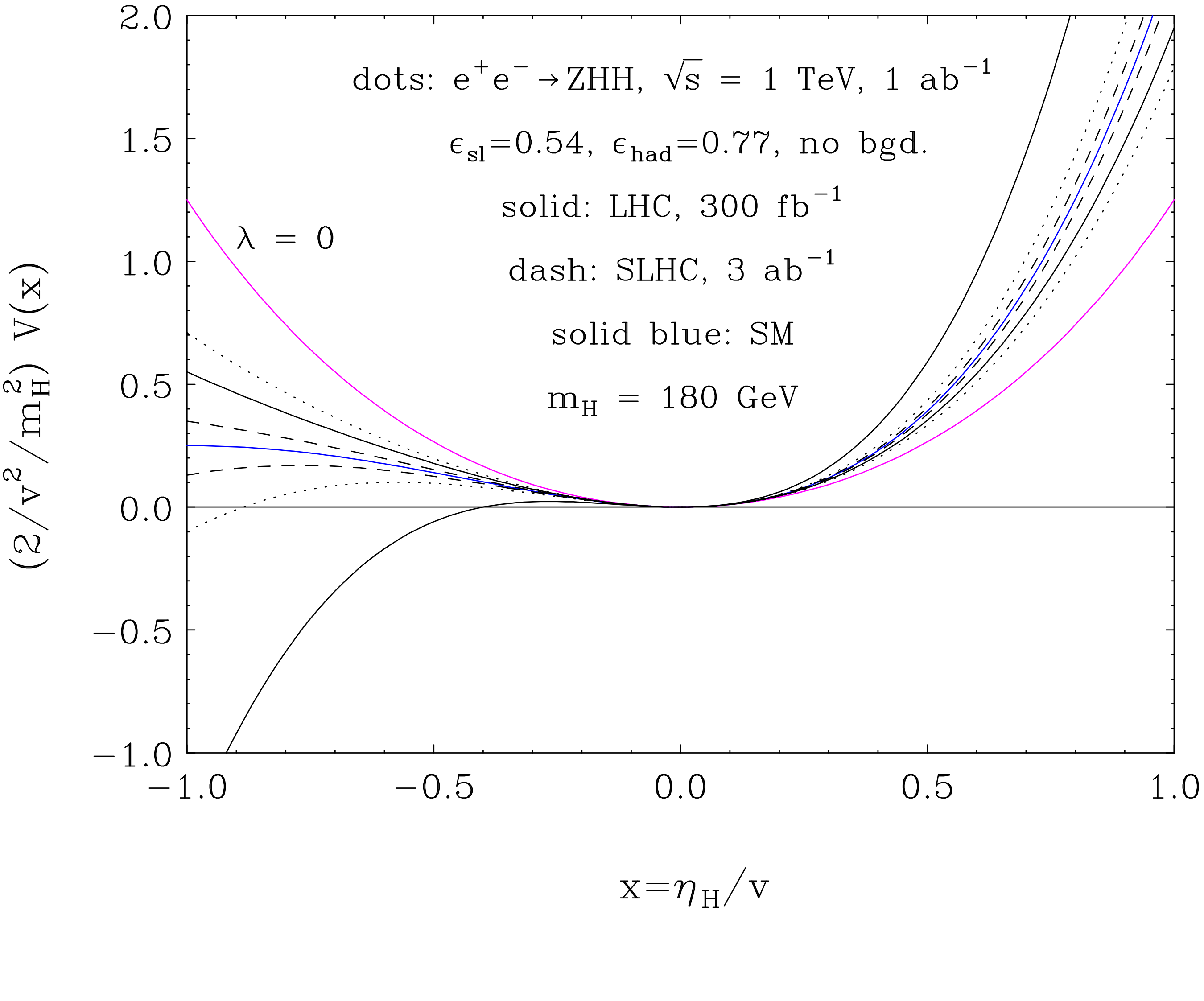
$M_H = 120$ GeV, ϵ_{ID} and QCD $Zb\bar{b}$ bkg
(in terms of λ_{SM}):

lumi	1σ upper	1σ lower
SLHC, 3000 fb^{-1}	+3.1	-1.6
VLHC, 300 fb^{-1}	+1.0	-0.86

Pretty grim, unless no TESLA...

LHC v. LC for HH

Complementarity!



SUMMARY

- LHC: confirm $\lambda \neq 0$ for $M_H > 150$ GeV?
  $\longrightarrow$ parton-level studies say yes
  $\longrightarrow$ ATLAS doing sim. to confirm (~ 1 year)
- (V/S)LHC: *no* access to λ if $M_H < 150$ GeV
- TESLA: excellent λ coverage $M_H < 150$ GeV
- TESLA: cannot address λ for $M_H > 150$ GeV
- Strong complementarity between (V/S)LHC and TESLA for studying Higgs potential
  $\longrightarrow$ TESLA precision Higgs data needed to make best use of (V/S)LHC data in HH, if $M_H \gtrsim 150$ GeV