Higgs Physics at a SuperLHC and a VLHC

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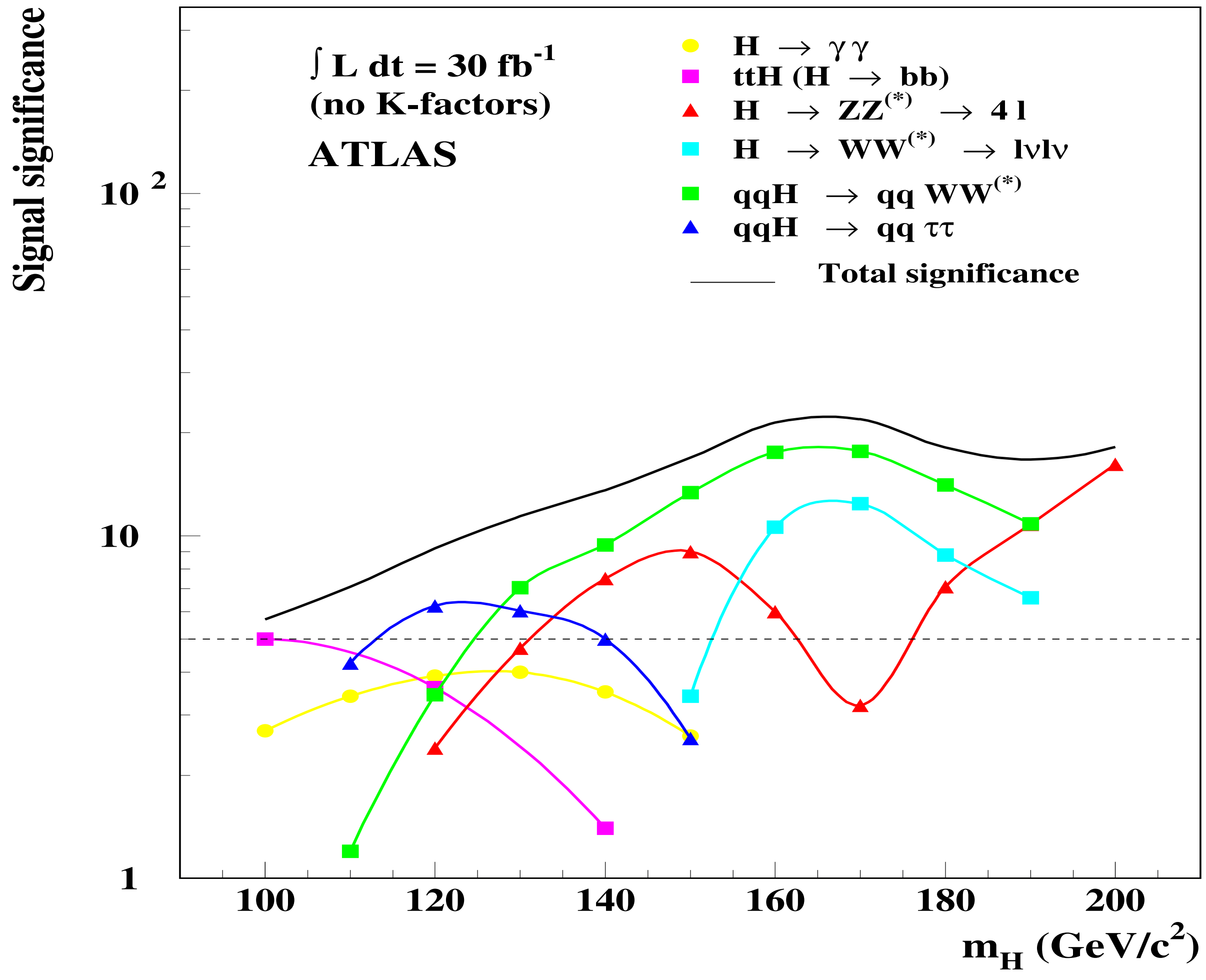
LHC SM Higgs overview

production	decay	M_H range (GeV)	mass peak
$gg \to H$	$\gamma\gamma$	110-140	$\surd$
	W^+W^-	<150-200+	($\surd$)
	$ZZ \to 4\ell$	>130	$\surd$
$pp \to Hjj$	$\tau^+\tau^-$	110-145	$\surd$
	W^+W^-	120-200+	$\surd$
	ZZ	120-200+	$\surd$
	$\gamma\gamma$	110-145	$\surd$
	invisible	*new trigger	$\times$
$q\bar{q} \to ZH$	invisible	110-170	$\times$
$pp \to t\bar{t}H$	$b\bar{b}$	100-120	$\surd$
	W^+W^-	130-200+	$\times$

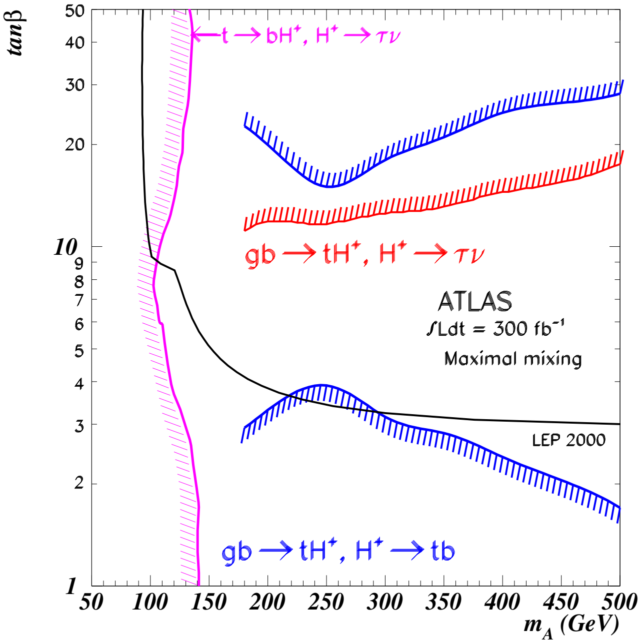
Latest for the new ATLAS TDR:

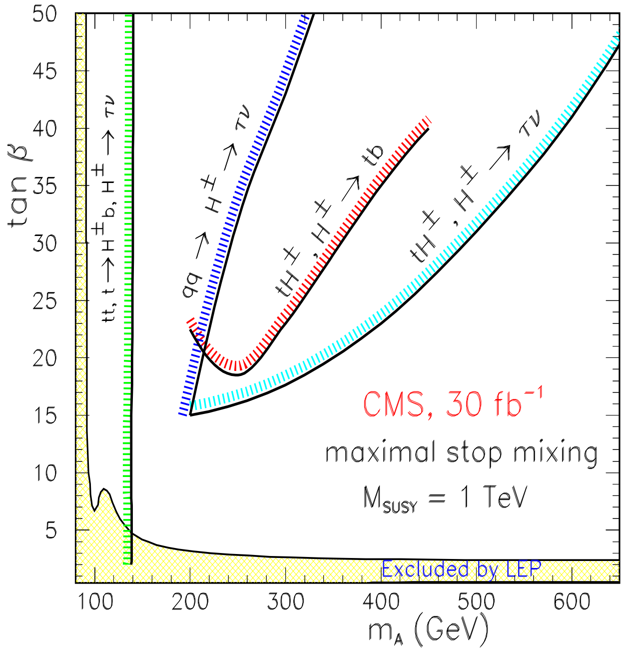


MSSM charged Higgs – more difficult!

[Assamagan & Coadou, APP(B33)1347]

[Banerjee & Maity, J.Phys.(G28)2443; Kinnunen, CMS-NOTE-2000/045]





WARNING!!

These studies must be redone due to several flaws:

1. PYTHIA had matrix element bug
2. HERWIG did not use running Yukawa coupling
3. not all PYTHIA studies used running Yukawa coupling

→ signal cross sections overestimated on average by factor 2

Point: $H^{\pm}$ may be very difficult to observe!

$t\bar{b}H^-/b\bar{b}h$ issue for MSSM

Getting correct σ_h b-incl/excl + kinematics:

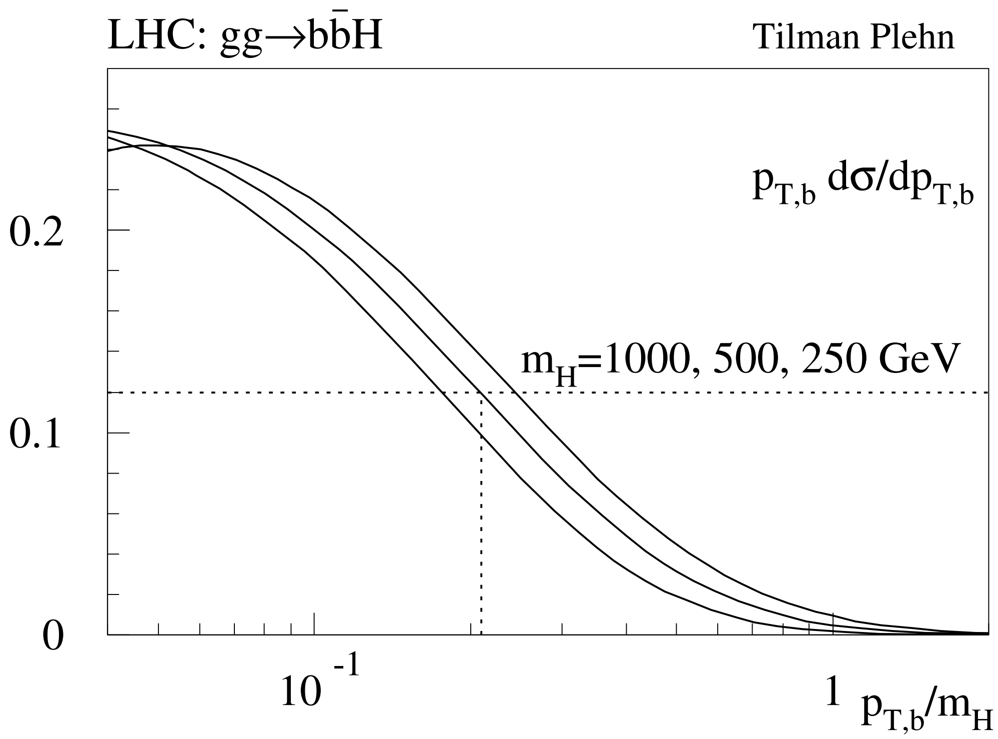
[Maltoni, Sullivan, Willenbrock, PRD(67)093005]

[Boos & Plehn, hep-ph/0304034]

$\rightarrow$ w/ excl. process, estimate appropriate μ_f

$\rightarrow$ evaluate incl. process with that μ_f

$\rightarrow$ mod. enhancement: logs understood!

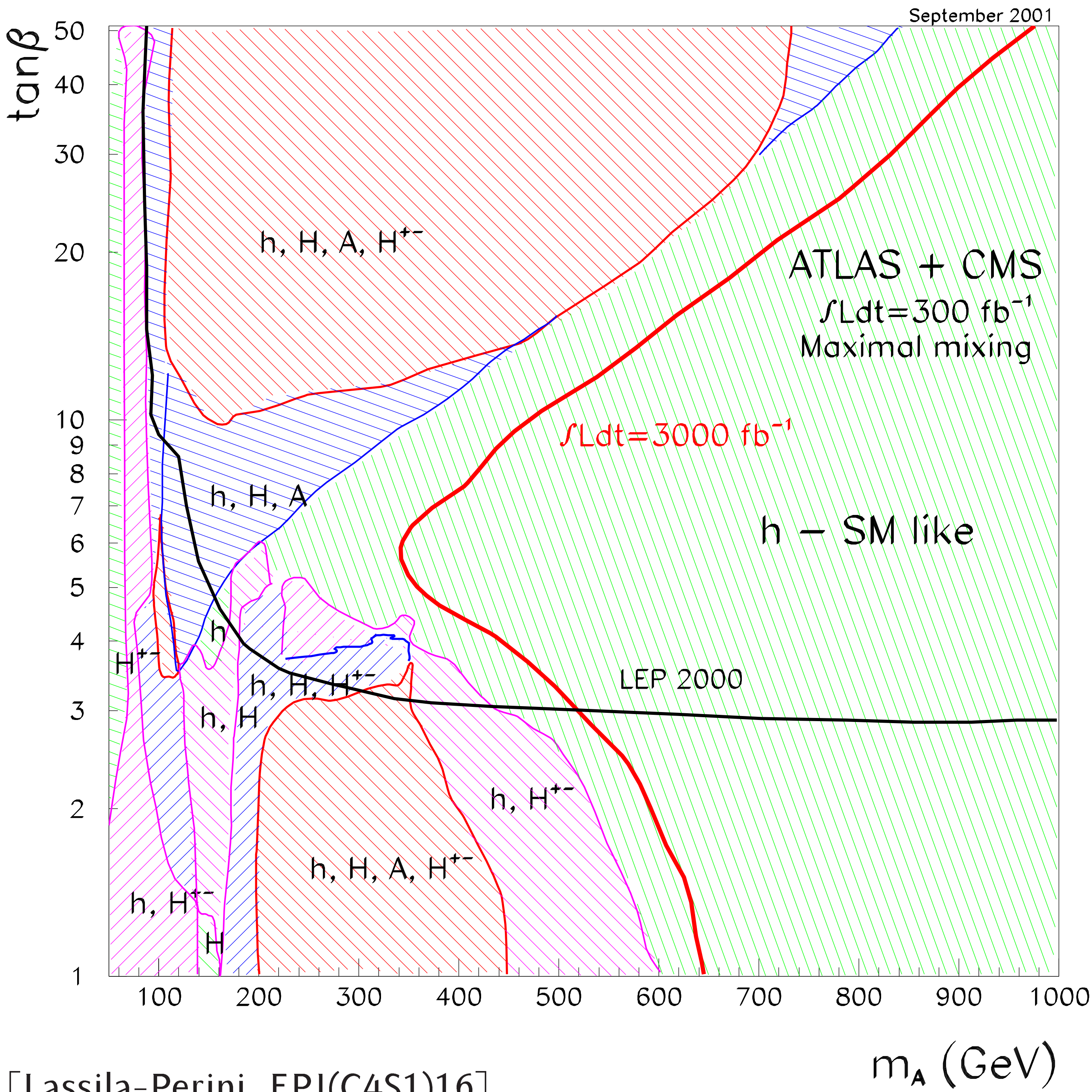


confirmed w/ stability of NNLO $bb \rightarrow h$

[Harlander & Kilgore, PRD(68)013001]

Point: some $b\bar{b}h$ calculations grossly overestimate rate

Broader: how many MSSM Higgses can LHC see?



[Lassila-Perini, EPJ(C4S1)16]

→ huge regions where $H^{\pm}$ cannot be seen

(and have just gotten bigger)

→ big regions where H, A cannot be seen

Decoupling limit is tough! What about SLHC/VLHC?

LHC can clearly observe at least one Higgs ("No-Lose Theorem") - BUT:

What does "find the Higgs" mean?

Observe bump in $m_{\gamma\gamma}$, $m_{4\ell}$, $m_{b\bar{b}}$? **HARDLY!**

Higgs boson is the agent responsible for EWSB and fermion mass generation[?]

$\rightarrow$ Measure properties of Higgs *candidate*

property	SM value	LHC?
charge	neutral, colorless	$\surd$
M_H	"light"	$\surd$
J^{CP}	0^+	$\surd$
g_{HVV}	$g^{\mu\nu}$ gauge coup	$(\surd)$
$g_{Hf\bar{f}}$	Yukawa ($\propto m_f$)	$(\surd)$
λ_{HHH} (pot.)	$M_H^2/2v^2$	$((\surd))$

As well as: observe all states!

Can (S/V)LHC measure H couplings?

Short answer: Yes, to a degree

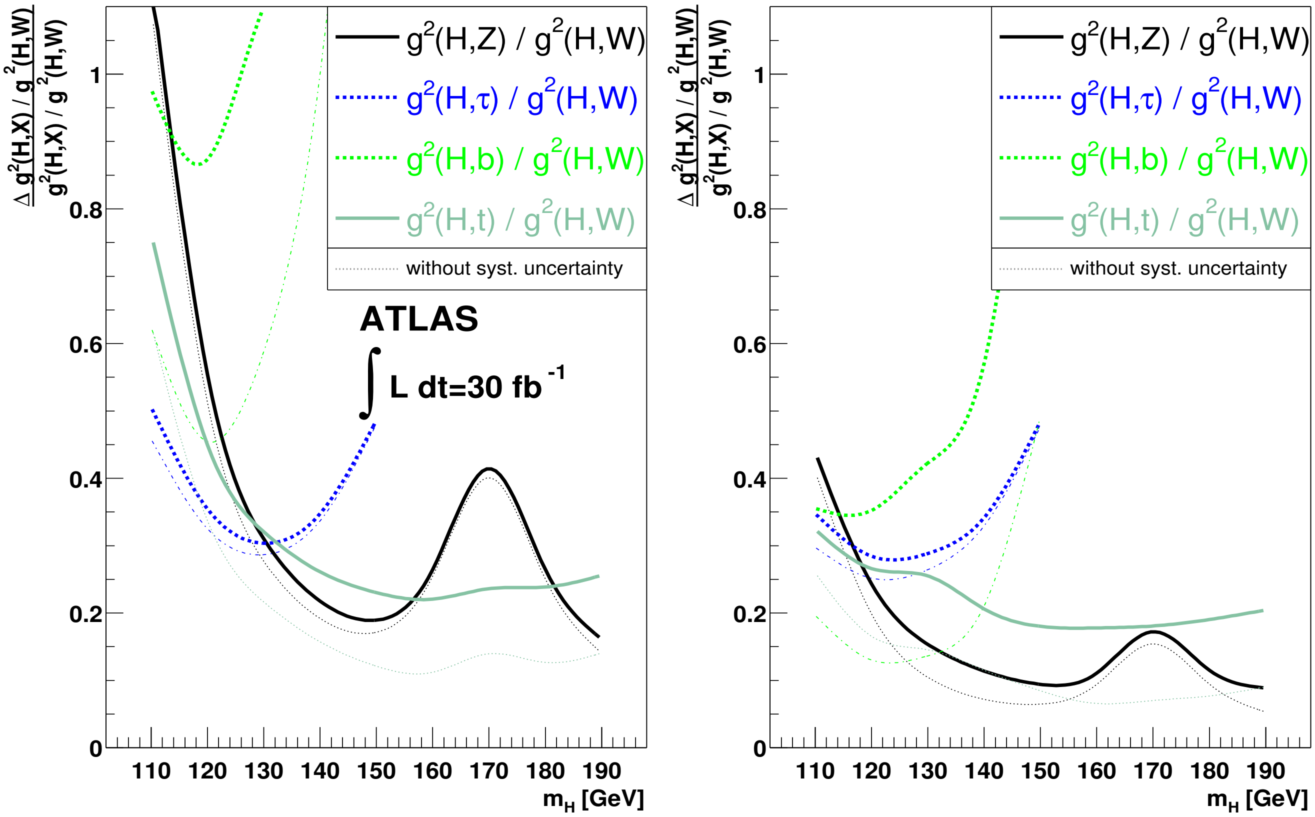
Problem:
for $M_H \lesssim 220$ GeV, no direct Γ^H_{tot} meas'mt

NEW:
Max. Likelihood fit, 15 LHC Higgs channels
[M. Dührssen, ATL-PHYS-2003-030]
$\rightarrow$ full treatment of systematic uncertainties
$\rightarrow$ Case 1: relative coups, no theory assumptions
BUT gets absolute lower limit on Γ^H_{tot}
$\rightarrow$ Case 2: absolute coups, Γ^H_{tot} assumption
$\rightarrow$ is still (mostly) statistics limited,
so would improve at SLHC
(VLHC not yet studied)

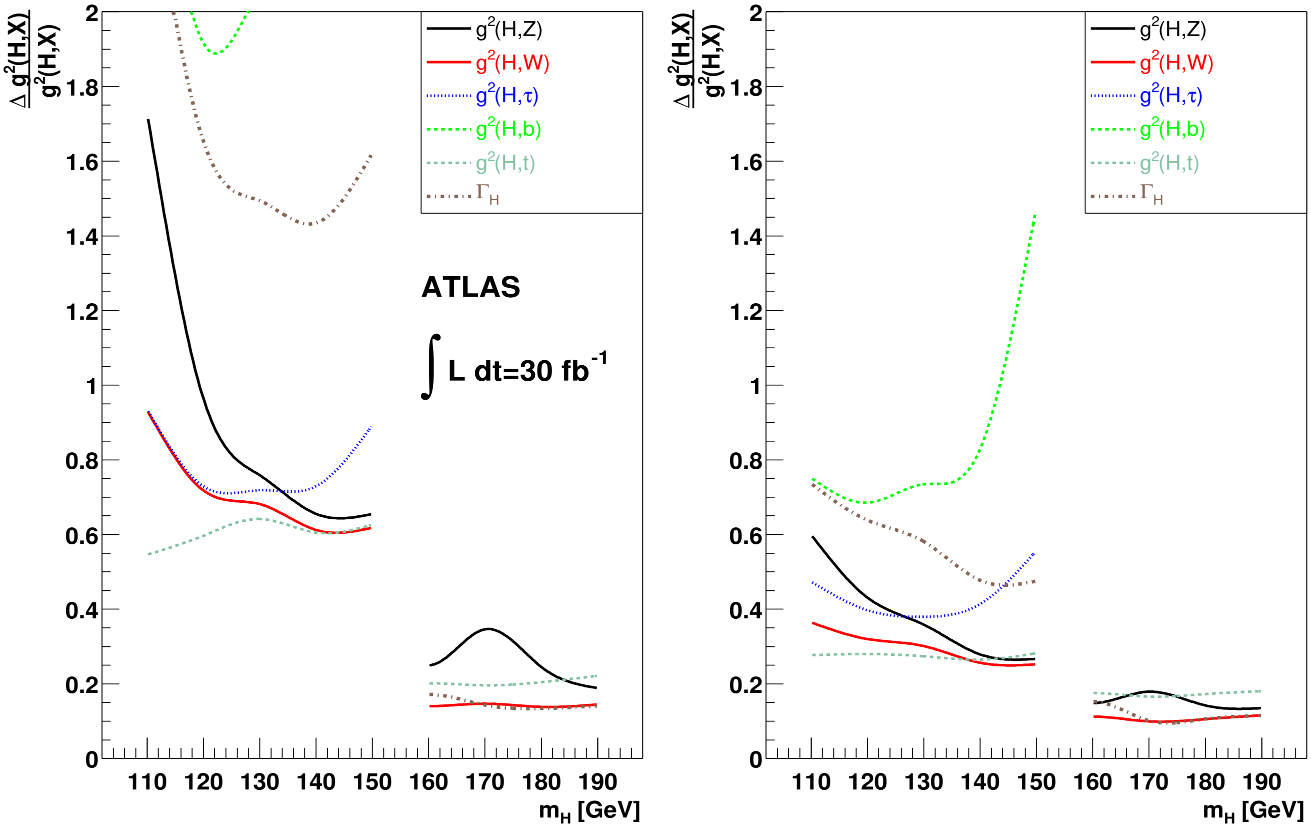
Ongoing study adds $H \rightarrow invis$ channels,
more WBF lumi reach, add'tl constraints...

LHC Higgs couplings analysis (Dührssen)

Case 1: rel. couplings, no theory assump.



Case 2: absolute couplings, Γ^H_{tot} assump.



SLHC/VLHC would greatly improve couplings analysis (espec. low M_H), but ultimately limited by QCD uncertainties

But many important questions remain:

1. Y_t is perhaps most important coupling!
2. no 2^{nd}-gen coup measured
3. Y_b/Y_τ ratio only very poorly known
4. unknown (invisible?) Higgs decays?
5. anomalous Higgs QCD coups? (Y_c, Γ_g)

LC: precision values for $g_Z, g_W, g_b, g_\tau, \Gamma_\gamma$
& reasonably good values for $g_c, \Gamma_g, \Gamma_{invis}$
(note: g_c would be first & only 2^{nd}-gen coup)

Where can hadron colliders still shine?

Top Yukawa

1. $t\bar{t}H, H \to b\bar{b}$: very weak @ LHC

   would benefit from statstics @ SLHC, σ @ VLHC

2. $t\bar{t}H, H \to \tau^+\tau^-$ (wanted for Y_b/Y_τ)

   initial LHC results *very* pessimistic;

   should be studied for SLHC & VLHC

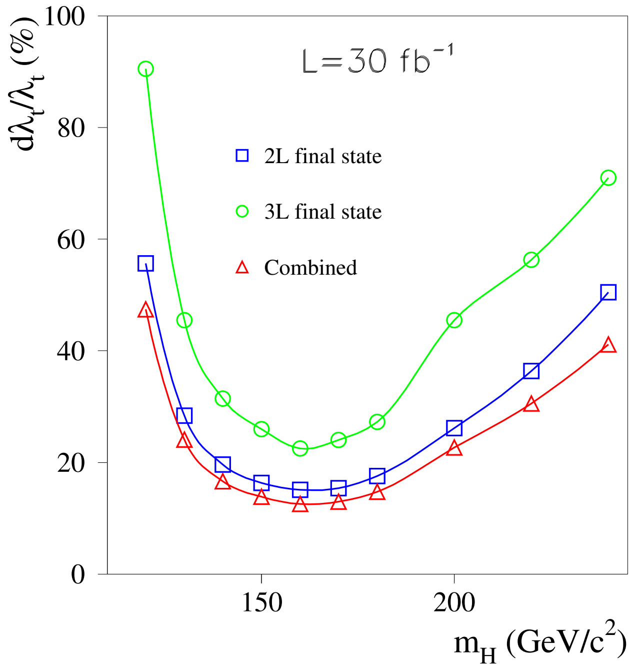
3. $t\bar{t}H, H \to \gamma\gamma$: promising @ VLHC!

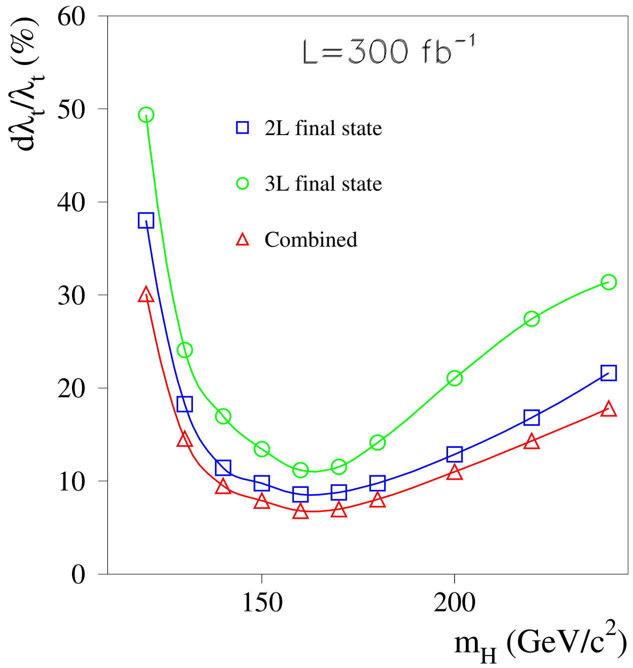
   $\delta Y_t/Y_t \sim 7\%$ for $M_H = 130$ GeV @ $\sqrt{s} = 100$ TeV

   [Belyaev, Maltoni, Reina, hep-ph/0110274]

4. $t\bar{t}H, H \to W^+W^- \to 2\ell, 3\ell$+jets ($M_H \gtrsim 135$)

   [Maltoni,DR,Willenbrock, PRD(66)034022];[ATL-PHYS-2002-019]

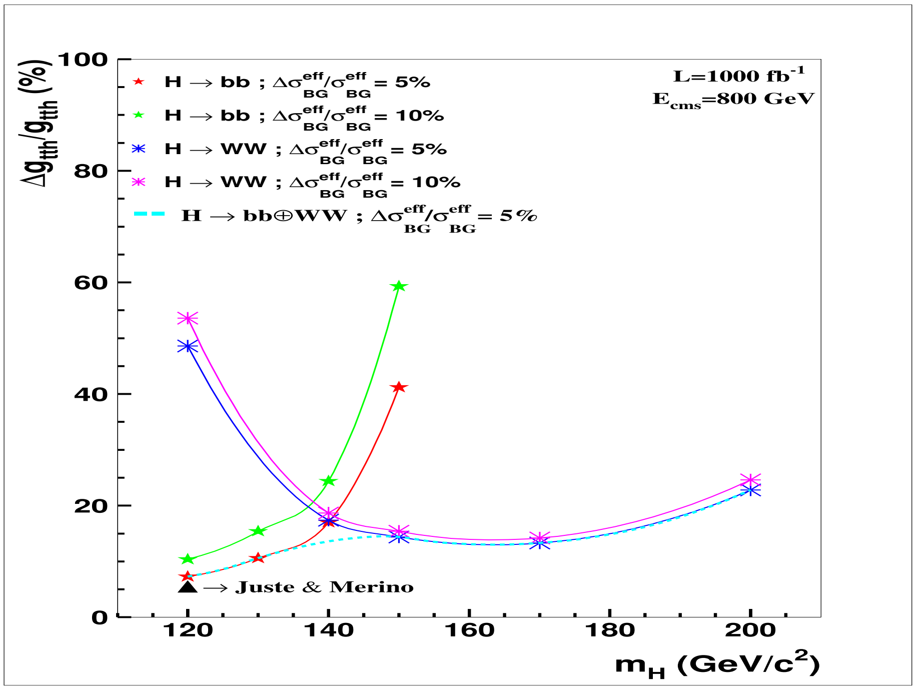




(statistical; assumes BR($H \to WW$) known)

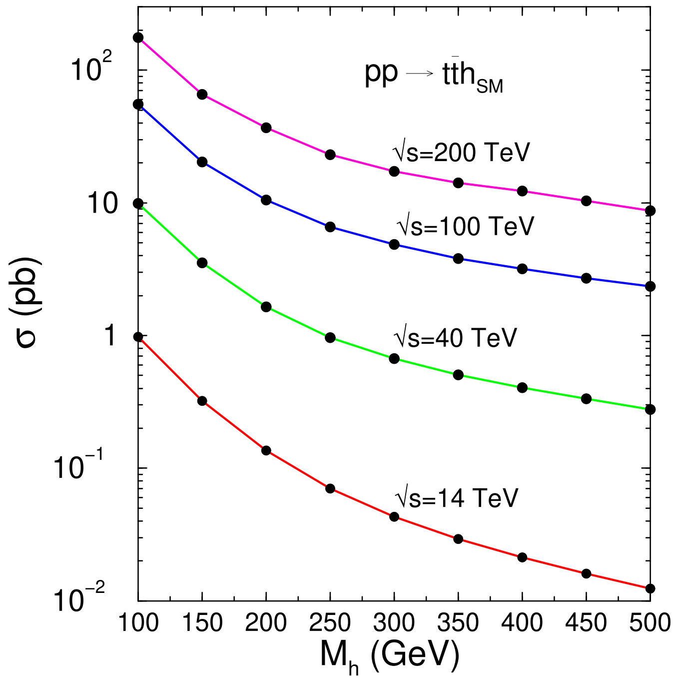
LC and VLHC on the Top Yukawa

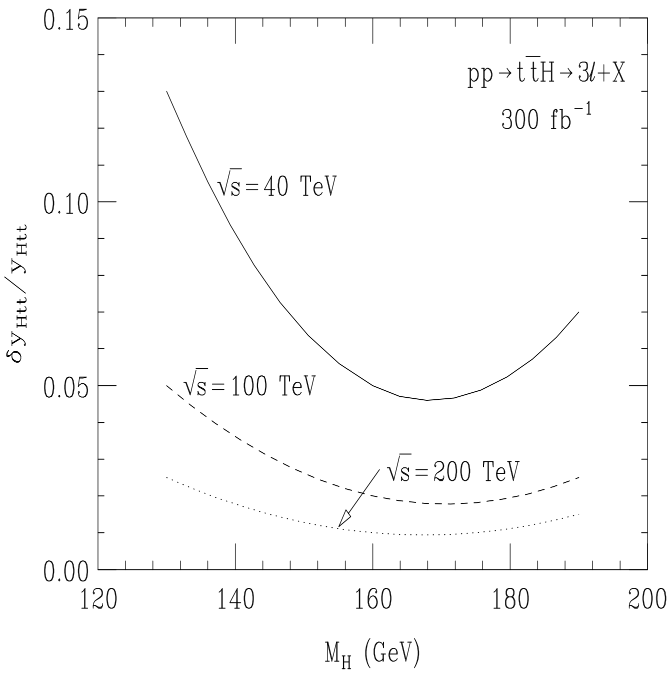
Multiple channels @ $\sqrt{s} = 800$ GeV: [A. Gay, St. Malo, April 2002]



LHC better for $M_H > 135$ GeV!

VLHC can turn this into a precision measurement:





Note: (S)LHC/VLHC still need LC precision data!

μ Yukawa

1. WBF $pp \to Hjj \to \mu^+\mu^- jj$

[Plehn,DR,PLB(520)108] (under study by ATLAS @ Bonn)

$\sqrt{S}$ [TeV]	M_H [GeV]	S/B	300 fb^{-1} sig.	$\delta Y_\mu / Y_\mu$	$\mathcal{L}_{5\sigma}$ [fb^{-1}]
14	120	1/7.5	1.8σ	30%	2300
14	140	1/7.5	1.2σ	43%	4900
40	120	1/5.3	3.3σ	17%	700
40	140	1/5.0	2.4σ	25%	1400
200	120	1/8.0	5.7σ	10%	230
200	140	1/7.9	4.0σ	13%	500

$\longrightarrow$ VLHC could provide $\mathcal{O}(10\%)$ on Y_μ

(better than LC)

Note: doubling Y_μ is spectacular signal!

2. Inclusive $gg \to H \to \mu^+\mu^-$

much larger rate, but capability debated

[Han & McElrath, PLB(528)81]

v. [Boos,Djouadki,Nikitenko,hep-ph/0307079]

What about an invisibly-decaying Higgs?

[1] WBF Higgs events allow observation:

[Eboli & Zeppenfeld, PLB(495)147]

Spectacular 95% CL probe over wide M_H range:

M_H (GeV)	100	120	130	150	200	300	400
100 fb^{-1}	4.8%	4.9%	5.1%	5.3%	6.2%	8.5%	11.7%

$\longrightarrow$ Under intense study by ATLAS and CMS:

1. CMS trigger redesigned to acommodate
2. ATLAS trigger redesign being considered

[2] ZH events allow observation:

fb^{-1} req'd for 5σ signal (100% invis BR):

[P. Gagnon, ATLAS]

M_H (GeV)	110	120	130	140	150	160	170
fb$^{-1}(5\sigma)$	18	23	32	45	60	67	82

Ripe for S/VLHC precision measurement!

The SM Higgs potential

Phenomenological effective potential:

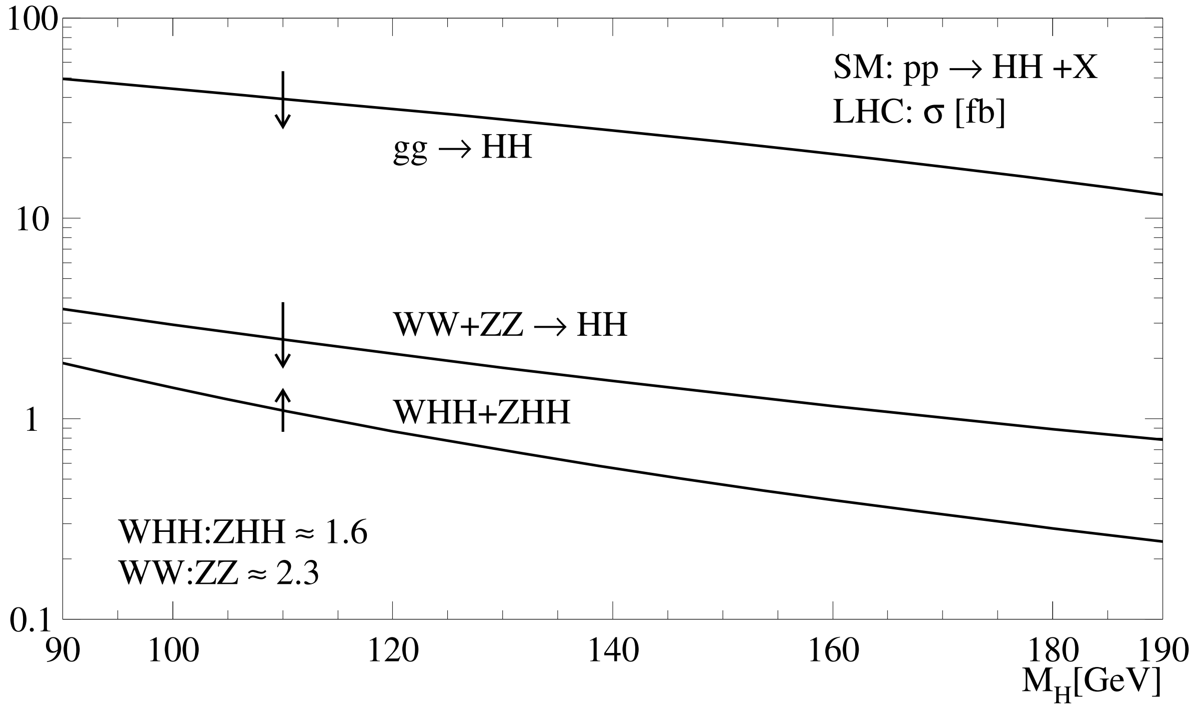
$$V(\eta_H) = \frac{1}{2} m_H^2 \, \phi_H^2 + \lambda \, v \, \phi_H^3 + \frac{1}{4} \tilde{\lambda} \, \phi_H^4$$

$\rightarrow$ λ, $\tilde{\lambda}$ free parameters

measure in HH, HHH direct production

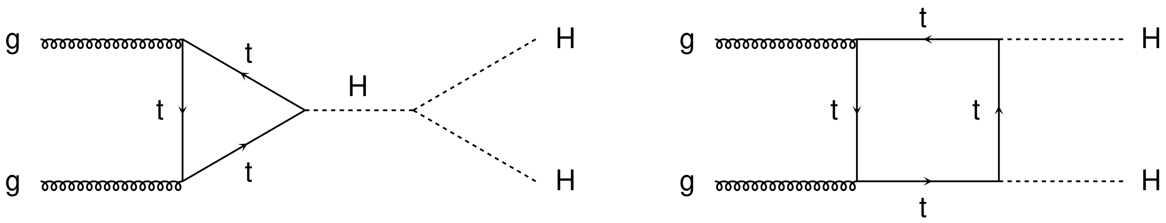
LHC: $gg \rightarrow HH$ dominates

20–50 fb, but huge backgrounds



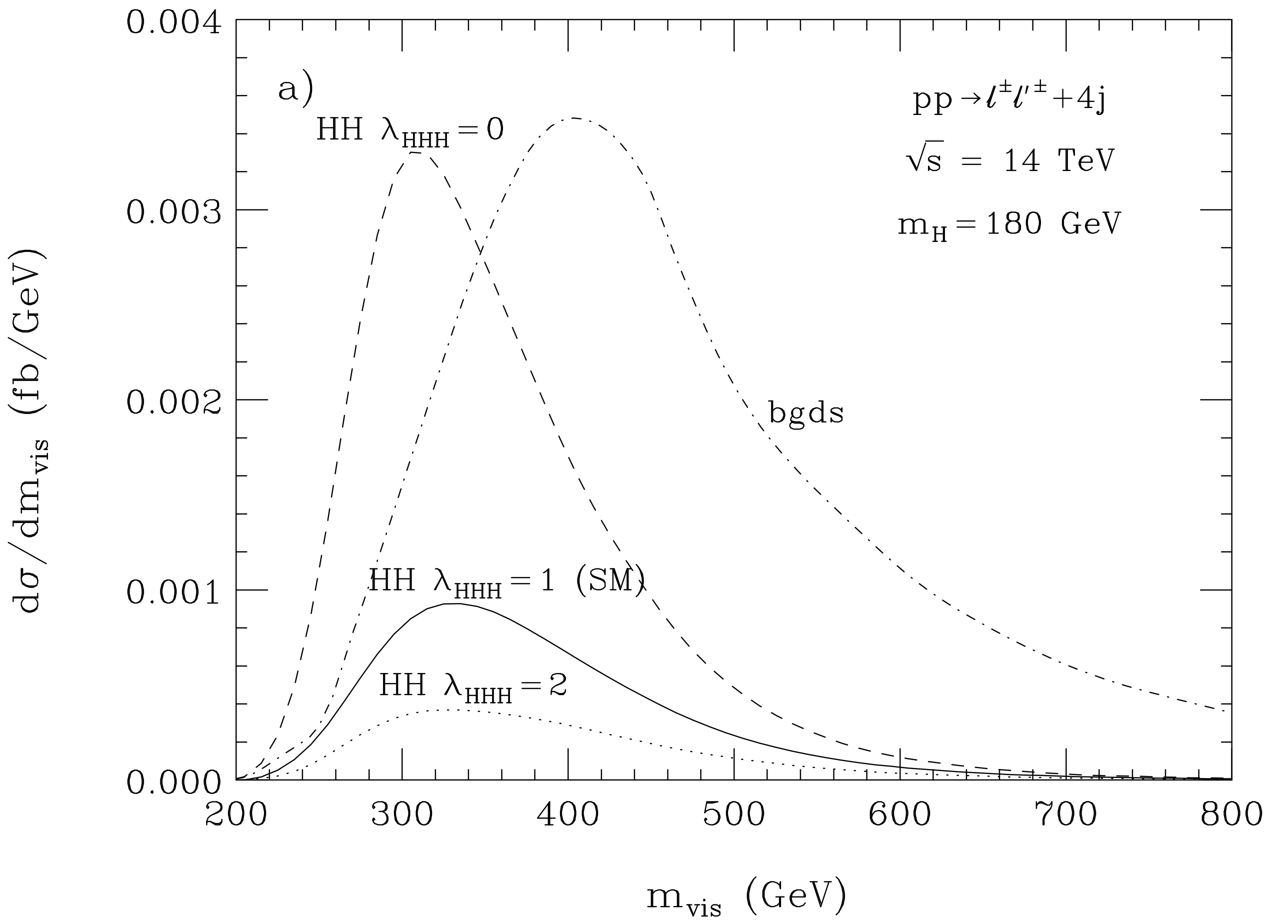
HH at the (S)LHC

SM diagrams interfere destructively!



Measure (no) m_{HH} peak for $\lambda = 0$.

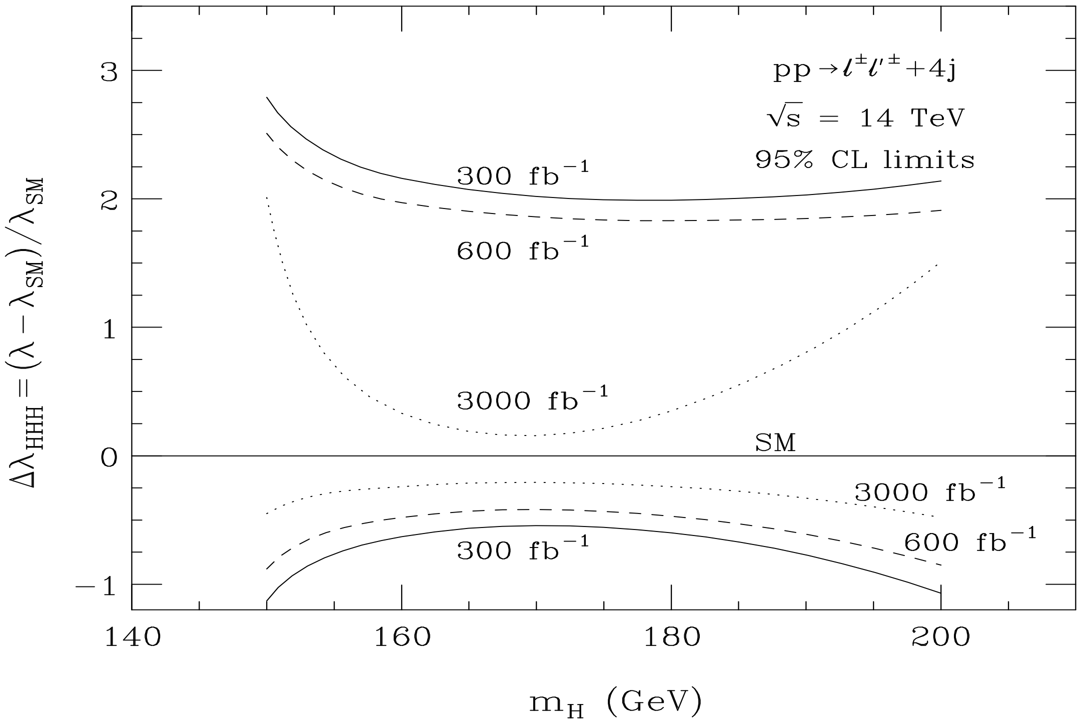
[Baur,Plehn,DR, PRL(89)151801, PRD(67)033003,(68)033001]



$M_H > 150$ GeV: $HH \to 4W \to$ multileptons

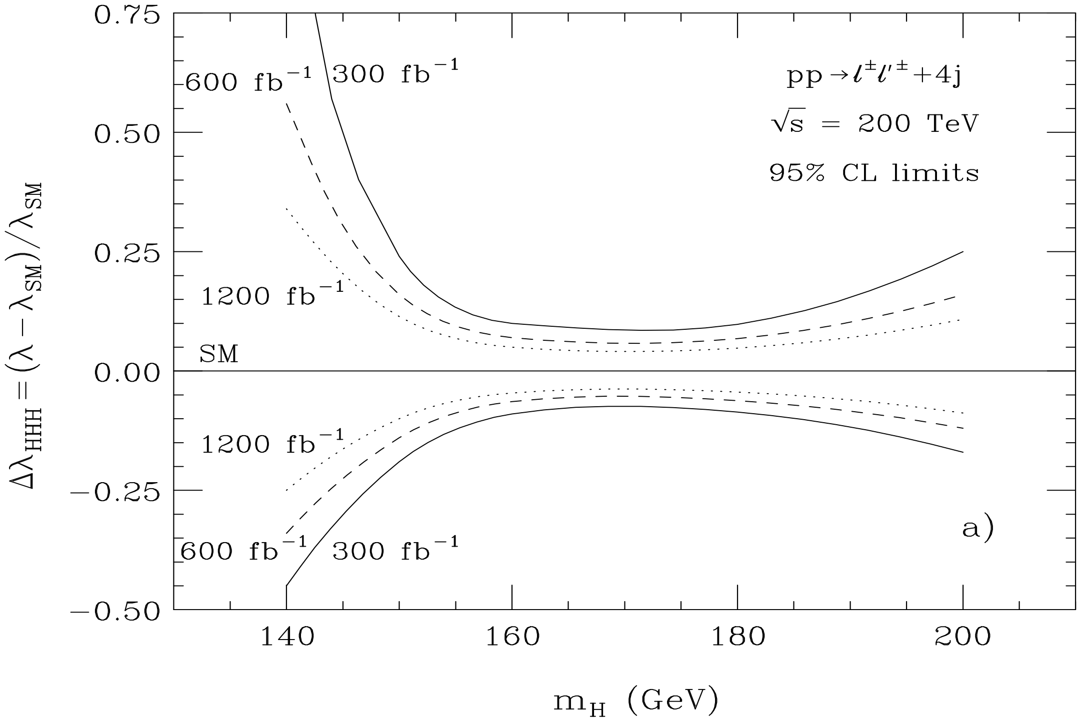
$\to$ LHC sees $\lambda \neq 0$ @ $> 95\%$ CL, $150 < M_H < 200$ GeV

$\to$ SLHC can measure λ @ $\sim 20\%$ level



$\to$ now under study by ATLAS (Freiburg)

$\to$ VLHC: precision measurement!

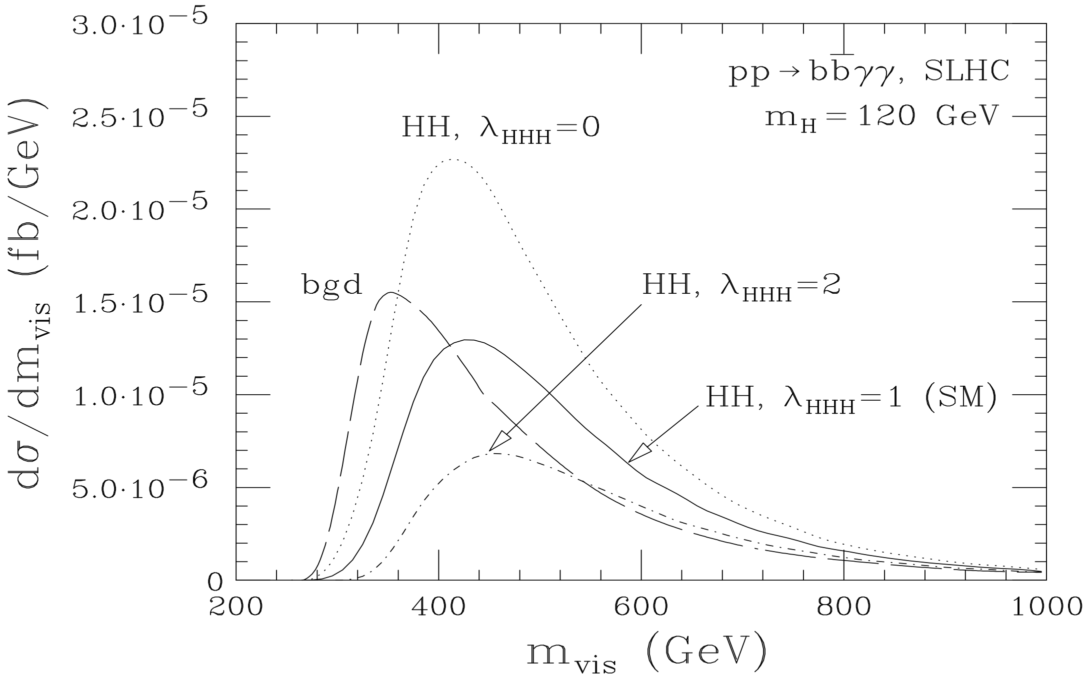


$M_H < 150$ GeV

$\longrightarrow HH \rightarrow 4b, bb\tau\tau$: no meaningful limits
(backgrounds simply enormous)

$\longrightarrow HH \rightarrow bb\gamma\gamma$ (1 rare decay) manageable!

[Baur,Plehn,DR,hep-ph/0310056]



machine	m_H = 120 GeV		m_H = 140 GeV	
lumi	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
VLHC	+0.30	+0.26	+0.62	+0.36
1200 fb^{-1}	-0.28	-0.22	-0.50	-0.32

$\longrightarrow$ VLHC competitive with LC

HHH *at the LHC/SLHC/VLHC*

Only way to measure λ_{4H} directly is by HHH production!

$\sigma_{HHH} \sim 100$ fb $\sim \sigma_{HH}/2$ @ $\sqrt{s} = 40$ TeV (effective theory) [Glover& v.d.Bij,NPB(309)282]

$\times$ BRs is very tiny - certainly hopeless @ (SLHC)

Should be examined for VLHC! ($\sqrt{s} = 100, 200$ TeV)

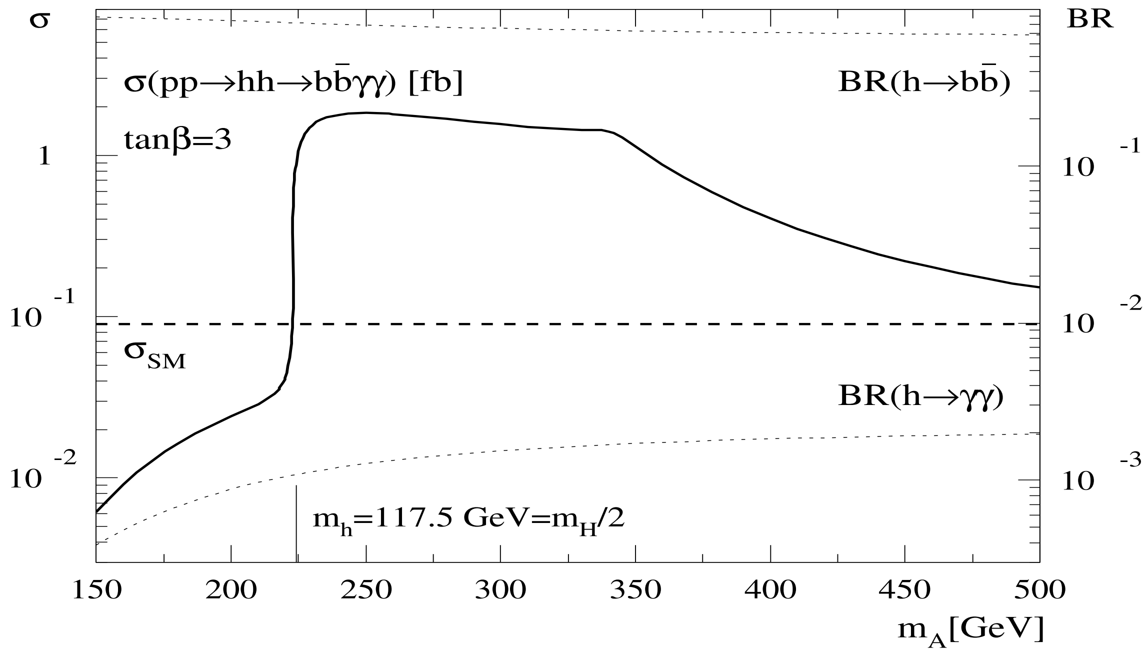
Note - full loop calculation under study:

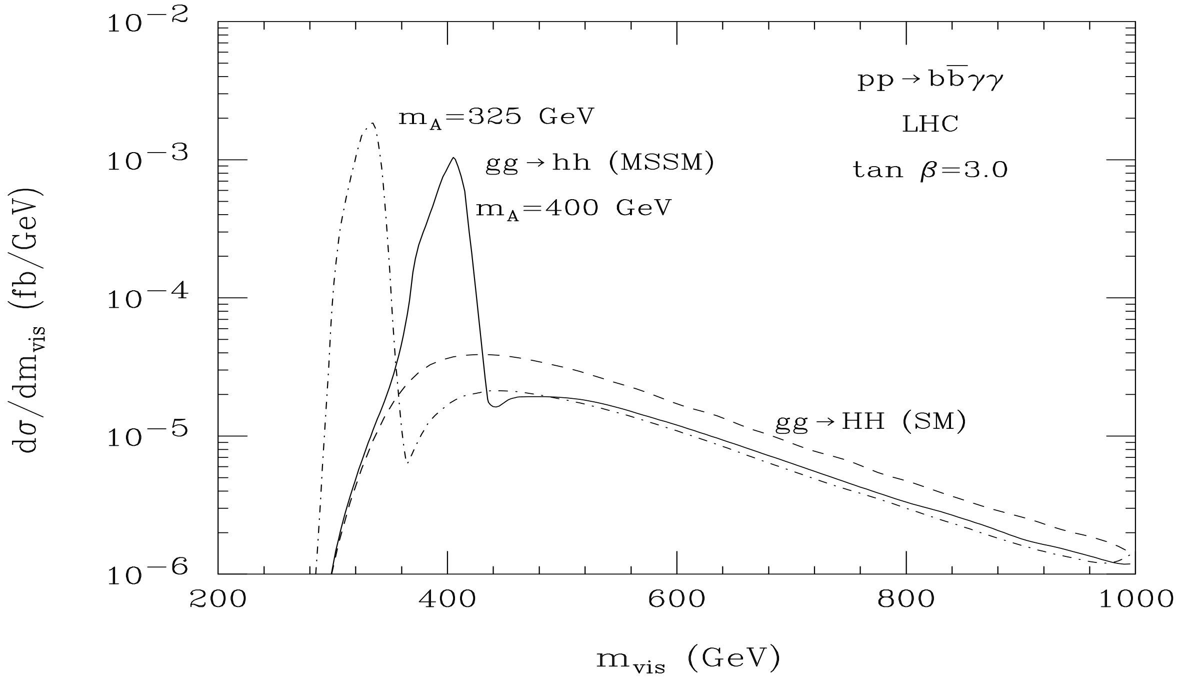
Thomas,Plehn,Zeppenfeld

What about MSSM $\phi_i\phi_j$ production?

In general, not possible (σ or BRs too small)

BUT! interesting @ small $\tan\beta$ [Baur,Plehn,DR]:





May be only non-SM Higgs evidence @ (S)LHC

Measuring λ_i's may not be directly possible!

(rely on M_{h_i}'s, $\tan\beta$, etc.)

What you can take home

- LHC has complete M_H coverage
  - $\longrightarrow$ can measure all properties somewhat
  - $\longrightarrow$ No-Lose Theorems for MSSM and NMSSM
  - $\longrightarrow$ but pot. problem observing all MSSM states
- May need VLHC to see full EWSB sector
- Most precise Higgs coups come from LC, but LC has some shortcomings:
  - $\longrightarrow$ top Yukawa (espec. for $M_H > 135$ GeV)
  - $\longrightarrow$ muon Yukawa (2^{nd}-gen. lepton coup)
  - $\longrightarrow$ very precise invisible Higgs BRs
- Hadron colliders superior for Higgs potential measurements in most cases
- Things out of (S)LHC reach - but VLHC?
  - $\longrightarrow$ extended Higgs sector total coverage
  - $\longrightarrow$ λ_{4H} (rest of potential)
- Need more study of non-(MS)SM EWSB!