The LHC and the Higgs*

*not just a fairy tale

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OUTLINE

1. Introduction
   What do we need to think about?
   What kind of machine is the LHC?

2. SM Higgs production and decay

3. Learn to ignore $t\bar{t}H$ and VH production

4. Searches in gluon fusion
   $H \to \gamma\gamma$
   $H \to ZZ$ and large M_H
   $H \to W^+W^-$
   the MSSM nightmare

5. Searches in weak boson fusion
   $H \to \gamma\gamma$
   $H \to W^+W^-$
   $H \to \tau^+\tau^-$
   the MSSM No-Lose Theorem

6. "Precision" measurements of Higgs properties

7. Concluding Remarks

Goal:

Understand the Higgs sector physics capabilities of the LHC, to turn on around 2005 (2007?)

With the question in mind,

"What could an NLC determine about a Higgs sector that the LHC can't?"

Some facts about hadron machines:

- CAN reconstruct heavy particle masses (to what resolution?)
- CAN NOT reconstruct a missing mass
- can sometimes reconstruct $\sqrt{\hat{s}}$ of a whole event

2 aspects of Higgs hunting to consider

1. production
2. decay

this is obvious BUT

the LHC is really a gluon machine

so Higgs physics will proceed very differently from that at LEP or the Tevatron!

→ production dominated by gluon fusion

→ desired decay modes ∴ much more limited (nasty QCD backgrounds)

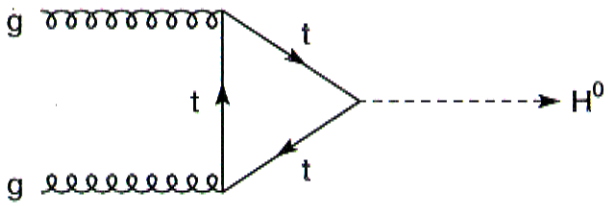
<u>Old lore</u>

- LHC has trouble w/ an MSSM Higgs sector
- forget about decent measurements of couplings (gauge), BR's, Γ^H_{tot}, etc.
- forget about $b\bar{b}$

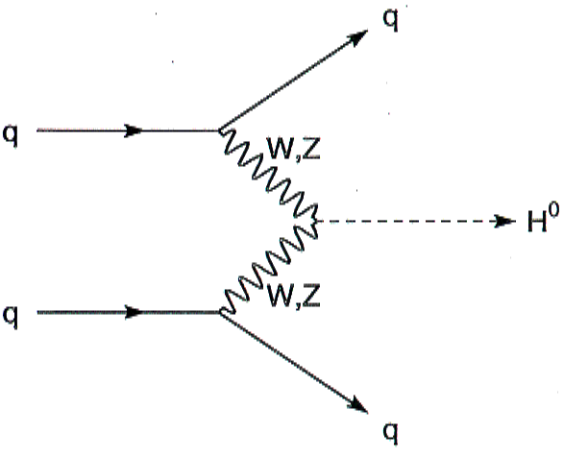
<u>Big Surprises</u>

- No-Lose Theorem for the MSSM
- 10% or better measurements <u>easy</u>
- forget about $b\bar{b}$ (alas...)

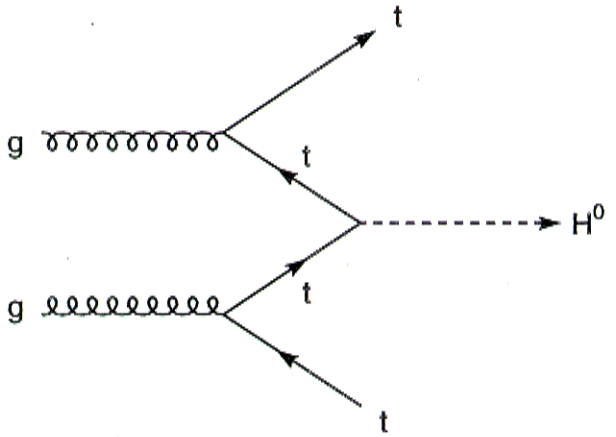
Production modes



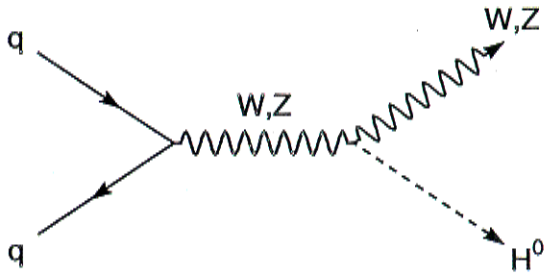
a) gg fusion



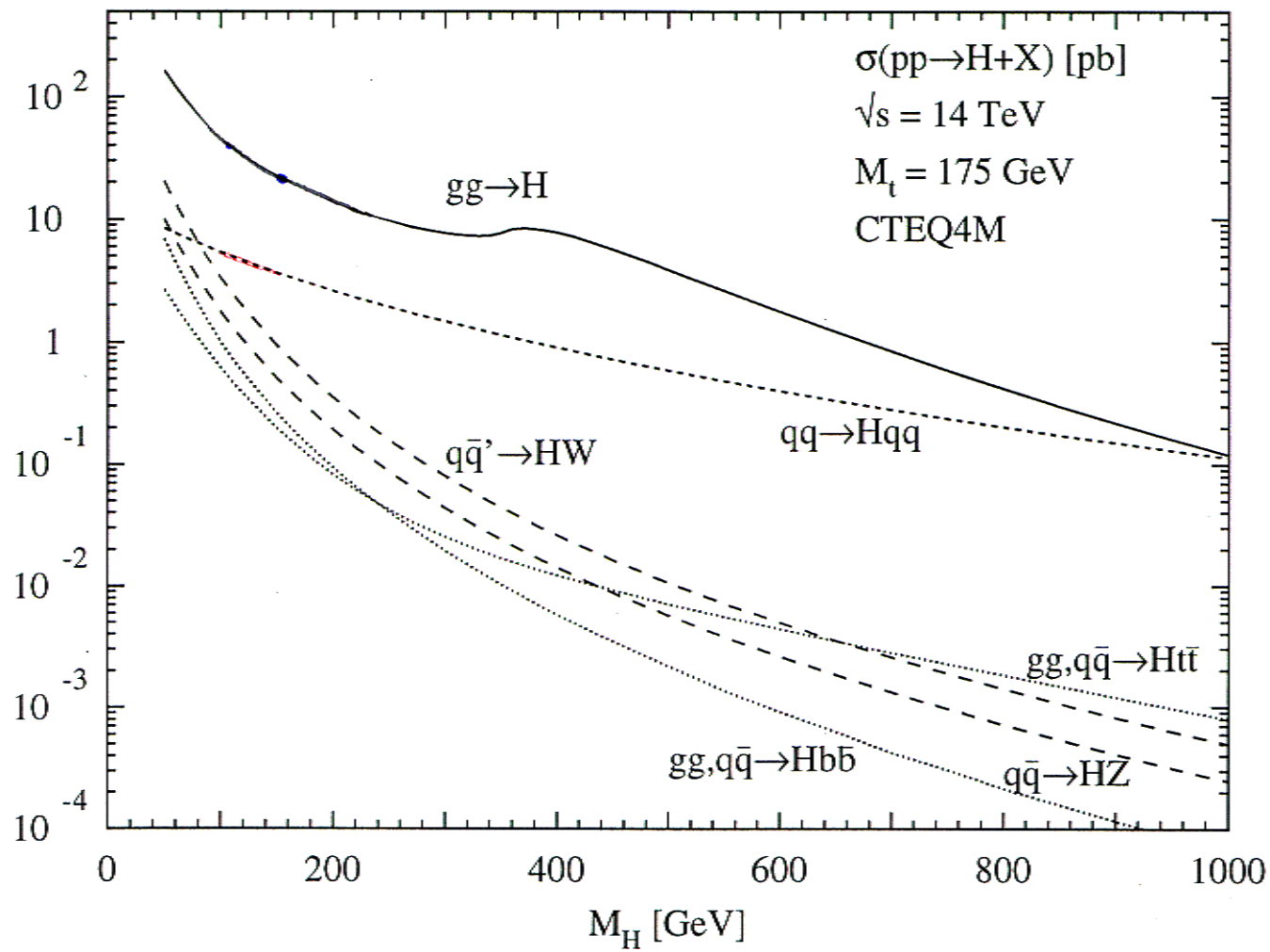
b) WW,ZZ fusion



c) tt fusion



d) W,Z bremsstrahlung



(Spira & Zerwas)

Why WH production won't work

low rate, large backgrounds, BR's

$\Rightarrow H \to b\bar{b}$ impossible, so use $H \to ZZ^* \to 4\ell$

CMS study ('99): assumes $10\ fb^{-1}/y$

M_H (GeV)	S/B	N_s (y^{-1})
150	0.78	2.7
200	38	3.8
300	8.8	0.9

<u>note!</u> can try $H \to \gamma\gamma$, but requires $\sim 300\ fb^{-1}$ to reach 5σ level

$t\bar{t}H$ production is "iffy"

CMS analysis for $M_H = 100$ GeV: $b\bar{b}b\bar{b}\,\ell\nu jj$ channel

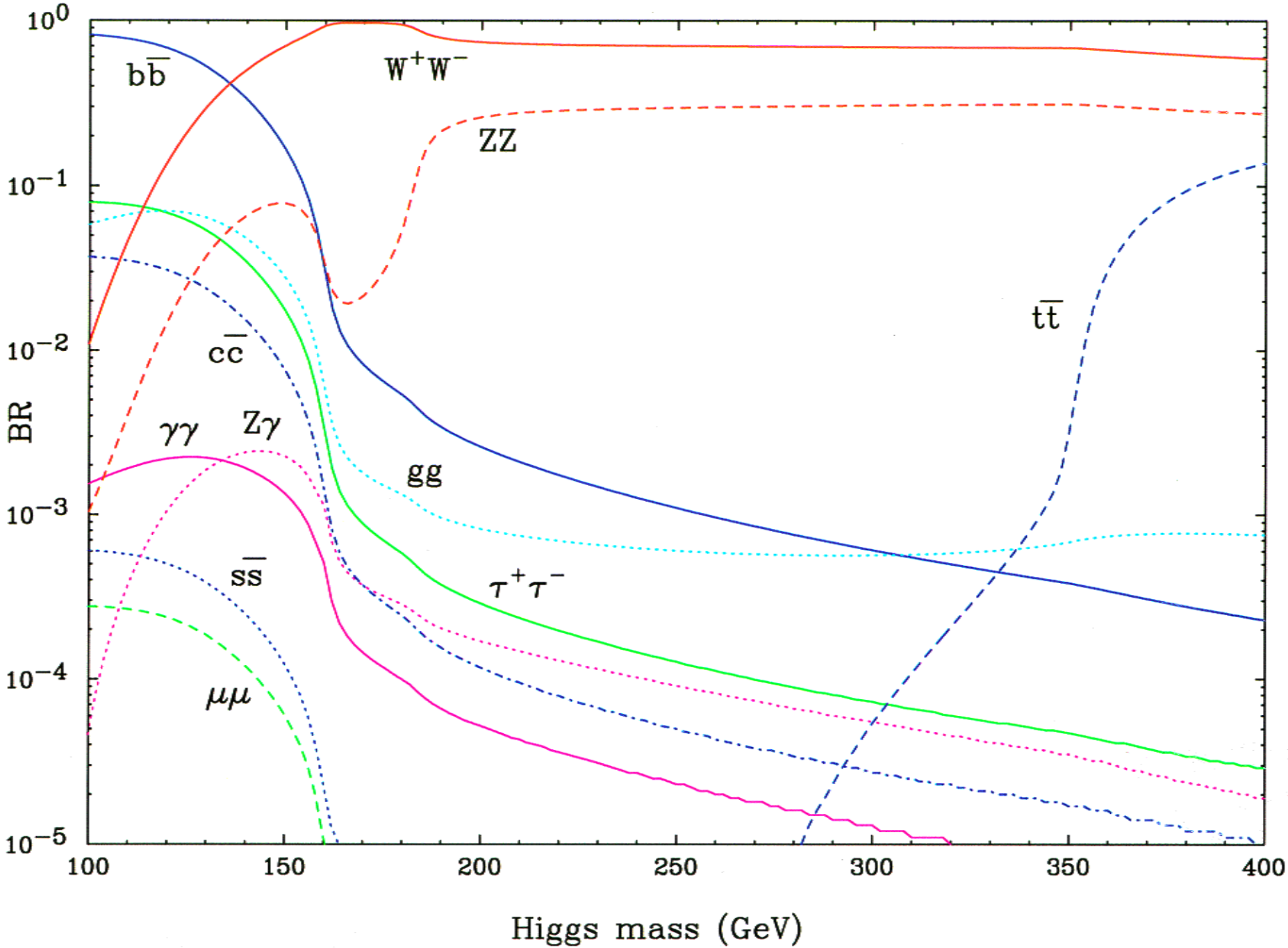
- hopeless if one tries to reconstruct W's, tops
- can never reconstruct a mass peak

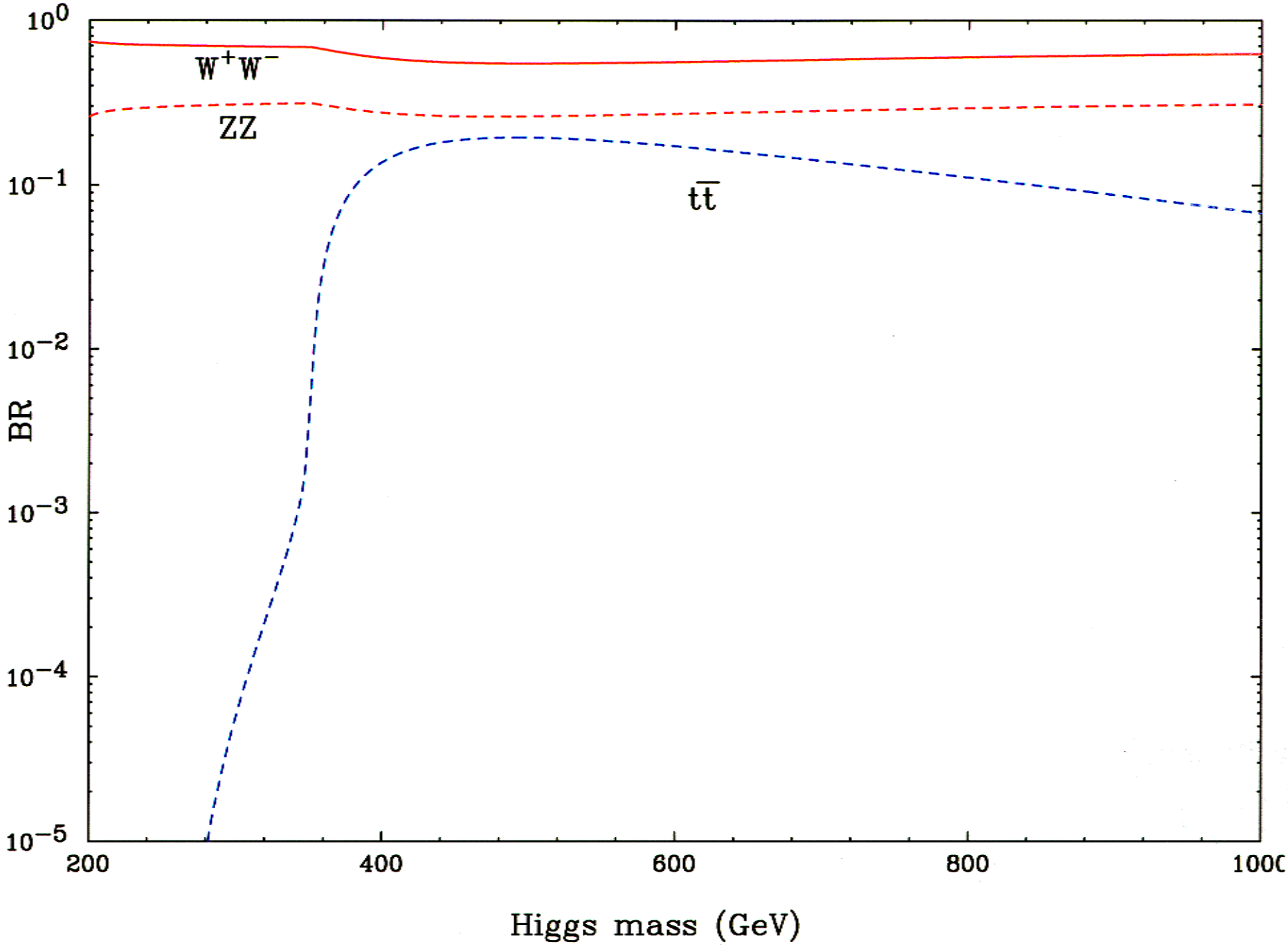
with $30\ fb^{-1}$ (~3 years) can get 4.0σ

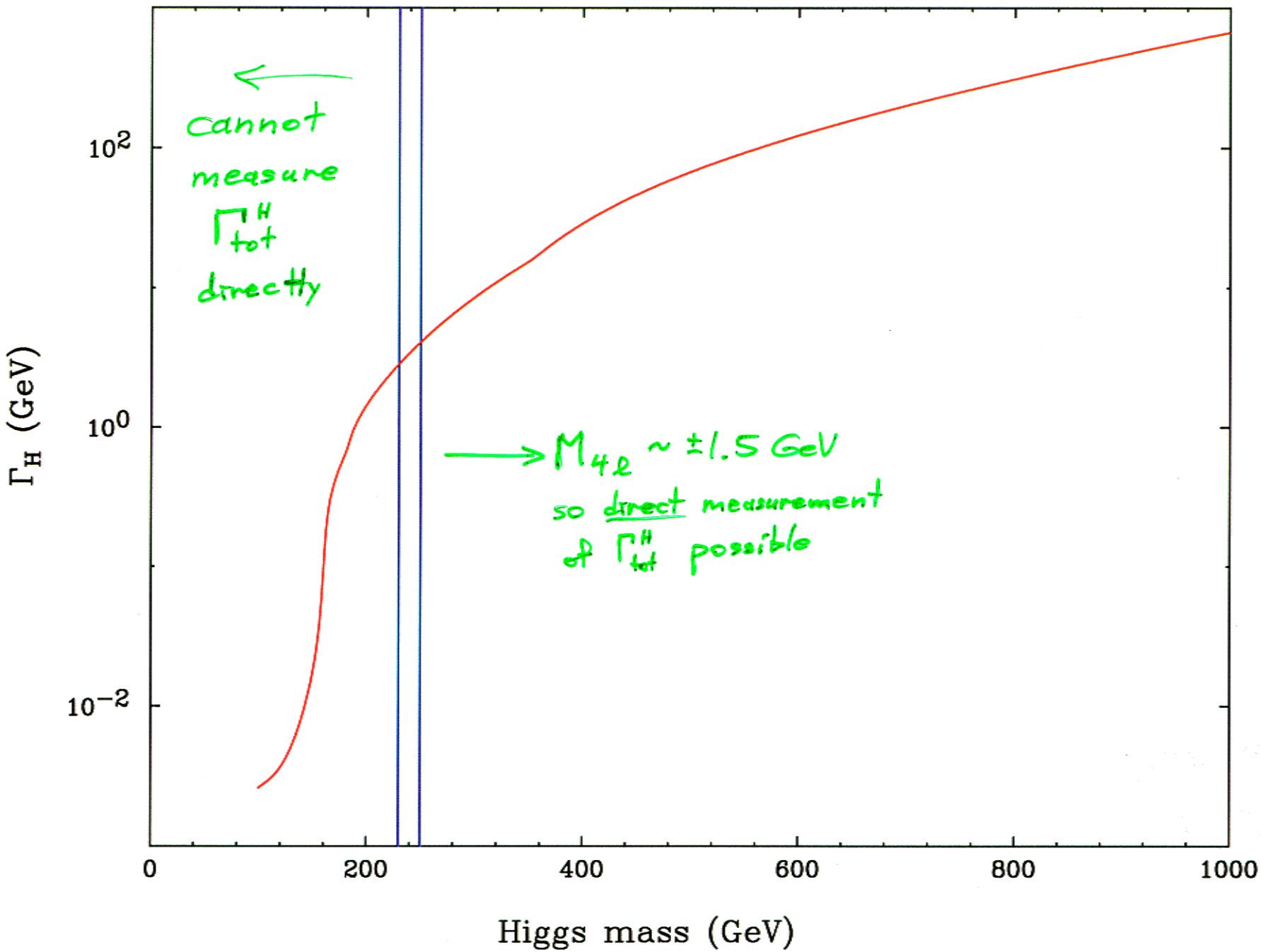
@ $M_H = 125$ GeV, cross section down by ~ factor 2!!

∴ will take several hundred fb^{-1} to get a handle on $t\bar{t}H$ coupling, IF Higgs is very light

<u>note:</u> CMS pursuing $b\bar{b}jjjjjjjj$ channel for M_H larger, but we are skeptical <u>so far</u>


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BR
100
150
200
250
300
350
400
Higgs mass (GeV)
$b\bar{b}$
W^+W^-
ZZ
$t\bar{t}$
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
gg
$s\bar{s}$
$\tau^+\tau^-$
$\mu\mu$


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BR
W^+W^-
ZZ
$t\bar{t}$
200
400
600
800
1000
Higgs mass (GeV)


cannot measure Γ^H_{tot} directly
$M_{4\ell} \sim \pm 1.5$ GeV
so direct measurement of Γ^H_{tot} possible
10^2
10^0
10^{-2}
Γ_H (GeV)
0
200
400
600
800
1000
Higgs mass (GeV)

$gg \to H$ is "obviously" the way to go

obviously, $b\bar{b}$ or $\tau^+\tau^-$ decays completely hopeless
(especially since $\sigma_M \sim \pm 20$ GeV)

$\therefore$ must rely on decays to EW gauge bosons

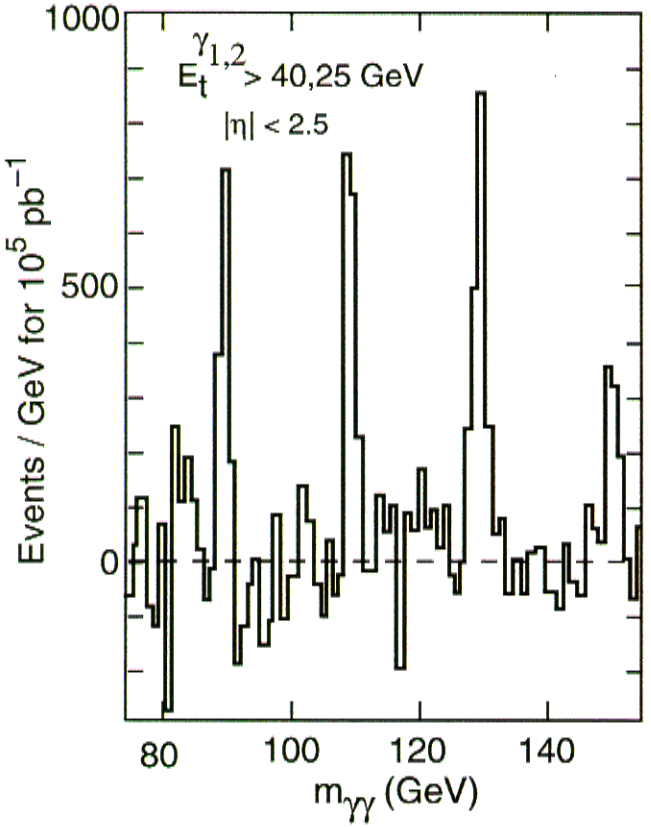
1. $H \to \gamma\gamma$ excellent mass resolution for 1–2 GeV
   narrow mass range $100 < M_H < 150$ GeV
   → CMS far superior to ATLAS for $\gamma\gamma$ mode

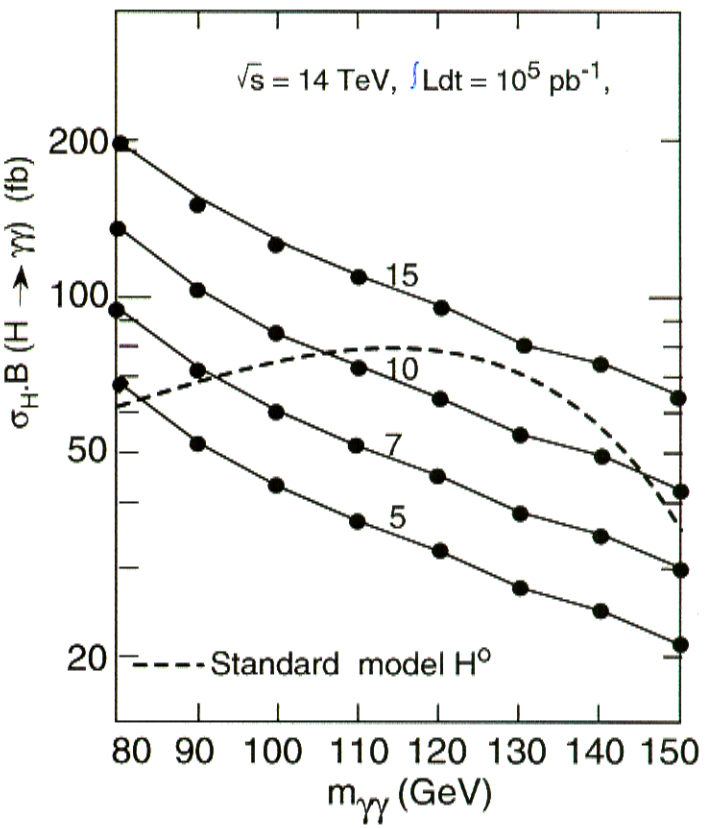
2. $H \to ZZ \to 4\ell$ "Golden mode"
   - direct measurement of Γ_H for $M_H \gtrsim 250$ GeV
   - preferred discovery mode for $M_H > 200$ GeV (clean; mass peak) $\sim 10\,fb^{-1}$ for 5σ
   - can add other Z decay modes for large M_H

3. $H \to WW$
   - previously thought useful only for large M_H (>300 GeV)
   - Dittmar + Dreiner pointed out lepton correlations in '96
     → now good for IM range (130--180)
   - covers "hole" at 155–180 GeV + overlaps other observable modes

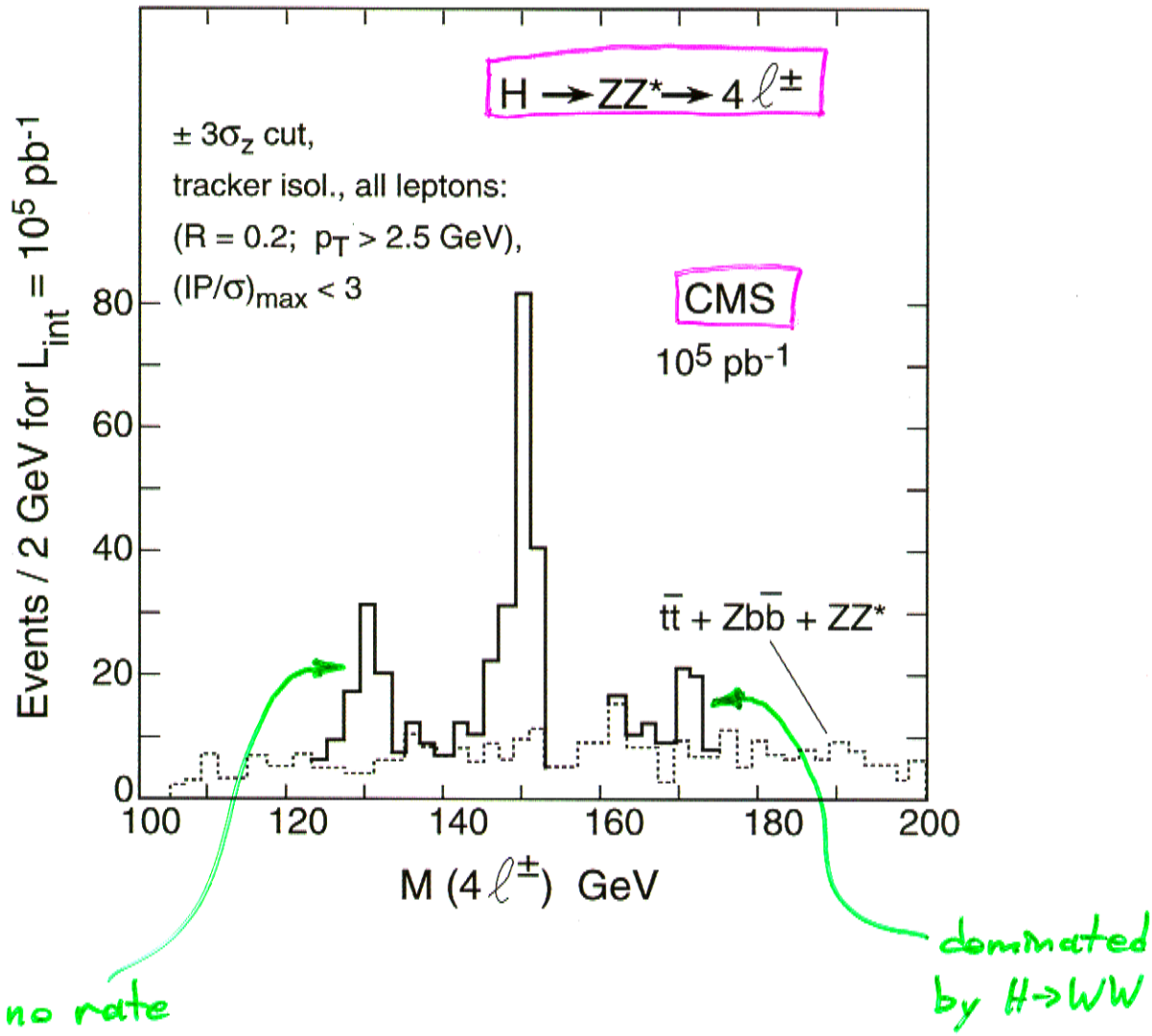
$H \to \gamma\gamma$ at CMS for $100 < M_H < 150$ GeV

$\Delta M_H \sim \pm 1$ GeV

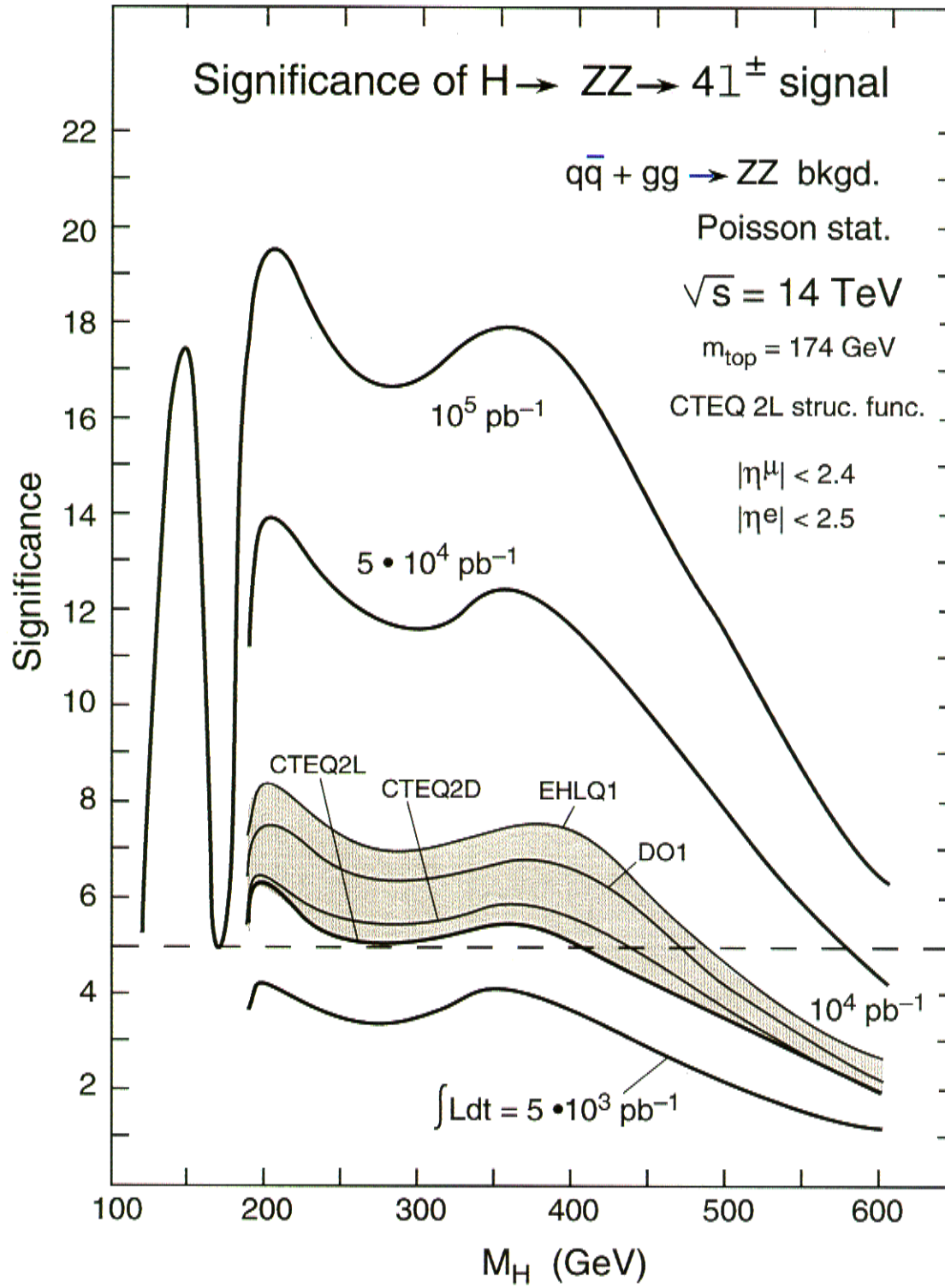




<u>note:</u> for $110 < M_H < 130$ GeV, required luminosity is ~ 20 fb^{-1} (2y) for 5σ


H → ZZ* → 4 ℓ±
± 3σz cut,
tracker isol., all leptons:
(R = 0.2; pT > 2.5 GeV),
(IP/σ)max < 3
CMS
10^5 pb^-1
tt̄ + Zbb̄ + ZZ*
Events / 2 GeV for Lint = 10^5 pb^-1
M (4 ℓ±) GeV
no rate
dominated by H→WW

CMS


Significance of H → ZZ → 4l± signal
qq̄ + gg → ZZ bkgd.
Poisson stat.
√s = 14 TeV
m_top = 174 GeV
CTEQ 2L struc. func.
|η^μ| < 2.4
|η^e| < 2.5
10^5 pb^-1
5 • 10^4 pb^-1
10^4 pb^-1
∫Ldt = 5 •10^3 pb^-1
CTEQ2L
CTEQ2D
EHLQ1
DO1
Significance
M_H (GeV)
22
20
18
16
14
12
10
8
6
4
2
100
200
300
400
500
600

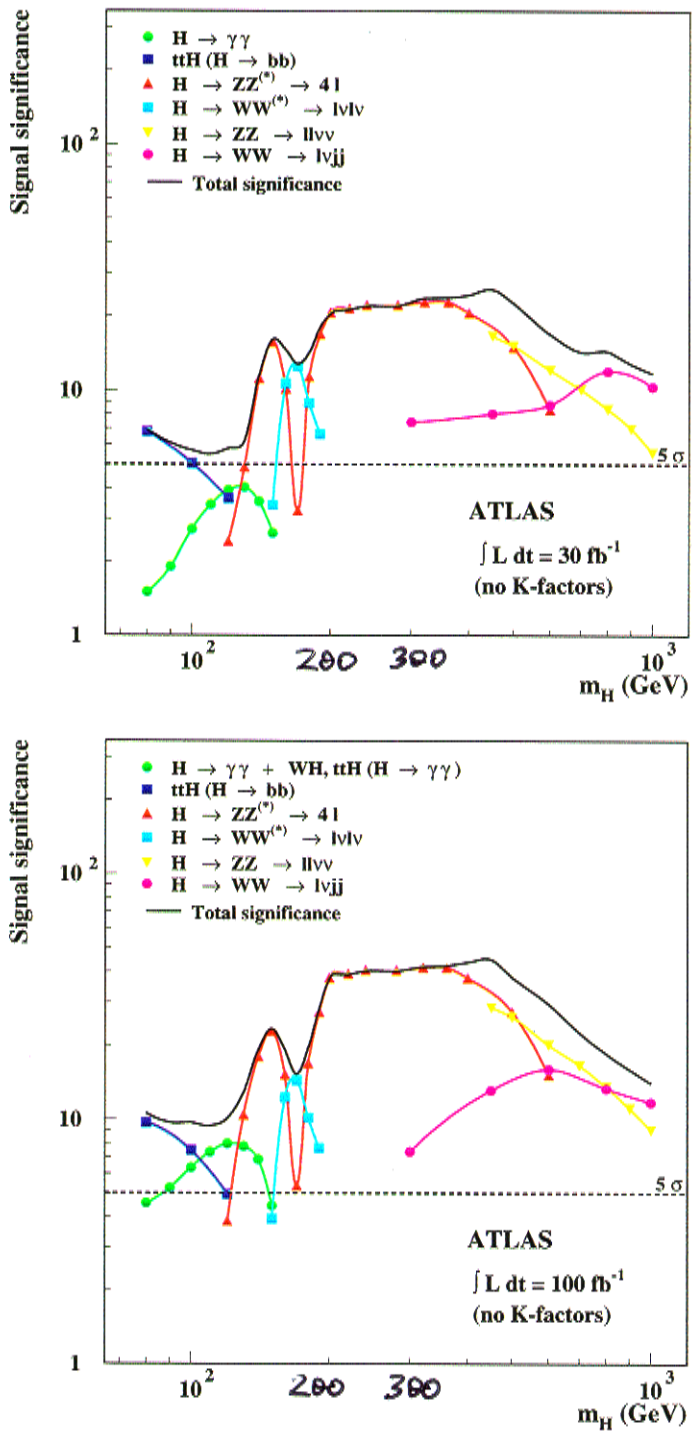


Figure 19-i ATLAS sensitivity for the discovery of a Standard Model Higgs boson. The statistical significances are plotted for individual channels, as well as for the combination of all channels, assuming integrated luminosities of 30 fb^{-1} (top) and 100 fb^{-1} (bottom). Depending on the numbers of signal and background events, the statistical significance has been computed as $S/\sqrt{B}$ or using Poisson statistics. In the case of the $H \rightarrow WW^*$ channel, a systematic uncertainty of ±5% on the total number of background events has been assumed (this uncertainty has been included in this case, since no mass peak can be reconstructed and the Higgs boson signal has therefore to be extracted from an excess of events).

$gg \to H \to \gamma\gamma, WW, ZZ$ isn't so bad...

- can discover + measure mass just about everywhere (well, some trouble for large M_H)

BUT

probably no $Hf\bar{f}$ coupling measurement

no Γ_H measurement for $M_H <\sim 250$ GeV

$t\bar{t}H$ and WH, ZH fairly useless to confirm or provide rigorous model test

and what about the MSSM ???

(may need an Advil for this...)

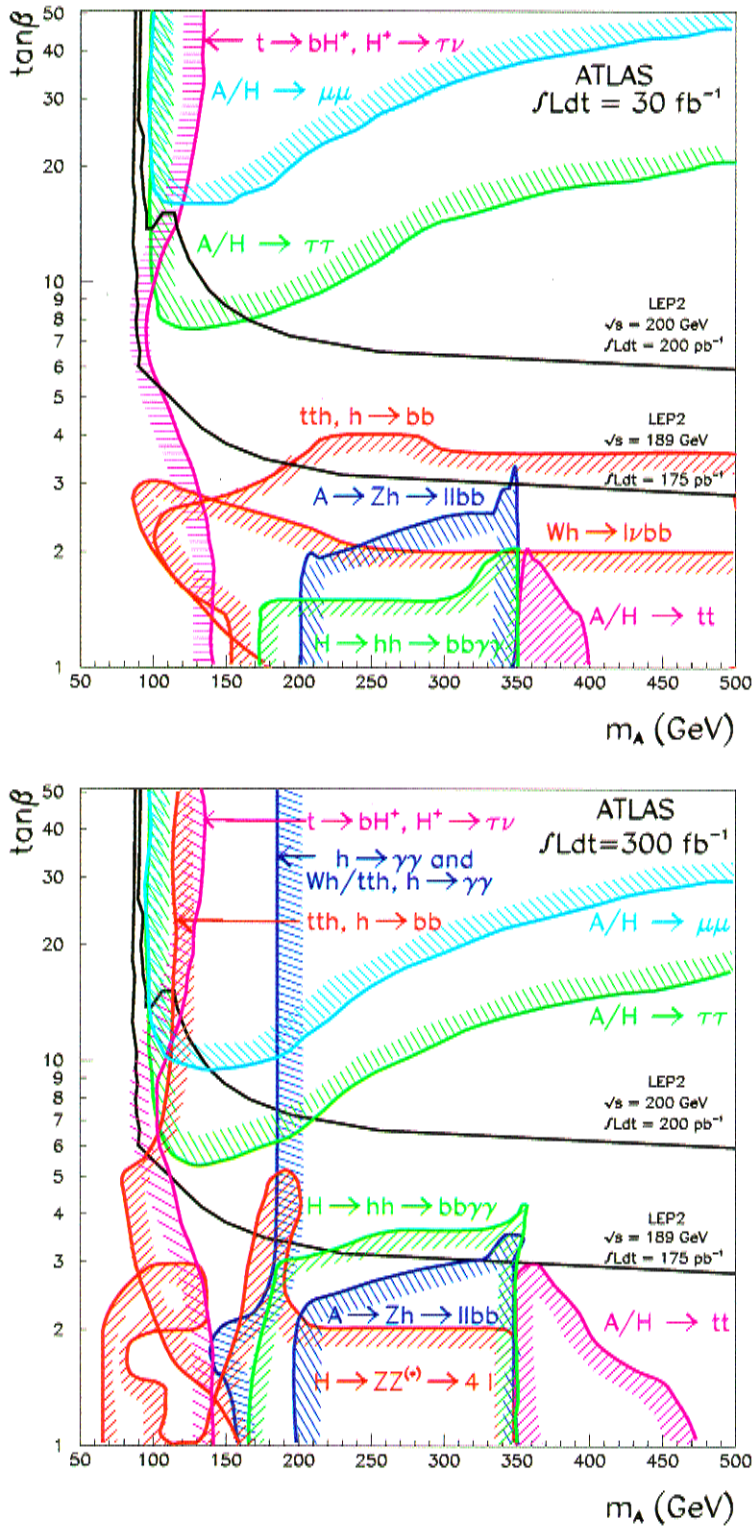


Figure 19-ii ATLAS sensitivity for the discovery of MSSM Higgs bosons (in the case of minimal mixing). The 5σ discovery contour curves are shown in the (m_A, tanβ) plane for individual channels and for integrated luminosities of 30 fb^{-1} (top) and 300 fb^{-1} (bottom). Also included are the present LEP2 limit (for an integrated luminosity of 175 pb^{-1} per experiment) and the expected ultimate LEP2 limit (for an integrated luminosity of 200 pb^{-1} per experiment at a centre-of-mass energy of 200 GeV).

$H \to \gamma\gamma$

Table 3: Signal $m_H = 120$ GeV and background $\gamma\gamma jj$ cross sections (fb) for successive levels of cuts.

cuts	σ_{Hjj}	QCD $jj\gamma\gamma$	EW $jj\gamma\gamma$	DPS
forward tagging + ID	2.2	215	62	83
+ staggered $p_{T(j,\gamma)}$	1.9	66	29	17
+ 2 GeV mass bin	1.3	0.87	0.34	0.24
+ efficiencies ($\epsilon = 0.473$)	0.63	0.41	0.16	0.12
$P_{surv,20}$	$\times 0.89$	$\times 0.30$	$\times 0.80$	$\times 0.30$
+ minijet veto	0.56	0.12	0.12	0.04

Table 4: Signal and total background $\gamma\gamma jj$ cross sections (fb) for various Higgs masses, after application of all cuts, ID efficiencies ($\epsilon = 0.473$) and a minijet veto with $p_T^{veto} = 20$ GeV.

Higgs mass (GeV)	100	110	120	130	140	150
$\epsilon \cdot \sigma_{Hjj} \cdot B(H \to \gamma\gamma)$ (fb)	0.37	0.48	0.56	0.56	0.48	0.33
$\epsilon \cdot \sigma_{QCD}$ (fb)	0.14	0.13	0.12	0.11	0.10	0.08
$\epsilon \cdot \sigma_{EW}$ (fb)	0.14	0.13	0.12	0.11	0.10	0.09
$\epsilon \cdot \sigma_{DPS}$ (fb)	0.05	0.04	0.04	0.03	0.03	0.02
$\epsilon \cdot \sigma_{bkg,tot}$ (fb)	0.33	0.31	0.28	0.25	0.22	0.19
S/B	1.1	1.6	2.0	2.3	2.2	1.8
$\sigma_{\rm Gaus}$ (50 fb $^{-1}$ low lum.)	3.8	5.0	6.0	6.2	5.7	4.3

$H \to W^{(*)}W^{(*)}$

Table 1: Signal rates $\sigma \cdot B(H \to e^{\pm}\mu^{\mp}\not{p}_T)$ for $m_H = 160$ GeV and corresponding background cross sections (fb) for successive levels of cuts.

cuts	Hjj	$t\bar{t}+jets$	QCD $WWjj$	EW $WWjj$	QCD $\tau\tau jj$	EW $\tau\tau jj$	S/B
forward tagging	17.1	1080	4.4	3.0	15.8	0.8	≈1/65
+ b veto		64					1/5.1
+ M_{jj}, ang. cuts	11.8	5.5	0.54	0.50	3.6	0.4	1.1/1
+ real τ rejection	11.4	5.1	0.50	0.45	0.6	0.08	1.7/1
$P_{surv,20}$	$\times\, 0.89$	$\times 0.29$	$\times 0.29$	$\times 0.75$	$\times 0.29$	$\times 0.75$	-
+ minijet veto	10.1	1.48	0.15	0.34	0.18	0.07	4.6/1
+ tag ID effic. ($\times 0.74$)	7.5	1.09	0.11	0.25	0.13	0.05	4.6/1

Table 2: Number of expected events for the Hjj signal after all cuts, ID efficiencies and a minijet veto with $p_T^{veto} = 20$ GeV, for 5 fb^{-1} at low luminosity; and Gaussian equivalent Poisson statistical significances. Total background is 5.5 events.

m_H	115	120	130	140	150	160	170	180	190	200
no. events	1.6	3.6	8.8	15.8	24.0	37.5	36.2	29.9	20.8	16.3
S/B	0.4	0.7	1.6	3.2	4.8	7.5	7.3	6.0	4.2	3.3
σ_{Gauss}	0.6	1.2	3.0	5.0	7.1	10.0	9.8	8.4	6.3	5.1

Higgs mass reconstruction in WW mode

Key: each W at rest at threshold ($M_H = 160$),

so $m_{e\mu} = m_{\nu\bar{\nu}}$

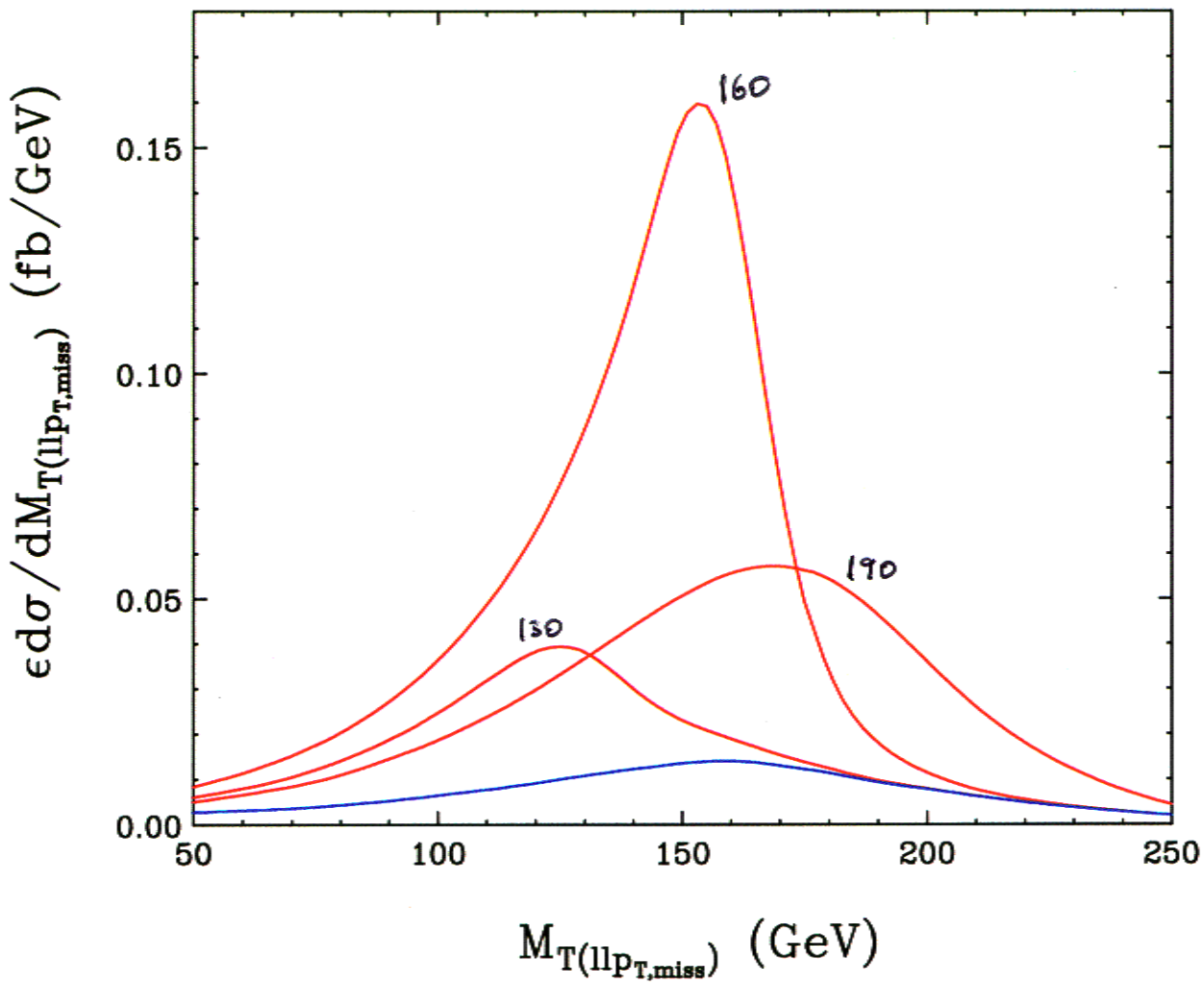
$$\therefore \quad E_{T_{e\mu}} = \sqrt{\vec{p}_{T_{e\mu}}^{\,2} + m_{e\mu}^2} \quad \& \quad \not{E}_T = \sqrt{\vec{\not{p}}_T^{\,2} + m_{e\mu}^2}$$

now calculate M_T (dilepton $-\not{p}_T$ system):

$$M_{T_{WW}} = \sqrt{\left(\not{E}_T + E_{T_{e\mu}}\right)^2 - \left(\vec{p}_{T_{e\mu}} + \vec{\not{p}}_T\right)^2}$$

... the approximation works reasonably well away from $M_H = 160$, but not quite as Jacobian

LHC: $VV \to H \to W^{(*)}W^{(*)} \to e, \mu, \not{p}_T$



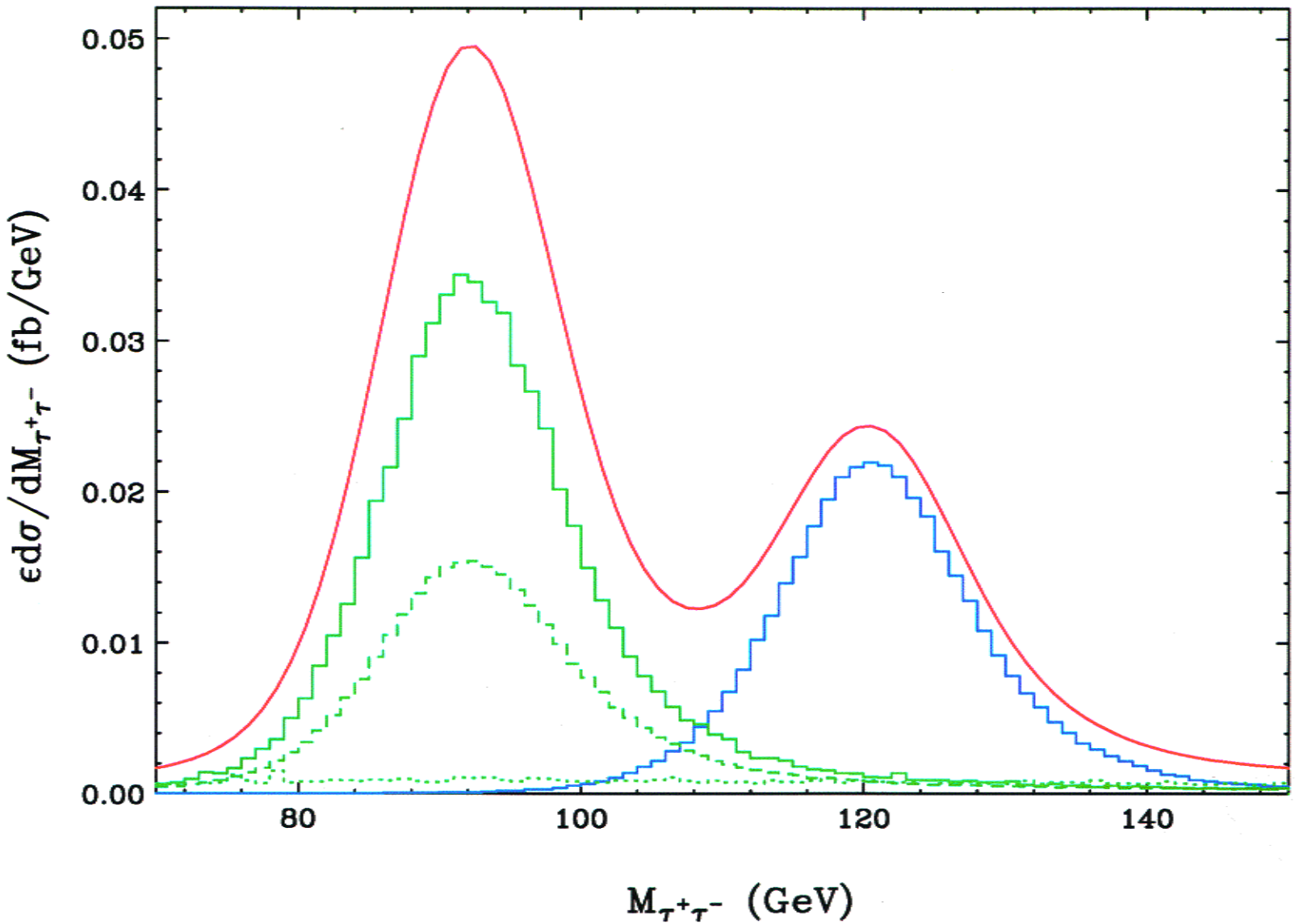
$\boxed{H \to \tau^+ \tau^-}$

Results after additional jet veto

Number of expected events for the signal and backgrounds:

- 60 fb^{-1} integrated luminosity
- all cuts
- veto on additional jets in central region
- efficiency factor for tagging jet ID $\epsilon_{tag} = 0.74$

m_H(GeV)	Hjj	QCD Zjj	EW Zjj	$Wj + jj$	$b\bar{b}jj$	σ_{Gauss}
110	24.2	6.3	3.4	0.3	0.8	5.7
120	20.6	1.8	1.2	0.3	0.7	7.4
130	16.0	0.9	0.7	0.3	0.6	6.3
140	10.0	0.6	0.5	0.4	0.5	4.7
150	4.8	0.4	0.4	0.3	0.4	2.6


0.05
0.04
0.03
0.02
0.01
0.00
80
100
120
140
$\epsilon d\sigma/dM_{\tau^+\tau^-}$ (fb/GeV)
$M_{\tau^+\tau^-}$ (GeV)

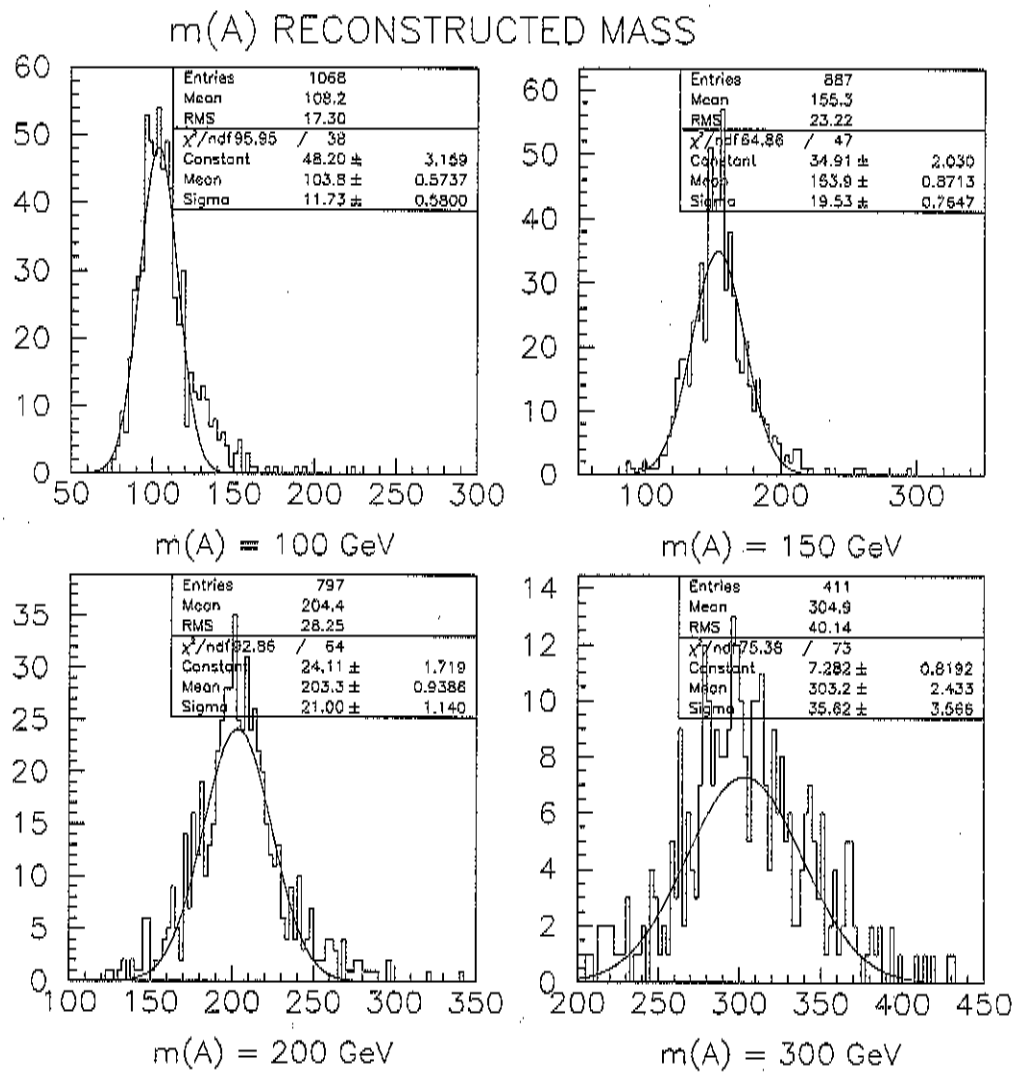
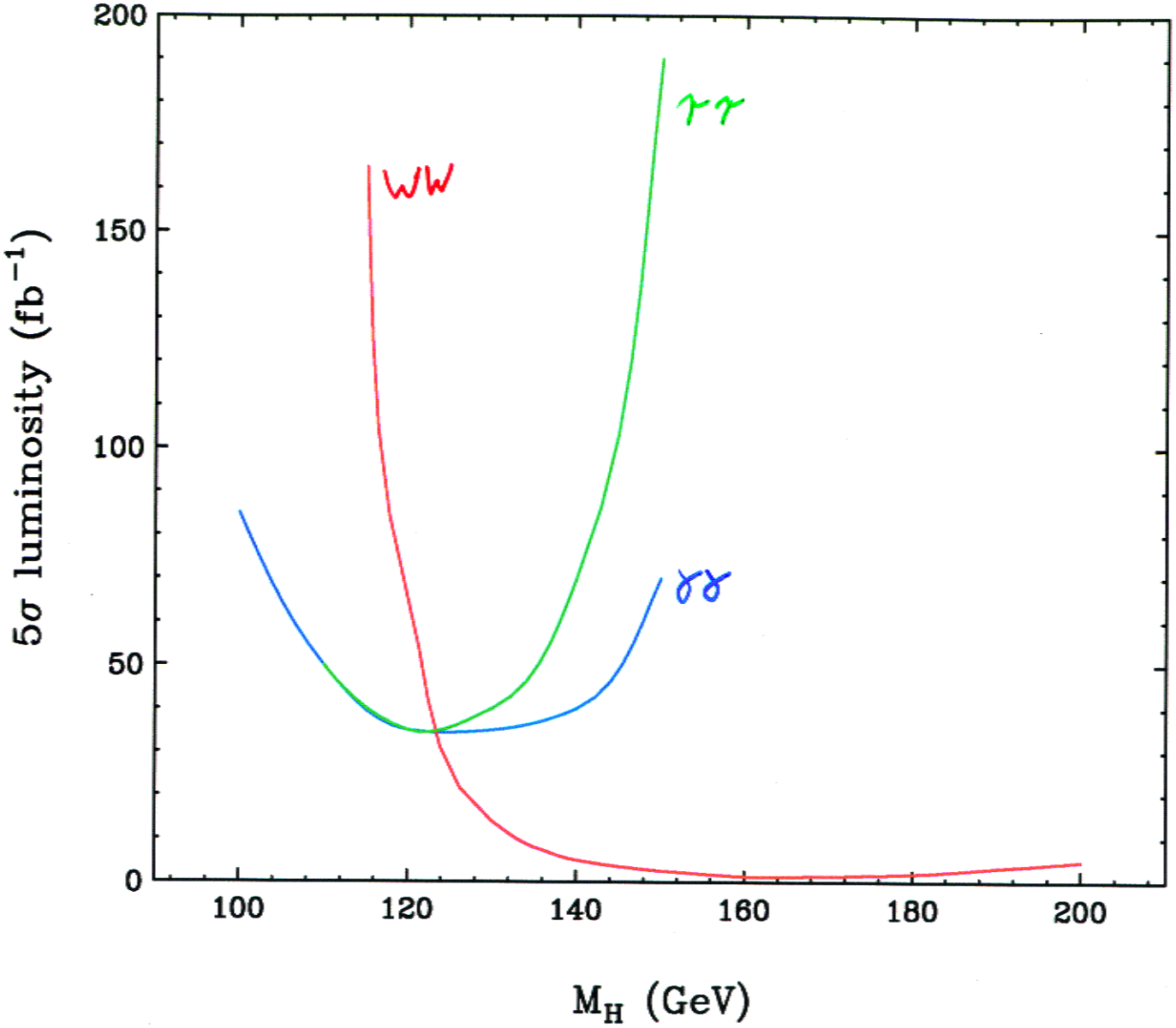


Figure 7: *Reconstructed $m_{\tau\tau}$ for m_A=100, 150, 200 and 300 GeV.*

(ATLAS)

WBF Higgs production at the LHC



5σ observational contours for 40 fb^{-}1 at the LHC
(analysis including tail contributions from other Higgs)

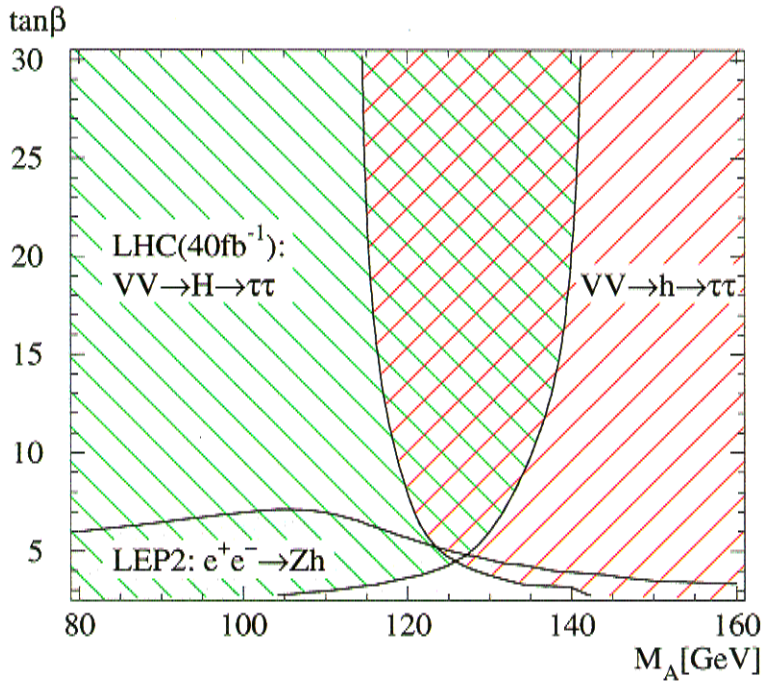


FIG. 1. maximal trilinear mixing, $A_t = \sqrt{6}M_{SUSY}$

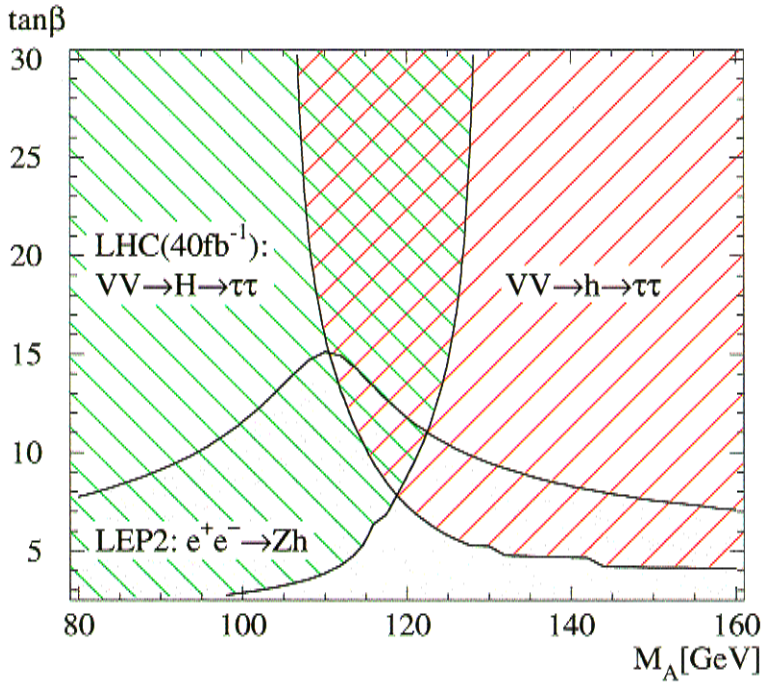


FIG. 2. no trilinear mixing, $A_t = 0$

- WBF $VV \to H$ at the LHC promises three new modes of Higgs observation

1. SM $H \to WW$ new likely discovery channel (130-200 GeV)
2. SM $H \to \gamma\gamma$ complements $gg \to H$ mode (110-150 GeV)
3. SM $H \to \tau\tau$ first measurement of $Hf\bar{f}$ coupling (110-150 GeV)
4. ability to measure ggH/VVH coupling ratios in all modes

- MSSM $VV \to (h, H) \to \tau\tau$ $(+\gamma\gamma)$ can observe <u>at least one</u> of h or H with only 40 fb $^{-1}$ over all MSSM $\tan(\beta)$-m_A space: the "No-Lose" Theorem

1. overlaps region covered by LEP
2. analysis/search technique identical for SM & MSSM

Determination of cross sections

(Zeppenfeld, Kinnunen, Nikitenko, Richter-Was)

Feb. 2000

examine $gg \to H \to \gamma\gamma, ZZ, WW$
$VV \to H \to \gamma\gamma, WW, \tau\tau$ for $100\ fb^{-1}$/exp. (3-4 years)

define $\sigma_H = \dfrac{N_{S+B} - \langle N_B \rangle}{\epsilon \int \mathcal{L} dt} = \dfrac{N_S}{\epsilon \int \mathcal{L} dt}$

statistical error $\dfrac{\Delta\sigma_H}{\sigma_H} \equiv \dfrac{\sqrt{N_S + N_B}}{N_S} = \dfrac{\sqrt{N_S + N_B}}{N_S}$

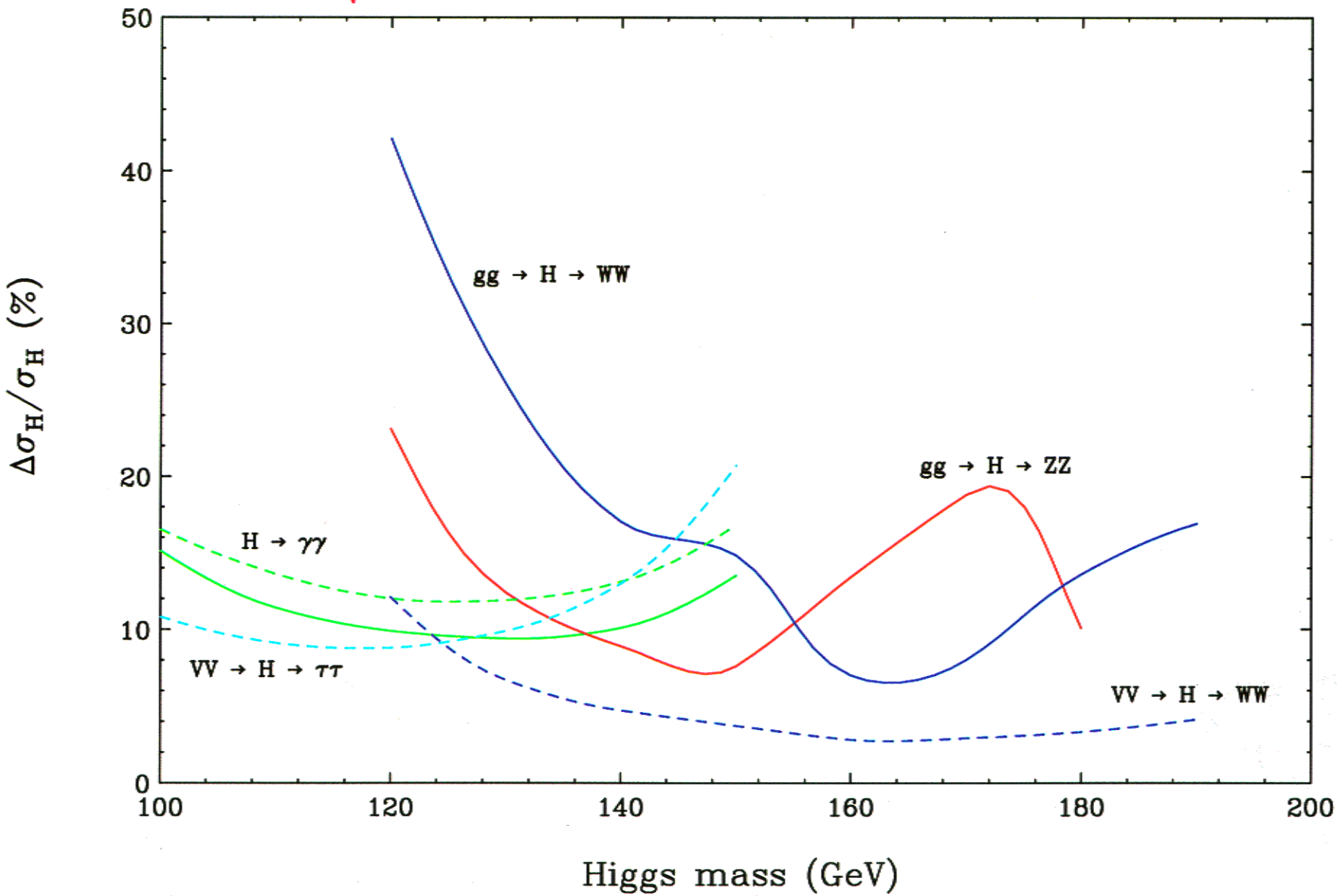
statistical errors dominate for $gg \to H \to \gamma\gamma, ZZ$
$VV \to H \to$ all

$gg \to H \to WW$ has no mass peak, so 5% syst. bkg. uncert. is included $\longrightarrow$ dominates for $\int \mathcal{L} dt \gtrsim 30\ fb^{-1}$

$VV \to H \to$ all have $S/B \gg 1$ $\therefore$ fairly independent of syst. uncertainties!

Relative errors in σ_H measurements at the LHC

Zeppenfeld, Kinnunen, Nikitenko, Richter-Was



Determination of couplings (ZKNR)

↳ replace by partial widths

$$\Gamma_f = \Gamma(H \to f\bar{f}) = c_s \frac{g_{Hff}^2}{8\pi} M_H \beta^3$$

$$\Gamma_V = \Gamma(H \to VV) = \frac{g^2}{64\pi} \frac{M_H^3}{M_W^2} \sqrt{1 - x_V} \left(1 - x_V + \frac{3}{4} x_V^2\right) \left[\times \tfrac{1}{2} \text{ for } V = Z\right]$$

$$\Gamma_\gamma = \Gamma(H \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024\pi^3} \frac{M_H^3}{M_W^2} \left[\text{complicated fn} \ldots\right]$$

→ rewrite σ's w/ Γ's using NWA
(valid for interm. mass H)

use 5% theor. unc. for $\sigma_{VV \to H}$

use 20% theor. unc. for $\sigma_{gg \to H}$

assume $\Gamma_Z = z\,\Gamma_W$ (SU(2))

↳ test @ 15% level for $M_H > 130$ GeV
via $\dfrac{B\sigma(gg \to H \to ZZ)}{B\sigma(gg \to H \to WW)}$

→ measure in WBF:

$$X_\gamma = \frac{\Gamma_W \Gamma_\gamma}{\Gamma}$$

$$X_\tau = \frac{\Gamma_W \Gamma_\tau}{\Gamma}$$

$$X_W = \frac{\Gamma_W^2}{\Gamma}$$

& gg fusion:

$$Y_\gamma = \frac{\Gamma_g \Gamma_\gamma}{\Gamma}$$

$$Y_Z = \frac{\Gamma_g \Gamma_Z}{\Gamma}$$

$$Y_W = \frac{\Gamma_g \Gamma_W}{\Gamma}$$

X, Y ratios test model to ~20% for $M_H > 130$ GeV (uncer^s drop out)

Determining Γ^H_{tot} at the LHC (ZKNR)

→ easy in the SM, usually easy in SM extensions

first, determine y for your model such that

$$\Gamma_b = y\,\Gamma_\tau$$

e.g., $y = 3 c_{QCD} \dfrac{m_b^2(M_H)}{m_\tau^2}$ for SM

→ Γ^H_{tot} dominated by decays to $b\bar{b}, \tau\tau, gg, \gamma\gamma, WW, ZZ$

$$\epsilon = 1 - \left(B(b\bar{b}) + B(\tau\tau) + B(gg) + B(\gamma\gamma) + B(WW) + B(ZZ) \right) \ll 1$$

1. most of MSSM parameter space satisfies this! (for h <u>and</u> H)
2. large $H f_{up} \bar{f}_{up}$ couplings would be observed in $\dfrac{\Gamma_g}{\Gamma_W}$

note that $\epsilon < \sim 0.1$ is sufficient to get Γ^H_{tot}

define an observable $\tilde{\Gamma}_W$:

$$\tilde{\Gamma}_W \equiv X_\tau (1+y) + X_W (1+z) + X_\gamma + \tilde{X}_g \quad = \frac{\Gamma_g \Gamma_W}{\Gamma} \text{ via best measurement}$$

$$= \left(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g\right) \frac{\Gamma_W}{\Gamma} = (1-\epsilon)\,\Gamma_W$$

now a lower bound on Γ_W

now get the Higgs total width :

$$\Gamma = \frac{\Gamma_W^2}{X_W} = \frac{1}{X_W}\left(X_\tau(1+y) + X_W(1+z) + X_\gamma + \tilde{X}_g\right)^2 \frac{1}{(1-\epsilon)^2}$$

error assumptions :

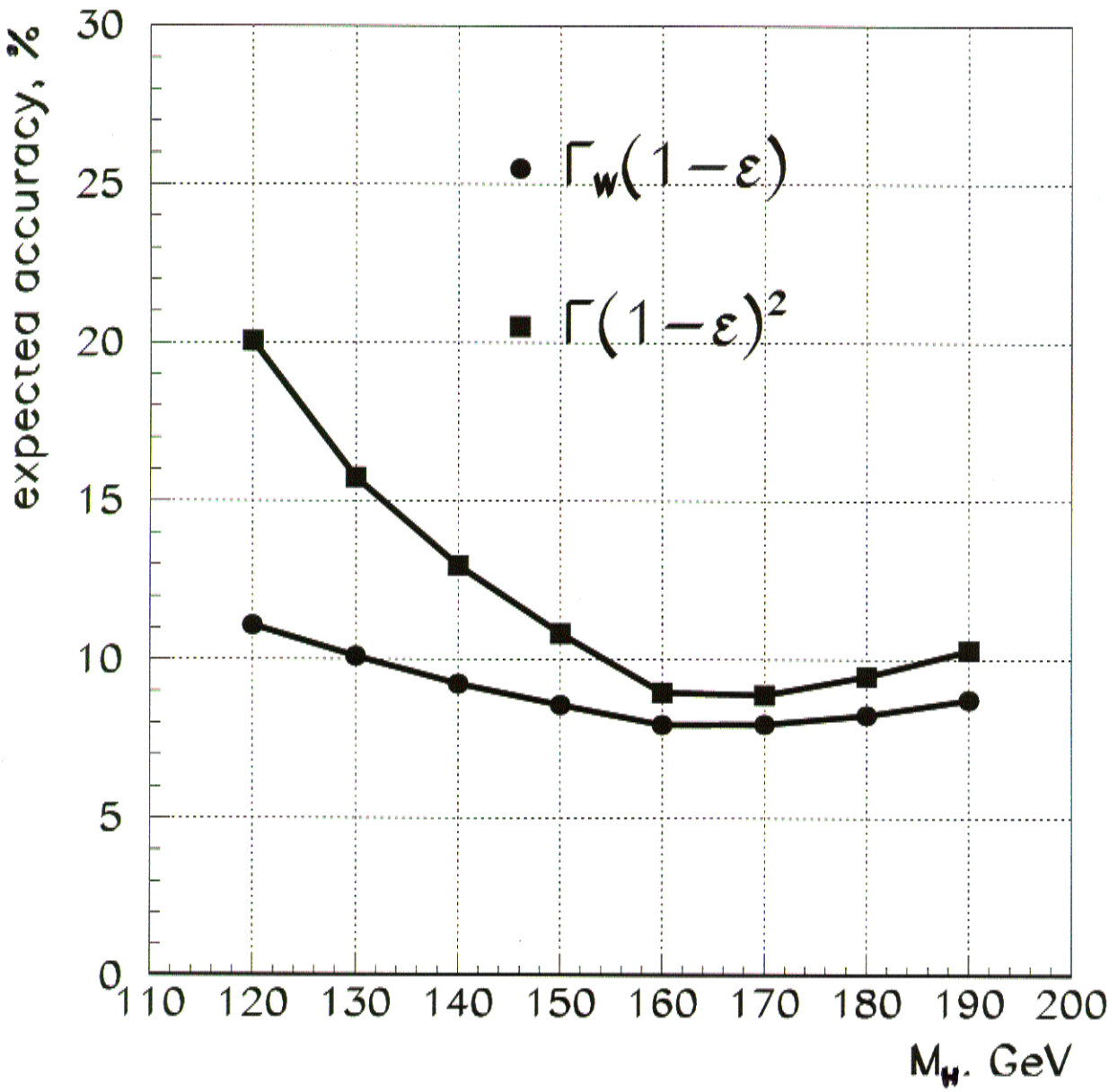
m_b	3.5%
$\sigma_{W\to H}$	5%
$\int \mathcal{L}\,dt$	5%

$$\frac{\Delta \tilde{\Gamma}_W}{\tilde{\Gamma}_W} \sim 10\%$$

Γ^H_{tot} measurement to 10–15% very promising!

(ZKNR)

Zeppenfeld, Kinnunen, Nikitenko, Richter-Wąs

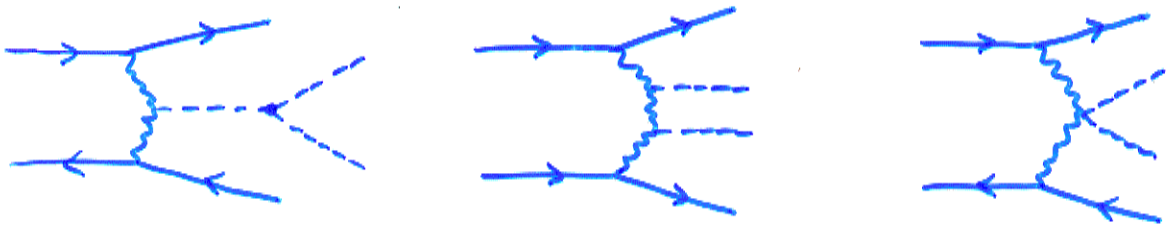


But what about λ ?? (self-coupling of H)

→ can be measured only by observing HH production

① double Higgs-strahlung

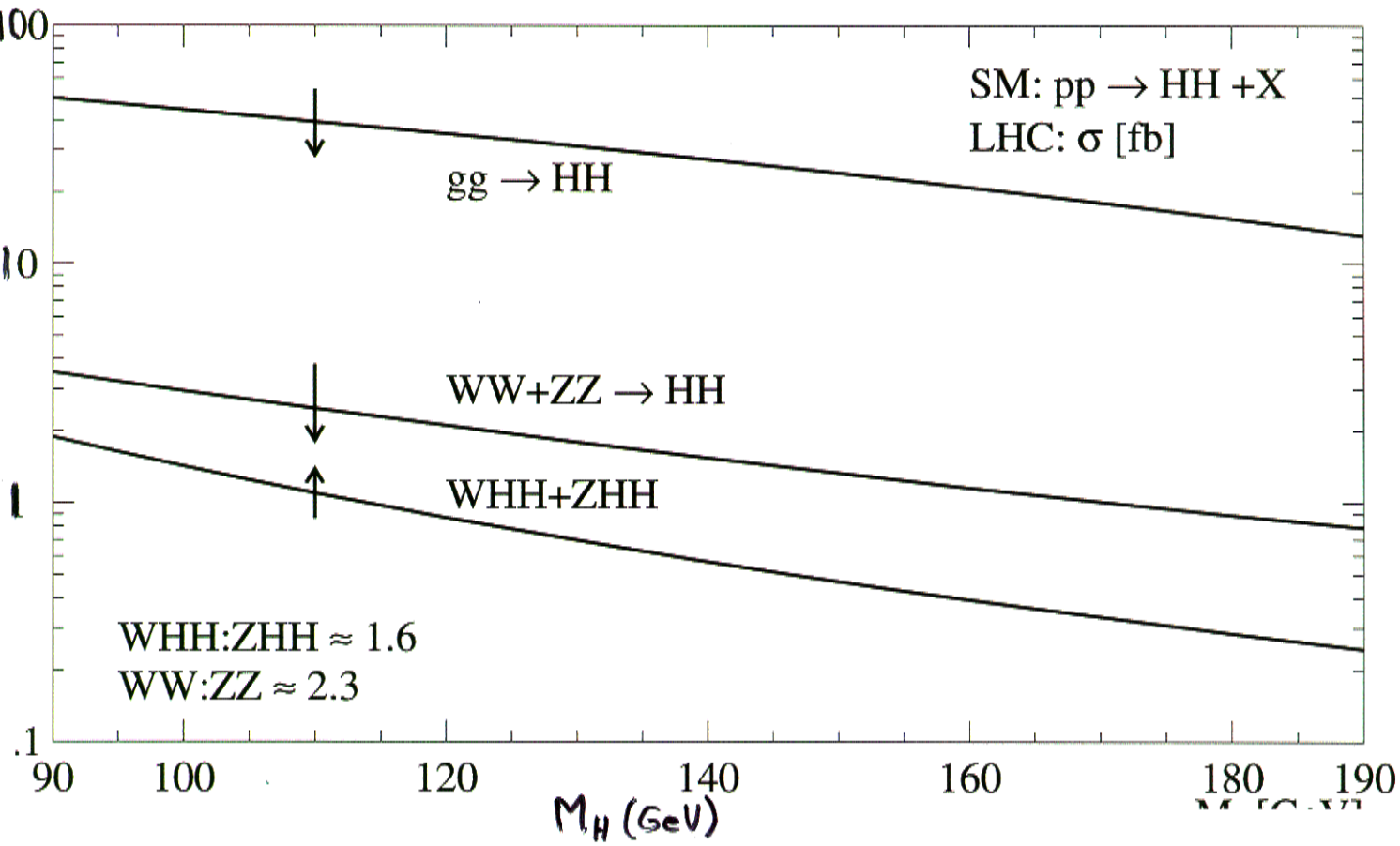
② $VV \to HH$



③ $gg \to HH$

LHC cross sections by Djouadi, Kilian, Muhlleitner & Zerwas

→ forget about WHH + ZHH


SM: pp → HH +X
LHC: σ [fb]
gg → HH
WW+ZZ → HH
WHH+ZHH
WHH:ZHH ≈ 1.6
WW:ZZ ≈ 2.3
100
10
1
.1
90
100
120
140
160
180
190
M_H (GeV)

let's play with the numbers a bit...

choose $M_H = 140$ GeV, $\int \mathcal{L} dt = 300\ fb^{-1}$ $\left\{ \begin{array}{l} Br(b\bar{b}) = 0.33 \\ Br(ZZ) = 0.07 \\ Br(WW) = 0.50 \end{array} \right.$

Try WBF first

(S/B > 1 typically, cleaner environment)

$\epsilon_{WBF} \sim \frac{1}{3}$

	σ(fb)	N_s
$b\bar{b}ZZ$	0.015	4.4
$b\bar{b}WW$	0.111	33.3
$b\bar{b}b\bar{b}$	0.037	11.1
$ZZZZ$	0.0014	0.4
$WWWW$	0.083	24.9
$WWZZ$	0.022	6.5

Ok, try $gg \to HH$

(nasty backgrounds w/o dual mass recon.)

$b\bar{b}ZZ$	1.3	400	$\to$ 13 in $b\bar{b}\ell\ell jj$
$b\bar{b}WW$	10.0	3000	$\to$ 300 in $b\bar{b}\ell\nu jj$
$b\bar{b}b\bar{b}$	3.3	1000	$\to$ 500 w/ ≥ 3 b-tags
$ZZZZ$	0.13	40	
$WWWW$	7.5	2250	$\to$ 600 in $\ell + 6j + \not{p}_T$
$ZZWW$	2.0	600	$\to$ 84 in $\ell + 6j + \not{p}_T$

but $t\bar{t}$+jets backgrounds make dim these prospects...

$\hookrightarrow N_B > 10^6$

Summary

- WZ, ZH or $t\bar{t}H$ production modes minimally useful
- $gg \to H$ by itself has capability to observe any M_H, BUT:
  1. $Hf\bar{f}$ coupling very difficult, impossible at some masses
  2. gauge couplings not determined very accurately
  3. no total width measurement for $M_H \lesssim 250$ GeV
  4. possible to completely miss MSSM h,H
- new work: $VV \to H$ complements $gg \to H$ and opens up new possibilities
  1. expect Higgs discovery with M_H in < 2 years
  2. $Hf\bar{f}$ coupling measurement easy!
  3. ratio of cross sections excellent test of physics model
  4. total width measurement at $10 - 15\%$
  5. No-Lose Theorem for the MSSM
- H self-coupling λ probably still undetermined