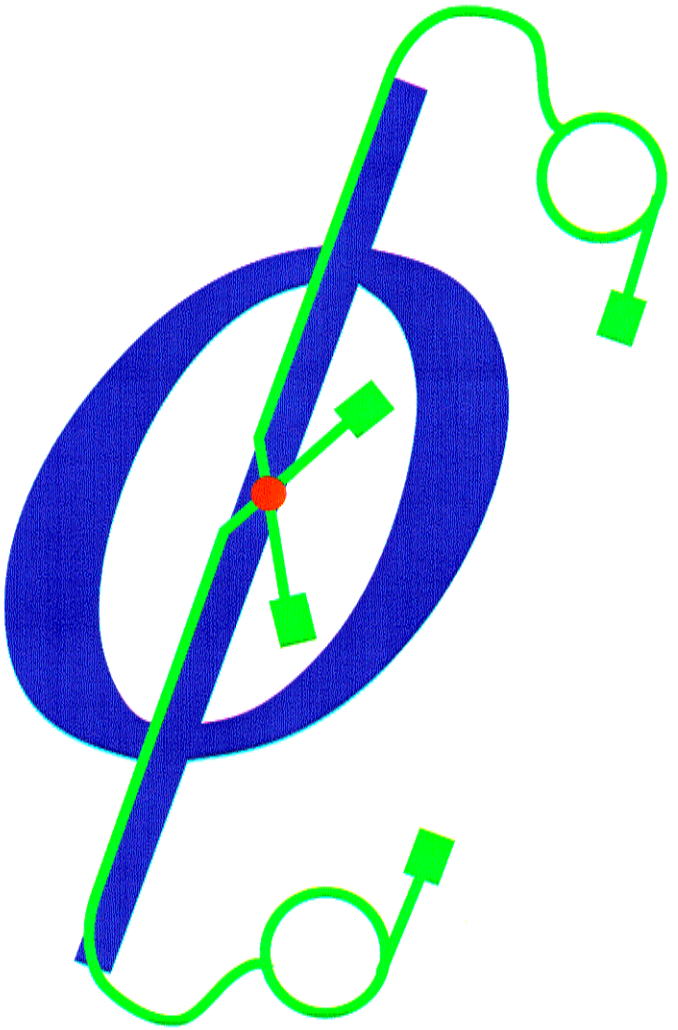
Linear Collider Snowmass Studies: Working Summary



Pinning down the Higgs with a Linear Collider

- Mass
- Width
- Branching Ratios
  (Cross-sections, couplings)
- CP nature

FNAL Linear Collider Physics Study Group,
FNAL, 9 Feb. 2000

Rick Van Kooten
("Rock"?)
Indiana University

Observation

Collisions of e^+e^- / $\mu^+\mu^-$ (modulo detector challenges)

- No problem at all if enough $\sqrt{s}$
- Detected in many decay modes
- Well-predicted backgrounds, good S/N
- Necessary vertexing proven in e^+e^-

"Higgsstrahlung" *WW* fusion

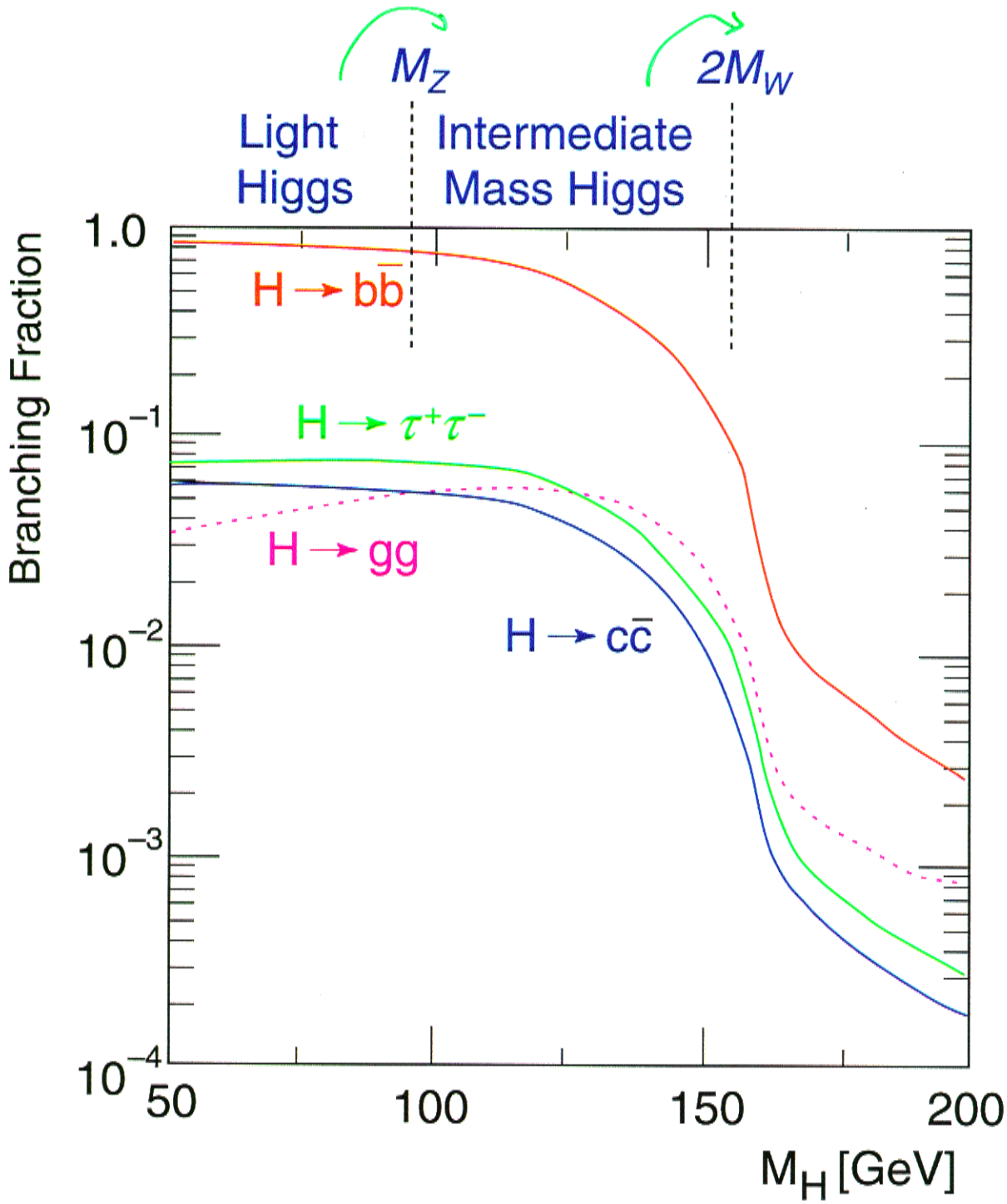
$e^+e^- \rightarrow Z^0 H$ or $e^+e^- \rightarrow H^0 \nu\bar{\nu}$

tag!

- $\rightarrow b\,\bar{b}$ ($100 \leq m_H \leq 150$ GeV)
- $\rightarrow WW^{(*)}$ ($m_H \geq 140$ GeV)
- $\rightarrow t\,\bar{t}^{(*)}$ ($m_H \gtrsim 2m_t$)

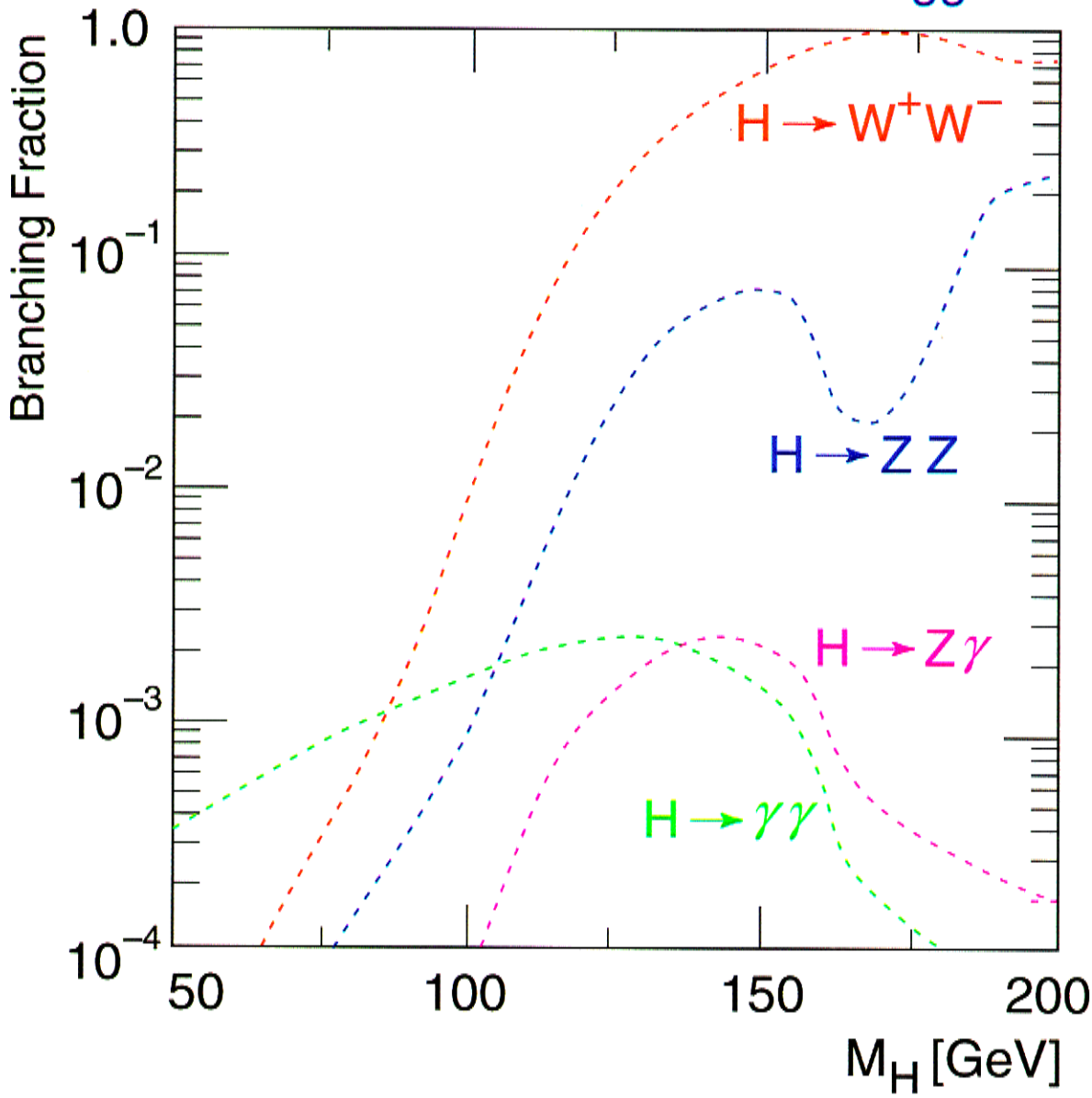
Principle Decay modes

Decay


M_Z
$2M_W$
Light Higgs
Intermediate Mass Higgs
Branching Fraction
1.0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to gg$
$H \to c\bar{c}$
50
100
150
200
M_H [GeV]

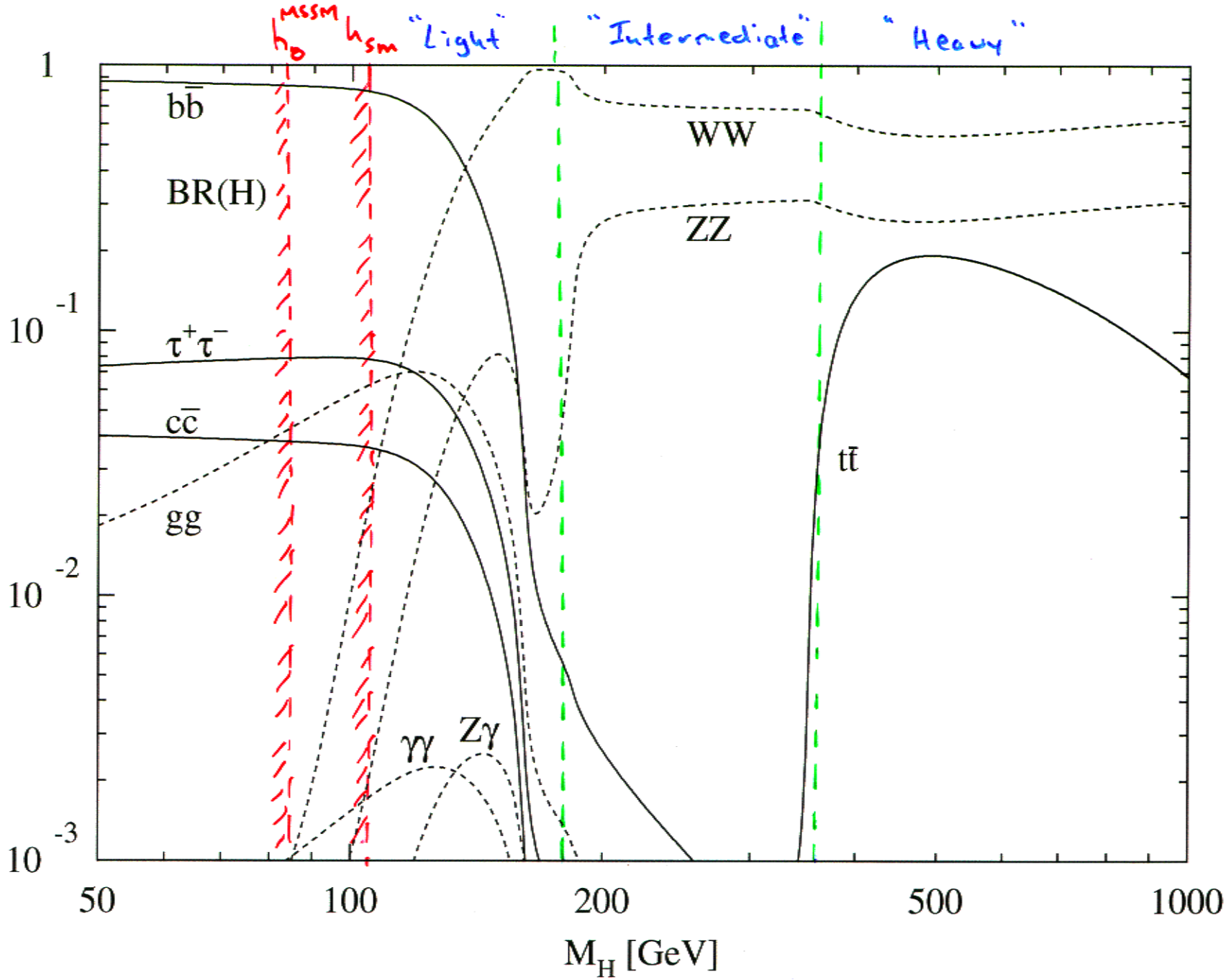
$M_H \gtrsim 700$ GeV "Obese" Higgs ⇒

Heavy Higgs



$H \to t\bar{t}$

@ $m_H > 2m_t$


MSSM
h_0
h_{SM}
"Light"
"Intermediate"
"Heavy"
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
BR(H)
$\tau^+\tau^-$
$c\bar{c}$
gg
WW
ZZ
$t\bar{t}$
$\gamma\gamma$
$Z\gamma$
50
100
200
500
1000
M_H [GeV]

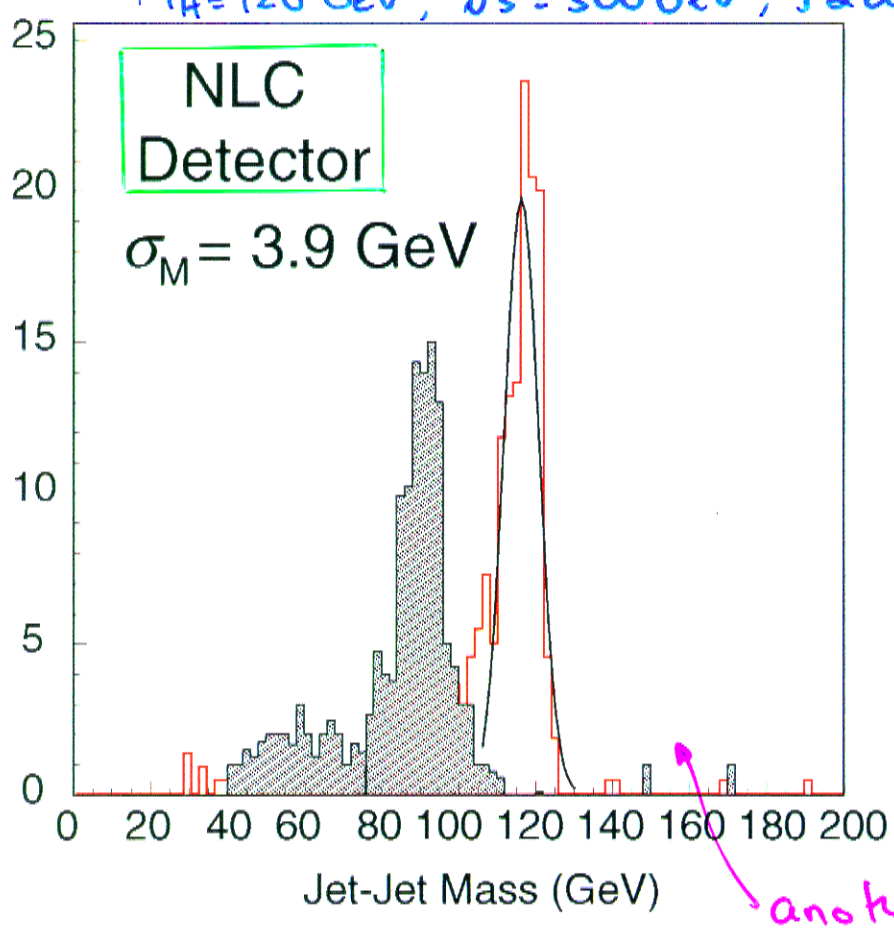
R. Van Kooten

HIGGS PROPERTIES

MASS MEASUREMENT

- SM: measure m_H, check σ, Br
- MSSM: $m_h \pm \Delta m_h$; $m_{A^0} \pm \Delta m_{A^0}$ constrain $\tan\beta$ and $m_{\tilde{t}}$
- Two methods: Jet-Jet Mass, Recoil Mass

$M_H = 120$ GeV, $\sqrt{s} = 300$ GeV, $\int \mathcal{L} dt = 10\ fb^{-1}$



NLC Detector, Recoil mass resolution:

$\sigma_M = 4.2$ GeV

($M_H = 120$ GeV)

Reasonable match between momentum & energy resolution

another ~ factor 2 with kinematic fitting

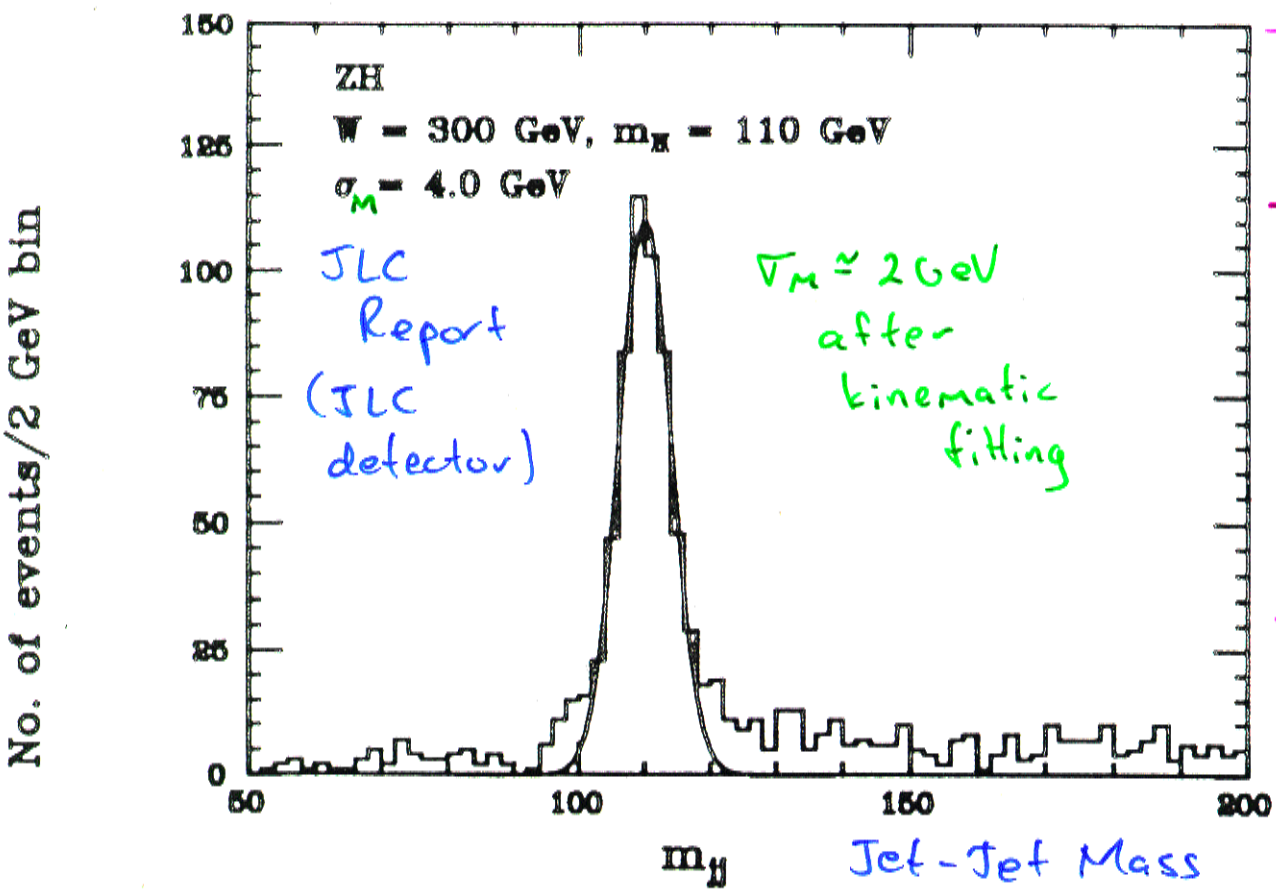
PINNING DOWN THE HIGGS

- Mass Measurement
  - Small beamstrahlung: recoil mass in

    $H^0 Z^0$, $Z^0 \to \ell^+\ell^-$ (e^+e^-, $\mu^+\mu^-$), $H^0 \to X$

  - Other modes (4-jet, 2 jet - 2 leptons)
    - constrain Z^0 jets to M_{Z^0}
    - allow for E_γ down beam axis, conserve four-momentum

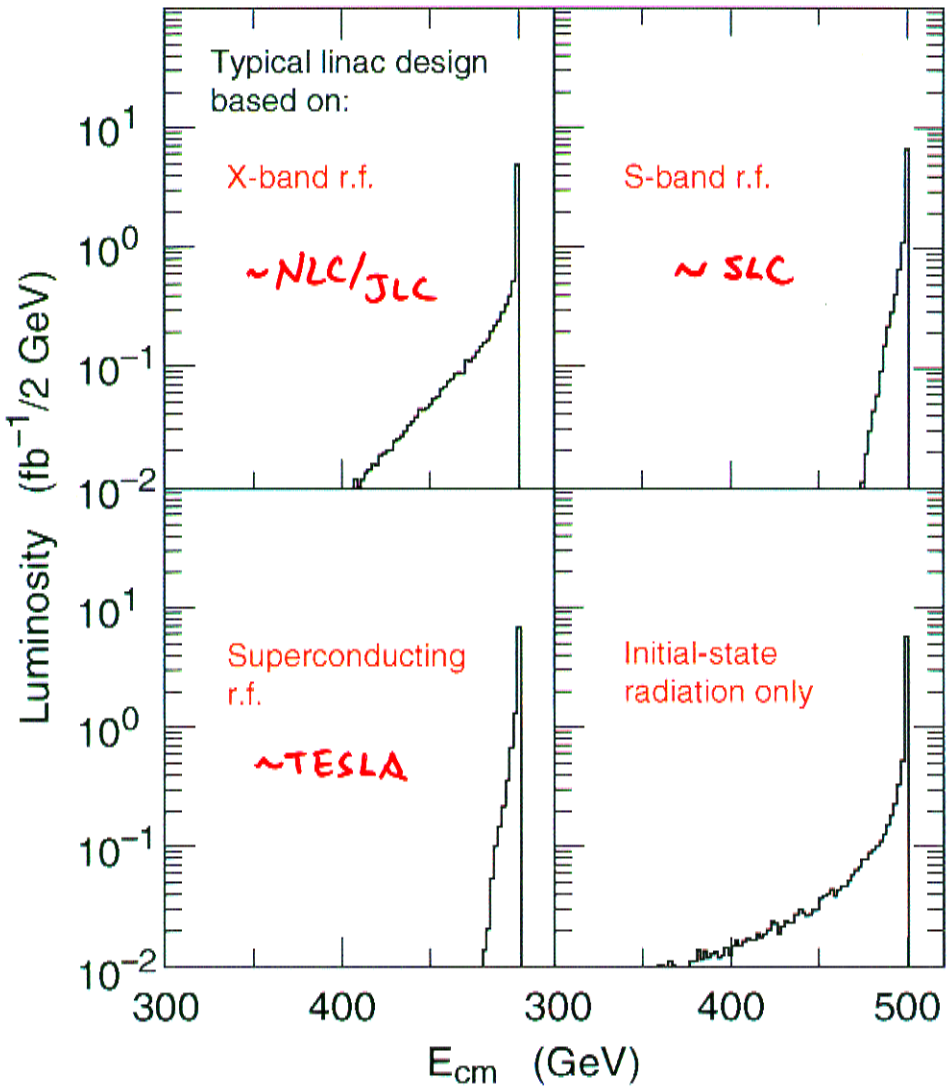
$\boxed{\Delta m_H \lesssim 200 \text{ MeV}}$ @ 300 GeV, 50 fb^{-1} up to $m_H \simeq 160$ GeV



SM: check Br and σ.

MSSM: know $m_h \pm \Delta m_h$, $m_A \pm \Delta m_A$ $\Rightarrow$ constrain $\tan\beta$, $m_{\tilde{t}}$

Beamstrahlung - radiation of photons in the beam-beam collision



... not too much of a problem compared to unavoidable ISR
⇒ use kinematic fits with missing momentum along the beam (z) axis

DETECTOR SIMULATIONS: ~LEP or SLC or JLC detectors

RVK

MASS RESOLUTION STUDIES

SNOWMASS

A. The Monte Carlos

(1) signal "HZHA" from CERN & European groups
(will put it in NLC simulation software area)

⇒ more flexible than PYTHIA

- beamstrahlung
- $H_{SM}Z$, h^0Z^0, H^0Z^0, h^0A^0, H^0A^0
  $h\nu\bar{\nu}$, $H\nu\bar{\nu}$ (WW and Z fusion)
  he^+e^- He^+e^-
- SUSY MSSM pole Higgs masses w/ two-loop improved RGE
- Forced decays of Z^0, (H, h, A)
- SUSY decays $\tilde{\chi}_1^0\tilde{\chi}_1^0$; $\tilde{\chi}_1^+\tilde{\chi}_1^-$
- Cascade decays $H \to AA$, $A \to Zh$
  $H, A \to hh$

(2) backgrounds PYTHIA 5.7

DETECTOR SIMULATIONS, SNOWMASS

"THE STRAWMEN"

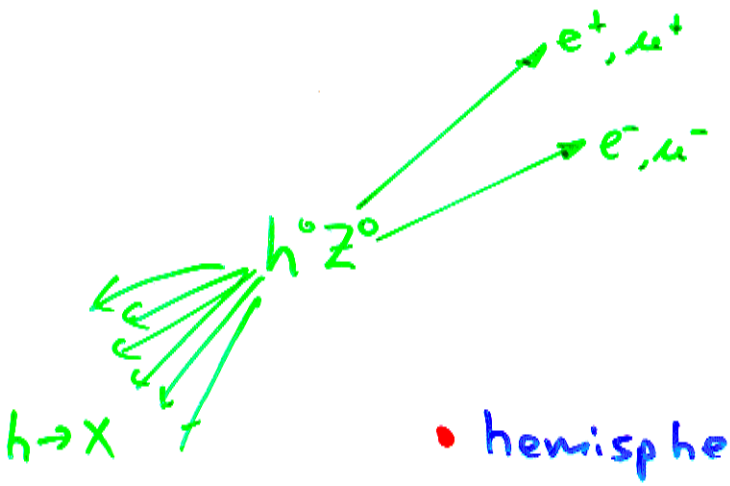
Smeared four-vectors with the following (assumed) set of parameters:

Detector	$\delta p_{(t)}/p_{(t)}$	$\delta E_{em}/E_{em}$	$\delta E_{had}/E_{had}$
"Compact"	$30\times10^{-4}\,p_{(t)}$ Worst	$\frac{0.05}{\sqrt{E}} \oplus 0.005$ Best	$\frac{0.30}{\sqrt{E}} \oplus 0.05$ Best
LEP/SLC	$5\times10^{-4}\,p_t$	$\frac{0.20}{\sqrt{E}} \oplus 0.03$	$\frac{0.90}{\sqrt{E}} \oplus 0.10$ Worst
JLC "super"	$1\times10^{-4}\,p_t$ Best	$\frac{0.15}{\sqrt{E}} \oplus 0.01$	$\frac{0.40}{\sqrt{E}} \oplus 0.05$

- all hermetic down to $|\cos\theta| < 0.98$ ($\sim 10°$) (better-now)
- very simplistic directional smearing (granularity) from calorimeters

RECOIL MASS ANALYSIS

- $M_H = 120$ GeV, 150 GeV @ $\sqrt{s} = 300$ GeV
  (for this type of analysis, ideal to sit at $\sqrt{s} \simeq M_Z + M_H + \sim 20\text{-}30$ GeV)



- thrust axis $|\cos\theta_{th}| < 0.7$
- $M_{e^+e^-}$: $75 \leq m_{e^+e^-} < 105$ GeV
- hemisphere vectors coplanar, collinear
- Small missing mass, and missing P_z
- Recoil mass:

$$M_{recoil} = \sqrt{(\sqrt{s} - P_{e^-} - P_{e^+})^2 + (\vec{P}_{e^-} + \vec{P}_{e^+})^2}$$

$\Rightarrow$ Completely driven by momentum resolution on leptons (and $\sim \delta E_{em}$ for e^+e^-)

and on energy spread

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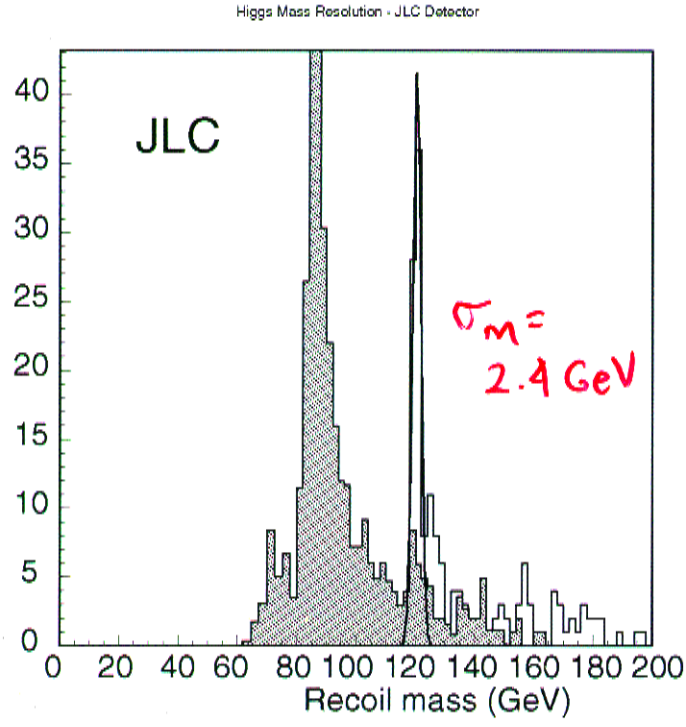
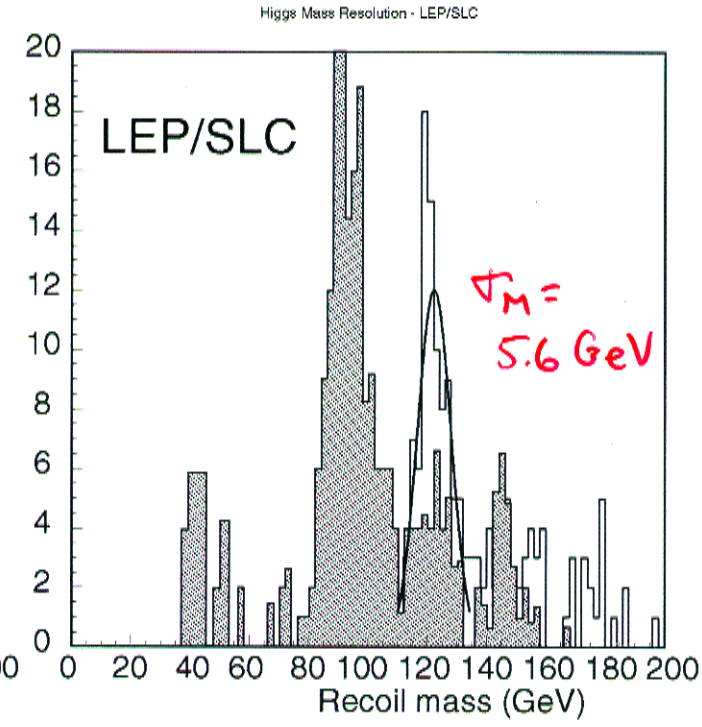
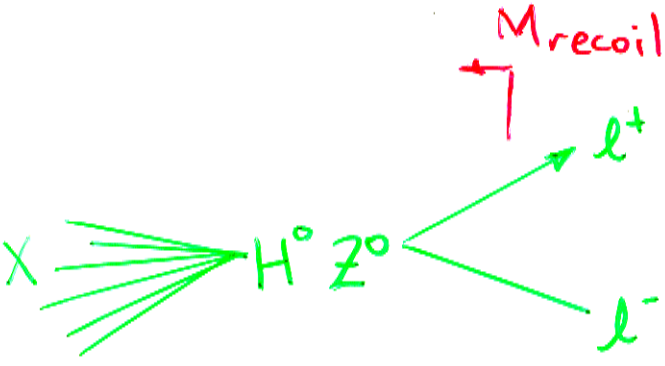
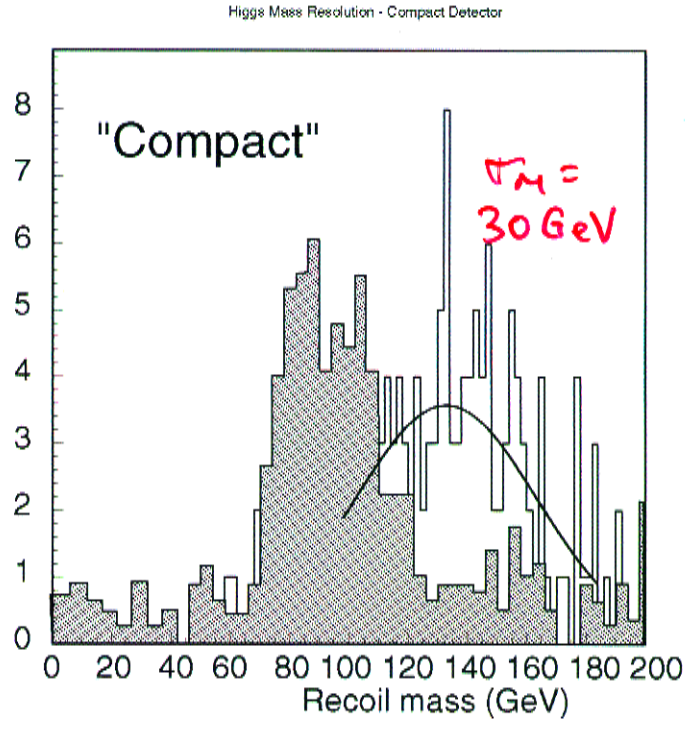
Recoil Mass

$M_H = 120$ GeV, $\sqrt{s} = 300$ GeV, $\int \mathcal{L} dt = 10 fb^{-1}$





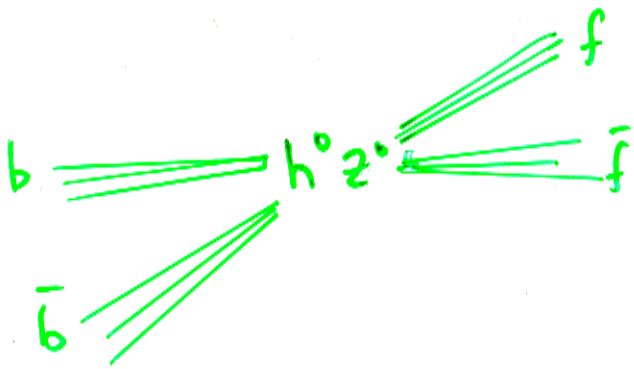




- Strong dependence on momentum resolution as expected

(or EM_{cal} for e^+e^- from Z^0)

JET-JET MASS ANALYSIS

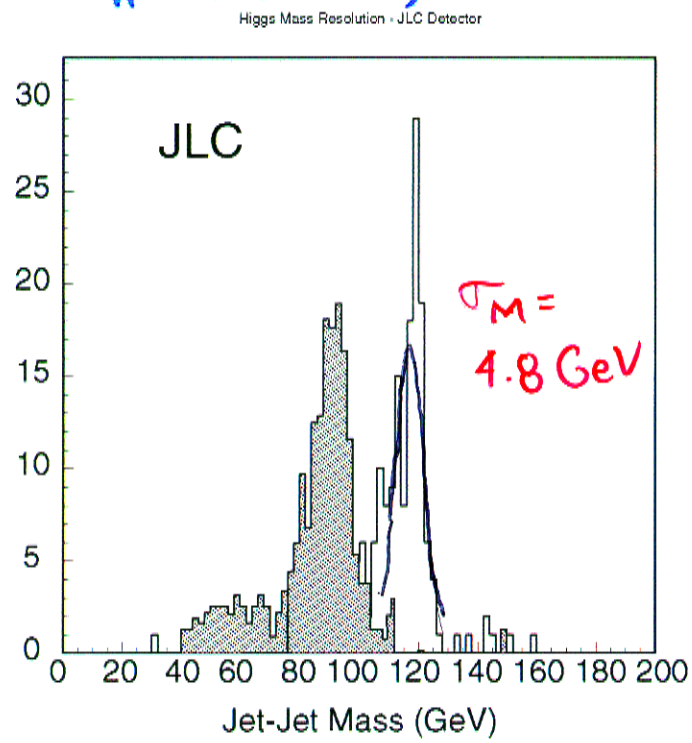


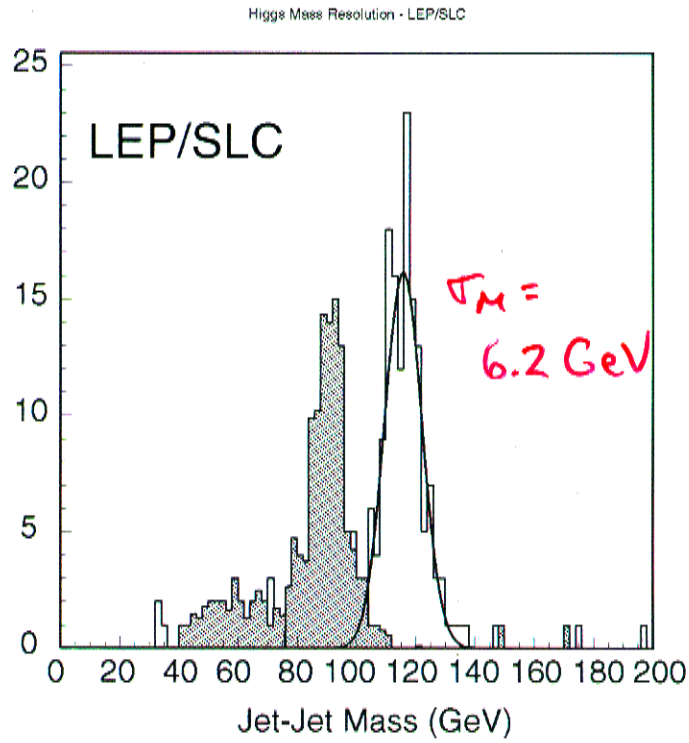
- thrust axis $|\cos\theta_{th}| < 0.7$
- Z^0 hemisphere ($q\bar{q}$ or $\ell^+\ell^-$)
  $75 \leq m_{hemi} \leq 105$ GeV
- hemisphere vectors coplanar, collinear
- small missing mass and missing P_z
- Demand at least one b-vertex in h^0 hemisphere
  (neural net, impact parameter significance, decay length significance)
- In ~~a~~ each h^0 hemisphere,
  look @ $M_{jet\text{-}jet}$ invariant mass
  (resolution depends on charged tracking and calorimetry)

RVK

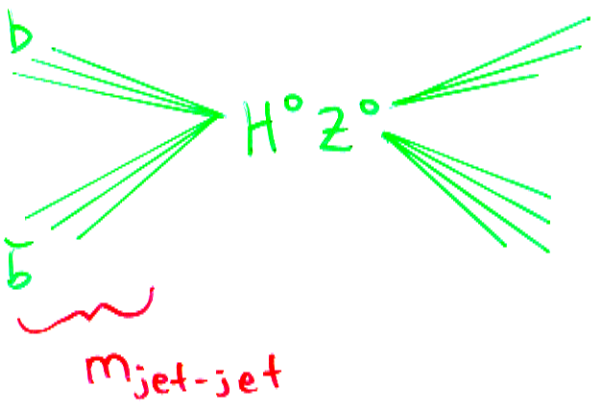
Jet-Jet Mass

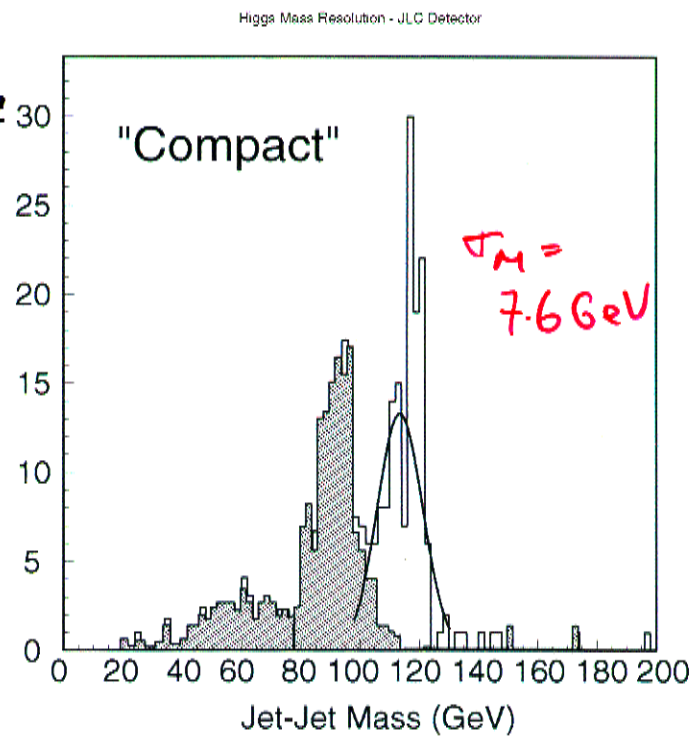
$M_H = 120$ GeV, $\sqrt{s} = 300$ GeV, $\int \mathcal{L} dt = 10 fb^{-1}$





- Gain ~factor of 2 in resolution when do kinematic fit to M_Z



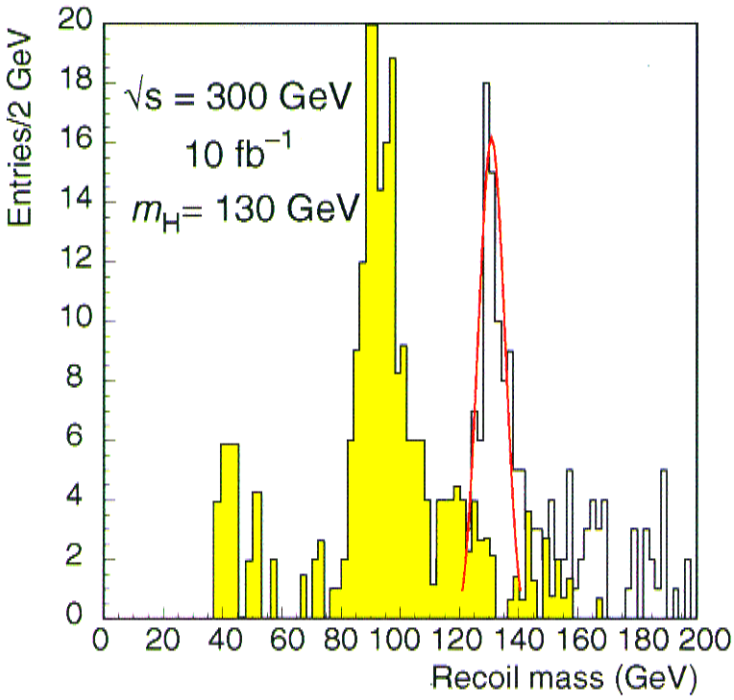


- trade-off between $\delta p/p$, $\delta E/E$

- Prior to Snowmass, three different "strawmen" detectors were compared. For simplicity, at Snowmass a single "NLC detector" was defined with better hadronic energy resolution, ⇒ (than LEP/SLC detector)

- Similar studies need to be repeated for detector optimization. Criteria for $\delta p/p$, $\delta E/E$ trade-off?

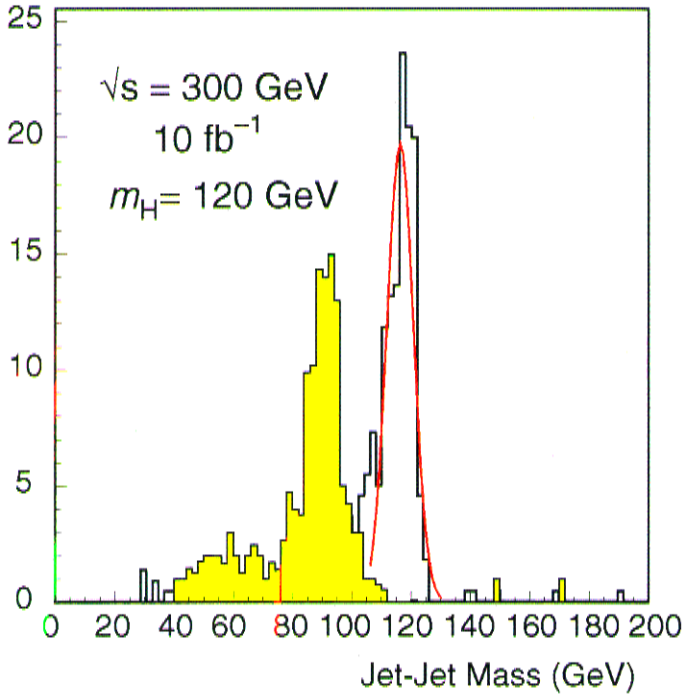
NLC Detector



Recoil Mass:

$\sigma_M = 4.2$ GeV

Matching these a reasonable criterion?



Jet-Jet Mass:

$\sigma_M = 3.9$ GeV

... or else need better recoil mass resolution for optimal error on $\sigma(Zh)$ determination?...

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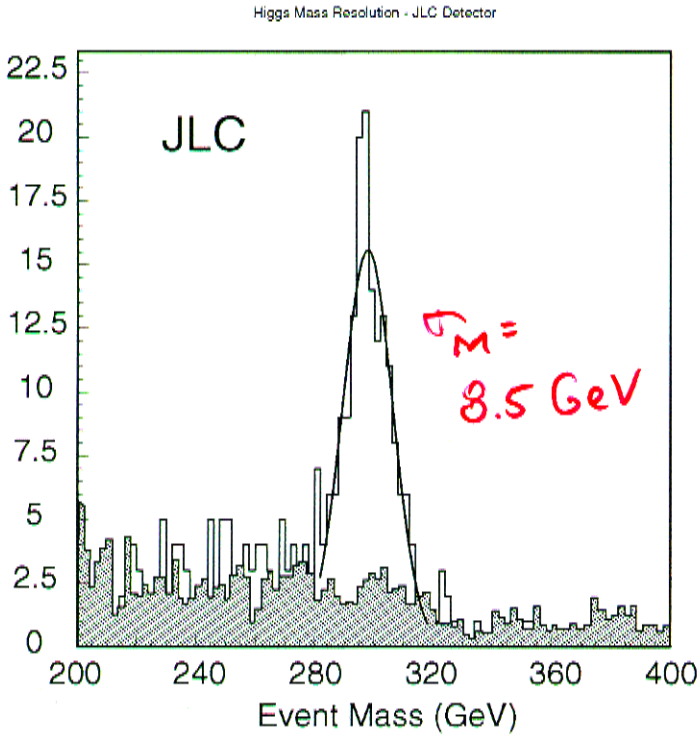
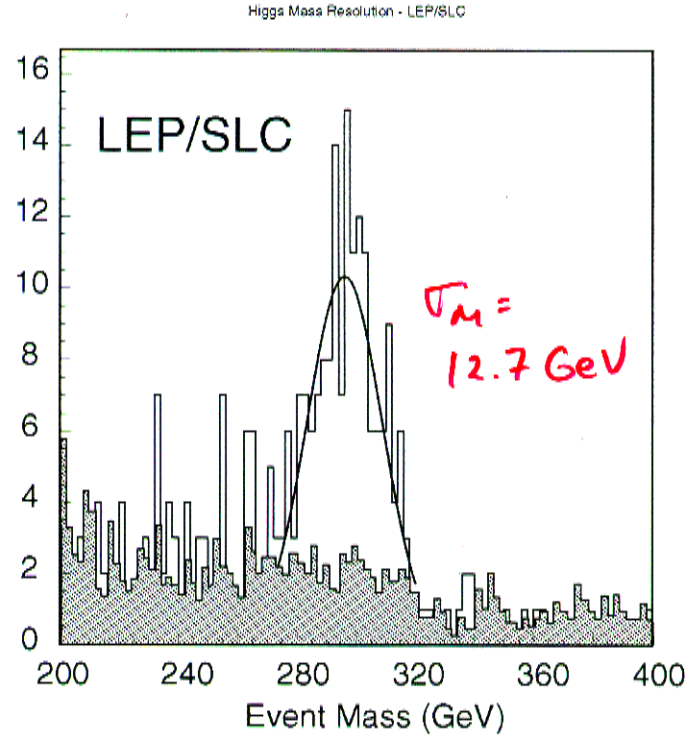
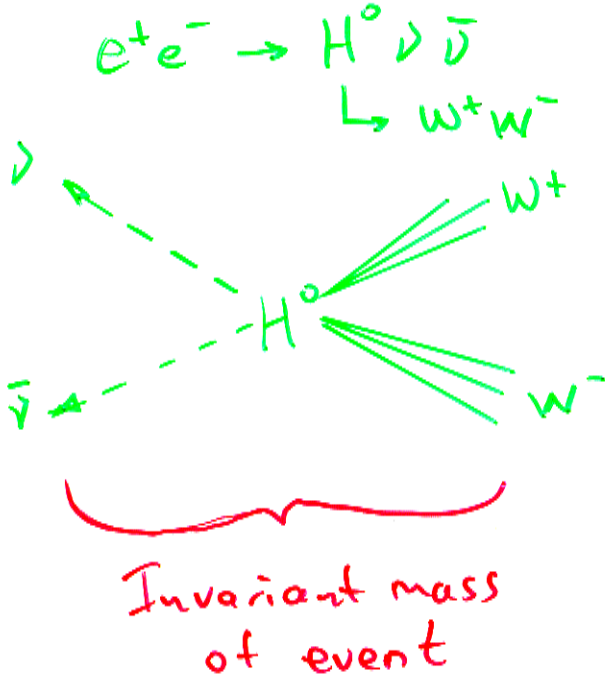
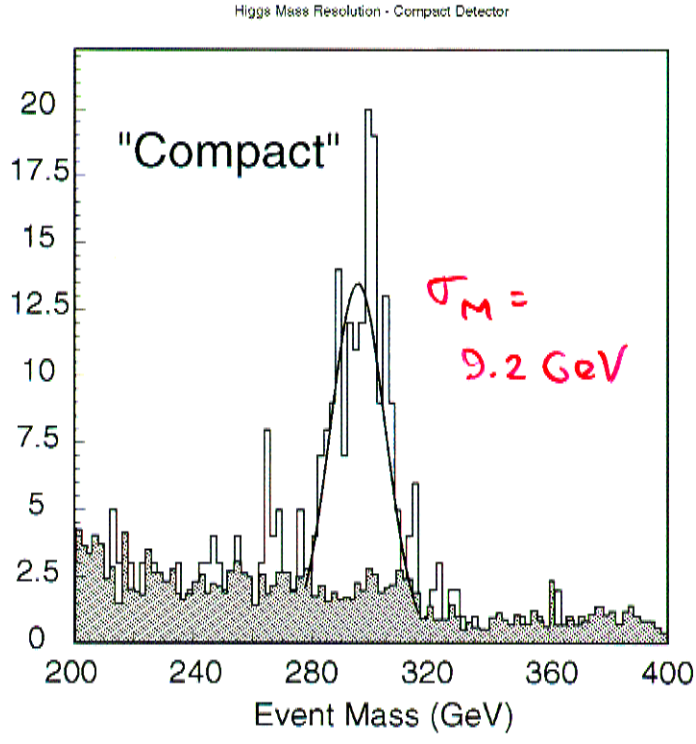
WW Fusion - Event Mass

$M_H = 300$ GeV, $\sqrt{s} = 500$ GeV, $\int \mathcal{L}\, dt = 50\ fb^{-1}$









- energy resolution (including hadronic) important here

- NLC Detector with 50 fb^{-1}:

$$\Delta m_H \simeq 140 \text{ MeV} \quad @ \quad m_H = 120 \text{ GeV}$$
$$\Delta m_H \simeq 200 \text{ MeV} \quad @ \quad m_H = 150 \text{ GeV}$$

$$\left(\text{scales as} \simeq \frac{\sigma_M}{\sqrt{S-B}} \right)$$

- Difficult to distinguish mass degenerate states at large $\tan\beta$ $\Rightarrow$

- Importance?

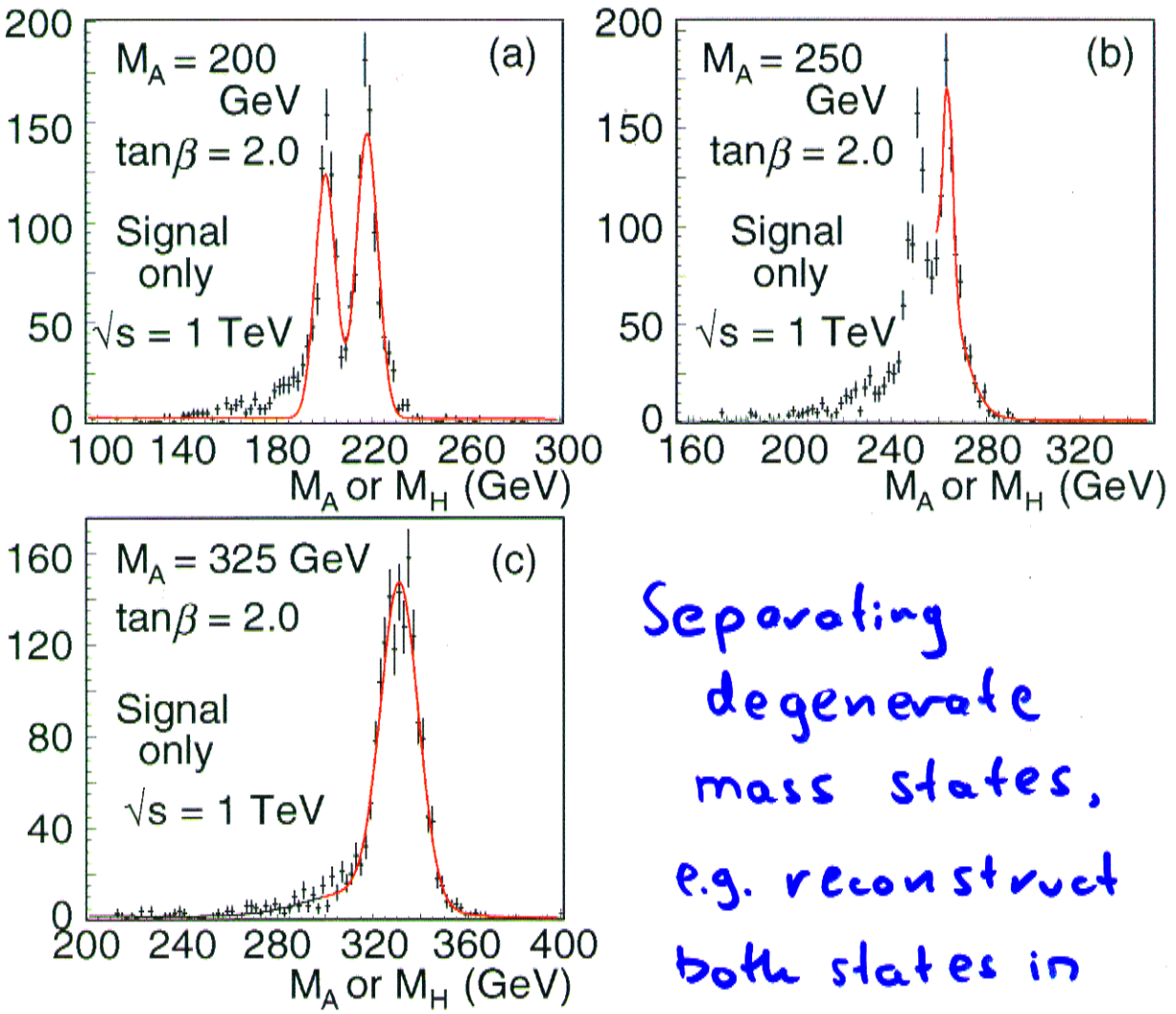
e.g. $m_{A^0} = 200$ GeV $\quad \tan\beta = 14$
$m_{\tilde{t}} = 260$ GeV $\quad m_t = 175$ GeV

$m_{h^0} = 120$ GeV ; if $\Delta m_{h_{SM}} = \pm 100$ MeV,

$\Delta m_{A^0} = 37$ GeV ; $\Delta \tan\beta = 0.7$; $\Delta m_t = 170$ MeV, $\Delta m_{\tilde{t}} = 1$ GeV

should measure better $\rightarrow$ constrain $\tan\beta$, $m_{\tilde{t}}$

- Summarize, extrapolate, + collate, (Snowmass)
(with Gunion)



Separating degenerate mass states, e.g. reconstruct both states in

$e^+e^- \to H^0A^0$

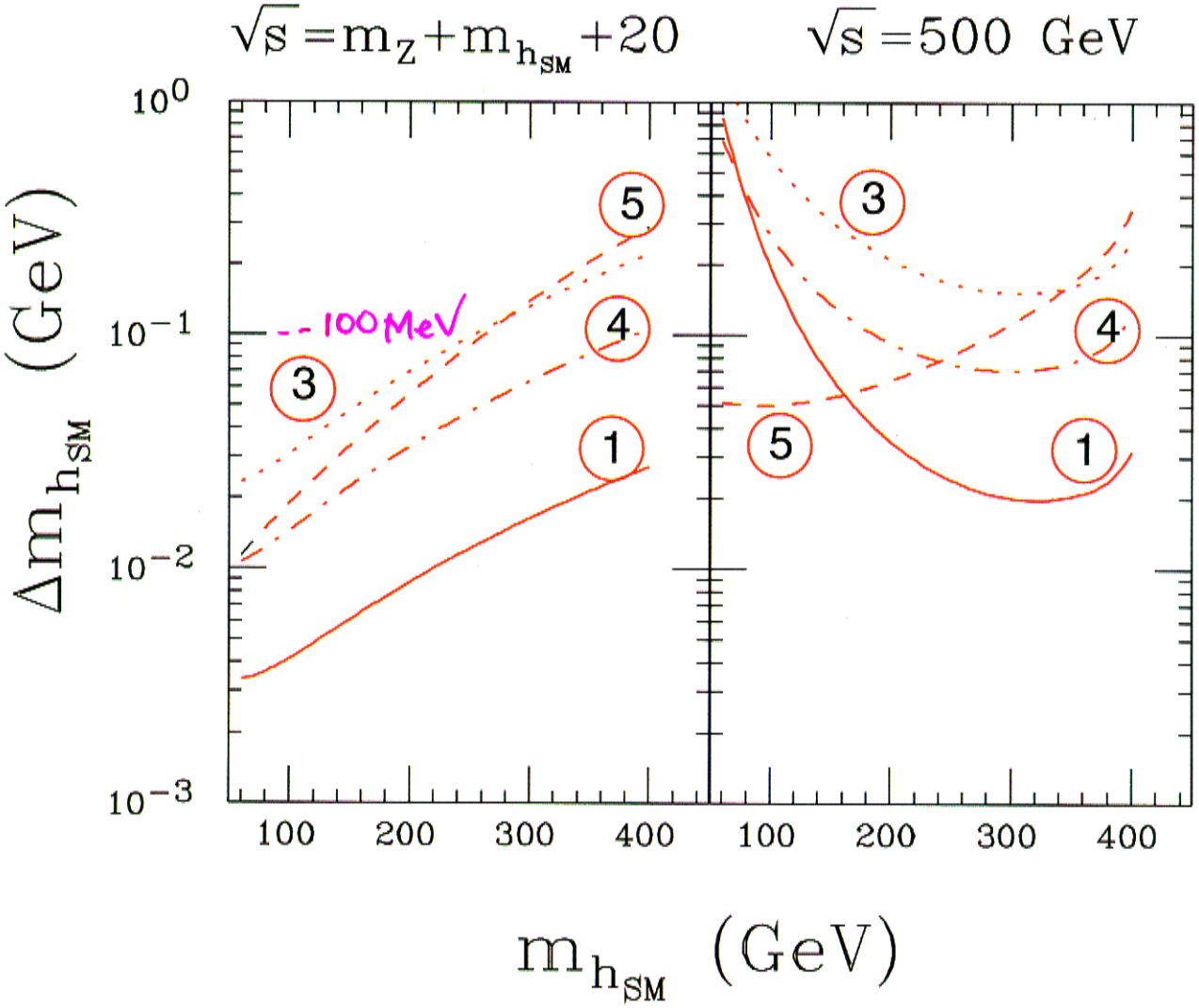
(signal only!)

e.g. separation good out to $\Delta M \simeq 20$ GeV

Precision on Higgs Mass

(with Gunion)

NLC only, recoil mass and direct, 200 fb^{-1}



1 "Super" JLC tracking

3 "Standard" NLC detector tracking, "standard" calorimetry

4 "Standard" NLC detector tracking, "CMS"-like calorimetry

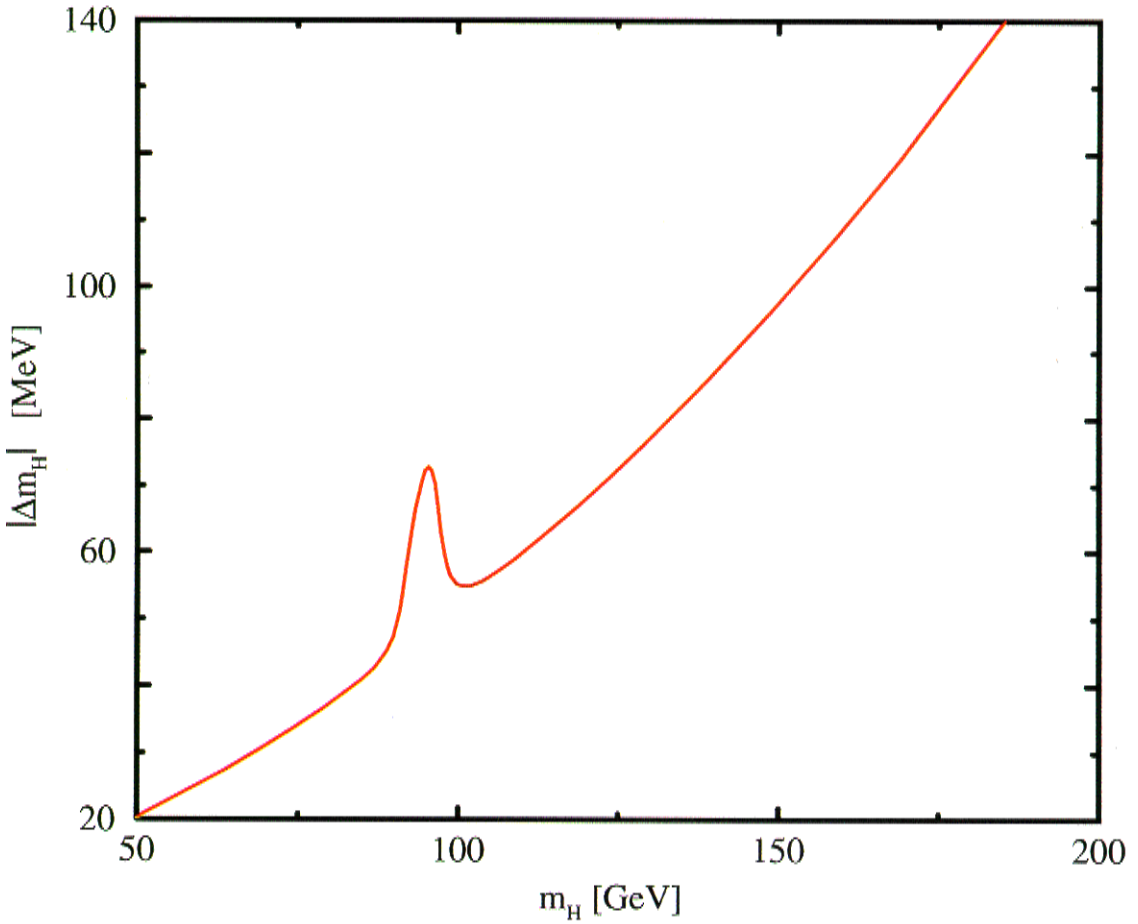
5 Jet-Jet reconstruction

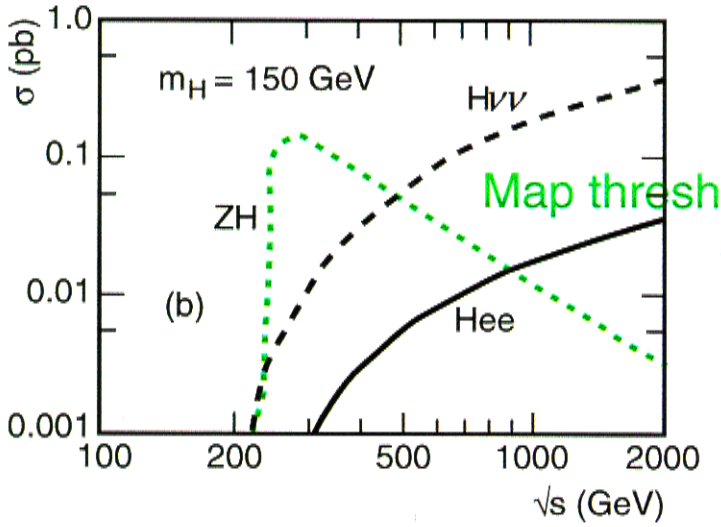
Precision on Higgs Mass

NLC only, special threshold runs, 50 fb^{-1}

Competitive!

Barger, Berger, Gunion, Han





Map threshold

$\sqrt{s} = M_Z + m_h + 0.5\ \mathrm{GeV}$

(c.f. M_W!)
@ LEP2

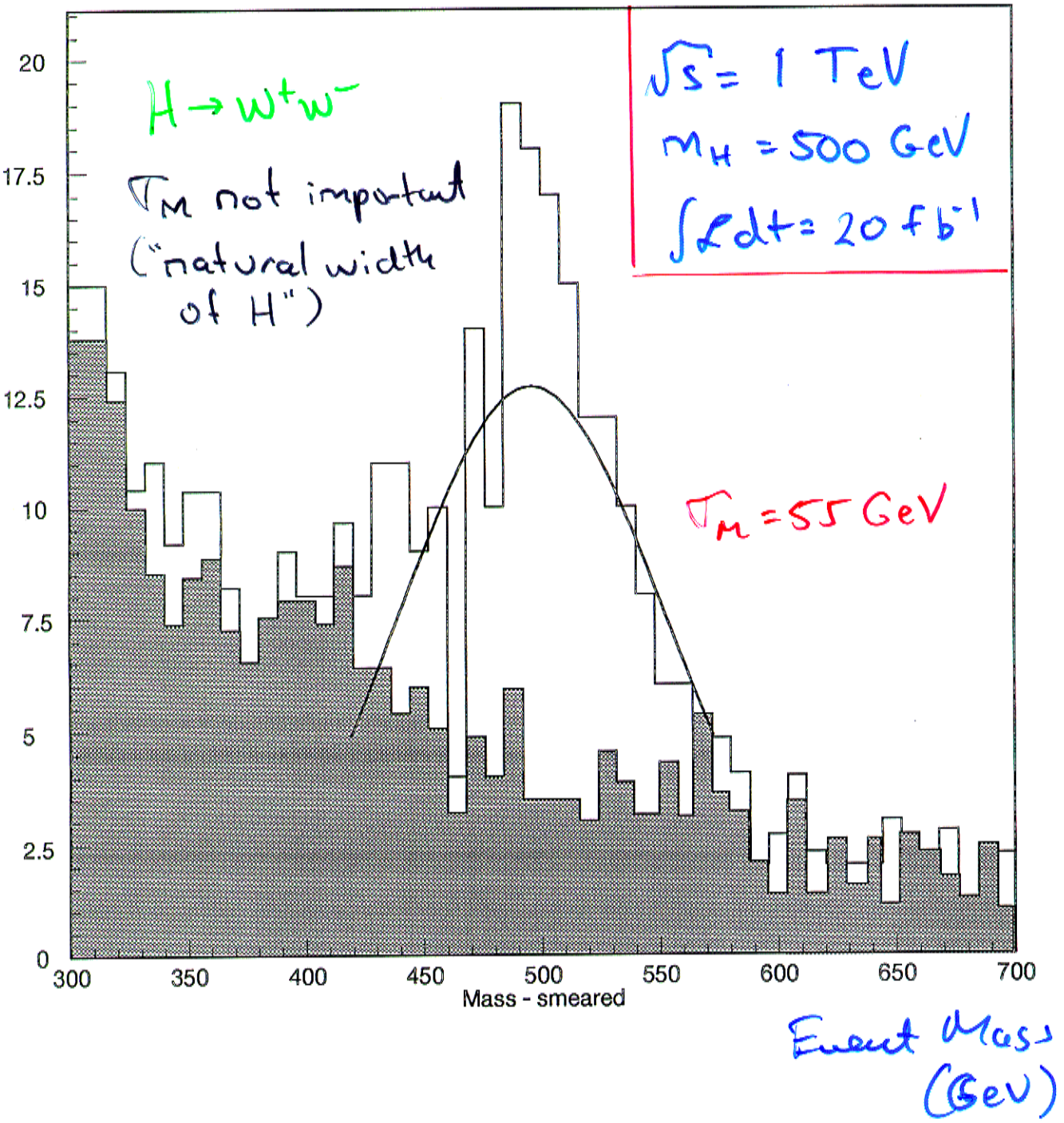
Table 7: Summary of approximate errors, $\Delta m_{h_{SM}}$, for $m_{h_{SM}} \leq 300$ GeV. LEP2 errors are for $L = 600$ pb^{-1}. Tev33 errors are for $L = 60$ fb^{-1}. LHC errors are for $L = 600$ fb^{-1} for ATLAS+CMS. NLC errors are given for a luminosity times efficiency of $L\epsilon = 200$ fb$^{-1} \times 0.6$ at both $\sqrt{s} = 500$ GeV and $\sqrt{s}_{Zh_{SM}} \equiv m_Z + m_{h_{SM}} + 20$ GeV.

(with Gunion + Poggioli)

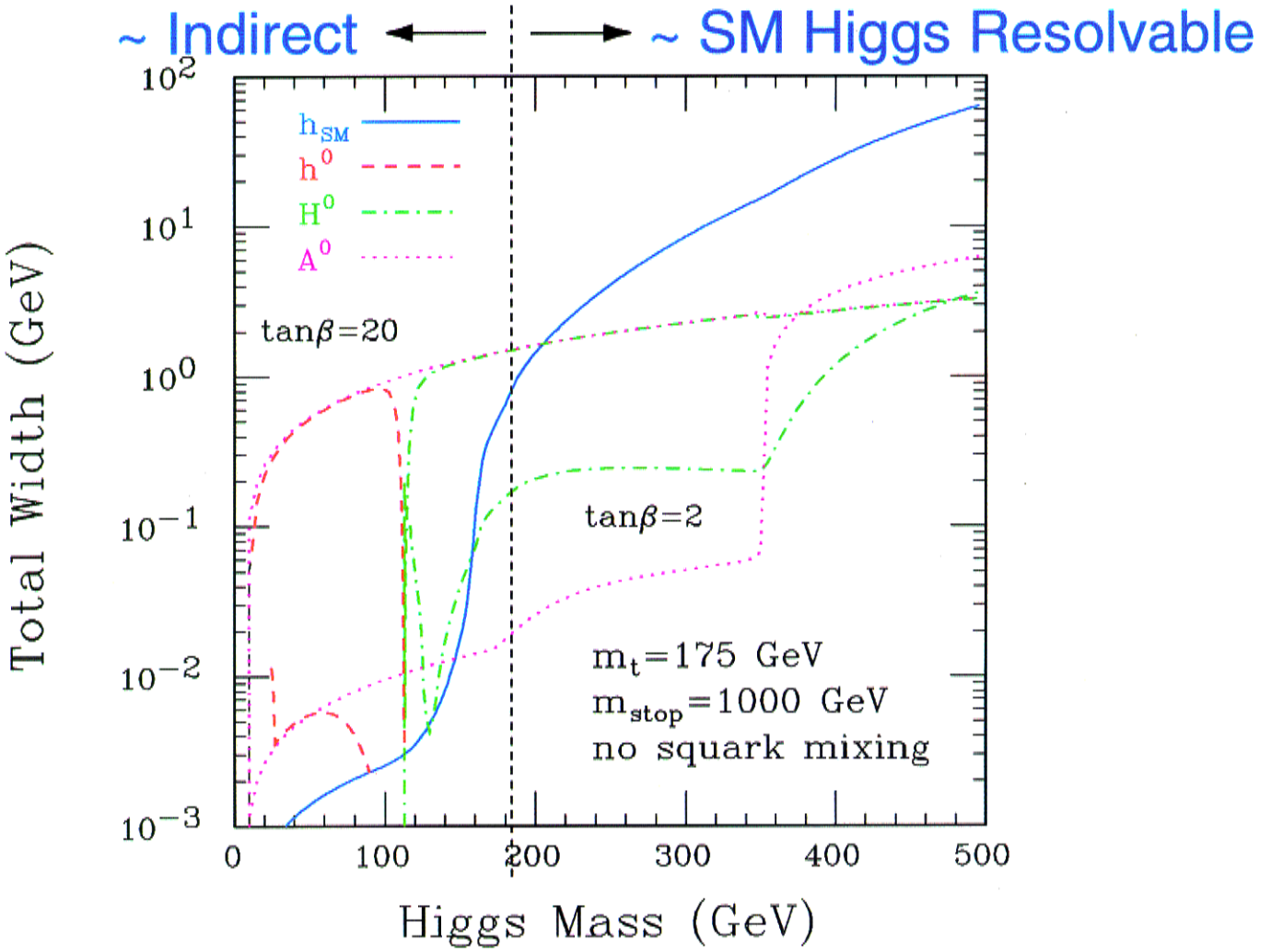
$\int \mathcal{L} dt = 200 fb^{-1}$

Machine/Technique	$\Delta m_{h_{SM}}$ (MeV)			
$m_{h_{SM}}$(GeV)	**80**	**m_Z**	**100**	**110**
LEP2	250	400	–	–
TeV33	960	?	1500	2000
LHC/$\gamma\gamma$ (stat+syst)	90	90	95	100
NLC/case-3 $\sqrt{s} = 500$	813	674	572	494
NLC/case-1 $\sqrt{s} = 500$	370	264	196	151
NLC/hadronic $\sqrt{s} = 500$	51	?	51	51
NLC/case-3 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	27	29	31	34
NLC/case-1 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	3.6	3.8	4.1	4.4
NLC/hadronic $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	15	17	19	22
NLC/threshold	40	70	55	58
FMC/scan	0.025	0.35	0.1	0.08
$m_{h_{SM}}$(GeV)	**120**	**130**	**140**	**150**
TeV33	2700	–	–	–
LHC/$\gamma\gamma$ (stat+syst)	105	110	130	150
LHC/4ℓ (stat+syst)	–	164	111	90
NLC/case-3 $\sqrt{s} = 500$	432	383	343	311
NLC/case-1 $\sqrt{s} = 500$	120	97	80	68
NLC/hadronic $\sqrt{s} = 500$	52	52	53	55
NLC/case-3 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	37	40	44	48
NLC/case-1 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	4.8	5.2	5.6	6.1
NLC/hadronic $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	24	27	30	34
NLC/threshold	65	75	85	100
FMC/scan	0.06	0.12	0.20	0.49
$m_{h_{SM}}$(GeV)	**170**	**190**	**200**	**300**
LHC/4ℓ (stat+syst)	274	67	56	90
NLC/case-3 $\sqrt{s} = 500$	261	225	211	153
NLC/case-1 $\sqrt{s} = 500$	50	39	35	20
NLC/hadronic $\sqrt{s} = 500$	58	62	65	113
NLC/case-3 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	56	65	70	133
NLC/case-1 $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	7.1	8.2	8.8	17
NLC/hadronic $\sqrt{s} = \sqrt{s}_{Zh_{SM}}$	41	51	56	140
NLC/threshold	120	150	170	?

Higgs Mass Resolution - LEP/SLC

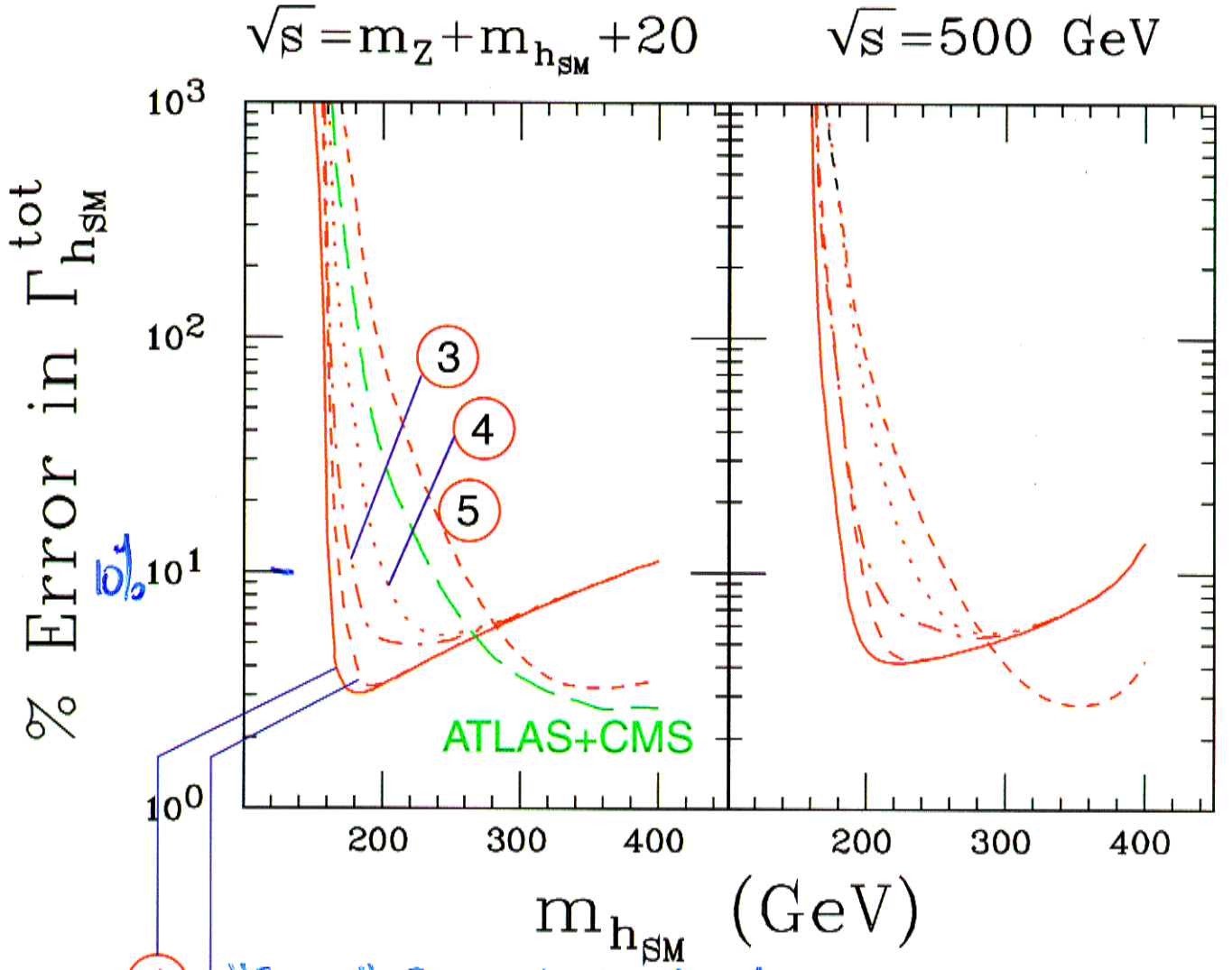


Total Width



- Indirectly: measuring $\sigma \cdot$ Br, then σ or Br separately
- Direct resolution of line shape for heavy Higgs states

Precision on Higgs Width



1. "Super" JLC detector tracking
2. As 1, but realistic systematics
3. "Standard" NLC detector tracking and calorimetry
4. As 3, but CMS-like Em calorimetry
5. Jet-Jet reconstruction

- How well can Br($h \to \gamma\gamma$) be measured at the NLC?

Brau, Gunion, Martin, Pitts

$e^+e^- \to Z^0 h^0$, $h^0 \to \gamma\gamma$

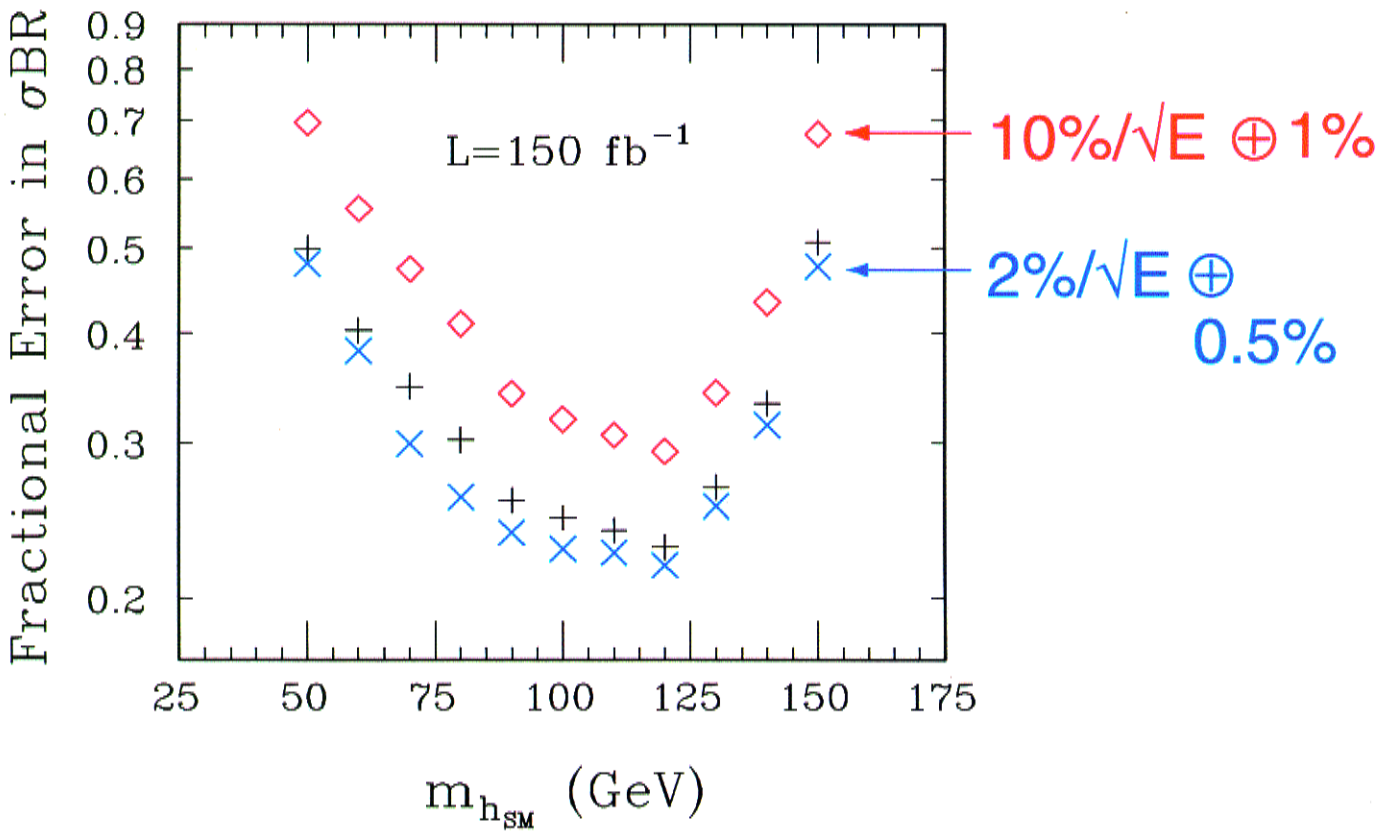
Done.

$e^+e^- \to h^0 \nu\bar{\nu}$, $h^0 \to \gamma\gamma$

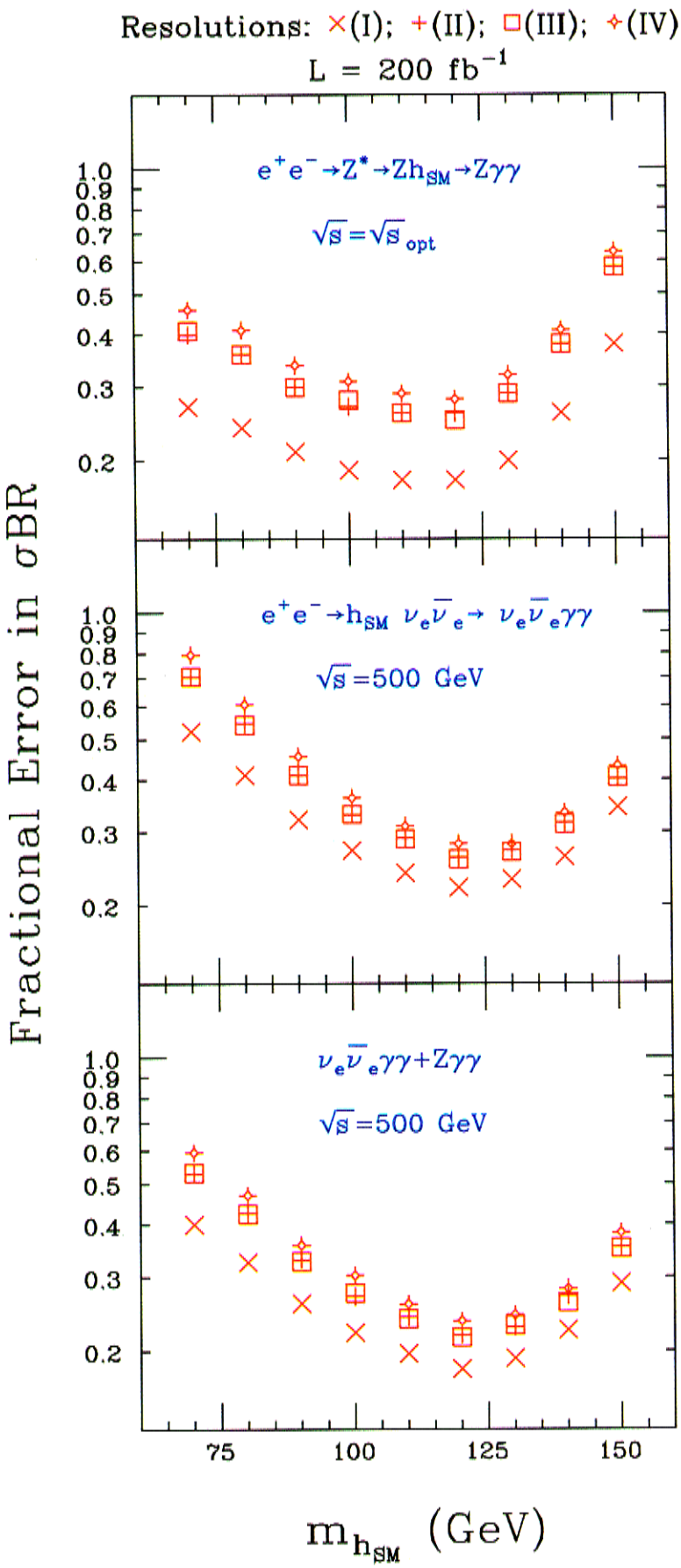
Tough but promising.

$e^+e^- \to Z^* \to Zh_{SM} \to Z\gamma\gamma$

Resolutions: ×(I); +(II); ◇(III)



plus improved estimate of $\Gamma(h \to \gamma\gamma)$ from $\gamma\gamma$ collisions ⇒



$\sigma\,\mathrm{Br}(h \to \gamma\gamma)$

× CMS detector EM resolution

+ □ Snowmass NLC detector EM resolutions

✧ JLC detector EM resolution

$$\boxed{\text{What about indirect } \Gamma_h^{tot} \text{ for lighter higgs??}}$$

"THE DANCE"

- At the LC: measure

$\sigma(e^+e^- \to Zh)\, Br(h \to \gamma\gamma)$ $\qquad$ $\sigma(e^+e^- \to \nu\bar{\nu}h)\, Br(h \to \gamma\gamma)$ $\Rightarrow$

$$Br(h \to \gamma\gamma) = \frac{\sigma(Zh)\, Br(h \to \gamma\gamma)}{\sigma(Zh)} \quad \text{or} \quad \frac{[\sigma(\nu\bar{\nu}h)\, Br(h \to \gamma\gamma)]\, Br(h \to b\bar{b})}{\sigma(\nu\nu h) \cdot Br(h \to b\bar{b})}$$

- At the LHC: measure

$\sigma(p\bar{p} \to Wh)\, Br(h \to \gamma\gamma)$ and $\sigma(pp \to t\bar{t}h)\, Br(h \to \gamma\gamma)$
and $\sigma(pp \to t\bar{t}h)\, Br(h \to b\bar{b})$

Also get $Br(h \to \gamma\gamma) \Rightarrow$ combine NLC+LHC, $\pm 16\%$

- At $\gamma\gamma$ collider, $\Gamma(h \to \gamma\gamma) \cdot Br(h \to b\bar{b})$

↑ are measure separately @ NLC (see later)

$\Gamma(h \to \gamma\gamma)$ to $\simeq \pm 7\%$

$$\boxed{\Gamma_h^{tot} = \frac{\Gamma(h \to \gamma\gamma)}{Br(h \to \gamma\gamma)} \quad \text{to } \simeq \pm 17\% \text{ (not great)}}$$

Branching Ratios

- Distinguish SM/MSSM/?? scenarios ⇒
- Hints of m_A even if A^0 is out of kinematic reach

Beauty of $e^+e^- \to Z^0 h^0$

Tag, Higgs mass peak in recoil mass, then look at $h \to X$

Ditto for $e^-e^- \to e^-e^- h^0$

tag both e^- at $\theta > 5^\circ$ (detector challenge)

- Snowmass projects: improve understanding, try to decrease relative errors on prior estimates of *Br*'s ⇒
  - implications of sophisticated flavour tagging on fermionic branching ratios ⇒

    Jackson, Rowson, Van Kooten
  - improvement of $\mathrm{Br}(h \to WW^*)$ and $\sigma(WW \to h) \cdot \mathrm{Br}(h \to WW^*)$

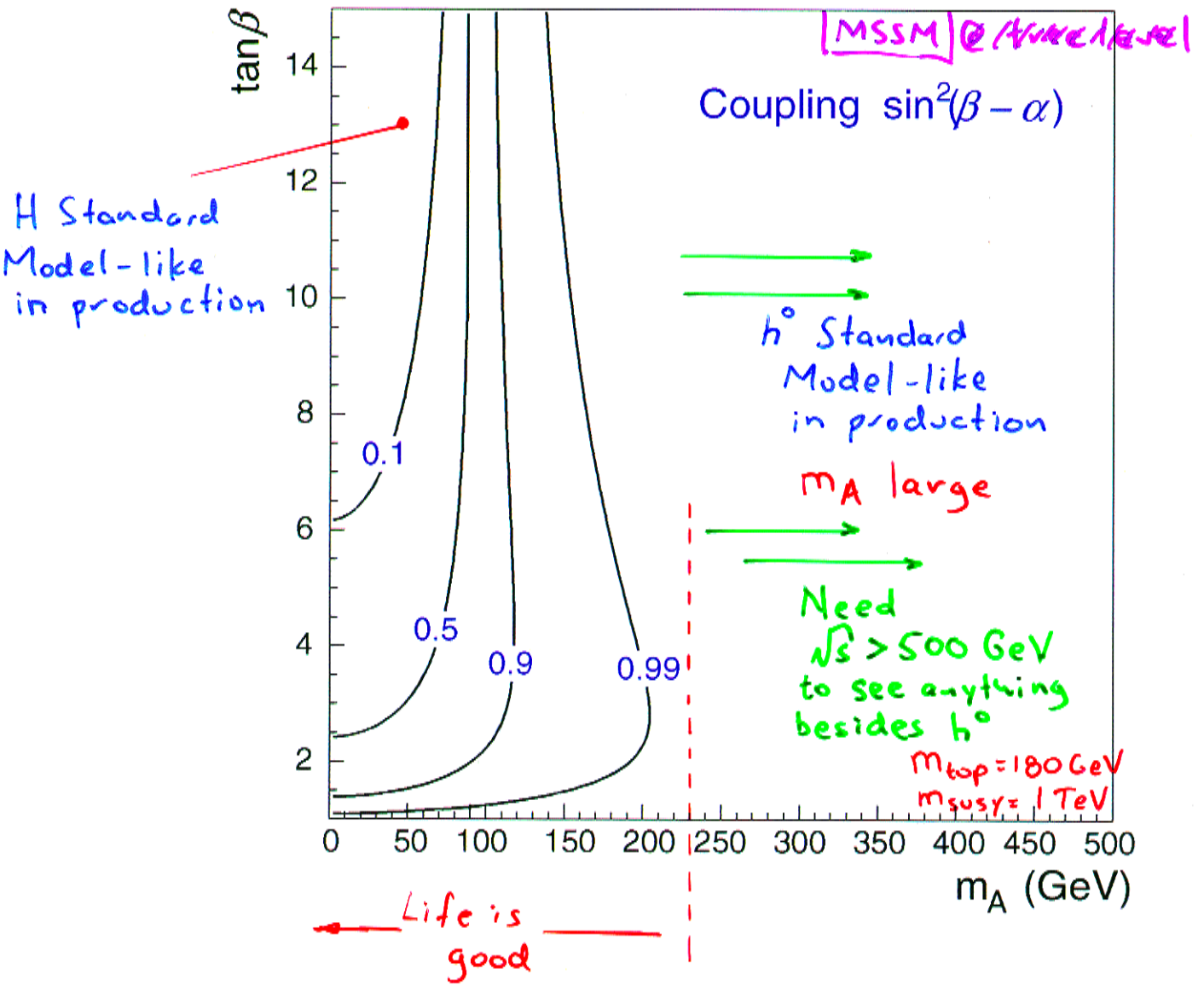
    (WW fusion, $e^+e^- \to h^0 \nu\bar{\nu}$)

Distinguishing H_{SM} from h^0_{MSSM} ⇒ Branching Ratios

Cross-Section, σ, proportional to:

$\sin^2(\beta-\alpha)$	$\cos^2(\beta-\alpha)$
hZ	HZ
$h\nu\bar{\nu}$	$H\nu\bar{\nu}$
HA	hA

Complementary!



See all the neutral Higgses @ $\sqrt{s} = 500$ GeV

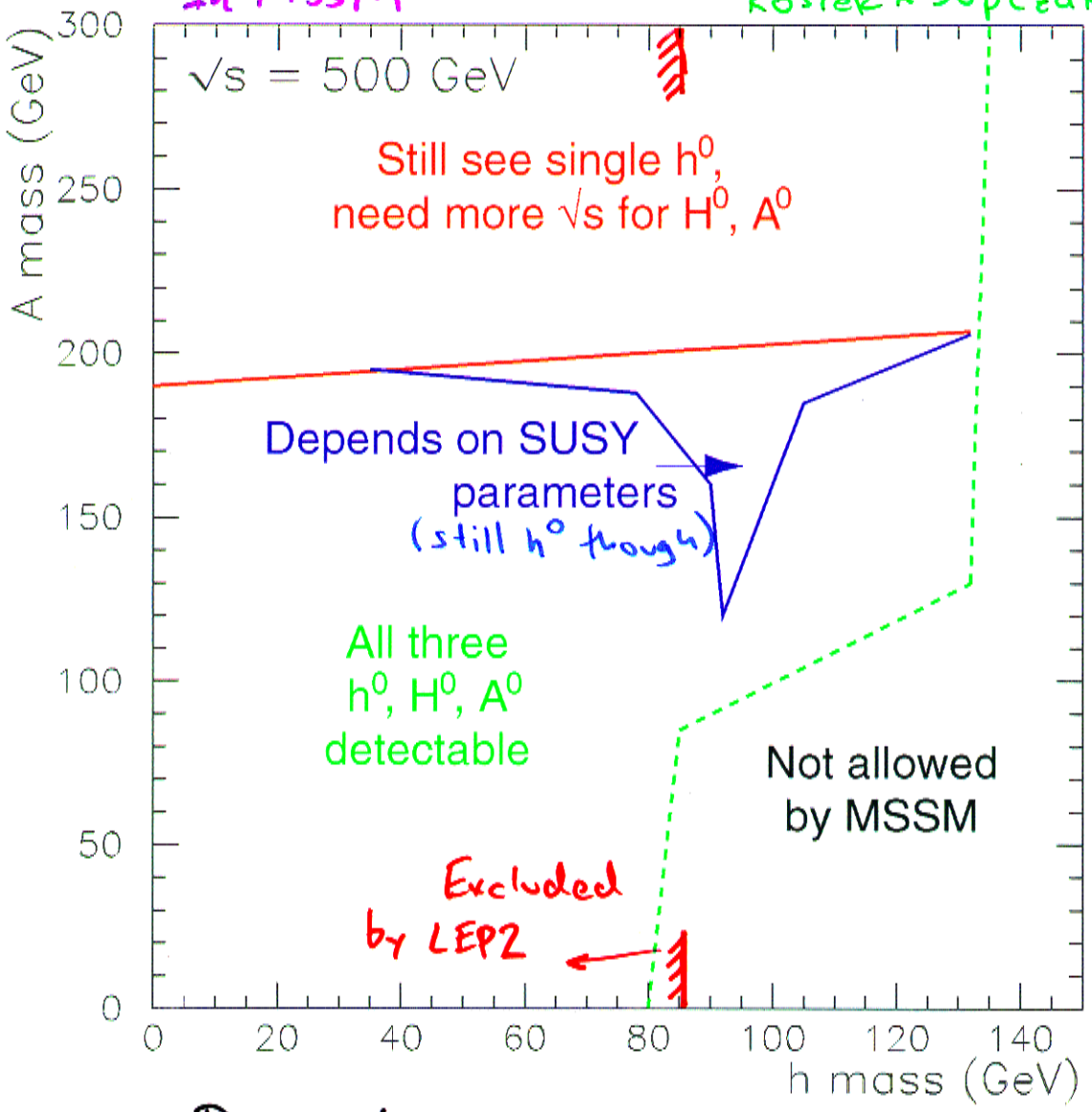
- MSSM / 2HDM:

$e^+e^- \to h^0 Z,\ h^0\nu\bar{\nu},\ H^0A^0,\ H^0Z^0,\ H^0\nu\bar{\nu},\ h^0A^0$
$\mu^+\mu^-$

needs confirmation for "decoupling" Higgs in other SUSY models

In MSSM

Rosiek & Sopczak



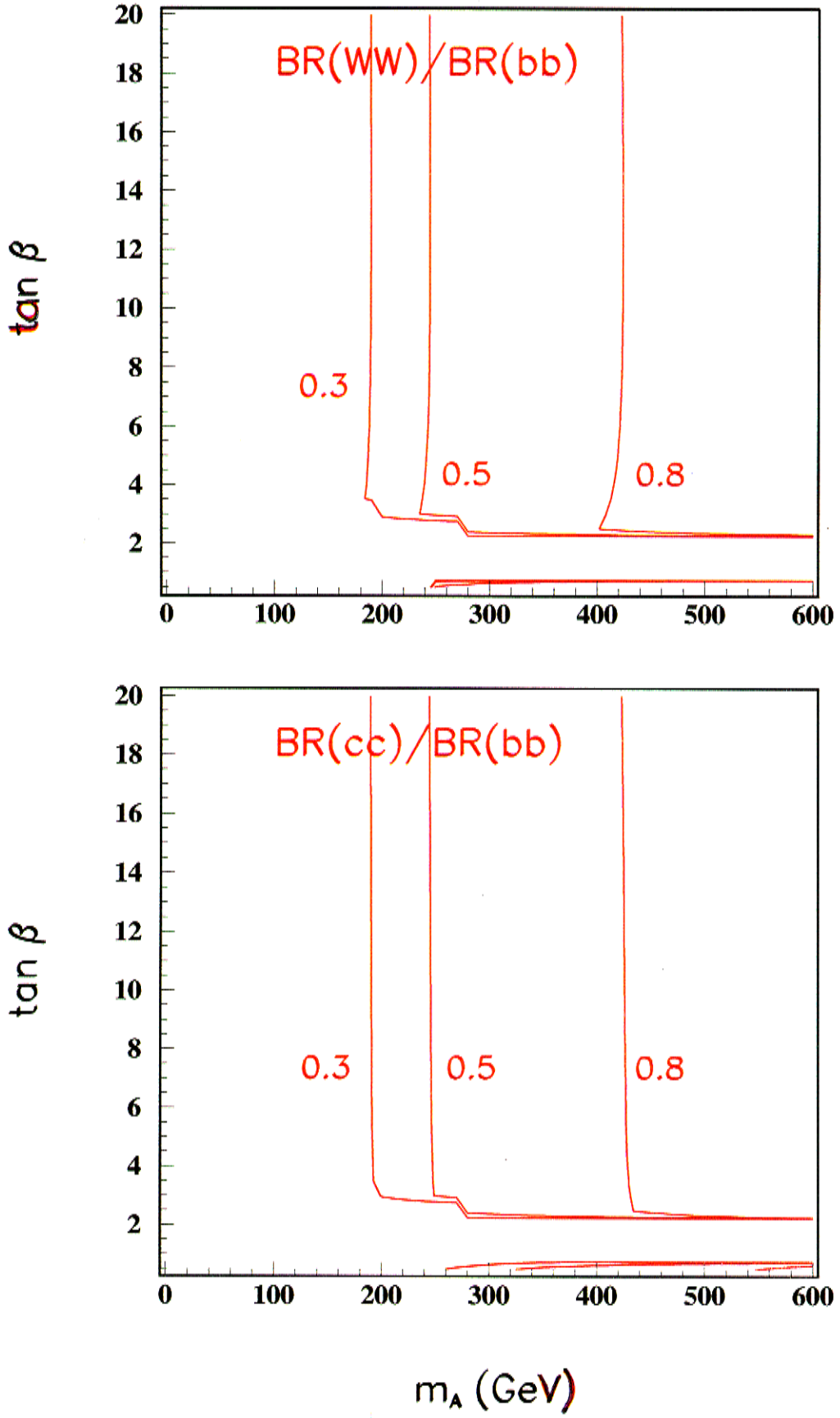
Snowmass Projects ⇒ check "no-lose" theorem

- Non-minimal SUSY / Extra Higgs singlets
- More general models, including exotic Higgs representations

Gunion, Haber, Kao, Moroi

NLC, Zh Mode: MSSM/SM Ratio Contours

m_{TOP}=175 GeV, m_h=110 GeV, Max. Mix.



1 Introduction

• Branching Ratios

A. Isamu + Kawagoe Nakamura

After the future discovery of Higgs, the precise measurement of Higgs properties gives us a lot of information.

For example, in the case SUSY is right and only one neutral higgs was discovered,

if the values $\begin{cases} m_h \\ \sigma_{tot} \cdot Br(h \to b\bar{b}) \\ \sigma_{tot} \cdot Br(h \to c\bar{c}) \end{cases}$

were measured,

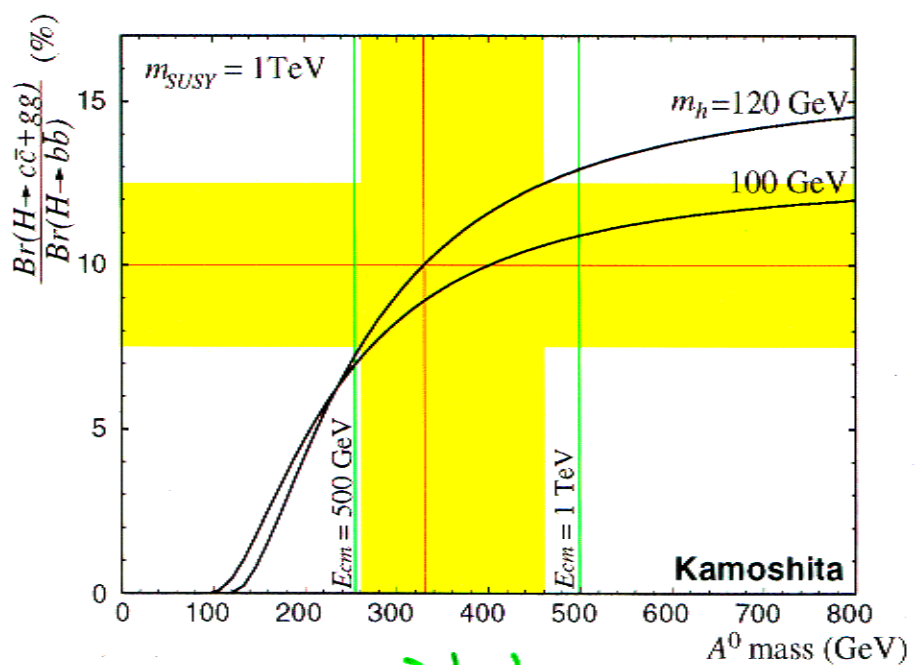
we could estimate A^0 mass from relation

$$\frac{Br(h \to c\bar{c})}{Br(h \to b\bar{b})} \approx \frac{m_c^2}{m_b^2} \cdot \left(\frac{1}{\tan\alpha \cdot \tan\beta}\right)^2$$

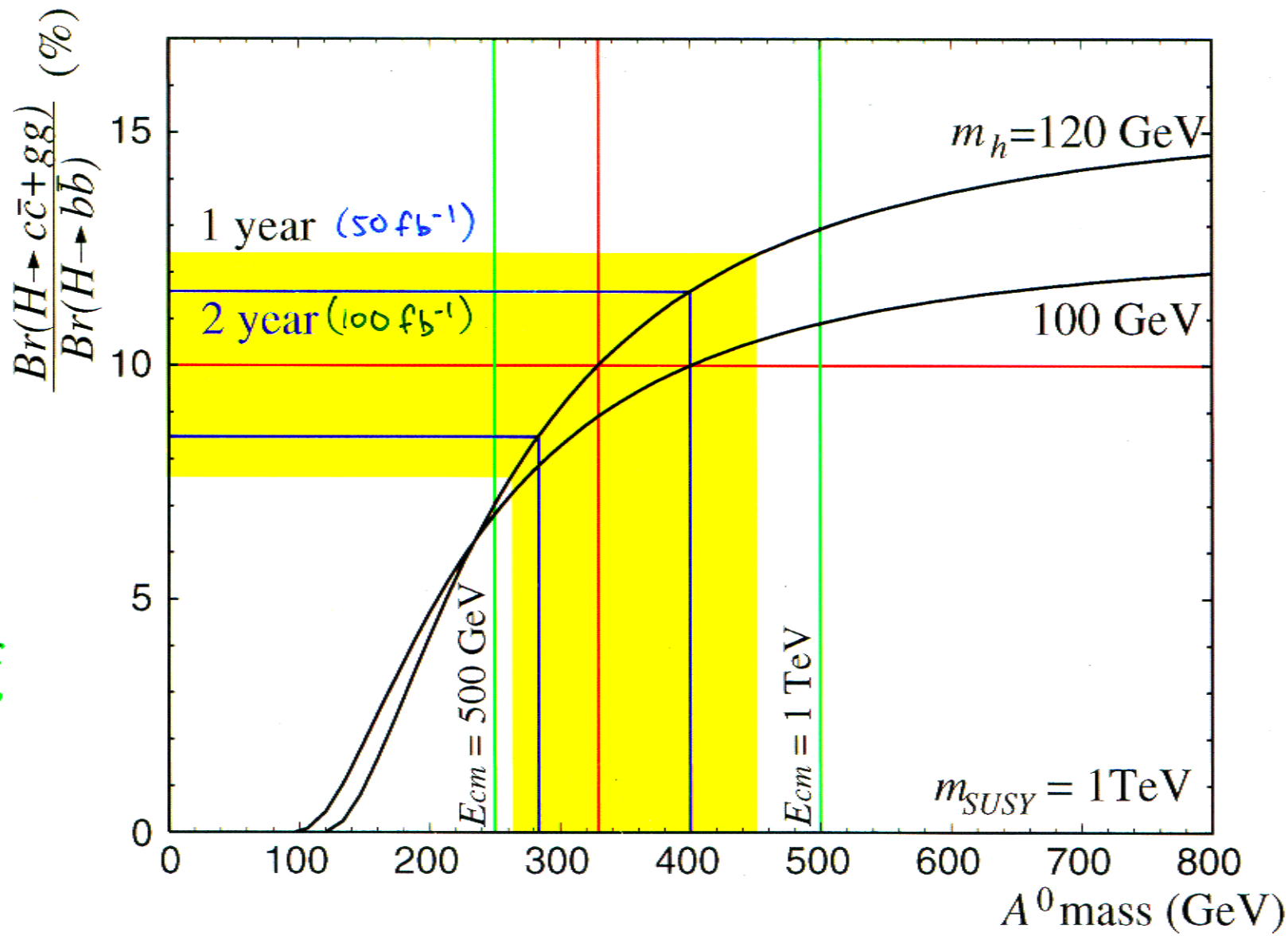
$$\approx \frac{m_c^2}{m_b^2} \cdot \left(\frac{m_h^2 - m_A^2}{m_A^2 - m_Z^2}\right)^2$$

Kamoshita-san's talk

e.g. see only the h^0:



→ look beyond kinematically accessible region



Systematics:

Δm_c

Δm_b

Indication of where the A^0 may lie

3 Event Selection

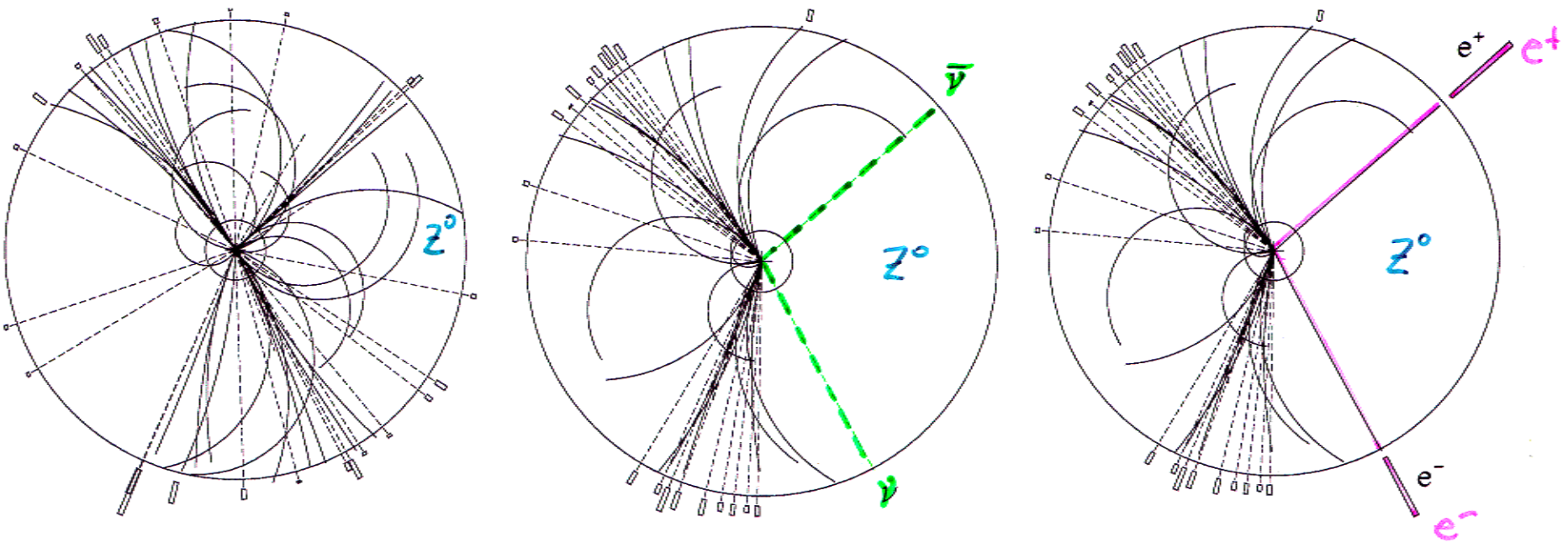
Isamu, Kawagoe, Nakamura

Strategy of this analysis

1. Select $Z^0 H^0$ event for each decay modes of Z^0
2. Determine the decay mode of Higgs using 3-D Impact Parameter

$\sqrt{s} = 300$ GeV, JLC detector

4 jet (~70 %) 2 jet (~20 %) 2 jet+ll (~10 %)

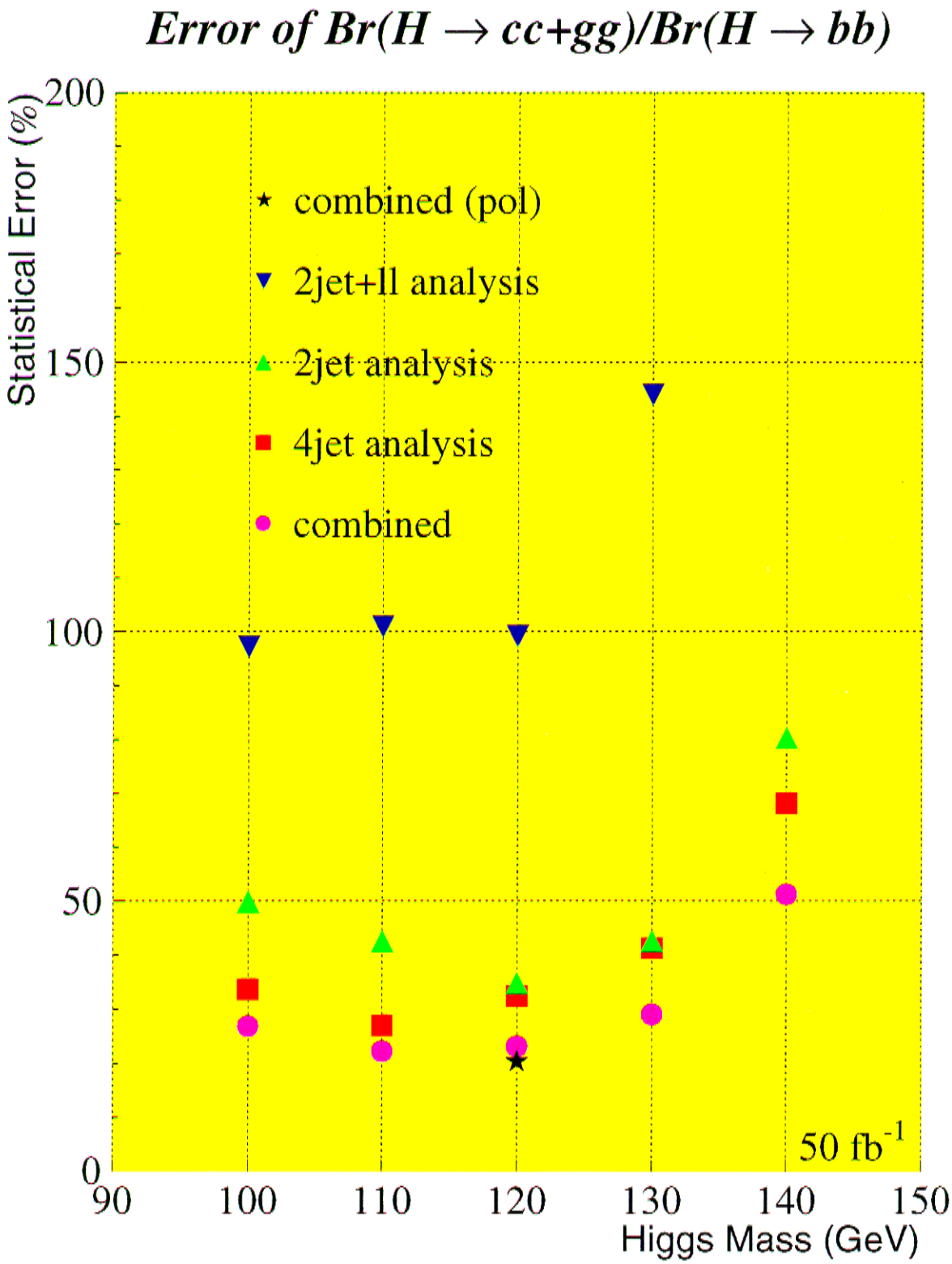


5 Measurement Error of the Branching Ratio

Statistical Error of Measurement (%)

$\frac{\Delta X}{X}$	no polarization				90 % polarization			
	4jet	2jet	2jet+ll	combined	4jet	2jet	2jet+ll	combined
σ_{tot}	—	—	15.1	—	—	—	13.9	—
$\sigma_{tot} \times Br(H \to b\bar{b})$	4.7	7.0	16.9	3.8	5.3	7.2	18.4	4.2
$\sigma_{tot} \times Br(H \to c\bar{c})$	62.1	71.4	164.0	45.1	53.2	62.1	174.0	39.4
$\sigma_{tot} \times Br(H \to c\bar{c} + gg)$	32.1	34.8	97.7	22.9	27.5	30.2	103.0	19.9
$\frac{Br(H \to c\bar{c})}{Br(H \to b\bar{b})}$	62.3	71.8	165.0	45.3	53.5	62.6	175.0	39.6
$\frac{Br(H \to c\bar{c} + gg)}{Br(H \to b\bar{b})}$	32.4	34.8	99.2	23.1%	28.0	31.1	105.0	20.4%

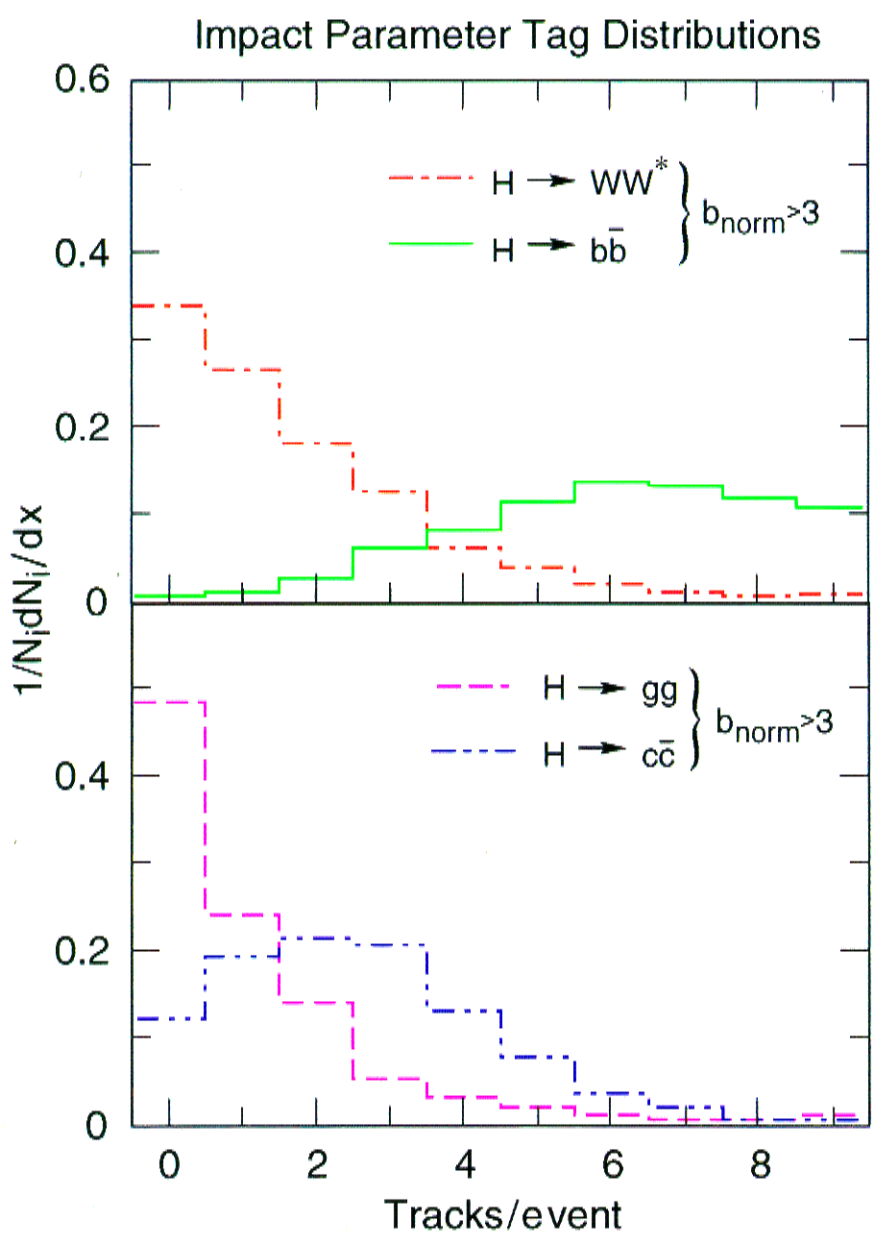
$m_H = 120$ GeV 50 fb^{-1}


Error of Br(H → cc+gg)/Br(H → bb)
Statistical Error (%)
200
150
100
50
0
90
100
110
120
130
140
150
Higgs Mass (GeV)
combined (pol)
2jet+ll analysis
2jet analysis
4jet analysis
combined
50 fb-1

b-Tagging

- Mostly normalized impact parameter used

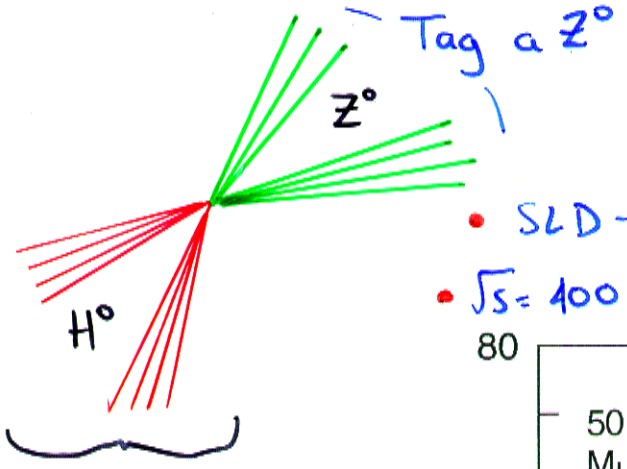
- Large boosts, longer decay lengths, charm + b vertices separated even more from I.P. ⇒ Use decay length info, too L/σ_L



$b_{norm} = \frac{b}{\sigma_b}$

"Significantly high-impact parameter" $b_{norm} > 3$

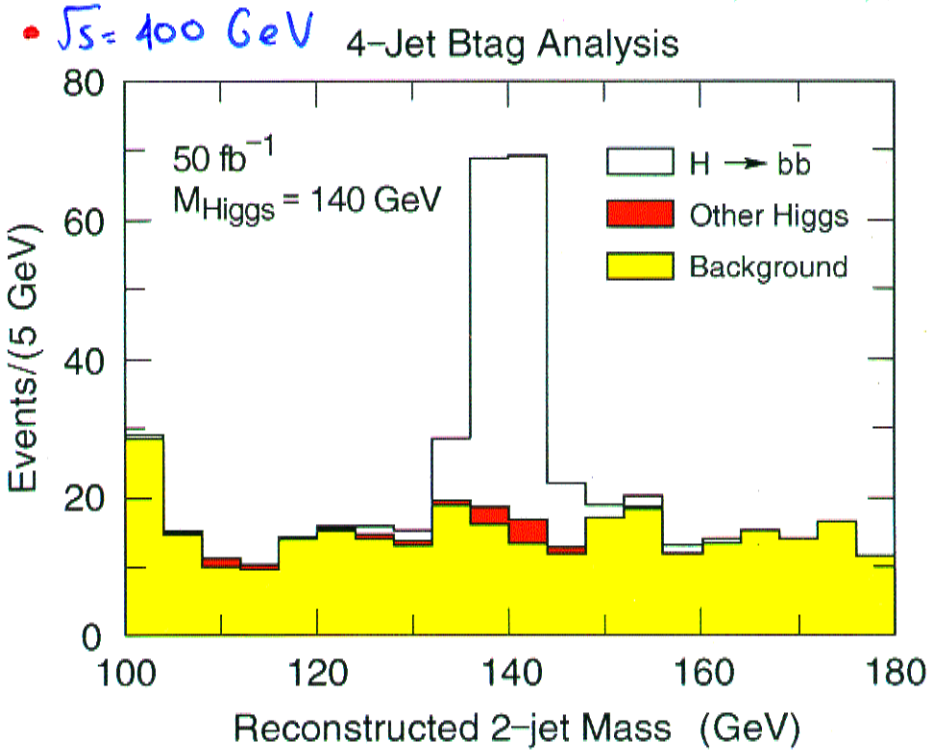
Hildreth
Barklow
Burke

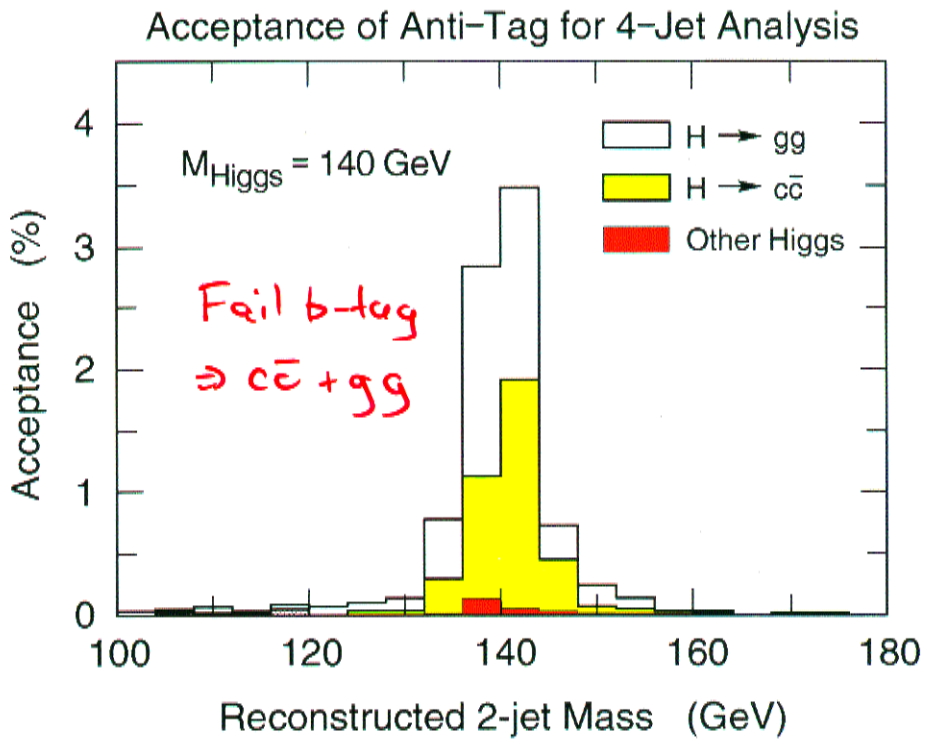


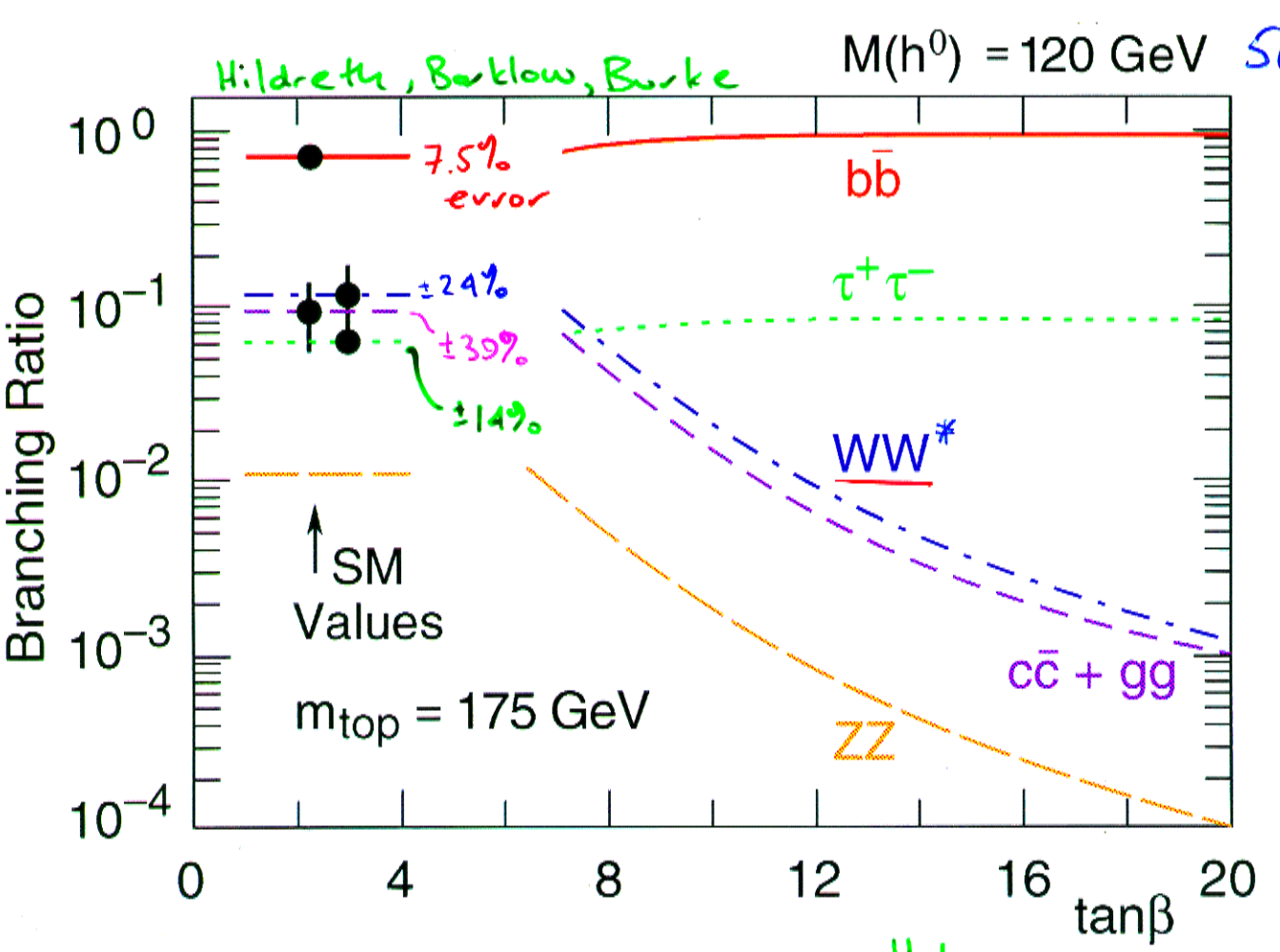
Flavour analyze these jets using vertex tag

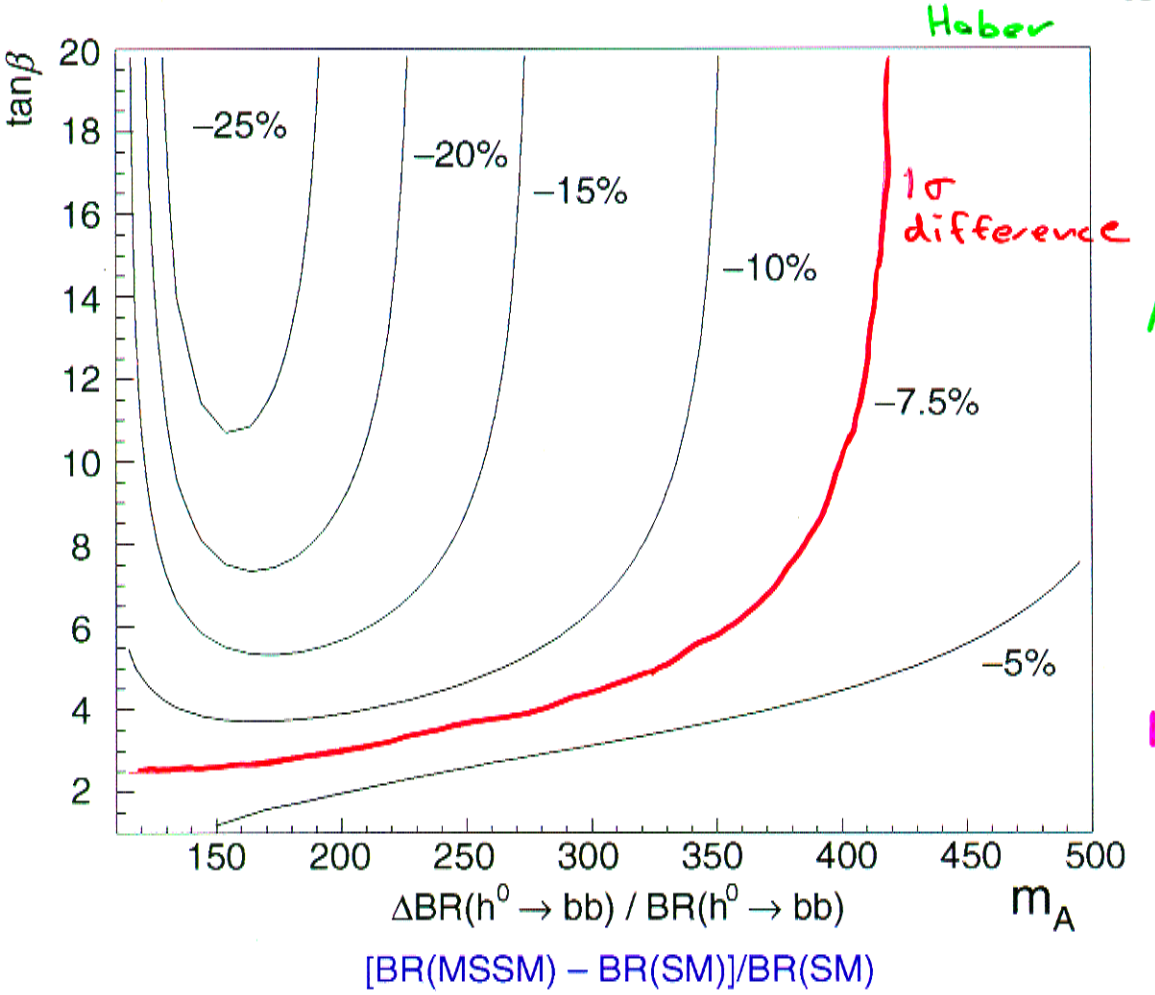
- SLD-like detector
- $\sqrt{s}$ = 400 GeV

Hildreth, Barklow, Burke





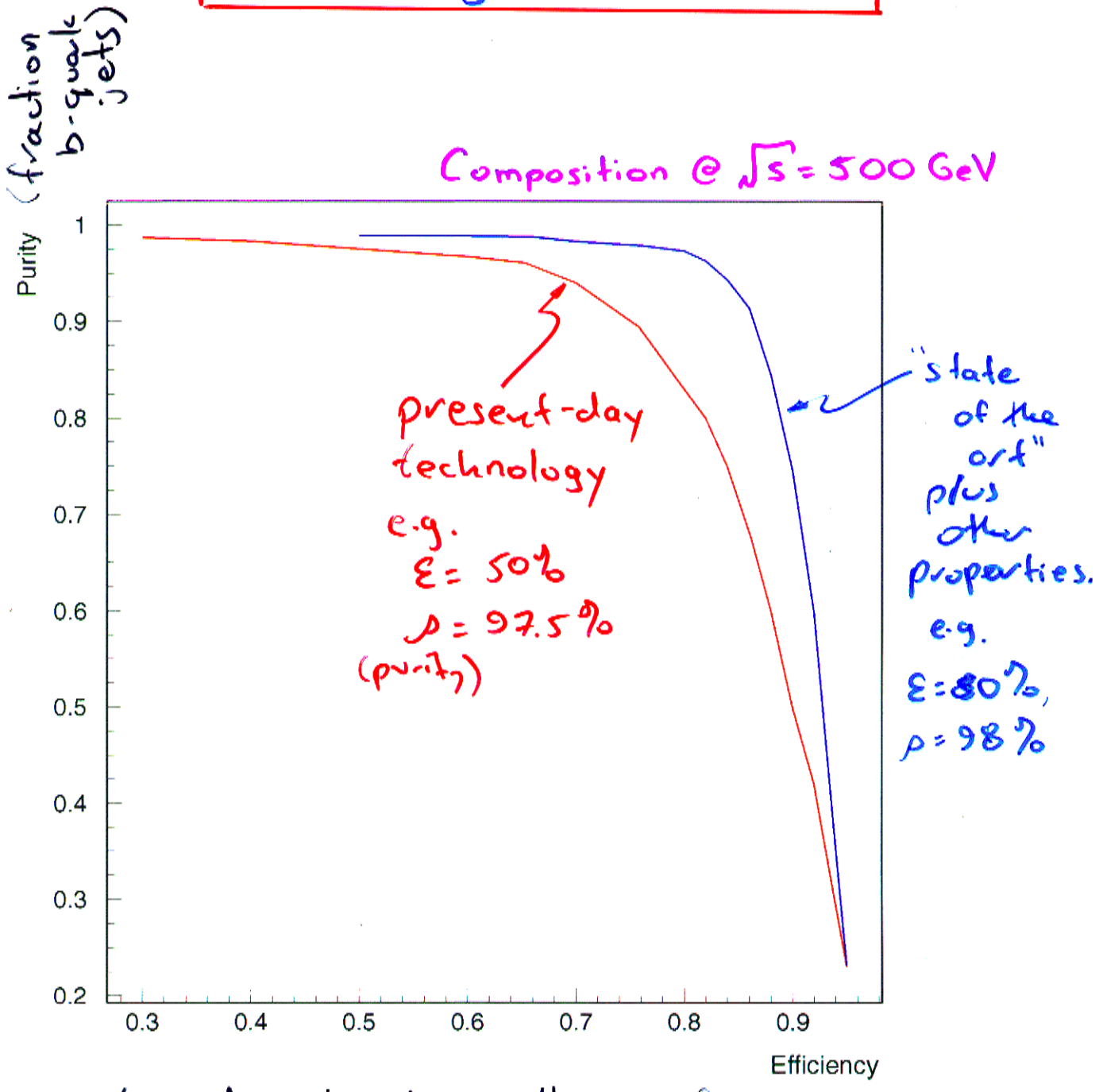




Again, more hints of where A° may be...

MORE RECENT

b-Tagging Performance

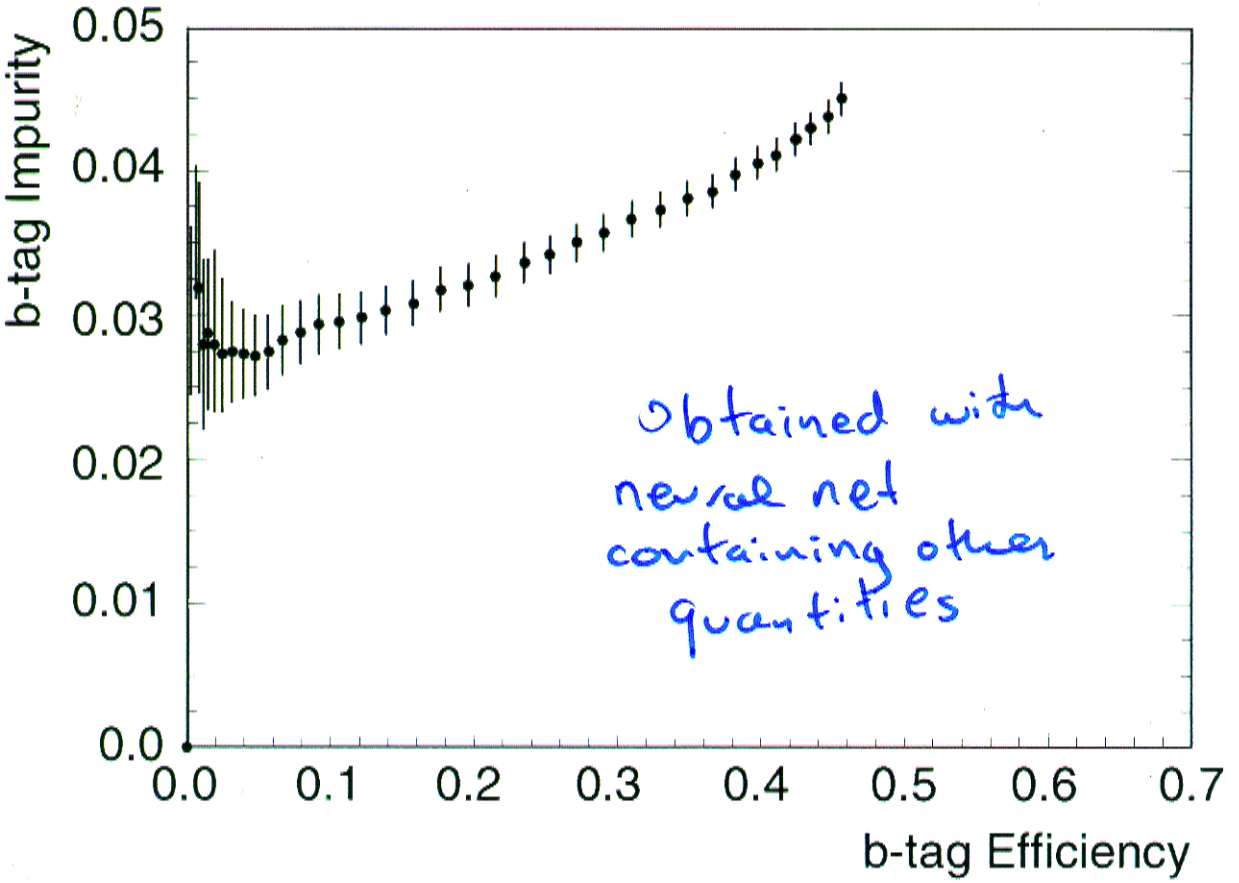


- Parametrised; subroutine call: for tagging b-quark jet

  Input ε, output ρ
  for i) conservative
  ii) agressive

  or

  Input ρ, output ε
  for "

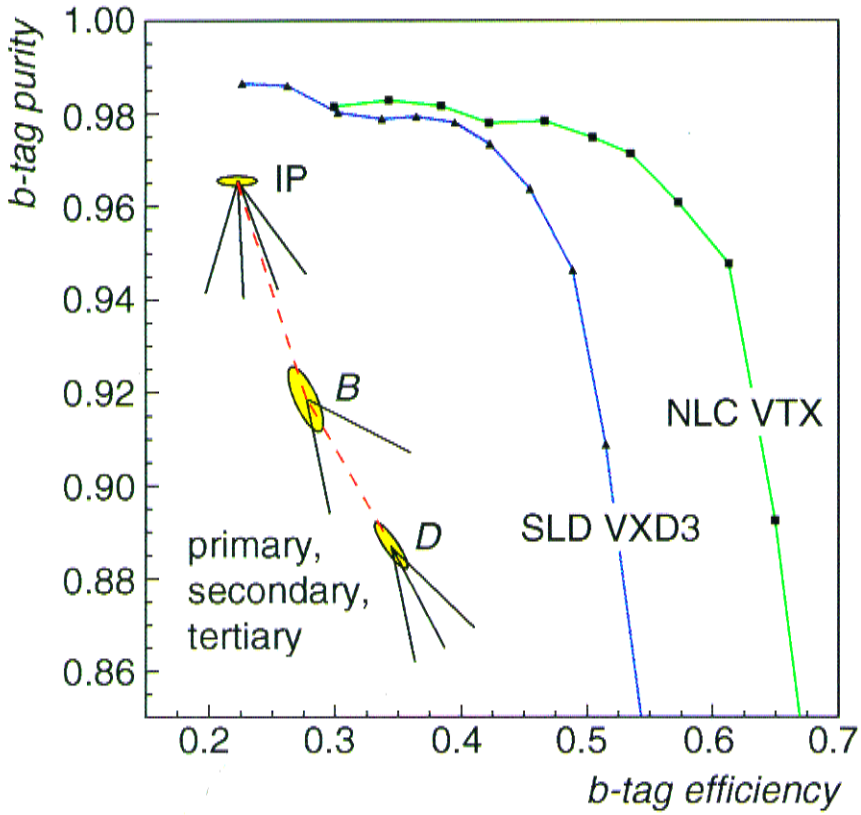


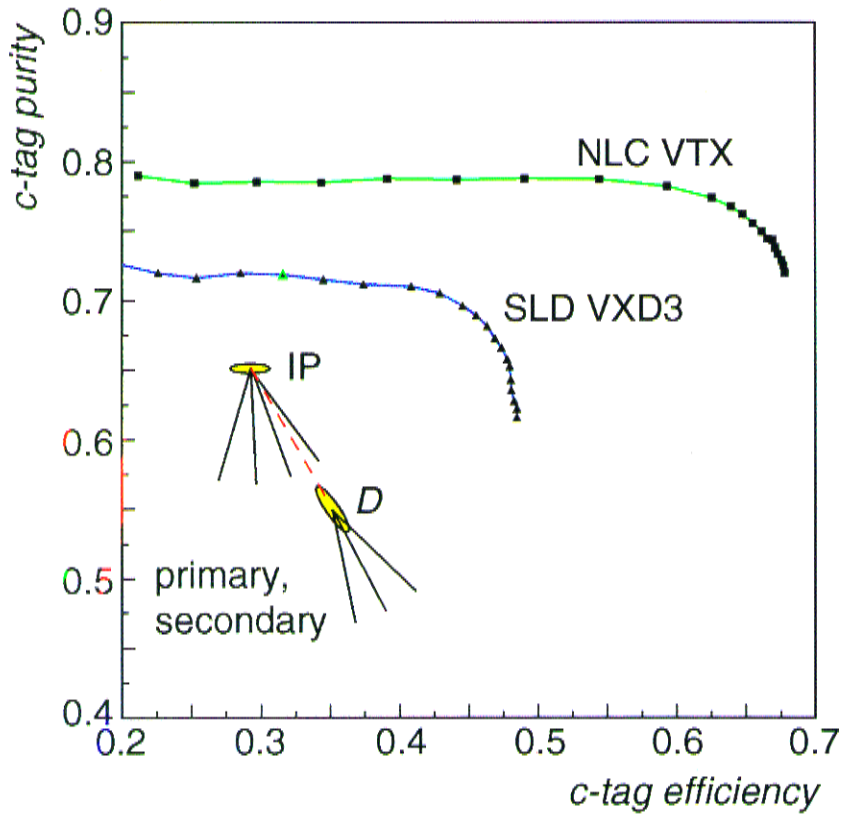
- Improves on tagging with b/σ_b only
- Possibilities for tagging charm and vertex tagging τau's
- Other methods too (c.f. D. Jackson's talk + C. Damerell's talk this workshop)

topological vertexing

- Know precisely where interaction point is
- State-of-the-art ~CCD vertex detector @ small radii ⇒ use to full advantage

TOPOLOGICAL TAGGING





- Use parameterized curves from Jackson & Damerell for Snowmass studies

Flavour Tagging

$\frac{Br(h \to c\bar{c})}{Br(h \to b\bar{b})}$ for $m_h \leq 130$ GeV

- $b\bar{b}$ channel

  Tag just one b quark (or both)

  $\varepsilon_{b\bar{b}} = 60\%$; Purity $\pi_{b\bar{b}} = 95.4\%$

  $\varepsilon_{c\bar{c}} = 2.6\%$

- $c\bar{c}$ channel

  Require tag of both c quark jets

  $\varepsilon_{c\bar{c}} = 40\%$; $\pi_{c\bar{c}} = 77.5\%$

  $\varepsilon_{b\bar{b}} = 11\%$

  $\varepsilon_{uds,g} = 0.2\%$

Results

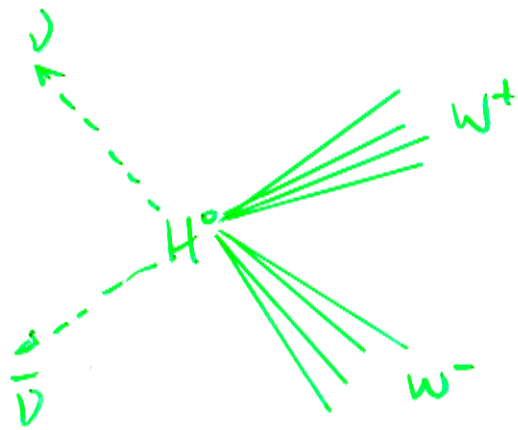
$\sigma(Zh) \cdot Br(h \to b\bar{b})$ to $\pm 2.5\% - 3.5\%$ if $m_h < 130$ GeV

$\sigma(Zh) \cdot Br(h \to c\bar{c})$ to $\pm 10\%$

include assumptions about e^+e^-h, $\nu\bar{\nu}h$ modes, distinguish SM/MSSM out to $m_{A^0} \simeq 450$ GeV @ 2σ.

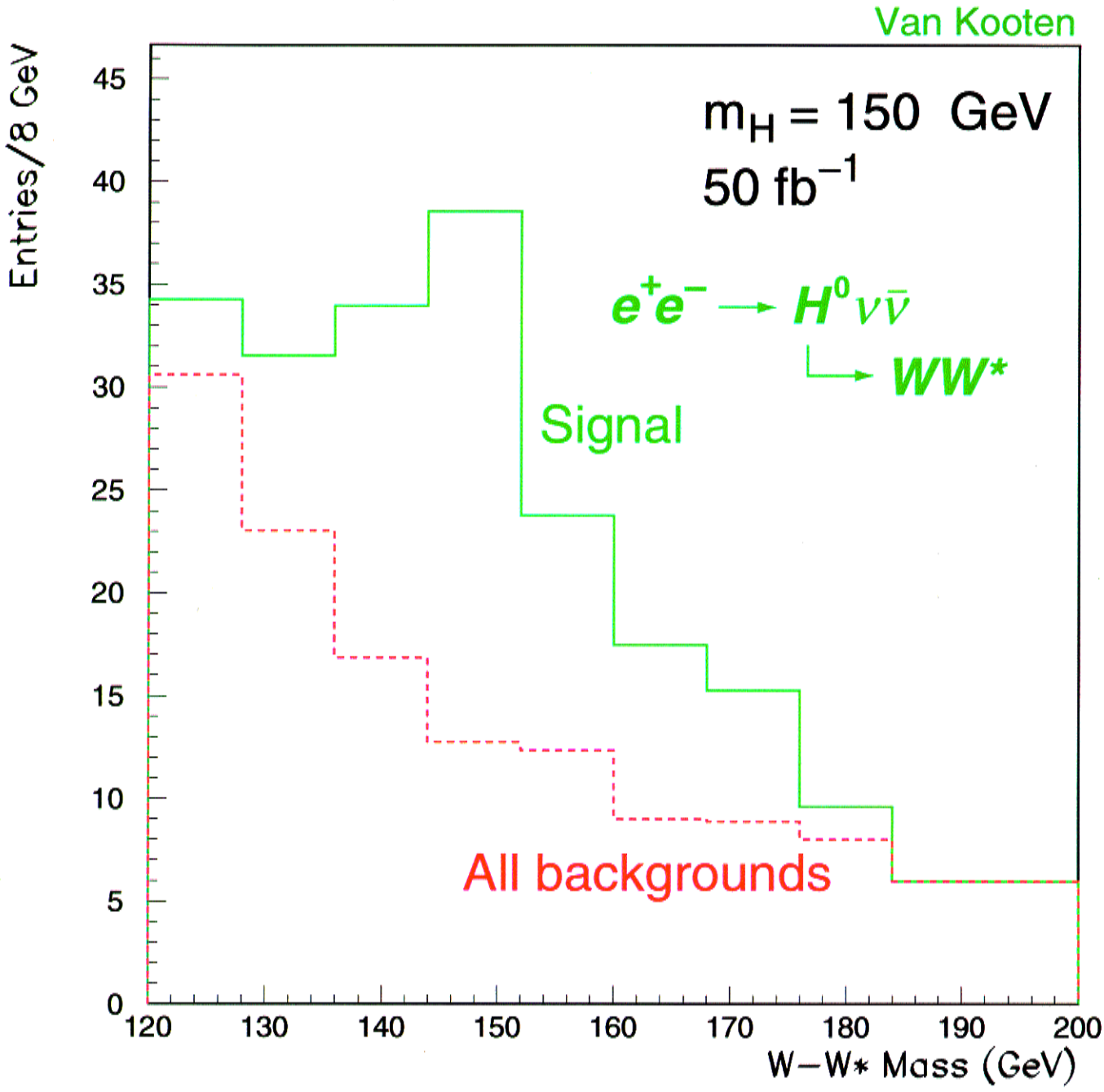
E. Event Mass Analysis

For Heavy Higgs $e^+e^- \to H\,\nu\bar{\nu}$
$\hookrightarrow W^+W^-$



- $|\cos\theta_{th}| < 0.8$
- Acoplanar jets, each reconstructing to $M > 60$ GeV, $\phi_{acop} > 15°$
- $P_{t\,miss} > 20\% \sqrt{s}$
- $\vec{P}_{miss}$ not down $10°$ hole
- Study invariant mass of entire event

  $\Rightarrow$ resolution depends on $\delta p/p$, $\delta E/E$



- Anti-b-tag for WW branching ratio, $\sigma(WW \to h)\cdot \mathrm{Br}(h \to WW^*)$ to 17%. (WWh coupling)
- Another analysis using hZ improves $\Delta\,\mathrm{Br}(h \to WW^*)$ from 24% to 17%

Interplay between $b\bar{b}$ and WW^* modes:

m_h	$BR(h \to WW^*)/BR(h \to b\bar{b})$
130	± 22%
140	± 11%
150	± 9%
170	± 28%

- MORE RECENT IMPRESSIVE WORK BY MARCO BATTAGLIA ($B_r(h \to b\bar{b})$, $h \to c\bar{c}$, ...)

CONCLUSIONS

- Mass, Width, Br measurements useful for providing handles for detector optimization in all three areas: $\frac{\delta_p}{p}$, $\frac{\delta_E}{E}$, vertexing.

COUPLINGS

"THE DANCE CONTINUES"

$200\ fb^{-1}$

- Inclusive $e^+e^- \to Zh$, $Z \to e^+e^-; \mu^+\mu^-$
  finds $\sigma(Zh)$
  Plus ZZ-fusion: $e^+e^- \to e^+e^- h$ (Gunion, Han, Sobey)
  $(ZZh)^2$ coupling to $\pm 6\%$

- $$\frac{[\sigma(Zh)\, Br(h \to b\bar{b})]}{\sigma(Zh)} = Br(h \to b\bar{b})$$ measure

- $(WWh)^2$ coupling
  i) $m_h \leq 140$ GeV
  $$\frac{[\sigma(\nu\bar{\nu}h)\, Br(h \to b\bar{b})]}{Br(h \to b\bar{b})} = \sigma(\nu\bar{\nu}h)$$ measure

  $\Rightarrow (WWh)^2$ coupling to $\pm(5-6)\%$

  ii) $m_h \geq 150$ GeV
  $$\frac{[\sigma(Zh)\, Br(h \to WW^*)]}{\sigma(Zh)} \quad \text{and} \quad \sigma(\nu\bar{\nu}h)\, Br(h \to WW^*)$$

  $\Rightarrow (WWh)^2$ coupling to $\pm(8-10)\%$

Table 4: Summary of approximate errors for branching ratios, coupling-squared ratios, couplings-squared and $\Gamma^{tot}_{h_{SM}}$ as determined using only data accumulated in $\sqrt{s} = 500$ GeV running at the NLC, assuming $L = 200$ fb^{-1} is accumulated. For $BF(h_{SM} \to \gamma\gamma)$ we have combined the NLC $\sqrt{s} = 500$ GeV results with results obtained using LHC data; the net accuracy so obtained for $BF(h_{SM} \to \gamma\gamma)$ is also reflected in the determination of $\Gamma^{tot}_{h_{SM}}$ following the indirect procedure. The errors for $\Gamma(h_{SM} \to \gamma\gamma)$ quoted are for $L = 50$ fb^{-1} accumulated in $\gamma\gamma$ collider running at $\sqrt{s} \sim m_{h_{SM}}/0.8$, and are those employed in the indirect $\Gamma^{tot}_{h_{SM}}$ determination.

$\int \mathcal{L} dt = 200\ fb^{-1}$

Quantity	Errors			
$m_{h_{SM}}$(GeV)	80	100	110	120
$(c\bar{c}h_{SM})^2/(b\bar{b}h_{SM})^2$	$\sim \pm 7\%$			
$(WWh_{SM})^2/(b\bar{b}h_{SM})^2$	–	–	–	$\pm 23\%$
$(\gamma\gamma h_{SM})^2/(b\bar{b}h_{SM})^2$	$\pm 52\%$	$\pm 33\%$	$\pm 29\%$	$\pm 26\%$
$(ZZh_{SM})^2$	$\pm 6\%$			
$BF(h_{SM} \to b\bar{b})$	$\pm 5\%$			
$BF(h_{SM} \to c\bar{c})$	$\sim \pm 9\%$			
$BF(h_{SM} \to WW^*)$	–			
$(WWh_{SM})^2$	$\pm 5\%$			
$(ZZh_{SM})^2/(WWh_{SM})^2$	$\pm 6\% - \pm 7\%$			
$BF(h_{SM} \to \gamma\gamma)$	$\pm 15\%$	$\pm 14\%$	$\pm 14\%$	$\pm 14\%$
$(\gamma\gamma h_{SM})^2$	$\sim \pm 7\%$			
$\Gamma^{tot}_{h_{SM}}$ (indirect)	$\pm 17\%$	$\pm 17\%$	$\pm 17\%$	$\pm 16\%$
$(b\bar{b}h_{SM})^2$	$\pm 20\%$	$\pm 19\%$	$\pm 19\%$	$\pm 19\%$
$m_{h_{SM}}$(GeV)	130	140	150	170
$(c\bar{c}h_{SM})^2/(b\bar{b}h_{SM})^2$	$\pm 7\%$	?		
$(WWh_{SM})^2/(b\bar{b}h_{SM})^2$	$\pm 16\%$	$\pm 8\%$	$\pm 7\%$	$\pm 16\%$
$(\gamma\gamma h_{SM})^2/(b\bar{b}h_{SM})^2$	$\pm 27\%$	$\pm 30\%$	$\pm 41\%$	–
$(ZZh_{SM})^2$	$\pm 5\%$			
$BF(h_{SM} \to b\bar{b})$	$\pm 6\%$		$\pm 9\%$	$\sim 20\%$?
$BF(h_{SM} \to c\bar{c})$	$\sim \pm 9\%$	?		
$BF(h_{SM} \to WW^*)$	$\pm 16\%$	$\pm 8\%$	$\pm 6\%$	$\pm 5\%$
$(WWh_{SM})^2$	$\pm 5\%$	$\pm 5\%$	$\pm 8\%$	$\pm 10\%$
$(ZZh_{SM})^2/(WWh_{SM})^2$	$\pm 7\%$	$\pm 7\%$	$\pm 9\%$	$\pm 11\%$
$BF(h_{SM} \to \gamma\gamma)$	$\pm 14\%$	$\pm 20\%$?	$\pm 41\%$	–
$(\gamma\gamma h_{SM})^2$	$\pm 15\%$	$\pm 17\%$	$\pm 31\%$	–
$\Gamma^{tot}_{h_{SM}}$ (indirect)	$\pm 13\%$	$\pm 9\%$	$\pm 10\%$	$\pm 11\%$
$(b\bar{b}h_{SM})^2$	$\pm 14\%$	$\pm 11\%$	$\pm 13\%$	$\pm 23\%$
$m_{h_{SM}}$(GeV)	180	190	200	300
$(ZZh_{SM})^2$	$\pm 5\%$		$\pm 6\%$	$\pm 9\%$
$(WWh_{SM})^2$	$\pm 11\%$	$\pm 12\%$	$\pm 13\%$	$\pm 24\%$
$(ZZh_{SM})^2/(WWh_{SM})^2$	$\pm 12\%$	$\pm 13\%$	$\pm 14\%$	$\pm 25\%$
$BF(h_{SM} \to WW)$	$\pm 6\%$	$\pm 7\%$	$\pm 8\%$	$\pm 14\%$?
$(\gamma\gamma h_{SM})^2$	$\pm 13\%$	$\pm 12\%$	$\pm 12\%$	$\pm 22\%$
$\Gamma^{tot}_{h_{SM}}$ (indirect)	$\pm 13\%$	$\pm 14\%$	$\pm 15\%$	$\pm 28\%$

CP Determination

- In Zh or $\mu^+\mu^-$ (s-channel) from angular correlations of decay products from:

$$h^0 \to \tau^+\tau^- \qquad \tau^- \to \pi^-\nu\bar{\nu}, \quad \tau^+ \to \pi^+\nu\bar{\nu}$$

$$h^0 \to t\,\bar{t} \qquad t \to Wb, \quad \bar{t} \to Wb$$

- Angular/energy distributions of $e^+e^- \to t\,\bar{t}\,h^0$
- $\gamma\gamma$ collisions: $N^{\parallel}$ = # Higgs, γ polarizations parallel
  = " " " perpendic.

$$\mathcal{A} = \frac{N^{\parallel} - N^{\perp}}{N^{\parallel} + N^{\perp}} = \begin{cases} +1, \text{ CP-even} \\ -1, \text{ CP-odd} \end{cases}$$

Snowmass projects:

- Realistic experimental simulations
- Consider general 2HDM models, compare distributions of $e^+e^- \to t\,\bar{t}\,h^0$ products with SM for identical cross-sections *He, Gunion* $\Rightarrow$

• More CP Determination

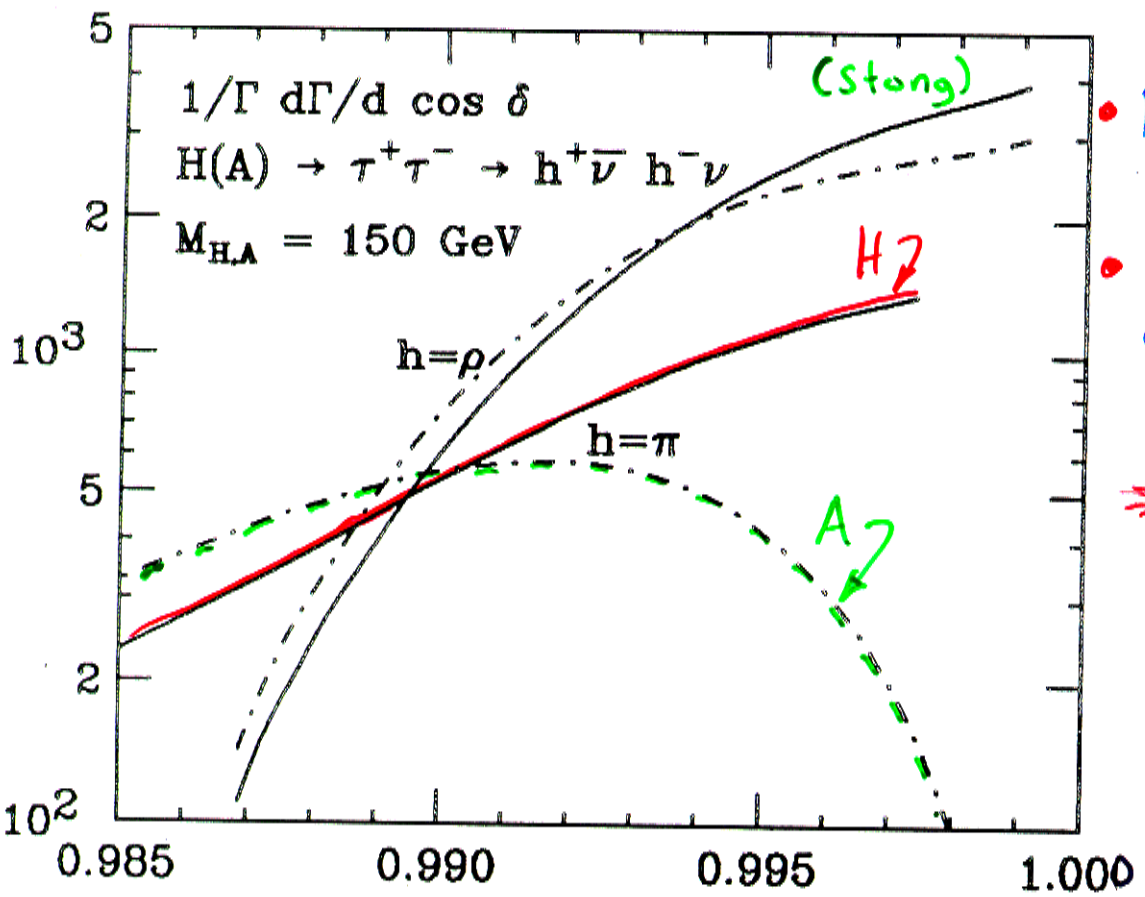
Problematic • $\phi \to W^+W^-$

$Z^0 Z^0 \to f\bar{f}$ } Correlations between decay planes of products
$\hookrightarrow f\bar{f}$

CP-odd has zero tree-level WW, ZZ couplings, CP-even swamps effect (Gunion)

Better • $\phi \to \tau^+\tau^-, t\bar{t}$, spin analyze decay products
$\Rightarrow$ angular correlations

Best • $\gamma\gamma \to \phi$ asymmetries



• Better for $\phi \to t\bar{t}$.

• τ polarization also useful in $\tilde{\tau}$ studies (Nojiri)

$\Rightarrow$ DETECTOR CHALLENGE, distinguish ρ, a_1, etc.

δ/π - angle between hadrons π or ρ

Even more on CP

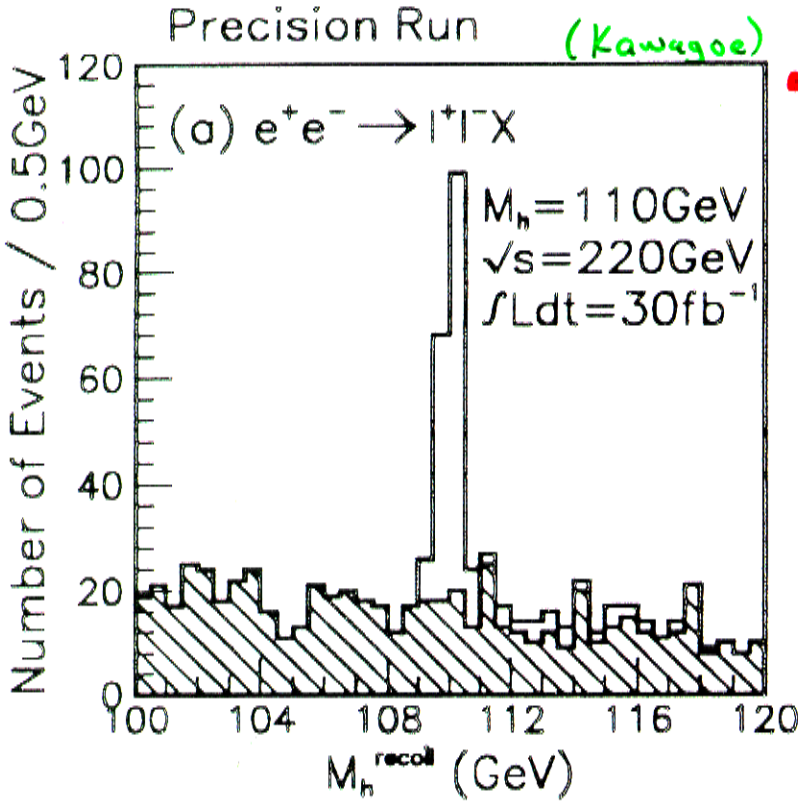
(Gunion)

- $h \to \gamma\gamma \Rightarrow$ scalar (not vector) (Yang's theorem)
- Substantial WWh, ZZh couplings?
  $\Rightarrow$ large CP = + component
- $(ZZh)^2 \sim (WWh)^2 \sim 1 \Rightarrow$ pure CP = +
  (unless Higgs representations higher than doublets)
- Zh production

$$\frac{d\sigma}{d\cos\theta} \propto \frac{8 M_Z^2}{s} + \beta^2 \sin^2\theta$$

But CP = − component only affects @ 1-loop level

and, If no CP = +, rate won't be enough to see!



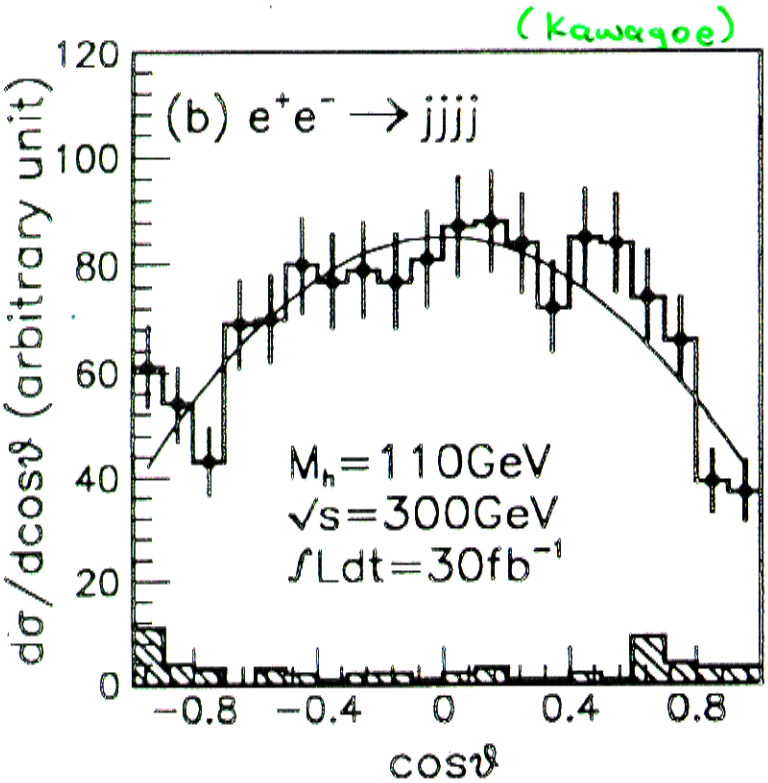
• Cross Section

Use $H^0 Z^0$, $Z^0 \to l^+l^-$, $H^0 \to X$

$$\sigma(e^+e^- \to h^0 Z) = \underbrace{\sin^2(\beta-\alpha)}_{\text{check}}\,\sigma(e^+e^- \to H_{SM} Z)$$

problem, usually ~ 1

$$\boxed{\begin{array}{ll} \Delta\sigma \simeq 7\% & \text{w/ } 30 fb^{-1} \\ \simeq 5\% & \text{w/ } 50 fb^{-1} \end{array}}$$

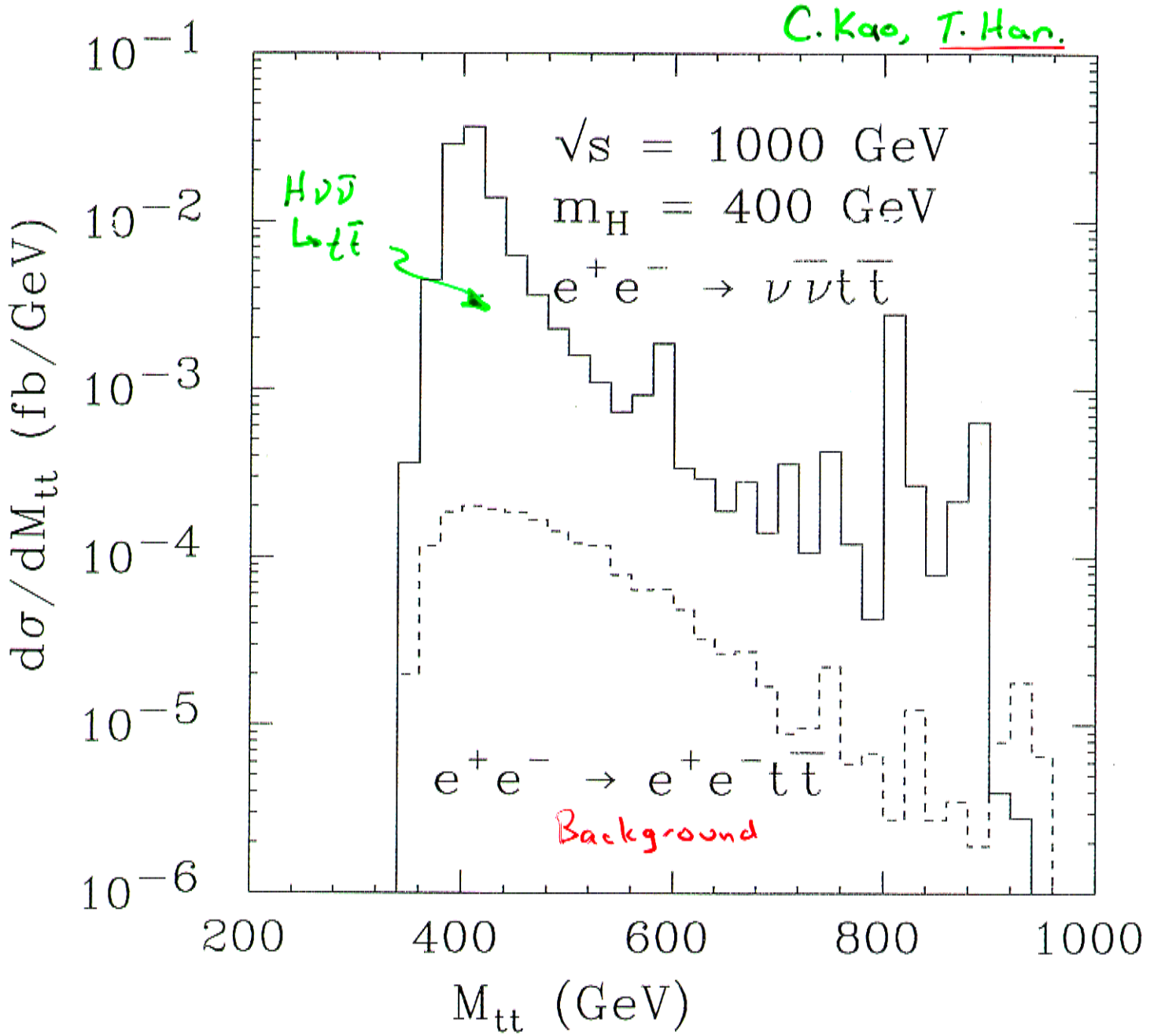


• Spin - Parity

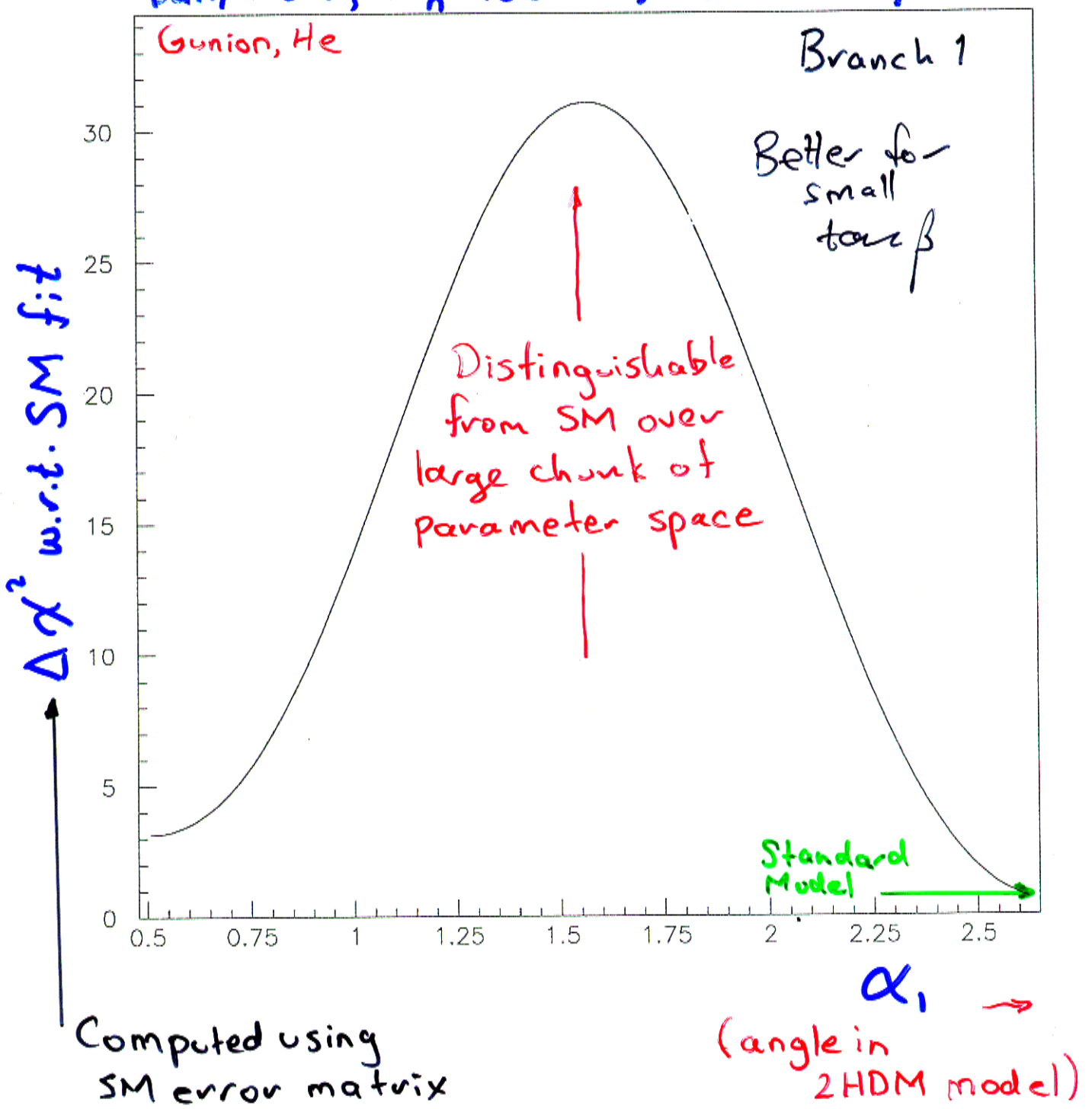
	Scalar	Pseudo Scalar
$\frac{d\sigma(e^+e^- \to \phi Z^0)}{d\cos\theta}$	$\propto \sin^2\theta$	$\propto (1-\sin^2\theta)$
$\frac{d\sigma(Z^0 \to f\bar{f})}{d\cos\theta_*}$	$\propto \sin^2\theta$	$\propto (1 \pm \cos\theta_*)$
	0^{++}	0^{-+}

in the high energy limit

★ ⇒ check if ZZh coupling is $\frac{2m_Z^2}{v}$!


C. Kao, T. Han.
$\sqrt{s}$ = 1000 GeV
m_H = 400 GeV
$e^+e^- \to \nu\bar{\nu}t\bar{t}$
$H\nu\bar{\nu}$
$\hookrightarrow t\bar{t}$
$e^+e^- \to e^+e^-t\bar{t}$
Background
$d\sigma/dM_{tt}$ (fb/GeV)
M_{tt} (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
200
400
600
800
1000

$\tan\beta = 0.5$, $m_h = 100$ GeV, $\sqrt{s} = 1$ TeV, $\int \mathcal{L} = 50\,fb^{-1}$



SUMMARY

- @ $\sqrt{s} = 500$ GeV, discovery of SM intermediate-mass Higgs no problem with $\int \mathcal{L} dt \simeq 10\ fb^{-1}$

- $\sqrt{s} = 500$ GeV allows the detection of <u>at least</u> the lightest MSSM Higgs h^0

⇒ If not seen, MSSM is ruled out.

- If A^0 not kinematically accessible, Branching Ratios can give <u>hints</u> of m_A, $\tan\beta$ and tell us where to go
- For definitive evidence, need $\sqrt{s} > 2 m_A$

⇒ Need more up-to-date $E_{cm} = 1-2$ TeV experimental simulations. → determine couplings! e.g. λ_{Hhh}

- A linear collider should be able to identify the beast → determine couplings!

- Just as LHC sweated to prove the feasability of $h^0 \to \gamma\gamma$, we need rock-solid proof of:
  - adequate b-tagging
  - experimental simulation of capability to say it is "the" Higgs (Murayama) at all reasonable $\sqrt{s}$