Higgs Boson Studies at an e^+e^- Linear Collider: Intermediate Mass and Heavy

LINE DRIVE A Fermilab Series of Linear Collider Double-Headers

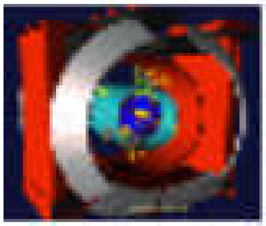
(Triple header? Relief pitching second game?)

Outline

- The NLC Collider and Detectors
- Mass region
- Profile of Higgs Boson, Part II
  - Cross sections
  - Branching Ratios
  - Couplings
- Width/Mass
- Nastier scenarios
- Conclusions/Summary

Acknowledgments:

TESLA TDR, FNAL Report, Orange Book authors/editors

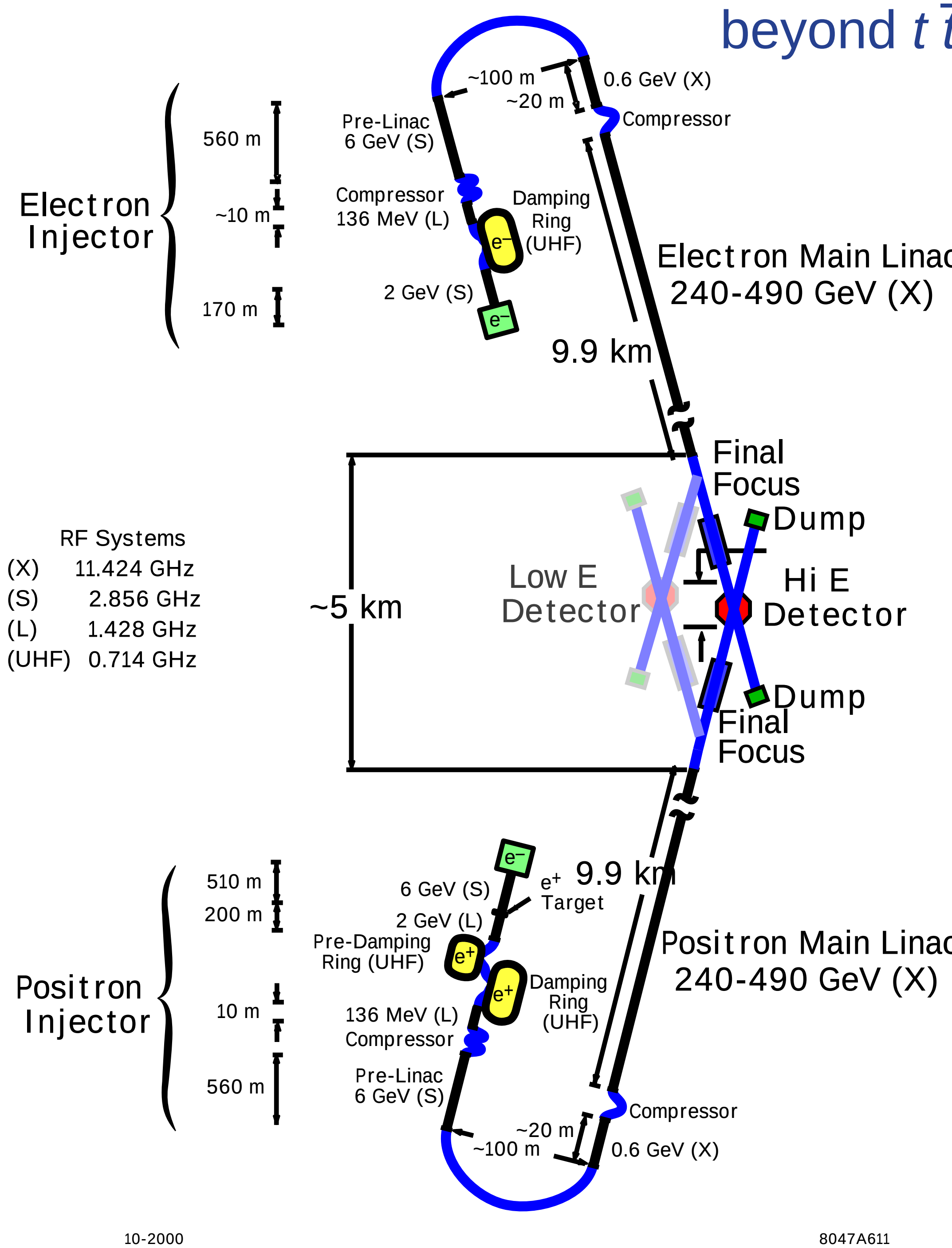


Workshop on the future of Higgs Physics

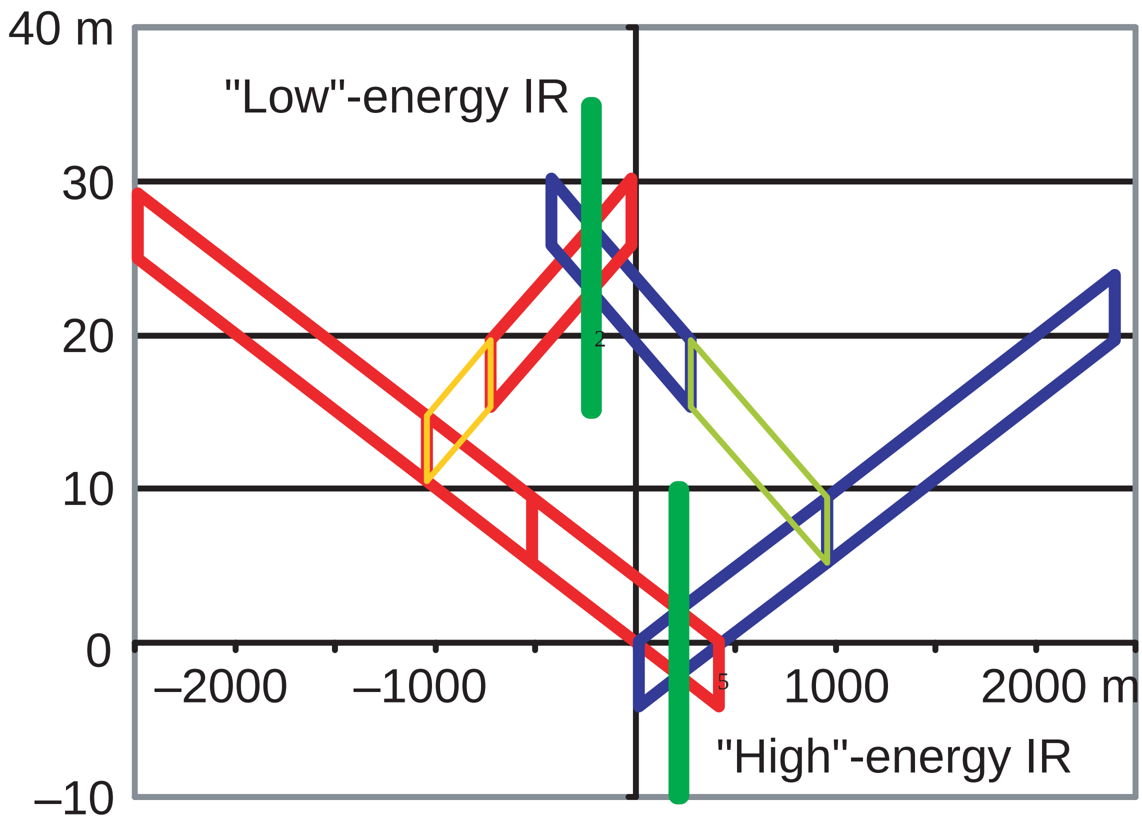
Rick Van Kooten
Indiana University
3 May 2001

NLC 2001

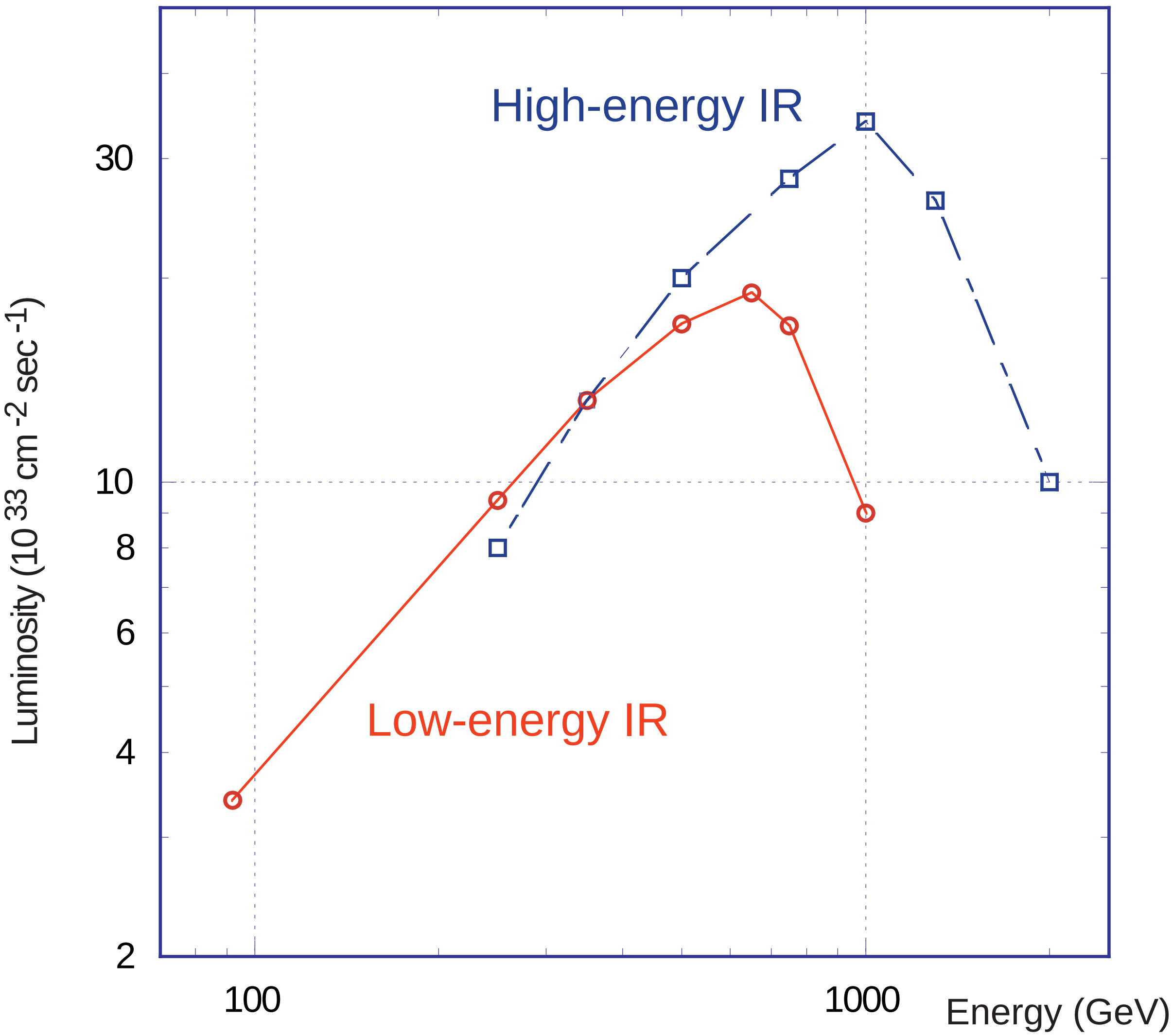
Baseline for NLC 2001: two linacs inclined at 20 mrad crossing angle, no bend angle at high-energy IP, can work at multi-TeV energies. Low-energy IP does have bend, max. energy well beyond $t\bar{t}$ threshold



Repetition Rate	120 Hz (can be split 60-60)
RF Frequency	11.4 GHz
Bunch Separation	1.4 nsec
Beamstrahlung	4.6%
Electron polarization	~80% (known to 0.25 – 1.0% from polarimetry)
Positron polarization possible	



- Lateral separation of 25 m, longitudinal separation of 440 m
- e.g., "L" or "SD" NLC detector at one IR, "SD" or "P" NLC detector at other, push-pull at either possible (e.g., *gg* operation?)



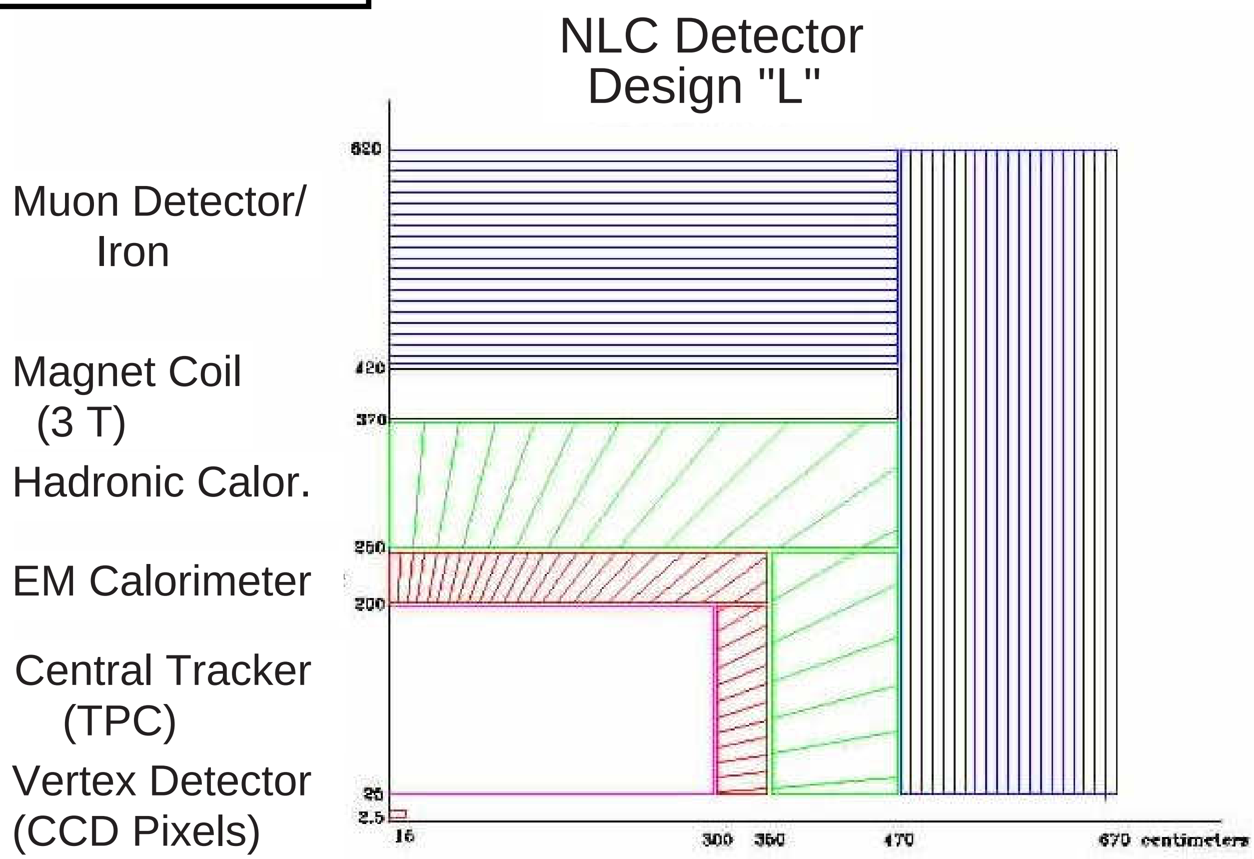
Low-energy IR

- Running at Z pole
- Scan W-pair threshold
- Scan HZ threshold
- Sit at HZ production peak ($\sqrt{s} \sim M_Z + M_h + \sim 20$ GeV) for precision property measurements
- Scan $t\bar{t}$ threshold

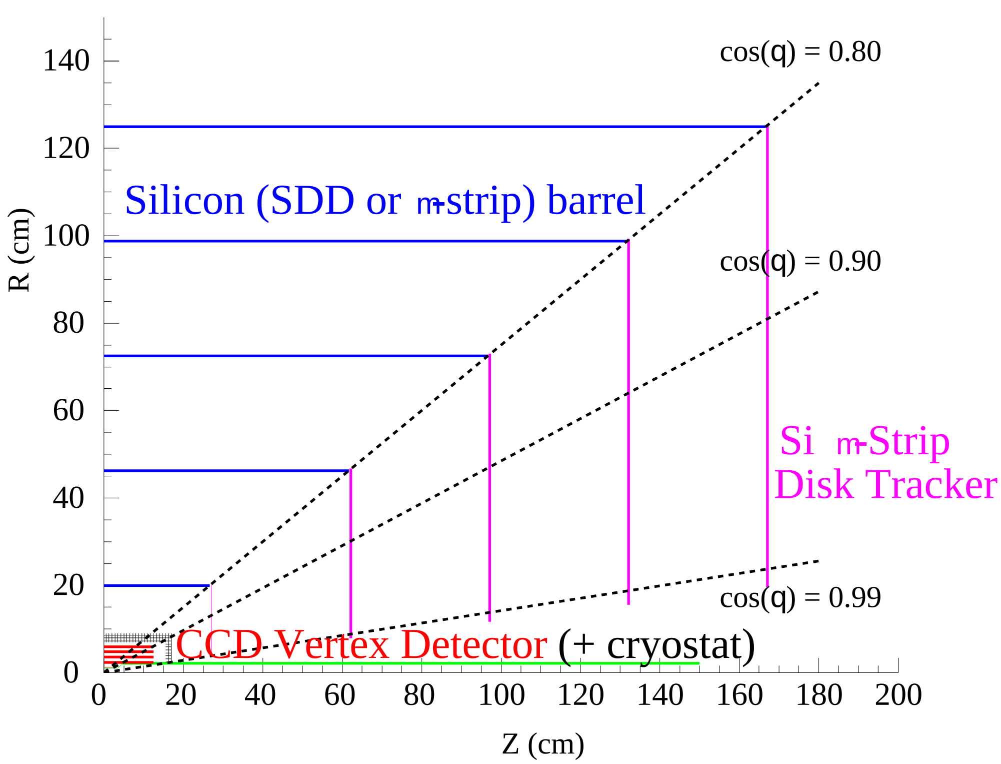
High-energy IR

- Rest of LC program (plus Higgs properties)
- Higgs self-coupling
- $t\bar{t}h$

NLC Detectors

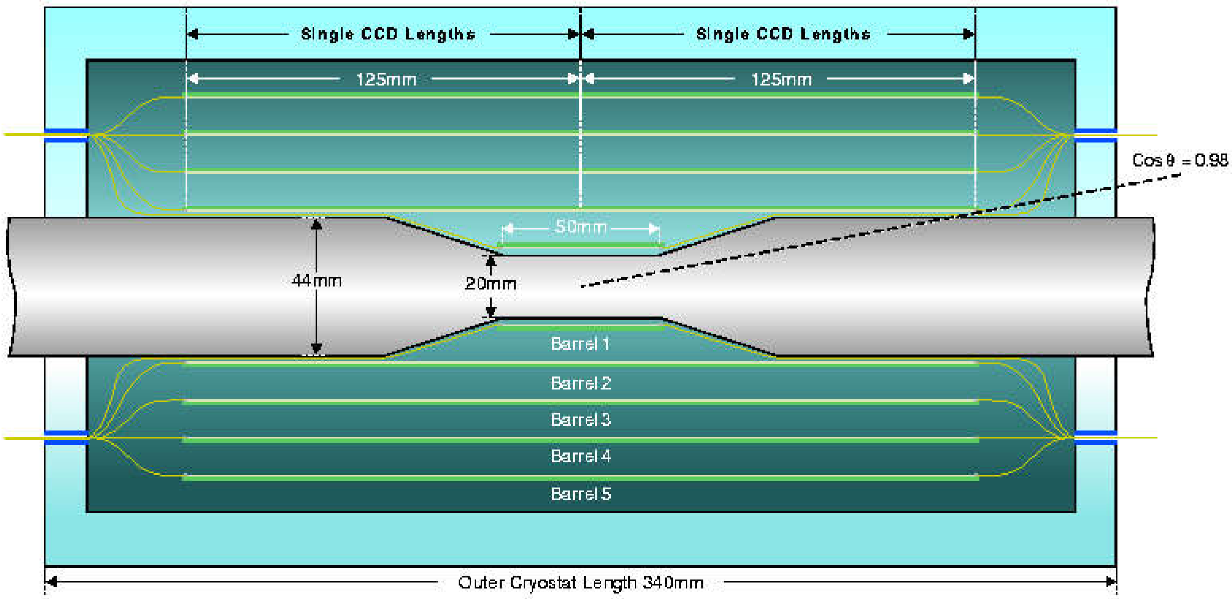


TRACKING SYSTEM FOR SD DETECTOR

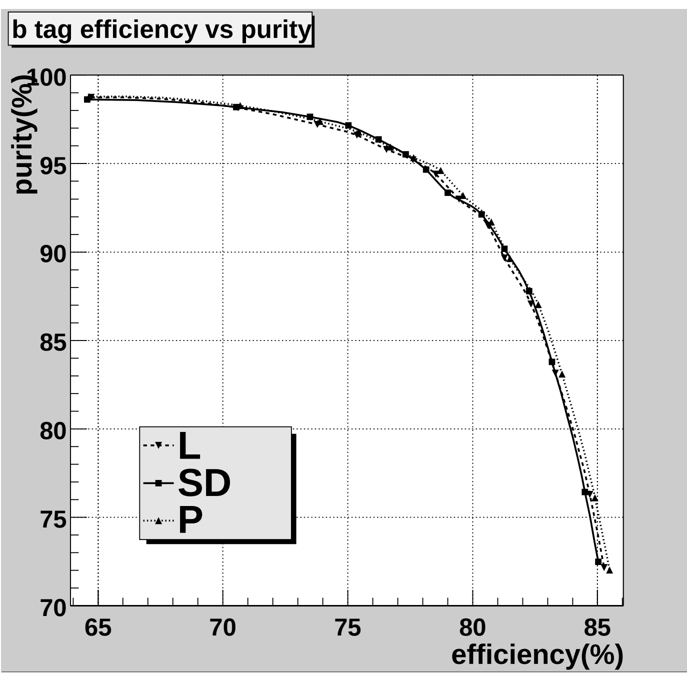


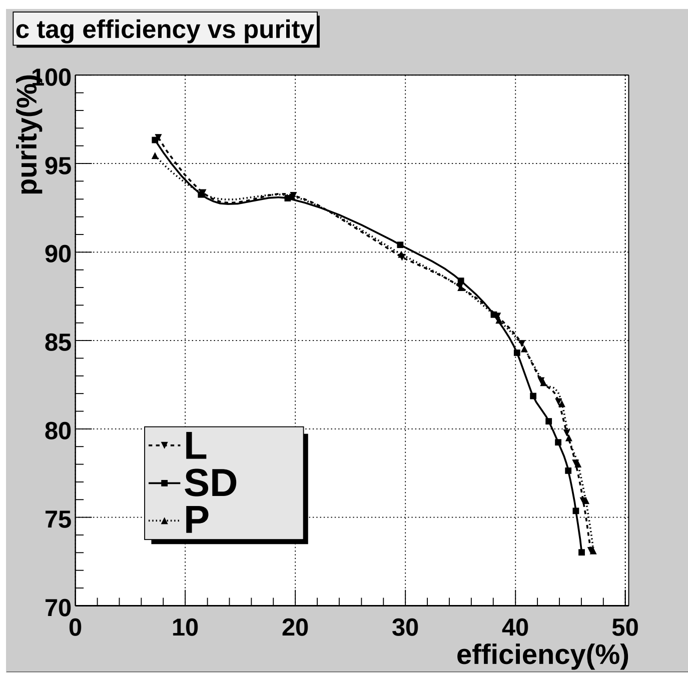
5 T,
Energy flow
calorimetry

5-Layer CCD Vertex Detector

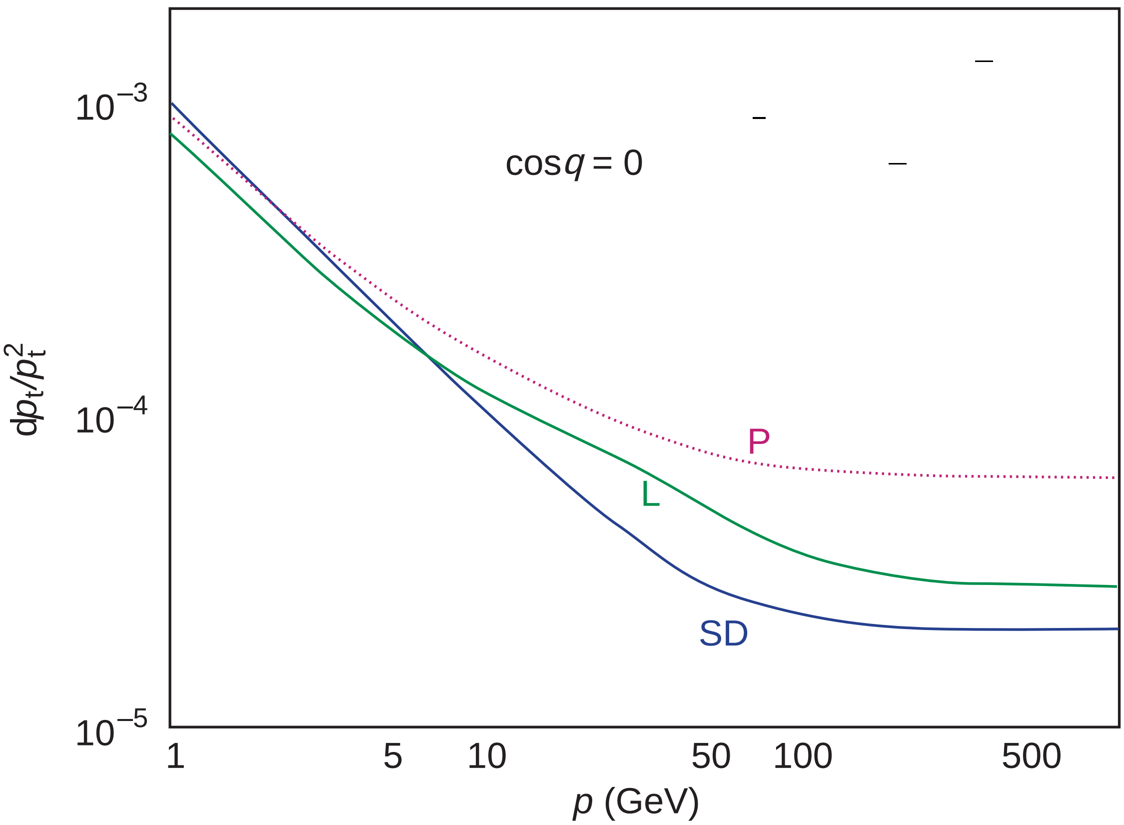


- *b* and *c*-quark tagging efficiency and purity similar for all detectors:

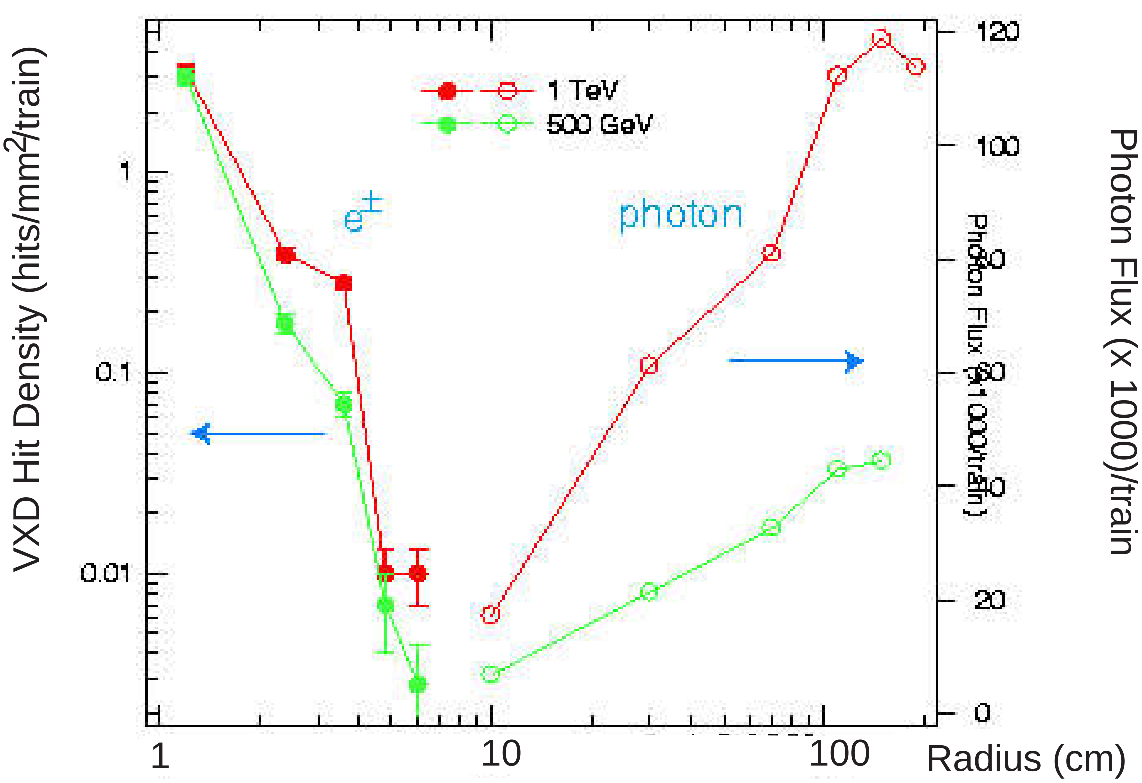




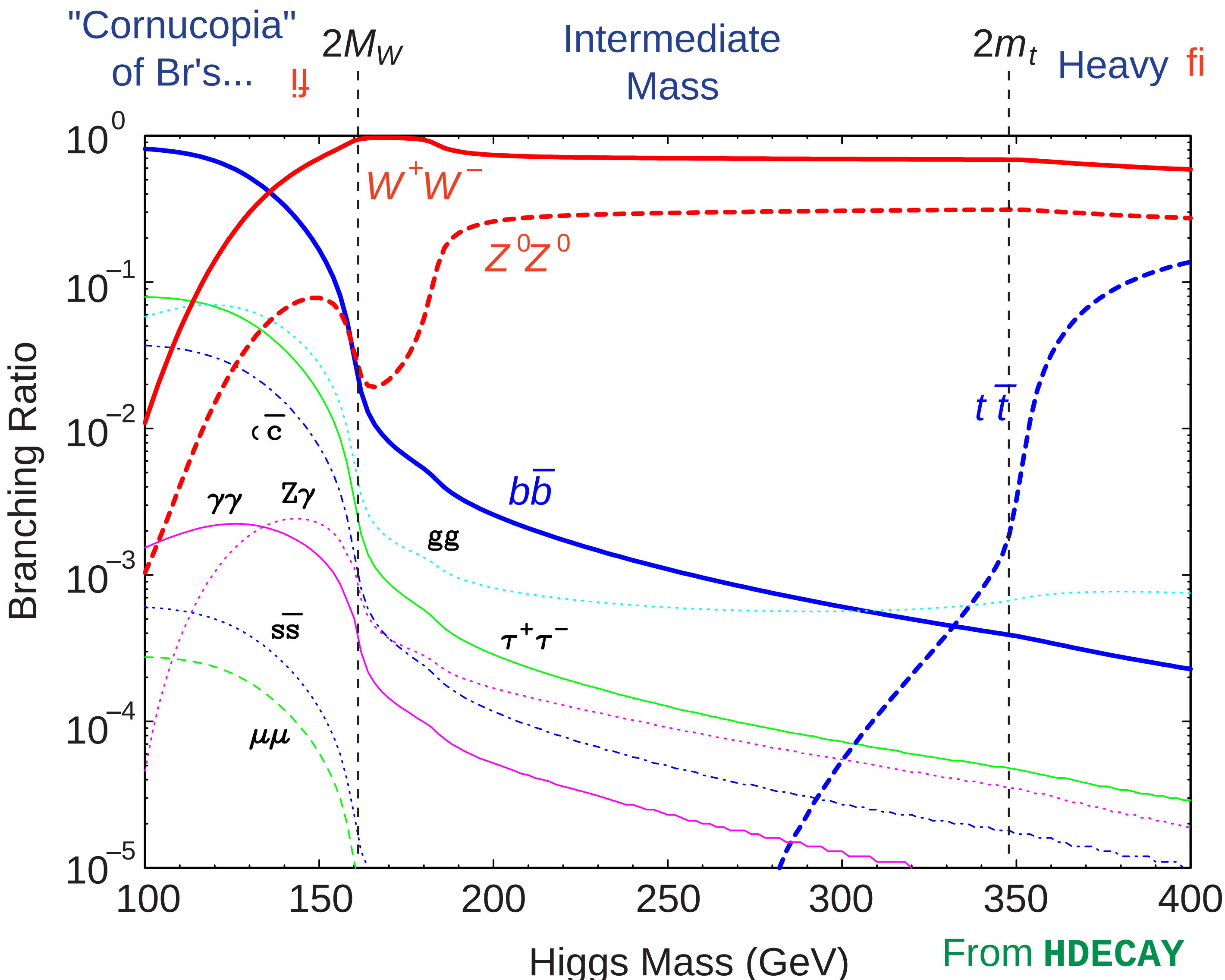
- Momentum Resolution



- $e^{\pm}$ and photon backgrounds in vertex detector and TPC



Branching Ratios



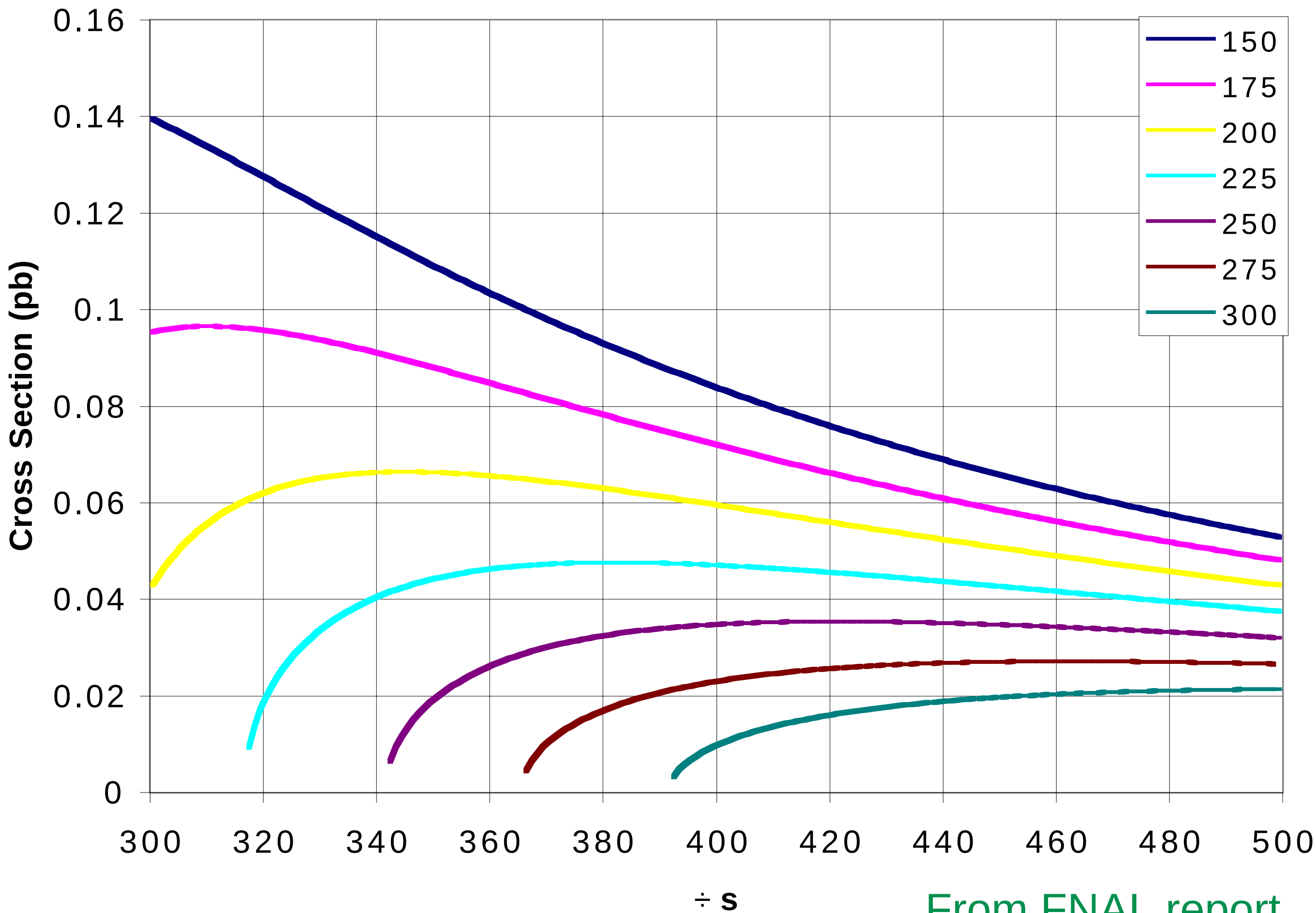
From **HDECAY**
(Spira et al.)

- For "SM-like" Higgs (for SM-only Higgs, much of intermediate/heavy mass region ruled out by precision measurements)
- Decays into weak bosons, fermion decays "rare" until top turns on

Cross Sections

For couplings: g_{hZZ} g_{hWW}

- Even for the intermediate mass range, the "nominal" $\sqrt{s}$ = 500 GeV not necessarily the best place to be to take advantage of the tagging utility of *hZ* associated production:



From FNAL report

- Strength of low-energy IR flexibility
- e.g., low end of range, M_h=160 GeV, $\sqrt{s}$ = 350 GeV, 500 fb^{-1}

$$\frac{\Delta\sigma(HZ)}{\sigma(HZ)} \sim 5\% \qquad \frac{\Delta\sigma(H\nu\bar{\nu})}{\sigma(H\nu\nu)} \sim 17\%$$

Measuring Br's

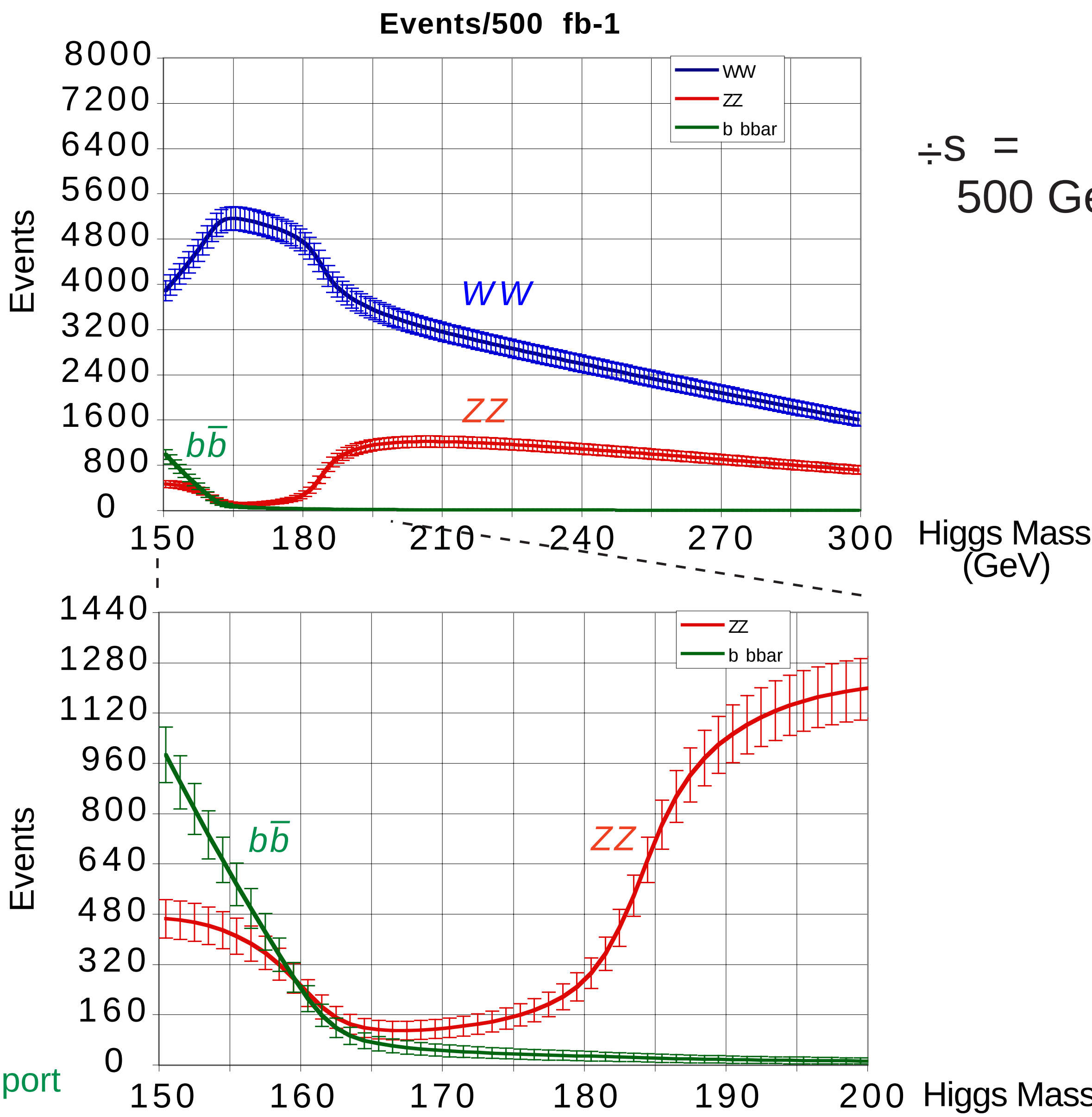
For couplings:

g_{hZZ} g_{hWW} g_{hbb} g_{htt}

- How far can one go measuring the "rare" decay into $b\bar{b}$?

  At low end of range, M_h=160 GeV, $\sqrt{s}$ = 350 GeV, 500 fb^{-1}, stat. error on dBr($b\bar{b}$)/Br($b\bar{b}$) ~ 6.5%, but degrades rapidly...

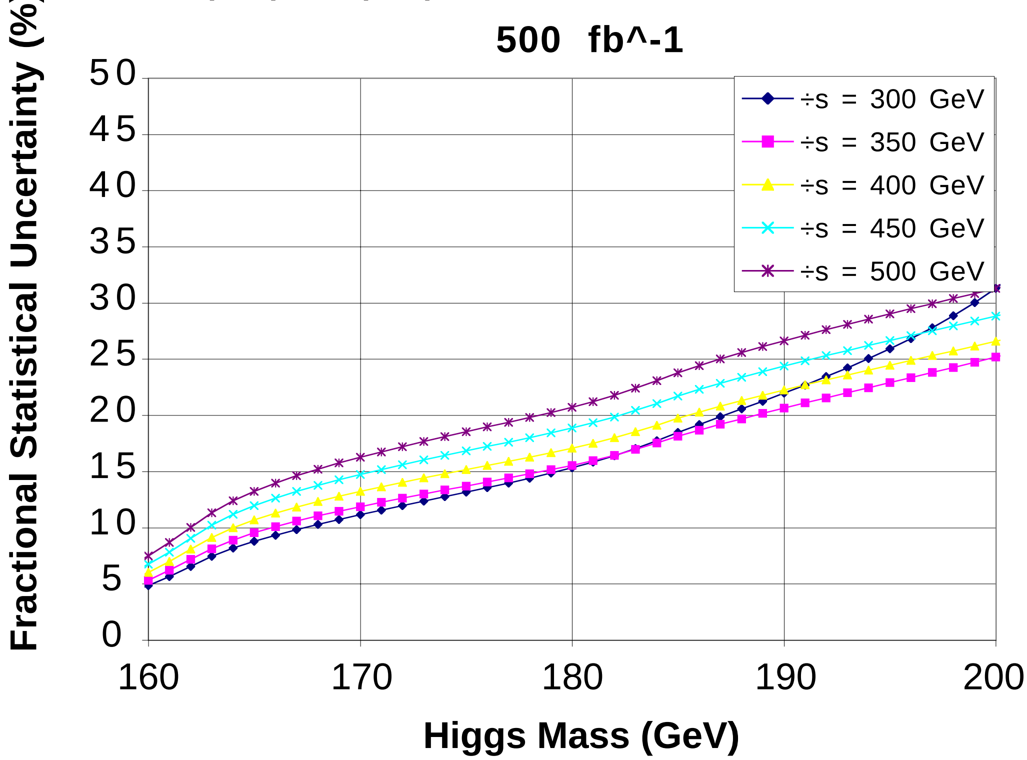
- Numbers of events, tag associated Z^0 with leptons, assuming also tags from hadronic Z^0 decays with reasonable mass cuts



$\sqrt{s}$ = 500 GeV

Adapted from FNAL Report

- dBr($b\bar{b}$)/Br($b\bar{b}$)

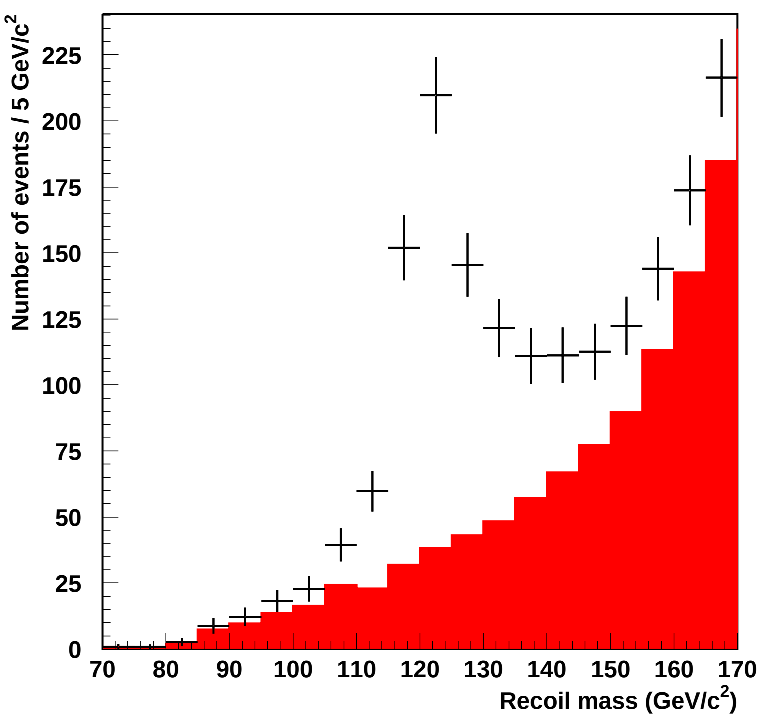


...but needs more full simulations

- dBr(*WW*)/Br(*WW*) ≤ 7% in mass range 150–200 GeV

e^+e^- Æ ZH Æ $q\bar{q}WW^{(*)}$ Æ $q\bar{q}\,q\bar{q}\,\ell n$

$M_{jet\text{-}jet} \sim M_z$, $M_{recoil} \sim M_h$, soft anti-b-tag



dBr(*WW*)/Br(*WW*) = 2.1% for M_h = 160 GeV, extend to higher masses

(Borisov, Richard)

- dBr(ZZ)/Br(ZZ) : provides detector benchmark, distinguishing hadronic Z decays from hadronic W decays

e.g., if identify one of the two Z 's (via leptons or bb) 40% of time, same luminosity,

dBr(ZZ)/Br(ZZ) ~ 8% for M_h = 210 GeV

degrades to

~ 17% for M_h = 160 GeV (TESLA TDR)

$$e^+e^- \rightarrow ZH \rightarrow Z\,Z\,Z^{(*)} \rightarrow \ell^+\ell^- q\bar{q}\,\ell^+\ell^-$$
$$\rightarrow q\bar{q}\,\ell^+\ell^- q\bar{q}$$

$M_{jet\text{-}jet} \sim M_Z$, $M_{\ell\ell qq} \sim M_h$

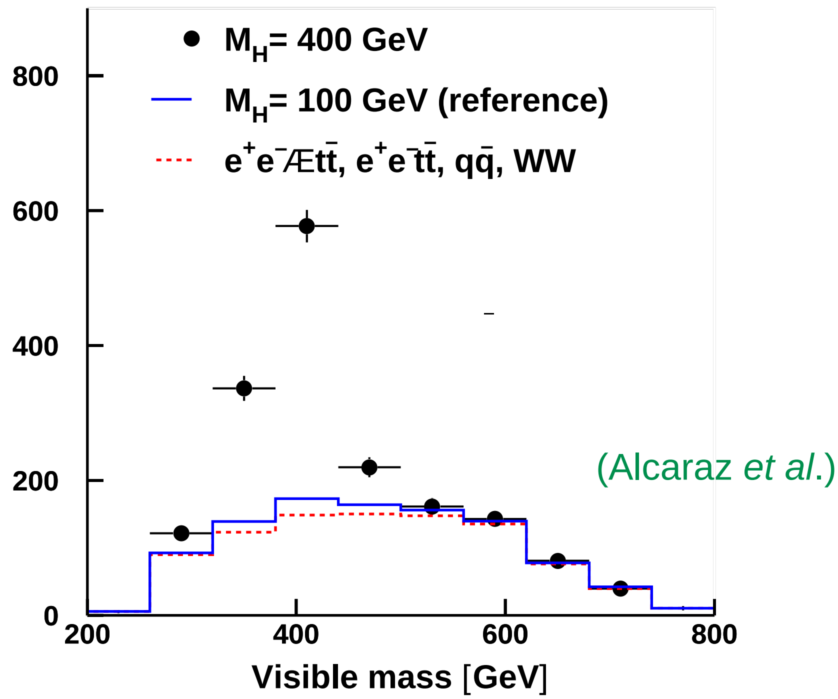
$M_{\ell\ell} \sim M_Z$

Heavy Higgs

For couplings:

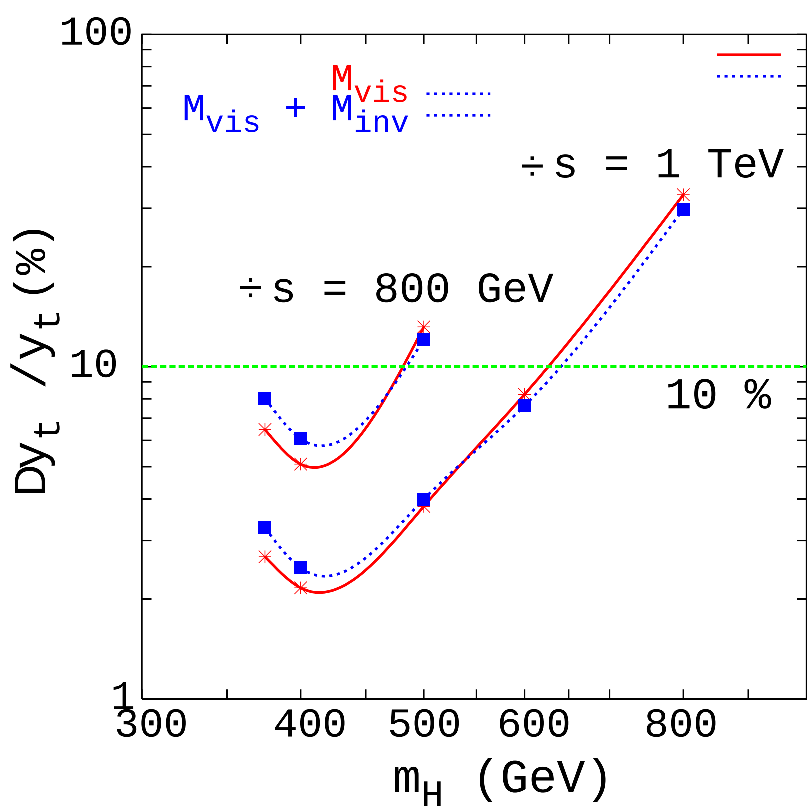
g_{hZZ} g_{hWW} g_{htt}

- No need for more difficult radiative *tth* production channel, *h* Æ *t* $\bar{t}$
- ÷s = 800 GeV
  1000 fb^{-1}



- *e^+e^-* Æ *$H n\bar{n}$* Æ *$t\bar{t} n\bar{n}$* Æ 6 jets + missing *E*
- 5s signal for range 350 < M_h < 500 GeV
- dBr(*t t*)/Br(*t t*) = 10% (24%)

  for M_h = 400 (500) GeV



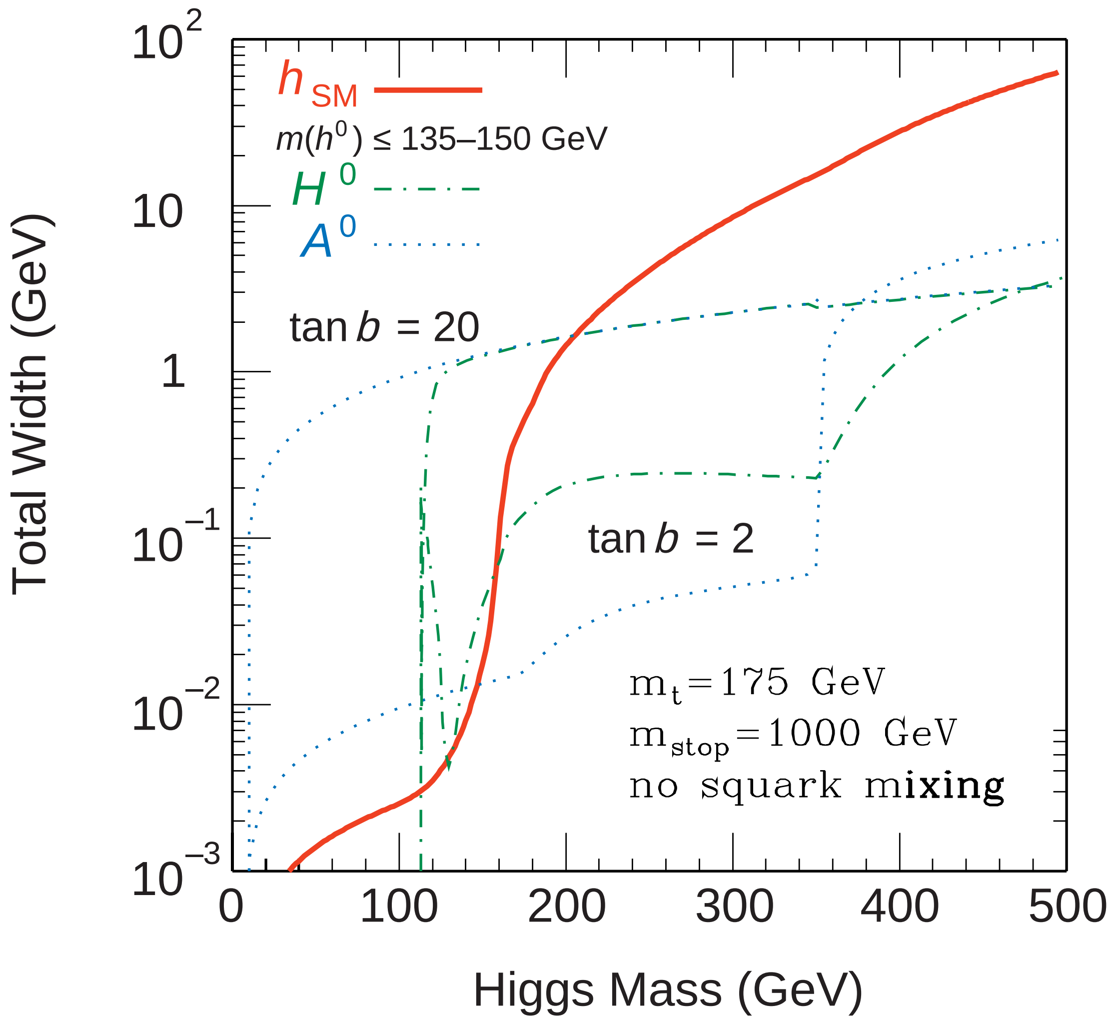
Couplings

Benchmark ⇒ $\sqrt{s}$ = 500 GeV
500 fb^{-1}

⇒

m_H (GeV)		120	140	160	200	400–500 $\sqrt{s}$ = 800 GeV
$\Delta\sigma_{ZH} / \sigma_{ZH}$		~6.5%	~6.5%	~6%	~7%	~10%
$\Delta\sigma_{H\nu\nu} Br(b\bar{b}) / \sigma Br$		~3.5%	~6%	~17%	–	–
$\frac{\delta g_{hxx}}{g_{hxx}}$ (from Br's)	$t\bar{t}$	7–20%	–	–	–	~10%
	$b\bar{b}$	~1.5%	~2%	~3.5%	~12.5%	–
	$c\bar{c}$	~20%	~22.5%	–	–	–
	$\tau^+\tau^-$	~4%	~5%	–	–	–
(e.g., HFITTER can be used for combining with cross section info)	WW^*	~4.5%	~2%	~1.5%	~3.5%	~8.5%
	ZZ^*	–	–	~8.5%	~4%	~10%
	gg	~10%	~12.5%	–	–	–
	$\gamma\gamma$	~7%	~10%	–	–	–
	g_{hhh}	~23%	–	–	–	–

Higgs Total Width



- Over much of range of intermediate and heavy Higgs masses, SM Higgs width is measurable and distinguishable from heavier SUSY states

Total Width Determination

Departures? fi New physics!

$m_H \gtrsim 115$ GeV

$$G_{tot} = \frac{G(H \text{Æ} WW^*)}{Br(H \text{Æ} WW^*)} \leftarrow \text{LC}$$

Where $G(H \text{Æ} WW^*)$ from:

- $s(H nn) \cdot Br(H \text{Æ} b\bar{b}) \leftarrow$ LC
- $\frac{s(HZ)}{s_{SM}(HZ)} \cdot G_{SM}(H \text{Æ} ZZ^*)$ (with $\leftarrow$ LC on $s(HZ)$)
  (coupling universality)
- $G_{SM}(H \text{Æ} WW^*)$

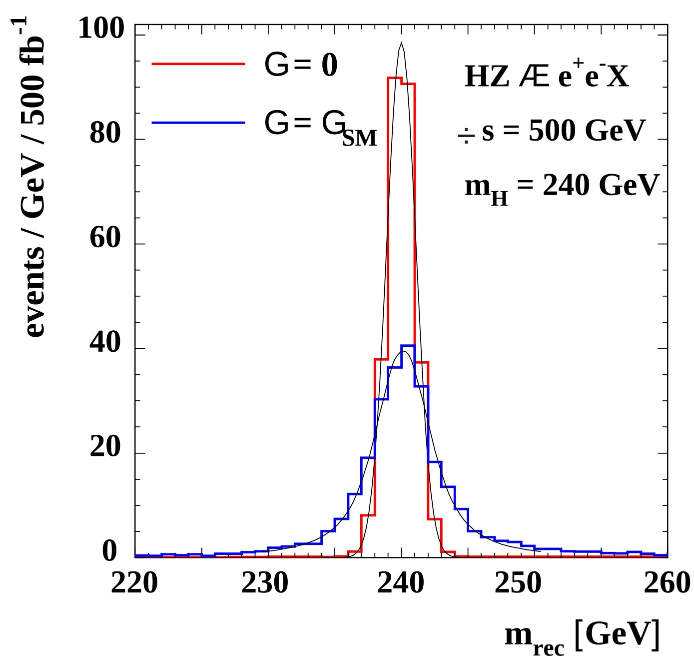
increasing assumptions

G_{tot} to ~10% with 200 fb^{-1} and 120 GeV Higgs, to a few percent for less than 150 GeV

$m_H \gtrsim 205$ GeV,

G_{tot}^{SM} ~ 2 GeV,

directly resolvable

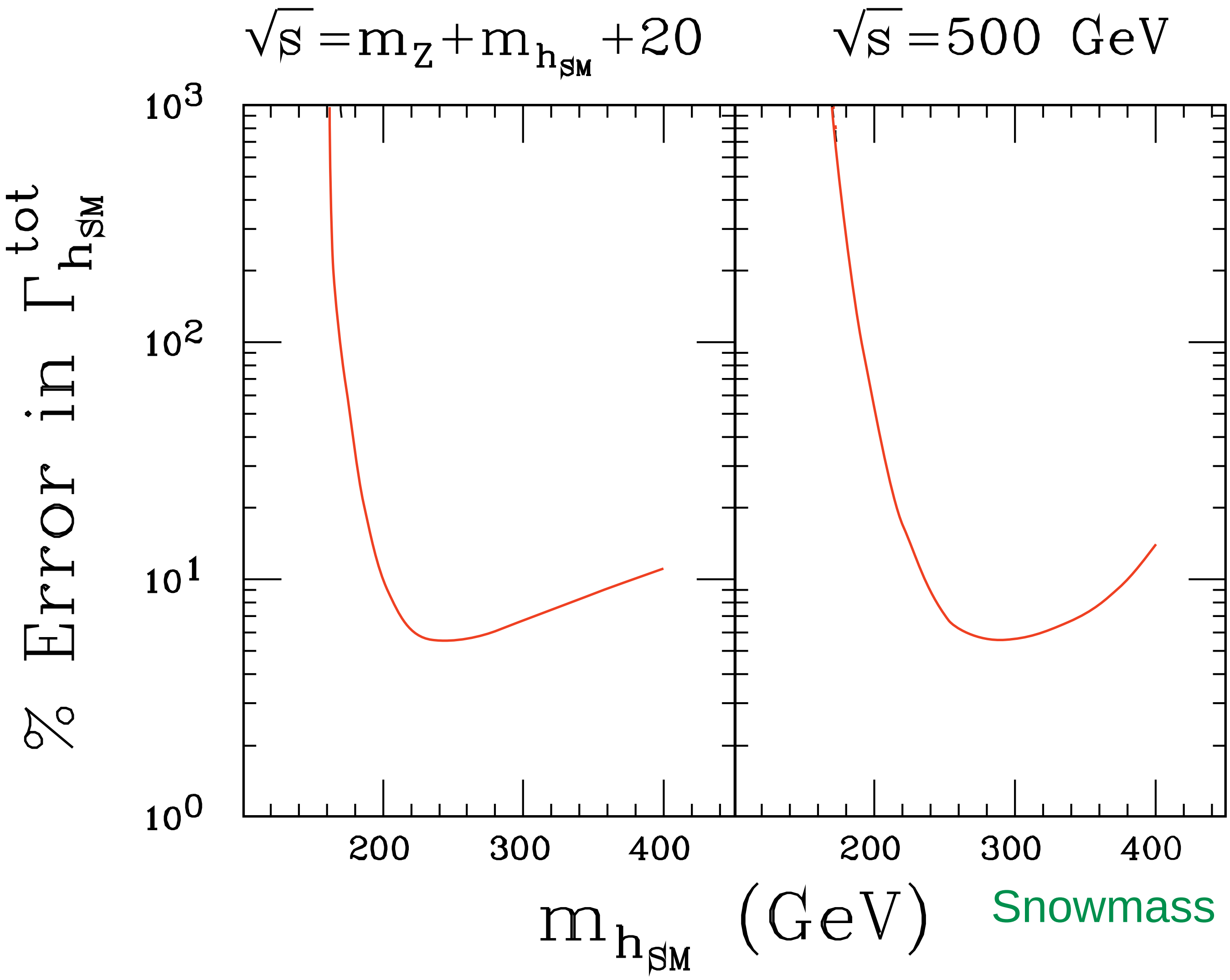


Plus: still do the above for indirect measurement:

$G(H \text{Æ} WW^*)$ from: • $s(H nn) \cdot Br(H \text{Æ} WW) \leftarrow$ LC

Check if observed Higgs boson gives all the mass to *W, Z*

- Using only direct width measurement only, NLC "L" detector estimated jet-energy resolution



Snowmass '96

- Complementary to indirect width determination

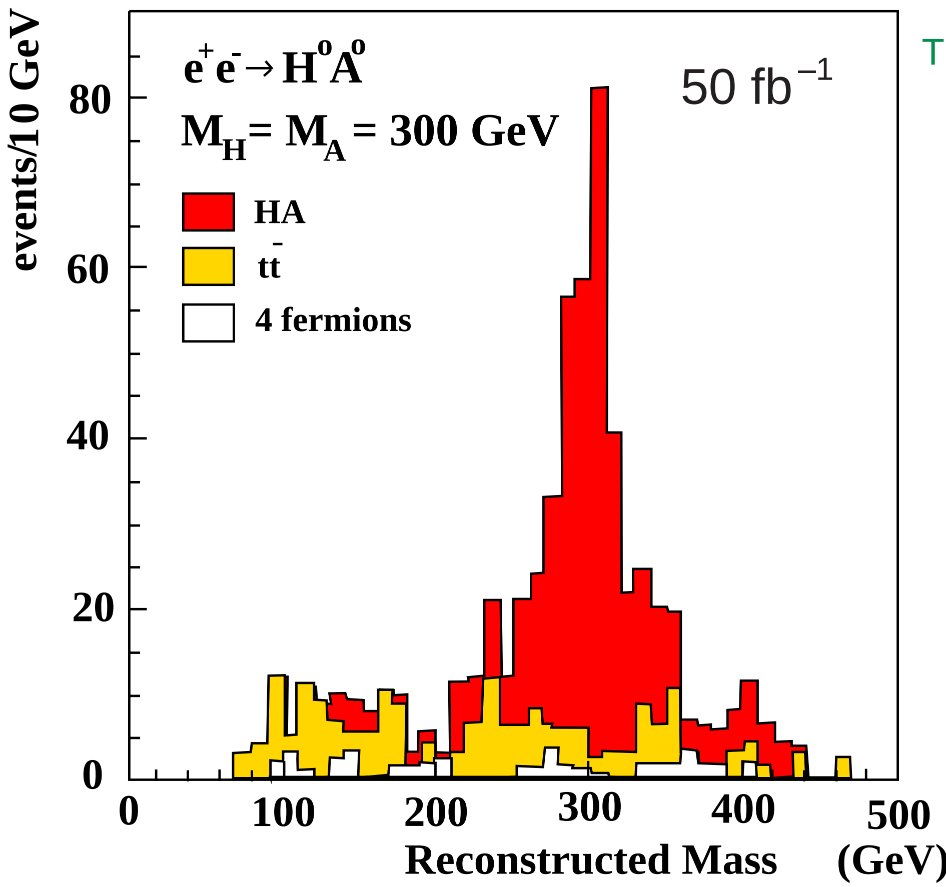
Heavy Higgs: SUSY States

Mass, *s* , Br's

fi SUSY parameters

e^+e^- Æ H^0A^0 Æ $b\bar{b}\,b\bar{b}$

- ÷s = 800 GeV, 200 fb^{-1}
- Close to mass degenerate, $M_A \sim M_H$ = 300 GeV



TESLA TDR

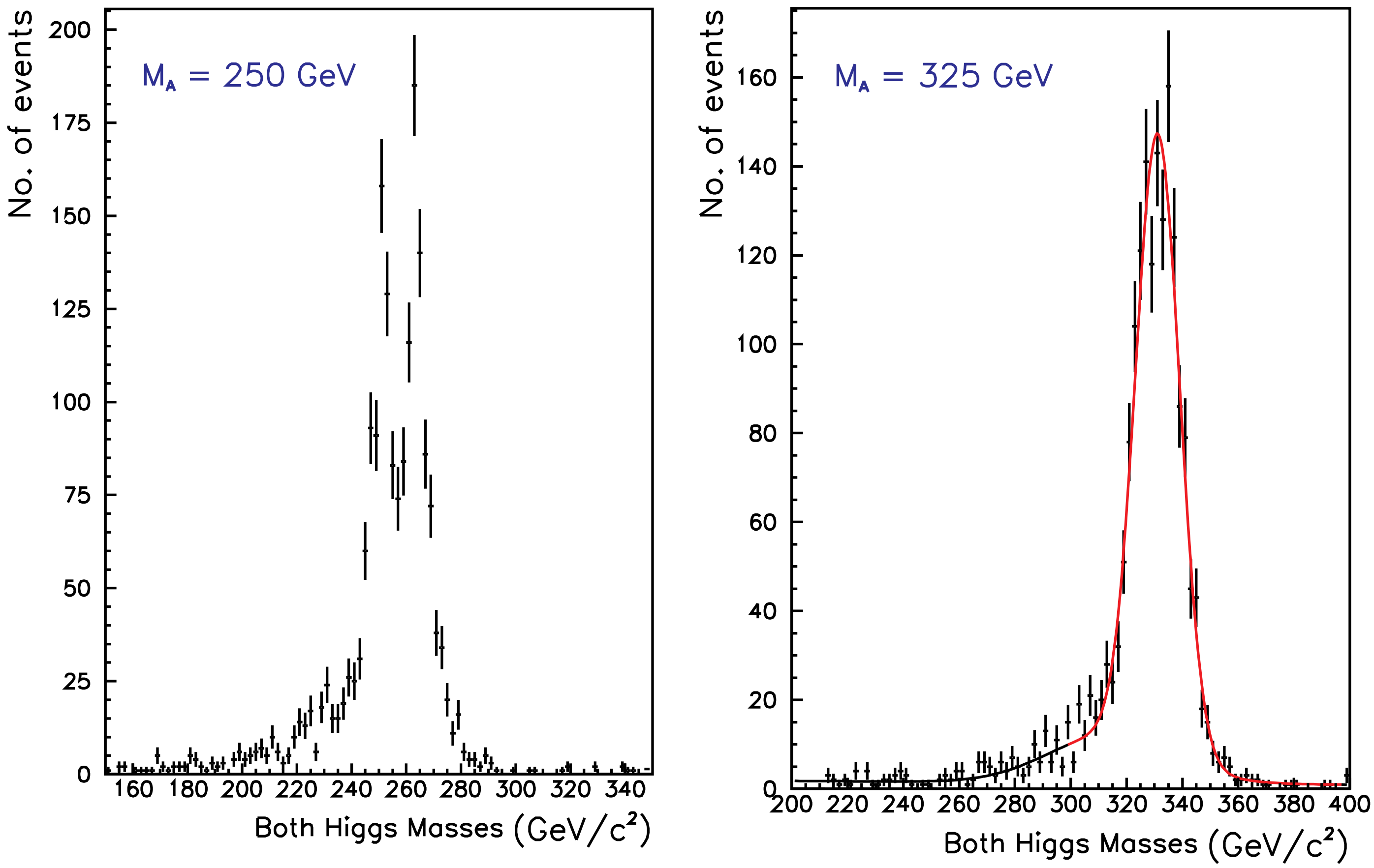
- $\frac{\mathrm{Ds} \cdot \mathrm{Br}^2}{\mathrm{s} \cdot \mathrm{Br}^2} = 5 - 11\%$ $\quad\quad$ $\frac{\mathrm{D}M_A}{} = 0.2 - 0.4\%$

for 260 < M_A < 340 GeV

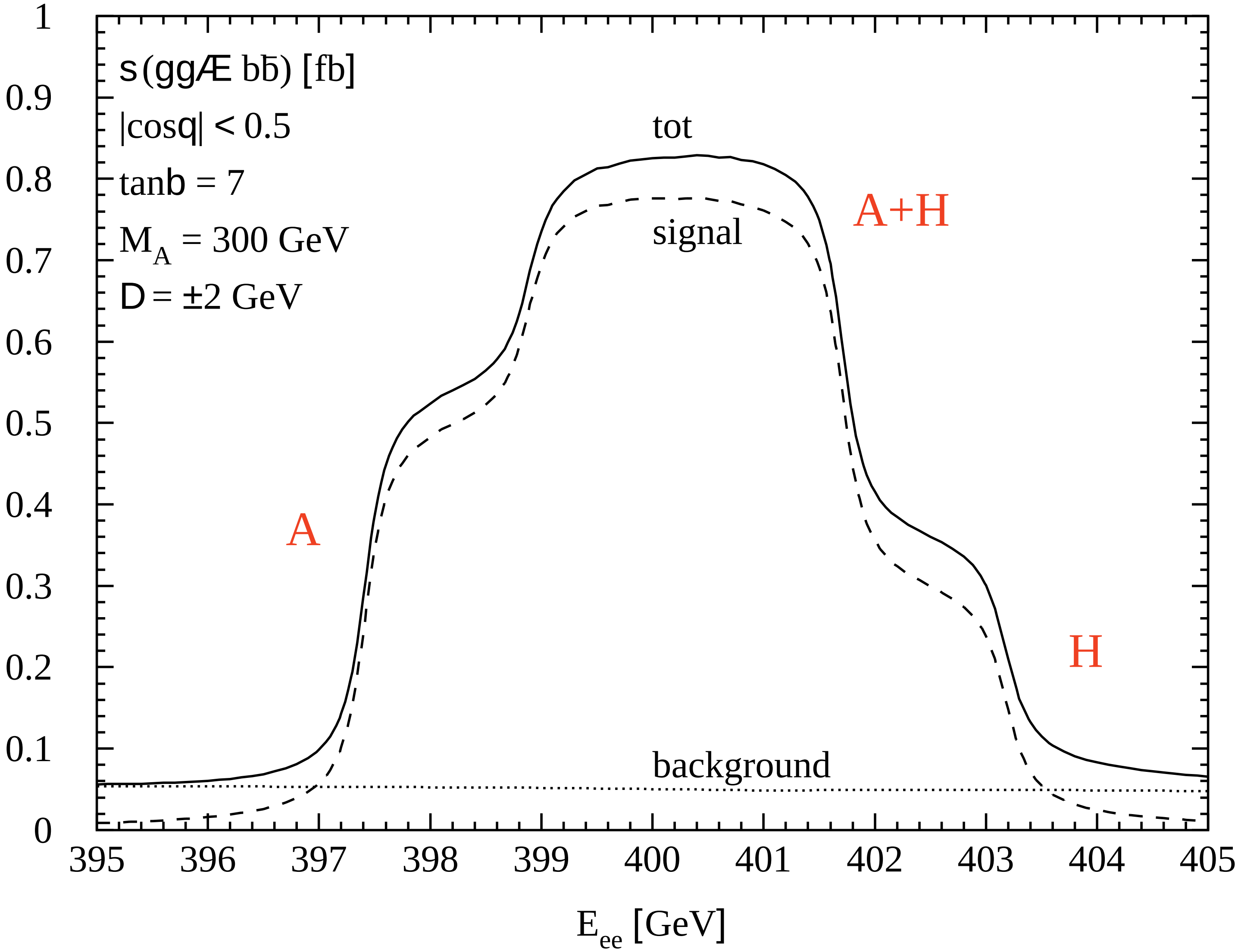
fi Similar precisions as for SM-like case

- Mass degeneracy, sample SUSY point, ~resolution of NLC "L" detector

$$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$$



- "ultimate" separation in *gg*?

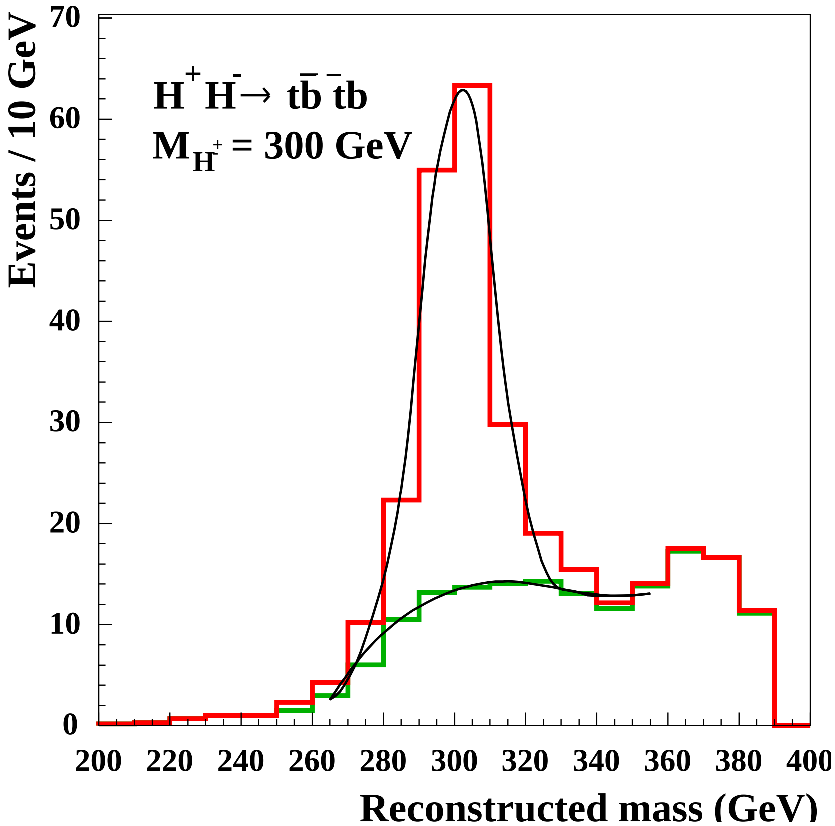


$$e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$$

$$\text{or} \quad \to W^+h^0 W^-h^0$$

$$\hookrightarrow b\bar{b}$$

- $\sqrt{s} = 800$ GeV, $500\ \text{fb}^{-1}$
- 8 jets, 4 of them *b* jets
- *b*-tagging, mass constraints



TESLA TDR

- $\frac{\Delta\sigma \cdot Br}{\sigma \cdot Br} < 15\%$ $\quad\quad$ $\Delta M_{H^\pm} = 1.0$ GeV

"Nastier stuff":

Invisible Decays

h Æ $\tilde{c}^0_1 \tilde{c}^0_1$

Æ *Majorons*

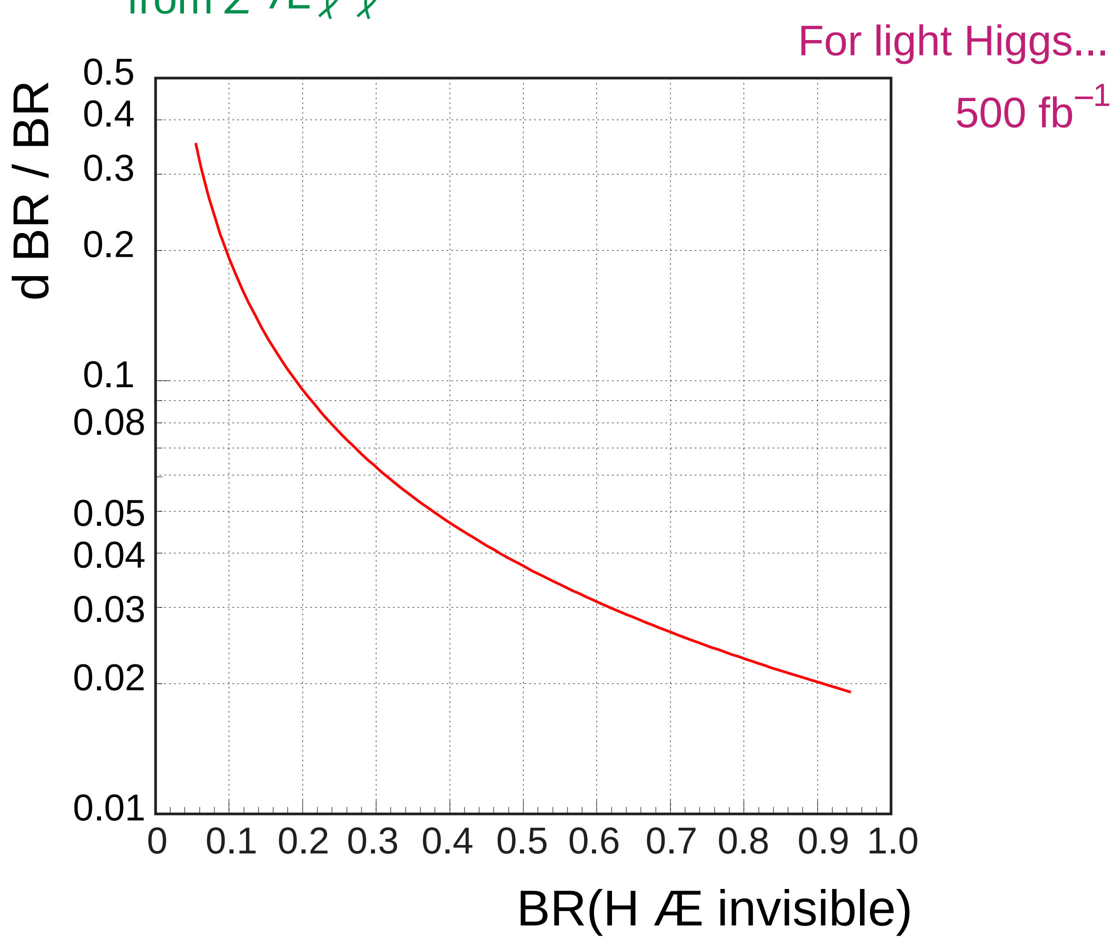
Æ *heavy neutrinos*

Æ *Higgs singlets*

- Handled with recoil mass in Higgstrahlung

  fi compare no. events tagged with Z Æ $\ell^+\ell^-$ with total no. observed Higgs decays into known states

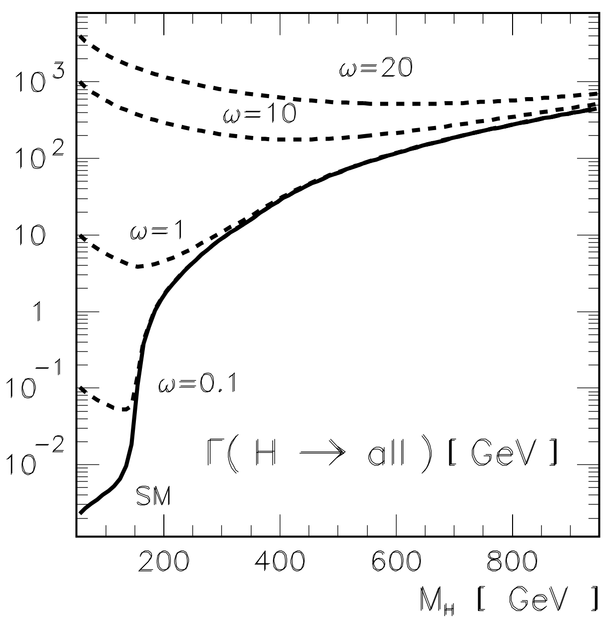
  fi number of events with no detector activity recoiling from Z Æ $\ell^+\ell^-$

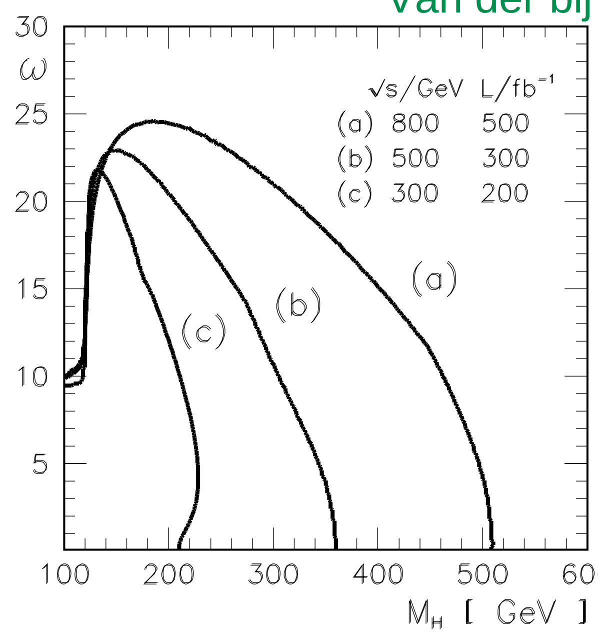


- "Stealth" model, Higgs decays to light Higgs singlets coupling with strength w to SM Higgs

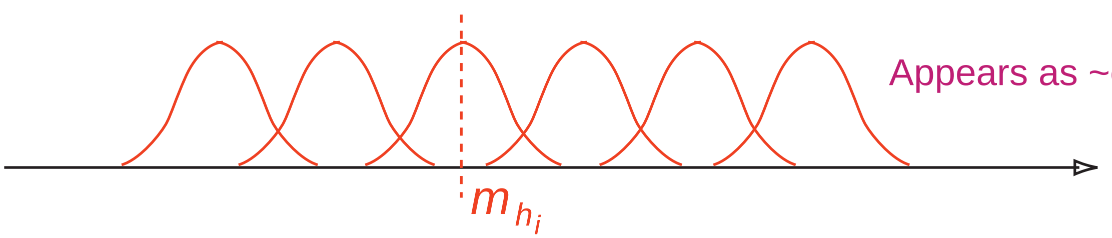
  fi can have large invisible width, no peak in recoil mass

Van der bij





- General SUSY, multiple fermiophobic Higgs, i of them with different masses, decaying: e^+e^- Æ $Z h_i$, h_iÆ $V V$ (Espinosa et al., Gunion et al.)



Sum Rule: $K_i = \frac{g^2_{h_iZZ}}{g^2_{hZZ,\,SM}}$ $\quad S_i K_i m^2_{h_i} \leq (200\ \mathrm{GeV})^2$

(for perturbativity up to GUT scale)

fi continuum still observable with $\gtrsim 200\ \mathrm{fb}^{-1}$

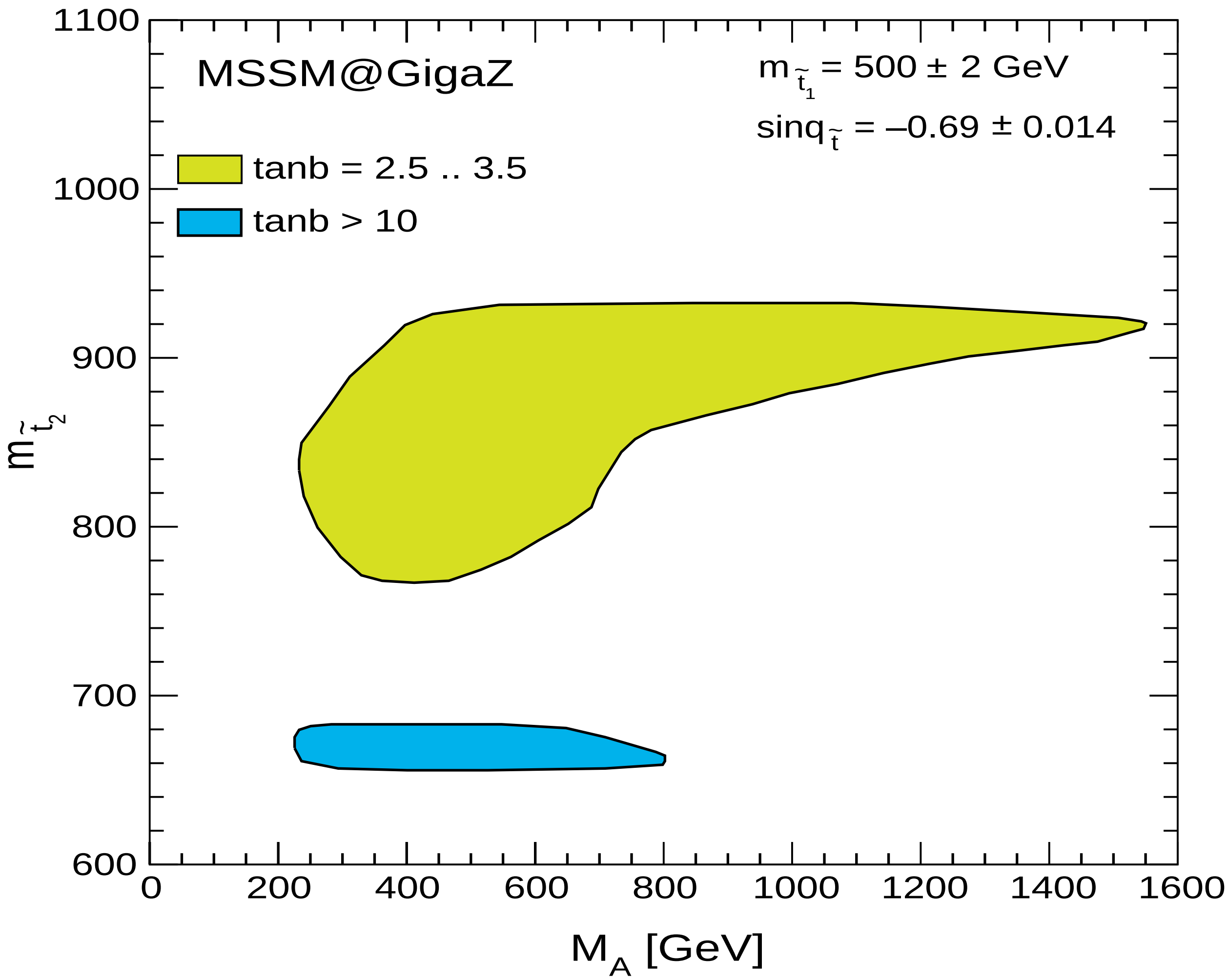
- Light decoupled Higgs with **no** *VV* couplings

  fi still produced through quartic couplings...

With 1000 fb^{-1}, still observable: ÷s = 500 GeV up to ~150 GeV; ÷s = 800 GeV up to ~250 GeV

Giga-Z Contribution

- e.g., no Higgs found in intermediate mass range
- Giga-*Z*: M_W $\sin^2\theta_{eff}$ plus M_h and SUSY



fi more indications of where heavier states may lie

Conclusion / Summary

Intermediate mass and heavy Higgs:

→ So the PDG entry (see Klaus Desch's talk) *may* be somewhat shorter (fewer Br's)...

But

- still powerful measurements, complementary, couplings to bosons and some fermions
- If heavy, how is it able to contradict precision EW?
  - → new physics? *More* PDG entries...!
- If no intermediate mass Higgs (e.g. at $\sqrt{s}$ = 500 GeV)
  - → Giga-Z measurements (no states)

    and/or

    light Higgs "profile"
    - → indications of where heavy states may be.

Linear Collider results still essential!