Linear Collider Higgs Studies

Outline:

- Plans back in Berkeley
- What has changed
- Current state of art
- What needs doing, detector issues

Talk to Linear Collider Detector (LCD) Working Group

SLAC, Stanford, CA
14 November 2000

Rick Van Kooten
Indiana University

Higgs Properties

Pinning it down...

- Mass (l)

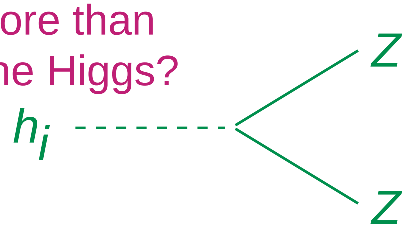
LHC, only t , t?

- Yukawa couplings: g_{ffH} µ m_f ? | *Br*'s, s
  (mass to fermions)

- Mass to vector bosons: g_{VVH} µ M_V^2 ? | *Br*'s, s

$V = Z,W$

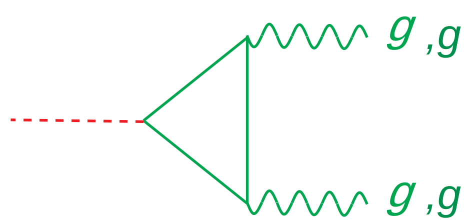
More than one Higgs?



fi $\frac{M_V^2}{v^2}$ w_i S w_i^2 = v

Fully generate mass of *Z* ?

- Decays to other bosons:



Sensitive to new physics

- Total Width (direct) or *Br*'s, s (indirect) or

- Spin, parity, CP nature | Ang. dist., s_{gg}

- Form of Higgs Potential, s_{ZHH}
  self-coupling, l $_{HHH,\ HHHH}$

Summary of Plans: Higgs WG (from Berkeley 2000)

- Older Snowmass studies, update:
  - $\Delta\Gamma(tot)/\Gamma(tot)$
  - $\Delta\sigma(x)/\sigma(x)$
  - $\Delta Br/Br$
  - $\Delta m_h/m_h$

vs m_h, int. luminosity

Compare LC/LHC (update numbers for LHC from D. Rainwater)

- Ensure that NLC 'S2'/'L2' detectors have similar *Br* precision performance as TESLA CDR/improved

$(\tau^+\tau^-)$ $c\bar{c}$ / $b\bar{b}$ / gg $\Rightarrow$ someone from vertex detector group? (Brau et. al.) plus FNAL Light Higgs Group

WW^* $\Rightarrow$ energy flow important

Important Br! For light higgs, fewer stats, used in total width determination

More SUSY interpretation? (FNAL group?)

- Confirm λ_{HHH} precision/feasiblity and lumi. needed (also needs theory input)

- Spin and CP - angular distributions
  - ttH - experimental simulation
  - $H \to \tau^+\tau^-$ $H \to t\bar{t}$

- Add Br(invisible!) Br($H \to ZZ^*$) $\sigma(Hee)$
  precision estimates

- Heavy/light $A^0/H^0/H^\pm$
  - Masses and separation of degeneracy
  - Br's and extraction of $\tan\beta$ and $\Delta\tan\beta$

W. Wester, Int. and Heavy Higgs
FNAL WG

- $\gamma\gamma$ Higgs studies J. Hill, $\gamma\gamma$ group

What has changed?

Results from LEP2, possible evidence? $\Longrightarrow$ *slide*

Two scenarios:

- CERN Council, scientific policy committee changes DG's decision to shutdown LEP2

- LEP2 shutdown, Fermilab enters the fray

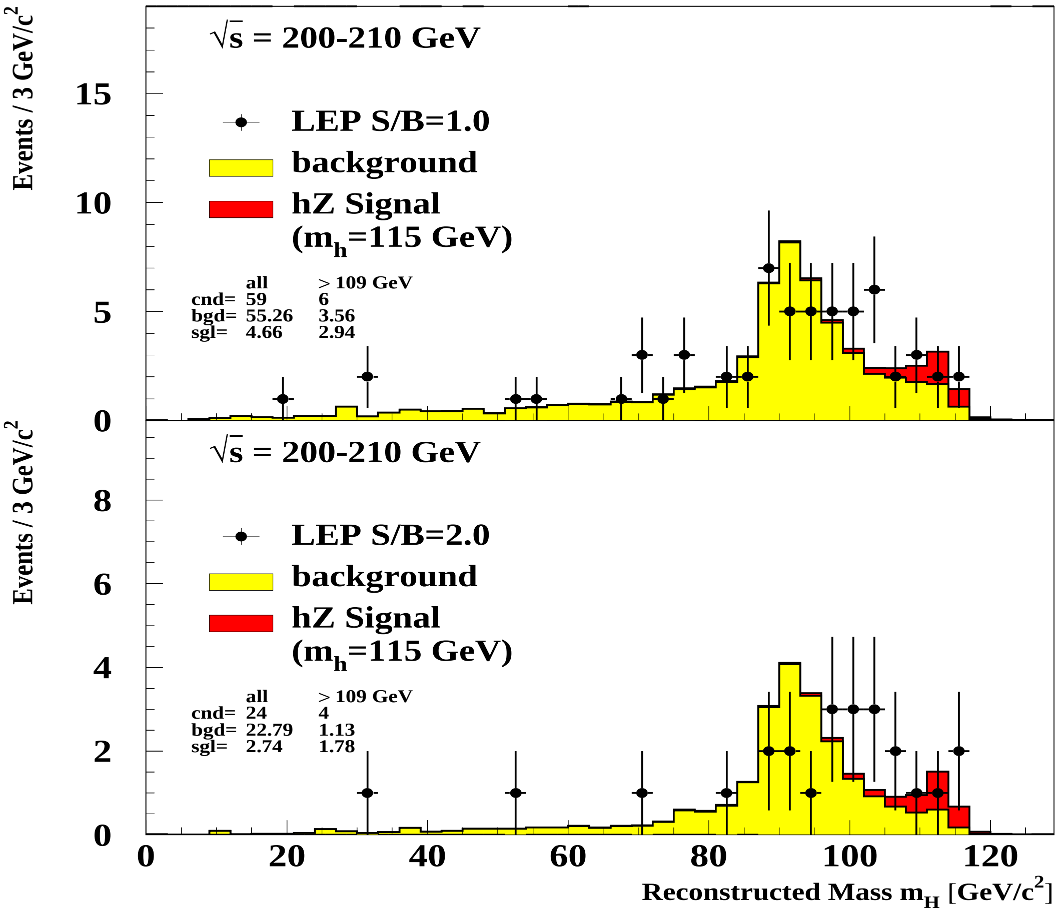
Either way (particularly second), substantial chunk of time where *we won't know* if it is there at 115 GeV or not $\Longrightarrow$ *slide*

Need to respond with LC strategy
if Higgs indeed at 115 GeV

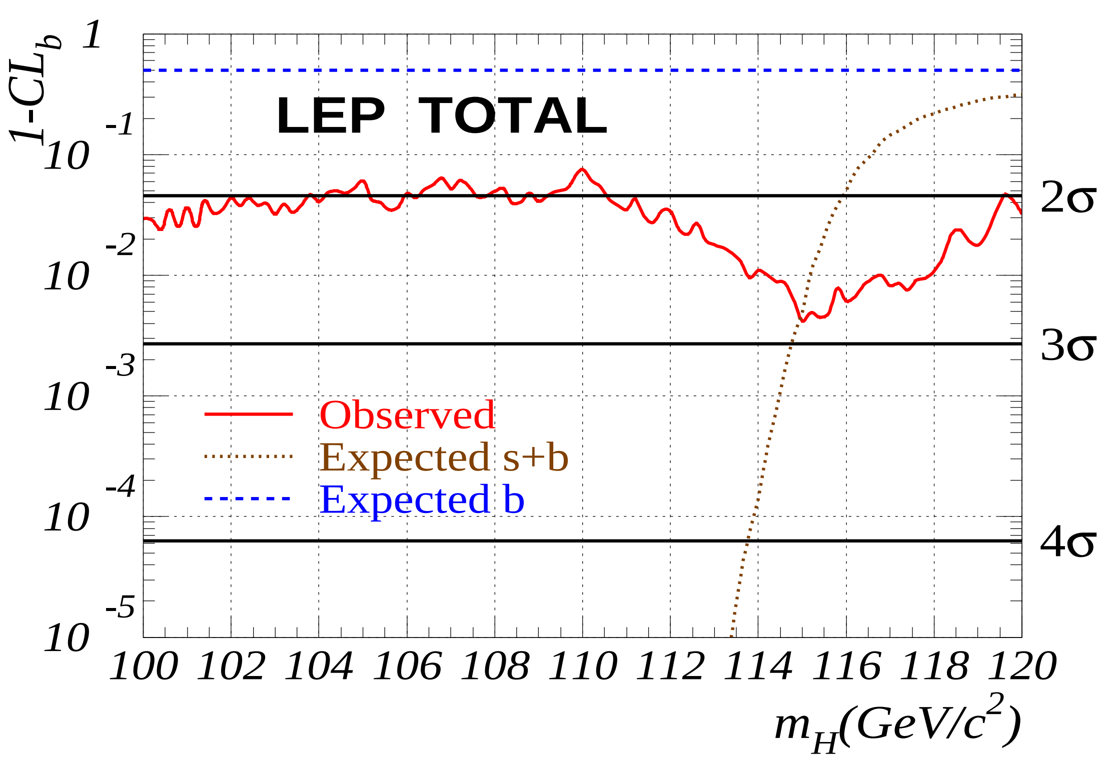
- Implications on properties if SUSY Higgs $\Longrightarrow$ *slide*
- Optimum running strategy: lower center-of-mass, run lower energy beam line (detector "P") at $\sigma(HZ)$ peak?

Results from LCWS2000: New "State of the Art"

- From Nov. 3 LEPC, all experiments combined:

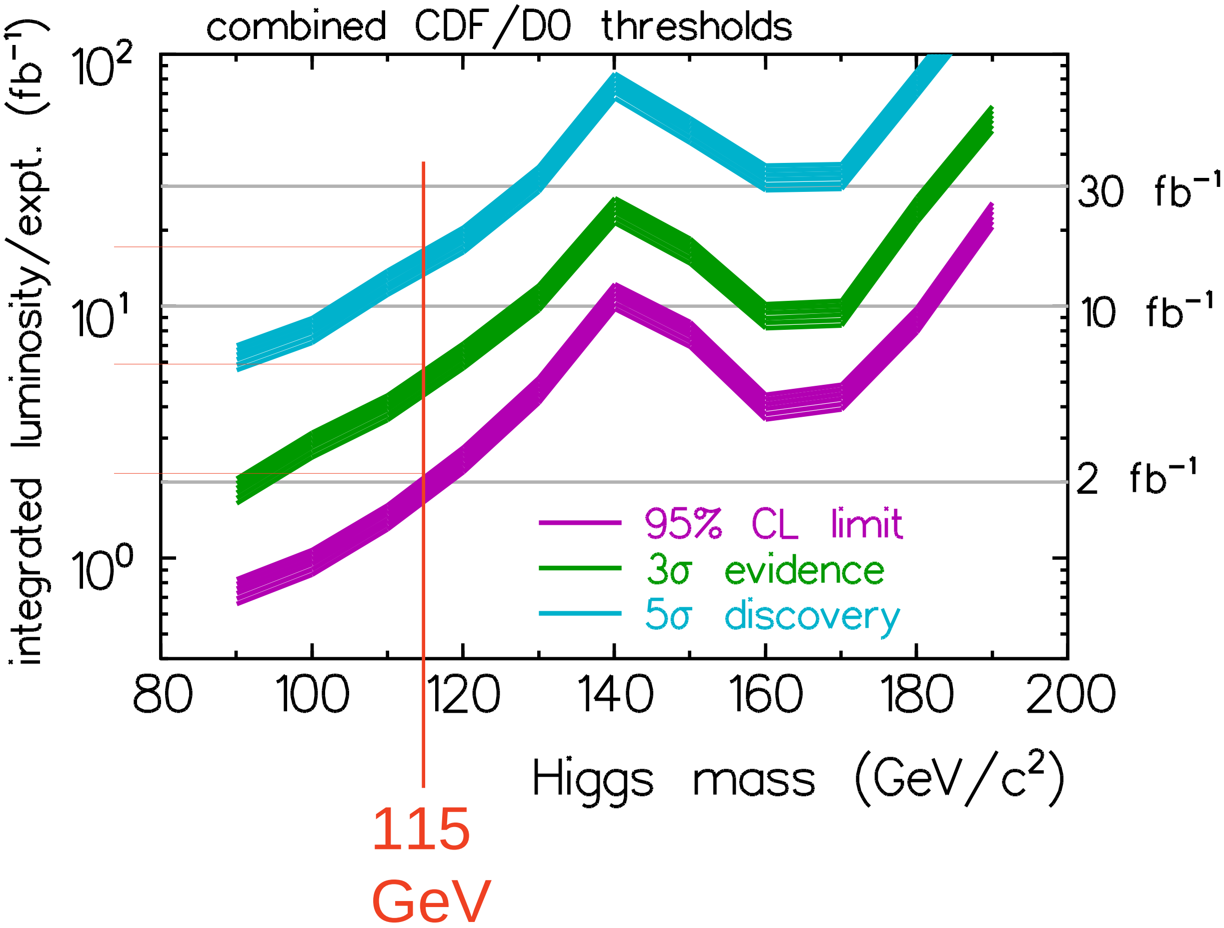


H



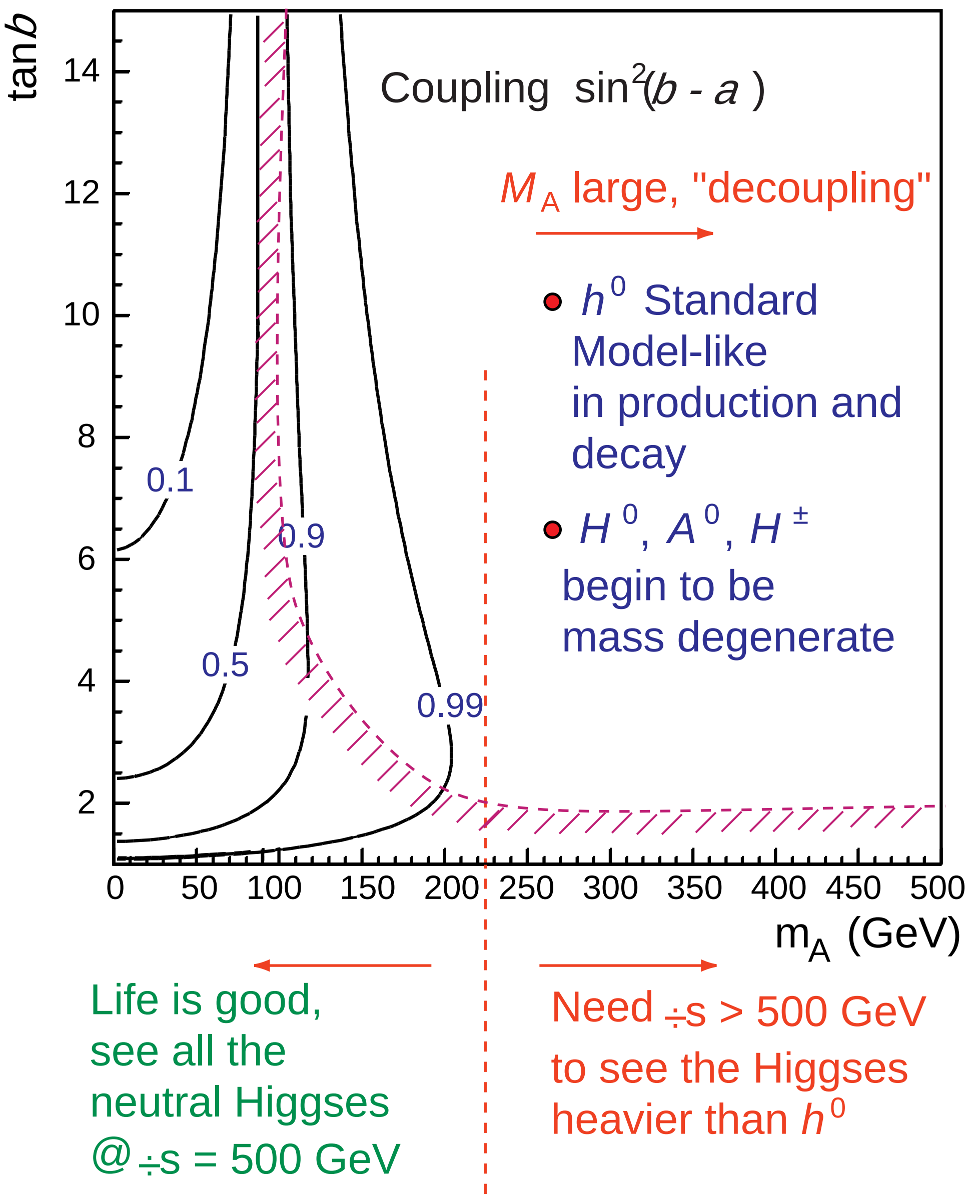
2.9 σ Effect

Mass "=" $115^{+1.3}_{-0.9}$ GeV



- Years, not months

- Even if SUSY Higgs, already close to SM Higgs properties fi even more need for precision measurements of properties



Excluded by LEP2 @ 95% C.L.

Approaching decoupling!

Life is good, see all the neutral Higgses @ ÷s = 500 GeV

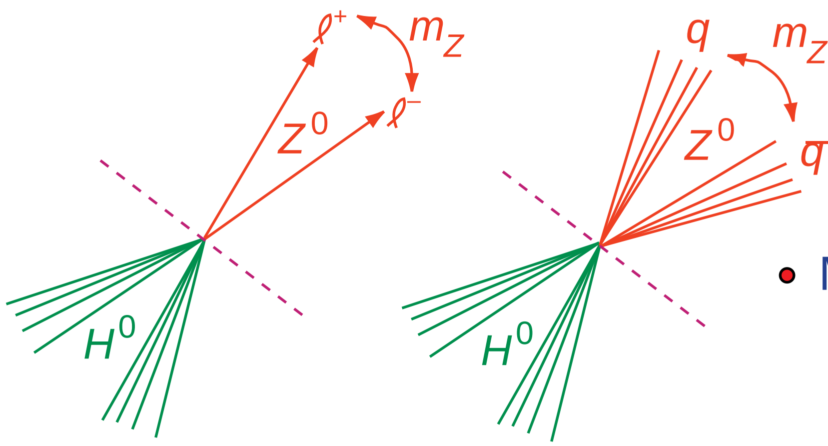
Need ÷s > 500 GeV to see the Higgses heavier than h^0

Mass

Recoil mass:

$$m^2_{\text{recoil}} = s - 2E_Z ÷s - M_Z^2$$

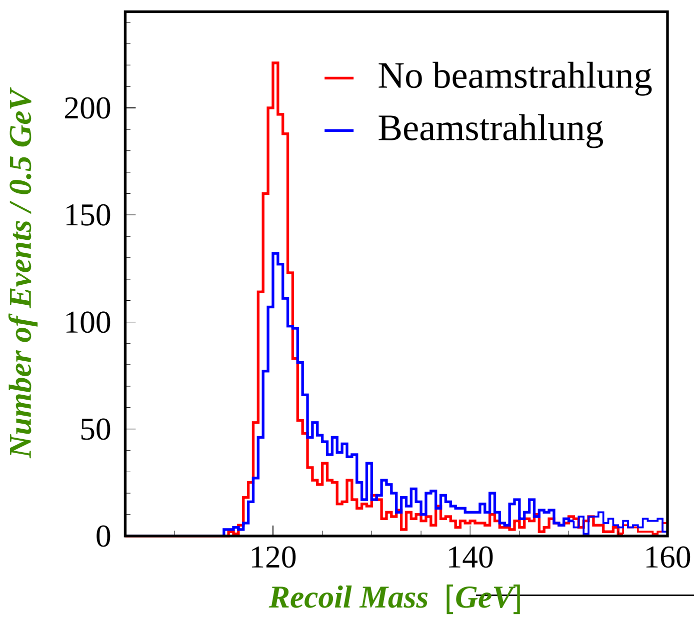
Include bremstrahlung and beamstrahlung effects

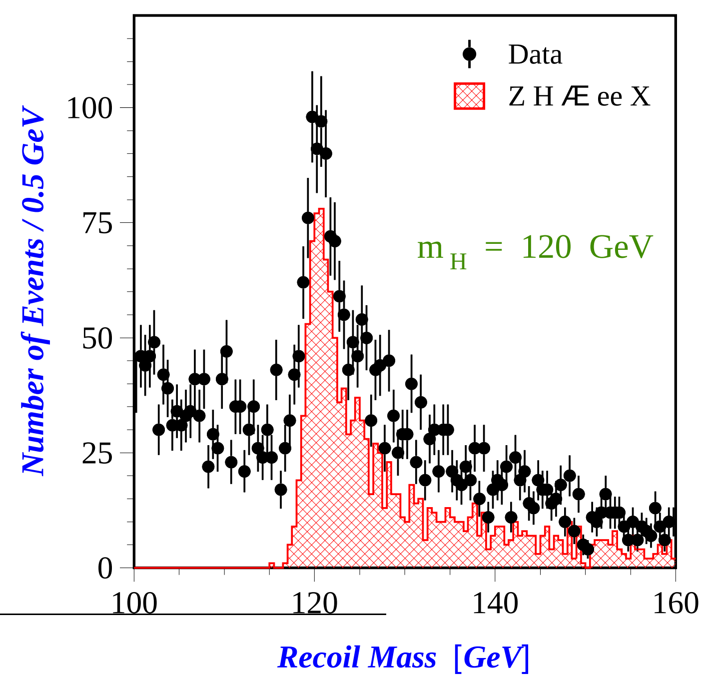


Decays to X, including invisible

- More precision from
  Z Æ e^+e^-
  Z Æ m^+m^- decays
  + vertex constraint

TESLA CDR Detector
Garcia-Abia, Lohmann





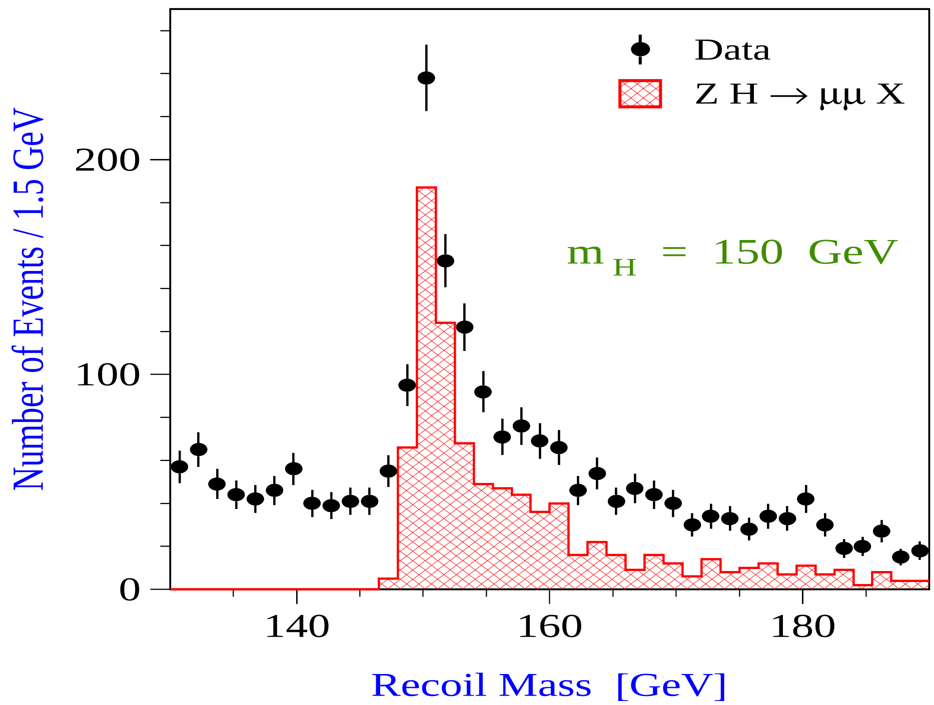
- Includes lepton id, systematics in effic. and 1% on luminosity
- ÷s = 350 GeV, 500 fb^{-1}

Dm_H = 140 MeV

Dm_H ~ 230 MeV 200 fb^{-1}

$$\frac{\text{Ds}_{ZH}}{\text{s}_{ZH}} = 3.5\% \text{ fi } \frac{\text{D}g_{ZZH}}{g_{ZZH}} = 1.8\%$$

Update



Mass (GeV)	Fit Cross Section (fb) /500 fb^{-1}	Stat. Error(%) /500 fb^{-1}
120	5.30 ± 0.13 (stat) ± 0.12 (syst)	2.4%
140	4.39 ± 0.12 (stat) ± 0.10 (syst)	2.7%
160	3.60 ± 0.11 (stat) ± 0.08 (syst)	3.0%

Mass

Direct Reconstruction: dijet invariant mass resolution

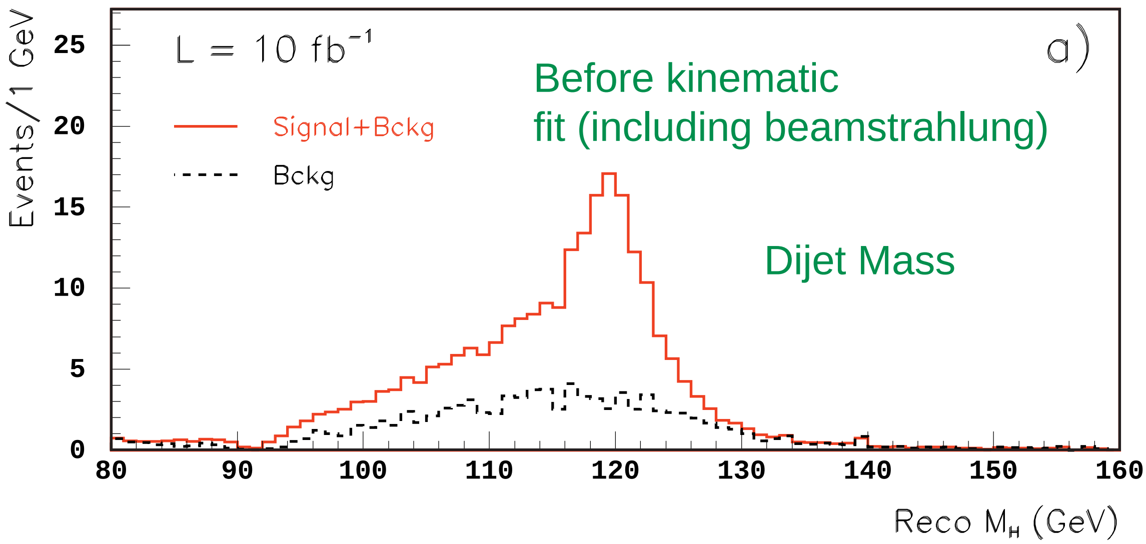
ZH Æ q$\bar{q}$H

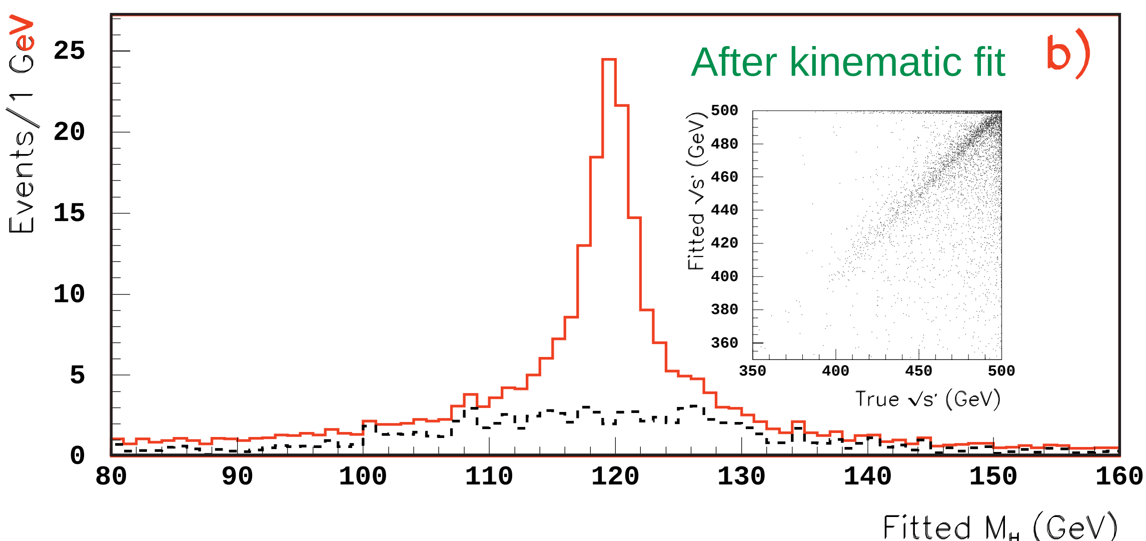
4 jets

Take 2-jet combo
inv. mass closest to *Z*

- ÷s = 500 GeV, m_h = 120 GeV
- realistic simulation, "L" LC detector, VDET @ r = 1.5 cm
- b-tag and neural net event selection (LEP2 tools)

Juste, '99





$\frac{Ds_{ZH}}{s_{ZH}}$ ~ 9.7% (stat.) fi $\frac{Dg_{ZZH}}{g_{ZZH}}$ ~ 4.9% (stat.) 10 fb^{-1}

Dm_H ~ 350 MeV (stat.) 10 fb^{-1}

Dm_H ~ 80 MeV (stat.) 200 fb^{-1}

Dm_H ~ 50 MeV (stat.) 500 fb^{-1}

- comparable to TESLA TDR

- How much gain from kinematic fit? What if channel prevents it?

Study of Energy Flow in Jet Reconstruction

R. Frey & M. Iwasaki, Univ. of Oregon

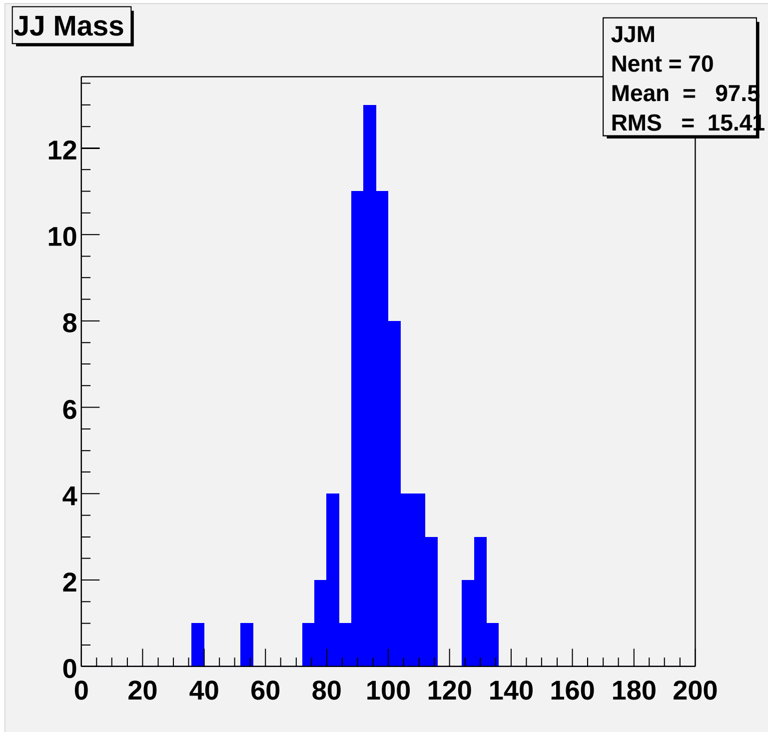
- Good jet reconstruction essential to explore and make use of all decay modes
  - multi-jet masses: e.g. Zh *vs* ZZ *vs* WW
  - reconstruct parton angles to extract quantum numbers, anomalous moments, e.g. WW, $t\bar{t}$, $t \to bqq'$
- Use combination of tracker and calorimeter which provides best resolution:
  tracker for $h^{\pm}$, EM cal. for π^0 (, HAD cal. for K_L^0, etc.)
- Requires excellent $\gamma - h^{\pm}$ id. $\Rightarrow$ EM Cal. segmentation
- Realistic modelling requires more-than-primitive cal. clustering algorithm(s)

This Study:

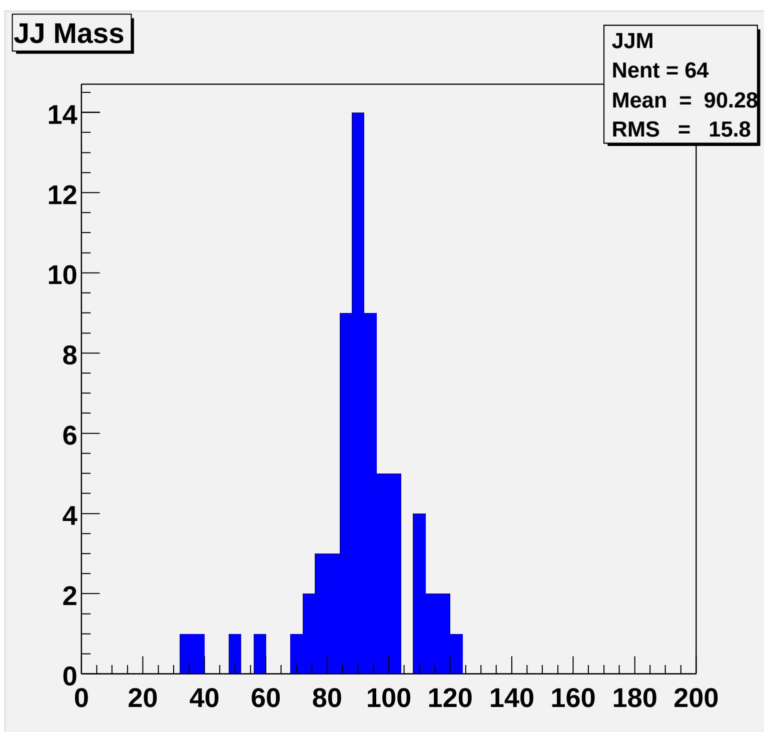
- Develop EFlow technique in LCD simulation
- Implications for detector design in terms of physics benchmarks
- Compare to other techniques for jet recon.

- Start with LCD Fast Simulation
- Move to Full Sim. (Gizmo/GEANT 4), clustering alg. (*c.f.* N. Graf talk)

- Energy Flow - Detector S; $d2D > 0.5$ cm, $(dE > 5$ GeV$)$, no R cut:



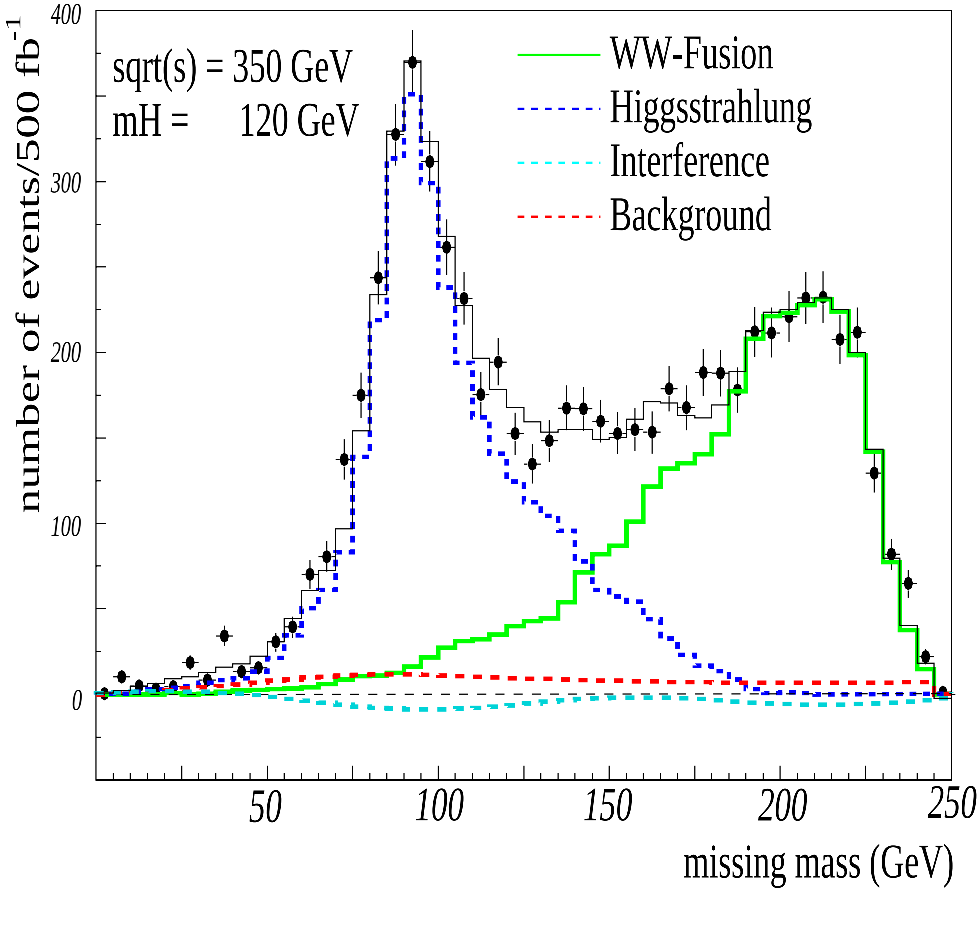
- Energy Flow - Detector L; $d2D > 1.5$ cm, $(dE > 5$ GeV$)$, no R cut::

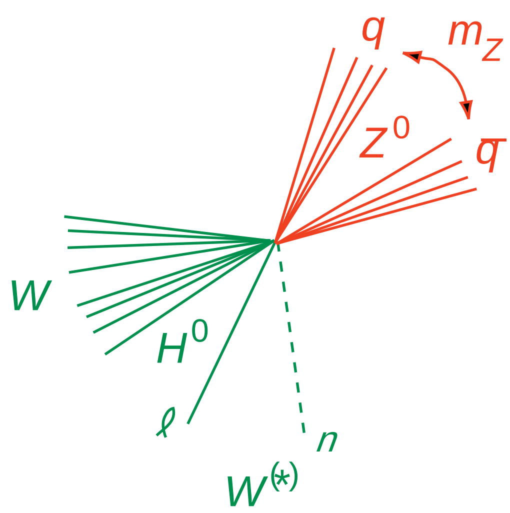


- Another good detector requirement check: recoil mass against jets (in particular, can isolate *WW* fusion channel)

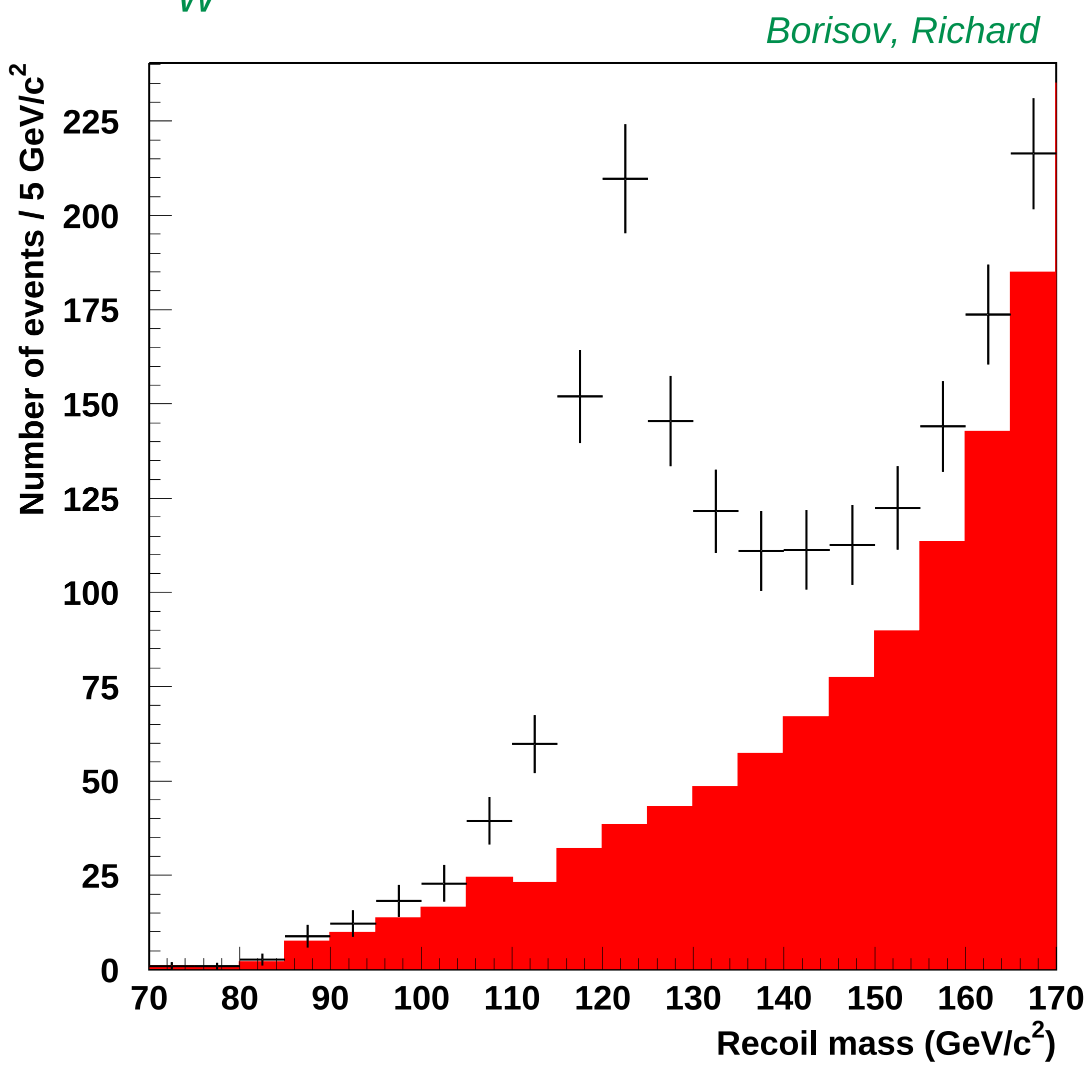
Jet-Jet Missing Mass for

$$e^+e^- \to H^0 \nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$$





- Recoil mass recoiling from any pair of jets with invariant mass within 10 GeV of M_Z
- $\sqrt{s}$ = 350 GeV, m_h = 120 GeV
  500 fb^{-1}
- anti-tag against b jets



$$\frac{\Delta Br(h \to WW^*)}{Br(h \to WW^*)} \sim 5.1\%$$

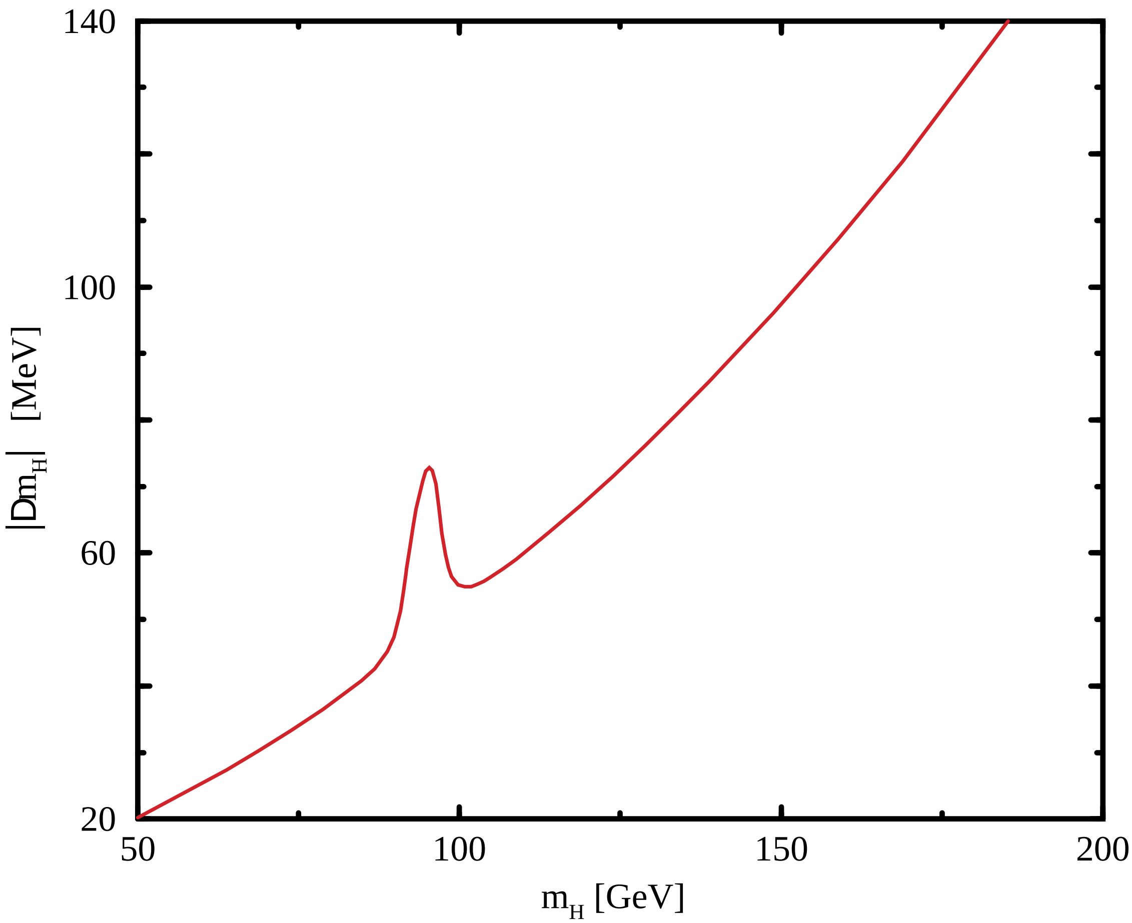
Mass (and Spin)

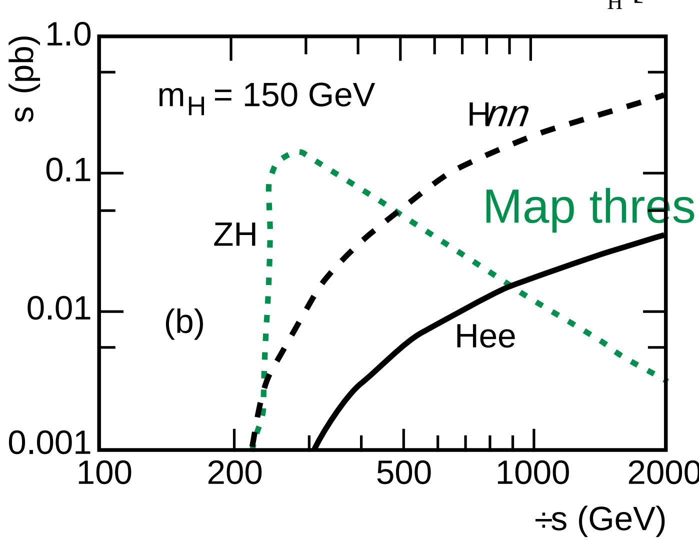
Scan threshold,
lower energy beam line??

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

Competitive!

Barger, Berger, Gunion, Han

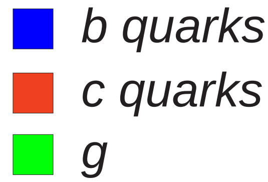




- Miller @ LCWS 2000

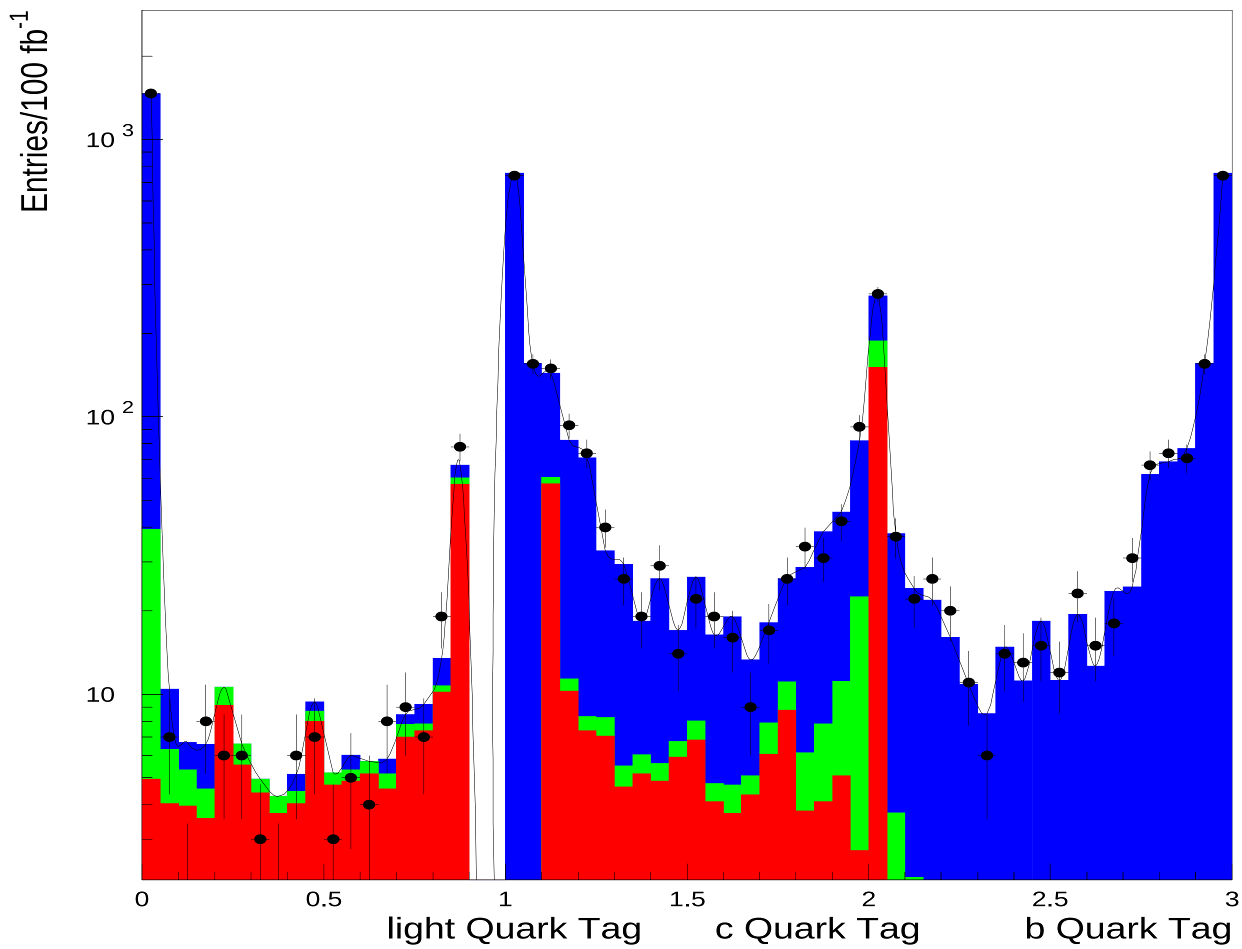
Map threshold fi general treatment of *b* dependence across threshold, gives spin info

(e.g. spin-0 linear in *b*)

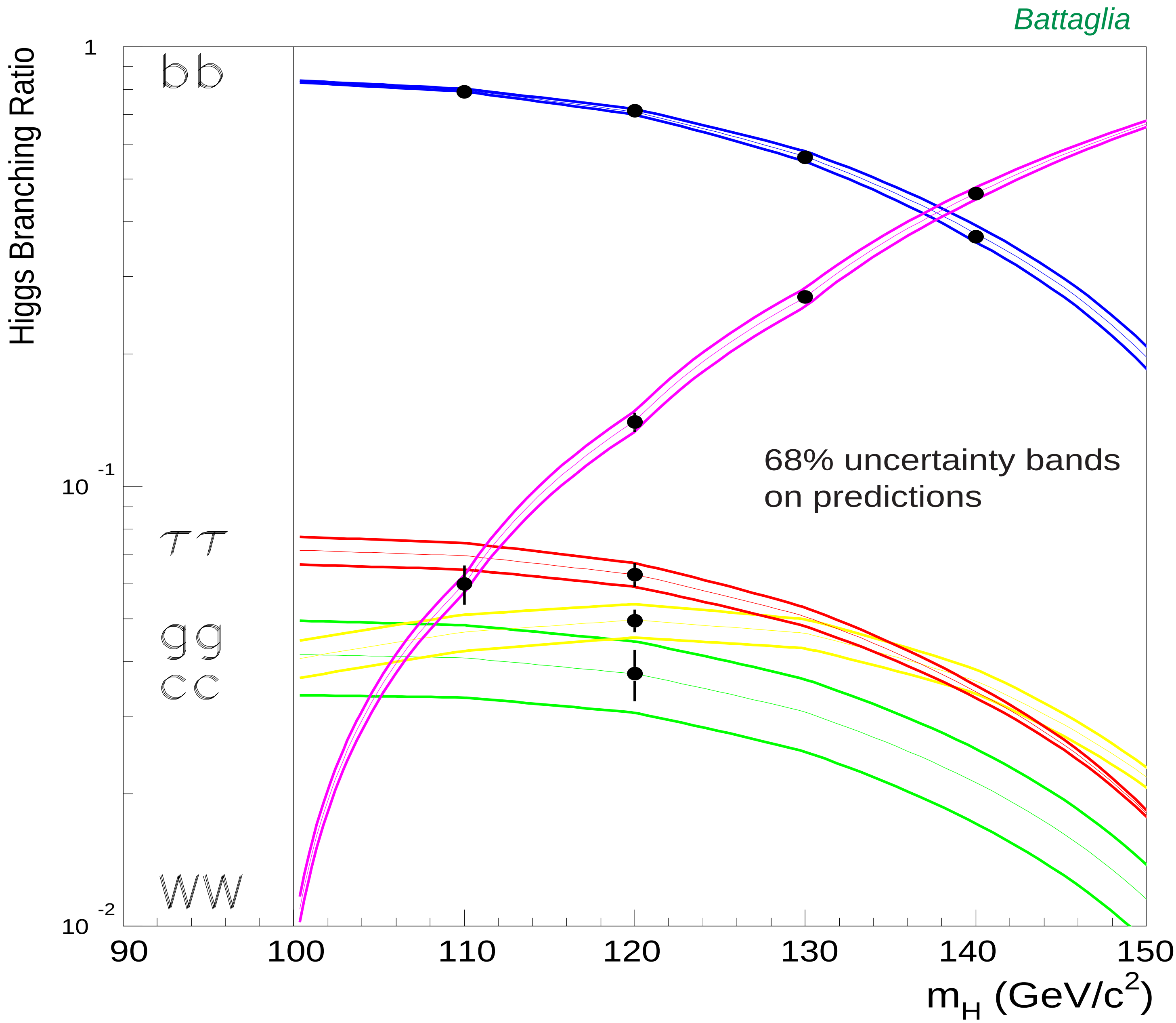


Battaglia

- $\surd s$ = 350 GeV, 500 fb^{-1}
- realistic simulation, TESLA CDR detector, CCD at small radii
- advanced jet flavour tagging techiques (topological and kinematic [e.g. vertex mass]) allows separation of light quarks and c quarks separately from b quarks



- Each candidate hadronic Higgs decay, compute light quark, cc, and bb di-jet flavour tagging probabilities
- Subtract background from Higgs peak sidebands
- Binned likelihood fit to the different flavour fractions



Battaglia
Higgs Branching Ratio
1
10^-1
10^-2
bb
ττ
gg
cc
WW
68% uncertainty bands
on predictions
90
100
110
120
130
140
150
m_H (GeV/c^2)

Event simulation

- Pandora-pythia and Pythia v5.7
  - beamstrahlung included and important
- Detector model : L2

$e^+e^- \to ZH$
  $H \to bb$
  $H \to \tau\tau$
  $H \to cc$
  $H \to gg$
  $H \to WW$
$e^+e^- \to WW$
$e^+e^- \to ZZ$
$e^+e^- \to qq$
$e^+e^- \to tt$

$\sqrt{s} = 500$ GeV
$M_H = 140$ GeV/c^2
$\int L = 500$ fb^{-1}
Analysis with $Z \to l^+l^-$ evts, scaled to $Z \to qq$
(OPAL, D. Strom)

Very Preliminary Results Presented in this Talk

Previous studies:
Hildreth, Barklow, Burke, PRD49, 3441 (1994)
M. Battaglia, HU-P-264 (1999)
G. Borisov, F. Richard, LAL-99-26 (1999)

Efficiencies and Purities

(M_H = 140 GeV/c^2 , $\sqrt{s}$ = 500 GeV,

Model L2)

	Eff.	Signal/Backg.
$H \rightarrow bb$	0.30	5.3
$H \rightarrow \tau\tau$	0.30	1.6
$H \rightarrow cc$	0.19	0.2
$H \rightarrow gg$	0.21	0.06
$H \rightarrow WW^*$	0.09	3.6

Preliminary (not optimized)

(My add: they are including neural net selection, additional ZVTOP studies)

Detector Parameter Dependence

Branching Ratio Errors

($M_H = 140$ GeV/c^2 , $\sqrt{s} = 500$ GeV,

$\int L = 500\ fb^{-1}$)

	L2	2.4 cm radius*	L2 3.0 μm res.
$H \rightarrow bb$	± .014	± .017	
$H \rightarrow \tau\tau$	± .005	± .006	
$H \rightarrow cc$	± .011(46%)	± .014 (60%)	
$H \rightarrow gg$	± .020(59%)	± .026 (78%)	
$H \rightarrow WW^*$	± .031	± .035	

*(optimistic-primary vtx)

(My add: they are including neural net selection, additional ZVTOP studies)

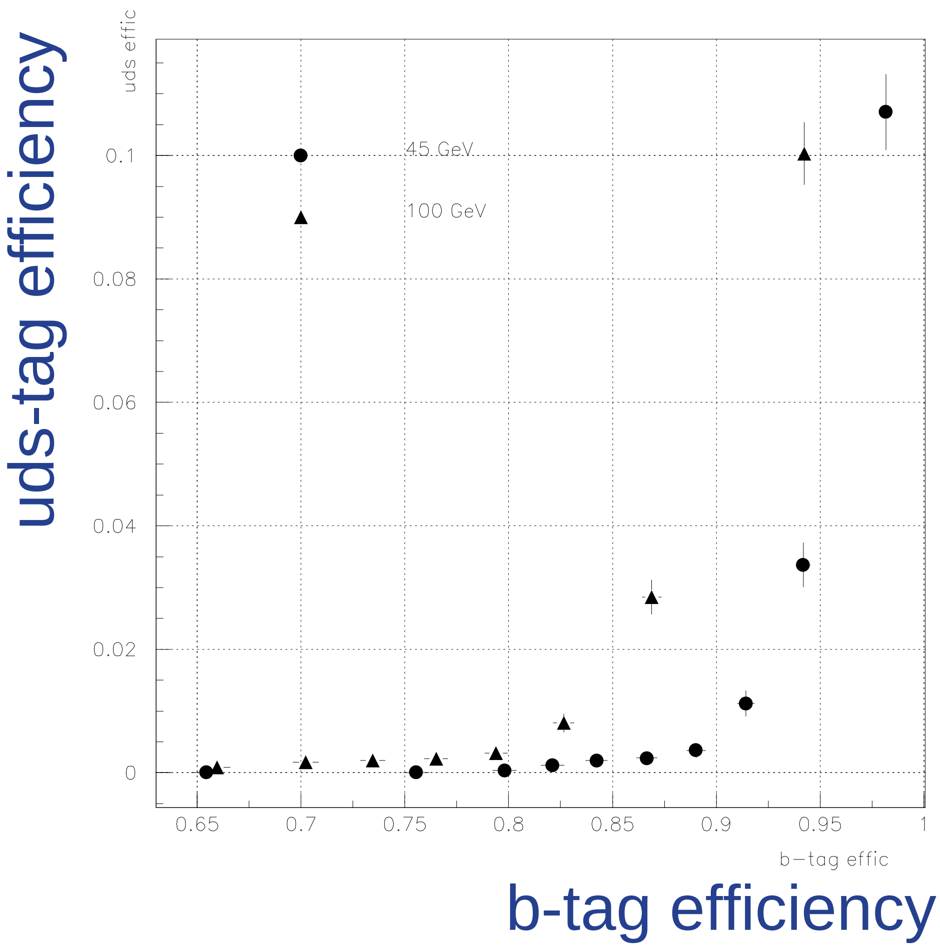
Preliminary (not optimized)

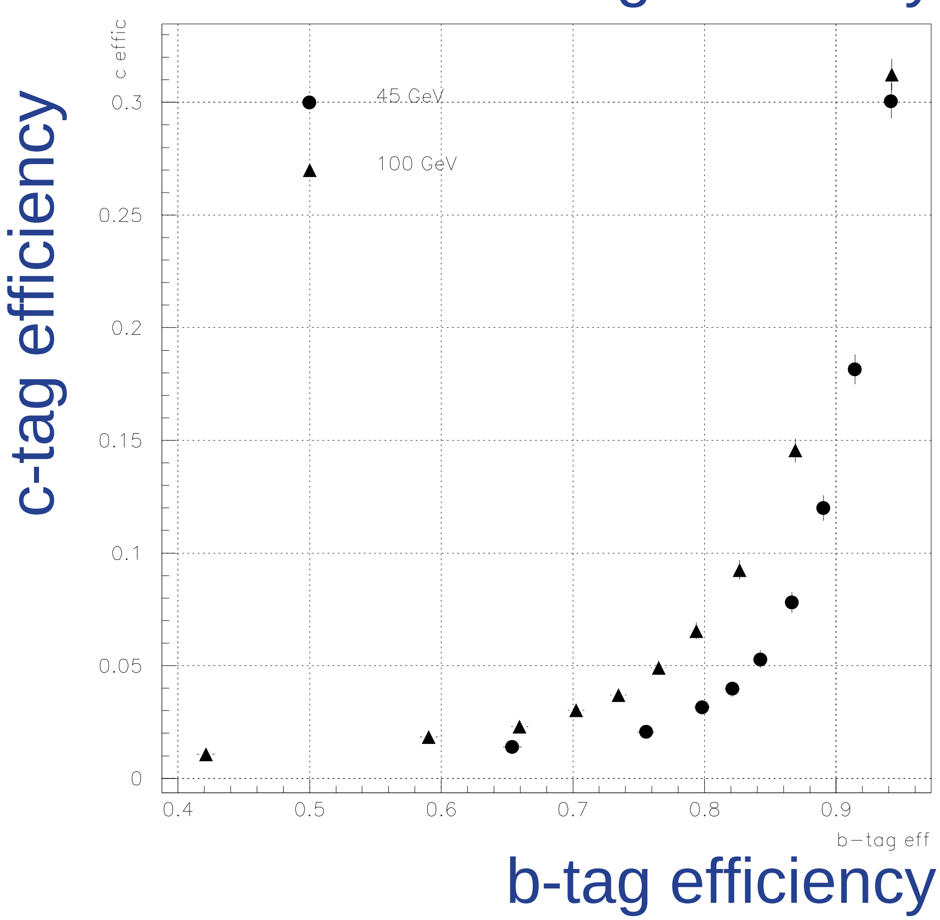
J. Brau, LCWS 2000, October 26, 2000

S. Xella

Running at different √s?

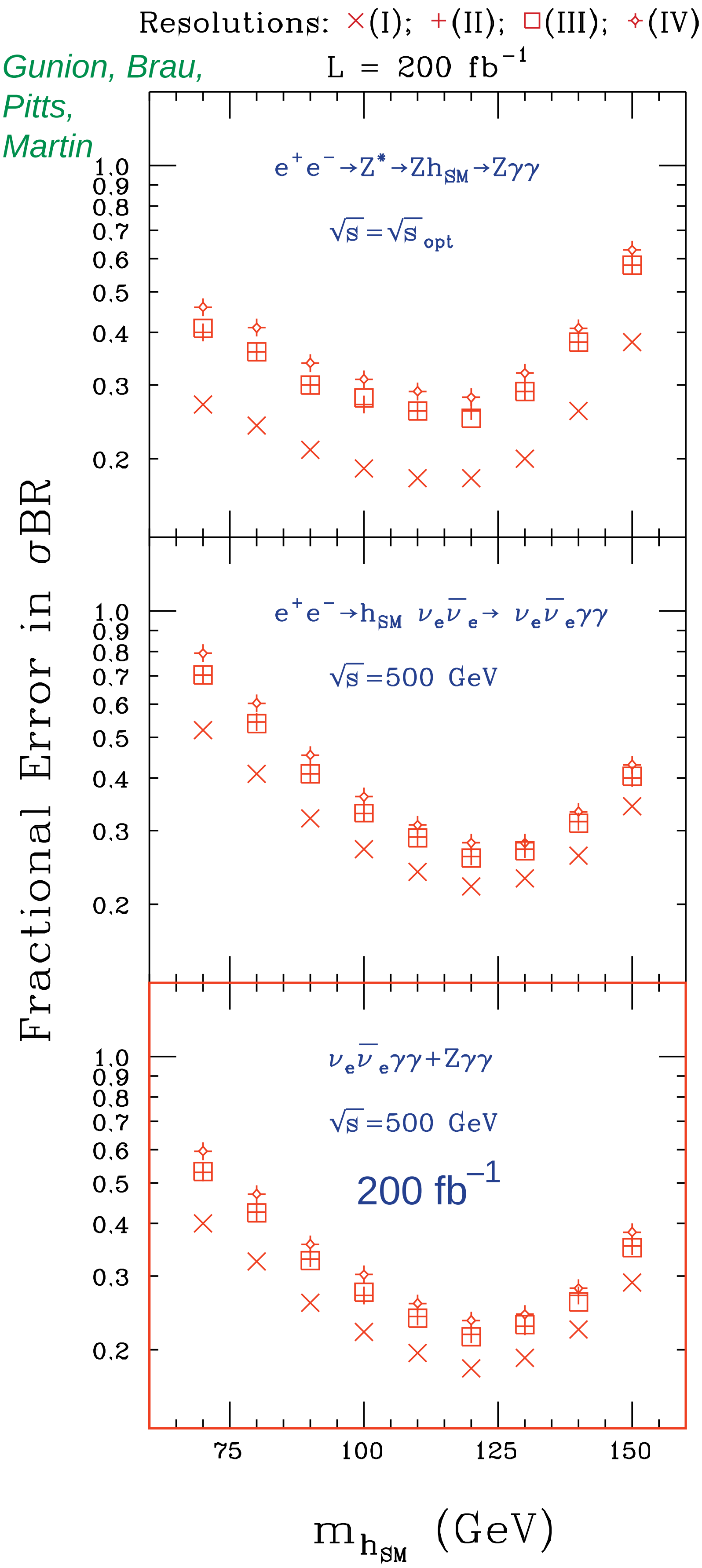
Monojets at 45 and 100 GeV





s Br(h Æ gg)

Gunion, Brau, Pitts, Martin



× CMS detector EM resolution

2%/÷E ≈ 0.5%

+ □ Snowmass NLC detector EM resolutions

10%/÷E ≈ 1.0%

✧ JLC detector EM resolution

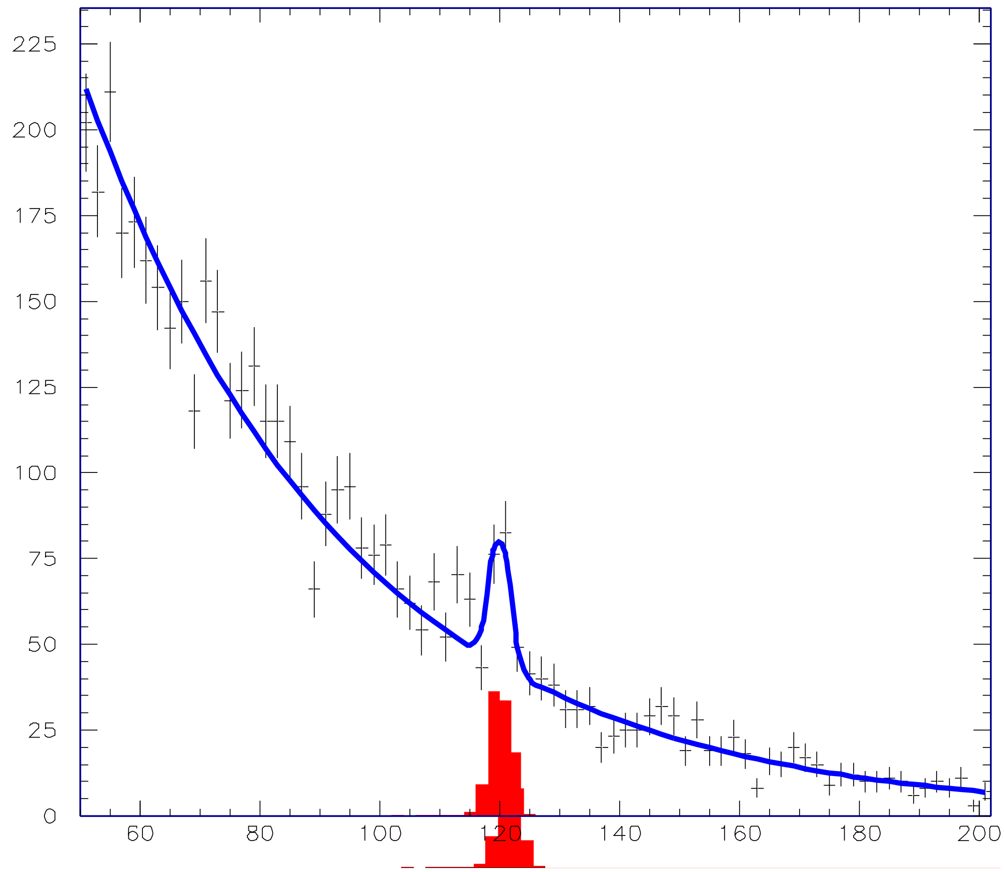
Brient, Reid, Schreiber

- ÷s = 350 GeV, m_h = 120 GeV 1000 fb^{-1}
- TESLA CDR detector,

DE / E = 10% / ÷E ≈ 0.6%

fi DBr(h Æ gg) / Br(h Æ gg) ~ 14% (stat.)

TESLA TDR Detector, Schreiber et al.



1000 fb^{-1}

14% relative error on $\gamma\gamma$ Br

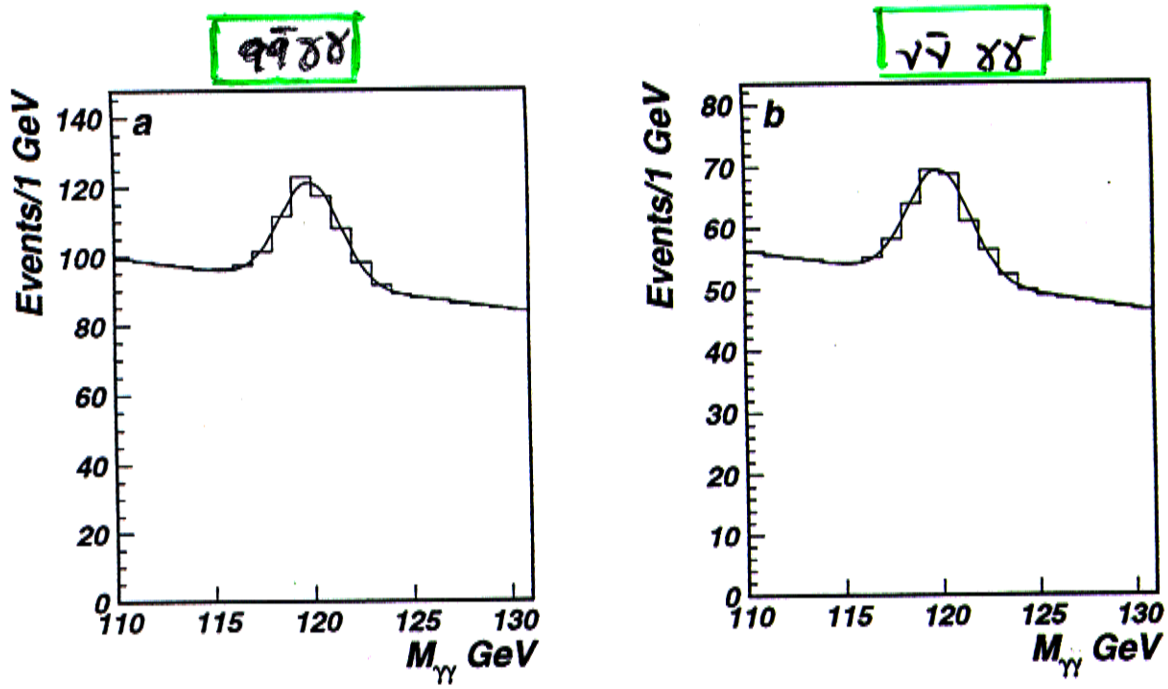


Figure 4: $M_{\gamma\gamma}$ invariant mass distributions for 350 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events

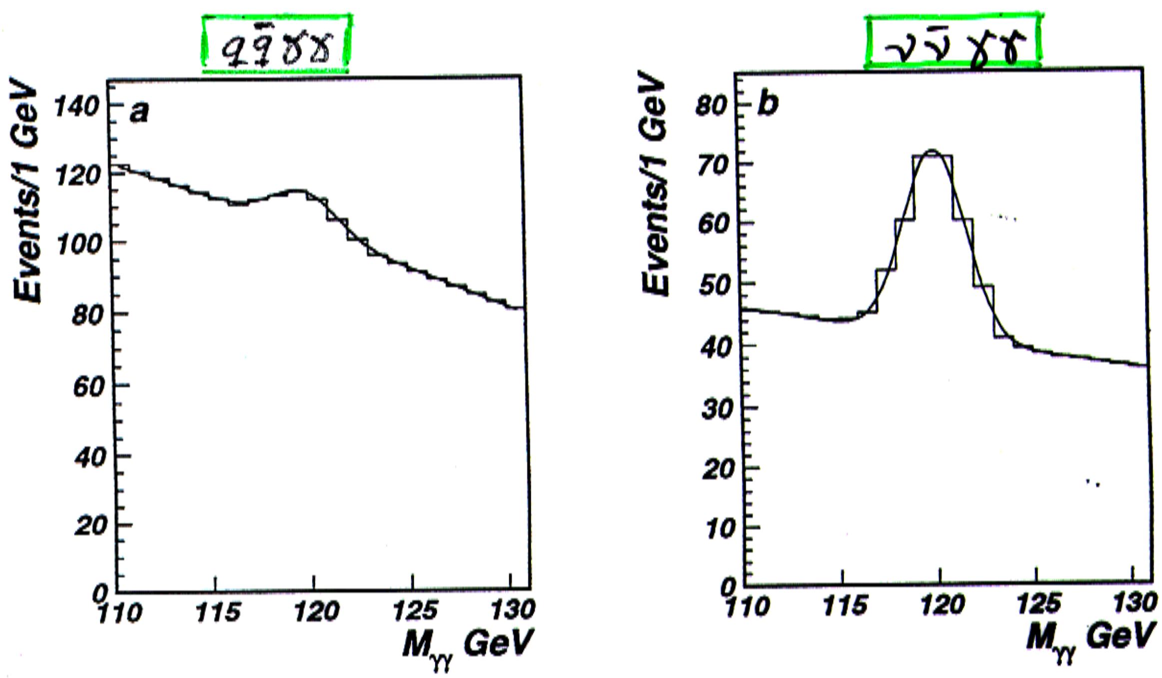


Figure 5: $M_{\gamma\gamma}$ invariant mass distributions for 500 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events

Invisible Decays

⇒ Can be 100%!

$H \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$

$\to$ *Majorons*

$\to$ *heavy neutrinos*

$\to$ *Higgs singlets* ← Gunion: "diabolical" multiple singlets decaying invisibly

$\to$ *"phions"* ("Stealthy model", Binoth, van der Bij, very large width in recoil mass)

covered with ~200–500 fb^{-1}

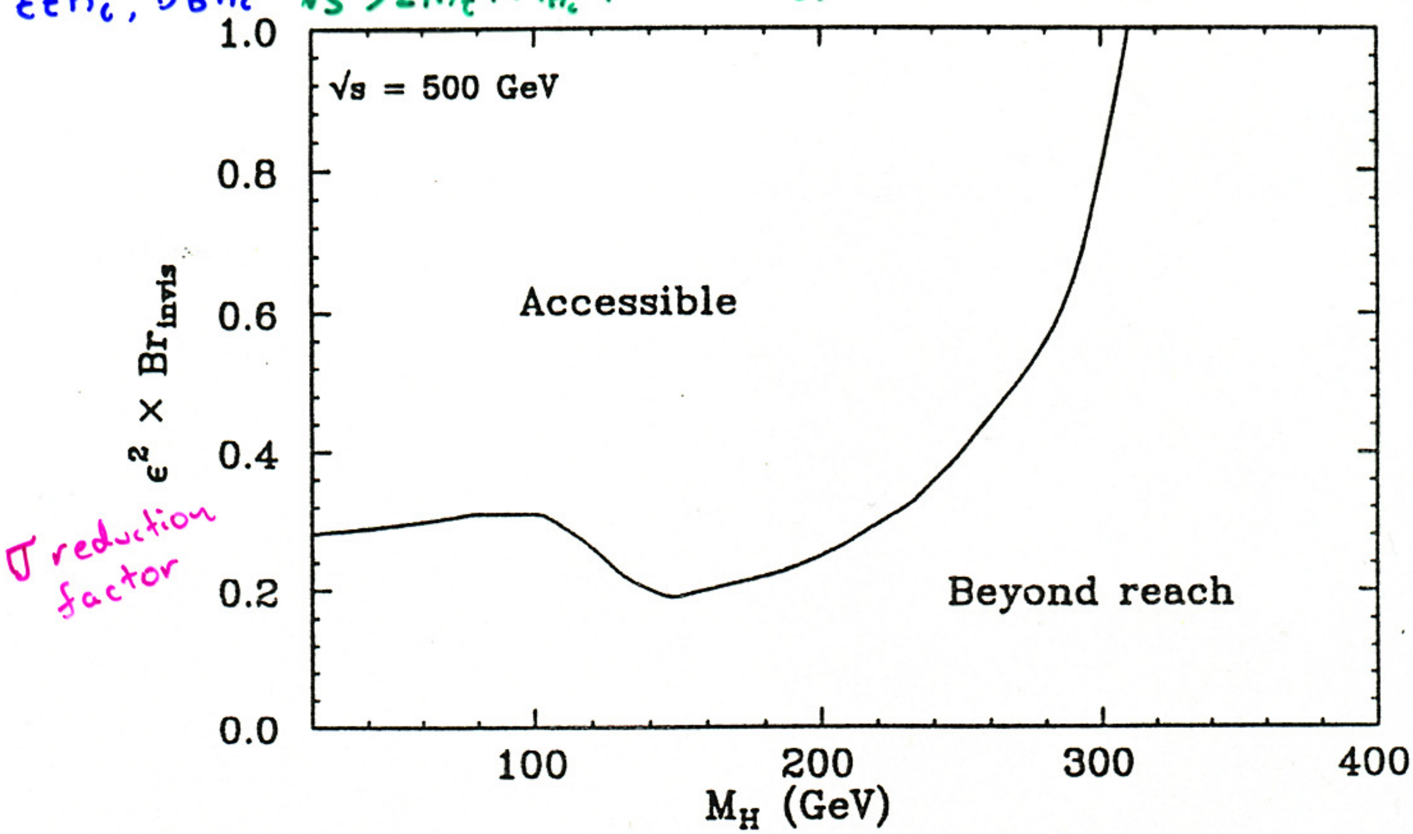
- Handled with recoil mass in Higgstrahlung (and missing *E*) (c.f. LHC)
- Measure *Br*(invisible)? How well?
- "Nastiest" – CP violating 2HDM Higgs w/ only fermionic couplings

$t\bar{t}h_i$, $b\bar{b}h_i$ $\sqrt{s} > 2m_t + m_{h_i}$ + lots lumi.

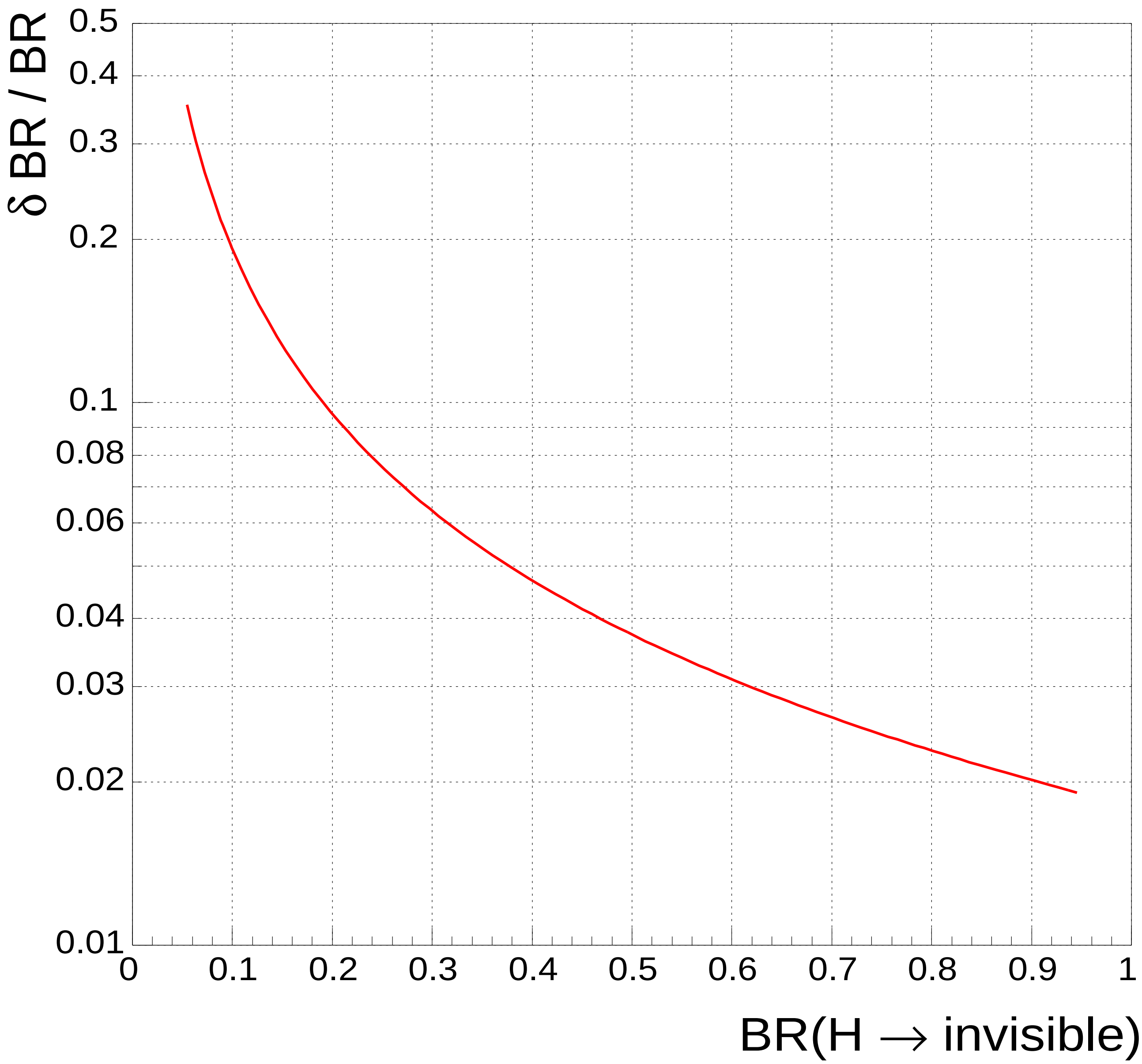
Eboli et al.

$\sqrt{s}$ = 500 GeV

10 fb^{-1}



Total No. Recoil – Number observed Higgs decays
(why not direct, *Z* recoiling against "nothing"?)



Total Width Determination

(older slide)

g g Collider, LC, LHC

How firm is this boundary??

$m_H \lesssim$ 115 GeV (almost ruled out by LEP2!)

$m_H \gtrsim$ 115 GeV

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

Where $G(H \text{Æ} WW^*)$ from:

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

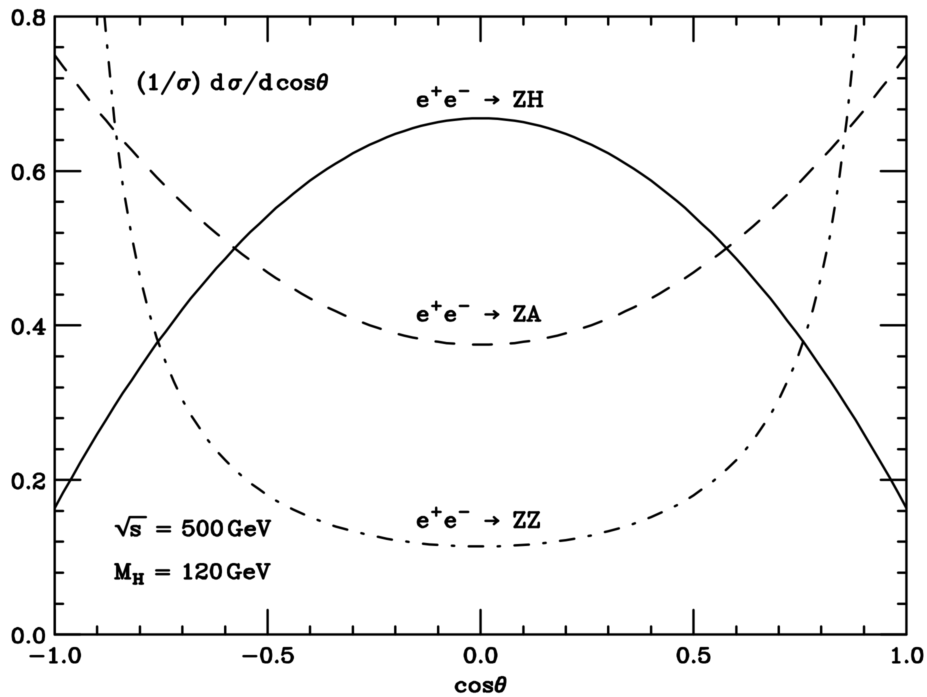
How well can we do *WW Br at 115 GeV?**

How well can we do *bb* Br at *m* > 160 GeV?

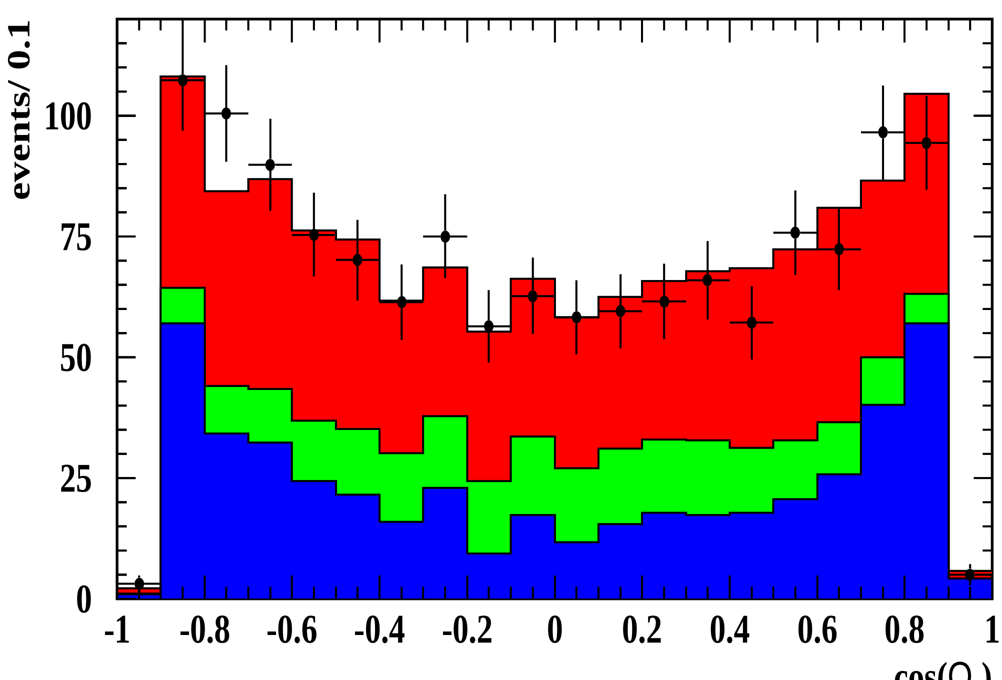
(Br just a few percent, "rare" decay, W. Wester, FNAL)

$m_H \gtrsim$ 205 GeV, G_{tot}^{SM} ~ 2 GeV, directly resolvable

Departures? fi **New physics!**



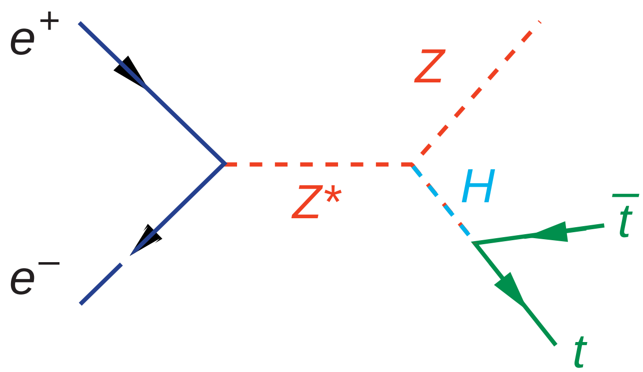
TESLA TDR:



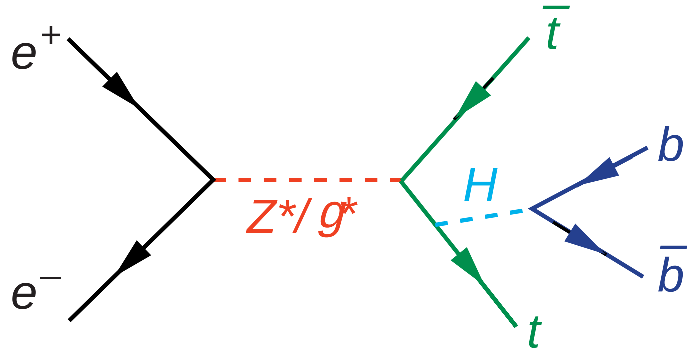
Sensitivity to A mixture: 0.13 (shape only) and 0.03 (shape plus s)

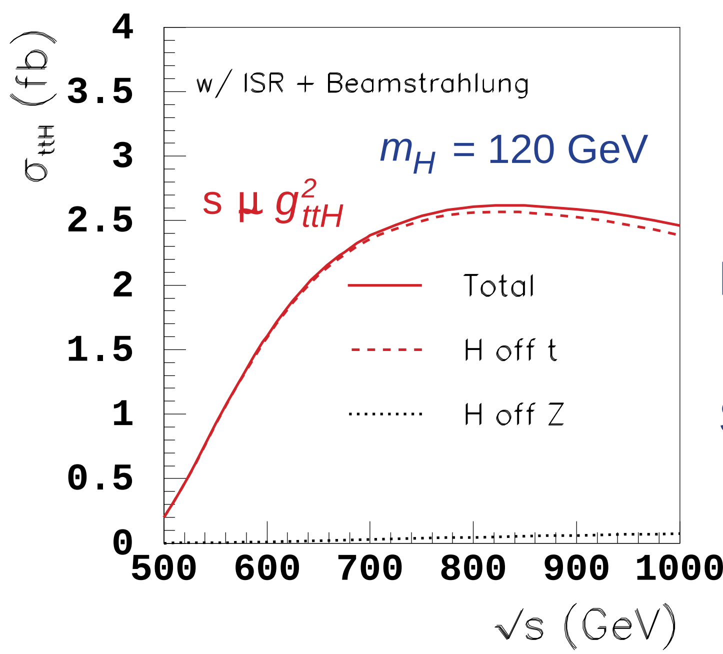
Coupling to top, g_{ttH}

- Heavy Higgs



- But if light, radiation off top





- needs large $\sqrt{s}$
- cross section decreases rapidly for heavier Higgs

Hadronic

$\Rightarrow$ 8 jets, 4 are *b* jets

Semileptonic

$\Rightarrow$ 6 jets, 4 are *b* jets, isolated lepton, missing *E*

Juste, Merino

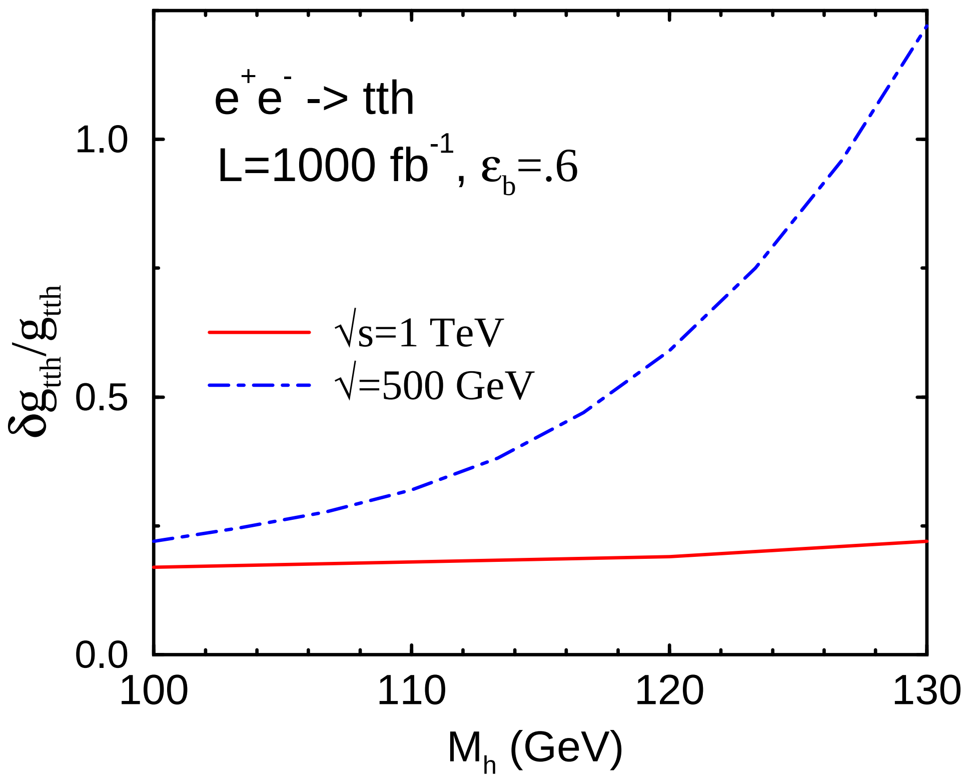
$\sqrt{s}$ = 800 GeV

m_H = 120 GeV

1000 fb^{-1} Neural net selection, some systematics

$$\Rightarrow \quad \frac{\Delta g_{ttH}}{g_{ttH}} \sim 6\%$$

Combine hadronic and semi-leptonic channels:



- Statistical error only in plot
- Interesting question is how well do you *need* to do?

- Juste and Merino (hep-ph/9910301): More sophisticated analysis with TESLA detector and neural net analysis
- Juste and Merino: $\sqrt{s} = 800\ GeV$; $M_h = 120\ GeV$

$$\frac{\delta g_{tth}}{g_{tth}} = 5.5\%$$

Experimental Issues

fi **systematics on precision measurements**

Luminosity Measurement (e.g. for *s*, *s* · *Br*)

- *Z g*
- Wide-angle (endcap) bhabha (out of mask)
- Good to 1%?

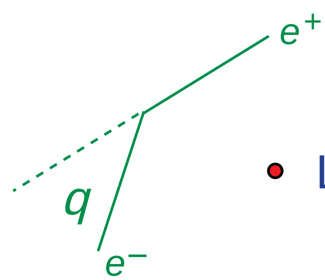
"Loopvergin" - Miller

Luminosity Spectrum (after ISR, beamstrahlung)

Frary, Miller
Kurihara

(e.g., for kinematic fits)

- extract from acollinearity angle distribution of bhabhas fi stable enough in time?



- Look at *ZZ* events

Event Overlap

- Many bunches per train
- msec spacing between trains
- nsec spacing between bunches
- high luminosity per bunch

⇒ Overlap of from hits due to beam-beam interactions
(e^+e^- cloud, hits in SiDET, CCD at small radii)

⇒ Tails on impact parameter distributions, particularly for soft tracks, flavour tagging systematics (stability, understanding eff., backg.)

⇒ Overlap of events
($\sigma_{\gamma\gamma}$ = 10 – 100 nb!, mostly two photon interactions:
1. virtual photon from each beam
2. virtual photon from one beam, real photon from beamstrahlung)

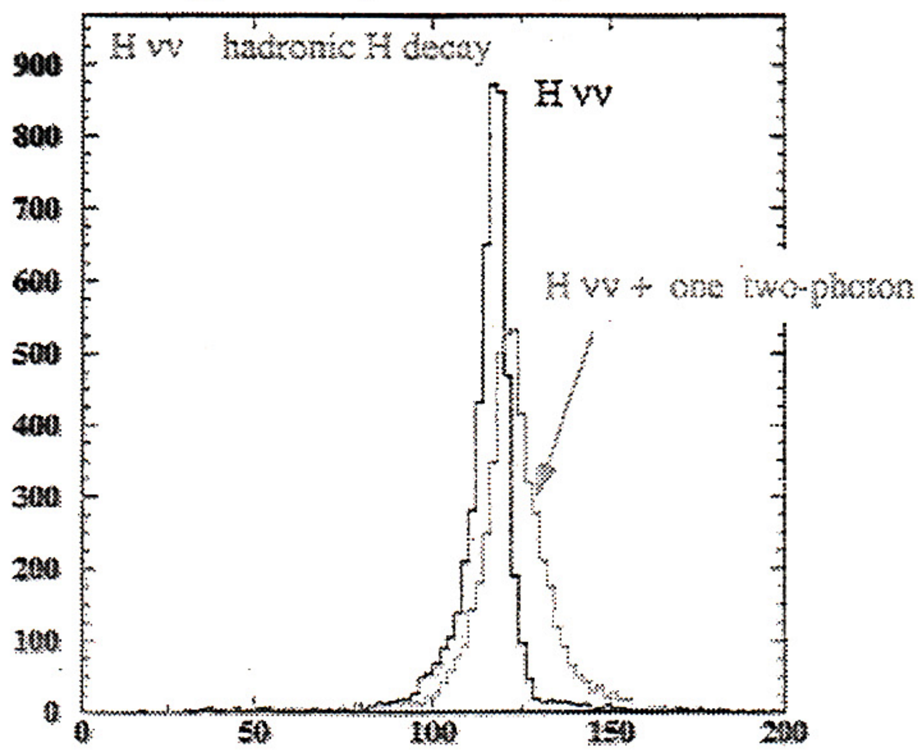
⇒ 1 – 20% probability of event overlap

⇒ "minijets": mostly low-p_t tracks more in forward region, but tails into central

⇒ can also affect flavour tagging

Tauchi
Yamashita, Kanzaki

Higgs Mass (visible mass) distribution



CP Determination

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

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

or H^0, A^0

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

- Angular/energy distributions of $e^+e^- \to t\bar{t}h^0$ (He & Gunion)
- $\gamma\gamma$ collisions: $N^{\parallel}$ = # Higgs, γ polarizations parallel

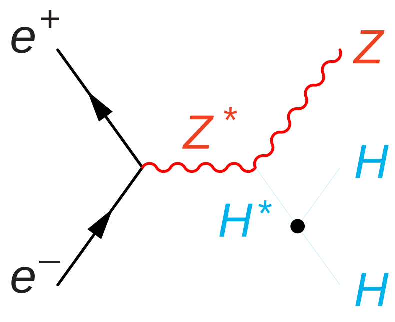
$N^{\perp}$ = " " " perpendic.

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

"Crispest"

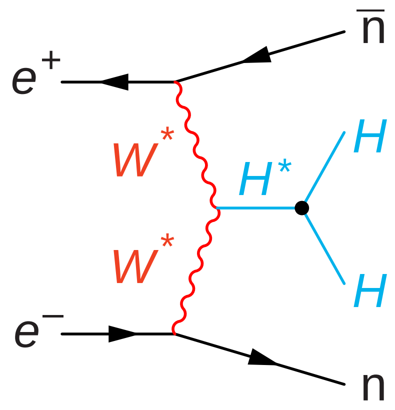
(leave on)

- Double Higgsstrahlung

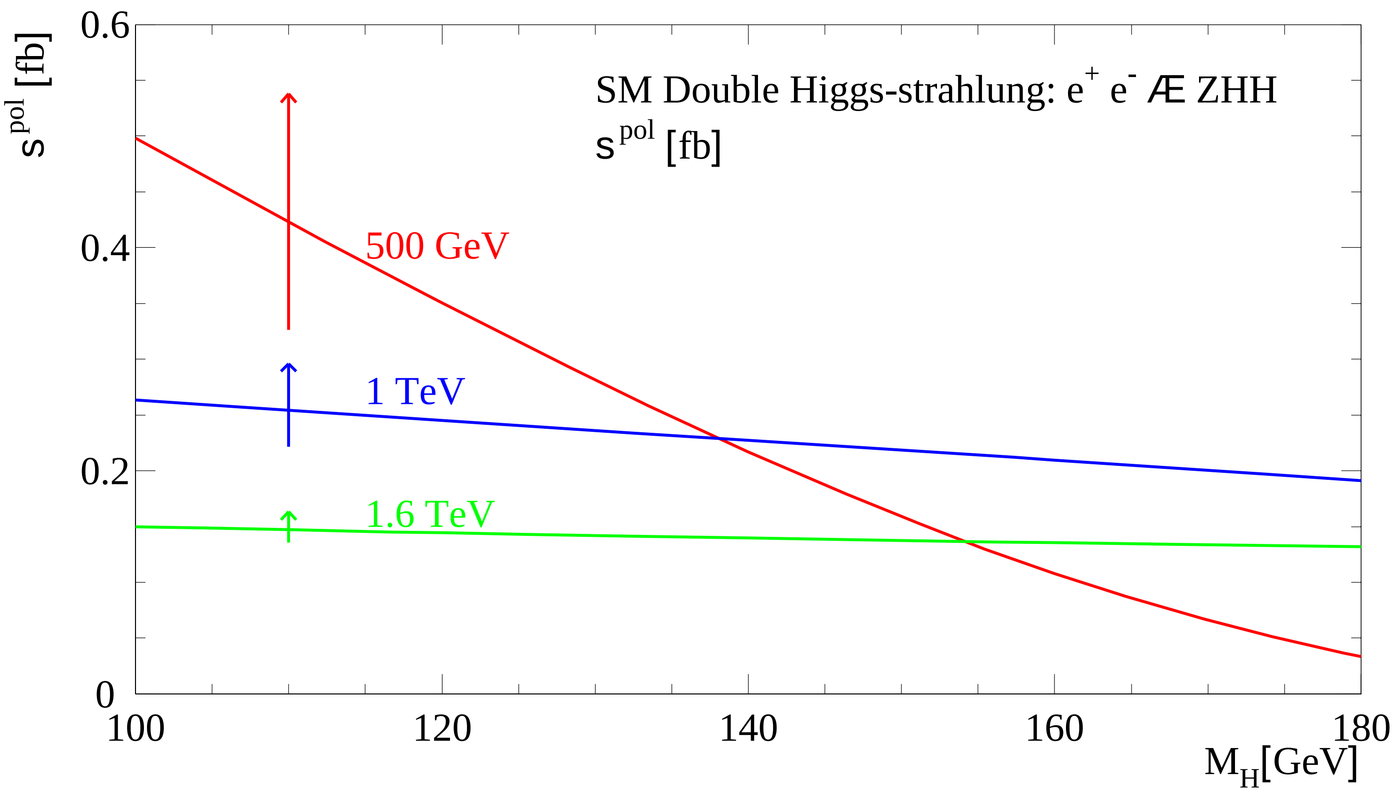


e.g., *Z* plus 4 *b*-jets

- *WW* Fusion



- *Plus triple higgs production in SUSY*



Djouadi, Kilian, Muhlleiner, Zerwas
Miller, Moretti
Bambade, Gay, Lutz

- High luminosity, 1000 fb^{-1}
- Polarization
- Acceptance and *b* tagging in forward region

fi l_{HHH} to ~ 15 – 20%

Quartic couplings ~hopeless, s (*ZHHH*) < 0.001 fb

Status/Plans

- Not a great deal of progress since Berkeley, but

    Vertexing/energy flow at Oregon

    FNAL Group: vertexing, spin, rare Br, intermediate mass (but Tevatron start-up, increasingly busy...)

    IU: finally approved for *other* 50% of NLC postdoc through university

    Please come help

- Meeting with Howie Haber, Andreas Kronfeld, Jack Gunion, RVK after LCWS2000: planning of Higgs organizational meeting, try before Christmas

- Need to take into account that we will probably need a strategy for what to do if a 115 GeV Higgs exists fi different ÷s?

    fi Higgs physics with "P" detector at 250 – 350 GeV? Threshold scans?

For Detector Studies

- Momentum resolution benchmark

HZ Recoil mass resolution

$\hookrightarrow \mu^+\mu^-$

Masses 115, 140, 160 GeV

$\sqrt{s}$ = 500, 350, 250 GeV

- Electromagnetic calorimetry benchmark

HZ Recoil mass resolution

$\hookrightarrow e^+e^-$

Masses 115, 140, 160 GeV

$\sqrt{s}$ = 500, 350, 250 GeV

$H \to \gamma\gamma$

Masses 115, 130

$\sqrt{s}$ = 500, 350, 250 GeV

- Jet energy & calorimetry benchmark

  HZ Direct reconstruction, 4 jets, plus kinematic fitting

  Masses 115, 140, 160 GeV

  $\sqrt{s}$ = 500, 350, 250 GeV

  HZ Recoil mass against jets
  $\hookrightarrow$ *jets*

  Masses 115, 140, 160 GeV

  $\sqrt{s}$ = 500, 350, 250 GeV

  $H\nu\nu$ Jet-Jet Missing Mass, distinguish fusion and Higgstrahlung
  $\hookrightarrow$ *bb*

  Masses 115, 140, 160 GeV

  $\sqrt{s}$ = 500, 350, 250 GeV

- Vertexing: already working with samples, consider including

  Mass of 115 GeV

  $\sqrt{s}$ = 350, 250 GeV?

  "P" Detector?