Higgs studies specific to the ILC

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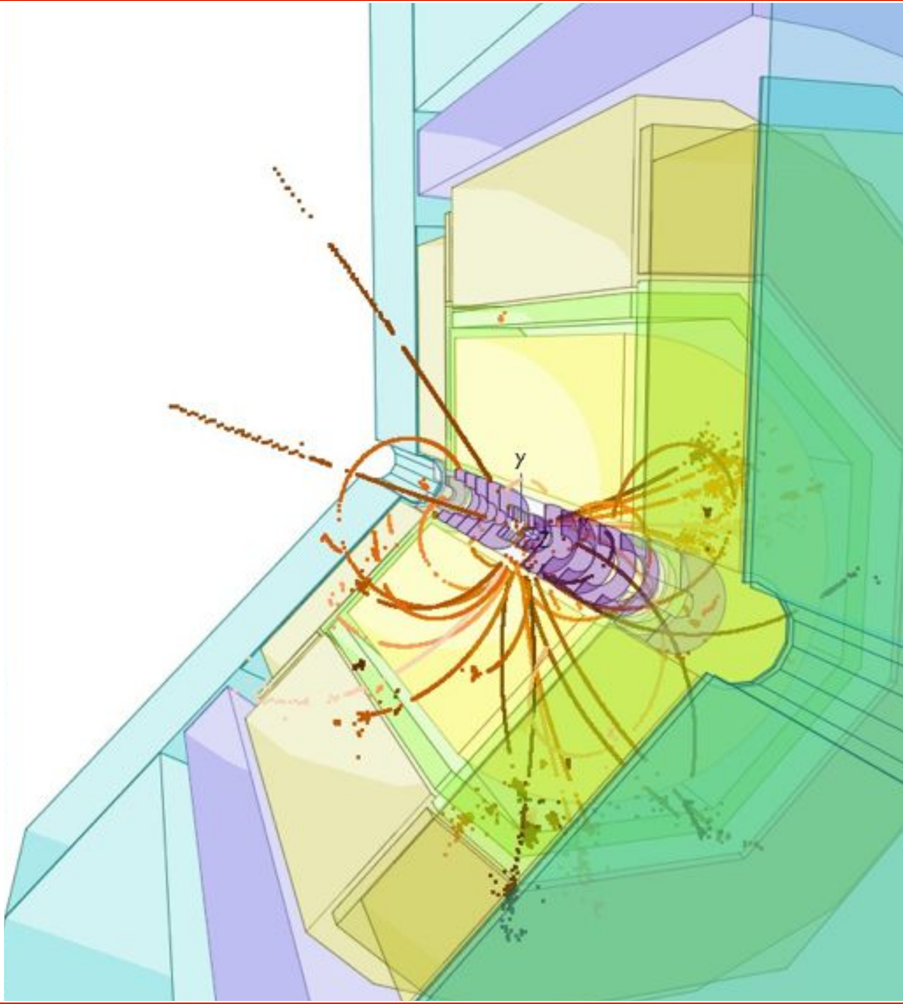
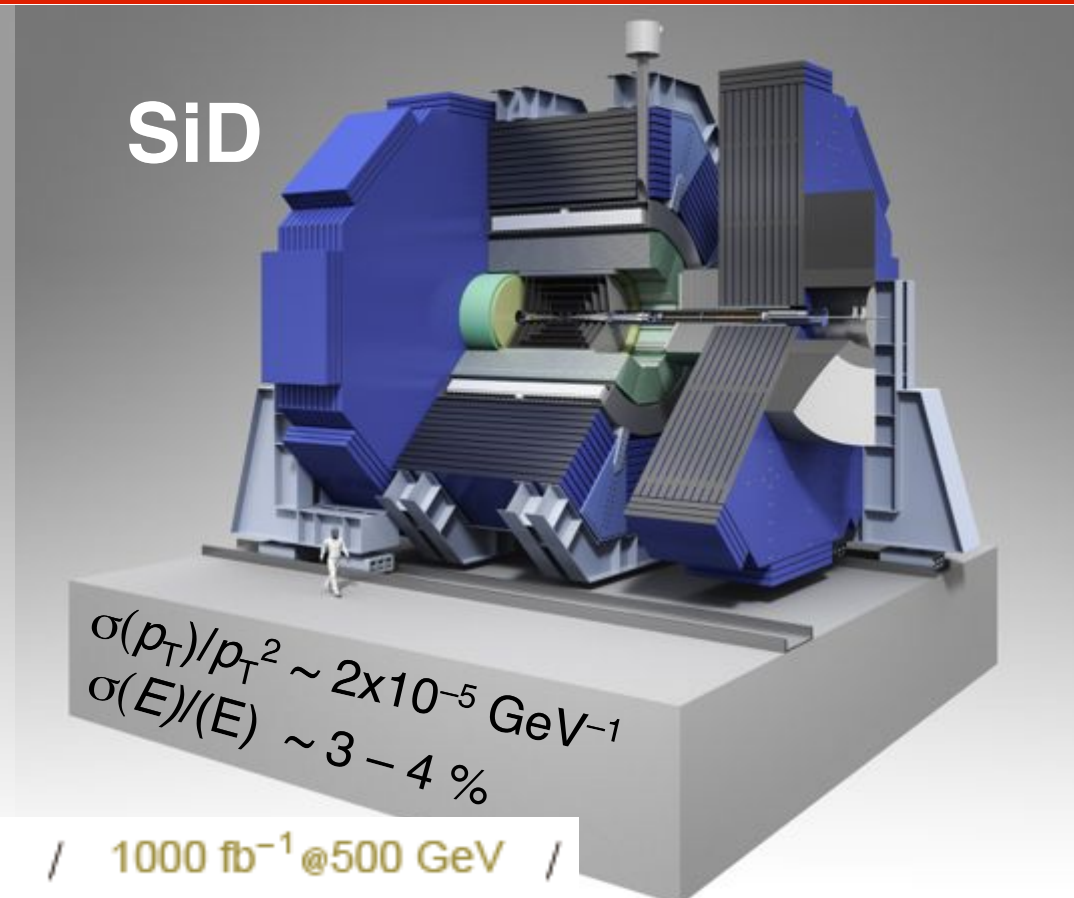
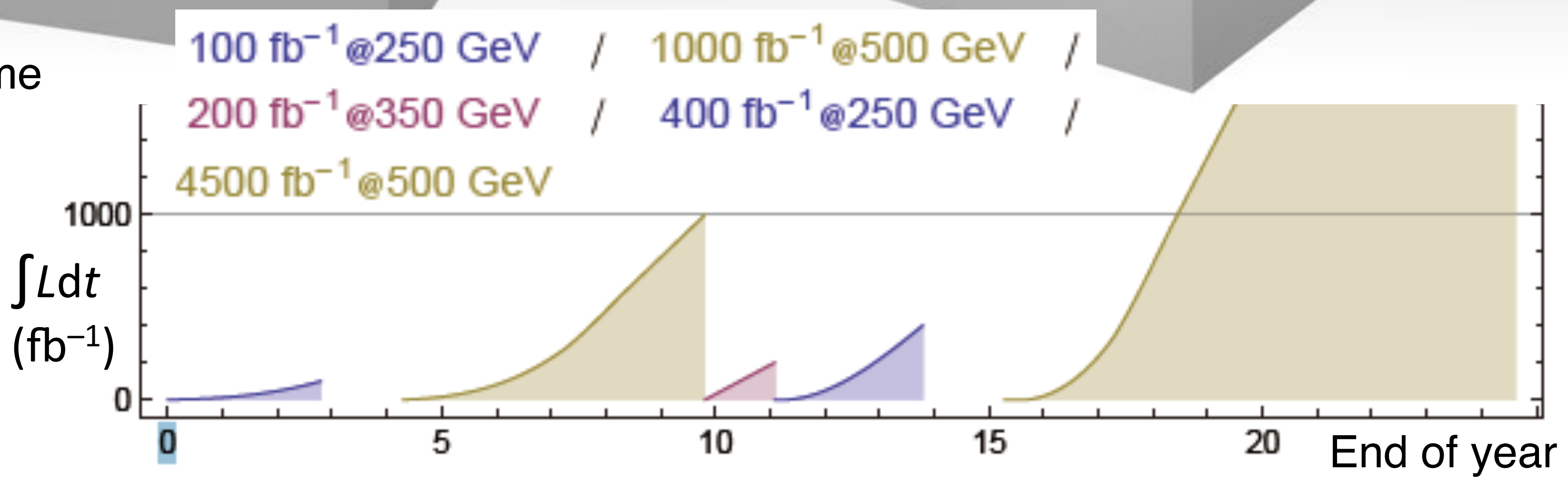


Context



Studies tend to assume
250 fb^{-1} at 250 GeV
500fb^{-1} – 2ab^{-1} at 500 GeV

Example staging scenario



Higgs overview

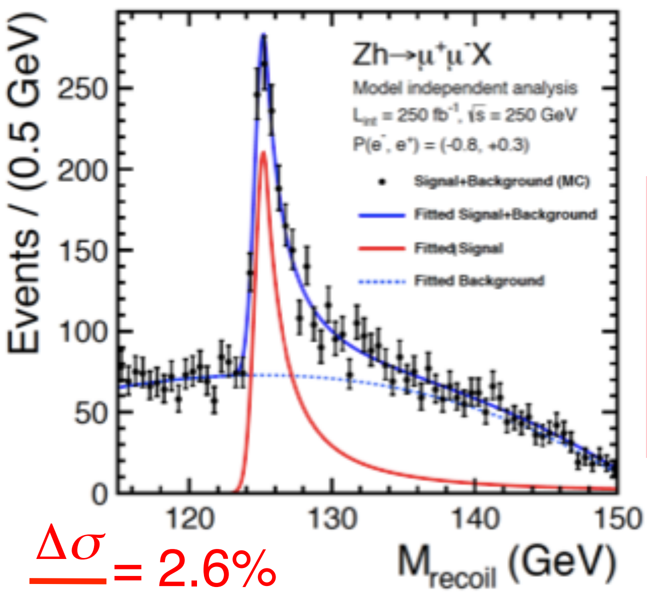
$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

σ x Br → Br → g coupling

σ from recoil mass (the key) → Γ_H total width

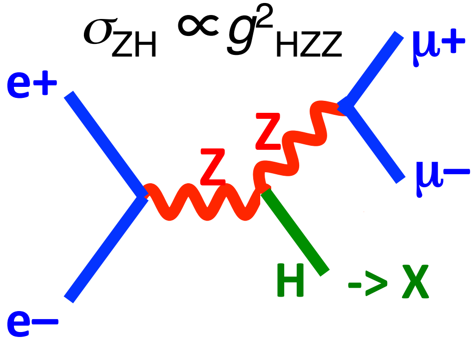
(need WW fusion for precision total width -> higher $\sqrt{s}$)

after Fujii/Tanabe



$\frac{\Delta\sigma}{\sigma} = 2.6\%$

$\sigma_{ZH} \propto g^2_{HZZ}$

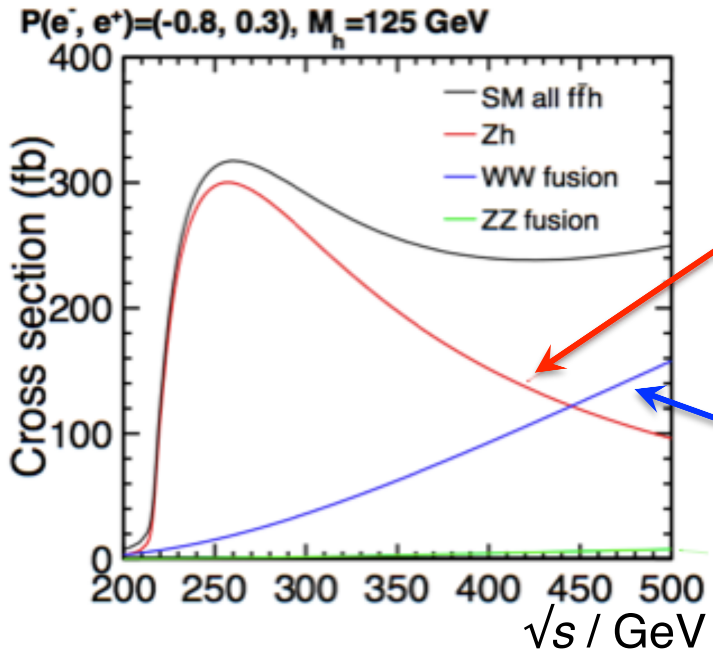


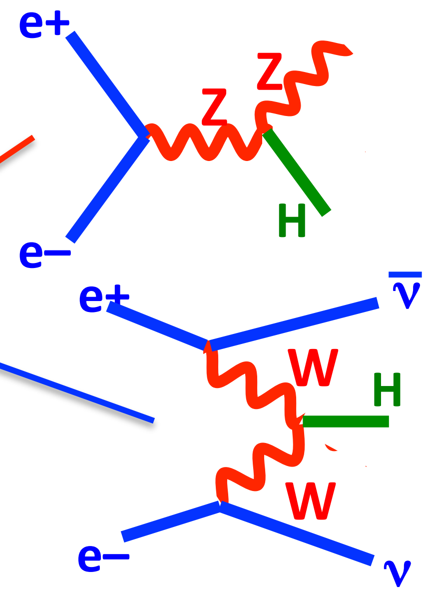
Outline: ***selection of topics that are new / updated***

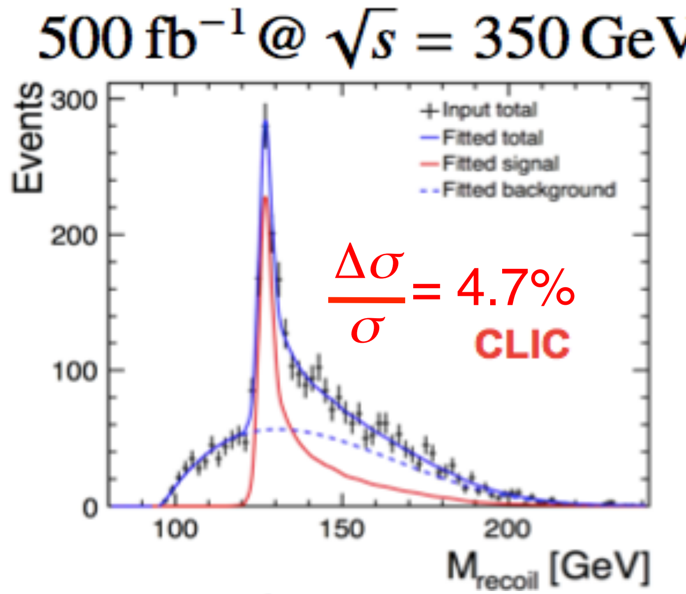
- Recoil analysis using Z->qq
- H -> bb / cc / gg
- Double Higgs production
- top Yukawa coupling

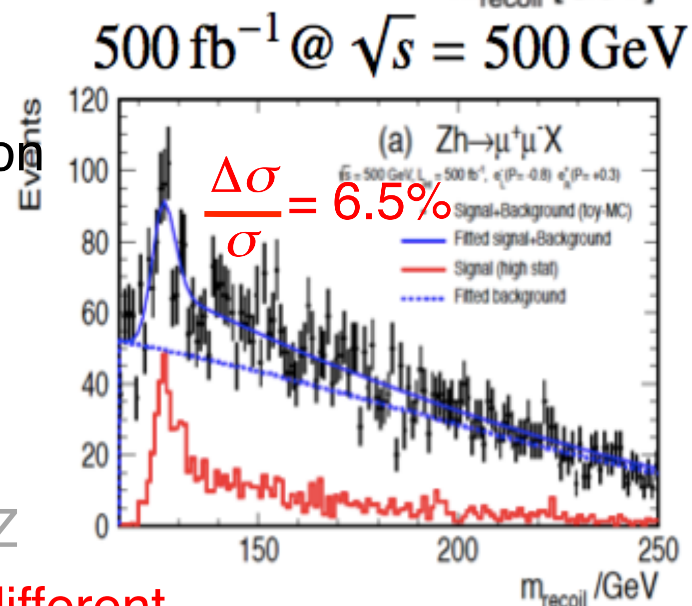
All preliminary / work in progress!

Recoil analysis for √s > 250 GeV

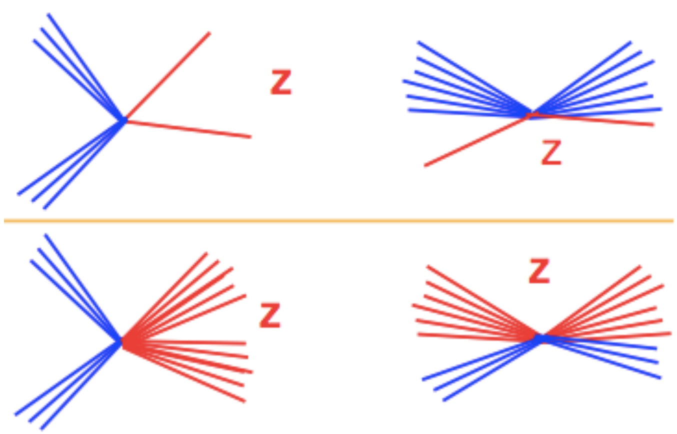








Higher $\sqrt{s}$: leptonic recoil does not provide required precision
-> can sensitivity be recovered using ***hadronic*** Z decay?



Issue:

Leptonic: muons 'obvious'

Hadronic: jet-finding blurs separation between H and Z

-> different efficiencies for different Higgs decays – can it be model-independent?

Hadronic recoil analysis strategy

$\sigma(ZH) = \sigma(ZH)\bullet BR(visible) + \sigma(ZH)\bullet BR(invisible)$

Mark Thomson

- consider possible visible Higgs decays:

2 jets from Z->qq, plus Higgs decay

H→qq : 2 jets = 4 'objects' to reconstruct
H→gg : 2 photons = 4 'objects'
H→tt : 2 taus = 4 'objects'
H→WW*→lνlν : 2 leptons = 4 'objects'
H→WW*→qqlν : 2 jets + lepton = 5 'objects'
H→WW*→qqqq : 4 jets = 6 'objects'
H→ZZ*→ννqq : 2 jets = 4 'objects'
H→ZZ*→qqll : 2 jets + 2 leptons = 6 'objects'
H→ZZ*→qqqq : 4 jets = 6 'objects'

≥4 'objects' to reconstruct in detector

Reconstruct as 4-jet topology; choose 5-jet instead if $-\log_{10}(y_{45})<3.5$ and 5-jet reco gives Z and H masses closer to 91, 126.

Kill some ZZ, WW backgrounds with m_{jj} cuts

- invisible Higgs decays:

H→ZZ*→νννν : 2 'objects'
H→BSM…?

Base selection on variables from Z->qq

HZ(Z->qq) selection

Mark Thomson

Select on variables from Z->qq:

$$70\,\text{GeV} < m_{q\bar{q}} < 110\,\text{GeV}$$

$$80\,\text{GeV} < m_{\text{recoil}} < 200\,\text{GeV}$$

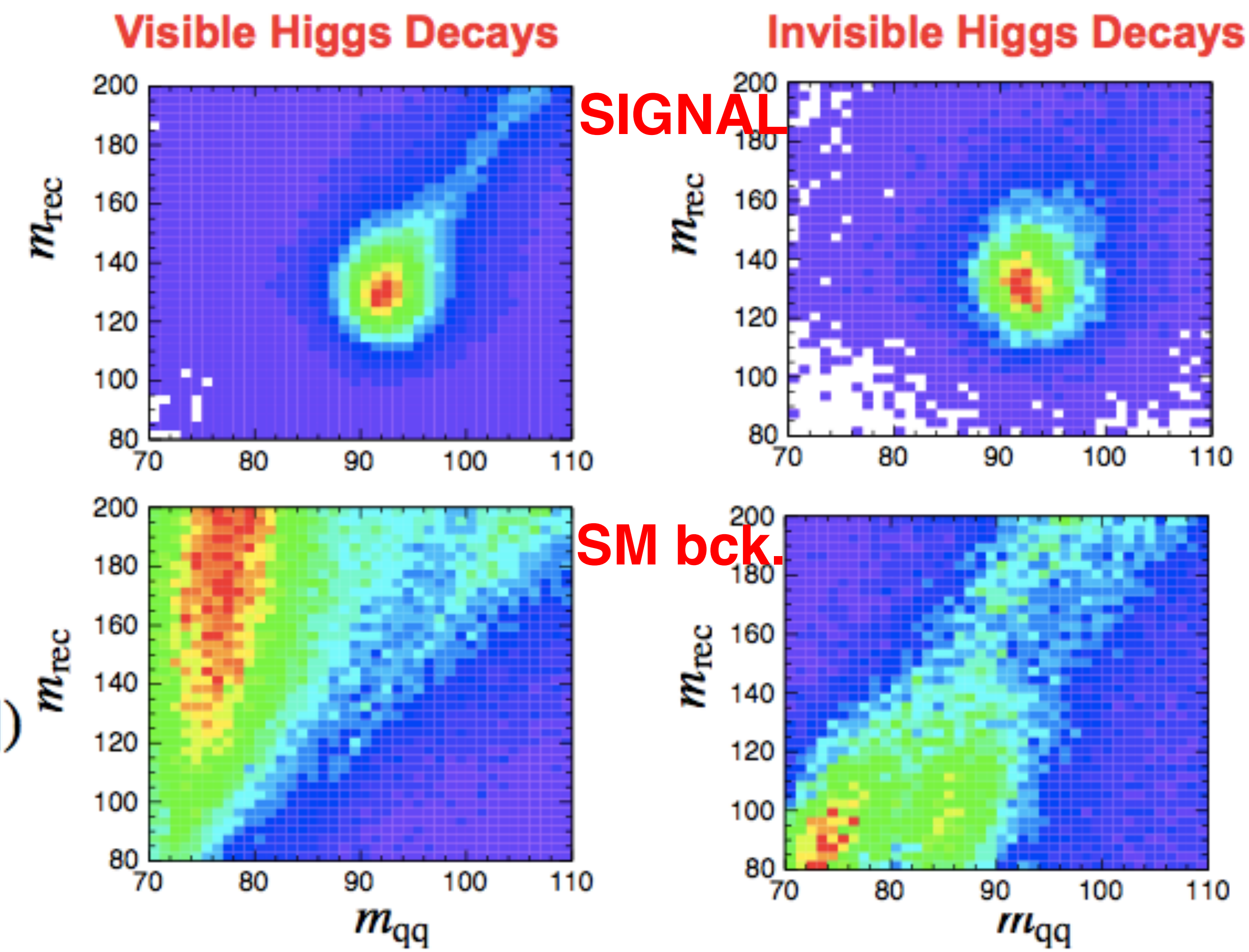
$$|\cos\theta_Z| < 0.9 \quad \text{(vis.)}$$

$$|\cos\theta_Z| < 0.7 \quad \text{(invis.)}$$

Two likelihood-based selections
Visible hypothesis (>2 jets)
Invisible hypothesis (2 jets)

$$L = P(m_{qq}, m_{rec}) \times P(|\cos\theta_Z|)$$

$$\mathcal{L}(\text{HZ}) = \frac{L(\text{HZ})}{L(\text{HZ}) + L(\text{back})}$$



HZ(Z->qq) efficiencies & results

Decay mode	$\varepsilon^{\mathrm{vis}}_{\mathscr{L}>0.65}$	$\varepsilon^{\mathrm{invis}}_{\mathscr{L}>0.60}$	$\varepsilon^{\mathrm{vis}} + \varepsilon^{\mathrm{invis}}$
$H \to$ invis.	<0.1 %	22.0 %	22.0 %
$H \to q\bar{q}/gg$	22.2 %	<0.1 %	22.2 %
$H \to WW^*$	21.6 %	0.1 %	21.7 %
$H \to ZZ^*$	20.2 %	1.0 %	21.2 %
$H \to \tau^+\tau^-$	24.7 %	0.3 %	24.9 %
$H \to \gamma\gamma$	25.8 %	<0.1 %	25.8 %
$H \to Z\gamma$	18.5 %	0.3 %	18.8 %
$H \to WW^* \to q\bar{q}q\bar{q}$	21.3 %	<0.1 %	21.3 %
$H \to WW^* \to q\bar{q}l\nu$	21.9 %	<0.1 %	21.9 %
$H \to WW^* \to q\bar{q}\tau\nu$	22.1 %	<0.1 %	22.1 %
$H \to WW^* \to l\nu l\nu$	24.8 %	0.1 %	25.0 %
$H \to WW^* \to l\nu\tau\nu$	20.5 %	0.8 %	22.1 %
$H \to WW^* \to \tau\nu\tau\nu$	16.4 %	2.5 %	18.9 %

Preliminary

Mark Thomson

Very similar efficiencies over wide range of topologies

Question:
How model-independent?

$$\frac{\sigma^{\mathrm{vis}} + \sigma^{\mathrm{invis}}}{\sigma^{\mathrm{SM}}_{\mathrm{HZ}}} = 1.000 \pm 0.017$$

Preliminary

ILC: 350 fb^{-1}
at 350 GeV
–80%, +30%

$\frac{\Delta\sigma}{\sigma} = 1.7\%$
hadronic
Preliminary

compare

$\frac{\Delta\sigma}{\sigma} = 2.6\%$
leptonic, 250 fb^{-1}
at 250 GeV

HZ(Z->qq) model independence

Tim Barklow

how much must we blow up $\Delta\sigma(ZH)\bullet BR(visible)$ to account for the fact that the efficiencies differ by as much as 7%?

Propagate uncertainties on all $\sigma.Br$ measurements to $\sigma(ZH)\bullet BR(visible)$

Handle BSM contribution:

We assume that Mark's vis+invis efficiency values cover all possible BSM decays since they cover all SM decays from completely invisible to fully hadronic multi-jet decays. Assuming no knowledge of the properties of the BSM decays we can then set

$$\xi_{BSM} = 0.5 * [\xi_{vis+invis}(max) + \xi_{vis+invis}(min)] = 0.5 * [0.258 + 0.188] = 0.22$$

$$\Delta\xi_{BSM} = 0.5 * [\xi_{vis+invis}(max) - \xi_{vis+invis}(min)] = .035$$

obtain the error $\tau_{BSM} = \dfrac{\Delta\sigma \bullet BR_{BSM}}{\sigma \bullet BR_{BSM}}$

from Michael Peskin's Higgs coupling fit

only use the leptonic recoil σ_{ZH}

no $\sum_i BR_i = 1$ constraint

→ model independent measurement of g_{BSM}

→ add this new model indepdendent hadronic recoil σ_{ZH} measurement to obtain a new error $\tau_{BSM} = 0.041$

iterate for new model-indep hadronic recoil uncertainty = 11% of stat error assuming no knowledge of BSM Higgs decays

Work in progress

H->bb/cc/gg

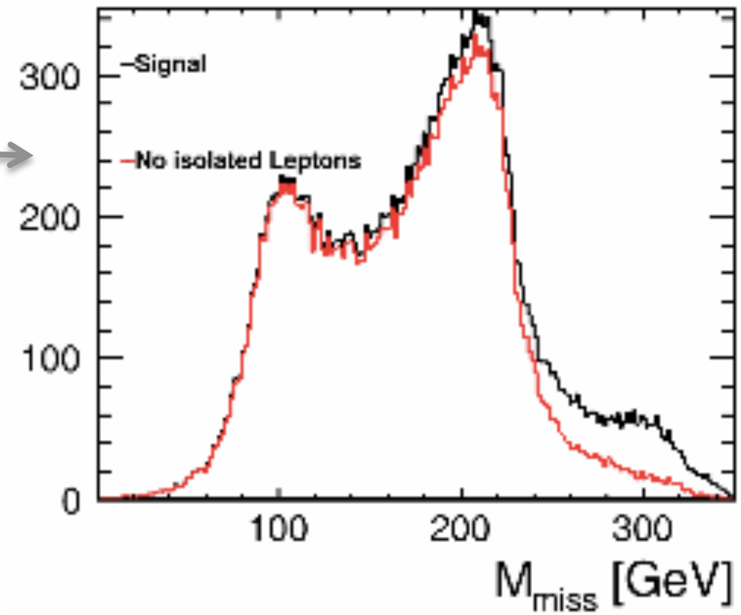
Felix Müller

H->bb/cc/gg enabled by e+e– and detector design

Example: 350 GeV vvH analysis – recently updated

Signature: 2 jets + missing mass

1. remove γγ overlay
2. event selection and BDT
3. flavour tagging
4. template fitting to event flavour likeness



first use 4-jet k_T clustering with large R
decluster the 4 jets from the γγ overlay
cluster into 2 jets using Durham

	condition	BG	Signal
		15042827,7	24663,1
isolated leptons	#iso lep = 0	12579833,8	21924,6
Transverse P	$240 > P_{t,vis} > 30$	887408,9	18526,5
Visible Mass	$135 > m_{vis}$	277267,9	17636,8
Angle between jets	0.27 > cos a	147209,6	16411,2
# tracks > 1GeV	$N_{chd} > 26$	44616,3	11306,0
max. jet mass	$135 > M_{j,max} > 40$	26375,8	10166,5
Durham minus	$Y_{12} > 0.05$	24821,5	10117,7
BDT	BDT > -0.02	6777,3	9538,1
LOI Study		11092,0	9543,0

BDT variables: all cut parameters, longitudinal momentum, global cosθ, thrust, thrust axis, jet masses, jet momenta, jet angles

LCFI Vertex / LCFI Plus

Flavour tagging using LCFI packages

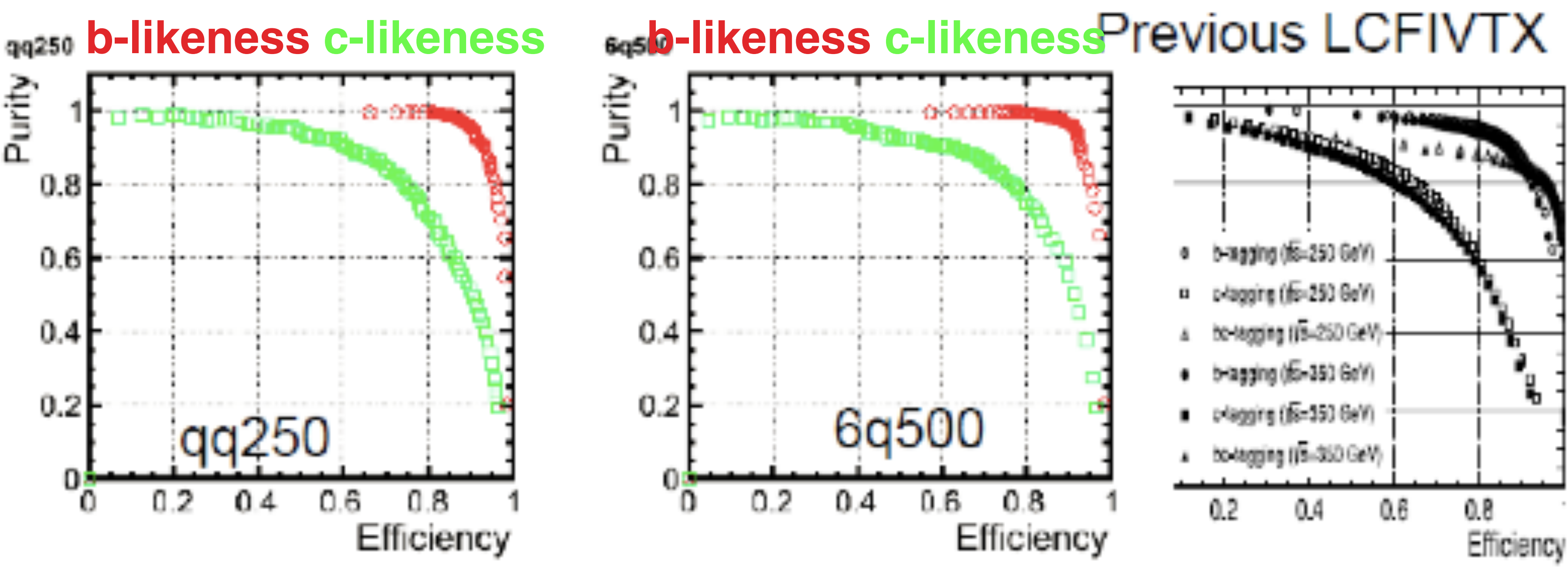
Runs vertexing and flavour identification jet-by-jet

Use observables based on secondary vertices (vertex mass, N_{trk}, probability, decay lengt

Includes K_S and Λ track removal and conversion removal

Tagger provides neural networks for b and c identification and b–c separation, separately for different N(vertices)

Updated package LCFIPlus includes jet-finding and uses TMVA

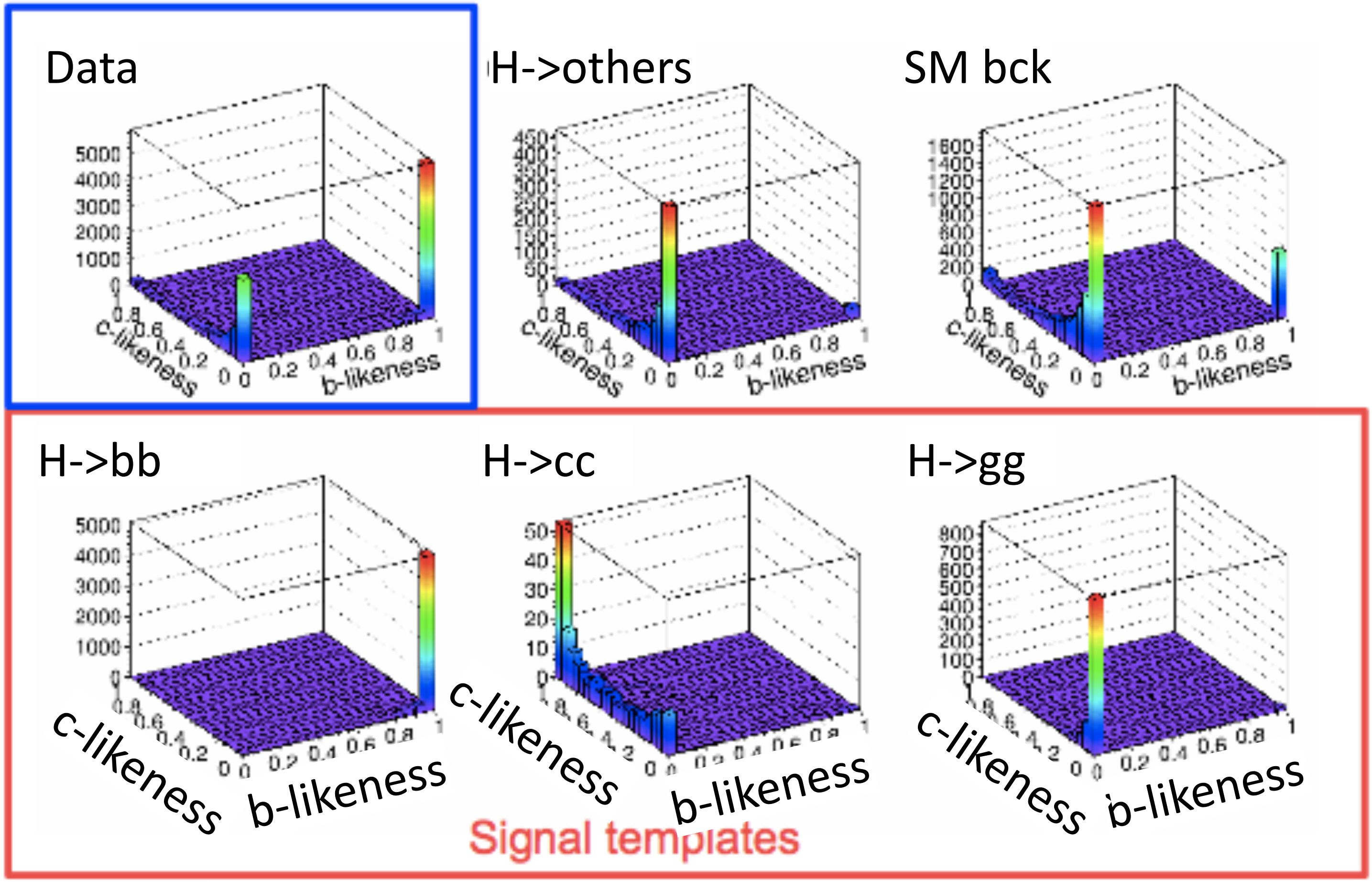


H->bb/cc/gg template fitting

Combine individual flavour tags to event flavour likeness

$$X_i = \frac{x_{i1} x_{i2}}{x_{i1} x_{i2} + (1 - x_{i1})(1 - x_{i2})}$$

(i = b, c, bc)



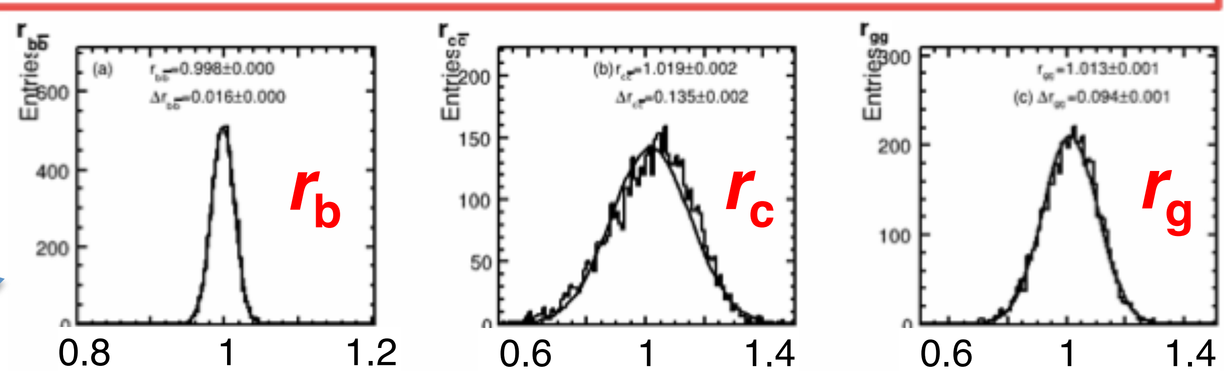
Construct 3-dimensional signal and background templates
(here projected in 2-d)

$$r_x = \frac{\sigma.\mathrm{Br}}{\sigma.\mathrm{Br}^{SM}(\mathrm{H\text{-}>xx})}$$

$$N^{\,data} = \Sigma r_x . N^{\,template}(\mathrm{H\text{-}>xx}) + N^{\,BG}$$

r_b , r_c , r_g are the fitted parameters

5000 pseudoexpts



H->bb/cc/gg other channels

H. Ono

ZH->qqH

qqh selection at 250 GeV (350 GeV)
1. $\chi^2<50$
2. $E_{vis}>200$ GeV (270 GeV)
3. $0.5<-Log_{10}(y_{34})<2.7$
4. # of particle in jet > 0
5. # of chd trk>20
6. $\lvert\cos\theta_{thrust}\rvert<0.90$
7. Thrust<0.9
8. $\theta_{hjj} > 110^o$ ($80<\theta_{hjj}<120^o$)
9. $\theta_{Zjj} > 90^o$ ($60<\theta_{Zjj}<100^o$)
10. $80<M_Z<100$ GeV
11. $115<M_h<135$ GeV
12. LR>0.50

LR inputs

1. Thrust
2. # of particles from h decay
3. $-Log_{10}(Y_{12})$
4. $-Log_{10}(Y_{23})$
5. Minimum jets angle in four jets
6. M_h

ZH-> llH

1. # of e/μ candidate >= 2
2. Selected isolated leptons = 2
3. $E_{vis}>200$ GeV
4. NPFOs > 30
5. Thrust>0.8
6. $\lvert\cos\theta_Z\rvert<0.9$
7. $70<M_{ll}<110$ GeV
8. $100<M_{jj}<150$ GeV
9. $120<M_{recoil} < 160$ GeV

Analyses proceed similarly to ZH->ννH, at 250 GeV and 350 GeV

H->bb/cc/gg results

- Compare sensitivity with results extrapolated from previous studies with m_H=120 GeV and no overlay
- bb sensitivity ~1%, gg ~8% at 250GeV, ~4% at 350GeV
- cc sensitivity is degraded – under investigation

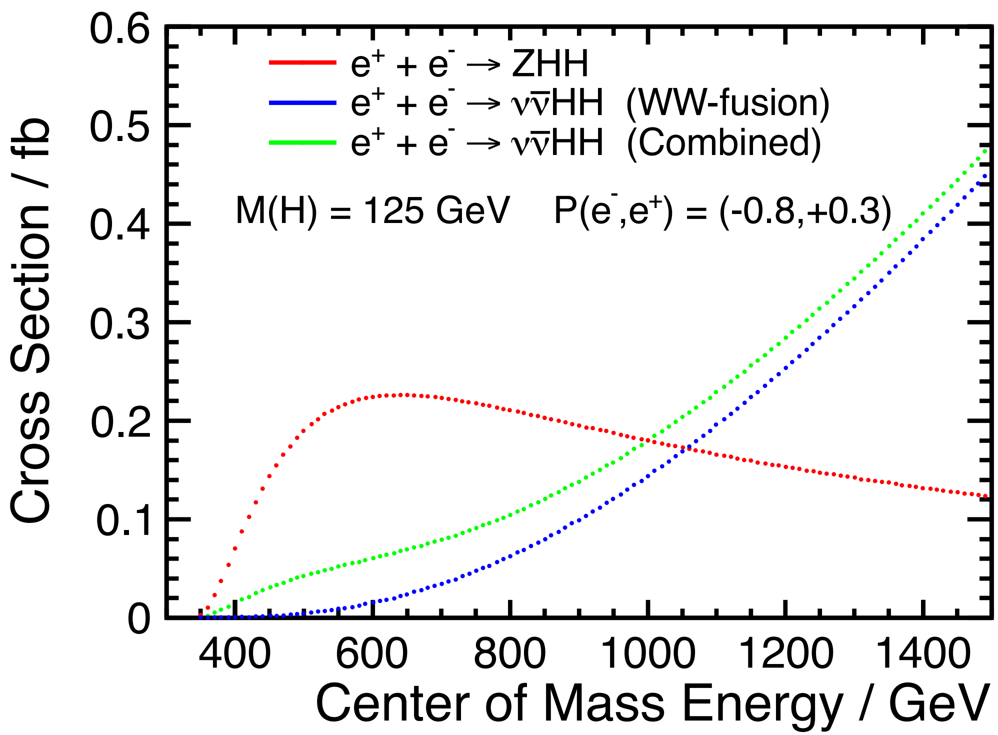
Updated results	250 GeV			350 GeV		
L(fb^{-1})	250 fb^{-1} P(-0.8,+0.3)			330 fb^{-1} P(-0.8,+0.3)		
ΔσBR/σBR	bb	cc	gg	bb	cc	gg
wh (WW and ZH)	1.6%	14.8%	9.7%	1.1%	14.6%	4.6%
ggh (ZH)	1.6%	24.0%	18.4%	1.5%	15.0%	13.2%
eeh (ZH)	4.4%	57.4%	36.3%	6.5%	>100%	>100%
μμh (ZH)	3.4%	34.0%	22.3%	4.6%	65.7%	30.9%
Combined	1.0%	11.6%	7.8%	0.9%	10.3%	4.3%
Extrapolated	1.1%	8.0%	6.8%	0.9%	6.5%	5.2%

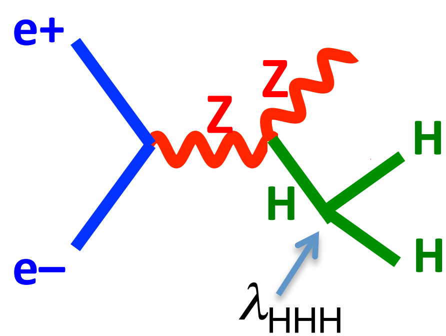
Work in progress

Double Higgs production

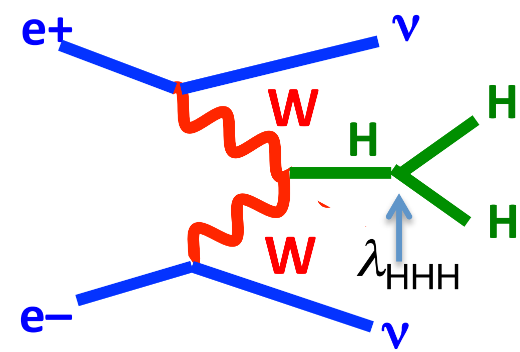
Tian/Durig/List/ Fujii/Kurata

Shape of Higgs potential probed by Higgs self-coupling





dominates around √s=500GeV



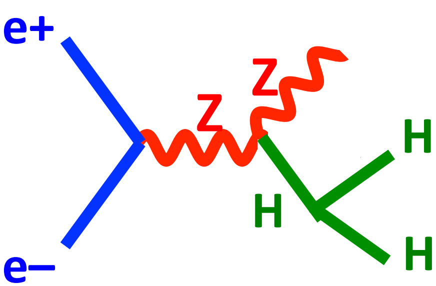
dominates at higher √s

- production cross-sections very small
- large SM background
- irreducible SM diagrams

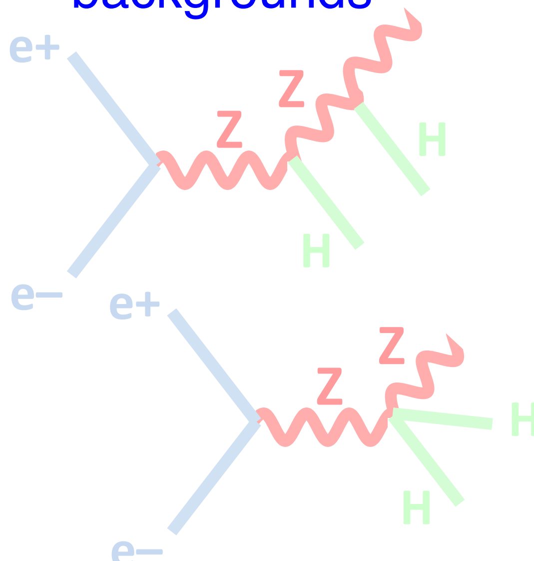
HH interference

$$\sigma = \lambda^2 S + \lambda I + B$$

Signal



Irreducible backgrounds



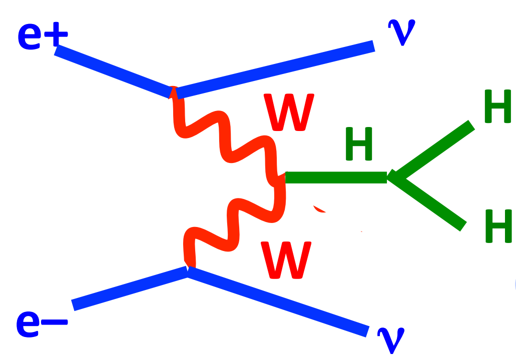
at 500 GeV

~~$\sigma_{ZHH} \simeq 0.018$ fb~~

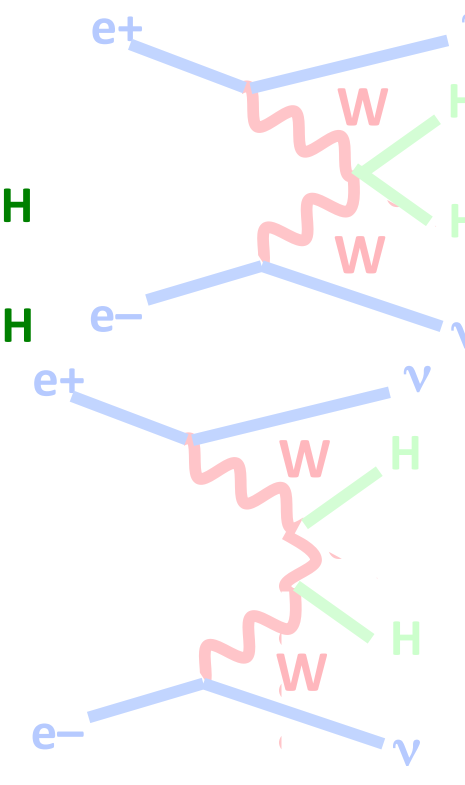
$\sigma_{ZHH} \simeq 0.19$ fb

$$\frac{\Delta\lambda}{\lambda} = 1.7\,\frac{\Delta\sigma}{\sigma}$$

Signal



Irreducible backgrounds



at 1 TeV

~~$\sigma_{\nu\nu HH} \simeq 0.16$ fb~~

$\sigma_{\nu\nu HH} \simeq 0.14$ fb

$$\frac{\Delta\lambda}{\lambda} = 0.8\,\frac{\Delta\sigma}{\sigma}$$

~~$\frac{\Delta\lambda}{\lambda} = 0.5\,\frac{\Delta\sigma}{\sigma}$~~

Junping Tian

HH modes

Search modes and main backgrounds:

llHH : llbb (ZZ, γZ, bbZ), lνbbqq (ttbar), llbbbb (ZZZ/ZZH)

$\nu\nu$HH: bbbb (ZZ, γZ, bbZ), $\tau\nu$bbqq (ttbar), $\nu\nu$bbbb (ZZZ/ZZH)

qqHH: bbbb (ZZ, γZ, bbZ), bbqqq (ttbar), qqbbbb (ZZZ/ZZH)

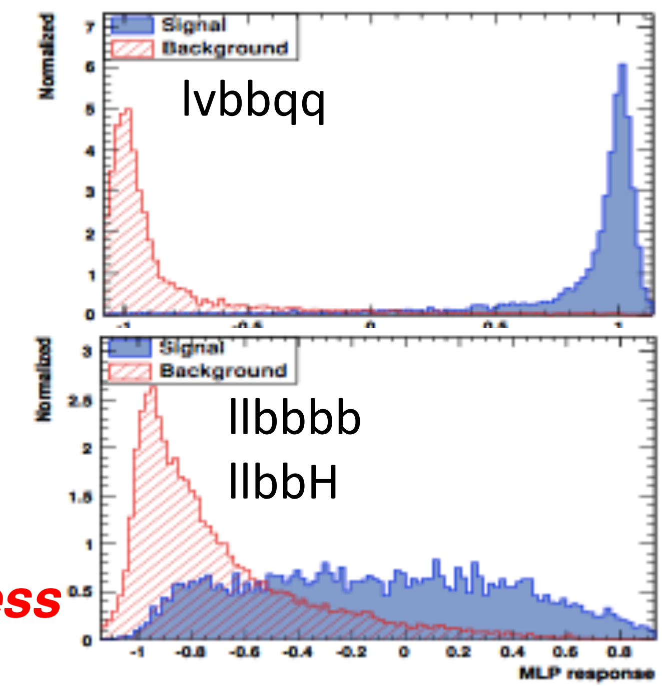
Issues:

- isolated lepton selection → need high efficiency and purity
- jet clustering and flavour tagging → need high efficiency and purity; avoid mis-clustering and wrong jet pairing
- boson mass reconstruction → avoid mis-clustering and wrong jet pairing
- suppressing backgrounds → train neural net to suppress each bckg.

Current results for √s=500 GeV:

1. just HH->bbbb $\frac{\Delta\lambda}{\lambda}$ = 59%

2. add HH->bbWW* $\frac{\Delta\lambda}{\lambda}$ = 48%

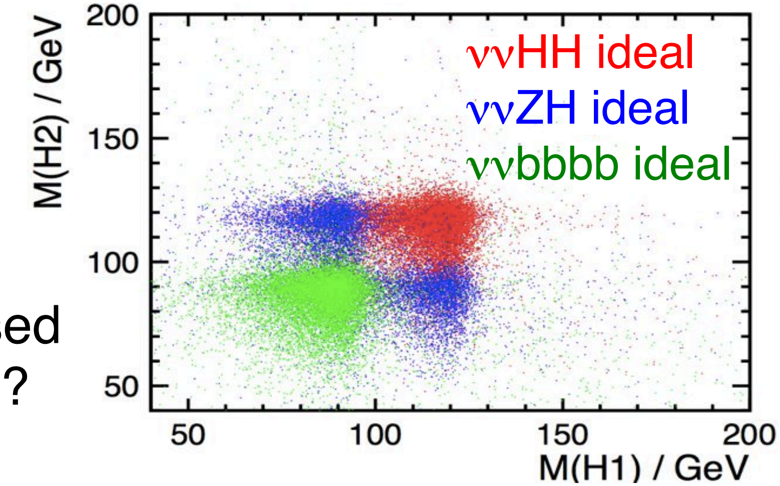


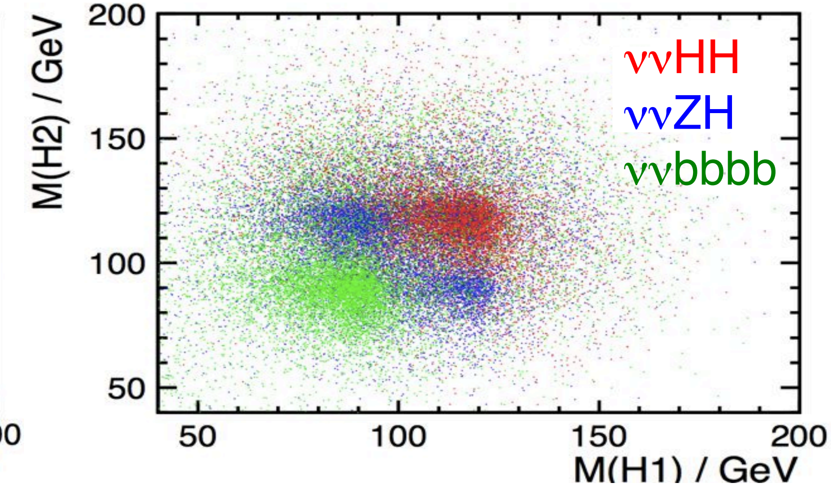
Work in progress

HH improvements

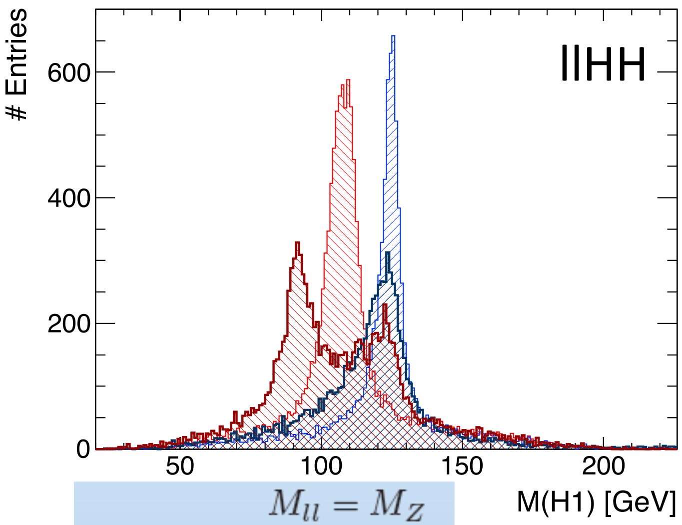
Ongoing improvement studies:

Jet clustering – mini-jet based clustering alg?



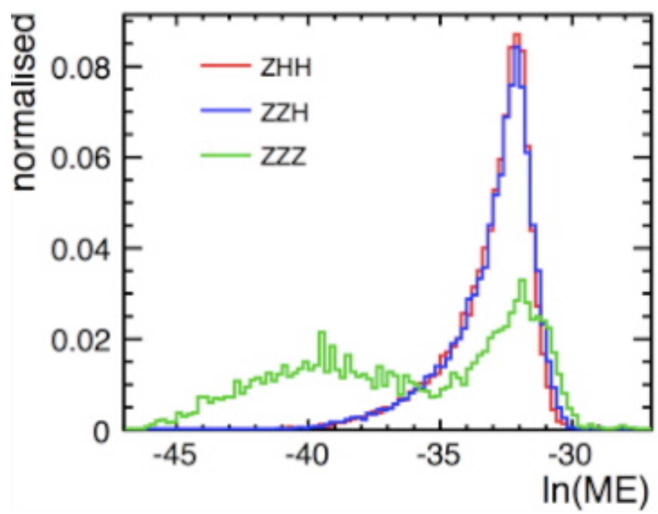


Kinematic fitter



$$M_{ll} = M_Z$$
$$M_{j_1 j_2} = M_{j_3 j_4}$$
$$\sum E_J + \sum E_l = \sqrt{s}$$
$$\sum \vec{p} = 0$$

Matrix element likelihood



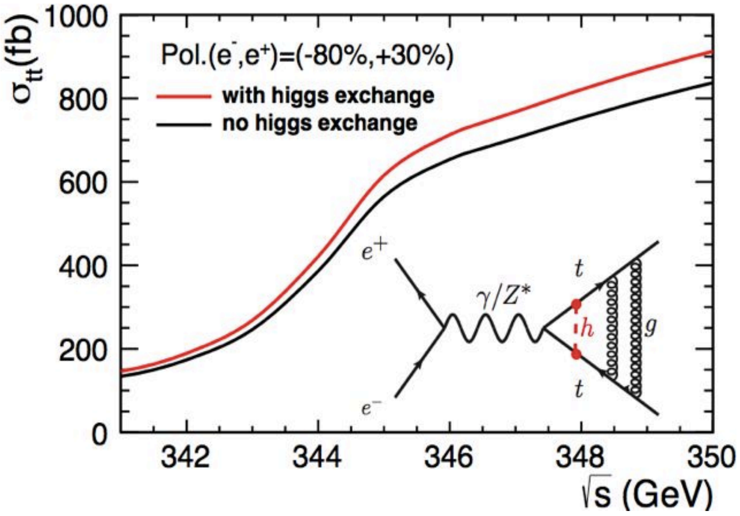
3. expect ~20% improvement from ongoing analysis development

$$\frac{\Delta\lambda}{\lambda} = 32\%$$

-> add 1ab^{-1} of 1TeV ILC running to get to 10%

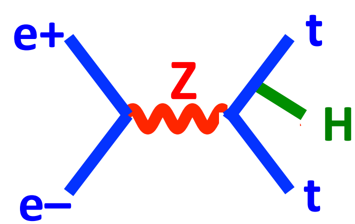
top Yukawa coupling

Yuji Sudo



First measurement of top Yukawa coupling can be made indirectly from top cross-section. 500 fb^{-1} at 500GeV gives 5.9% precision.

Direct search:



Backgrounds:
ttZ, ttg(g->bb), tbW

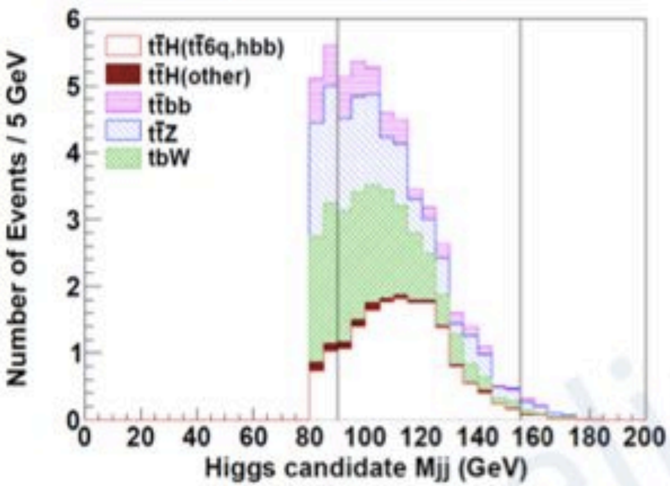
ttH->8 jets and lν+6 jets analyses:

- (identify isolated lepton)
- cluster as 6 or 8 jets
- flavour tag
- χ^2 for jet pairing

$$\chi^2 = \left(\frac{\Delta angle(j_1, j_2) - \Delta angle(higgs\ jj)}{\sigma_{\Delta angle(higgs\ jj)}}\right)^2 + \left(\frac{m_{j_3 j_4 j_5} - M_{top}}{\sigma_{M_{top}}}\right)^2 + \left(\frac{m_{j_4 j_5} - M_W}{\sigma_{M_W}}\right)^2 + \left(\frac{m_{j_6 j_7 j_8} - M_{top}}{\sigma_{M_{top}}}\right)^2 + \left(\frac{m_{j_7 j_8} - M_W}{\sigma_{M_W}}\right)^2$$

ttH

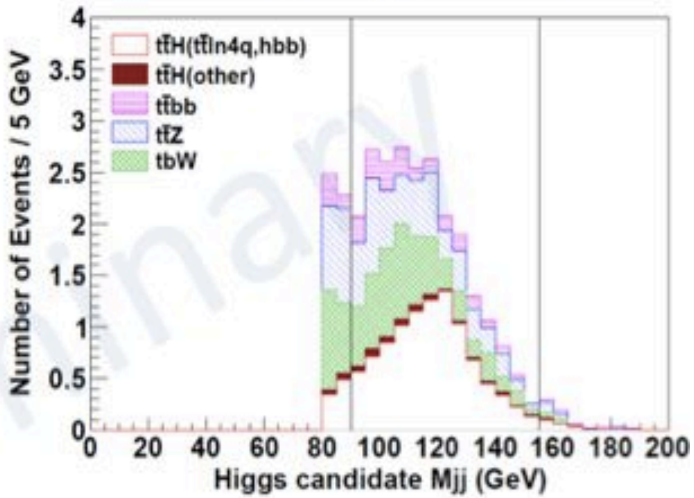
tth→8jets



- $\sqrt{s}$ = 500 GeV, 500 fb^{-1}
- Nsig = 14.7
- Nbkgd = 24.5
- $\mathrm{Nsig}/\sqrt{\mathrm{Nsig}+\mathrm{Nbkgd}}$ = 2.351,

Preliminary

tth→lν+6jets



- $\sqrt{s}$ = 500 GeV, 500 fb^{-1}
- Nsig = 9.77
- Nbkgd = 13.4
- $\mathrm{Nsig}/\sqrt{\mathrm{Nsig}+\mathrm{Nbkgd}}$ = 2.029,

This ongoing analysis:

-> $\frac{\Delta g_{ttH}}{g_{ttH}} = 17\%$

steep $\sqrt{s}$ dependence

Higher lumi
and more channels:

Analysis	Polarization Luminosity	Precision coupling y_t
t t H (500 GeV)	(−0.8, +0.3) 1.6 ab^{-1}	≈ 9%
t t̄ H (1 TeV)	(∓0.8, ±0.2) 1.0 ab^{-1}	4.3% – 4.5%
HiLumi scenario	500 GeV (−0.8, +0.3) + 1 TeV (−0.8, +0.2)	≈ 2%

Signal enhancement

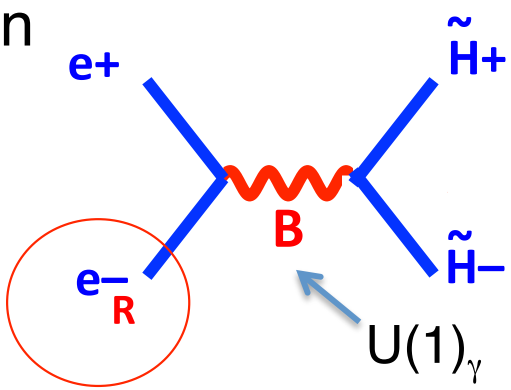
Cross sections in fb $m_H = 125$ GeV					
Mode	$\sqrt{s}$ (GeV) =	250	350	500	1000
ZH	unpolar.	211	134	64.5	16.1
	polar.	318	198	95.5	22.3
$\nu_e \bar{\nu}_e H$	unpolar.	20.8	34.1	71.5	195
	polar.	36.6	72.5	163	425
e^+e^-H	unpolar.	7.68	7.36	8.86	20.1
	polar.	11.2	10.4	11.7	24.7

Snowmass Higgs WG arxiv: 1310.8361

P(e−, e+) = (−0.8, 0.3) for 250, 350, 500 GeV

P(e−, e+) = (−0.8, 0.2) for 1TeV

Decomposition



Only $\tilde{H}^\pm$ components of $\tilde{\chi}_1^\pm$ contribute

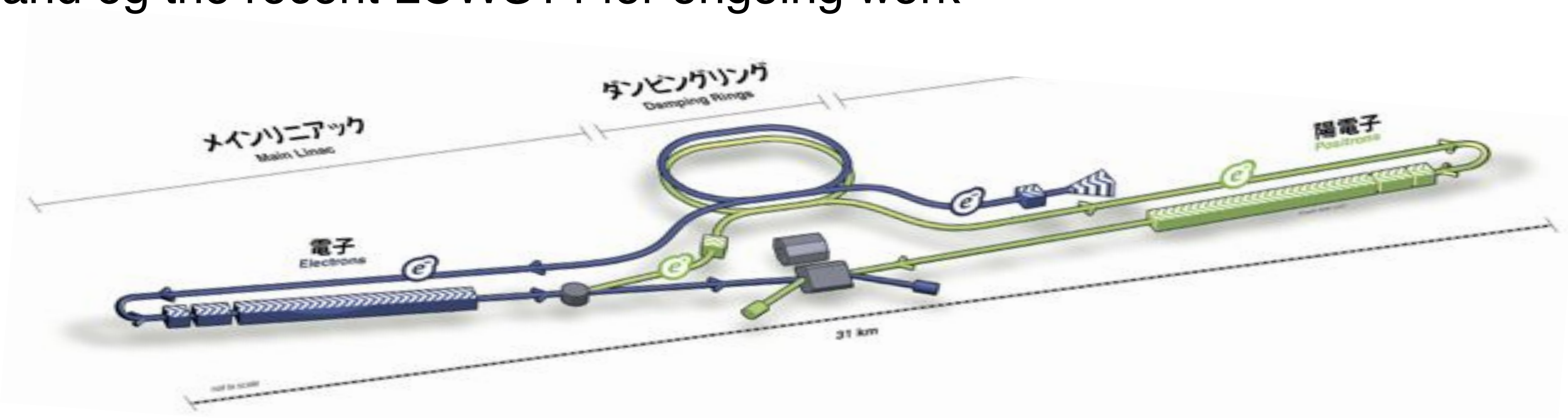
$$\tilde{\chi}_1^\pm = \alpha \tilde{W}^\pm + \beta \tilde{H}^\pm$$

A lot of activity in physics & detector groups in the ILC collaborations!

Focused here on new/updated studies in Higgs physics specific to ILC:

- new hadronic recoil study
- H->bb/cc/gg
- Higgs self-coupling
- top Yukawa coupling

Much more going on – see ILC Higgs White Paper for completed studies and eg the recent LCWS14 for ongoing work



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