Higgs Physics at Lepton Colliders

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Fermilab
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Outline:

- Facilities
- Where we are now
- Strawman list of projects

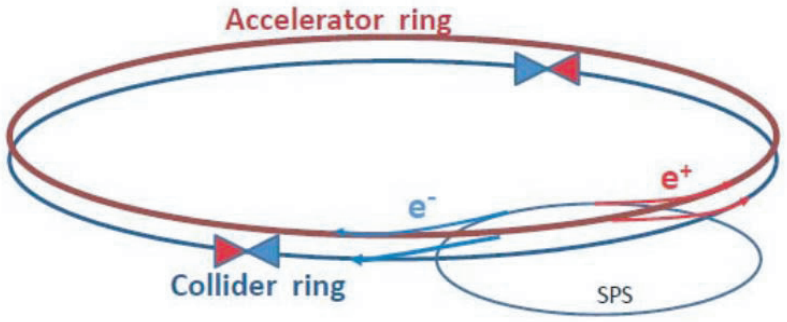
Lepton Collider Facilities

e^+e^-

Circular (~no beamstrahlung: full $\sqrt{s}$, recirculating beams, multiple detectors, no energy upgrade)

$\sqrt{s} = 240$ GeV
~peak of $\sigma(ZH)$

LEP3
Stacked ring in LHC tunnel (on top of LHC?)
Short beam lifetime (minutes), top-up injection



$\sqrt{s} = 350$ GeV
Allows $t\bar{t}$ scan
$t\bar{t}H$ production & scan

TLEP (Triple LEP)
80 km new tunnel (later for VLHC?)

DLEP (...)
53 km new tunnel

SuperTristan, similar in Japan

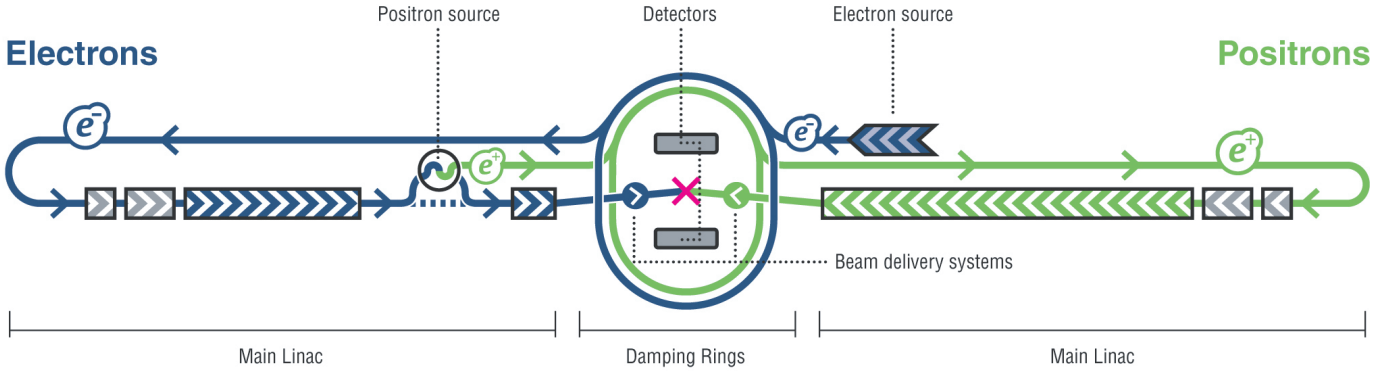
Lepton Collider Facilities

e^+e^-

Linear (staged, energy upgrade; beamstrahlung: $\sqrt{s_{\rm eff}} < \sqrt{s}$)

$\sqrt{s} = 250$ GeV †
$= 500$ GeV
$= 1$ TeV

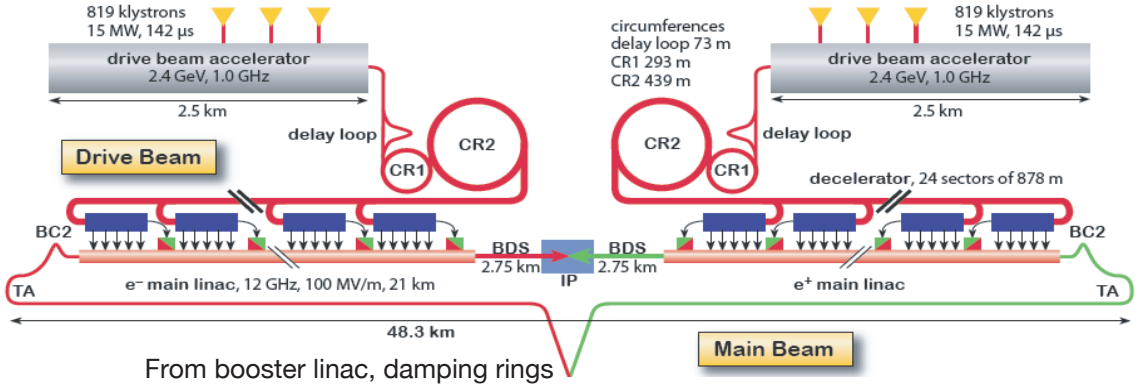
ILC (International Linear Collider)
Superconducting cavities, ~30 km long



† cost does not scale linearly!

$\sqrt{s} = 500$ GeV
$= 1.5$ TeV
$= 3$ TeV

CLIC (Compact Linear Collider)
Two beams: low E, high current drive; ~48 km long



(looking at lower energy options, 250 GeV)

Lepton Collider Facilities

e^+e^-

	ILC	ILC	ILC	CLIC	CLIC	CLIC	LEP3
√s [GeV]	250	500	1000	500	1500	3000	240
Luminosity [10^{34} $cm^{-1}s^{-1}$]	0.75	1.8	4.9	1.3	3.7	5.9	1 per IP
>0.99 √s fraction	87%	58%	45%	54%	38%	34%	100%
polarization e^-	80%	80%	80%	80%	80%	80%	-
polarization e^+	30%	30%	20%	>50%?	>50%?	>50%?	-
beam size σ_x [nm]	729	474	335	100	60	40	71000
beam size σ_y [nm]	7.7	5.9	2.7	2.6	1.5	1	320
Power [MW]	128	162	300	235	364	589	200

From T. Wyatt

- plus "GigaZ"/"TeraZ" options, 10^9– 10^{11} Z^0
- scan of $e^+e^- \to W^+W^-$

→ precision electroweak & indirect Higgs parameters

Lepton Collider Facilities

$\mu^+\mu^-$

(~no beamstrahlung, multiple detectors, energy upgradable, small footprint, still lots of R&D needed & proof of principle; follow-on to neutrino factory?)

Multi-TeV, but can be a Higgs factory running at H(125) pole

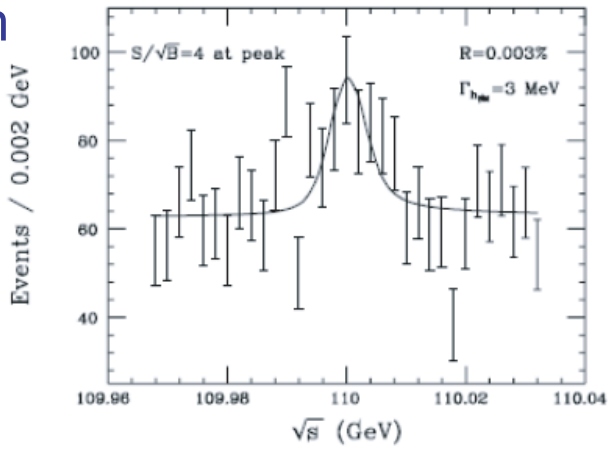
(F)MC – (First) Muon Collider

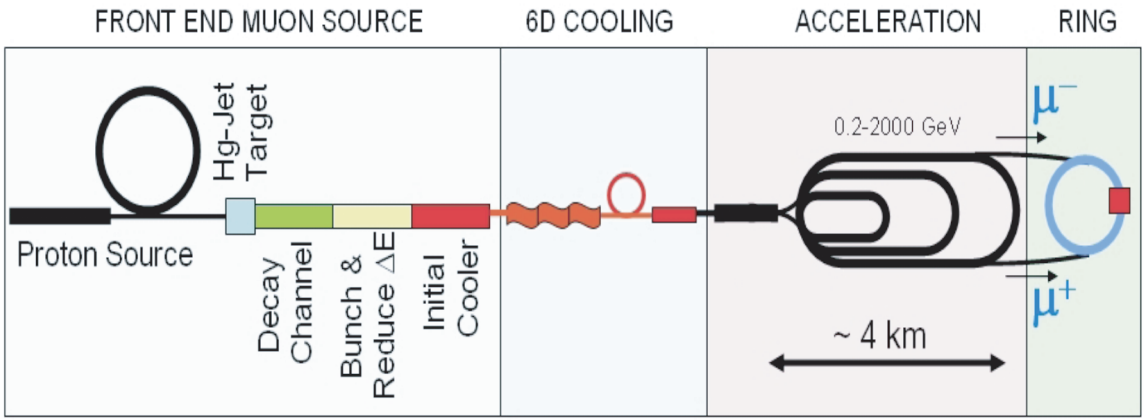
s-channel Higgs production (factor m_μ^2/m_e^2 larger)

Beam energy spread ~10^{-5}

Scan: m_H to ~100's keV; width to ~1 MeV

2 MeV bins





"Lepton" Collider Facilities

$\gamma\gamma$

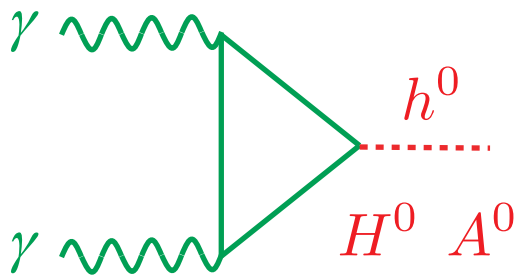
(low energy (~80 GeV) electron beams (don't need positrons), ~small footprint, still lots of R&D & proof of principle)

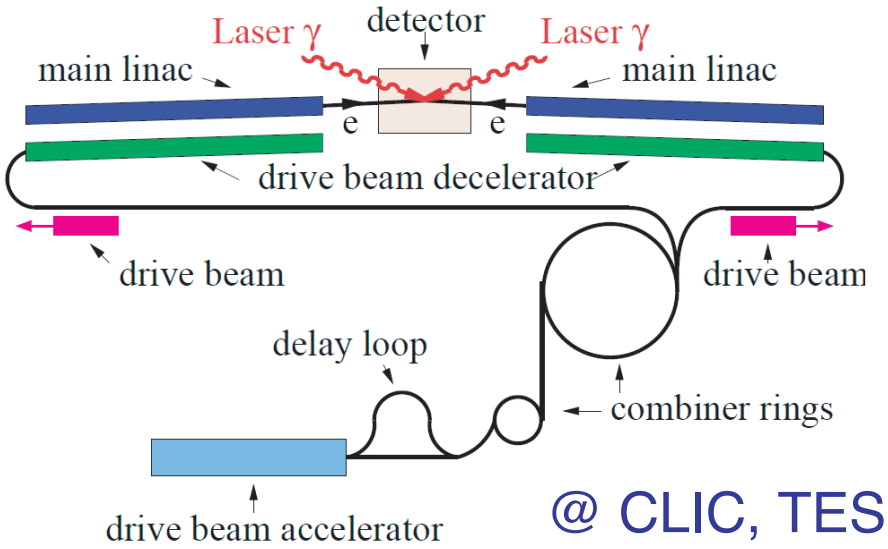
Tune to run at H(125) pole as Higgs factory

PC - Photon Collider

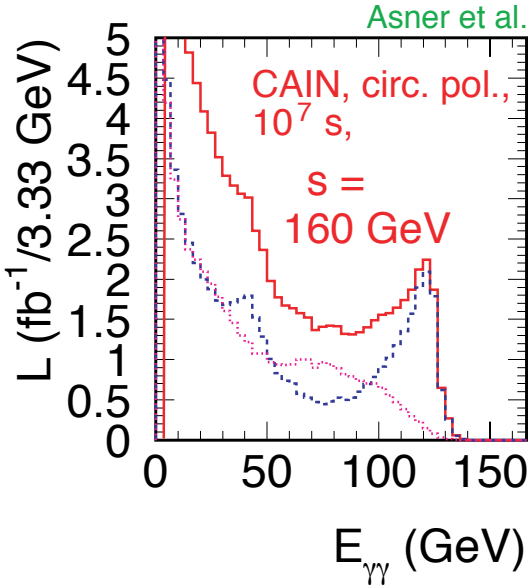
Backscatter lasers off of electron beams

Higgs Br's, CP nature, distinguish SM/SUSY/THDM (laser polarization)





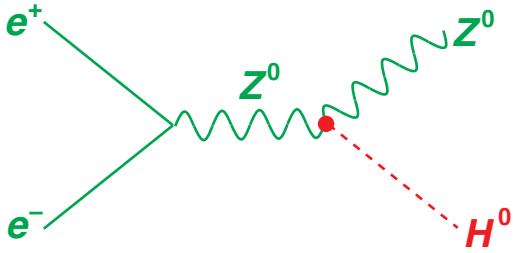
@ CLIC, TESLA (ILC), recirculating linacs (SAPPHiRE)



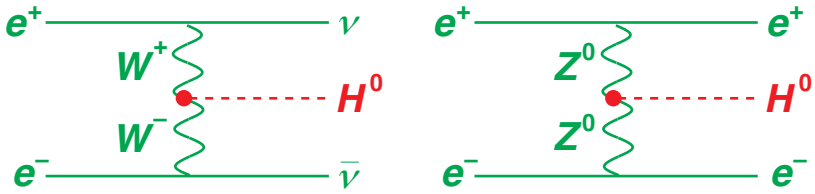
Target:

$\sim 0.3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

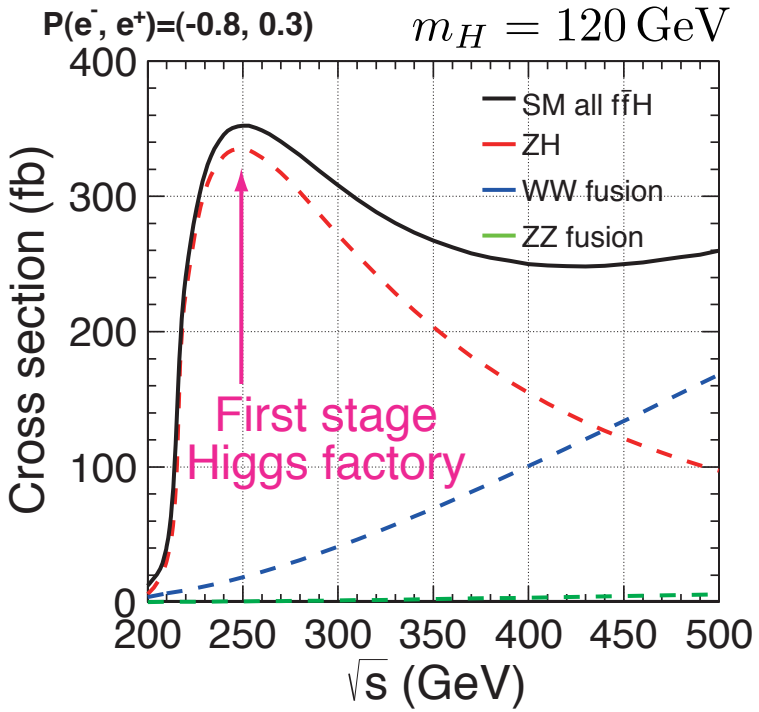
Higgs Production



- "Higgs"strahlung

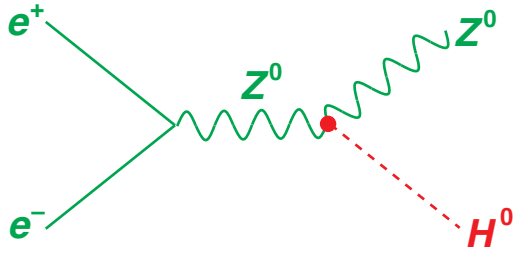


- Fusion

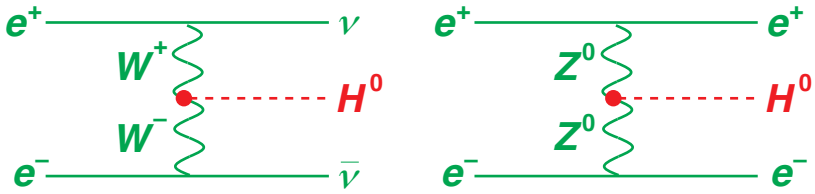


- Clean
- Democratic
- Calculable
- Polarization

Higgs Production



- "Higgs"strahlung

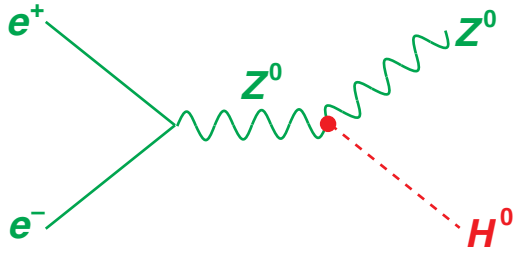


- Fusion

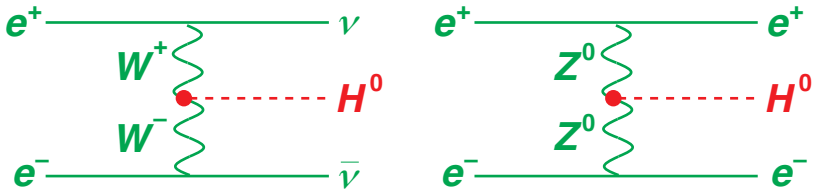
~5 year program:

$m_H = 125\,\text{GeV}$	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000

Higgs Production



- "Higgs"strahlung



- Fusion

Typical 5-year runs: Approx. rule of thumb...

$m_H = 125\,\text{GeV}$	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
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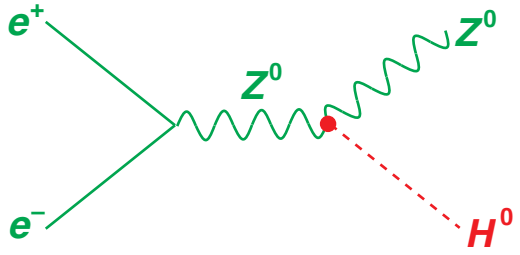
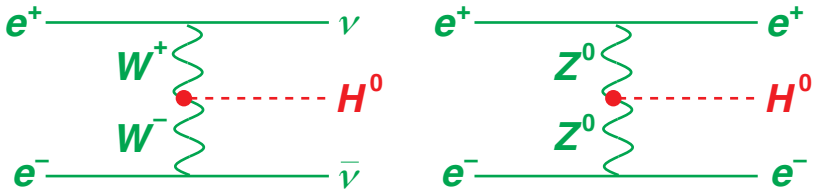
Higgs Production



- "Higgs"strahlung



- Fusion

~5 year program:

$m_H = 125\,\text{GeV}$	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV	125 GeV
$\sigma(e^+e^- \to ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb	
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb	
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1000 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}	
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000	
# $H\nu_e\bar{\nu}_e$ events	2,000	10,500	37,500	210,000	460,000	970,000	
$\sigma(\mu^+\mu^- \to H)$							50 pb
#H events							25,000

Where we are

Studies of measurements of mass, J^{PC}, couplings, etc., going on for ~20 years so generally mature, in decent shape, and fairly up-to-date, but still holes, always room for improvements, and *now responding to 125 GeV state*

ILC
CLIC

Common organization under Linear Collider Board

Accelerator
Physics

Recent documents:

- *ILC Reference Design Report V2: Physics*, arXiv:0709.1893
- *ILC Detailed Baseline Design Report/Physics*, lcsim.org/papers/DBDPhysics.pdf (draft)
- *CLIC Conceptual Design Report*, arXiv:1202.5940

Full simulations:

ILD detector
CLIC-ILD detector

TPC-based tracking, arXiv:1006.3396

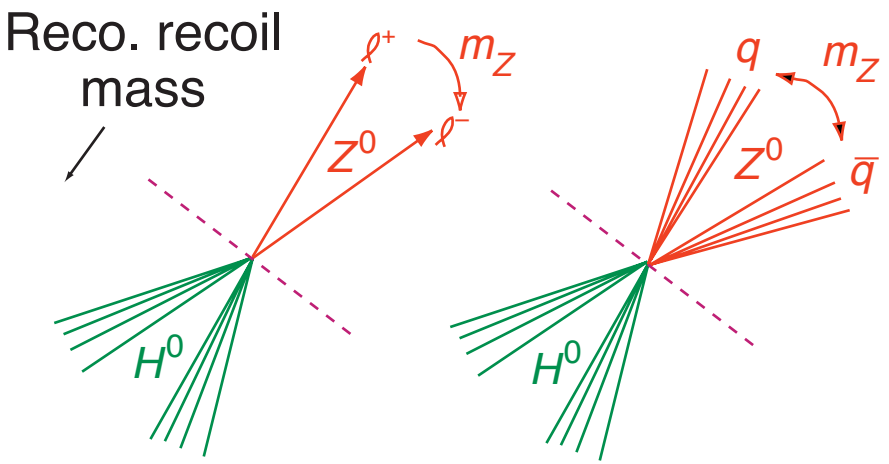
Mod. vertex, very forward cov., had. cal depth

SiD detector
CLIC-SiD detector

Silicon-based tracking, arXiv:0911.0066

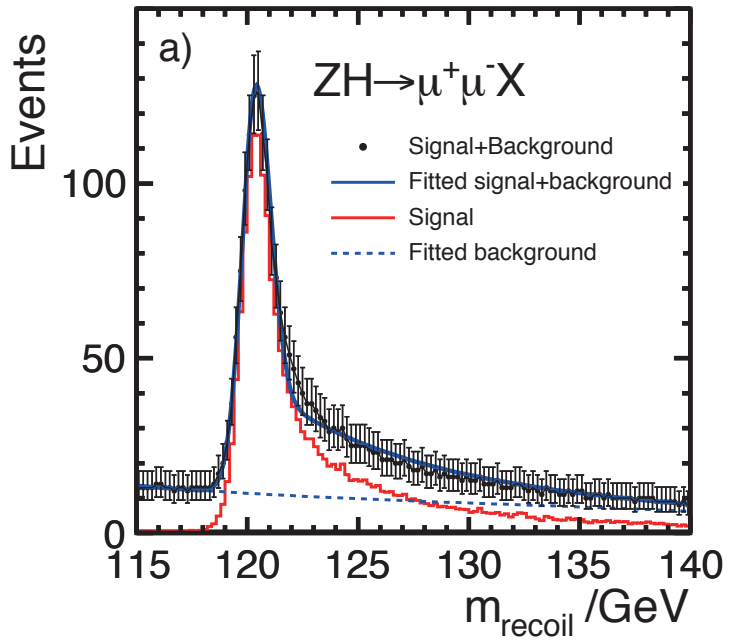
"Cross calibration" of charge

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, Higgstrahlung



- $\sigma(ZH)$ measurement independent of Higgs decay mode
- Completely model independent measurements of *Br*'s/couplings (instead of $\sigma \cdot$Br as LHC) including to invisible/dark matter
- Access to total Higgs width (~4 MeV)

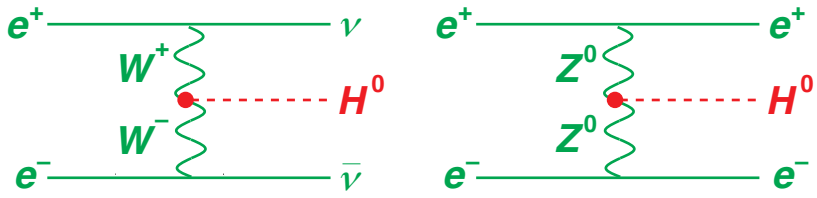
ILD@ILC, m_H= 250 GeV, 250 fb^{-1}



$\sqrt{s}$	250 GeV	350 GeV
Int. $\mathcal{L}$	250 fb^{-1}	350 fb^{-1}
$\Delta(\sigma)/\sigma$	3 %	4 %
$\Delta(g_{\mathrm{HZZ}})/g_{\mathrm{HZZ}}$	1.5 %	2 %

$$\Delta m_H \simeq 32\,\mathrm{MeV}$$

$\sqrt{s} \geq 500\,\mathrm{GeV}$, Fusion



- Also measure these cross sections for input to couplings

Typical precisions, couplings:

	250/350 GeV	500 GeV†	3 TeV
$\sigma \times Br(\mathrm{H} \to \mathrm{bb})$ *p*	1.0/1.0 %	0.6 %	0.2 %
$\sigma \times Br(\mathrm{H} \to \mathrm{cc})$ *u*	7/6 %	4 %	3 %
$\sigma \times Br(\mathrm{H} \to \tau\tau)$ *p*	6*/6 %	5 %	?
$\sigma \times Br(\mathrm{H} \to \mathrm{WW})$	8/6 %	3 %	?
$\sigma \times Br(\mathrm{H} \to \mu\mu)$	−/−	?	15 %
$\sigma \times Br(\mathrm{H} \to \mathrm{gg})$ *u*	9/7 %	5 %	?
$\sigma \times Br(H \to \gamma\gamma)$	30 %	15 %	
$\sigma \times Br(H \to \mathrm{invis.})$ *p*	$\simeq 7\,\%$		
	$< 1\,\%$ (95%C.L.)		

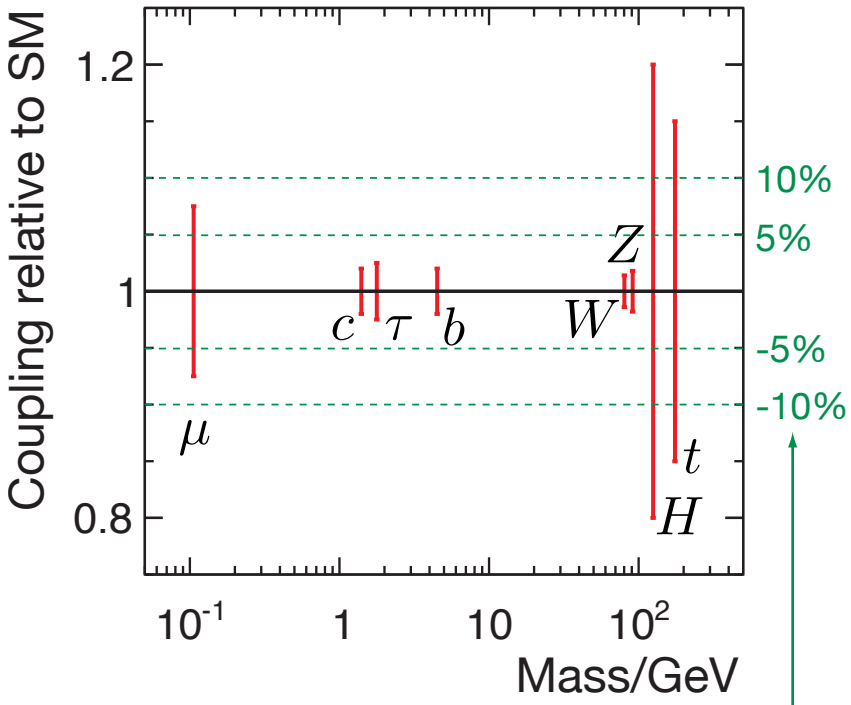
	250/350 GeV	500 GeV†	3 TeV
g_{Hbb}	1.6/1.4 %	?	2 %
g_{Hcc}	4/3 %	2 %	2 %
$g_{\mathrm{H}\tau\tau}$	3*/3 %	2.5 %	?
g_{HWW}	4/3 %	1.4 %	< 2 %
$g_{\mathrm{H}\mu\mu}$	−/−	–	7.5 %
$\frac{g_{\mathrm{HWW}}}{g_{\mathrm{HZZ}}}$	?/?	?	< 1 %*
g_{Htt}	−/−	15 %	?
g_{HZZ}	1.5 %		

p = greatly improved precision
u = unique

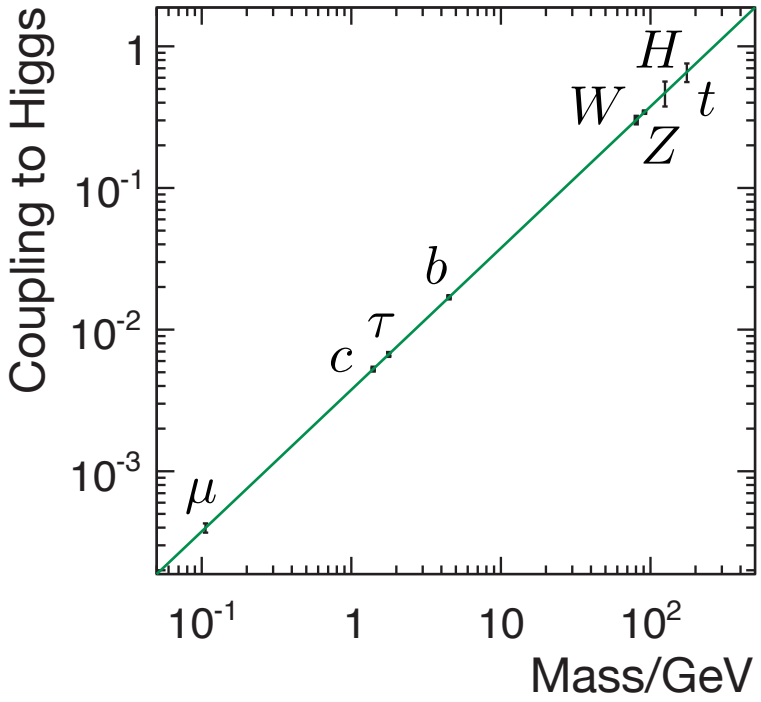
From $t\bar{t}H$ production

$$\Delta\Gamma_{\mathrm{tot}}/\Gamma_{\mathrm{tot}} \simeq 5\%$$

Couplings

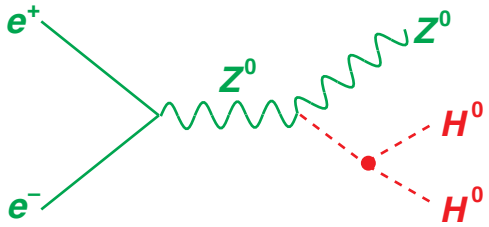


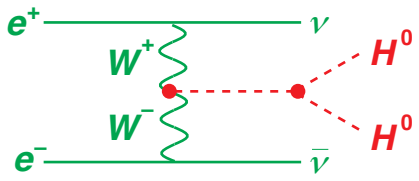
Check

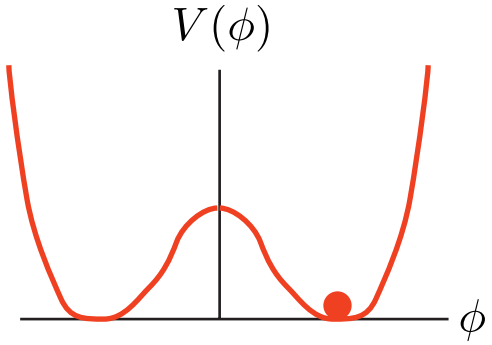


Also part of charge,
expected deviations?

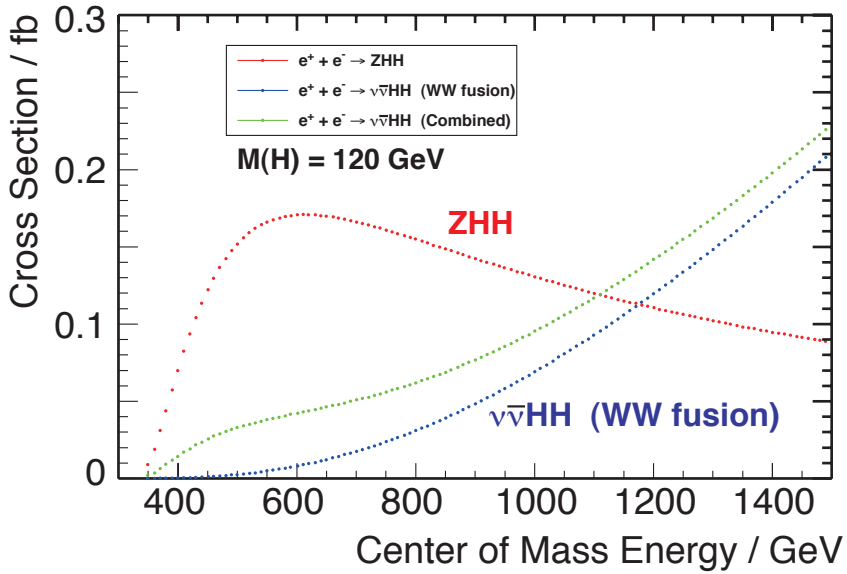
Self-Coupling







$$V(\phi) = \mu^2\phi^\dagger\phi + \boldsymbol{\lambda}(\phi^\dagger\phi)^2$$

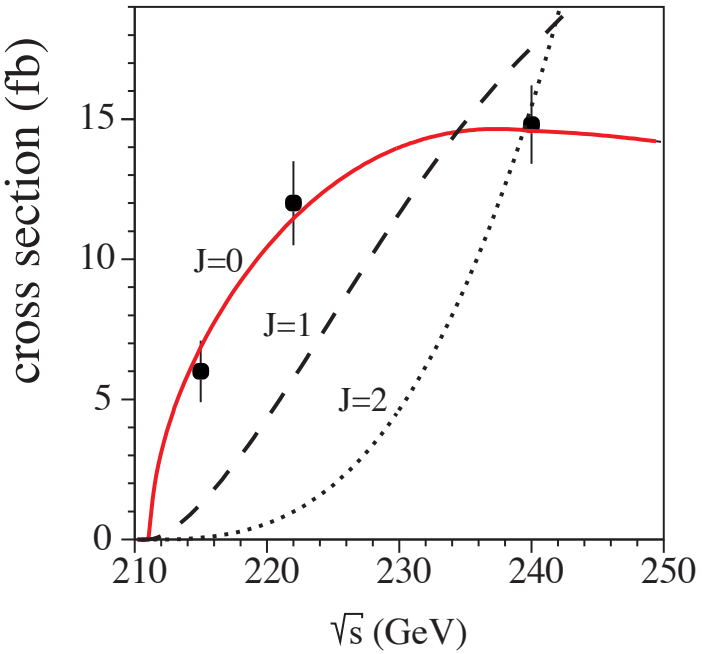


- Tough analysis, low rate
- Separate non-self-coupling contributions by *HH* invariant mass

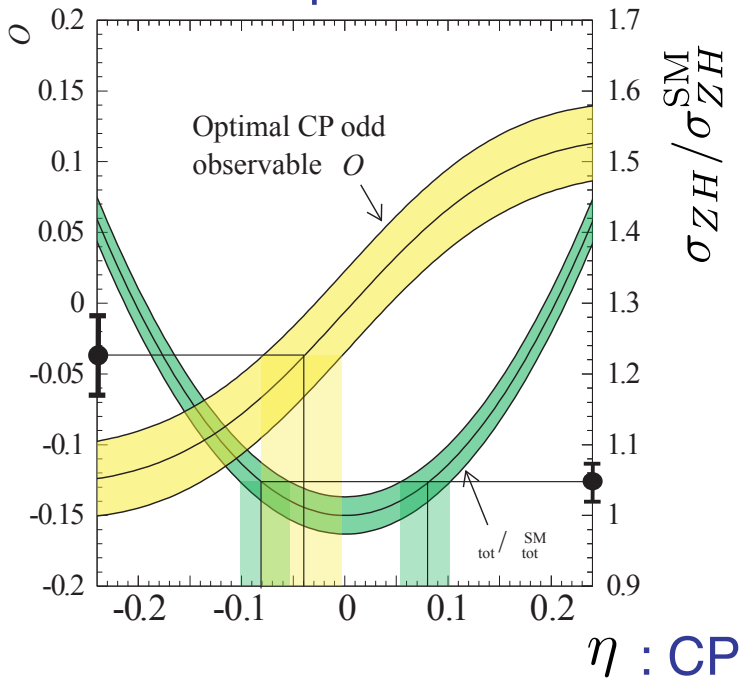
$$\Delta\lambda/\lambda \simeq 20 - 40\%$$

Spin & CP

- scan $e^+e^- \to ZH$:



- total rate + optimal observable



η : CP-odd admixture to ~4%

Plus:

- Angular analysis of decay products of polarized taus in $H \to \tau^+\tau^-$, admixture to ~6°
- Measure threshold behavior in scan of $e^+e^- \to t\bar{t}H$

(no *HVV* coupling and projection out of CP-even component)

Extended Higgs Sectors

SUSY/THDM's as an *example*

- If the $H(125)$ is actually a heavy (CP-even) H^0

  there may exist a lighter h^0 → covered by lepton colliders

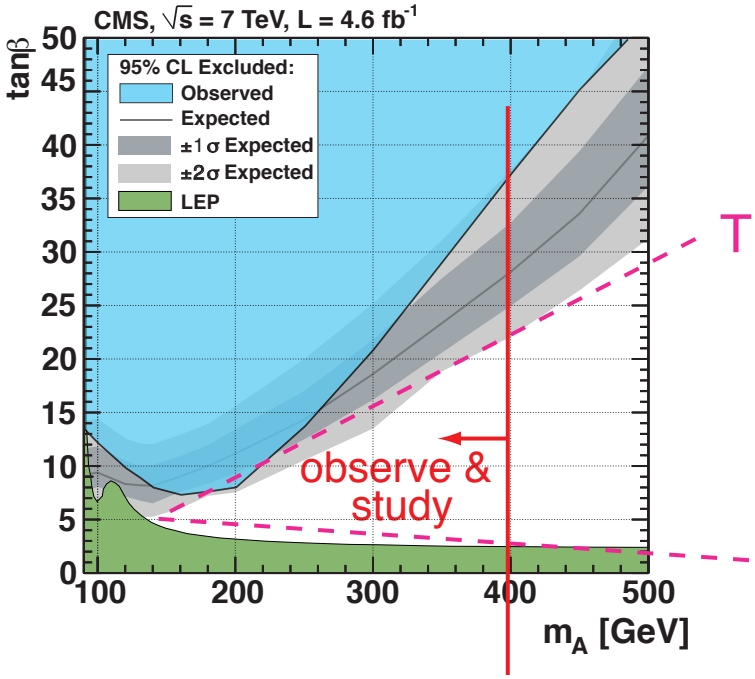
- If the $H(125)$ is actually a light (CP-even)

  there may heavier H^0, A^0 → produce and study by

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

$$\mu^+\mu^- \to H^0, A^0$$

$$\gamma\gamma$$



The "wedge", LHC sees only h^0, and not the heavier states

$\sim \sqrt{s}/2$ of e^+e^- collider

Strawman Project List

- As a starting point for discussion
- Coordinating with LCWS Higgs group (meeting in Arlington in 2 weeks)
  (Tim Barklow, Heather Logan)

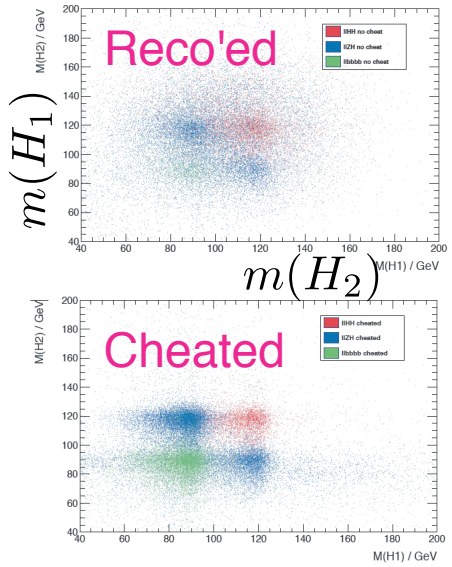
Synergies & Overlaps with other HEF Working Groups

- Electroweak:
  - vector boson scattering and unitarity recovery
    (dynamics of EWSB, composite Higgs?)
  - Giga-Z/Tera-Z indirect Higgs measurements vs. direct Higgs
- Top:
  - $t\bar{t}$ scan (g_{Htt} to ~30%)
  - $(t\bar{t}H)$
- New Particles:
  - Higgs decays into NP's, "weird/exotic" Higgs decays
  - Overlap with SUSY models and multiple Higgs
- Flavor & CP:
  - Flavor and CP-violating Higgs decays

Higgs as a window into new physics

Strawman Project List

Examples as a flavor



The "tough stuff" warrants more attention,
particularly Higgs self-coupling and $t\bar{t}H$

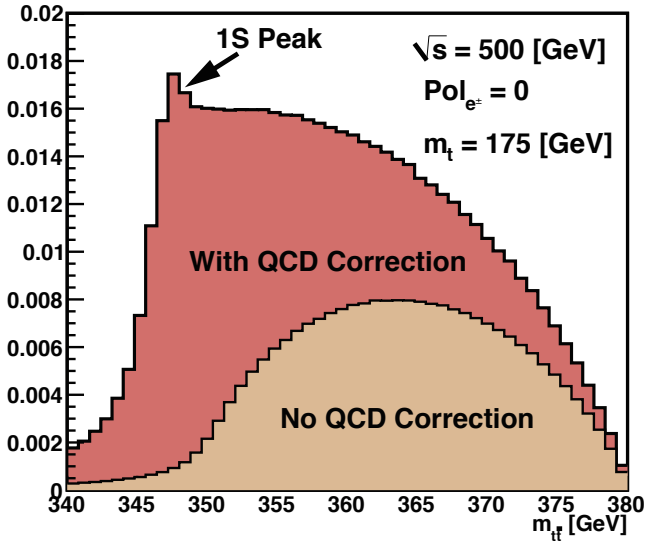
Higgs self-coupling:

- Full simulations of signals and backgrounds of
  $e^+e^- \to ZHH$ at 500 GeV
  $\to \nu\bar{\nu}HH$ at 1000 GeV (better extraction with fewer backgs from diagrams with no self-coupling)
- Fast simulations may have been too optimistic (jet/particle confusion)
- Employ latest "boosted objects" technology plus particle flow in these "jet-heavy" topologies
- Precision vs. $\sqrt{s}$
- How does the analysis change in the presence of a modified *VVH* and/or *VVHH* coupling? What about unitarity violation at very high *HH* invariant mass, if there are non-SM coupling strengths? New observables?

Strawman Project List

$t\bar{t}H$

- A benchmark for the ILD/SiD detectors, so continued work
- More full simulations of ttH at 350 GeV (scan), 500 GeV, and 1000 GeV (recent studies including *tt* bound states results in larger cross sections)



- Employ latest "boosted objects" technology plus particle flow in these "jet-heavy" topologies
- Precision vs. $\sqrt{s}$

Strawman Project List

Br's

- Continued full simulations of $e^+e^- \to ZH$ followed by

  $H \to \tau^+\tau^-$ (and CP studies, share LHC tau tools)

  $\to ZZ^*$

  $\to Z\gamma$ (is it worth it? what does it buy us? better at higher *E*?)

- Theory work on $H \to Z\gamma$ vs. $H \to \gamma\gamma$
- Further refine work on $Br(H \to \text{invis.})$ at various $\sqrt{s}$ (using all polarization handles)
- Do $H \to b\bar{b}, c\bar{c}, gg$ rate measurements take take into account $b\bar{b}g, c\bar{c}g$ and gluon splittings $g \to c\bar{c}, b\bar{b}$ correctly? Need an improved event generator?

- Further explorations of accessible Higgs coupling measurements at $\sqrt{s}$ ~240-350 GeV at LEP3, TLEP, SuperTristan circular colliders and comparison to precisions at low-energy linear collider. LEP3 used CMS detector for simulation; also do with ATLAS detector and/or ILD/SiD?

Strawman Project List

Couplings

- Collaborate with LHC Higgs Xsec WG, use similar framework, handling of theory and exp. uncertainties, presentation (e.g., κ_V, κ_f for departures from SM; dimension-6 operators to be studied in systematic way) to allow for clearer comparisons and combinations.

- In each case, determine *value added* that lepton collider measurements will bring to those Higgs parameters that we project we will have from the LHC. (Sometimes lepton collider studies done too much "in isolation" or "stand alone")

Extended Higgs sectors

- In almost all cases, current analyses much less mature and can be improved

Strawman Project List

More facility specific:

Muon Collider

- as a Higgs factory: utility of operation at the Higgs pole
- full simulations of energy scan for direct width measurement (to 1 MeV?); uncertainty on Higgs mass; what do different levels of precision buy us?
- at higher energies: scans of heavier Higgses, rare decays, etc.

Photon Collider

- revisit as a cost-effective, low-energy Higgs factory: more sophisticated simulations? what can and cannot be done?

"Roll your own"

Strawman Project List

More facility specific:

Muon Collider

- as a Higgs factory: utility of operation at the Higgs pole
- full simulations of energy scan for direct width measurement (to 1 MeV?); uncertainty on Higgs mass; what do different levels of precision buy us?
- at higher energies: scans of heavier Higgses, self-coupling?

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- revisit as a cost-effective, low-energy Higgs factory: more sophisticated simulations? what can and cannot be done?

"Roll your own"

Discoveries at the level of recent "Higgs-like" state come along only every few decades

Use the impetus to fully exploit this opportunity

Come join the fun!