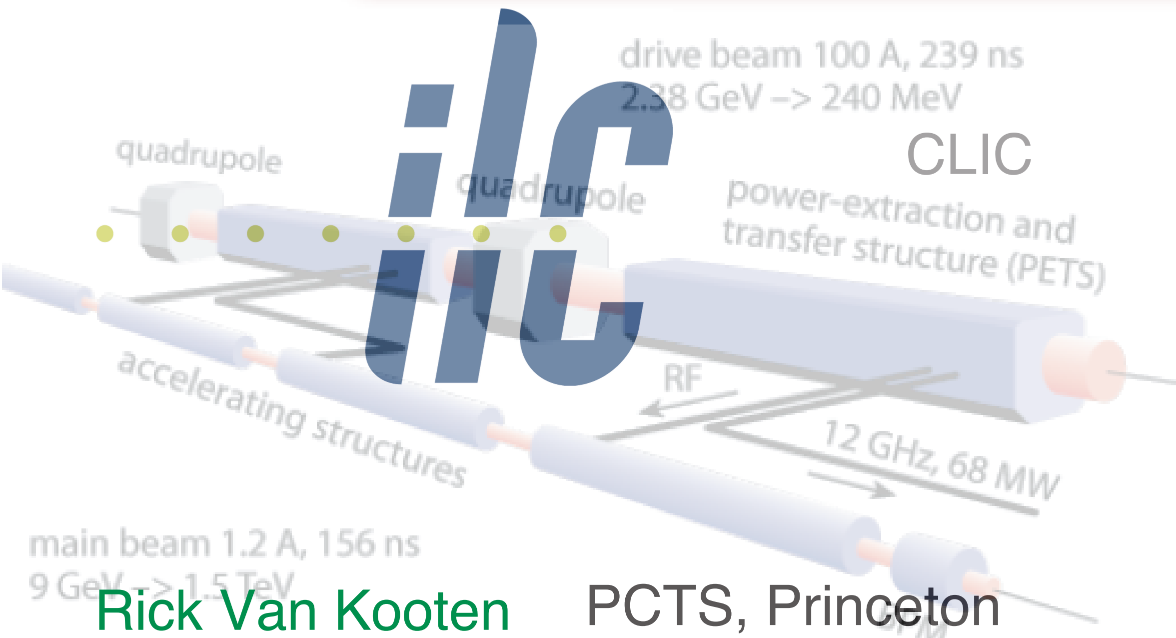
Implications of Higgs Discovery on LC/e^+e^- Factories



Outline:

- Implications
- Physics
- Facilities
- Organization
- Property measurements
- Some comparisons

Rick Van Kooten
Indiana University

PCTS, Princeton
April 25 – 26, 2013

What we know

Implications for ILC/e^+e^-

- Scalar Mass ~125 GeV
- SM-like couplings to WW and ZZ

  → major production reactions present in e^+e^-

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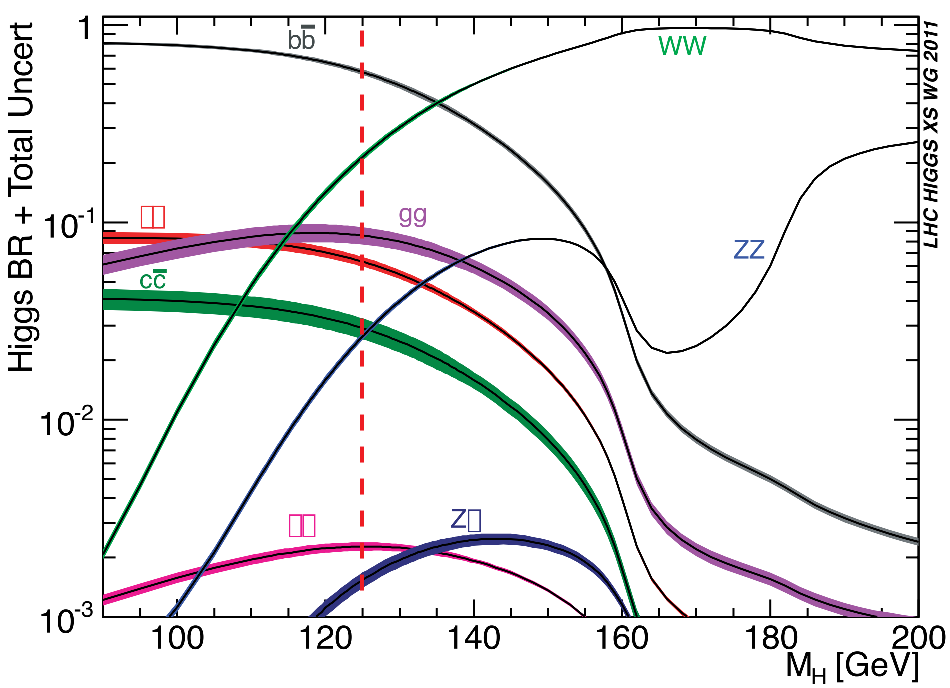

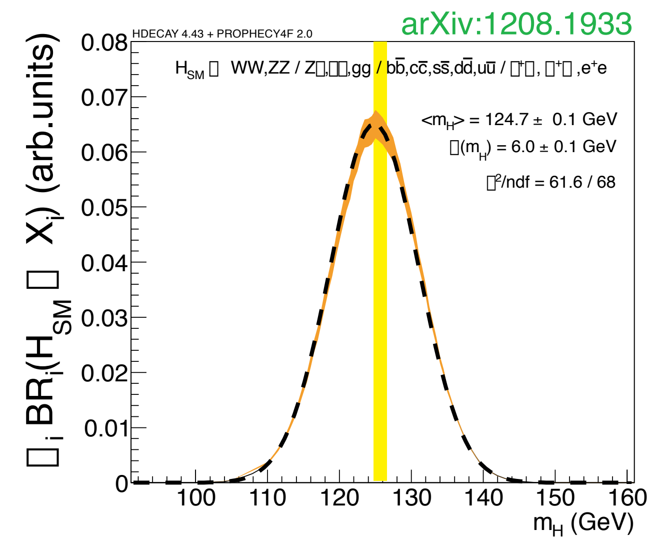

Mass of "maximum opportunity"
in terms of the study of its decays
and couplings to other particles

What we know

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accessible to $E_{cm} \geq 250\,\mathrm{GeV}$

flurry of machine options being considered

political trigger, particularly for ILC in Japan

What we know

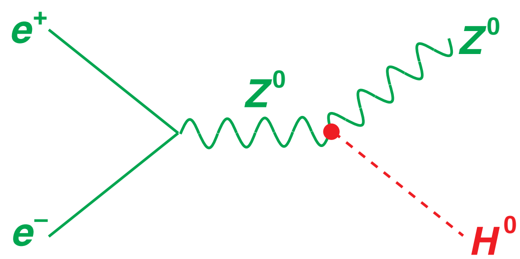
Implications for ILC/e^+e^-

- Scalar Mass ~125 GeV
- SM-like couplings to WW and ZZ
  - ⟶ major production reactions present in e^+e^-
- SM-like *Br*'s expected
- $t\bar{t}H$ coupling exists $(gg \to H, H \to \gamma\gamma)$
  - ⟶ direct $e^+e^- \to t\bar{t}H$ exists (need higher collision energies)
- J^{PC} mainly 0^{++} (but want sensitive tests of small admixtures)

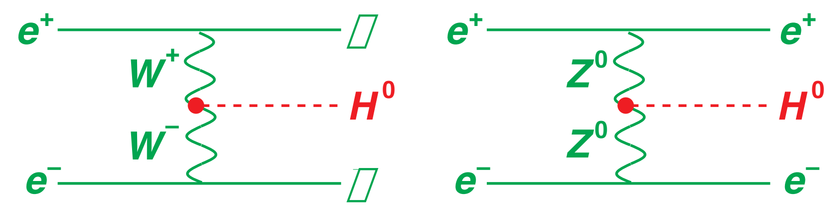
accessible to $E_{cm} \geq 250\,\mathrm{GeV}$

flurry of machine options being considered

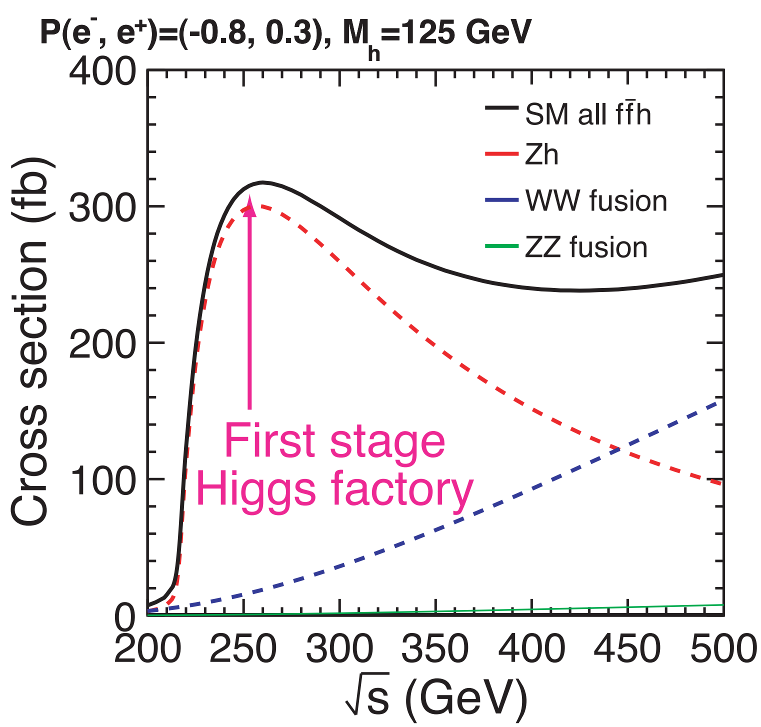
Higgs Production



• "Higgs"strahlung



• Fusion



- Clean
- Democratic

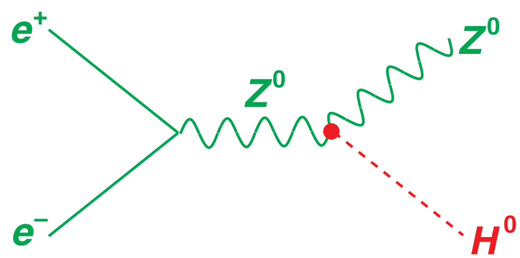
  1 Higgs in ~$10^9 - 10^{12}$ *pp* collisions

  1 Higgs in 1% of all e^+e^- collisions
- Calculable
- Longitudinal Polarization

  (linear colliders): can boost signal, control SM backgrounds

  (unpolarized cross section at ~200 fb for circular colliders, transverse polarization available)

Higgs Production



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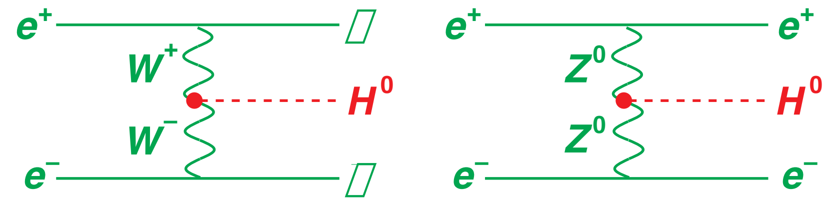

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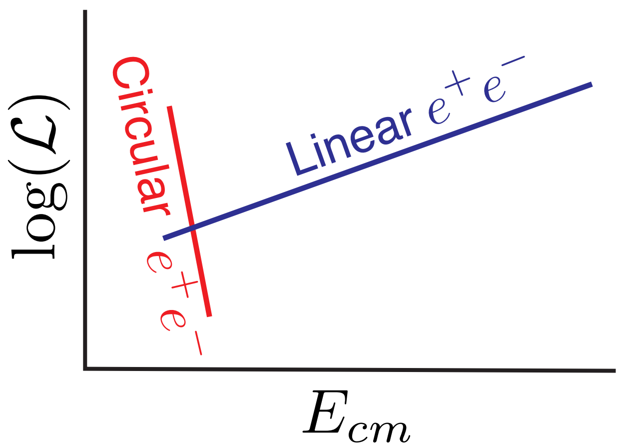
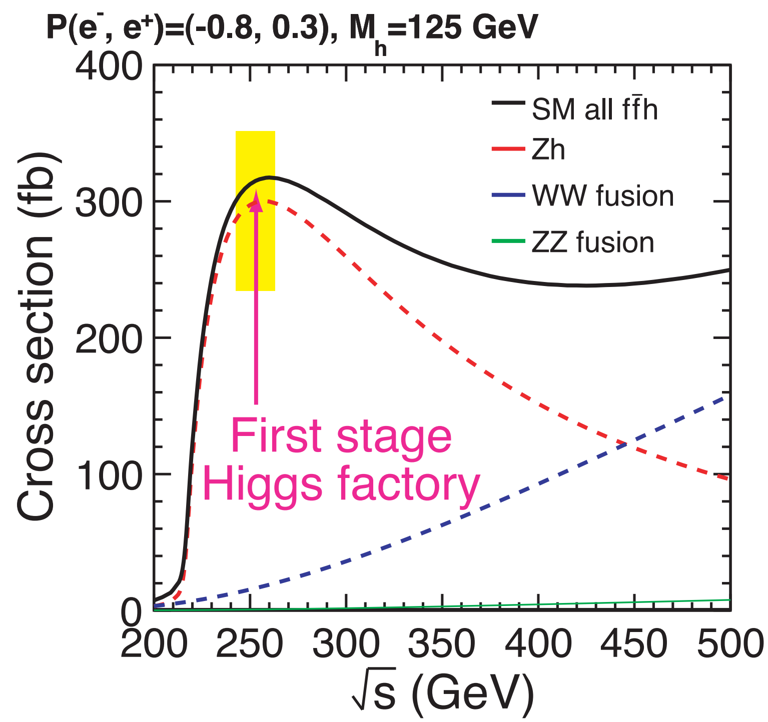
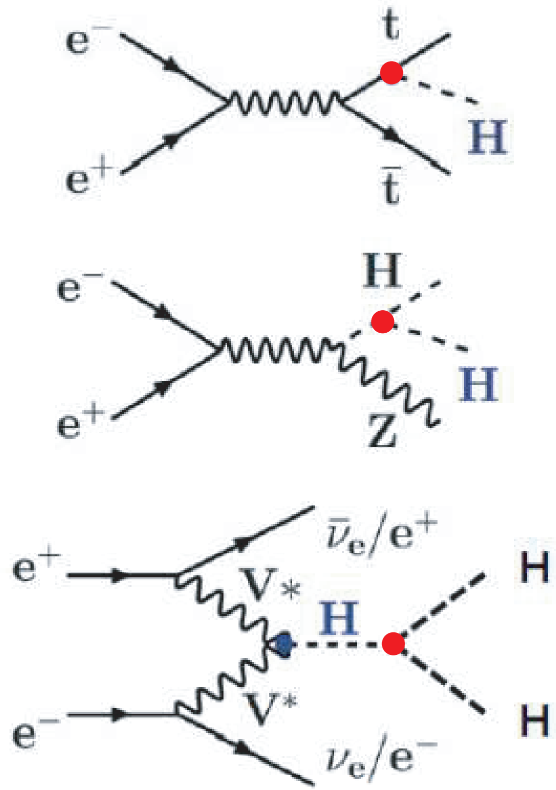


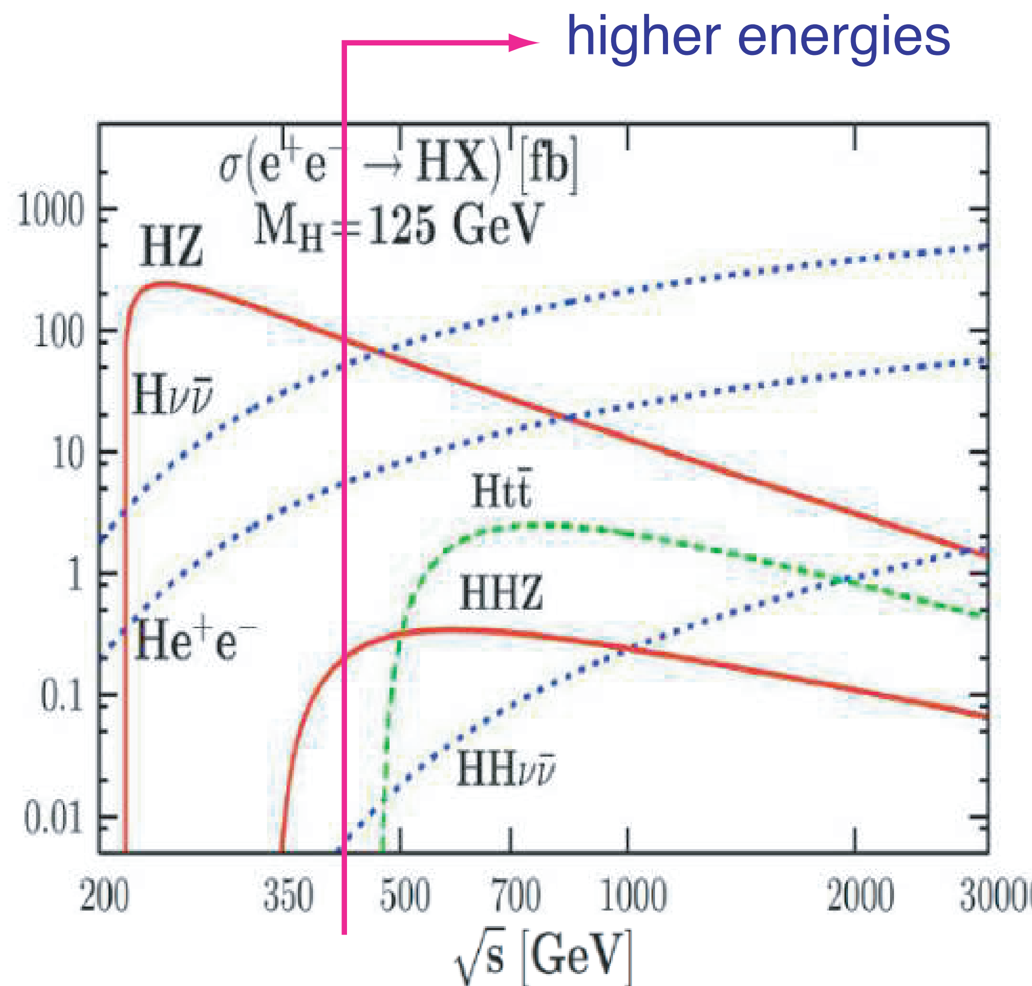


→ circular machines usually

$$E_{cm} \simeq 240\,\mathrm{GeV}$$

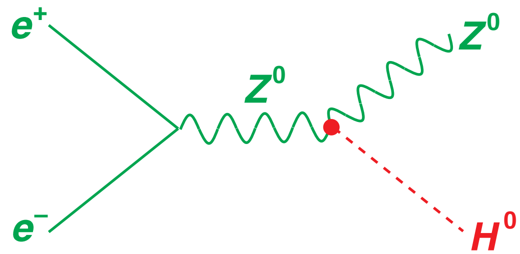
Higgs Production





- (direct) coupling to top
- self-coupling

Higgs Production



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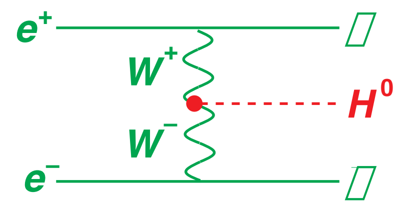
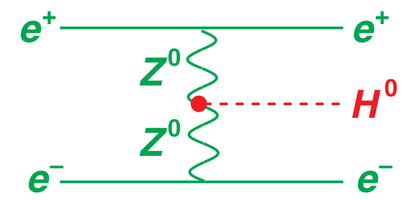




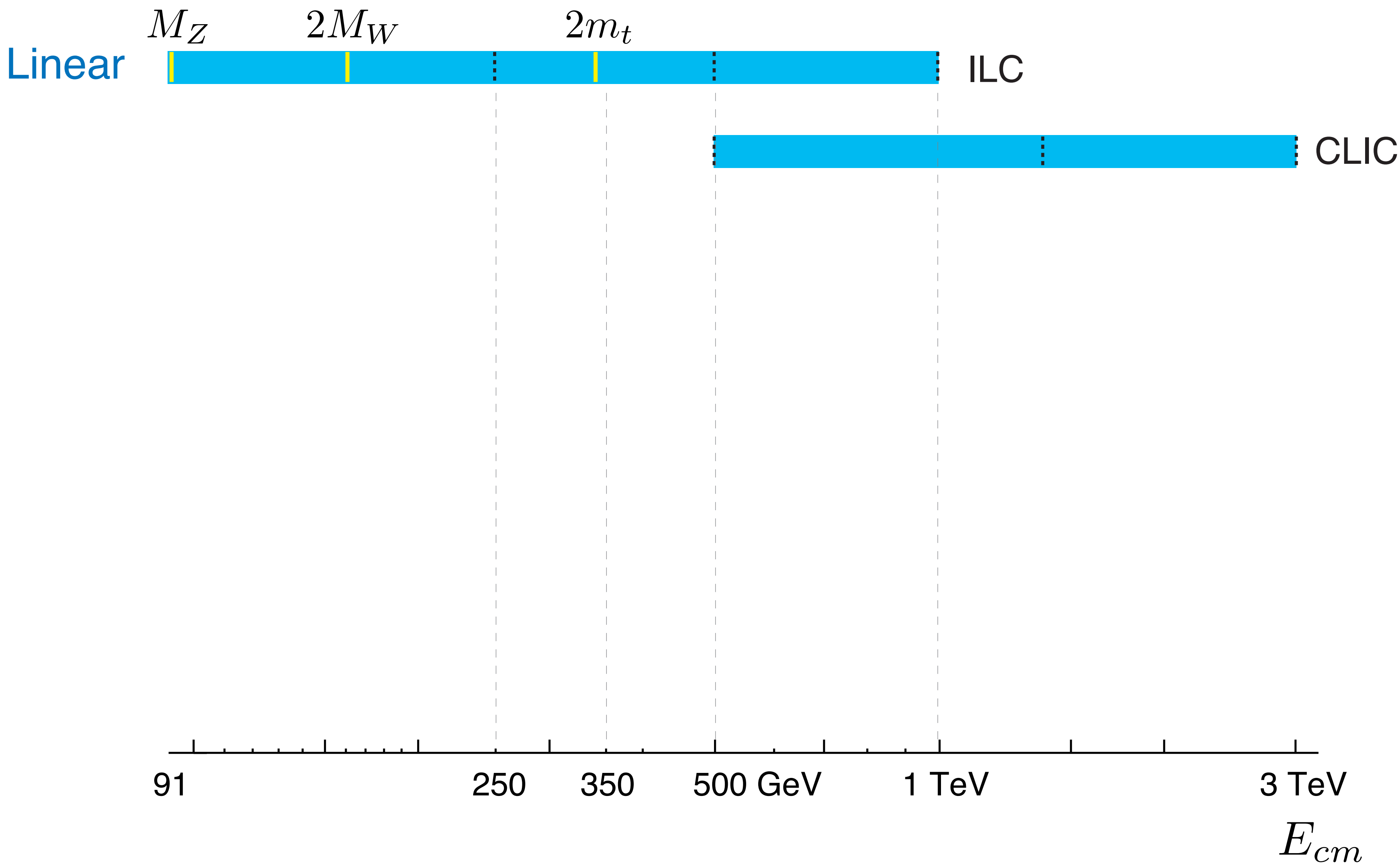
- Fusion

Typical ILC program, 3 – 5 years each energy:

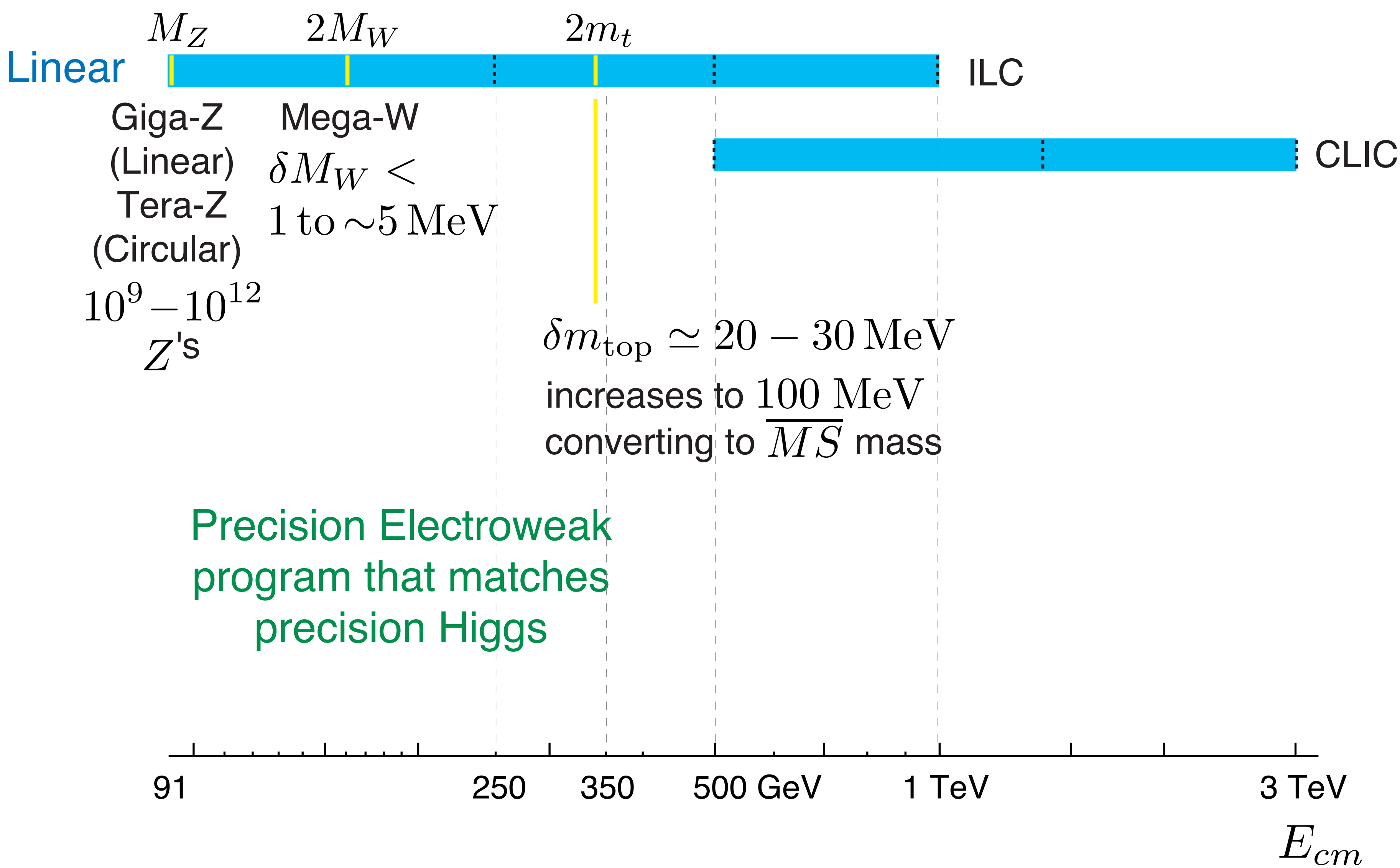
	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \rightarrow ZH)$	300 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \rightarrow \nu\nu H)$	18 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. Luminosity	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	75,000	45,500	28,500	13,000	7,500	2,000
# $\nu\nu$H events	4,500	10,500	37,500	210,000	460,000	970,000

Polarized

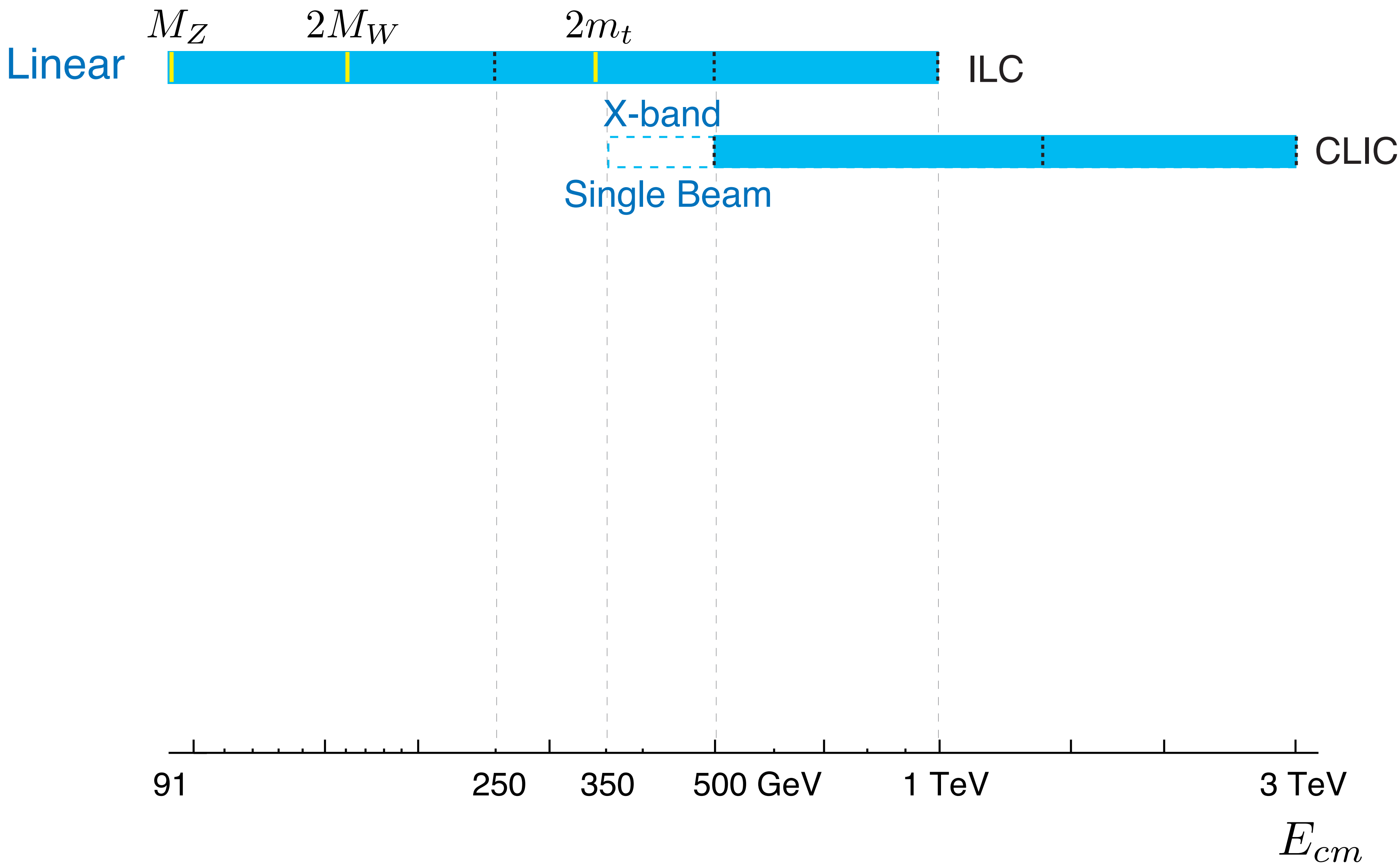
e^+e^- Facilities

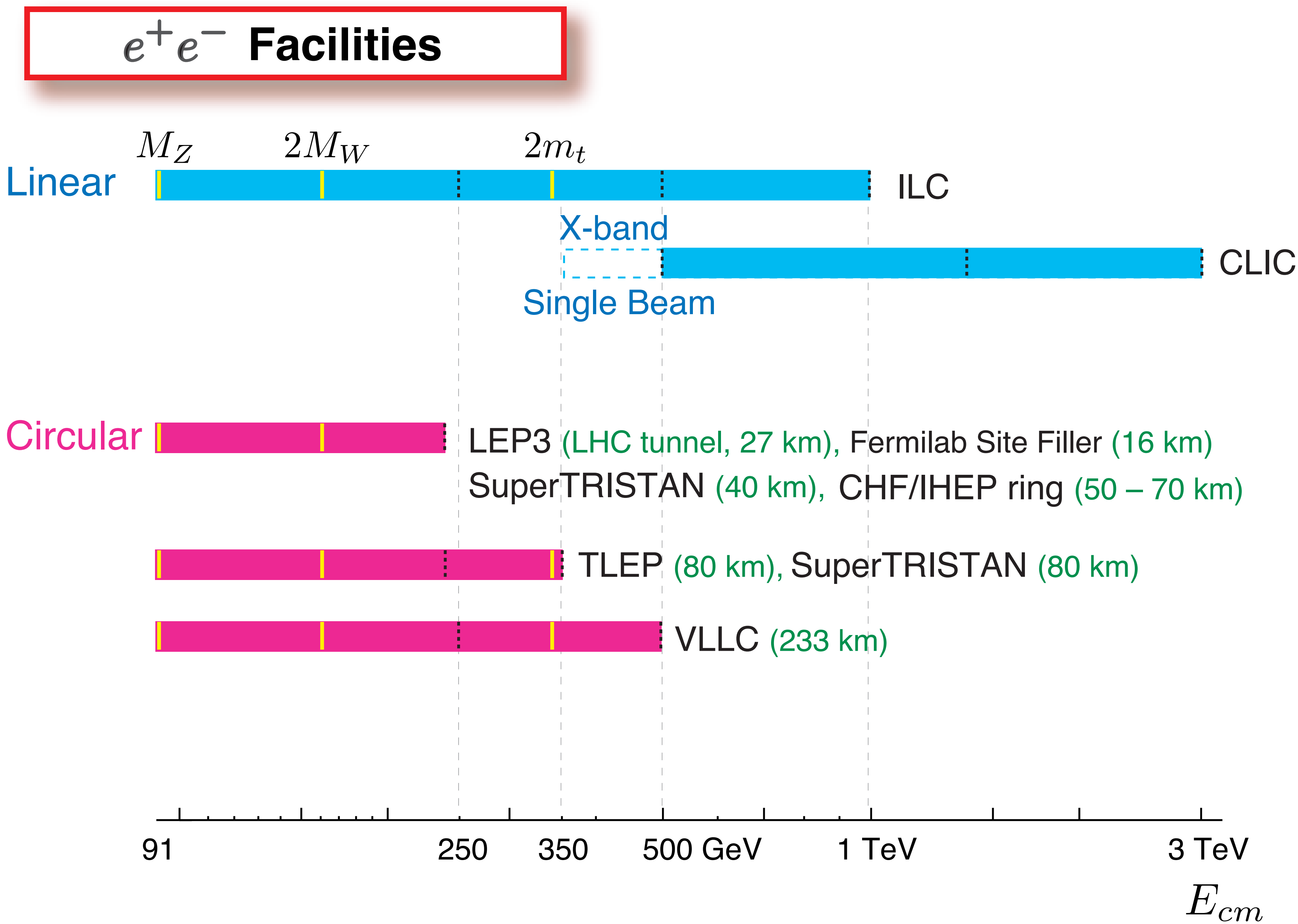


e^+e^- Facilities

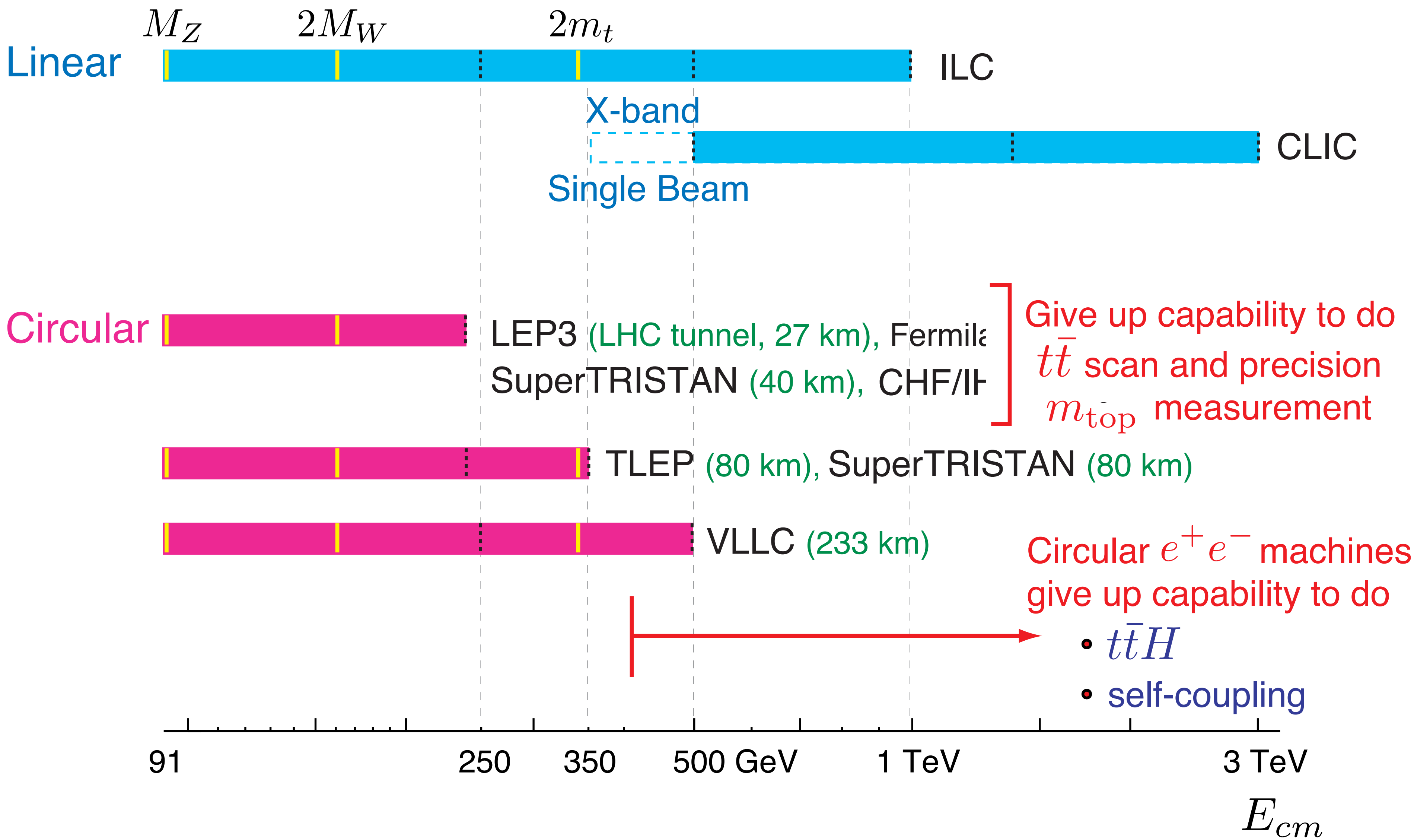


e^+e^- Facilities

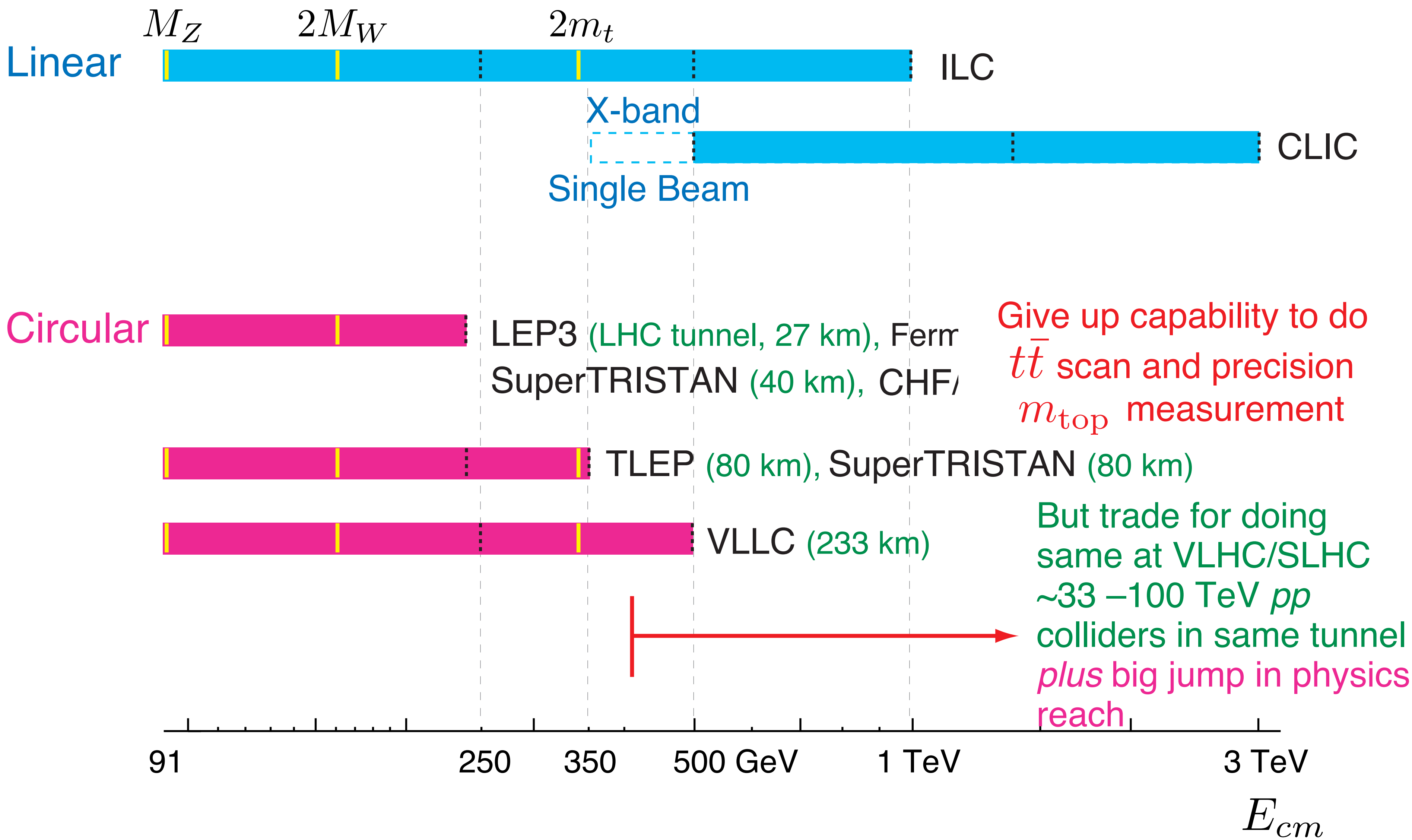



e^+e^- Facilities
M_Z
$2M_W$
$2m_t$
Linear
ILC
X-band
CLIC
Single Beam
Circular
LEP3 (LHC tunnel, 27 km), Fermilab Site Filler (16 km)
SuperTRISTAN (40 km), CHF/IHEP ring (50 – 70 km)
TLEP (80 km), SuperTRISTAN (80 km)
VLLC (233 km)
91
250
350
500 GeV
1 TeV
3 TeV
E_{cm}

e^+e^- Facilities



e^+e^- Facilities

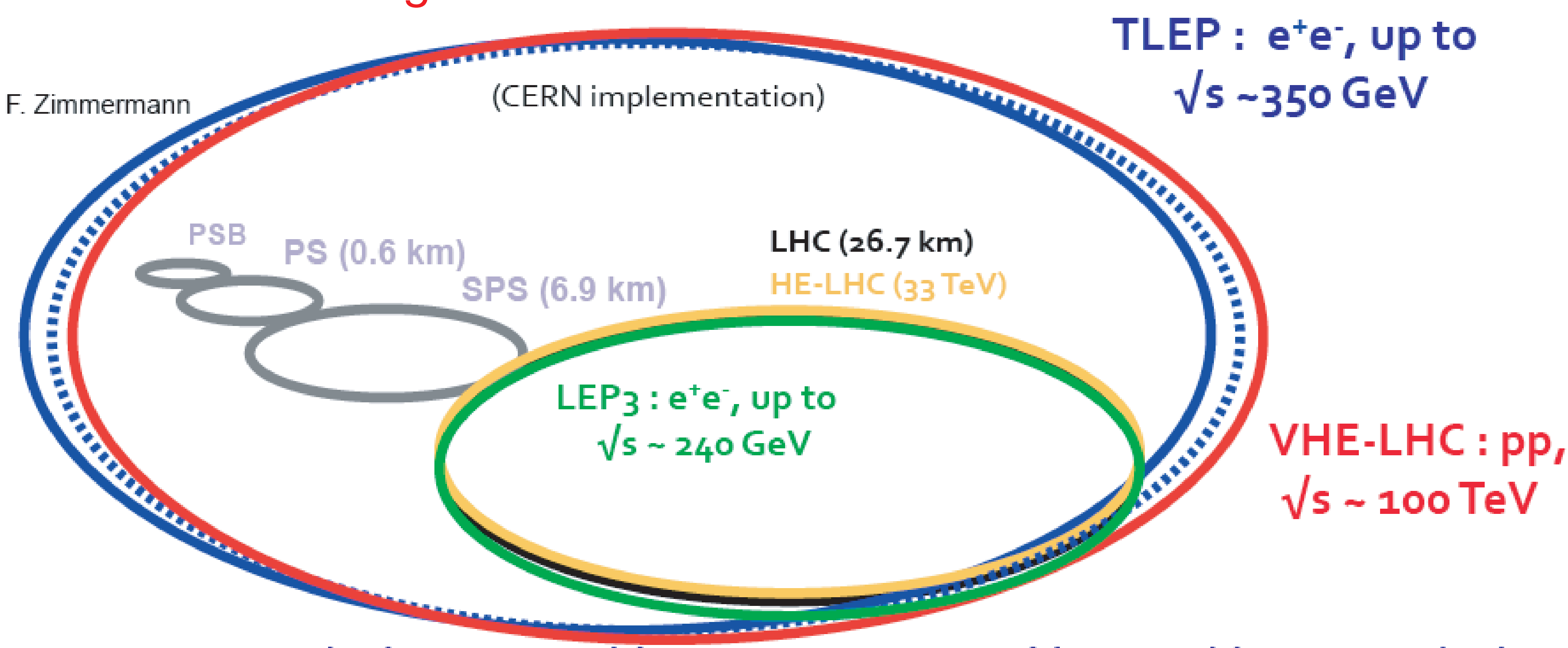


Circular

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

Short beam lifetime (minutes), top-up injection from separate accelerating ring

New ~80 km ring:



- At White Paper stage, planning Conceptual Design Report

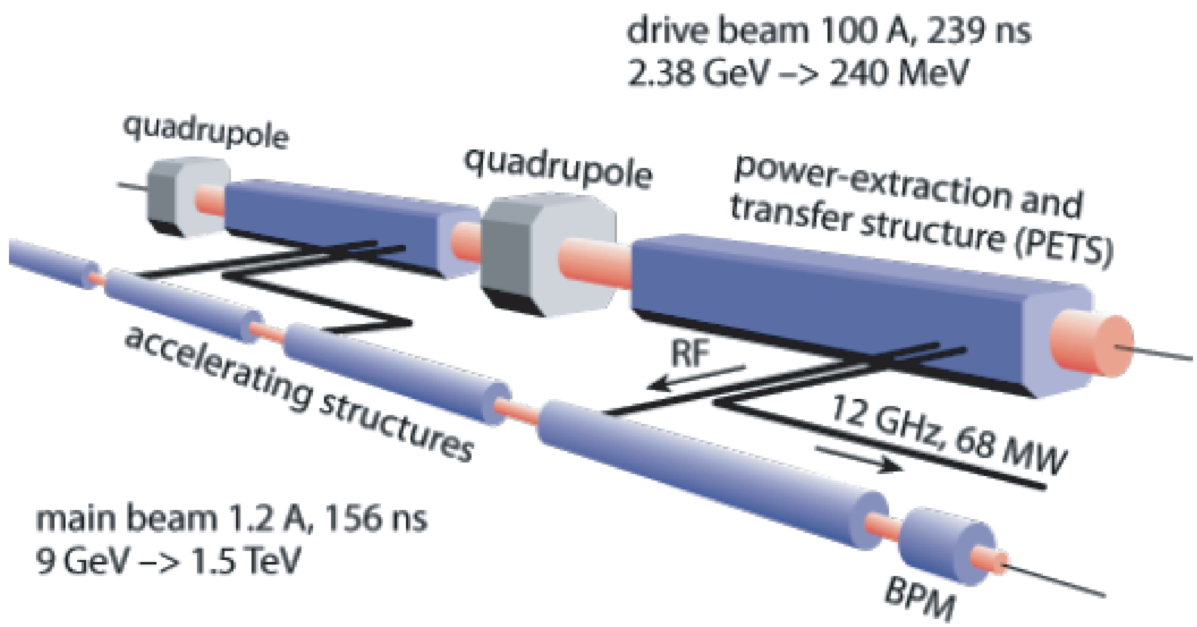
Linear

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

(looking at lower energy options)

CLIC (Compact Linear Collider)

Two beams: low E, high current drive; ~48 km long



- Conceptual Design Report completed in 2012
  http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php

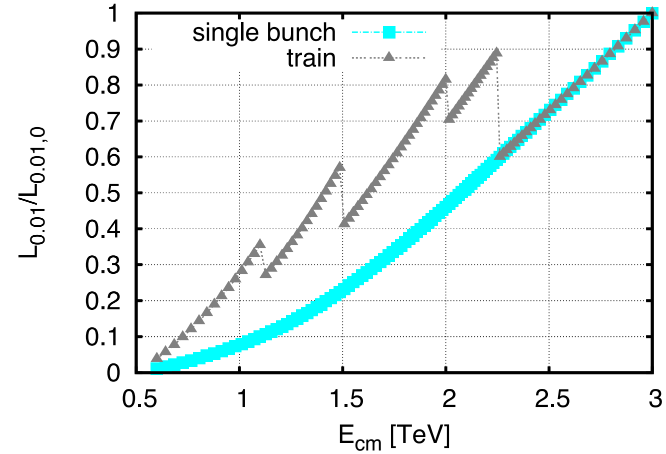
CLIC Staging Plan

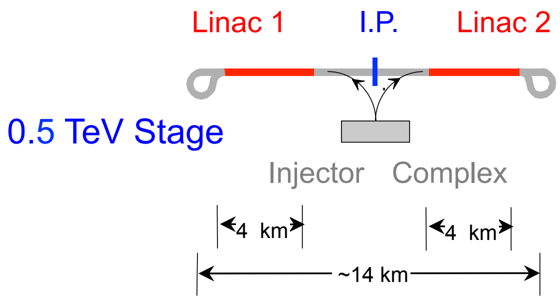
CLIC two-beam scheme compatible with energy staging to provide the optimal machine for a large energy range.

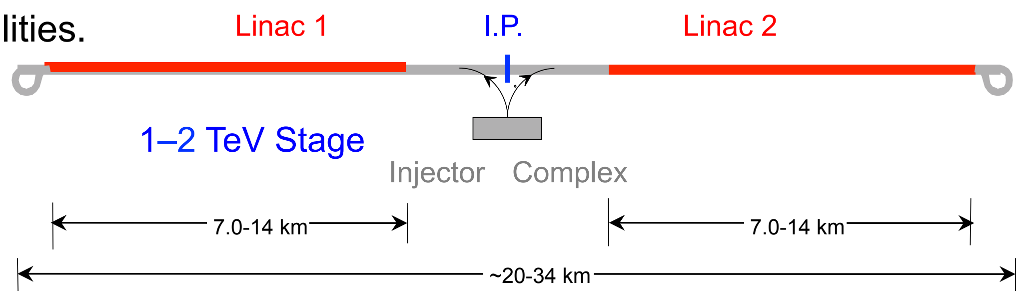
Lower energy machine can run most of the time during the construction of the next stage.

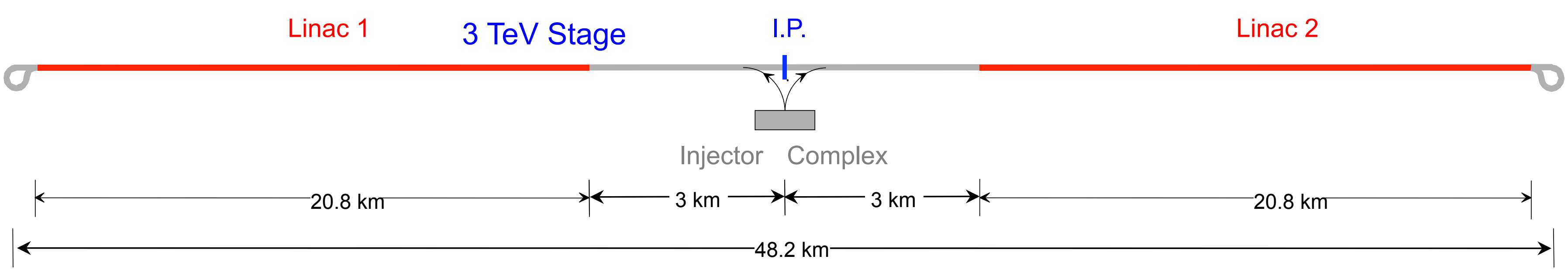
Recently studies have begun on a **~375 GeV first stage** with single beam, switching to two-beam at higher energies which reuses the low energy facilities.

Need to operate at lower than nominal energy







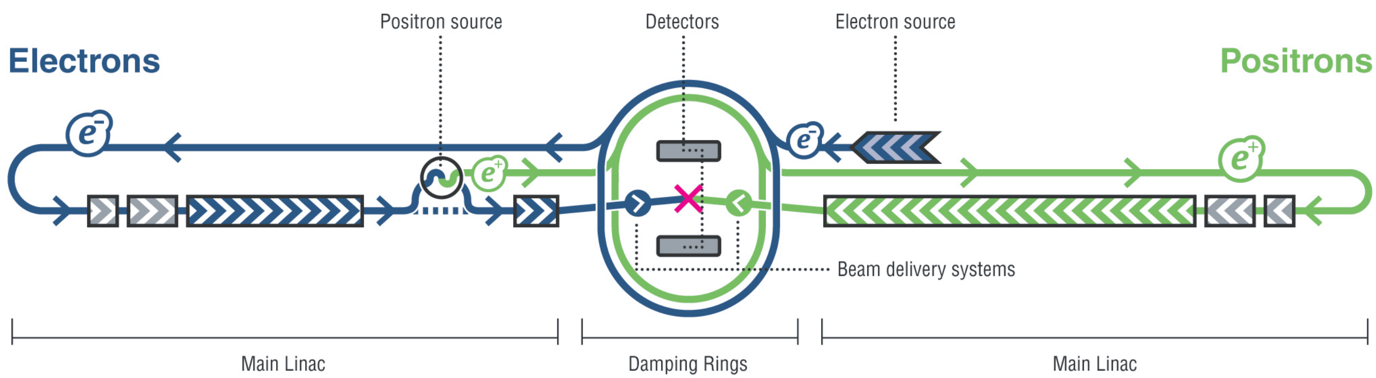


Linear

$$\sqrt{s} = 250 \text{ GeV}^{\dagger}$$
$$= 500 \text{ GeV}$$
$$= 1 \text{ TeV}$$

†cost does not scale linearly!

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



- ILC Technical Design Report (2013) (including full costing)

  Draft versions of Detailed Baseline Design Report, Physics & Detectors:

  http://ific.uv.es/~fuster/DBD-Chapters/

  Final version

  (including Accelerator via multi-year Global Design Effort)

  will be available in 2013

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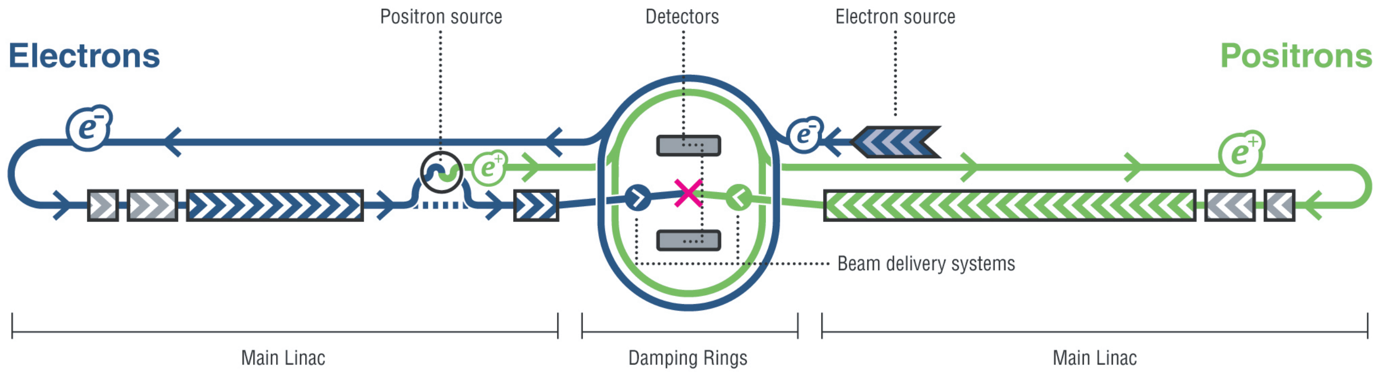

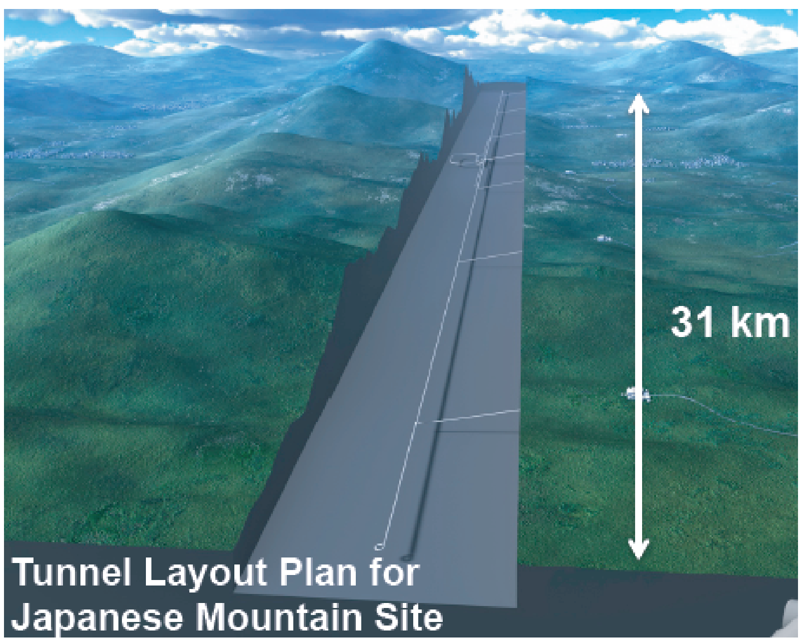

Implication of Higgs discovery:
political trigger point

Hitoshi Muryama, BNL Energy Frontier Meeting
https://indico.bnl.gov/materialDisplay.py?contribId=57&sessionId=11&materialId=slides&confId=571

Tomohiko Tanabe, Princeton Snowmass Higgs Meeting
http://physics.princeton.edu/indico/contributionDisplay.py?contribId=13&sessionId=7&confId=127

Situation in Japan

- March 2012: Japan Association of High Energy Physicists:

  "*Should a new particle such as a Higgs boson with a mass below approximately 1~TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e+e– linear collider. In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time*."

- Oct. 2012: Japan Association of High Energy Physicists:

  "*On the basis of these developments and following the subcommittee's recommendation on ILC, JAHEP proposes that ILC be constructed in Japan as a global project with the agreement of and participation by the international community*.
  Staging:
  – A Higgs factory with a CM energy of ~250 GeV to start
  – Upgraded in stages to ~500 GeV (ILC baseline)
  – Technical expandability to ~1 TeV to be secured

Situation in Japan

- KEK 2013 Roadmap:
  "*aims at starting the construction under international framework within the duration of this roadmap (5 years from 2014)*."

- Guideline for cost sharing
  The host country to cover 50% of the expenses (construction) of the overall project of the 500 GeV machine.
  The actual contribution, however, should be left to negotiations among the governments.

Situation in Japan

Dec. 2012: new political party elected, new prime minister Shinzo Abe

ILC explicited mentioned twice in campaign policy document

In his State of the Union equivalent speech

Answered questions on it in parliament

'Federation of Diet Members for Promotion of the ILC', two ministers to be visiting D.C.

Situation in Japan

Dec. 2012: … w
prime min…

ILC explicit… gn
policy doc…

In his State… h

Answered …

'Federation… n
of the IL… D.C.

LC Organization

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:* white papers for Snowmass

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

e^+e^- Higgs Factories

LHC already and likely to continue doing a spectacular job!

Necessary increased precision on:

- Mass
- CP admixture
- Separate cross sections
- Separate branching fractions
- Total width

Complementary to LHC

Remember: if expect deviations of only a few %,
need $\frac{\text{few \%}}{5}$ for a 5σ "discovery"...

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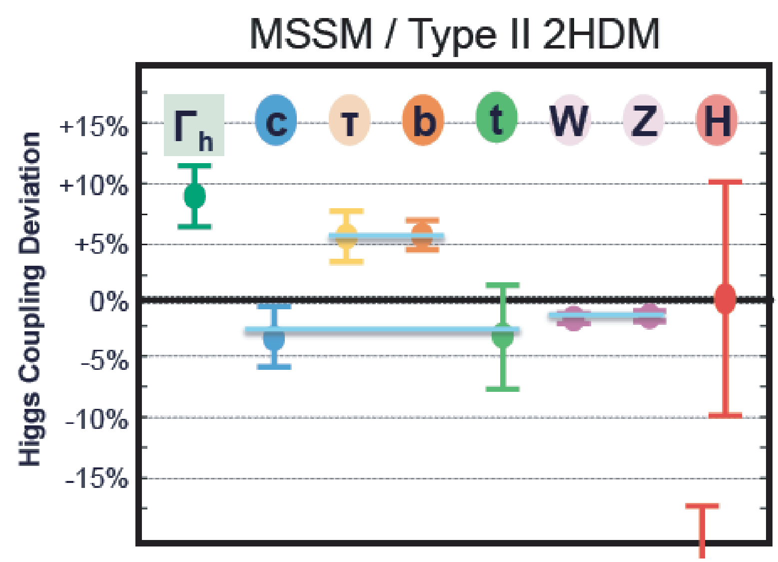
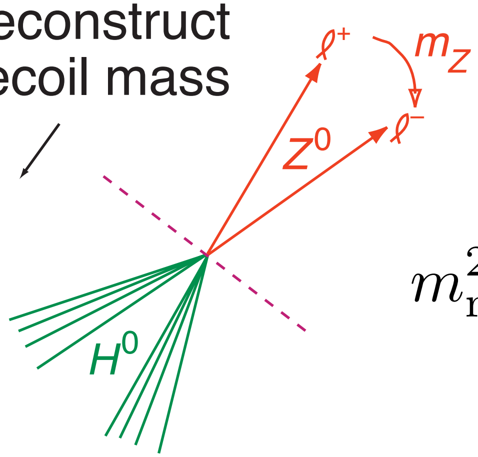
...although there may be patterns:



$\sqrt{s} \simeq 250\,\mathrm{GeV}$, Cross Section

The first step...

Reconstruct recoil mass

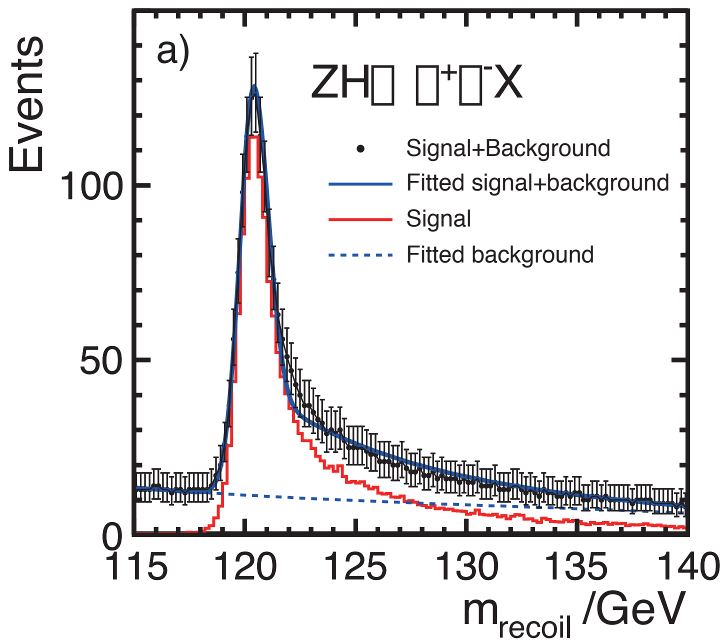


- $\sigma(ZH)$ measurement independent of Higgs decay mode

$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

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

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



$\sqrt{s}$	$250\,\mathrm{GeV}$	$350\,\mathrm{GeV}$
Int. $\mathcal{L}$	$250\,\mathrm{fb}^{-1}$	$350\,\mathrm{fb}^{-1}$
$\Delta\sigma_{ZH}/\sigma_{ZH}$	2.5%	4%
$\Delta g_{HZZ}/g_{HZZ}$	1.3%	2%

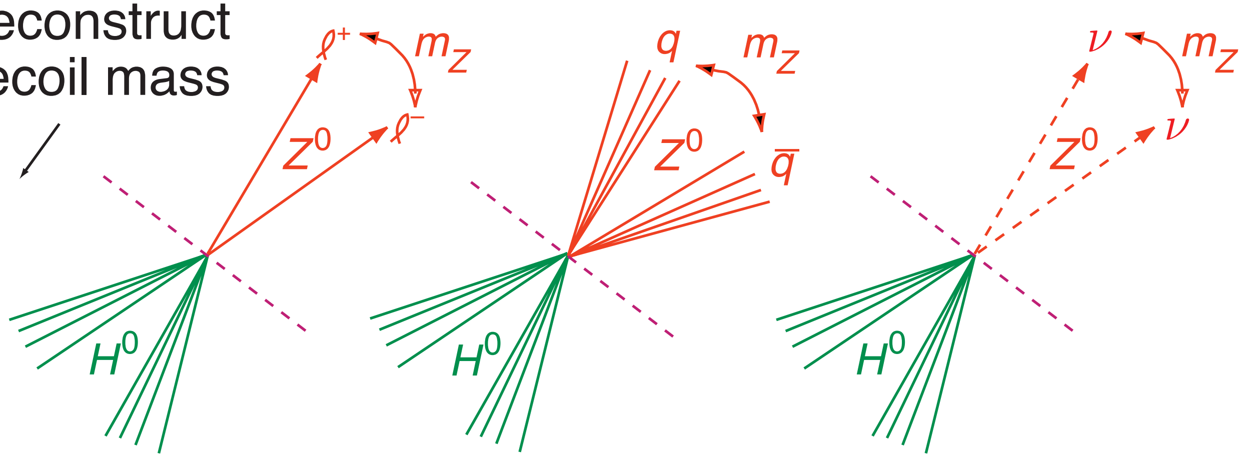
So important

→ Can we do better than this?

(small systematics, e.g., lumi syst., understanding of isolated leptons)

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, ***Br's***

Reconstruct recoil mass



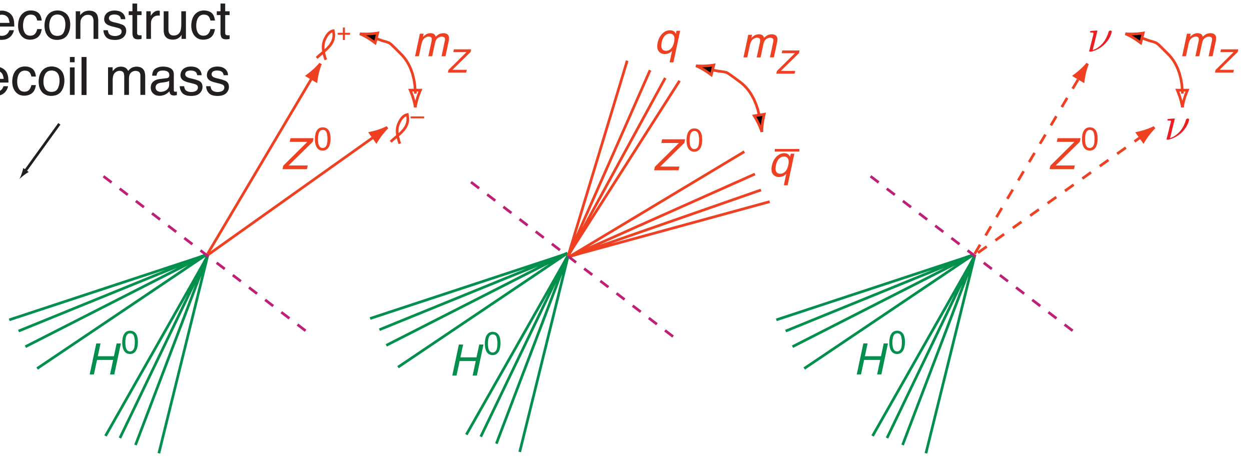
- Completely model independent measurements of *Br*'s/couplings (instead of $\sigma \cdot$ Br as LHC) including to invisible/dark matter or *exotic* decays

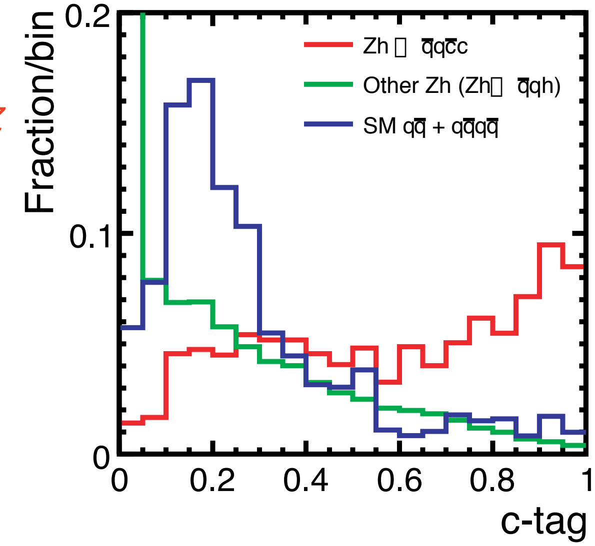
$$\mathcal{B}(H \to \text{invis.}) < 0.8\%\ (95\%\ \text{C.L.})$$

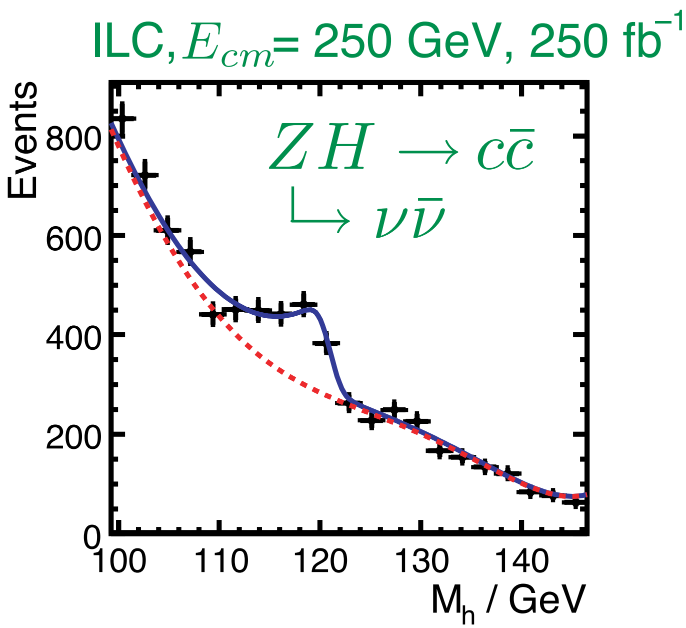
Essential! Could be happening at LHC and we would not know

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, *Br's*

Reconstruct recoil mass







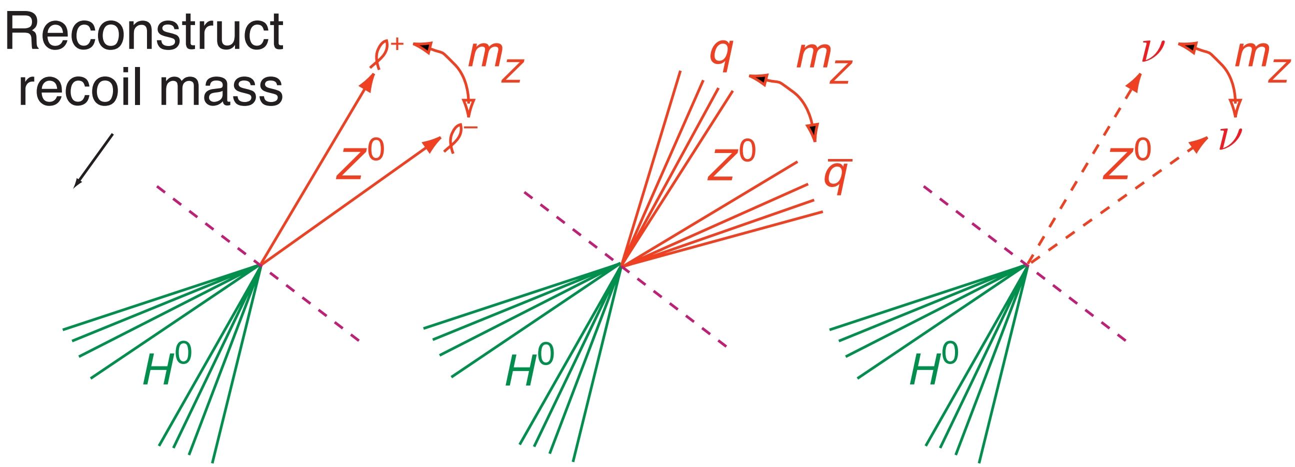
- Completely model independent measurements of *Br*'s/couplings (instead of $\sigma \cdot$Br as LHC) including to invisible/dark matter or *exotic* decays

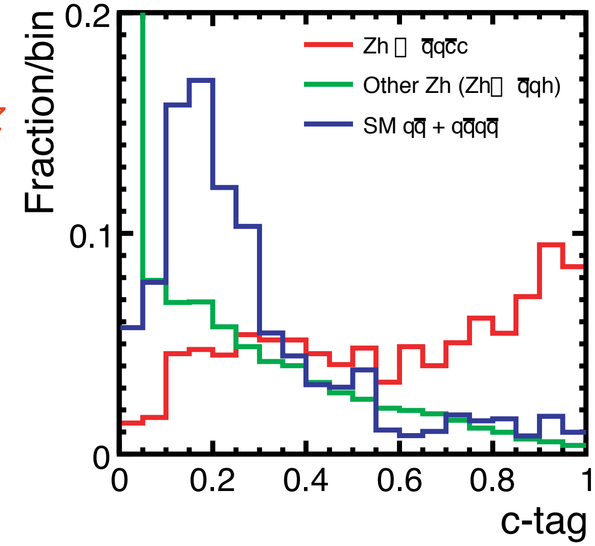
$$\Delta(\sigma \cdot \mathcal{B}(H \to c\bar{c}))/(\sigma \cdot \mathcal{B}) = 6.9\%$$

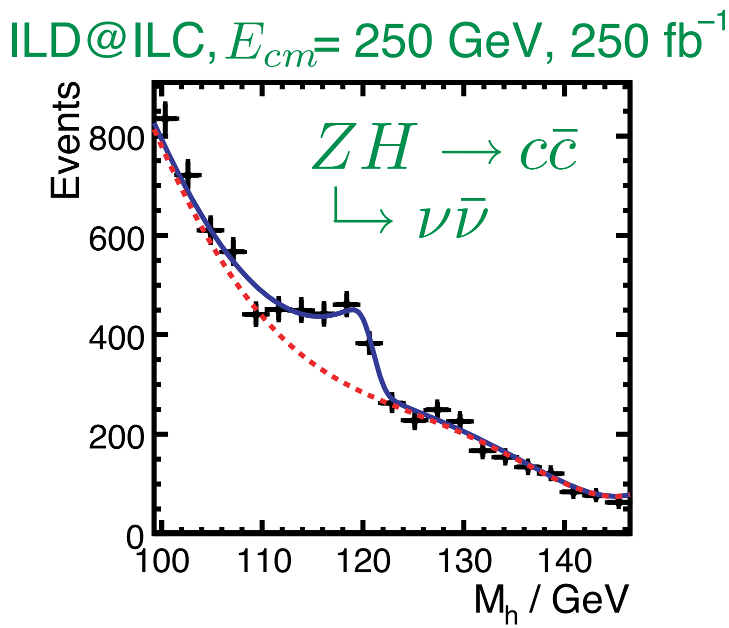
Similarly:

$$\Delta(\sigma \cdot \mathcal{B}(H \to b\bar{b}))/(\sigma \cdot \mathcal{B}) = 1.0\%$$

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, *Br's*

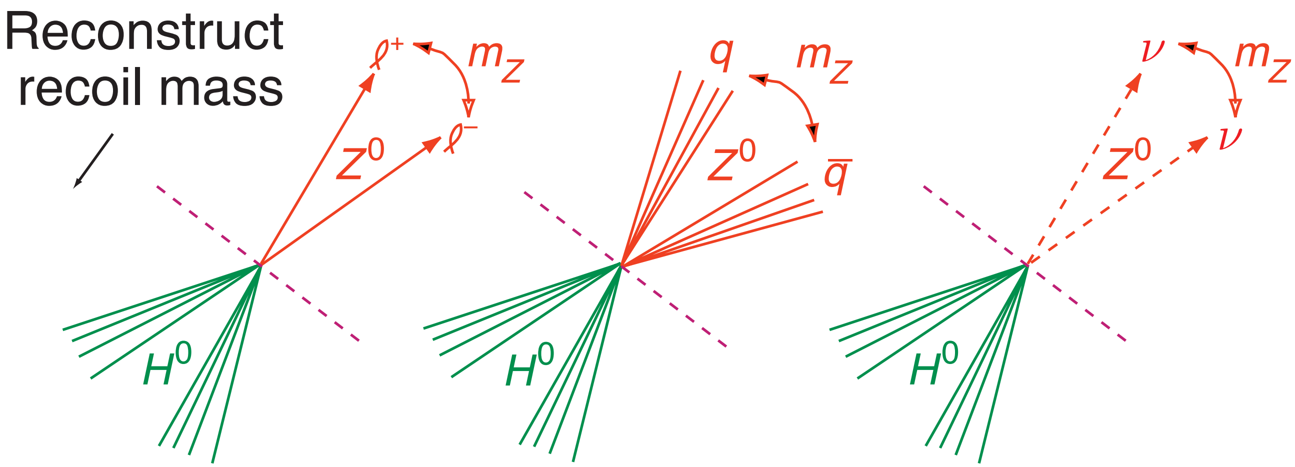




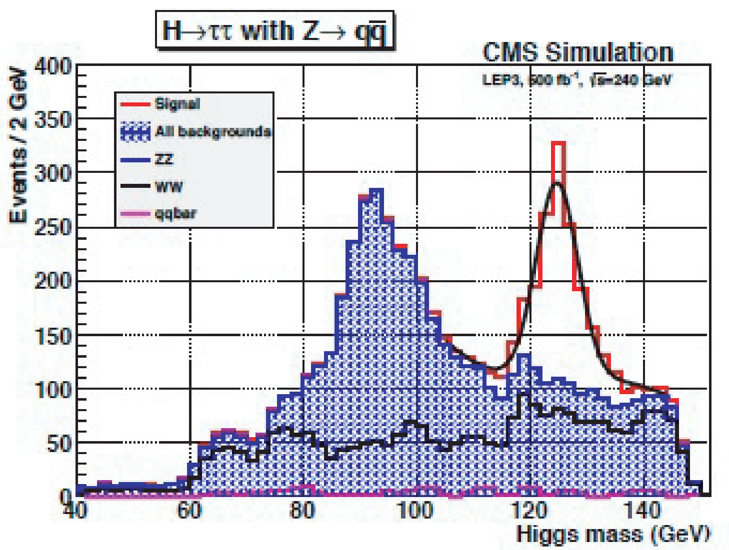


- Completely model independent measurements of *Br*'s/couplings (instead of $\sigma \cdot$Br as LHC) including to invisible/dark matter or *exotic* decays
- extraction of *Br*'s will always include
  $\oplus\ \Delta(\sigma_{ZH})$ (e.g., ±2.5%)
  (although correlated across all Br's)

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, *Br's*



CMS@LEP3, E_{cm}= 240 GeV, 500 fb^{-1}



- Completely model independent measurements of *Br*'s/couplings (instead of $\sigma \cdot$Br as LHC) including to invisible/dark matter or exotic decays

$$ZH \to \tau^+\tau^-$$
$$\hookrightarrow q\bar{q}$$

- Experimentally, not much difference between circular and linear machines

$\sqrt{s} \simeq 250\,\text{GeV}$, *Br's*

ILC, E_{cm}= 250 GeV, 250 fb^{-1} , polarization $(e^-, e^+) = (-0.8, +0.3)$

mode	BR	$\sigma \cdot BR\,(\text{fb})$	$N_{evt}/250\,\text{fb}^{-1}$	$\Delta(\sigma\,BR)/(\sigma\,BR)$	$\Delta BR/BR$
$h \to b\bar{b}$	65.7%	232.8	58199	1.0%	2.7%
$h \to c\bar{c}$	3.6%	12.7	3187	6.9%	7.3%
$h \to gg$	5.5%	19.5	4864	8.5%	8.9%
$h \to WW^*$	15.0%	53.1	13281	8.1%	8.5%
$h \to \tau^+\tau^-$	8.0%	28.2	7050	3.6%	4.4%
$h \to ZZ^*$	1.7%	6.1	1523	26%	26%
$h \to \gamma\gamma$	0.29%	1.02	255	23-30%	23-30%

Physics Volume, Techical Design Report (DBD), updated March 31

$\oplus\ 2.5\%$
fully correlated
across all *Br*'s

$\sqrt{s} \simeq 250\,\mathrm{GeV}$, Total Width

$$\Gamma_{\rm tot} = \frac{\Gamma(H \to ZZ^*)}{\mathcal{B}(H \to ZZ^*)}$$

prop. to $\sigma(ZH), g^2_{HZZ}$

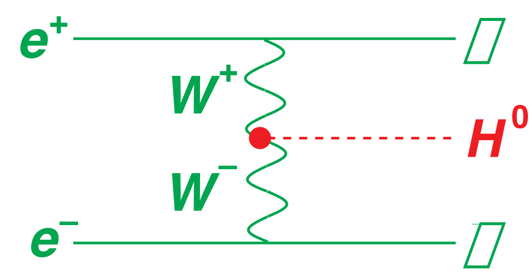
small, large error

Instead:

$$\Gamma_{\rm tot} = \frac{\Gamma(H \to WW^*)}{\mathcal{B}(H \to WW^*)}$$

prop. to $\sigma(\nu\bar{\nu}H), g^2_{HWW}$

smallish



$$\Delta\Gamma_{\rm tot}/\Gamma_{\rm tot} \simeq 11\%$$

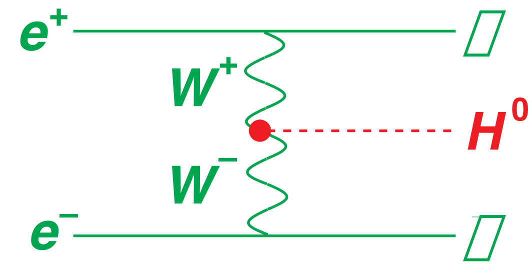
How to do better??

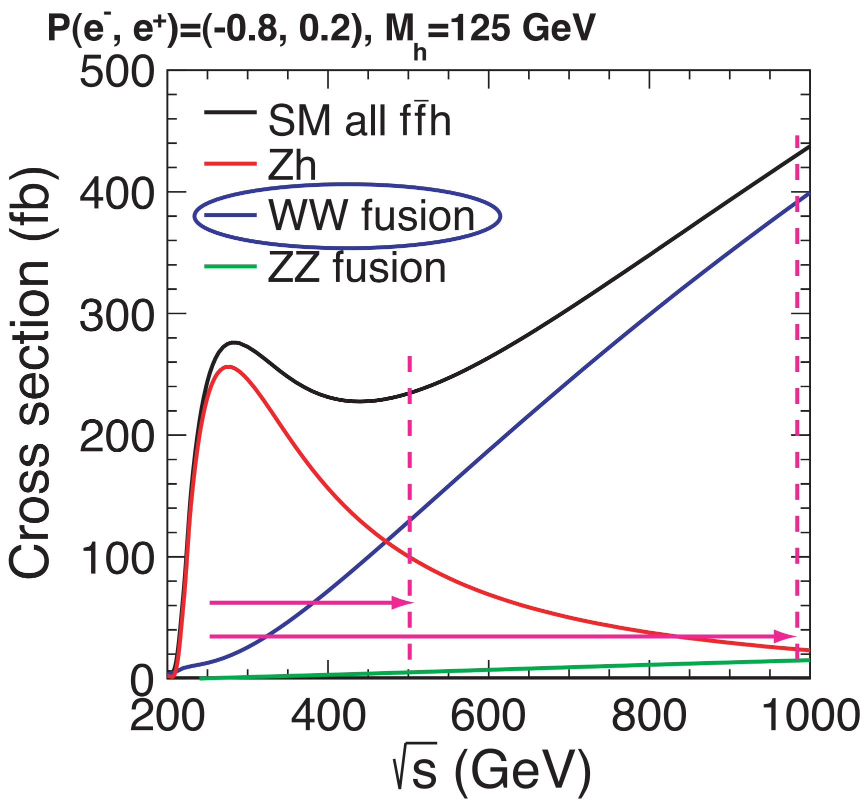
$\sqrt{s} \simeq 500\,\mathrm{GeV}$, Total Width

Instead:

$$\Gamma_{\rm tot} = \frac{\Gamma(H \to WW^*)}{\mathcal{B}(H \to WW^*)}$$

prop. to $\sigma(\nu\bar{\nu}H), g^2_{HWW}$





Move to higher energies, e.g., $\sqrt{s} = 500\,\mathrm{GeV}$

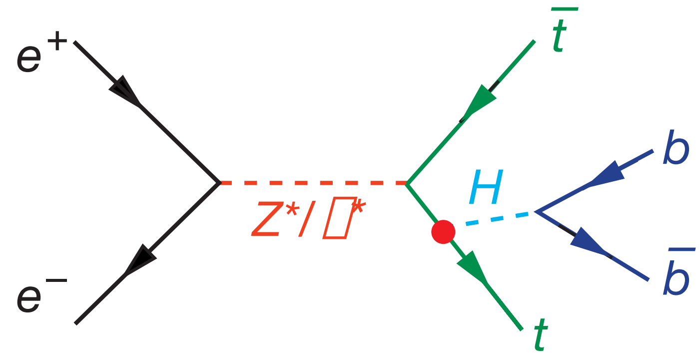
$\Delta\Gamma_{\rm tot}/\Gamma_{\rm tot} \simeq 6\%$

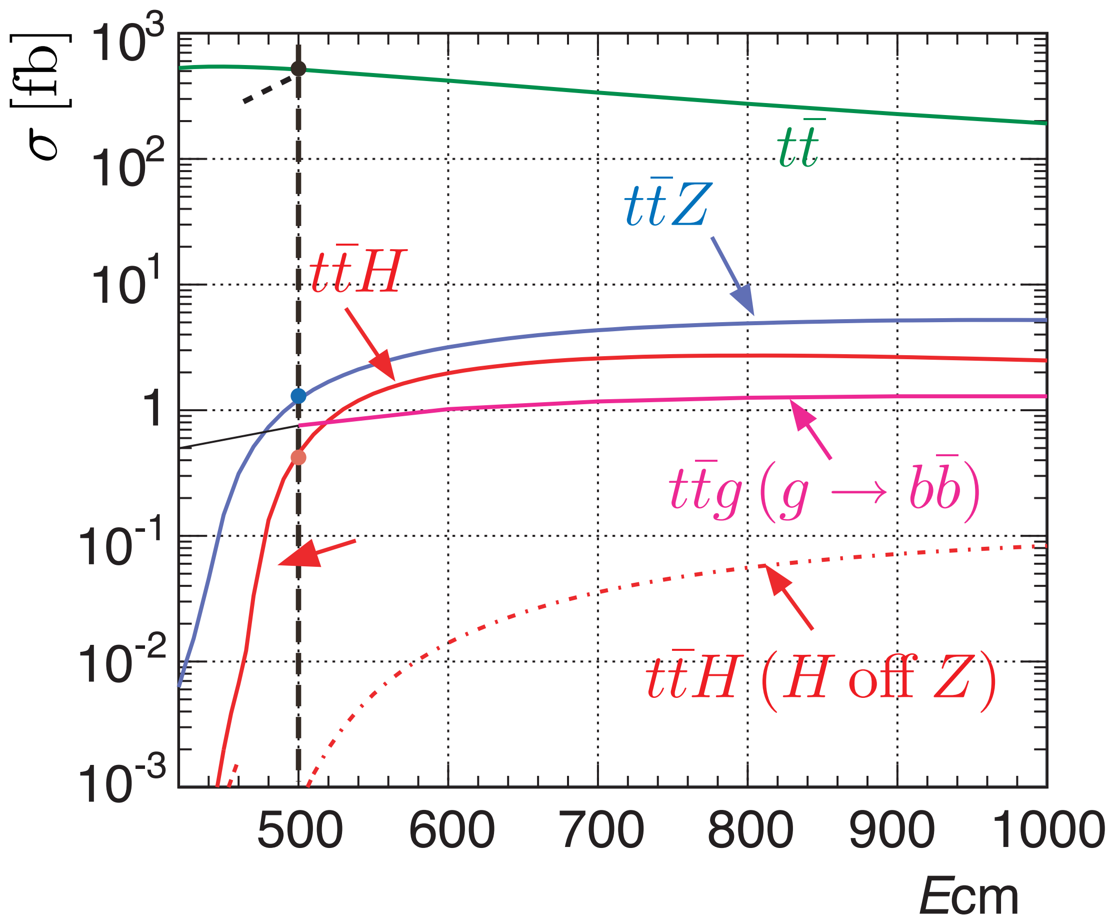
Keep measuring *Br*'s!

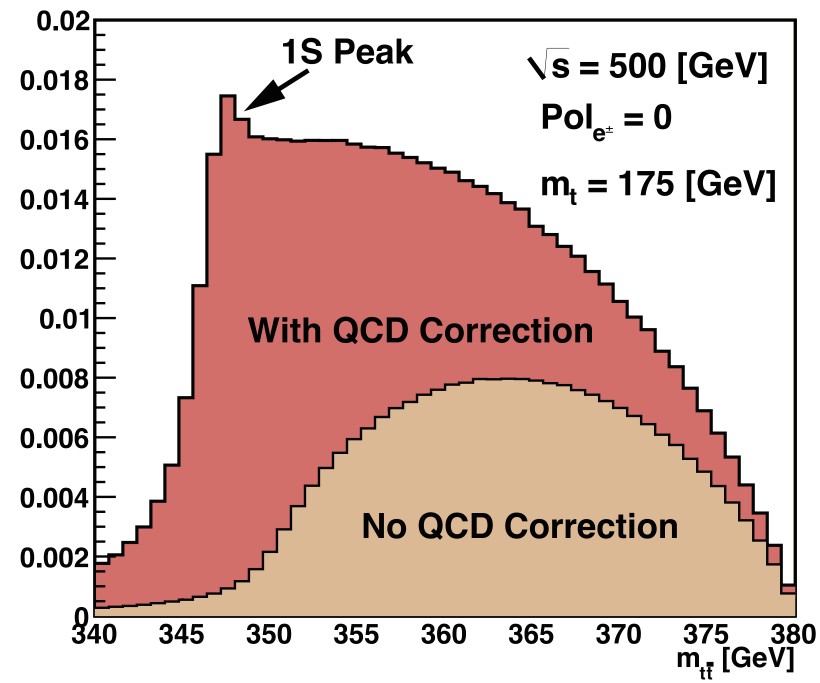
...and now the stuff that is tough for most machines...

$t\bar{t}H$

- 6-jet and 8-jet modes:





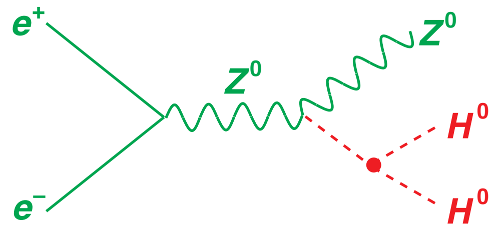


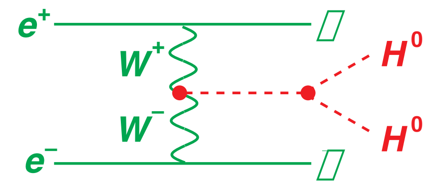
- Now feasible at 500 GeV! Complicated, multi-jet system, four *b* jets

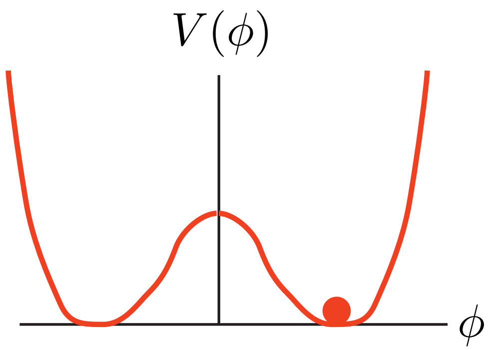
$$\Delta g_{ttH}/g_{ttH} = 10\% \ \ (1\ \mathrm{ab}^{-1})$$

- Better at higher energies (aside from larger fraction of non-ttH components)

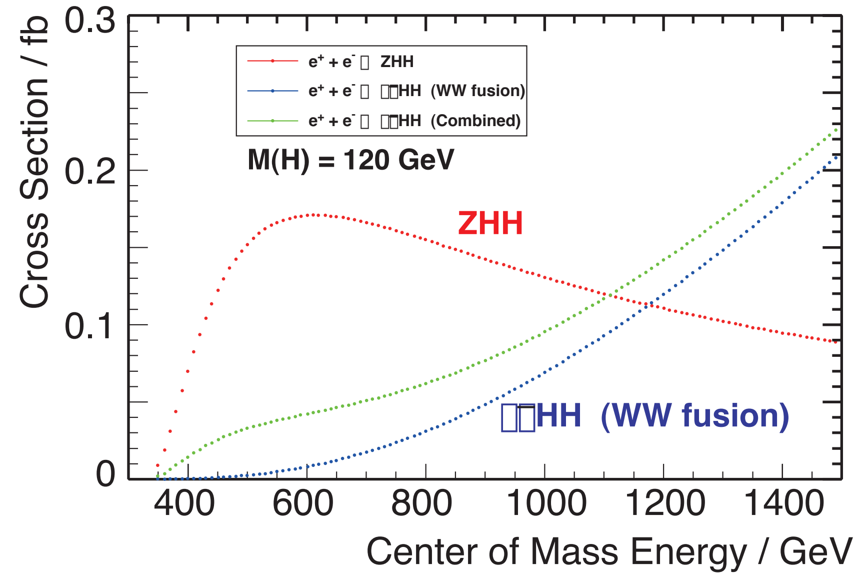
Self-Coupling







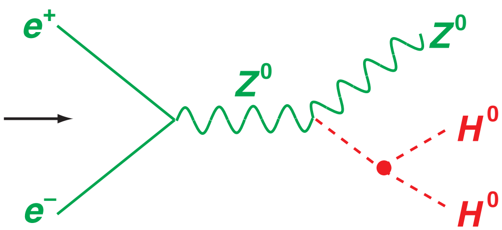
$$V(\phi) = \mu^2 \phi^\dagger \phi + \boldsymbol{\lambda} (\phi^\dagger \phi)^2$$

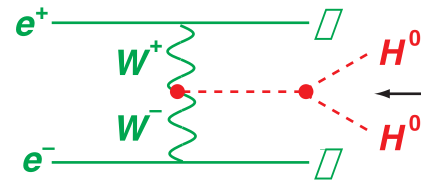


- Tough analysis, low rate
- Separate non-self-coupling contributions by *HH* invariant mass
- Uses $H \to b\bar{b}$; b-jet "color singlet" assignment is tough

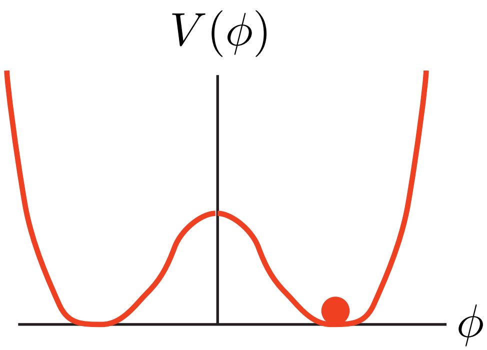
Self-Coupling

$$\frac{\Delta\lambda}{\lambda} = 1.66\frac{\Delta\sigma}{\sigma} \longrightarrow$$

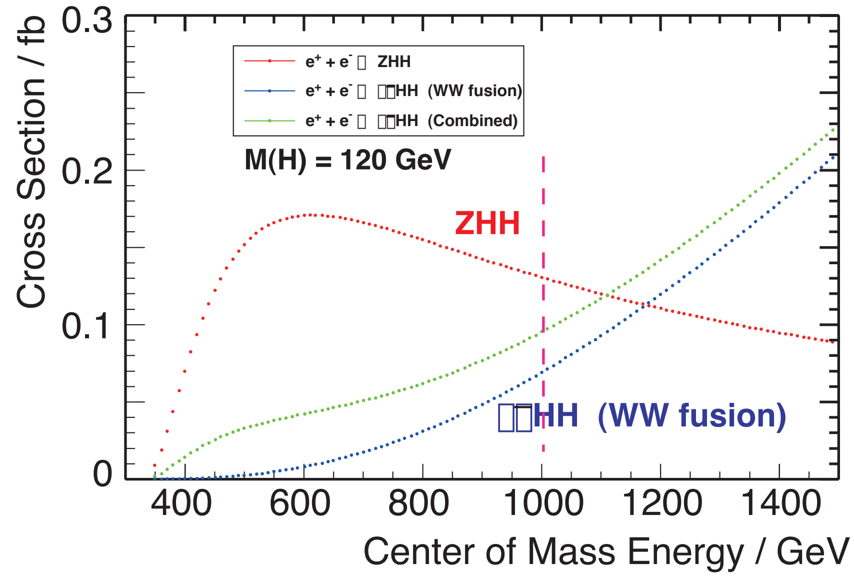




$$\longleftarrow \frac{\Delta\lambda}{\lambda} = 0.76\frac{\Delta\sigma}{\sigma}$$



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



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Tough Stuff

process	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [ab^{-1}]	(P_{e^-}, P_{e^+})	$(\Delta\sigma \cdot BR)/(\sigma \cdot BR)$	$\Delta g/g$
$t\bar{t}h$	500	1	(-0.8,+0.3)	25%	13%
Zhh	500	2	(-0.8,+0.3)	32% →	53%
$t\bar{t}h$	1000	1	(-0.8,+0.2)	8.7%	4.5%
$\nu\bar{\nu}hh$	1000	2	(-0.8,+0.2)	26% →	21%

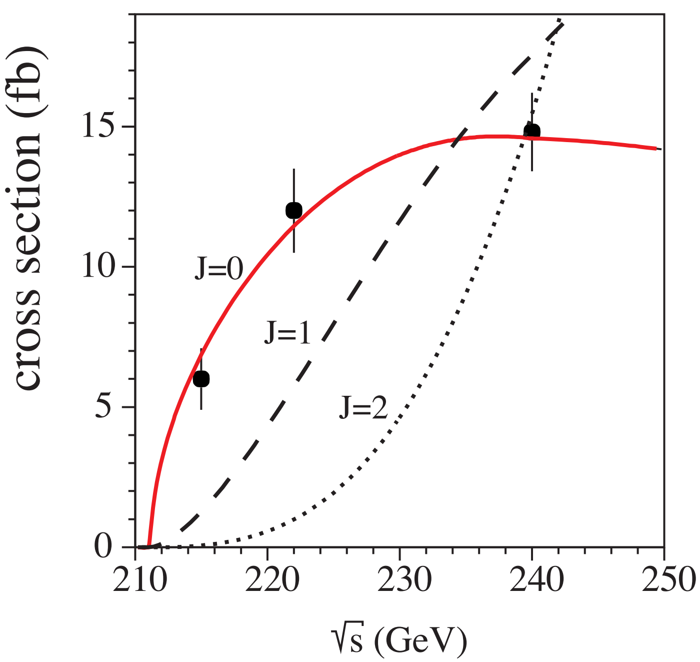
Collecting...

	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	$250\,\mathrm{fb}^{-1}$ at $250\,\mathrm{GeV}$ (-0.8,+0.3)		$500\,\mathrm{fb}^{-1}$ at $500\,\mathrm{GeV}$ (-0.8,+0.3)		$1\,\mathrm{ab}^{-1}$ at $1\,\mathrm{TeV}$ (-0.8,+0.2)
mode	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$
$h \to b\bar{b}$	1.1%	10.5%	1.8%	0.66%	0.47%
$h \to c\bar{c}$	7.4%	-	12%	6.2%	7.6%
$h \to gg$	9.1%	-	14%	4.1%	3.1%
$h \to WW^*$	6.4%	-	9.2%	2.6%	3.3%
$h \to \tau^+\tau^-$	4.2%	-	5.4%	14%	3.5%
$h \to ZZ^*$	19%	-	25%	8.2%	4.4%
$h \to \gamma\gamma$	29-38%	-	29-38%	20-26%	7-10%
$h \to \mu^+\mu^-$	100%	-	-	-	32%

...input to global analysis

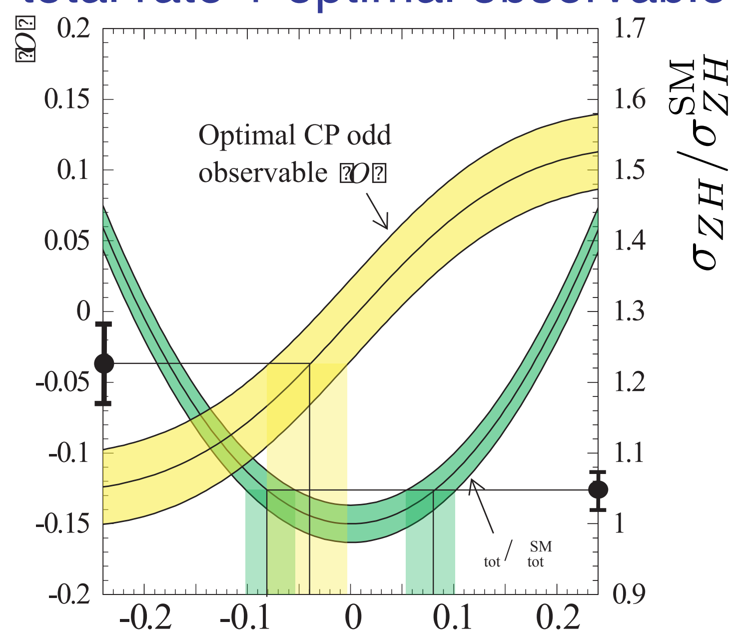
Spin & CP

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



Spin (will be) moot aside from "conspiracy theories"?

- total rate + optimal observable



η : *Bosons:* CP-odd admixture to ~4%

Fermions:

- Angular analysis of decay products of polarized taus in $H \to \tau^+\tau^-$, CP-oddadmixture to ~ 6°

Combination Assumptions

More constrained ↓

- $$\sum_i \mathcal{B}_i = 1$$
- $$|g_{HWW}| < g_{HWW}|_{\rm SM}$$
  $$|g_{HZZ}| < g_{HZZ}|_{\rm SM}$$
- $$g_{HWW}/g_{HZZ} = \cos^2\theta_w$$
- No invisible or undetectable Higgs decays

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Global Analysis

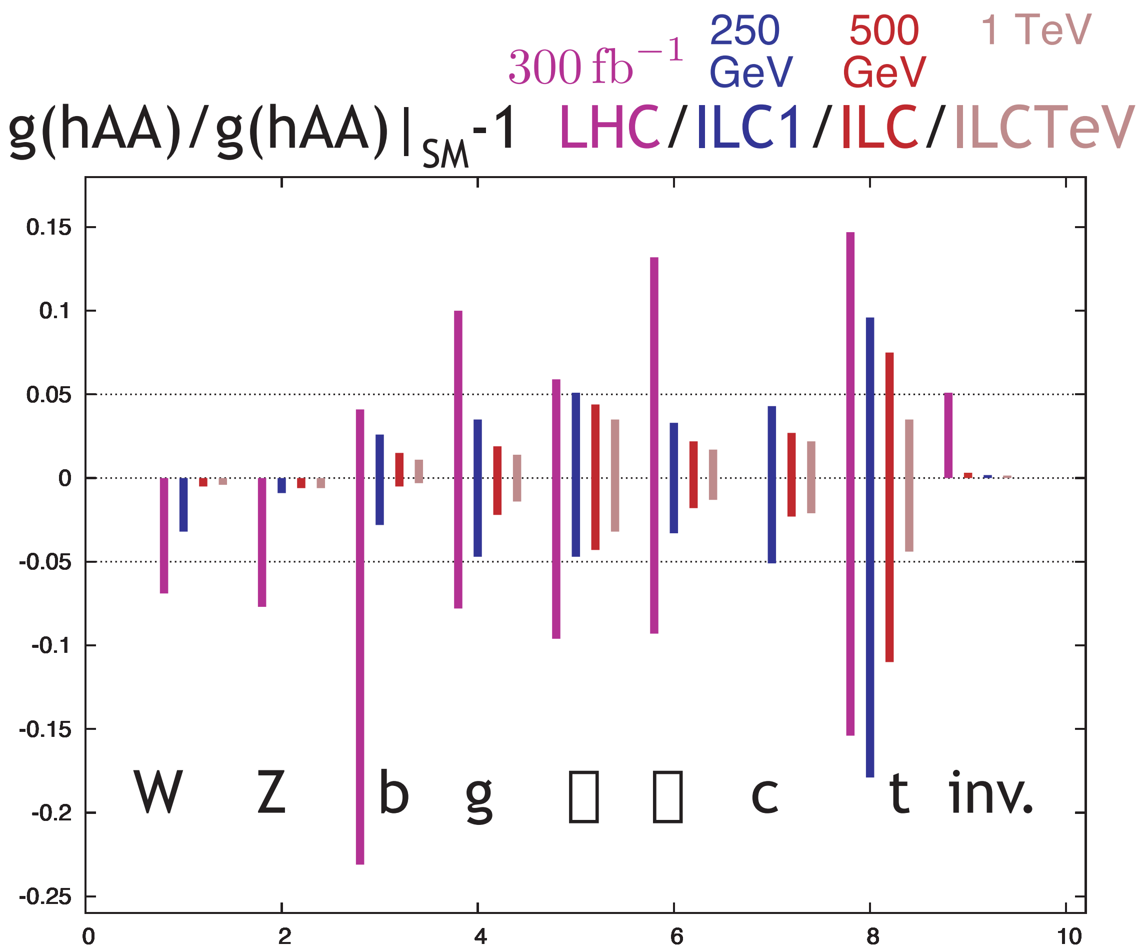
Expected Higgs boson coupling precisions in %:

Mode	LHC 300 fb^{-1}	ILC(250) 250 fb^{-1}	ILC(500) 500 fb^{-1}	ILC(1000) 1000 fb^{-1}
WW	4.1	1.9	0.24	0.17
ZZ	4.5	0.44	0.30	0.27
$b\bar{b}$	13.6	2.7	0.94	0.69
gg	8.9	4.0	2.0	1.4
$\gamma\gamma$	7.8	4.9	4.3	3.3
$\tau^+\tau^-$	11.4	3.3	1.9	1.4
$c\bar{c}$	–	4.7	2.5	2.1
$t\bar{t}$	15.6	14.2	9.3	3.9
$\mu^+\mu^-$	–	–	–	16.
self	–	–	–	20.
BR(invis.)	< 9	< 0.44	< 0.30	< 0.26
Γ_{tot}	20.3	4.8	1.6	1.2

Physics Volume, ILC Techical Design Report (DBD), updated March 31

arXiv:1207.2516 [hep-ph]

Global Analysis



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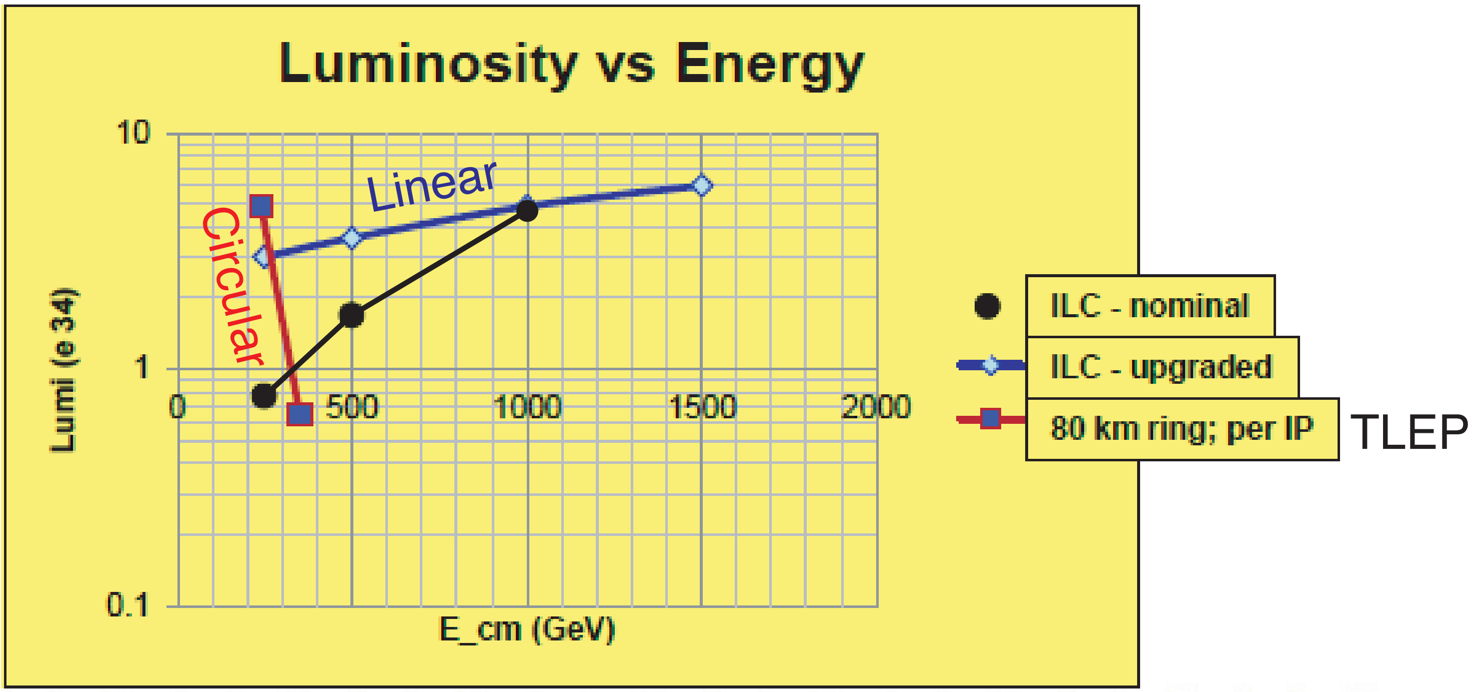
e^+e^- Linear and Circular Comparisons

$$\int \mathcal{L}dt \; {}^{+\text{ optimistic}}_{-\text{ pessimistic}}$$



- In consultation with accelerator physicists, proponents investigating luminosity upgrades and their impact

$$\mathcal{L} = 0.75 \rightarrow 3.0 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$$

e^+e^- Linear and Circular Comparisons

Example Apples and Oranges:

- Assumptions going into global analyses of Higgs couplings
- Ignoring multiple IP's/detectors of circular machines
- Beam-beam effects of multiple IP's tend to reduce luminosity
- Not including correlated uncertainties into table entries (e.g., σ_{ZH})
- What's a year?

Snowmass year = $1 \times 10^7\,\mathrm{sec}$ (usually to take into account uptime)

	ILC	LEP3
$\mathcal{L} =$	0.75	$1.0 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

"The integrated luminosities for the ILC and CLIC were based on a model with slow initial build-up for machine operation."

Physics case as a Higgs Factory (1)

- **Number of Higgs bosons produced at √s = 240-250 GeV**

	ILC-250	LEP3-240	TLEP-240
Lumi / IP / 5 years	250 fb^{-1}	500 fb^{-1}	2.5 ab^{-1}
# IP	1	2 - 4	2 - 4
Lumi / 5 years	250 fb^{-1}	1 - 2 ab^{-1}	5 - 10 ab^{-1}
Beam Polarization	80%, 30%	–	–
$L_{0.01}$ (beamstrahlung)	86%	100%	100%
Number of Higgs	70,000	400,000	2,000,000
Upgradeable to	ILC 1TeV CLIC 3 TeV ?	HE-LHC 33 TeV	VHE-LHC 100 TeV

- **In a given amount of time, Higgs coupling precisions scale like**
  - e.g., for g_{HZZ} : 1.5% for ILC : 0.65% for LEP3 : 0.2% for TLEP

e^+e^- Linear and Circular Comparisons

My personal take:

- LHC is where Higgs properties are being measured, so fully exploit!
- Taking uncertainties into account, for direct Higgs properties:

ILC (at only 250) ~ 240 GeV Circular (e.g., LEP)

(but lose top threshold scan!!)

- ILC at higher energies is essential; momentum in Japan

Circular machine luminosity roughly prop. to circumference

- For sheer luminosity and follow-up physics reach, hard to beat TLEP + *pp* collider, *but what about time scales and total cost*?

(both sizes deserve CDR...)

e^+e^- Linear and Circular Comparisons

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(deserves CDR...)

Discussion welcome!