Physics Opportunities of 500 GeV - 3 TeV Lepton Colliders

M. E. Peskin
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One of the most important goals of the next global accelerator will be to measure the properties of the Higgs boson to high precision. Our expectation is that this will expose deviations from the Standard Model predictions whose pattern will point to a model of new physics.

This makes a strong case for e+e- experiments at 250 GeV (see the talk of Junping Tian in session 129).

It will also be important to produce top quarks in e+e- at 350 GeV, to measure the top quark mass to better than 50 MeV and study the physics of the top quark threshold.

But, is there such a specific motivation for higher energy lepton collider experiments ?

In this talk, I will point to 3 topics:

Completing the precision measurement of the Higgs boson profile.

Measuring the interactions of the top quark with high precision.

Searching for well-motivated new particles from BSM physics.

In principle, lepton colliders in the 500-3000 GeV energy regime could be either e+e- or μ+μ- colliders.

In general, I will quote projected accuracies of measurements from studies for the e+e- colliders ILC and CLIC. These are based on full detector simulation including all SM backgrounds.

For μ+μ- colliders, there are no studies at this level. It is known that machine backgrounds are severe, due to muons decaying into the detector from upstream. Optimistically, one might expect that the same performance as at e+e- colliders can be achieved using detectors of the future (e.g. timing calorimeters). However, this ought to be demonstrated, not assumed.

One should also note that the time structure of collisions at CLIC and ILC allows high precision trackers with very low material budget. This tracking information is also used in energy flow calorimetry. These colliders also allow very forward calorimeters for extremely good hermeticity. It is important to distinguish high precision experiments that need these capabilities from discovery experiments that can tolerate lower measurement quality.

There are two important Higgs couplings that cannot be measured directly below 500 GeV — the self-coupling and the Higgs-top quark Yukawa coupling.

The Yukawa coupling brings in issues to be discussed later, so begin with the self-coupling.

Models of baryogenesis at the electroweak scale typically require a large enhancement of the Higgs self coupling (factor 1.5 to 3). On the other hand, this coupling is hard to measure due to the very small cross sections for hh production.

The self-coupling can be measured at 500 GeV using the process $e^+e^- \to Zhh$.

The ILC projection for 4 ab-1 at 500 GeV is

$$\Delta\lambda/\lambda = 27\%$$

for the SM value of λ, and 15% if λ is a factor 2 higher.

Additional information can be obtained from

$$e^+e^- \to \nu\overline{\nu}hh$$

ILC and CLIC studies give

$\Delta\lambda/\lambda = 10\%$	$\Delta\lambda/\lambda = +11\%/-7\%$
ILC 1 TeV, 8 ab-1	CLIC 1.5 TeV, 2.5 ab-1 + 3 TeV, 5 ab-1

It is not clear that high energy is an advantage. One should study how low an energy still allows this accuracy.

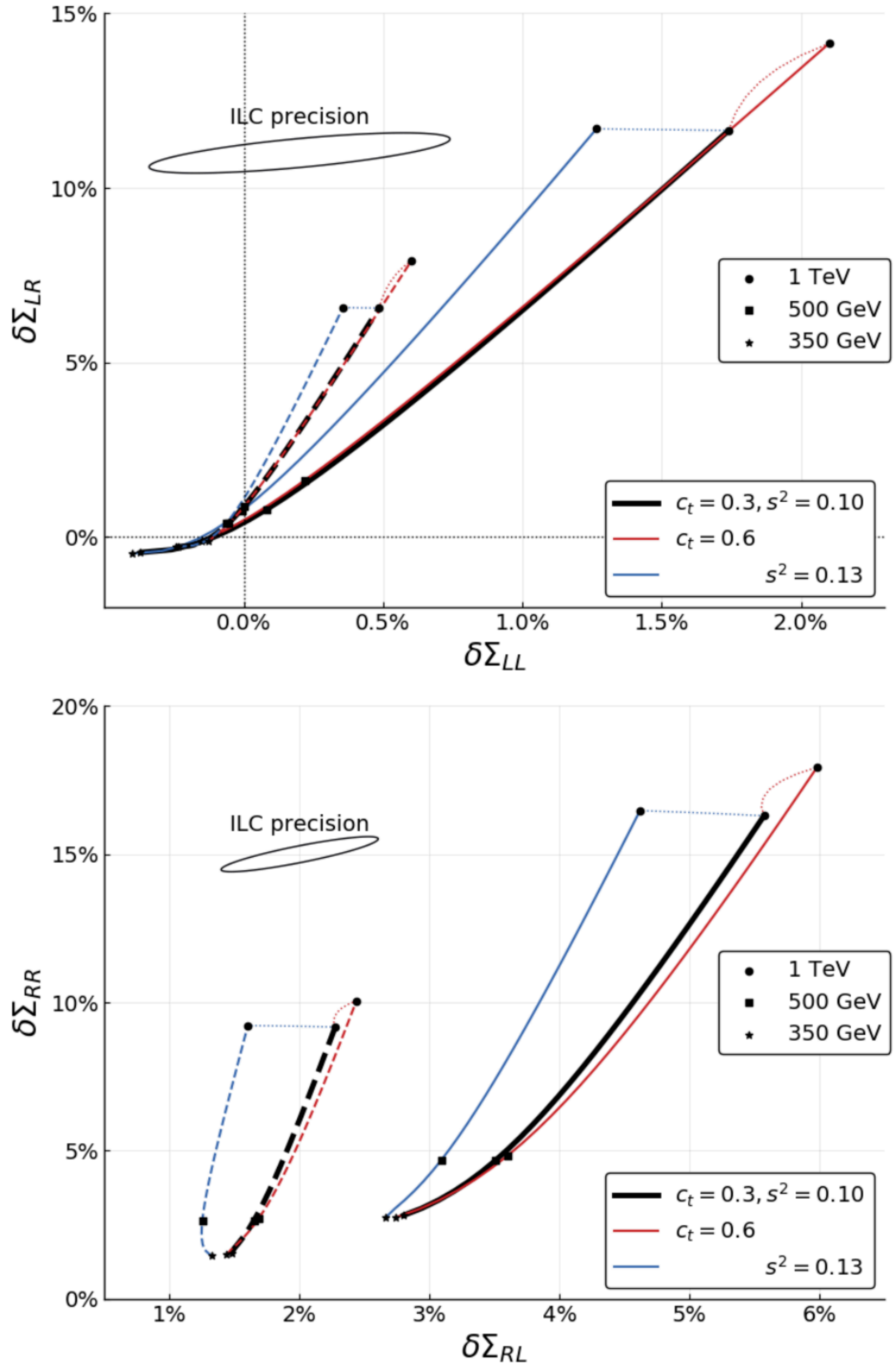
We still know relatively little about the electroweak couplings of the top quark. The gluon and photon couplings are protected at $Q^2 = 0$ by gauge invariance; the W and Z couplings are not.

In composite models of Higgs bosons, the top quark must share this compositeness to allow such a large top quark mass. The t_L and t_R may have different structure. The t_L is more constrained as the partner of b_L, so the largest deviations are expected in the t_R.

polarized cross section deviations in

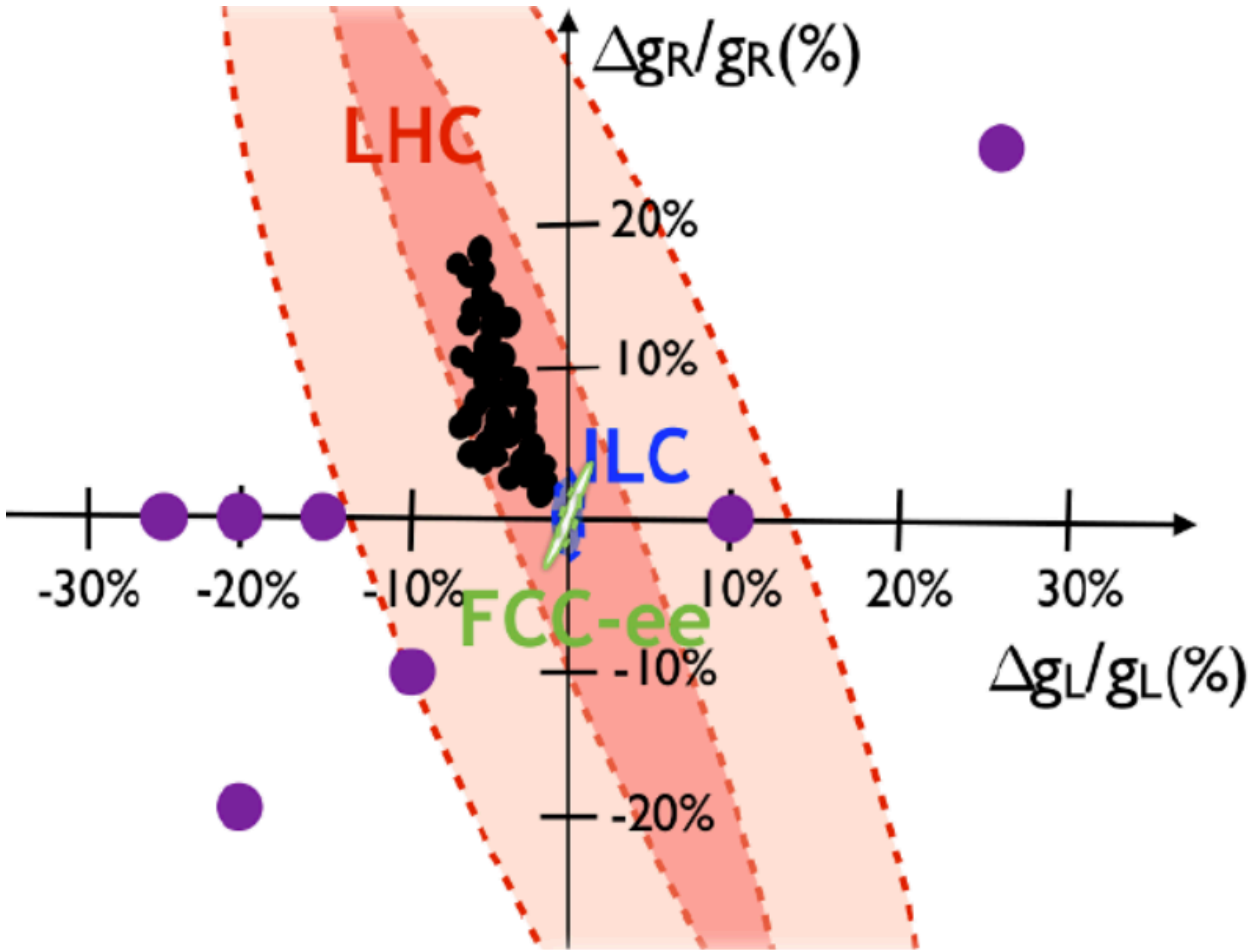
$$e^+e^- \to t\bar{t}$$

in one class of Randall-Sundrum models



MEP and Yoon 1811.07877

Note that deviations grow as s/m_t^2 .



e+e- capability vs a variety of composite Higgs models, from arXiv:1604.08122

The interpretation of these effects in a general SMEFT framework is very tricky. There are two types of new physics effects,

form factor type corrections (10 of these), e.g.,

$$g_w \overline{Q}_L \gamma^\mu Q_L \ \Phi^\dagger \overleftrightarrow{D}_\mu \ \Phi$$

and 4-fermion operator corrections (7 of these), e.g.

$$\overline{Q}_L \gamma^\mu Q_L \ \bar{\ell}_R \gamma_\mu \ell_R$$

Their effects tend to be degenerate at a single energy. So it is necessary to measure $e^+e^- \to t\bar{t}$ with polarized beams at a series of energies, the higher the better.

Durieux et al.
arXiv:1907.10619

Poeschl et al have written an LoI to explore this topic in more detail.

	10-parameter fit ILC250 + ILC500	17-parameter fit + ILC1000
$C_{\varphi t}/\Lambda^2$	0.01	0.09
$C^3_{\varphi Q}/\Lambda^2$	0.005	0.04
$C^1_{\varphi Q}/\Lambda^2$	0.005	0.04
C_{tW}/Λ^2	0.02	0.014
C_{tB}/Λ^2	0.02	0.015
$C_{t\varphi}/\Lambda^2$	0.54	0.54
$C_{\varphi b}/\Lambda^2$	0.007	0.008
C_{bW}/Λ^2	0.09	0.17
C_{bB}/Λ^2	0.13	0.17
$C_{\varphi tb}/\Lambda^2$	1.9	1.9
C_{eu}/Λ^2	—	0.0006
C_{ed}/Λ^2	—	0.0005
C_{eq}/Λ^2	—	0.0004
C_{lu}/Λ^2	—	0.0006
C_{ld}/Λ^2	—	0.0009
C^-_{lq}/Λ^2	—	0.0006
C^+_{lq}/Λ^2	—	0.0005

The measurement of the top quark - Higgs Yukawa coupling inherits these difficulties.

ILC analysis of $e^+e^- \to \bar{t}th$ at 1TeV, 8 ab-1, with a 1-parameter fit, gives an accuracy of 1.6%. However, this needs to be reconsidered in a full SMEFT analysis.

(A similar caution should be applied to LHC measurements.)

Now turn to BSM particle production.

A few preliminary remarks are in order.

First, unlike the case of h and t processes, the premium here is on high energy.   For the discovery of BSM particles, we should generally choose accelerator designs that maximize the luminosity at the highest energies, sacrificing cleanliness that might be needed for high precision.

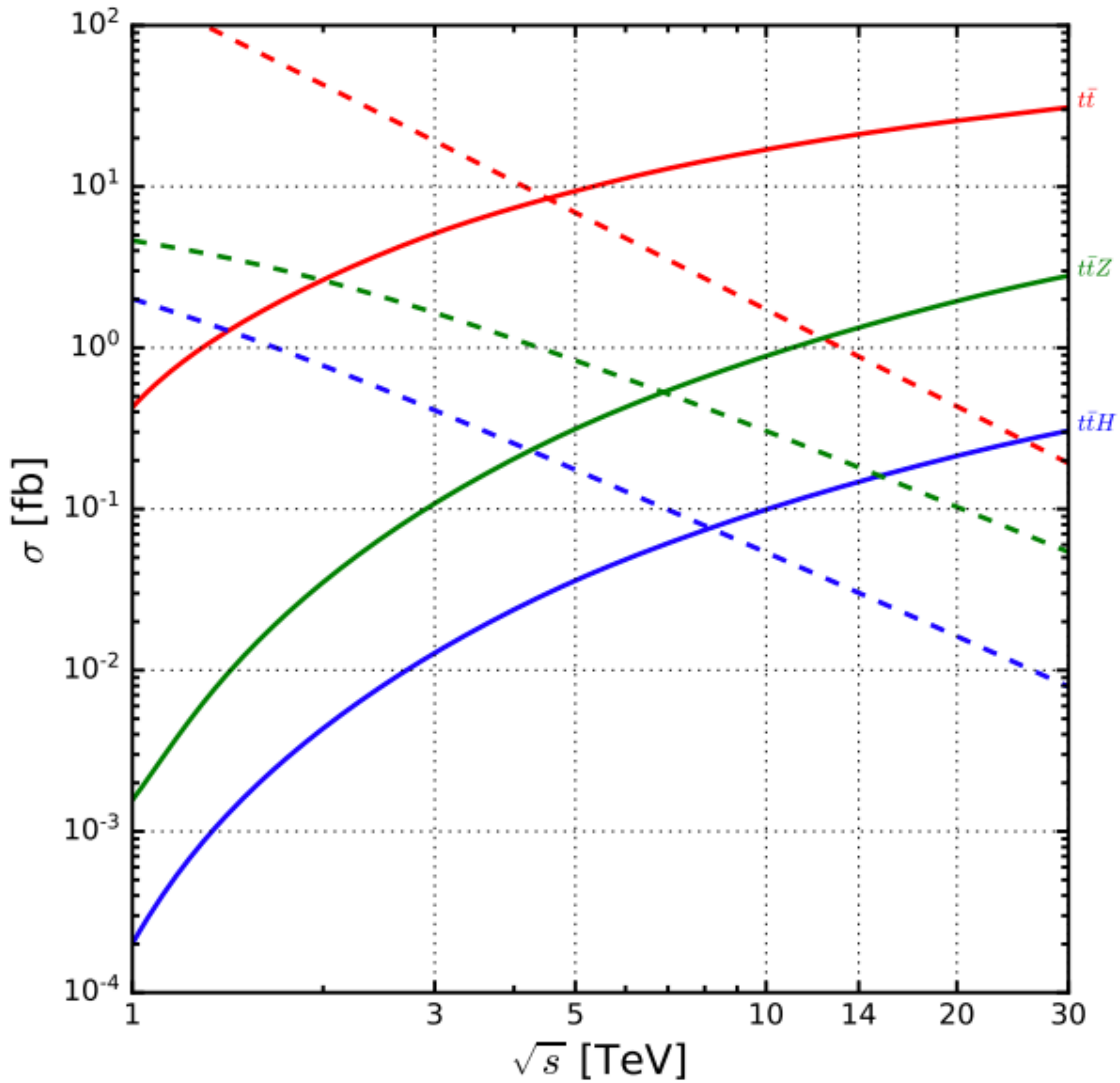
Analyses done with one CM energy generally scale easily with increased CM energy, as long as the luminosity can be kept sufficiently high.

Second, a 3 TeV collider can pair produce only particles with masses below 1.5 TeV. This should be compared to the discovery reach of the HL-LHC,

1.5 - 1.8 TeV for top quark partners
0.9 - 1.2 TeV for heavy leptons, charginos

If these particles are discovered at the HL-LHC, lepton colliders can add to the information. But, the window for discovery after an HL-LHC exclusion is narrow.

Third — a crucial point made by the Tao Han and Fabio Maltoni groups — there is a crossover between $\ell^+\ell^-$ annihilation production of new particles and WW fusion production.



Costantini et al
arXiv:2005.10289

Above $\sqrt{s} =$ 5 TeV, new particle searches will generally be made in the WW mode.

This removes the premium on a narrow CM energy of parton collisions. It makes $e^+e^-,\ \mu^+\mu^-,$ and $\gamma\gamma$ colliders much more equivalent from the physics point of view.

My personal opinion is that $\gamma\gamma$ colliders, driven by e^-e^- linear colliders with advanced acceleration technologies, will be the winner at extremely high energies.

Let's now discuss specific motivated targets for BSM searches:

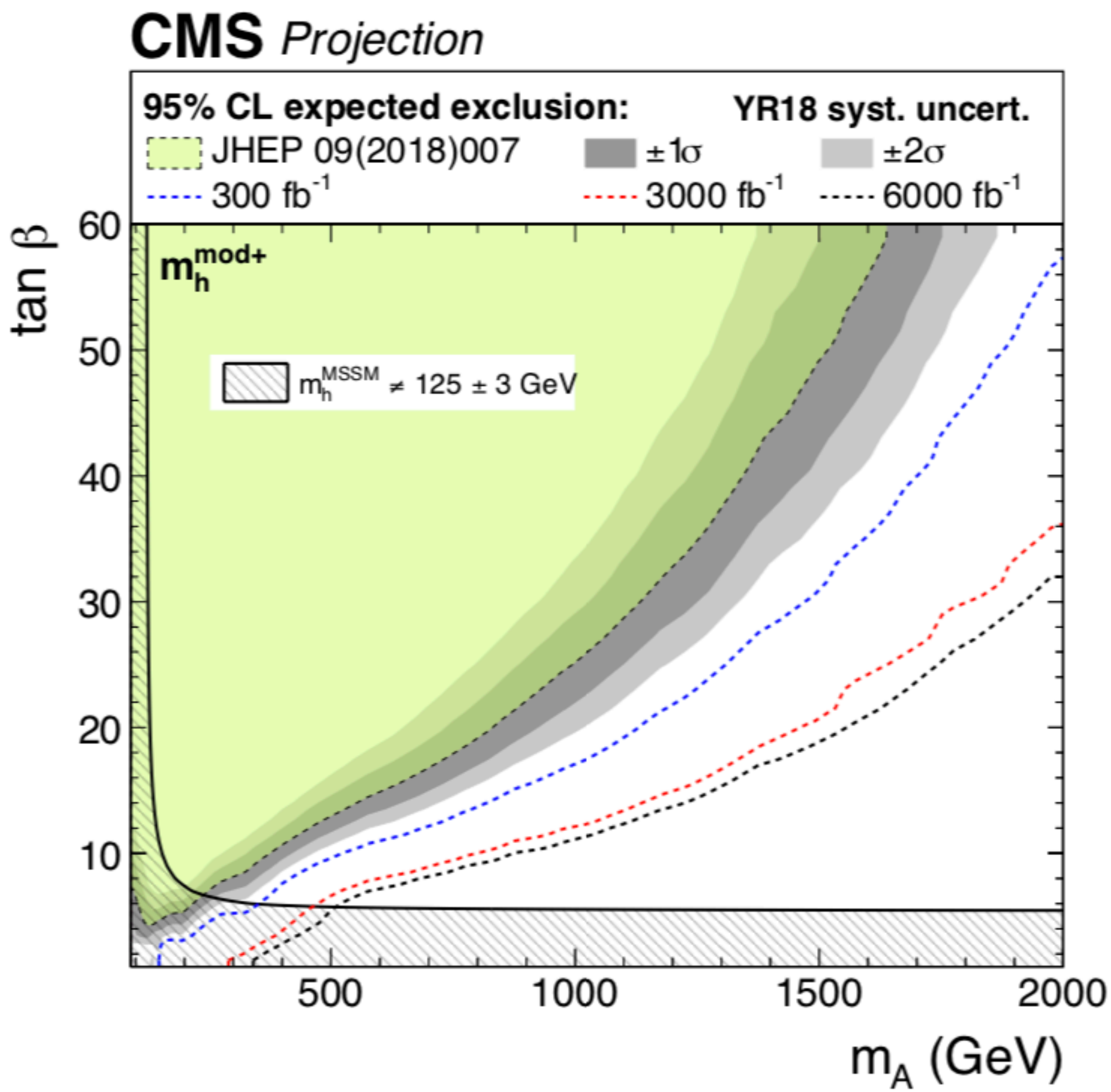
Extended Higgs sector:

Given our ignorance of the Higgs sector, it seems simplistic to assume only one Higgs particle.

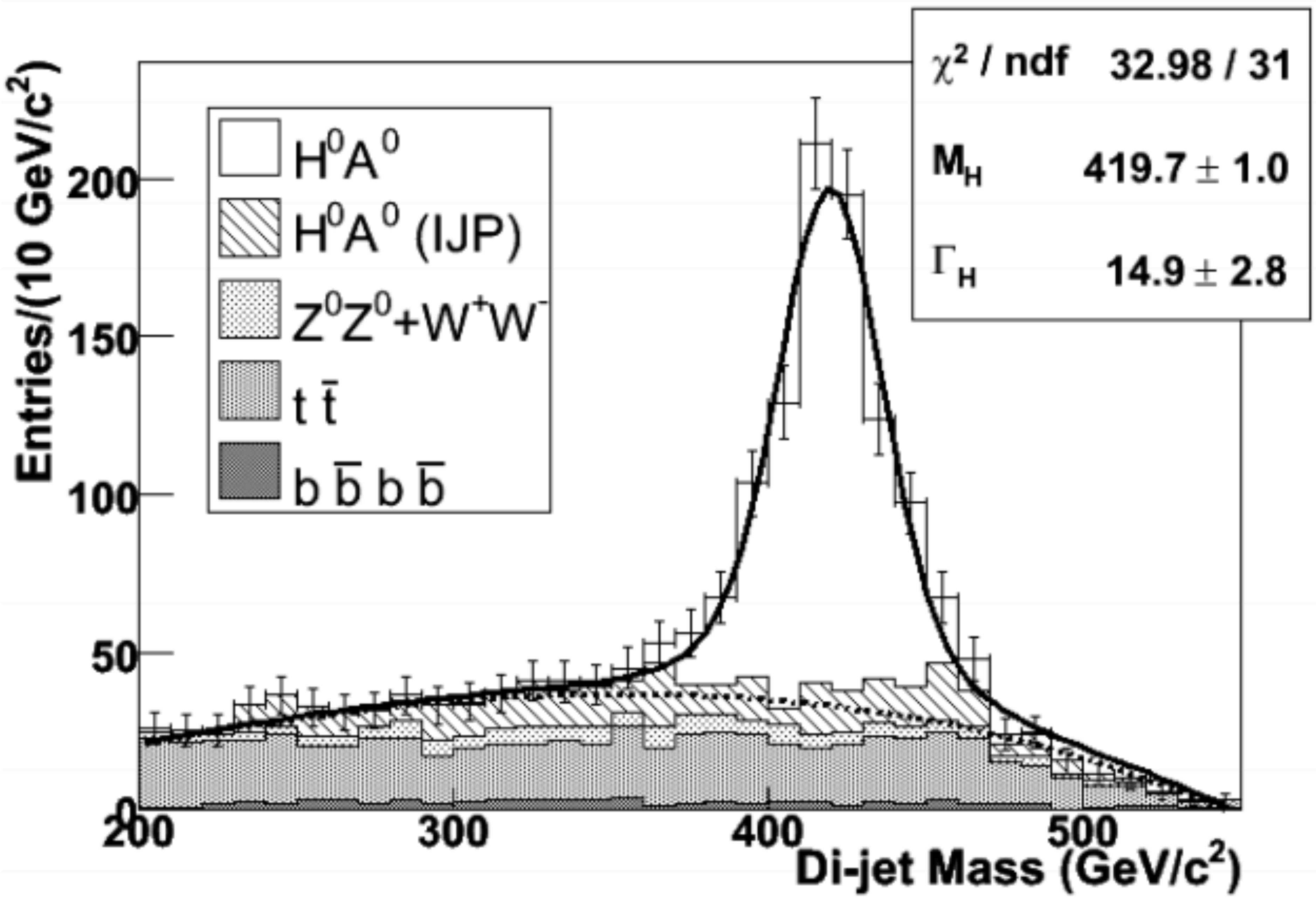
In many models, especially Supersymmetry, extended Higgs sectors are required.

A solution to the flavor problem might be different fundamental Higgs bosons for each generation. These mix to form the observed spectrum, with the eigenstate coupling mainly to (b,t) the lightest.

It is acknowledged that there are gaps in the HL-LHC reach for extended Higgs bosons. These can be easily filled by a high-energy lepton collider.



At lepton colliders, given that the lighter h is very SM-like, the heavier H boson is produces at full strength in $\ell^+\ell^- \to H^0 A^0$ and is visible as a 2-jet resonance.



Battaglia, Kelley, Hooberman, arXiv:0805.1506

Important dark matter candidates are the unmixed neutral wino and higgsino states in supersymmetry.

These give the observed dark matter relic density with masses of 3 TeV (wino) and 1 TeV (higgsino). These states are notably difficult to discover in hadron collisions. The 3 TeV wino is disfavored by the absence of the $\widetilde{w} \to 2\gamma$ annihilation signal in cosmic γ-ray observations.

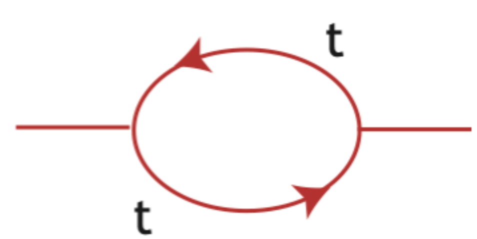
At e+e- colliders, new particles can be discovered in the $e^+e^- \to \gamma + (\mathrm{missing})$ signature almost up to $\sqrt{s}/2$.

see: Berggren et al, arXiv:1307.3566,
Baer et al, arXiv:1404.7510,

An approach to solving the hierarchy problem given LHC constraints on colored top partners is "neutral naturalness".

that is,

New particles are needed to cancel the renormalization of the Higgs boson mass by the top quark loop.



These particles could be color-neutral. Then the production cross sections at the LHC are much lower, but the particles will be obvious in any decay mode at lepton colliders.

Many more BSM particles are targeted in studies. Please see:

de Blas et al. The CLIC potential for New Physics
arXiv:1812.02093

Fujii et al. Tests of the Standard Model at the ILC
arXiv:1903.11299

some examples:

Z' resonances	10 - 20 TeV	x ECM/1 TeV
Lepton compositeness	200 - 300 TeV	x ECM/1 TeV

Conclusions:

There is a robust physics case for lepton colliders in the 500 GeV - 3 TeV region. This rests on 3 pillars:

Completion of the SM Higgs profile by measuring the Higgs self coupling and the Higgs-top Yukawa coupling.

(ECM ~ 1 TeV should be sufficient)

Precision study of top quark interactions

(several values of ECM are needed; 1 TeV is adequate but higher is better)

Search for BSM resonances and pair-production

(emphasizes the highest possible energies)

Can this accelerator be a step toward 10-50 TeV ECM ?

One more comment is essential:

For practical reasons and because of its compelling physics case, the next step in lepton colliders must be a 250 GeV machine. We need this as soon as possible.

Let's not lose sight of this in the pursuit of higher energies. There might not be a future of accelerator-based particle physics if this machine is not realized.

On the other hand, an e+e- linear collider can provide a site, a tunnel, and infrastructure to vault to higher energies.