

# Lepton Colliders for the Future

The discovery of a low-mass Higgs boson at the LHC has intensified the need for precision measurements to understand its character and to sense new physics.

The completion of the ILC Technical Design Report, the CLIC Conceptual Design Report, new ideas for  $e^+e^-/\mu\mu/\gamma\gamma$  Higgs factories, and the interest in Japan in hosting the ILC have focused the planning for future lepton colliders.

- ❖ Summary of the physics program
- ❖ Lepton colliders on the market
- ❖ Considerations for going forward

# The Landscape

The 2013 “Snowmass” CSS2013 workshops have extensively studied the physics imperatives for the field in the overlapping Energy, Intensity and Cosmic Frontiers. The reports and talks give a detailed view of what we need to know, what facilities can be envisioned to attack the main questions, and how well each may do in answering them.

The Snowmass process was not charged to articulate priorities for US HEP, folding in budgetary constraints – that remains for the P5 panel to be convened this fall.

Nigel Lockyer, next Fermilab Director: “ Snowmass report ideally should demonstrate to DOE that:

- ❖ We have consensus on the key science questions in which the U.S. must be involved
- ❖ We are clear on which of these are so important that offshore is viable and/or required
- ❖ We are prepared to combine constraints and goals in P5 process ”

## Concrete Goals: the science cases

### I. What are the scientific cases which motivate HL LHC running:

*“Phase 1”*: circa 2022 with  $\int \mathcal{L} dt$  of approximately  $300 \text{ fb}^{-1}$

*“Phase 2”*: circa 2030 with  $\int \mathcal{L} dt$  of approximately  $3000 \text{ fb}^{-1}$

How do the envisioned upgrade paths inform those goals?

Specifically, to what extent is precision Higgs Boson physics possible?

### II. Is there a scientific necessity for a precision Higgs Boson program?

### III. Is there a scientific case today for experiments at higher energies beyond 2030?

High energy lepton collider?

A high energy LHC?

Lepton-hadron collider?

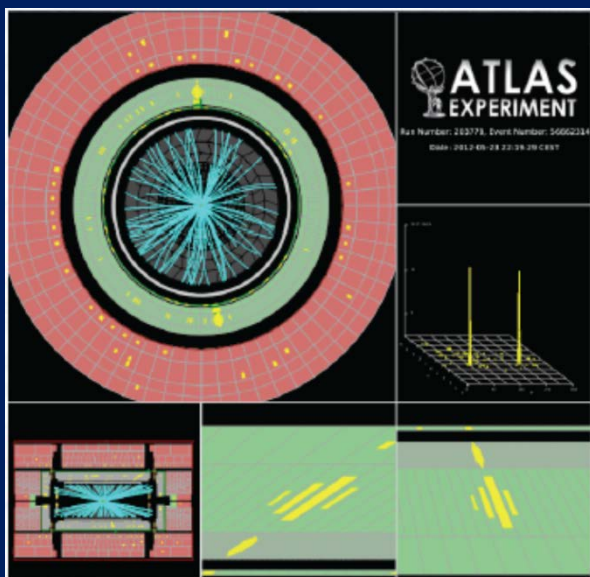
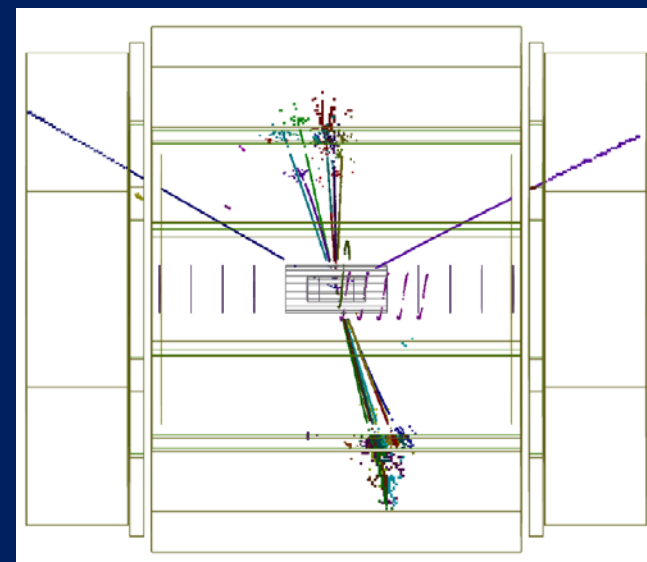
VLHC?

The Snowmass talks and reports (drafts are now available) and should be required reading for us all.

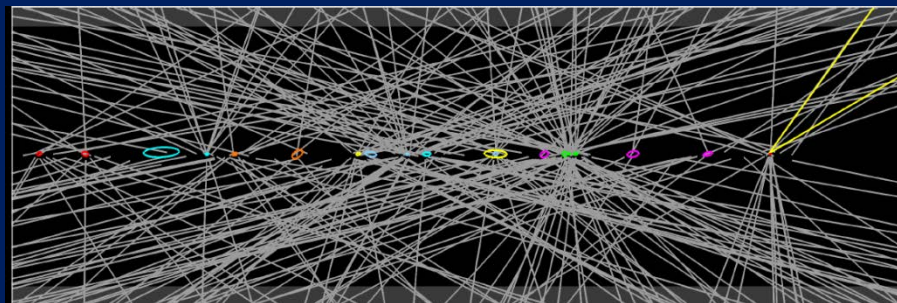
# Why Lepton Colliders?

Compared to hadron colliders, the events are “clean” – one observes just the hard process, without extra particles produced in the primary collision, and without pileup from additional collisions during the bunch crossing.

$$e^+e^- \rightarrow Z(\mu\mu)H(bb) \text{ at ILC}$$



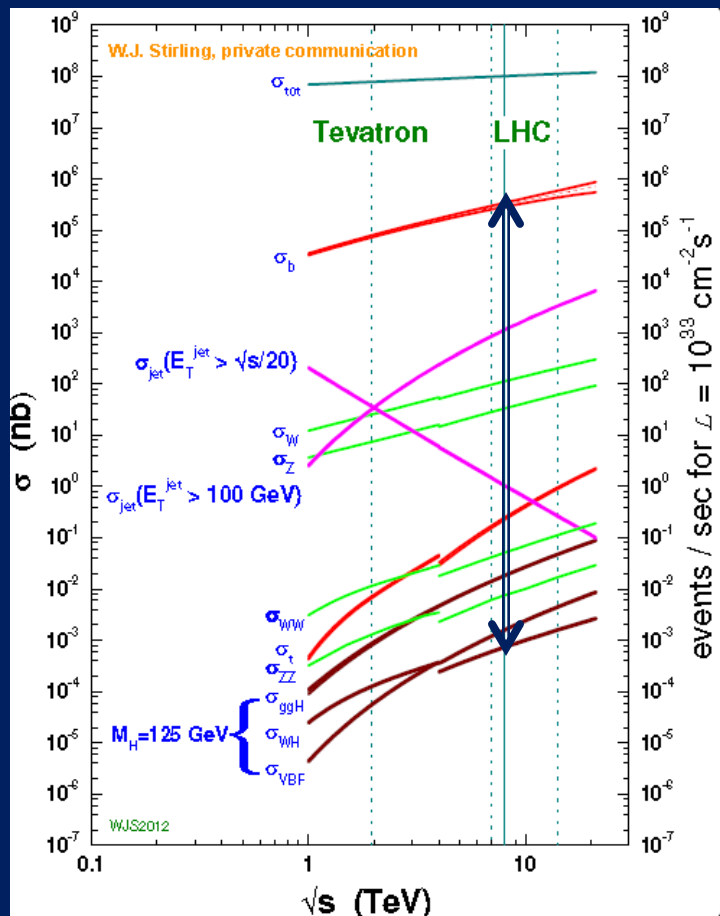
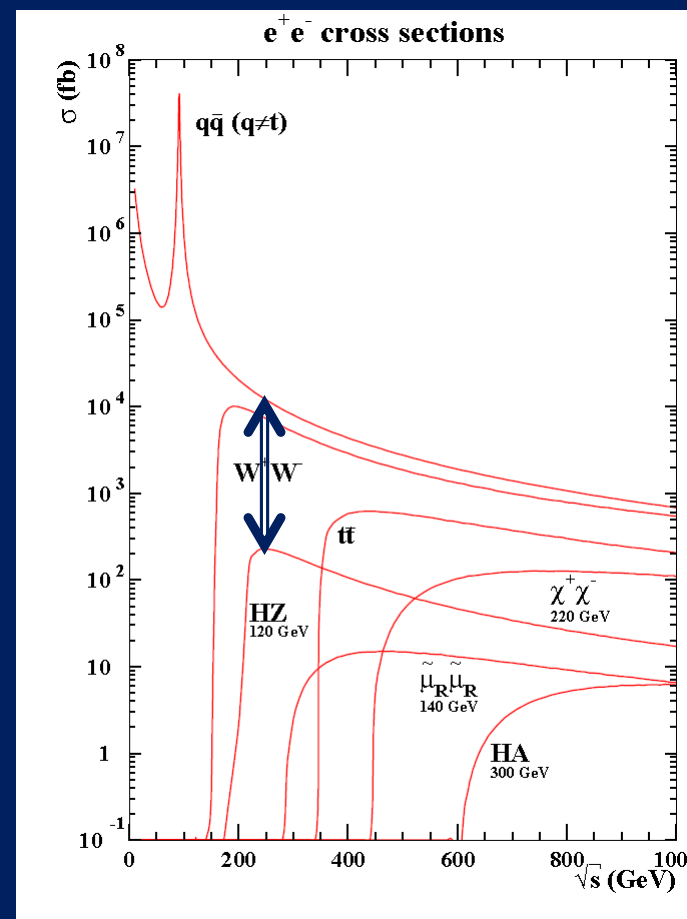
$$gg \rightarrow H(\gamma\gamma) (+ X) \text{ at LHC}$$



# Why Lepton Colliders?

Interesting processes are a large fraction of the total rate. Various signal cross sections are similar. Backgrounds are typically not a problem. No trigger is required.

$e^+e^- \rightarrow HZ$  is 1% of  $e^+e^- \rightarrow qq$



Backgrounds for hadron production are huge. Multi-level triggers must be used and calibrated.

**LHC:  $pp \rightarrow H W/Z$  is  $10^{-9}$  of  $pp \rightarrow b\bar{b}$**

## Why Lepton Colliders?

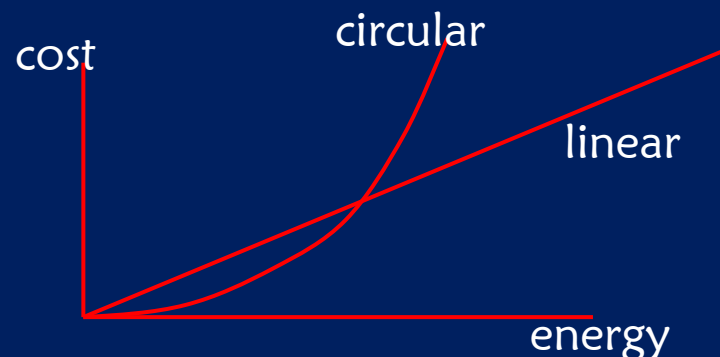
- ❖ In contrast to  $pp$  where the interacting partons are distributed in momentum within the beam particles, in  $e^+e^-$  the beam particles are the partons. The partonic collision energy in  $e^+e^-$  is thus nearly a  $\delta$ -function at  $2E_{\text{bm}}$  rather than a convolution over PDFs.
- ❖ Moreover, the virtual  $\gamma/Z$  intermediate state tells us that the final state quantum numbers are  $J^{PC} = 1^{--}$ .
- ❖ And the partons can be polarized: In ILC,  $\mathcal{P}(e^-) = \pm 80\%$  and  $\mathcal{P}(e^+) = \pm 30\%$ . Since at high energies, right- and left-handed fermions are distinct particles, one can enhance signal processes or suppress backgrounds by appropriate choices of beam polarization.
- ❖ Cross sections in  $\ell^+\ell^-$  can be calculated to  $O(0.1\%)$  accuracy; unlike QCD, higher order terms are small. This means that the sensitivity to new physics at high mass scales is enhanced.

# Circular vs. Linear Lepton Colliders

Synchrotron radiation grows rapidly with E

$$\Delta E/\text{turn} \sim (E/m)^4/R \quad (\text{synchrotron radiation})$$

e.g. LEP2:  $\Delta E=3.4 \text{ GeV/turn} \rightarrow P_{\text{loss}} \sim 20 \text{ MW}$ )



With new high gradient Superconducting RF, we can go beyond LEP. For the 350 GeV circular TLEP collider with 81 km circumference, each particle loses 9.3 GeV per turn that has to be made up with  $\sim 100 \text{ MW}$  of RF. (The tunnel length in a 350 GeV circular machine is 2xlonger than for same energy linear machine.)

In a Linear Collider, go to long, single-pass linacs to reach desired energy. Collide the beams just once (but electrons are cheap!). But the full energy has to be made on one traverse of the machine rather than in multiple passes, so need more RF in the LC and RF is expensive.

The beamstrahlung losses (radiation in the field of the other beam) are similar for circular and linear  $e^+e^-$  machines. But in the circular machines, the lower energy electrons fail to stay in orbit, so the beam lifetime is about 1 minute and a full energy accelerator is needed to periodically top-up the beams.

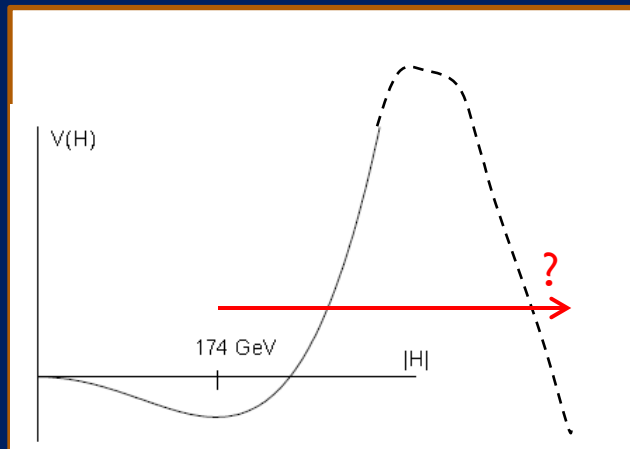
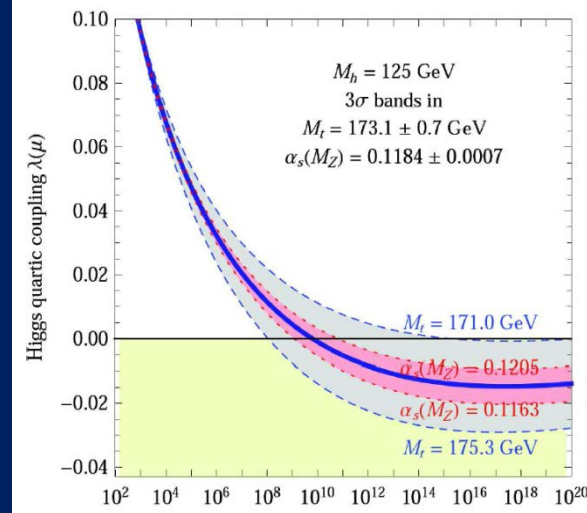
$\mathcal{L}$  falls with  $E_{\text{cm}}$  in circular collider; grows with  $E_{\text{cm}}$  in linear collider.

A circular muon storage ring is immune to synchrotron radiation. ( $m_\mu \sim 200m_e$ )



# Physics case – Higgs

Assuming the LHC found the SM Higgs, we now know the potential:  $V(H) = \mu^2 |H|^2 + \lambda |H|^4$ , with  $\lambda = 0.13$  and  $\mu^2 = -89 \text{ GeV}^2$ . But  $\lambda$  is a running coupling and becomes negative at  $\sim 10^{10} \text{ GeV}$ , giving an unstable Higgs potential. Whether our Higgs lives in a low-energy metastable state for the lifetime of the universe is unknown.



The hierarchy problem concerns the scale disparity between  $m_H$  and  $m_{\text{Planck}}$ . If we had only the SM, nothing prevents a low mass Higgs (but fine tuning makes it very odd). But as soon as there is new physics, the new heavy particles generate loop corrections to  $m_H$  making it diverge. Thus, new physics creates a crisis for the SM-like Higgs and had better stabilize it.

Thanks to Steve Martin

There are hints of this New Physics:

- ❖ ugliness of fine-tuning the EW scale
- ❖ Higgs potential instability
- ❖ particulate dark matter
- ❖ strong CP problem suggests NP  $\sim 10^{10} - 10^{12} \text{ GeV}$ ;
- ❖ force unification needs a non-SM spectroscopy;
- ❖ Majorana neutrino masses suggest scales  $\sim 10^{16} \text{ GeV}$



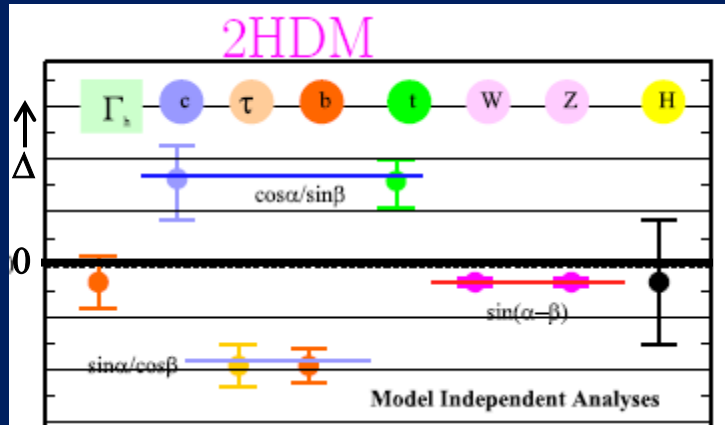
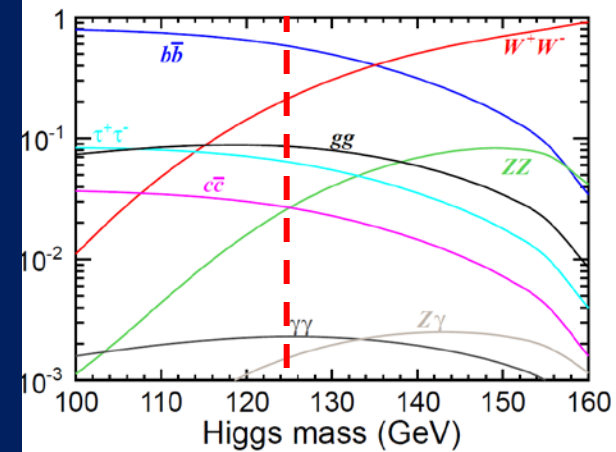
Find the NP! Precision study of the Higgs is urgently needed.



# Higgs couplings

The LHC has discovered *a* higgs particle. Is it the SM Higgs, or the result of some new physics (or a combination of both)? (It could be the MSSM h.)

At 125 GeV, the set of observable decays is about optimal!



Precise measurements of Higgs couplings can reveal the nature of the Higgs. Non-zero  $\Delta = (g_{Hxx}^{OBS}/g_{Hxx}^{SM}) - 1$  will tell us there is new physics. The pattern of the changes tells us what kind of new physics.

**Few % precision is needed.**

Example model  $\Delta$ 's

MSSM ( $T \equiv \tan\beta$ )

$$\Delta_{VV} = -0.3\% (200/M_A)^2 (5/T)^2$$

$$\Delta_{cc} = -1.7\% (200/M_A)^2 (5/T)^2$$

$$\Delta_{bb} = +40\% (200/M_A)^2$$

Littlest Higgs (top partner 1 TeV)

$$\Delta_{gg} = -(5\% - 9\%)$$

$$\Delta_{\gamma\gamma} = -(5\% - 6\%)$$

Randall Sundrum radion/  
SM mix ( $\delta = \sin\theta_{mix}$ ,  
 $f = \text{warp scale}$ )

$$\begin{aligned} \Delta_{VV} = \Delta_{ff} &= -\delta^2/2 + v\delta/f \\ &= -(5\% \pm 8.5\%) \end{aligned}$$

# Higgs couplings

Observable:  $\sigma(AA \rightarrow h) \cdot \text{BR}(h \rightarrow BB) \sim g^2(hAA) g^2(hBB) / \Gamma_{\text{Tot}}$

$\Gamma_{\text{Tot}}$  is unmeasurably small ( $\sim 4$  MeV), so must be inferred. The dominant contributor to  $\Gamma_{\text{Tot}}$  is  $h \rightarrow bb$  which is very difficult for LHC to measure precisely, though some help may be possible using boosted Higgs. And there could be invisible decays. Thus it seems that LHC will measure ratios of couplings rather than absolute values, but not at the precision needed to discern models for new physics. (Estimate LHC in  $300 \text{ fb}^{-1}$  gets to  $\delta\Gamma_{\text{tot}}/\Gamma_{\text{tot}} = 20\%$ .)

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L} dt$ ( $\text{fb}^{-1}$ )	300/exp	3000/exp	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
$\kappa_\gamma$	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	-/5.5/<5.5%	1.45%
$\kappa_g$	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
$\kappa_W$	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
$\kappa_Z$	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
$\kappa_\ell$	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d$	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
$\kappa_u$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

**LHC** will get to several % level on relative couplings; **Lepton colliders** give <1%. Probing new TeV scale physics through Higgs couplings requires sub % level.

Certainly LHC will do better as it works with existing data. (The more aggressive LHC estimates assume reduction of all exp'tl systematics with  $1/\sqrt{\mathcal{L}}$  and theory uncertainties  $\times 1/2$ .) But then, the future lepton colliders will do better with data too.

## Snowmass The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

*The light Higgs boson must be explained.*

*An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.*

2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.
3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

Brock, CSS2013

# Top Quark

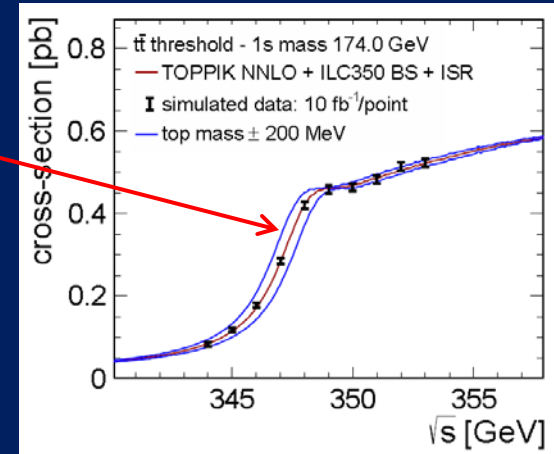
The measured value of  $M_H$  together with the large  $M_t$  causes the Higgs potential to become unstable at high mass scales.

Precise measurement of  $M_t$  can tell us if the universe becomes unstable (or metastable).

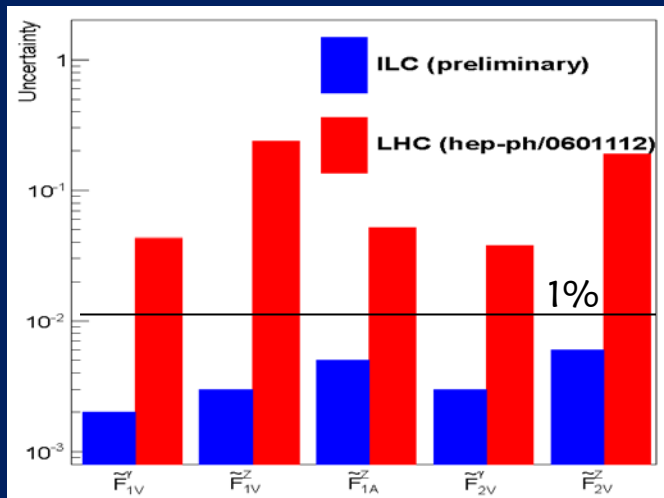
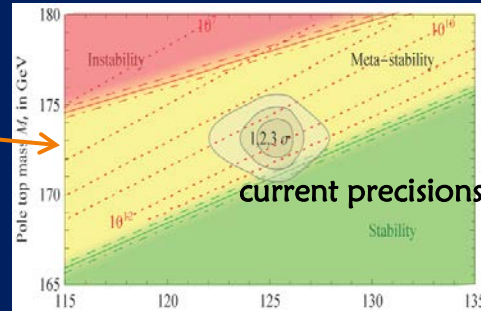
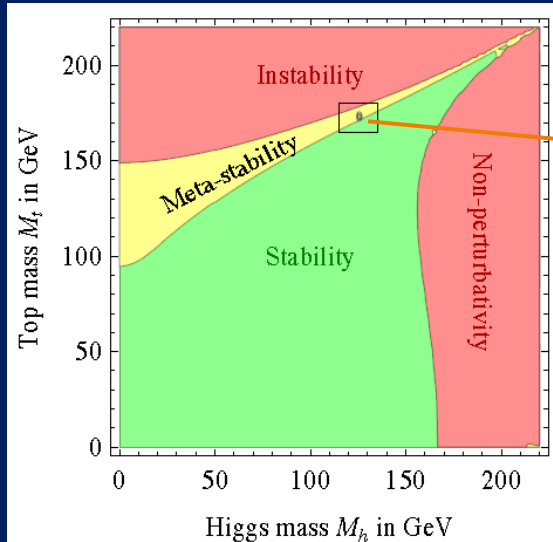
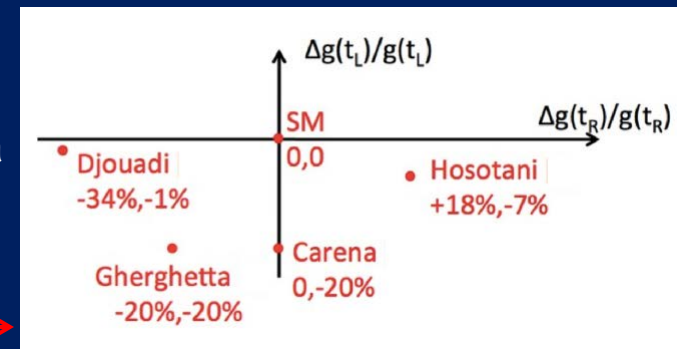
$\sigma_{tt}$  can be calculated in a well defined mass scheme to  $\sim 2\%$  at lepton colliders.

Well-calibrated lepton beam energy allows a threshold scan that can measure  $M_t$  to  $\sim 100$  MeV (LHC  $\delta M_t \sim 500$  MeV) and  $\alpha_s$  to  $\pm 0.001$ .

Beam polarization allows measurement of top V/A couplings to Z/ $\gamma$  much more precisely than LHC



These couplings distinguish, e.g., extra dimension Randall Sundrum model variants.



## Snowmass

### The Top Quark physics message

1. Top is intimately tied to the problems of symmetry breaking and flavor
2. Precise and theoretically well-understood measurements of top quark masses are possible both at LHC and at  $e^+e^-$  colliders.
3. New top couplings and new particles decaying to top play a key role in models of Higgs symmetry breaking.

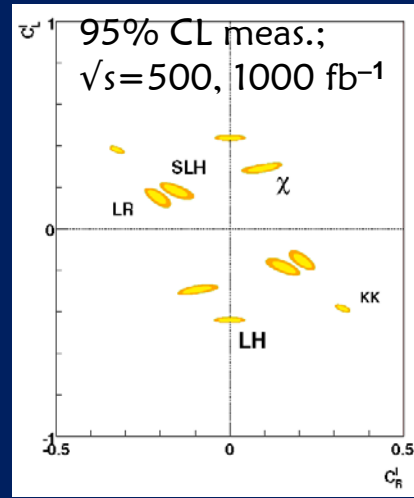
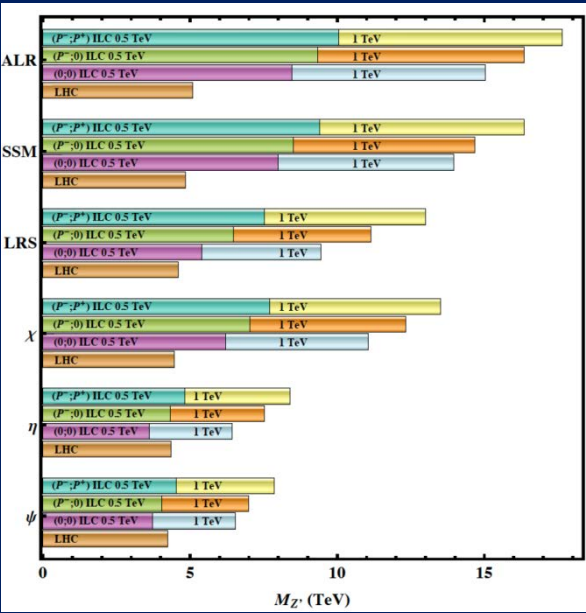
***LHC will search for the particles;***

***Linear Colliders for coupling deviations.*** Brock, CSS2013



# Precision Measurements

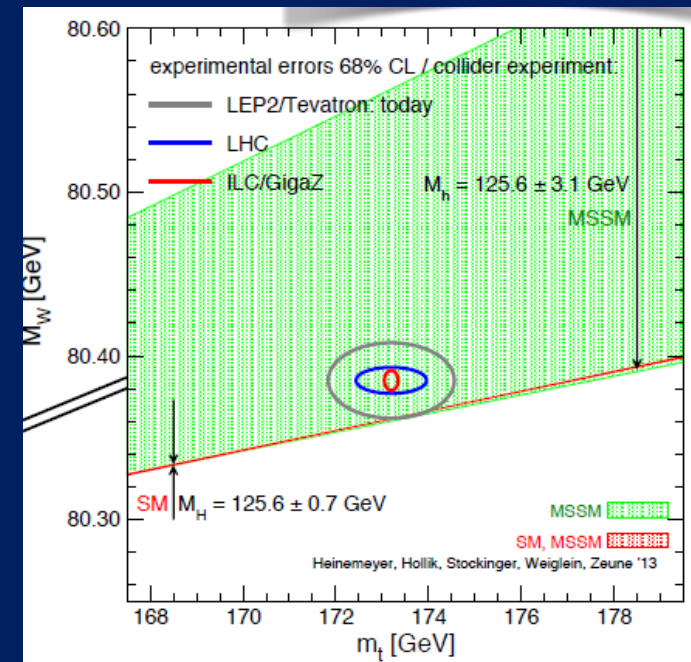
The lepton colliders, with variable beam polarizations, well defined initial states and simple final states allow many precision measurements that are sensitive to New Physics at high mass scales.



One example: Many models predict massive  $Z'$  states. The reach for 1 TeV ILC is larger than 14 TeV LHC by  $\sim 5-10$  TeV. Polarization helps here. Measurements of L and R couplings can distinguish which model.

Scan of  $WW$  threshold could give  $\delta M_W = 5$  MeV.  
 Current precision = 15 MeV.  
 Precision EW measurements search for New Physics.

Running at  $Z$  pole improves precision EW measurements substantially:  
 $\delta \sin^2 \theta_{\text{eff}}^l$   $1.7 \cdot 10^{-4} \rightarrow 1.3 \cdot 10^{-5}$  from  $A_{\text{LR}}^l$ , resolving existing tensions with SM or giving clear evidence for new physics.



### The EW physics message

1. The precision physics of W's and Z's has the potential to probe indirectly for particles with TeV masses.

*This precision program is within the capability of LHC, linear colliders, TLEP.*

2. Measurement of VB interactions probes for Higgs sector resonances.

*In such theories, expect correlated signals in triple and quartic gauge couplings.*

### The NP Physics Message

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.
2. LHC and future colliders will give us impressive capabilities for this study.
3. This search is integrally connected to searches for dark matter and rare processes.
4. A discovery in any realm is the beginning of a story in which high energy colliders play a central role.

Lepton colliders would play a crucial role in extending our understanding of the Higgs and electroweak symmetry breaking, new physics beyond the SM, CP violation and dark matter.

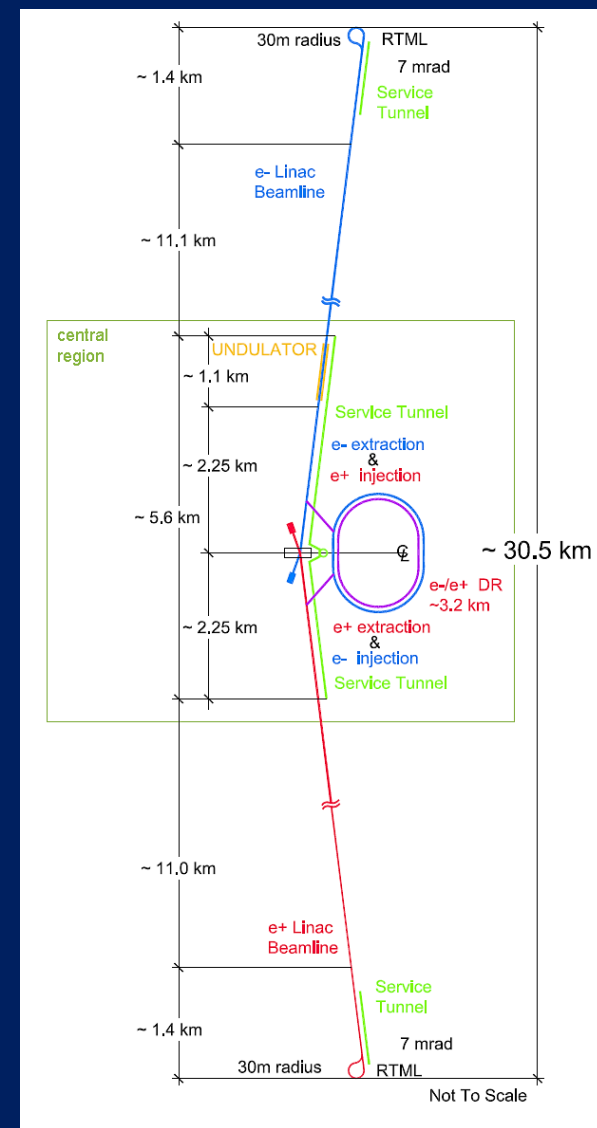


# Cast of Characters – ILC

The ILC employs  $\sim 11$  km linacs for both  $e^+$  and  $e^-$  with  $\mathcal{P}^- = \pm 80\%$  and  $\mathcal{P}^+ = \pm 30\%$  for  $\sqrt{s} = 200 - 500$  GeV. Site length = 30.5 km.

- Superconducting RF cavities operated at 31 MV/m have been demonstrated with good yield and high Q.
- 1312 bunches  $\Delta t_b = 554$  ns; 200 ms between bunch trains.
- R&D showed that damping ring requirements (e-cloud, fast kickers, etc.) can be met.
- The final focus spot size is close to demonstration.
- Can upgrade to 1 TeV (increase linac length with higher gradient cavities) and to larger  $e^+$  polarization.

ILC is judged ready for project start with detailed, site dependent engineering.



Technical Design Report (Physics, Accelerator design, Accelerator R&D, Detectors):

<http://www.linearcollider.org/ILC/Publications/Technical-Design-Report>

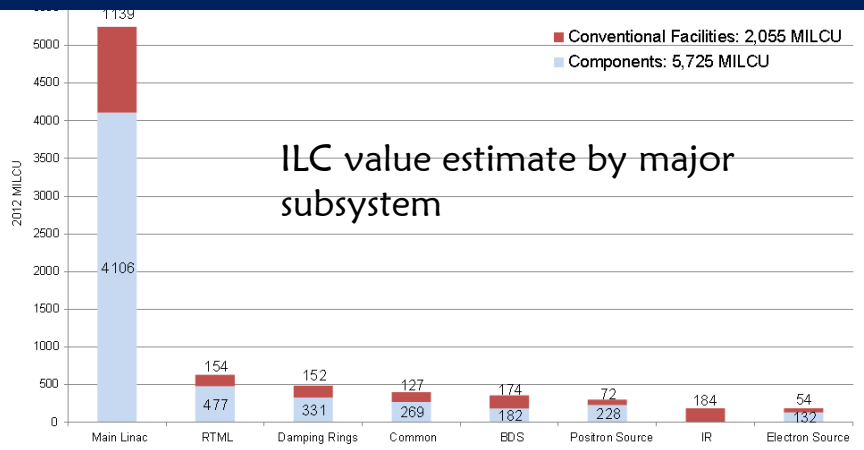
# Cast of Characters – ILC

Two detectors (ILD and SiD) were validated based on subsystem tests and extensive simulations of physics performance.

Many novel features:

- ❖ Particle flow calorimetry gives  $\delta E_{\text{jet}}/E_{\text{jet}} \sim 3\text{--}4\%$  (coil outside Hcal)
- ❖ Power pulsed electronics to keep material budget low, thus ...  
Low mass tracking and vertex detectors  $\delta p_T/p_T^2 = 5 \times 10^{-5} \text{ GeV}^{-1}$  at high  $p_T$   
Excellent separated vertex resolution for b, c,  $\tau$  tagging
- ❖ Triggerless operation; time stamp bunch crossing, read out after bunch train
- ❖ Detectors alternate on beam line ( $\sim 2$  day turnaround).

ILC cost done using Purchasing Power Parity for purchased items, lab fabrication and assembly, and estimated labor in participating institutes.



Value estimate: 7780M ILCU (1 ILCU = 1\$US(2012)) + 22.613M man-hrs labor.

Uncertainties of 26% on Value estimate and 24% on manpower.

(no contingency, inflation, R&D costs, operations, detectors)

Japan has announced its interest in hosting ILC and supporting 50% of the cost. Site choice recommendation this summer. Discussions ongoing with potential partners over the next few years.



## We welcome the initiative for ILC in Japan

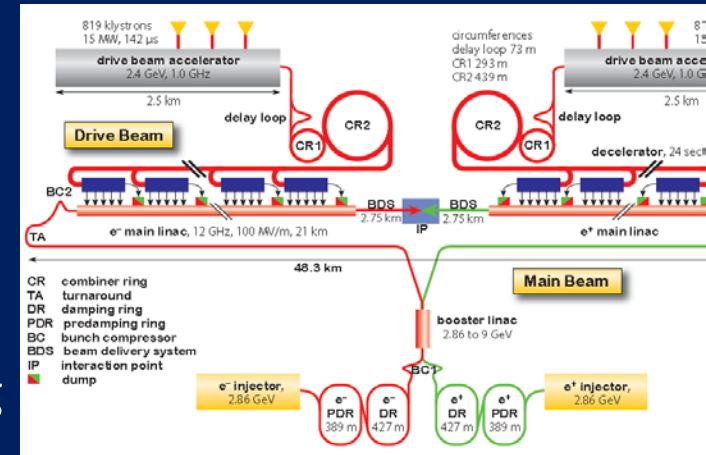


- ❖ U.S. accelerator community is capable to contribute
  - ✧ Supported by the physics case as part of a balanced program
- ❖ ILC design is technically ready to go
  - ✧ TDR incorporates leadership U.S. contributions to machine physics & technology
    - SRF, high power targetry (e<sup>+</sup> source), beam delivery, damping rings, beam dynamics
- ❖ Important that there is an upgrade path of ILC to higher energy & luminosity ( $> 500$  GeV,  $> 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>)

*We are experienced & ready to do it*

# Cast of Characters – CLIC

CLIC employs high gradient (100 MV/m) acceleration using high frequency (12 GHz) room temperature RF derived from deceleration of intense drive beams in room temperature cavities. The bunches are spaced by 0.5 ns in 175 ns long trains, separated by 20 ms. CLIC is envisioned in stages starting at  $\sim 500$  GeV going up to 3 TeV. Polarization similar to ILC.



Overall length: 13 km (500 GeV), 48 km (3 TeV)

Overall power needs are  $\sim 250$  MW (500 GeV) [compare to 164 MW ILC] and 589 MW (3 TeV).

2012 CLIC Conceptual Design Report <http://project-clic-cdr.web.cern.ch/project-CLIC-CDR/>  
Remaining R&D to demonstrate feasibility will take  $\sim 4$  years.

Slightly modified ILD and SiD detectors have been used to demonstrate the physics capabilities up to 3 TeV. The small  $\Delta t$  between bunches means that full time stamping of events is not possible, but the pileup and beamstrahlung backgrounds seem manageable, and power pulsing is feasible.

Potentially higher CLIC energy than ILC gives commensurate improvement in New Physics studies, Higgs self-coupling, top quark Yukawa coupling ...

# Cast of Characters – Circular $e^+e^-$ machines

See ICFA Workshop report:  
Fermilab-CONF-13-037-APC

Several circular  $e^+e^-$  machines have been discussed, some based on existing rings or site restrictions, and some new ones with larger radius that could evolve to very high energy hadron colliders. The parameters in the table are illustrative.

Parameter	Units	LEP3	TLEP	TLEP	Super Tristan	FNAL SiteFiller	CEPC
Energy	GeV	240	240	350	240	240	240
Lumi	$10^{34}$	1	4.9	0.65	1	0.52	3.85
Circumf.	km	26.7	81	81	40	16	70
$\Delta E/\text{turn}$	GeV	7	2.1	9.3	3.5	10.5	2.4



LEP & TLEP



Fermilab Site Filler



Super Tristron



# Cast of Characters – Circular $e^+e^-$ machines

## Circular collider Advantages

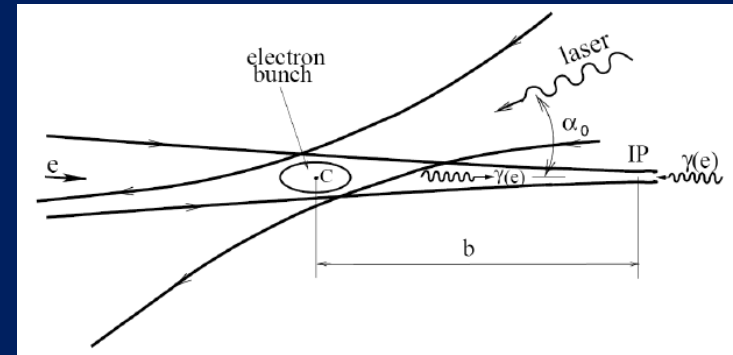
- ❖ Higher luminosity than linear for  $E < 240$  GeV
- ❖ Mature technology
- ❖ Some existing tunnels could be considered (but they are in use!)
- ❖ More than one IP
- ❖ New large rings could evolve to a high energy pp collider in future

## Challenges

- ❖ Limited energy reach (larger rings could just make tt threshold)
- ❖ Beamstrahlung limits beam lifetime: Need rapid top up from dedicated full energy accelerator in same tunnel
- ❖ Beamstrahlung E loss requires lattice with large  $\Delta p$  acceptance
- ❖ Synchrotron radiation heat and radioactivity load on vacuum and RF
- ❖ Low emittance difficult to achieve; beam-beam effects are large
- ❖ Designs are still primitive; no realistic costing

# Cast of Characters – $\gamma\gamma$ Colliders

Backscatter laser photons on the incoming polarized  $e^-$  beam just before the IP. Polarization is essential to give small  $\gamma$  energy spread.



- ❖  $\gamma\gamma$  collider can be accommodated with linear or circular (ERL) electron machines.
- ❖ Can produce Higgs via  $\gamma\gamma \rightarrow H$  with  $E_\gamma = 63$  GeV ( $E_e = 80$  GeV) compared with  $E_{bm} = 120$  GeV for  $e^+e^-$ . Cross section comparable to  $e^+e^- \rightarrow ZH$
- ❖ If restrict to  $\gamma\gamma$  collisions, only electron linacs are needed, but this would limit the physics program.
- ❖ Laser system is  $O(kJ)$ , with separate pulses of  $O(J)$ . Though such systems may be provided by the inertial fusion program, they are not available now. The optical cavities for storing laser energy are complex.
- ❖ Extensive R&D and design is still needed.



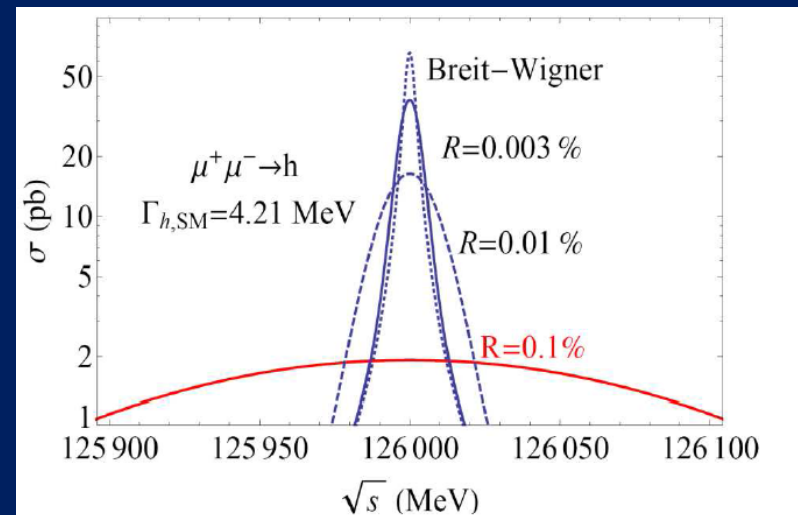
# Cast of Characters – Muon Collider

Muons evade the synchrotron radiation constraints (but they decay), thus the final collider ring can be small, fitting on e.g. FNAL site. Could envision  $\sqrt{s}$  up to 4 TeV where radiation from decay  $\nu$  interactions becomes large.

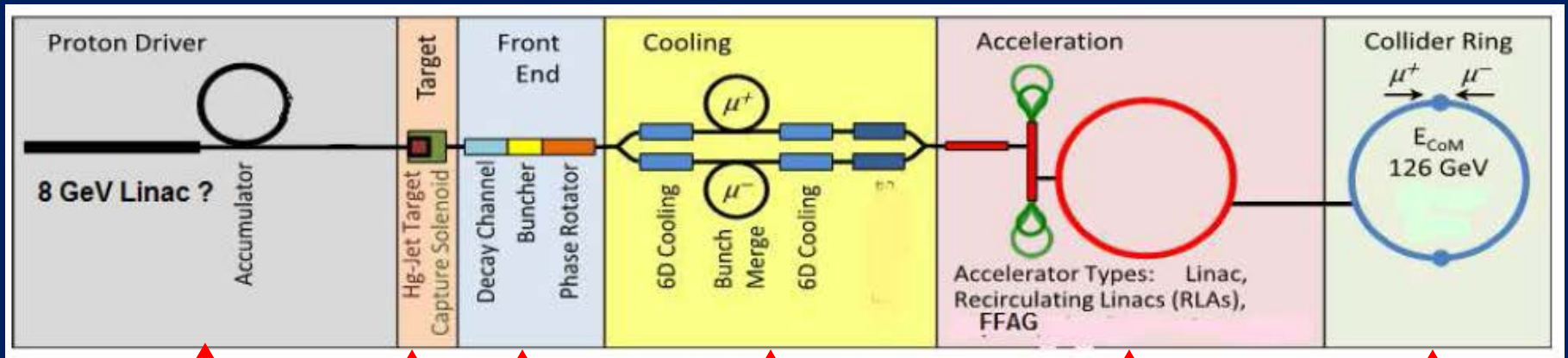
For use as Higgs factory, the  $s$ -channel production  $\mu^+\mu^-\rightarrow H$  XS is large (41 pb compared to 0.2pb for  $ee\rightarrow ZH$ ). Luminosity is low but number of Higgs is comparable to ILC.

Beam energy spread is small and  $E_\mu$  can be measured very accurately using  $g-2$  muon spin precession frequency. But with the small width of the Higgs (4.2 MeV) the demands on energy resolution and absolute energy calibration are large, and the transverse to longitudinal emittance exchange needed will cost luminosity.

Need  $\Delta E/E$  of 0.003% and energy calibration and control to a similar accuracy to get accurate  $\Gamma_H$  measurement.



# Cast of Characters – Muon Collider



4 MW proton driver, 3ns pulses

Pion decay channel

Hg target in solenoid

$\mu$  ionization cooling and beam manipulations

Acceleration

Collider rings

## Advantages

- s-channel Higgs ( $E_{cm} = 126$  GeV)
- Can get to multi-TeV
- Small footprint
- Staging options available
- No synchrotron radiation
- No beamstrahlung
- Excellent energy resolution/calib.

## Disadvantages

- 4D & 6D phase space cooling not demonstrated
- Getting energy spread of 0.003%
- 20T solenoid for Hg target
- RF in strong B field
- Muon decay background for expts
- Proof of principle R&D not yet done

## Snowmass advice

The Snowmass studies make a compelling case that the discovery of the Higgs boson has dramatically changed the landscape. While it so far conforms to the Standard Model profile, the need for precision study of its properties is paramount.

The 14 TeV LHC and luminosity upgrades will make a big step in filling in the Higgs profile and in searching for new phenomena.

A lepton collider can substantially improve understanding of the Higgs properties, and is sensitive to new physics above the LHC scale. If Japan goes forward with ILC, the US should be a part of it .

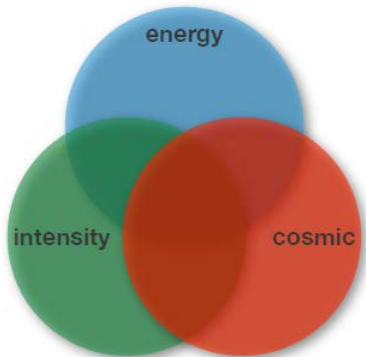
It should be emphasized that new discoveries on the Intensity frontier (e.g. “is the neutrino Majorana?”) and the Cosmic frontier (e.g. “do massive dark matter particles exist?”) will change the nature of the questions for the Energy frontier.

## Snowmass advice

I borrow here observations from the Snowmass summary talks of Brock and Shipsey ...

those circles are pithy

but they force us to be tribal



The three Frontiers and the logo from the last P5 report serve to embody our field for the public, and for government.

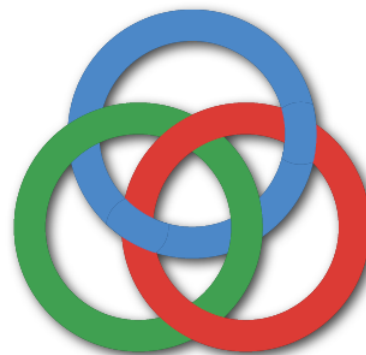
But the large areas where the colors overlap are critical for progress in all Frontiers. Major advances come from the combination of measurements and discoveries in all three areas.

But the emphasis on 'relevance' for societal problems like energy and climate, and the general belt-tightening, has led to constricted funding for esoteric science like HEP.

Global planning and responsible international cooperation are necessary to realize our goals

## a great scientific nation

plans for balance:



- precision experiments* ---> discovery through inducing quantum loops
- neutrino experiments* ---> discovery by inducing quantum mixing
- astrophysical experiments* ---> discovery by capturing cosmic quanta
- theoretical studies* ---> discovery through mathematics
- annihilating beam experiments* ---> discovery by producing on-shell states

## Considerations

- ❖ We have a Higgs boson and a top quark, which are both intimately tied to Electroweak symmetry breaking. We need precision measurements of their properties to determine whether we are in the Standard Model or have new physics. Any proposed lepton collider would provide the precise studies that would go well beyond what the LHC will do. This could be a lepton collider program in the 240 – 350 GeV range. But even for the Higgs BRs, going to 500 GeV or higher gives substantial improvements.
- ❖ The desired top energy of a lepton collider obviously depends on what the LHC will see in 2015 when it runs at  $\sim 14$  TeV. For example, many Supersymmetry models have Susy gauge bosons and sleptons that are much lighter than the squarks and gluinos, and the clean environment of the lepton collider allows their study if the energy is high enough. Fortunately, if there is New Physics in the LHC 14 TeV energy range, the direct evidence for it will show up quickly.
- ❖ There is advantage to having a lepton collider operating while the LHC is running; discoveries at one machine stimulate new studies at the other.

# Considerations

- ❖ Circular  $e^+e^-$  colliders cannot go above  $\sim 350$  GeV. Considerable design effort still remains. There are other obstacles for near term projects:
  - CERN is presently busy with LHC upgrades
  - Japan is pushing KEKb, ILC, HyperK
  - The Fermilab site filler is uncomfortably small, and US priorities are on the Intensity Frontier
  - China could proceed, but a buildup of accelerator expertise would be needed.
- ❖ A muon collider, though full of interesting challenges, is far from being demonstrated as a viable project.
- ❖ CLIC offers high energy but with large power budget, has several years left to reach a technical design, and competes with the LHC upgrade program.
- ❖ We have one lepton collider ready to go – the ILC. With upgrade, could reach 1 TeV. The design is mature, we have conceptual designs of powerful detectors, and we have a large international collaboration. We have a country that is interesting in hosting it! And we have a pretty solid cost estimate – which is unfortunately large.
- ❖ Even if the US were to undertake 10% of the ILC cost, the US share would not fit into the existing DOE HEP budget without starving everything else. At present Congressional funding levels for basic research(HEP in particular) are declining. So a US entry would require buy-in at higher reaches of government.



## Considerations

Expensive new projects enter the “valley of death” following the completion of the R&D and technical design, when the hard political work of forging governmental approvals begins. The bones of the SSC lie in this valley. Often additional costs not clearly understood at the beginning later loom to dampen government’s enthusiasm. Achieving such projects as international collaborations further complicates the passage through the valley, as we are seeing with ITER. But political and economic climates change rapidly on the time scale of such projects, so we must be prepared to capitalize on windows of opportunity.

Competing advocacies by physicists for one or the other flavor of lepton collider also do not help. Is it better to wait still longer to assess the best energy range, or to collect around a proposal that satisfies many, if not all, of the desires, but is ready to go now? Our ability to see 10 sides of every question is not always a benefit.



# Conclusions

- ❖ We have established that precision study of the newly discovered Higgs boson is a key question for the next generation of experiments.
- ❖ Lepton colliders offer the potential to substantially expand our understanding the Higgs beyond LHC experiments.
- ❖ Direct sighting of New Physics can come from direct production at high energy, through deviations in precision observables, or from studies of the cosmos. Lepton colliders can help explain such new discoveries and will extend the reach of New Physics.
- ❖ Any lepton collider will be expensive and will require global cooperation. Multiple colliders are unlikely. We have one candidate machine that is ready to go, and a country interested in hosting it. We should nourish that possibility.

Many thanks to the authors of the ILC Physics TDR, CLIC CDR and the 2012 ICFA “Accelerators for a Higgs Factory” report, to Snowmass organizers, M. Peskin, C. Brock, B. Barletta, and to the many people whose slides I borrowed.