Lessons for a muon collider from the CLIC 3 TeV studies

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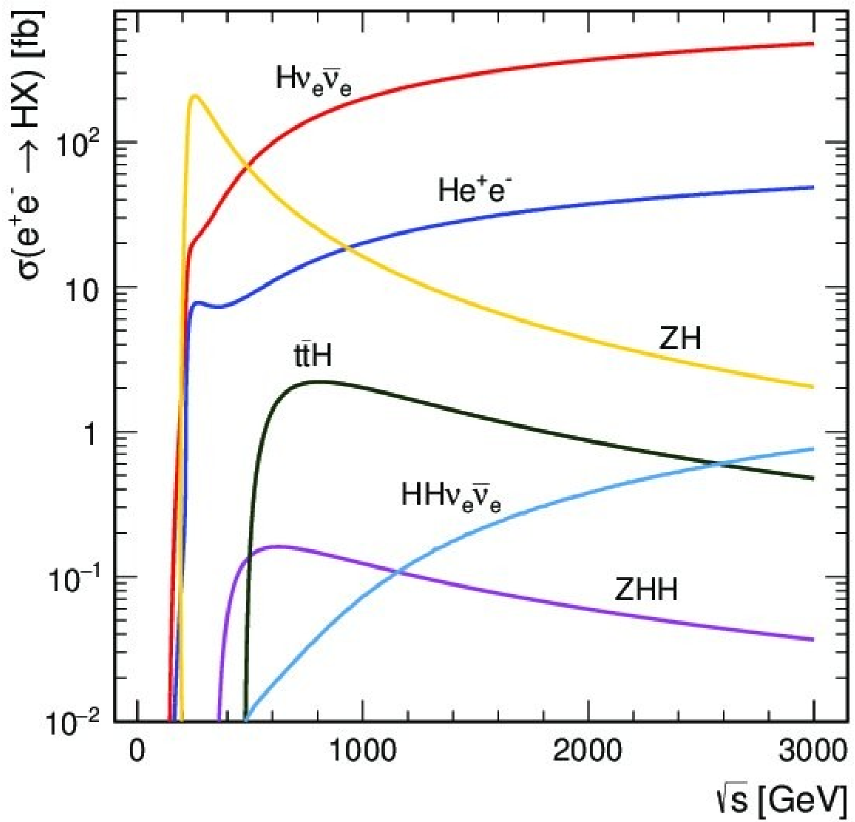
The next large-scale facility

The priority of HEP is a precision machine for Higgs and top physics

Physics	$\sqrt{s}$ [GeV]
EW precision	m_Z
$e^+e^- \to ZH$	250
$e^+e^- \to t\bar{t}$	$2m_t$
$e^+e^- \to H\nu\bar{\nu}$	~400
$e^+e^- \to ZHH$	500
$e^+e^- \to t\bar{t}H$	550



We have developed mature technologies to build a Higgs factory and to cover all SM thresholds ($t\bar{t}$, VBF, HH, $t\bar{t}H$ production).

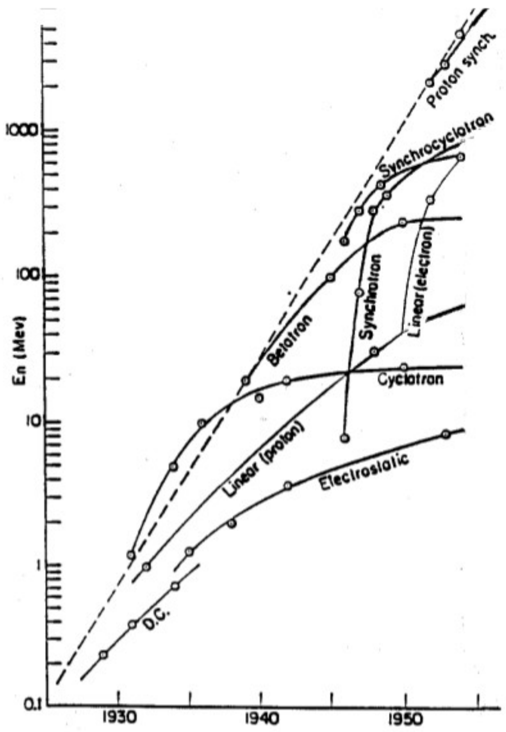
This is NOT why we need a muon collider.

The next-to-next large-scale facility

The next-to-next machine should continue the exploration of the energy frontier

Looking for new phenomena a higher energy scales with direct searches and "boosted" precision measurements (more on that later)

Exploration of the energy frontier

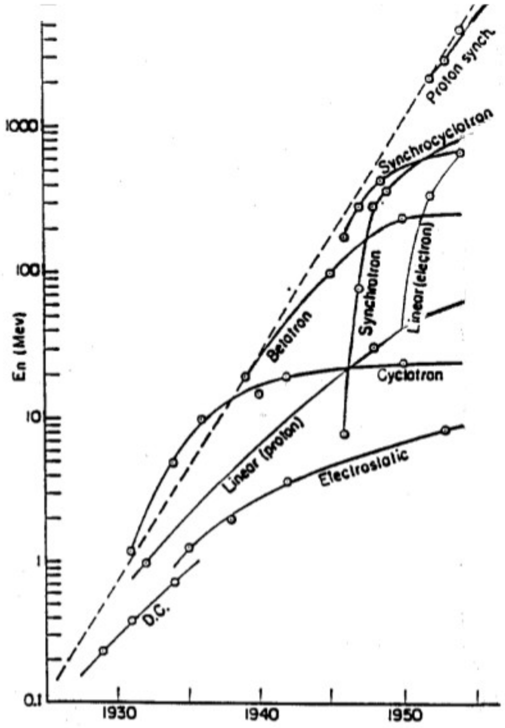


Livingston’s 1954 law: a factor 10 increase every 10 years!

Even in the early days it was clear that this was not an adiabatic development of one technology;

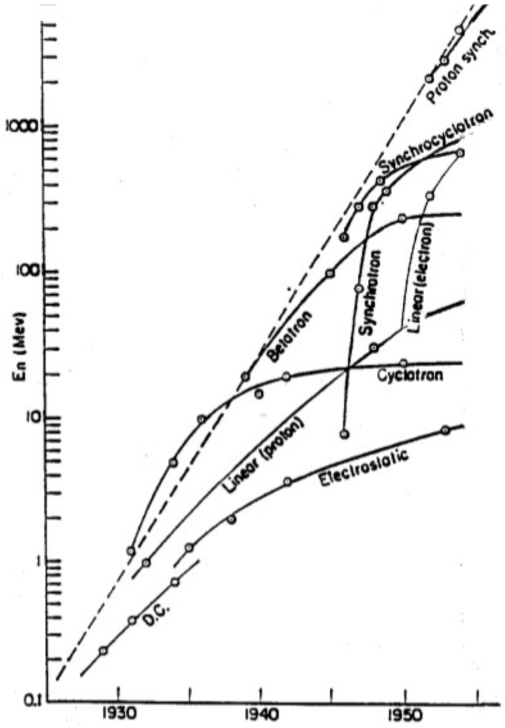
sustained progress is the result of a sequence of breakthroughs.

Exploration of the energy frontier



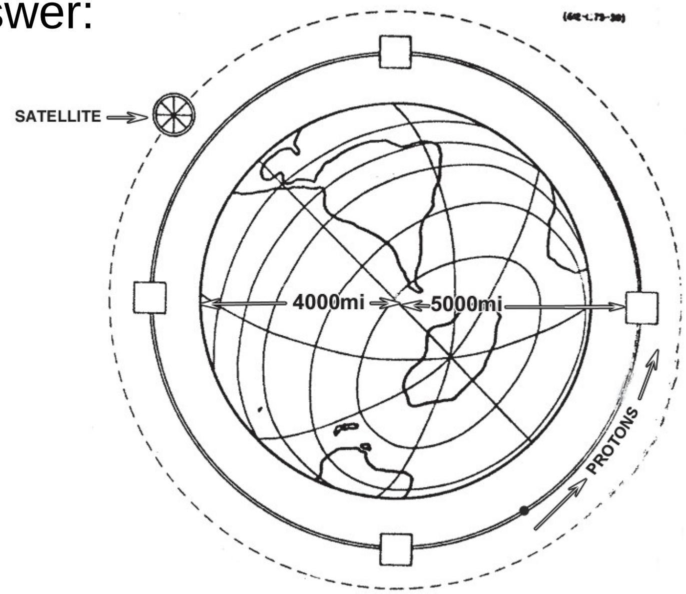
generator → cyclotron → synchrotron → ?

Exploration of the energy frontier



generator → cyclotron → synchrotron → ?

Fermi's answer:



Planet-sized fixed-target machine

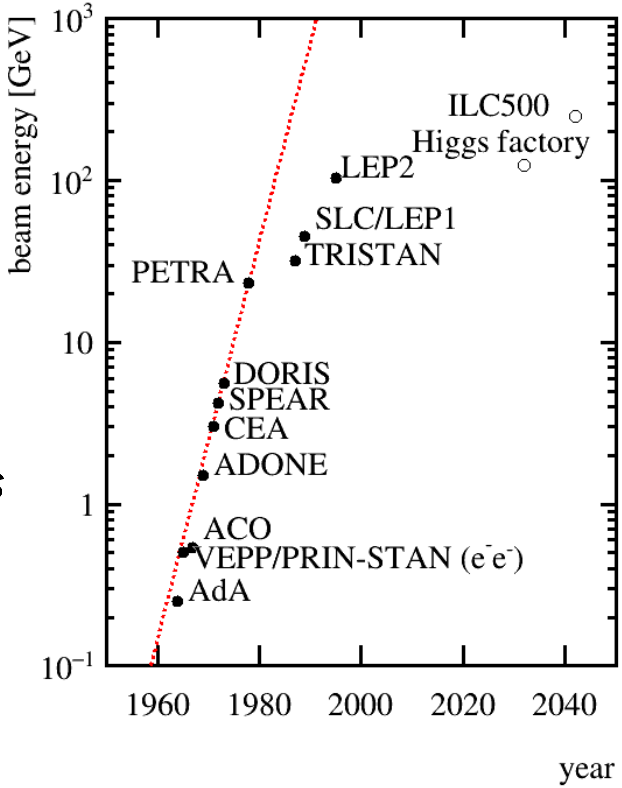
Exploration of the energy frontier

generator → cyclotron → synchrotron → e⁺e⁻ collider → ?

Wideröe/Touschek's answer:

1-meter "Anello di Accumulazione"

Exponential progress until PETRA in '78



Exploration of the energy frontier

generator → cyclotron → synchrotron → e^+e^- collider → ?

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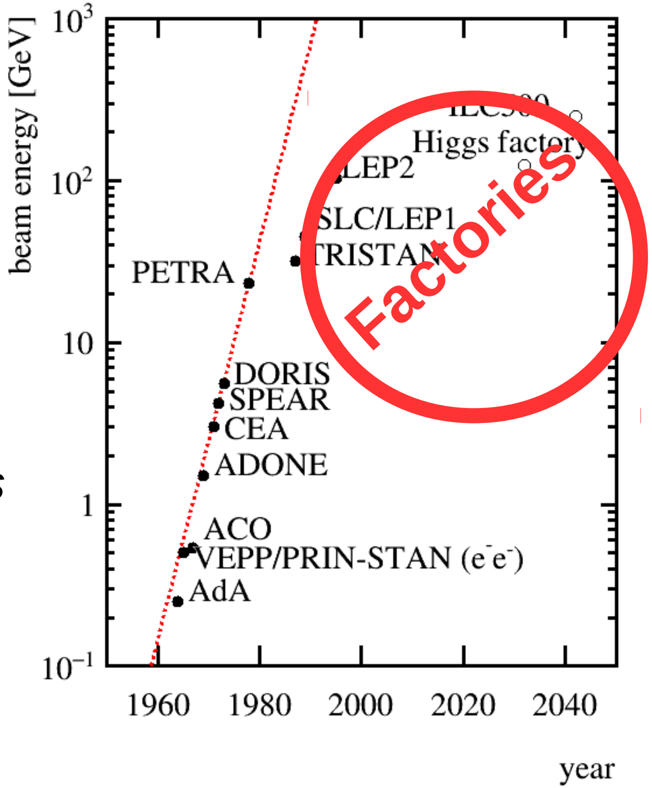


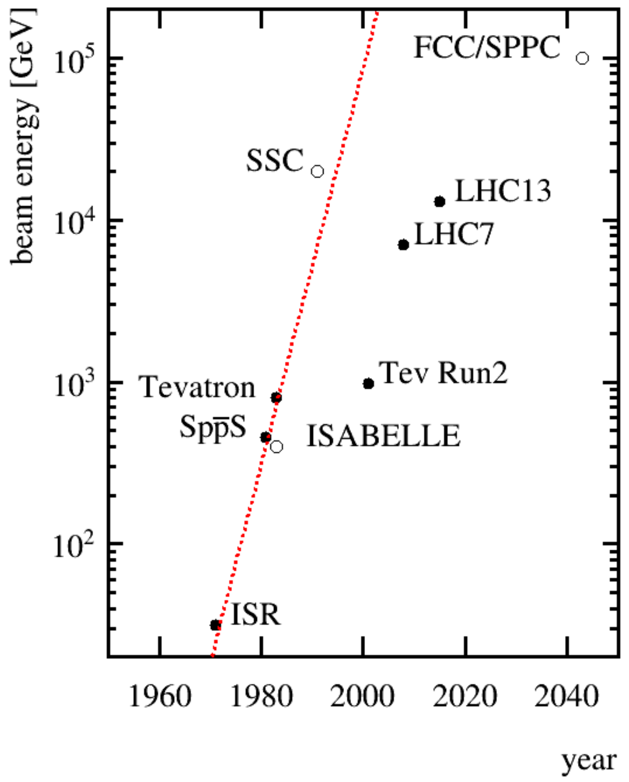
Exploration of the energy frontier

generator → cyclotron → synchrotron → e^+e^- collider → hadron collider → ?

Magnets drive progress in hadron colliders

ISR (1971)	1.2 T
$Sp\bar{p}S$ (1981)	2 T?
Tevatron (1983)	4 T
LHC (2008-1)	8.3 T
FCC/SPPC (2045?)	16-20 T

Superconducting (Tevatron, LHC, FCC/SPPC)
NbTi→Nb3Sn→HTS?



Exponential series 1-2-4-8-16 is right, but time gaps are gradually opening up (10-25-40 years)

The muon collider option

generator → cyclotron → synchrotron → e^+e^- collider → hadron collider → muon collider

The scaling laws (size, efficiency) are favourable for a multi-TeV muon collider

A 3-15 TeV center-of-mass energy corresponds to ~20-100 TeV in hadron collider terms

Demonstrate now that a muon collider is a cost-effective and viable alternative

Threats:
inertia is in favour of established technology; we need very solid arguments
performance in terms of luminosity remains uncertain (source & cooling)
progress of R&D on “best effort” basis, without proper funding, is too slow

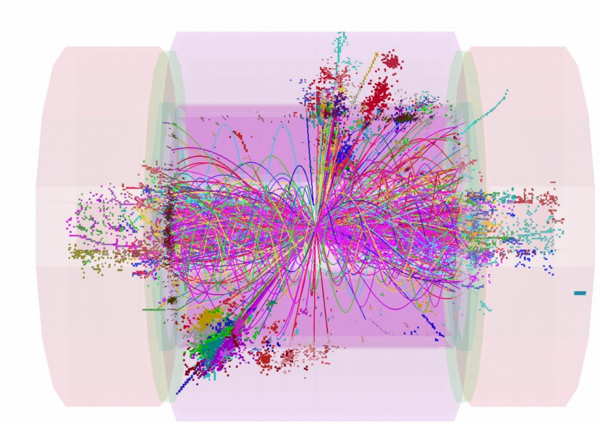
Muon collider detector studies

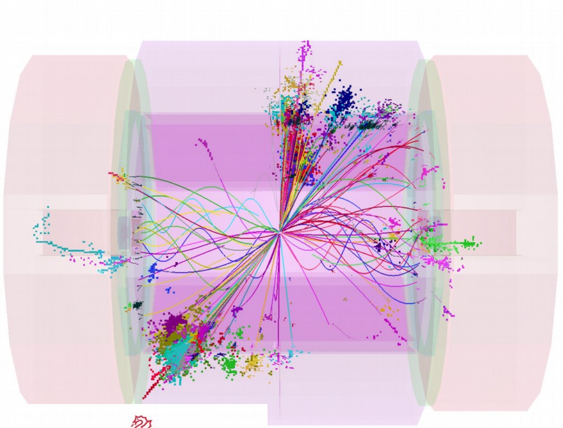
What can performance and reconstruction experts do?

ADOPT ILC/CLIC full-simulation infrastructure to demonstrate reconstruction

→ use what exists; don't loose precious time by starting from scratch
→ use collider-specific backgrounds, time structure and energy reach
→ set up a core software team (DESY for ILC, CERN for CLIC)

Example: CLIC3000 jet reconstruction with $\gamma\gamma \rightarrow$ background (before/after timing cuts)





Timing requirements
Hadron collider algorithms

CLIC CDR, arXiv:1209.4039

Robust e+e- algorithms

VLC, arXiv:1607.05039

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Muon collider physics & detector studies

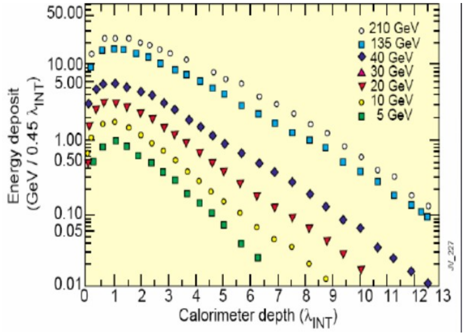
What can detector experts do?

ADAPT detector design to your environment

→ Every collider is different in the details, the ILC/CLIC design is not optimal for μ-coll
→ CLIC overhauled ILC design to cope with harsher environment:
  all-silicon tracker, better timing, deeper calorimeter, larger vertex detector
→ involve the R&D collaborations, as they are the main knowledge base

Example: depth of the calorimeter is more important at higher energy

ILD ECAL+HCAL adds up to ~7Λ,
CLIC increased to 8.5Λ to better contain 1.5 TeV jets
At a 15 TeV collider, we must rethink the overall design



Muon collider physics & detector studies

What can detector experts do?

IMPROVE detector design and technology

→ ILC/CLIC design is not written in stone
→ technology choices are just a “snapshot” of what’s available (i.e. LGADs)
→ Muon collider is not for tomorrow

Muon collider physics studies

What can phenomenologists do? Or better: teams of theorist and experimentalists

Physics prospect studies for 3 TeV and 15 TeV $\mu\mu$ collisions

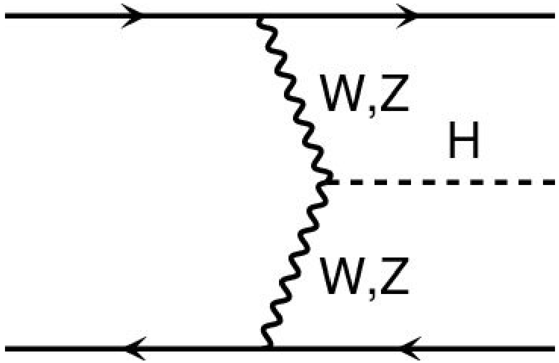
→ recycle and extend CLIC results for 3 TeV (this talk)
→ establish luminosity targets for machine developers
→ genuinely new explorations for 15 TeV (with ALEGRO?)

(see arXiv:1901.06150)

Example: VBF production in e^+e^- vs. $\mu^+\mu^-$ vs. e^-e^-

In many processes, the LHC is no longer predominantly a $q\bar{q}$ collider ($gg \rightarrow$ H, $t\bar{t}$, VBF production)

For many purposes, a 15 TeV μ-coll is a vector-boson collider (see Buttazzo et al., 1807.04743)



Physics at a 3 TeV lepton collider

In a nutshell...

Extensive set of studies has been published

→ CLIC summary report, arXiv:1812.06018
→ New Physics, arXiv:1812.02093
→ Top Physics, arXiv:1807.02441
→ Higgs Physics, arXiv:1608.07538

+ recent addenda: Robson et al., arXiv:2001.05278
Burrows et al., arXiv:2001.05373

Comparison to other projects

→ European strategy document, arXiv:1910.11775

CERN-2018-005-M
14 December 2018

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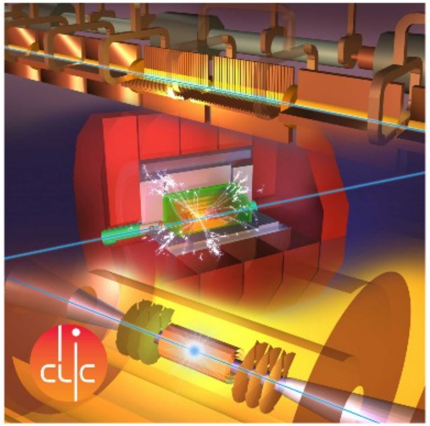
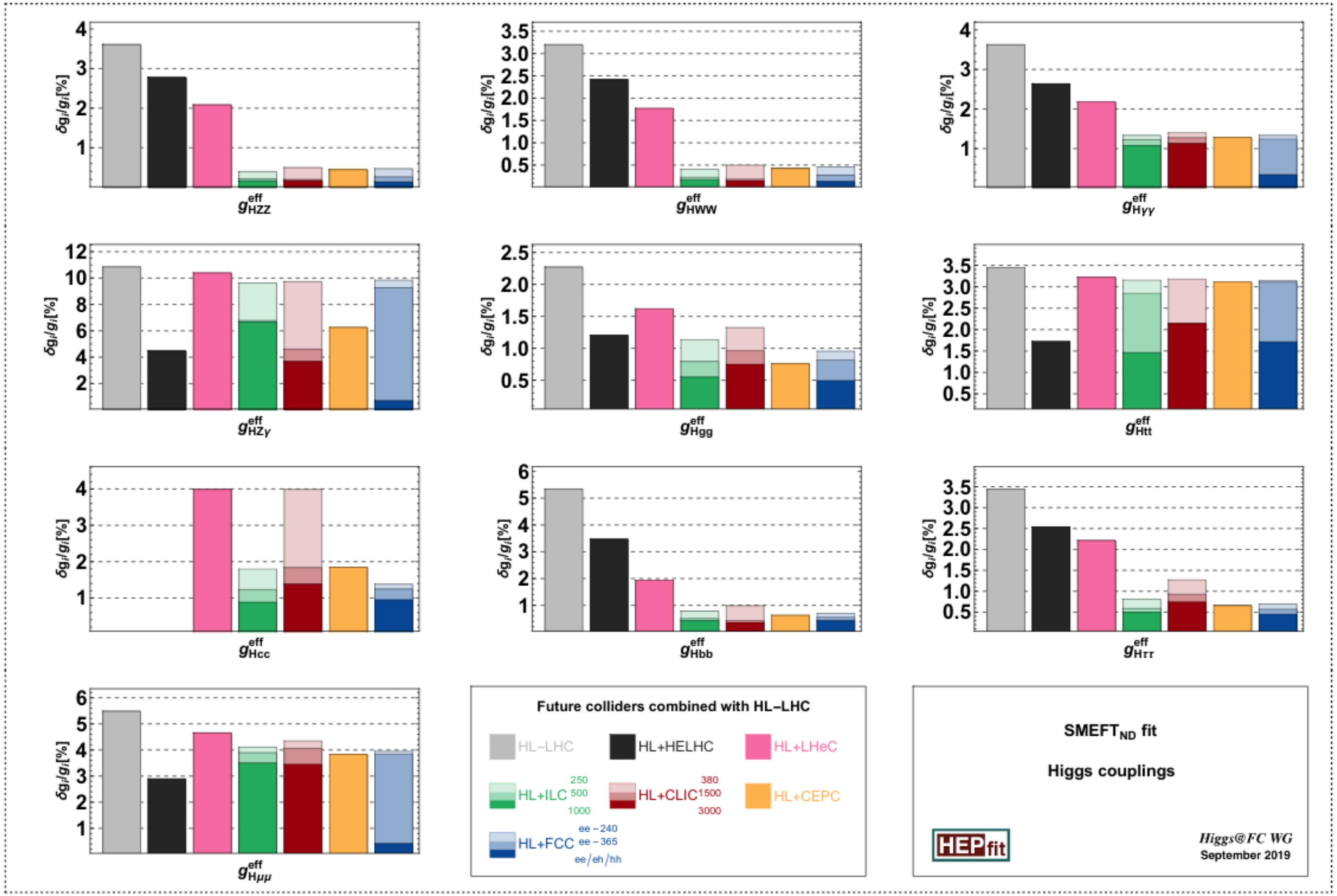


THE COMPACT LINEAR COLLIDER (CLIC)
2018 SUMMARY REPORT

GENEVA
2018

Physics briefing book,
arXiv:1910.11775

Higgs couplings



CLIC380 is good, with the smallest integrated luminosity

Adding CLIC1500 yields very competitive results for Z, W couplings (VBF process) and for top Yukawa (ttH, direct)

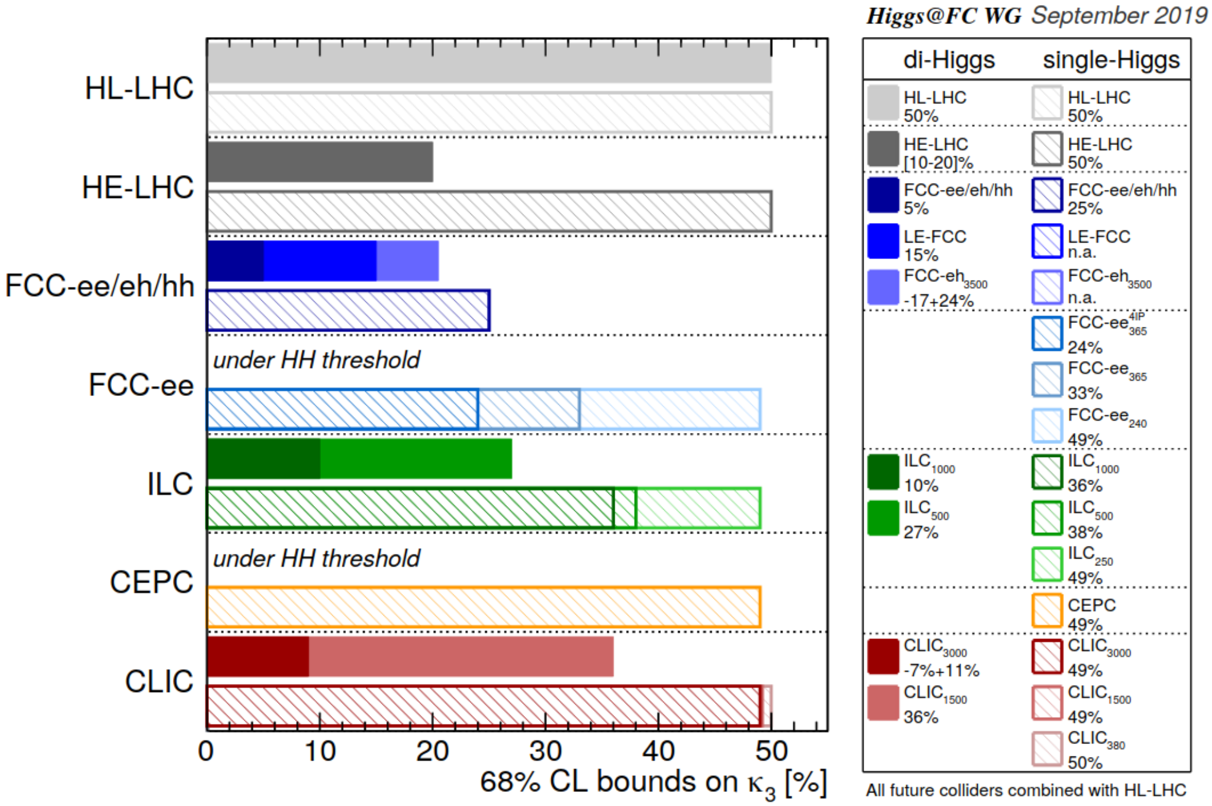
CLIC3000 most useful in rare decay channels

New processes open up well above 250 GeV; a complete characterization requires energy > 550 GeV

Physics briefing book, arXiv:1910.11775

Higgs self-coupling

See also arXiv:1910.00012



The Higgs self-coupling is too important to establish only indirectly!

Energy AND luminosity are needed:

$4ab^{-1}$ at ILC500 : 27%

$8ab^{-1}$ at ILC1000 : 10%

$2.5ab^{-1}$ CLIC1500 : 36%

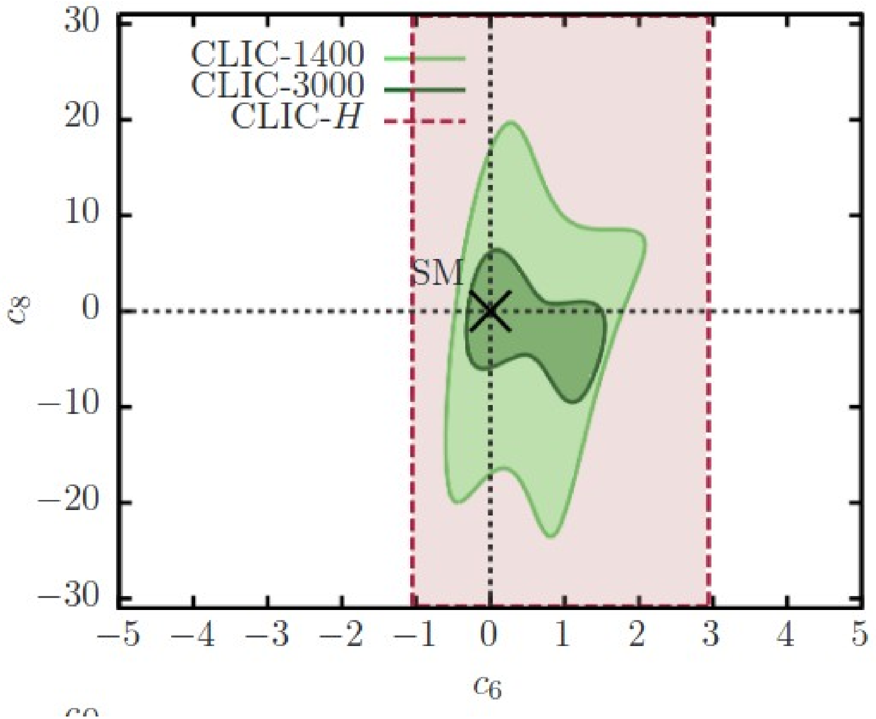
$5ab^{-1}$ at CLIC3000 : ~10%

Beware of the small print

- comparing direct & indirect determination (top@LEP vs. Tevatron)
- prospects obtained under different assumptions (LC: full-sim=2 x fast-sim)

Higgs self-coupling and beyond

ArXiv:1910.00012 and
arXiv:1802.07616



Why stop at the triple coupling?

Quartic coupling accessible:
- Loop corrections to HH production
- Triple Higgs production $e^+e^- \rightarrow \nu\nu HHH$ cross section ~ 1 ab at 3 TeV

Competes with 100 TeV pp collider

(Durieux, Perello, Vos, Zhang, arXiv:1807.02121)

Top quark couplings

EFT analysis of $e^+e^- \rightarrow t\bar{t}$ production

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

$$\mathcal{O}^-_{\varphi q} = \tfrac{1}{2}(iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q) - \tfrac{1}{2}(iH^\dagger \overleftrightarrow{D}^a_\mu H)(\bar{Q}\sigma^a\gamma^\mu Q) \qquad \mathcal{O}_{\varphi t} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$$

.... **Vertex operators.: c**

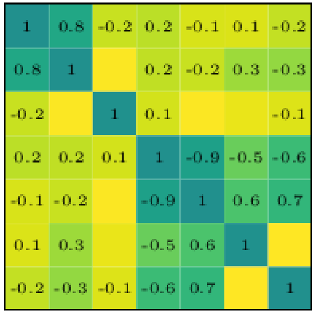
$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}\sigma^a t)\,\tilde{H}W^a_{\mu\nu} \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{H}B_{\mu\nu}$$

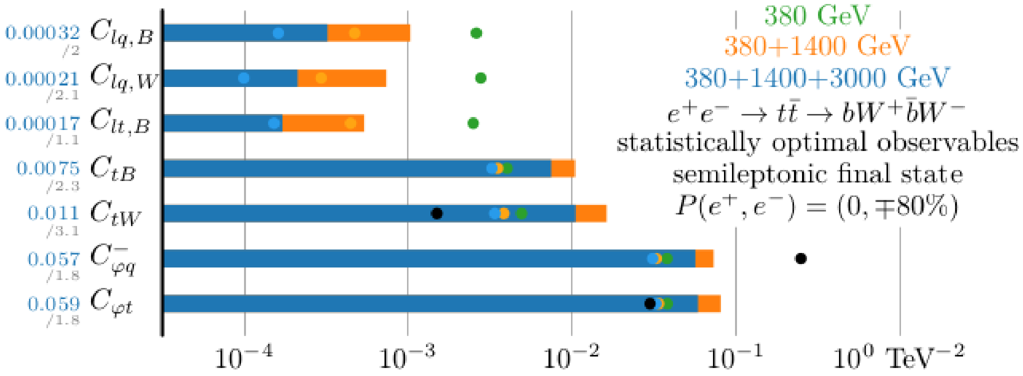
.... **Dipole operators.: E**

$$\mathcal{O}_{lq,B} = (\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e + \tfrac{1}{2}\bar{L}\gamma^\mu L)) \qquad \mathcal{O}_{lq,W} = (\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma^\mu L)$$

$$\mathcal{O}_{lt,B} = (\bar{t}\gamma_\mu t)(\bar{e}\gamma^\mu e + \tfrac{1}{2}\bar{L}\gamma^\mu L))$$

.... **4-fermion op. : E²**





Two runs at different √s are needed to constrain global fit

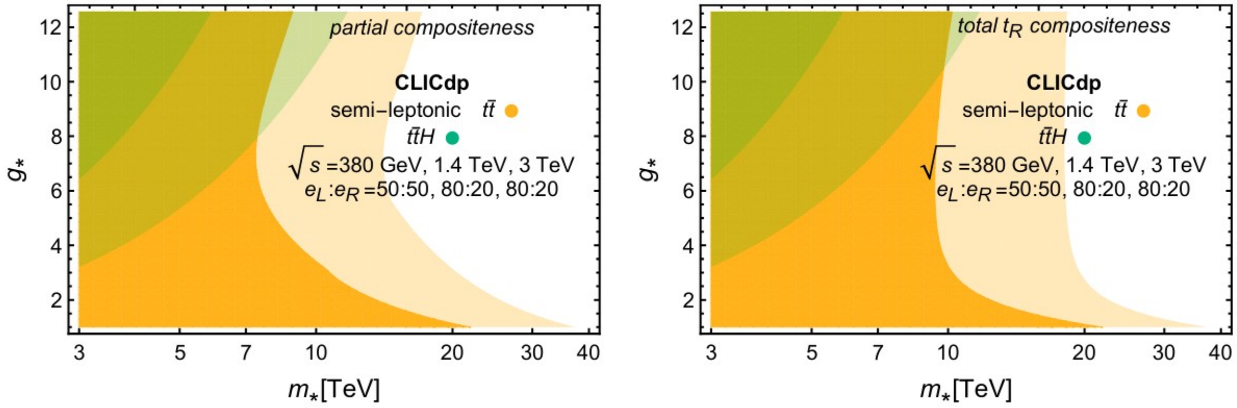
CLIC3000 provides superb constraints on 4-fermion operator coefficients

A broader lesson

The combination of precision and energy determines the BSM sensitivity

“boosted sensitivity”

A lepton collider with a similar per-constituent energy reach is a superior discovery machine



See also:
WW TGC in Higgs fit
energy helps accuracy,
arXiv:1609.08157

Physics briefing book, arXiv:1910.11775

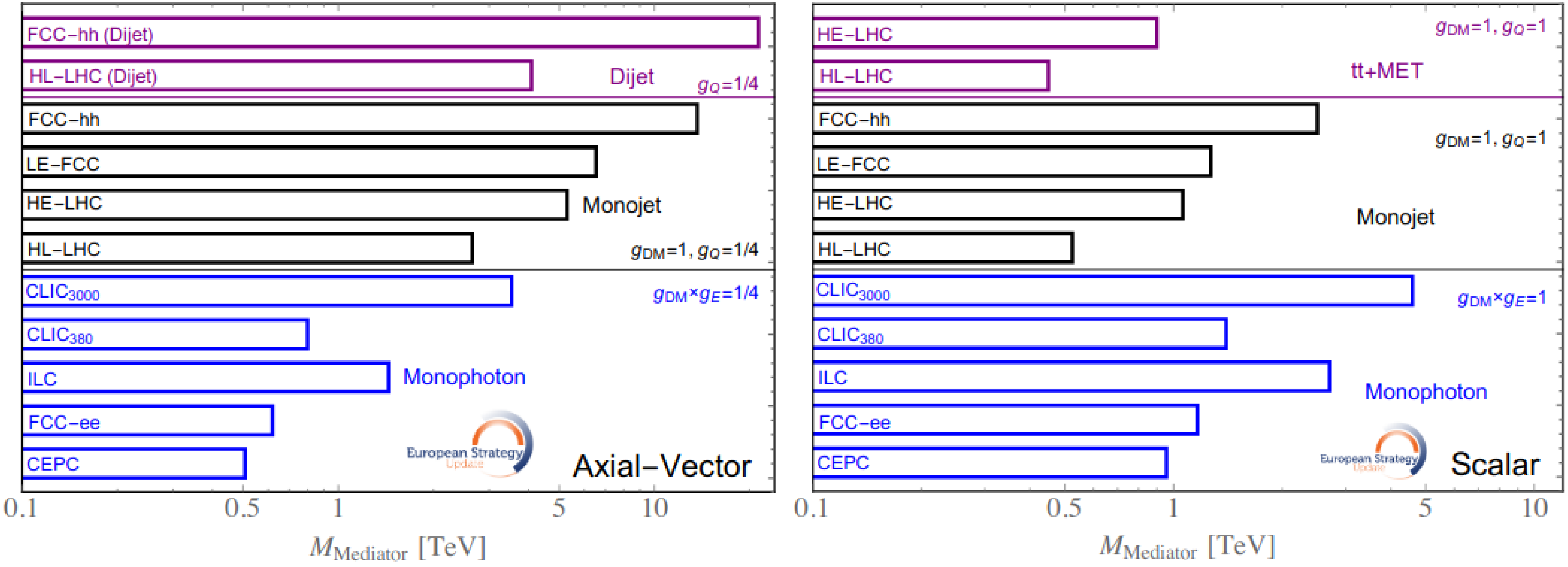
Direct BSM reach

A lepton collider directly probes the weak interactions, where we *expect* new phenomena, without digging through tons of QCD first

Signal can be reconstructed better (much reduced pile-up, kinematic constraints), and Standard Model background rates can be predicted precisely

A lepton collider with a similar per-constituent energy reach is a superior discovery machine

Direct BSM reach: dark matter



A high-energy lepton collider can compete with the highest-energy pp colliders, even in mass reach for direct searches

Lepton and hadron colliders are complementary in their assumptions about BSM (i.e. lepto-philic vs. leptophobic scenarios)

Summary

The effort for the CLIC CDR is a good example to follow for the muon collider project

A good baseline detector model, simulation and reconstruction software exist
(but do adapt and improve after adopting it)

The prospected Higgs, top, NP physics potential of CLIC at 3 TeV is a good starting point for the muon collider physics case (but do extend, and do explore out-of-the-box for 15 TeV)

High-energy l^+l^- collisionsextend the LHC + Higgs factory SM programme in important ways (Higgs self-coupling, VBF Higgs production, growing NP sensitivity in $l^+l^- \rightarrow WW$ and $l^+l^- \rightarrow f\bar{f}$)

BSM potential competes with and complements the highest-energy hadron collider