Detector & physics studies for a linear e^+e^- collider

CEPC workshop, Rome, 24 May 2018

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on behalf of the Linear Collider Collaboration

Acknowledgements and disclaimer

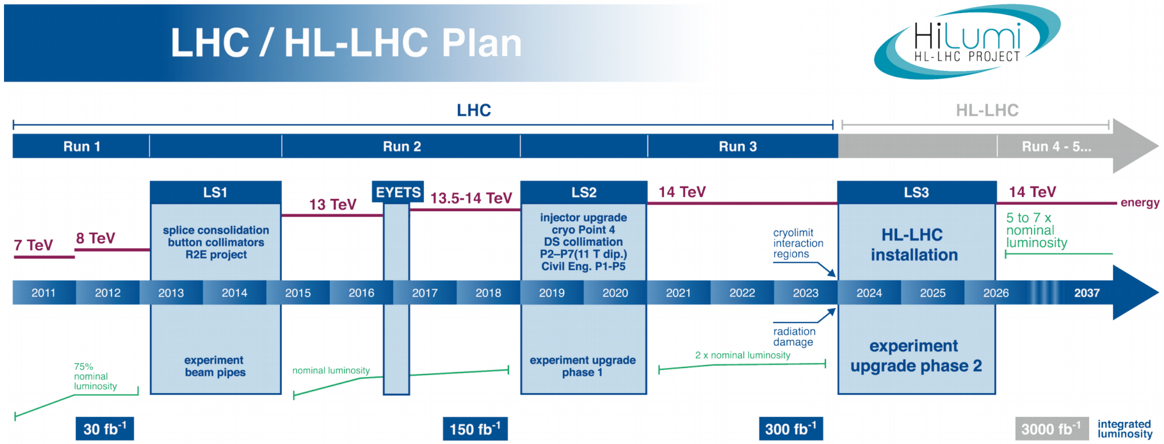
This talk is a personal view and does not necessarily reflect the position of projects I'm involved in (LCC, ILC, ILD, CLIC)

Most of the material is based on studies in the framework of ILD or CLICdp, and would not have been possible without a large effort of many people to design detectors, develop MC tools, etc.

Present and future projects

Particle physics' current energy-frontier installation

HL-LHC collects
3 ab^{-1} by 2037



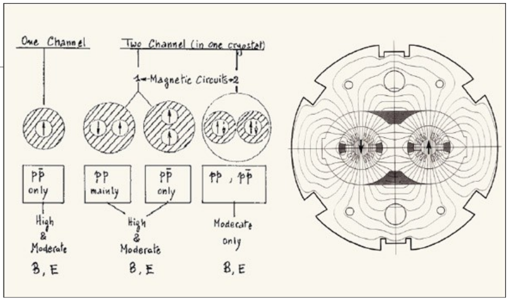
Long-term future may include a 27 TeV “energy doubler” at CERN or a brand-new hadron collider with a center-of-mass energy up to 100 TeV

A brief history of collider physics

Particle physics was so easy back then!

1972: a 5M$ collider starts operation on a SLAC parking lot
1974: Two colliders in one country discover the same particle

1984: First LHC workshop



1994: SSC canceled, LHC approved

2005: envisaged start of the LHC
2010: start of the LHC

2020: decide next energy-frontier facility?

HEP needs a plan!

2035: start of operation of collider XXX

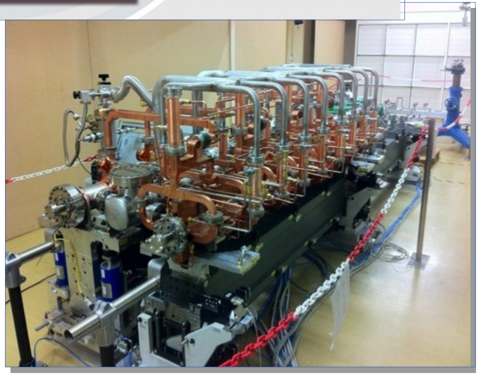
Accelerating cavities

SLC was built with 17 MV/m cavities (1989-1998)

Intense R&D and industrialization program to improve acceleration gradient

→ 35 MV/m super-conducting cavities
(mature & industrialized, XFEL/ILC)

→ 100 MV/m "warm" cavities
(concept proven in large-scale tests, CLIC)



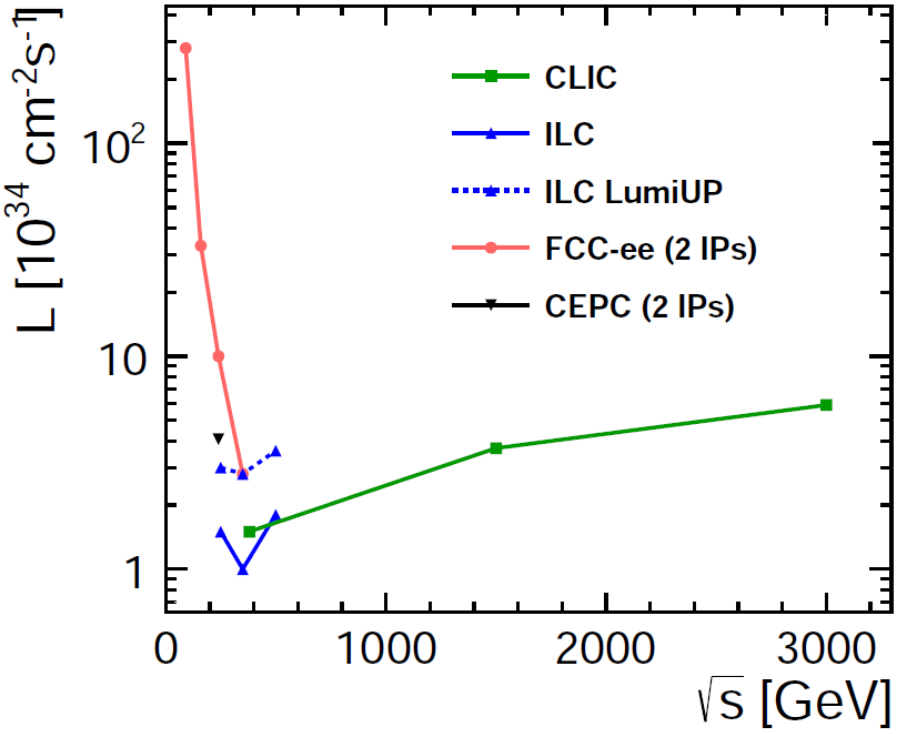
→ Plasma wakefield (when?)

See Daniel Schulte's talk, this morning

Or these excellent reviews of the future of cold and warm RF technologies

e^+e^- collider projects:

- ILC (TDR, negotiations):
  250, 500, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (pre-CDR, TDR ~2020):
  250 GeV, $t\bar{t}$ production?
- FCC-ee (CDR 2018):
  90, 160, 240, 350, 370 GeV



Detailed design reports for ILC/CLIC
CEPC/FCC-ee CDR expected soon

Clear complementarity:

Circular is superior at low energy, linear is the only option at high energy

ILC operating scenario

ILC-NOTE-2015-068
DESY 15-102
IHEP-AC-2015-002
KEK Preprint 2015-17
SLAC-PUB-16309
June 25, 2015

ILC Operating Scenarios

ILC Parameters Joint Working Group

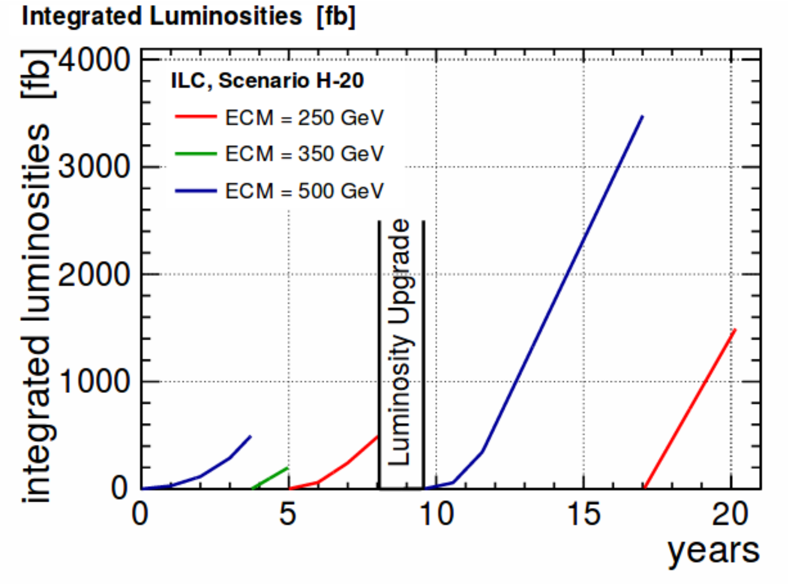
T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya

Abstract

The ILC Technical Design Report documents the design for the construction of a linear collider which can be operated at energies up to 500 GeV. This report summarizes the outcome of a study of possible running scenarios, including a realistic estimate of the real time accumulation of integrated luminosity based on ramp-up and upgrade processes. The evolution of the physics outcomes is emphasized, including running initially at 500 GeV, then at 350 GeV and 250 GeV. The running scenarios have been chosen to optimize the Higgs precision measurements and top physics while searching for evidence for signals beyond the standard model, including dark matter. In addition to the certain precision physics on the Higgs and top that is the main focus of this study, there are scientific motivations that indicate the possibility for discoveries of new particles in the upcoming operations of the LHC or the early operation of the ILC. Follow-up studies of such discoveries could alter the plan for the centre-of-mass collision energy of the ILC and expand the scientific impact of the ILC physics program. It is envisioned that a decision on a possible energy upgrade would be taken near the end of the twenty year period considered in this report.

Scenario H-20 accumulates:
- 2 ab^{-1} at 250 GeV
- 4 ab^{-1} at 500 GeV
- 200 fb^{-1} at top threshold

in several stages over 20 years



ILC envisages 80% electron and 30% positron polarization
LR:RL:LL:RR=40:40:10:10
See: arXiv:1801.02840

ILC operating scenario

To reduce the cost of the initial project, the focus of the project is 250 GeV operation

Physics case of standalone 250 GeV with 2 ab^{-1} run worked out in arXiv:1710.07621

Committee on Future Projects in High Energy Physics (JAHEP, Japan)

With the discovery of the 125 GeV Higgs boson at the LHC,construction of the International Linear Collider (ILC) with a collision energy of 250 GeV should start in Japan immediately without delay so as to guidethe pursuit of particle physics beyond the Standard Model through detailedresearch of the Higgs particle. In parallel, continuing studies of new physicsshould be pursued using the LHC and its upgrades.

ICFA Statement on the ILC Operating at 250 GeV as a Higgs Boson Factory (Ottawa, November 2017)

The discovery of a Higgs boson in 2012 at the Large Hadron Collider (LHC) at CERN is one of the most significant recent breakthroughs in science and marks a major step forward in fundamental physics. Precision studies of the Higgs boson will further deepen our understanding of the most fundamental laws of matter and its interactions. The International Linear Collider (ILC) operating at 250 GeV center-of-mass energy will provide excellent science from precision studies of the Higgs boson. Therefore, ICFA considers the ILC a key science project complementary to the LHC and its upgrade. ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider. ICFA emphasizes the extendibility of the ILC to higher energies and notes that there is large discovery potential with important additional measurements accessible at energies beyond 250 GeV. ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project, led by Japanese initiative.

CLIC operating scenario

CLIC technology has the unique capability to reach a center-of-mass energy of 1.5-3 TeV

The staging scheme envisages:

- 500 fb^{-1} at 380 GeV (initial stage)
- 100 fb^{-1} at 350 GeV (threshold scan)

Top, Higgs indirect BSM

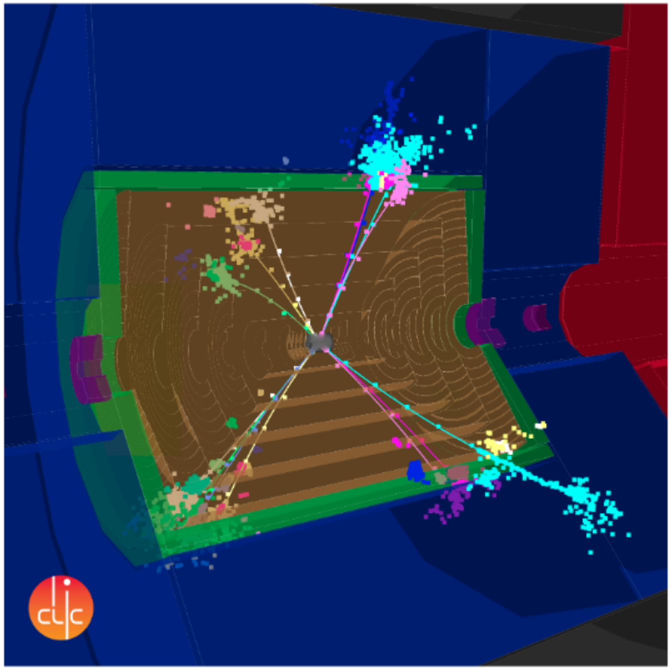
- 1.5 ab^{-1} at 1.5 TeV
- 3 ab^{-1} at 3 TeV

$t\bar{t}H$, HH, direct BSM

arXiv:1608.07537v3 [physics.acc-ph] 27 Mar 2017

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

LC detector R&D

Next-generation pixel detectors

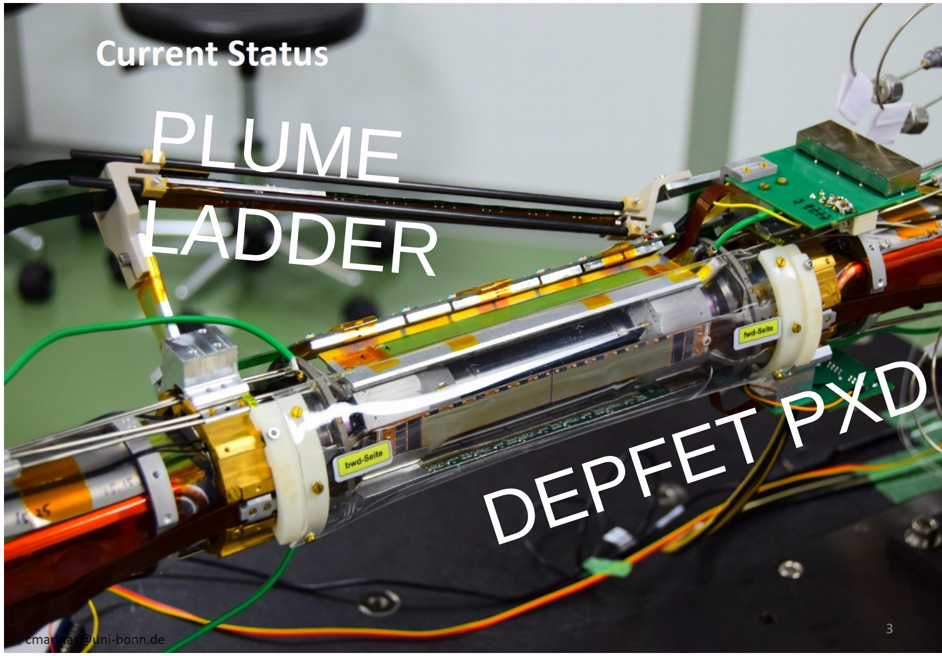
Vertex detector R&D for linear collider has yielded several new technologies that are mature enough to make their way into experiments:

CMOS (STAR, Mu3e, ALICE, ATLAS)

DEPFET (Belle II, X-ray imaging)

FPCCD, SOIPIX have prototypes that meet most LC (and CEPC?) requirements

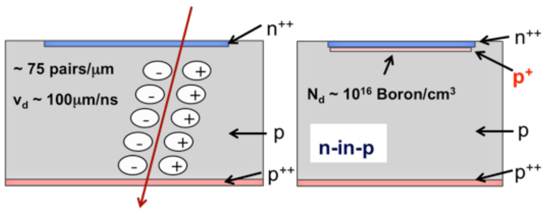
If high read-out speed is required:
- ultra-thin hybrid detectors
- depleted CMOS
- 3D integrated devices

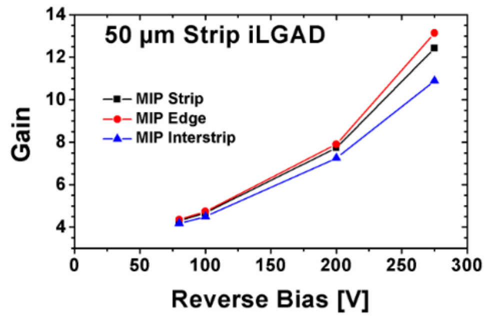


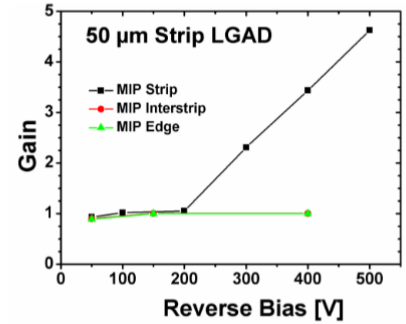
BEAST2 commissioning detector at Belle II: DEPFET + CMOS + hybrid pixels

4D tracking

The advent of ultra-fast position-sensitive silicon detectors…





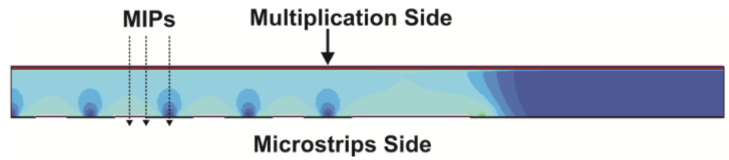


LGAD =

Low-Gain Avalanche Detectors

iLGAD = inverted LGAD

(uniform gain, higher cost)



Technology CNM/RD50

P. Fernandez, et al, NIM A658 98-102 (2011).

G. Pellegrini et al., NIM A 765 (2014)

Ultra-Fast Silicon Detectors

Santa Cruz, Florence 2012 (60-100 ps)

Characterization

Turin/CNM/UCSC, arXiv:1312.1080 (20 ps)

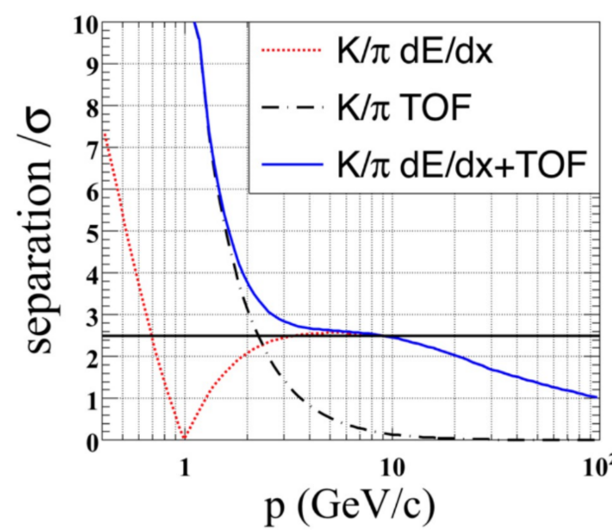
The hype spreads

several groups (10 ps)

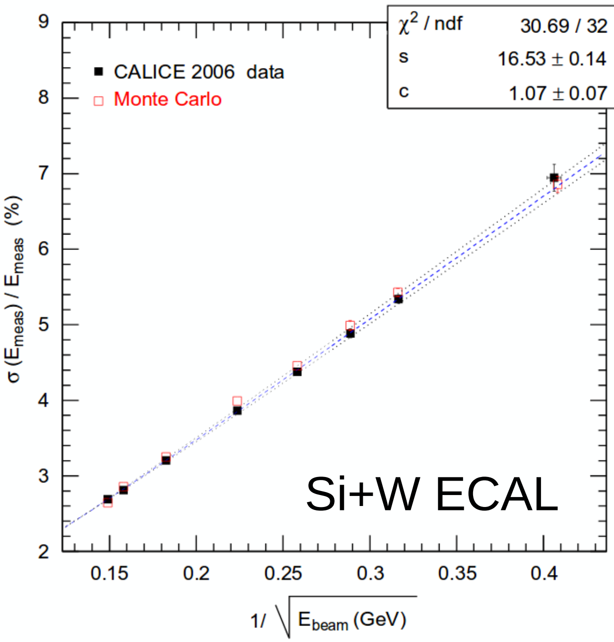
Opportunity for PID

Combining dE/dx from the CEPC TPC (3% resolution) with a 50 ps TOF measurement from the silicon yields a very good separation up to 10 GeV

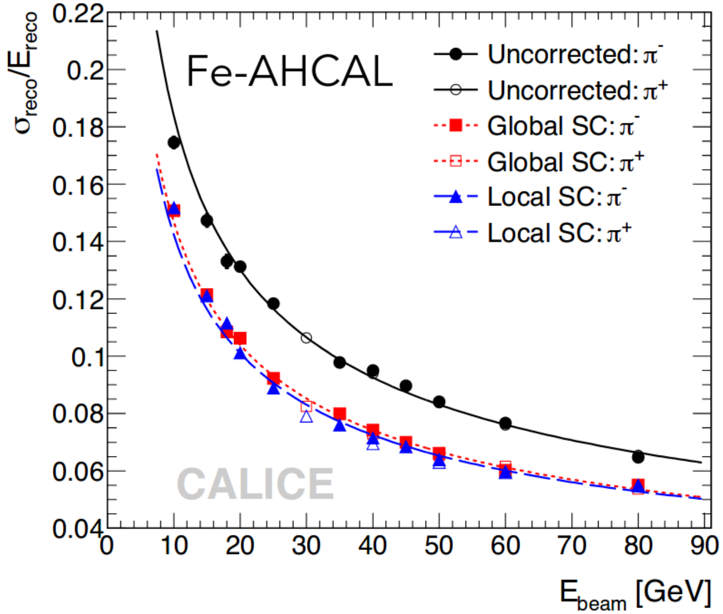
Manqi Ruan, LCWS17



Highly granular calorimetry: research



NIM A608, 372 (2009)



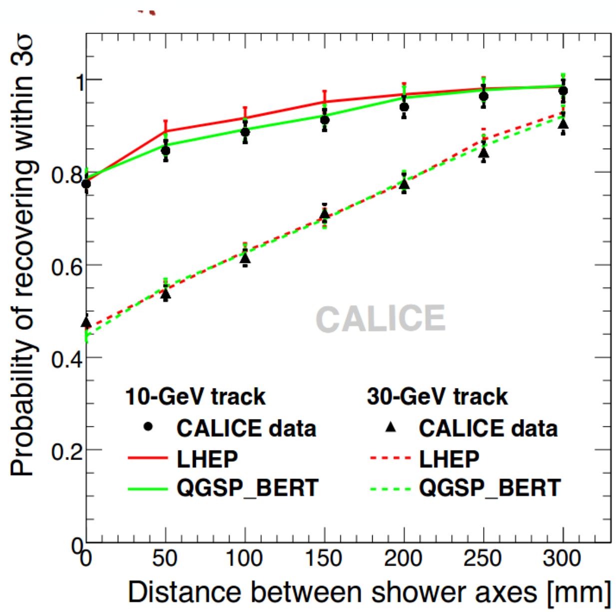
JINST 7 P09017 (2012)

Realistic prototypes: EM and hadronic resolution

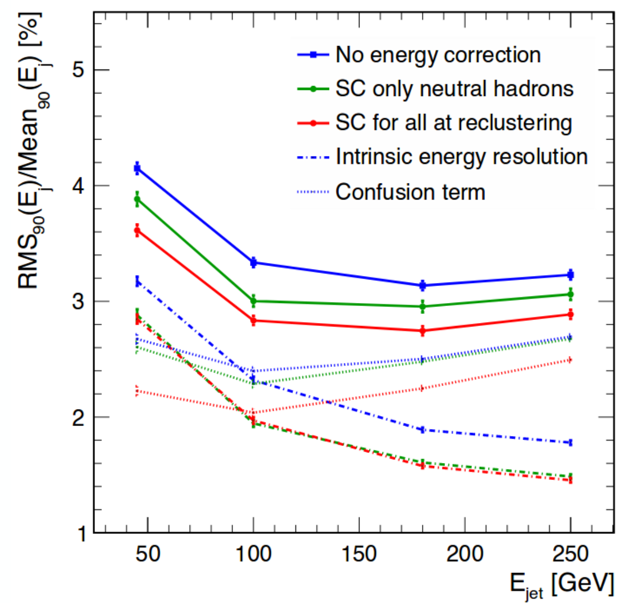
Monte Carlo + Pandora: particle-flow performance of the complete system

3% jet energy resolution superb substructure measurements

Validated with TB

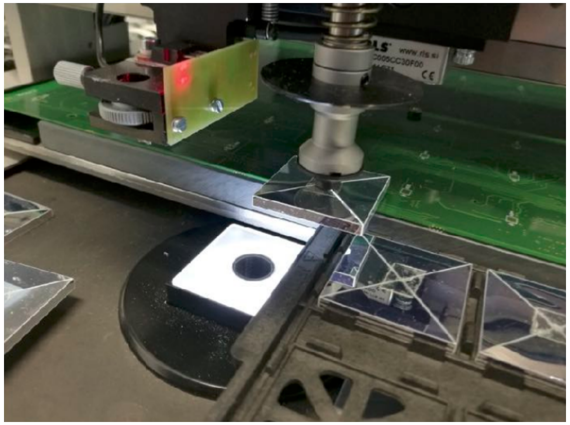


JINST 6 P07005 (2011)



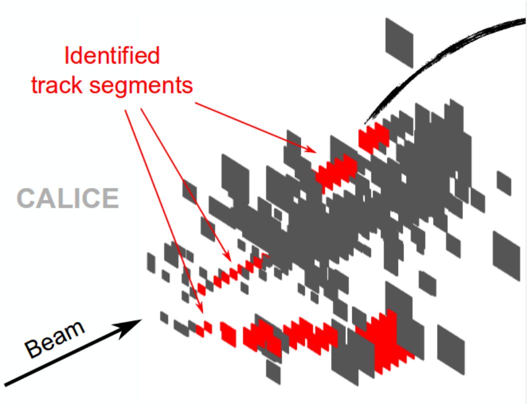
EPJ C77, 698 (2017)

Highly granular calorimeter: development



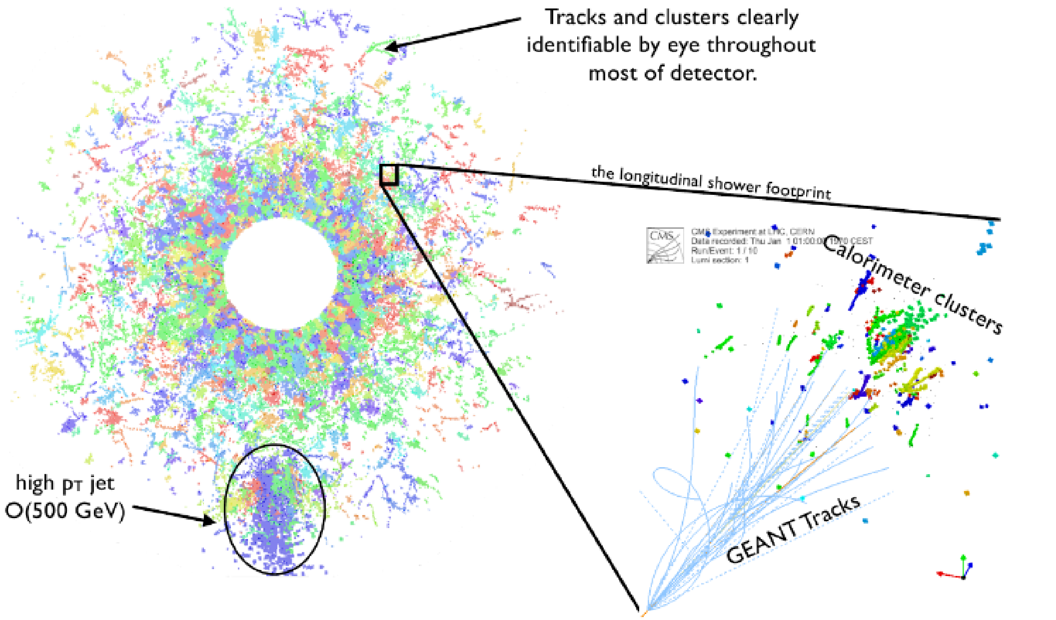
Industrial-style integration

Calibration scheme



CALICE development is well beyond the performance & proof-of-principle stage

CMS HGCAL to demonstrate a complete highly granular calorimeter can be built and operated successfully



LC detector design & performance

Detector design

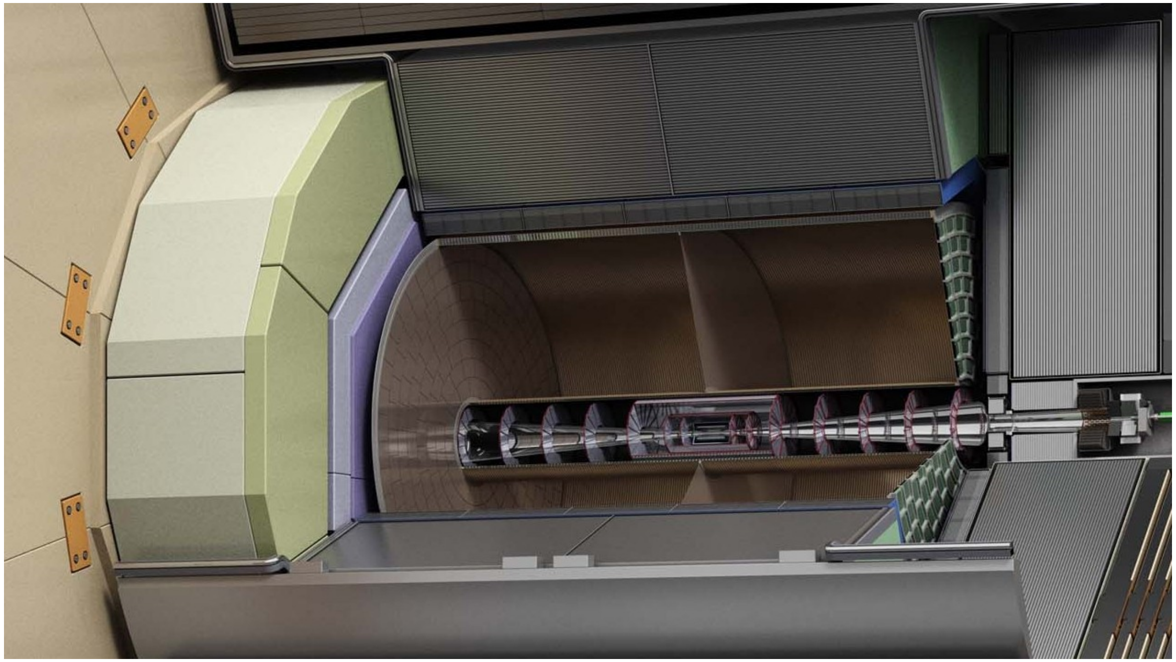
Detailed design of the experiment
informed by 20 years of R&D
optimized for benchmark performance
extensively documented for TDR

ILC detector designs succesfully ported to CLIC environment and then developed further. Ready for CEPC to adopt, adapt and improve!

ILD: large detector, silicon + gaseous tracking

SiD: compact, 5 T B-field, all-silicon tracking

CLIC: deep CALO, modified forward region, larger VXD

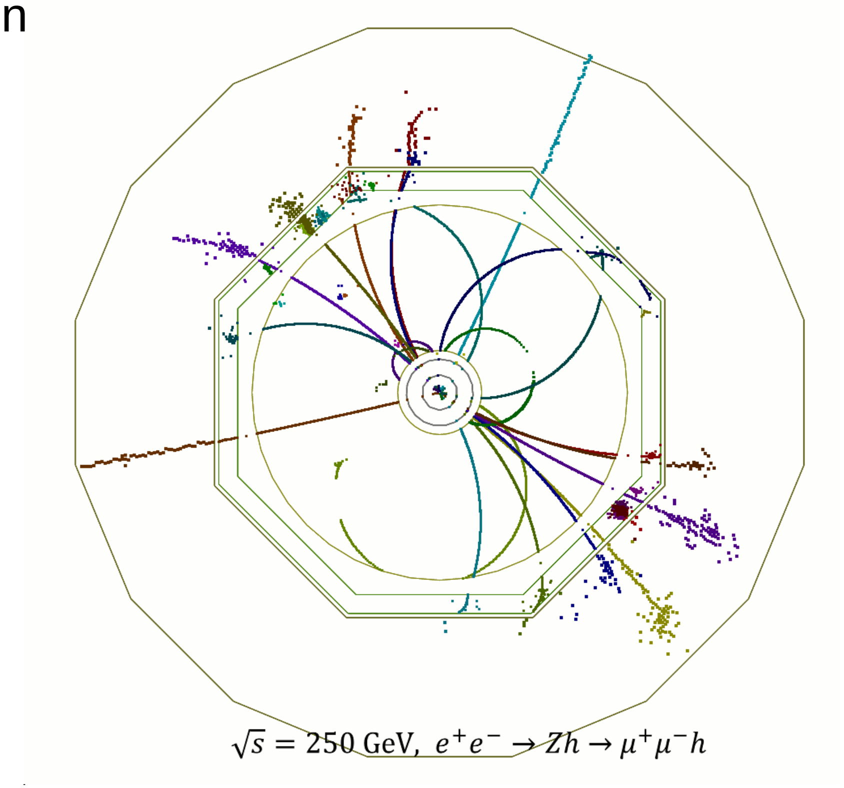


Detector performance

Detector performance and physics benchmarks studies are made possible by a large effort on simulation and reconstruction software

Core software packages:
Persistency: LCIO
Geometry: DD4HEP
Reco framework: Marlin
Grid submission toolkit: iLCDirac

High-level reconstruction algorithms
LCFI vertex + flavour tagging
PandoraPFA (+Arbor)
FastJet + VLC jets



Detector optimization

Complex multi-parameter problem

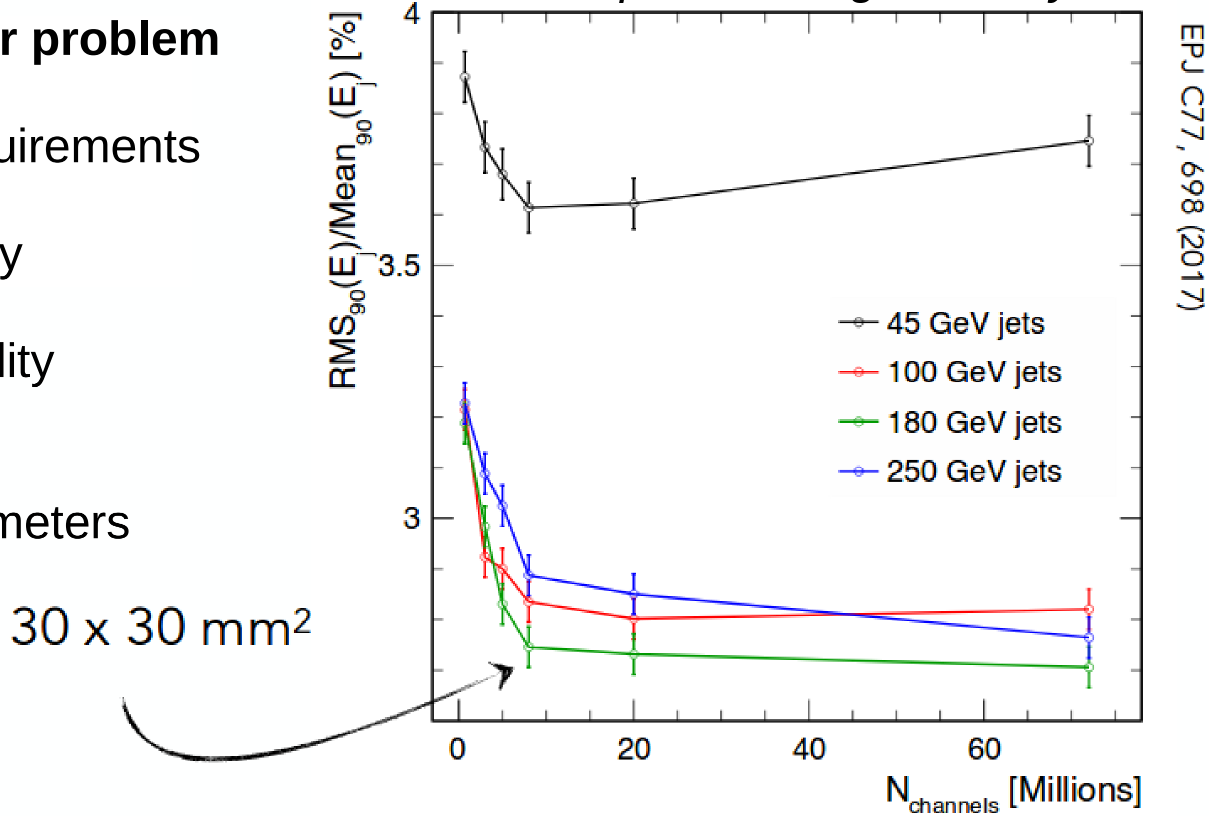
Benchmark studies → requirements

Detector R&D → feasability

Costing studies → feasability

MC studies →
optimal detector parameters

Example: HCAL granularity



ILC and CLIC detector concepts have extensively documented the impact of calorimeter granularity, tracker parameters, and vertex detector performance

LC physics potential

Precision physics at e^+e^- colliders

For precision there is nothing like e^+e^-

Machine: per mille level control over luminosity, polarization and beam energy calibration

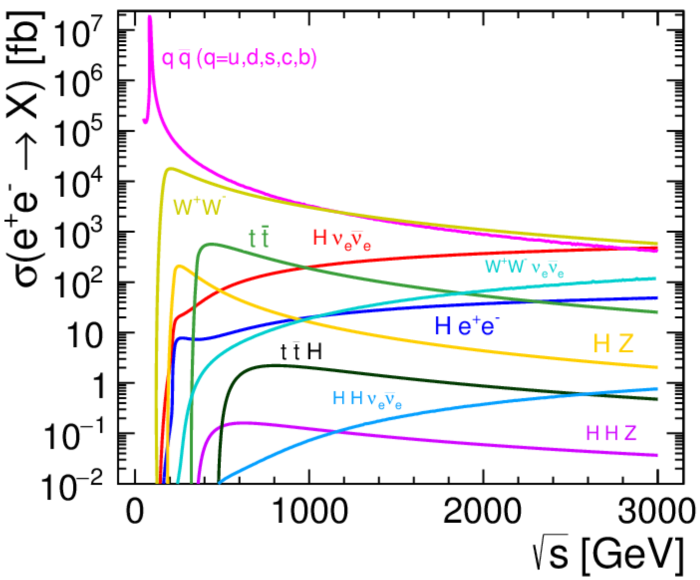
Selection: democratic cross sections allow for truly inclusive measurements (no trigger!)

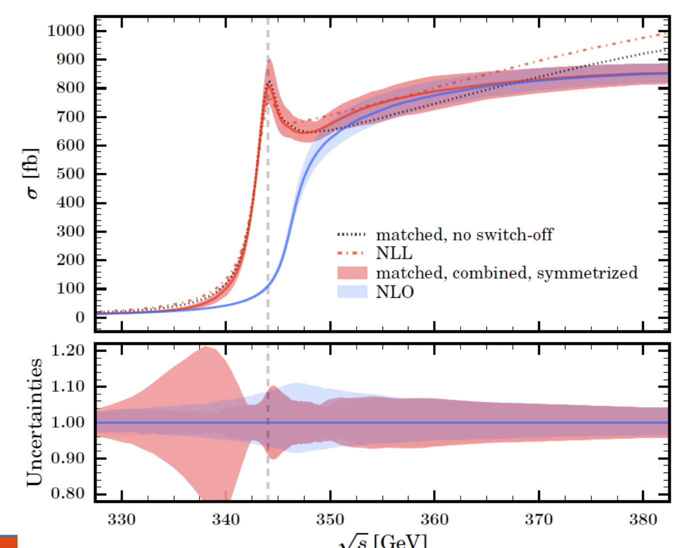
Detector: very little pile-up or radiation damage

Theory: no PDFs, small QCD corrections
Predictions at few per-mille level already today!

Example: top quark pair production
LHC13: ~5% (NNLO scale + PDF)
LC500: ~0.5% (N^3LO scale + EW)
See also: arXiv:1706.03432, arXiv:1609.03390

Challenge: excellent detectors must make sure the experiment matches few per mille theory precision





Effective field theory

Extend SM Lagrangian with D6 operators. Effect suppressed by new physics scale Λ

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

(59 Wilson coefficients represents general high-scale NP compatible with gauge invariance)

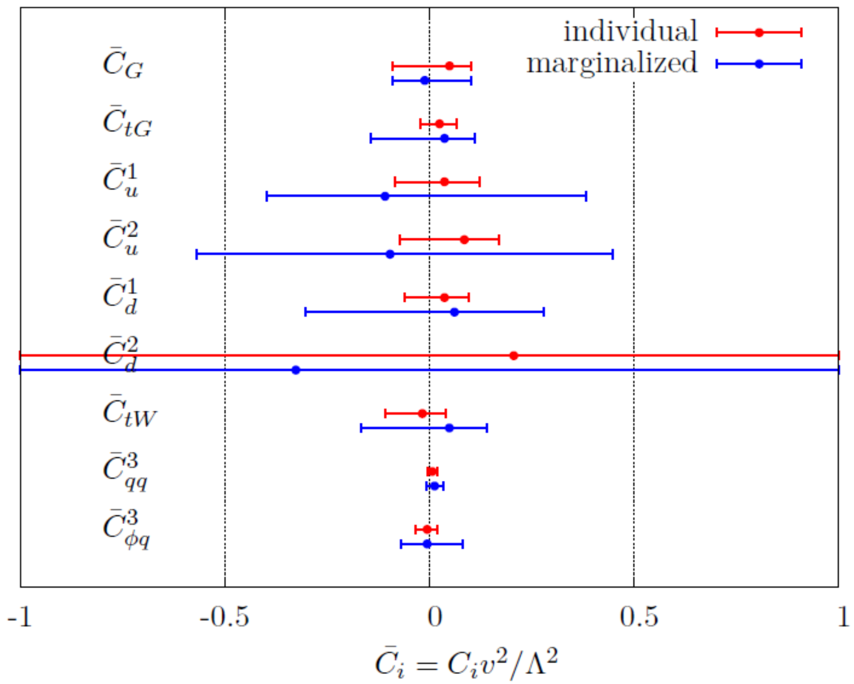
Economy: EFT limits can be mapped on many NP scenarios

Connection: EFT relates measurements in different sectors (EW, Higgs, top)

Standard: LHC increasingly use EFT to interpret measurements (i.e. LHCtopWG)

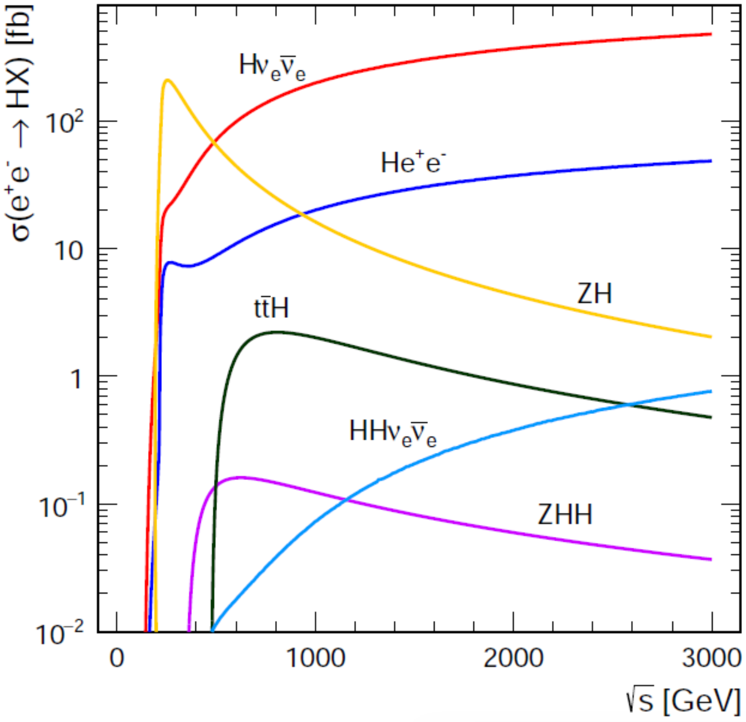
LC pioneers Higgs couplings + EWPO + WW fit in EFT framework *arXiv:1708.08912*

Michael Peskin: SMEFT + ILC = GOLD
(source: Facebook)

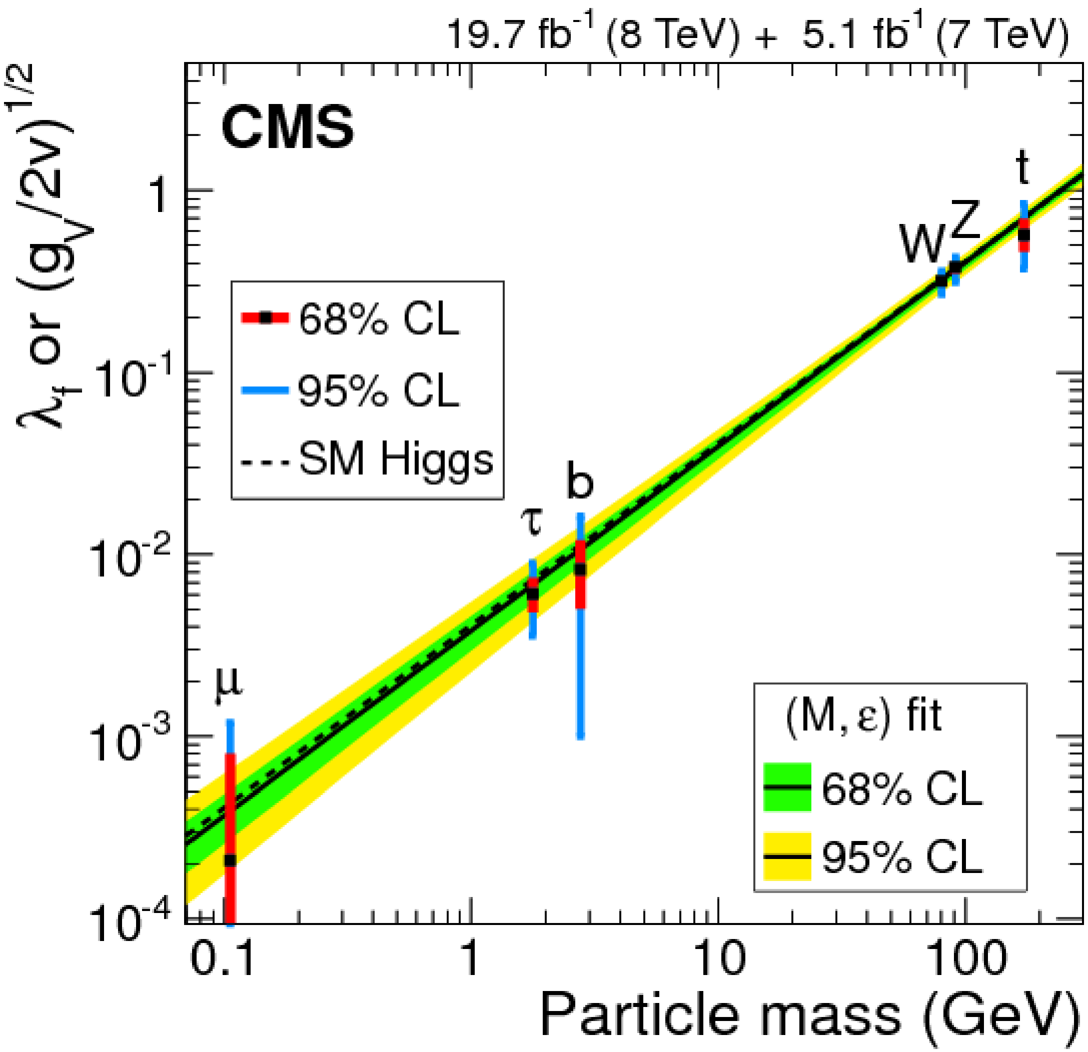


Fit to Tevatron + LHC top results
arXiv:1506.08845, arXiv:1512.03360

LC Higgs physics potential



Higgs couplings: LHC



LHC run 1 Legacy paper:
arXiv:1606.02266

$\mu = 1.09 \pm 0.11$.

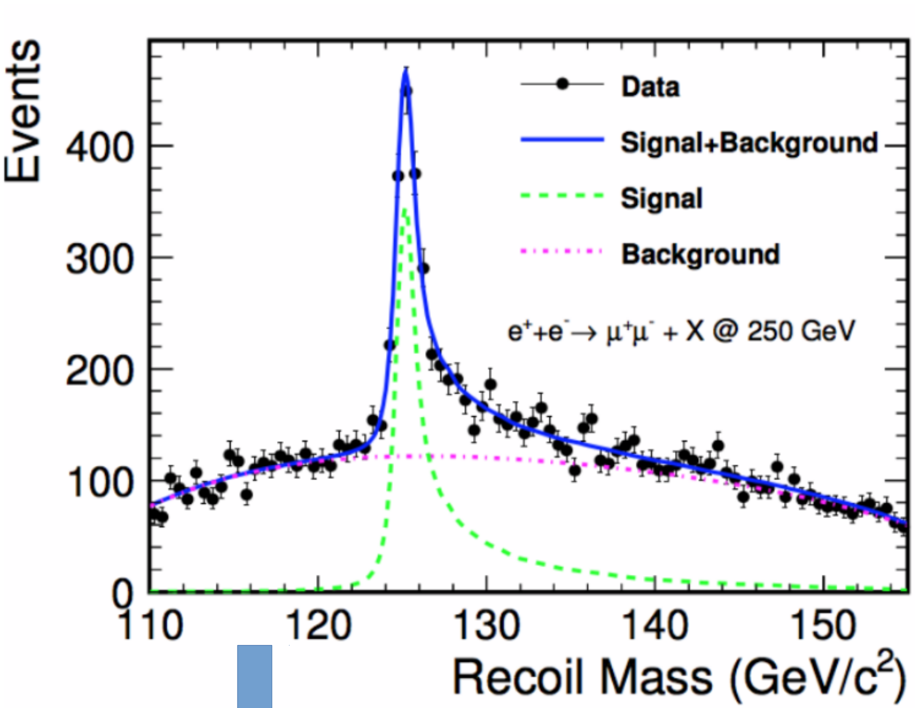
VBF production: 5.4 σ
H → ττ decay 5.5 σ

“The data are consistent with the SM predictions for all parameterisations considered.”

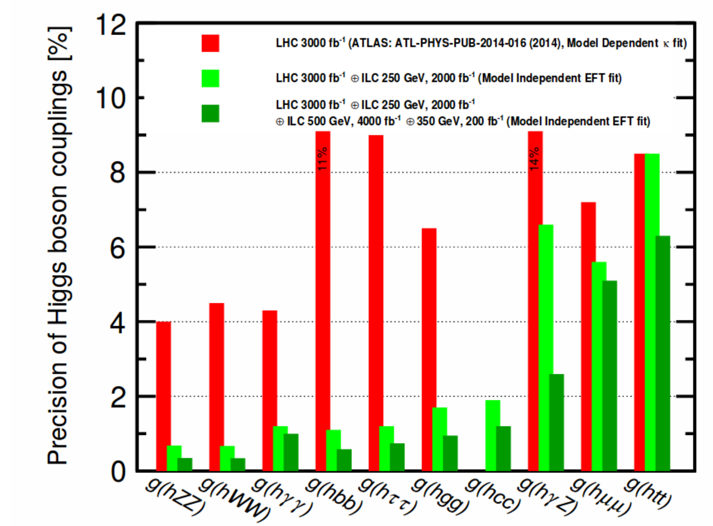
LHC + HL-LHC reaches 5-10%

Higgs coupling measurements

Higgs recoil-mass analysis is a goldmine



Standard couplings

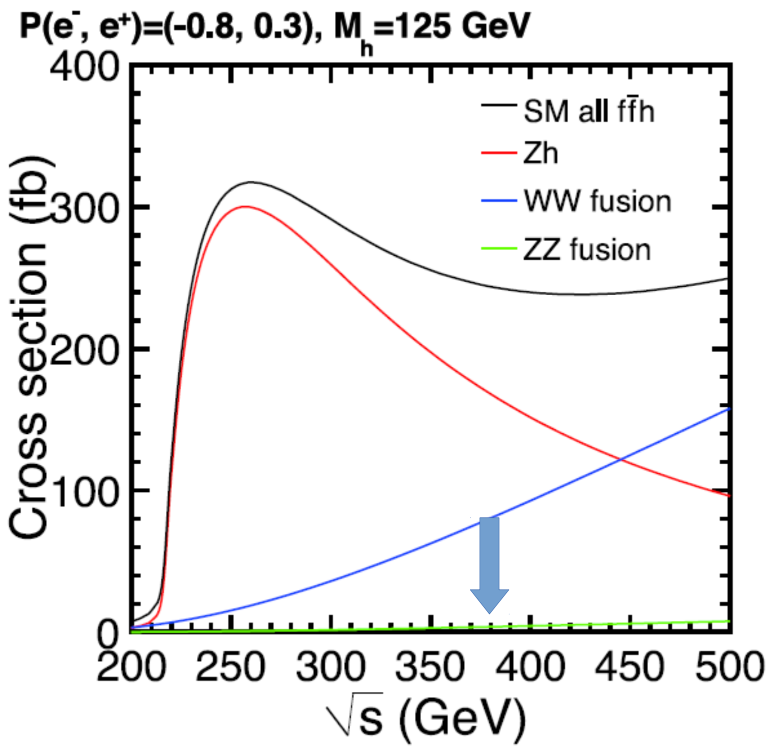


Exotic decays
limit on invisible decays
is upper limit (0.3%)
Dedicated analysis ???

Invisible decays

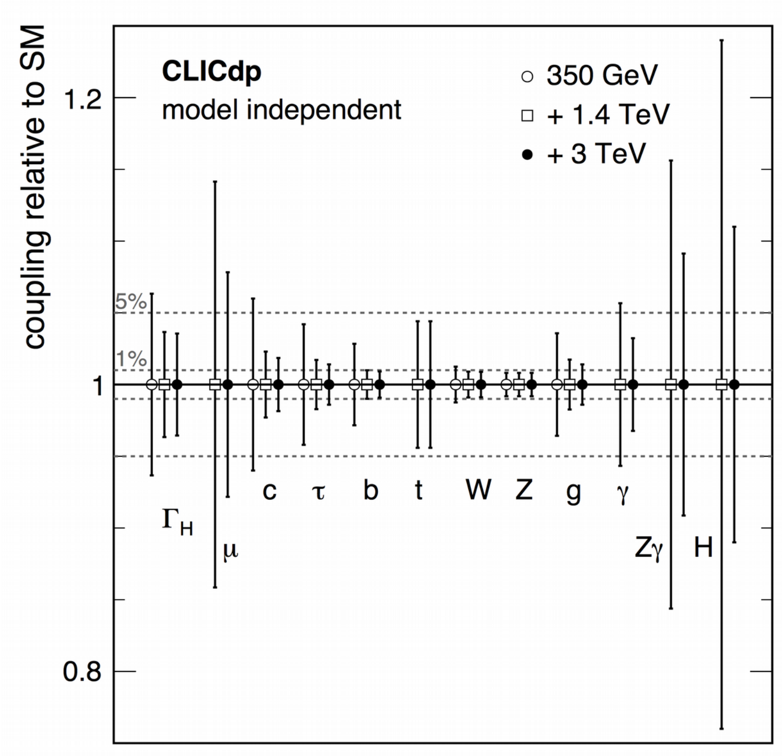
The 250 GeV ILC is expected to be sensitive to invisible Higgs decays with branching ratios as small as 0.3% [20], a factor of 20 below the expected HL-LHC sensitivity, arXiv:1710.07621

Higgs couplings: CLIC



CLIC staging scenario

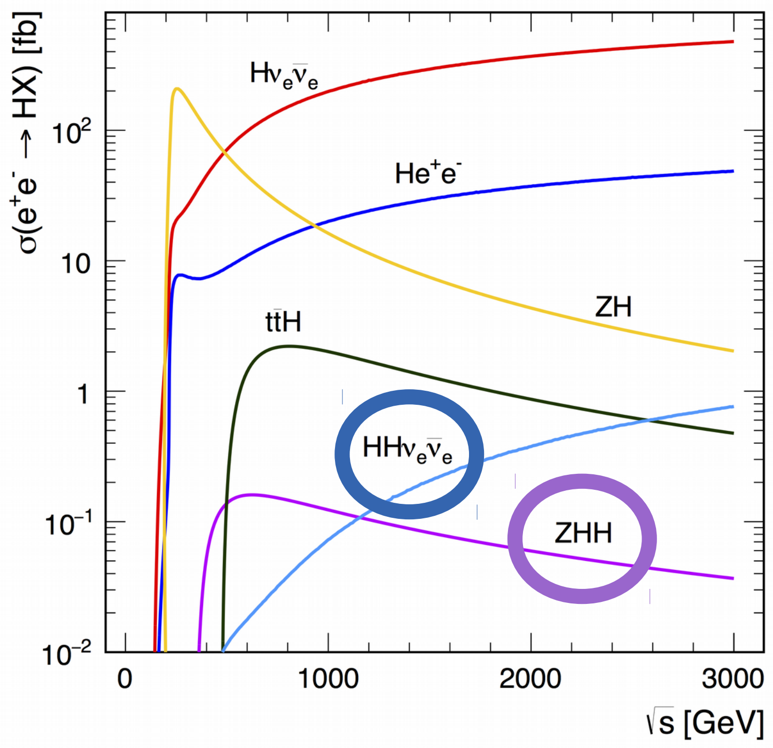
An initial run at 380 GeV gives access to both Higgsstrahlung and VBF



Initial run is already very good
0.38 TeV + 1.5 TeV + 3 TeV better still!

Higgs paper: arXiv:1608.07538

Higgs self-coupling



Large deviations from SM prediction in composite Higgs and some SUSY scenarios

Crucial test of the Higgs mechanism

Small rates, complex final states, challenging jet clustering and combinatorics

Very hard at any collider... Sophisticated full simulation study of (Z)bbbb and (Z)WWWW

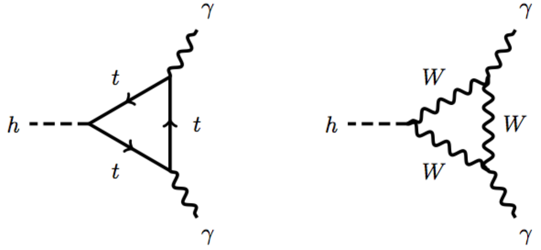
ILC with 4 ab^{-1} at $\sqrt{s}$ = 500 GeV: measure the self-coupling λ with 26% precision. (10% when combined with 1 TeV).

CLIC at 1.4 TeV and 3 TeV: measure λ to 10%.

Top Yukawa coupling

At the LHC the top quark Yukawa coupling is inferred from the observed gg → H and H → γγ rates.

Run I result: $k_t = 1.43 \pm 0.23$



The top Yukawa coupling can be measured directly in associated ttH production.

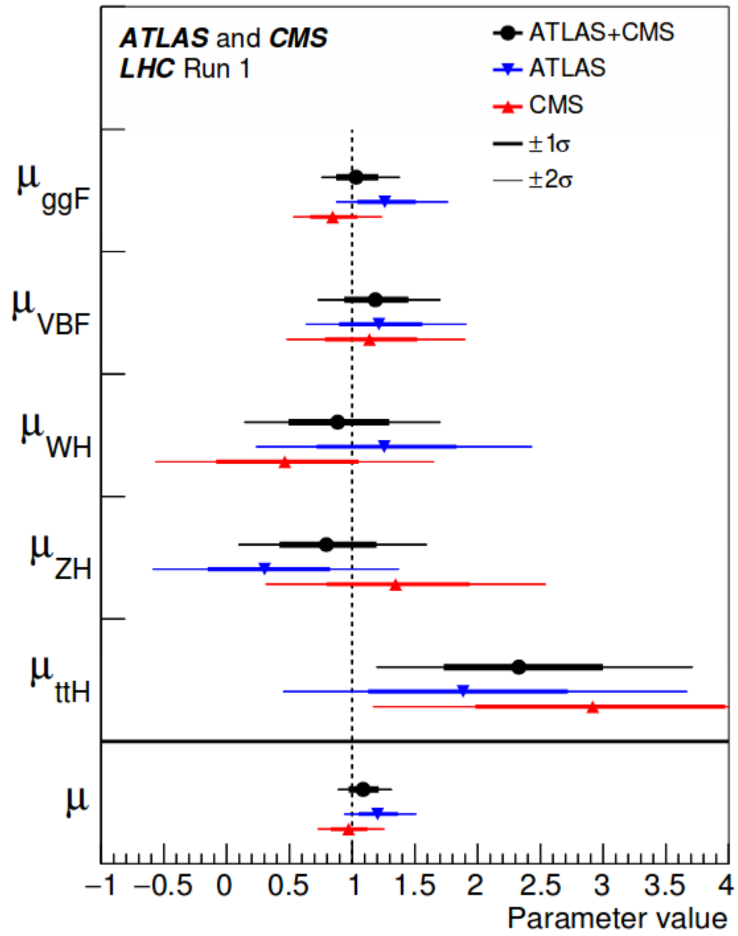
Run I result: $\mu_{ttH} = 2.3 \pm 0.7$

CMS observation:

Prospects for full LHC programme:

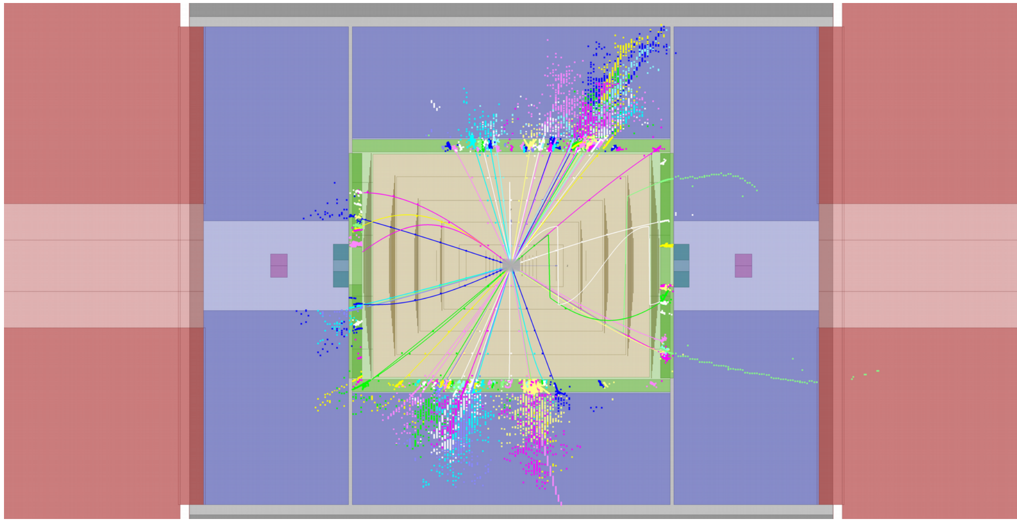
K_u → 14-15% (300/fb)

K_u → 7-10% (3/ab) *Snowmass Higgs report*



Top quark Yukawa coupling

Complex multi-jet events: $t\bar{t}H$, $H \rightarrow b\bar{b}$
Exclusive jet reconstruction
0 leptons → 8 jets
1 lepton → 6 jets



Challenges:

Small signal sample
Large background rejection
Jet reconstruction and pairing

ILC : 3% with 4 ab^{-1} at 550 GeV *arXiv:1506.05992*

ILC : 4% with 1 ab^{-1} at 1 TeV *arXiv:1409.7157*

CLIC : 3.8% with 1.5 ab^{-1} at 1.4 TeV *arXiv:1608.07538*

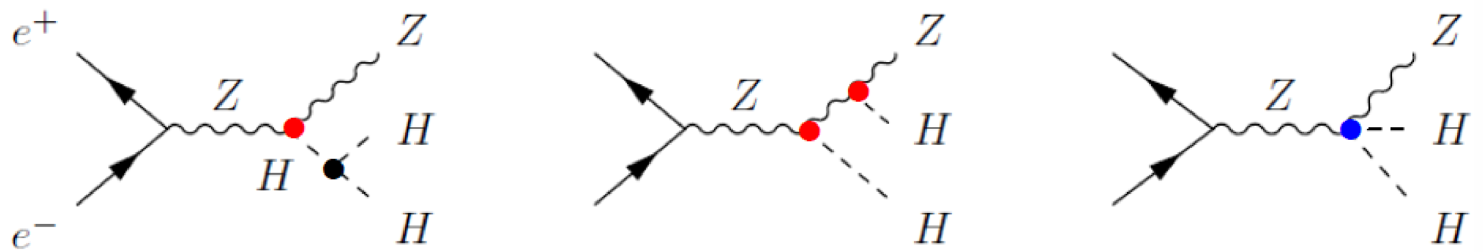
FCChh target: 1% precision *arXiv:1507.08169*

EFT – Higgs self coupling

D6 operators in di-Higgs production

ZHH * = (trilinear) self-coupling, ZZH * and (cuartic) coupling ZZHH * + host of other operators

g_{ZZH} g_{ZZHH} (and other, BSM, couplings) in $\sigma(e^+e^- \to HHZ)$



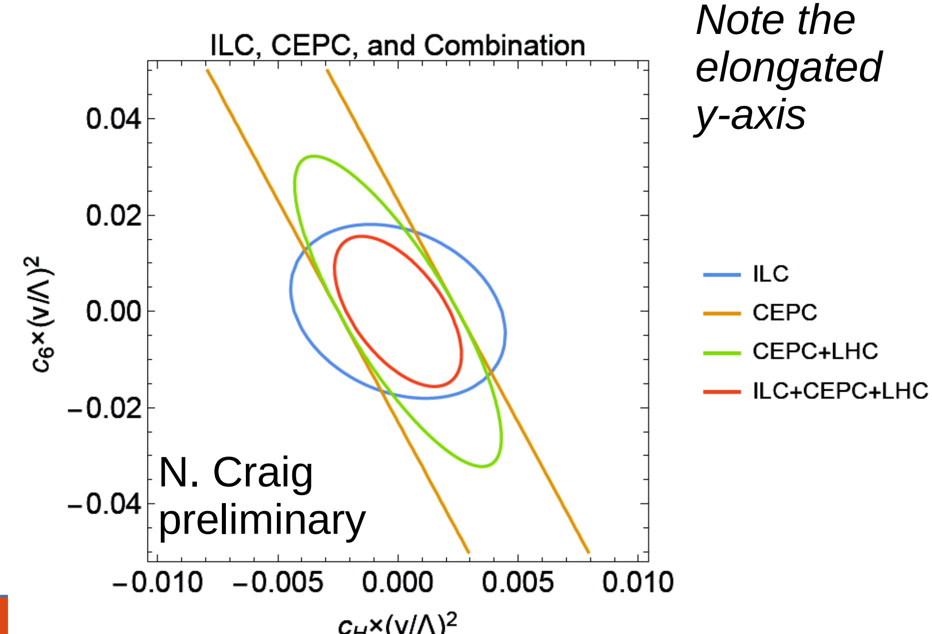
Understand the constraint on trilinear Higgs coupling (operator coefficient c_6) in a global fit to the Higgs sector + EWPO + TGC

Compare with “indirect model-dependent constraint” from ZH production rate *(McCullough, arXiv:1312.3322)*

2D fit in C_H – C_6 plane: complementary constraints from LHC-LC-CEPC

Input LHC: 50% Input ILC: 26%

Note the elongated y-axis



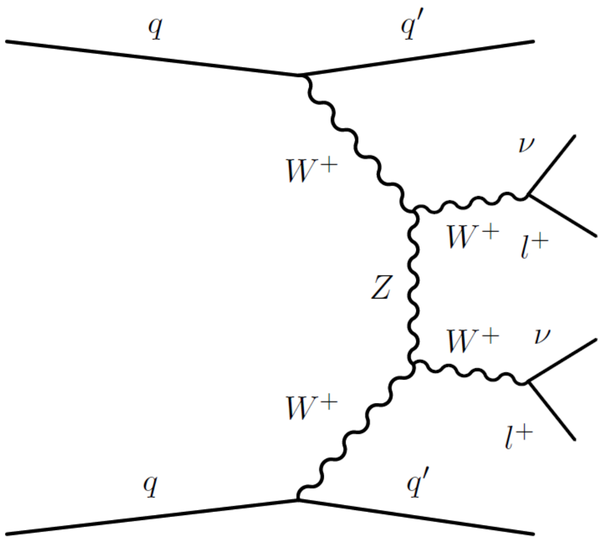
LC VBS physics potential

Vector boson scattering

The process that demanded a Higgs boson...

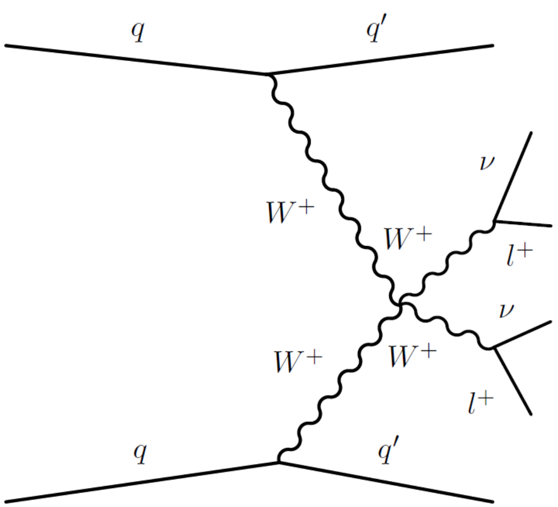
EWK process isolated during run I at the LHC using same-sign WW and WZ production

Forward “tag” jets, high-mass VV' system
ATLAS arXiv:1611.02428
CMS arXiv:1410.6315

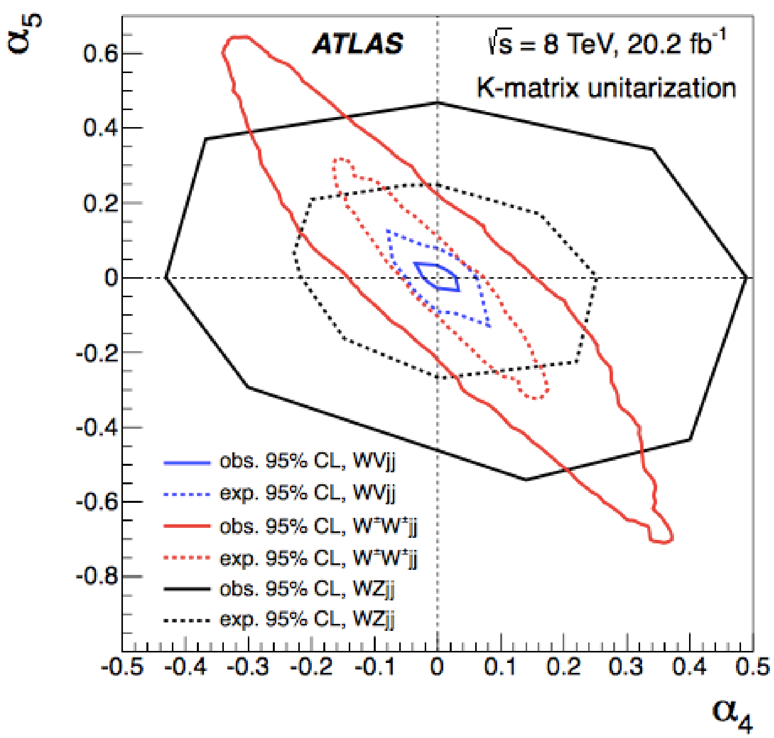


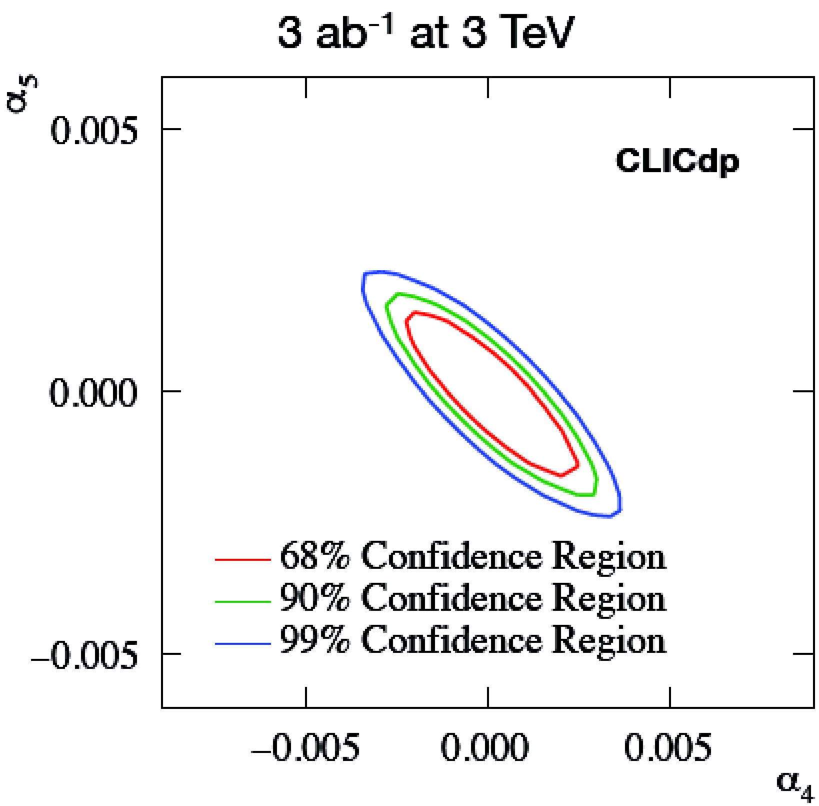
Test Higgs-suppression of longitudinal VBS, constrain anomalous couplings (aTGC and aQGC), measure Higgs properties, Campbell, Ellis arXiv:1502.02990

Towards a global fit of a complete vector boson EFT, including all relevant aTGC and aQGCs, and Higgs operators



Limits on anomalous quartic couplings: LHC vs. CLIC

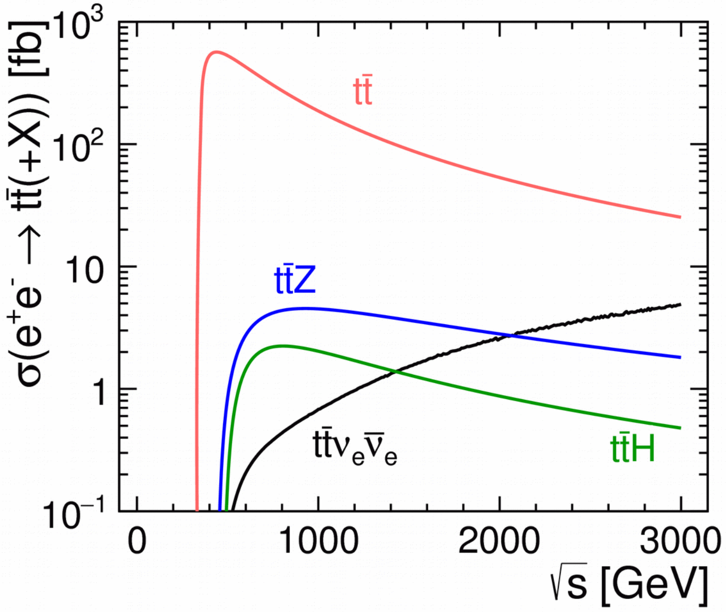




ATLAS run-I, *from Green, Meade, Pleier, arXiv:1610.07572*

CLICdp prospects for 3 TeV

LC top physics potential

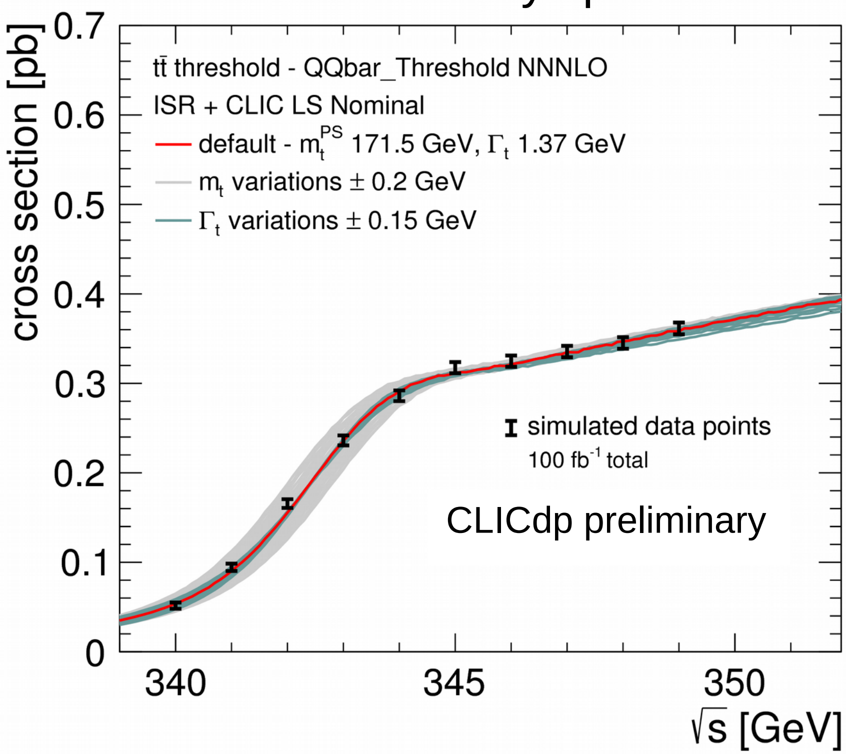


Threshold scan: experiment

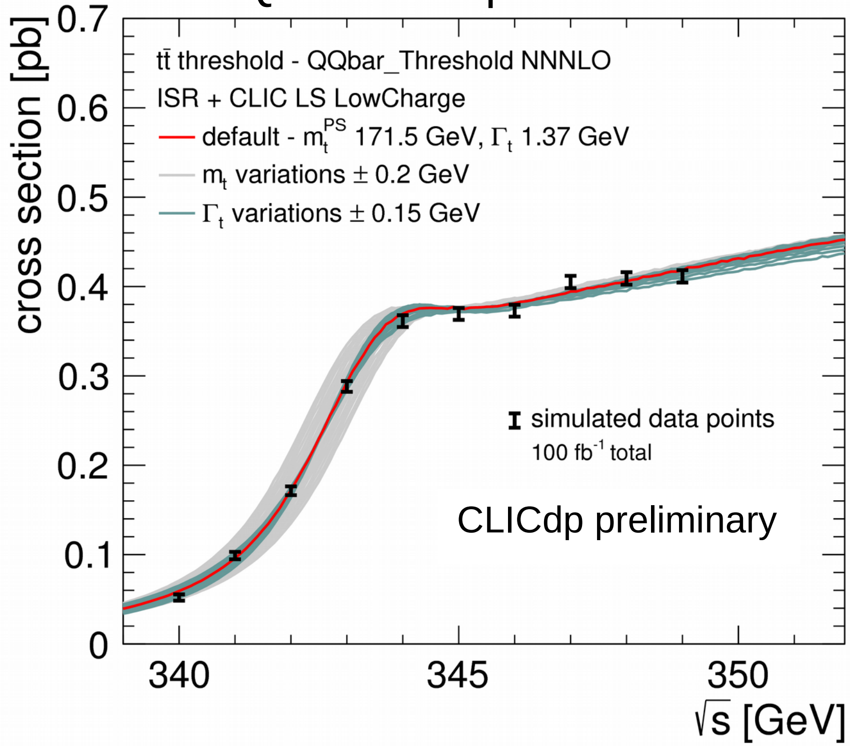
Detailed estimates of the precision in multi-parameter fits

Martinez, Miquel, EPJ C27, 49 (2003), Horiguchi et al., arXiv:1310.0563, Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Nominal luminosity spectrum



Low Q machine parameters



The machine parameters can be tuned (at a cost in instantaneous luminosity) to minimize the impact of the luminosity spectrum on the threshold shape

Higher precision - per unit luminosity – in the mass extraction + potential gain in the width measurement. The details of the scan can be further optimized.

Threshold scan: potential

A multi-parameter fit can extract the PS mass with excellent precision

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental systematics:	25-50 MeV	*including LS, arXiv:1309.0372*

This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

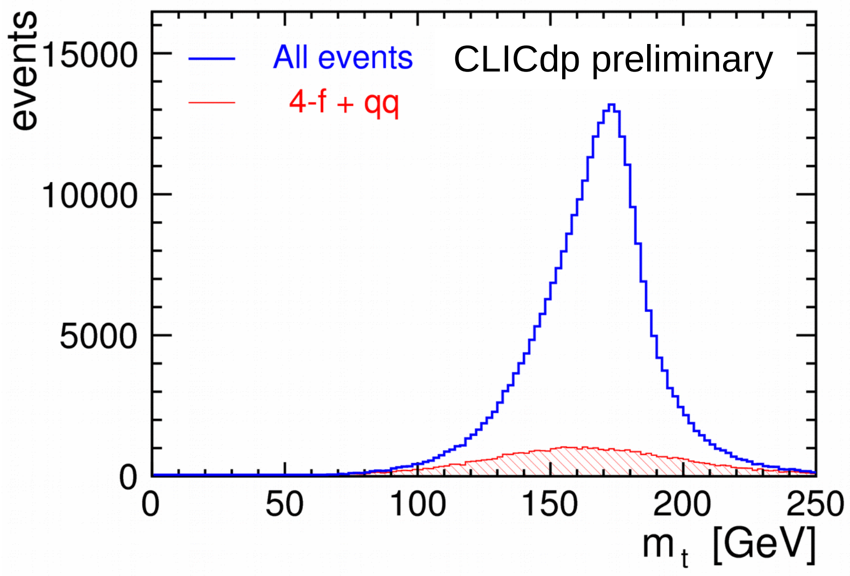
A very competitive top quark mass measurement:

$\Delta m_t \sim 50$ MeV *(= 3×10^{-4}, cf. $\Delta m_b \sim 1\%$)*

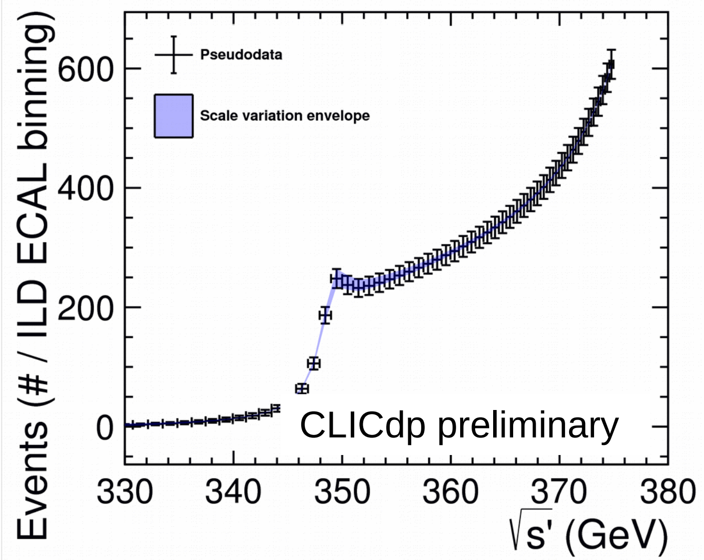
This is a real prospect, not a target! Build the machine and we perform the measurement.

Top quark mass: alternatives

LHC style “direct reconstruction”
Understand MC mass post-hoc



Radiative events: “return-to-threshold”
Access to the running of the mass



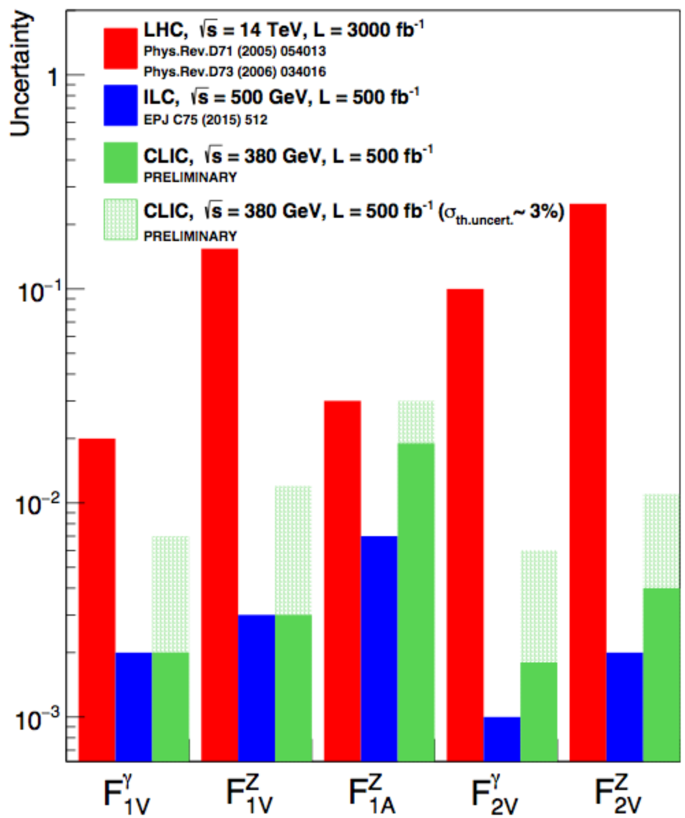
There are (at least) two further ways to determine the top quark mass with ~100 MeV statistical precision using the 380 GeV data

Potential of the high-energy run remains to be explored (see hep-ph/0703207)

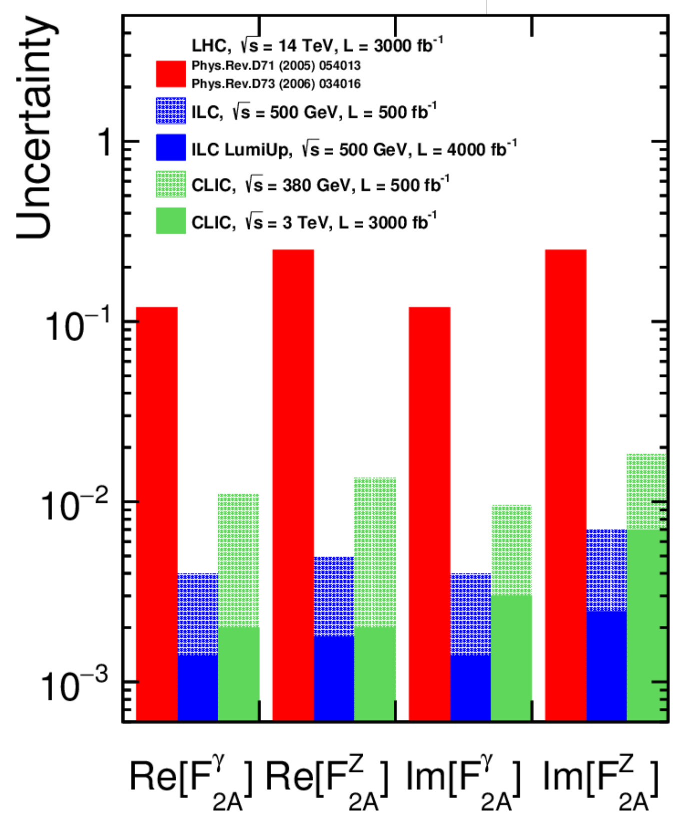
Top anomalous couplings

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

CLIC staging, CERN-2016-004
based on arXiv:1505.06020



arXiv:1710.06737

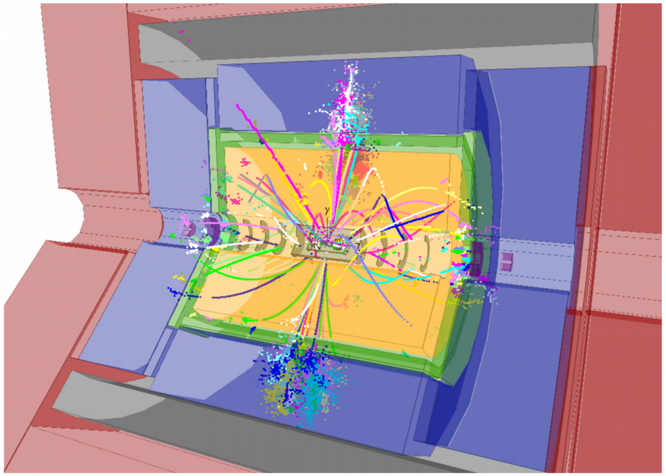


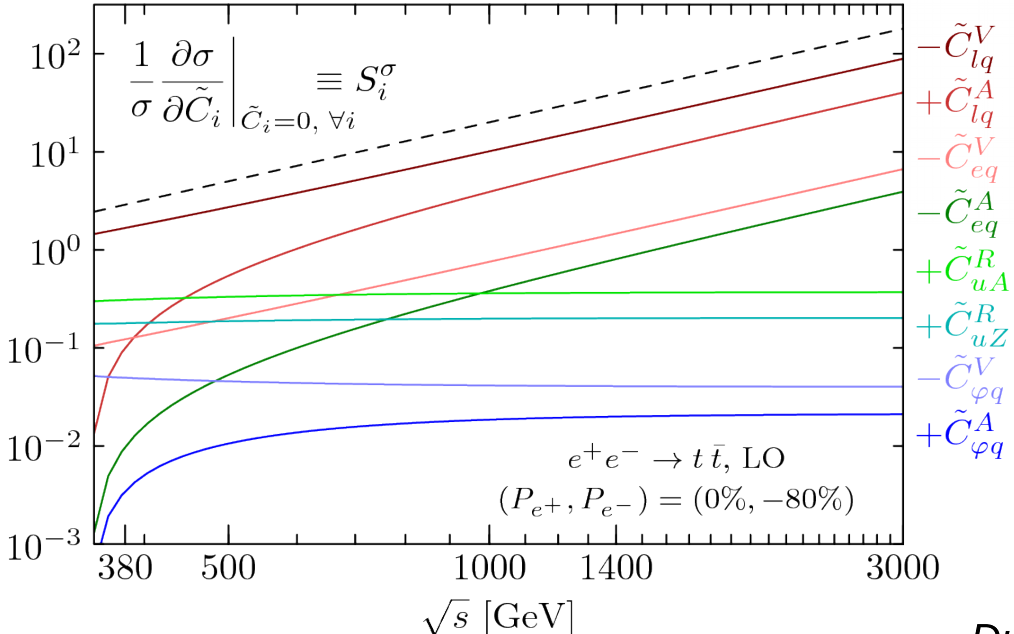
Measurements in pair production in early stage have excellent BSM sensitivity

Top physics at high energy

Top reconstruction at sqrt(s) > 1 TeV challenges jet reconstruction: arXiv:1607.05039

Top tagging studied in detail in CLIC top paper





Impact of 4-fermion operators μ E^2
→ best constrained at high energy

Impact of 2-fermion operators ~ c
→ best constrained at low energy

Durieux, Perelló, Vos, Zhang

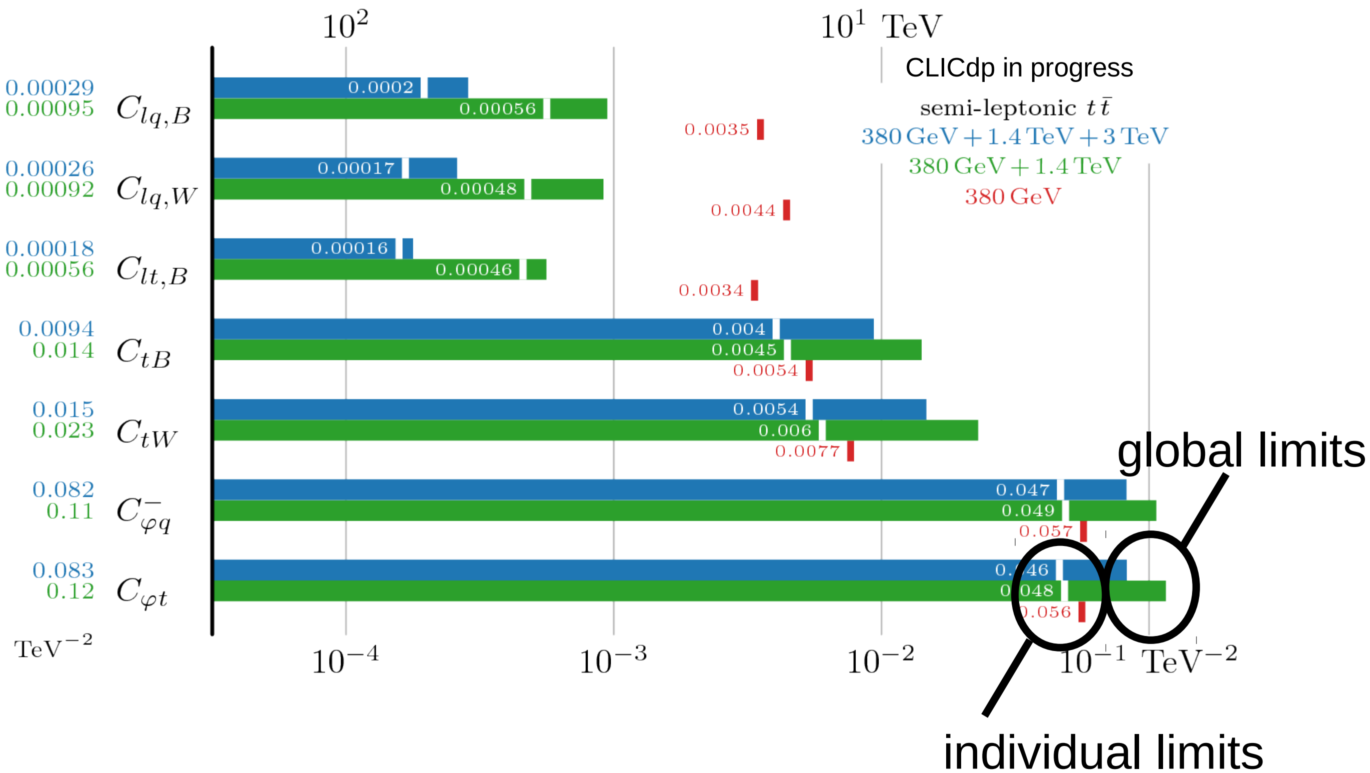
Global EFT fit

Global 7-parameter fit – top-philic scenario

380GeV+1.4TeV+3TeV
(indiv. + global limits)

380GeV+1.4TeV
(indiv. + global limits)

380 GeV
(individual limits only)



CLIC top physics program provides tight constraints on all 7 coefficients
cf. current Tevatron+LHC limits from TopFitter collaboration are O(10)
all operator limits significantly exceed HL-LHC prospects
limits on 4-fermion and dipole moment operators are excellent!

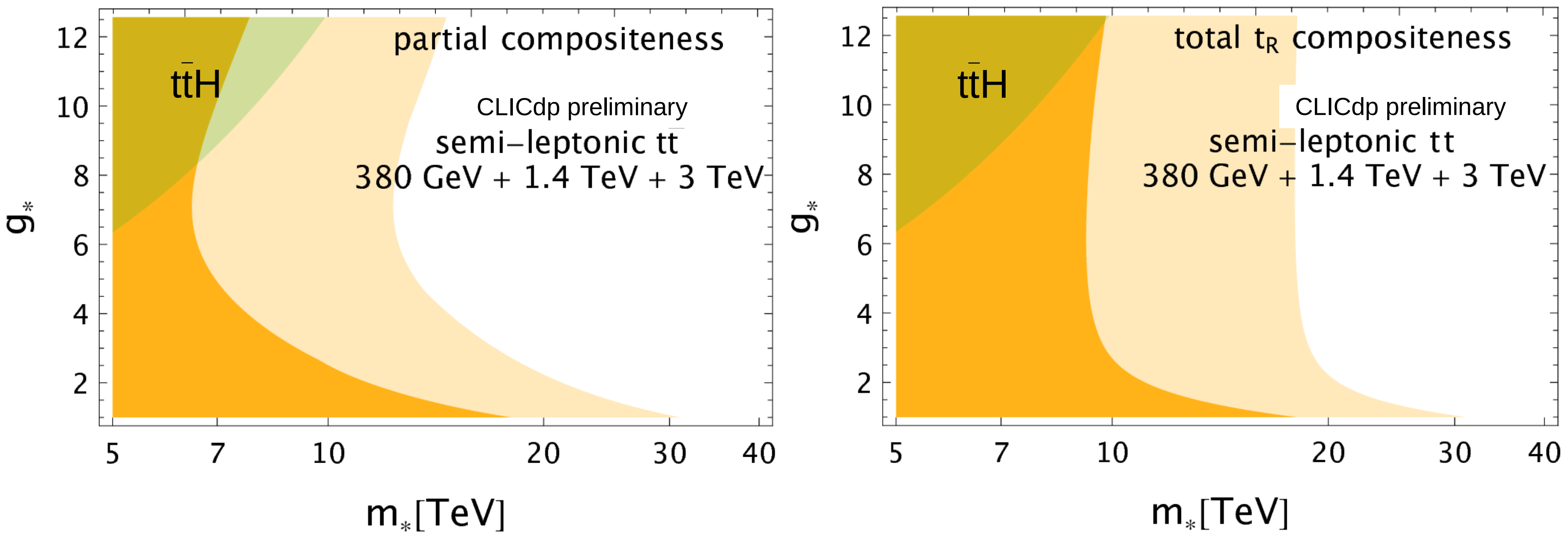
From EFT to concrete scenario

Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

The top quark is naturally composite in this framework (*Pomarol 2008*), the only viable option to generate the top Yukawa coupling (*Ratazzi 2008*)

Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)

Pessimistic 5σ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV



Summary

HEP needs a plan!

The European strategy update must decide on the global future of HEP.

LC community has made significant progress towards a **complete** proposal

- comprehensive detector R&D program → technologies already on the market

- particle-flow detector concept → optimal global performance

The LC physics program complements the LHC + HL-LHC in important ways.

- Higgs couplings: **sub-%**
- Top Yukawa coupling: **3-4%**
- Higgs self-coupling: **~10%**
- vector-boson scattering: **order of magnitude**
- top mass measurement: **Δm_t ~ 50 MeV**
- top quark EW couplings: **order of magnitude**

And much more that I haven't discussed

A **real** chance for HEP to explore the energy regime 1-10 TeV

LC-CEPC synergy to be exploited more fully

Topical cross-project studies and workshops