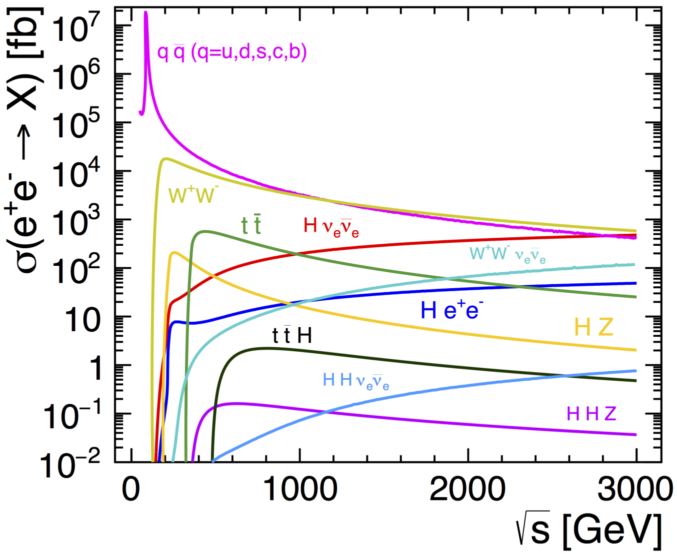
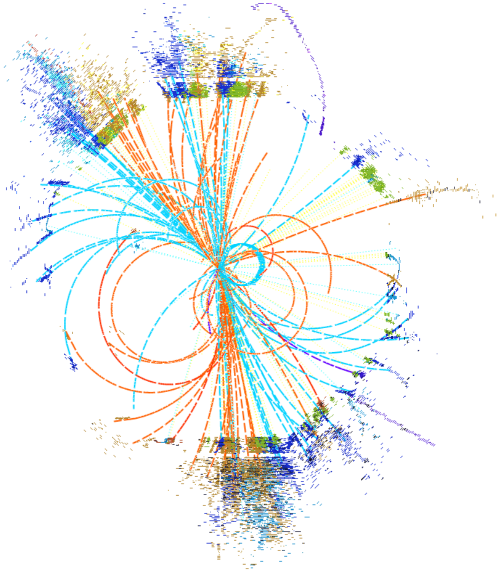
CLIC overview

Philipp Roloff (CERN)
on behalf of the CLICdp collaboration

07/09/2017
Corfu Summer Institute:
Workshop on the Standard Model and Beyond



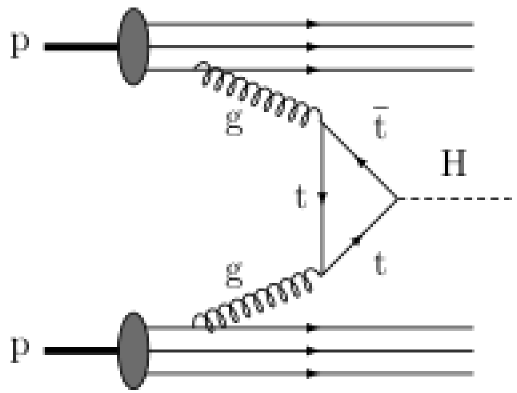


Introduction:

- CLIC accelerator
- Staged implementation
- Detector requirements and concept

Hadron and e^+e^- colliders

Hadron colliders:

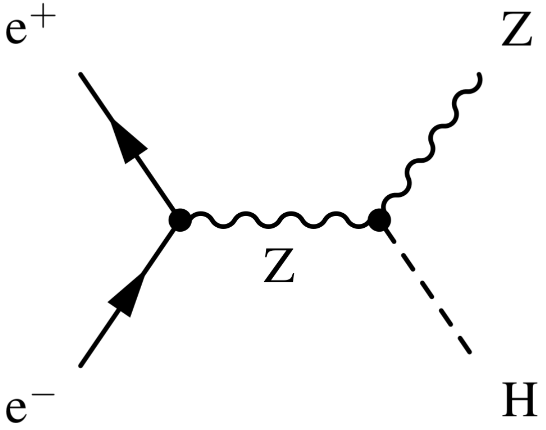


- **Proton is compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:

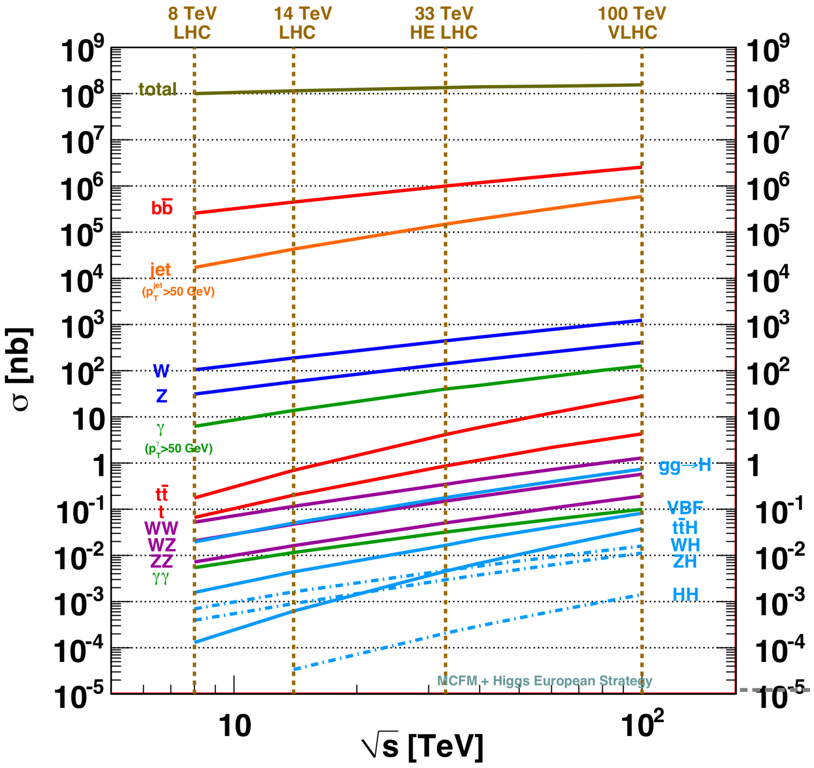


- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

- **High energies ($\sqrt{s}$ > 350 GeV) require linear colliders**

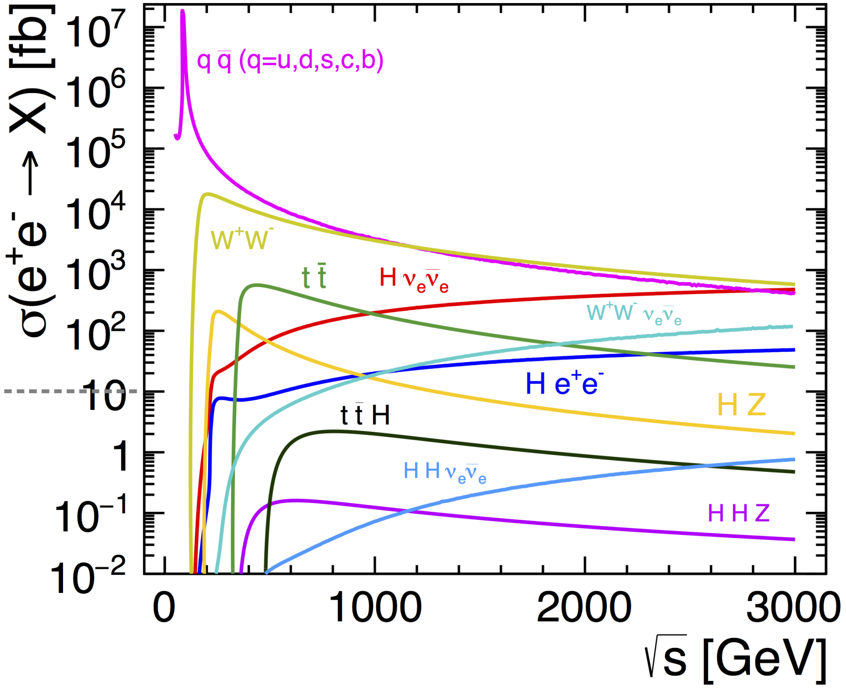
- **Clean experimental environment**
→ Less / no need for triggers
→ Lower radiation levels

pp and e^+e^- collisions



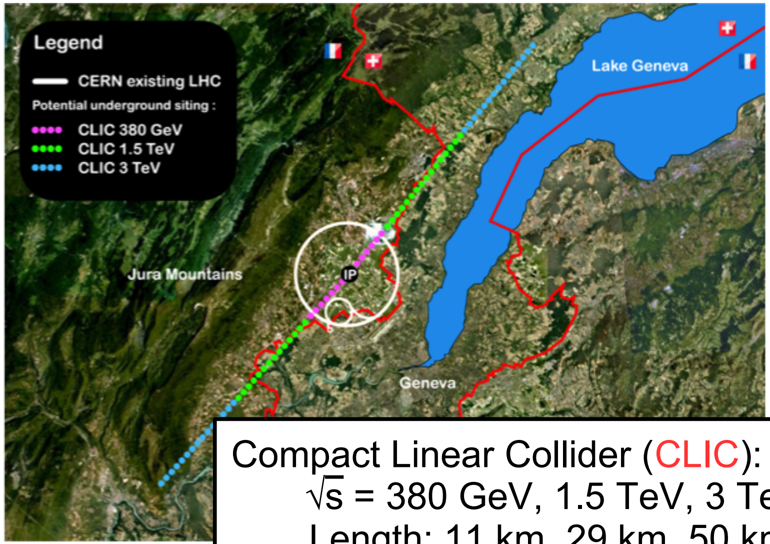
8 orders of Magnitude!

pp collisions:
Interesting events need to be found in huge number of collisions

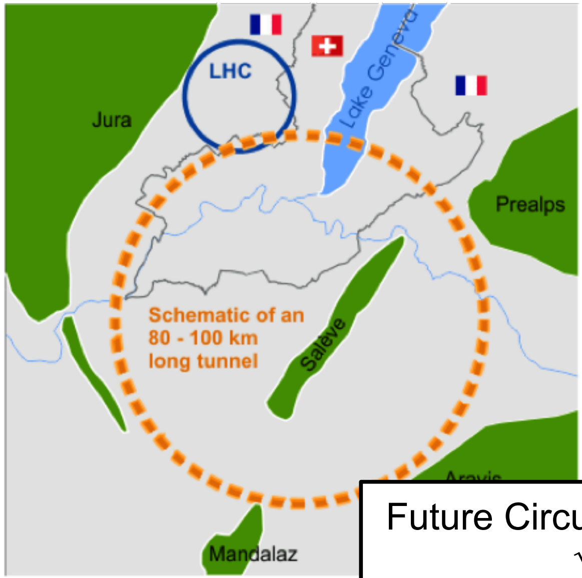


e^+e^- collisions:
More “clean”, all events usable

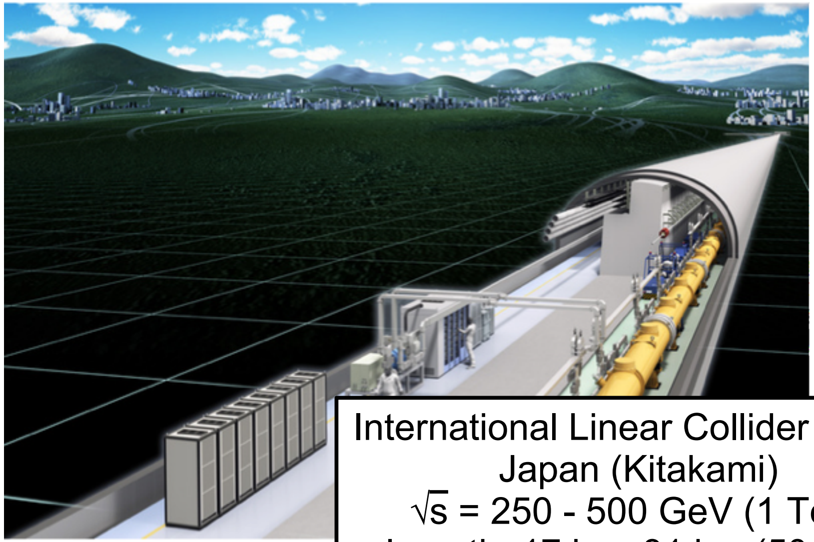
Studies of high-energy e^+e^- colliders



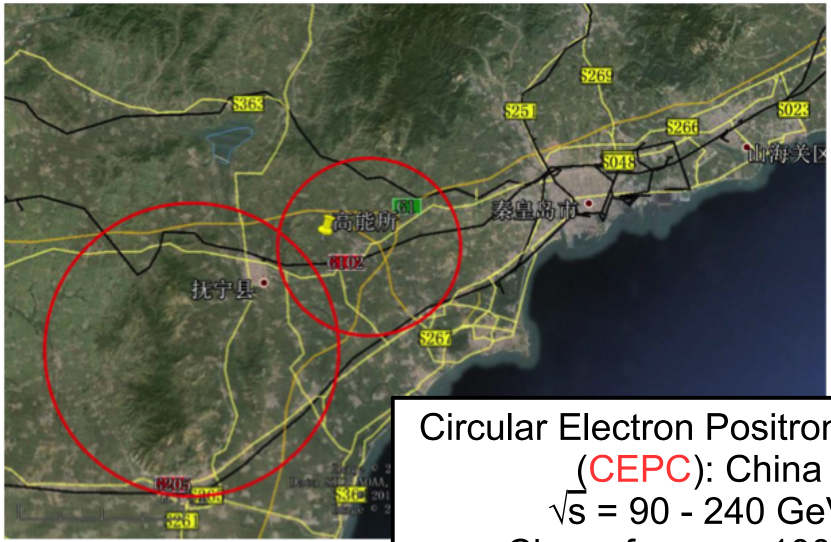
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 350 GeV
Circumference: 97.75 km

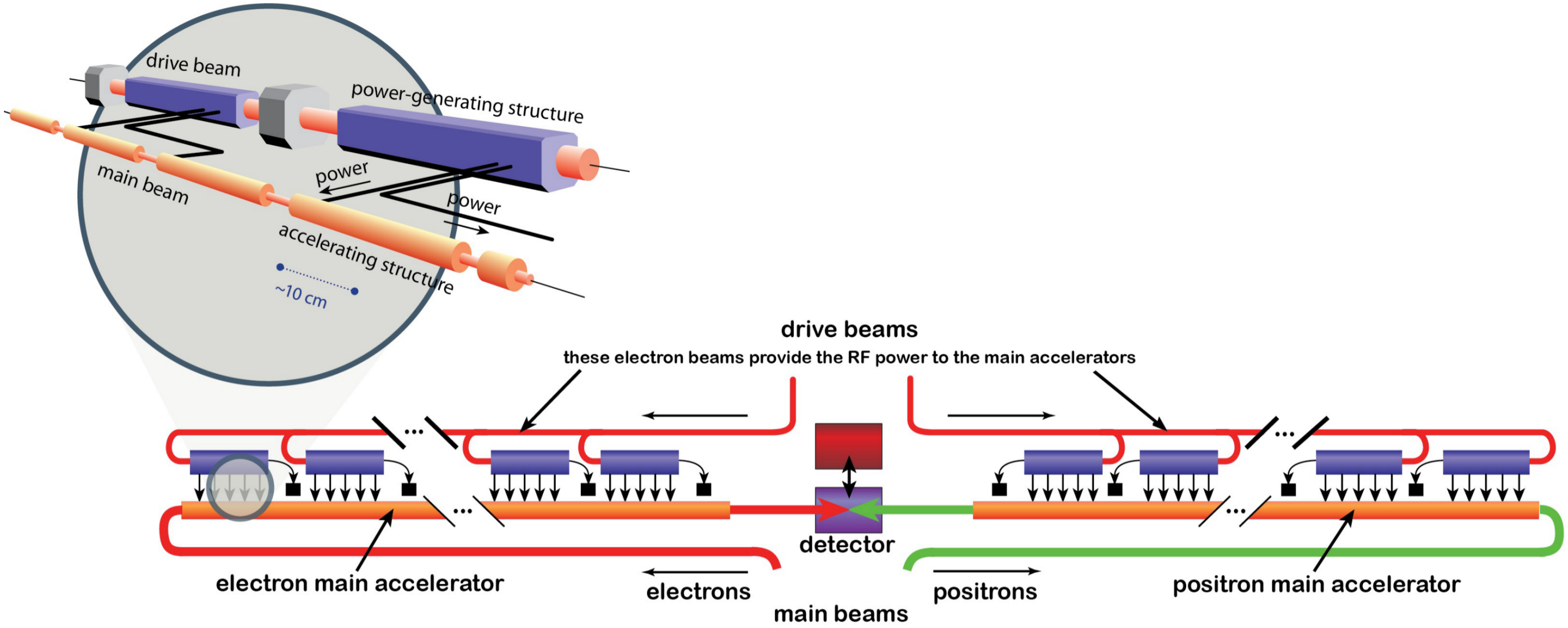


International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)

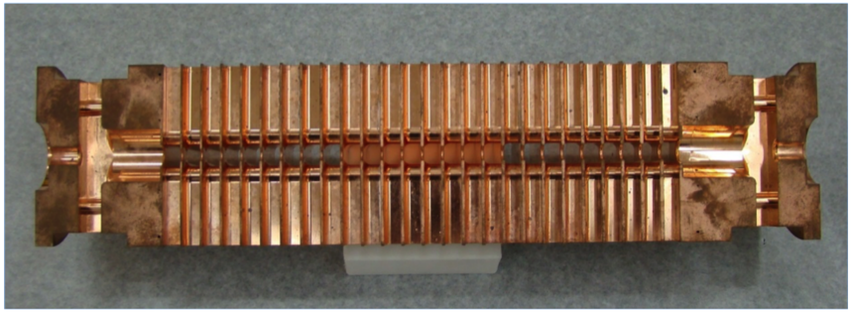


Circular Electron Positron Collider
(CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

The Compact Linear Collider (CLIC)



Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
(in several stages)
- Length: 50 km (for 3 TeV)
- P(e^-) = ±80%

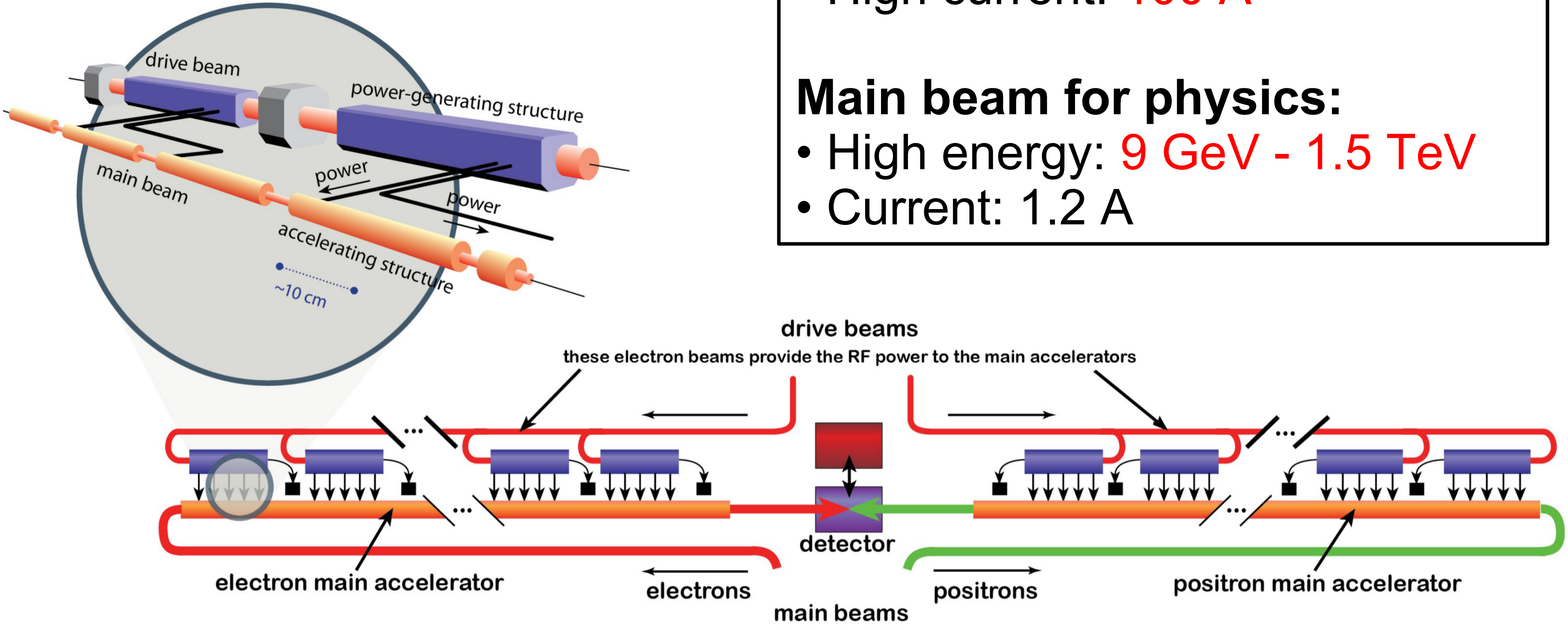


CLIC acceleration scheme

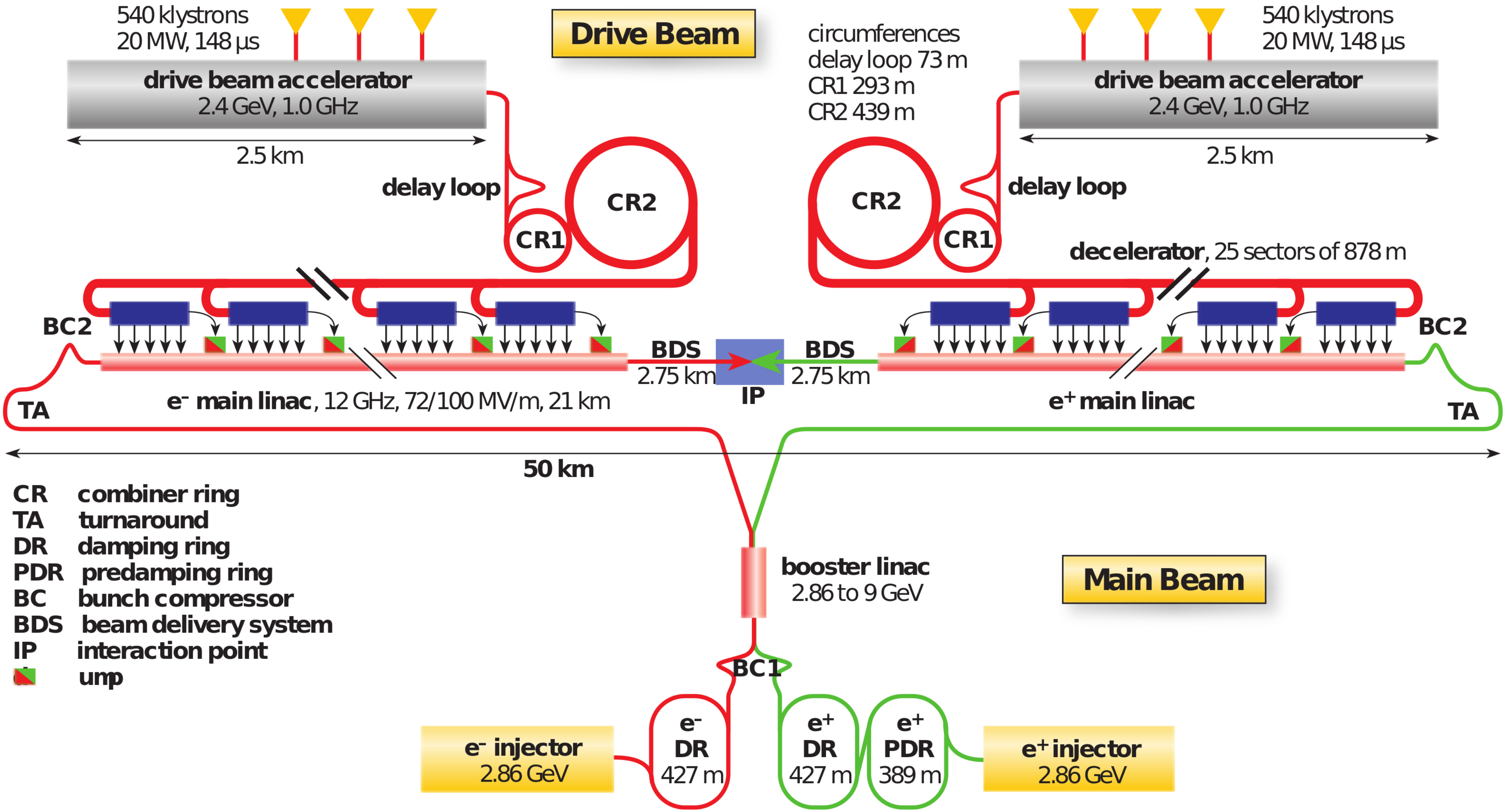
Drive beam supplies RF power:
- 12 GHz bunch structure
- Low energy:

2.4 GeV - 240 MeV
- High current: 100 A

Main beam for physics:
- High energy: 9 GeV - 1.5 TeV
- Current: 1.2 A



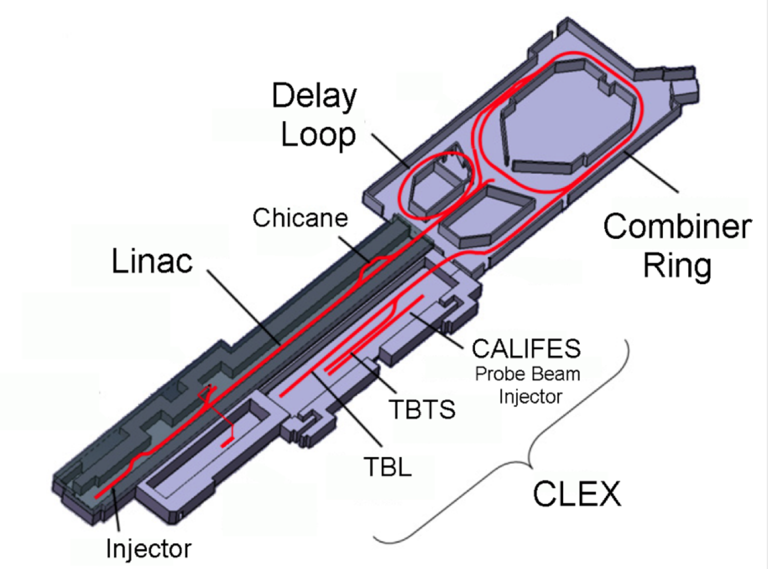
CLIC layout at 3 TeV



CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**ump**

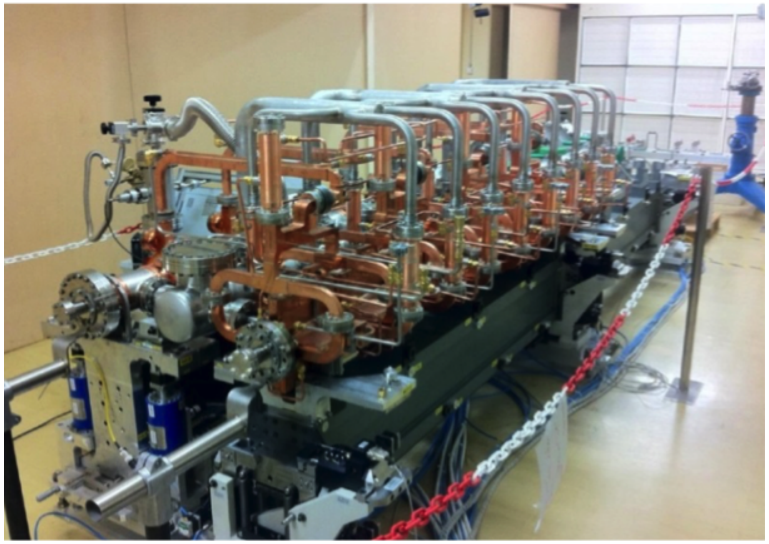
The CLIC Test Facility (CTF3)

CTF3 successfully demonstrated:
- Drive beam generation
- RF power extraction
- Two-beam acceleration up to a gradient of 145 MeV/m

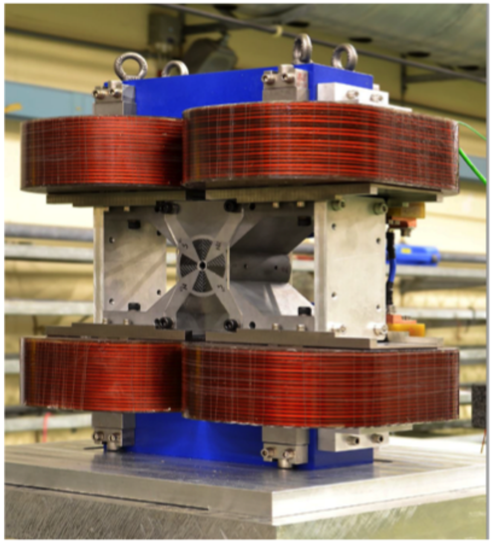


- CTF3 completed its mission in 2016
- A new facility since 2017 (based on the CTF3 probe beam): **CERN Linear Electron Accelerator for Research (CLEAR)**

CLIC accelerator R&D



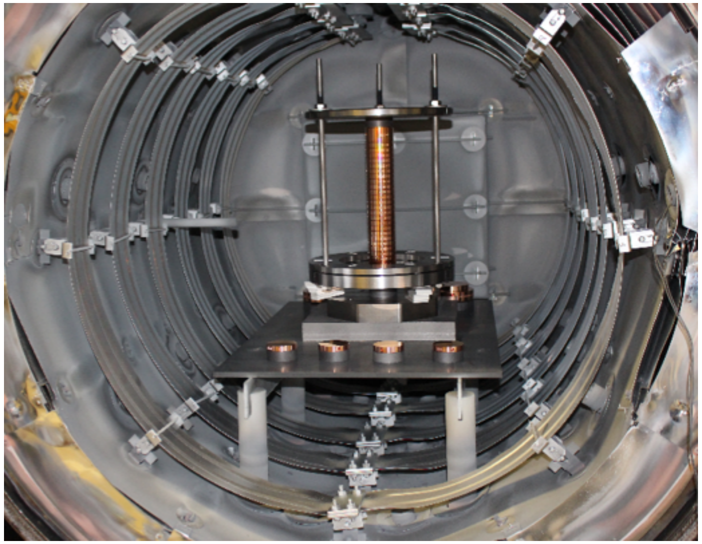
Mechanical tests of 2-beam module



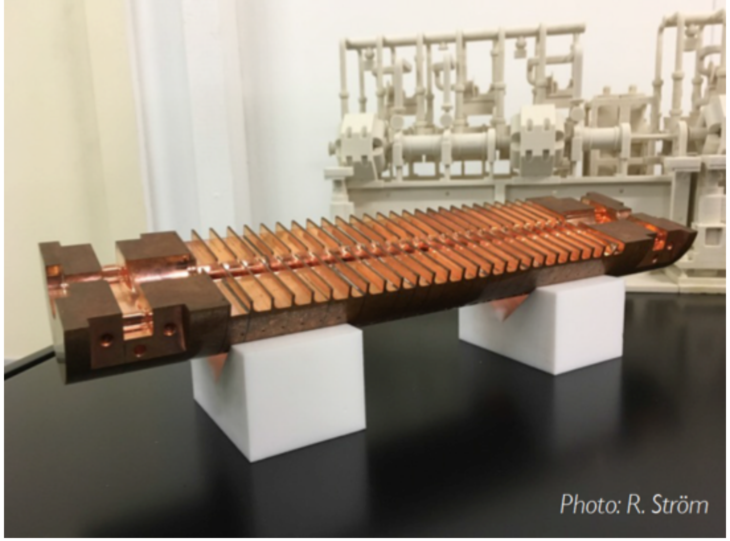
Prototype final focus quadrupole

Tunable permanent magnet

Accelerator structure, 1 disk



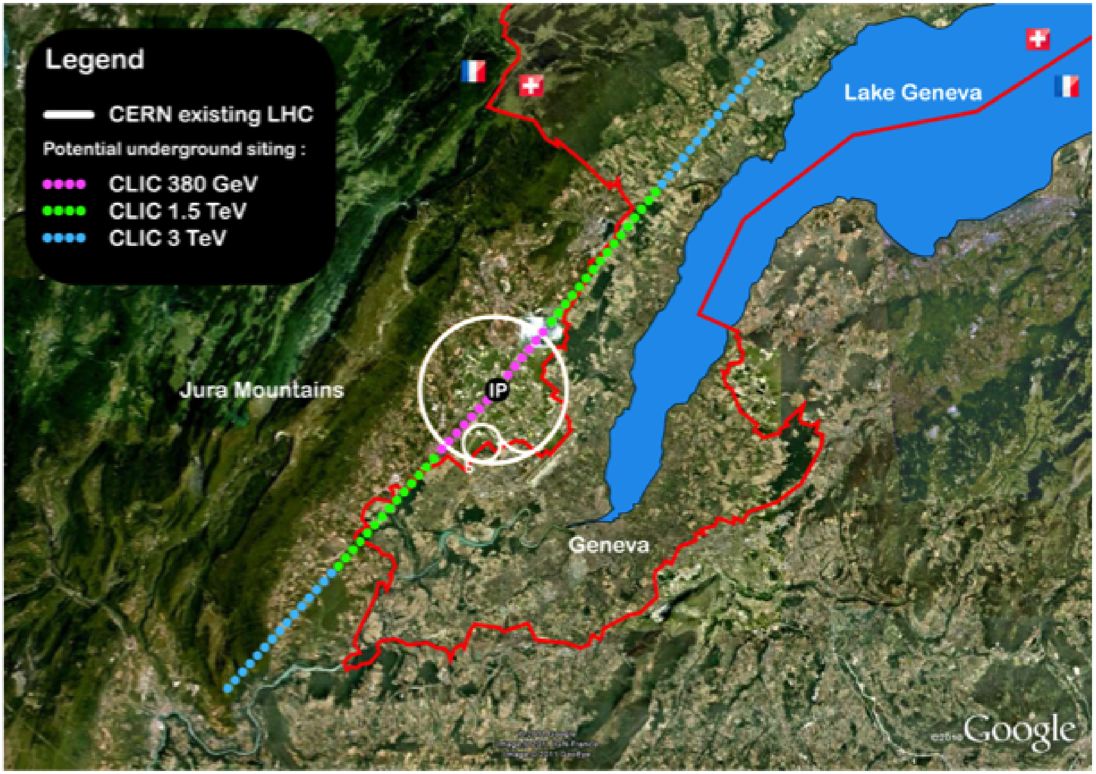
Brazing of a CLIC structure

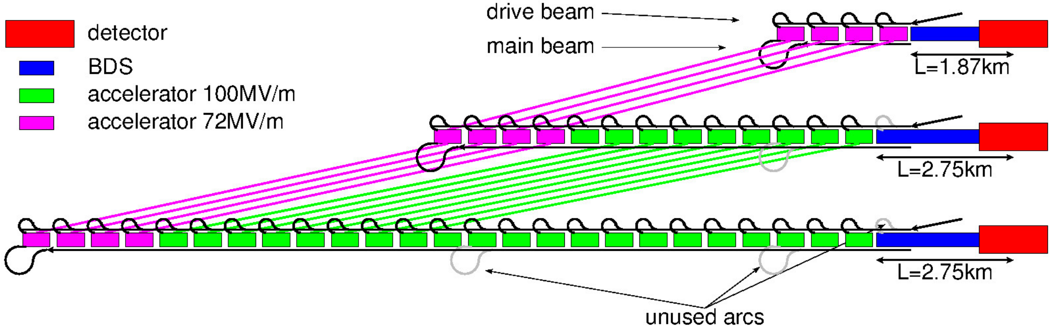


Cut through a CLIC acceleration structure

Photo: R. Ström

CLIC staged implementation





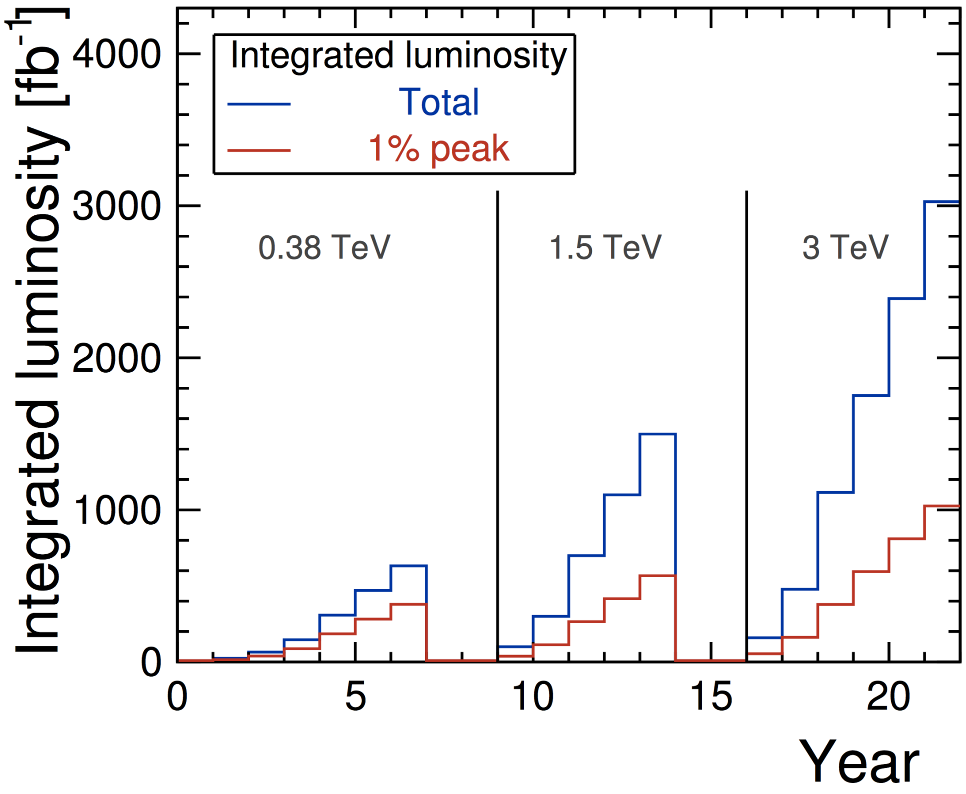
CLIC would be implemented in several energy stages

Baseline scenario:

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

→ The strategy can be adapted to possible LHC discoveries at 13/14 TeV!

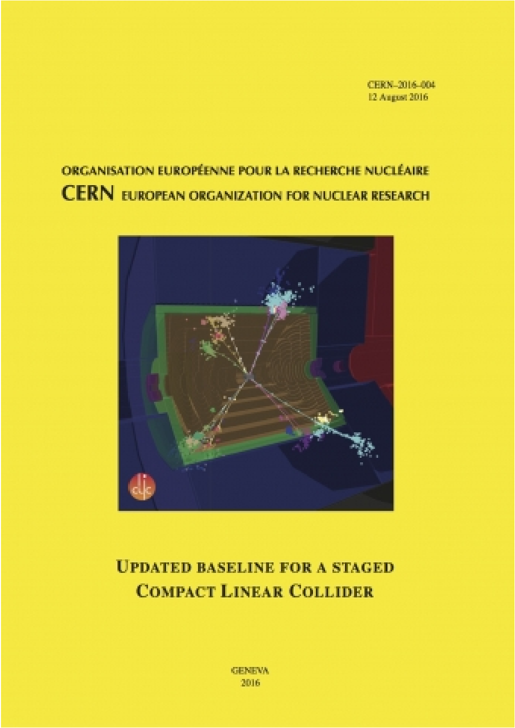
New baseline scenario



NB: Many physics studies in the following assume a slightly different scenario (500 fb^{-1} at 350 GeV, 1.5 ab^{-1} at 1.4 TeV, 3 ab^{-1} at 2 TeV)

- Initial stage at 380 GeV optimised for Higgs and top measurements (including $t\bar{t}$ threshold scan)

- Baseline scenario of 22 years presented in CERN-2016-004



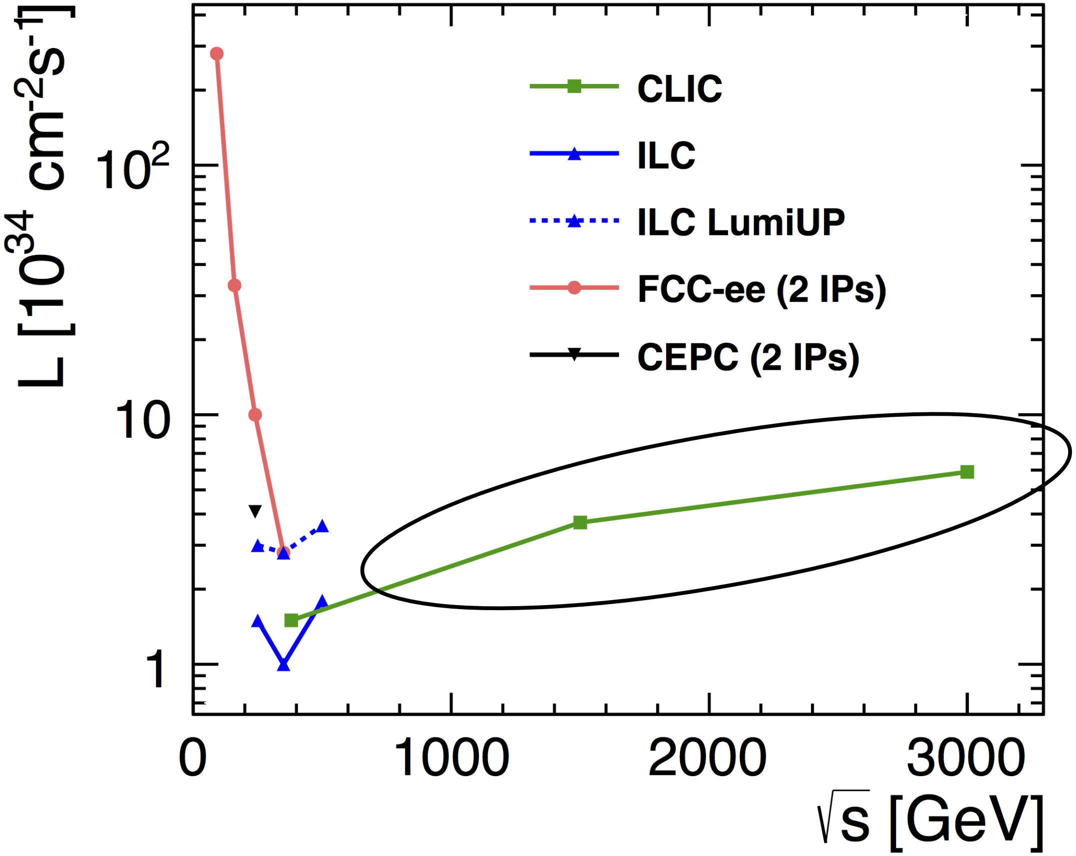
CERN-2016-004
12 August 2016

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

GENEVA
2016

Comparison to other e^+e^- collider options



Linear colliders:
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

Circular colliders:
- Large luminosity at lower energies
- Luminosity decreases with energy

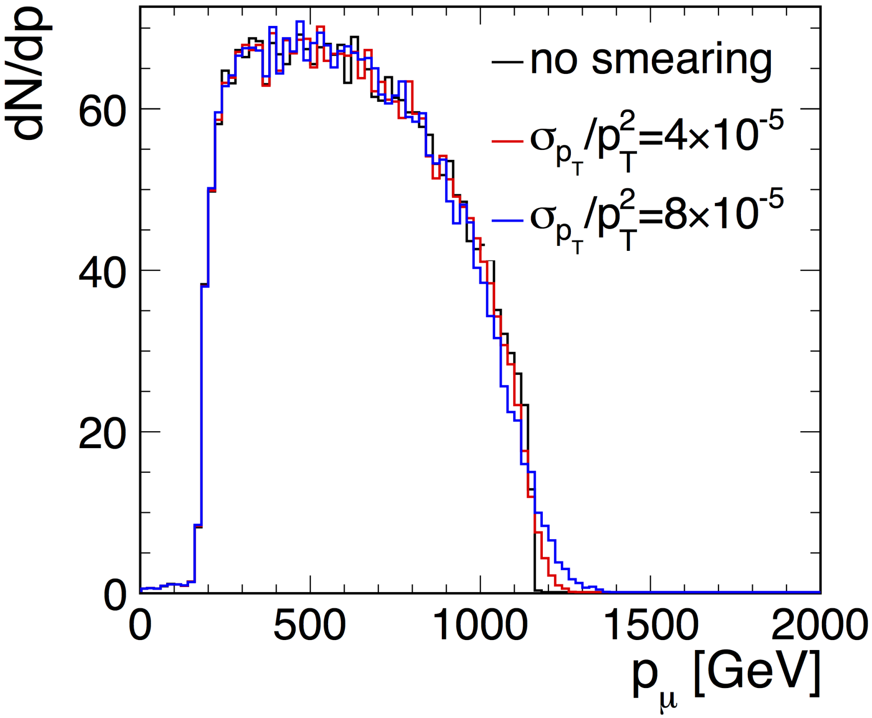
NB: Peak luminosity at LEP2 (209 GeV) was ≈10^{32} $\mathrm{cm^{-2}s^{-1}}$

CLIC is the only mature option for a multi-TeV e^+e^- collider

Detector requirements

- **Momentum resolution**
(e.g. Higgs recoil mass, H → $\mu^+\mu^-$, leptons from BSM processes)

$$\frac{\sigma(p_T)}{p_T^2} \sim 2\times10^{-5}\,GeV^{-1}$$



$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

- **Jet energy resolution**
(e.g. W/Z/h separation)

$$\frac{\sigma(E)}{E} \sim 3.5-5\%\ for\ E=1000-50\,GeV$$

- **Impact parameter resolution**
(b/c tagging, e.g. Higgs couplings)

$$\sigma(d_0)=\sqrt{a^2+b^2\cdot GeV^2/(p^2\sin^3\theta)},\ a\approx5\,\mu m,\ b\approx15\,\mu m$$

- **Lepton identification, very forward electron tagging**

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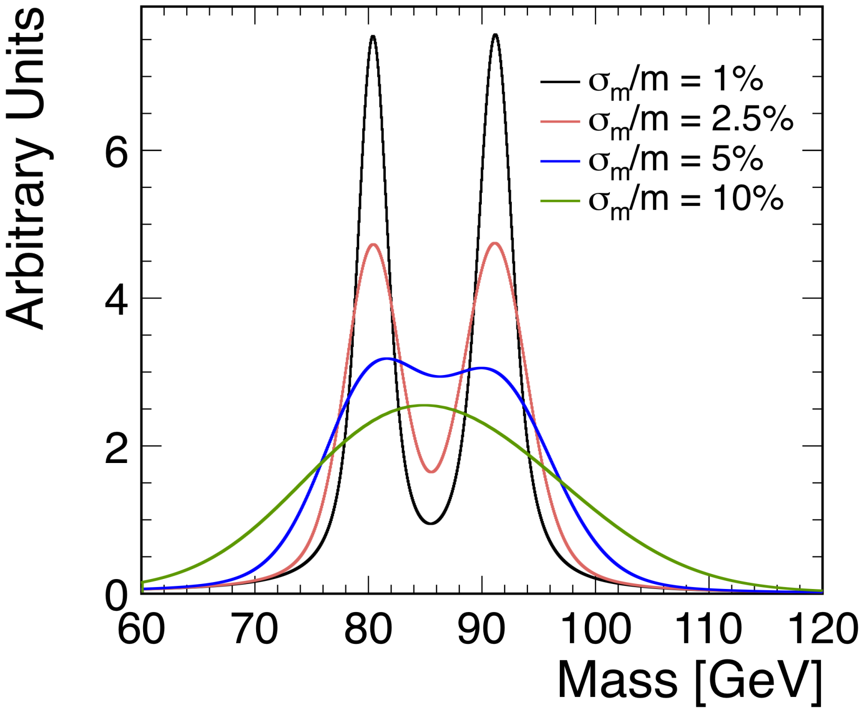

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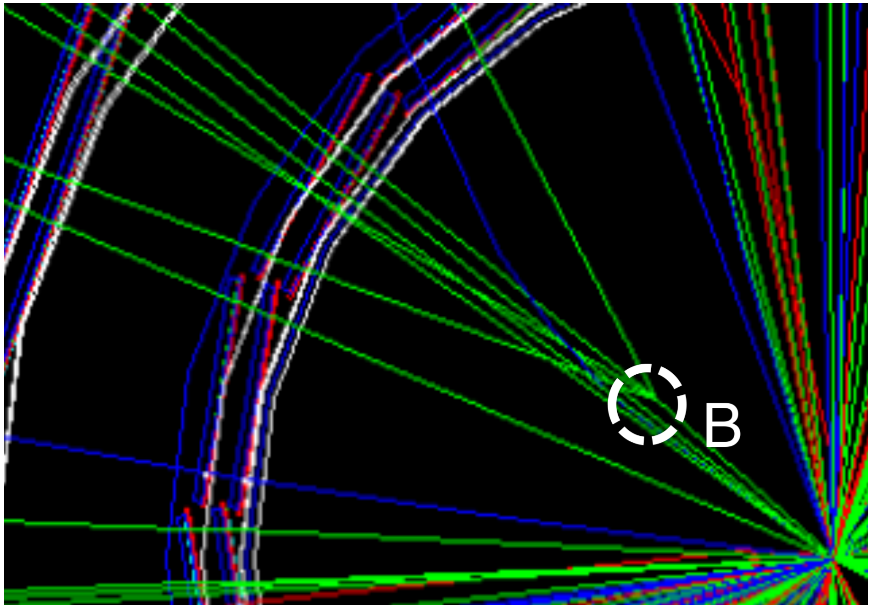

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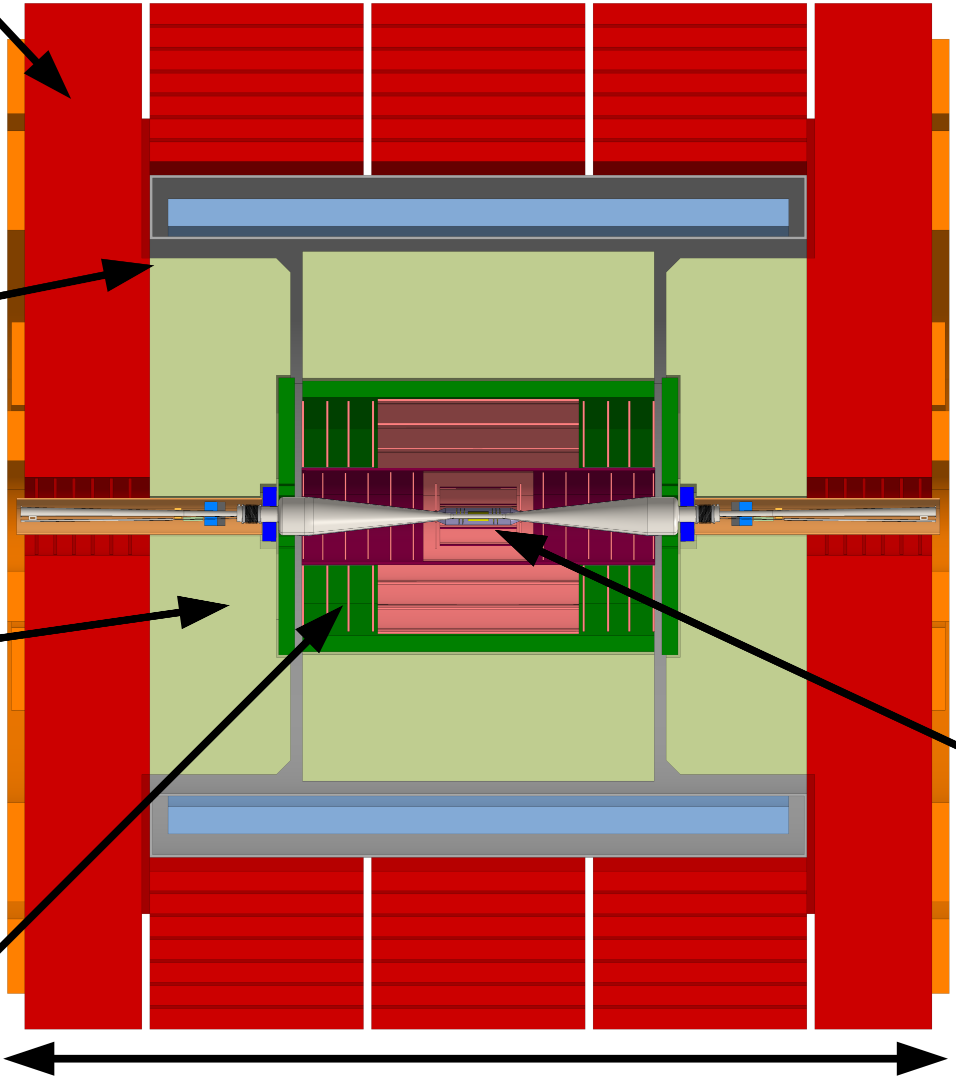
CLIC detector concept



Instrumented return yoke for muon ID

Strong solenoid magnet (4 T)

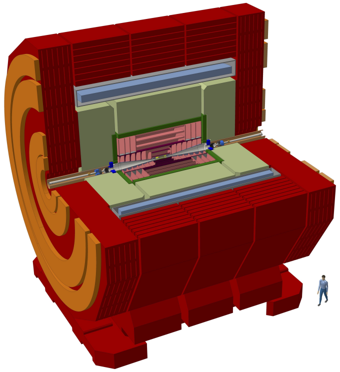
3.) Fine grained (PFA) calorimetry, 1+7.5 λ

2.) Main trackers: silicon-based (large pixels / short strips)

Complex forward region with compact calorimeters

1.) Ultra low-mass vertex detector with ≈ 25 x 25 μm^2 pixels

≈11.4 m

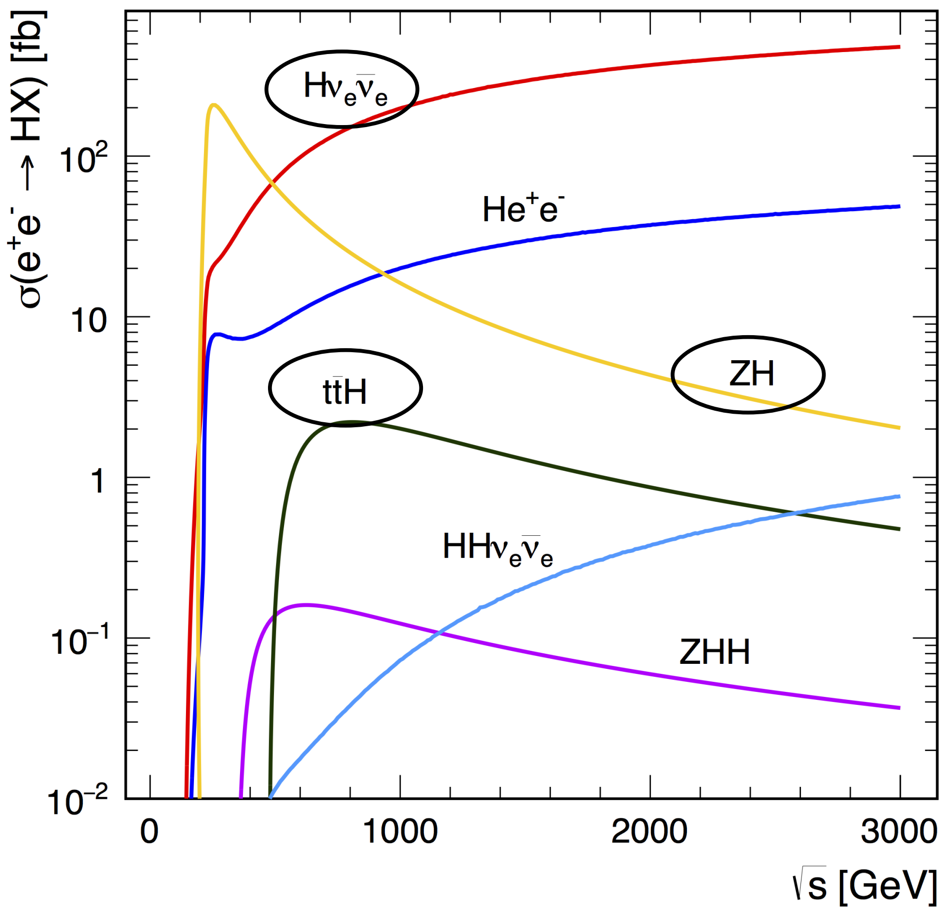


CLICdp-Note-2017-001

Higgs physics:

- Single Higgs production
- EFT analysis
- Double Higgs production

Single Higgs production



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

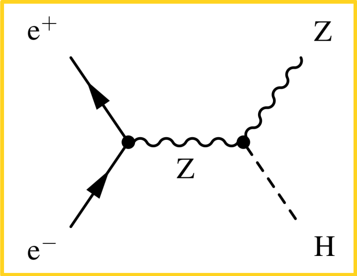
- $\sigma \sim 1/s$, dominant up to ≈ 450 GeV

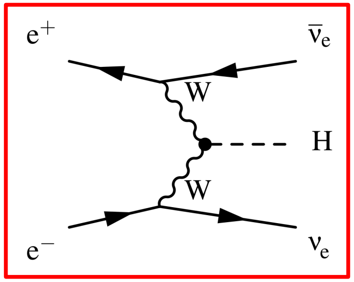
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

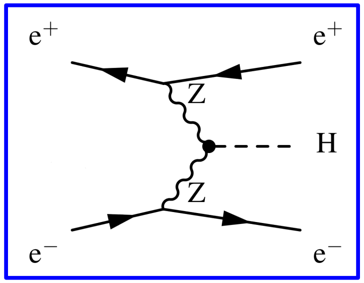
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy

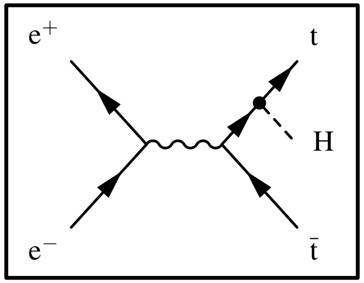
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling









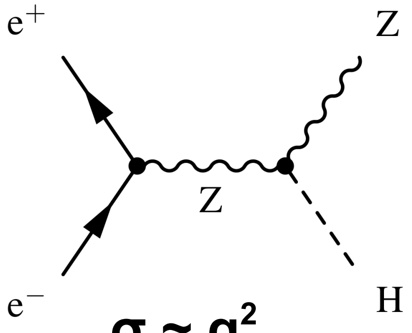
Higgsstrahlung: $e^+e^- \rightarrow ZH$

Using $Z \rightarrow e^+e^-, \mu^+\mu^-$:

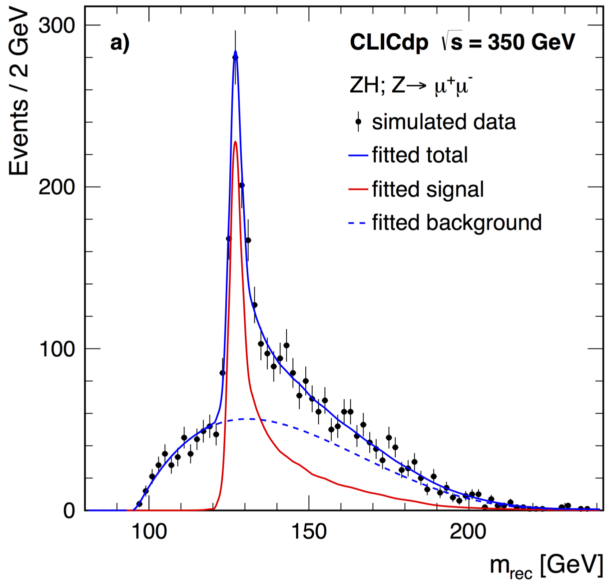
- HZ events can be identified from the Z recoil mass

→ Model-independent measurement of the g_{HZZ} coupling

- Best precision at 240/250 GeV (tracking resolution, beam energy spectra)



$\sigma \sim g^2_{HZZ}$

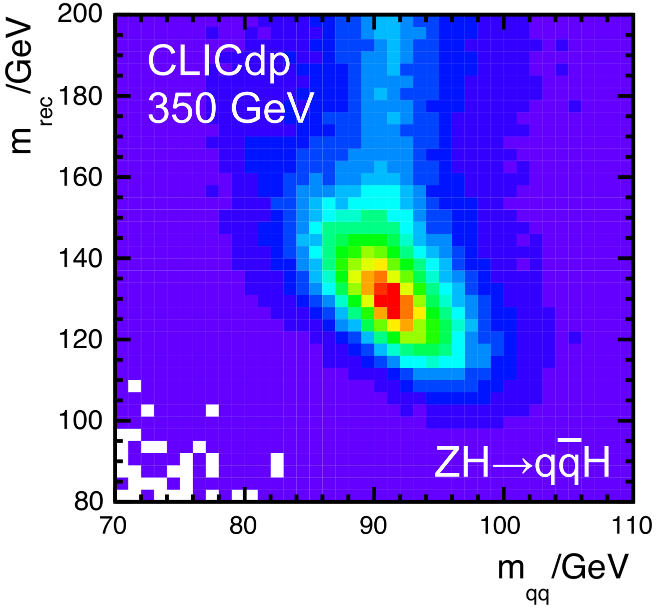


Using $Z \rightarrow q\bar{q}$:

- Almost model-independent measurement of g_{HZZ} possible using hadronic Z decays

→ Substantial improvement in precision possible

- Better precision at 350 GeV found than at 250 GeV or 420 GeV



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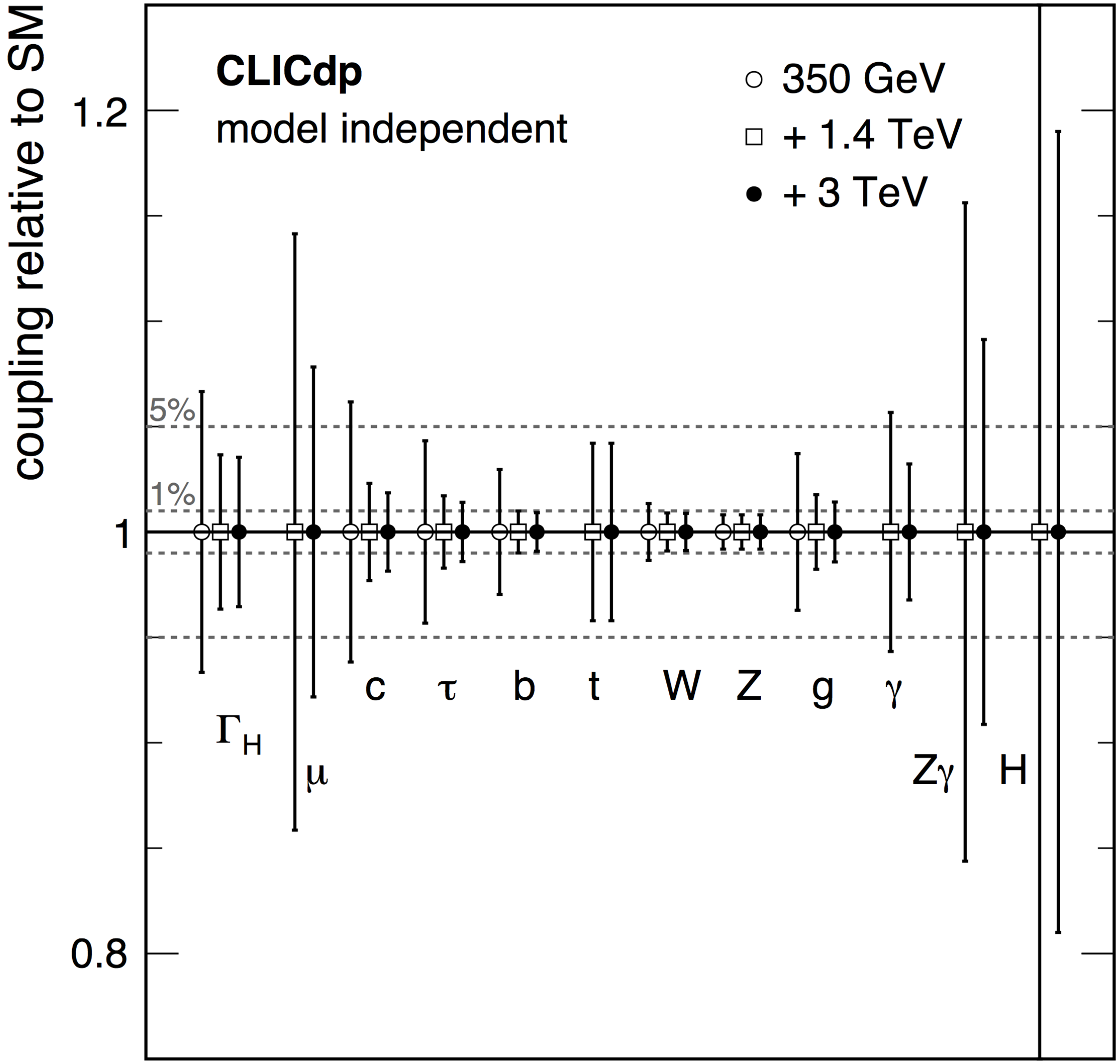
Higgs properties at CLIC



Fully model-independent analysis only possible at lepton colliders

NB: All projections are based on benchmark studies using full detector simulations

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Higgs physics at the CLIC electron–positron linear collider

H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], N. Alipour Tehrani[4], C. Balázs[5], Y. Benhammou[1], M. Benoit[6], B. Bilki[7], J.-J. Blaising[8], M. J. Boland[9], M. Boronat[10], O. Borysov[1], I. Božović-Jelisavčić[11], M. Buckland[12], S. Bugiel[13], P. N. Burrows[14], T. K. Charles[5], W. Daniluk[15], D. Dannheim[4], R. Dasgupta[13], M. Demarteau[7], M. A. Díaz Gutierrez[2], G. Eigen[16], K. Elsener[4], U. Felzmann[9], M. Firlej[13], E. Firu[17], T. Fiutowski[13], J. Fuster[10], M. Gabriel[18], F. Gaede[4,19], I. García[10], V. Ghenescu[17], J. Goldstein[20], S. Green[21], C. Grefe[4,b,d], M. Hauschild[4], C. Hawkes[23], D. Hynds[4], M. Idzik[13], G. Kačarević[11], J. Kalinowski[24], S. Kananov[1], W. Klempt[4], M. Kopec[13], M. Krawczyk[24], B. Krupa[15], M. Kucharczyk[15], S. Kulis[4], T. Laštovička[25], T. Lesiak[15], A. Levy[1], I. Levy[1], L. Linssen[4], S. Lukić[11,b], A. A. Maier[4], V. Makarenko[3], J. S. Marshall[21], V. J. Martin[22], K. Mei[21], G. Milutinović-Dumbelović[11], J. Moroń[13], A. Moszczyński[15], D. Moya[26], R. M. Münker[4,e], A. Münnich[4,f], A. T. Neagu[17], N. Nikiforou[4], K. Nikolopoulos[23], A. Nürnberg[4], M. Pandurović[11], B. Pawlik[15], E. Perez Codina[4], I. Peric[27], M. Petric[4], F. Pitters[4,g], S. G. Poss[4], T. Preda[17], D. Protopopescu[28], R. Rassool[9], S. Redford[4,b,h], J. Repond[7], A. Robson[28], P. Roloff[4,a,b], E. Ros[10], O. Rosenblat[1], A. Ruiz-Jimeno[26], A. Sailer[4], D. Schlatter[4], D. Schulte[4], N. Shumeiko[3,c], E. Sicking[4], F. Simon[18,b], R. Simoniello[4], P. Sopicki[15], S. Stapnes[4], R. Ström[4], J. Strube[4,i], K. P. Świentek[13], M. Szalay[18], M. Tesař[18], M. A. Thomson[21,b], J. Trenado[29], U. I. Uggerhøj[30], N. van der Kolk[18], E. van der Kraaij[16], M. Vicente Barreto Pinto[6], I. Vila[26], M. Vogel Gonzalez[2,j], M. Vos[10], J. Vossebeld[12], M. Watson[23], N. Watson[23], M. A. Weber[4], H. Weerts[7], J. D. Wells[31], L. Weuste[18], A. Winter[23], T. Wojtoń[15], L. Xia[7], B. Xu[21], A. F. Żarnecki[24], L. Zawiejski[15], I.-S. Zgura[17]

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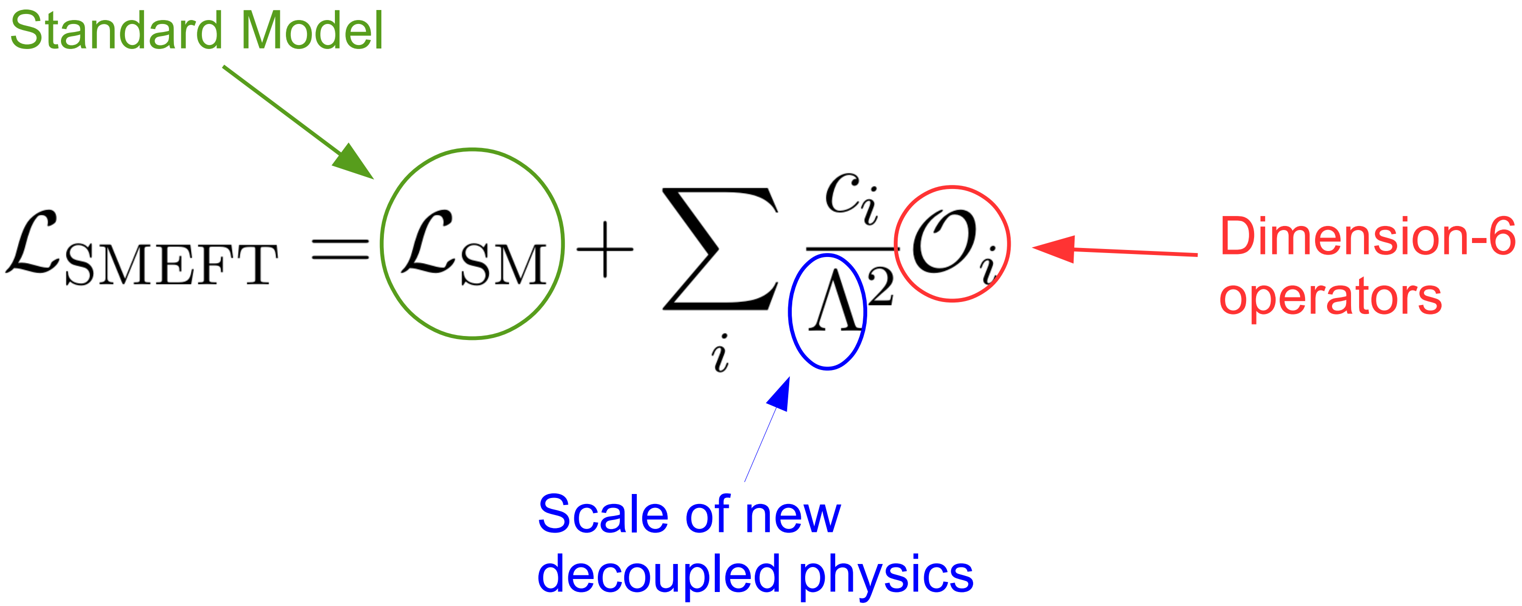
Eur. Phys. J. C 77, 475 (2017)

BSM potential of Higgs production & $e^+e^- \rightarrow W^+W^-$

Effective Field Theory:



Standard Model

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

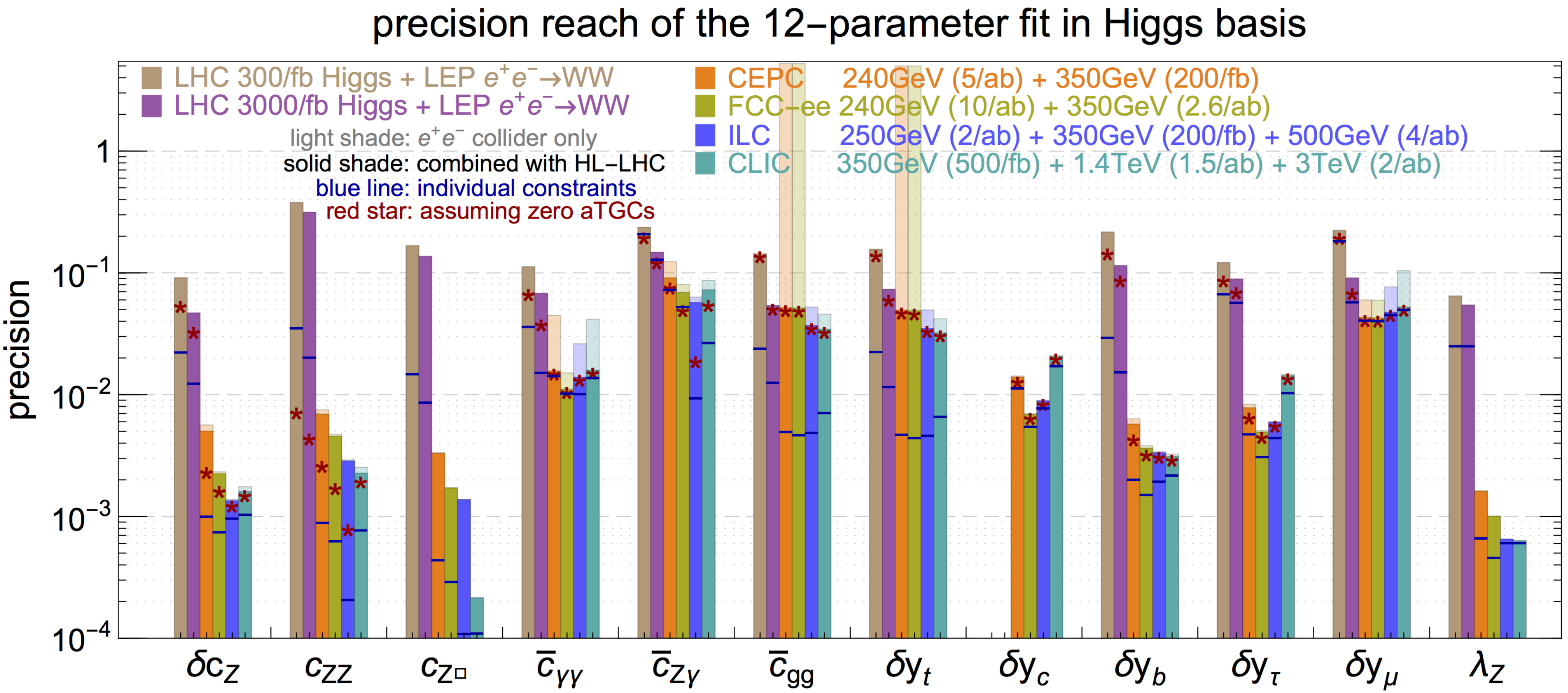
Dimension-6 operators

Scale of new decoupled physics

- Model-independent framework for probing indirect signs of new physics → very useful for comparison of future collider options / parameters

- **Input to fits:** Higgs production in Higgsstrahlung and WW fusion, $e^+e^- \rightarrow t\bar{t}H$, weak boson pair production: $e^+e^- \rightarrow W^+W^-$

Comparison of different collider options

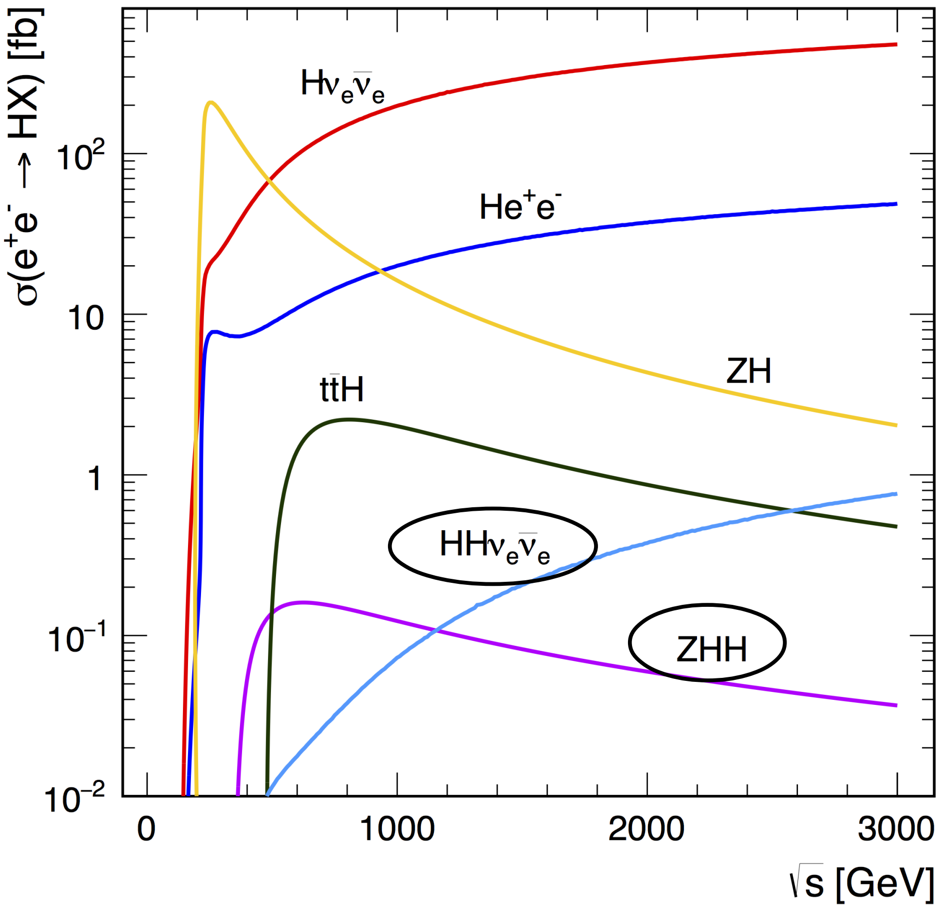


precision reach of the 12−parameter fit in Higgs basis

- Many EFT parameters can be measured significantly better at CLIC compared to the HL-LHC
- H→$c\bar{c}$ only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 1705, 096 (2017)

Double Higgs production



$e^+e^- \to$ ZHH:

- Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \lesssim 0.2$ fb)

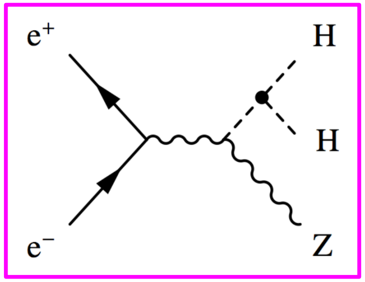
$e^+e^- \to HH\nu_e\bar{\nu}_e$:

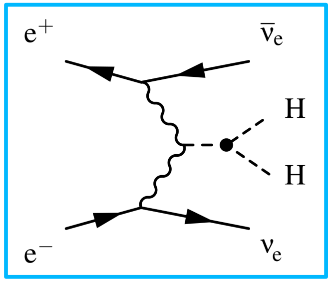
- Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
- Benefits from high-energy operation

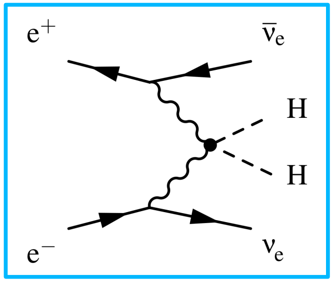
Projected precisions:

- $\Delta(\lambda)$ = 16% for CLIC from total cross section assuming 3 ab^{-1} at 3 TeV (→ $\Delta(\lambda) \approx$ 10% from differential distributions)

Eur. Phys. J. C 77, 475 (2017)







Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

Top physics:

- Top quark mass
- Top electroweak couplings

Top quark mass

$t\bar{t}$ threshold scan:

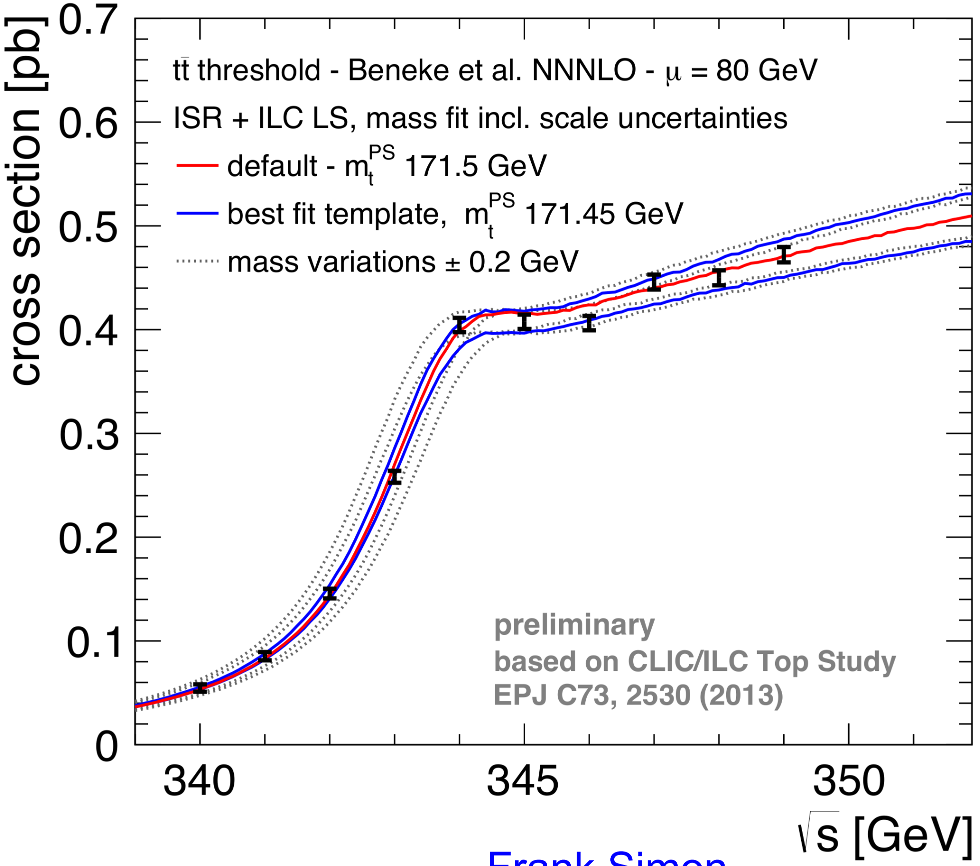
- Measurement at different centre-of-mass energies in the $t\bar{t}$ production threshold region (data also useful for Higgs physics)

- Expected precision on 1S mass: ≈50 MeV (independent of accelerator, currently dominated by theory NNLO scale uncertainty)

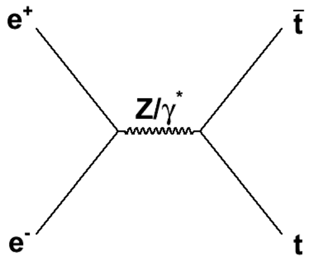
- Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the $\overline{\text{MS}}$ mass scheme

Phys. Rev. Lett. 114, 142002 (2015)

- Precision at the LHC limited to several hundred MeV



Frank Simon, topLC 2017



Top electroweak couplings

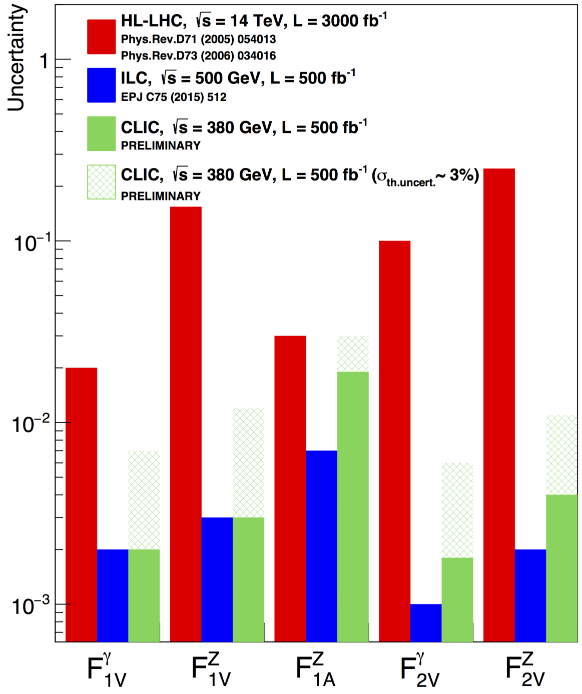
- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving

CPV

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

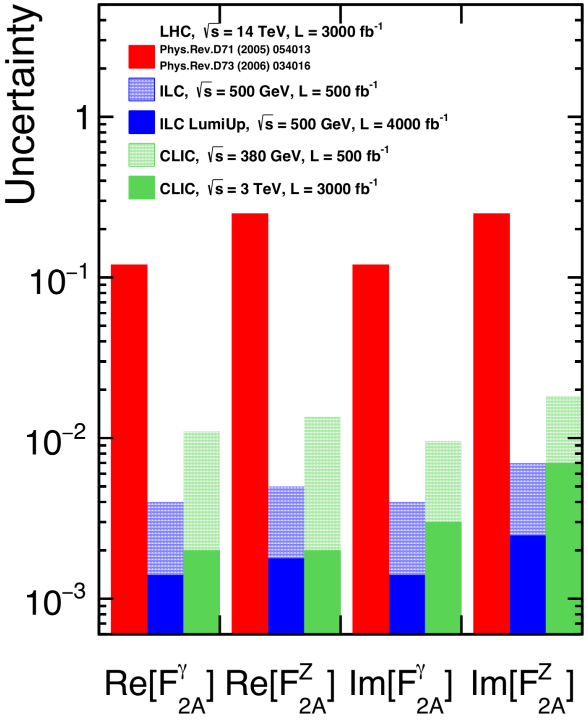


CERN-2016-004

- New physics would modify the $t\bar{t}V$ vertex

- CLIC 1-2 orders of magnitude better than HL-LHC

Interesting top physics program at the first CLIC stage at 380 GeV



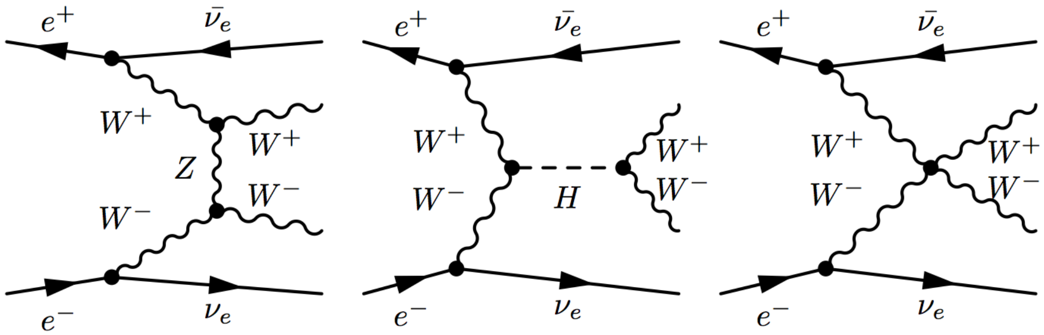
Martín Perelló, topLC 2017

Precision measurements and direct BSM searches:

- Vector boson scattering
- Z' using $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \gamma\gamma$
- Direct BSM searches

Vector boson scattering

- Vector boson scattering (VBS) gives insight into the mechanism of electroweak symmetry breaking

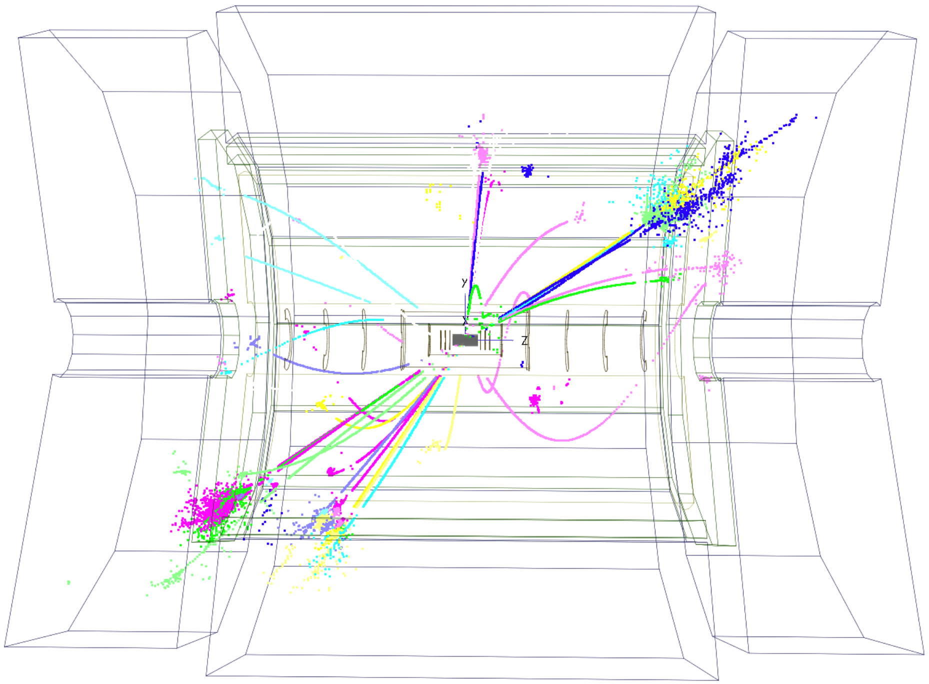


- Example processes investigated for high-energy CLIC operation:

$$e^+e^- \to W^+W^-\nu\bar{\nu}$$
$$e^+e^- \to ZZ\nu\bar{\nu}$$

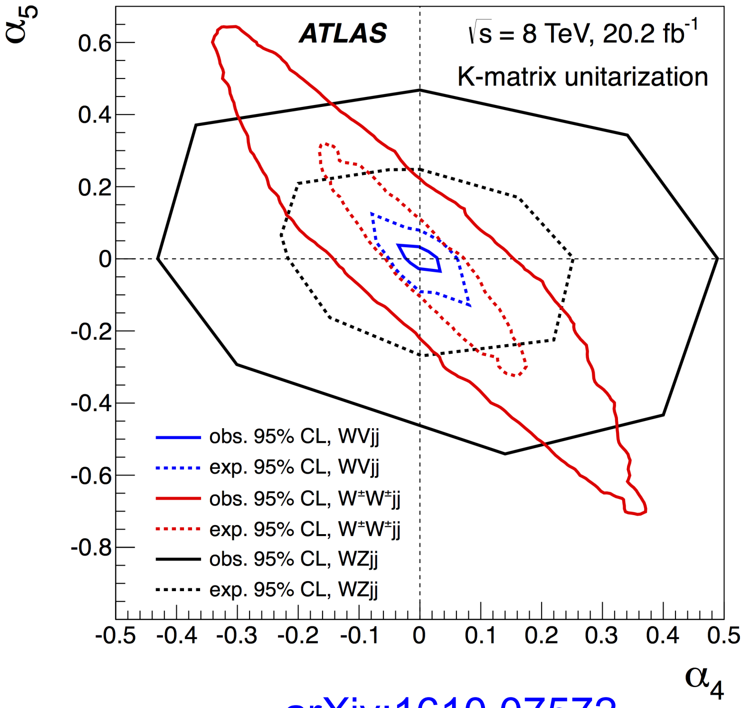
- Search for additional resonances or anomalous couplings

- At CLIC fully hadronic events can be used (in contrast to hadron colliders): $W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \to q\bar{q}q\bar{q}\nu\bar{\nu}$ → largest event samples and full kinematic information



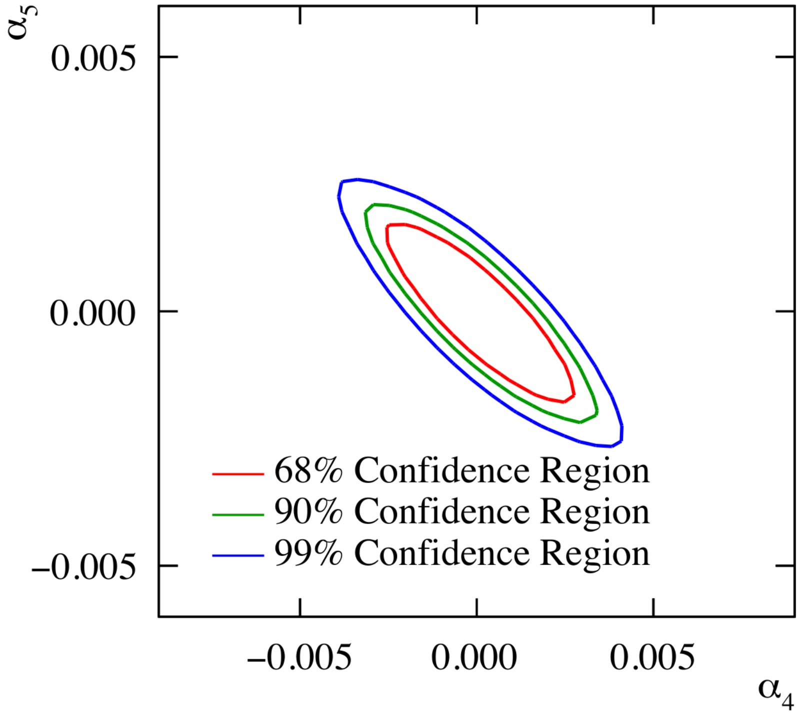
VBS: results and comparison to LHC

ATLAS, $\sqrt{s}$ = 8 TeV



arXiv:1610.07572

CLIC, $\sqrt{s}$ = 3 TeV



1D fit (68% CL):

L = 2 ab^{-1}

$-0.00102 < \alpha_4 < 0.00112$

$-0.00070 < \alpha_5 < 0.00074$

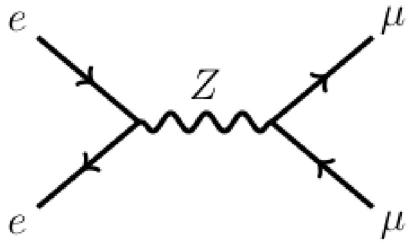
→ Sensitivity significantly better than 8 TeV LHC

Other precision measurements benefitting from high energy

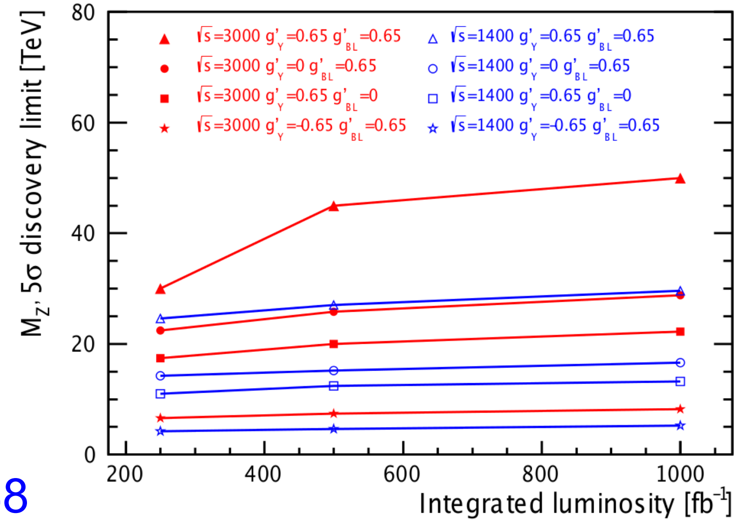
Example: Z' using $e^+e^- \to \mu^+\mu^-$

HL-LHC sensitive up to ≈7 TeV

CLIC provides discovery reach up to tens of TeV

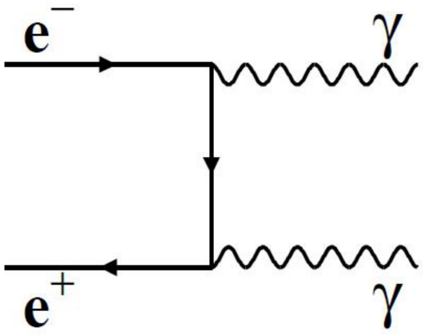


$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$



arXiv:1208.1148

Example: $e^+e^- \to \gamma\gamma$



$\sqrt{s}$ = 3 TeV,
L = 2 ab^{-1}

Unique to lepton colliders,
CLIC about 15 times better than LEP 2

Scenario:	CLIC reach (95% CL):	LEP limit (95% CL):
QED cutoff parameter Λ (electron size)	6.33 TeV ($3.1 \cdot 10^{-18}$ cm)	≈390 GeV
Contact interactions: Λ'	20.1 TeV	≈830 GeV
Extra dimensions: $M_s/\Lambda^{1/4}$	15.9 TeV	≈1 TeV
Excited electron: M(e*)	4.87 TeV	≈250 GeV

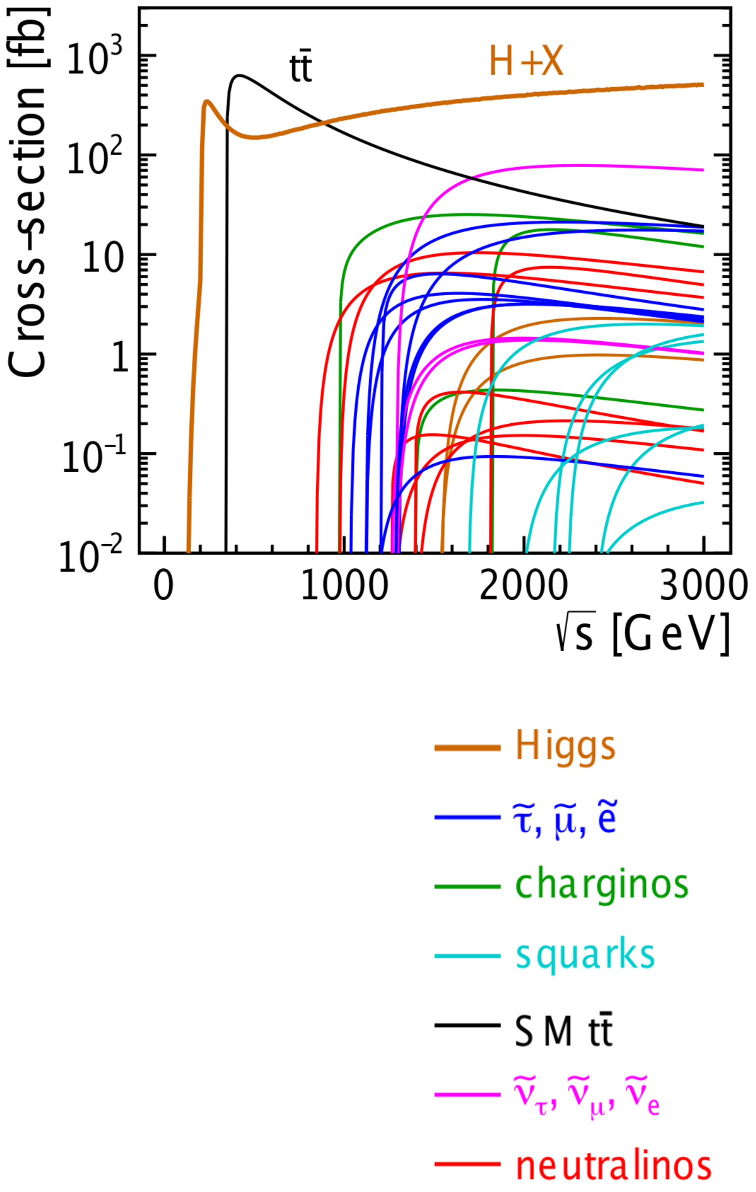
Direct searches

- Direct observation of new particles coupling to $\gamma^*/Z/W$
→ precision measurement of new particle masses and couplings

- The sensitivity often extends up to the kinematic limit
(e.g. $M \le \sqrt{s}/2$ for pair production)

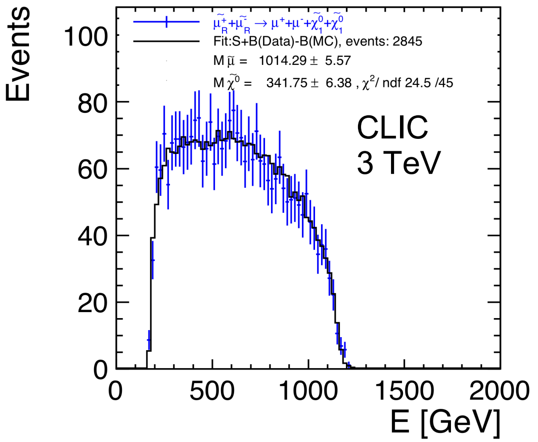
- Very rare processes accessible due to low backgrounds (no QCD)
→ CLIC especially suitable for electroweak states

- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Reconstruction of SUSY particles

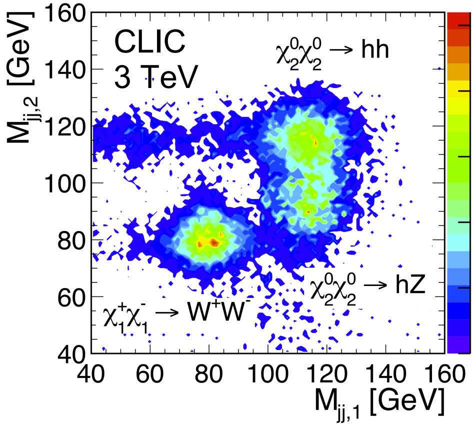
Endpoints of energy spectra:



$m(\tilde{\mu}_R)$: ± 5.6 GeV
$m(\tilde{e}_R)$: ± 2.8 GeV
$m(\tilde{\nu}_e)$: ± 3.9 GeV
$m(\tilde{\chi}_1^0)$: ± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$: ± 3.7 GeV

slepton masses:
1.0 - 1.1 TeV

$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$



Jet reconstruction

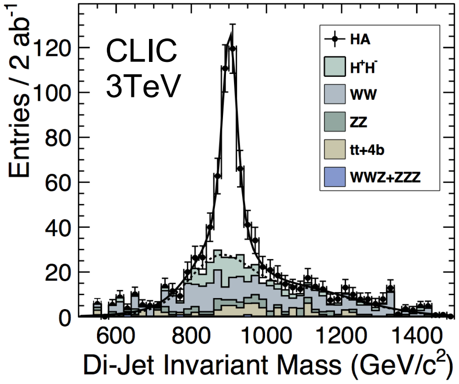
Precision on the measured gaugino masses (few hundred GeV):
1 - 1.5%

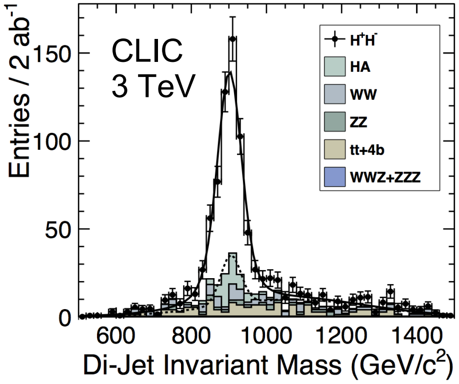
$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$
$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$
$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Complex final states:

$$e^+e^- \to HA \to b\bar{b}b\bar{b}$$
$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t}$$

≈ 0.3% precision on heavy Higgs masses

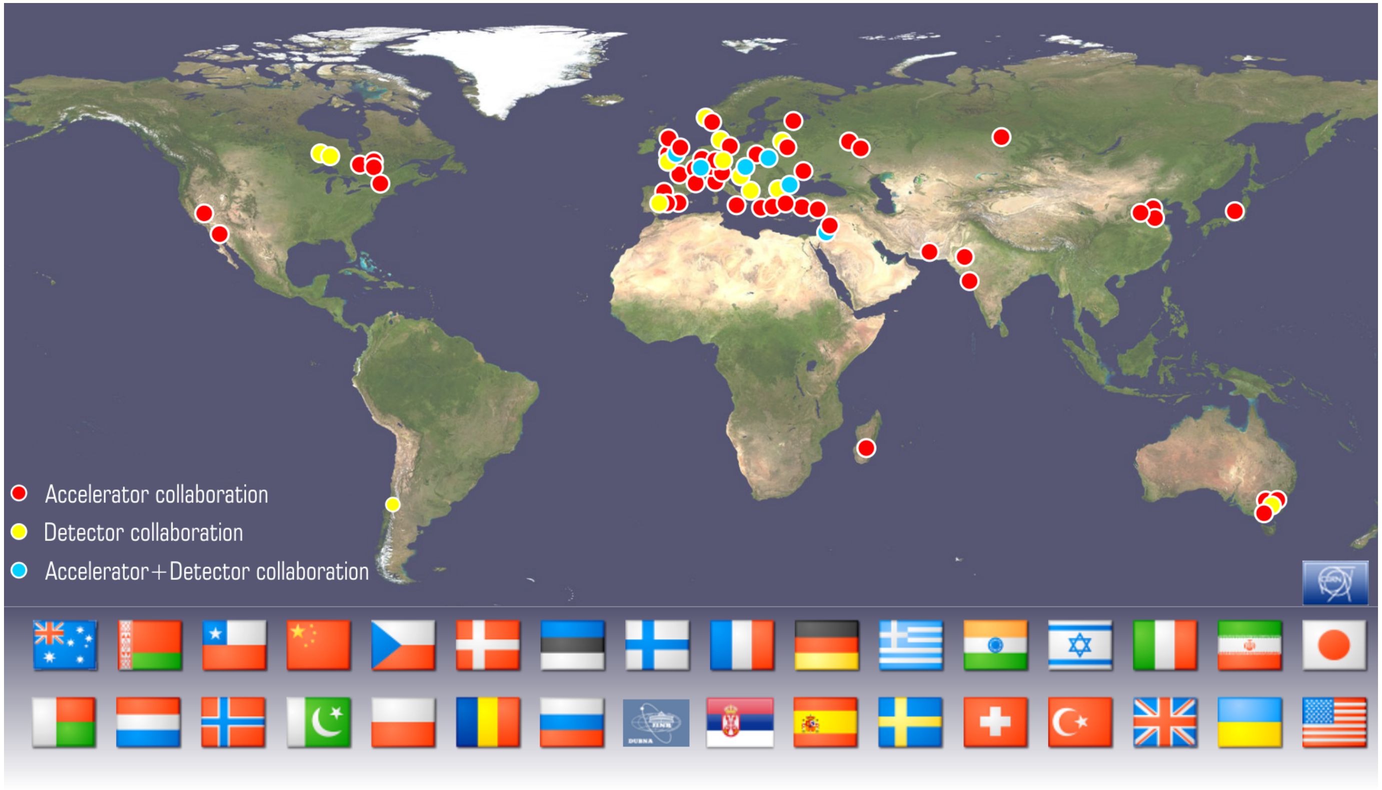




CLIC collaborations

The CLIC studies are carried by two active collaborations:
- CLIC accelerator collaboration: http://clic-study.web.cern.ch/
- CLIC detector and physics collaboration: http://clicdp.web.cern.ch/

Together
≈ 80 institutes



Upcoming events:
- LCWS 2017: http://agenda.linearcollider.org/event/7645/
- CLIC Workshop 2018: http://indico.cern.ch/event/656356/

Summary and conclusions

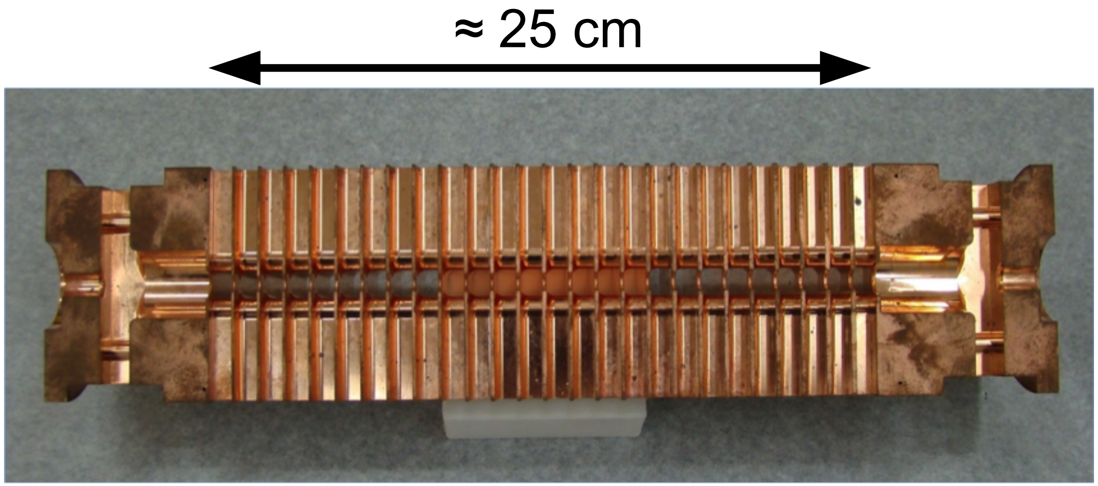
- CLIC is the only mature option for a multi-TeV electron-positron collider
- Very active R&D projects for accelerator and physics/detector
- Energy-staging → optimal for physics:

380 GeV:	Optimised for precision SM Higgs and top physics
1.5 TeV, 3 TeV:	Best sensitivity for BSM searches, rare Higgs processes and decays

- The energies of the TeV stages will depend on the LHC results

Backup slides

CLIC accelerating structures

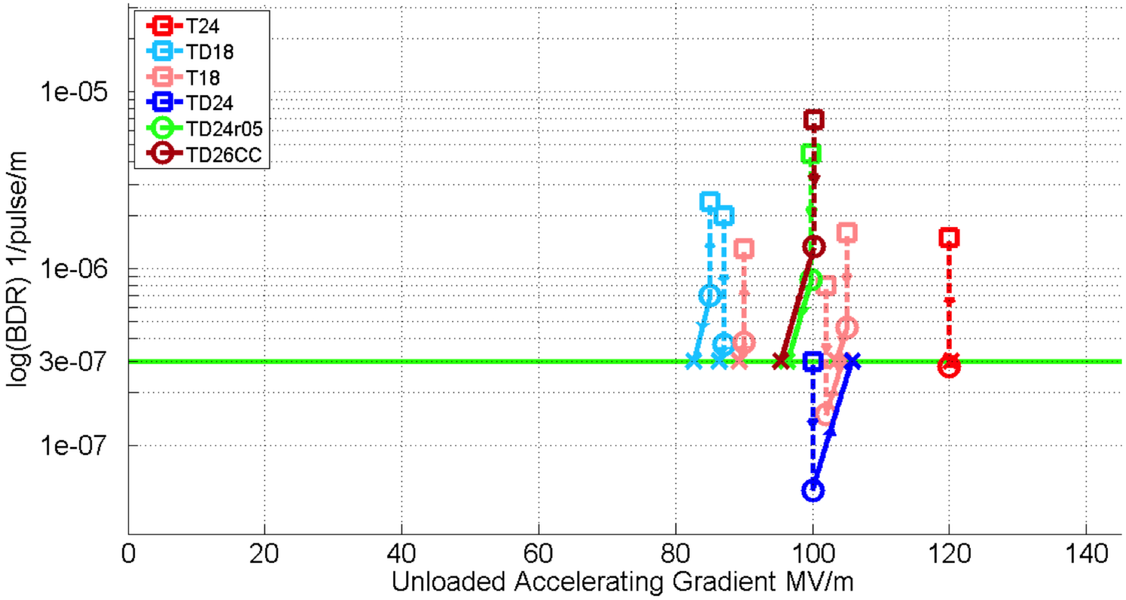


- 12 GHz (X-band)
- Break down rate (BDR): $p \leq 3 \cdot 10^{-7}\ \mathrm{m}^{-1}\mathrm{pulse}^{-1}$

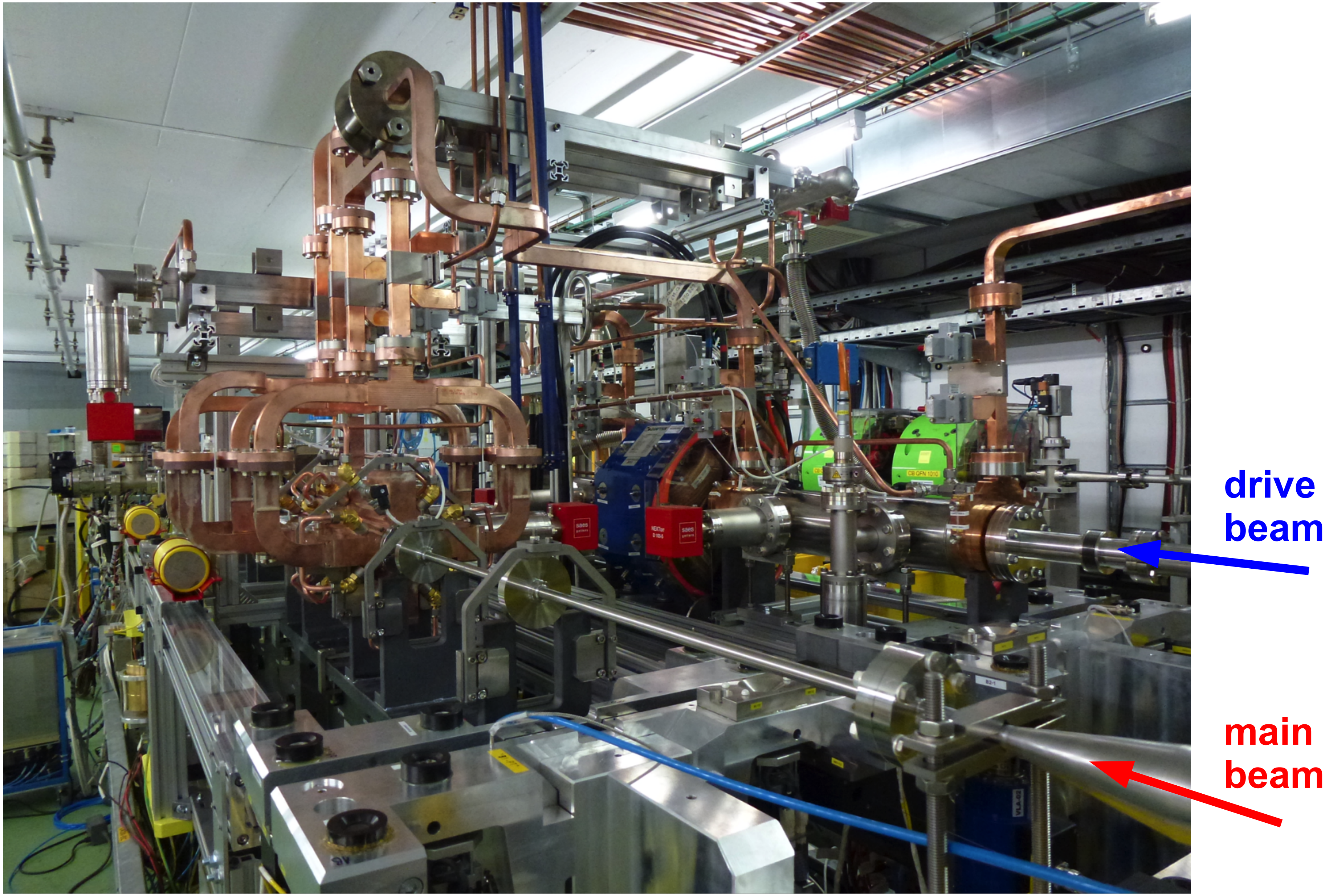
R&D programme established gradient O(100MV/m)

Shorter pulses have less breakdowns

Now focussing on:
- Further improvements
- Preparation for mass production
- Cost reduction



2-beam acceleration module in CTF3



drive beam

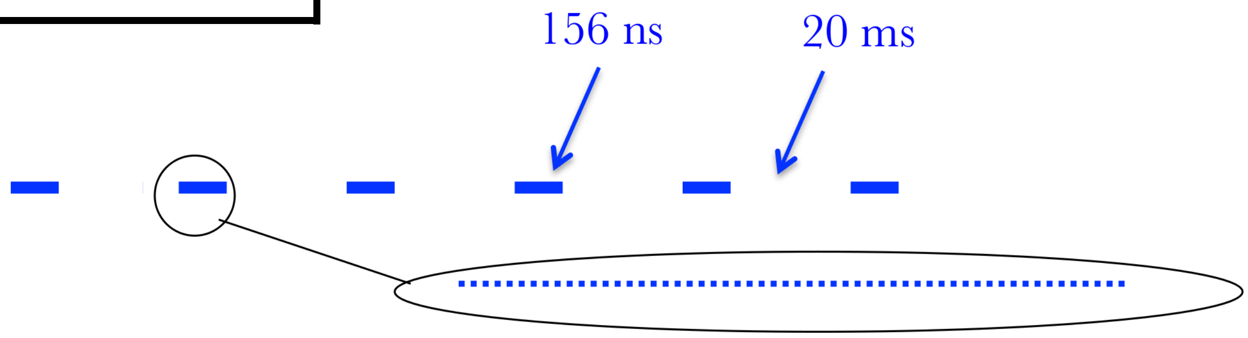
main beam

CLIC experimental conditions

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$5.9 \cdot 10^{34}$
Bunch separation	0.5 ns
#Bunches / train	312
Train duration	156 ns
Train rep. rate	50 Hz
Crossing angle	20 mrad
Particles / bunch	$3.72 \cdot 10^{9}$
σ_x/σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

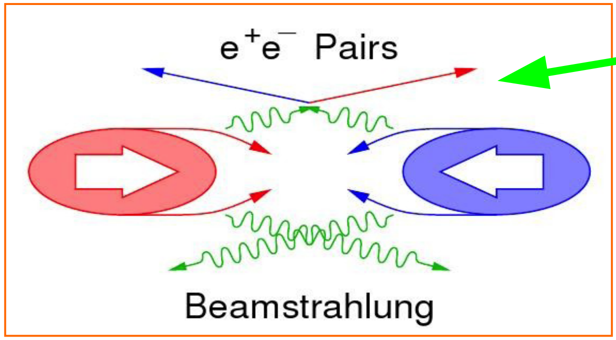
Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

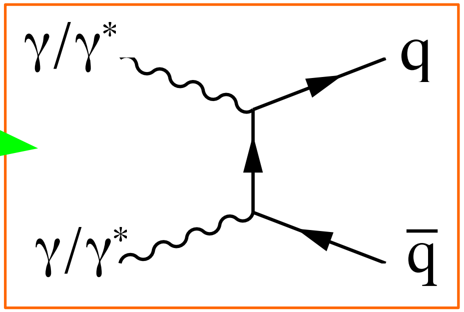


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

Beam-induced backgrounds



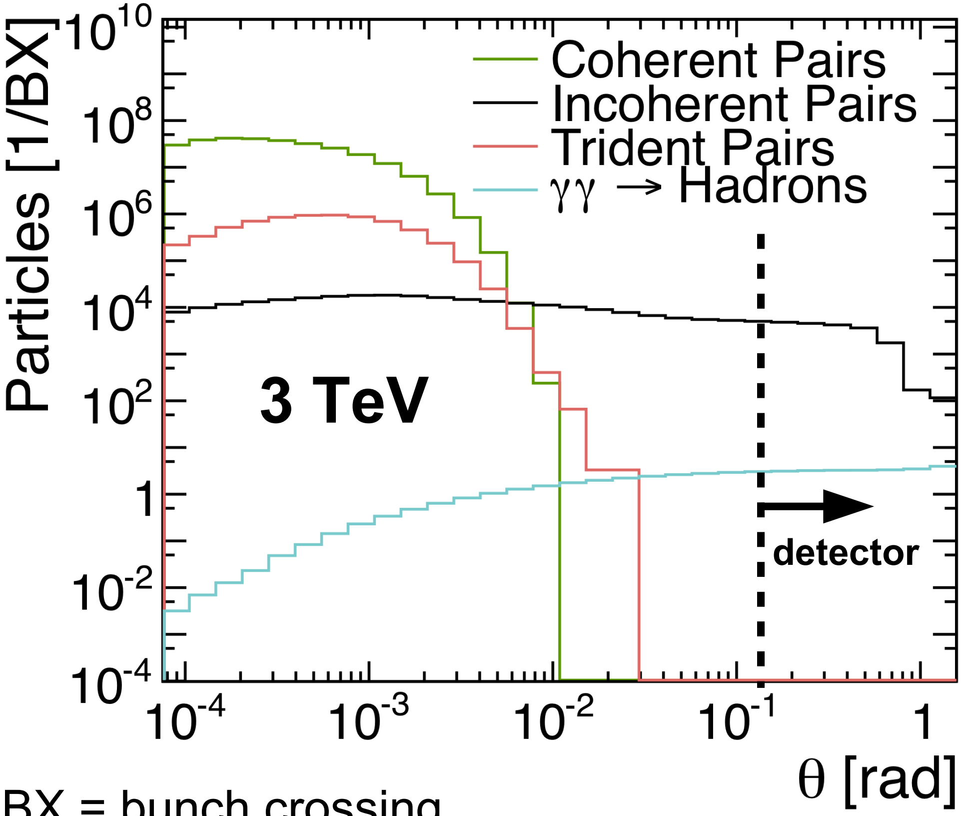
- e^+e^- pairs
- γγ → hadrons



Coherent e^+e^- pairs:
$7 \cdot 10^8$ per BX, very forward
Incoherent e^+e^- pairs:
$3 \cdot 10^5$ per BX, rather forward
→ Detector design issue
(high occupancies)

γγ → hadrons
- "Only" 3.2 events per BX at 3 TeV
- Main background

in calorimeters and trackers
→ Impact on physics

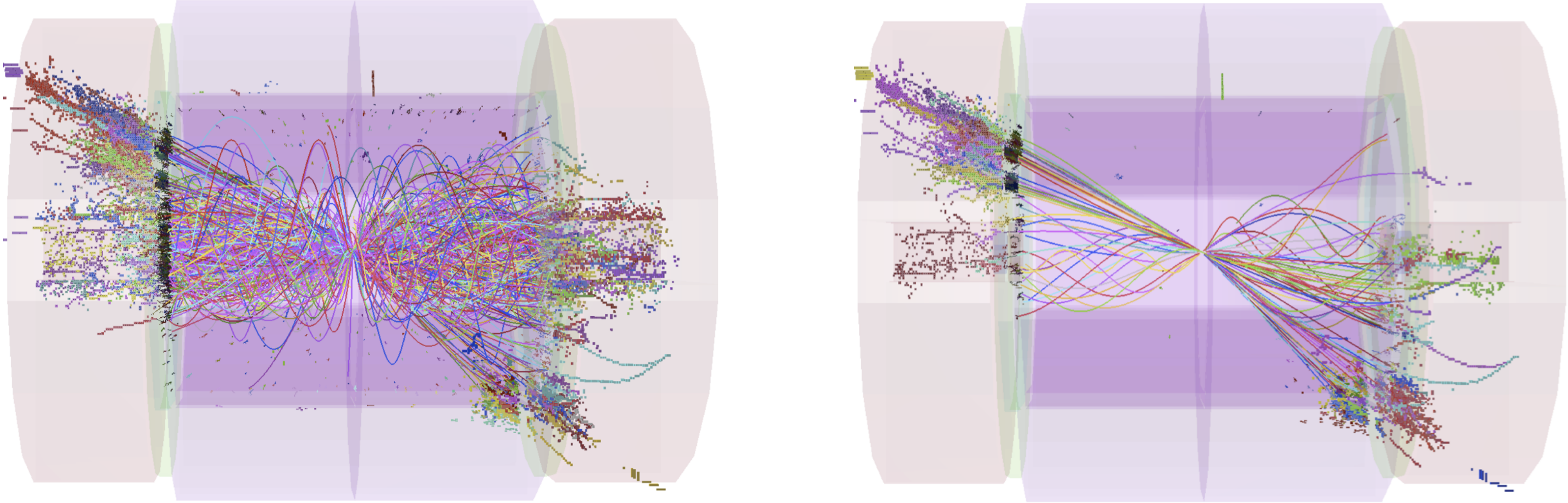


BX = bunch crossing

Background suppression

Beam-induced background from γγ → hadrons can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles

(= particle flow objects)

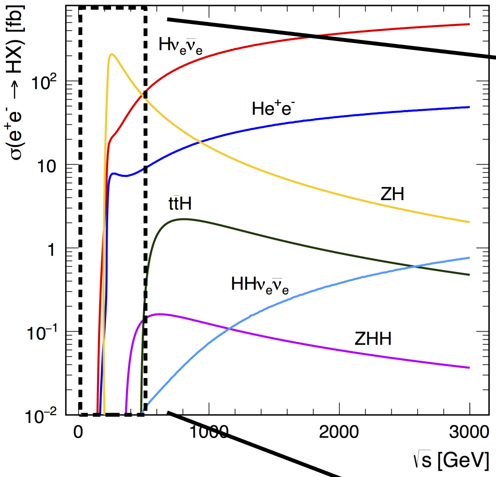


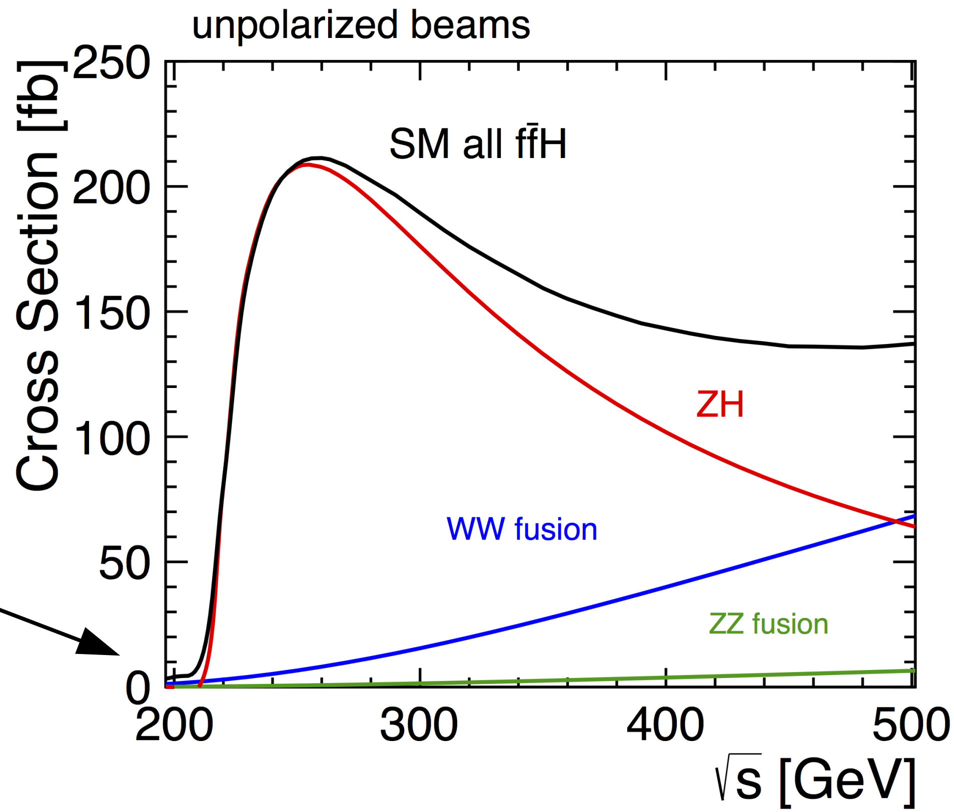
$e^+e^- \to t\bar{t}$ at 3 TeV with background from $\gamma\gamma \to$ hadrons overlaid

1.2 TeV background
in the reconstruction window
(≥ 10 ns) around physics event

100 GeV background
after timing cuts

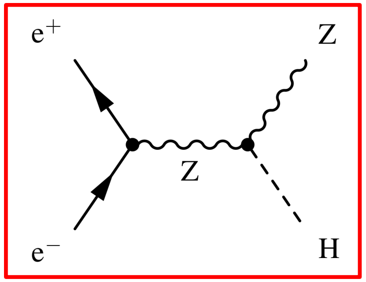
Closer look at $\sqrt{s}$ < 500 GeV

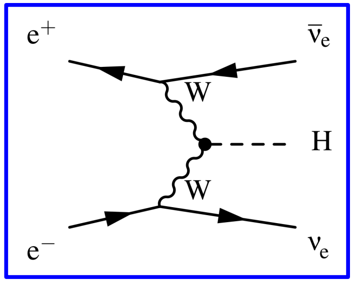




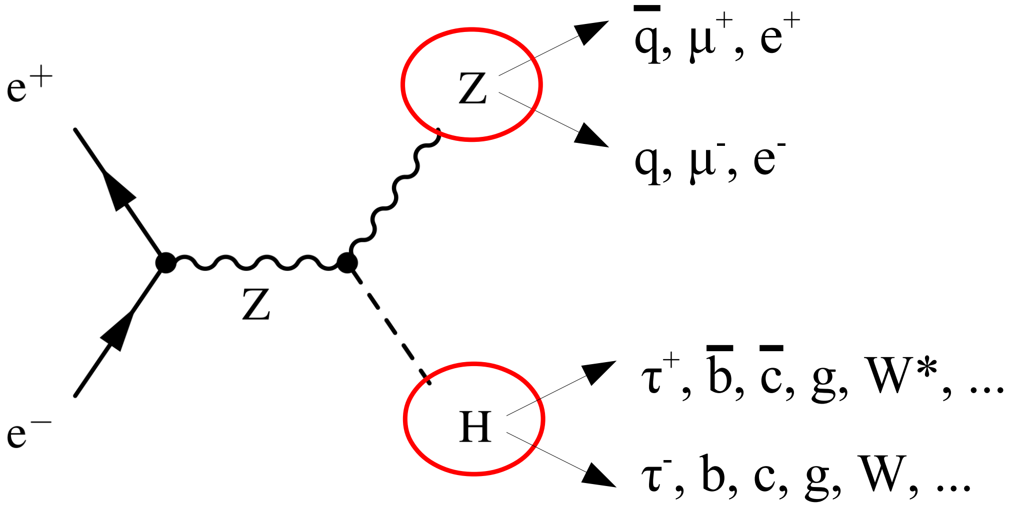
$\sqrt{s}$ = 240/250 GeV:
(CEPC, FCC-ee, ILC)
Maximum of the Higgsstrahlung cross section

$\sqrt{s}$ = 350/380 GeV:
(FCC-ee, ILC, CLIC)
Also allows to access the WW fusion process
→ Additional information for combined analysis





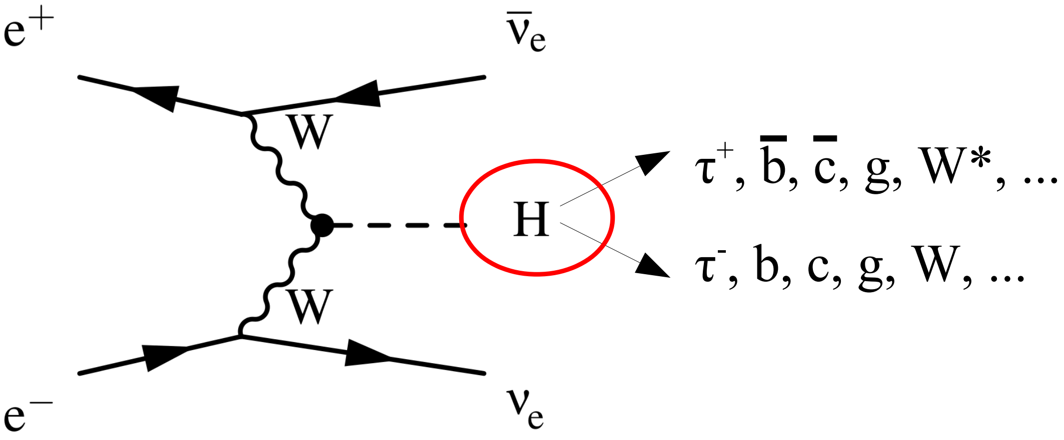
σ x BR measurements



At 350 GeV:
Higgsstrahlung

$$\boxed{\sigma \sim g^2_{HZZ} g^2_{HVV/Hff} / \Gamma_H}$$

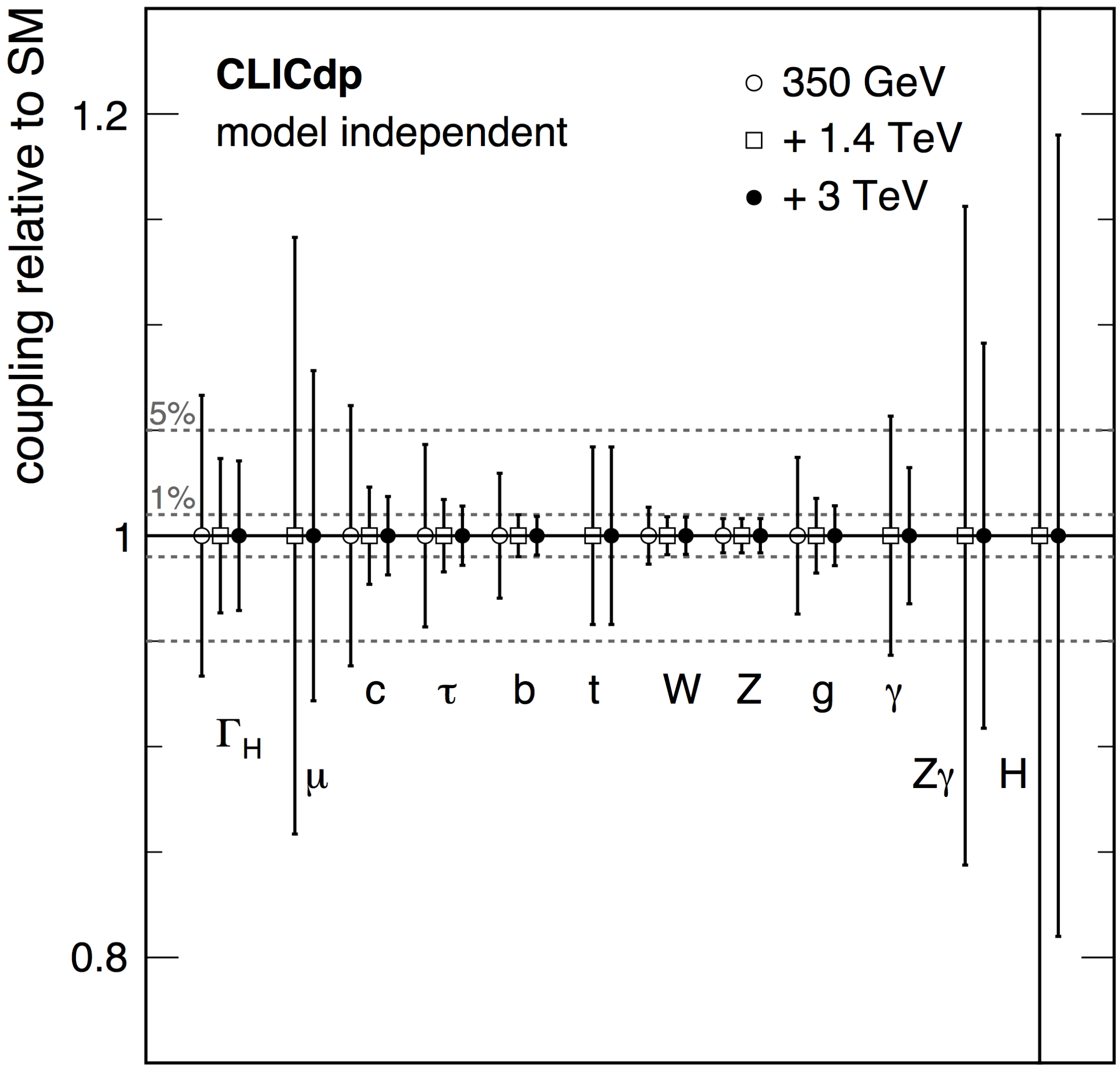
+ BR(H→inv.) < 0.97% at 90% CL



At 350 GeV and higher:
WW fusion

$$\boxed{\sigma \sim g^2_{HWW} g^2_{HVV/Hff} / \Gamma_H}$$

Higgs properties at CLIC (1)



- Fully model-independent analysis only possible at lepton colliders

- All results limited by 0.8% from σ(HZ) measurement

- The Higgs width is extracted with 6.7-3.5% precision

CLICdp Collab.
arXiv:1608.07538
accepted by EPJC

Higgs properties at CLIC (2)

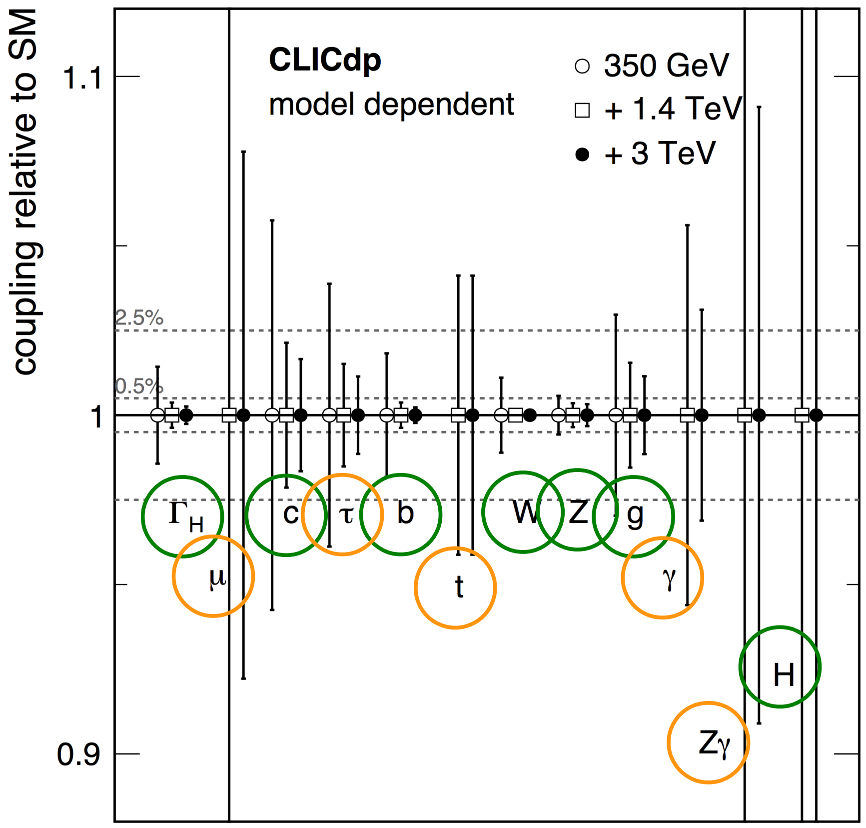
Model dependent fit:

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

BR$_i$: SM branching fractions (prediction)

Only SM Higgs decays:

$$\boxed{\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \sum_i \kappa_i^2 \, BR_i}$$



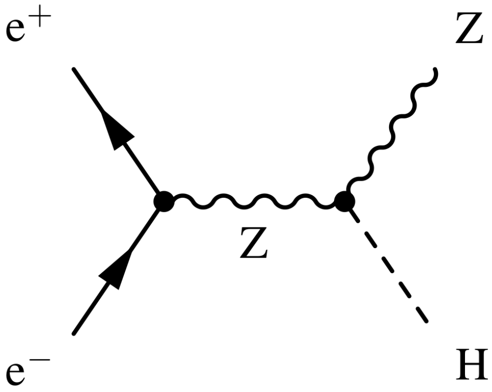
○ significantly better than HL-LHC or not possible at hadron colliders

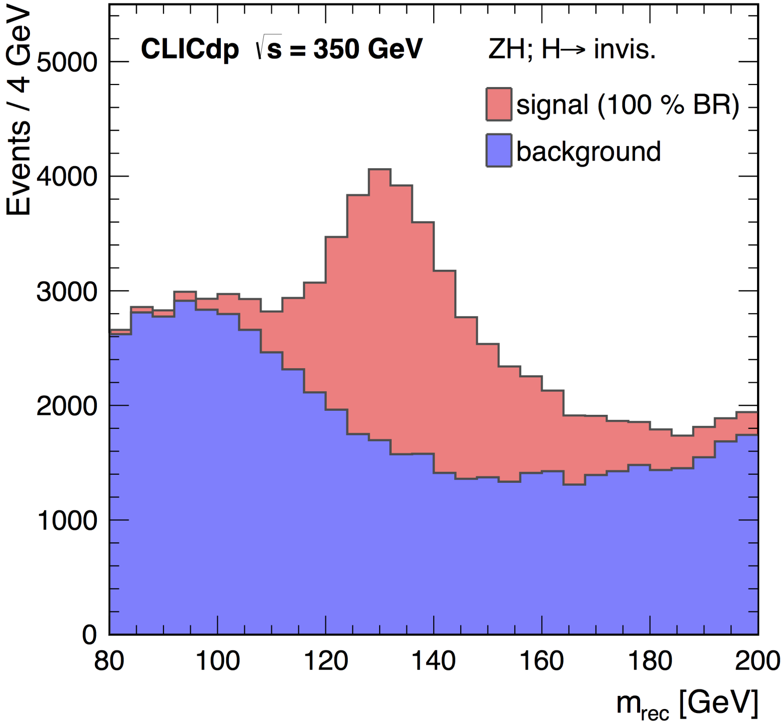
○ similar to HL-LHC

Invisible Higgs decays

The recoil mass technique also allows to identify invisible Higgs decays in a model-independent manner

Example:
BR(H→inv.) < 0.97% at 90% CL
for CLIC at 350 GeV

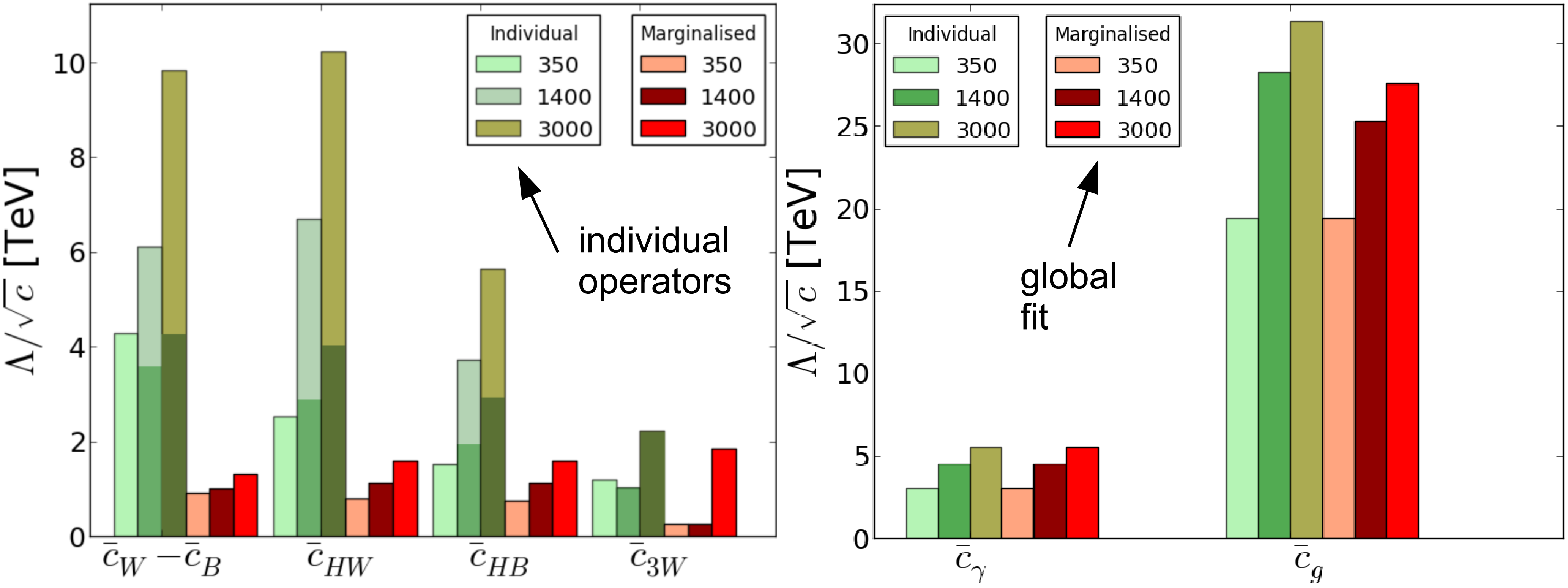




Recoil mass from $Z \rightarrow q\bar{q}$ assuming all Higgs bosons decay invisibly

CLIC sensitivities to dimension-6 operators

Individual CLIC energy stages



individual operators

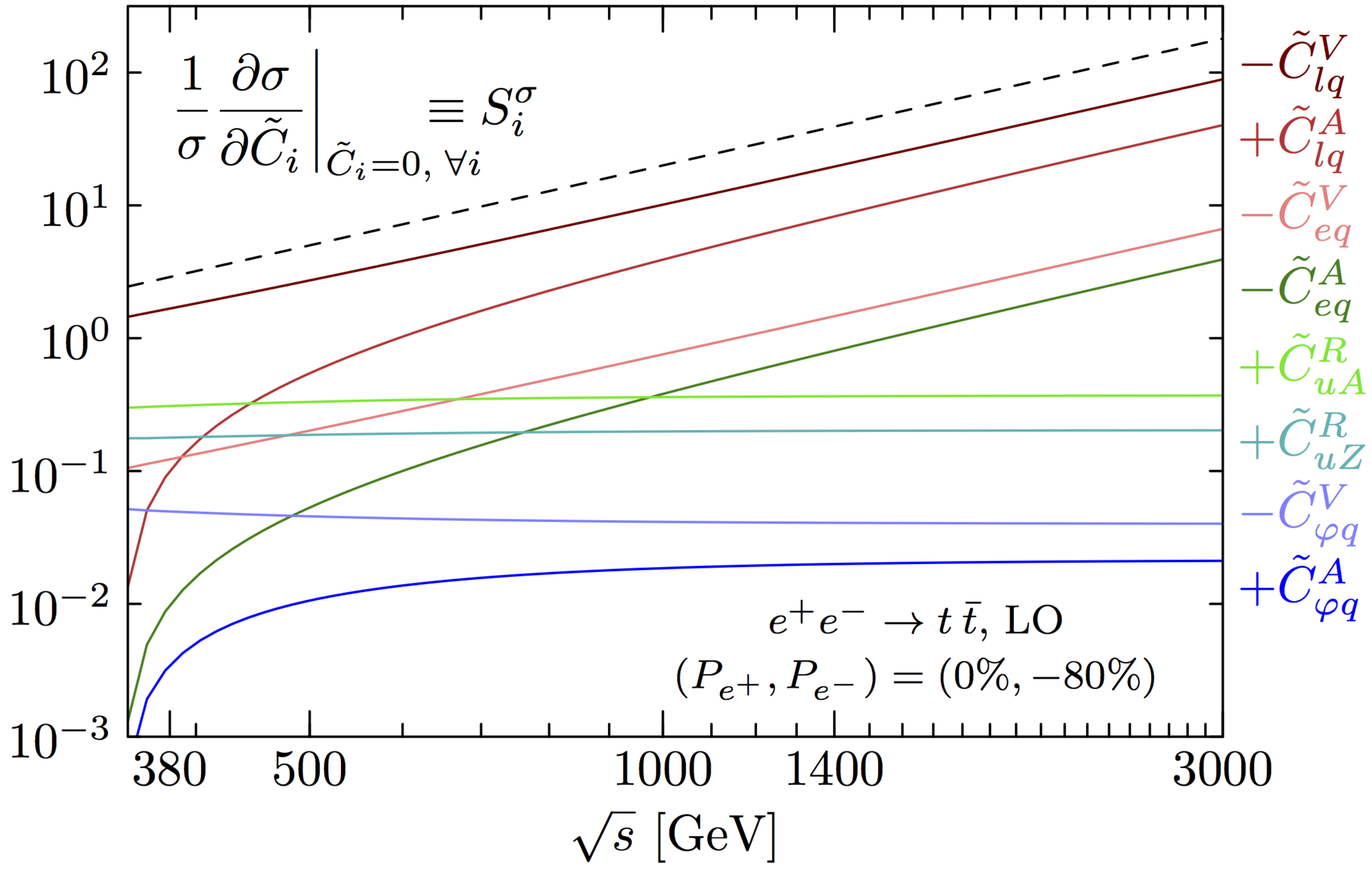
global fit

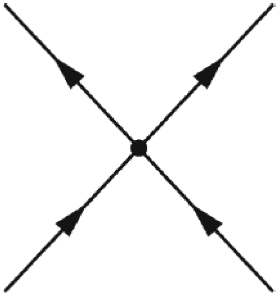
Sensitivity enhanced by higher centre-of-mass energy

JHEP 1705, 096 (2017)

What about $t\bar{t}$ at high energy?

Dependence of $\sigma(e^+e^- \to t\bar{t})$ on dimension-6 operators:





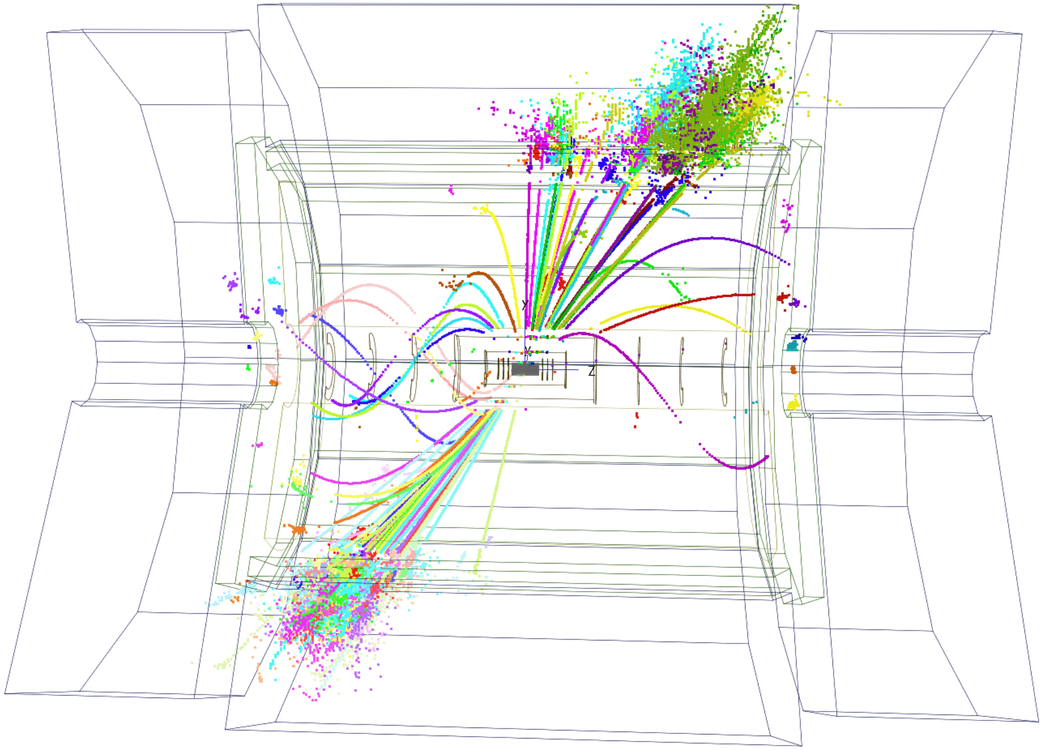
Four-fermion operators:
Sensitivity rises steeply
with energy
→ best measured
at high energy

Vertex operators:
Sensitivity flat in energy
for several operators
→ best measured
at 380 GeV (most $t\bar{t}$ events)

Durieux, Perelló,
Vos, Zhang,
to be published

The top pair production measurements at 380 GeV and at high energy provide complementary information

Boosted top reconstruction at CLIC



$e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$ at $\sqrt{s} = 3$ TeV

- Hadronic decays of high-energy top quarks do not lead to three separated jets

- Instead, reconstruction of the top in a “large” jet and identification of substructure compatible with $t \rightarrow Wb \rightarrow q\bar{q}b$

- Studied ≈10 years for the LHC, new and active effort for CLIC including different approaches

- Also useful for $t\bar{t}H$, top squarks, ...

VBS: experimental aspects

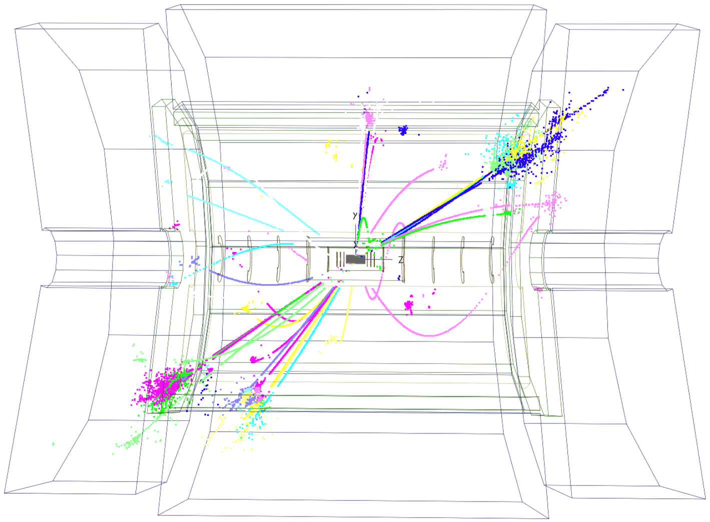
- At CLIC fully hadronic events can be used (in contrast to hadron colliders):
$W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$
→ largest event samples and full kinematic information

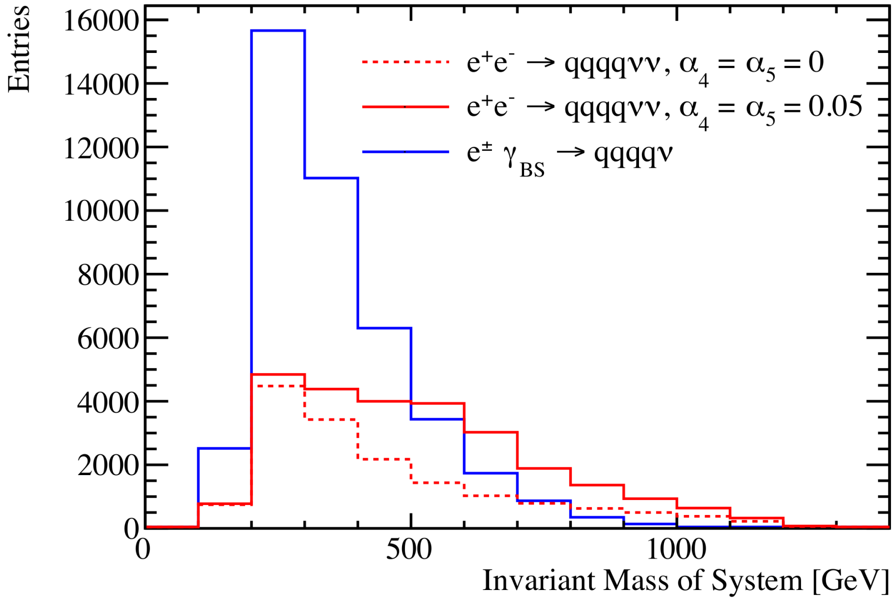
- Extract the operator coefficients α_4 and α_5 from invariant mas of the final-state bosons

- Most important background after event selection: $e^{\pm}\gamma_{BS} \rightarrow qqqq\nu$
(γ_{BS}: photon originating from Beamstrahlung)

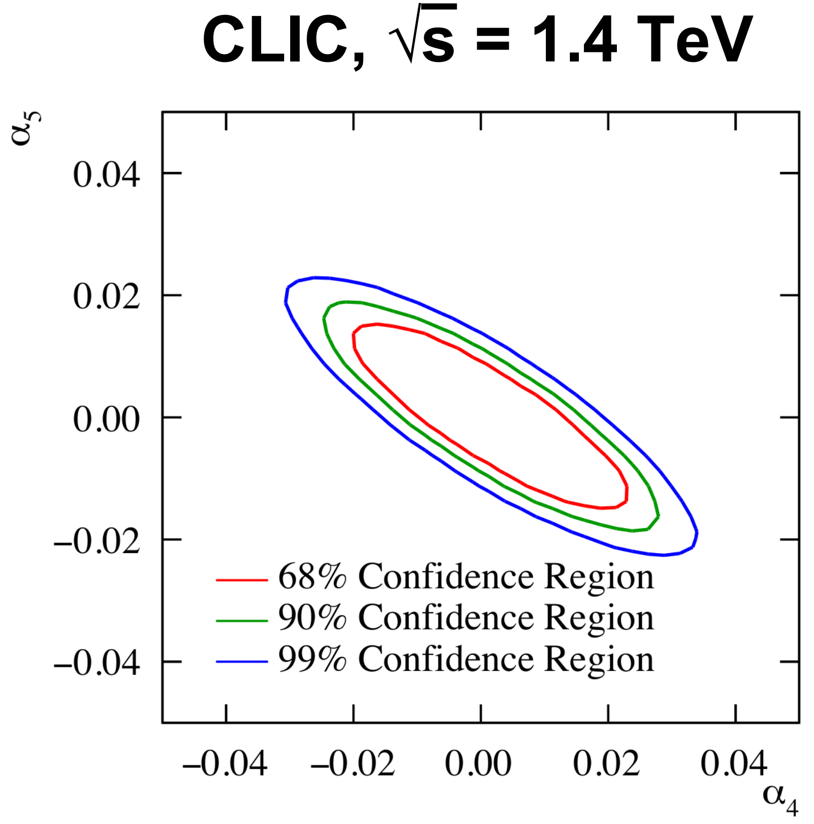
$$\alpha_4 = F_{S,0}\, v^4/16$$
$$\alpha_5 = F_{S,1}\, v^4/16$$

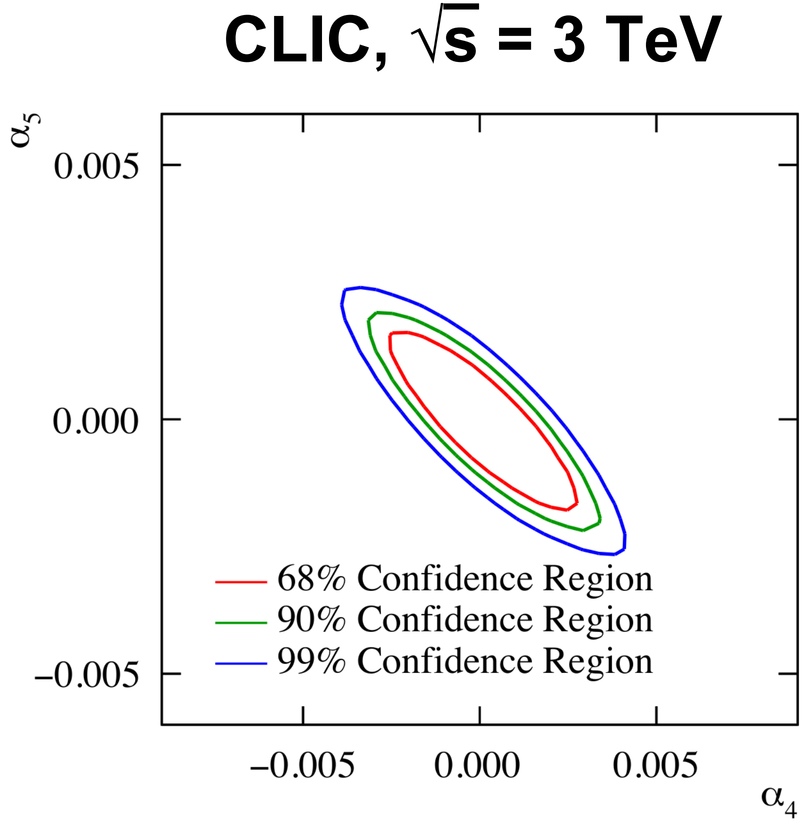
CLIC, √s = 1.4 TeV





VBS: results





1D fit (68% CL):

$-0.0082 < \alpha_4 < 0.0116$

$-0.0055 < \alpha_5 < 0.0078$

1D fit (68% CL):

$-0.00102 < \alpha_4 < 0.00112$

$-0.00070 < \alpha_5 < 0.00074$

→ Sensitivity almost one order of magnitude better at 3 TeV

Precision study of $e^+e^- \to \mu^+\mu^-$

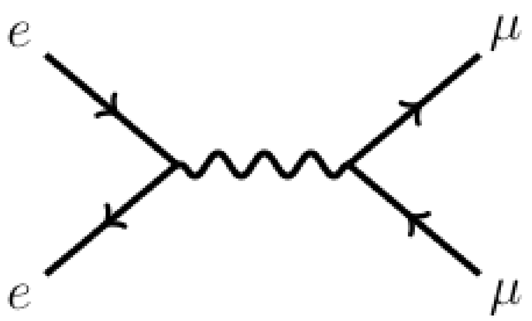
Minimal anomaly-free Z' model:
Charge of the SM fermions under U(1)' symmetry:
$Q_f = g_Y'(Y_f) + g'_{BL}(B-L)_f$

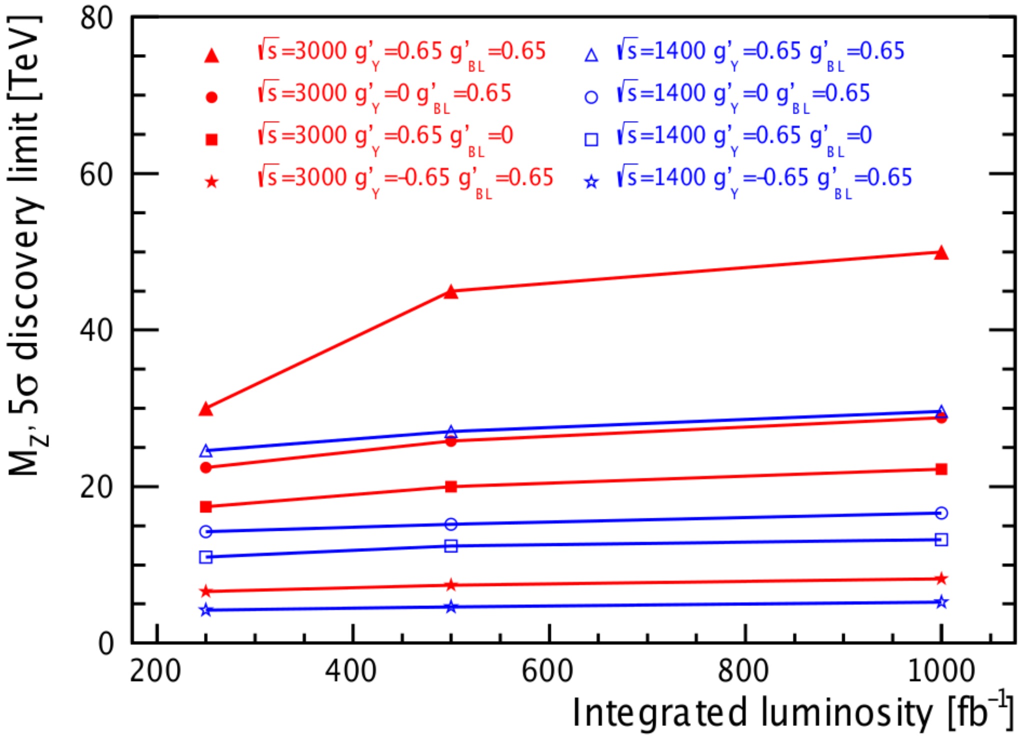
Observables:
- total $e^+e^- \to \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry

($\pm80\%$ e^- polarisation)

If LHC discovers Z' (e.g. for M = 5 TeV):
Precise measurement of the effective couplings

Otherwise:
Discovery reach up to tens of TeV
(depending on the couplings)



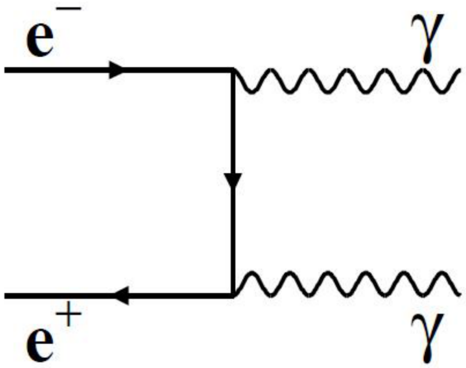


Blaising, Wells, arXiv:1208.1148

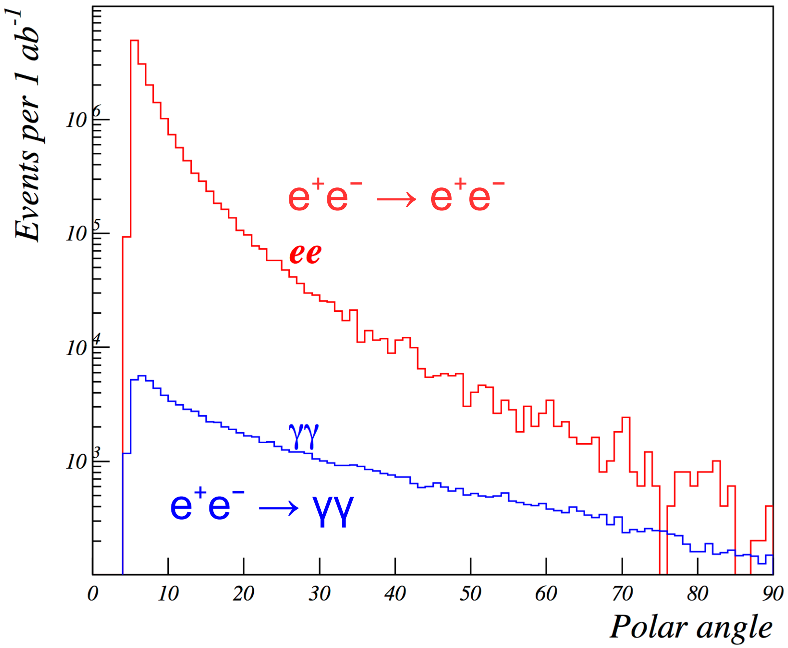
Precision study of $e^+e^- \rightarrow \gamma\gamma$

New physics searches with $e^+e^- \rightarrow \gamma\gamma$:
deviation from QED expectation

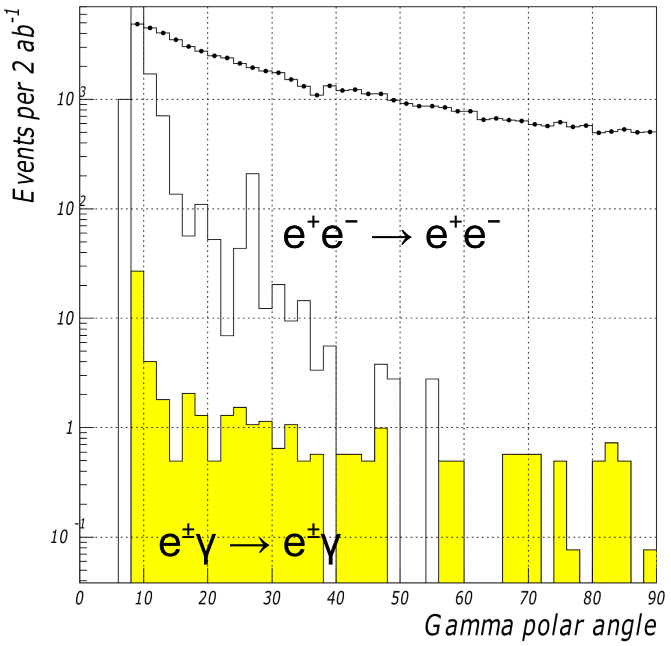
Events with small energy loss
due to Beamstrahlung and ISR are selected
→ two back-to-back photons
(track veto crucial)



Signal and main background

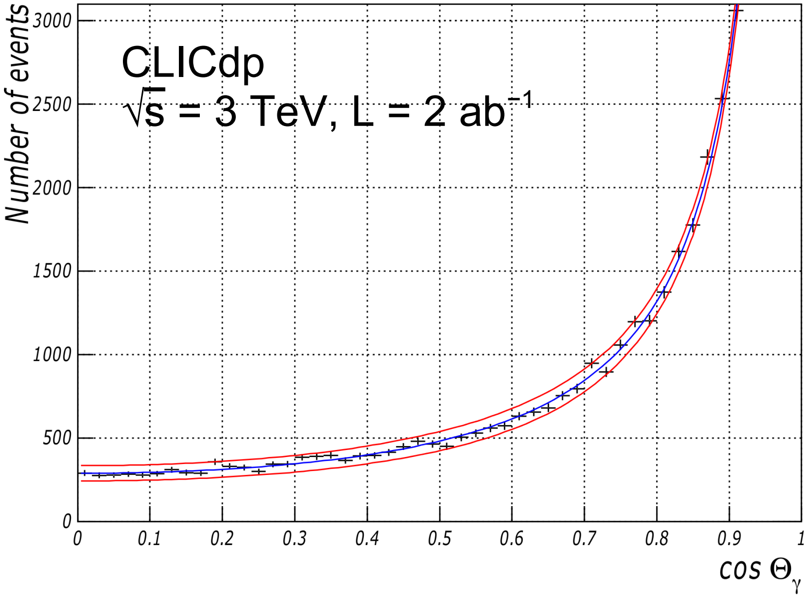


After selection:



$e^+e^- \rightarrow \gamma\gamma$: results and interpretation

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta)$$



Example: QED cutoff parameter Λ (simplest Ansatz)

CLIC: L = 2 ab^{-1}, ΔL/L = 0.5%

Scenario:	CLIC reach (95% CL):	LEP limit (95% CL):
QED cutoff parameter Λ (electron size)	6.33 TeV ($3.1 \cdot 10^{-18}$ cm)	≈390 GeV
Contact interactions: Λ'	20.1 TeV	≈830 GeV
Extra dimensions: $M_s/\Lambda^{1/4}$	15.9 TeV	≈1 TeV
Excited electron: M(e*)	4.87 TeV	≈250 GeV

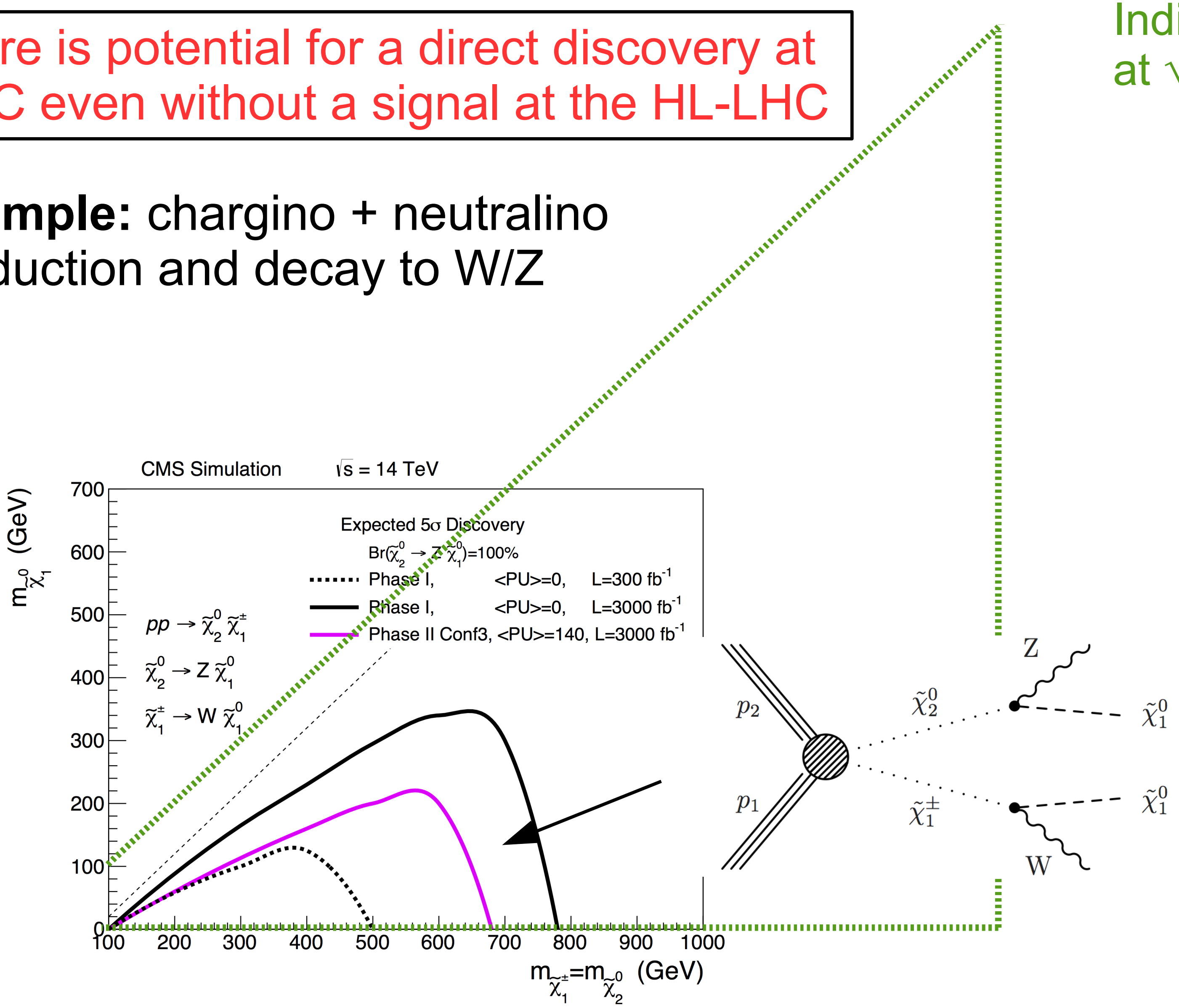
→ CLIC at 3 TeV factor 15 - 30 better than the LEP limits

Heavy electroweak states (1)

There is potential for a direct discovery at CLIC even without a signal at the HL-LHC

Indicative CLIC reach at $\sqrt{s}$ = 3 TeV

Example: chargino + neutralino production and decay to W/Z



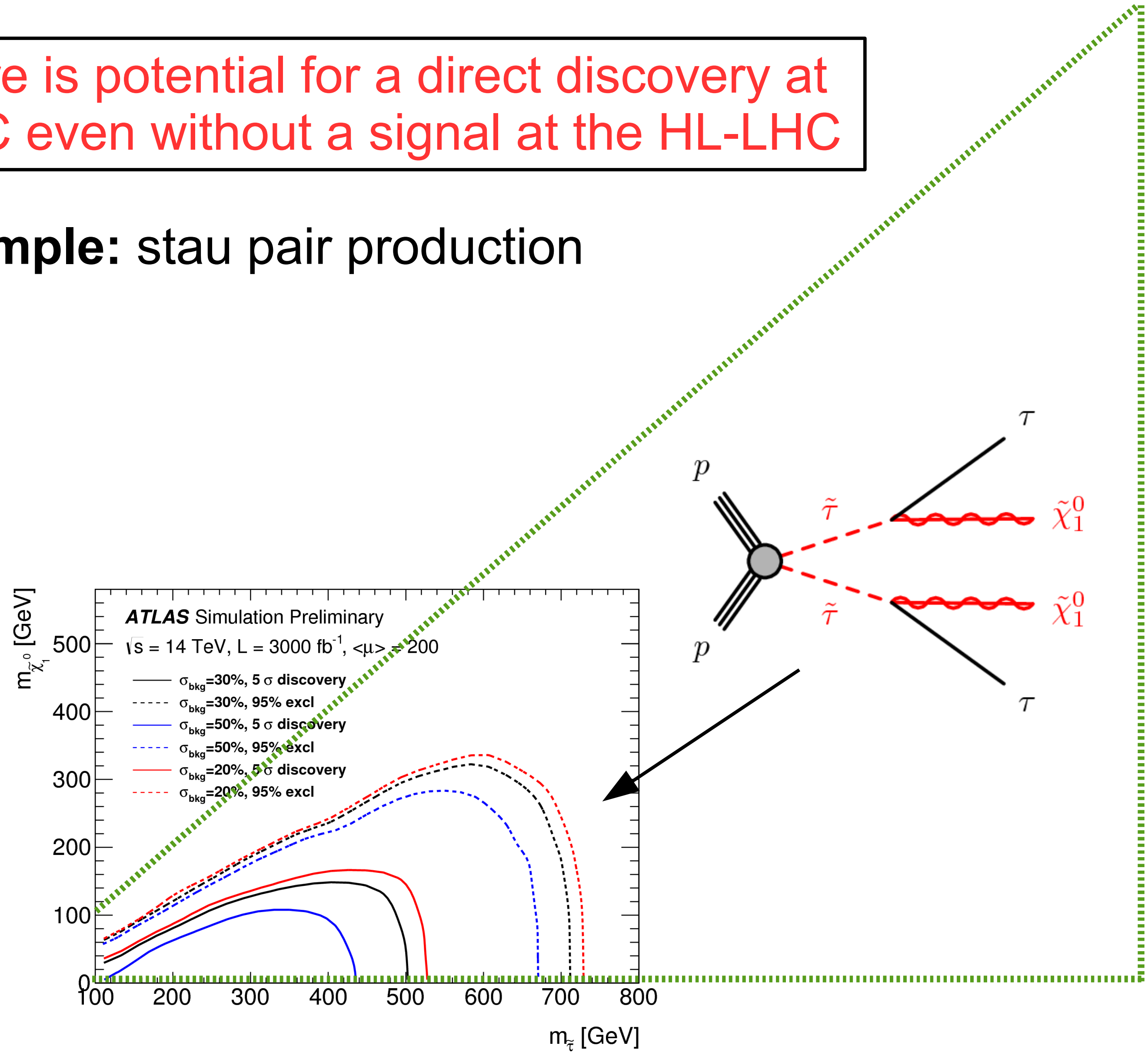
CMS-PAS-FTR-13-014

(similar projection: ATL-PHYS-PUB-2014-010)

Heavy electroweak states (2)

There is potential for a direct discovery at CLIC even without a signal at the HL-LHC

Example: stau pair production



Indicative CLIC reach at $\sqrt{s}$ = 3 TeV

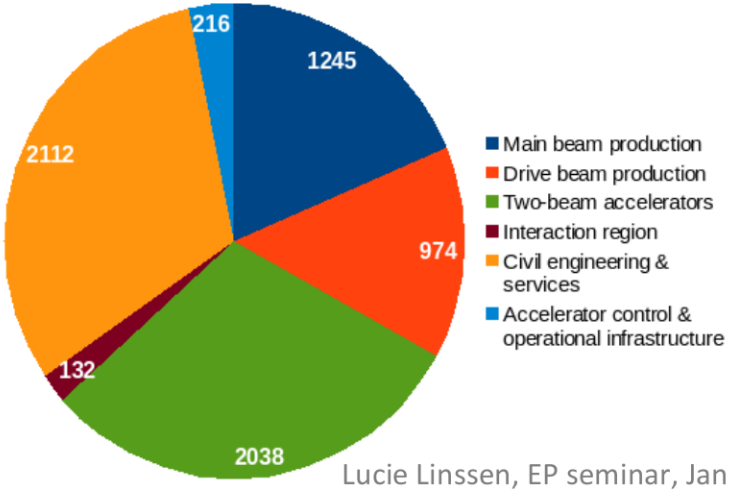
ATLAS-PHYS-PUB-2016-021

CLIC cost estimate

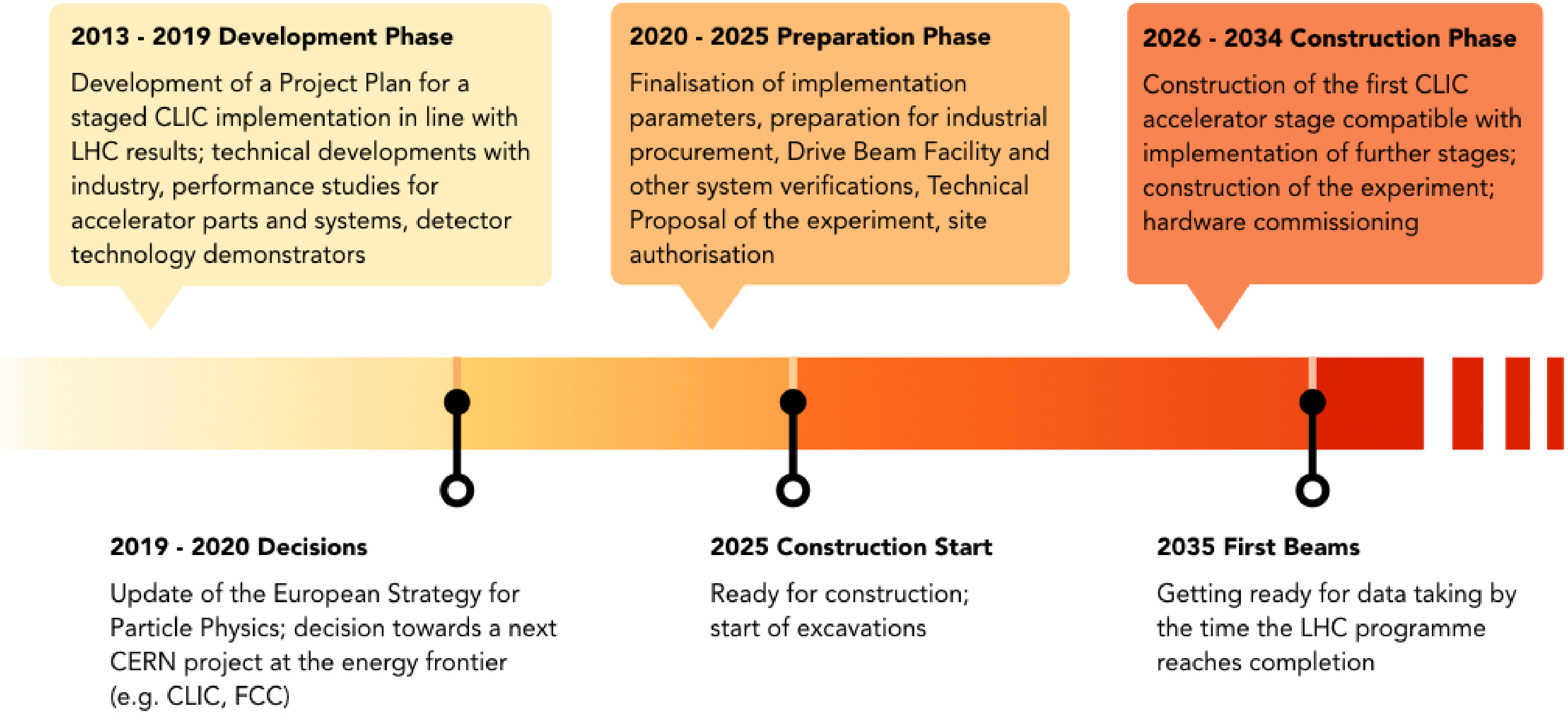
Preliminary estimate (scaled from CDR) with room for improvement.
New estimate will be provided for European Strategy Update.

System	**Value for 380 GeV** (MCHF of Dec 2010)
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operation infrastructure	216
TOTAL	**6690**

Value for the CLIC accelerator at $\sqrt{s}$ = 380 GeV (11.4 km site length)



CLIC timeline



2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion