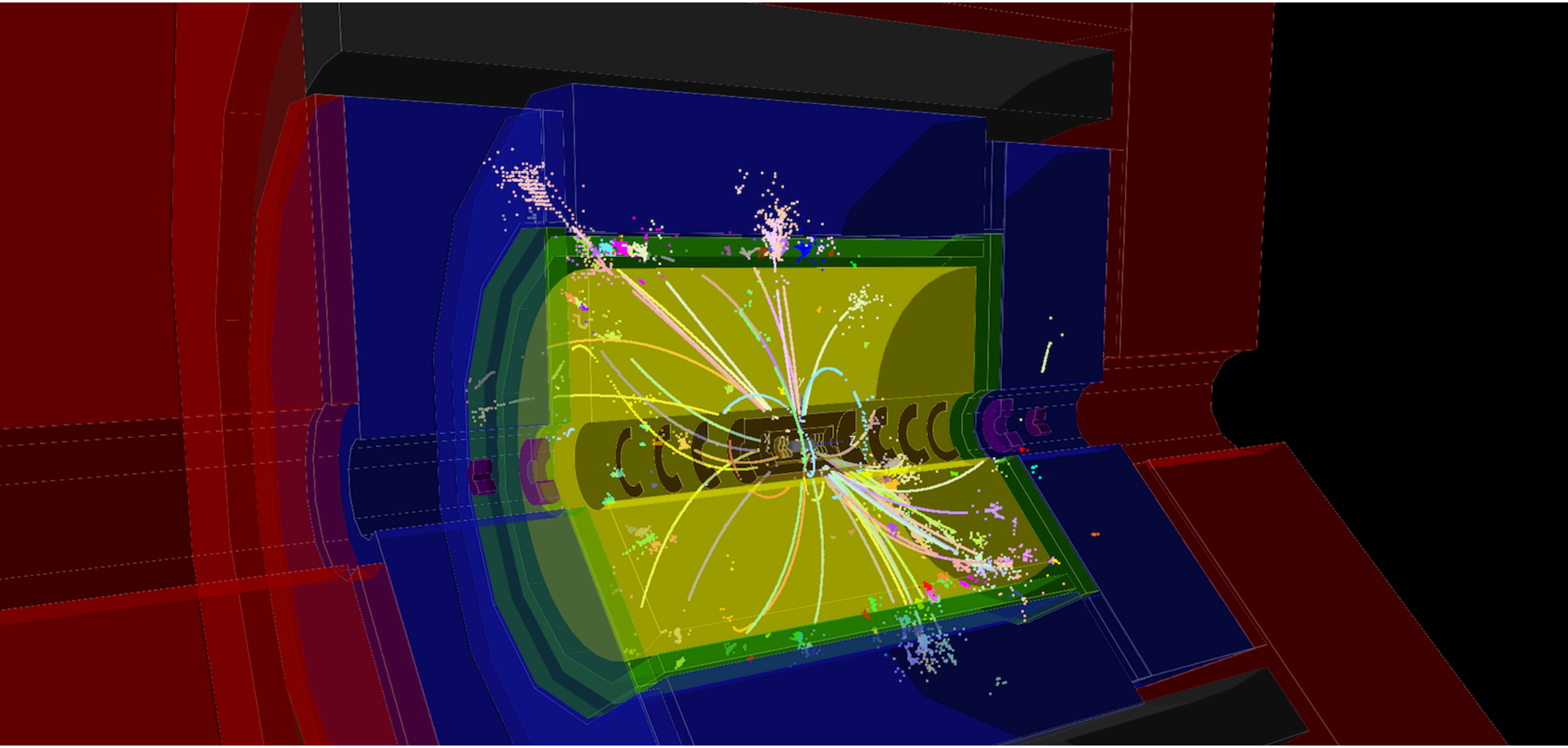
Physics at CLIC



Lucie Linssen, CERN
on behalf of the CLICdp collaboration

CERN, EP Seminar, January 24th 2017

With many thanks to my CLIC and CLICdp colleagues for presentation material

outline

- Open questions in physics / high-energy colliders
- The CLIC accelerator
- Experimental conditions at CLIC
- The CLIC detector model
- Physics at CLIC
  - Higgs physics
  - Top quark physics
  - Direct BSM searches
  - Indirect BSM probes
- CLIC timeline
- Summary

open questions in particle physics

Some of the main open questions in particle physics today:

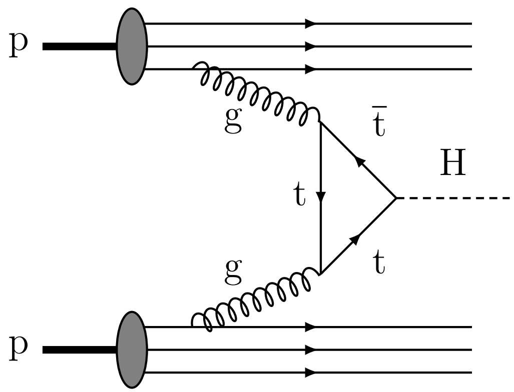
- Full understanding of the Higgs properties and EWSB
  - → hierarchy / naturalness problem
- Why are there three fermion families?
- What is the origin of matter-antimatter asymmetry?
- Full understanding of neutrino masses and oscillations
- What is dark matter?
- What is causing the accelerated expansion of the universe?
- What is gravity?
- ……

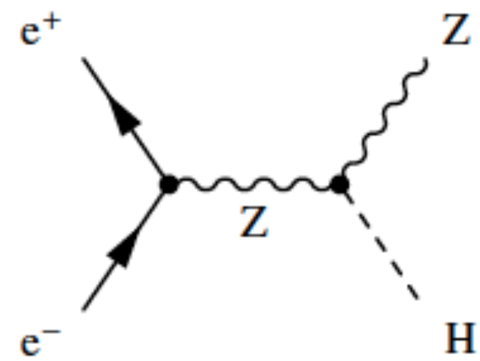
There are many parallel approaches to searching for the answers

…. **among which: high-energy particle colliders => pp and/or e^+e^- colliders**

Still unclear at what energy scales will we find our answers

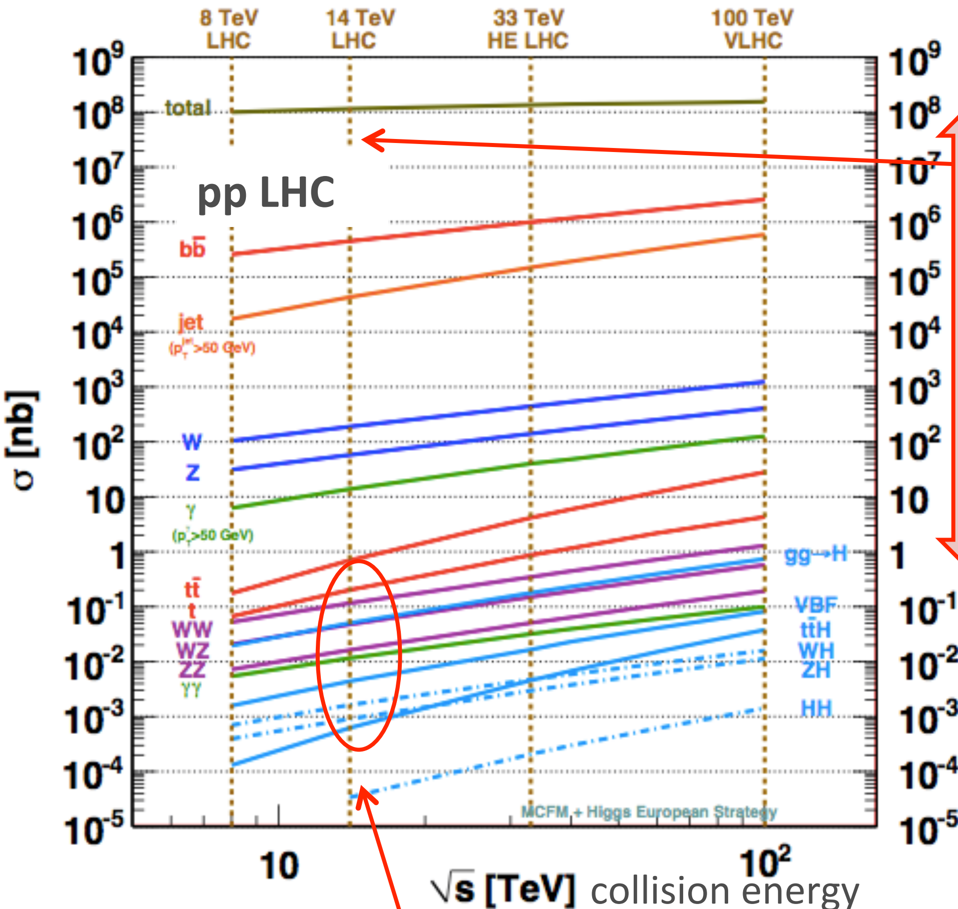
pp collisions / e^+e^- collisions





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	High energy (>≈350 GeV) e^+e^- requires **linear** collider

pp collisions / e^+e^- collisions

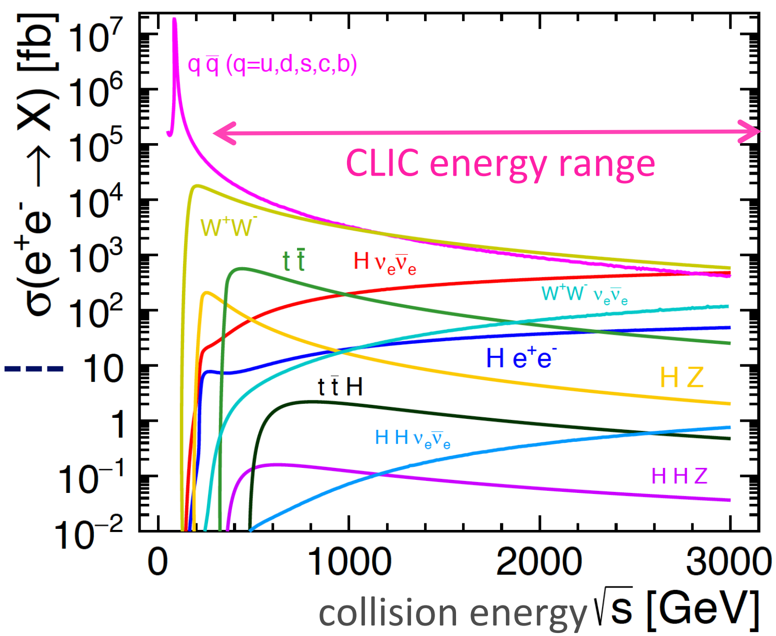


LHC total cross section

factor > 100 million !!

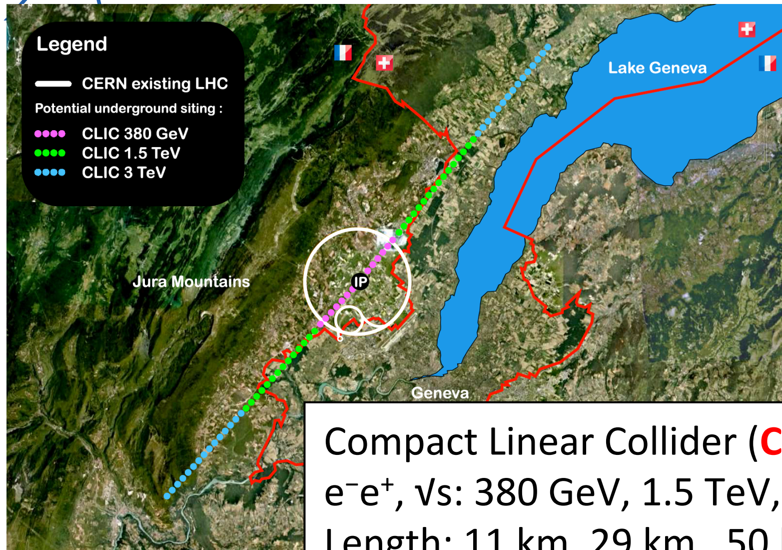
at LHC much of the interesting physics needs to be found among a huge number of collisions

e^+e^- CLIC

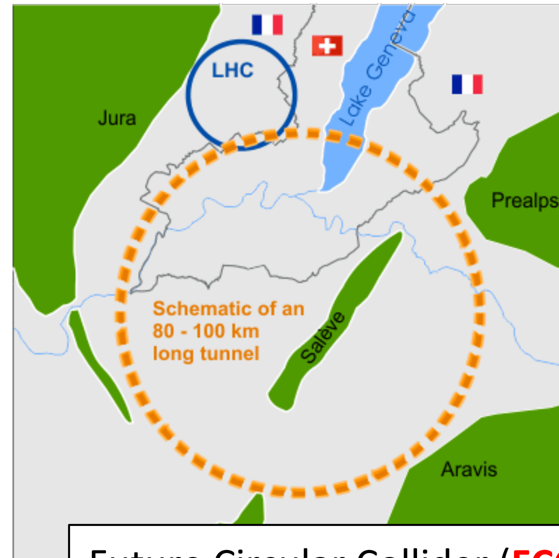


e^+e^- events are more "clean"

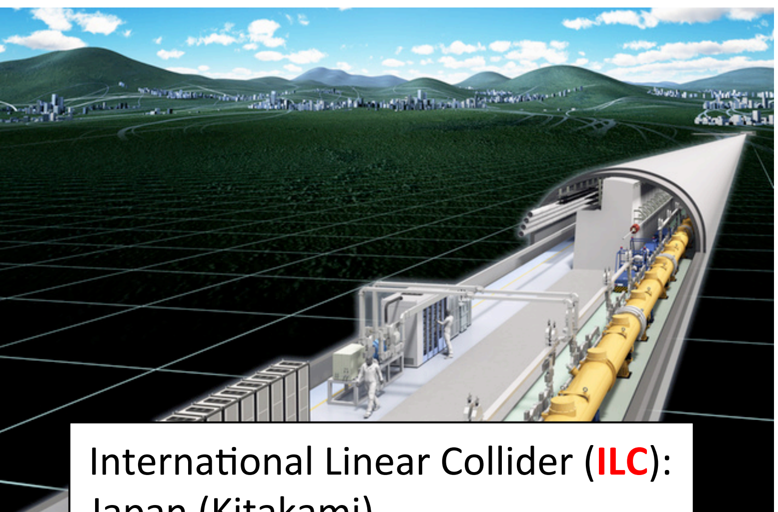
studies of high-energy e^+e^- colliders



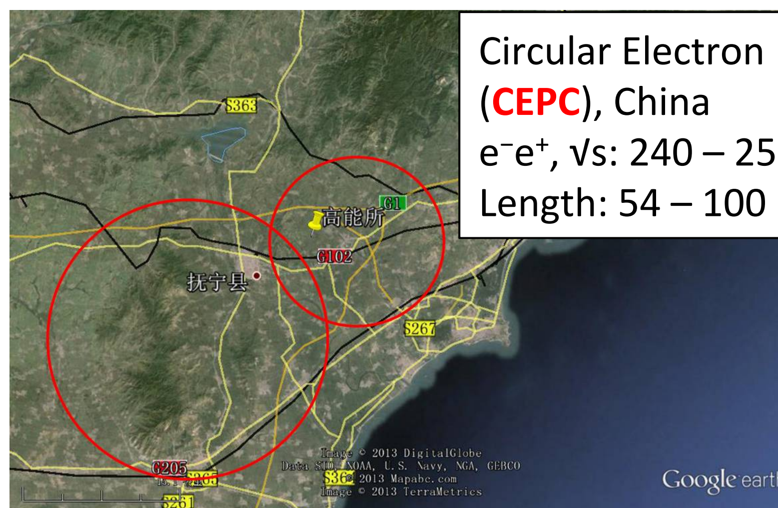
Compact Linear Collider (**CLIC**): CERN
e^-e^+, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC**): CERN
e^-e^+, $\sqrt{s}$: 90 - 350 GeV; pp, $\sqrt{s}$: ~100 TeV
Circumference: 90 - 100 km

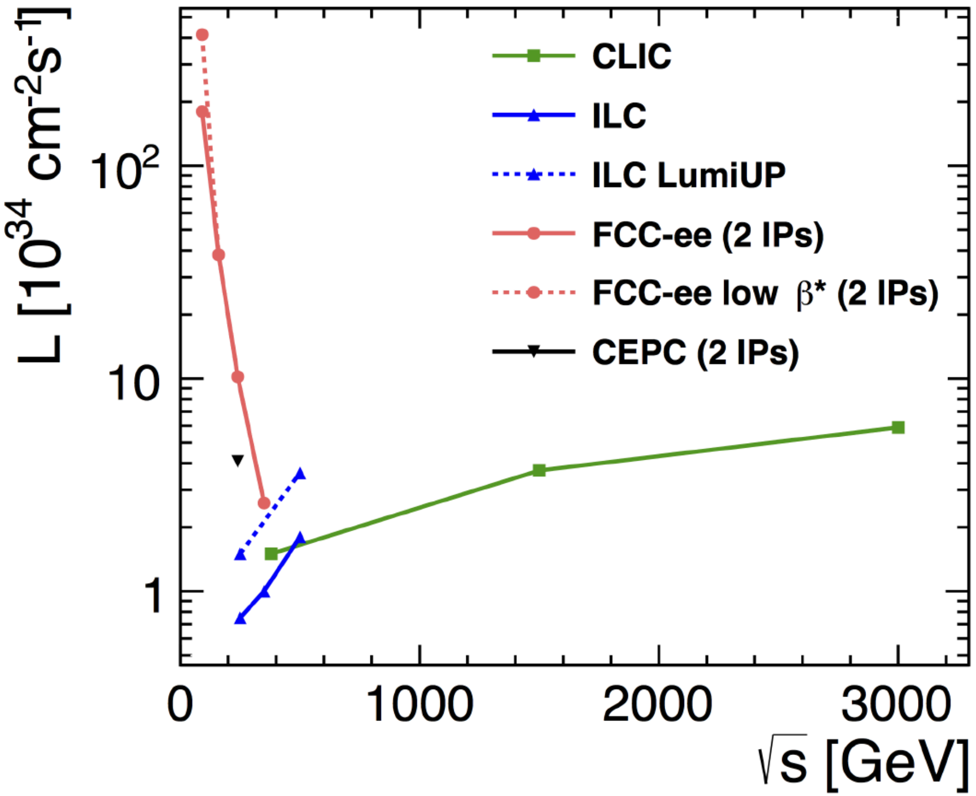


International Linear Collider (**ILC**):
Japan (Kitakami)
e^-e^+, $\sqrt{s}$: 500 GeV (1 TeV)
Length: 31 km (50 km)



Circular Electron Positron Collider
(**CEPC**), China
e^-e^+, $\sqrt{s}$: 240 – 250 GeV; SPPC pp,
Length: 54 – 100 km

luminosity performance e^+e^- colliders



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

Note: Peak luminosity at LEP2 (209 GeV) was ~10^{32} $cm^{-2}s^{-1}$

CLIC 2-beam acceleration scheme

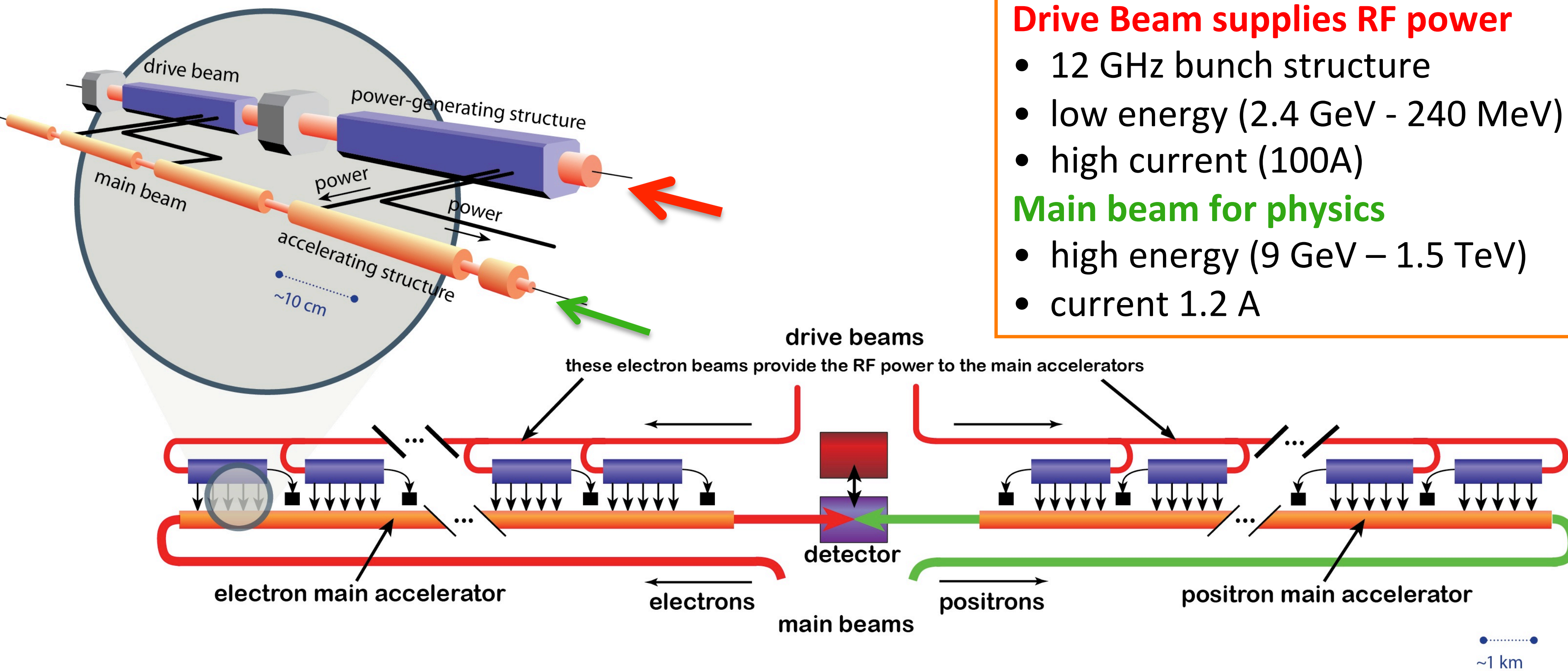
High centre-of-mass energy requires high-gradient acceleration

- High gradients feasible in normal conducting structures with high RF frequency (12 GHz)
- Initial transfer from wall plug to beam (klystron) is efficient at lower frequency (~1 GHz)
- To keep power low, apply RF power only at the time when the beam is there.

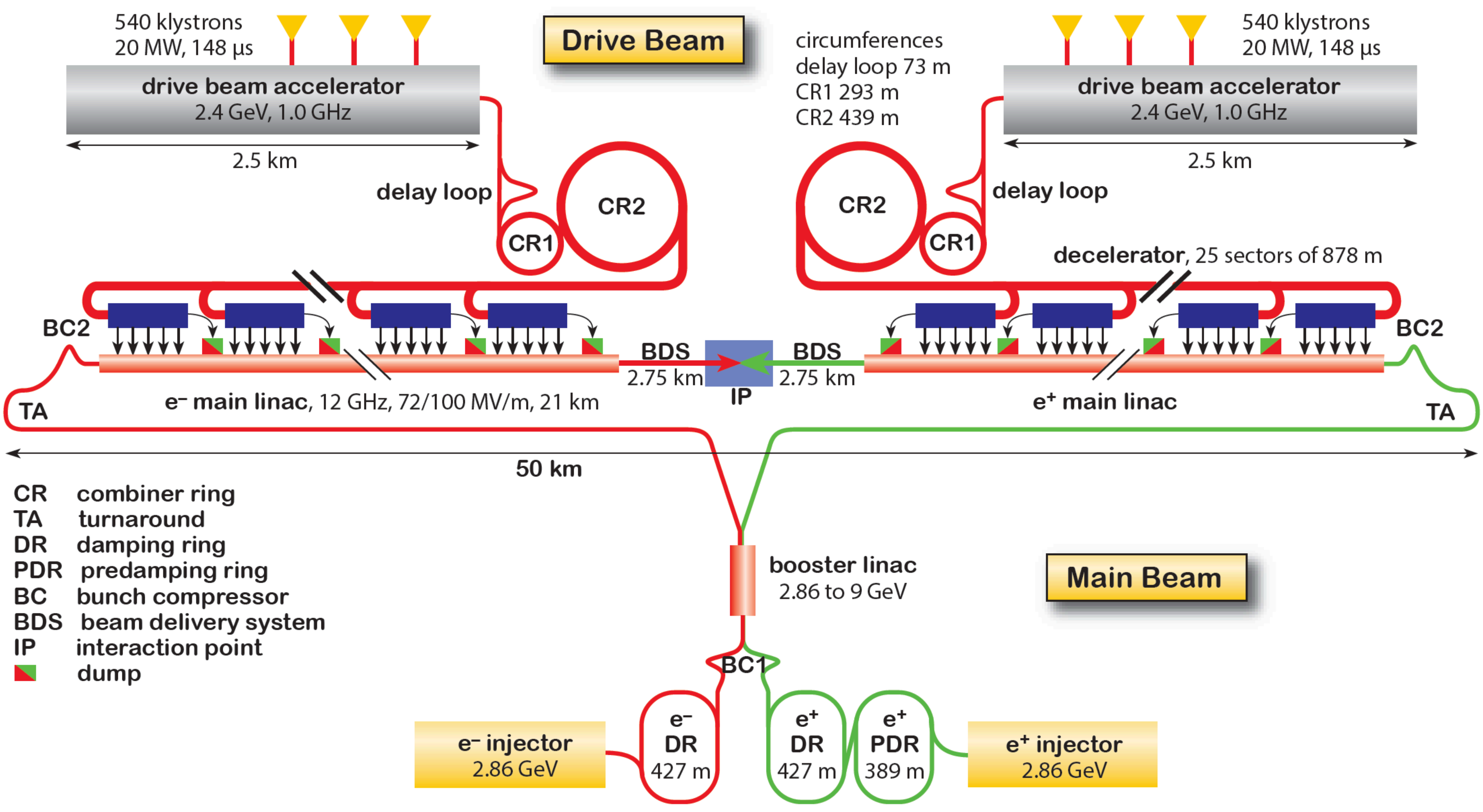
CLIC uses a 2-beam acceleration scheme at 12 GHz, gradient of 100 MV/m

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



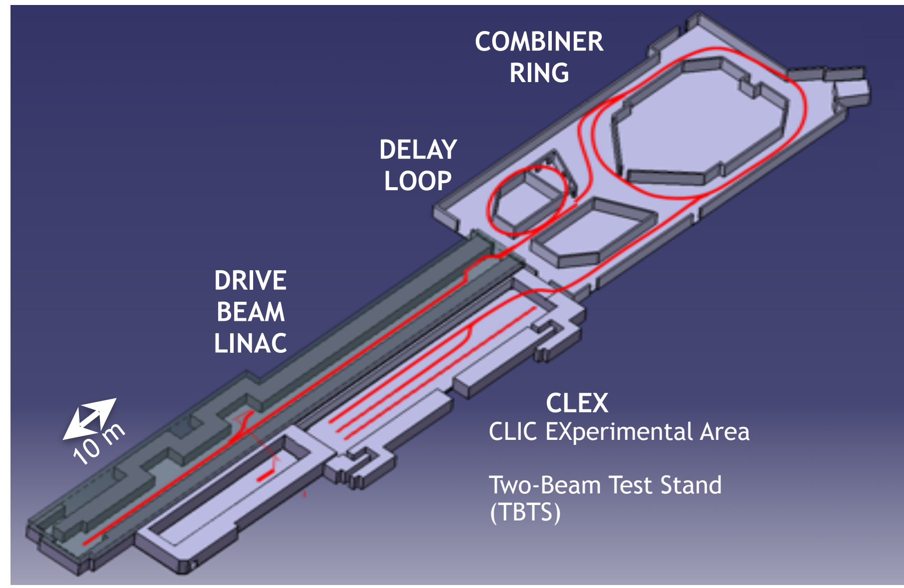
CLIC layout at 3 TeV



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 starts operating in 2017

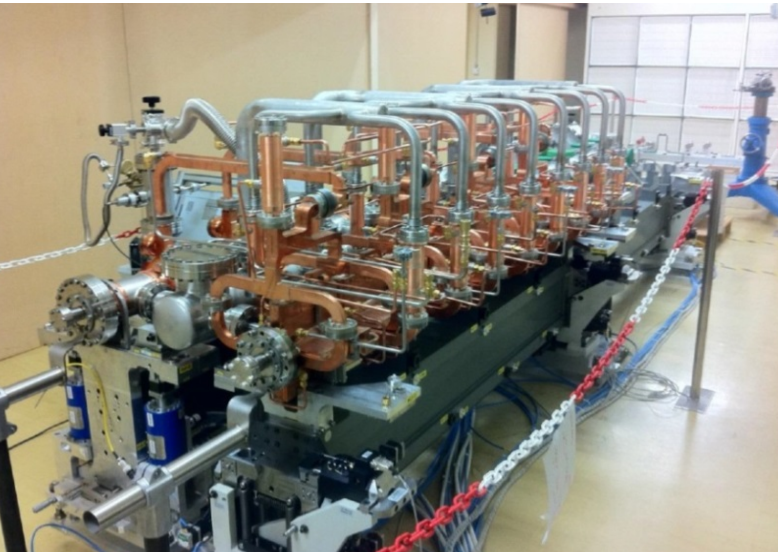
(it's based on the current CFT3 probe beam)

CLEAR, Cern Linear Electron Accelerator for Research

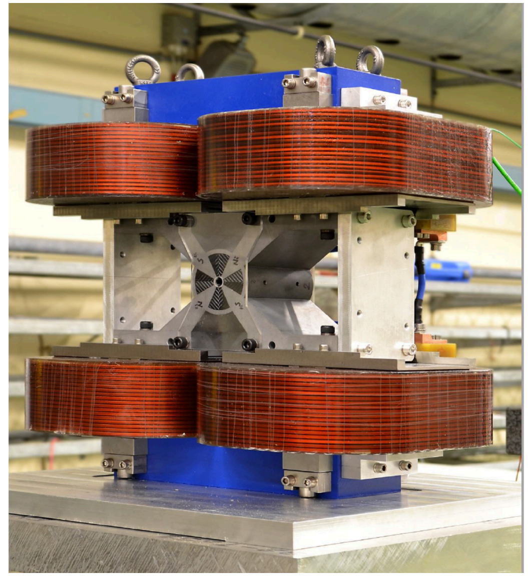
2-beam acceleration module in CTF3

CLIC accelerator, some pictures

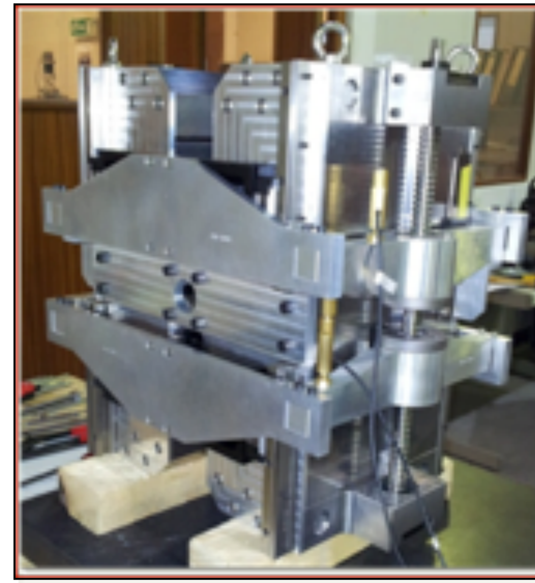
CLIC mechanical tests of 2-beam module



prototype final focus quadrupole

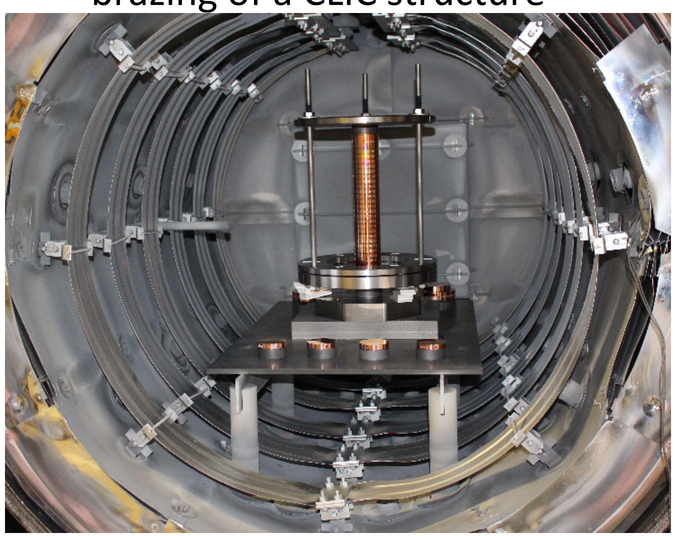


tunable permanent magnet

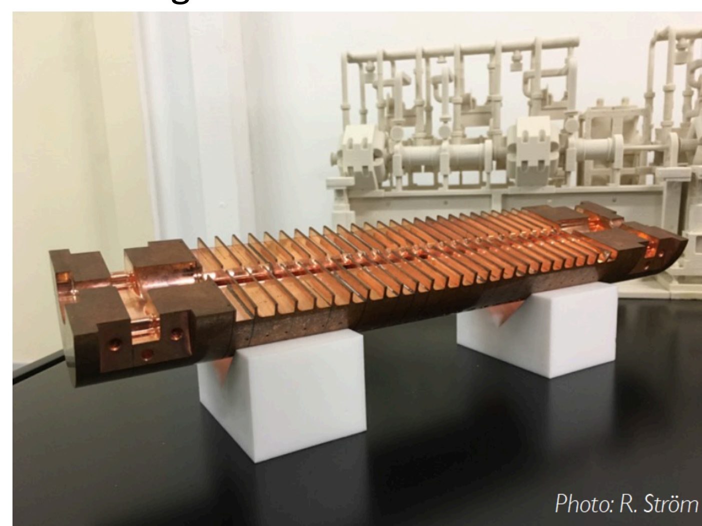


accelerator structure, 1 disk

brazing of a CLIC structure



cut through a CLIC acceleration structure

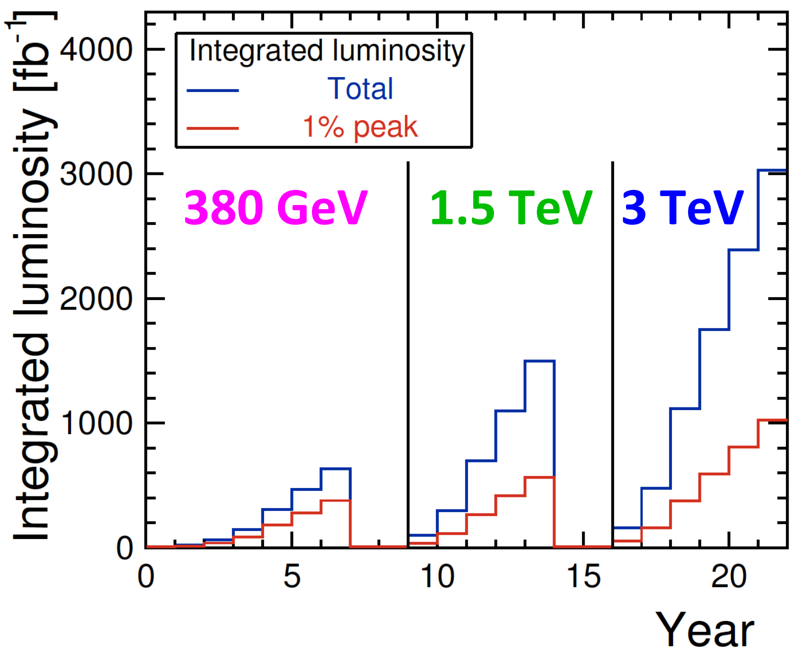


CLIC staging scenario

New CLIC staging baseline: CERN yellow report: CERN-2016-004
With "affordable" first stage at 380 GeV, focused on Higgs physics and top quark physics

Physics potential best exploited in a staged approach:

- **380 GeV (350 GeV)**, 600 fb^{-1} : precision Higgs and top physics (including top threshold scan)
- **1.5 TeV**, 1.5 ab^{-1} : BSM searches, precision Higgs, ttH, HH, top physics
- **3 TeV**, 3 ab^{-1} : BSM searches, precision Higgs, HH, top physics



Integrated luminosity including commissioning with beam and stops for energy upgrades

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

Dedicated to top mass threshold scan

Staging can be adapted to possible LHC discoveries

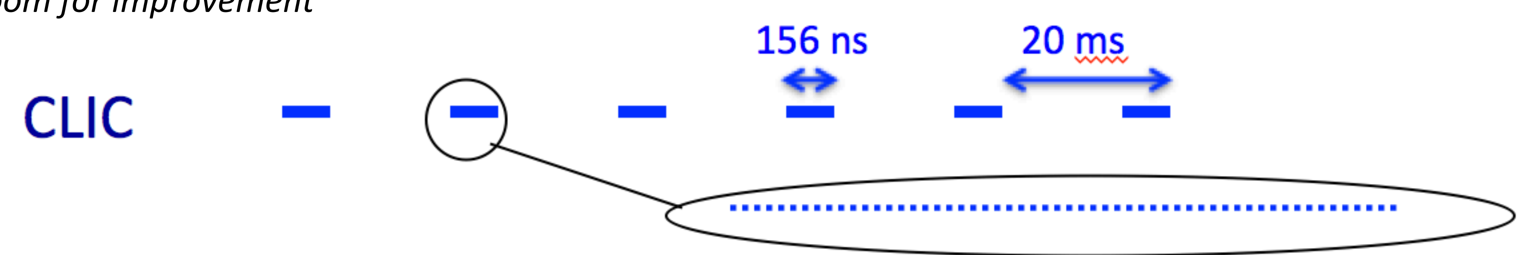
CLIC accelerator parameters

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathscr{L}$ ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
$\mathscr{L}$ above 99% of $\sqrt{s}$ ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	11.4	29	50
Repetition frequency (Hz)	50	50	50
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	70	44	44
Estimated power consumption* (MW)	252	364	589

Drives timing requirements for CLIC detector

Very small beam

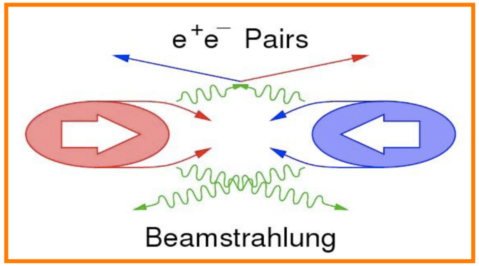
*scaled from CDR, with room for improvement



1 train = 312 bunches, 0.5 ns apart

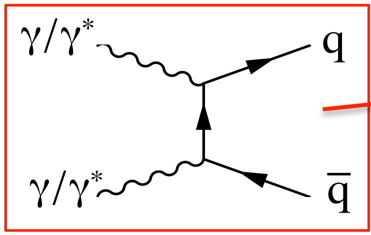
- not to scale -

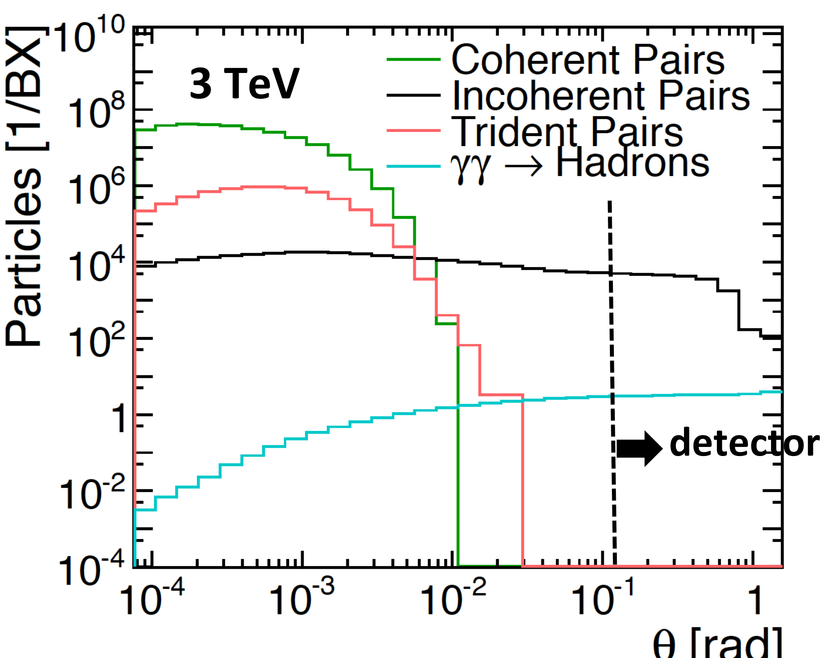
CLIC accelerator environment

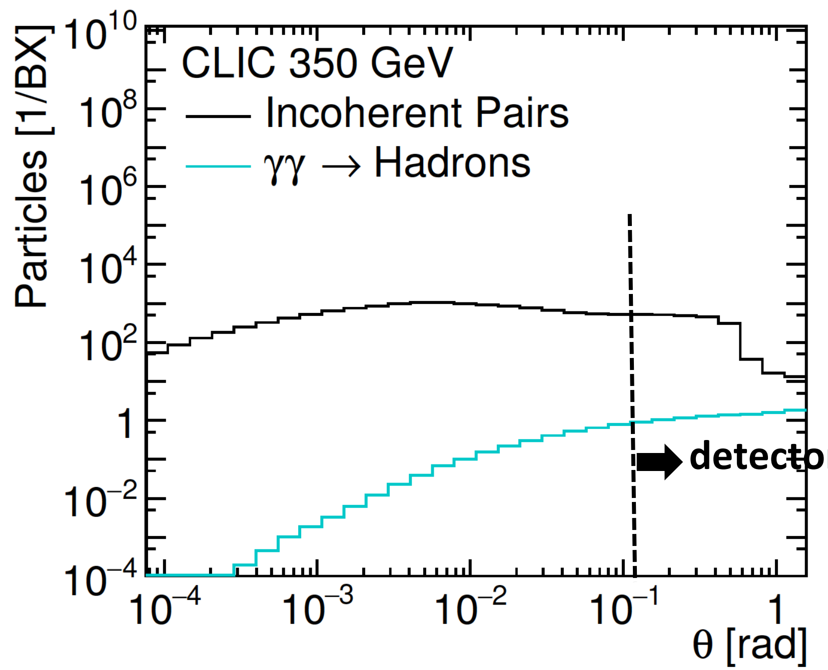


Beam-beam background at IP:

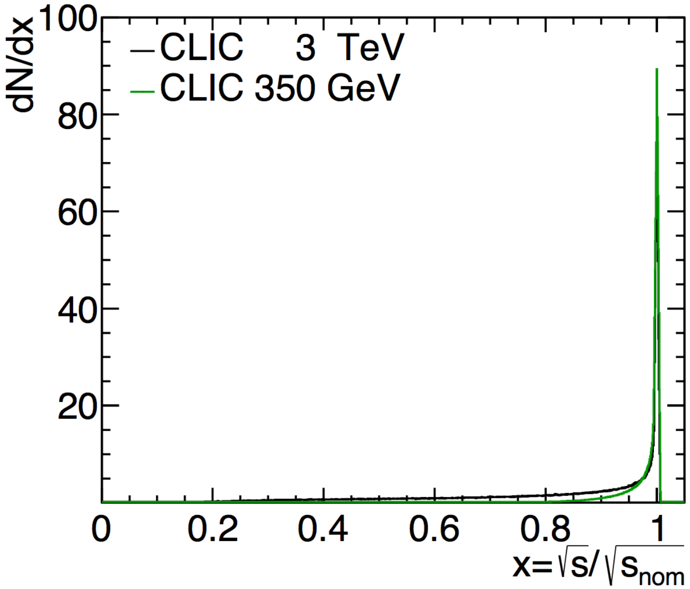
- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background** → Simplified picture: Design issue (small cell sizes)
    - High occupancies
  - **γγ to hadrons** → Impacts on the physics; Needs suppression in data
    - Energy deposits

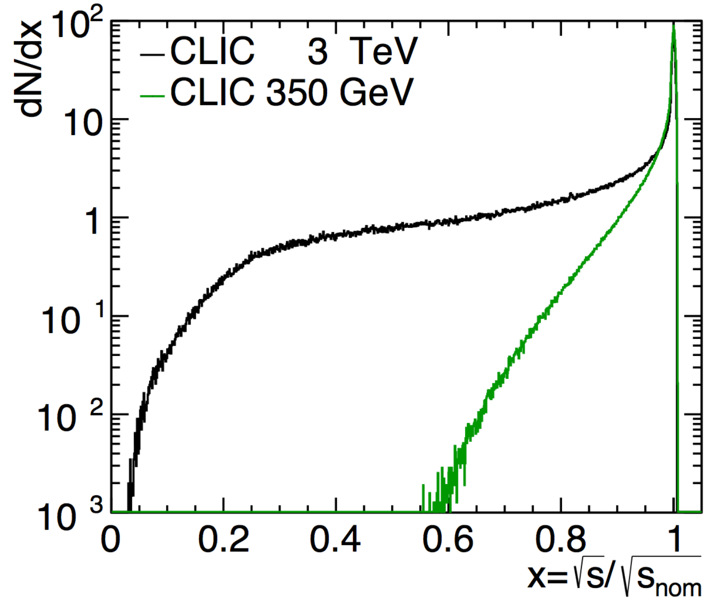






luminosity spectrum





Beamstrahlung ➔ important energy losses right at the interaction point

Most physics processes are studied well above production threshold => profit from full spectrum

Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV

Eur.Phys.J. C74 (2014) no.4, 2833

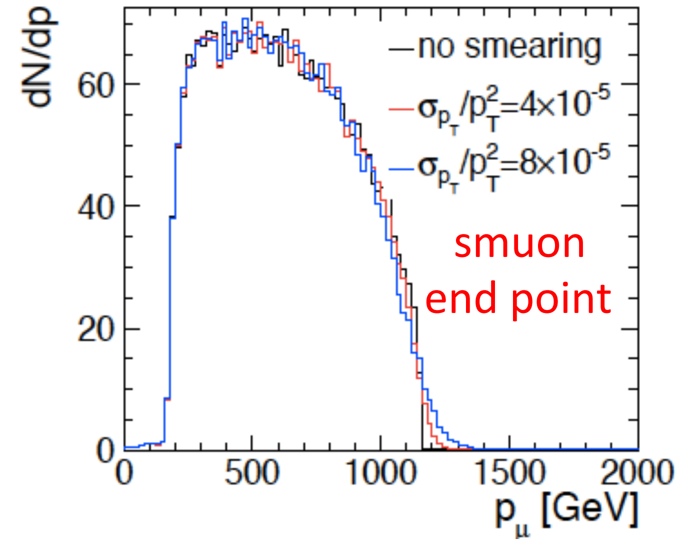
Fraction $\sqrt{s}/\sqrt{s_{nom}}$	350 GeV	3 TeV
>0.99	68%	36%
>0.9	95%	57%
>0.8	99.1%	68%
>0.7	99.9%	77%
>0.5	~100%	88%

CLIC detector requirements (from physics)

★ **momentum resolution:**

e.g, $g_{H\mu\mu}$, Smuon endpoint

$$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}$$

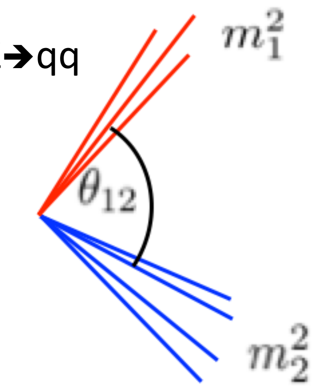


★ **jet energy resolution:**

e.g. W/Z/H di-jet mass separation, ZH with Z➔qq

$$\frac{\sigma_E}{E} \sim 3.5-5\ \%$$

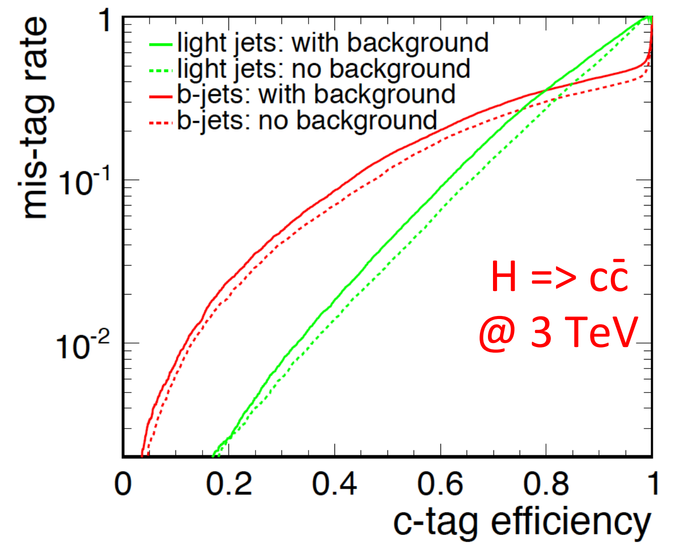
(for high-E jets, light quarks)



★ **impact parameter resolution:**

e.g. c/b-tagging, Higgs BR

$$\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu m$$



★ **angular coverage, very forward electron tagging**

+ requirements from CLIC experimental conditions

new CLIC detector model

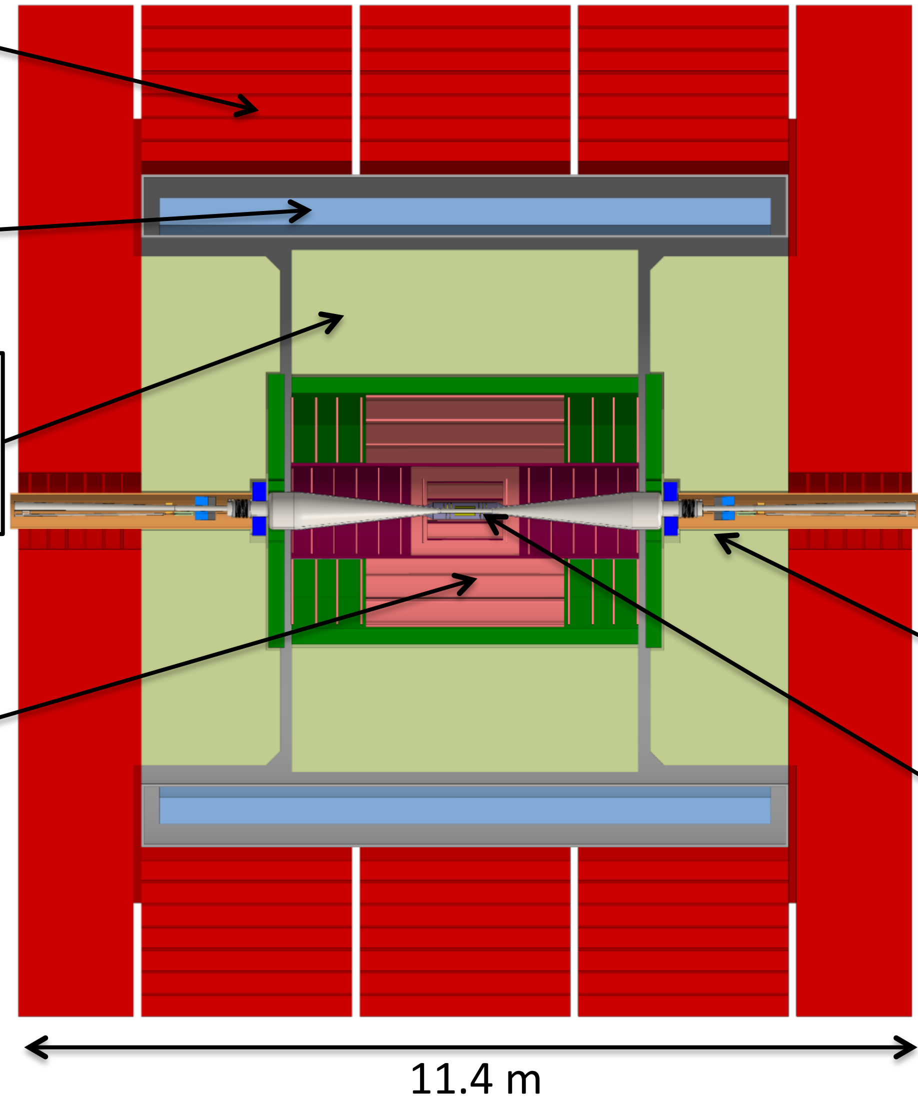
**** more in upcoming detector seminar ****

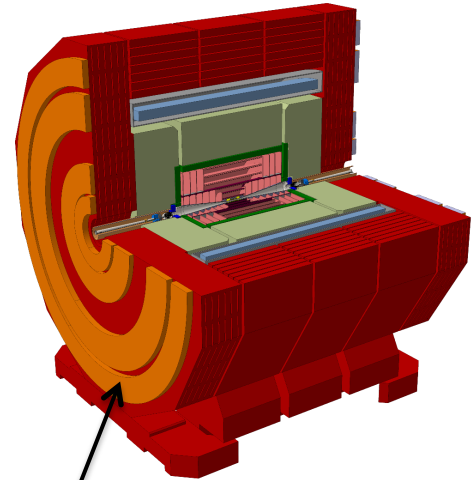
return yoke (Fe) with muon-ID detectors

Superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)





end-coils for field shaping

forward region with compact forward calorimeters

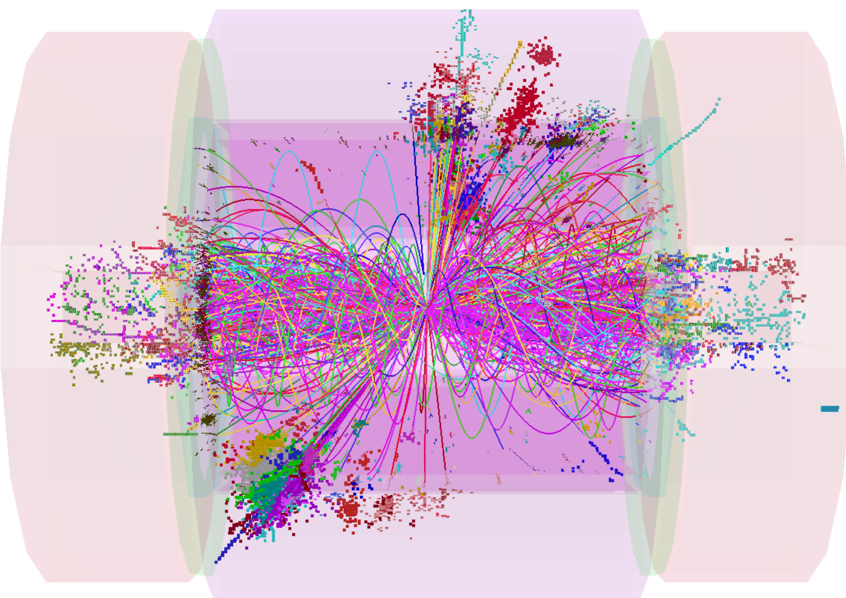
ultra low-mass vertex detector, ~25 µm pixels

Note: final beam focusing is outside the detector

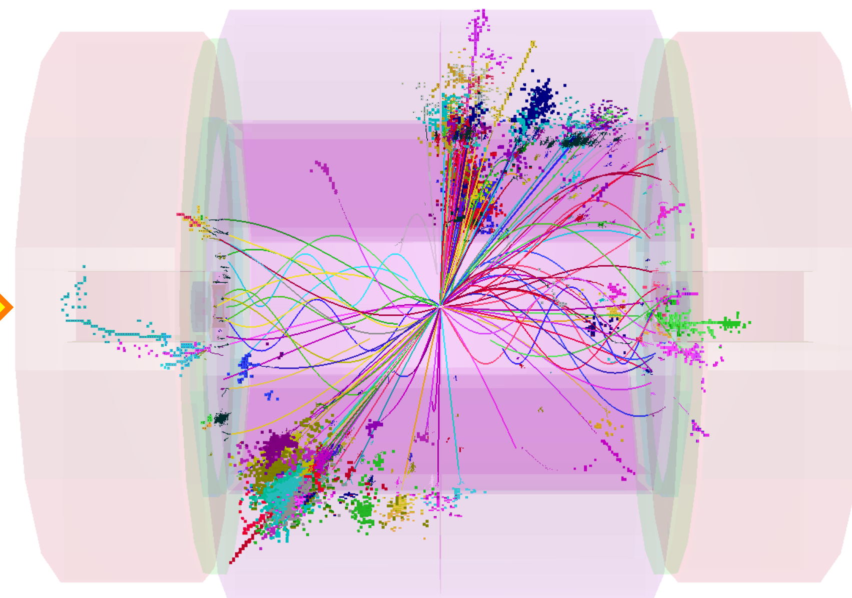
beam-induced background rejection (1)

Beam-induced background from γγ ➔ hadrons can be efficiently suppressed by applying ***p_t* cuts and timing cuts on individually reconstructed particles** (particle flow objects)

1.2 TeV



100 GeV



$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8 \text{ jets}$$

1.2 TeV background in reconstruction window (>=10 ns) around main physics event

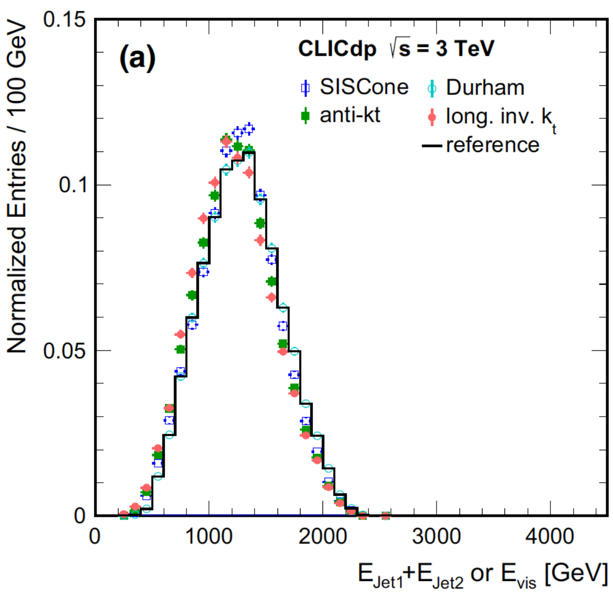
100 GeV background after tight cuts

beam-induced background rejection (2)

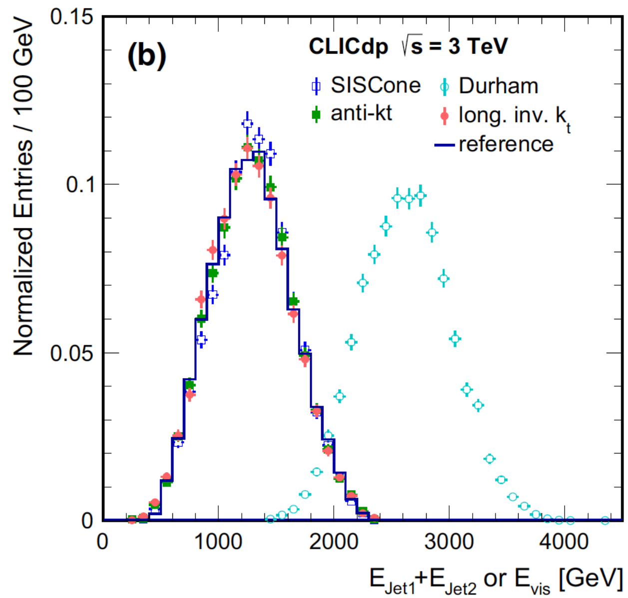
Beam-induced background from γγ ➔ hadrons is further reduced by applying **adapted jet reconstruction algorithms**

Example: ***squark study*** at √s = 3 TeV (with assumed squark mass of 1.1 TeV)

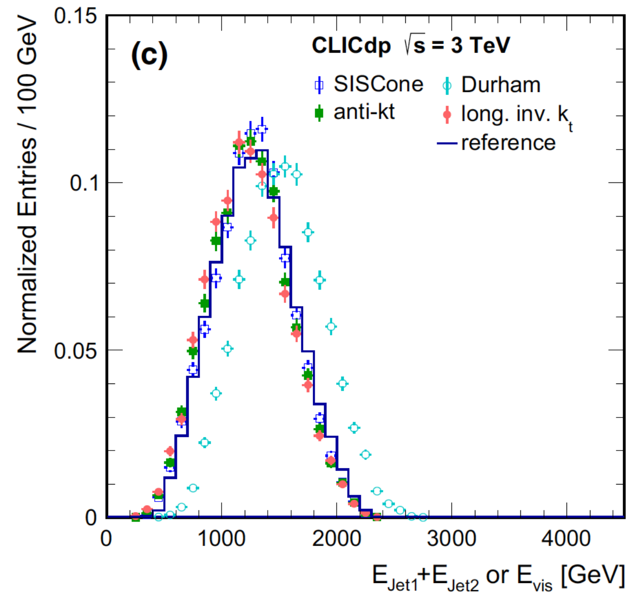
$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



No γγ ➔ hadrons background



With γγ ➔ hadrons bkg from 60 bunch crossings



With γγ ➔ hadrons bkg from 60 bunch crossings + use of p_t and timing cuts

Traditional Durham-ee jet algorithm inadequate <=> use of “LHC-like” jet algorithms effective

From Eur.Phys.J. C75 (2015) no.8, 379, see also arXiv:1607.05039

the CLIC physics program

- Higgs boson
- Top quark
- BSM (direct and indirect)

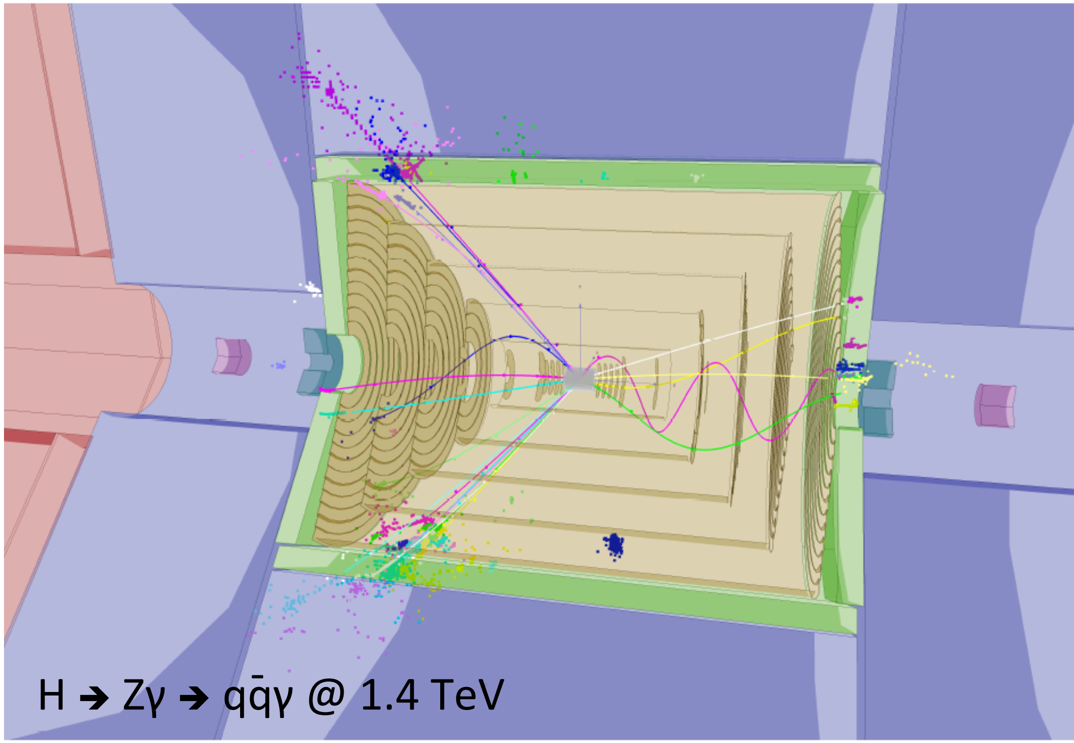
Physics benchmark studies use the two CLIC CDR detector models
Geant4-based detector simulation and event reconstruction

Note: most results represent statistical accuracy (dominant). Systematic errors studied in a few cases (ongoing)

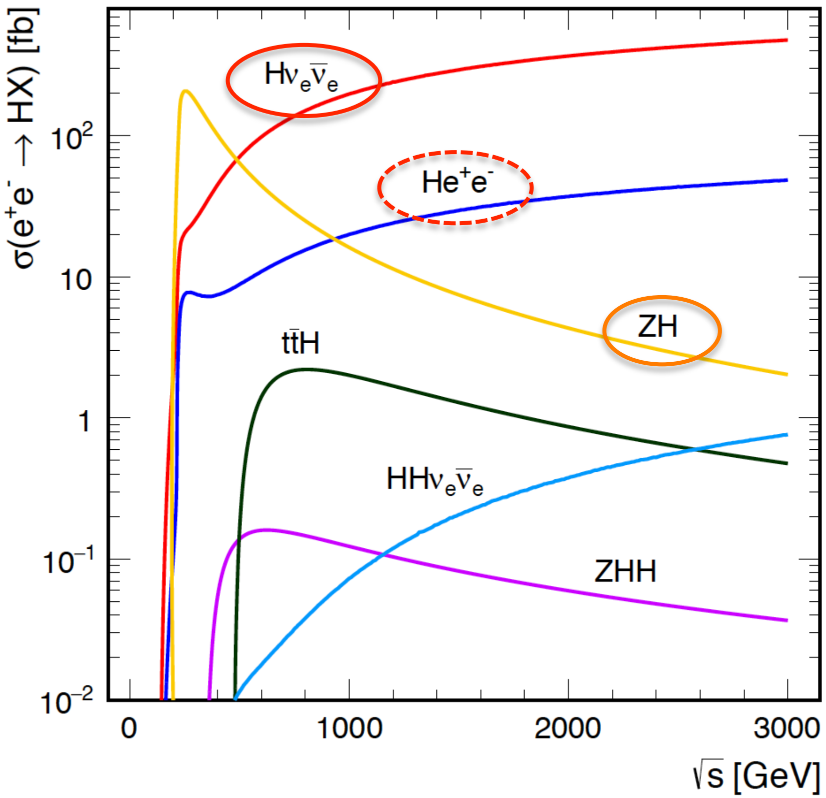
Note: the staging scenario used for most benchmark studies was a bit different from the new CLIC baseline

stage	$\sqrt{s}$	L_{int} (fb^{-1})
1	350 GeV	500
2	1.4 TeV	1500
3	3 TeV	2000

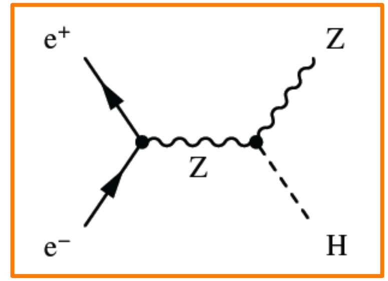
↗ *Scenario used for benchmarks*



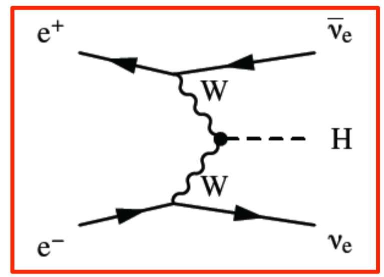
Higgs physics at CLIC



Dominant processes:



Higgsstrahlung
$\sigma \sim 1/s$
Higgs id. from Z recoil



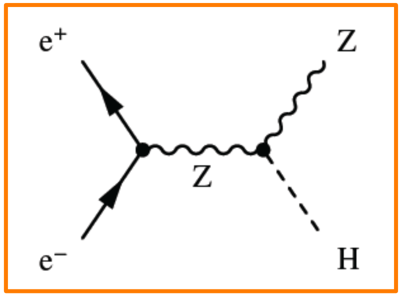
WW(ZZ) - fusion
$\sigma \sim \log(s)$
Large stat. at high E

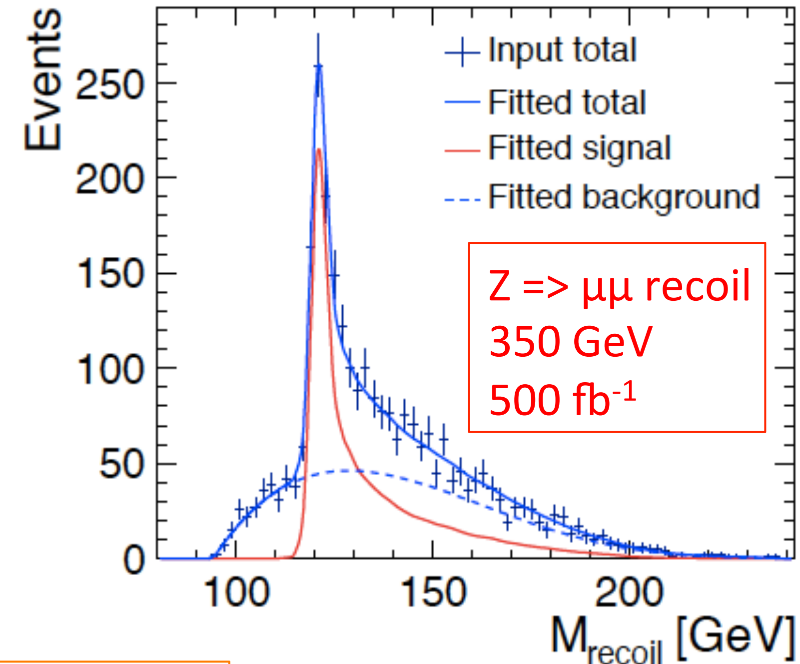
	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

For unpolarised beams.
Hνν increases ×1.8 for
-80% e$^-$ polarisation
(CLIC baseline)

high selection efficiencies !

Higgsstrahlung $e^+e^- \to ZH$ @ ~350 GeV





ZH events, selected through **recoil mass** against Z

$m^2_{rec} \approx s + m^2_Z - 2\sqrt{s}(E1+E2)$

model-independent measurement

$\Delta\sigma_{HZ} \sim g^2_{HZZ}$

Z => μμ	BR~3.5%	very clean	$\Delta(\sigma_{HZ}) = \pm 3.8\%$
Z => ee	BR~3.5%	very clean	
Z => $q\bar{q}$	BR~70%	almost model independent	$\Delta(\sigma_{HZ}) = \pm 1.8\%$

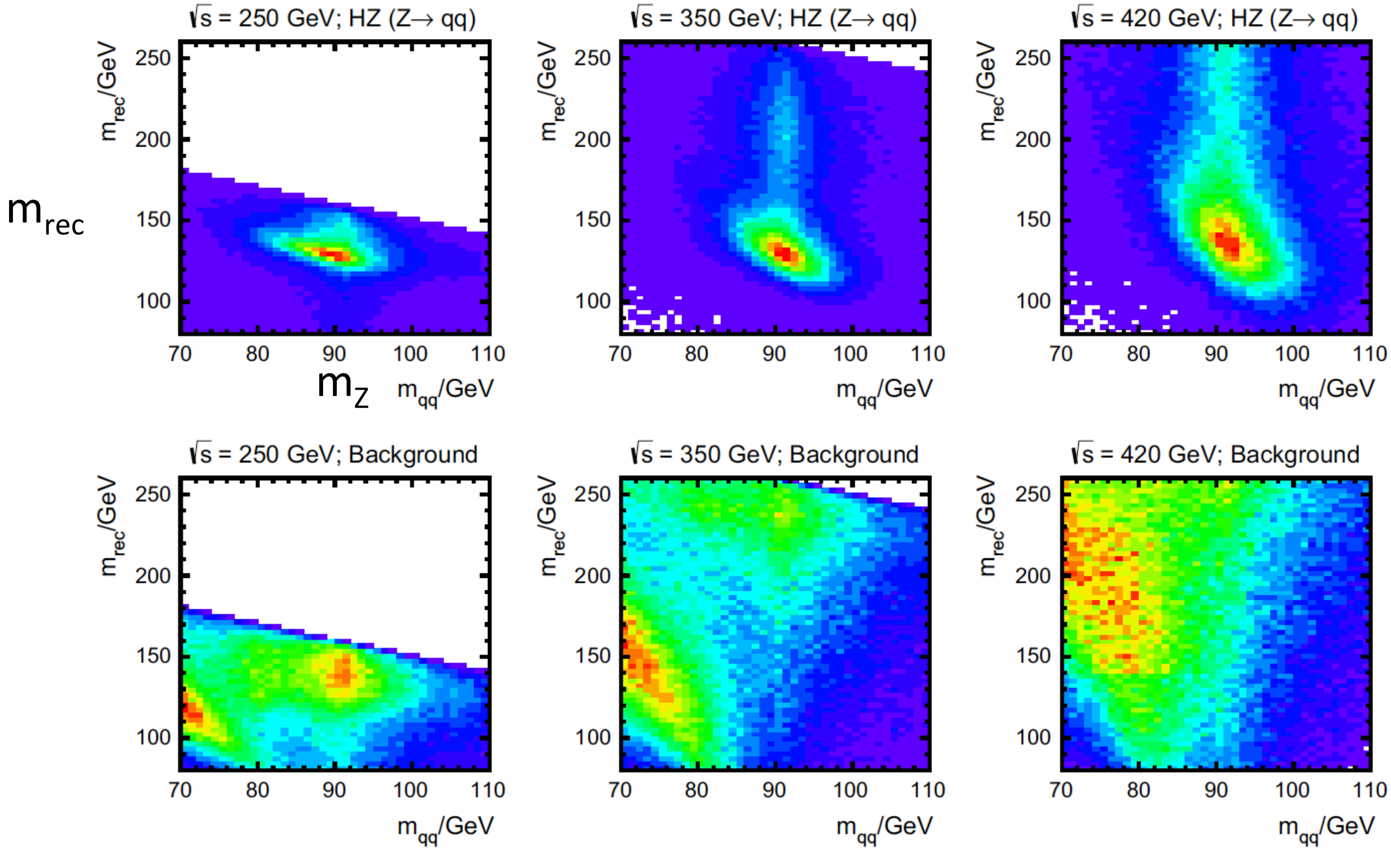
$\Delta(g_{HZZ}) = \pm 0.8\%$

ZH => $H q\bar{q}$ **access to invisible Higgs decay** BR(H=>inv) < 1% @ 90% CL

ZH → $Hq\bar{q}$: better precision at 350 GeV than at 250 GeV or 420 GeV (trade-off between detector resolution and physics background, see next slide)

Higgsstrahlung $e^+e^- \rightarrow ZH$ @ 250, 350, 420 GeV

√s = 250 GeV | √s = 350 GeV | √s = 420 GeV



signal

background

Eur. Phys. J. C (2016) 76: 72

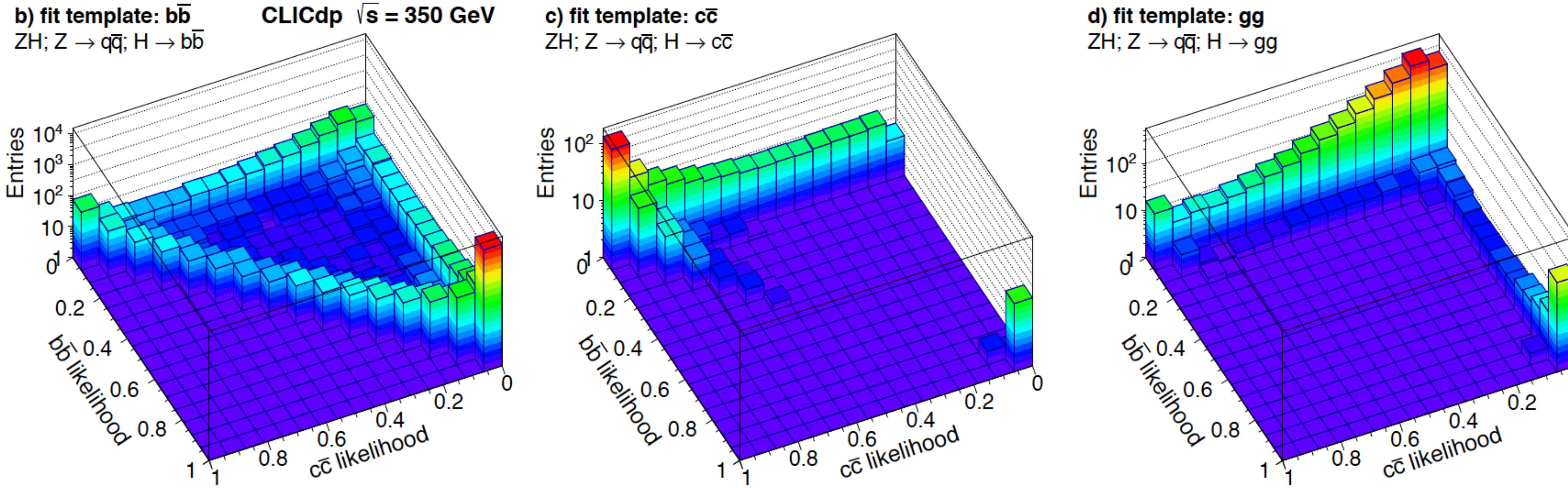
$\sqrt{s}$	$\mathscr{L}$	σ(HZ)	Δ $\sigma_{vis.}$	Δ $\sigma_{invis.}$	Δ σ(HZ)
250 GeV	500 fb^{-1}	136 fb	±3.63 %	±0.45 %	±3.65 %
350 GeV	500 fb^{-1}	93 fb	±1.71 %	±0.56 %	±1.80 %
420 GeV	500 fb^{-1}	68 fb	±2.42 %	±1.02 %	±2.63 %

Together with top physics this drives the choice of CLIC lower energy stage @ 380 GeV

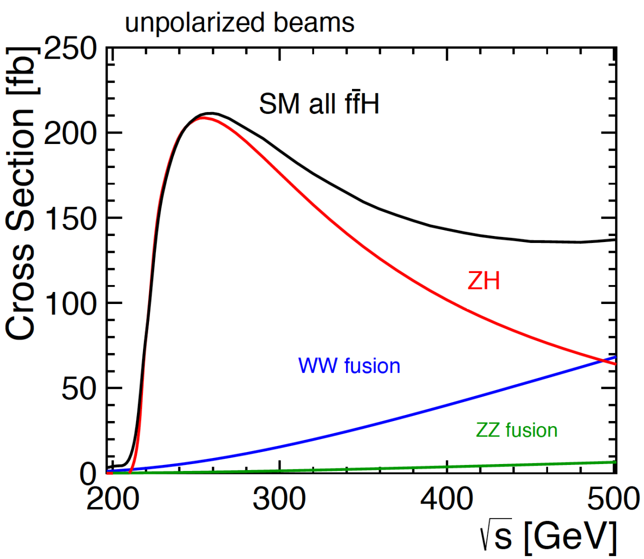
simultaneous extraction H => bb,cc,gg @ 350 GeV

$b\bar{b}$ likelihood versus $c\bar{c}$ likelihood for different event classes

H ➔ $b\bar{b}$ H ➔ $c\bar{c}$ H ➔ gg



arXiv:1608.07538

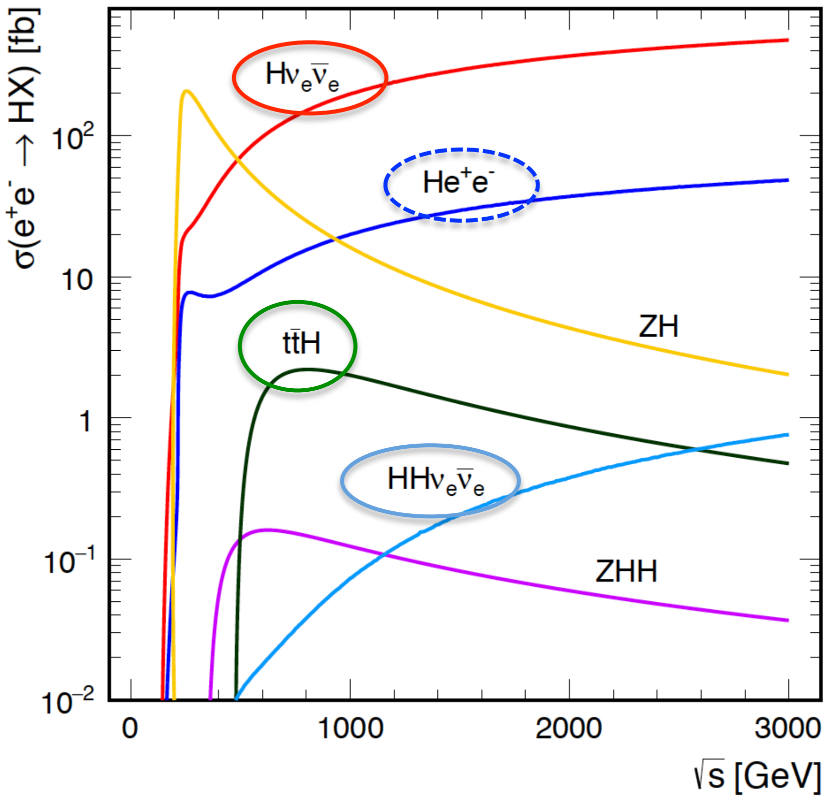


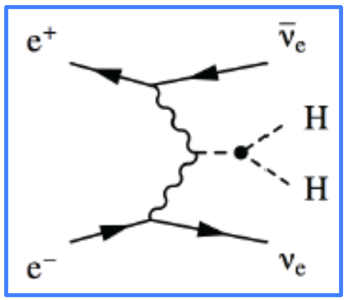
Simultaneous extraction of 2 production and 3 decay modes

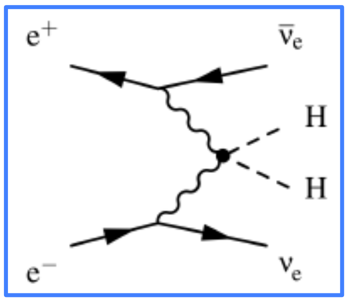
$\Delta(\sigma\times BR)_{SM}/(\sigma\times BR)_{SM}$ at 350 GeV, 500 fb^{-1}

Decay	Statistical uncertainty Higgsstrahlung	Statistical uncertainty WW-fusion
$H \to b\bar{b}$	0.84 %	1.9 %
$H \to c\bar{c}$	10.3 %	14.3 %
$H \to gg$	4.5 %	5.7 %

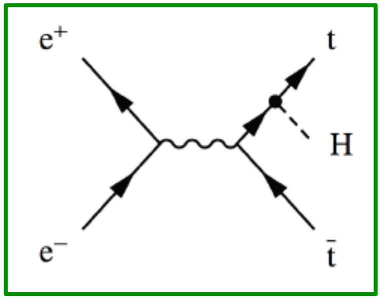
Higgs physics above 1 TeV







Vector boson fusion:
$e^+e^- \rightarrow H\nu\nu$, $e^+e^- \rightarrow He^+e^-$
High σ + increased luminosity
Gives access to rare Higgs decays



$t\bar{t}H$ production:

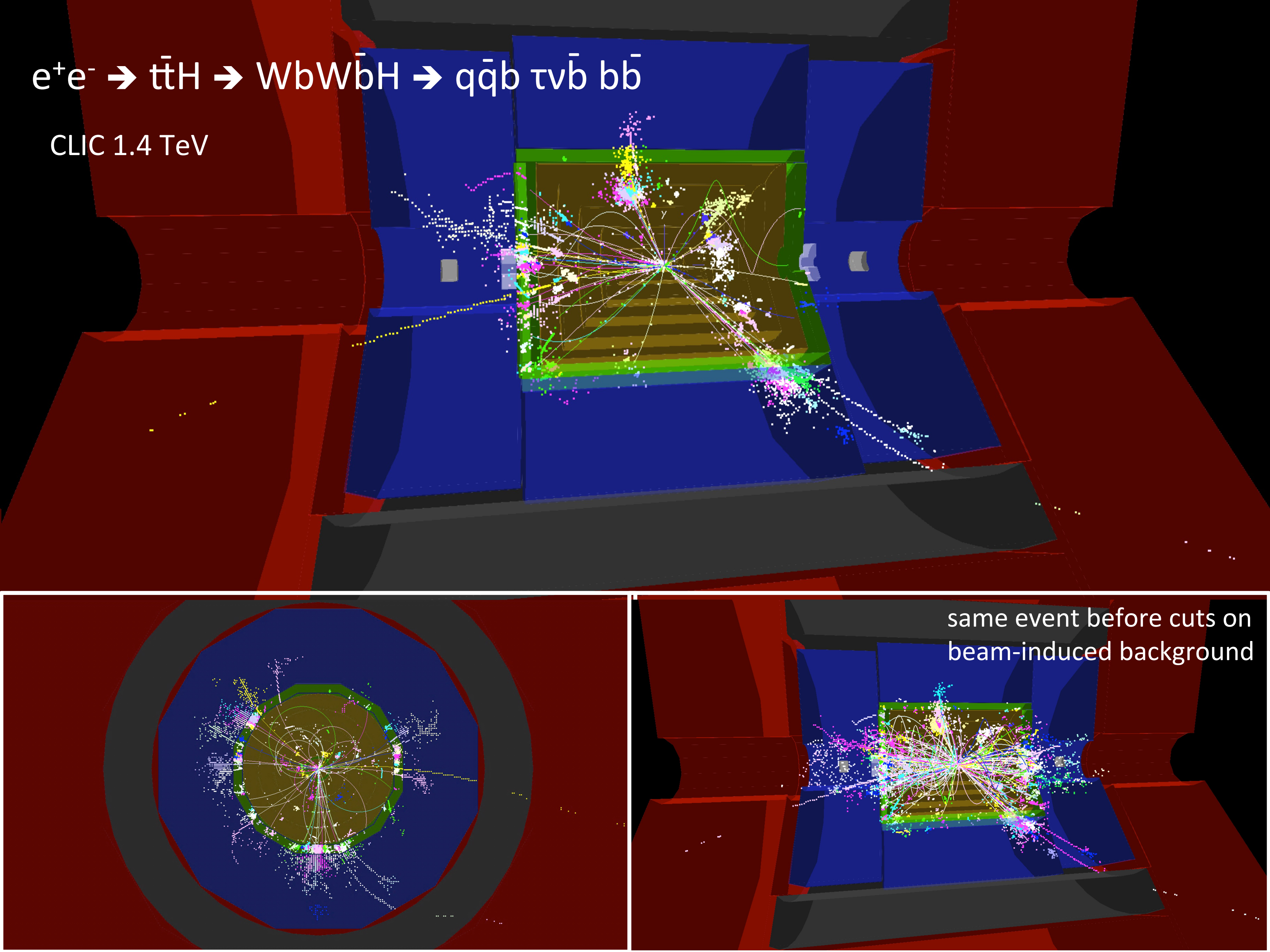
- Extraction of Yukawa coupling y_t
- Best at √s above 700 GeV

Studied at 1.4 TeV, 1.5 ab^{-1}

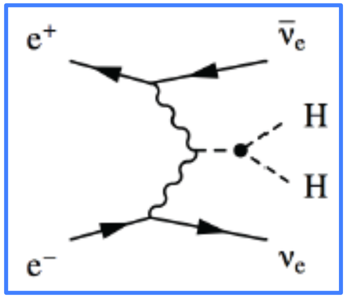
- Fully hadronic (8 jets)
- Semi-leptonic (6 jets + lepton + ν)

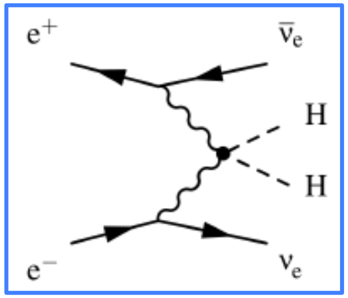
Statistical accuracy:

- **$\Delta(g_{Htt})$ = ±4.4%** at 1.4 TeV


$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$
CLIC 1.4 TeV
same event before cuts on beam-induced background

double Higgs production

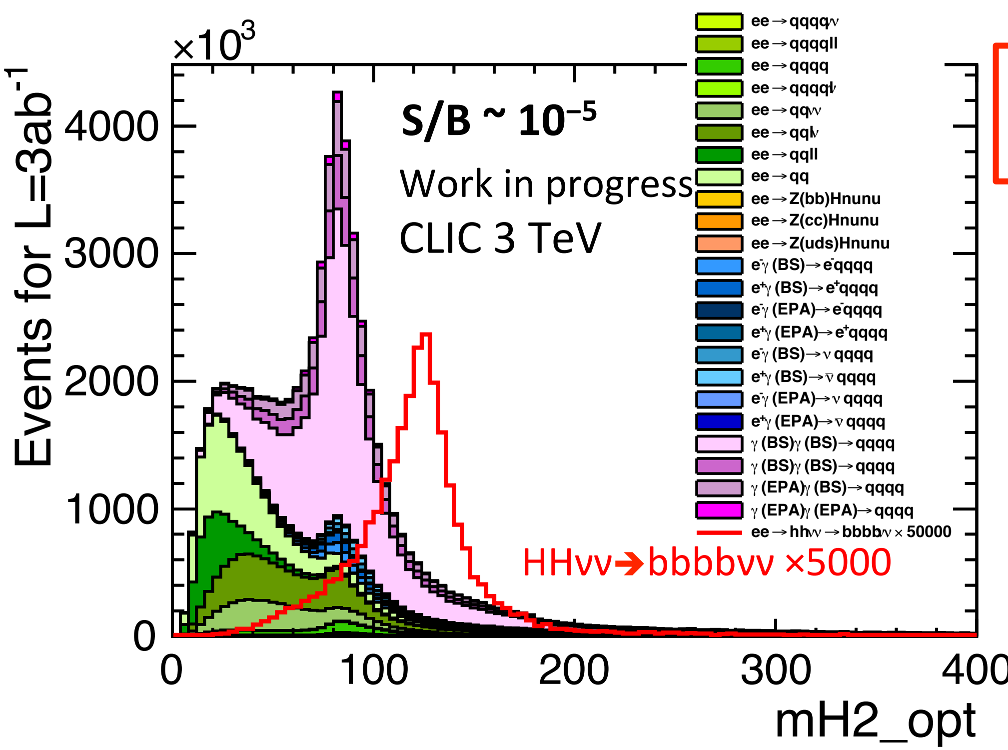




- Cross section sensitive to g_{HHH} and g_{WWHH}
- Small cross section (225/1200 evts @ 1.4/3 TeV)
- Large backgrounds

⇒ Requires high energy and high luminosity

Most promising final states:
*bbbbνν and bbWW*νν*



⇒ $\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$
for operation at 1.4 TeV + 3 TeV with polarisation

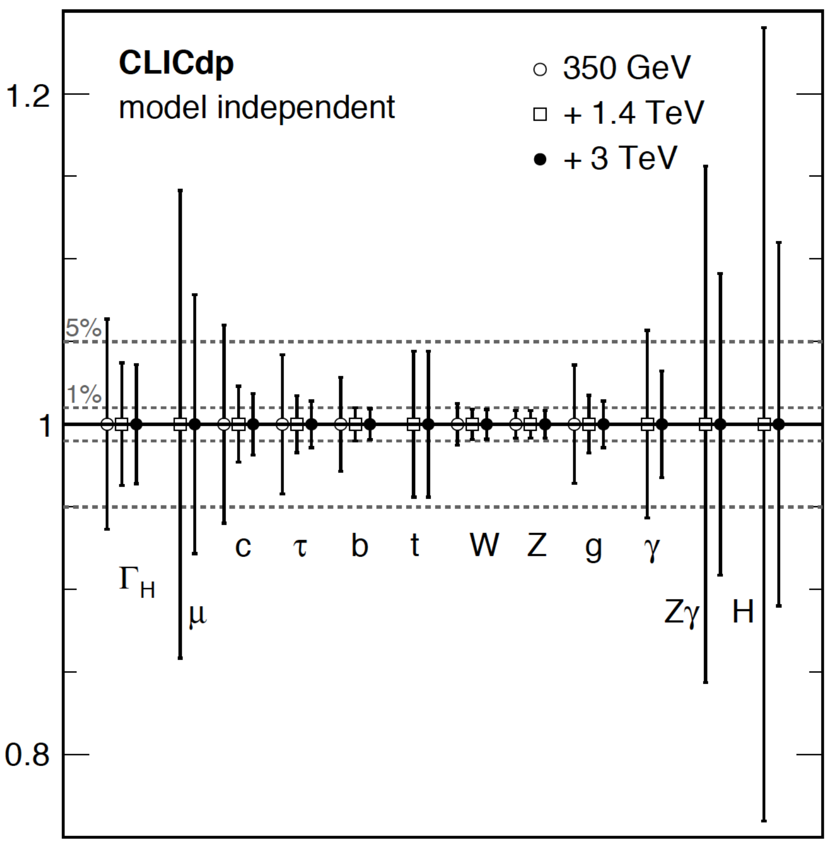
Process with strong sensitivity to BSM

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

arXiv:1305.6397

combined CLIC Higgs results

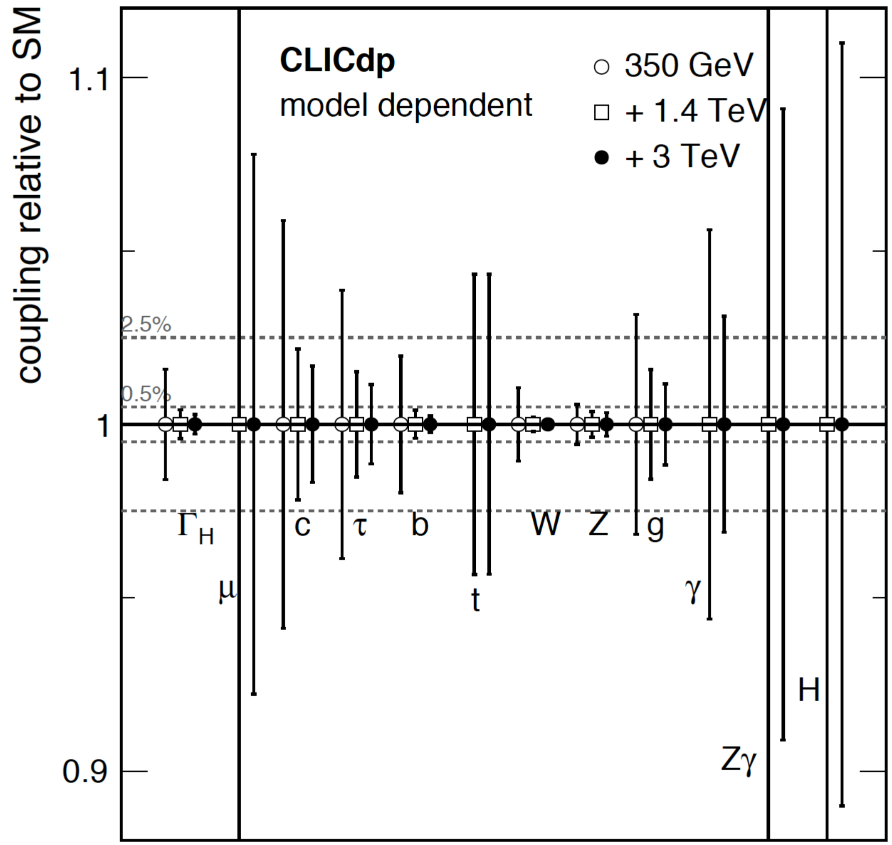
Model-independent



arXiv:1608.07538

Higgs width is a free parameter, allows for additional non-SM decays

Model-dependent



LHC-like fit, assuming SM decays only. Fit to deviations from SM BR's

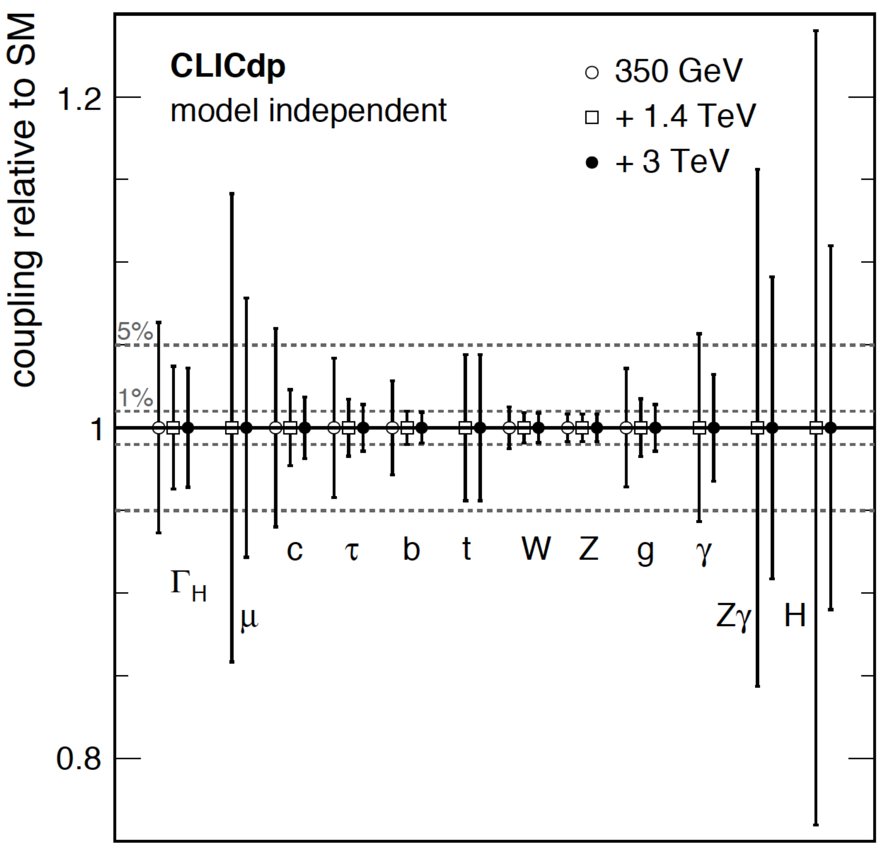
Full CLIC program, ~5 yrs of running at each stage (plots assume 80% e^- polarisation above 1 TeV):

- Model-independent: down to ±1% for most couplings
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±3.6% (MI), ±0.2% (MD, derived)

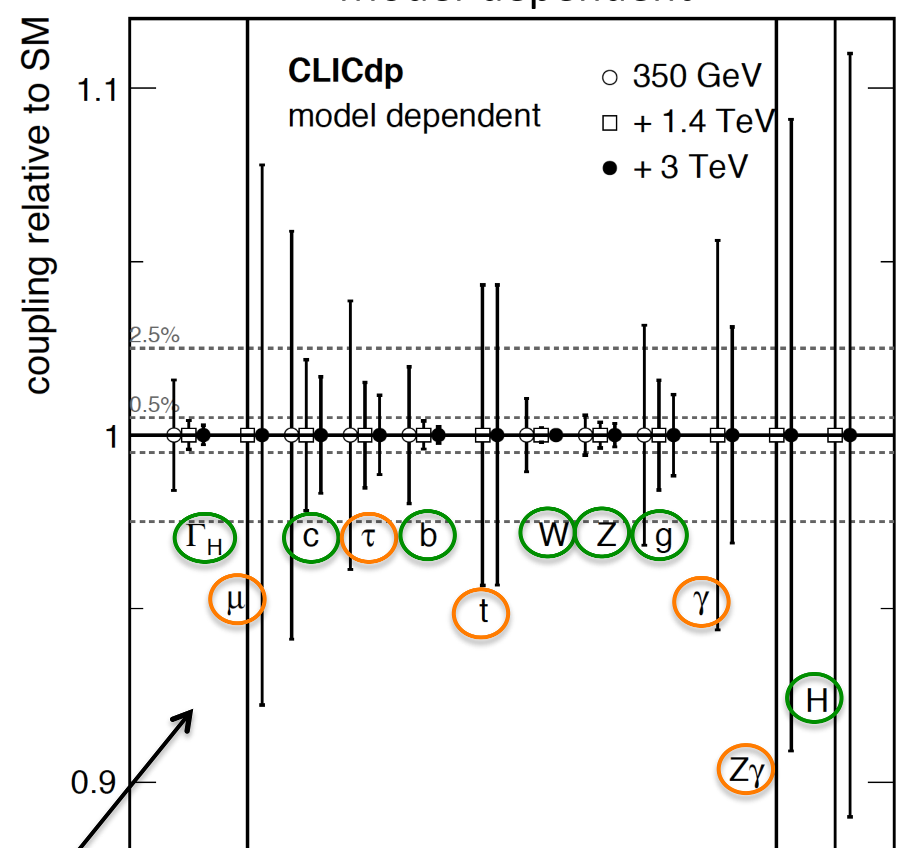
combined CLIC Higgs results

indicative comparison with HL-LHC capabilities

Model-independent



Model-dependent

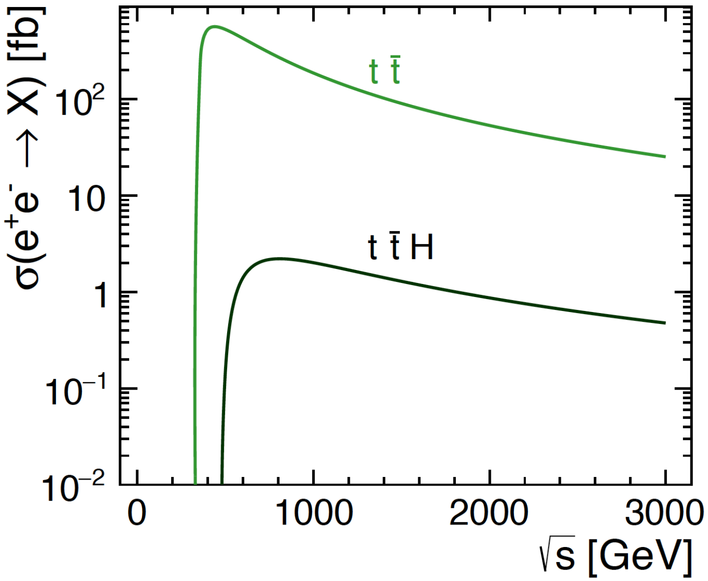


CLIC (and other e^+e^- colliders) can do model-independent measurements

LHC-like fit, assuming SM decays only.
Fit to deviations from SM BR's

- (green circle) Accuracy significantly better than HL-LHC
- (orange circle) Accuracy comparable to HL-LHC

top quark physics



Motivation:

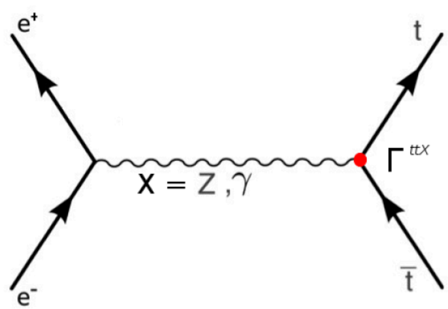
- Top quark is the heaviest known particle
- Yukawa coupling to Higgs boson y_t~1
  - ➔ key to understanding EWSB
- Top quark decays before hadronising
  - ➔ test ground of QCD
- Large loop contrib. to many precision measurements
- Sensitive to many BSM scenarios ➔ a window to BSM
- So far top quark only measured at hadron colliders

Top physics programme currently studied for CLIC:

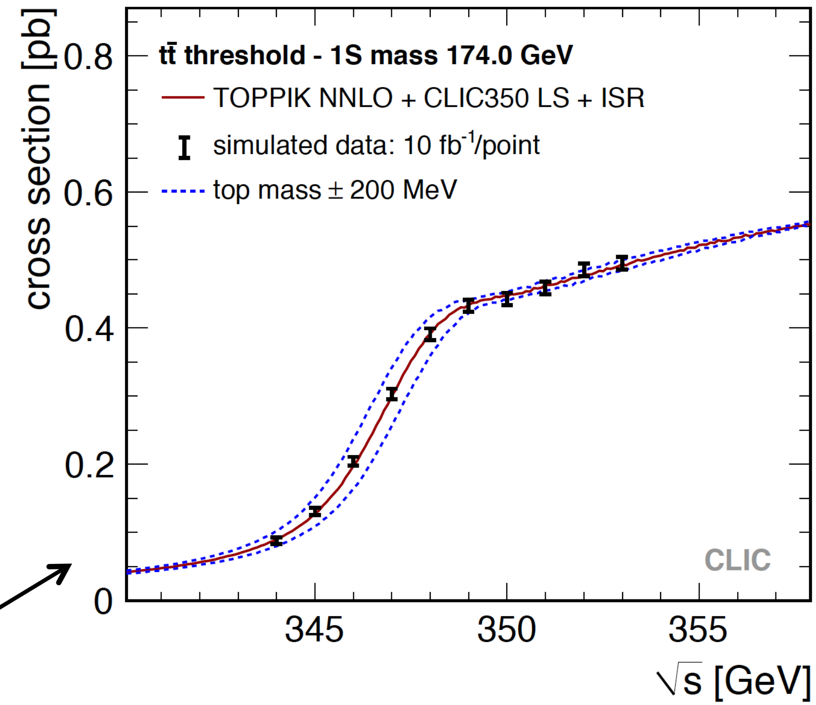
- Top quark mass measurement through $t\bar{t}$ threshold scan
- Top quark mass measurement through reconstruction
- Electroweak couplings to the top quark @ 380 GeV
- Electroweak couplings to the top quark above 1 TeV
- Yukawa coupling though $t\bar{t}H$ production
- Measurement of V_{tb} in single top production
- Rare (CP violating) decays
- ....

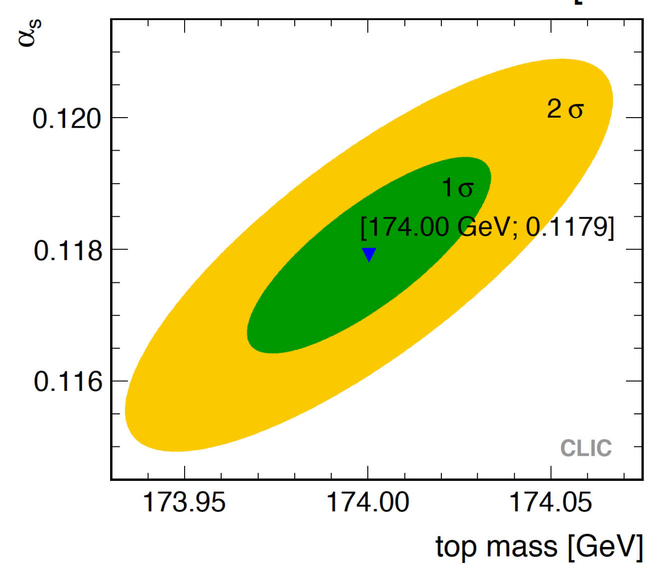
threshold scan of top pair production

- **Top pair production cross section around the $t\bar{t}$ threshold**
- Resonant-like structure, very sensitive to m_{top}, and α_s



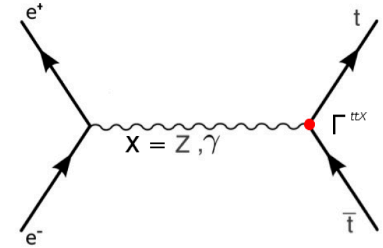
- Measurement at 10 different √s, 10 fb^{-1} each
- Expected precision on 1S mass: ≈50 MeV
  (dominated by theory NNNLO scale uncertainty)
- Theoretical uncertainty ≈10 MeV when transforming 1S mass to $\overline{\text{MS}}$ scheme





Eur.Phys.J. C73 (2013) 2530

top quark couplings to Z and γ

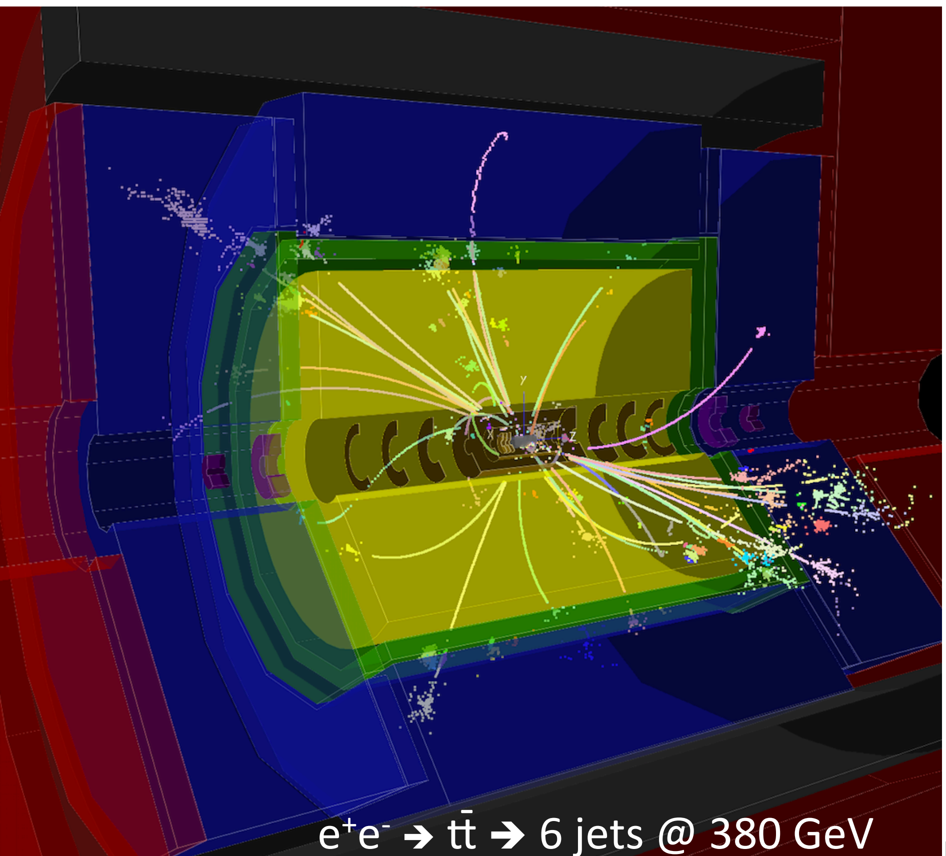


Top quark pairs are produced via Z/γ
New physics would modify the ttV vertex

The general form of the coupling can be described as:

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

CP violating term



At a linear collider the **γ and Z form factors** can be disentangled *using beam polarisation*, by measuring:

- Production cross section
- Forward-backward asymmetry
- Helicity angle distribution (in leptonic decays)
- … analysis being improved using b-jet charge distribution

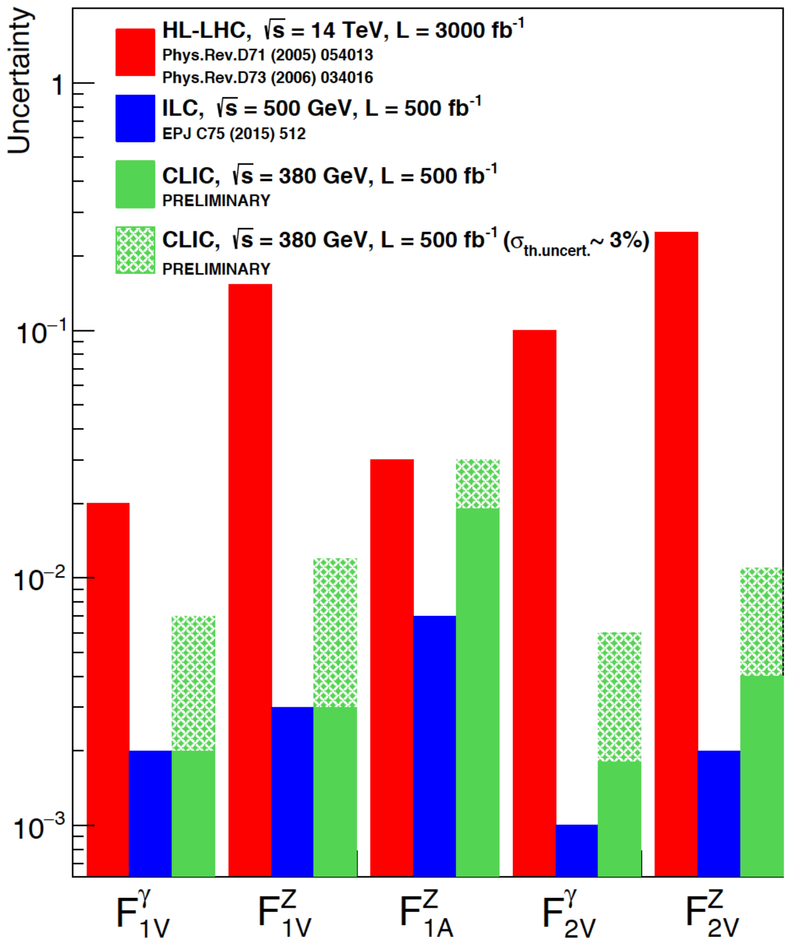
Illustrated in next slides:

- **CLIC results at 380 GeV, 500 fb^{-1}**
- **Better sensitivity to BSM expected for multi-TeV operation**

top quark couplings to Z and γ

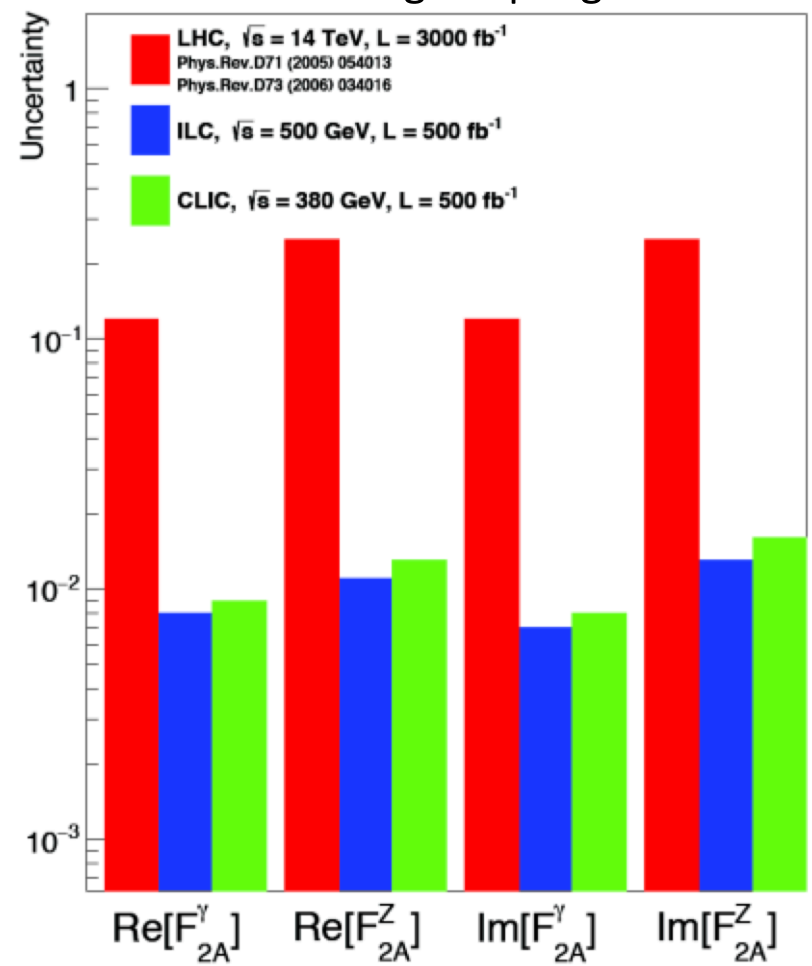
Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)

CP-conserving couplings



CERN-2016-004

CP-violating couplings

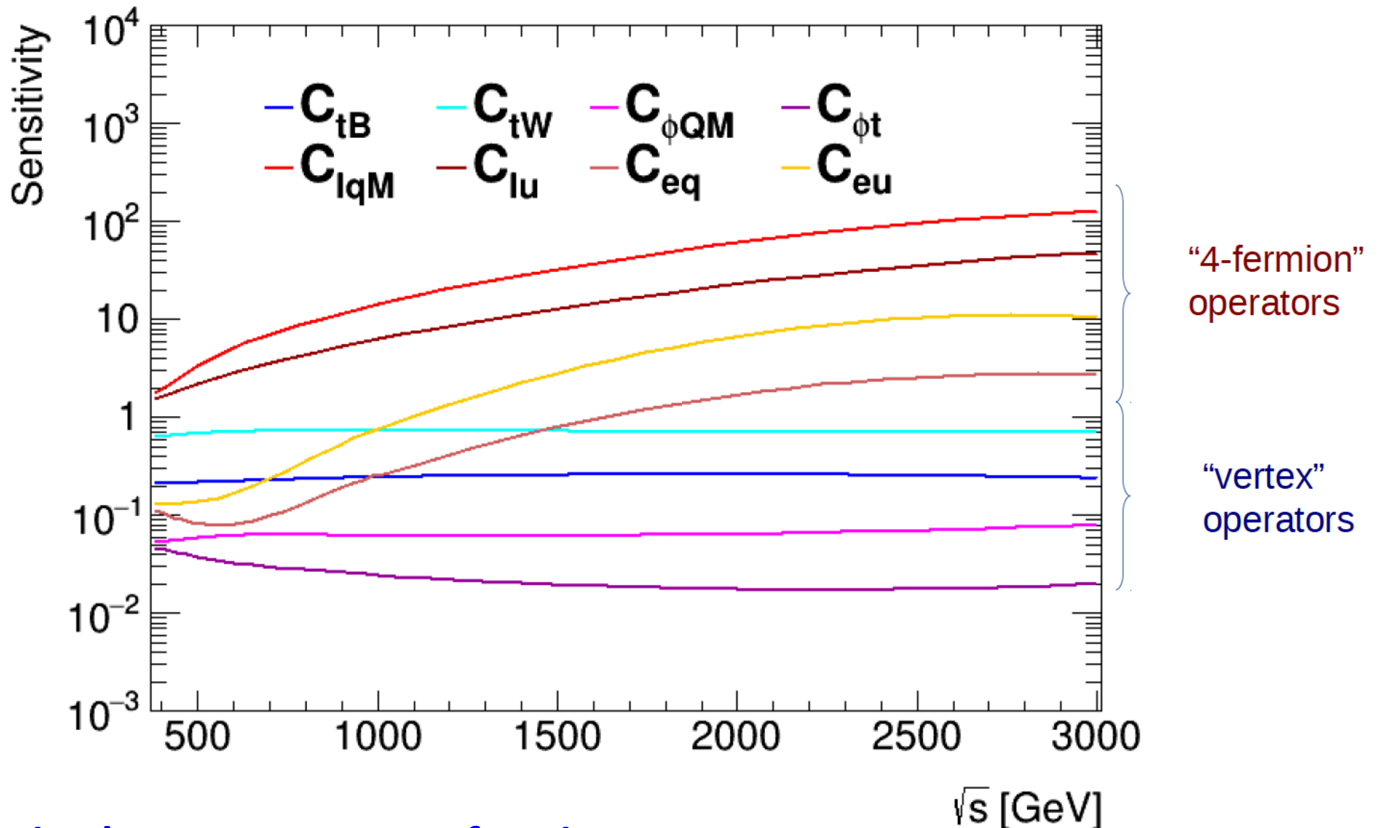


M. Vos at ECFA LC 2016

electroweak couplings to top at high √s

Studied at generator level in an *effective operator approach* (instead of Form Factor approach)

Sensitivity:
Relative change in cross-section due to non-zero operator coefficient
$\Delta\sigma\ (C)\ /\ \sigma\ /\ \Delta C$



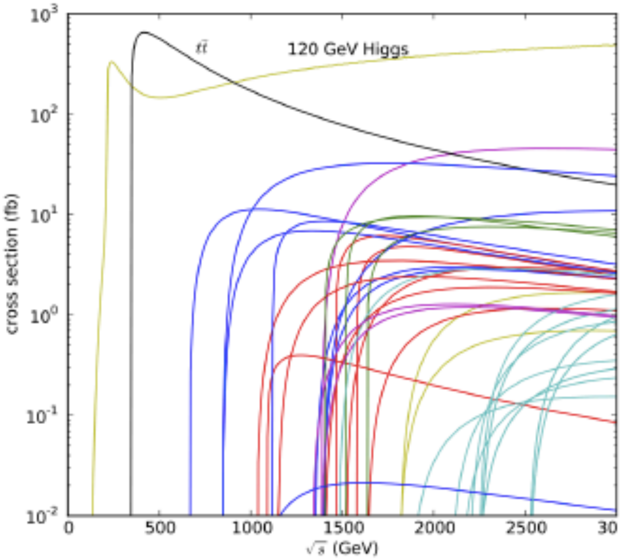
=> multi-TeV energies give better access to 4-fermion operators.

Full detector simulation studies of tt production at 1.4 TeV, 3 TeV are ongoing

M. Vos @ TopLC'2016

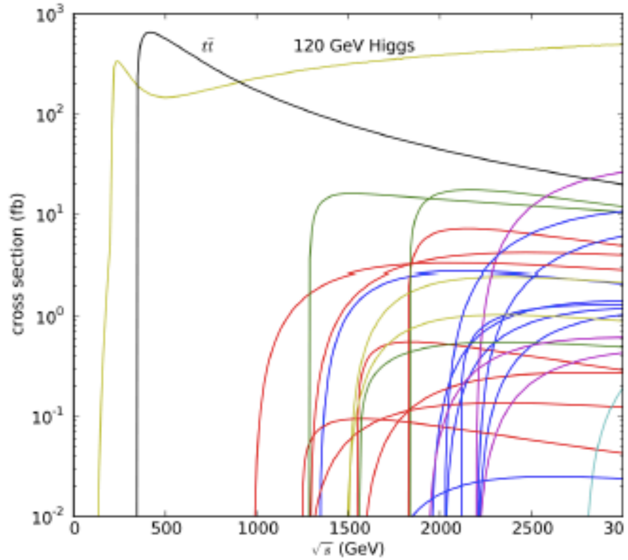
direct BSM sensitivity

using SUSY as a benchmarking tool



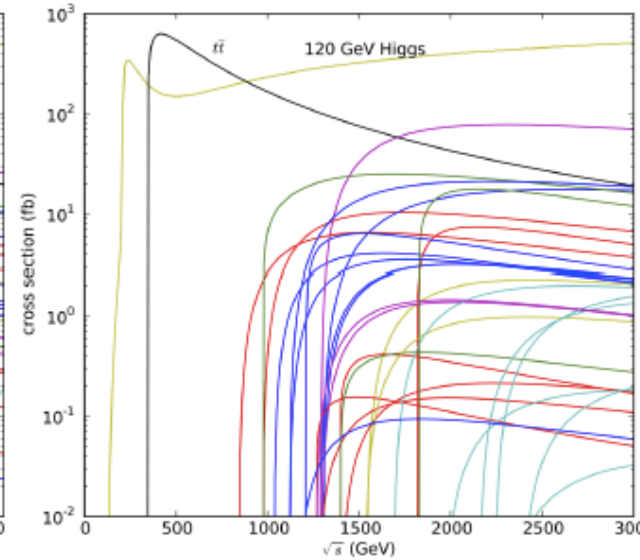
“model I”, 3 TeV:

- Squarks
- Heavy Higgs



“model II”, 3 TeV:

- Smuons, selectrons
- Gauginos



“model III”, 1.4 TeV:

- Smuons, selectrons
- Staus, Gauginos

— Higgs
— $\tilde{\tau}, \tilde{\mu}, \tilde{e}$
— charginos
— squarks
— SM $t\bar{t}$
— $\tilde{\nu}_\tau, \tilde{\nu}_\mu, \tilde{\nu}_e$
— neutralinos

Wider capability than only SUSY: reconstructed particles can be interpreted as “states of given mass, spin and quantum numbers”

→ In general, **O(1%)** precision on masses and production cross sections found

CERN-2012-003 CERN-2012-007

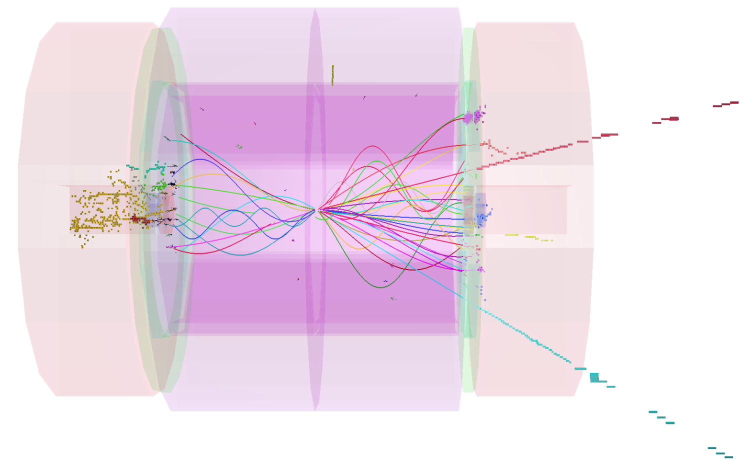
the simplest case: slepton at 3 TeV

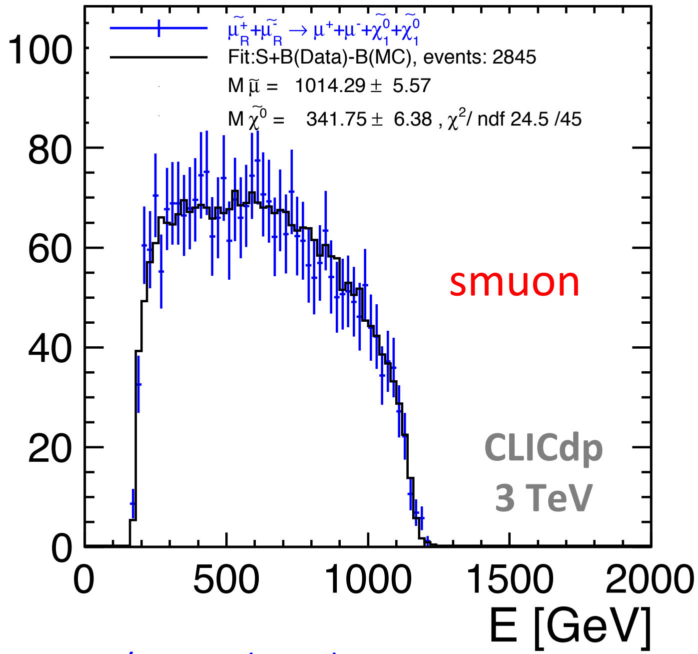
Slepton production at CLIC very clean

slepton masses ~ 1 TeV

Investigated channels include

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





- Leptons and missing energy
- Masses from analysis of endpoints of energy spectra

result: $\Delta m/m \leq 1\%$

$m(\tilde{\mu}_R)$	:	± 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

Systematics due to uncertainty on luminosity spectrum studied:
syst. well below stat. error

10.1007/JHEP09(2013)001

di-jet masses: gauginos at 3 TeV

$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$

$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$

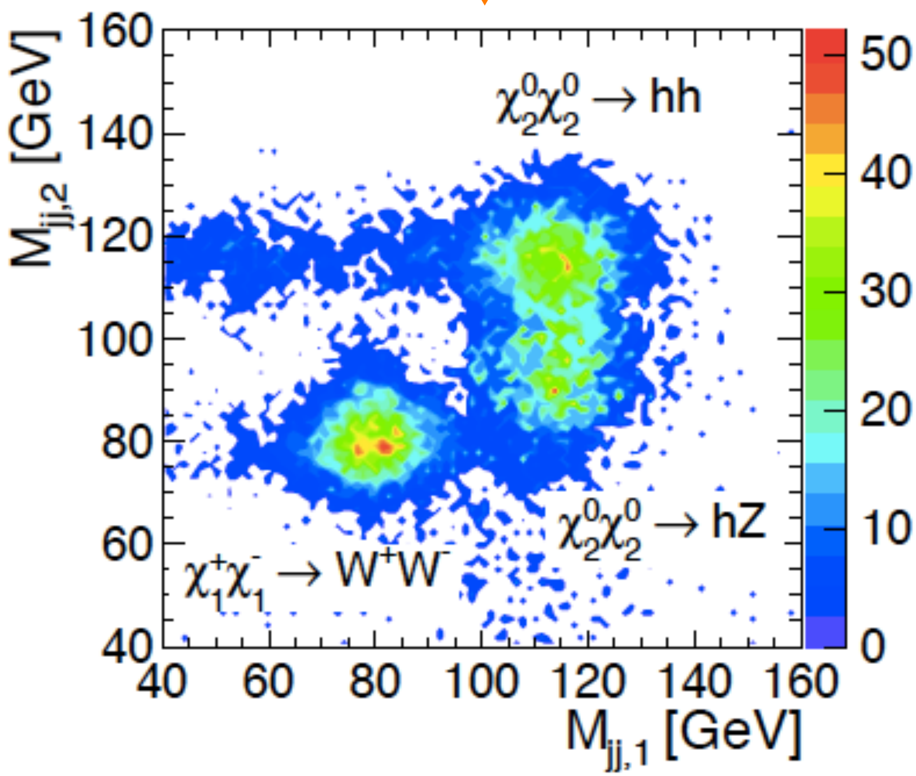
Chargino and neutralino pair production

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\,\%$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\,\%$$

- separation using di-jet invariant masses (test of PFA)



$m(\tilde{\chi}_1^\pm)$: $\pm 7\,\mathrm{GeV}$

$m(\tilde{\chi}_2^0)$: $\pm 10\,\mathrm{GeV}$

use slepton study result

$m(\tilde{\chi}_1^0)$: $\pm 3\,\mathrm{GeV}$

result: $\Delta m/m \leq 1\%$

LCD-Note-2011-037

results of SUSY benchmarks

Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
	Neutralino	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Large part of the SUSY spectrum measured at <1% level

CERN-2012-007

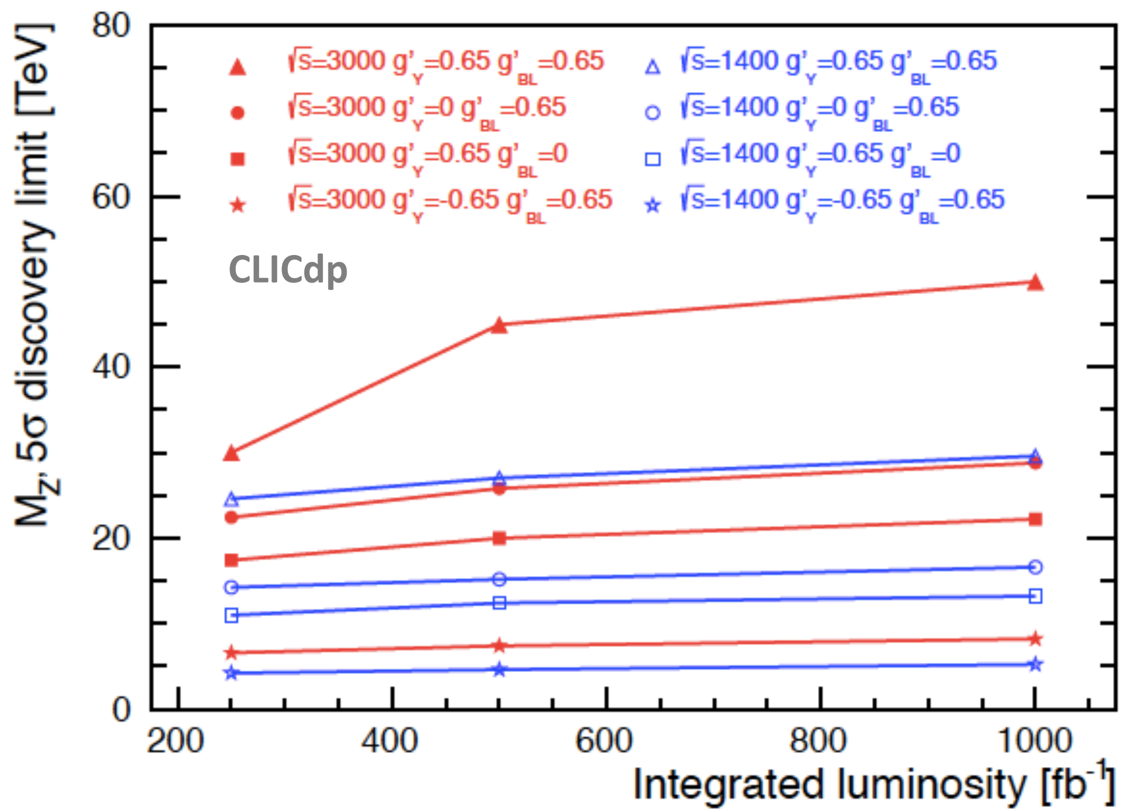
BSM example: Z' via indirect measurement

Minimal anomaly-free Z' model

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

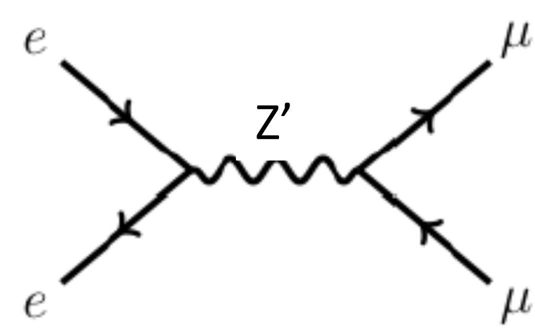
Generator-level study

Observables:
- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry
  (with ±80% e^- polarisation)



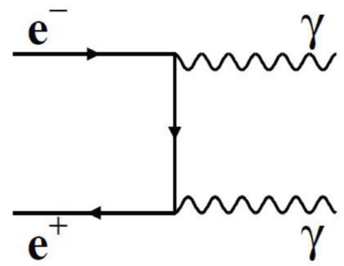
If LHC discovers Z'
(e.g. for $M_{Z'}$=5 TeV)
CLIC precision measurement of effective couplings

Otherwise:
CLIC discovery reach up to tens of TeV (depending on the couplings



arXiv:1208.1148

test of QED: precision study of $e^+e^- \rightarrow \gamma\gamma$



Possible deviations from QED cross sections and angular γγ spectrum can test extension of QED (finite electron size, extra dimension, mass of excited electrons..)

Finite electron size => energy cut off Λ

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

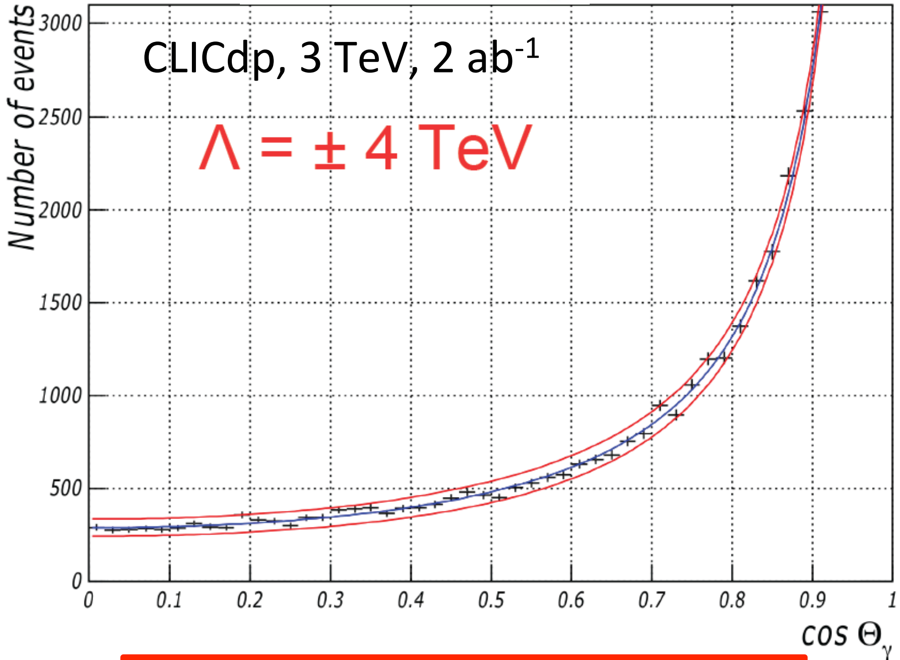
=> ***two back-to-back photons***

Events selected with small energy loss due to Beamstrahlung and ISR

Main backgrounds:

ee ➔ ee and eγ ➔ eγ

So e/γ identification in forward region is important



Fit result: Λ > 6.33 TeV

(or electron size < 3.1×10^{-18} cm)

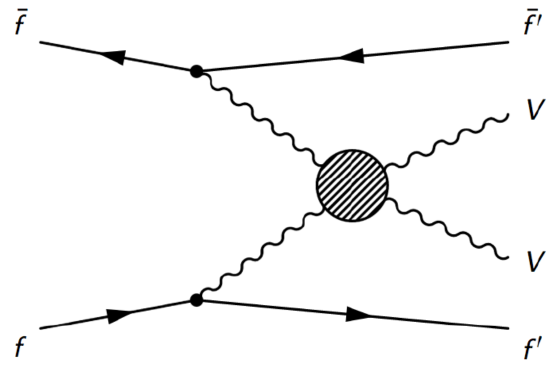
Combined LEP data: Λ > 431 GeV

(or electron size < 4.6×10^{-17} cm)

I. Boyko @ CLIC'16

test of EWSM: vector boson scattering

- Vector boson scattering provides an important test of electroweak symmetry breaking => *Sensitive to new physics in the Higgs sector*
- Search for *additional resonances* and *anomalous quartic gauge boson couplings*
- Deviations from SM parametrised in terms of 2 couplings: F_{S0}, F_{S1}

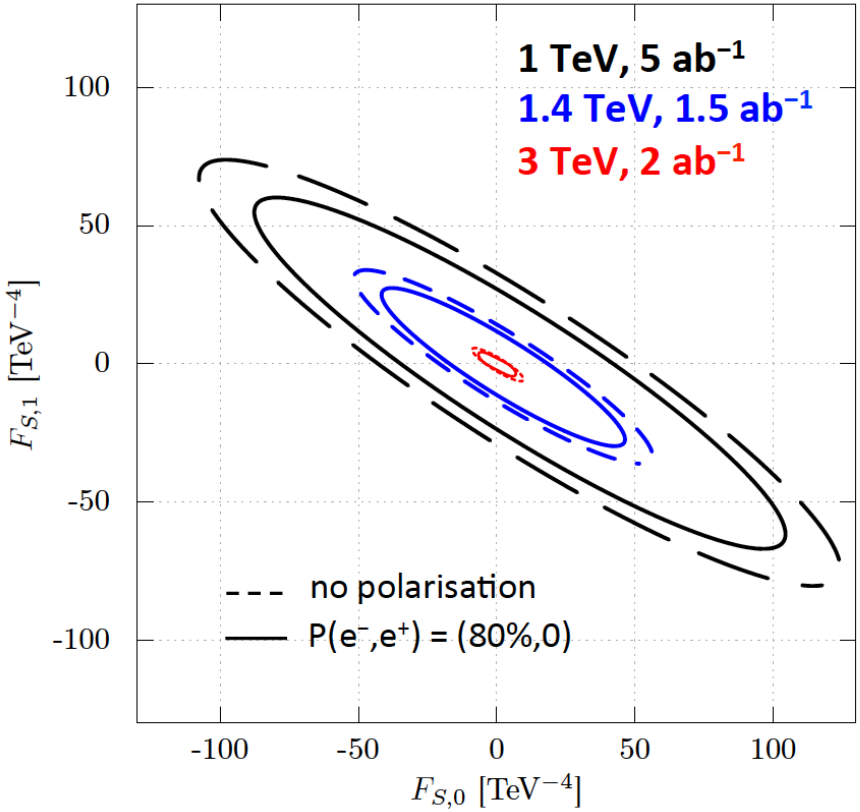


WW, ZZ study done at <u>generator level</u> with separation of hadronic W and Z decays from full simulation

$\Delta F_{S0,1}$ ~5 TeV^{-4} (@ 3 TeV)

~100 times better than LHC @ 8 TeV

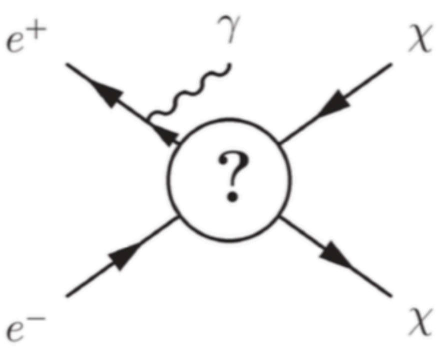
Full detector simulation study ongoing



arXiv:1607.03030

further indirect assessments

ee → γ + E_T^{miss}



Generic
Dark matter study
Only observable:
ISR photon

Benchmark study ongoing

SM Effective Field Theory (SM EFT)

Dimension-6 operators, model-independent approach

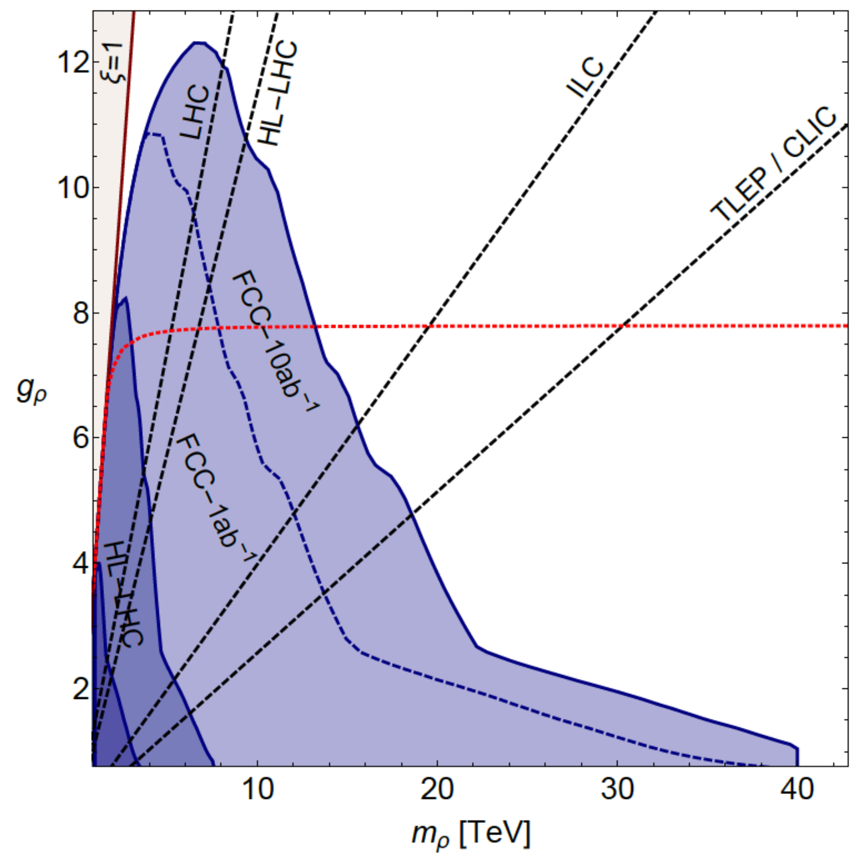
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Using e+e- → ZH, Hνν and W^+W^-
At three CLIC energy stages

- Study shows high-energy CLIC as a powerful indirect probe for new physics
- Importance of studying ***HZ at high energy***

Minimal Composite Higgs scenario

2-parameter model:
Resonance mass $\boldsymbol{m_\rho}$
Coupling SM fermions to EW gauge bosons, $\boldsymbol{g_\rho}$



Comparison of direct and indirect measurements
Allowed region above the dashed lines
CLIC/FCC-ee very sensitive to large g_ρ

arXiv:1701.04804

arXiv:1502.01701

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

collaborations / announcements

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, here at CERN:

The CLIC workshop 2017, March 6-10:
https://indico.cern.ch/event/577810/

LC top quark physics workshop 2017, June 7-9:
http://indico.cern.ch/event/595651/

summary

Proton-proton and electron-positron colliders yield complementary information

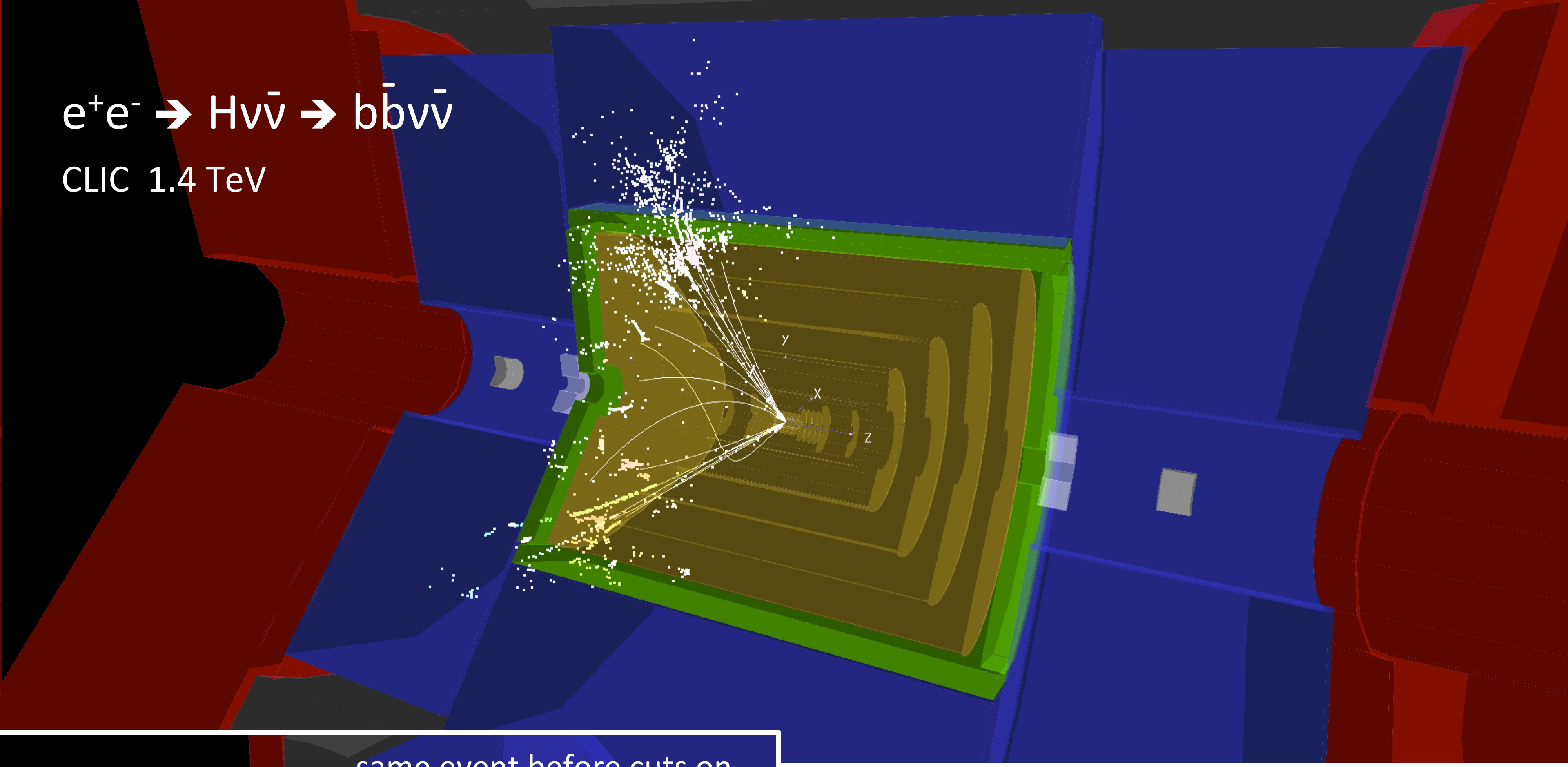
CLIC offers a wealth of accurate e^+e^- physics measurements
CLIC offers an "affordable" first stage at 380 GeV with guaranteed physics
CLIC is upgradable up to 3 TeV

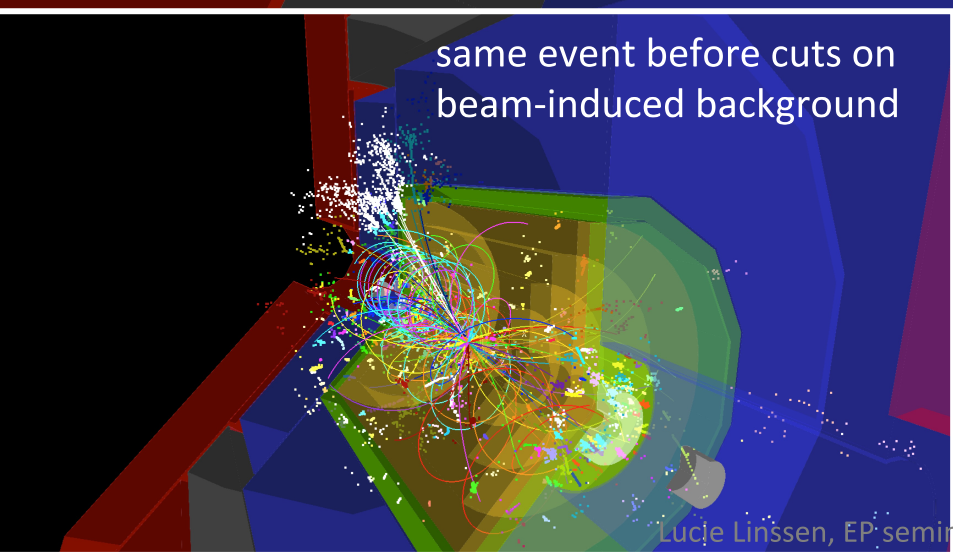
It's a powerful tool to address the open questions in particle physics

CLIC is one of the options for CERN after the LHC, next to HE-LHC/FCC-hh/FCC-ee

- Many years of R&D have been invested in CLIC
- Large-scale tests have confirmed the technology
- It is well understood and technically mature, no show-stopper identified
- CLIC can gear up towards construction within a few years

CLIC offers interesting R&D in very active collaborations
Welcome to join !


$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$
CLIC 1.4 TeV
y
x
z


same event before cuts on
beam-induced background

thank you !

SPARE SLIDES

CLIC Higgs results (σ×BR), 350 GeV

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	0.84 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc} / \Gamma_H$	10.3 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		4.5 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau} / \Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW} / \Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	14.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.7 %

Table 28: Summary of the precisions obtainable for the Higgs observables in the first stage of CLIC for an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 350$ GeV, assuming unpolarised beams. For the branching ratios, the measurement precision refers to the expected statistical uncertainty on the product of the relevant cross section and branching ratio; this is equivalent to the expected statistical uncertainty of the product of couplings divided by Γ_H as indicated in the third column.

CLIC Higgs results (σ×BR), 1.4+3 TeV

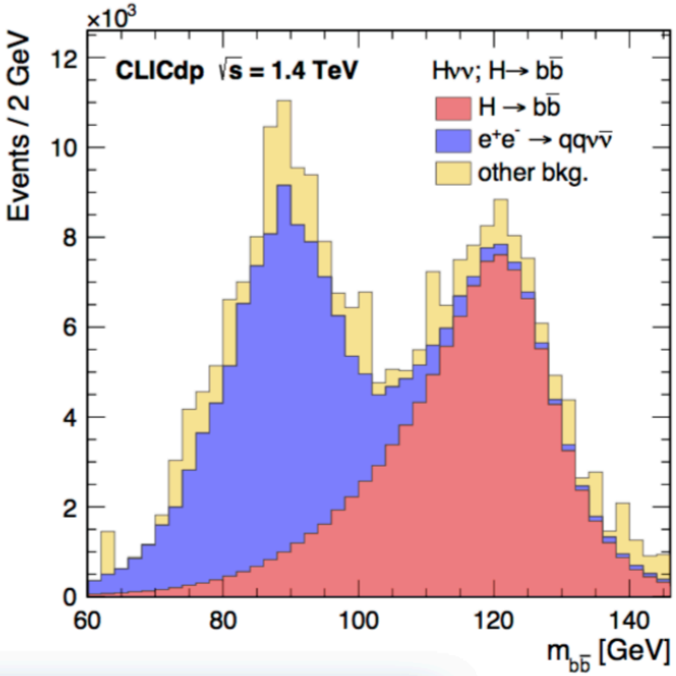
Channel	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	Statistical precision 3 TeV 2.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	44 MeV
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc} / \Gamma_H$	6.1 %	6.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	4.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	4.2 %	4.4 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	38 %	25 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	10 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	30 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	1.0 %	0.7 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	5.6 %	3.9 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	1.8 %	2.3 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb} / \Gamma_H$	8.4 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	32 %	16 %
$HH\nu_e\bar{\nu}_e$	with −80 % e^- polarisation	λ	24 %	12 %

Table 29: Summary of the precisions obtainable for the Higgs observables in the higher-energy CLIC stages for integrated luminosities of 1.5 ab^{-1} at $\sqrt{s} = 1.4$ TeV, and 2.0 ab^{-1} at $\sqrt{s} = 3$ TeV. In both cases unpolarised beams have been assumed. The '–' indicates that a measurement is not possible or relevant at this centre-of-mass energy. Numbers marked with $*$ were extrapolated from $\sqrt{s} = 1.4$ TeV to $\sqrt{s} = 3$ TeV as explained in the text. For the branching ratios, the measurement precision refers to the expected statistical uncertainty on the product of the relevant cross section and branching ratio; this is equivalent to the expected statistical uncertainty of the product of couplings divided by Γ_H, as indicated in the third column. For the measurements from the $HH\nu_e\bar{\nu}_e$ process, the measurement precisions give the expected statistical uncertainties on the self-coupling parameter λ.

Higgs mass measurement at high energy

The Higgs mass can be extracted from $e^+e^- \rightarrow \nu\nu H \rightarrow \nu\nu bb$ events

- Good signal purity in the signal region, dominant background is e+e– → vvqq
- Mass extracted using templates for different Higgs mass hypotheses
- Uncertainty is estimated using toy MC



Dataset	Δm_H, unpolarised	Δm_H, $P(e^-) = -80\%$
1.4 TeV	47 MeV	35 MeV
3 TeV	44 MeV	33 MeV
1.4 + 3 TeV	32 MeV	24 MeV

ATLAS & CMS combined (7 and 8 TeV data):

M_H = 125.09 ± 0.21 (stat.) ± 0.11 (syst.) Phy. Rev. Lett. 114, 191803 (2015)

HL-LHC projection: **ΔM_H = 50 MeV** arXiv:1310.8361

top quark => rare decays

In the standard model **FCNC top decays** are strongly suppressed:

$$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14},\quad BR(t \to c\,Z) \sim 1 \cdot 10^{-14},\quad BR(t \to c\,H) \sim 3 \cdot 10^{-15}$$

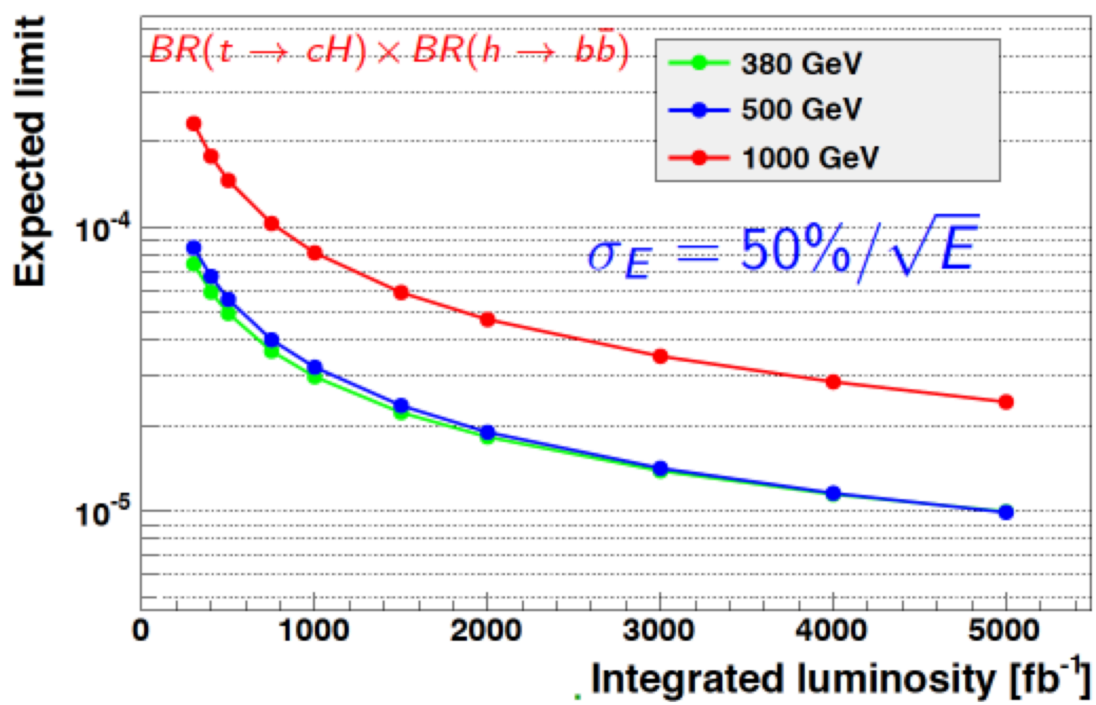
Significant enhancement is possible in many New Physics scenarios

Decay *t* ➔ *c H* most interesting

- Enhancement up to $10^{-5} - 10^{-2}$
- Test of Higgs boson couplings
- Well constrained kinematics
- Seems most difficult for LHC
  - Run II: BR < 0.46%
  - HL-LHC: BR < 2×10^{-4}

Full simulation study is ongoing

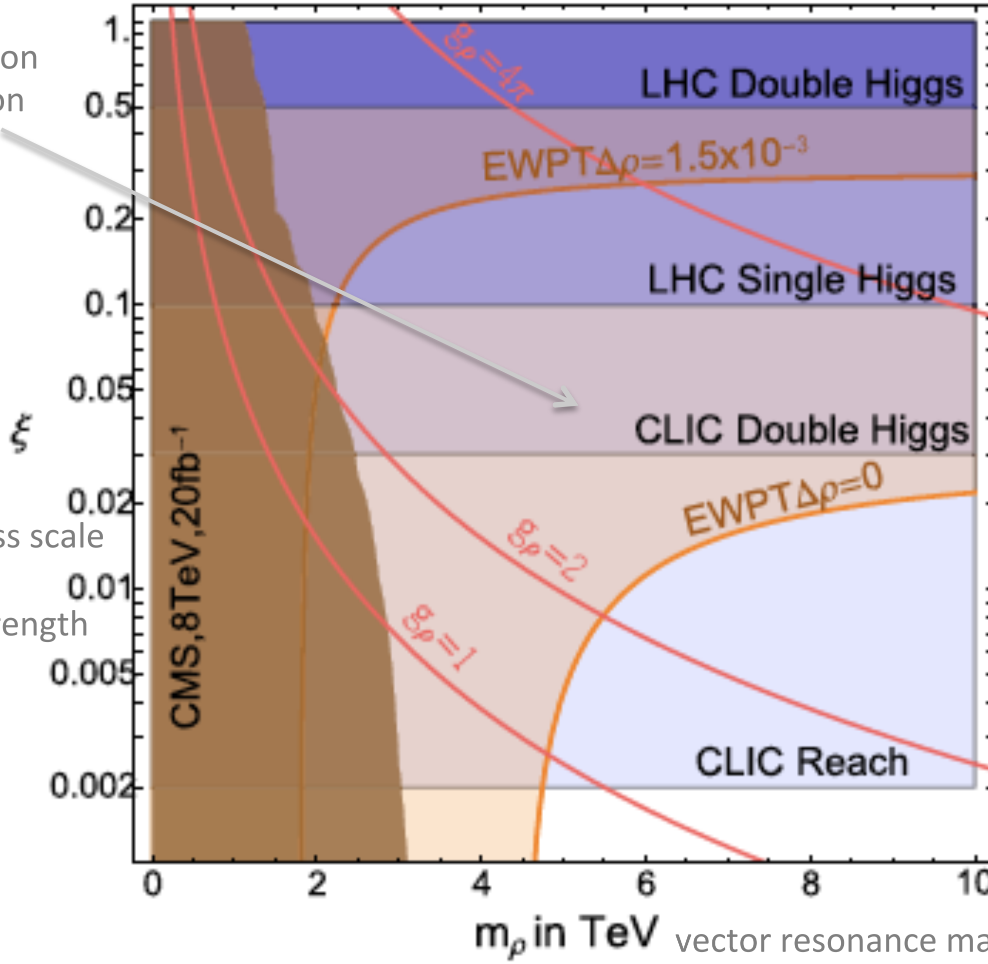
Parton level simulation results, 2HDM (II)



A.F. Zarnecki @ TopLC'2015

composite Higgs bosons

allowed region EW precision tests



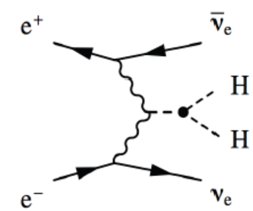
dimensionless scale parameter, measures strength of Higgs interactions

vector resonance mass of the composite theory

LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search WZ =>3 leptons

Allows to probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV

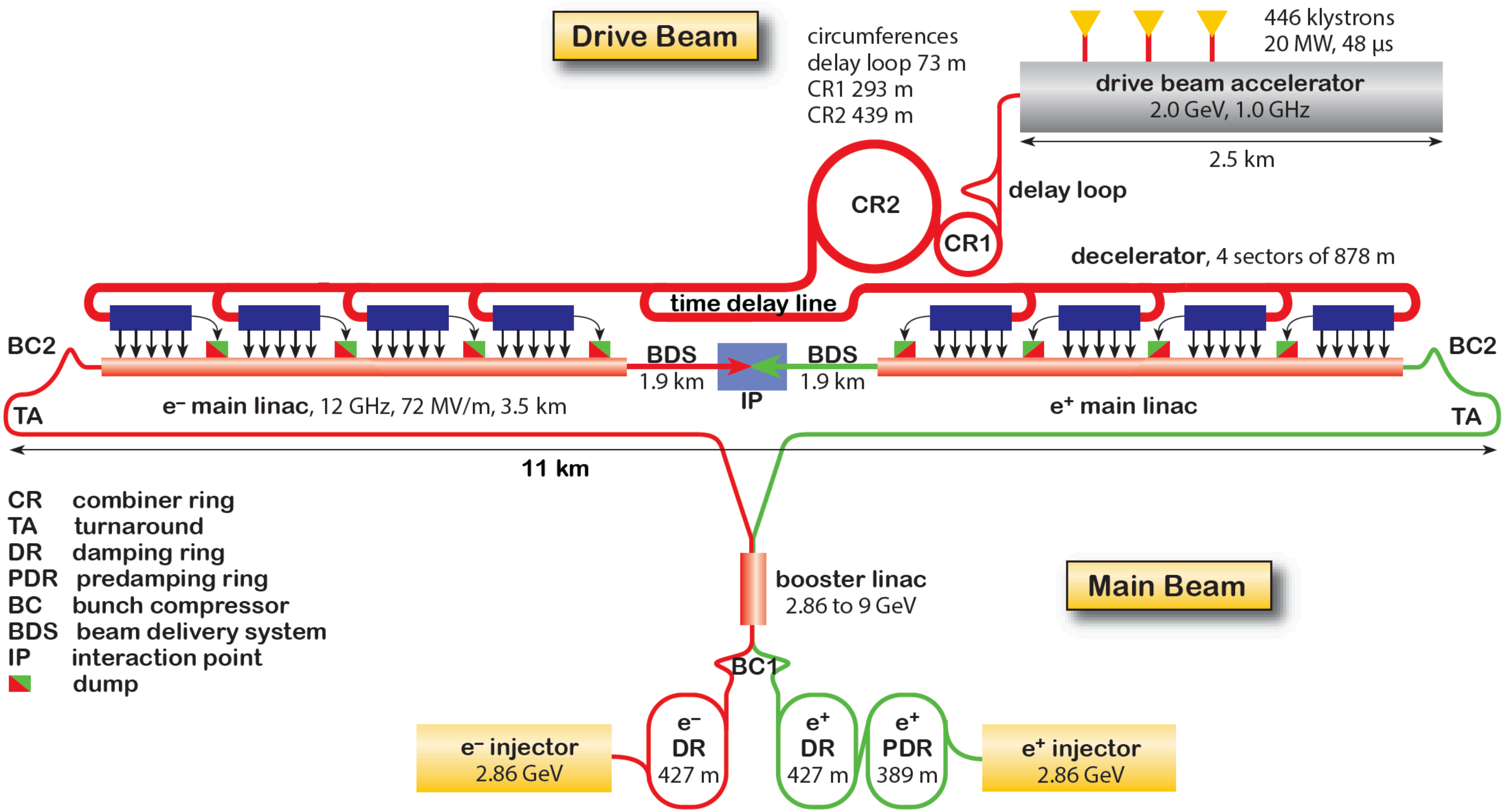
(70 TeV scale if combined with single Higgs production)

CLIC BSM discovery reach

New particle / phenomenon	Unit	CLIC reach
Sleptons, charginos, neutralinos, sneutrinos	TeV	≈1.5 TeV
Z' (SM couplings)	TeV	20
2 extra dimensions M_D	TeV	20-30
Triple Gauge Coupling (95%) (λ_γ coupling)		0.0001
Vector boson scattering $\Delta F_{S,0,1}$	TeV^{-4}	5
μ contact scale	TeV	60
Higgs composite scale	TeV	70
Electron size (test of QED extension)	cm	3.1×10^{-18}

CLIC discovery reach for BSM phenomena, studied for 2 ab^{-1} at 3 TeV. Depending on the exact models used, quoted values generally extend significantly beyond the HL-LHC reach.

CLIC layout at 380 GeV

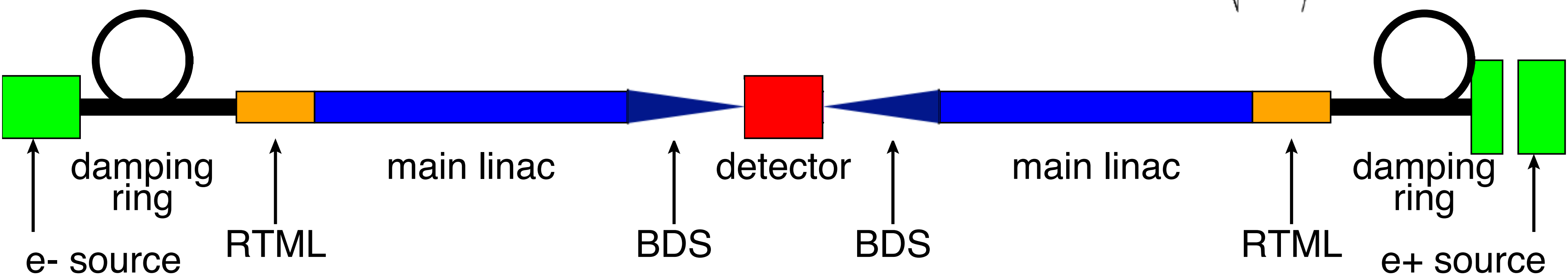


some linear accelerator basic

The key parameters: Energy and luminosity

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$



The critical steps:

1) Create low emittance beams (sources, injector, damping rings, ring to main linac - RTML)
2) Acceleration in main linac (high gradient => 100 MV/m)
3) Efficient energy transmission to the beam (high power at high frequency, 12 GHz)
4) Nano-beams: Squeeze the beam (Beam Delivery System- BDS), i.e. reduce β

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 √s = 380 GeV (11.4 km site length)