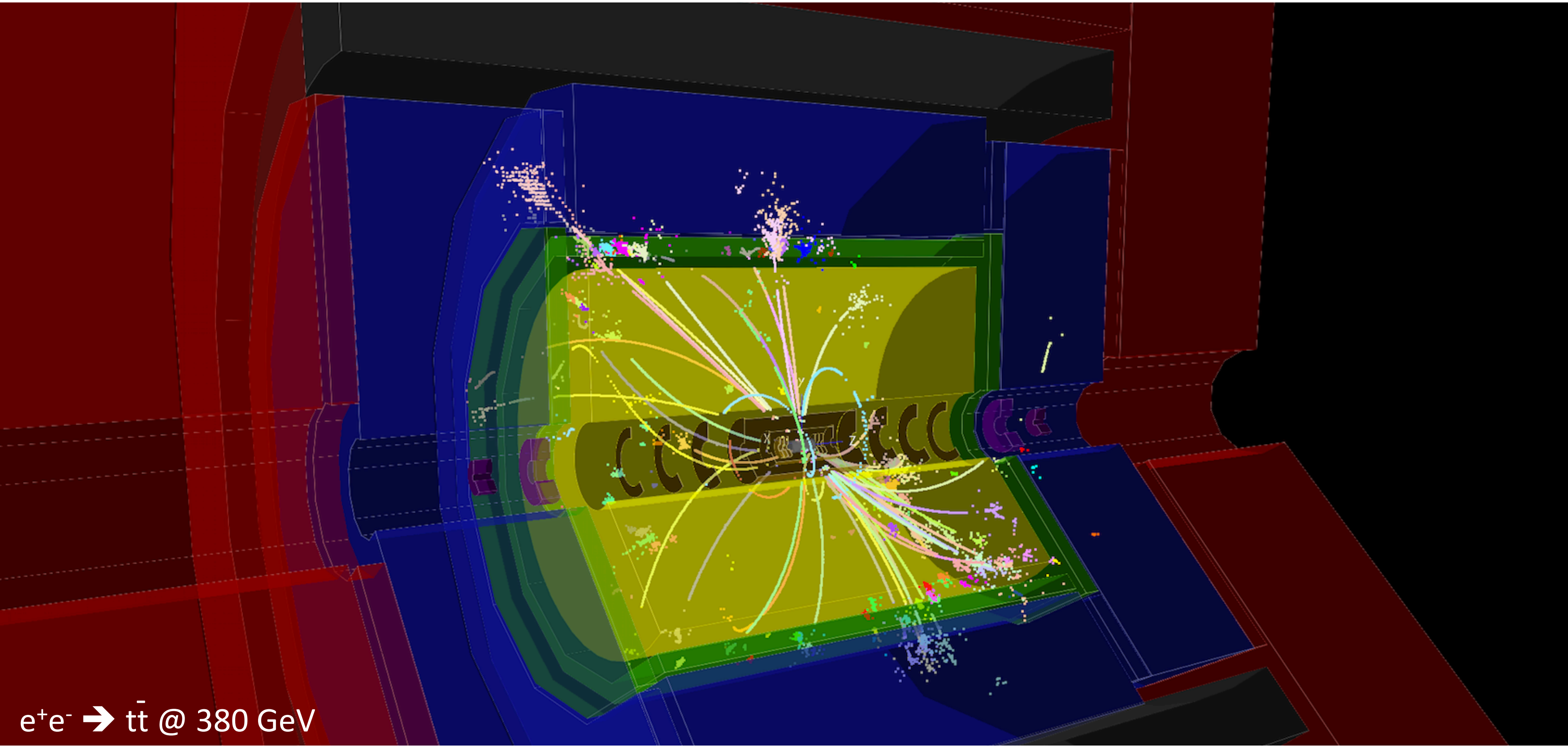
CLIC detector and physics

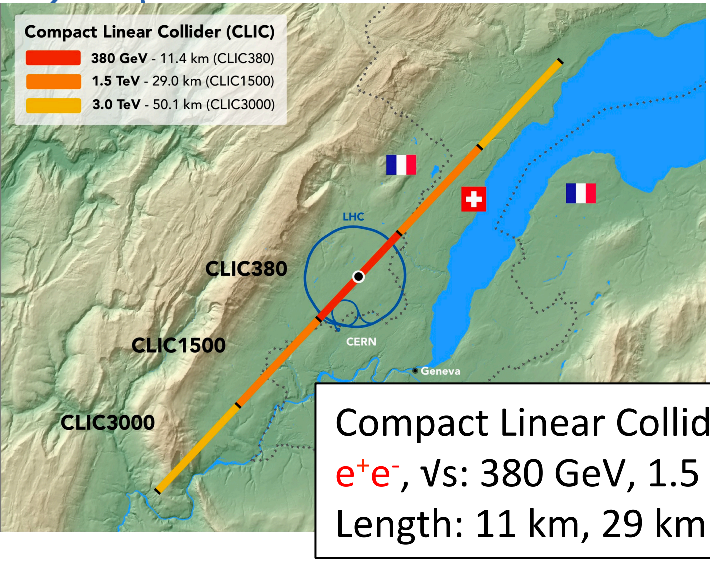


$e^+e^- \rightarrow t\bar{t}$ @ 380 GeV

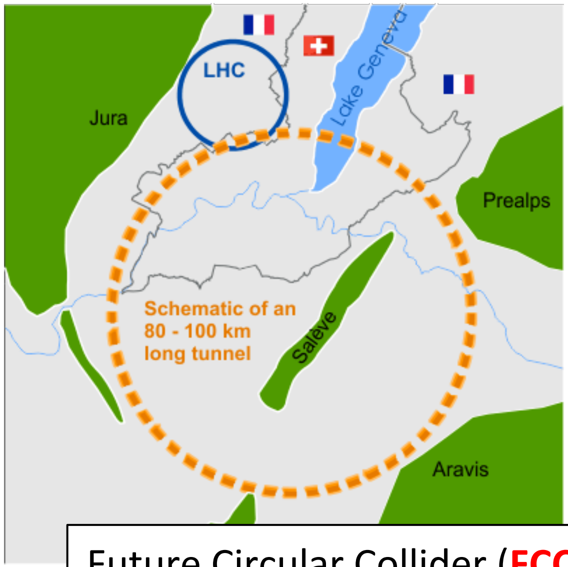
Lucie Linssen, CERN
on behalf of the CLIC and CLICdp collaborations

ECFA plenary, Nov 17th 2017
With many thanks to my CLIC and CLICdp colleagues for presentation material

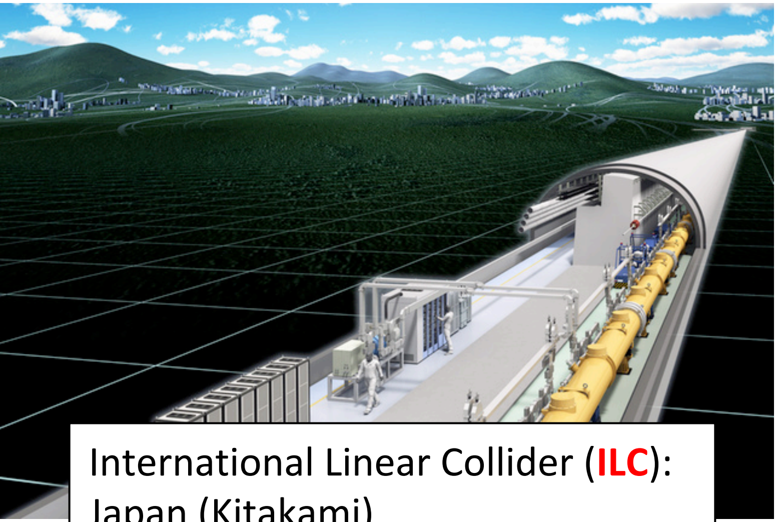
studies of high-energy e^+e^- colliders



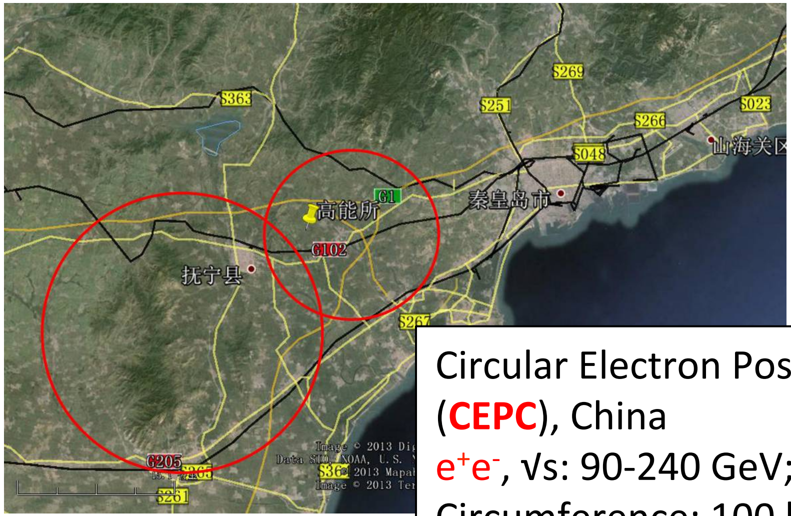
Compact Linear Collider (**CLIC**): CERN
e^+e^-, $\sqrt{s}$: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, $\sqrt{s}$: 90 - 350 GeV; FCC-hh pp
Circumference: 97.75 km



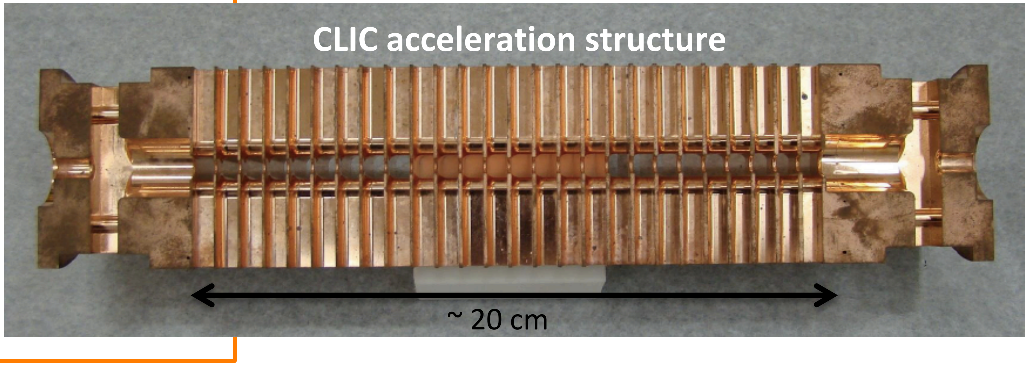
International Linear Collider (**ILC**):
Japan (Kitakami)
e^+e^-, $\sqrt{s}$: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



Circular Electron Positron Collider
(**CEPC**), China
e^+e^-, $\sqrt{s}$: 90-240 GeV; SPPC pp,
Circumference: 100 km

CLIC in a nutshell

- **e^+e^- collisions @ √s 380 (350) GeV - 3 TeV**
- Luminosity: a few 10^{34} $cm^{-2}s^{-1}$
- 2-beam acceleration scheme
- At room temperature
- Accelerating gradient 100 MV/m
- CDR published in 2012


CLIC acceleration structure

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 √s ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Bunch separation (ns)	0.5	0.5	0.5
Number of bunches per train	352	312	312
Repetition frequency (Hz)	50	50	50
Beam size at IP $\sigma_x/\sigma_y/\sigma_z$ (nm/nm/µm)	150 / 2.9 / 70	~60 / 1.5 / 44	~40 / 1 / 44
Accelerator gradient (MV/m)	72	72/100	72/100
Site length (km)	**11**	**29**	**50**
Estimated power cons. P_{wall} (MW)	**252**	364	589

$\mathscr{L}$ increases with √s

beamstrahlung effect

"bunch train"

very small bunch size

key development focus

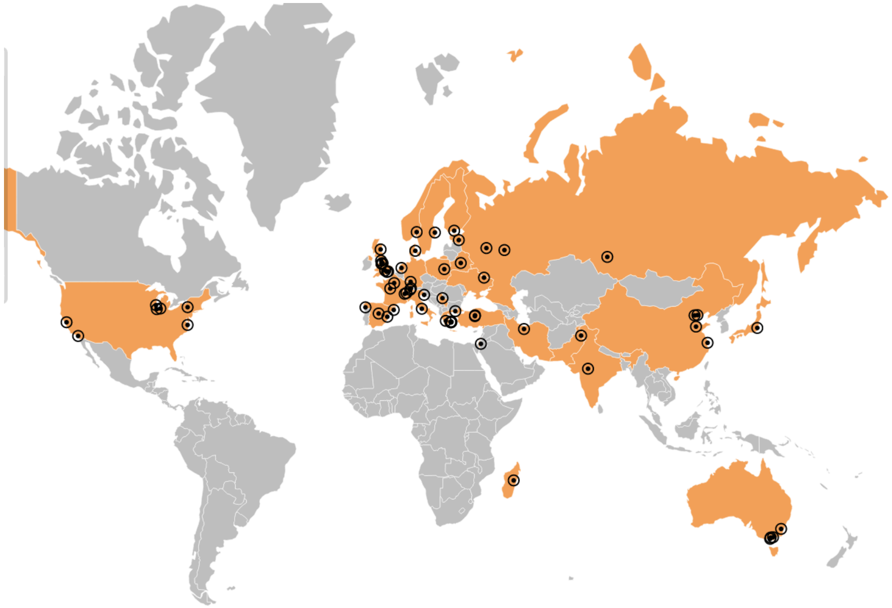
CLIC collaborations

CLIC/CTF3 accelerator collaboration
~60 institutes from **28 countries**

http://clic-study.web.cern.ch/

CLIC accelerator studies:

- CLIC accelerator design and development
- (Construction and operation of CTF3)



CLIC detector and physics (CLICdp)
29 institutes from **18 countries**

http://clicdp.web.cern.ch/

Focus of CLIC-specific studies on:

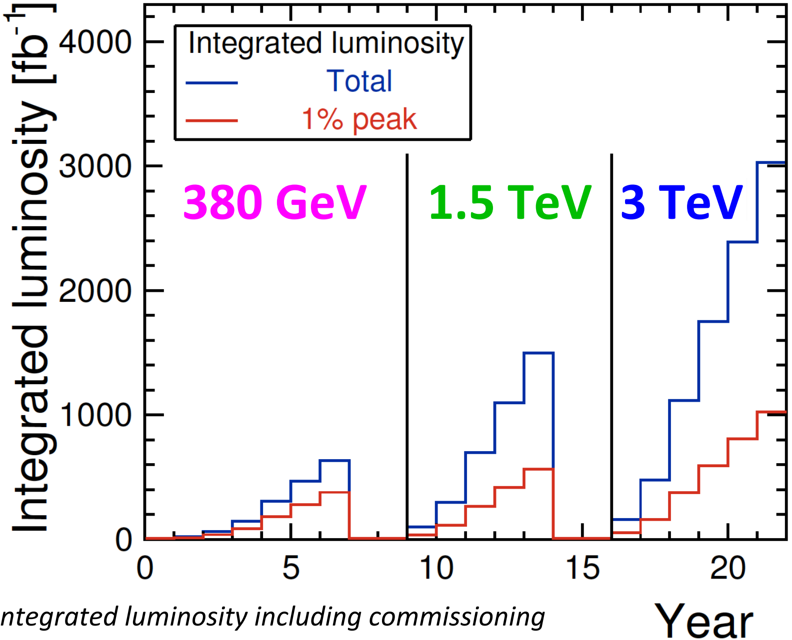
- Physics prospects and simulation studies
- Detector optimisation + R&D for CLIC

CLICdp Participating Institutes

CLIC staging scenario

The CLIC program builds on energy stages:

Maximizes **physics output, enables *realistic* funding profiles, delivers key physics *early***



Integrated luminosity including commissioning with beam and stops for energy upgrades

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

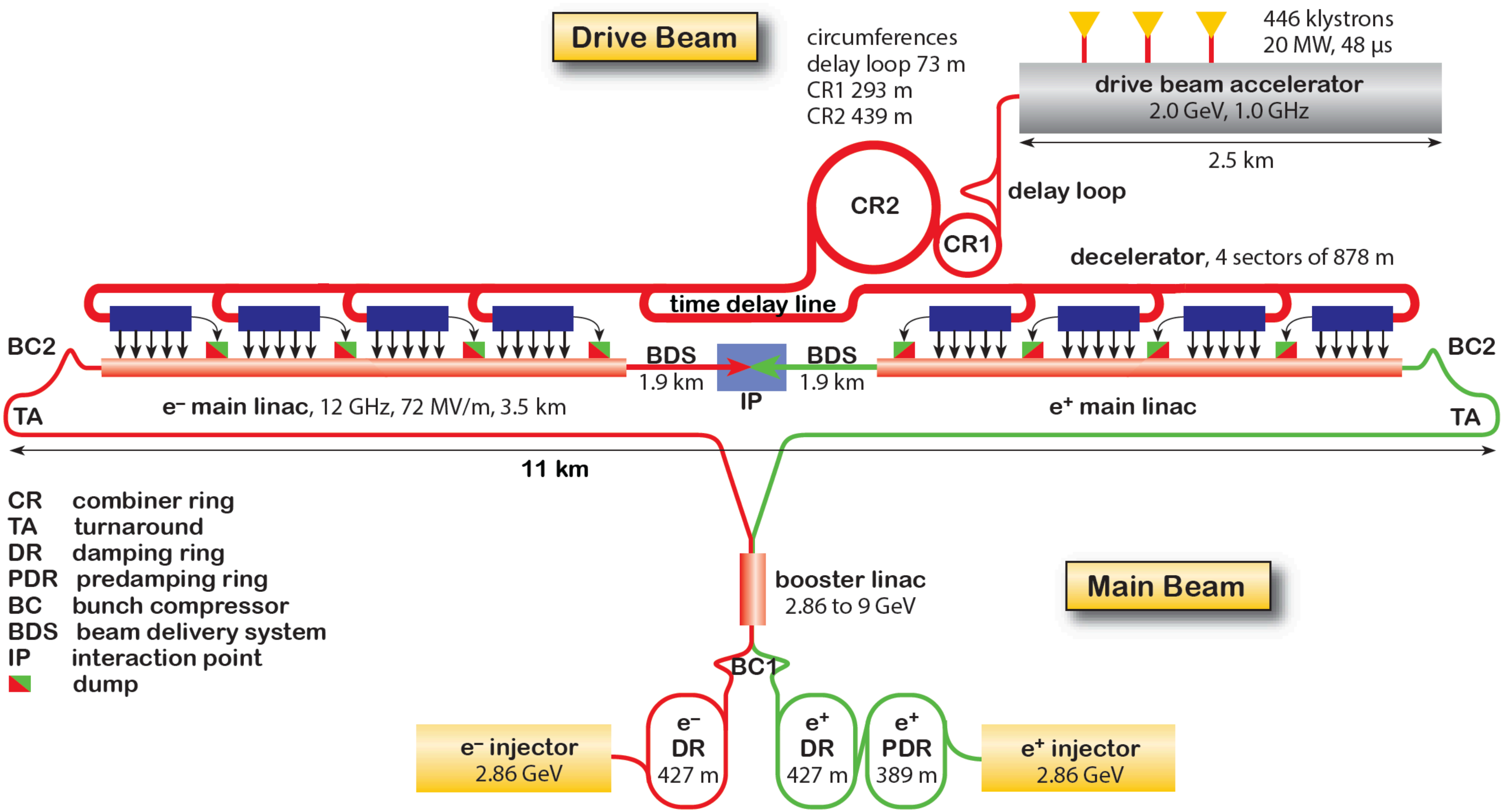
Dedicated to top mass threshold scan

CERN-2016-004

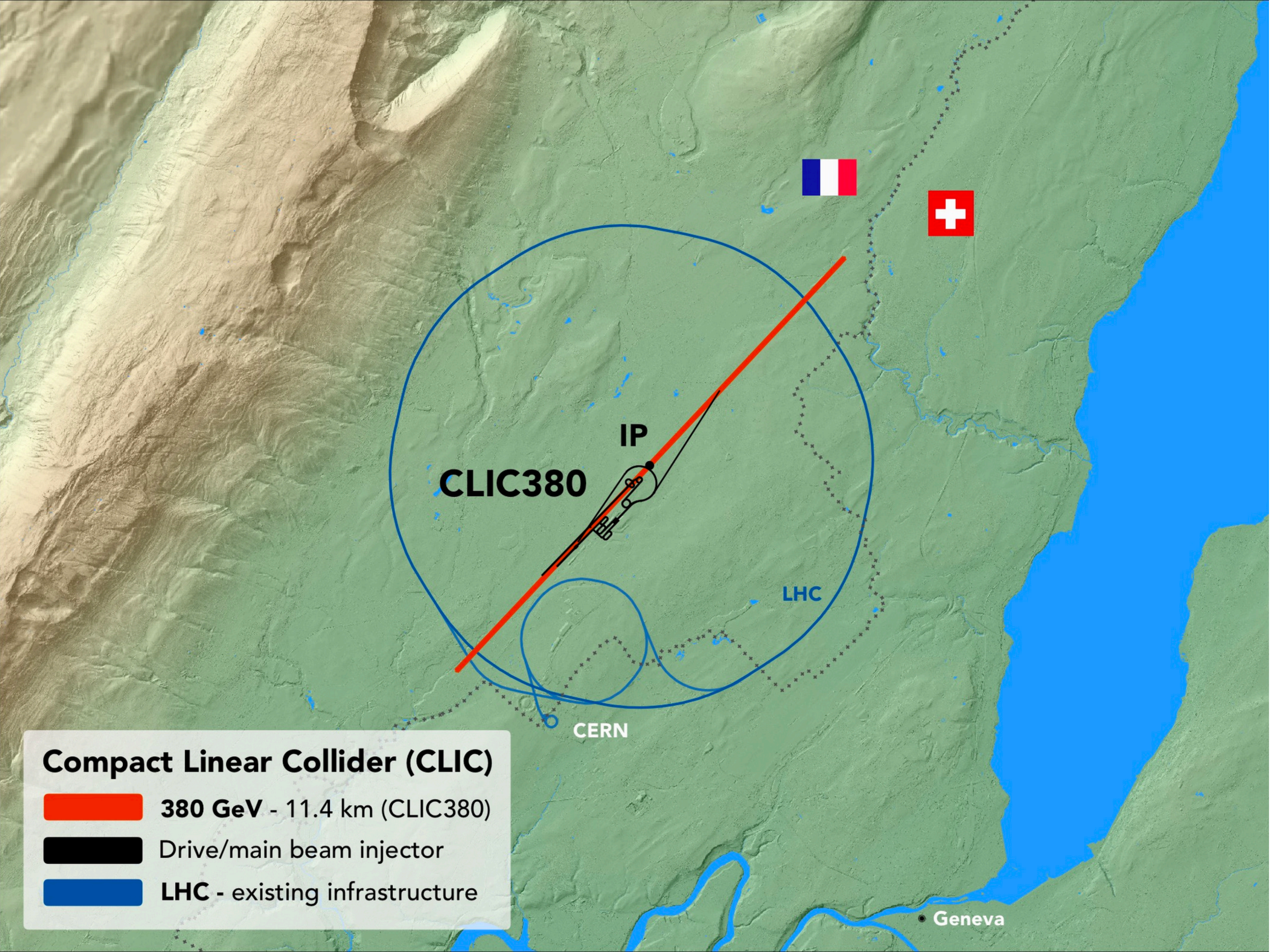
- **380 GeV (350 GeV)**, 600 fb^{-1} : precision Higgs and top physics
- **1.5 TeV**, 1.5 ab^{-1} : BSM searches, precision Higgs, ttH, HH, top physics
- **3 TeV**, 3 ab^{-1} : BSM searches, precision Higgs, HH, top physics

CLIC is extendable! May profit from even more advanced technologies for high-E stages

CLIC layout at 380 GeV



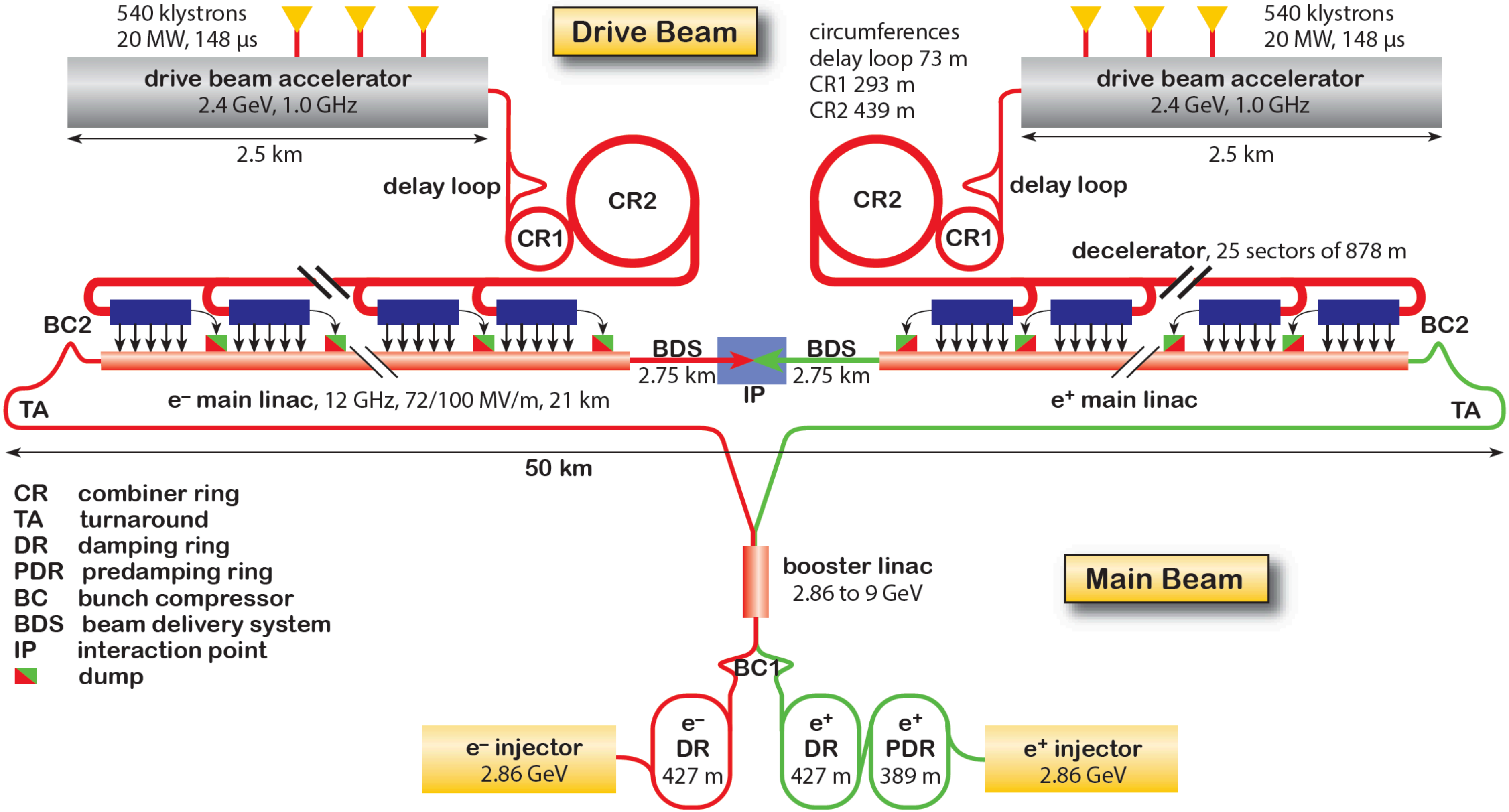
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump



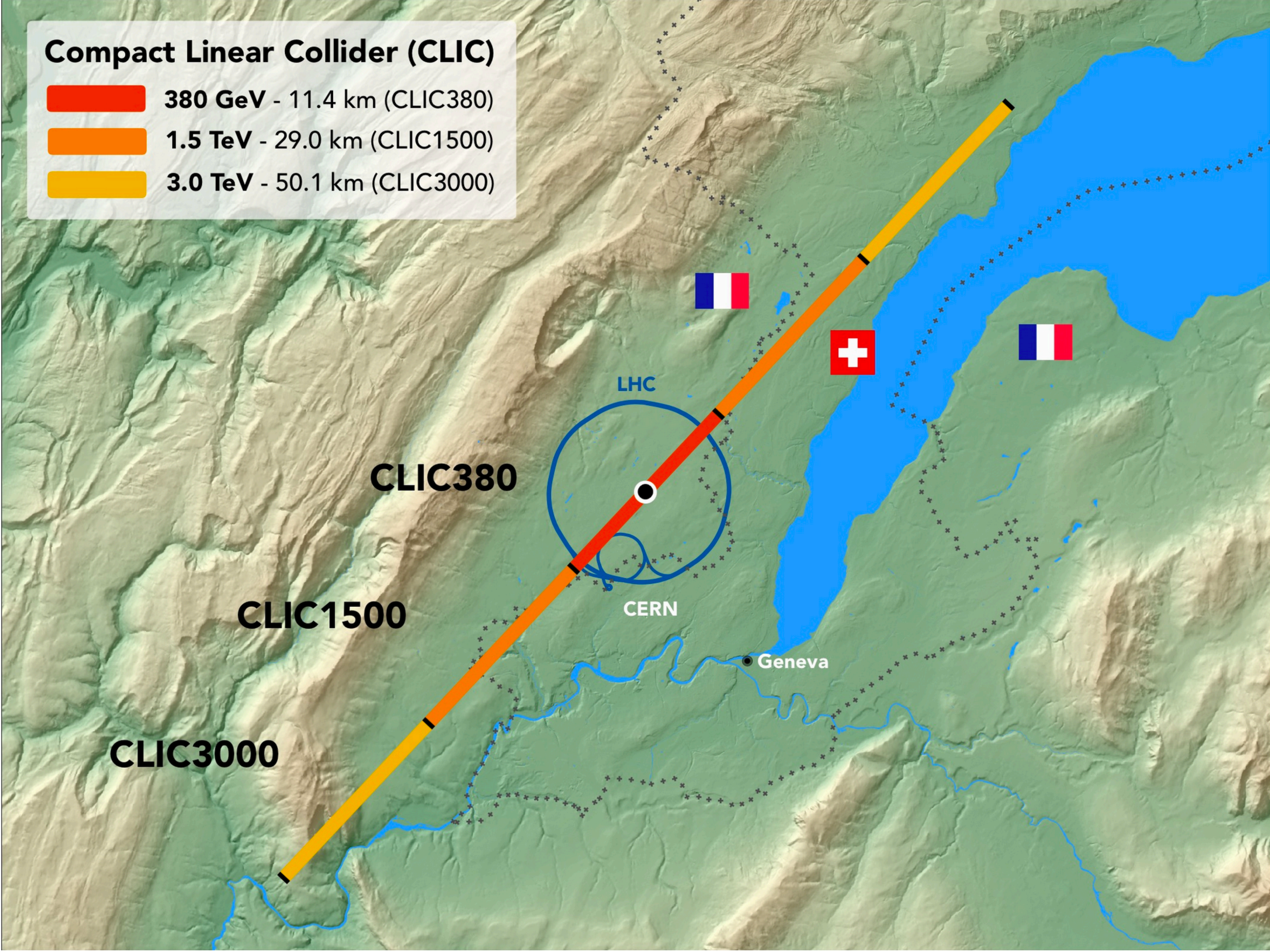
Compact Linear Collider (CLIC)

- 🟥 **380 GeV** - 11.4 km (CLIC380)
- ⬛ Drive/main beam injector
- 🟦 **LHC -** existing infrastructure

CLIC layout at 3 TeV



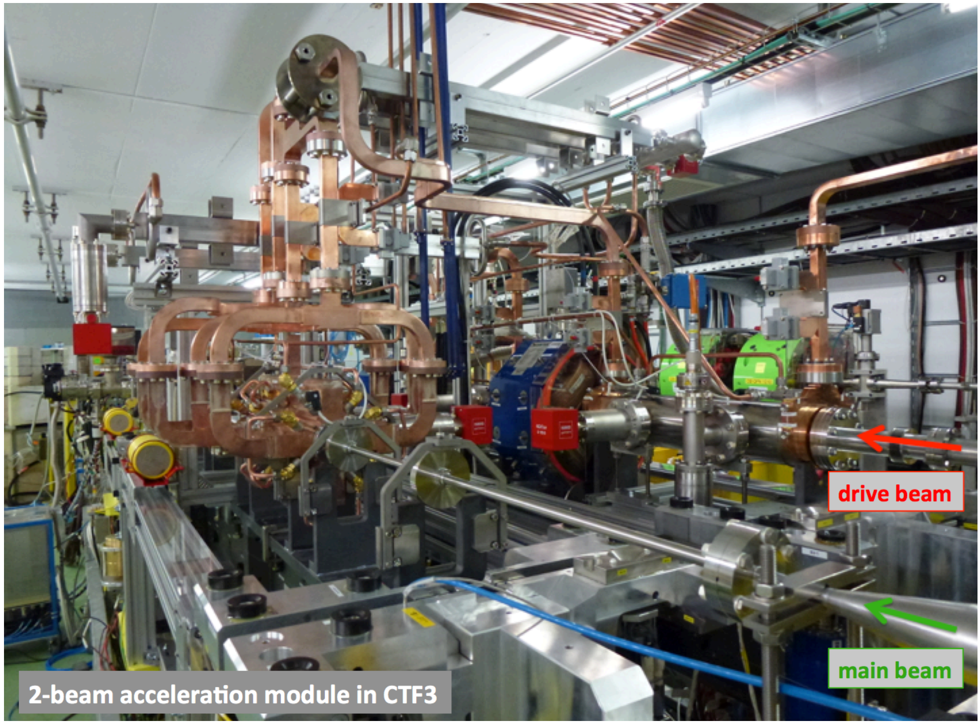
CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥🟩	**dump**


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

CLIC test facility CTF3

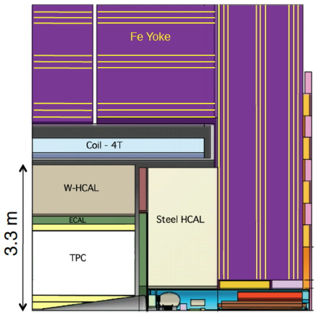
CTF3 successfully demonstrated:

- ✓ drive beam generation
- ✓ RF power extraction
- ✓ two-beam acceleration up to a gradient of 145 MeV/m

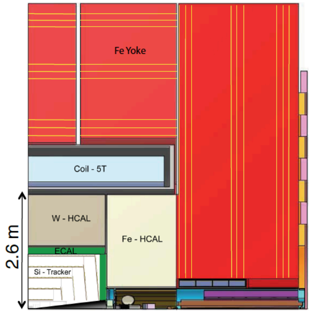


2-beam acceleration module in CTF3

the CLIC physics program



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

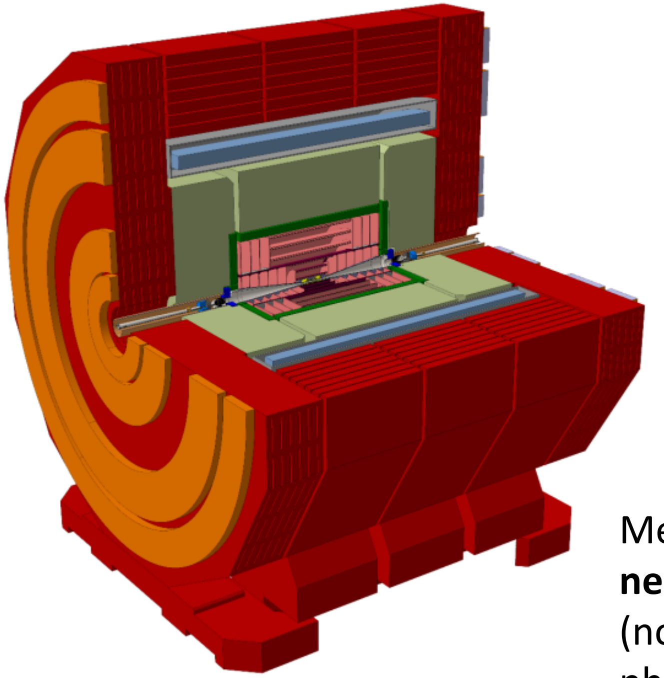


- Physics benchmark studies use the two CLIC CDR detector models (2012)
- Geant4-based detector simulation and event reconstruction
- Include effects of beam-induced backgrounds and luminosity spectrum

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

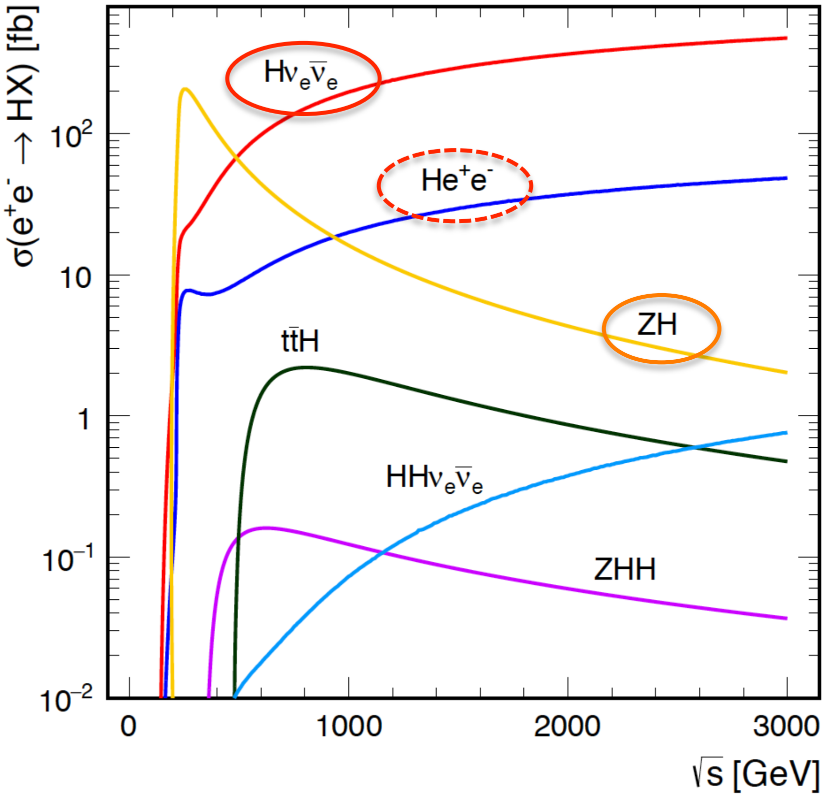
stage	$\sqrt{s}$	L_{int} (fb^{-1})
1	350 GeV	500
2	1.4 TeV	1500
3	3 TeV	2000

↗ *Scenario used for benchmarks*

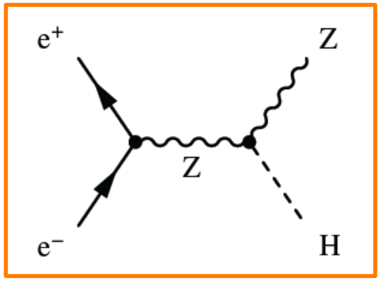


Meanwhile:
new optimised CLICdet
(not yet used for physics benchmarks)

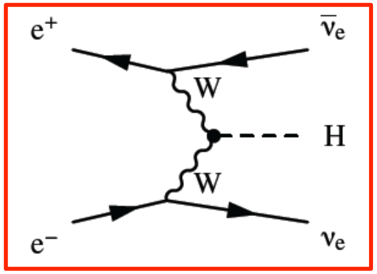
Higgs physics at CLIC



Dominant processes:



Higgsstrahlung
σ ~ 1/s
Higgs id. from Z recoil



WW(ZZ) - fusion
σ ~ log(s)
Large stat. at high E

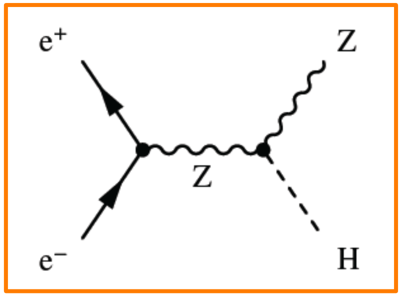
	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{\text{int}}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

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

No trigger needed !

EPJC (2017) 77: 475

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

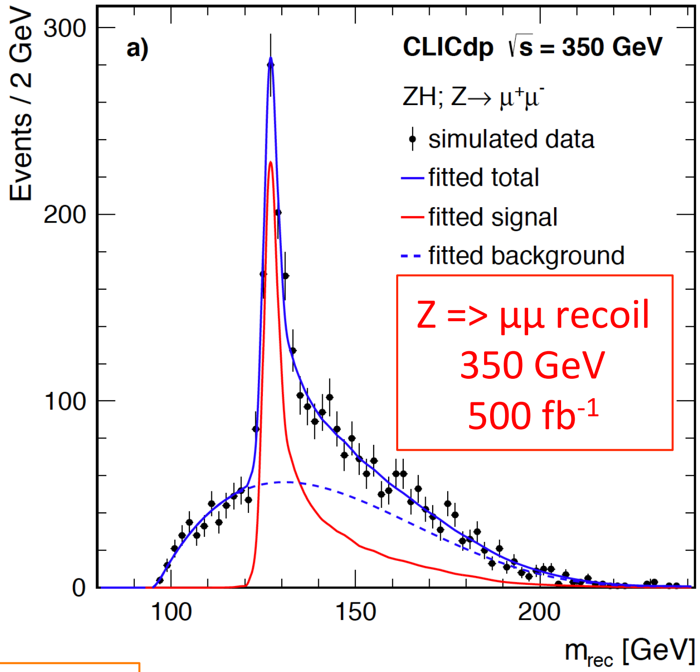


ZH events, selected through **recoil mass** against Z

$$m_{rec}^2 \approx s + m_Z^2 - 2\sqrt{s}(E1+E2)$$

model-independent measurement

$$\sigma_{HZ} \sim g_{HZZ}^2$$



Z => μμ recoil
350 GeV
500 fb^{-1}

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

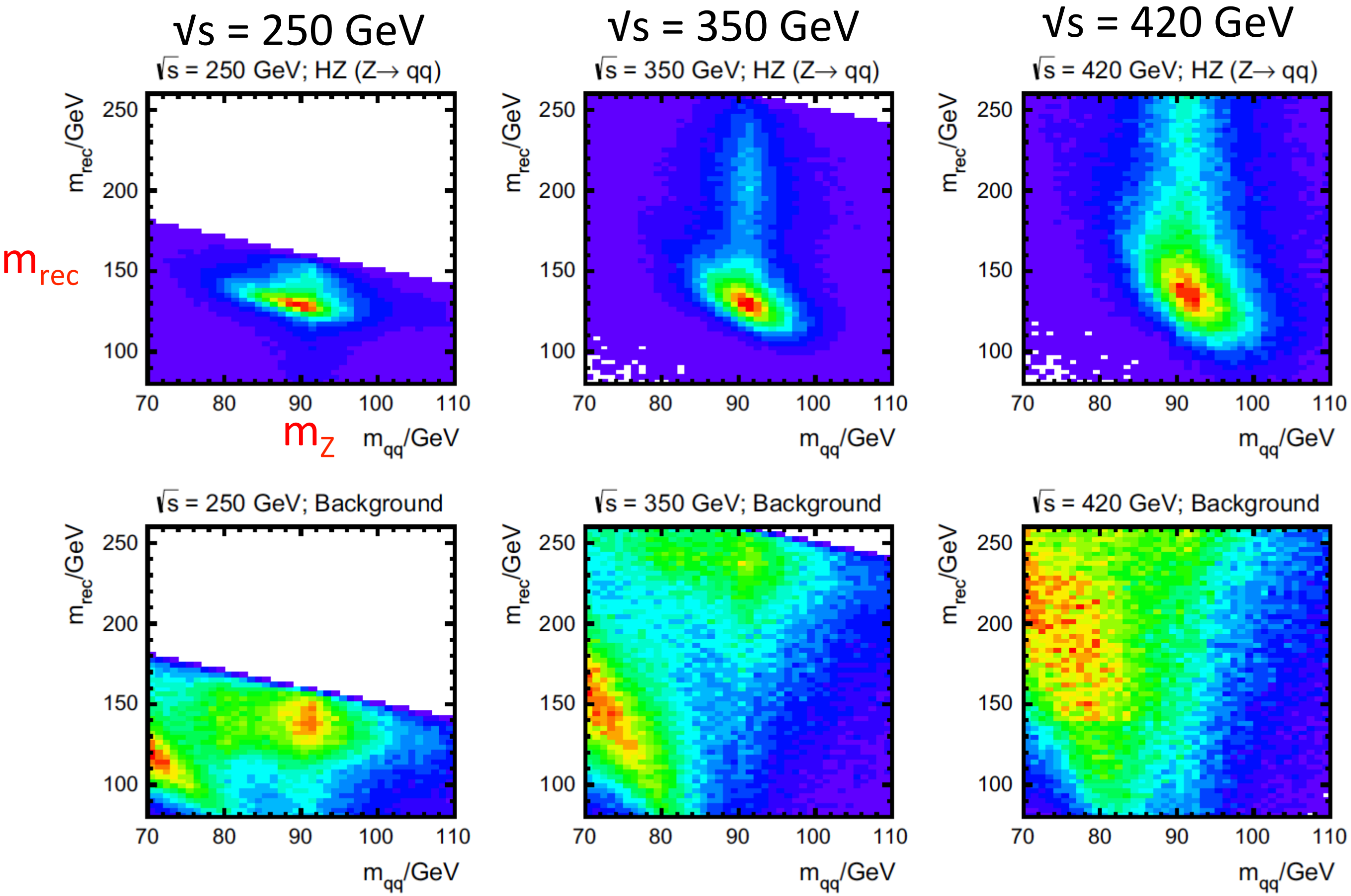
$\Delta(g_{HZZ})$ = ±0.8%

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

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

EPJC (2017) 77: 475 = arXiv:1608.07538

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



signal

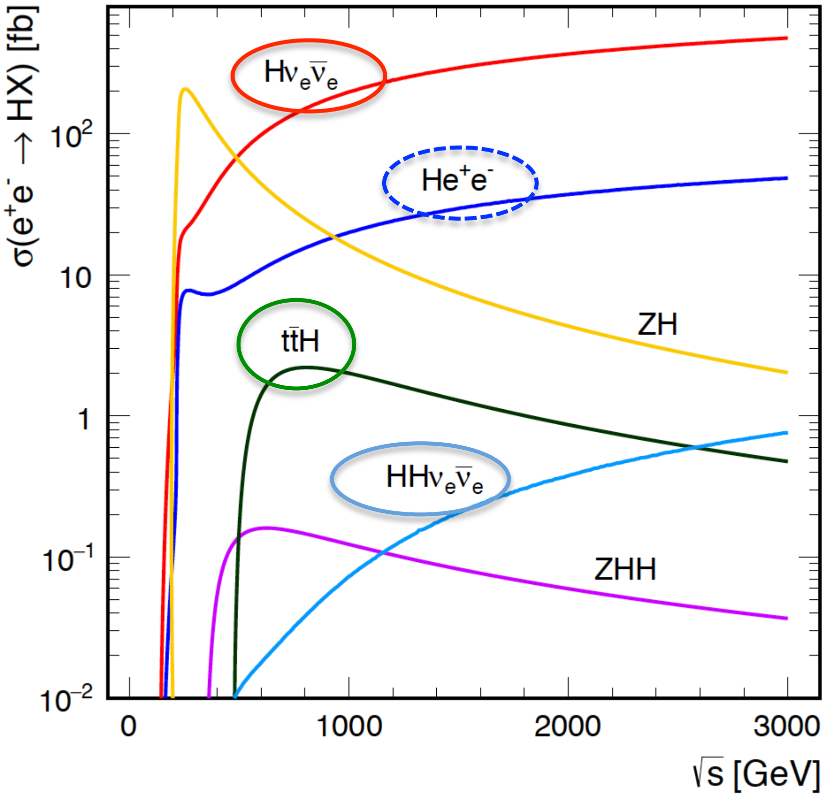
background

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

$\sqrt{s}$	$\mathscr{L}$	σ(HZ)	Δ σvis.	Δ σinvis.	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

Higgs physics above 1 TeV

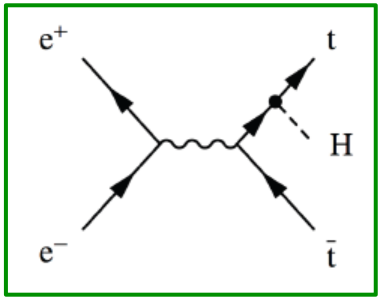


Vector boson fusion:

$e^+e^- \to H\nu\nu$, $e^+e^- \to He^+e^-$

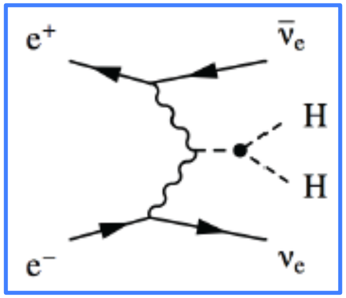
High σ + increased luminosity

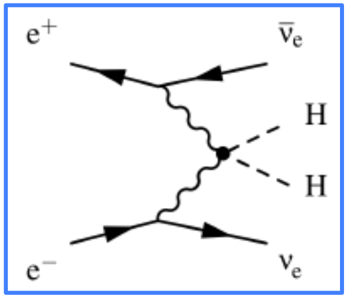
Gives **access to rare Higgs decays**



$t\bar{t}H$ production:

- Extraction of Yukawa coupling y_t
- Best at √s above 700 GeV
- **$\Delta(g_{Htt})$ = ±4.2% at 1.4 TeV (1.5 ab^{-1})**



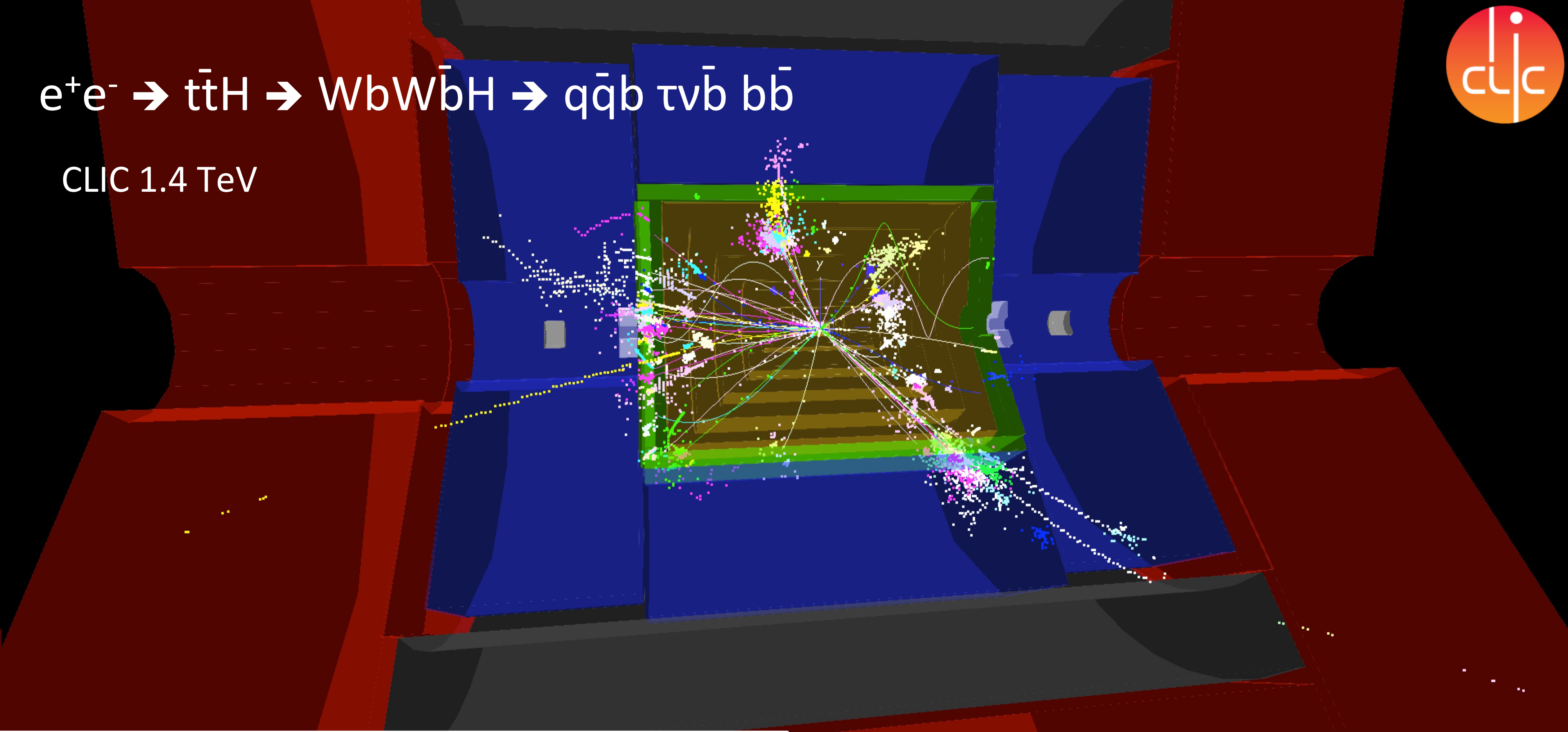


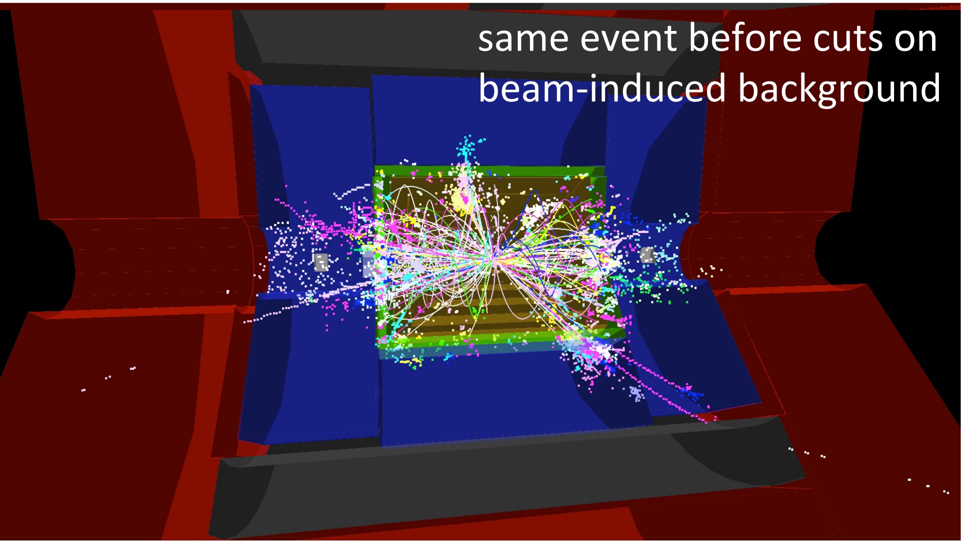
HH production => Higgs self-coupling λ:

- Projected precisions with -80% e^- polarisation
- **Δ(λ) = ±16% for 1.4 TeV (1.5 ab^{-1}) + 3 TeV (3 ab^{-1})**
- (**Δ(λ) = ±10%** using differential distributions, in progress)

$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\ \tau\nu\bar{b}\ b\bar{b}$

CLIC 1.4 TeV





same event before cuts on beam-induced background

Highly granular calorimetry + precise hit timing

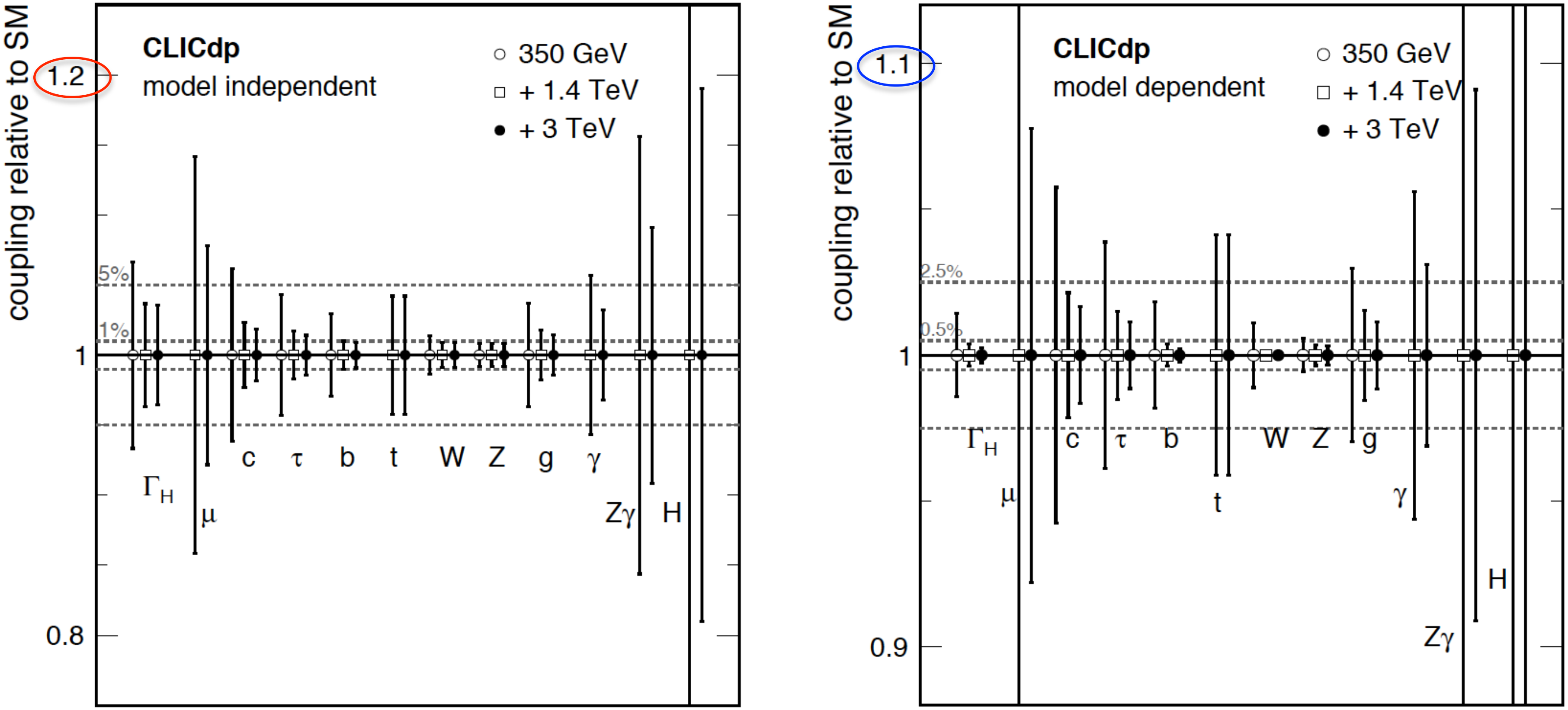
↓

Very effective in suppressing backgrounds for fully reconstructed particles

combined CLIC Higgs coupling results

Model-independent

Model-dependent



arXiv:1608.07538

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

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):

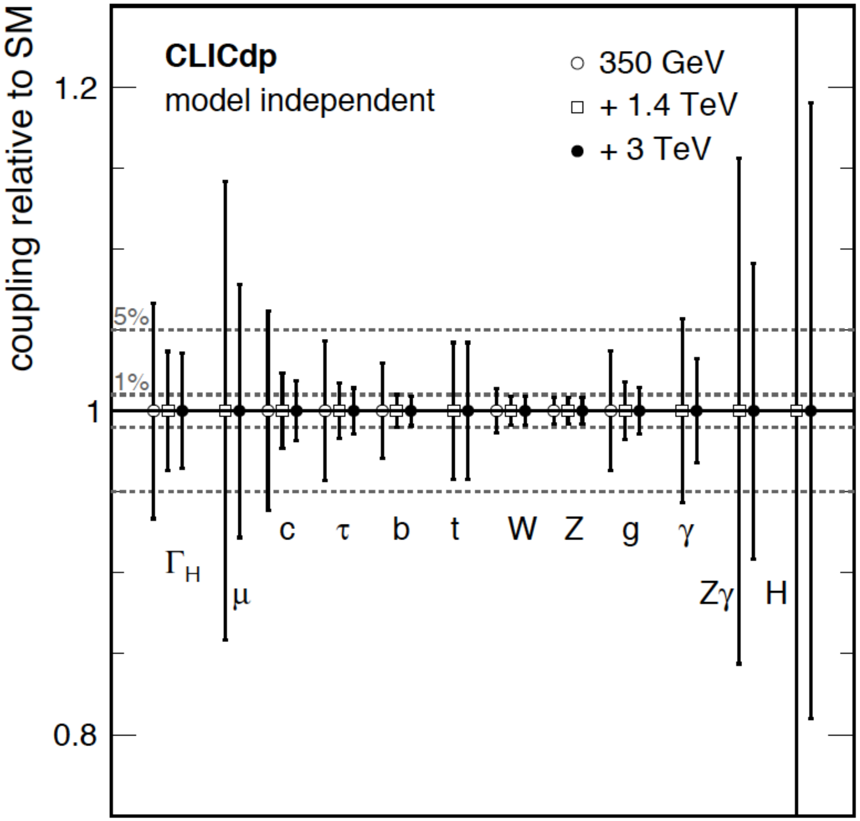
- Model-independent: down to ±1% for most couplings
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±3.5% (MI), ±0.3% (MD, derived)

combined CLIC Higgs coupling results

indicative comparison with HL-LHC capabilities

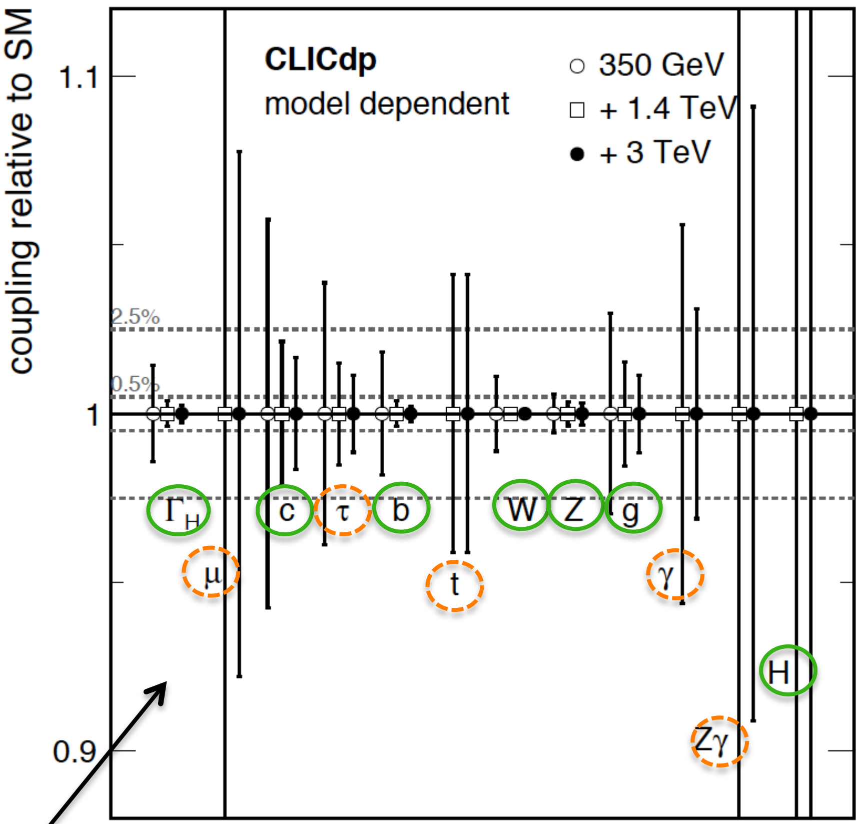
arXiv:1608.07538

Model-independent



e^+e^- colliders can perform model-independent measurements

Model-dependent



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

◯ Accuracy significantly better than HL-LHC
◌ Accuracy comparable to HL-LHC

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

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

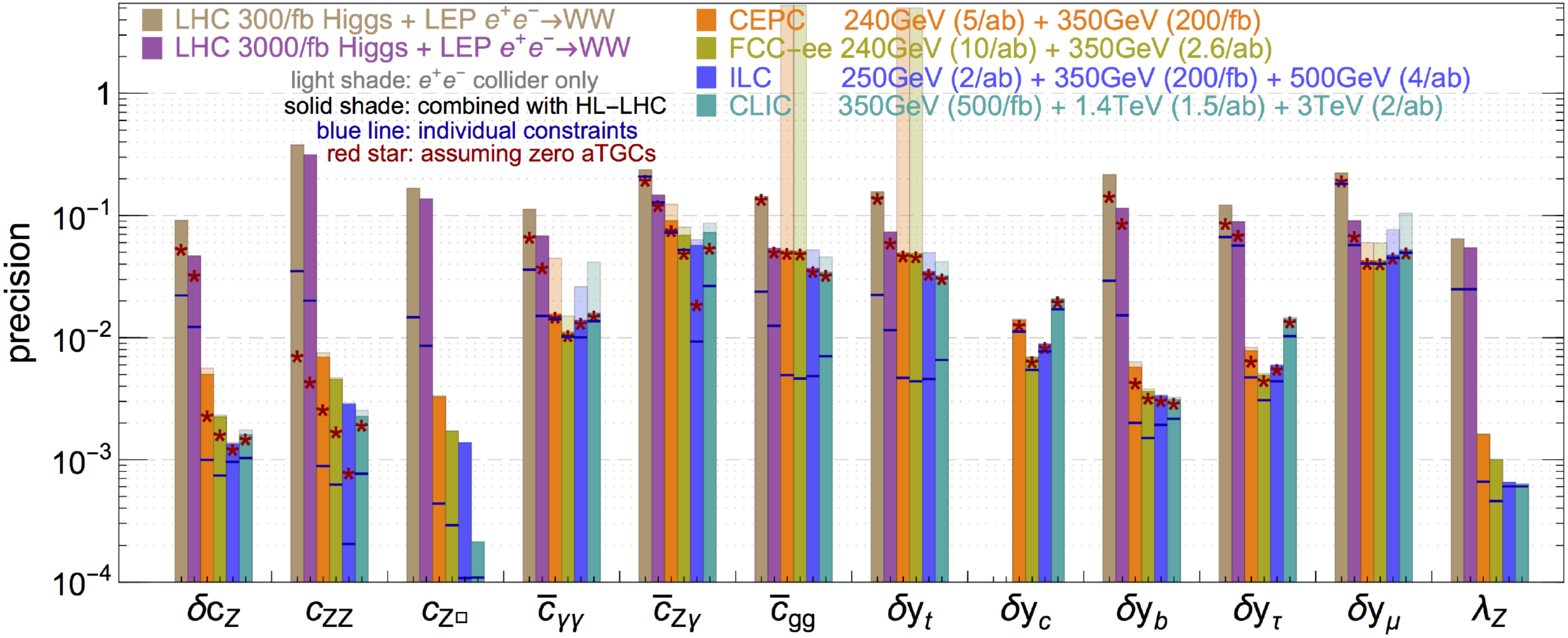
Scale of new decoupled physics

- Model-independent framework for probing indirect signs of new physics
  => useful for comparison of future collider options

- **Input to the fits**: Higgs production through HZ and WW fusion, $e^+e^- \rightarrow t\bar{t}H$, e^+e^- => W^+W^-

Comparison between collider options

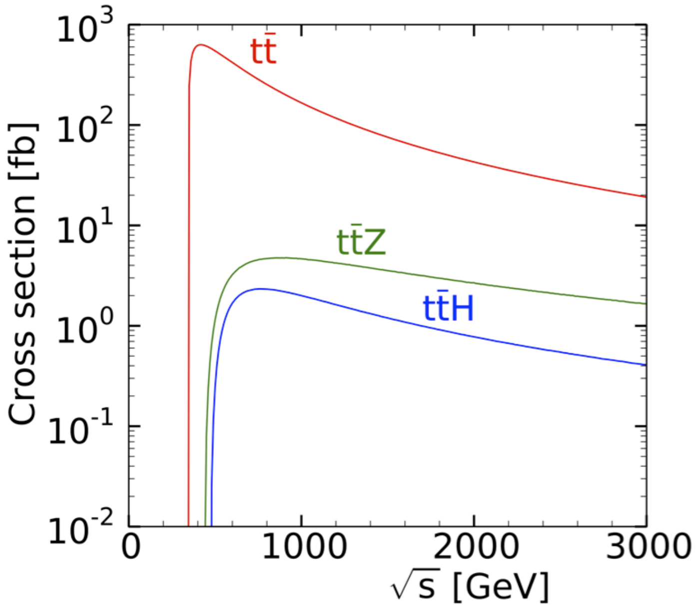
Precision reach of the 12-parameter fit in Higgs basis



- Many EFT parameters can be measured significantly better at CLIC than at HL-LHC
- H➔c$\bar{c}$ only accessible at lepton colliders

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

top quark physics



Motivation:

So far top quark only measured at hadron colliders

Precision top physics in $e^{+}e^{-}$:

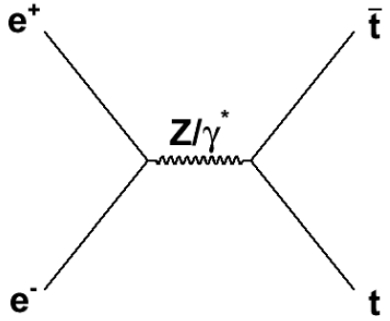
- sensitive to many BSM scenarios
- understanding EWSB
- test ground of QCD

Top physics programme currently studied for CLIC:

- Top quark **mass**
  - $t\bar{t}$ threshold scan at 350 GeV;
  - reconstructed mass above threshold
- **Electroweak couplings** to the top quark
  - at 380 GeV, and above 1 TeV (boosted top)
- **Couplings** in $t\bar{t}H$ and $t\bar{t}Z$ production
- **Rare decays** (strongly suppressed in SM)
- Searches using **boosted top quarks**, e.g. stop

CLIC top physics overview paper in preparation

top quark physics examples



Threshold scan

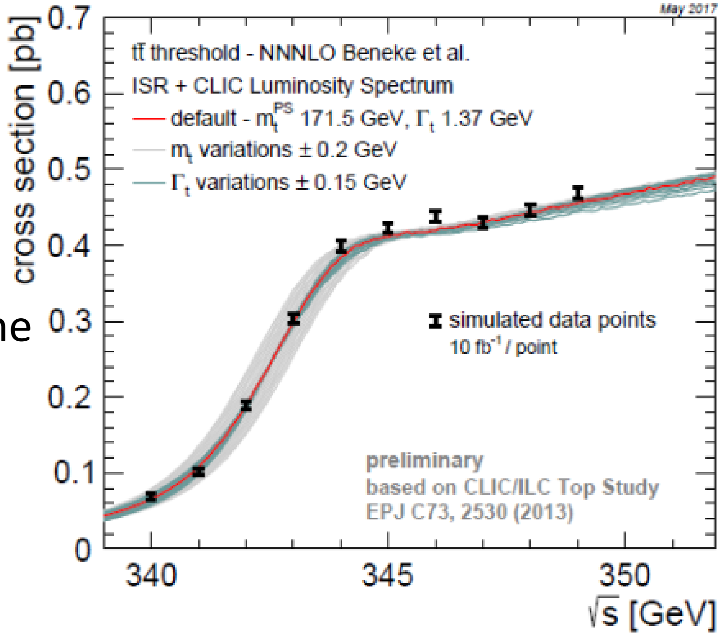
~100 fb^{-1} around 350 GeV

1S mass precision ~50 MeV

Dominated by theory scale NNLO

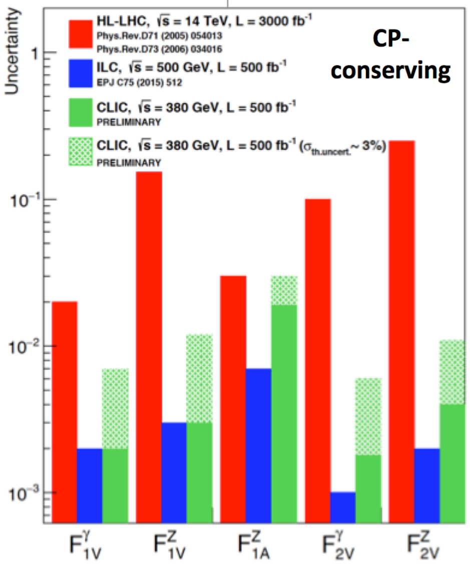
10 MeV uncertainty 1S to $\overline{\text{MS}}$ scheme

Phys. Rev. Lett. 114, 42002 (2015)

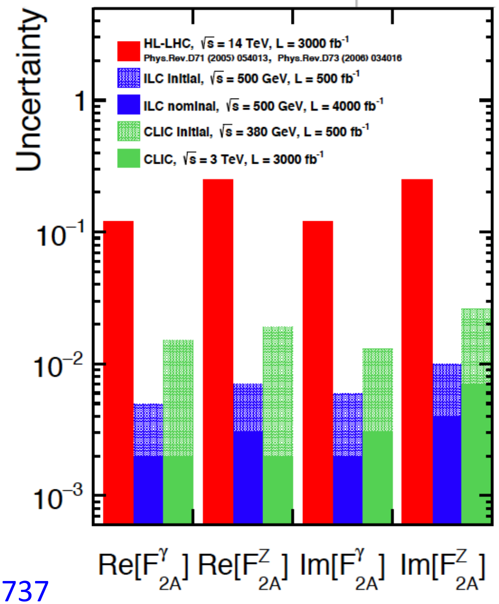


Expected coupling precision at **LHC**, **ILC** (500 GeV) and **CLIC** (380 GeV, 3 TeV)

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



arXiv:1608.07537



arXiv:1710.06737

Anomalous couplings

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

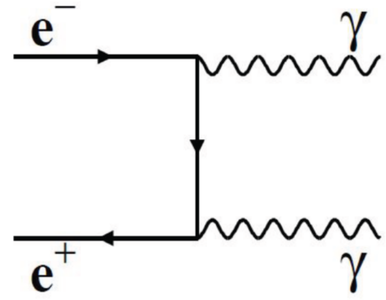
CLIC 1-2 orders of magnitude better than HL-LHC

Significant advantage of high $\sqrt{s}$ for CP violating couplings

indirect measurements: $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \mu^+\mu^-$

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

3 TeV, 2 ab^{-1}



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

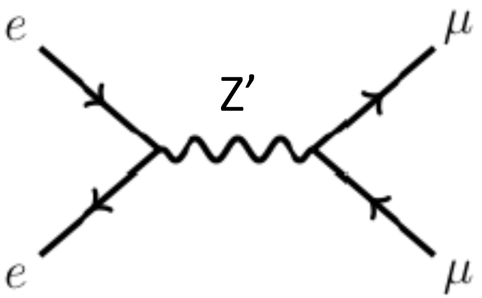
I. Boyko 2017

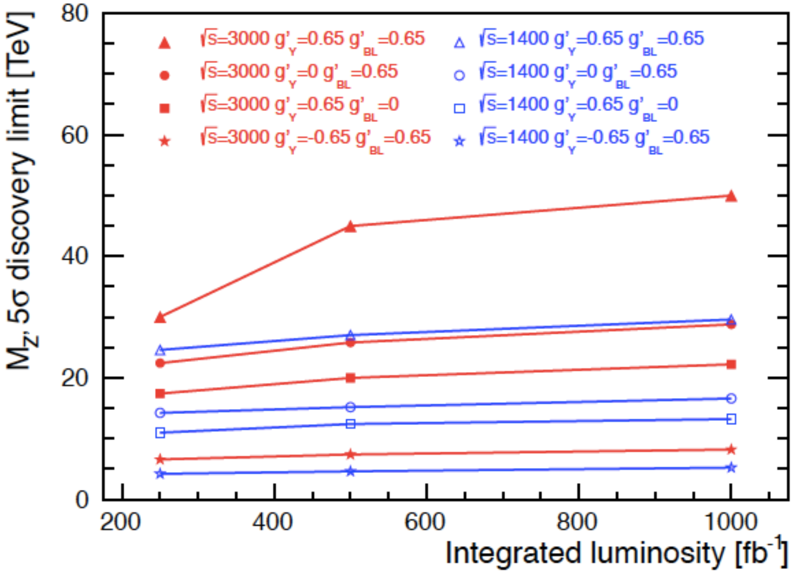
Unique to lepton colliders
CLIC ~15 times better than LEP2

Example: $e^+e^- \rightarrow \mu^+\mu^-$
1.4 TeV / 3 TeV

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

HL-LHC sensitive up to ~7 TeV





CLIC provides discovery reach up to tens of TeV

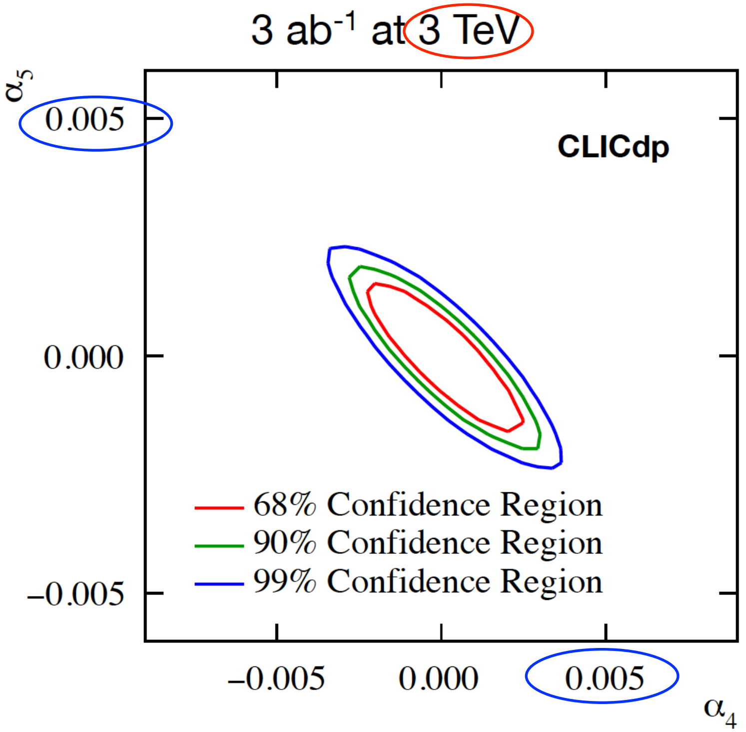
arXiv:1208.1148

vector boson scattering

Vector boson scattering

- sensitive to anomalous gauge couplings
- important test of electroweak symmetry breaking

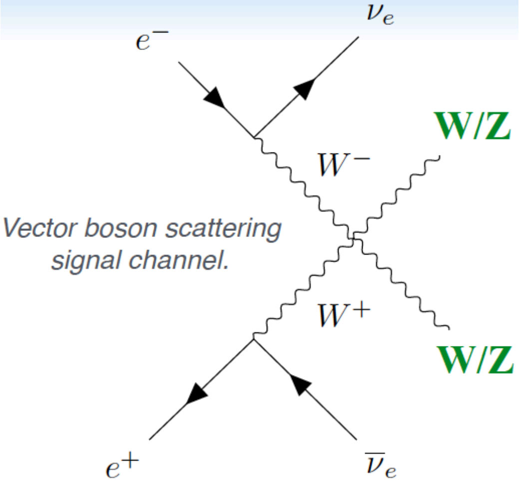
Effective field theory approach, parameters α_4, α_5



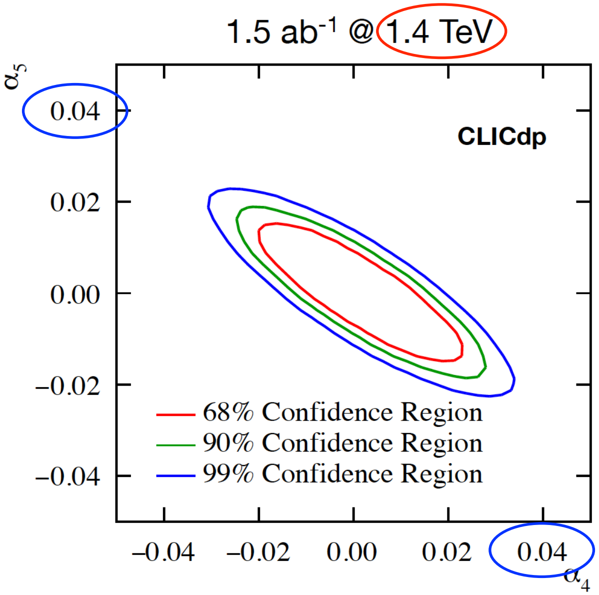
3 ab^{-1} at 3 TeV

Sensitivity improves strongly with √s

See also arXiv:1607.03030



Vector boson scattering signal channel.

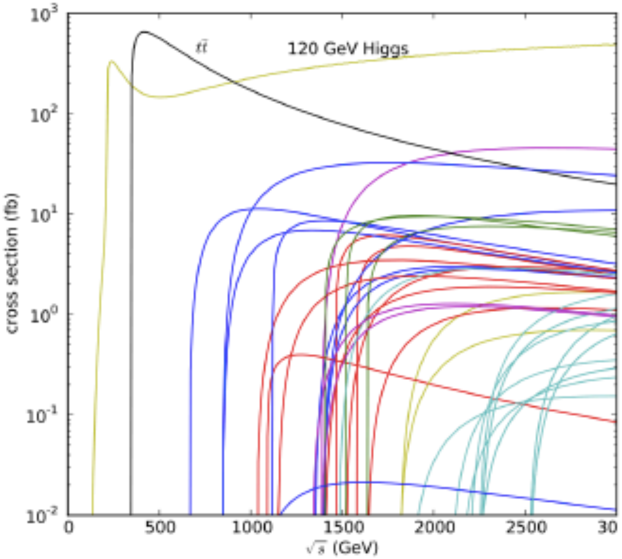


1.5 ab^{-1} @ 1.4 TeV

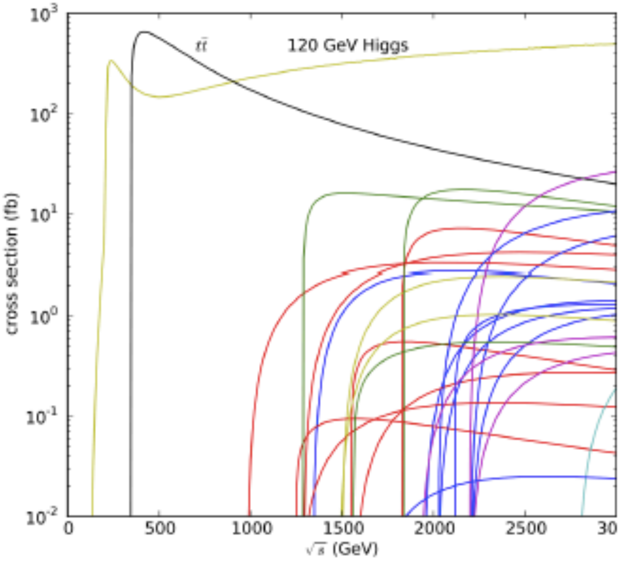
See also ATLAS arXiv:1610.07572

direct BSM sensitivity

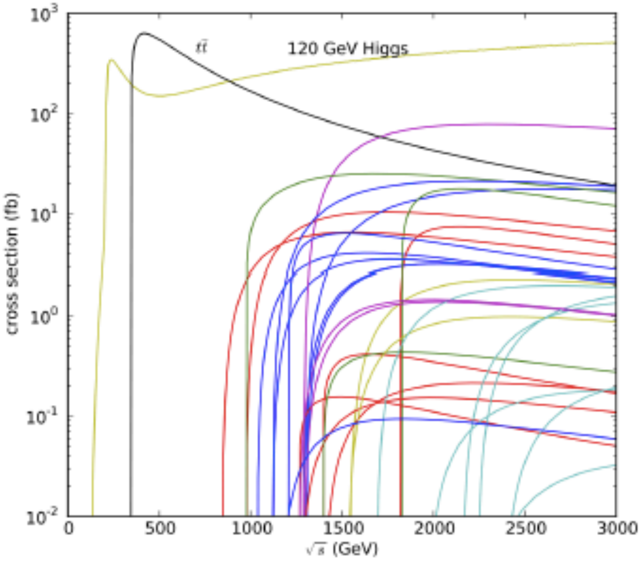
using SUSY as a benchmarking tool



"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

CERN-2012-003 CERN-2012-007

results of SUSY benchmarks

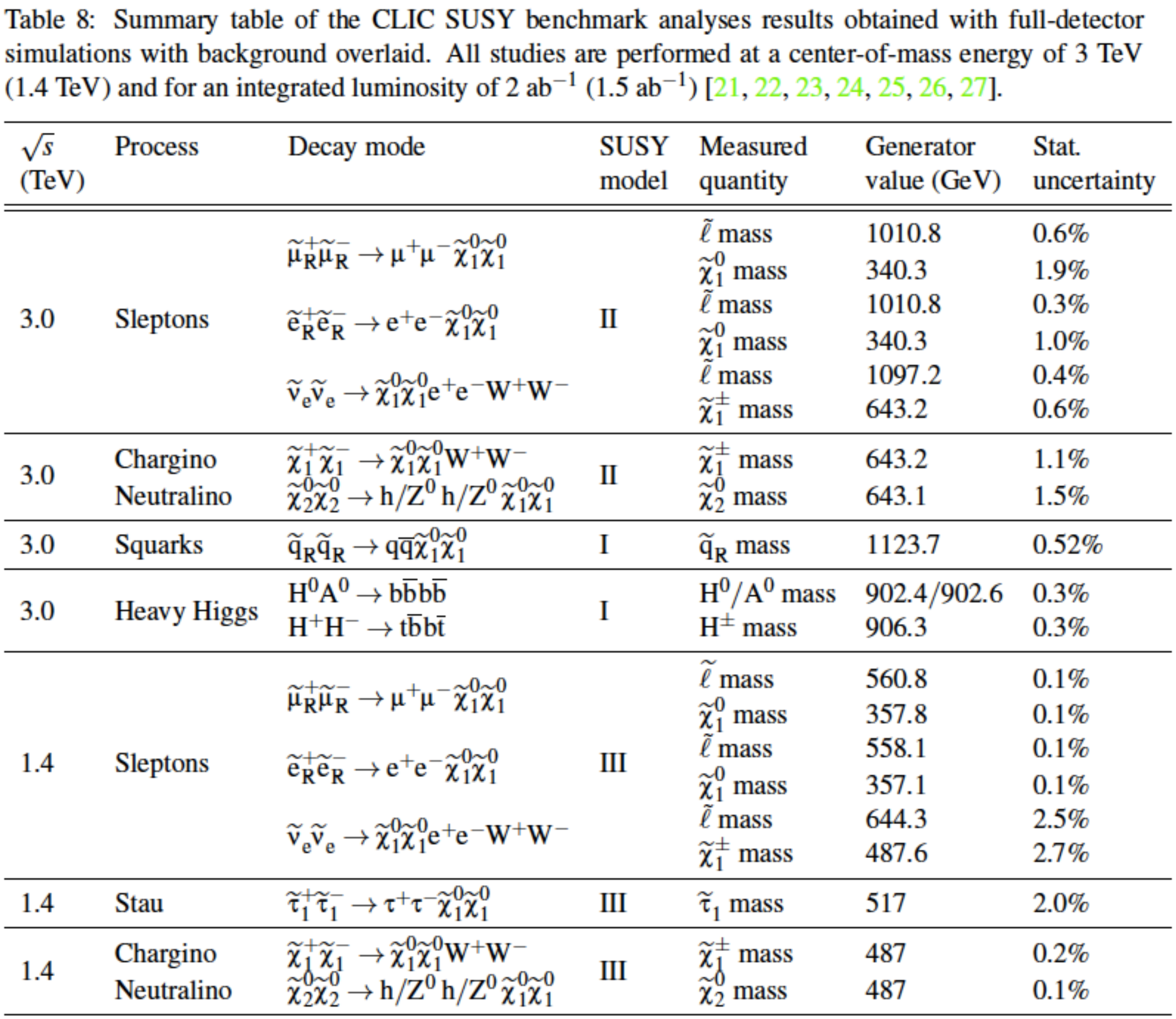


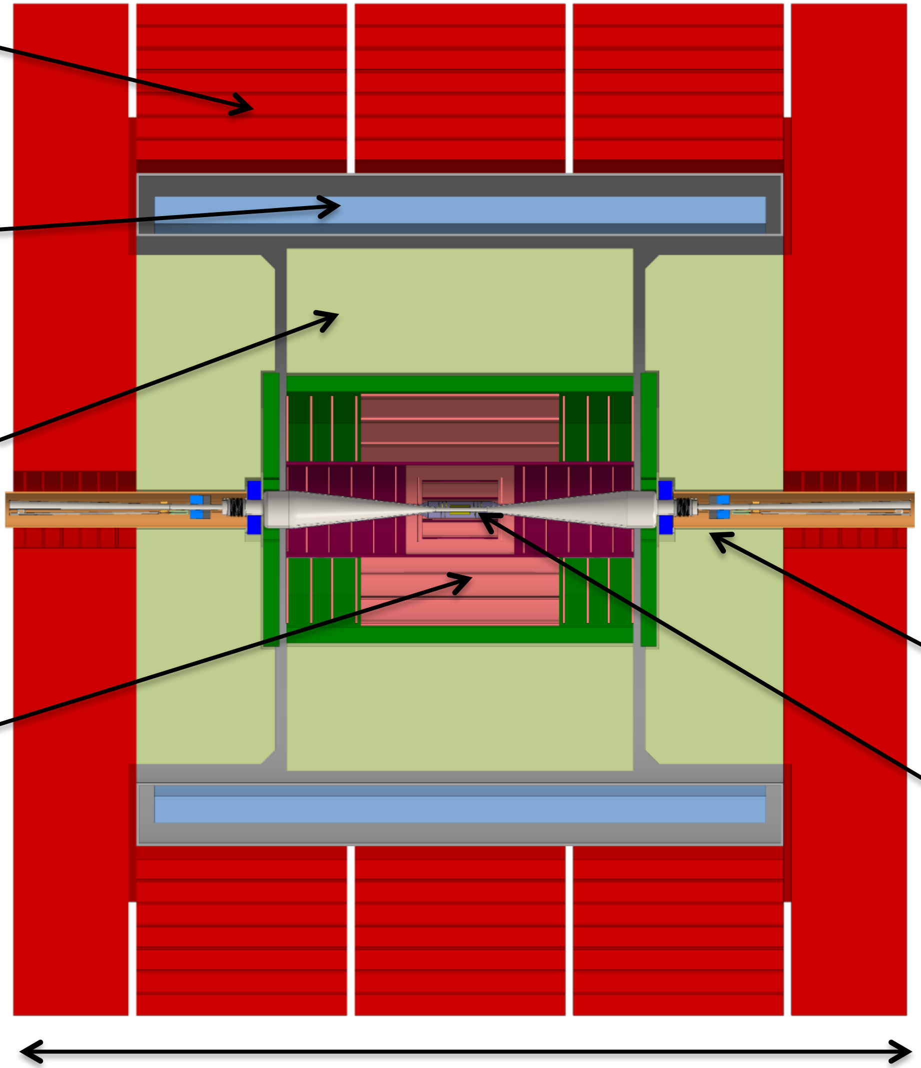
Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (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 Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ 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 Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

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

CERN-2012-007

the (new) CLIC detector model



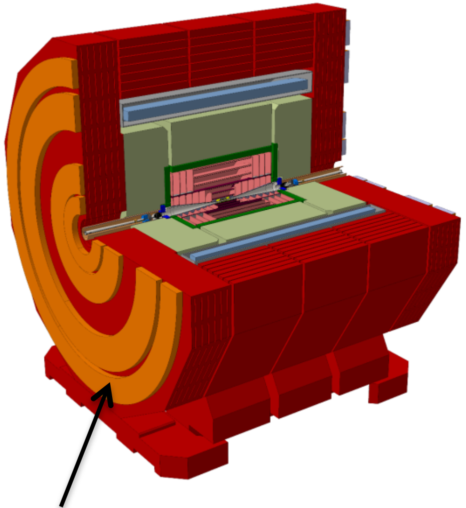
11.4 m

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

low-mass vertex detector, ~25 µm pixels

Note: final beam focusing is outside the detector

CLICdp–Note–2017–001

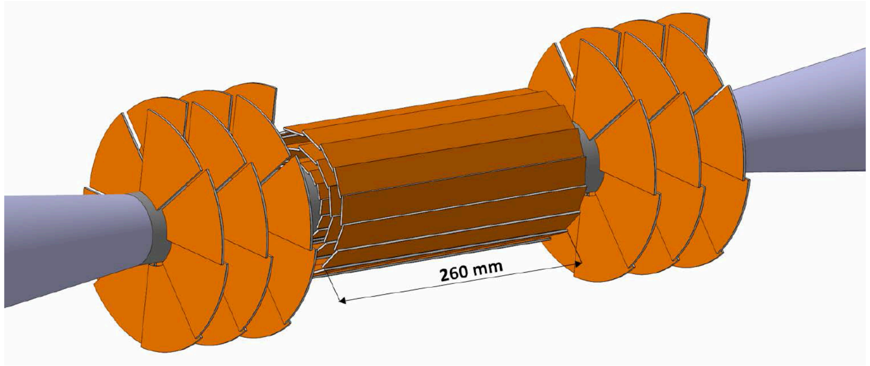
CLIC silicon pixel R&D (vertex and tracker)

Parameter	vertex	tracker
Hit position resolution (μm)	3	7
Time stamping (ns per slice)	10	10
Material per layer (X_0)	<0.2%	<1-1.5%
Silicon thickness (μm)	~100 (50+50)	~200
Power (mW/cm^2, incl. power pulsing)	<50	<150
Radiation level NIEL (n_{eq} cm^{-2}/yr)	$<4\times10^{10}$	$<10^{10}$
Radiation level TID (Gy/yr)	<200	<1

Performance requirements for the CLIC tracking system

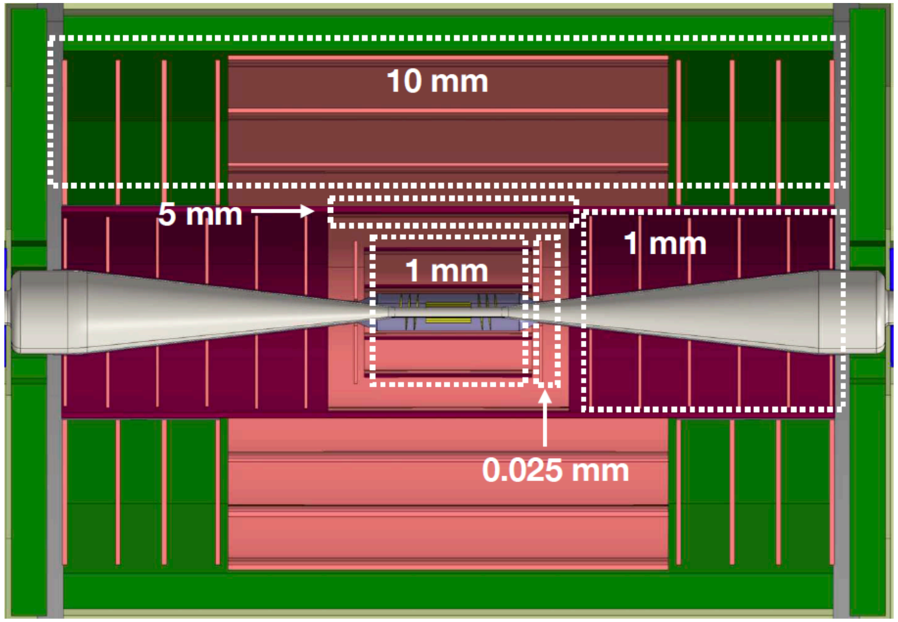
Layout of the CLIC tracker

maximum strip lengths indicated (assuming 50 μm strip width) taking into account occupancies from beam-induced background)



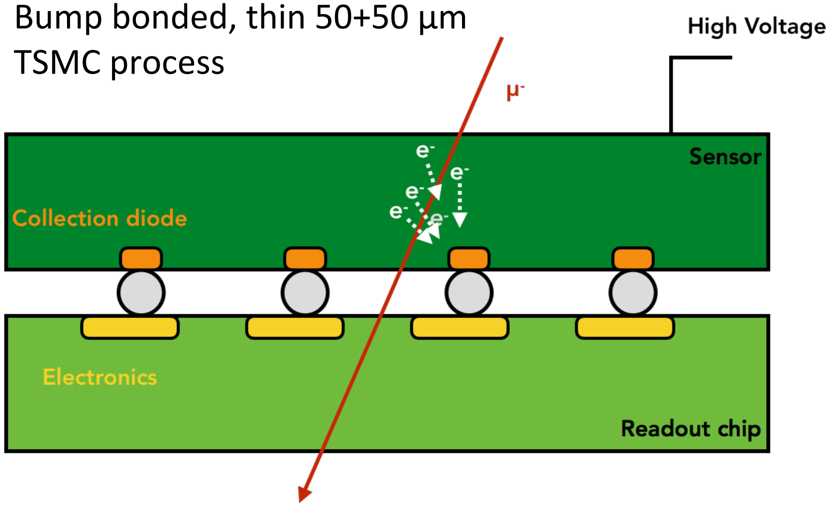
Layout of the CLIC vertex detector

(with spiraling discs for air cooling purposes)

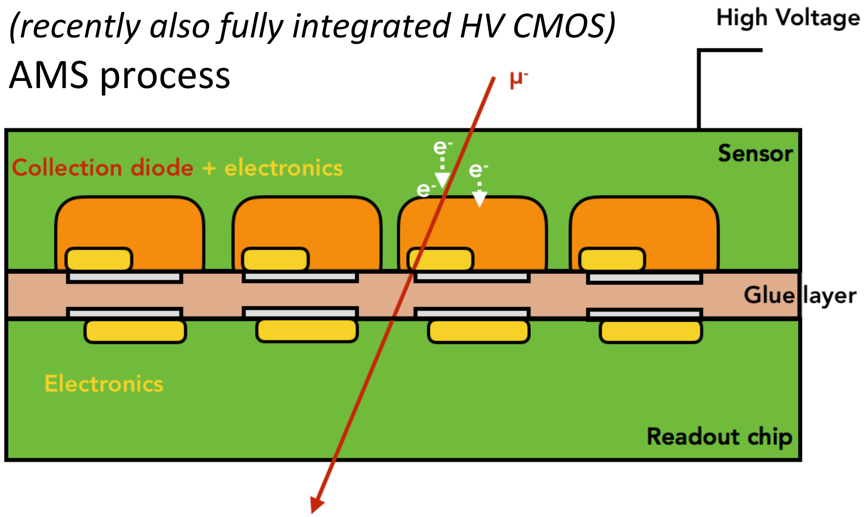


Si technologies pursued in CLIC R&D

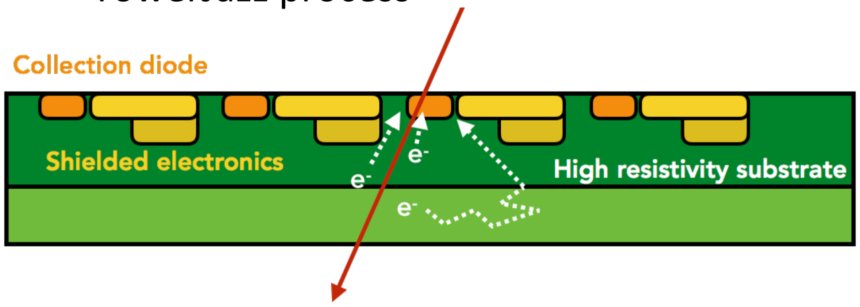
Hybrid: Si sensor + ASIC (65 nm)
Bump bonded, thin 50+50 μm
TSMC process



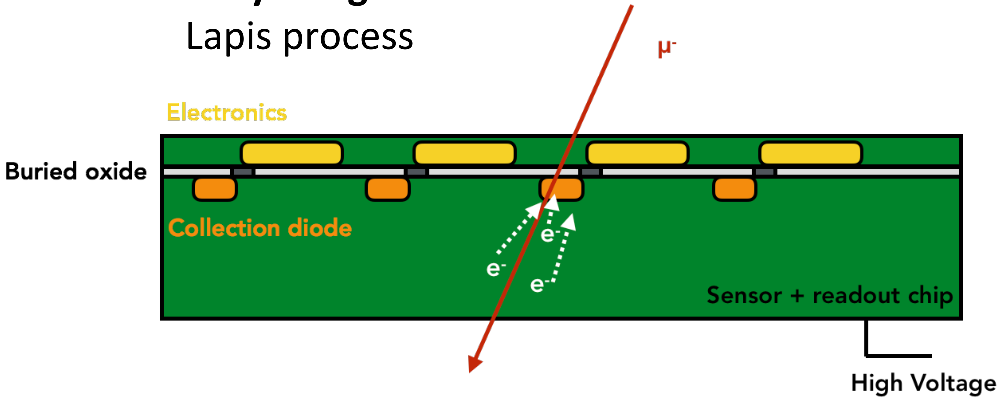
Hybrid: HV CMOS active sensor + ASIC (65 nm)
Capacitive coupling (glue)
(recently also fully integrated HV CMOS)
AMS process



Fully integrated: HR CMOS
TowerJazz process



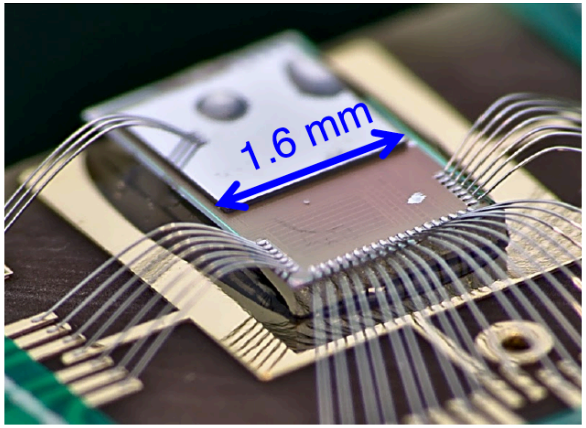
Fully integrated: SOI
Lapis process



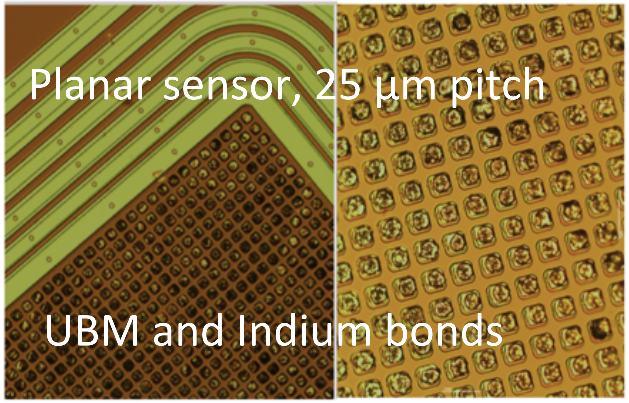
Systematics R&D studies have focused on Pixel implementation, with Pixel sizes around 25×25 μm^2
Studies equally valid for the main tracker, even though it will have larger cell sizes

CLIC silicon vertex and tracker R&D (1)

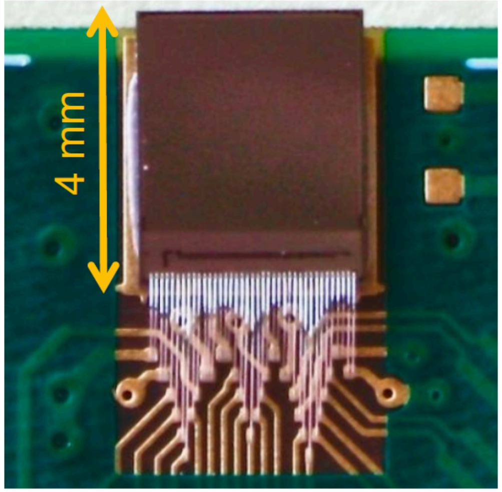
CLICpix (65 nm) + 50 µm sensor



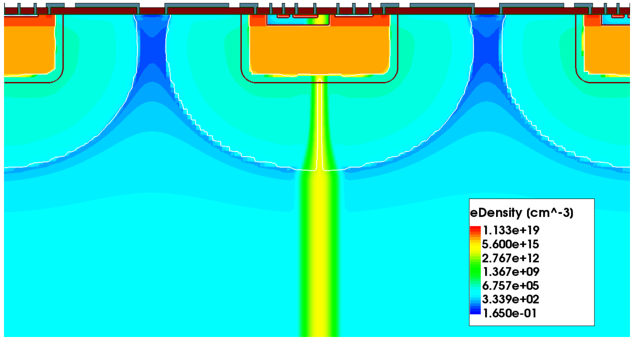
Bump-bonding, 25 µm pitch



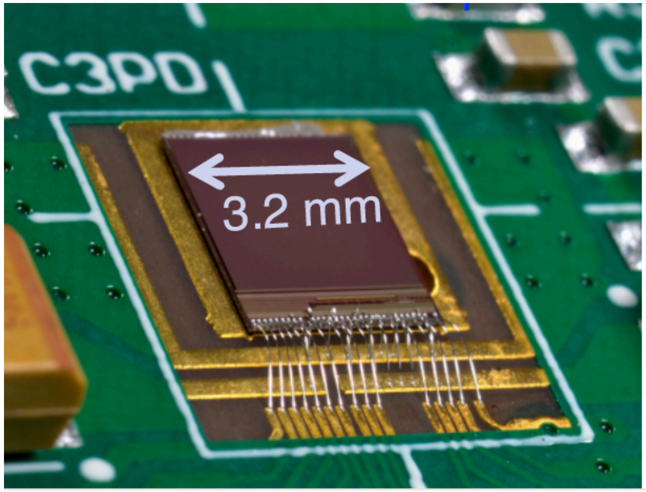
CLICpix2 ASIC (65 nm)



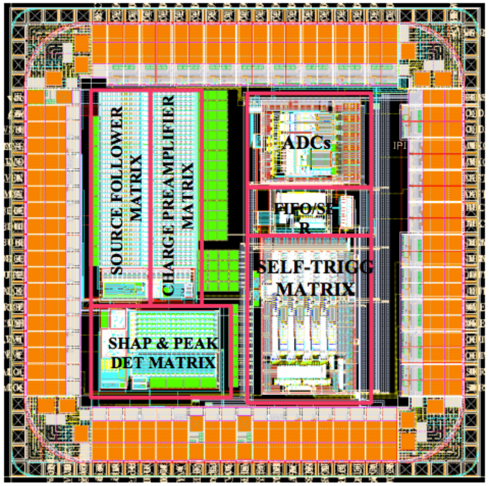
TCAD simulations, HV-CMOS sensor



C3PD HV-CMOS sensor, thinned 50 µm



SOI sensor design

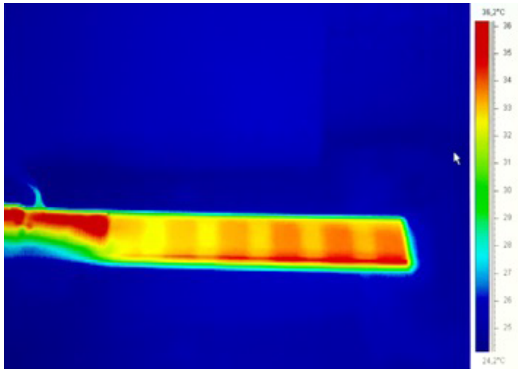


Recent presentation on vertex R&D

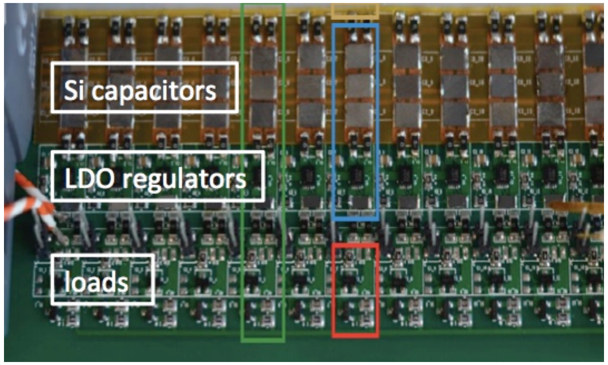
Recent presentation on tracker R&D

CLIC silicon vertex and tracker R&D (2)

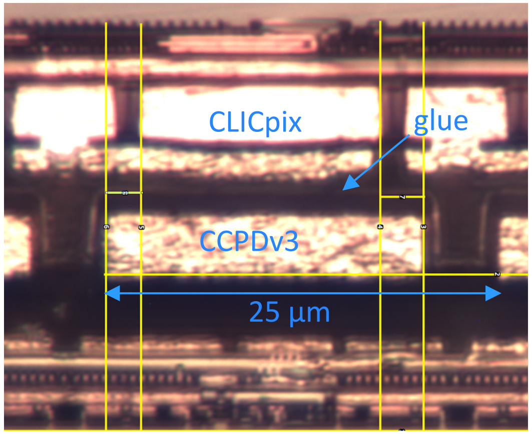
micro-channel cooling test

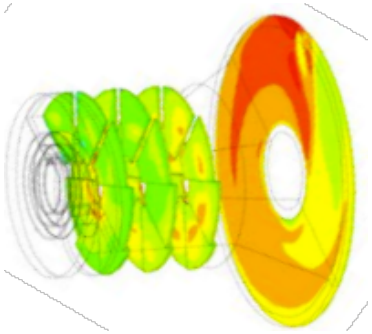


power delivery + pulsing

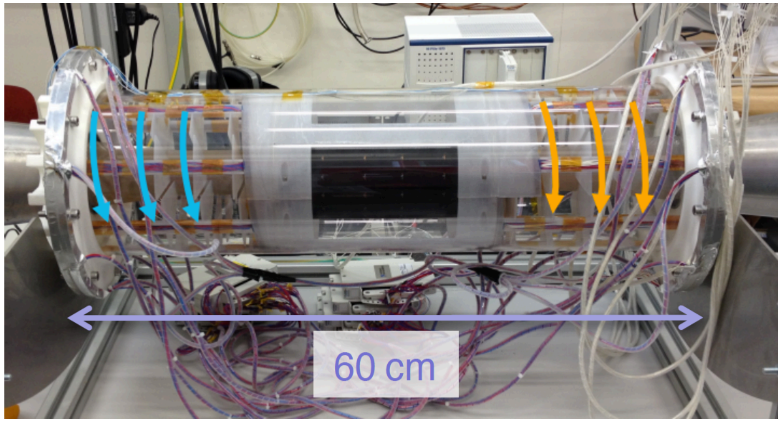


Flip-chip gluing (AC-coupling)

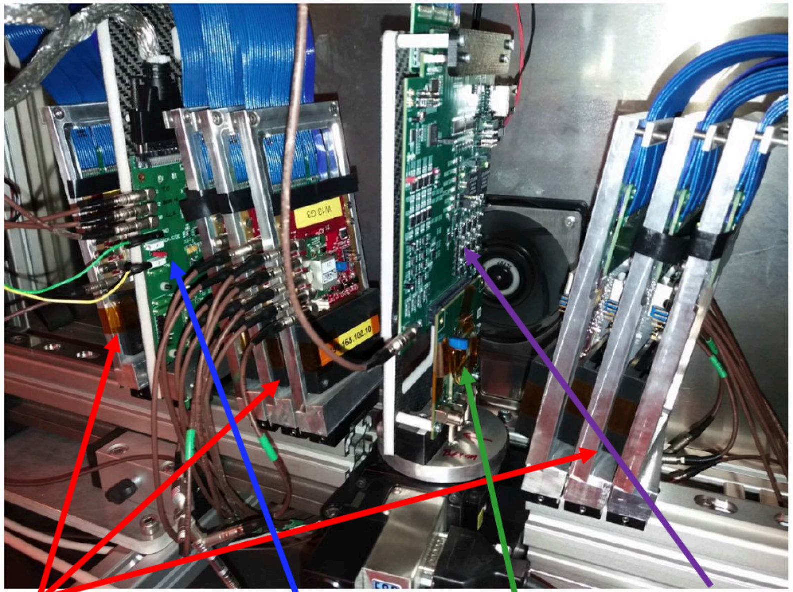




Air cooling simulation
and
1:1 scale test set up



SOI and C3PD+CLICpix2 in Timepix3 telescope at SPS



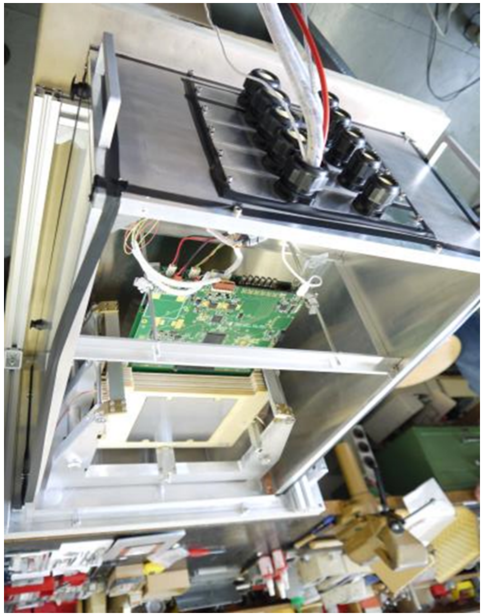
Fine-grained calorimetry

Fine-grained calorimetry: ECAL, HCAL, LumiCal, BeamCal
R&D for CLIC is carried out by the **CALICE** and **FCAL** collaborations

	layers	**cell sizes**	**active material**
ECAL	40	5×5 mm^2	silicon
HCAL	60	3×3 cm^2	scintillator+SiPM

	layers	**Θ mrad**	**active material**
LumiCal	40	38 - 110	silicon
BeamCal	40	10 - 40	GaAs (tbc)

Developments and beam tests of CMS HGCal are an important test bed for CLIC



FCAL calorimeter module

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

summary

CLIC offers a wealth of accurate e^+e^- physics measurements

"Affordable" first stage at 380 GeV with guaranteed physics

Upgradable up to 3 TeV

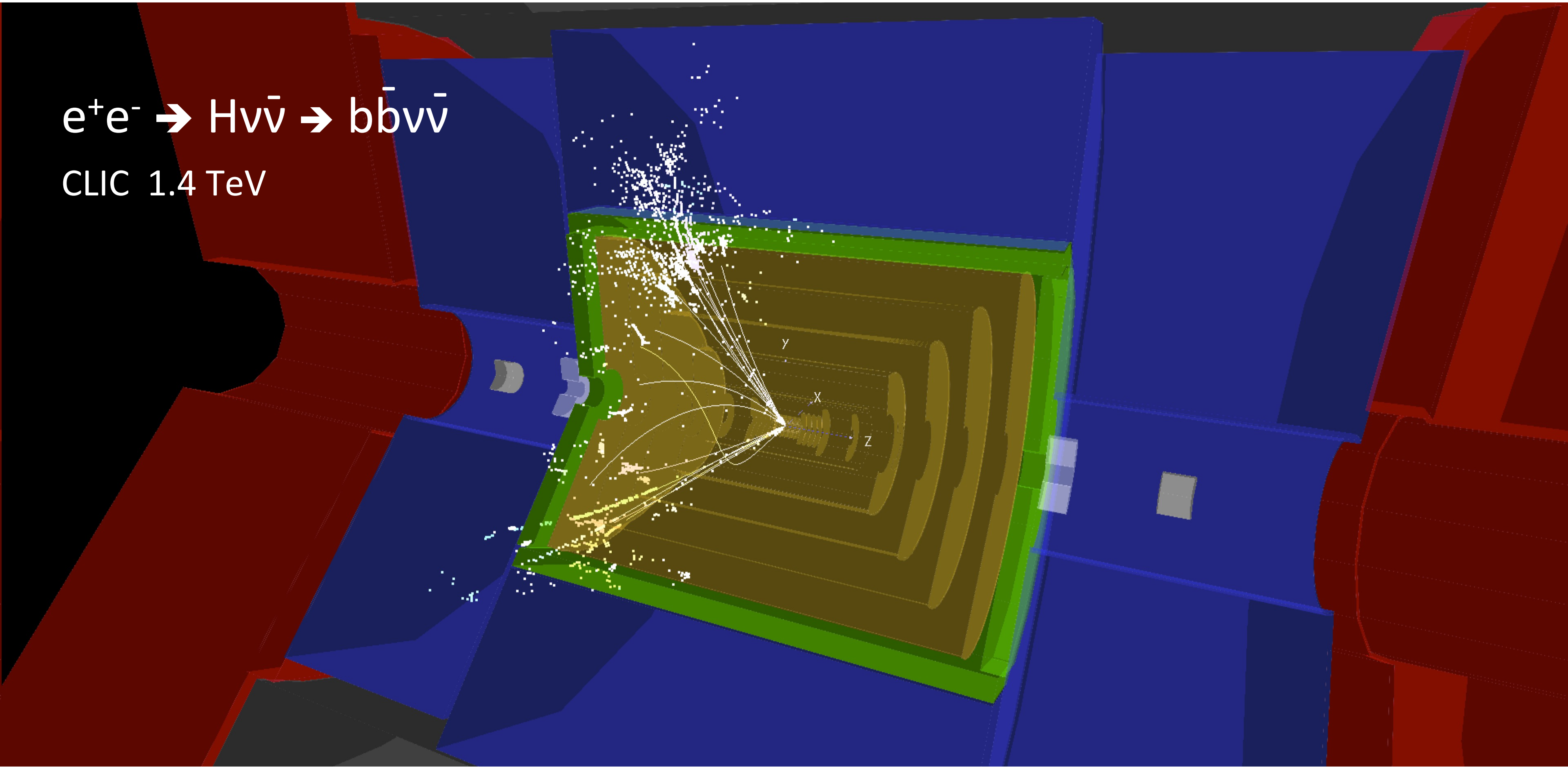
A powerful tool to address the open questions in particle physics

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

Welcome to join!

THANK YOU !



$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

CLIC 1.4 TeV

$H \rightarrow b\bar{b}$ (58% BR): selection efficiency ~40% (1.4 TeV), ~50% (380 GeV)

RESERVE SLIDES

CLICdp documents in preparation for next European Strategy

CLICdp reports serving as ingredients for a CLIC(dp) summary report:

- **Updated Baseline for a Staged Compact Linear Collider** (380 GeV, 1.5 TeV, 3 TeV) ✓
  - arXiv:1608.07537, CERN-2016-004
- **Higgs Physics at the CLIC Electron-Positron Linear Collider** ✓
  - arXiv:1608.07538, Eur. Phys. J. C77 (2017) no.7, 475
- **The new optimised CLIC detector model CLICdet** ✓✓
  - CLICdp note CLICdp_Note_2017_001 (detector/SW validation in progress)
- **Overview of CLIC top physics**
  - CLIC top physics publication => complete draft before the end of 2017
- **Extended BSM studies**
  - CLIC BSM overview publication in 2018
- **CLIC R&D report** => with main CLIC technology demonstrators
  - Summary publication(s) in 2018
- **Plan for the period ~2019-2025** in case CLIC would be supported by next strategy

Common CLIC accelerator + CLICdp summary report is under discussion

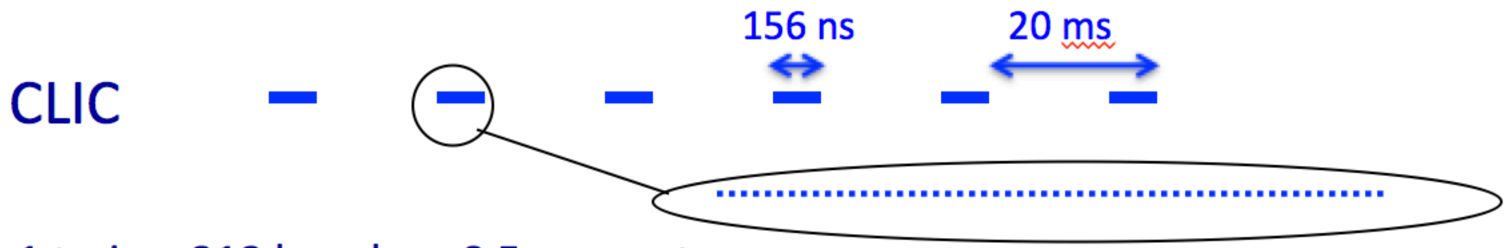
CLIC accelerator parameters

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

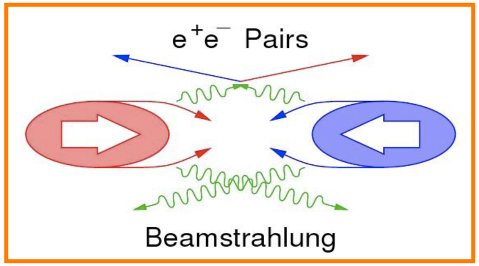
**scaled from CDR, with room for improvement*



1 train = 312 bunches, 0.5 ns apart

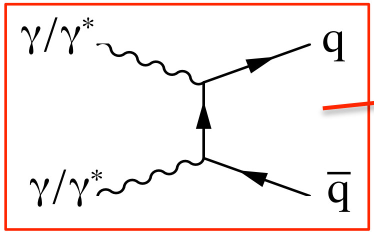
- not to scale -

CLIC accelerator environment

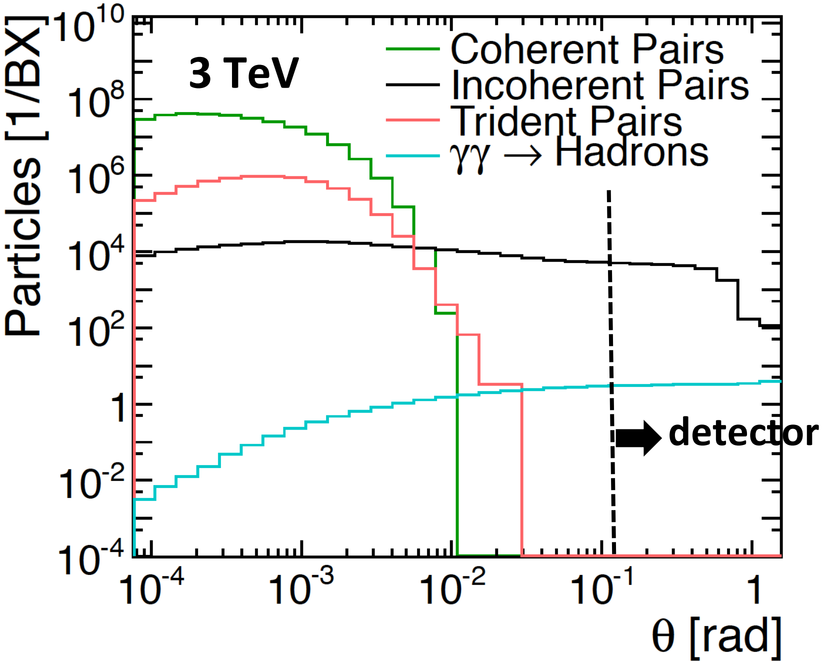


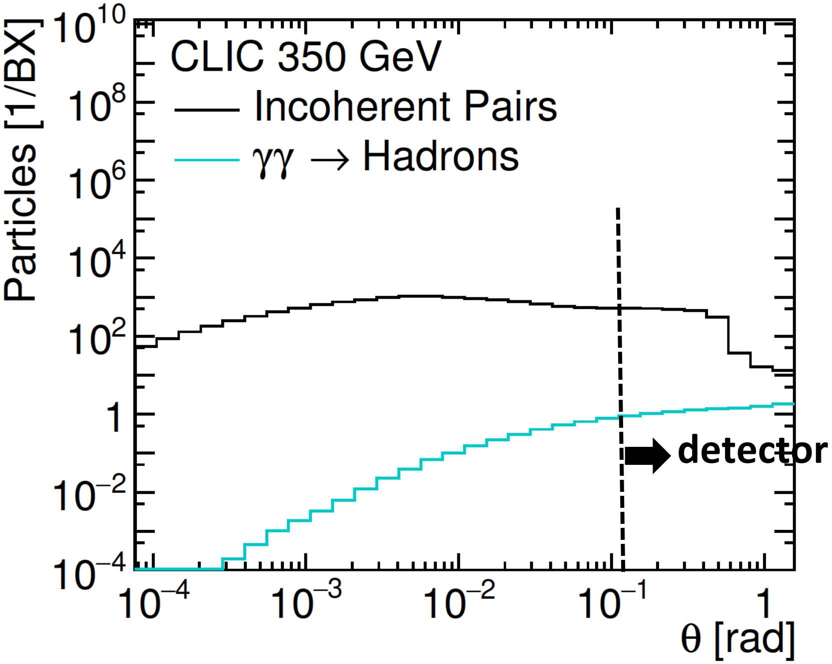
Beam-beam background at IP:

- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background** → Simplified picture: **Design issue** (small cell sizes)
    - High occupancies

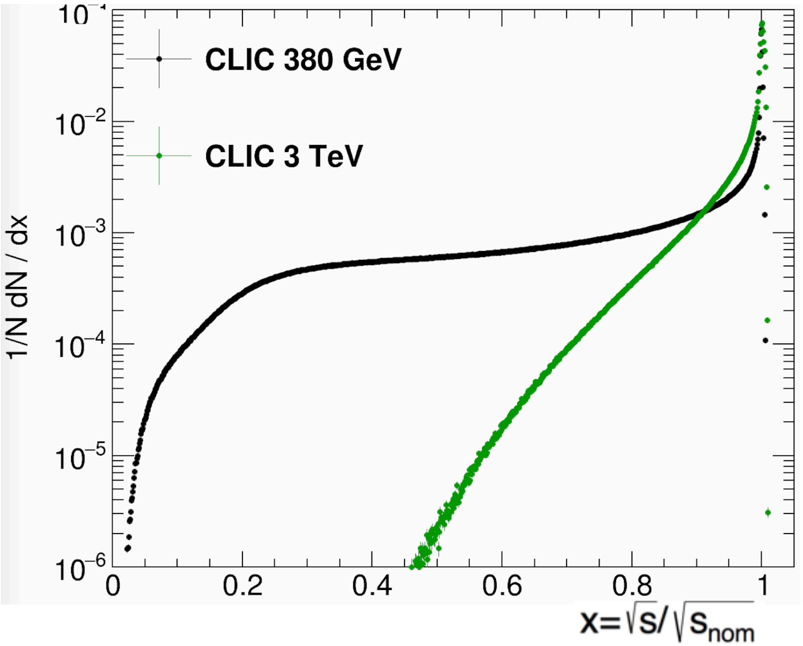


  - **γγ to hadrons** → Impacts on the physics **Needs suppression in data**
    - Energy deposits





luminosity spectrum



Beamstrahlung ➔ important energy losses right at the interaction point

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

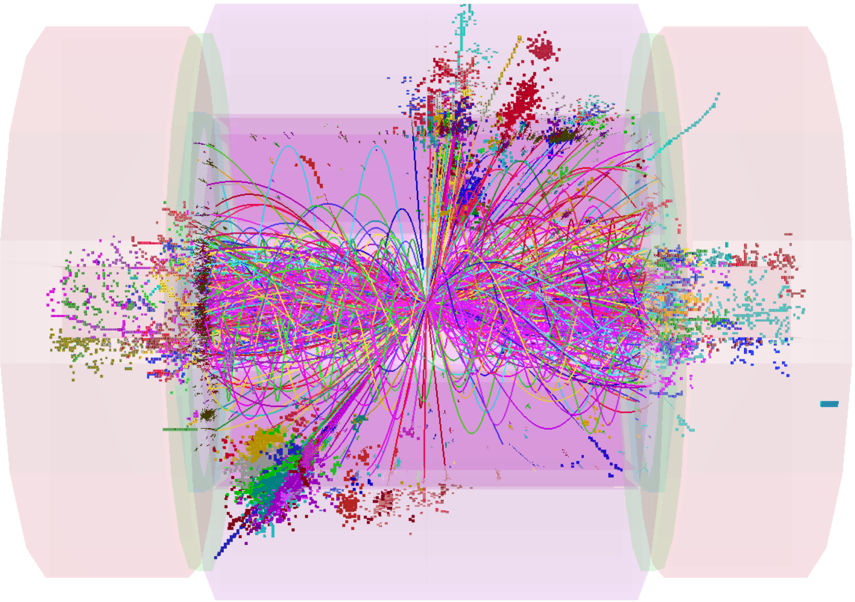
Luminosity spectrum can be measured in situ using large-angle Bhabha scattering events, to 5% accuracy at 3 TeV
Eur.Phys.J. C74 (2014) no.4, 2833

Fraction $\sqrt{s}/\sqrt{s_{nom}}$	**380 GeV**	**3 TeV**
>0.99	63%	36%
>0.9	91%	57%
>0.8	98%	68%
>0.7	99.5%	77%
>0.5	~100%	88%

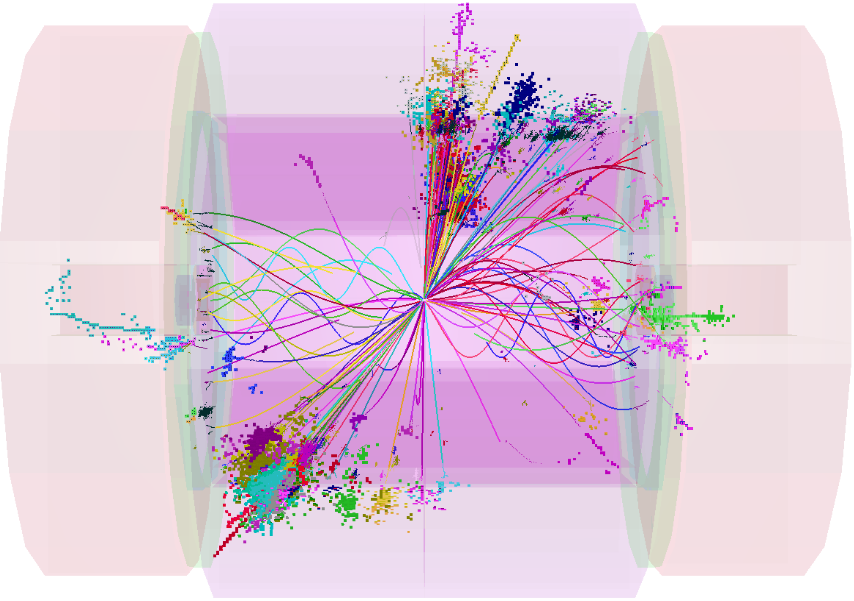
beam-induced background rejection (1)

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

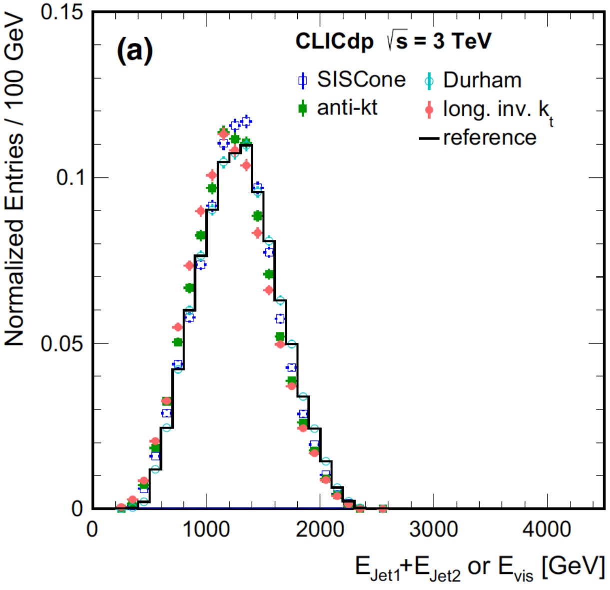
100 GeV background after tight cuts

beam-induced background rejection (2)

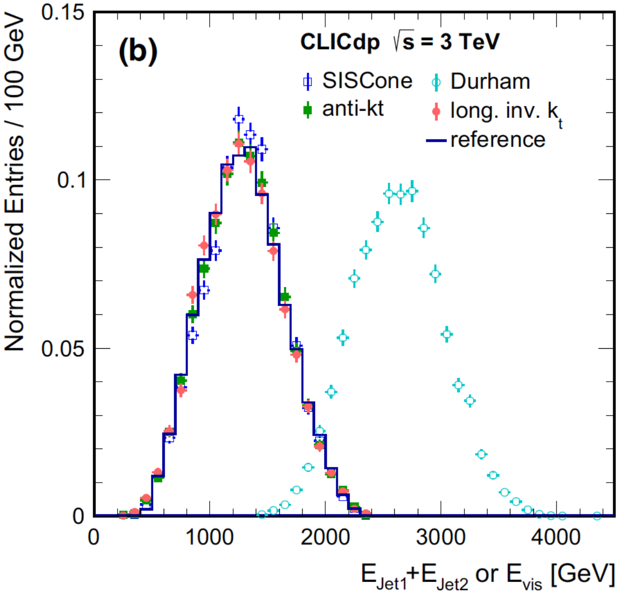
Beam-induced background from γγ ➔ hadrons is further reduced by applying **adapted jet reconstruction algorithms**

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

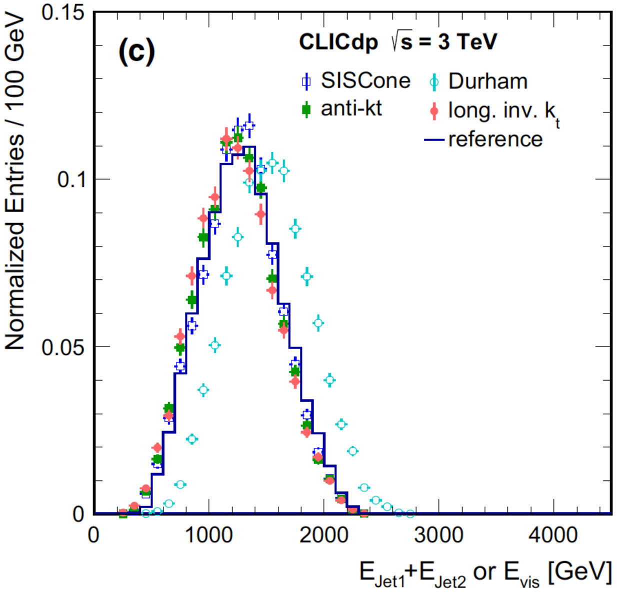
$$e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$$



No γγ ➔ hadrons background



With γγ ➔ hadrons bkg from 60 bunch crossings

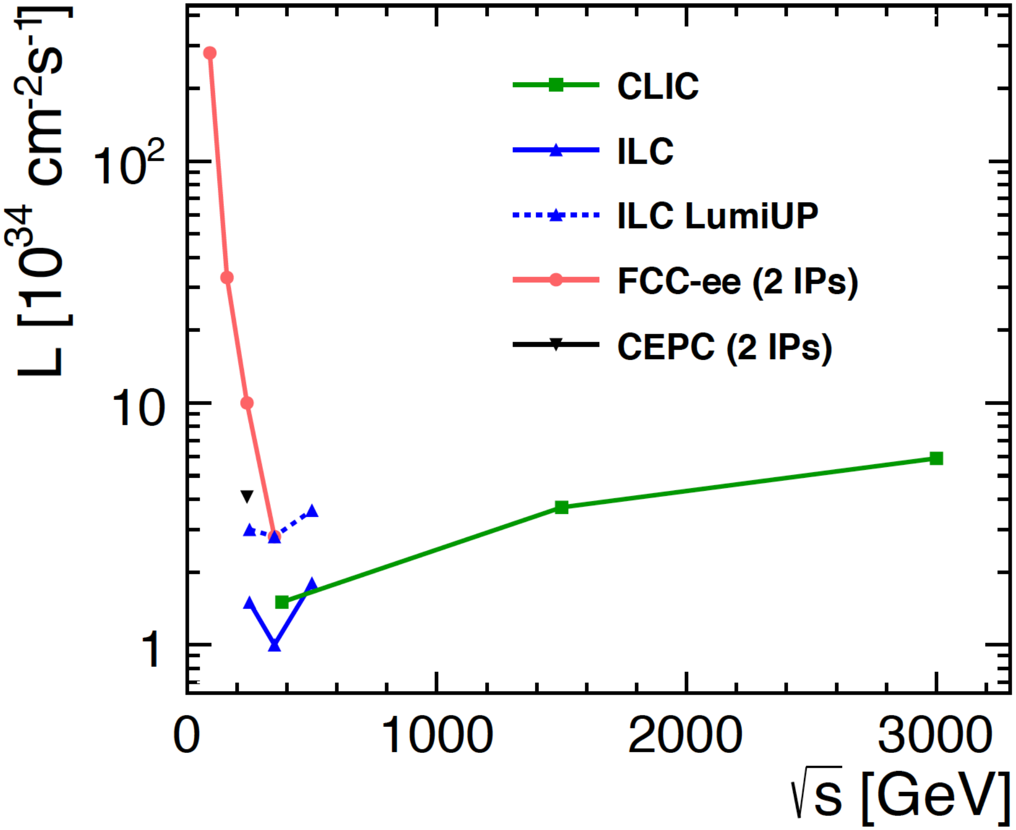


With γγ ➔ hadrons bkg from 60 bunch crossings + use of p_t and timing cuts

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

luminosity performance e^+e^- colliders



Linear colliders:

- Can reach much higher energies
- Luminosity rises with energy
- Beam polarisation at all energies

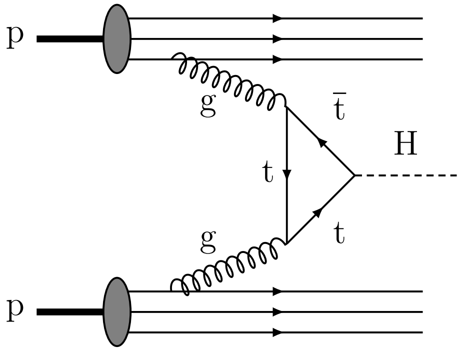
Circular colliders:

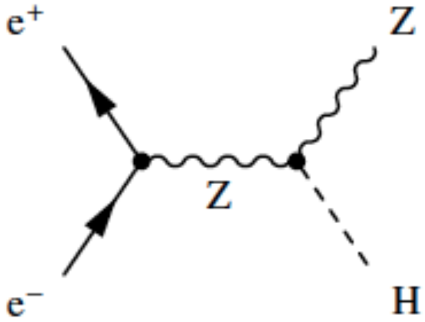
- Huge luminosity at lower energies
- Luminosity decreases with energy

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

pp collisions / e^+e^- collisions

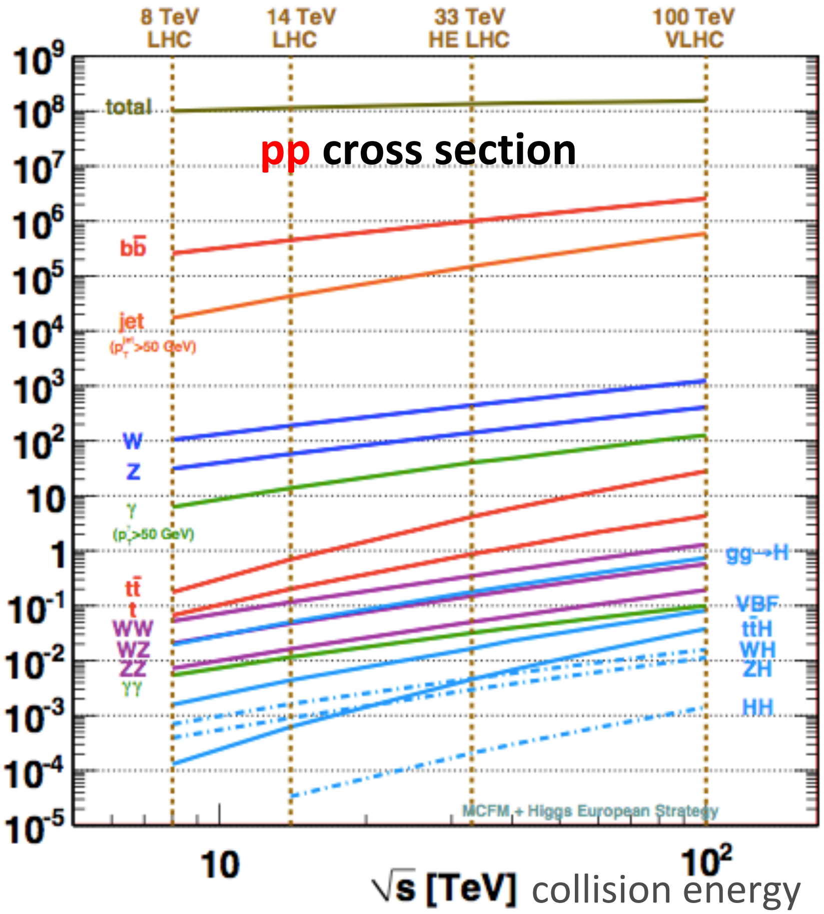
to tackle the open questions in particle physics





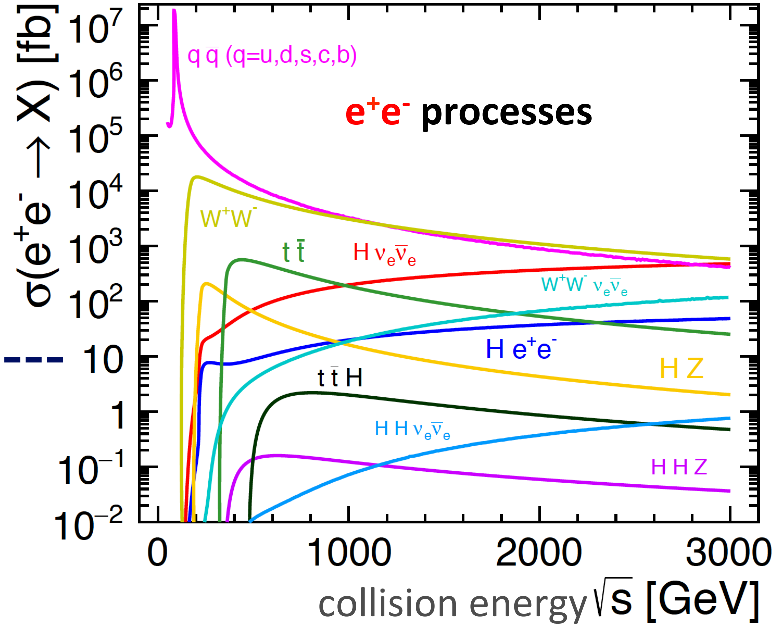
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state unknown → Limits achievable precision	**e^+/e^- are point-like** → Initial state well defined (√s / opt: polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Less / no need for triggers → Lower radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
Very high-energy **circular** pp colliders feasible	High energies (>≈350 GeV) require **linear** collider

pp collisions / e^+e^- collisions



factor > 10^8

pp and e^+e^- collisions provide complementary physics information => important for our field to have both !



- Interesting **pp** events need to be found within a huge number of collisions

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

CLIC detector requirements (from physics)

- ★ **momentum resolution:**

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

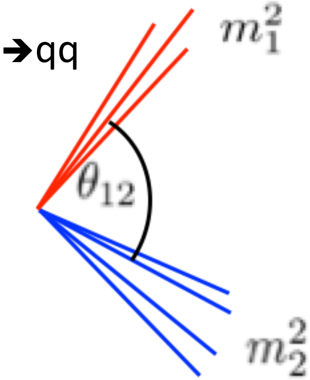
$$\boxed{\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\,\mathrm{GeV}^{-1}}$$

- ★ **jet energy resolution:**

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

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

(for high-E jets, light quarks)



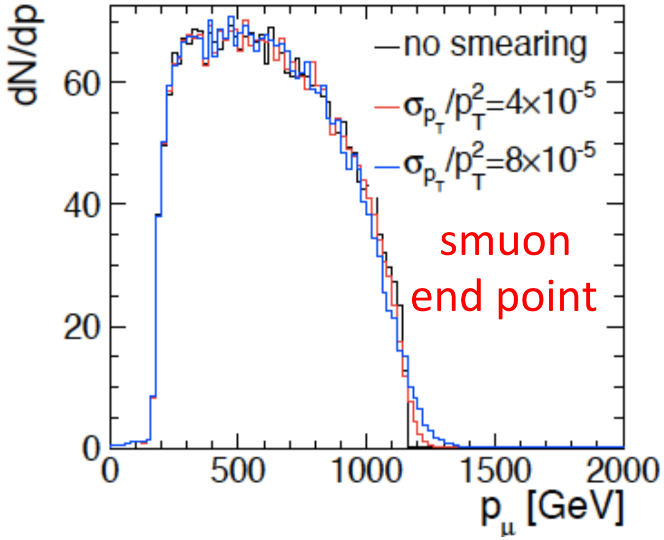
- ★ **impact parameter resolution:**

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

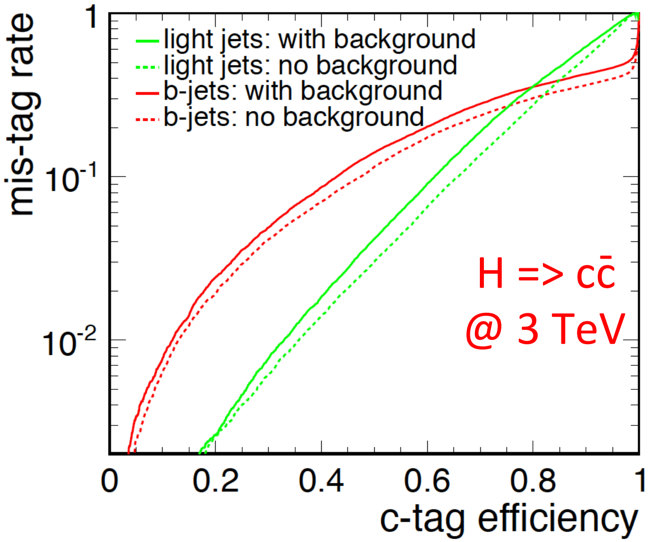
$$\boxed{\sigma_{r\phi} = 5 \oplus 15/(p[\mathrm{GeV}]\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

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

\+ requirements from CLIC experimental conditions



smuon
end point

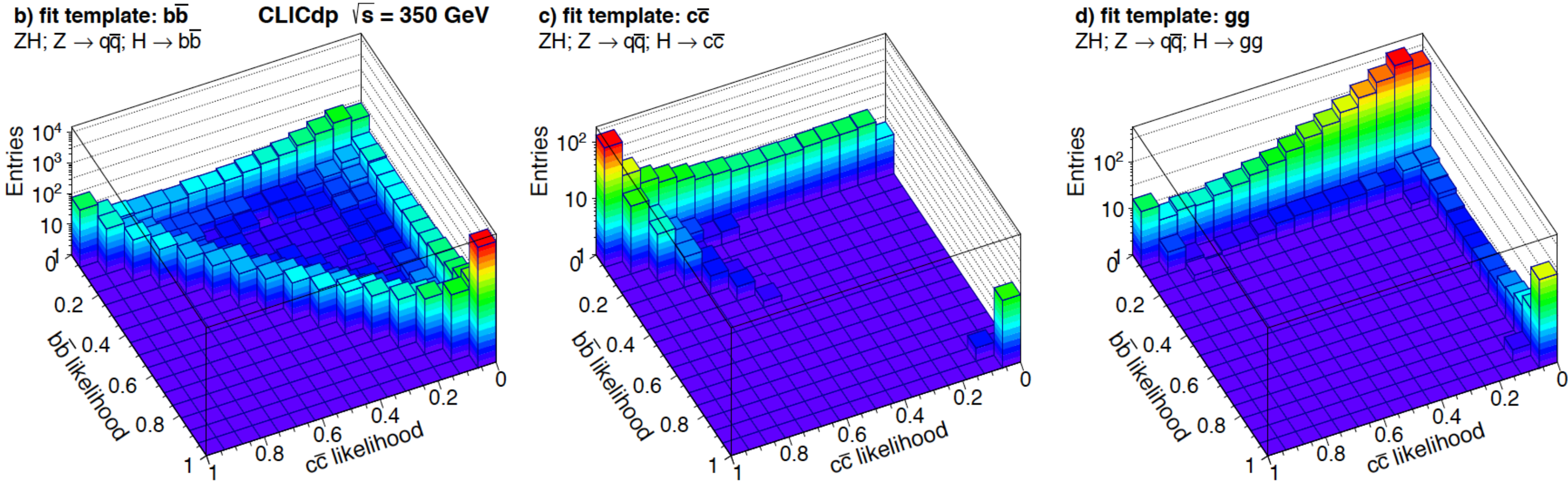


H => $c\bar{c}$
@ 3 TeV

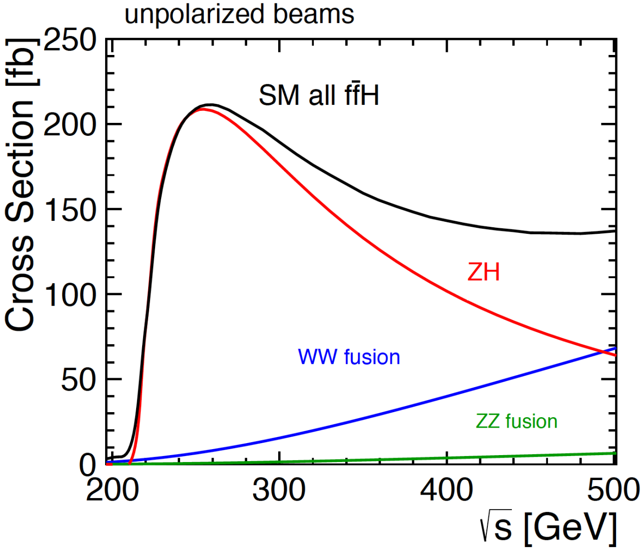
simultaneous extraction H => bb,cc,gg @ 350 GeV

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

H ➔ $b\bar{b}$ H ➔ $c\bar{c}$ H ➔ gg



arXiv:1608.07538

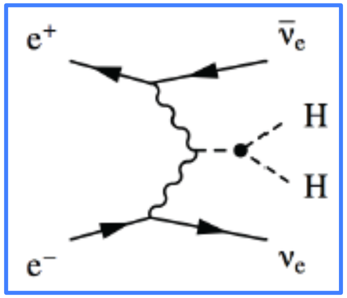


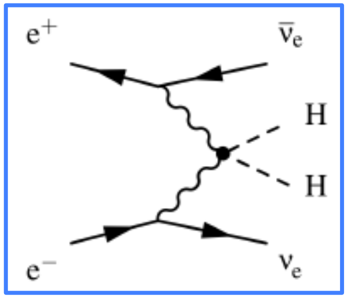
Simultaneous extraction of 2 production and 3 decay modes

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

Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \to b\bar{b}$	0.86 %	1.9 %
$H \to c\bar{c}$	14 %	26 %
$H \to gg$	6.1 %	10 %

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**

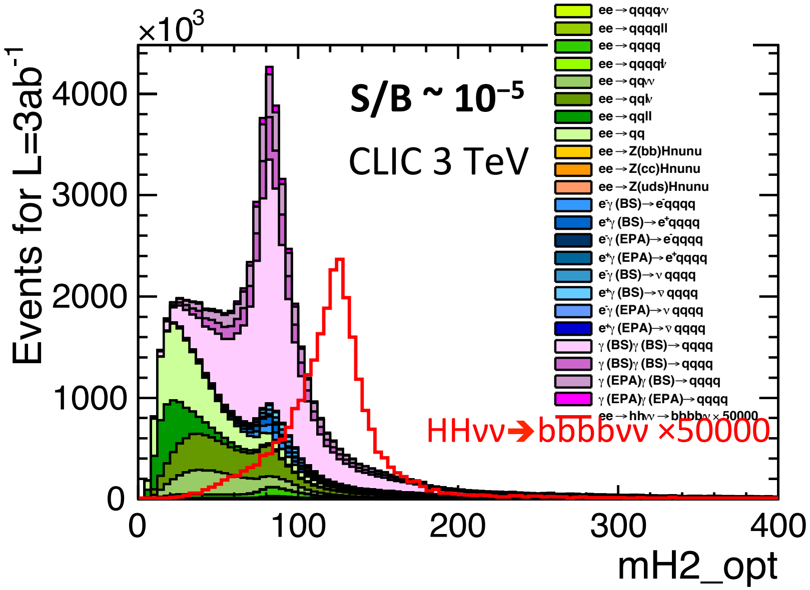
*Most promising final states: bbbbνν and bbWW*νν*

Recent re-analysis including key additional background processes:

Assuming -80% e^- polarisation:

- at 1.4 TeV, 1.5 ab^{-1} $\Delta g_{HHH}/g_{HHH}$ ±40%
- at 3 TeV, 2 ab^{-1} $\Delta g_{HHH}/g_{HHH}$ ±22%
- => combined: $\Delta g_{HHH}/g_{HHH}$ ±19%

arXiv:1608.07538



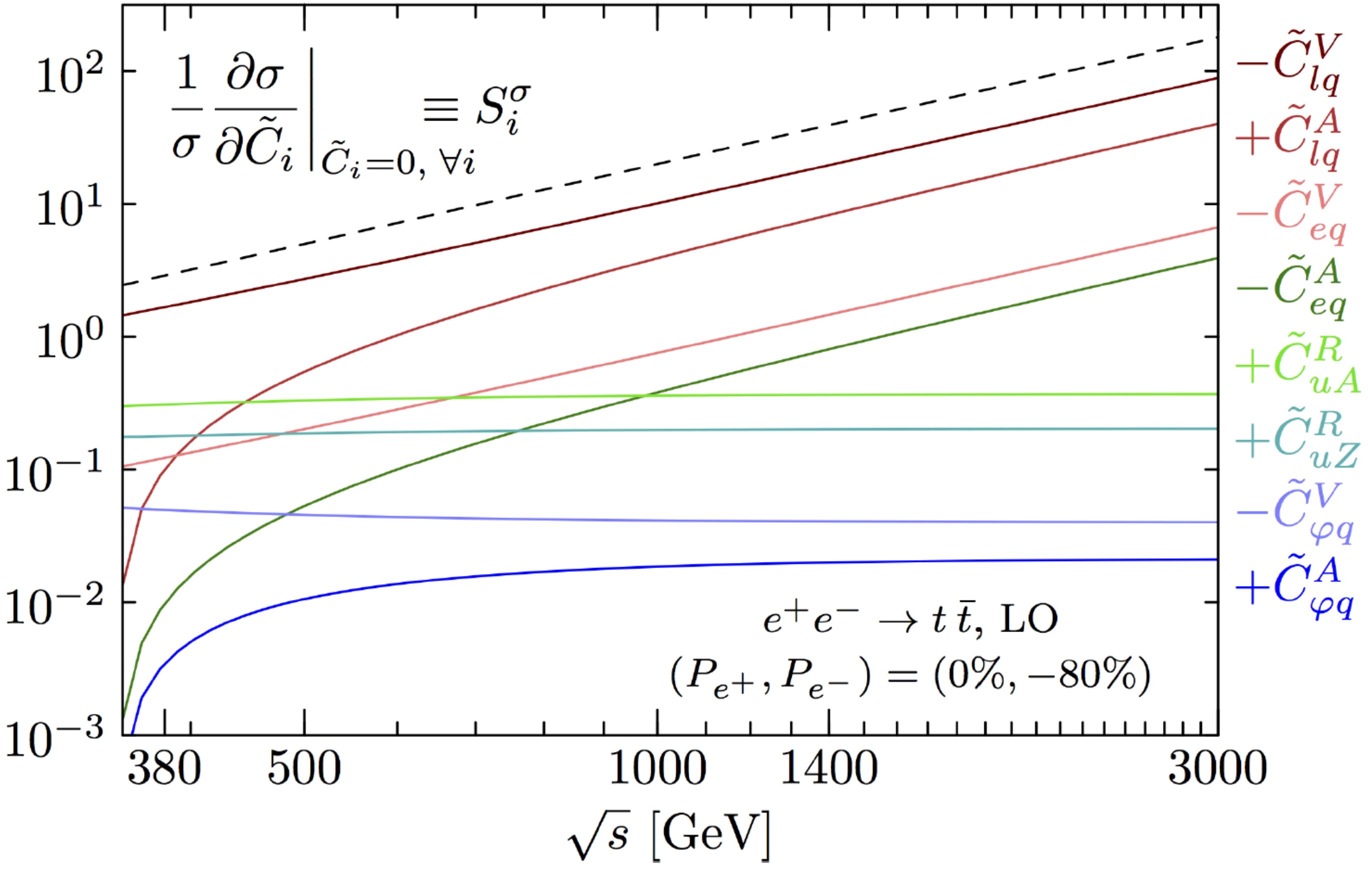
Ongoing: simultaneous extraction Δg_{HHH} and Δg_{WWHH}
Using kinematic variables => improved result

Expected combined $\Delta g_{HHH}/g_{HHH}$ ≈ ±12% for 3 ab^{-1}

work in progress

electroweak couplings to top at high √s

Studied at generator level in a *dimension-6 operator approach* (instead of Form Factor approach)



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

Vertex operators:
Sensitivity flat in E
→ best measured at 380 GeV stage
(most tt events)

Durieux, Perello, Vos, Zhang to be published

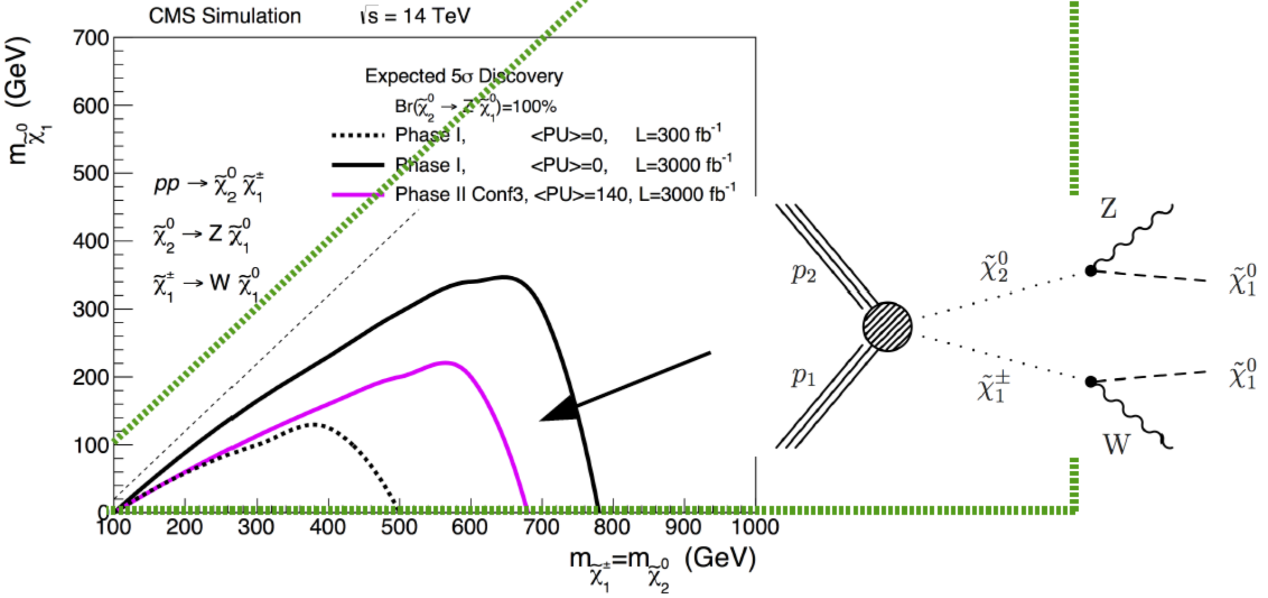
=> Full detector simulation studies of $t\bar{t}$ production at 1.4 TeV, 3 TeV are ongoing

heavy electroweak states (1)

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

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

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



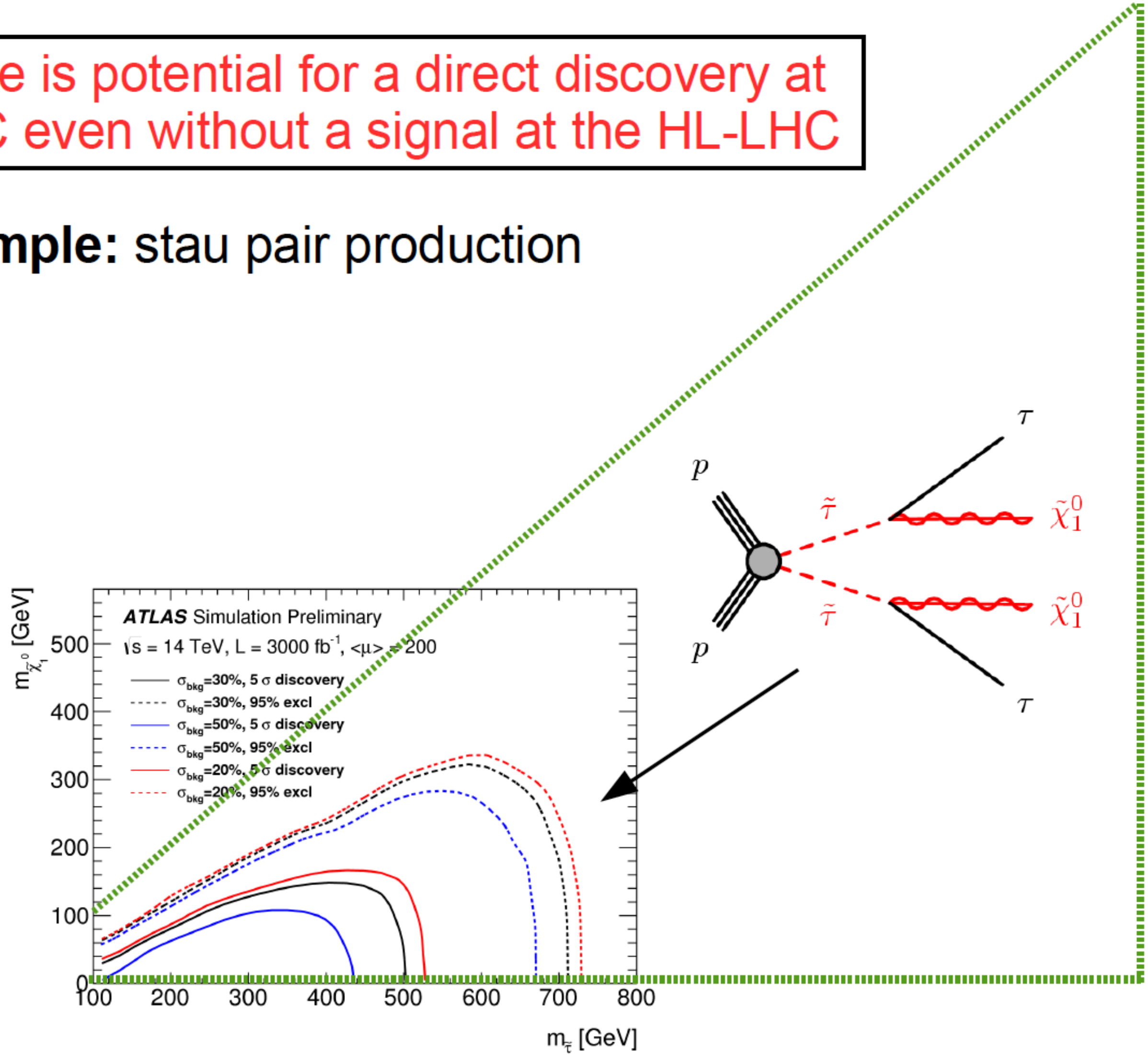
CMS-PAS-FTR-13-014

(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 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.

Higgs Global Fit: Effect of Theory Uncertainties

MD fit w/o theory uncertainties

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
κ_{HZZ}	0.6 %	0.4 %	0.3 %
κ_{HWW}	1.1 %	0.2 %	0.1 %
κ_{Hbb}	1.8 %	0.4 %	0.2 %
κ_{Hcc}	5.8 %	2.1 %	1.7 %
$\kappa_{H\tau\tau}$	3.9 %	1.5 %	1.1 %
$\kappa_{H\mu\mu}$	–	14.1 %	7.8 %
κ_{Htt}	–	4.1 %	4.1 %
κ_{Hgg}	3.0 %	1.5 %	1.1 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	3.1 %
$\kappa_{HZ\gamma}$	–	15.6 %	9.1 %
$\Gamma_{H,\text{md, derived}}$	1.4 %	0.4 %	0.3 %

MD fit with theory uncertainties

κ_{HZZ}	0.6 %	0.5 %	0.5 %
κ_{HWW}	1.2 %	0.5 %	0.5 %
κ_{Hbb}	2.6 %	1.5 %	1.4 %
κ_{Hcc}	6.3 %	3.2 %	2.9 %
$\kappa_{H\tau\tau}$	4.2 %	2.1 %	1.8 %
$\kappa_{H\mu\mu}$	–	14.2 %	7.9 %
κ_{Htt}	–	4.2 %	4.1 %
κ_{Hgg}	5.1 %	4.0 %	3.9 %
$\kappa_{H\gamma\gamma}$	–	5.9 %	3.5 %
$\kappa_{HZ\gamma}$	–	16.0 %	9.8 %
$\Gamma_{H,\text{md, derived}}$	2.0 %	1.1 %	1.1 %

decay mode	theo. uncertainty
ZZ	2.1 %
WW	2.1 %
γγ	2.8 %
Zγ	6.8 %
bb	1.8 %
cc	4.6 %
gg	7.2 %
ττ	2.3 %
μμ	2.4 %

- Uncertainties from LHCHXSWG, combined theory and parametric (quark mass, α_s) uncertainties, symmetrized to preserve fit means

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.

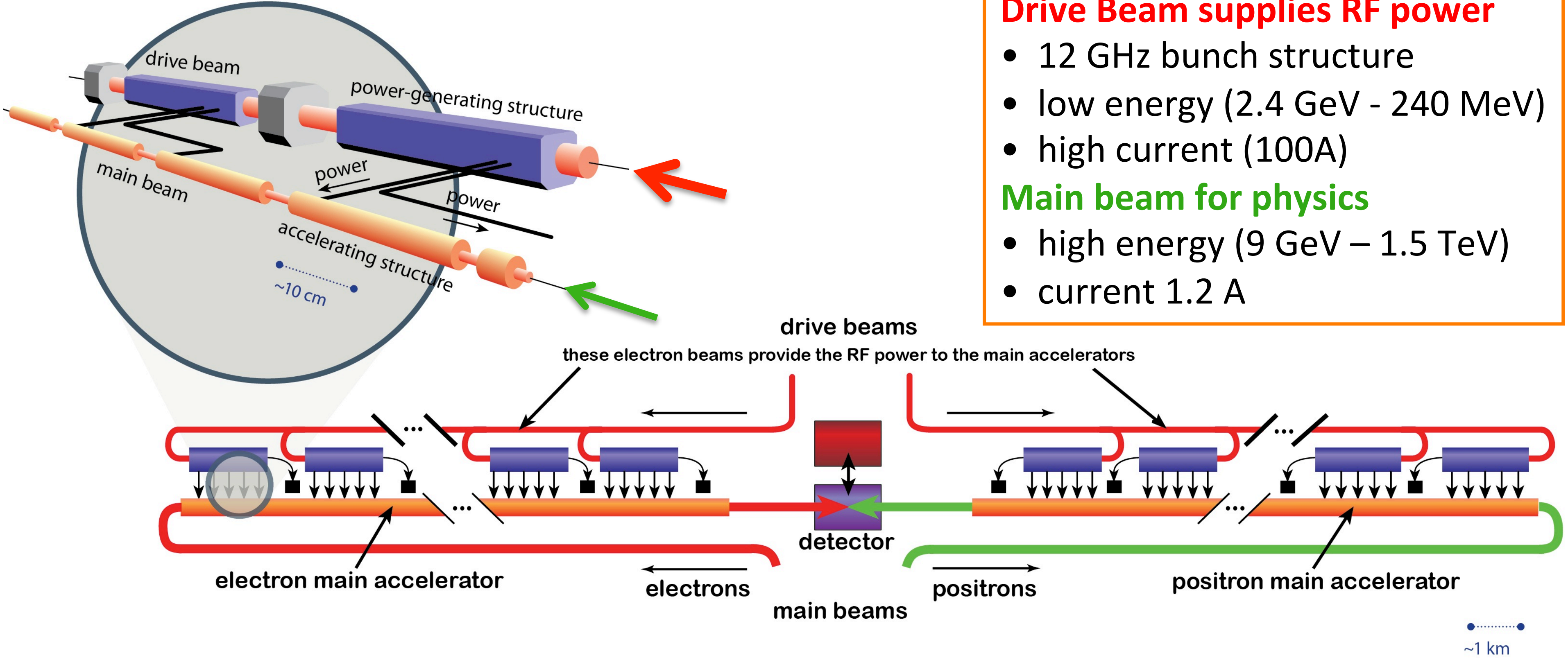
CLIC uses a 2-beam acceleration scheme at 12 GHz, gradient of 100 MV/m

Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

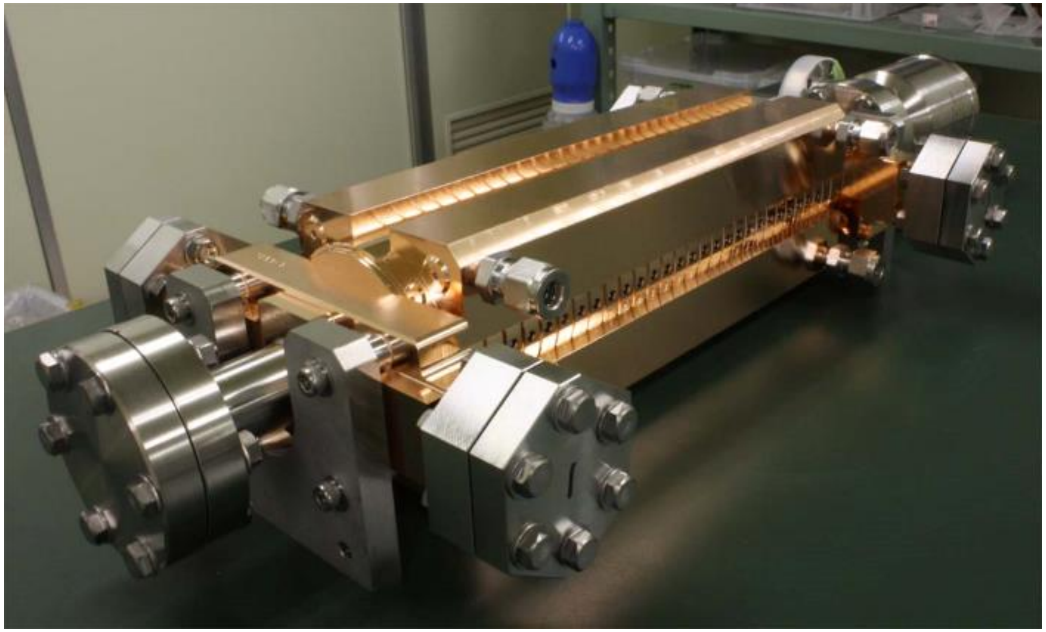
Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



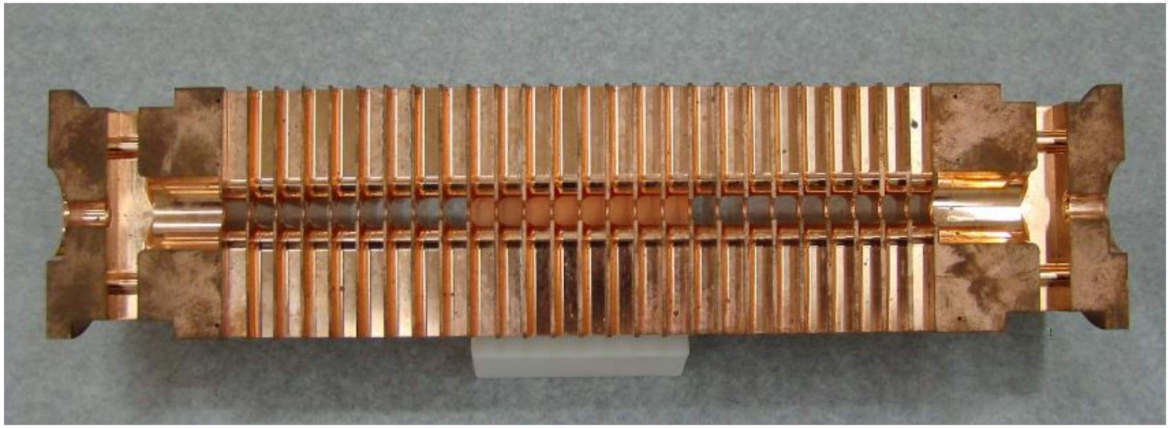
CLIC accelerator structure

Outside



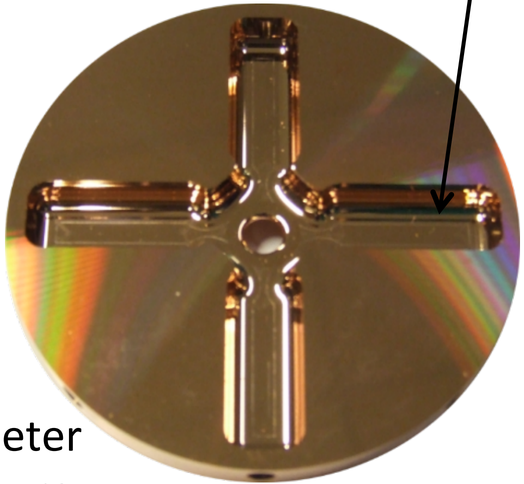
11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

Inside



25 cm

Micron–precision disk

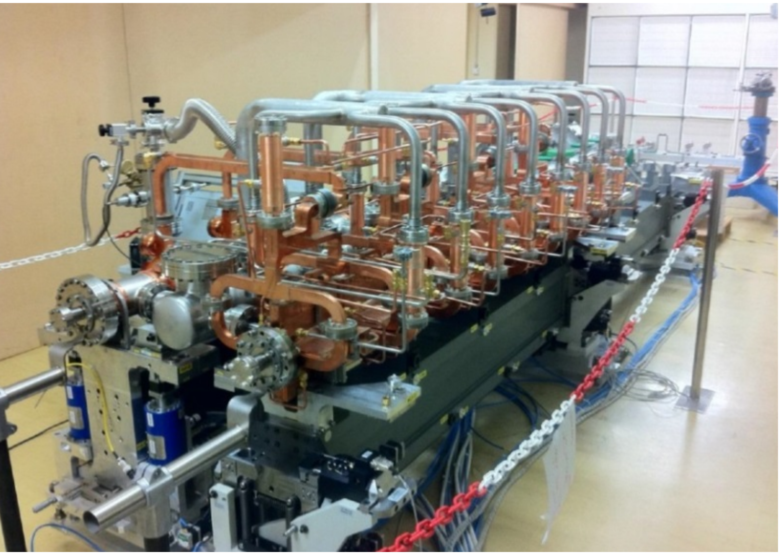


HOM damping waveguide

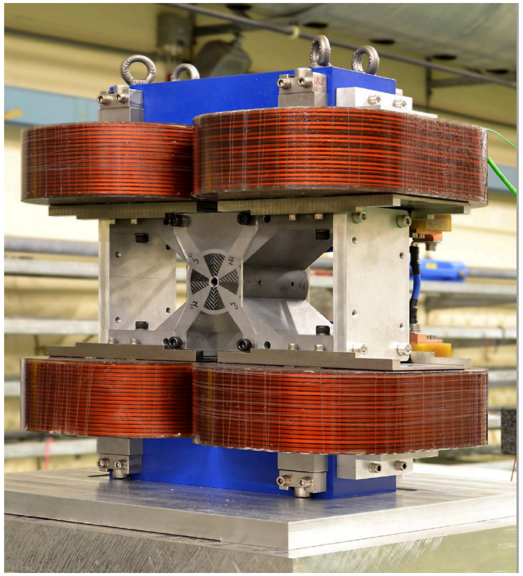
6 mm diameter beam aperture

CLIC accelerator, some pictures

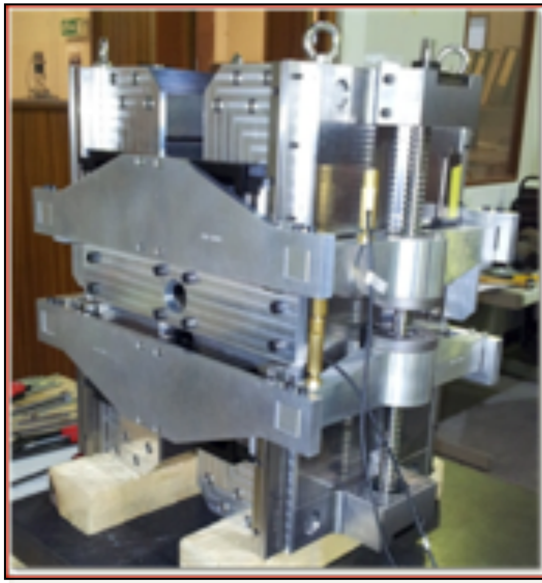
CLIC mechanical tests of 2-beam module



prototype final focus quadrupole

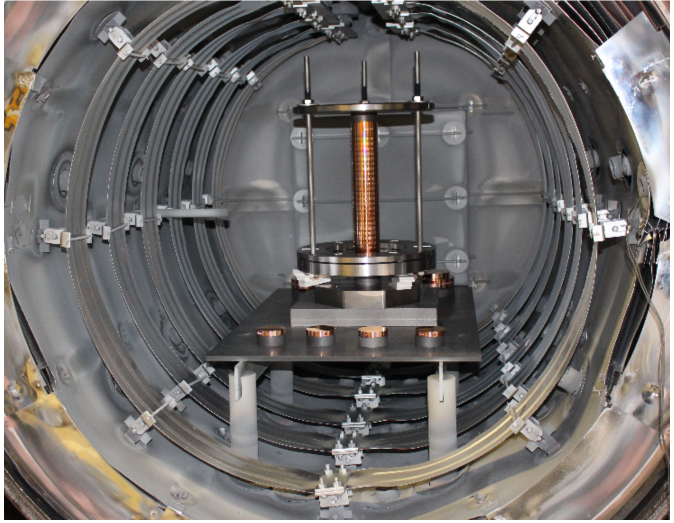


tunable permanent magnet



accelerator structure, 1 disk

brazing of a CLIC structure



cut through a CLIC acceleration structure

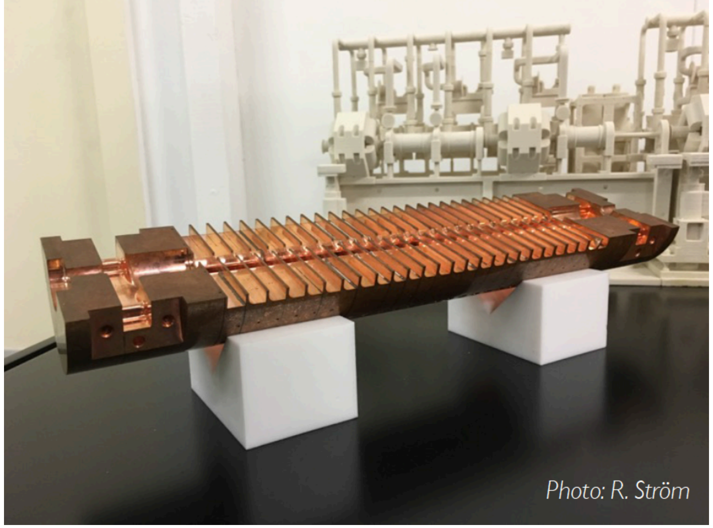


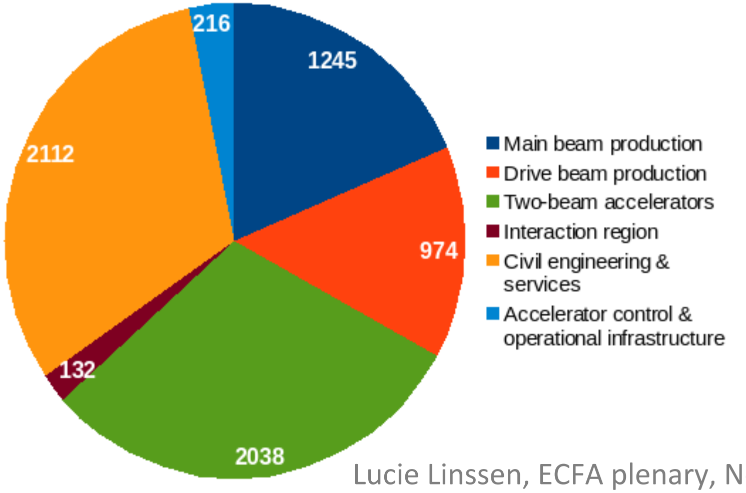
Photo: R. Ström

CLIC cost estimate

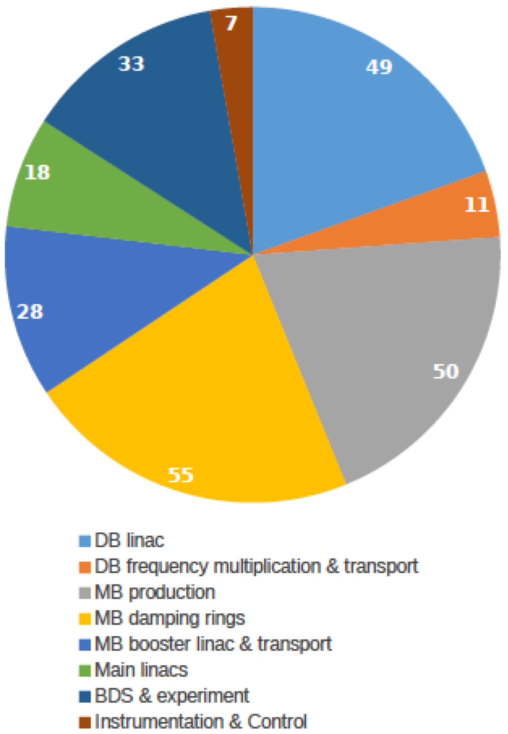
Preliminary estimate (scaled from CDR) with room for improvement.
New estimate will be provided for European Strategy Update.

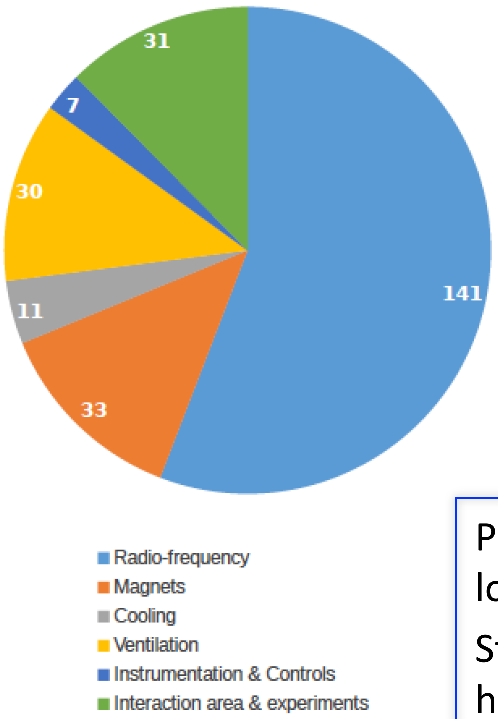
System	**Value for 380 GeV** (MCHF of Dec 2010)
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operation infrastructure	216
TOTAL	**6690**

Value for the CLIC accelerator at √s = 380 GeV (11.4 km site length)



Power and energy

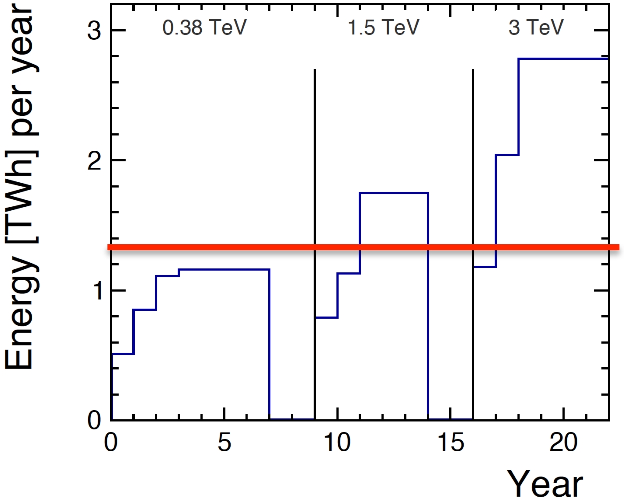




Power/energy reductions are being looked at

Structures are already optimised, however large contributions from:

- Klystrons => increase efficiency
- Magnets
- Ventilation/cooling => optimisation



CERN energy consumption 2012
1.35 TWh