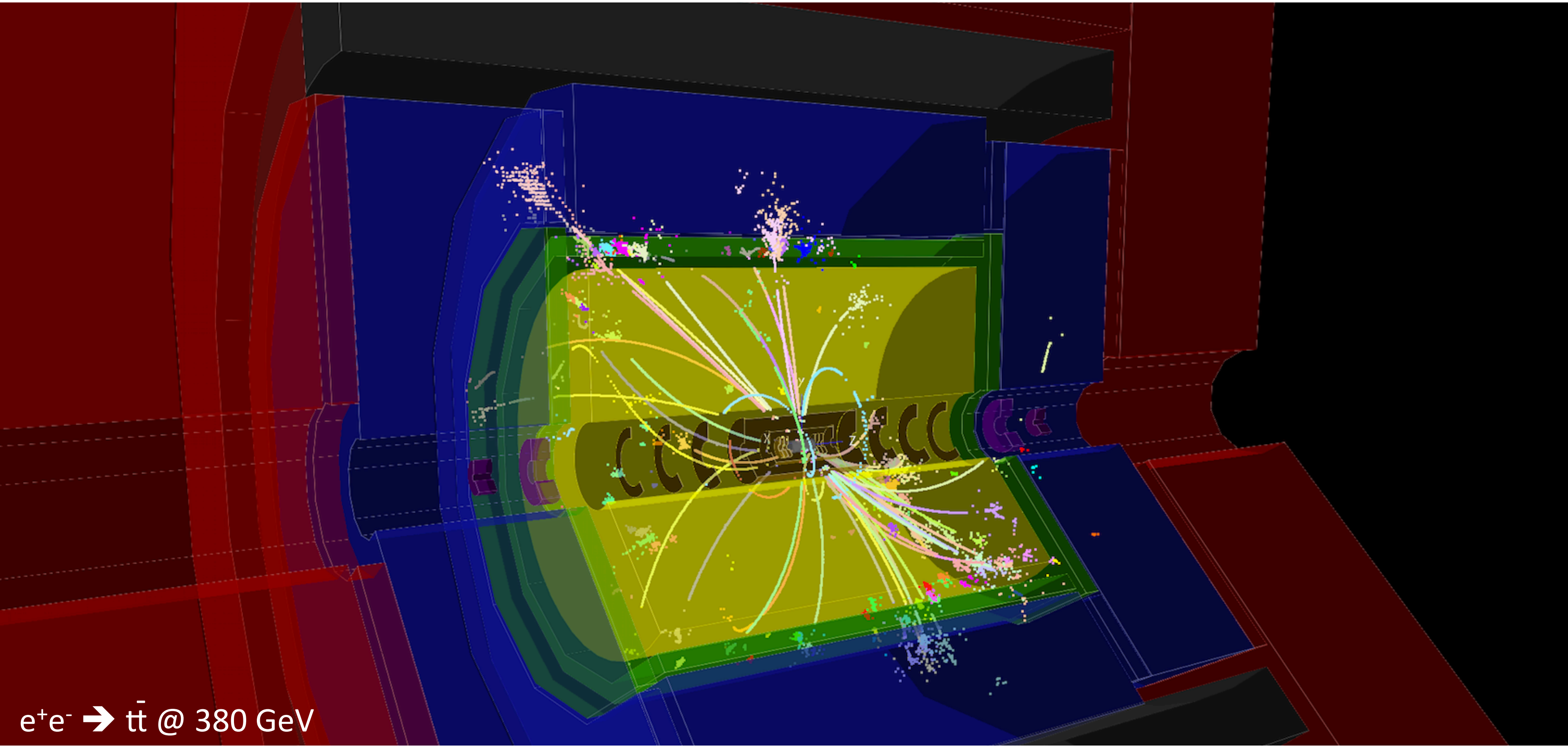
Physics at CLIC



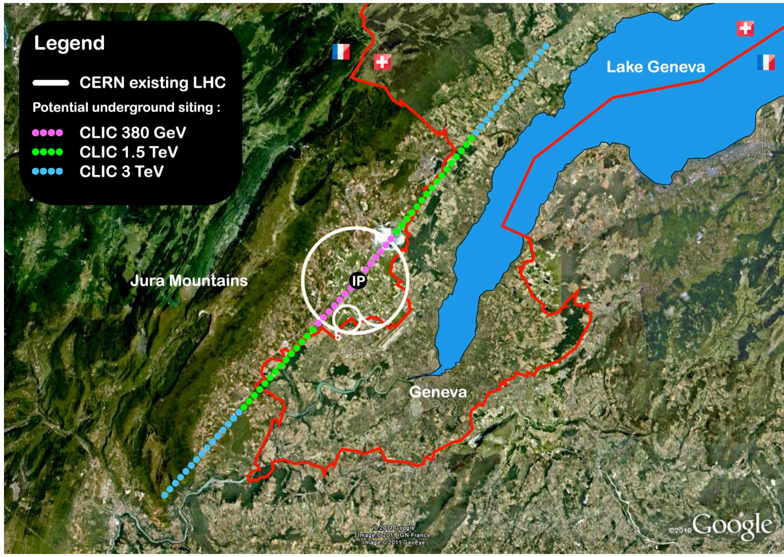
Lucie Linssen, CERN
on behalf of the CLIC and CLICdp collaborations

CERN, July 17th 2017

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

CLIC in a nutshell

- **e⁺e⁻ collisions @ √s 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



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"

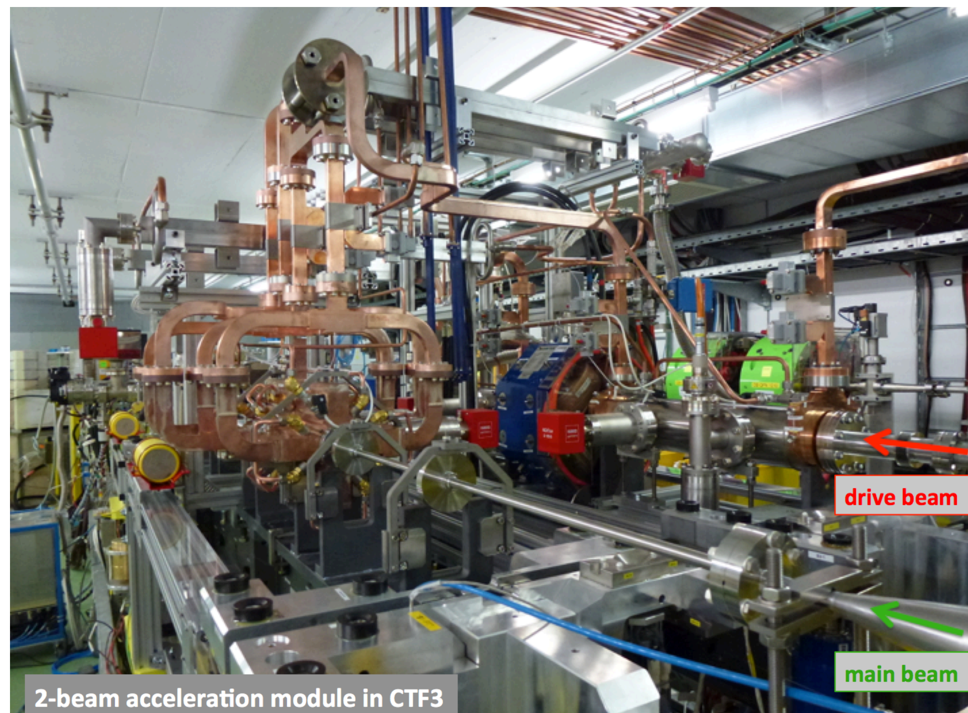
very small bunch size

key development focus

CLIC test facility CTF3

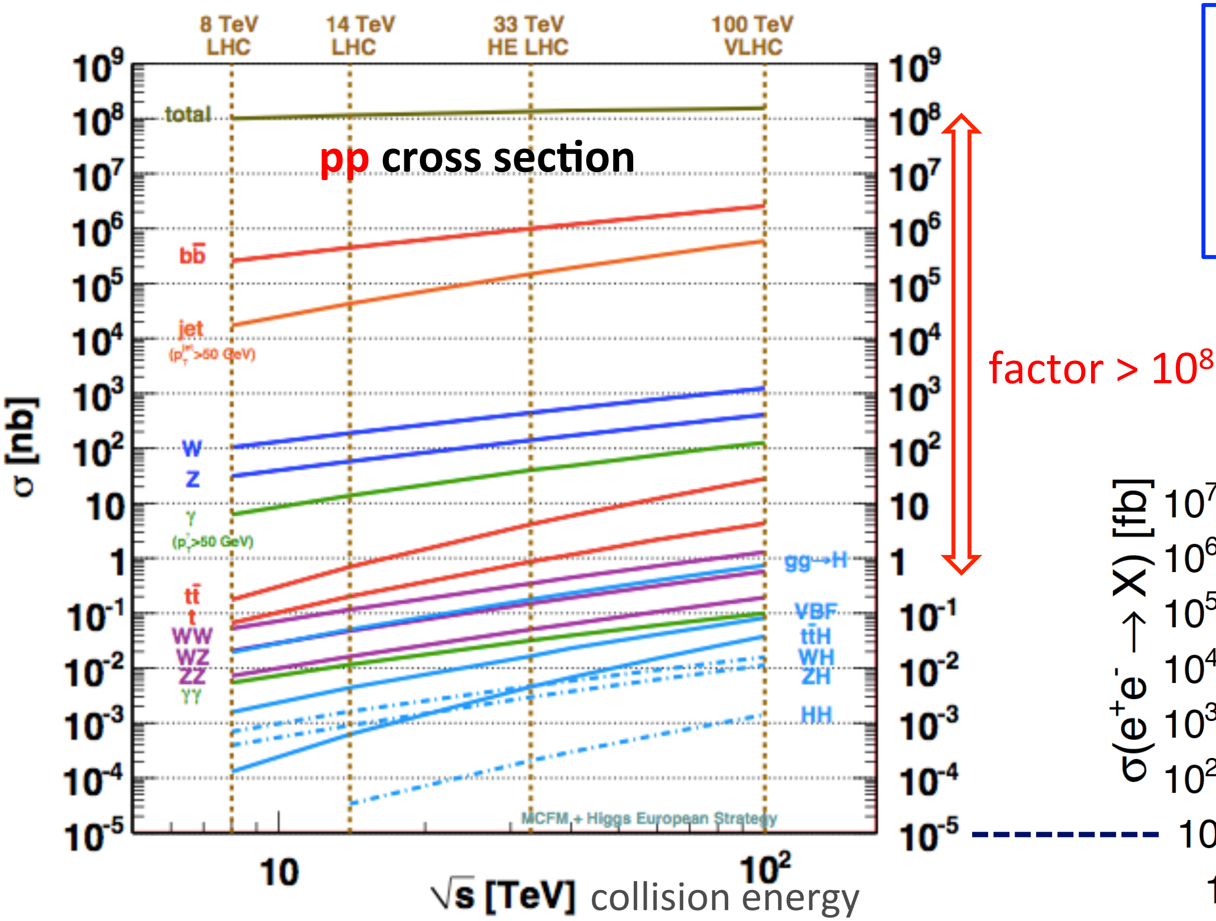
CTF3 successfully demonstrated:

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

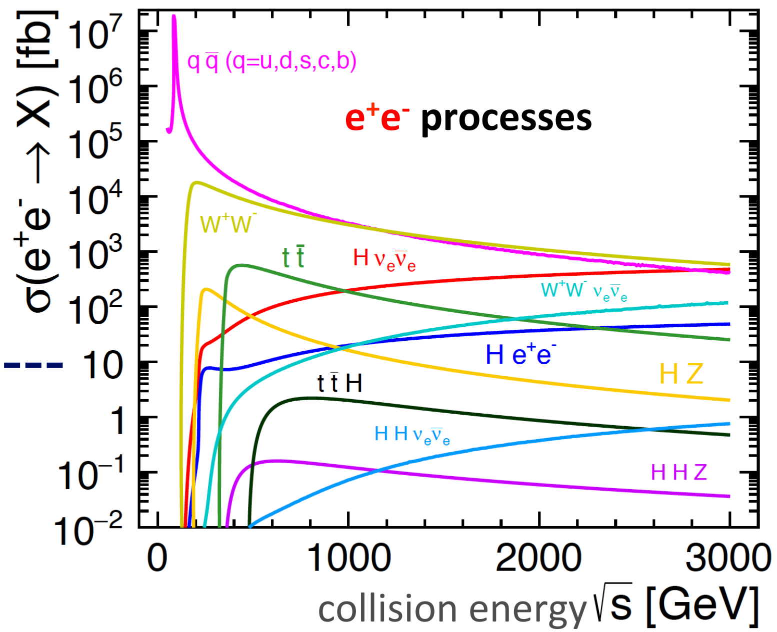


2-beam acceleration module in CTF3

pp collisions / e+e- collisions



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



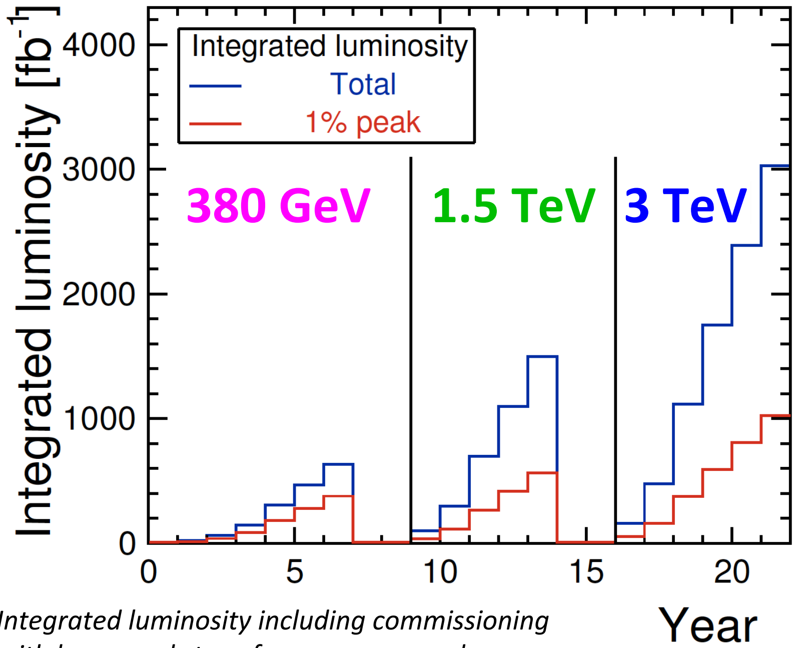
- Interesting **pp** events need to be found within a huge number of collisions

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

CLIC 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

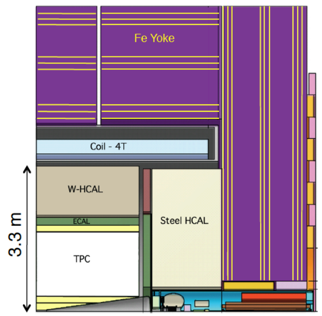
Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

Dedicated to top mass threshold scan

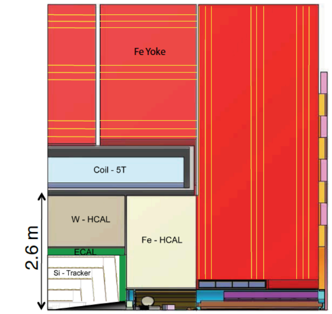
- **380 GeV (350 GeV)**, 600 fb^{-1} : precision Higgs and top physics
- **1.5 TeV**, 1.5 ab^{-1} : BSM searches, precision Higgs, ttH, HH, top physics
- **3 TeV**, 3 ab^{-1} : BSM searches, precision Higgs, HH, top physics

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

the CLIC physics program



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

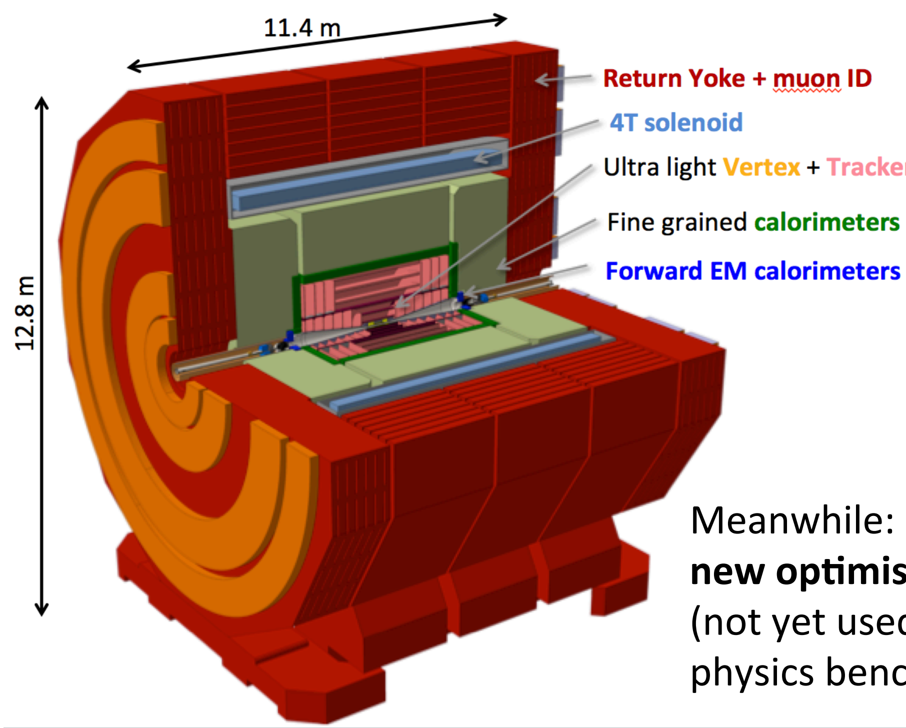


- Physics benchmark studies use the two CLIC CDR detector models
- Geant4-based detector simulation and event reconstruction
- Include effects of beam-induced backgrounds and luminosity spectrum

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

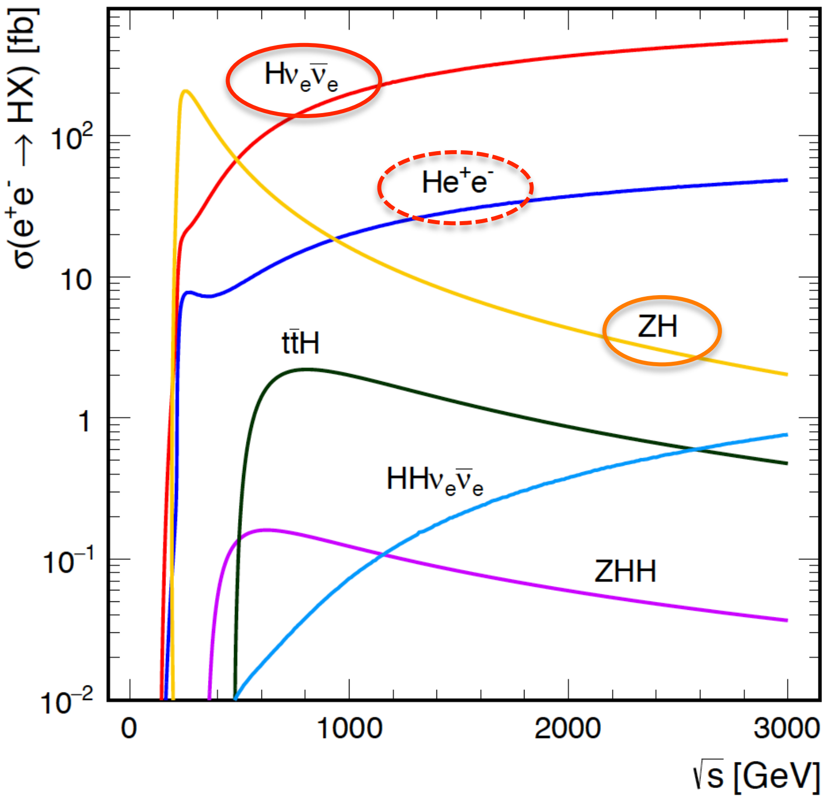
stage	√s	L_{int} (fb^{-1})
1	350 GeV	500
2	1.4 TeV	1500
3	3 TeV	2000

↗ *Scenario used for benchmarks*

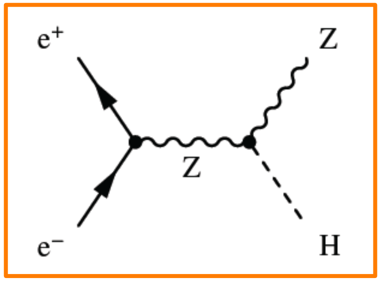


Meanwhile:
new optimised CLICdet
(not yet used for physics benchmarks)

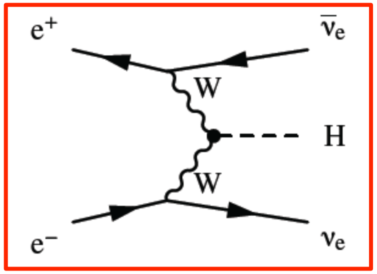
Higgs physics at CLIC



Dominant processes:



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



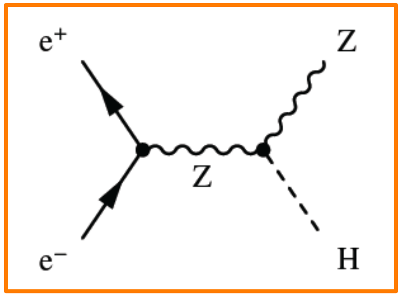
WW(ZZ) - fusion
σ ~ log(s)
Large stat. at high E

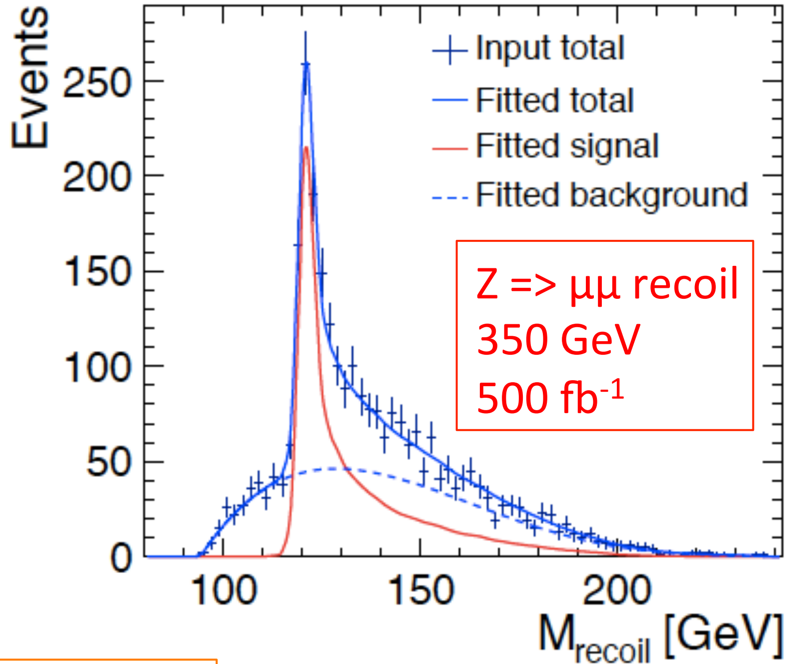
	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

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

high selection efficiencies !

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

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

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	$\Delta(\sigma_{HZ}) = \pm 1.8\%$

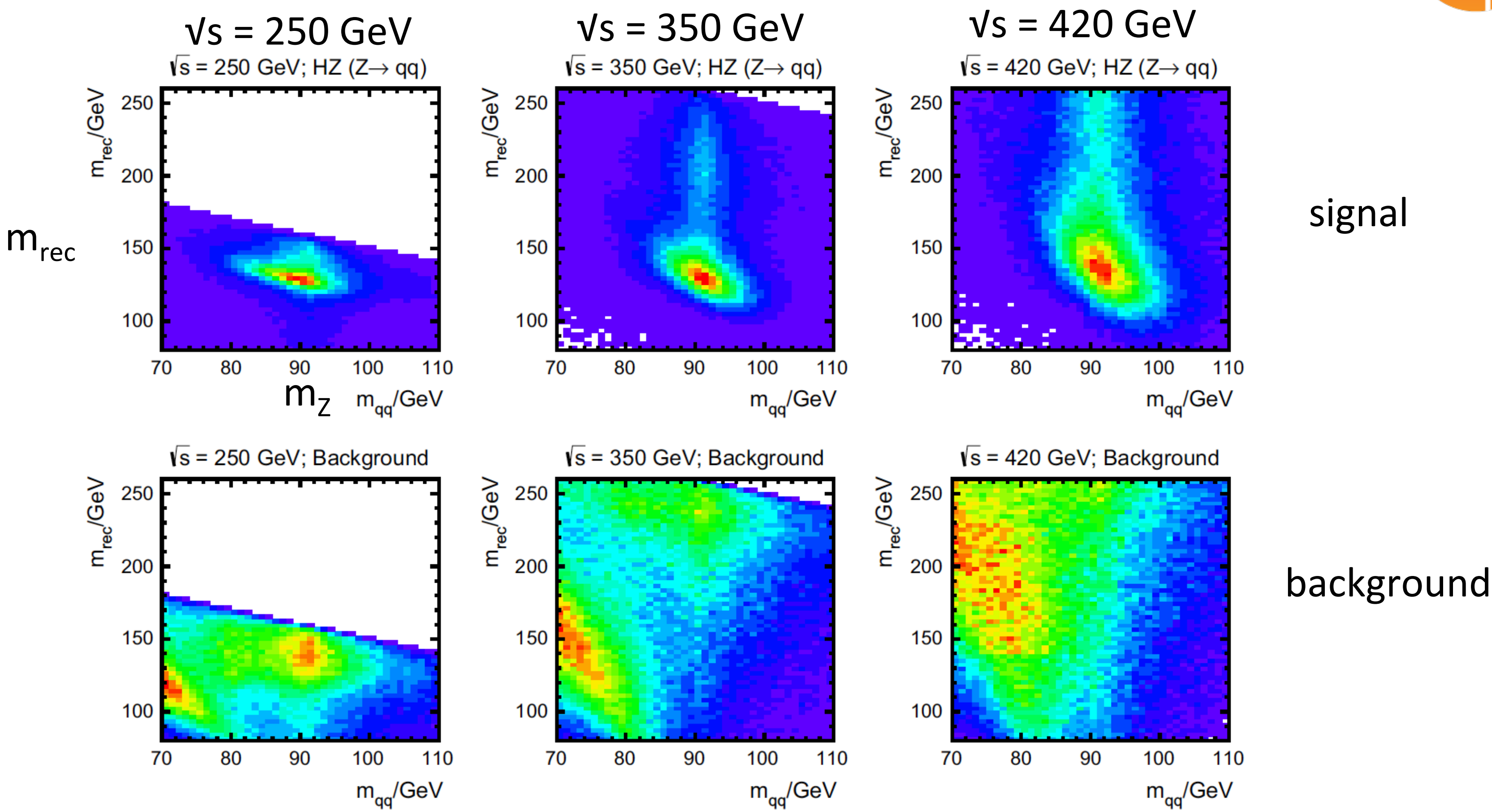
$\Delta(g_{HZZ}) = \pm 0.8\%$

arXiv:1608.07538

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)

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



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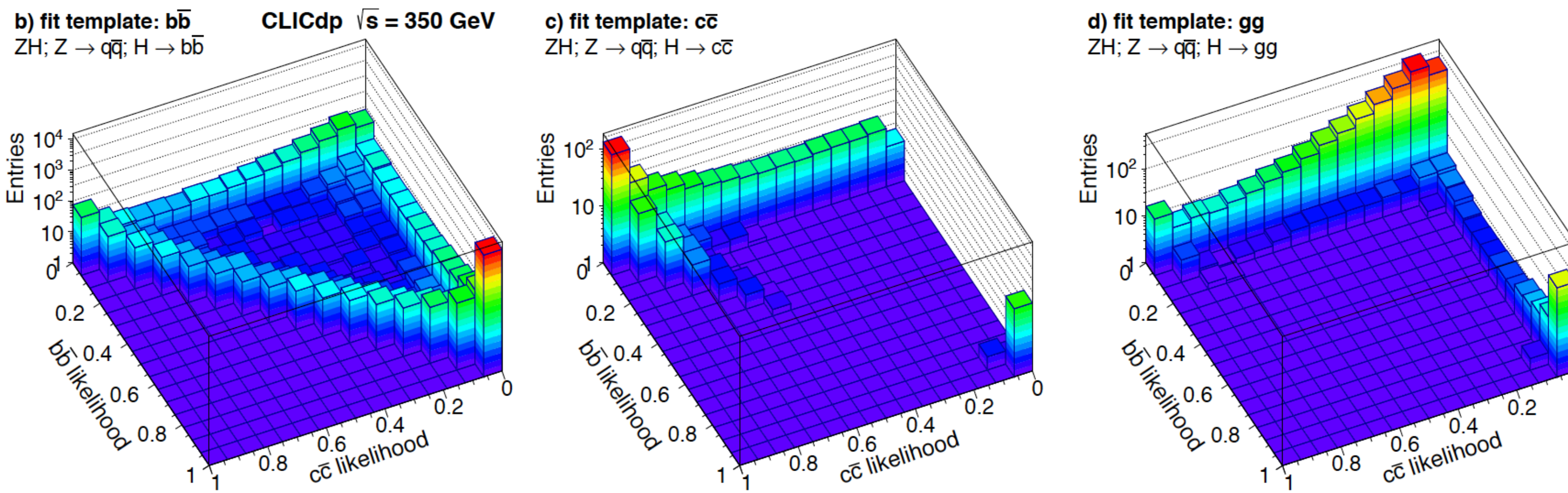
$\sqrt{s}$	$\mathscr{L}$	σ(HZ)	$\Delta\sigma_{vis.}$	$\Delta\sigma_{invis.}$	$\Delta\sigma(HZ)$
250 GeV	500 fb^{-1}	136 fb	±3.63 %	±0.45 %	±3.65 %
350 GeV	500 fb^{-1}	93 fb	±1.71 %	±0.56 %	±1.80 %
420 GeV	500 fb^{-1}	68 fb	±2.42 %	±1.02 %	±2.63 %

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

$H \rightarrow b\bar{b}$ | $H \rightarrow c\bar{c}$ | $H \rightarrow gg$



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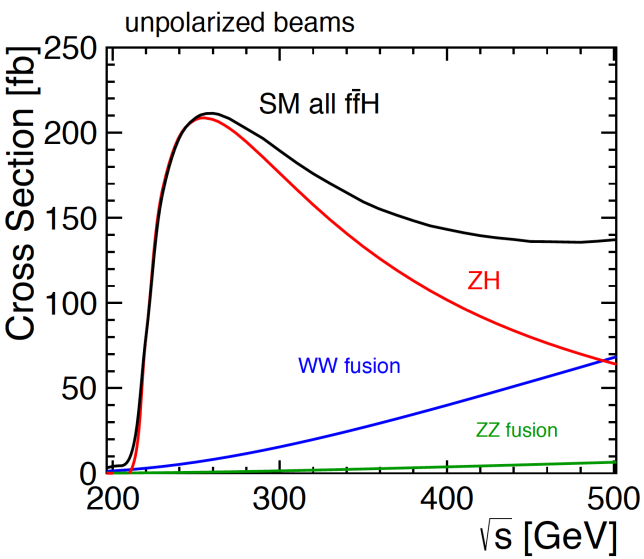
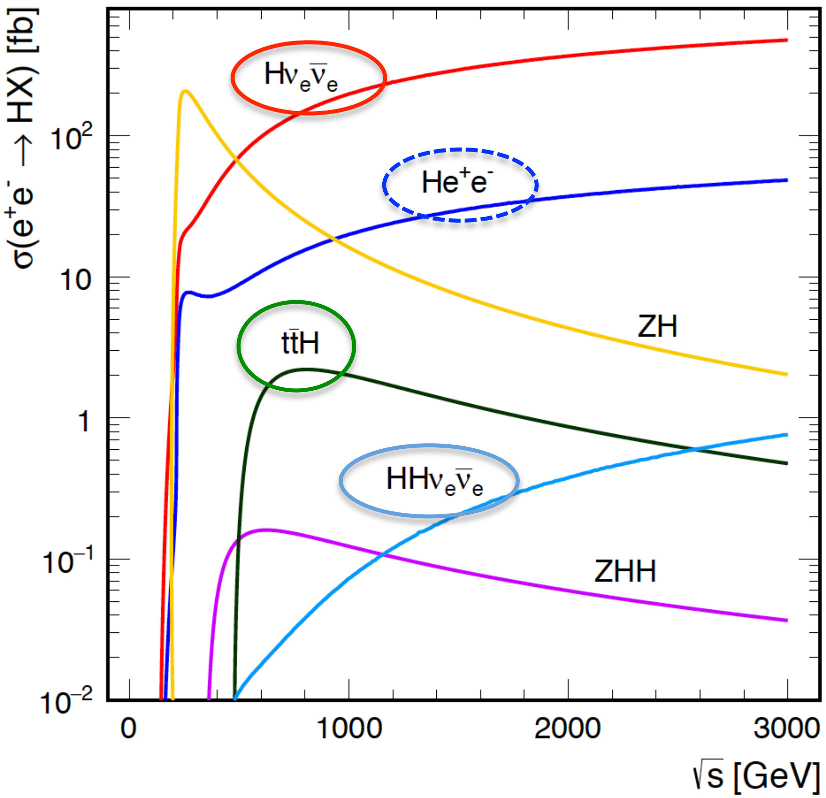


Simultaneous extraction of 2 production and 3 decay modes

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

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

Higgs physics above 1 TeV

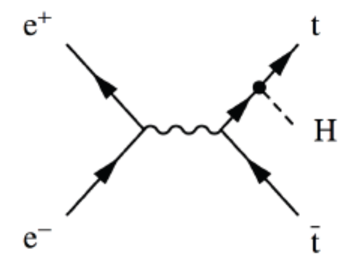


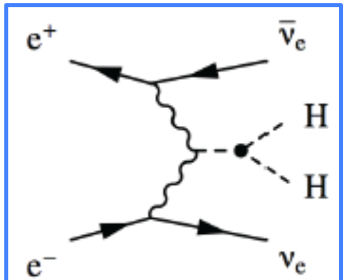
Vector boson fusion:

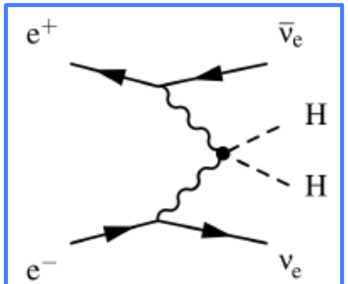
$e^+e^- \rightarrow H\nu\nu$, $e^+e^- \rightarrow He^+e^-$

High σ + increased luminosity

Gives **access to rare Higgs decays**







$t\bar{t}H$ production:

- Extraction of Yukawa coupling y_t
- Best at $\sqrt{s}$ above 700 GeV

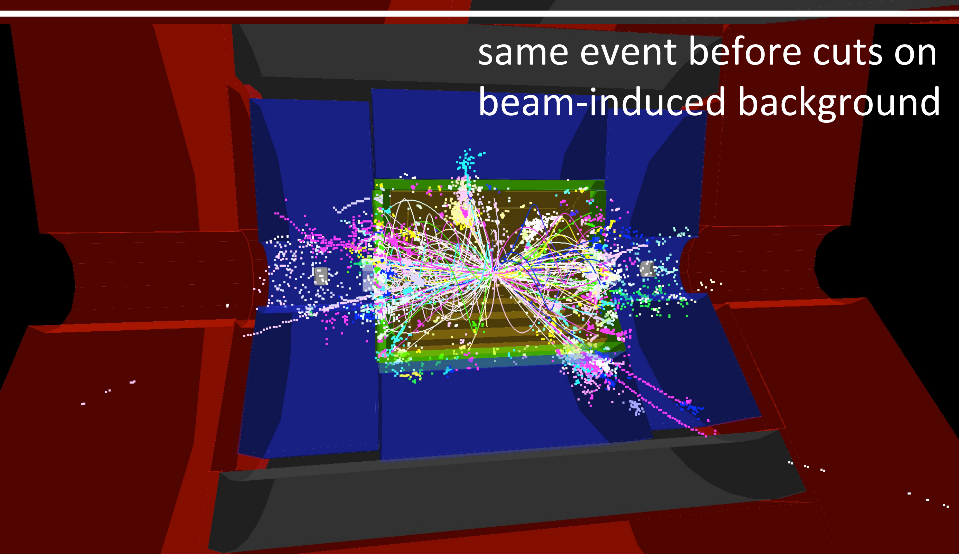
Studied at 1.4 TeV, 1.5 ab^{-1}

Statistical accuracy:

- **$\Delta(g_{Htt}) = \pm 4.2\%$ 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

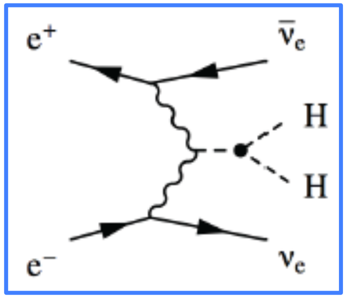


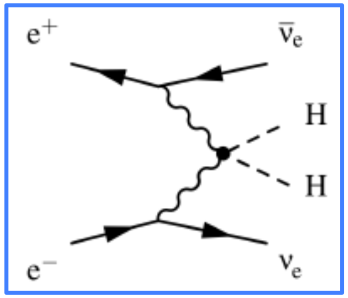
Highly granular calorimetry + precise hit timing

↓

Very effective in suppressing backgrounds
for fully reconstructed particles

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**

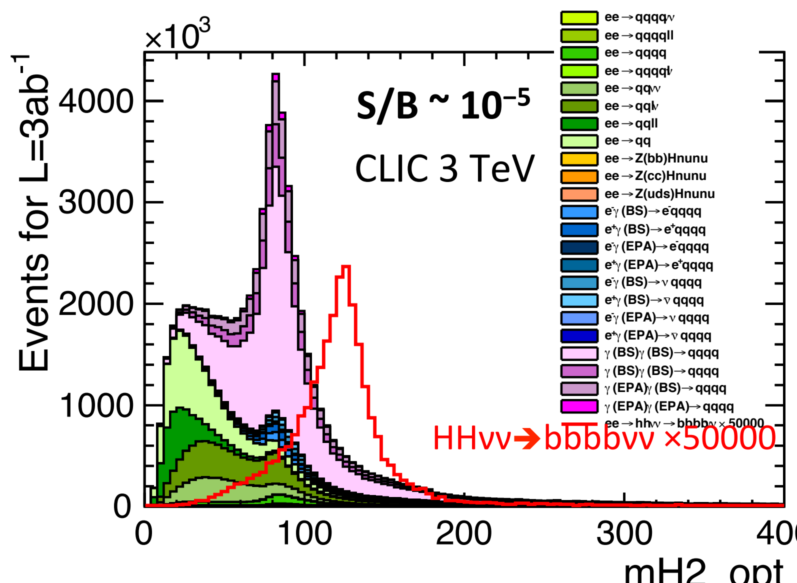
*Most promising final states: bbbbνν and bbWW*νν*

Recent re-analysis including key additional background processes:

Assuming -80% e^- polarisation, 2 ab^{-1}:

- at 1.4 TeV $\Delta g_{HHH}/g_{HHH}$ ±40%
- at 3 TeV $\Delta g_{HHH}/g_{HHH}$ ±22%
- => combined: $\Delta g_{HHH}/g_{HHH}$ ±19%

arXiv:1608.07538



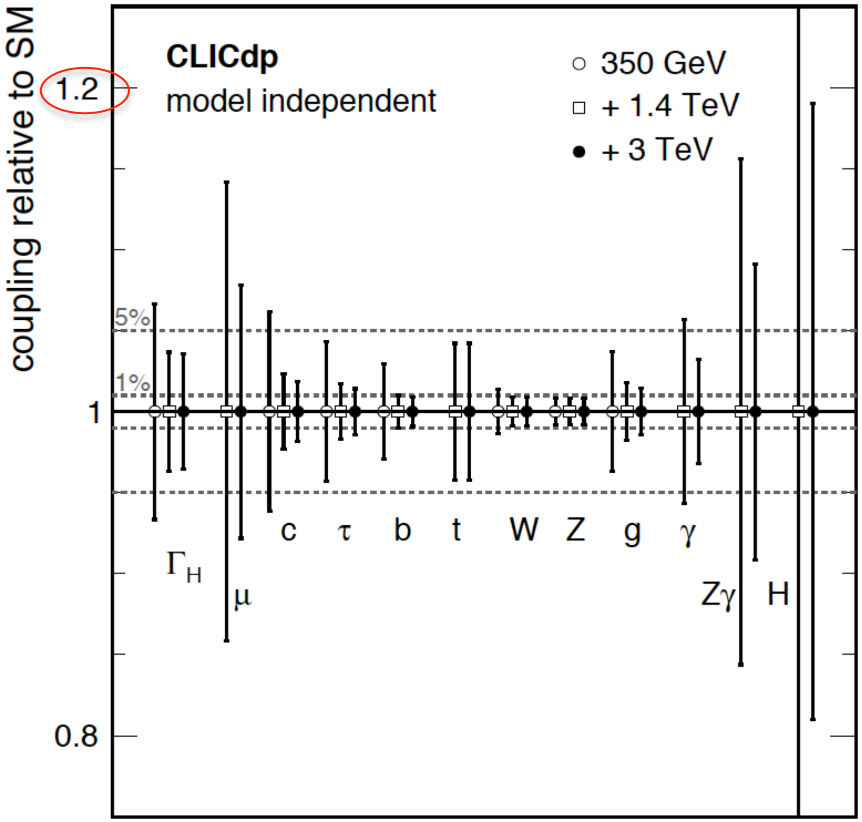
Ongoing: simultaneous extraction Δg_{HHH} and Δg_{WWHH}
Using kinematic variables => improved result

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

work in progress

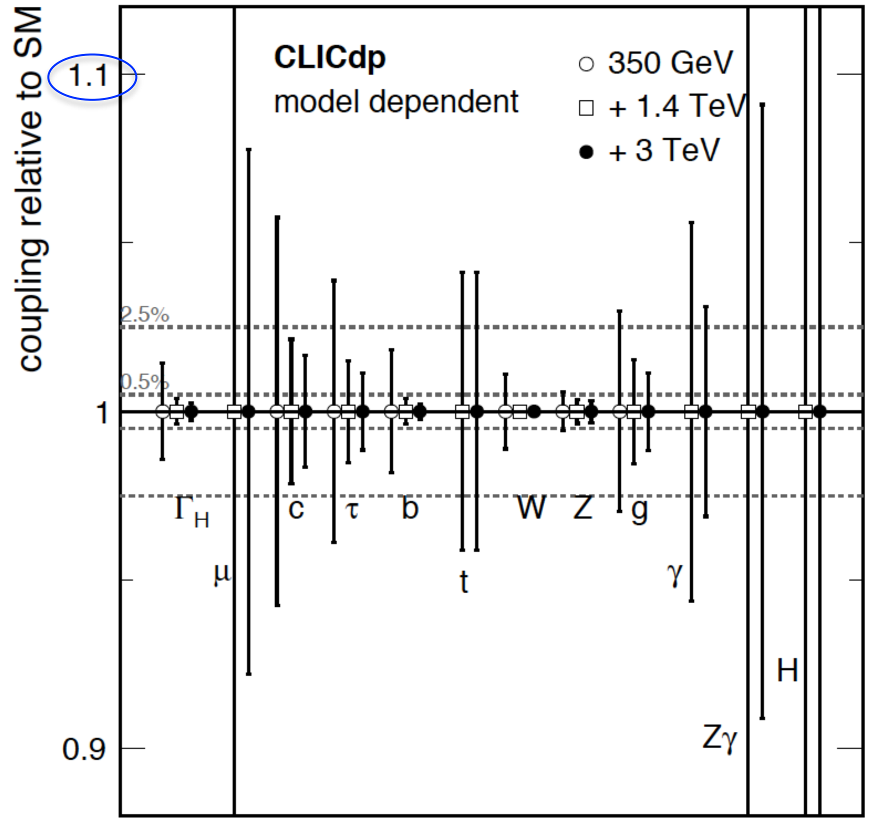
combined CLIC Higgs results

Model-independent



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

arXiv:1608.07538

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

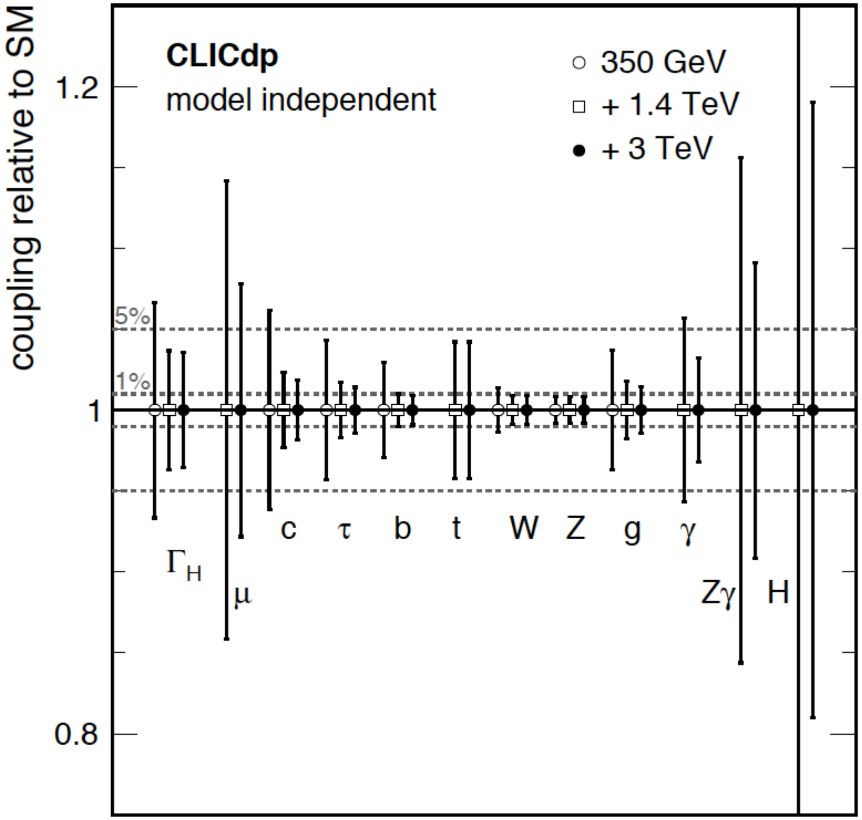
- Model-independent: down to ±1% for most couplings
- Model-dependent: ±1% down to ± few ‰ for most couplings
- Accuracy on Higgs width: ±3.5% (MI), ±0.3% (MD, derived)

combined CLIC Higgs results

indicative comparison with HL-LHC capabilities

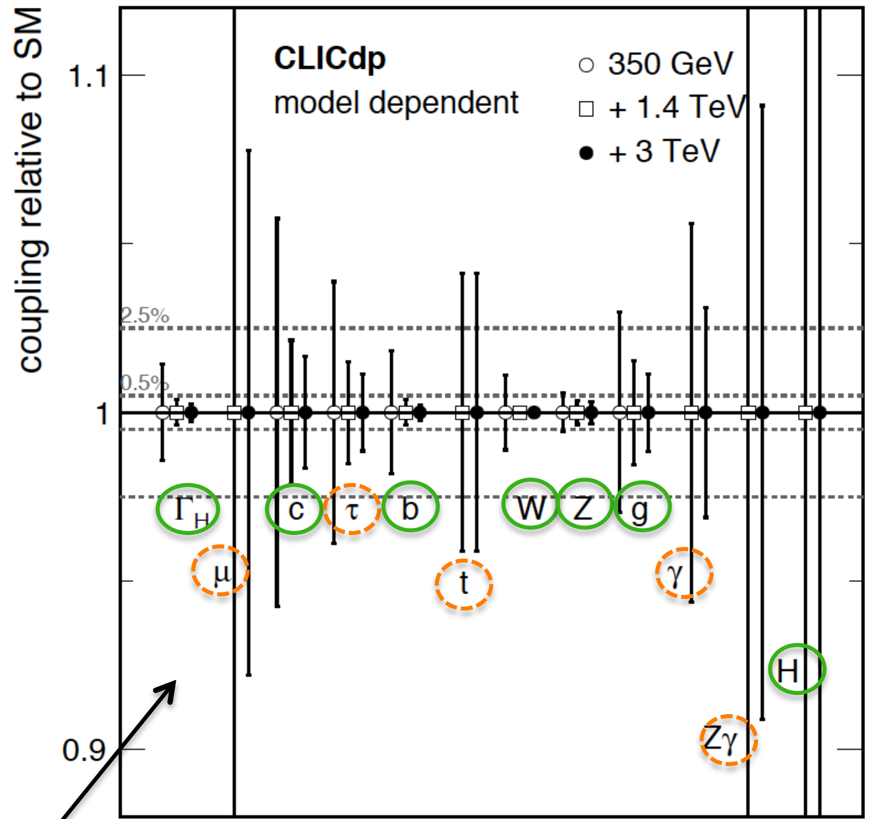
arXiv:1608.07538

Model-independent



e⁺e⁻ colliders can perform model-independent measurements

Model-dependent

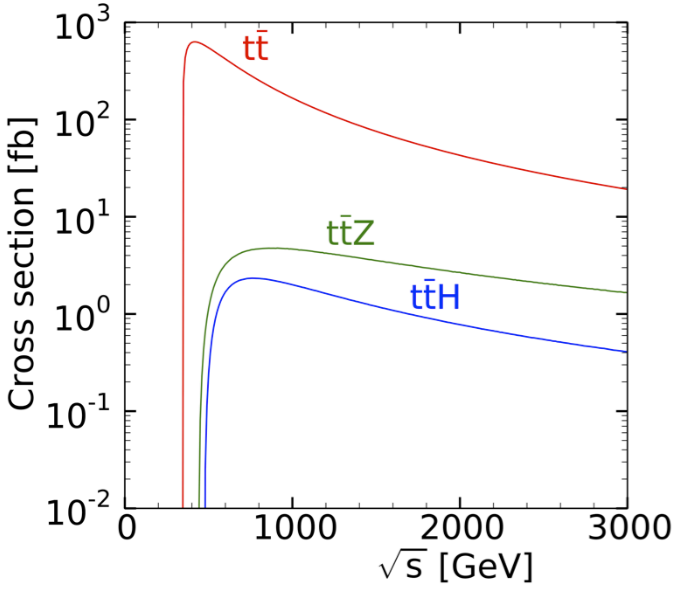


LHC-like fit, assuming SM decays only.
Fit to deviations from SM BR's

Green circle: Accuracy significantly better than HL-LHC

Orange dashed circle: Accuracy comparable to HL-LHC

top quark physics



Motivation:

So far top quark only measured at hadron colliders

Precision top physics in e^+e^-:

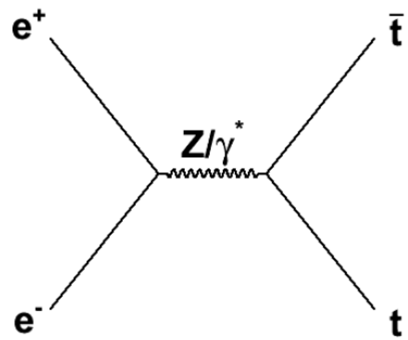
- sensitive to many BSM scenarios
- understanding EWSB
- test ground of QCD

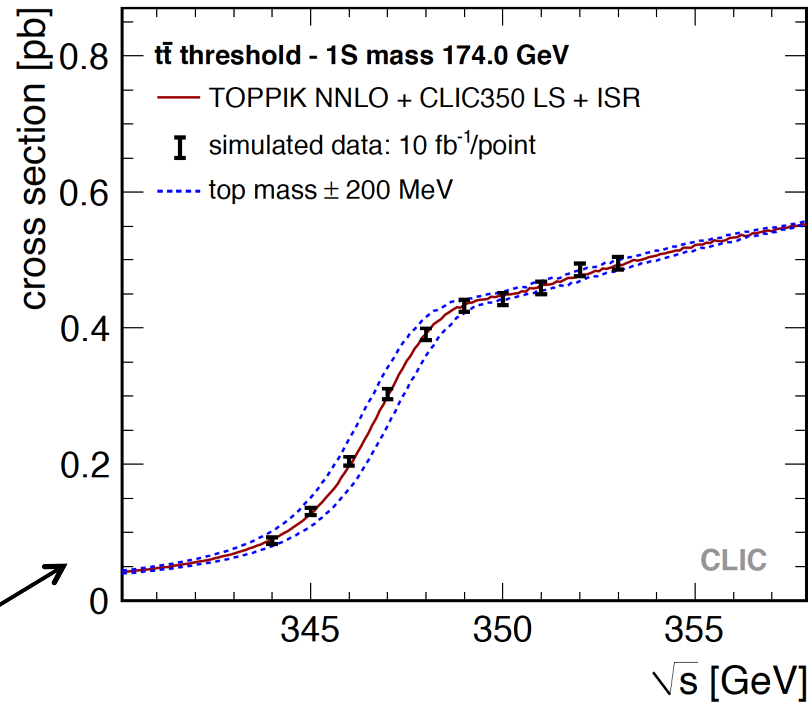
Top physics programme currently studied for CLIC:

- 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)
- **Yukawa coupling** through $t\bar{t}H$ production
- **Measurement of V_{tb}** in single top production
- **Rare decays** (strongly suppressed in SM)
- Searches using **boosted top quarks**, e.g. stop

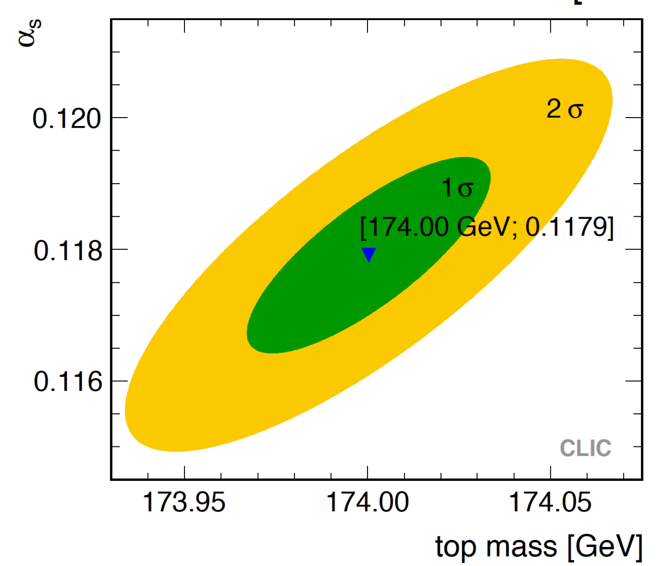
threshold scan of top pair production

- **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



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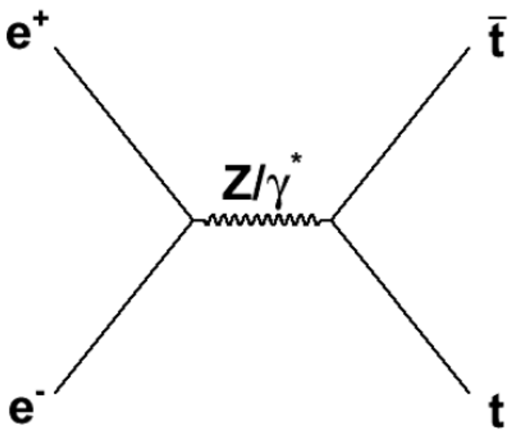
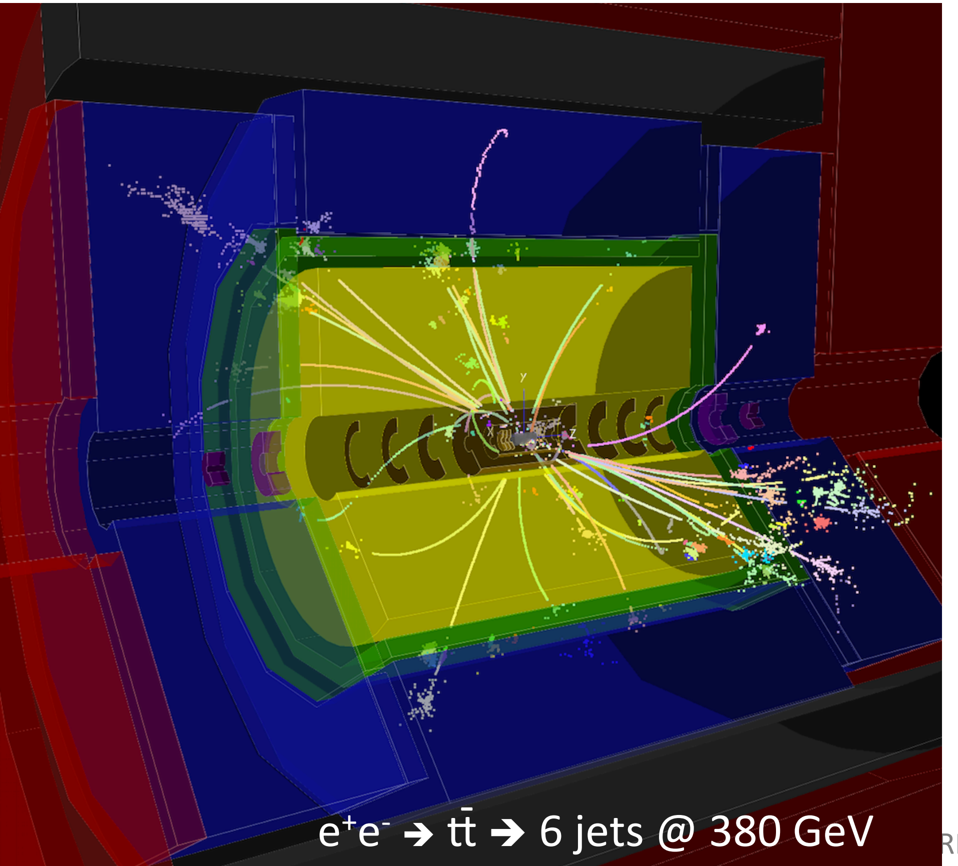
top quark couplings to Z and γ

Top quark pairs are produced via Z/γ

New physics would modify the $t\bar{t}Z/t\bar{t}\gamma$ vertex





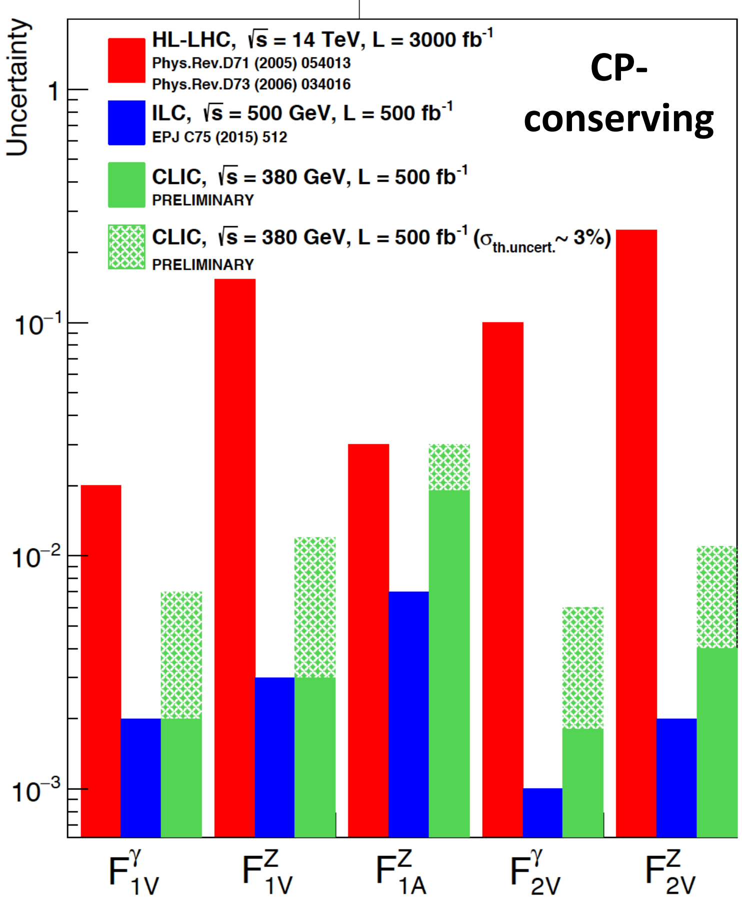
γ and Z form factors can be disentangled *using beam polarisation* by measuring:

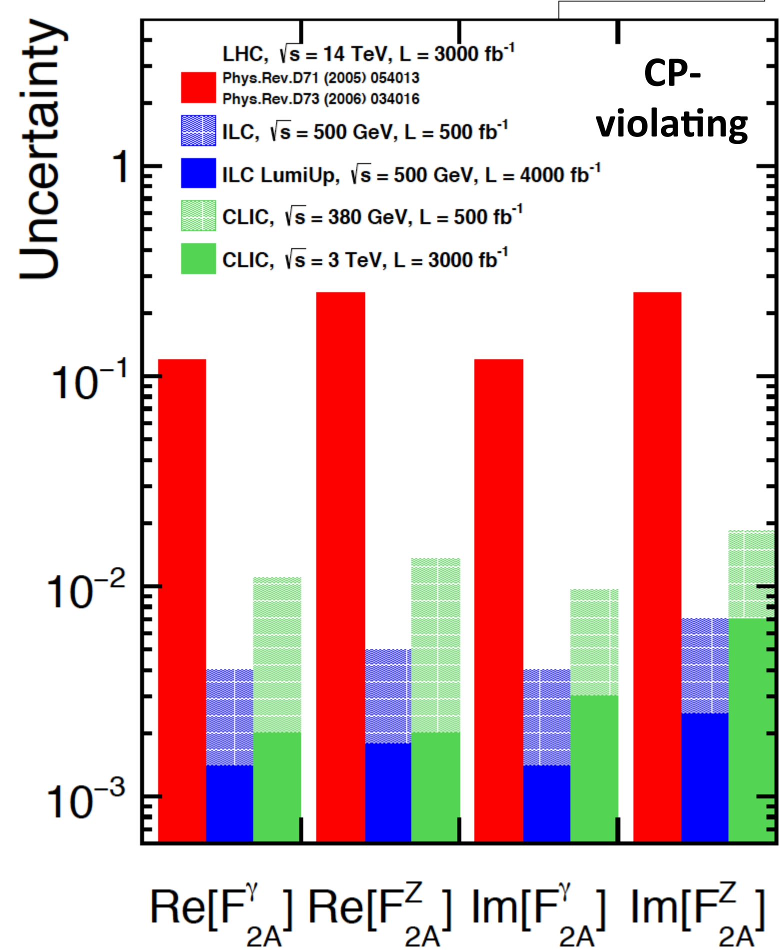
- Production cross section
- Forward-backward asymmetry
- Helicity angle distribution (in leptonic decays)

top quark couplings to Z and γ

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:1307.8102

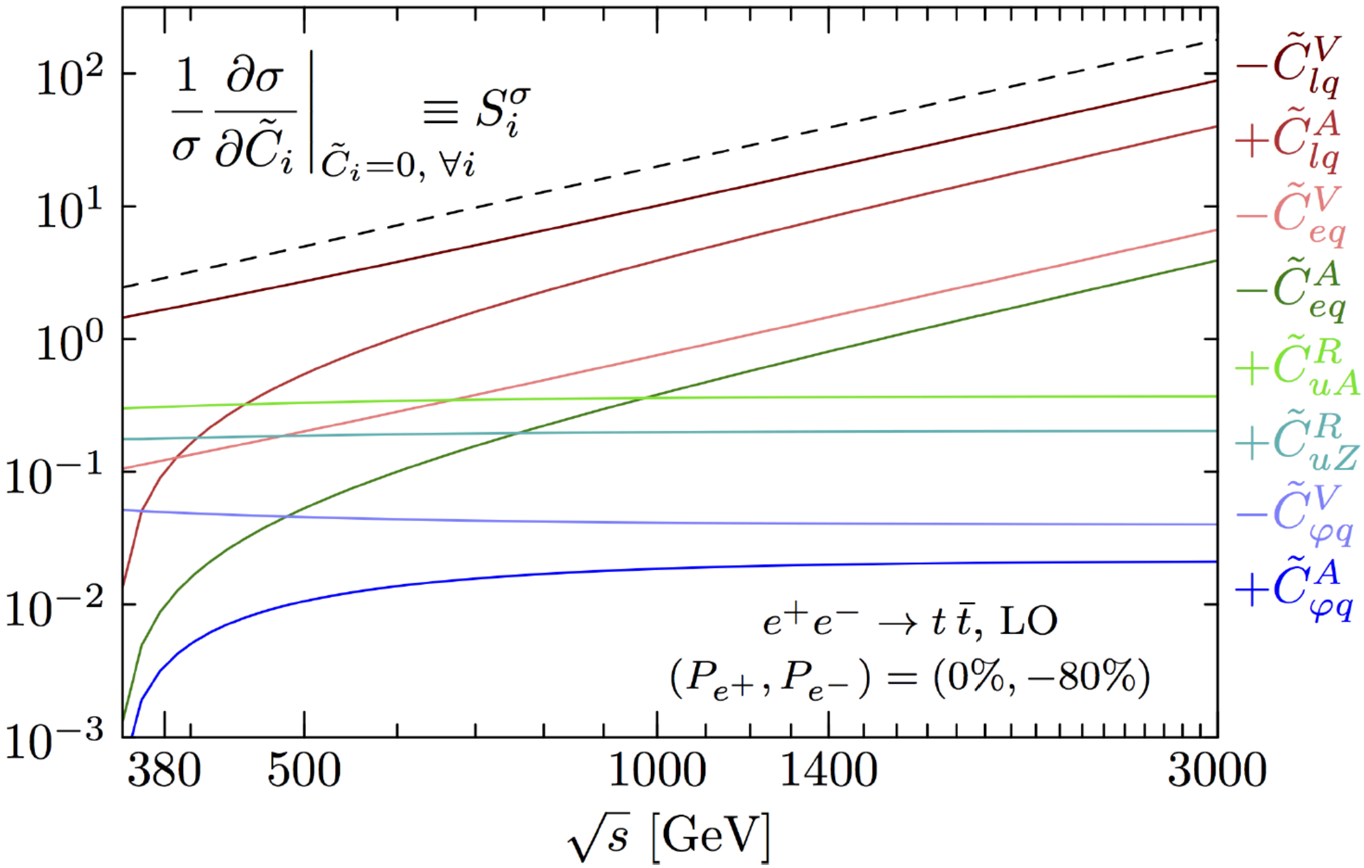
CERN-2016-004

M. Perello @ LC top 2017

e^+e^- measures top couplings more than an order of magnitude better than HL-LHC

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

indirect measurement: study of $e^+e^- \rightarrow \gamma\gamma$

Precision QED

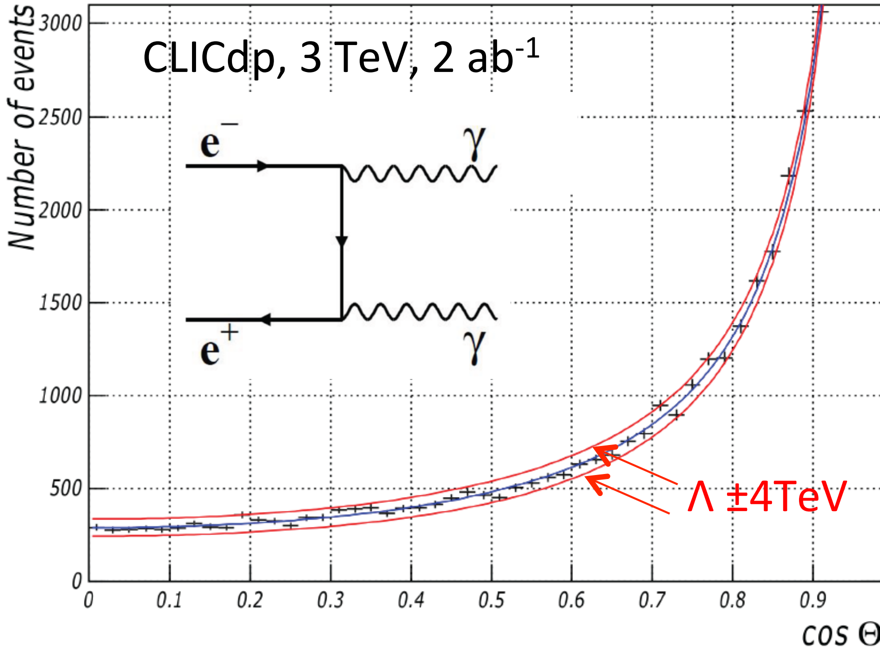
from cross section and angular γγ spectrum

$\Rightarrow$ **can test extension of QED**

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

Fit result: Λ > 6.33 TeV
(or electron size < 3.1×10^{-18} cm)

I. Boyko @ CLIC'16



CLIC 3 TeV 2 ab^{-1}

Scenario	ΔL = 0.2 %	ΔL = 0.5 %	ΔL = 1 %	LEP limit
QED cut-off (finite electron size) Λ_{QED} (95% CL)	6.52 TeV	6.33 TeV	6.01 TeV	~ 390 GeV
Contact interactions Λ' (95% CL)	20.7 TeV	20.1 TeV	18.9 TeV	~ 830 GeV
Extra dimensions $M_S/\lambda^{1/4}$ (95% CL)	16.3 TeV	15.9 TeV	15.3 TeV	~ 1 TeV
Excited electron M_{e^*} (95% CL)	5.03 TeV	4.87 TeV	4.7 TeV	~ 250 GeV

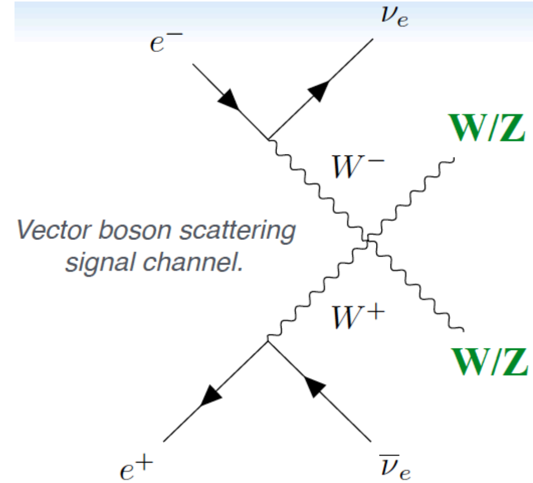
Accuracy depends weakly on error ΔL on luminosity

vector boson scattering

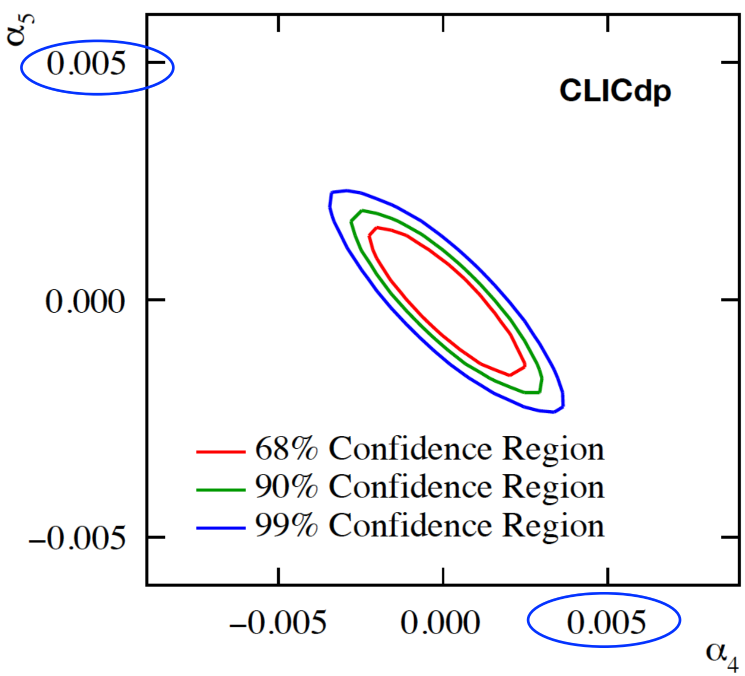
Vector boson scattering

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

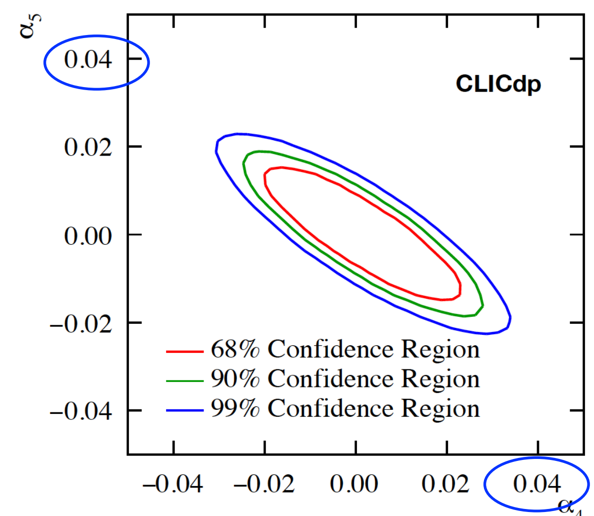
Effective field theory approach, parameters α_4, α_5



3 ab^{-1} at 3 TeV



1.5 ab^{-1} @ 1.4 TeV

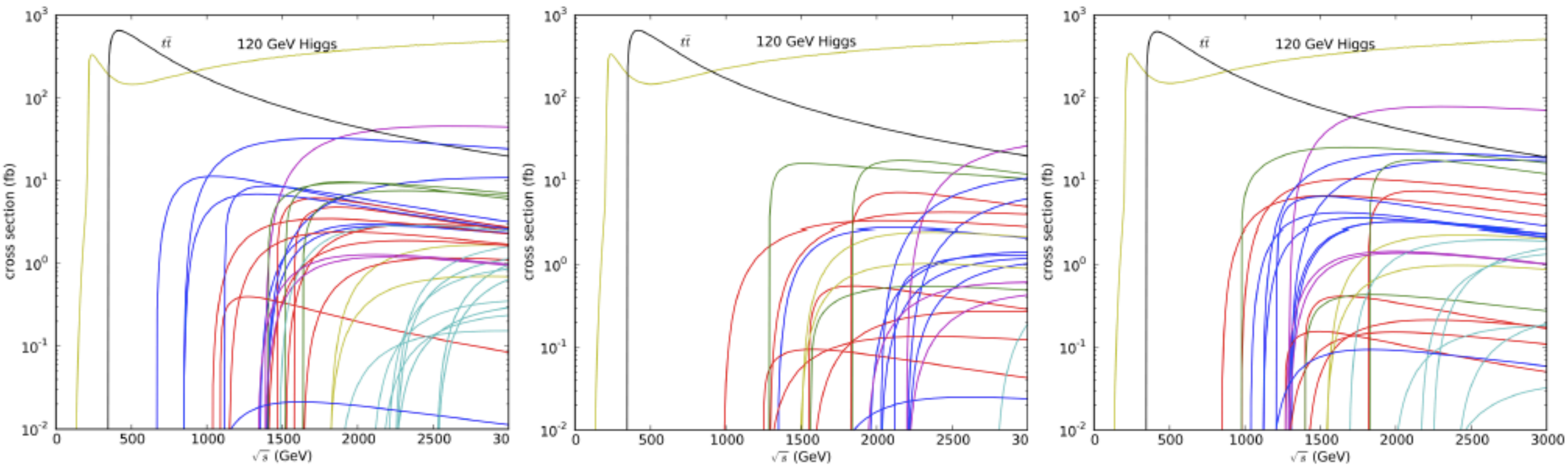


Sensitivity improves strongly with √s
CLIC result expected significantly better than HL-LHC

see also arXiv:1607.03030

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

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

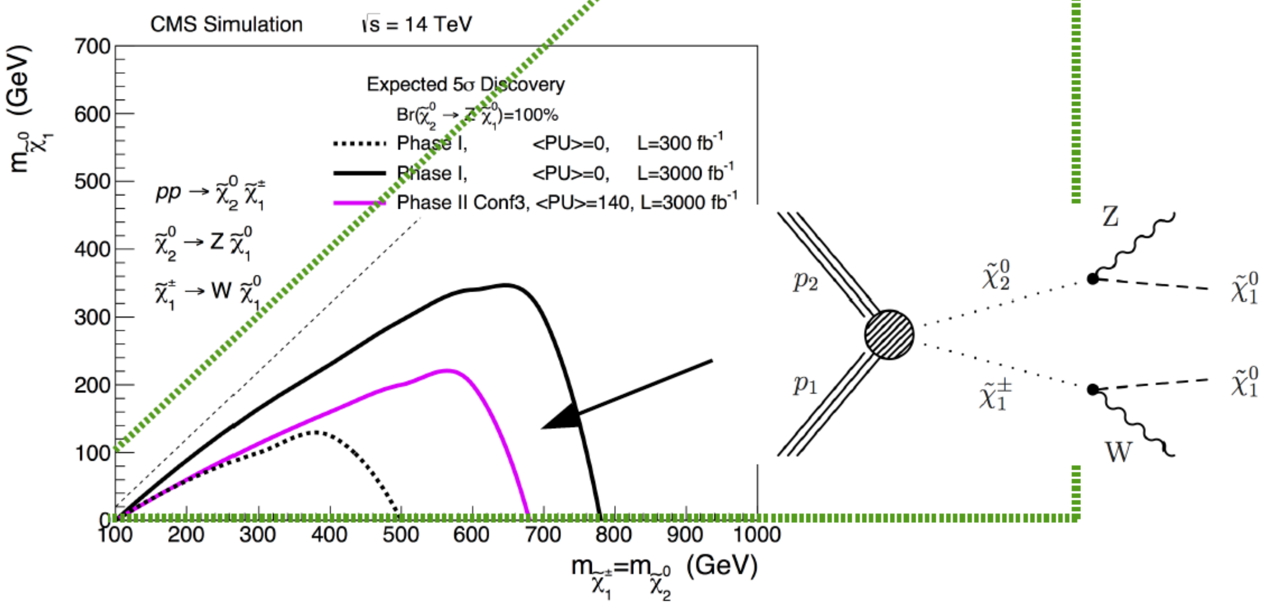
CERN-2012-007

heavy electroweak states (1)

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

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

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



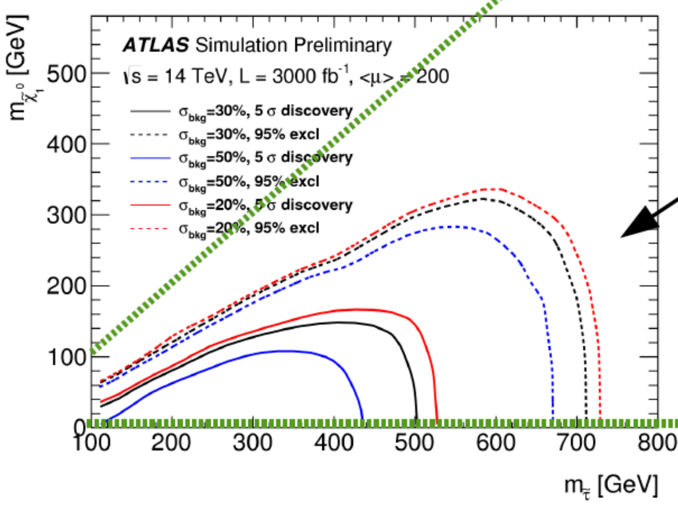
CMS-PAS-FTR-13-014

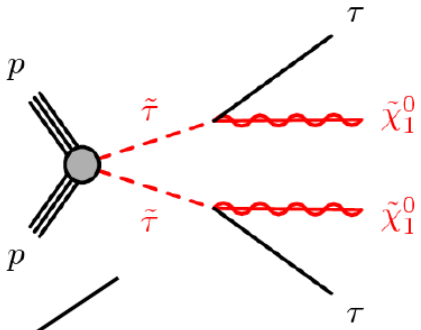
(similar projection: ATL-PHYS-PUB-2014-010)

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

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

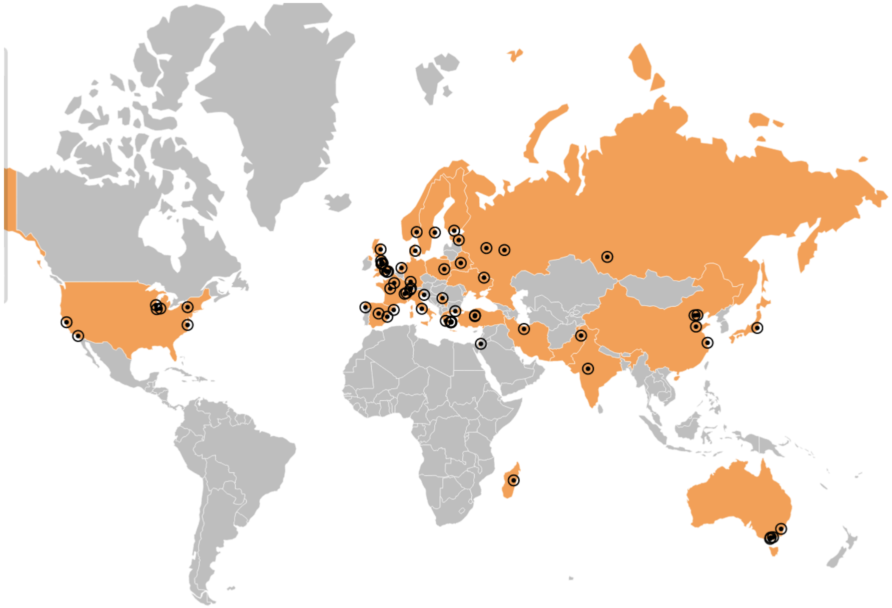
CLIC collaborations

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

summary

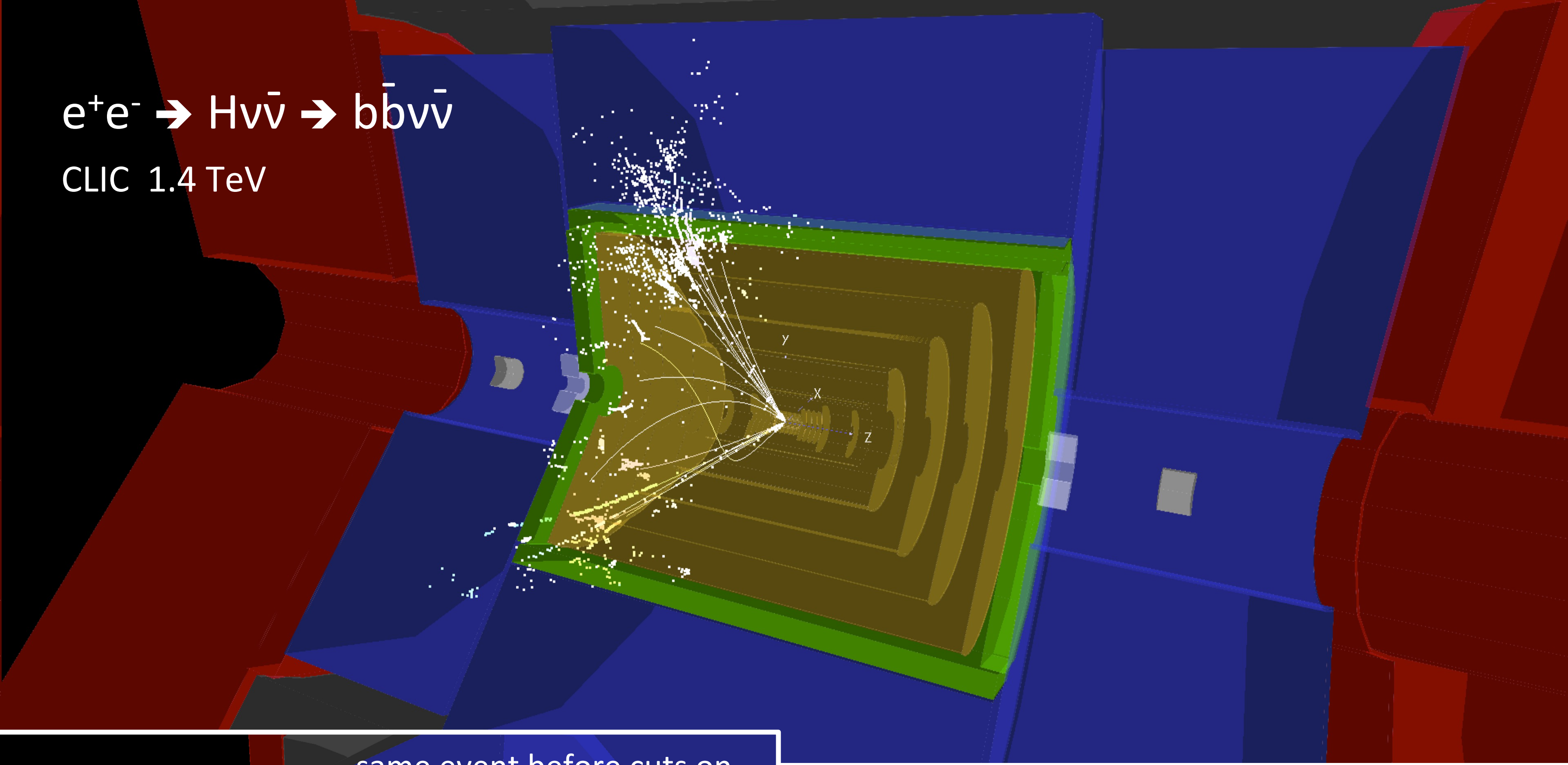
CLIC offers a wealth of accurate e^+e^- physics measurements
"Affordable" first stage at 380 GeV with guaranteed physics
Upgradable up to 3 TeV

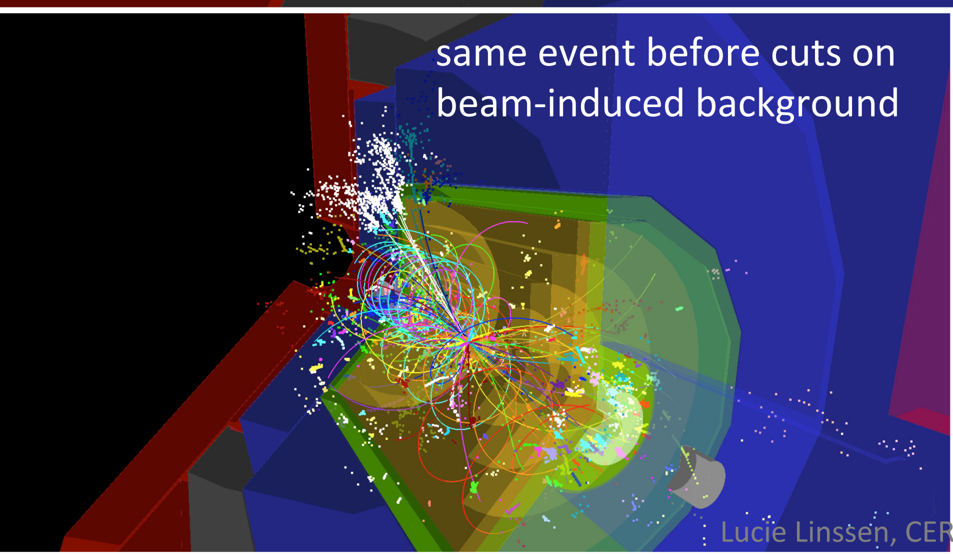
A powerful tool to address the open questions in particle physics

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!


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


same event before cuts on
beam-induced background

thank you !

SPARE SLIDES

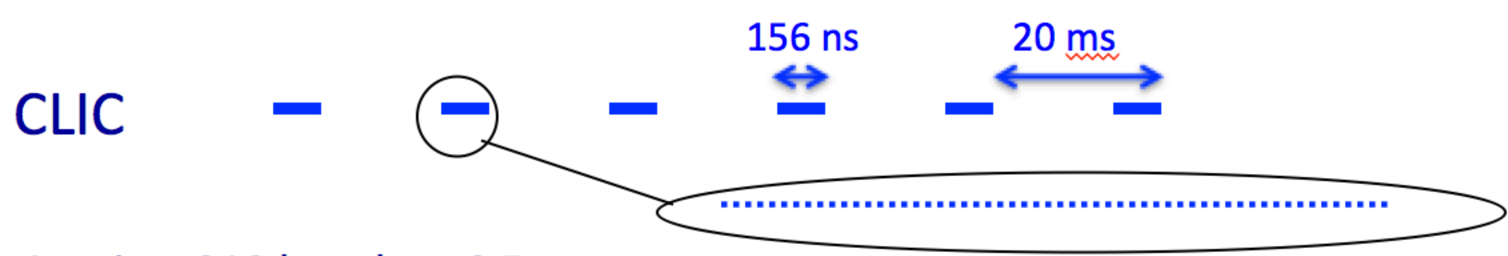
CLIC accelerator parameters

Parameter	380 GeV	1.5 TeV	3 TeV
Luminosity $\mathcal{L}$ ($10^{34} cm^{-2} sec^{-1}$)	1.5	3.7	5.9
$\mathcal{L}$ above 99% of √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

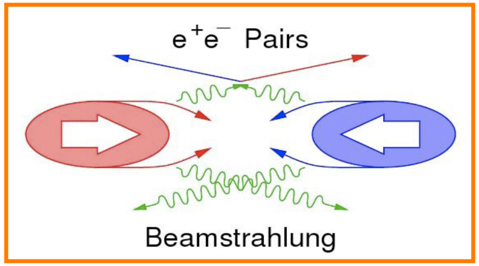
**scaled from CDR, with room for improvement*



1 train = 312 bunches, 0.5 ns apart

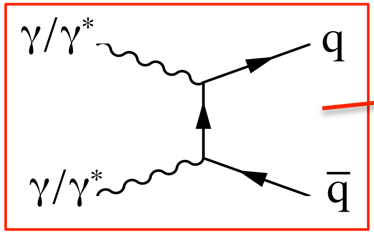
- not to scale -

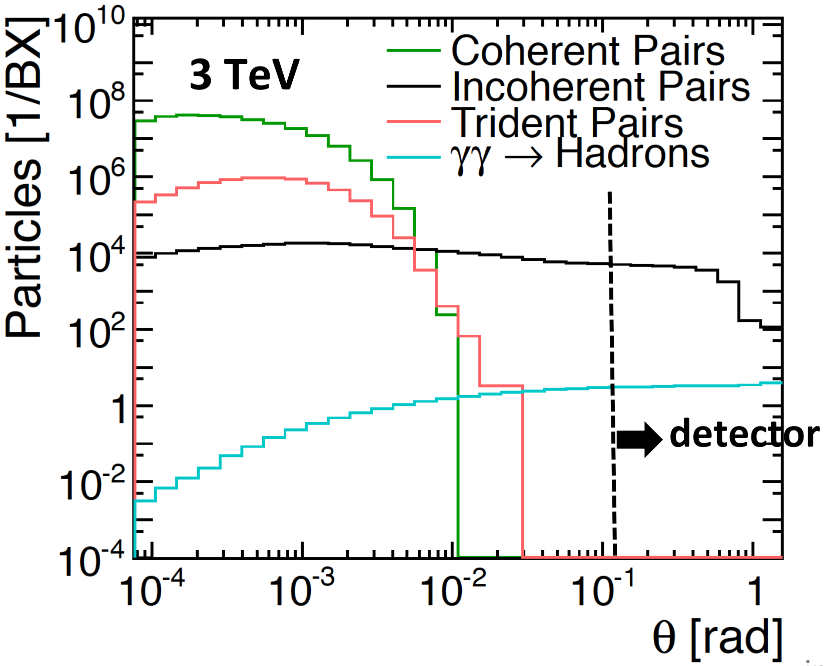
CLIC accelerator environment

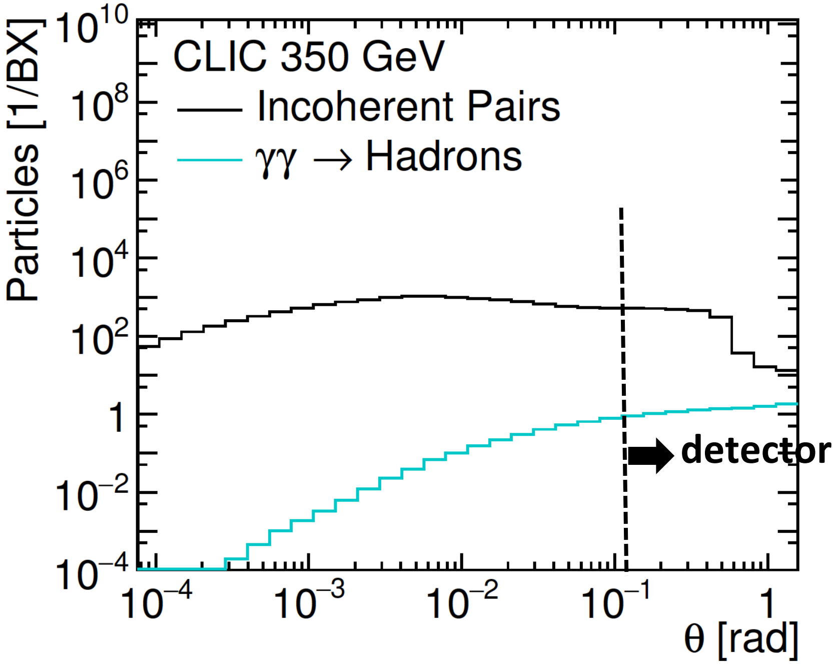


Beam-beam background at IP:

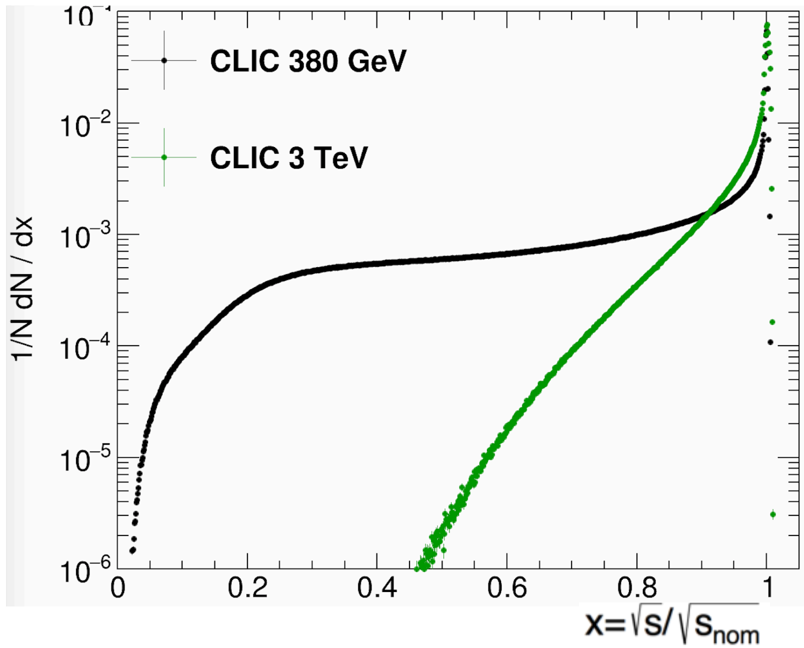
- Small beams => very high E-fields
  - **Beamstrahlung**
  - **Pair-background** → Simplified picture: **Design issue** (small cell sizes)
    - High occupancies
  - **γγ to hadrons** → Impacts on the physics, **Needs suppression in data**
    - Energy deposits







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

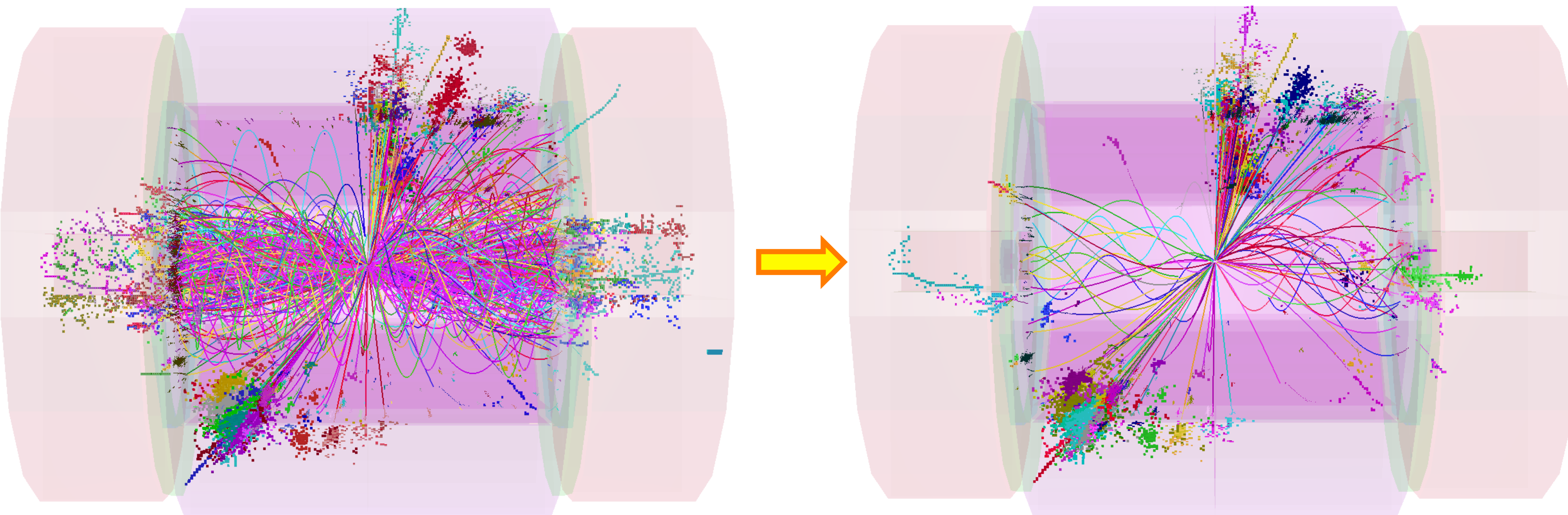
Fraction $\sqrt{s}/\sqrt{s_{nom}}$	380 GeV	3 TeV
>0.99	63%	36%
>0.9	91%	57%
>0.8	98%	68%
>0.7	99.5%	77%
>0.5	~100%	88%

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

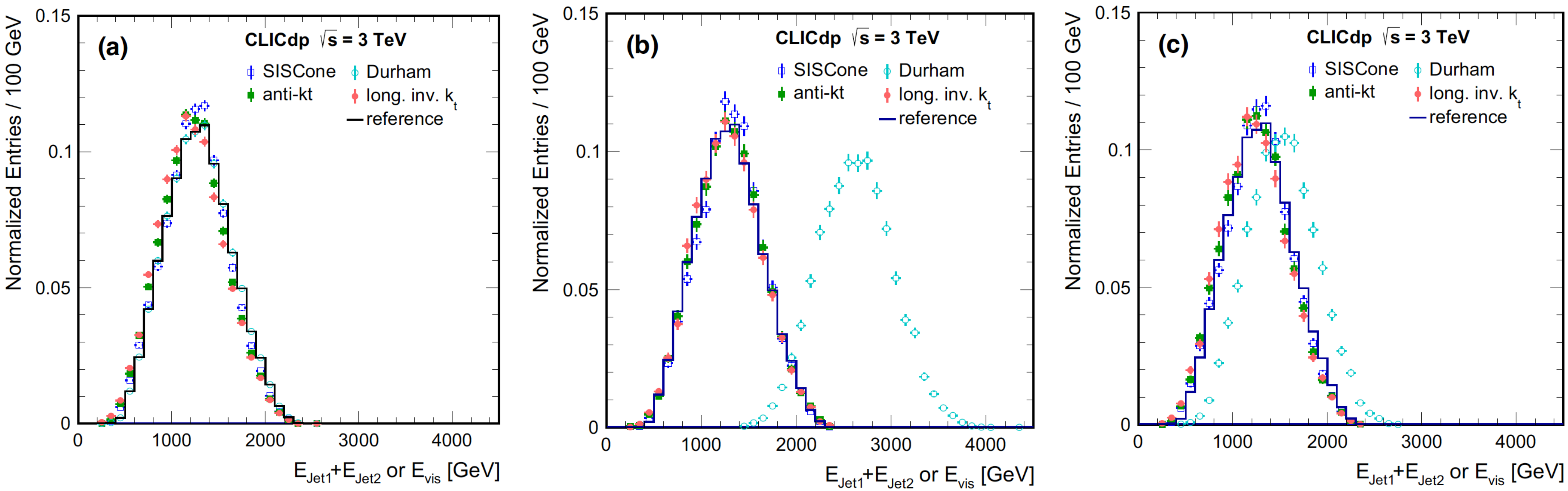
100 GeV background after tight cuts

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)

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



No γγ ➔ hadrons background

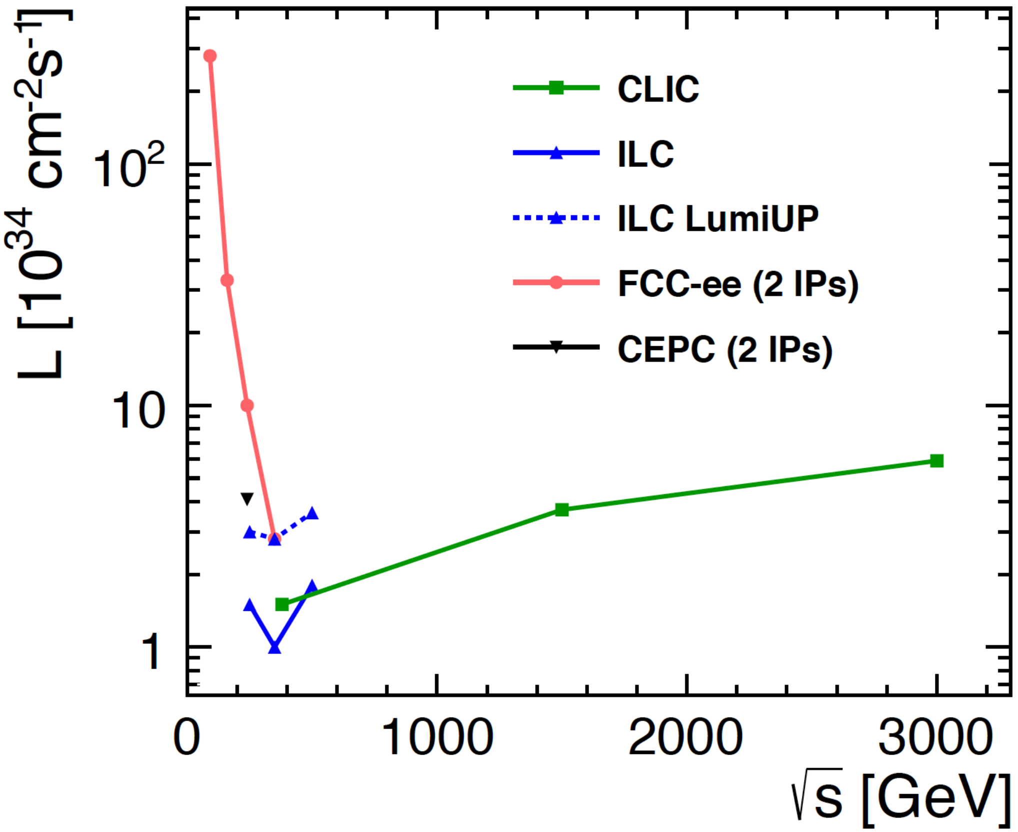
With γγ ➔ hadrons bkg from 60 bunch crossings

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

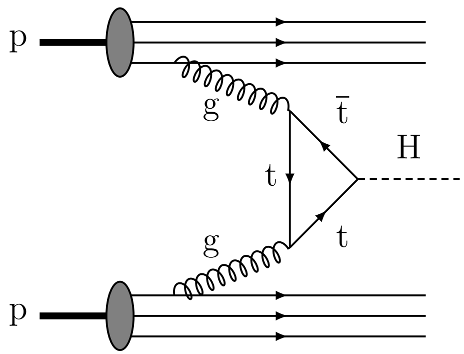
Circular colliders:

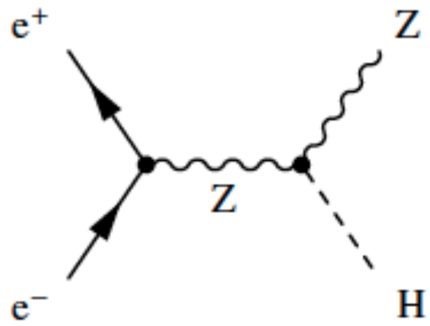
- Huge luminosity at lower energies
- Luminosity decreases with energy

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

BSM example: Z' via indirect measurement

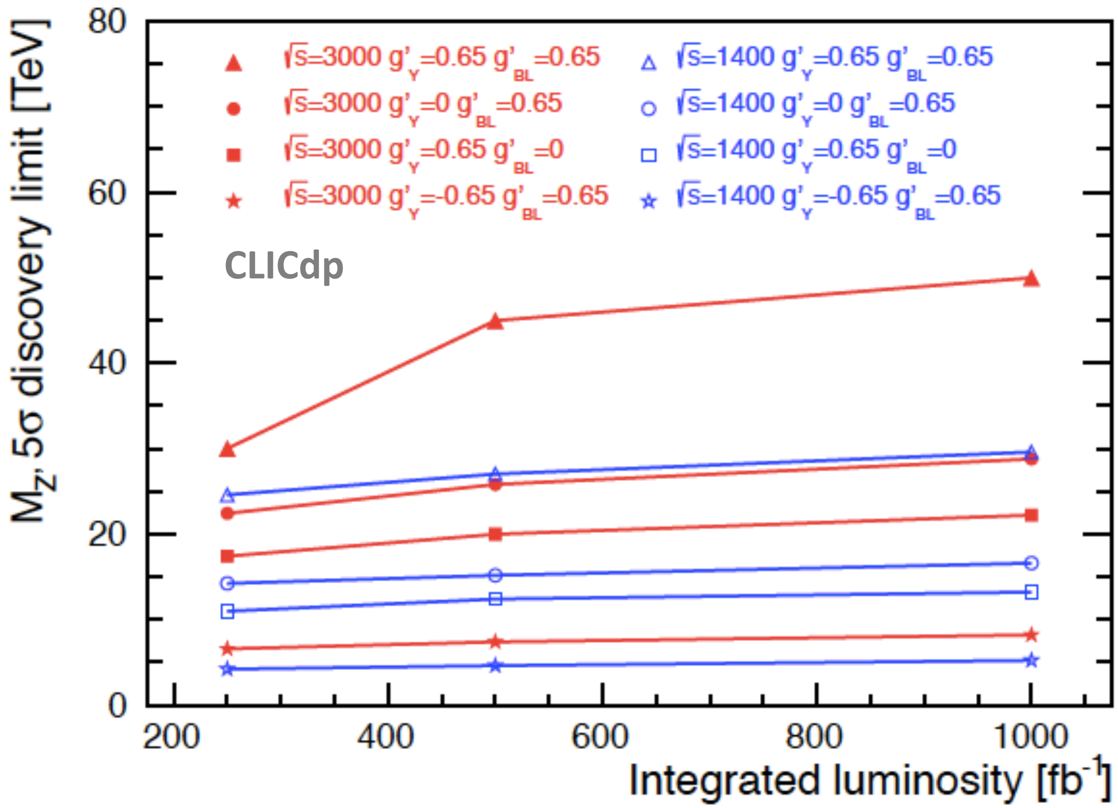
Minimal anomaly-free Z' model

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

Generator-level study

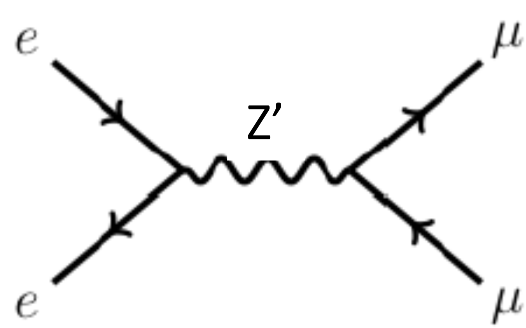
Observables:
- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

(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

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 %
$\Gamma_{H,md,derived}$	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 %
$\Gamma_{H,md,derived}$	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 %

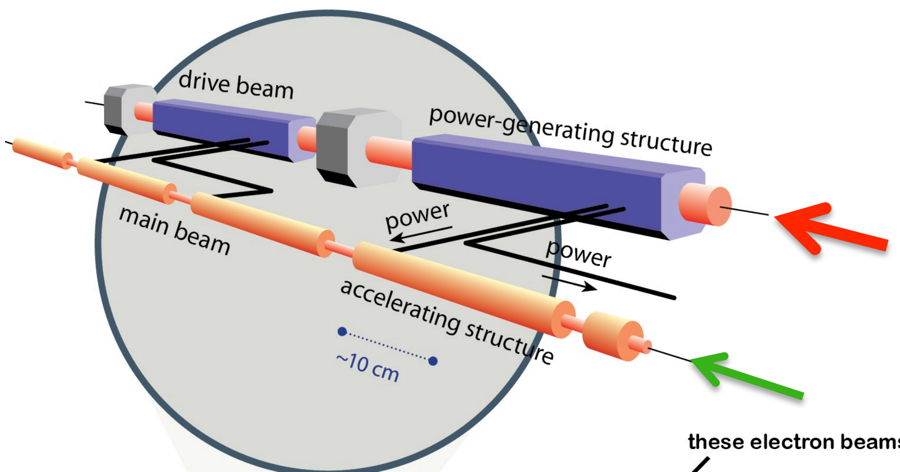
- Uncertainties from LHCHXSWG, combined theory and parametric (quark mass, α_s) uncertainties, symmetrized to preserve fit means

CLIC 2-beam acceleration scheme

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

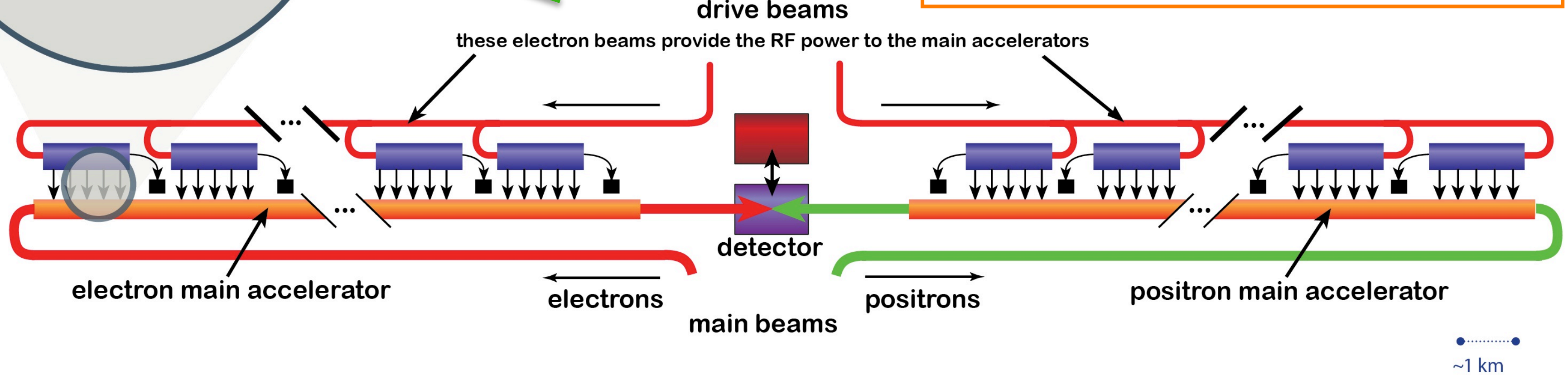
- High gradients feasible in normal conducting structures with high RF frequency (12 GHz)
- Initial transfer from wall plug to beam (klystron) is efficient at lower frequency (~1 GHz)
- To keep power low, apply RF power only at the time when the beam is there.

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

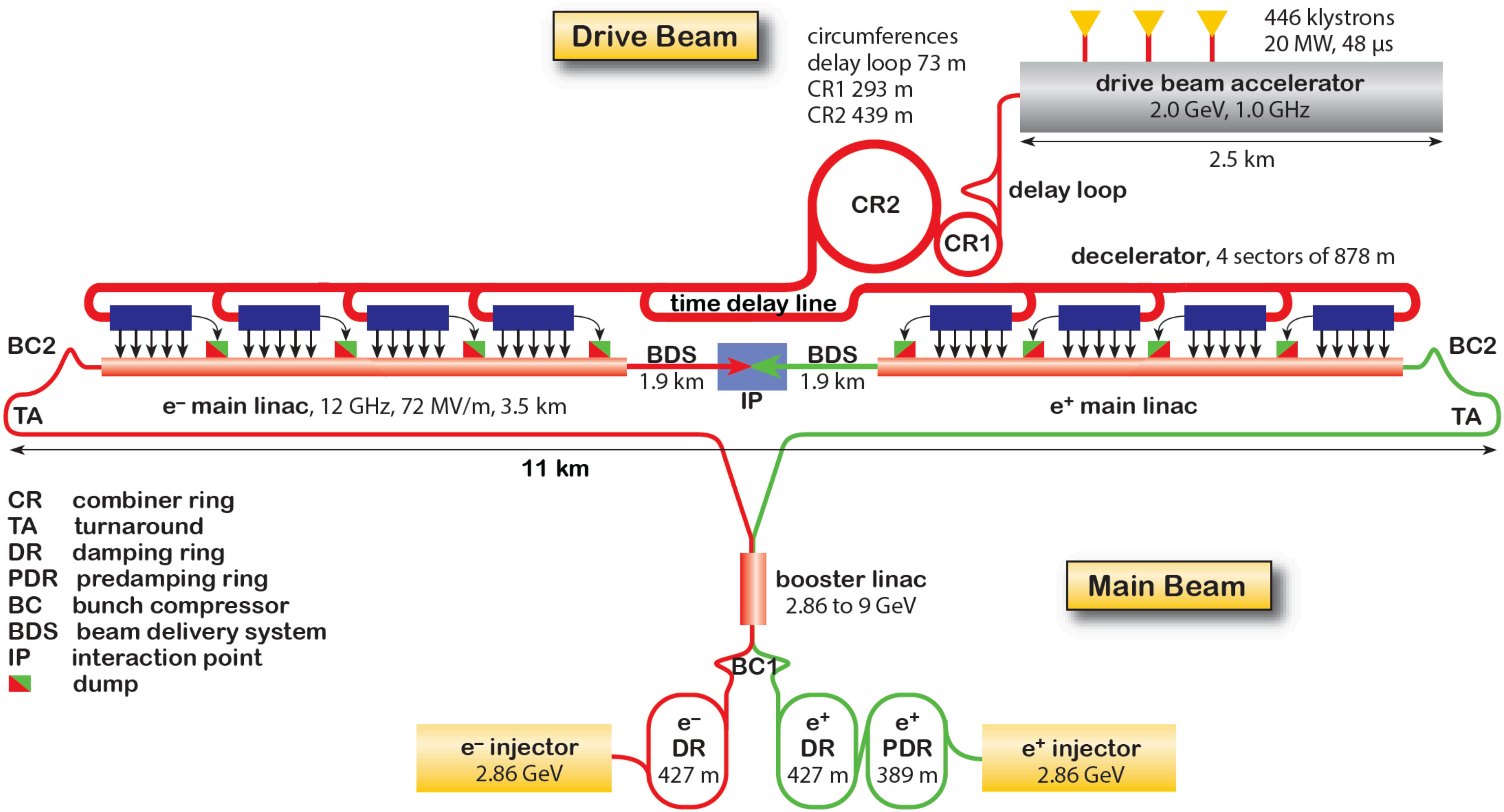


Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

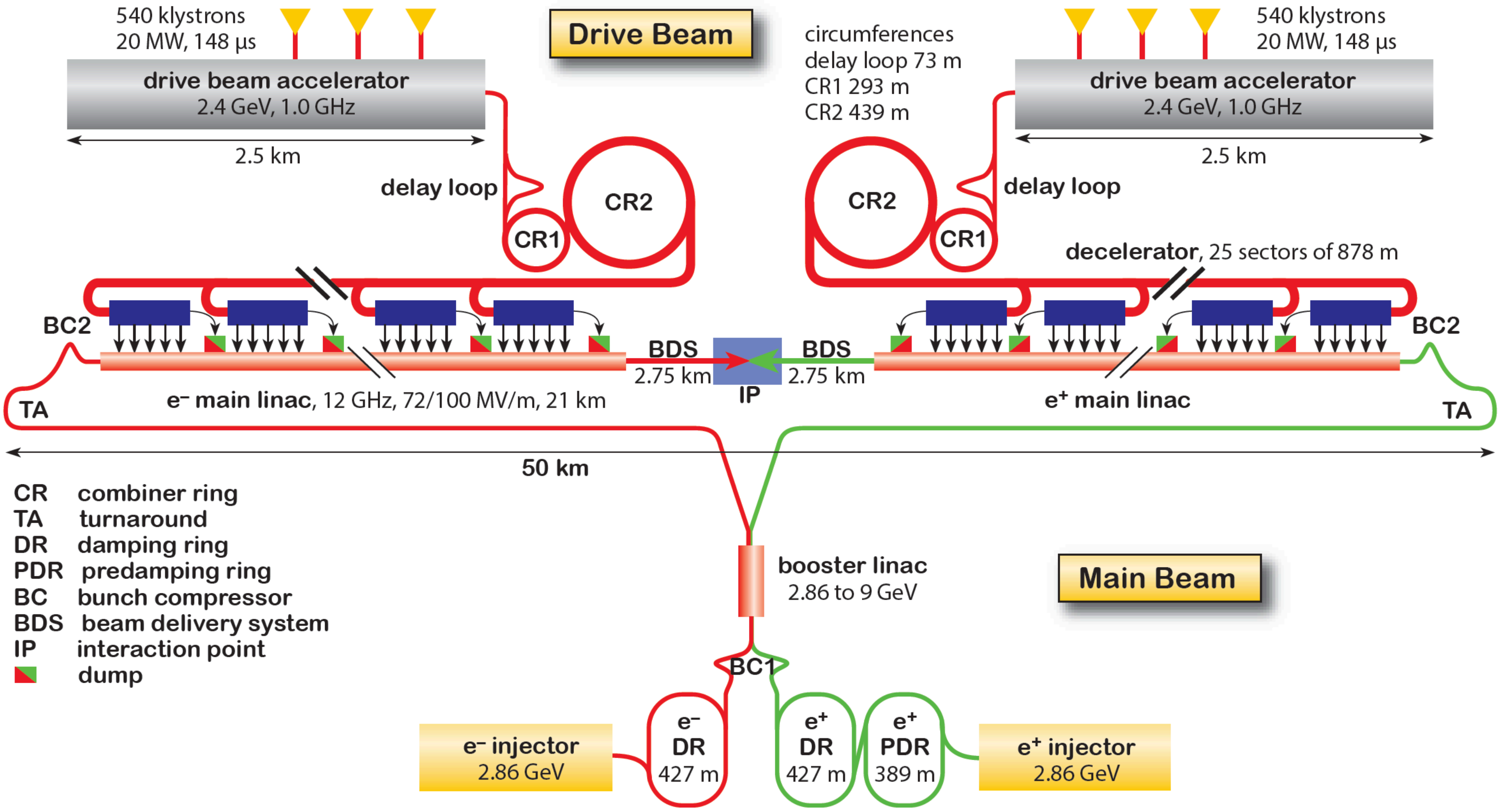
Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



CLIC layout at 380 GeV

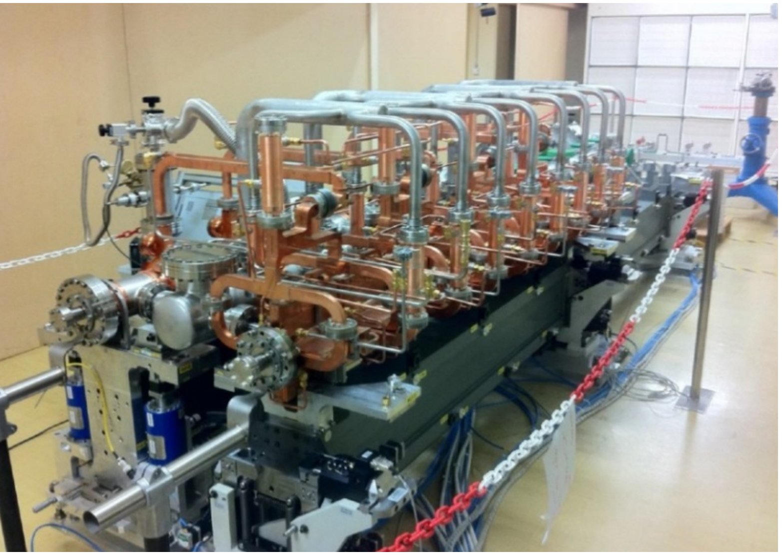


CLIC layout at 3 TeV

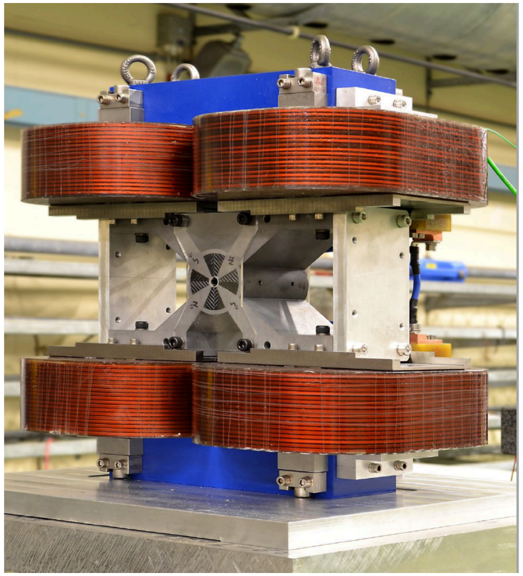


CLIC accelerator, some pictures

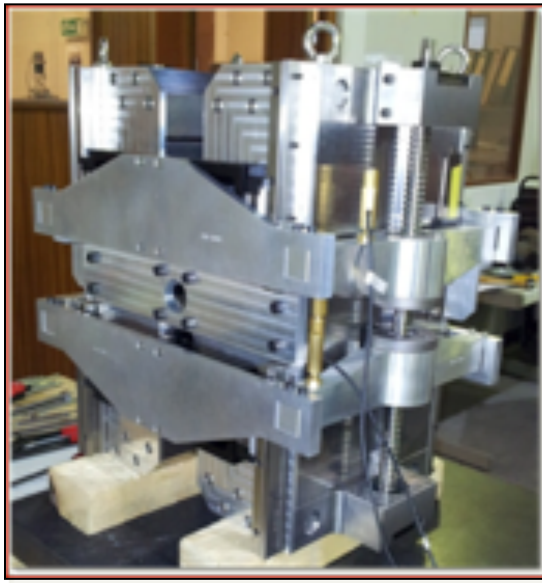
CLIC mechanical tests of 2-beam module



prototype final focus quadrupole

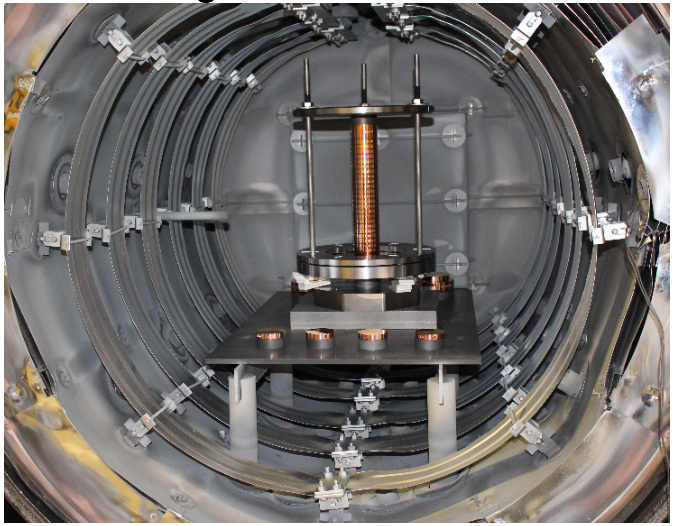


tunable permanent magnet

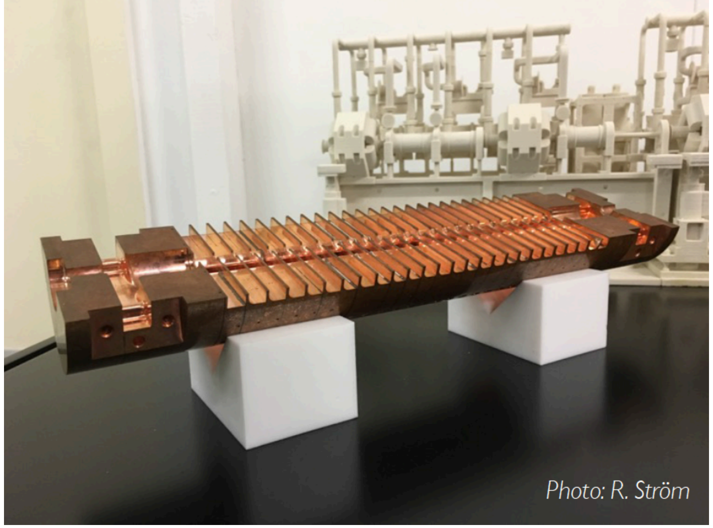


accelerator structure, 1 disk

brazing of a CLIC structure

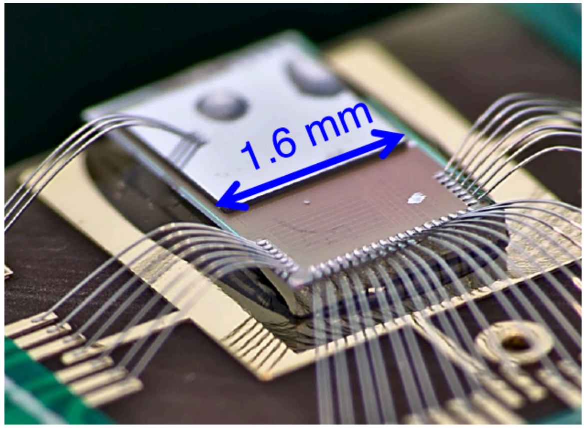


cut through a CLIC acceleration structure

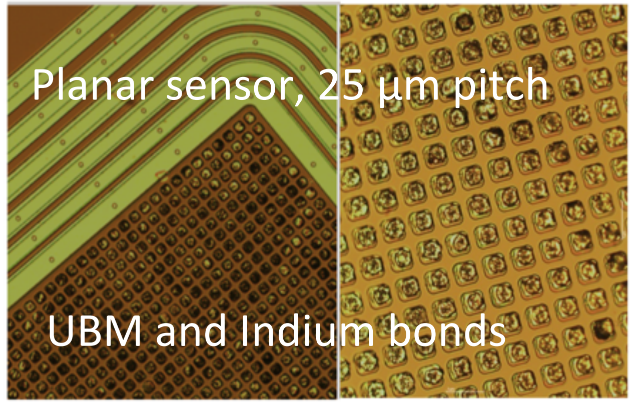


CLIC silicon vertex and tracker R&D (1)

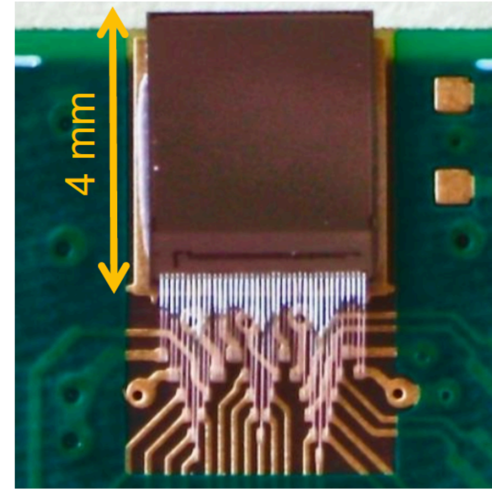
CLICpix (65 nm) + 50 µm sensor



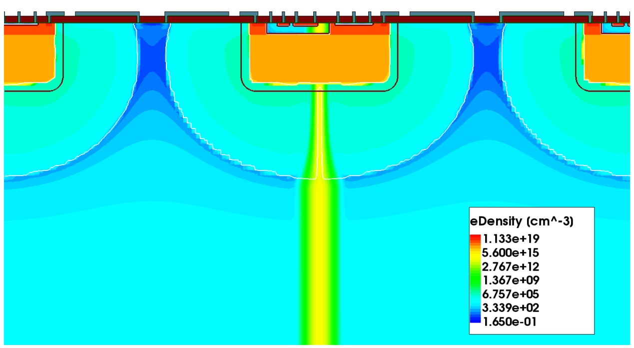
Bump-bonding, 25 µm pitch



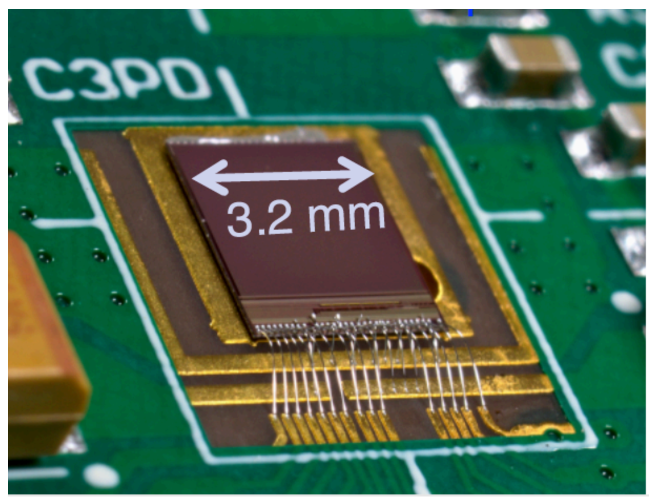
CLICpix2 ASIC (65 nm)



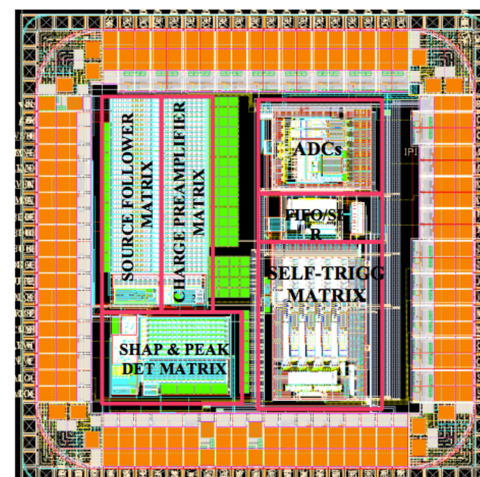
TCAD simulations, HV-CMOS sensor



C3PD HV-CMOS sensor, thinned 50 µm

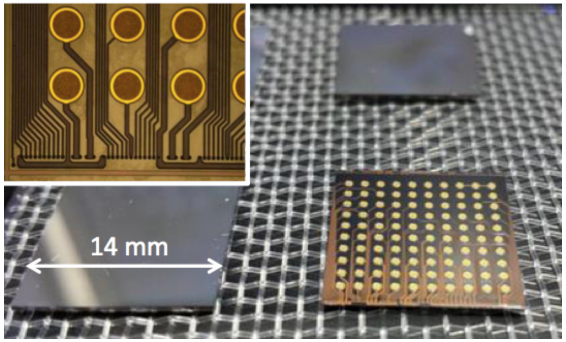


SOI sensor design

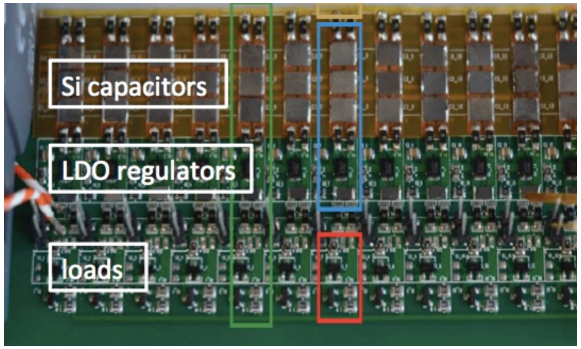


CLIC silicon vertex and tracker R&D (2)

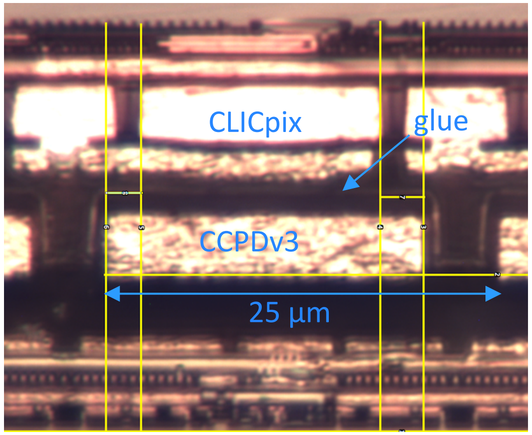
TSV interconnect technology

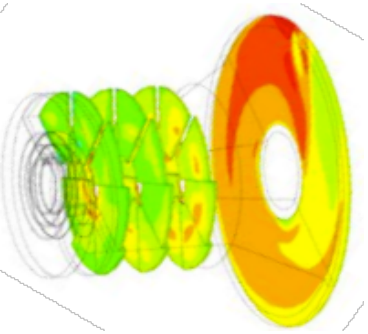


power delivery + pulsing

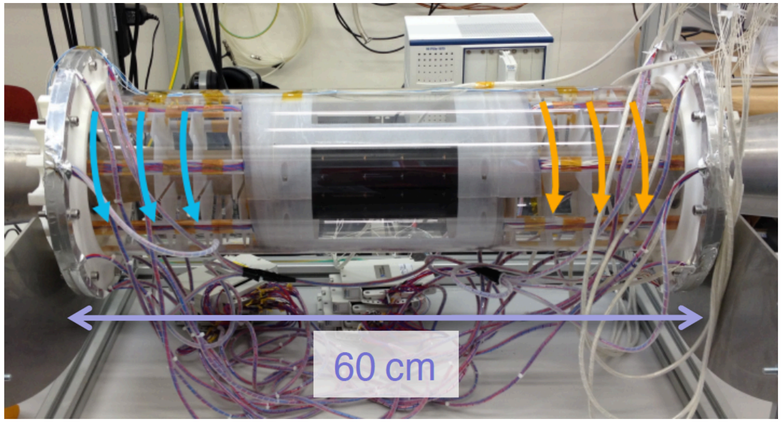


Flip-chip gluing (AC-coupling)

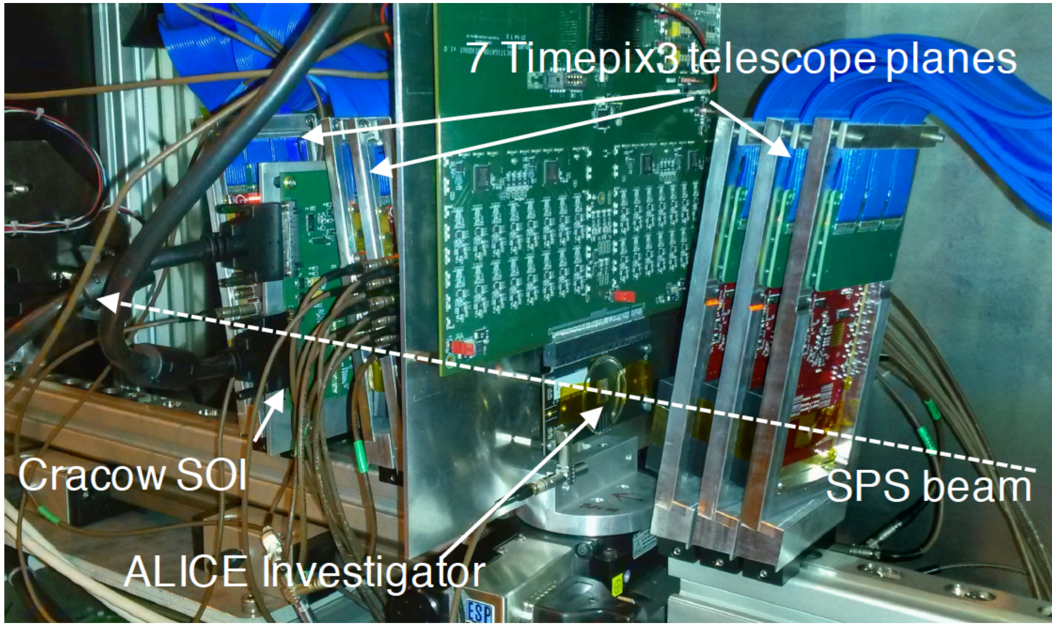




Air cooling simulation
and
1:1 scale test set up



LCD Timepix3 telescope at 2016 SPS test beam

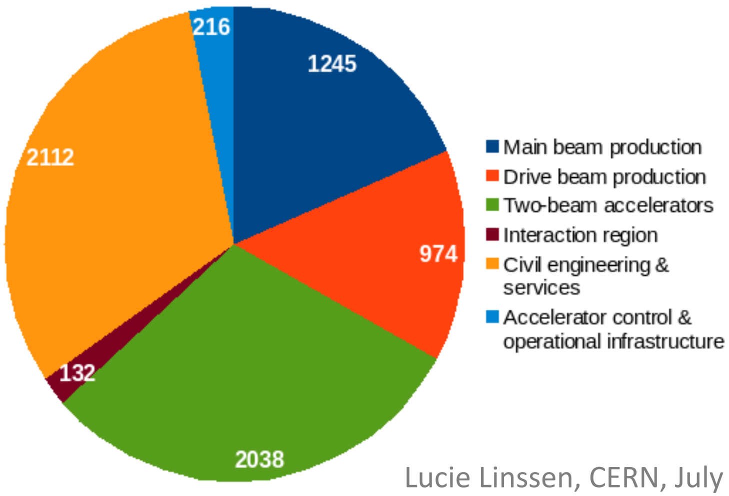


CLIC cost estimate

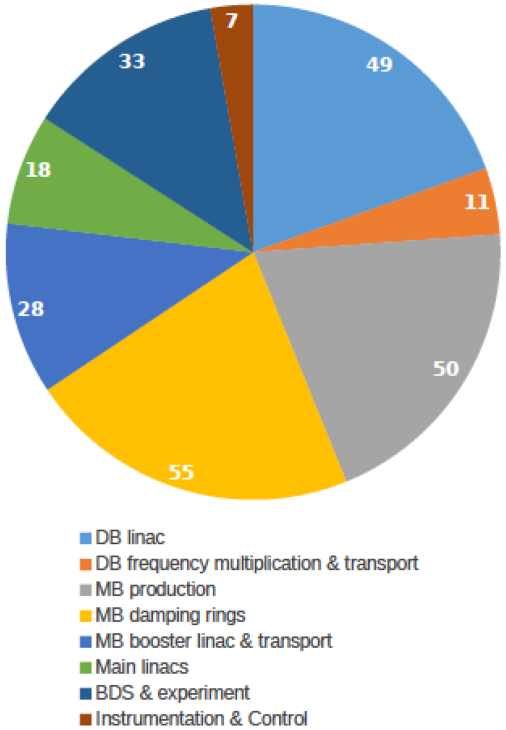
Preliminary estimate (scaled from CDR) with room for improvement.
New estimate will be provided for European Strategy Update.

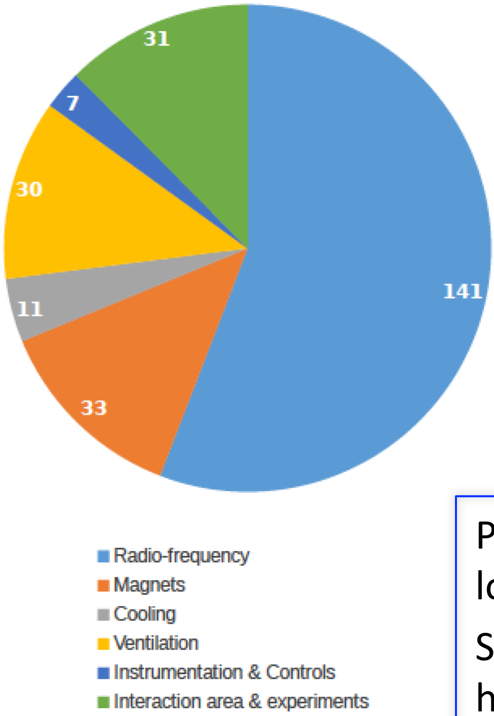
System	Value for 380 GeV (MCHF of Dec 2010)
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operation infrastructure	216
TOTAL	**6690**

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



Power and energy

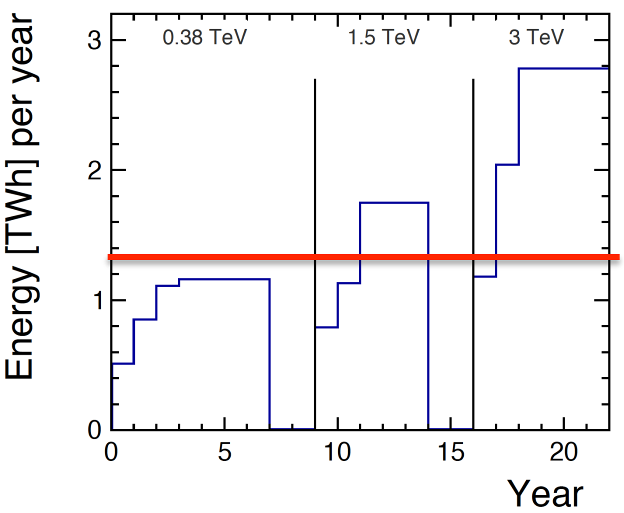




Power/energy reductions are being looked at

Structures are already optimised, however large contributions from:

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



CERN energy consumption 2012
1.35 TWh