Physics scope of CLIC, a future TeV-scale e^+e^- linear collider

Symposium-talk, in honor of Halina Abramowicz's birthday, January 5th 2014

Lucie Linssen, CERN

on behalf of the CLIC detector and physics study

Outline

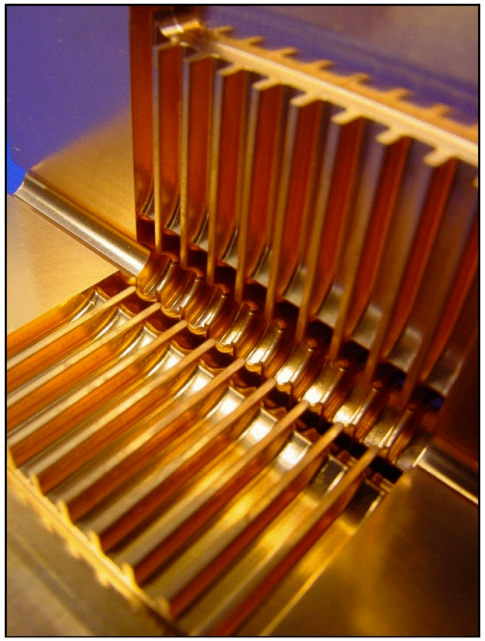
- Introduction to CLIC accelerator/detectors
- Overall Physics scope and √s energy staging
- Selected physics subjects:
  - Higgs
  - Top
  - Searches for New Physics
- Summary

- Introduction to CLIC accelerator/detectors

ILC and CLIC in just a few words

Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

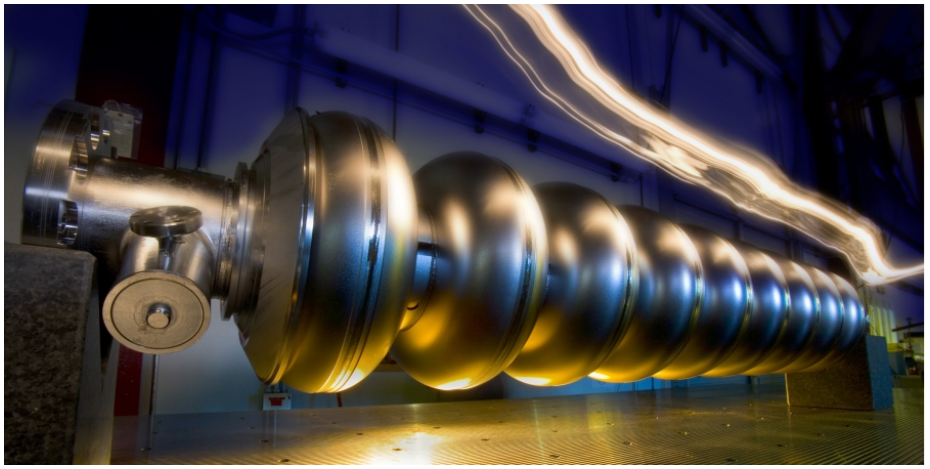
CLIC



- 2-beam acceleration scheme, at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

CLIC focus is on energy frontier reach !

ILC



- Superconducting RF cavities
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

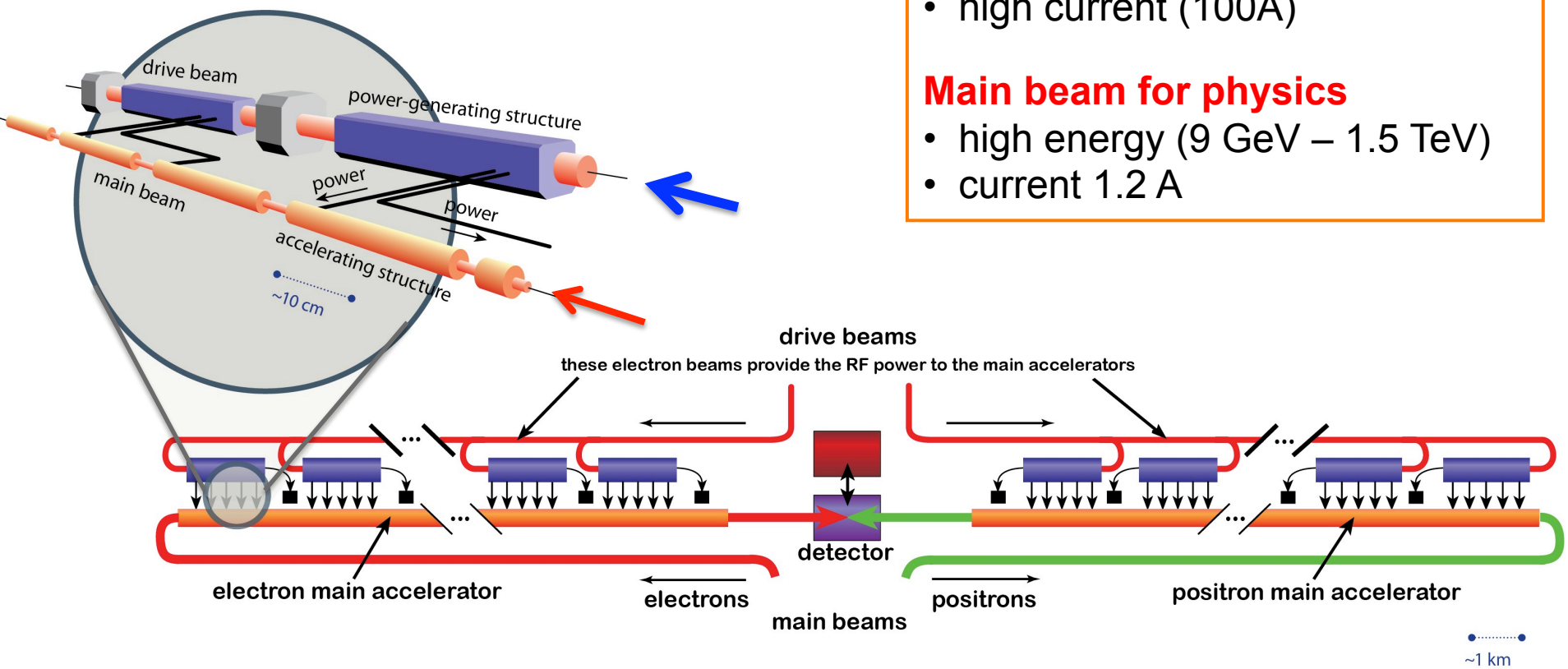
CLIC two-beam acceleration scheme

Accelerating gradient: 100 MV/m

Two Beam Scheme:

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

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



CLIC layout at 3 TeV

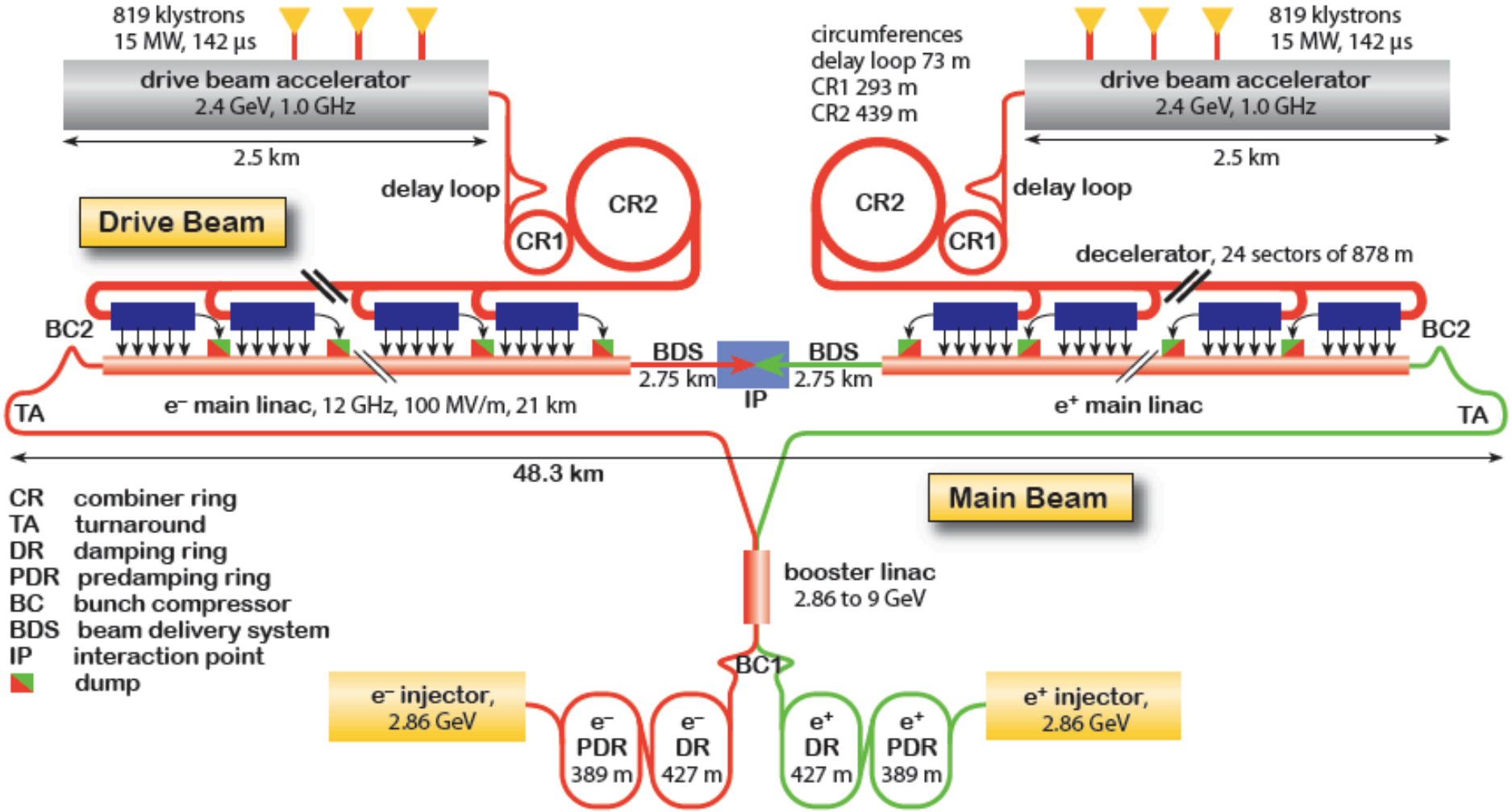
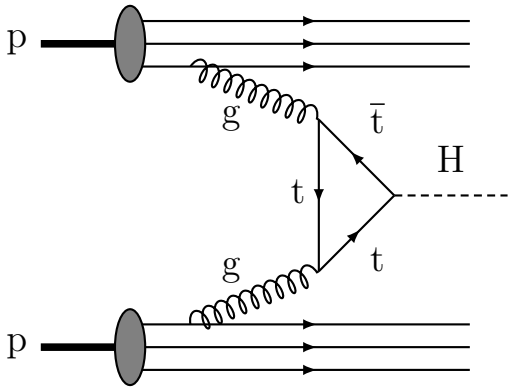
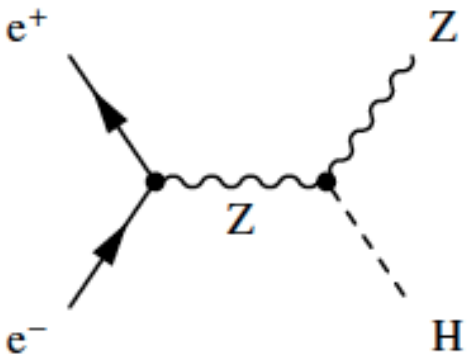


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

Hadron vs. lepton colliders

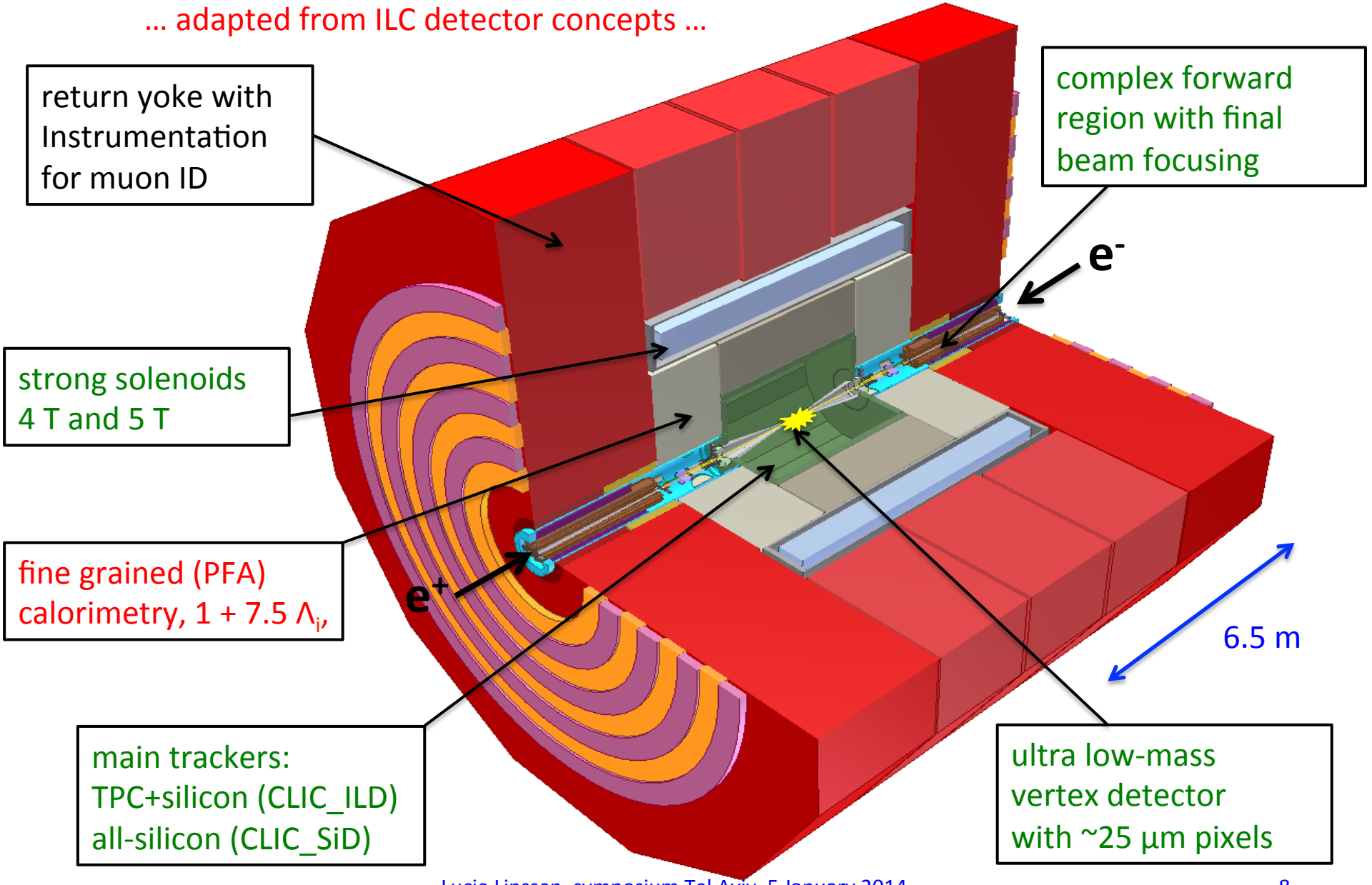




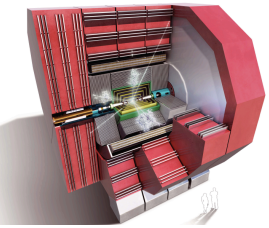
p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	e^+/e^- are point-like → Initial state well defined (√s / polarization) → High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron rad.)
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Cleaner experimental environment → trigger-less readout → Low radiation levels
High cross-sections for colored-states	Superior sensitivity for electro-weak states

CLIC detector concepts (1)

… adapted from ILC detector concepts …



CLIC detector concepts (2)

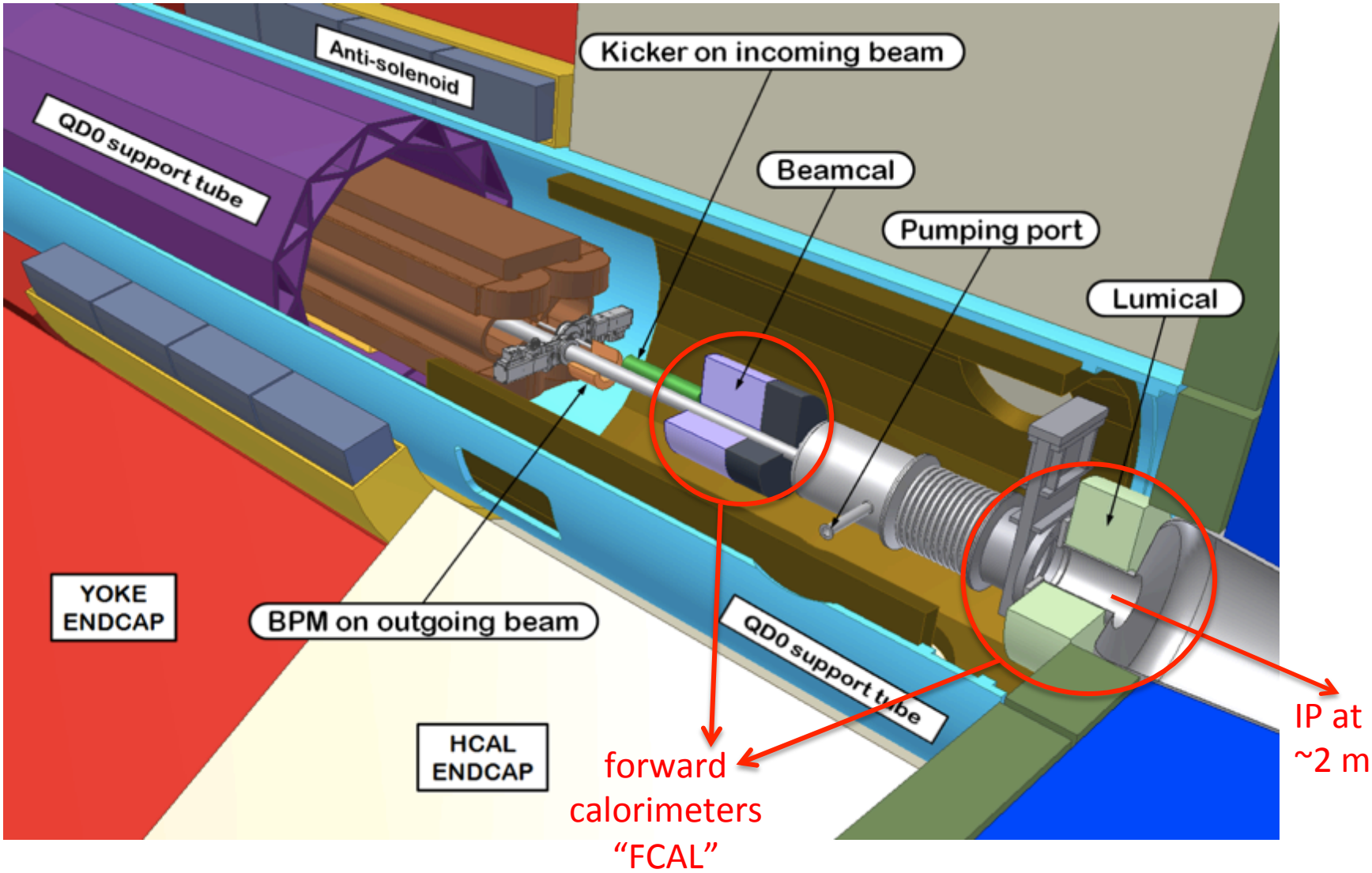


forward calorimeters **"FCAL"**

Important for:

- Acceptance
- Luminosity measurement
- Beam feedback

details of forward detector region



Compare experiment CLIC ⇔ LHC

In a nutshell:

CLIC detector:

- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (1ns, 10ns)
- **"No" issue of radiation damage (10^{-4} LHC)**
- **Beam crossings "sporadic"**
- **No trigger, read-out of full 156 ns train**

LHC detector:

- **Medium-high precision:**
  - Very precise ECAL (CMS)
  - Very precise muon tracking (ATLAS)
- **Overlapping minimum-bias events:**
  - High background rates, high energies
  - High occupancies
  - Can use vertex separation in z
  - Need precise time-stamping (25 ns)
- **Severe challenge of radiation damage**
- **Continuous beam crossings**
- **Trigger has to achieve huge data reduction**

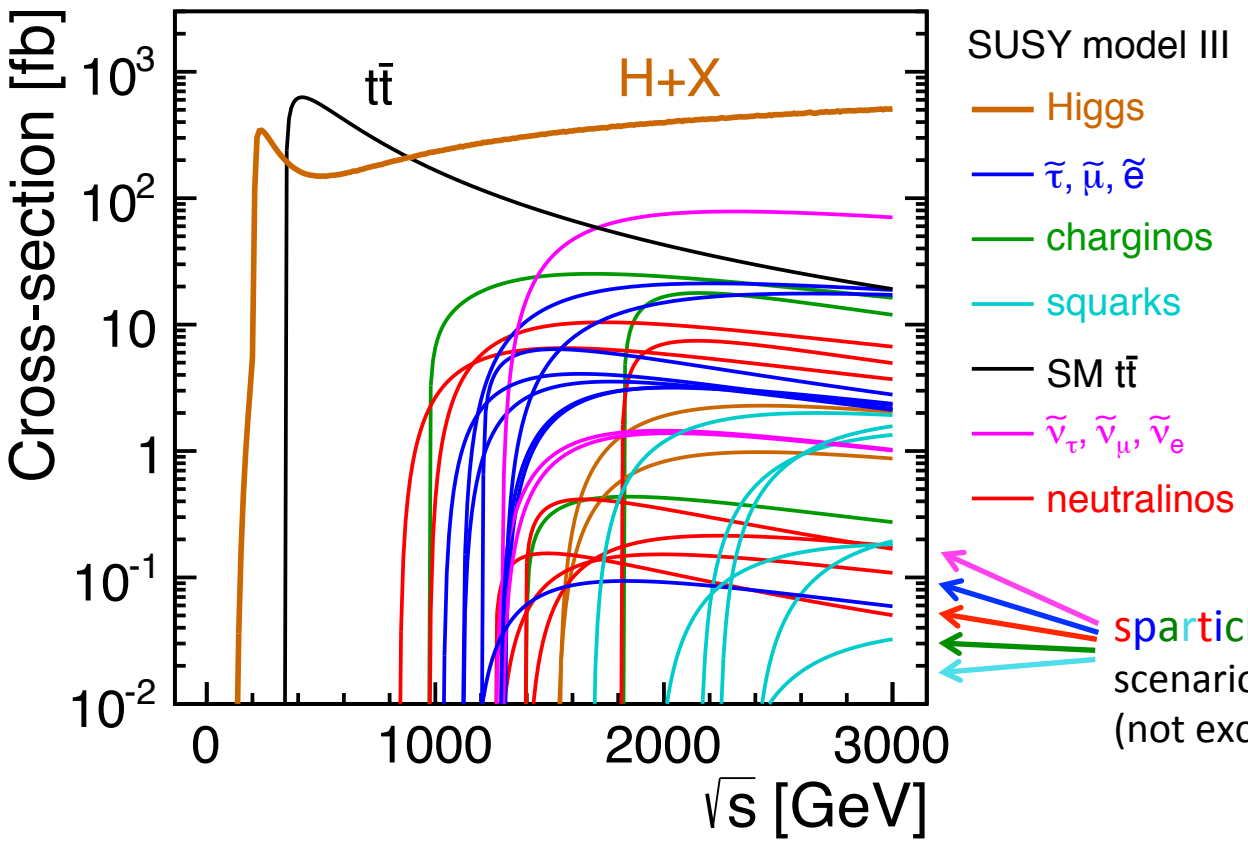
- Overall Physics scope and √s energy staging

Physics at CLIC

CLIC: e^+e^- collider, staged approach

- 500 fb^{-1} @ 350 – 375 GeV : precision Higgs and top physics
- 1.5 ab^{-1} @ ~1.5 TeV : precision Higgs, precision SUSY, BSM reach, …
- ~2 ab^{-1} @ ~ 3 TeV : Higgs self-coupling, precision SUSY, BSM, …

reachExact energies of TeV stages would depend on LHC results



Example SUSY model

sparticles in **SUSY** example scenario
(not excluded by LHC results)

Physics at CLIC

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- 500 fb^{-1} @ 350 – 375 GeV : precision Higgs and top physics
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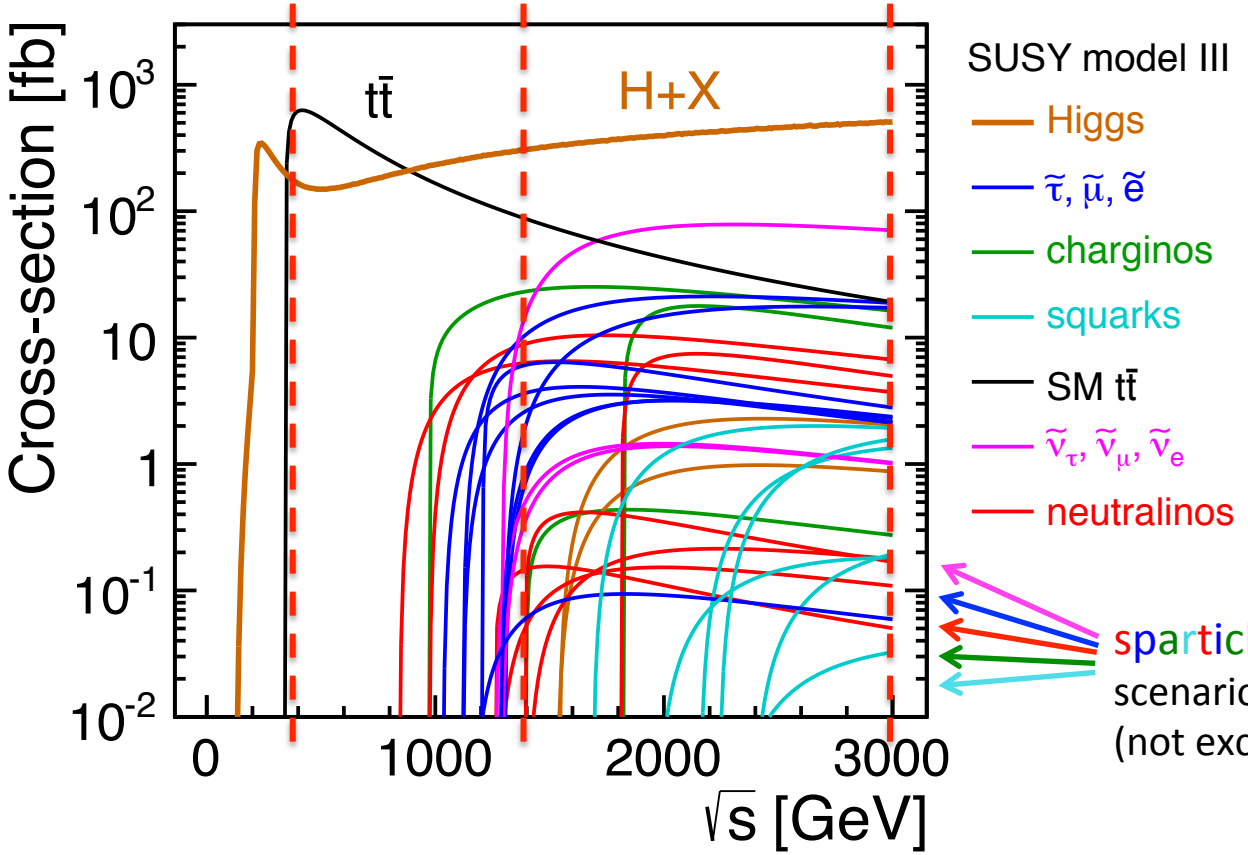
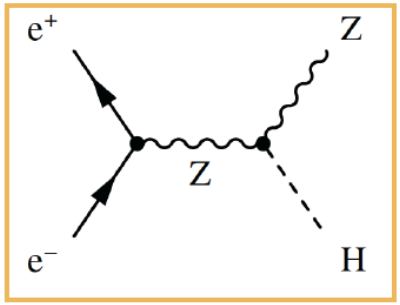


Example of energy staging

sparticles in **SUSY** example scenario
(not excluded by LHC results)

- Higgs physics



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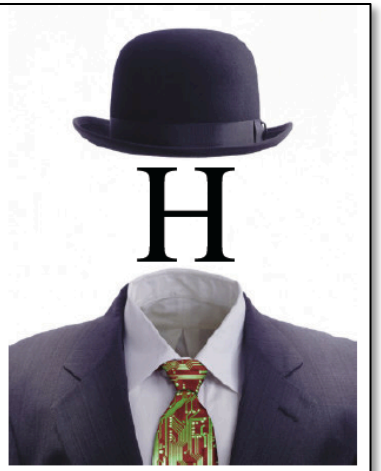
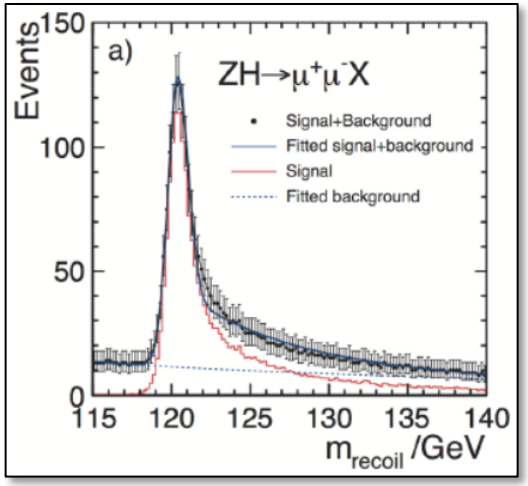
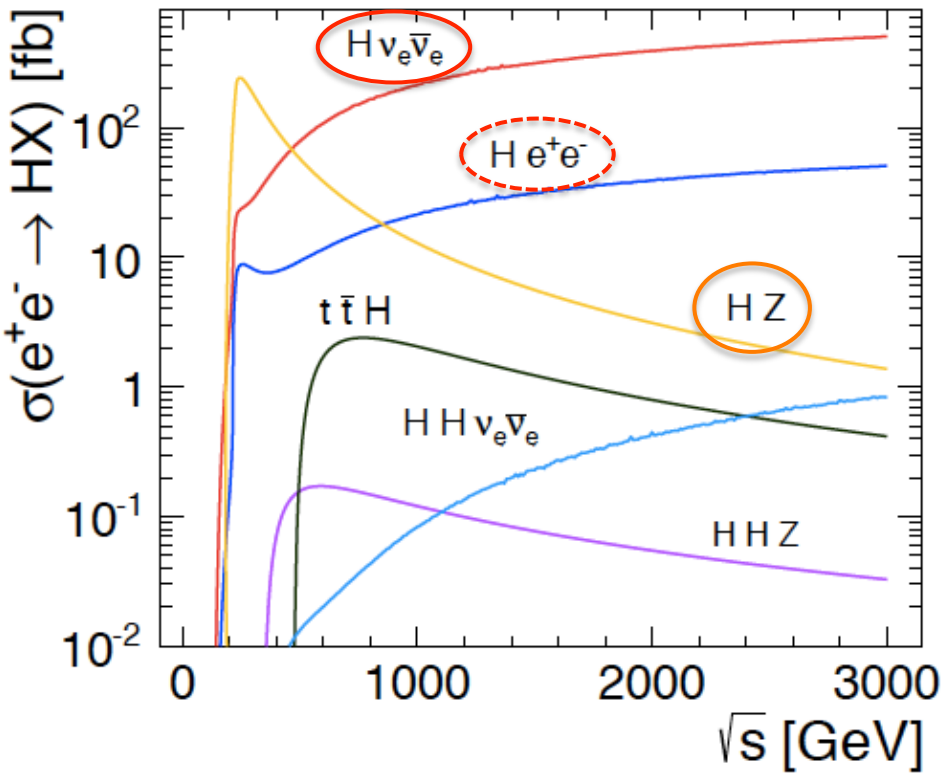
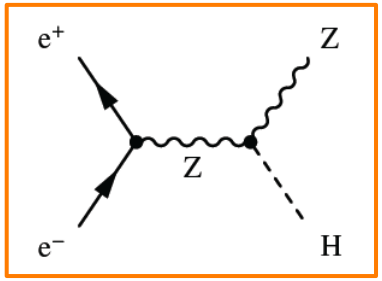




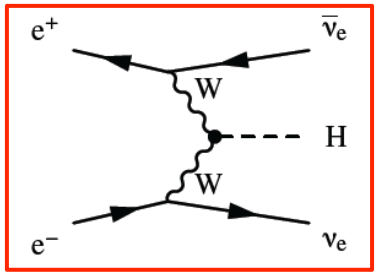
Higgs physics at CLIC



Dominant processes:



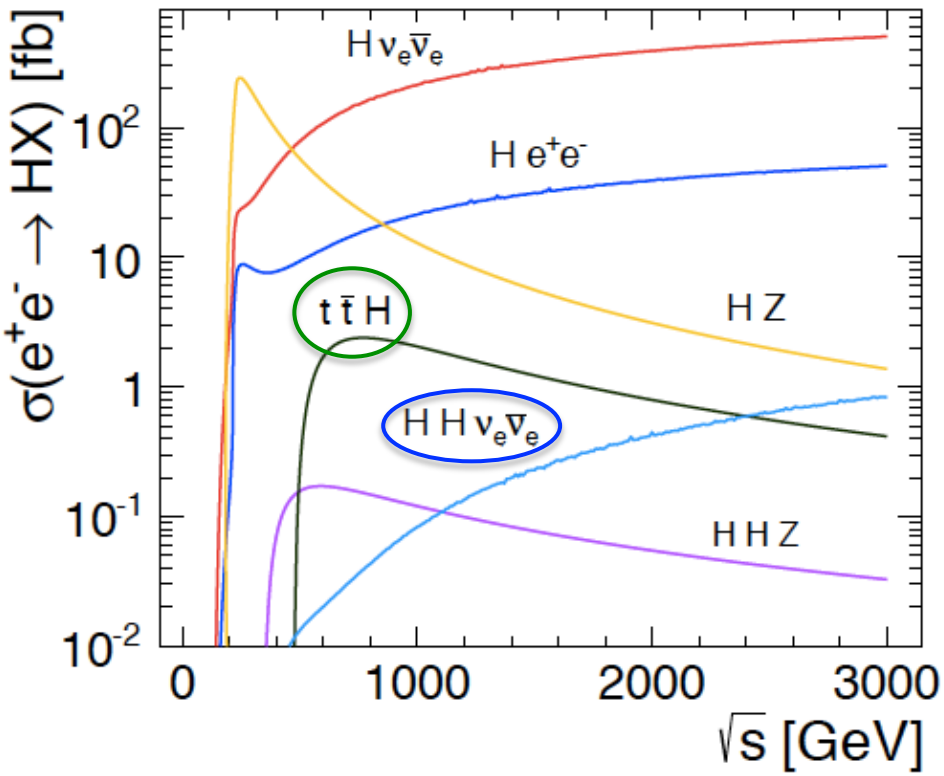
Higgsstrahlung decreases with √s



W(Z) - fusion increases with √s

	350 GeV	1.4 TeV	3 TeV
$\mathscr{L}_{\text{int}}$	500 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	68,000	20,000	11,000
# $H\nu_e\bar{\nu}_e$ events	26,000	370,000	830,000
# He^+e^- events	3,700	37,000	84,000

Higgs physics at CLIC

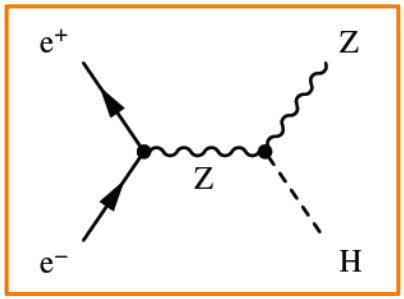


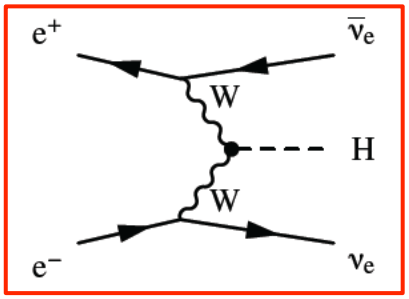
Higgs-Strahlung: $e^+e^- \rightarrow ZH$
- Measure H from Z-recoil mass
- Model-independent meas.: m_H, σ
- Yields absolute value of g_{HZZ}

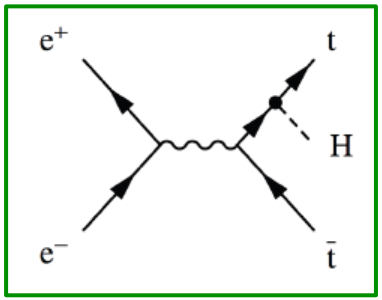
WW fusion: $e^+e^- \rightarrow H\nu_e\nu_e$
- Precise cross-section measurements in ττ, μμ, qq, … decay modes
- Profits from higher √s (≳350 GeV)

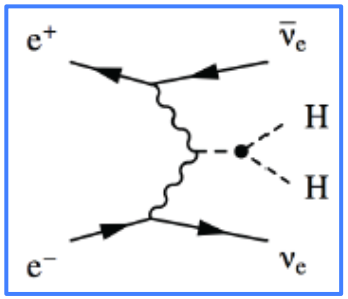
Radiation off top-quarks: $e^+e^- \rightarrow ttH$
- Measure top Yukawa coupling
- Needs √s≳700 GeV

Double-Higgs prod.: $e^+e^- \rightarrow HH\nu_e\nu_e$
- Measure tri-linear self coupling
- Needs high √s (≳1.4 TeV)

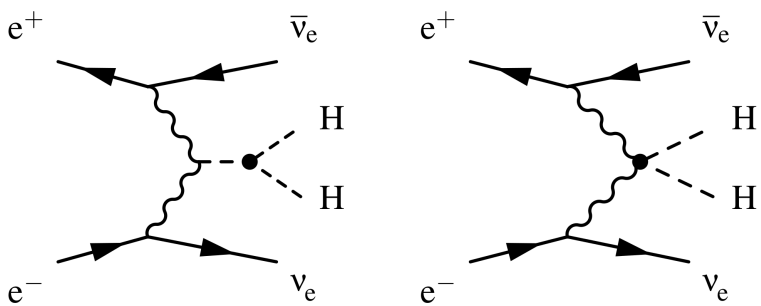


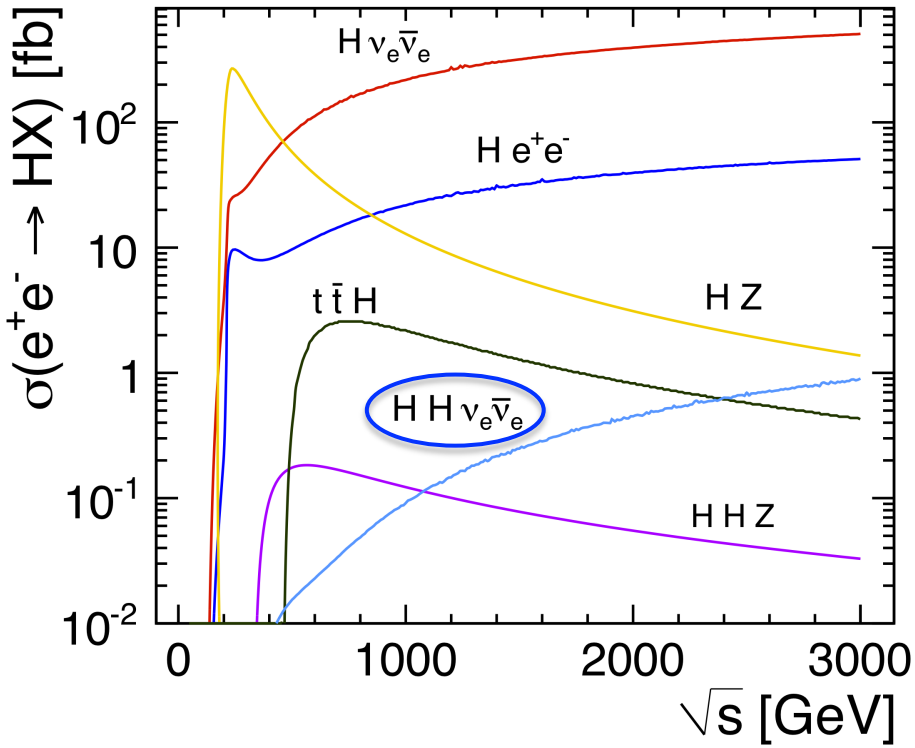






Double Higgs production





- The HHv_ev_e cross section is sensitive to the Higgs self-coupling, λ, and the quartic g_{HHWW} coupling
- $\sigma(HHv_ev_e)$ = 0.15 (0.59) fb at 1.4 (3) TeV
  → high energy and luminosity crucial

	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
$\Delta(\lambda)$	28%	16%
$\Delta(\lambda)$ for $p(e^-)$ = 80%	21%	12%

← results obtained for m_H=120 GeV

Summary of Higgs measurements

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	tbd	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	29%*	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	tbd	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarization	λ	–	21%	12%

Summary of results from detailed Higgs benchmark simulation studies, with full-detector simulation and overlay of beam-induced backgrounds

http://arxiv.org/abs/1307.5288

To be combined with recent result:

$$\frac{\Delta(\sigma(HZ)\times BR(Z\to qq))}{\sigma(HZ)\times BR(Z\to qq)} \approx 2.2\%$$

Work in progress !

* Preliminary
\+ Estimate

CLIC Higgs global fits

Work in progress !

★ Model-independent global fits

80% electron polarisation assumed above 1 TeV

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
m_H	120.00 MeV	30.00 MeV	20.00 MeV
λ	–	21.00%	10.00%
Γ_H [%]	5.47	4.23	4.11
g_{HZZ} [%]	1.00	1.00	1.00
g_{HWW} [%]	1.87	1.05	1.03
g_{Hbb} [%]	2.06	1.11	1.05
g_{Hcc} [%]	3.28	1.50	1.26
g_{Htt} [%]	–	4.15	4.13
$g_{H\tau\tau}$ [%]	3.55	1.68	1.64
$g_{H\mu\mu}$ [%]	–	11.03	5.37
g_{Hgg} [%]	3.67	1.29	1.15
$g_{H\gamma\gamma}$ [%]	–	5.60	5.59

★ ~1 % precision on many couplings

- limited by g_{HZZ} precision

★ Constrained "LHC-style" fits

- Assuming no invisible Higgs decays (model-dependent):

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}}$$

$$\Gamma_{H,md} = \sum_i \kappa_i^2 \, BR_i$$

Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
$\Gamma_{H,model}$ [%]	1.62	0.29	0.22
κ_{HZZ} [%]	0.45	0.32	0.24
κ_{HWW} [%]	1.53	0.15	0.11
κ_{Hbb} [%]	1.69	0.33	0.21
κ_{Htt} [%]	3.07	1.04	0.74
$\kappa_{H\tau\tau}$ [%]	3.45	1.35	1.31
κ_{Hgg} [%]	3.62	0.79	0.56
$\kappa_{H\gamma\gamma}$ [%]	–	5.52	5.51

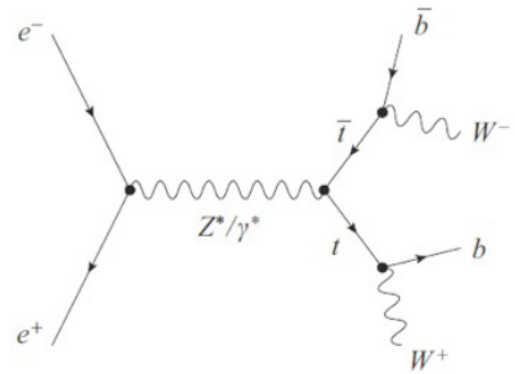
★ sub-% precision for most couplings

- Top physics

Top physics at CLIC

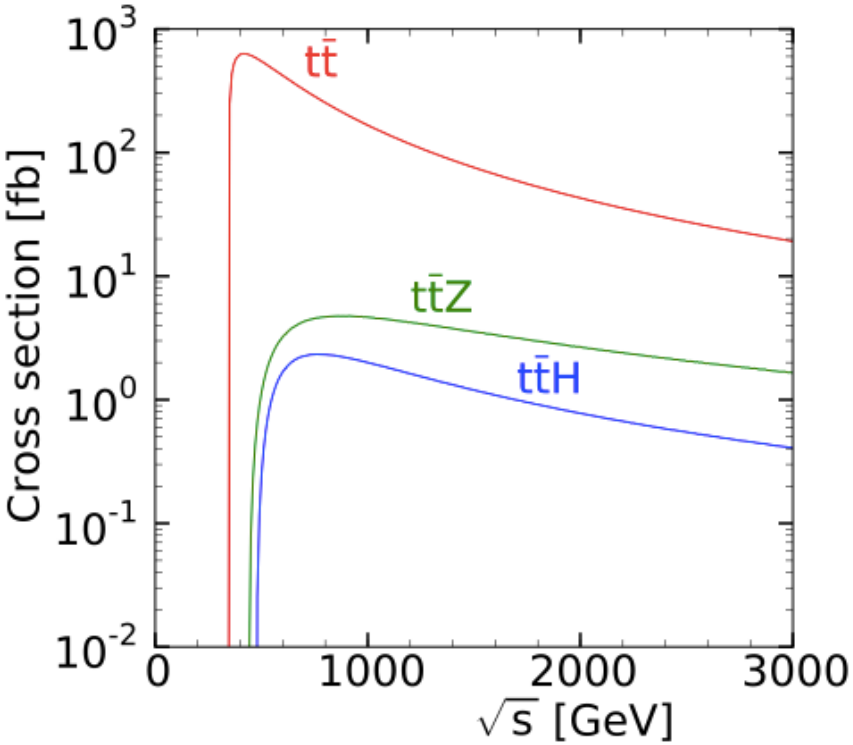
Exploration of scope for top physics at CLIC is in an early stage:

- Existing studies concentrate on top mass measurements
- Coupling to the Higgs (as part of Higgs studies)

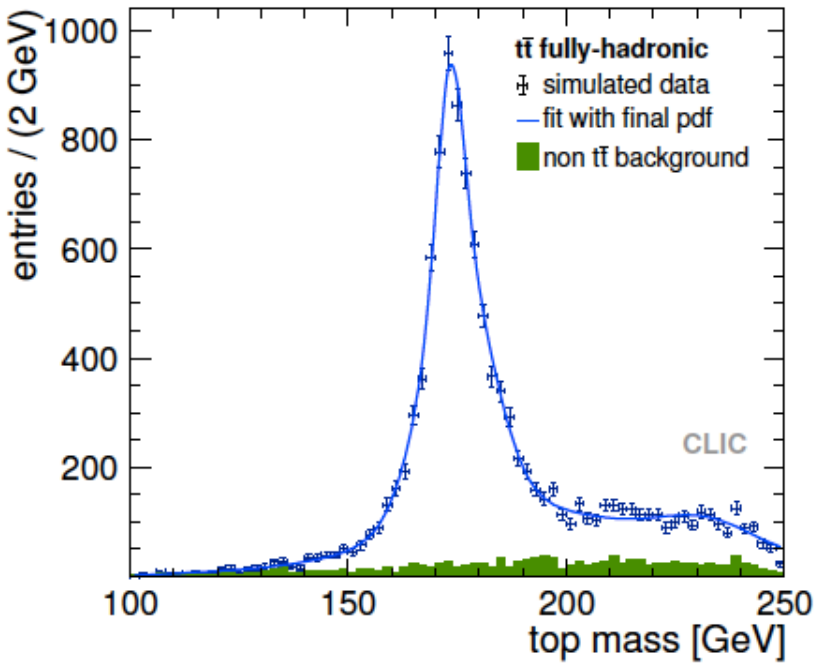


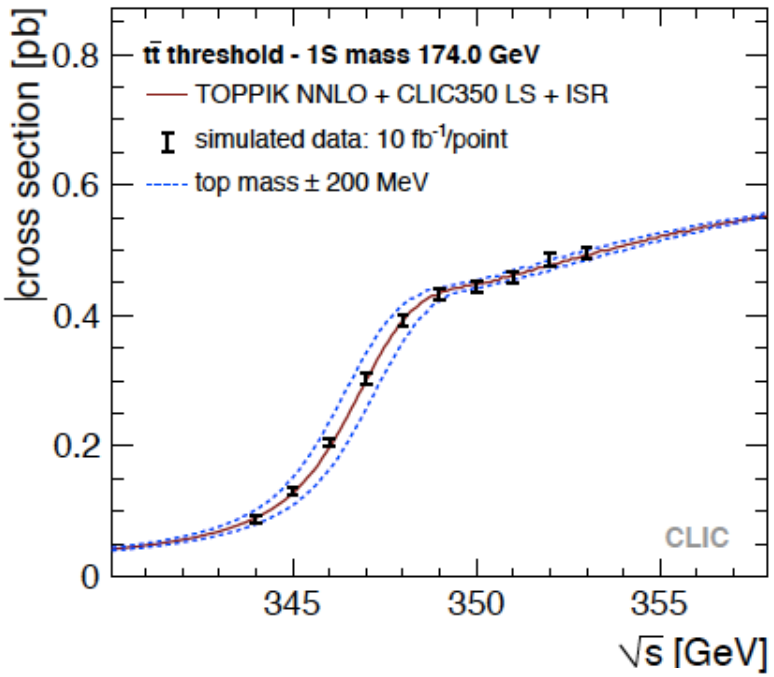
Plans for next studies include:

- Asymmetries to study couplings to γ, Z
- Measurement of couplings to W
- Sensitivity to CP violation
- Flavour-changing top decays
- ….



Results of top benchmark studies





$\sqrt{s}$ (GeV)	Technique	Measured quantity	Integrated luminosity (fb^{-1})	Unit	Generator value	Stat. error
350	Threshold scan	Mass α_S	10×10	GeV	174 0.118	0.033 0.0009
500	Invariant mass	Mass	100	GeV	174	0.080

right

left plot

Final result is dominated by systematic errors (theor. normalisation, beam-energy systematics, translation of 1S mass to $\overline{MS}$ scheme) => 100 MeV error on top mass

- CLIC potential for New Physics

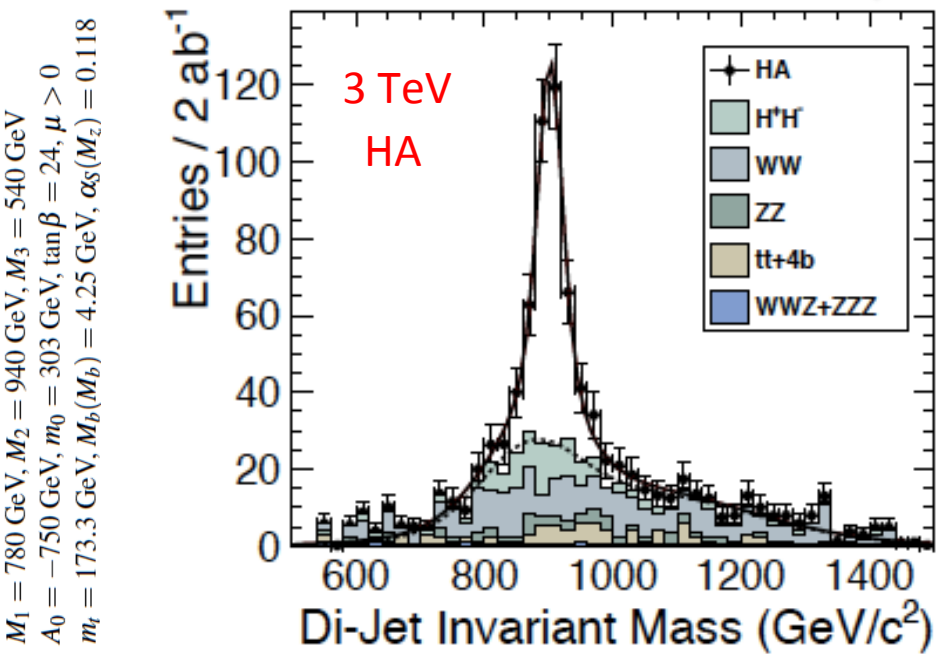
Sensitivity to Higgs partners

Higgs multiplet BSM ➔ searches **accessible up to √s/2**

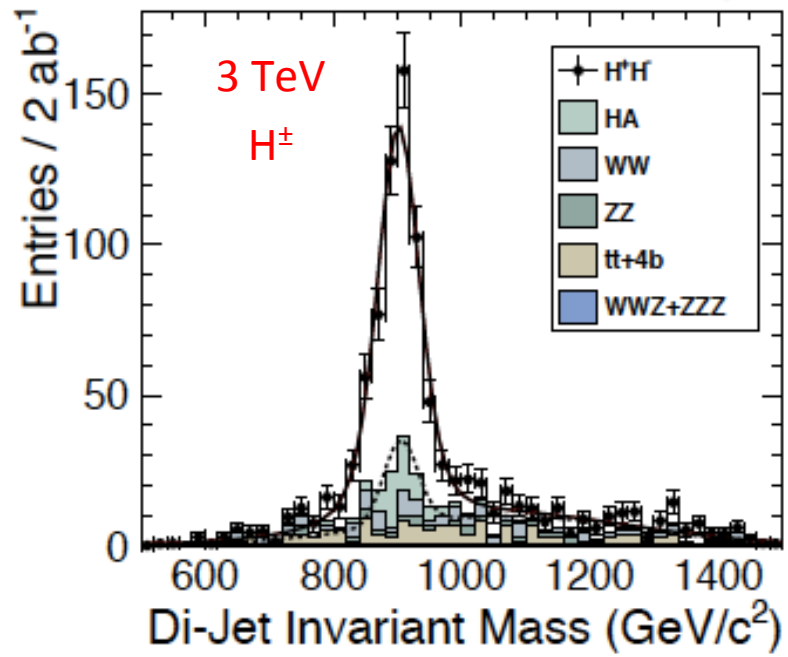
Example MSSM benchmark study at 3 TeV, 2 ab^{-1}

Multi-jet final states
Full simulation studies with background overlay

m_{A^0/H^0} : ± 2.8 GeV ↓



$m_{H^\pm}$: ± 2.4 GeV ↓



SUSY => slepton study, 3 TeV

Slepton production at CLIC very clean

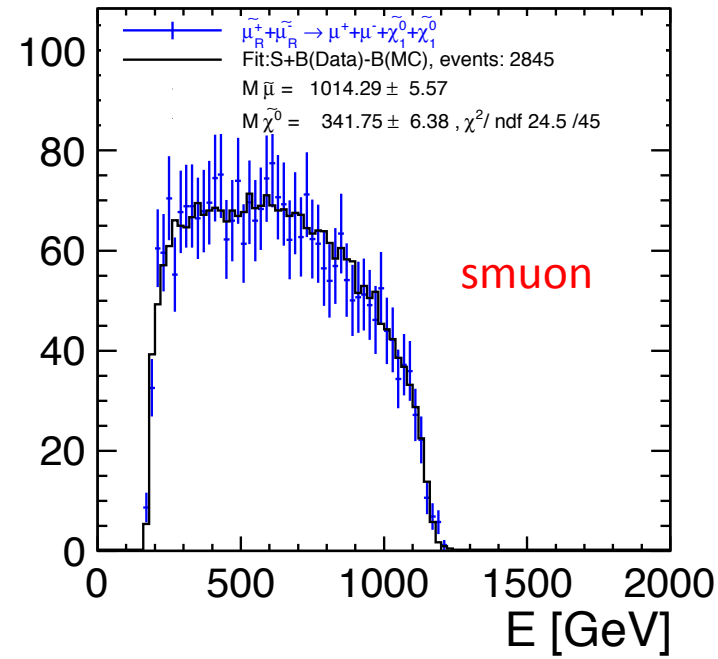
SUSY "*model II*": slepton masses ~ 1 TeV

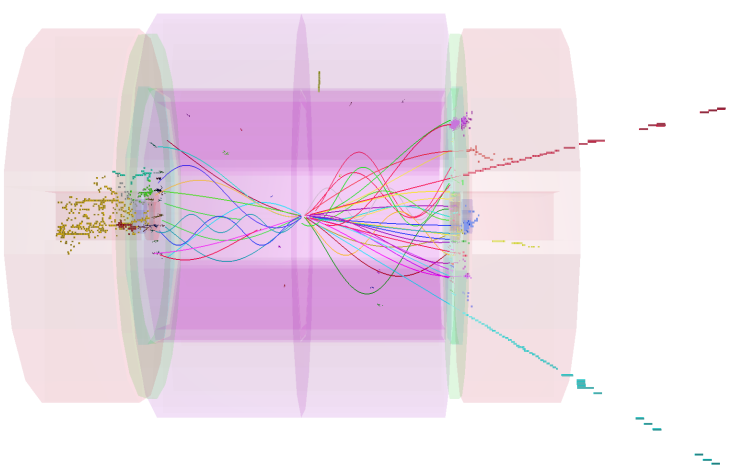
Channels studied include

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

Leptons and missing energy

Masses from analysis of endpoints of energy spectra





stat. error, all channels combined

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

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

gaugino pair production, 3 TeV

Example

SUSY "*model II*": $m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$ $m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$

Pair production and decay:

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

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

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

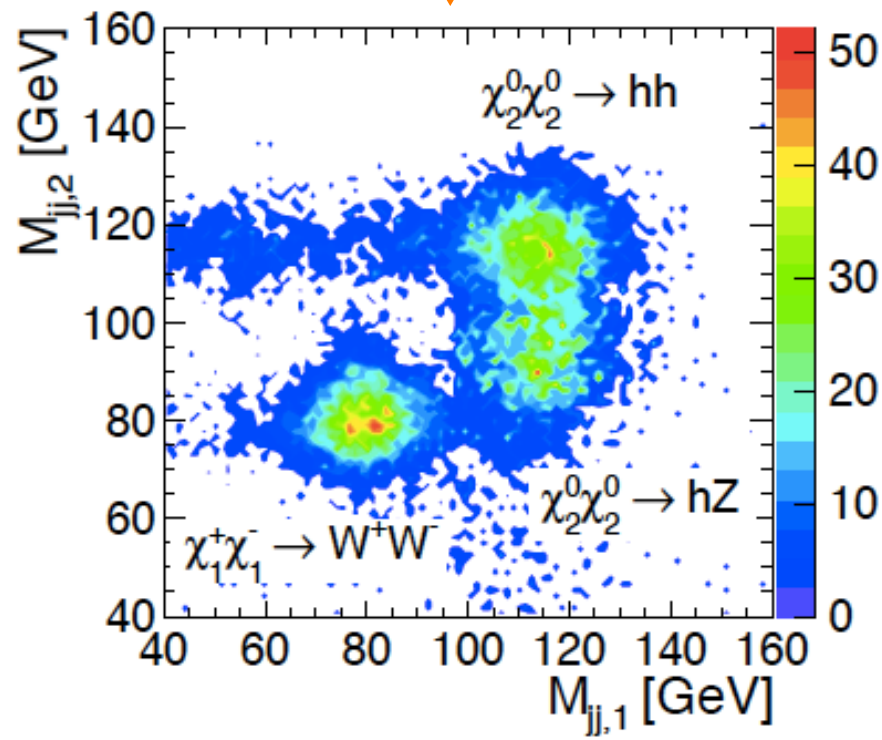
$m(\tilde{\chi}_1^\pm)$: $\pm 7\,\mathrm{GeV}$

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

use slepton study result

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

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



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].

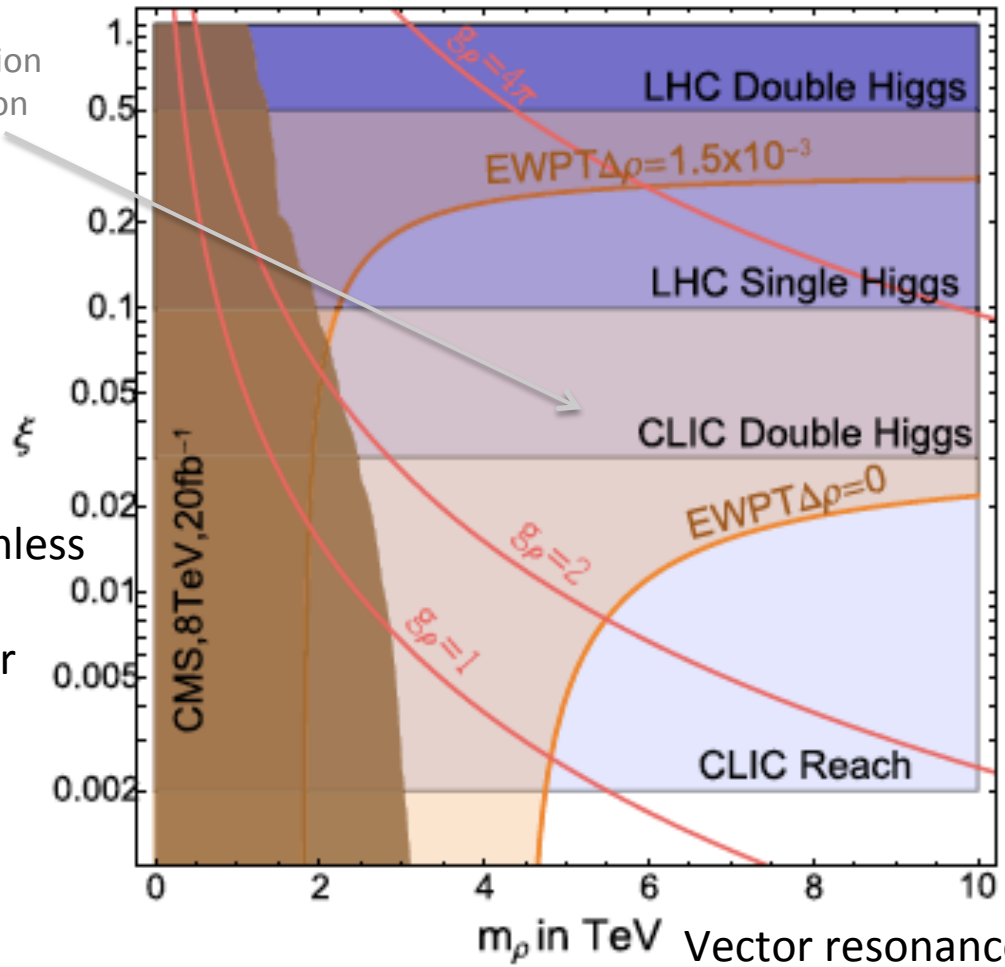
$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ 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

Higgs compositeness

allowed region EW precision tests

dimensionless scale parameter

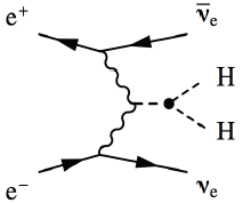


Vector resonance mass

LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search WZ =>3 leptons

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

(60 TeV scale if combined with single Higgs production)

Indirect Z' search

Indirect Z' search in $e^+e^- \Rightarrow \mu^+\mu^-$

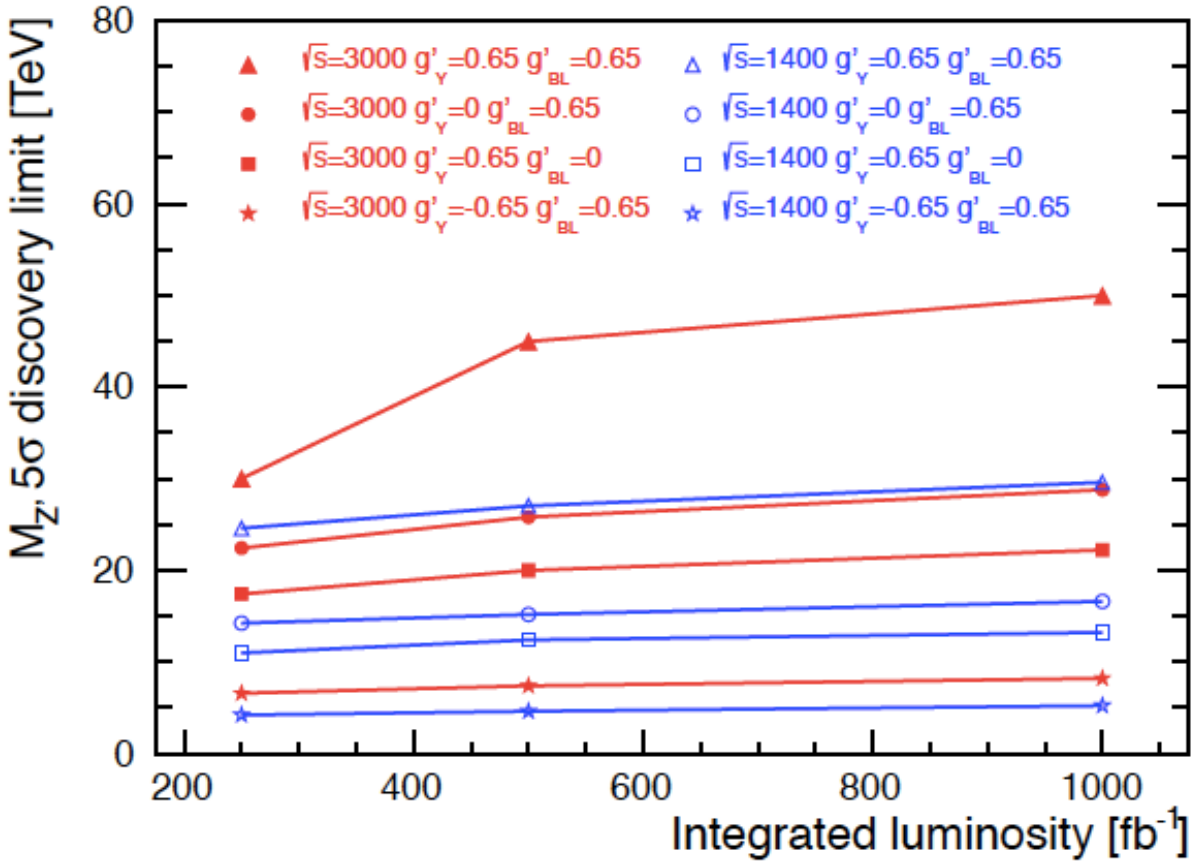


Fig. 14: 5σ limit for a $M_{Z'}$ discovery as function of the integrated luminosity for different values of the couplings g'_Y and g'_{BL}. The limits shown are determined from the combined observables σ and A_{FB} at $\sqrt{s} = 3$ TeV and 1.4 TeV.

CLIC reach for New Physics

CLIC at 3 TeV

New particle	LHC (14 TeV)	HL-LHC	CLIC3
squarks [TeV]	2.5	3	$\lesssim$1.5
sleptons [TeV]	0.3	-	$\lesssim$1.5
Z' (SM couplings) [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0001
μ contact scale [TeV]	15	-	60
Higgs composite scale [TeV]	5–7	9–12	70

Direct observation

Loop / effective operator

Table 10: Discovery reach of various theory models for different colliders [5]. LHC at $\sqrt{s}$ = 14 TeV assumes 100 fb^{-1} of integrated luminosity, while HL-LHC is with 1 ab^{-1}, and CLIC3 is $\sqrt{s} = 3$ TeV with up to 2 ab^{-1}. TGC is short for Triple Gauge Coupling, and "μ contact scale" is short for LL μ contact interaction scale Λ with $g = 1$.

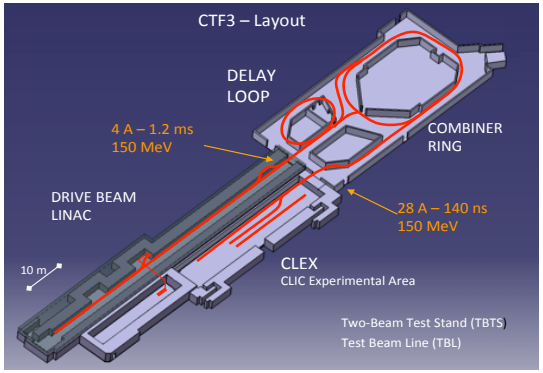
further reading

- **CLIC CDR** (#1), A Multi-TeV Linear Collider based on CLIC Technology, CERN-2012-007, https://edms.cern.ch/document/1234244/
- **CLIC CDR** (#2), Physics and Detectors at CLIC, CERN-2012-003, arXiv:1202.5940
- **CLIC CDR** (#3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, CERN-2012-005, http://arxiv.org/abs/1209.2543
- Physics at the CLIC e+e- Linear Collider, Input to the Snowmass process 2013, http://arxiv.org/abs/1307.5288

CLIC strategy and objectives

2013-18 Development Phase

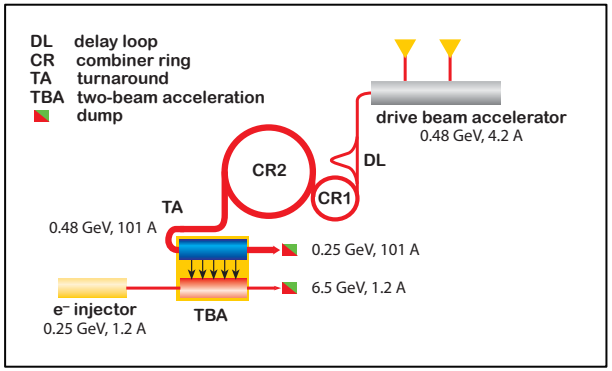
Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



4-5 year Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

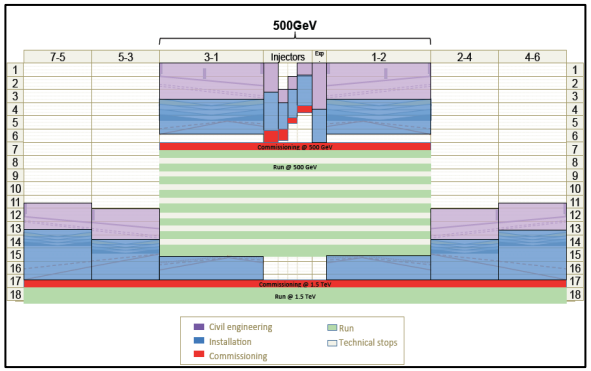
Prepare detailed Technical Proposals for the detector-systems.



Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

CLIC detector and physics study

Country	Partner	Representative in the IB
Australia	Australian Collaboration for Accelerator Science (ACAS)	M. Boland
Belarus	NC PHEP, Belarusian State University, Minsk	K. Afanaciev
Chile	The Pontificia Universidad Católica de Chile, Santiago	M.A. Diaz Gutierrez
Czech Republic	Institute of Physics of the Academy of Sciences of the Czech Republic, Prague	T. Lastovicka
Denmark	Department of Physics and Astronomy, Aarhus University	U. Uggerhoj
France	Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Annecy	Y. Karyotakis
Germany	MPI Munich	F. Simon
Israel	Tel Aviv University	A. Levy
Norway	University of Bergen	G. Eigen
Poland	Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Cracow	M. Idzik
Poland	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow	L. Zawiejski
Romania	Institute of Space Science	T. Preda
Serbia	Vinca Institute for Nuclear Sciences, Belgrade	I. Bozovic-Jelisavcic
Spain	Spanish Network for Future Linear Colliders	A. Ruiz
Switzerland	CERN	K. Elsener
United Kingdom	The School of Physics and Astronomy, University of Birmingham	N. Watson
United Kingdom	University of Cambridge	M. Thomson
United Kingdom	University of Glasgow	A. Robson
United Kingdom	University of Oxford	Ph. Burrows
USA	Argonne National Laboratory, High Energy Physics Division	H. Weerts

Light-weight cooperation structure
No engagements, on best-effort basis
With strong collaborative links to ILC
http://lcd.web.cern.ch/LCD/Home/MoC.html

CLICdp: 20 institutes

Focus of CLIC-specific studies on:

- Physics prospects and simulation studies
- Detector optimisation for CLIC

Collaboration is also…

Israel 21st CERN member state !

summary

- **CLIC is the only mature option for a multi-TeV e^+e^- collider**
- Very active R&D projects for accelerator and physics/detector
- Energy staging ➔ optimal physics exploration, with possible stages at 350 GeV, 1.4, and 3 TeV
- CLIC @ 350 GeV
  - Precision Higgs measurements: mass, branching ratios, absolute coupling
  - Top physics (precision on top mass at O(100 MeV))
- CLIC @ 1.4 and 3 TeV
  - Improved precision of many observables and access to rare Higgs decays
  - Trilinear Higgs self-coupling at the 10% level
  - Top Yukawa coupling with ttH
  - Discovery machine for BSM physics at the energy frontier
    - Direct + indirect sensitivity

CLIC =>

Physics at ~~high energy~~

high altitude

or……

what happens to a beer at 3842 m altitude ?

SPARE SLIDES

Staged approach, scenario A+B

A

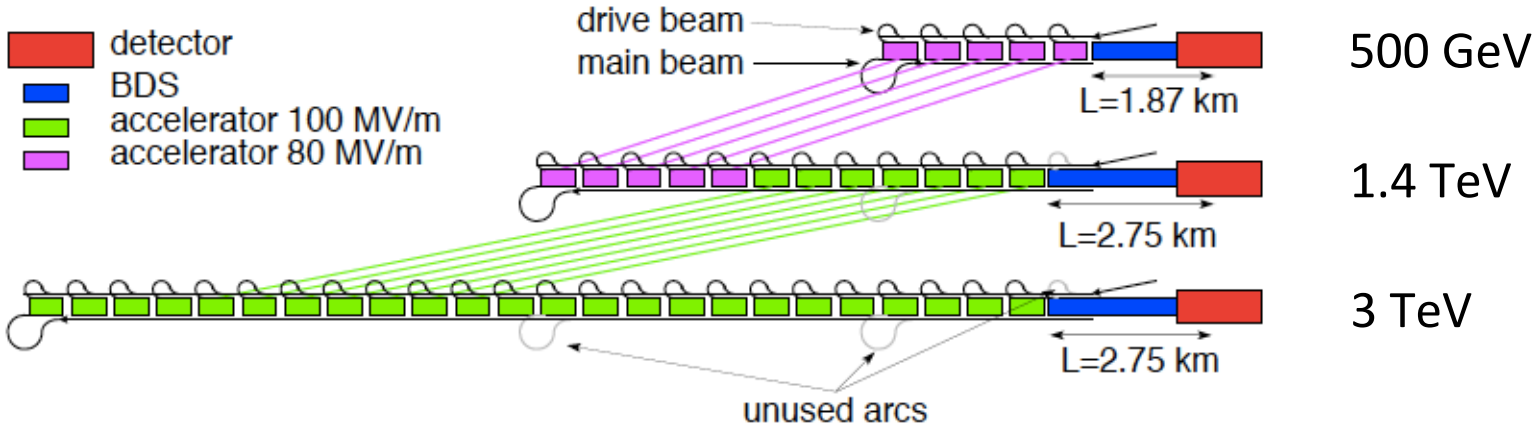


Fig. 3.5: Simplified upgrade scheme for CLIC staging scenario A. The coloured lines indicate the required movement of the modules from one stage to the next.

B

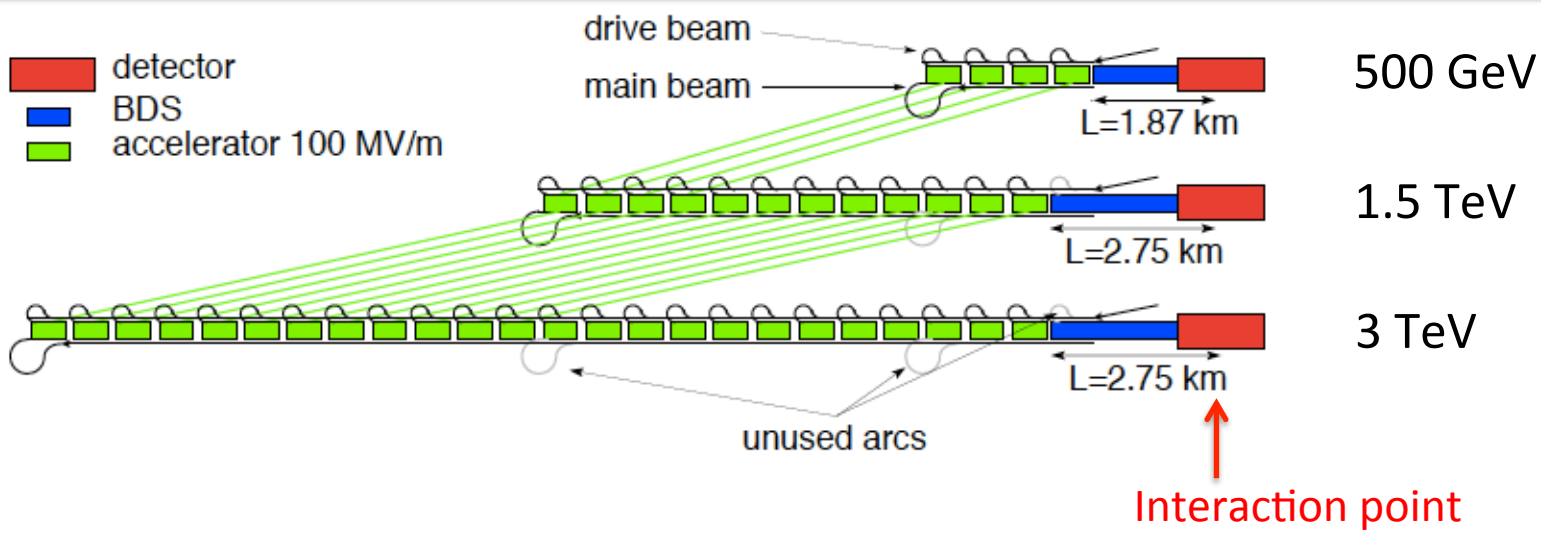


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

CLIC layout at 500 GeV

A

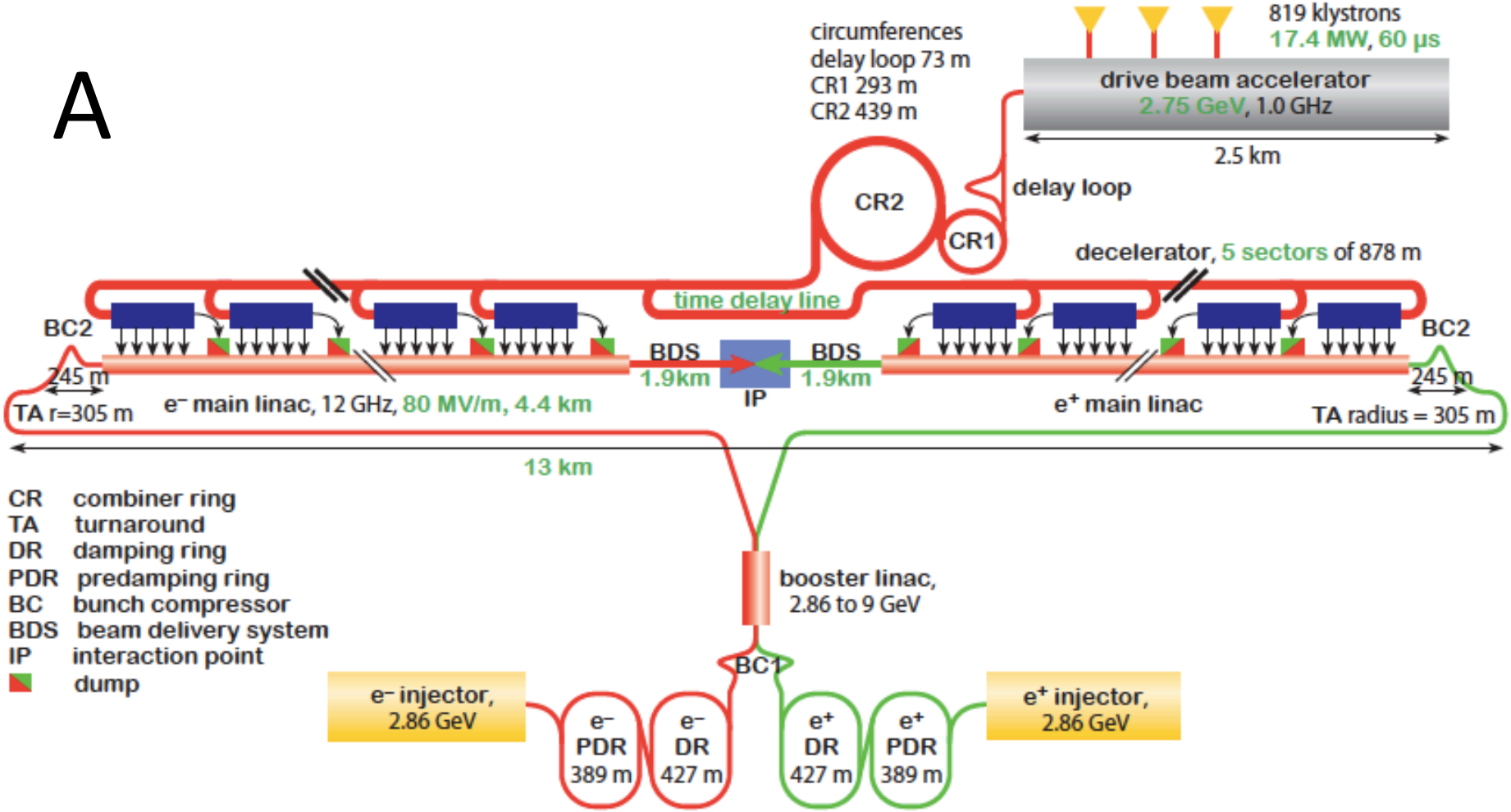


Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV. (scenario A)

Parameters, scenario A

Table 3.3: Parameters for the CLIC energy stages of scenario A.

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	µm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\approx$ 60/1.5	$\approx$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

Parameters, scenario B

Table 3.4: Parameters for the CLIC energy stages of scenario B.

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\approx$ 60/1.5	$\approx$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Integrated luminosity

Possible scenarios "A" and "B", these are **"just examples"**

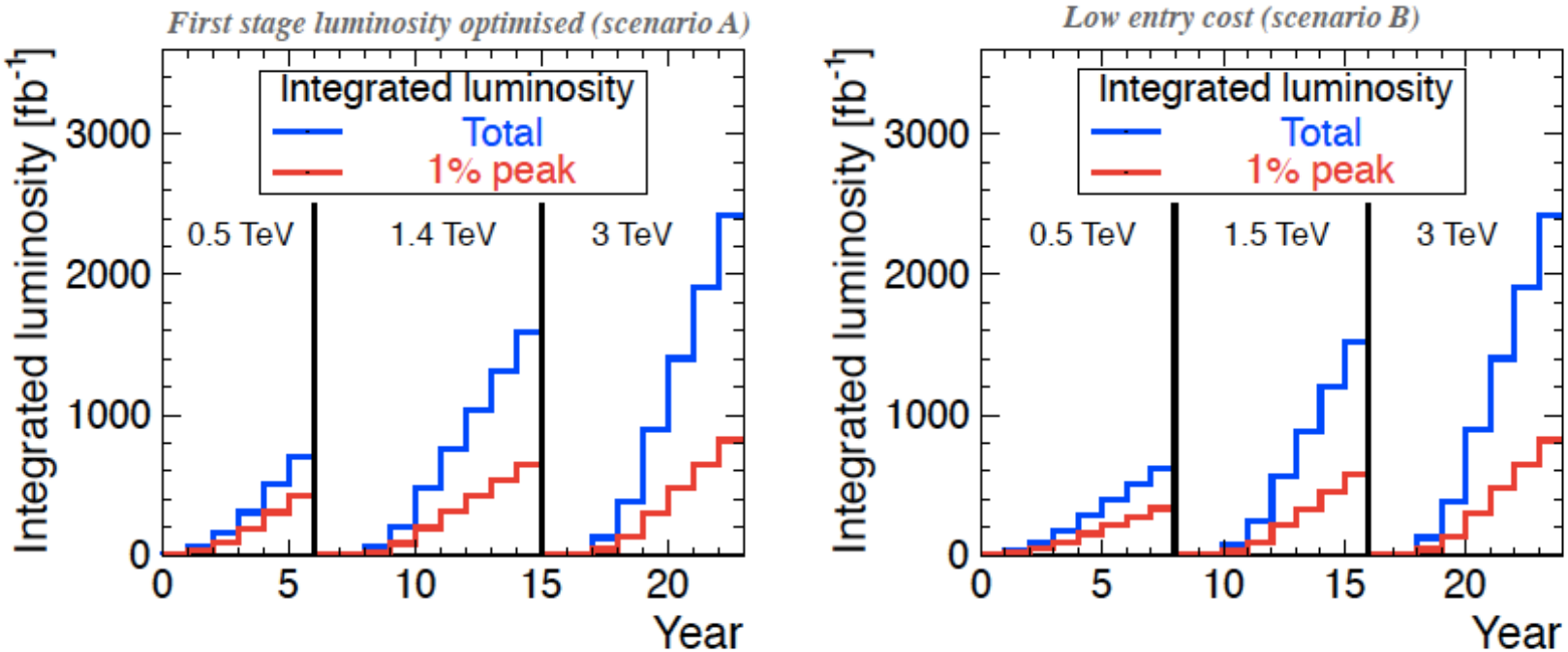


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

=> CLIC can provide an evolving and rich physics program over several decades

CLIC, possible implementation

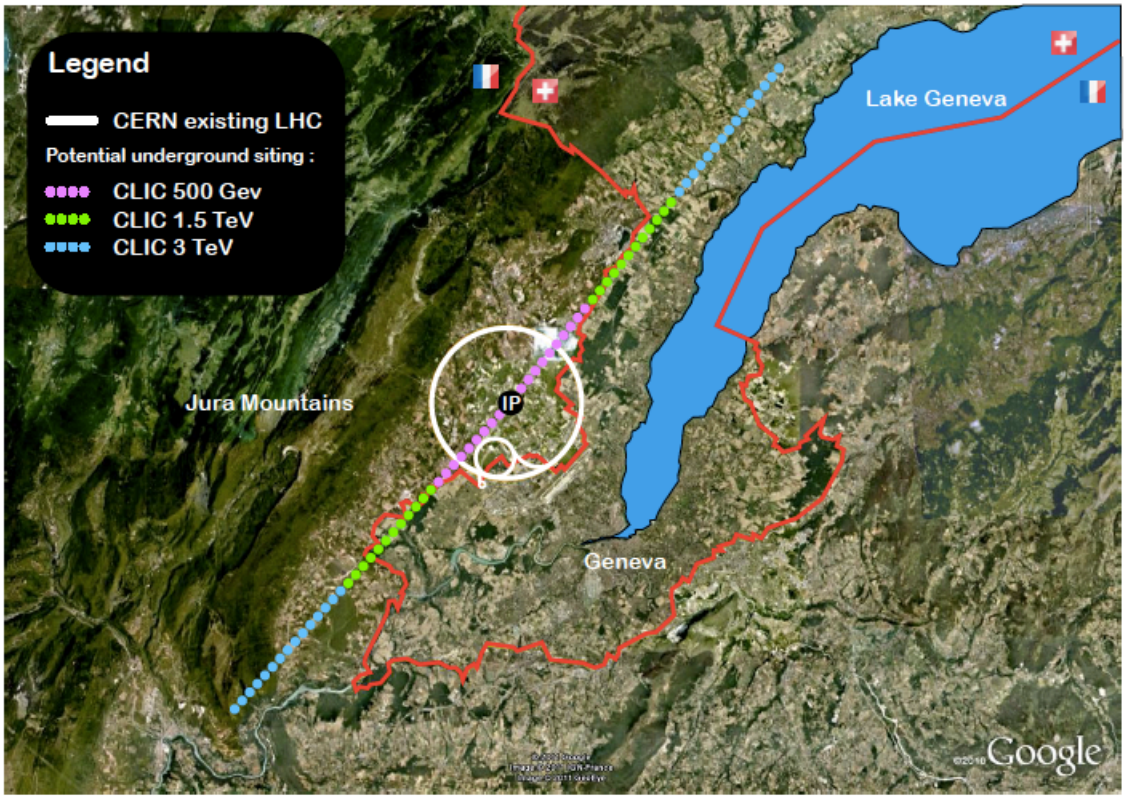


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].

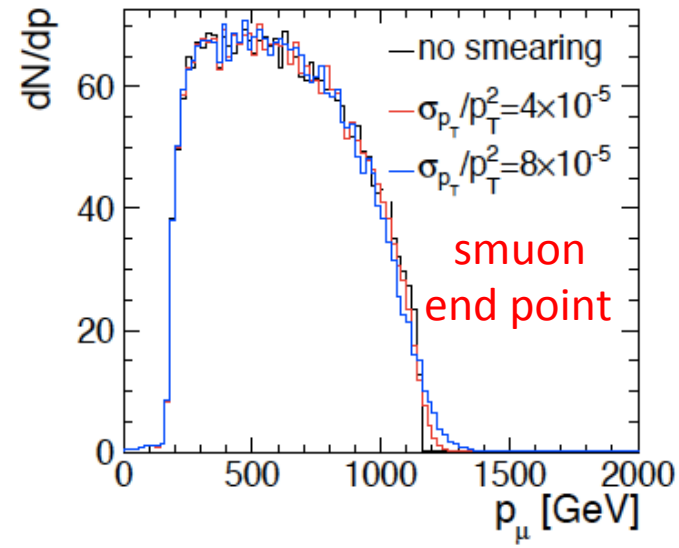
physics aims => detector needs

★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

$$\sigma_{p_T}/p_T^2 \sim 2\times 10^{-5}\ \mathrm{GeV}^{-1}$$

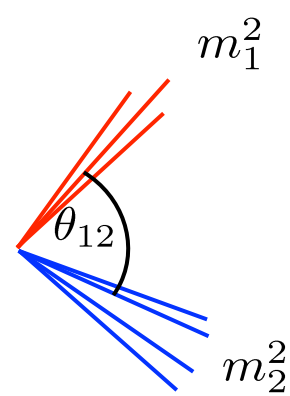


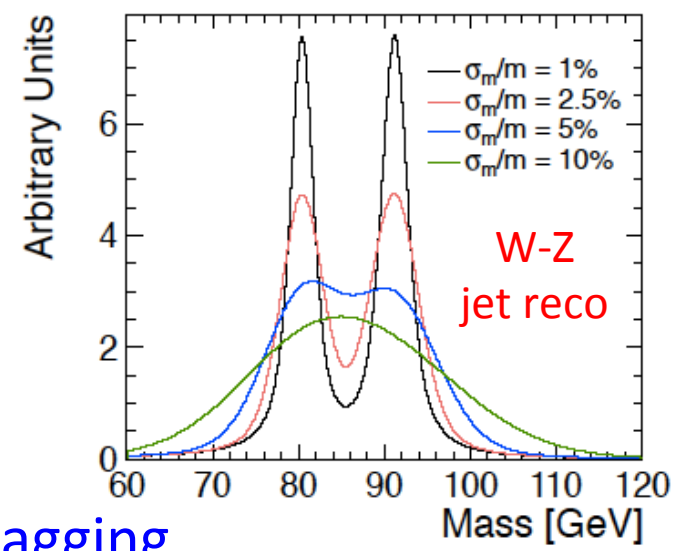
★ jet energy resolution:

e.g. W/Z/h di-jet mass separation

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

(for high-E jets)





★ impact parameter resolution:

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

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

★ angular coverage, very forward electron tagging

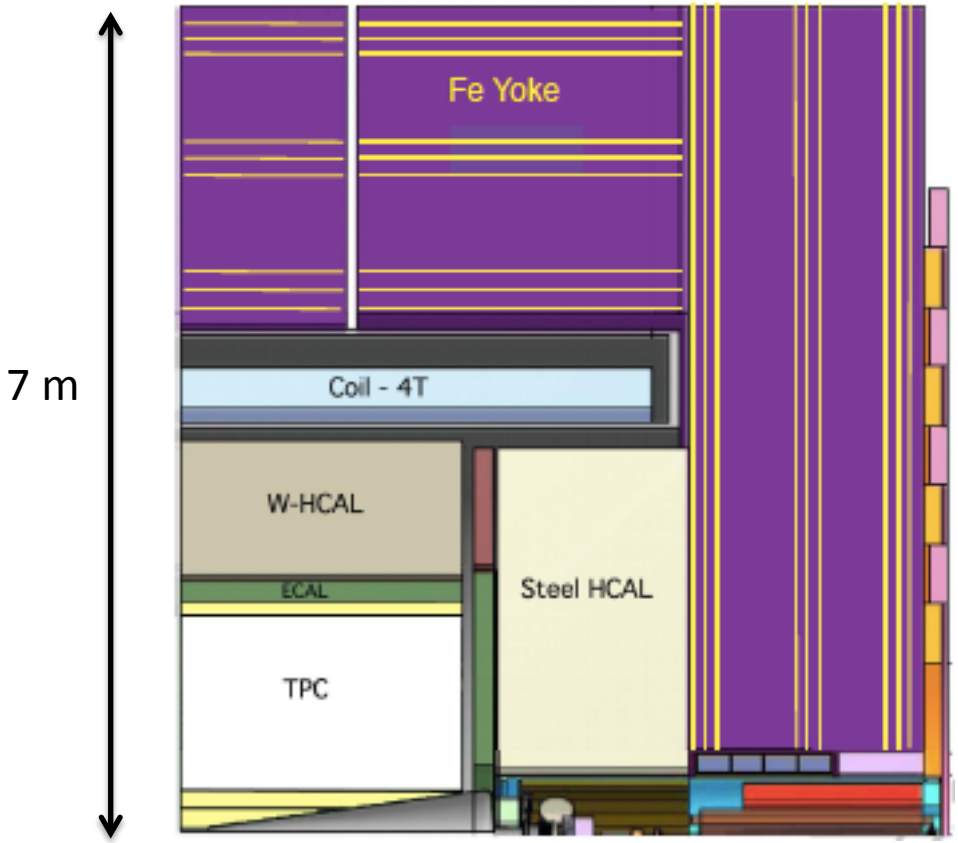
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

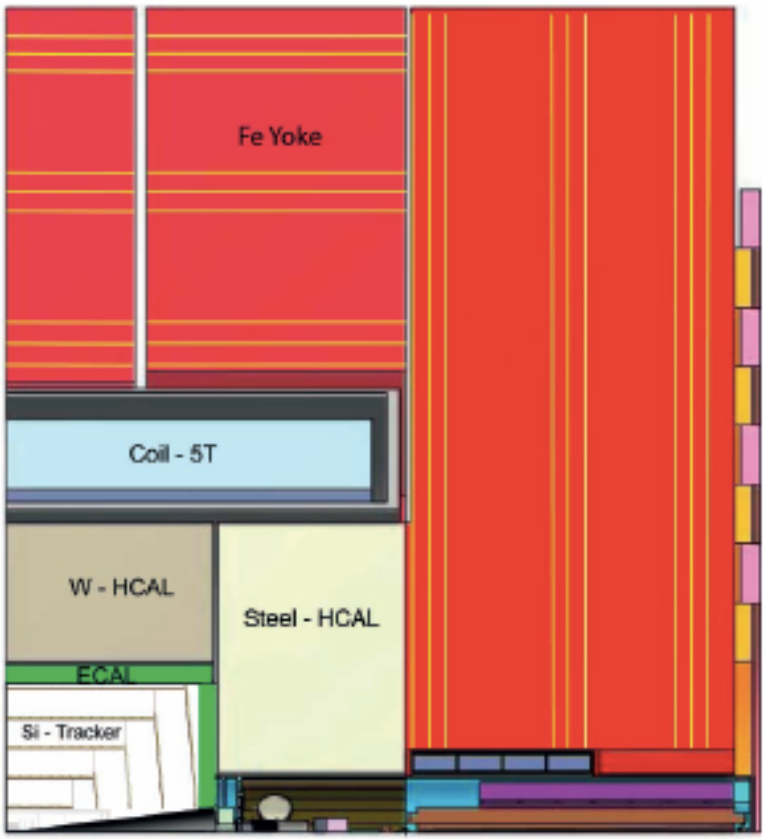
Based on initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

CLIC_ILD



CLIC_SiD

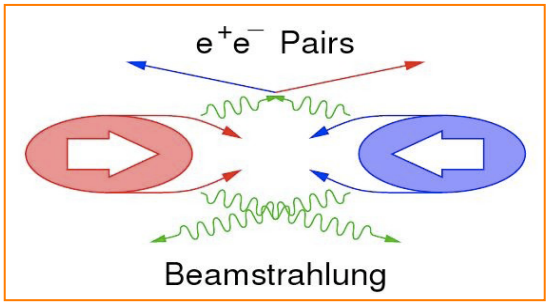


CLIC machine environment (1)

	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44

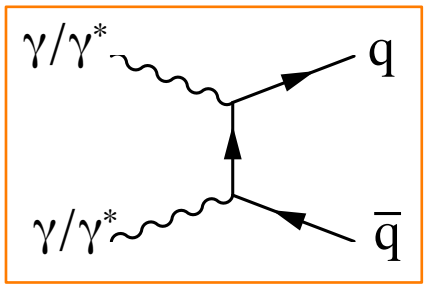
Drives timing requirements for CLIC detector

very small beam size



Beam related background:

- Small beam profile at IP leads very high E-field
  - **Beamstrahlung**
    - Pair-background
    - γγ to hadrons



CLIC machine environment (2)

Coherent e^+e^- pairs
- 7×10^8 per BX, very forward

Incoherent e^+e^- pairs
- 3×10^5 per BX, rather forward

$\gamma\gamma \rightarrow$ hadrons
- 3.2 events per BX
- main background in calorimeters
  - ~19 TeV in HCAL per bunch train

➔

Simplified view:

Pair background
- Design issue (high occupancies)

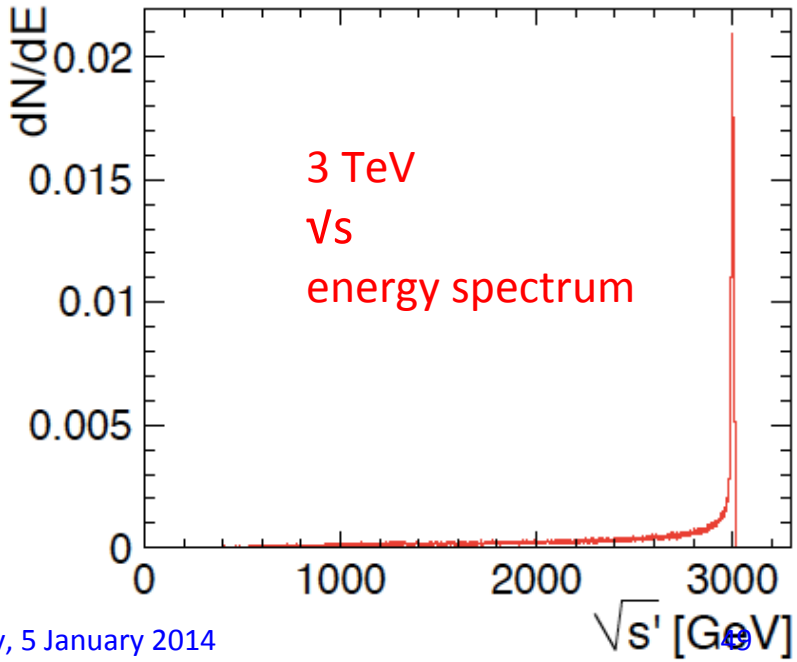
$\gamma\gamma \rightarrow$ hadrons
- Impacts on the physics
- Needs suppression in data

Beamstrahlung ➔ important energy losses right at the interaction point

E.g. full luminosity at 3 TeV:
5.9×10^{34} cm^{-2}s^{-1}

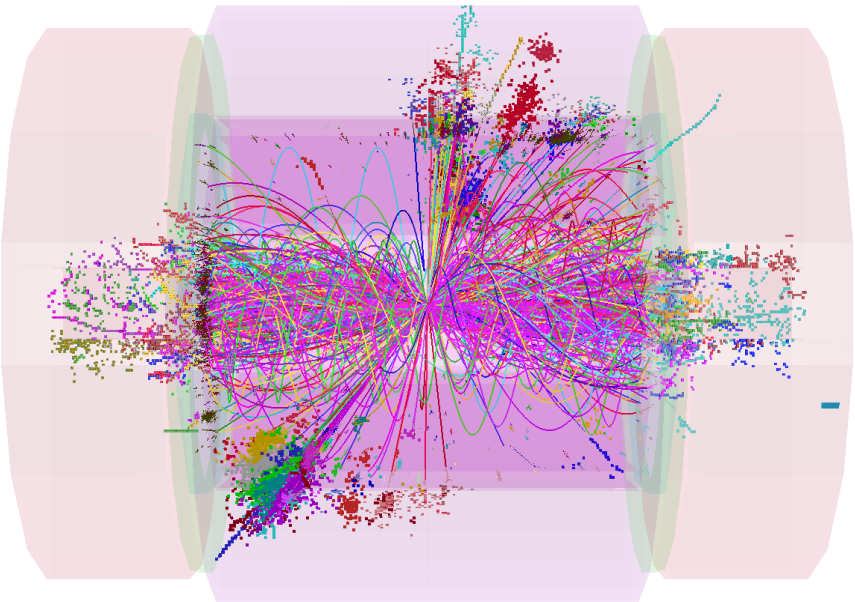
Of which in the 1% most energetic part:
2.0×10^{34} cm^{-2}s^{-1}

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

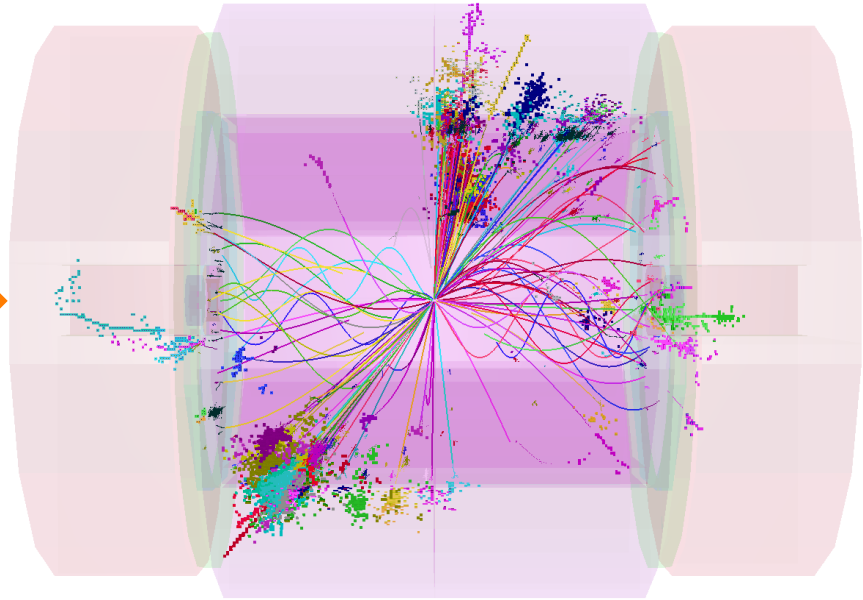


combined p_T and timing cuts

1.2 TeV



100 GeV



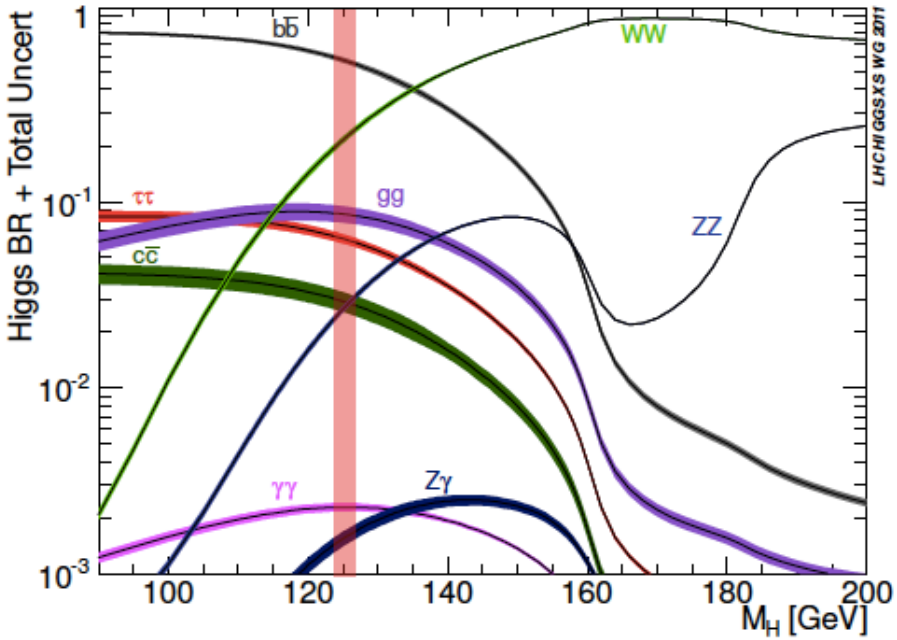
$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t} \rightarrow 8 \text{ jets}$$

1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

Higgs Decay Processes

- SM Higgs branching ratios depend only on the Higgs mass
- 125 GeV Higgs has sizable branching ratios to large number of final states
  - $H \to b\bar{b}$: 58%
  - $H \to WW^*$: 22%
  - $H \to gg$: 8.5%
  - $H \to \tau^+\tau^-$: 6.4%
  - $H \to ZZ^*$: 2.7%
  - $H \to c\bar{c}$: 2.7%
  - $H \to \gamma\gamma$: 0.23%
  - $H \to Z\gamma$: 0.15%
  - $H \to \mu^+\mu^-$: 0.022%
- Measuring all these decay channels is excellent test of Standard Model



European Strategy statements => high-energy frontier

2006 statement "4":

4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.*

proton-proton
or
electron-positron

at high-energy frontier

2013 statement "d":

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

FCC and CLIC at energy frontier

2014

pp and ee design studies at high-energy frontier

FCC

CLIC

under/for discussion !

CDR

PIP

Progress tracking:

CERN "MAC" machine advisory committee

+

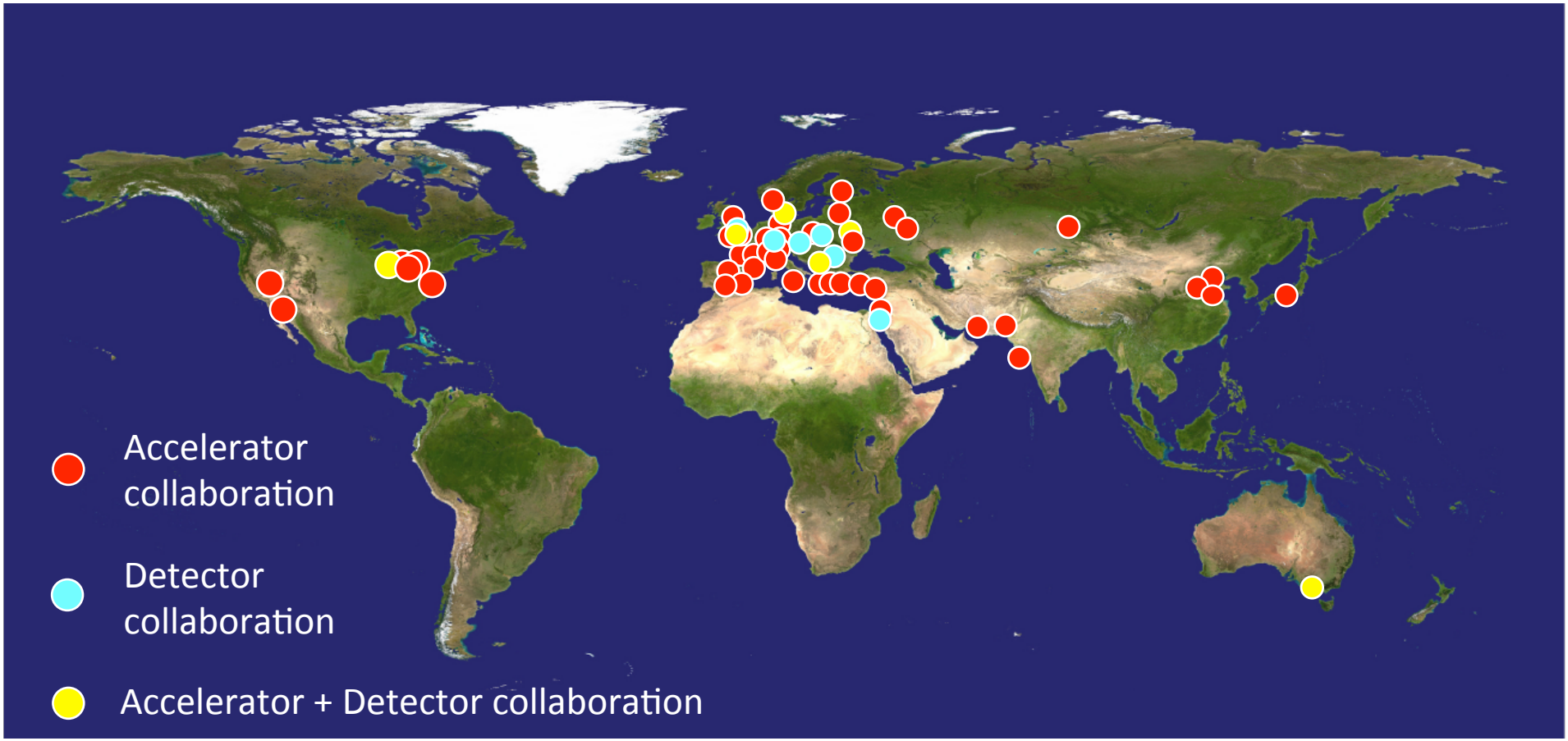
Common pp/ee physics studies at energy frontier (follow-up by SPC or ECFA or ???)

~2018

next European strategy update

(PIP = Project Implementation Plan)

CLIC collaboration(s)



Entity	IB chair	Spokesperson	# institutes
CLIC/CTF3 collaboration	L. Rivkin (EPFL)	R. Corsini (CERN)	~50
CLIC detector & physics study	F. Simon (MPI Münich)	L. Linssen (CERN)	20

Within the CERN structure: Linear Collider study leader => S. Stapnes
Linear Collider Detector project leader => L. Linssen