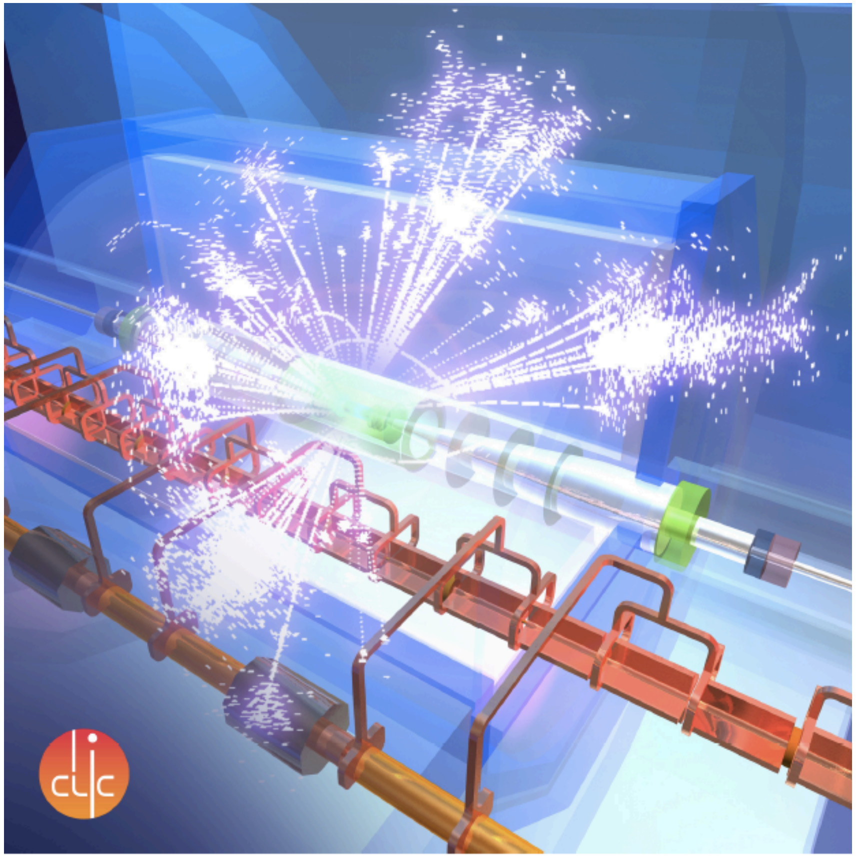
CLIC: physics and detectors at a future TeV-scale e+e- linear collider



Lucie Linssen, CERN

on behalf of the CLIC detector and physics study

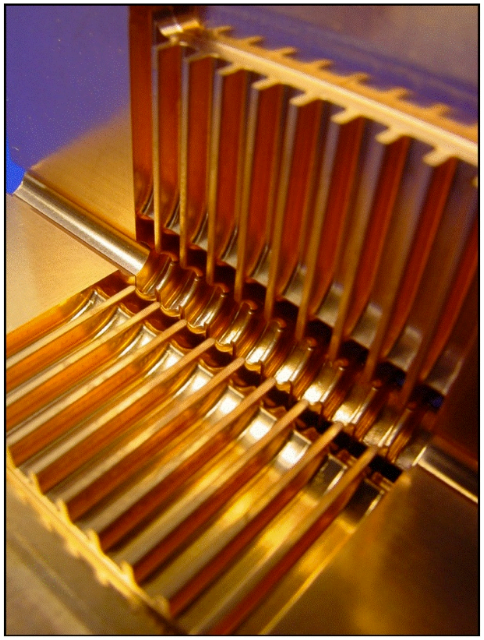
Outline

- CLIC accelerator, intro
- Physics motivation
- Motivation/implementation of $\sqrt{s}$ energy staging
- CLIC detectors + (a bit of) R&D
- Results of benchmark studies
    - Higgs
    - top
    - SUSY
- CLIC strategy and timeline
- Summary

ILC ad CLIC in just a few words

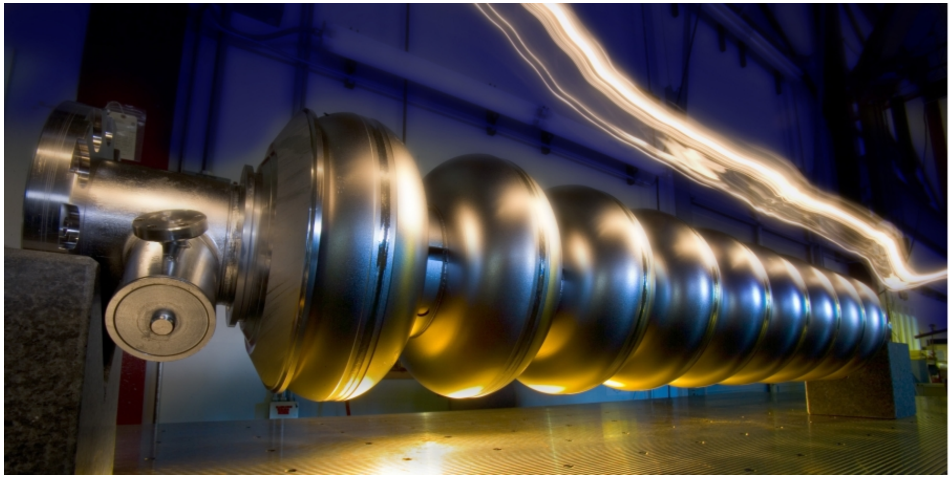
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

CLIC



•2-beam acceleration scheme, at room temperature
•Gradient 100 MV/m
•√s up to 3 TeV
•Physics + Detector studies for 350 GeV - 3 TeV

ILC



•Superconducting RF cavities (like XFEL)
•Gradient 32 MV/m
•√s ≤ 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

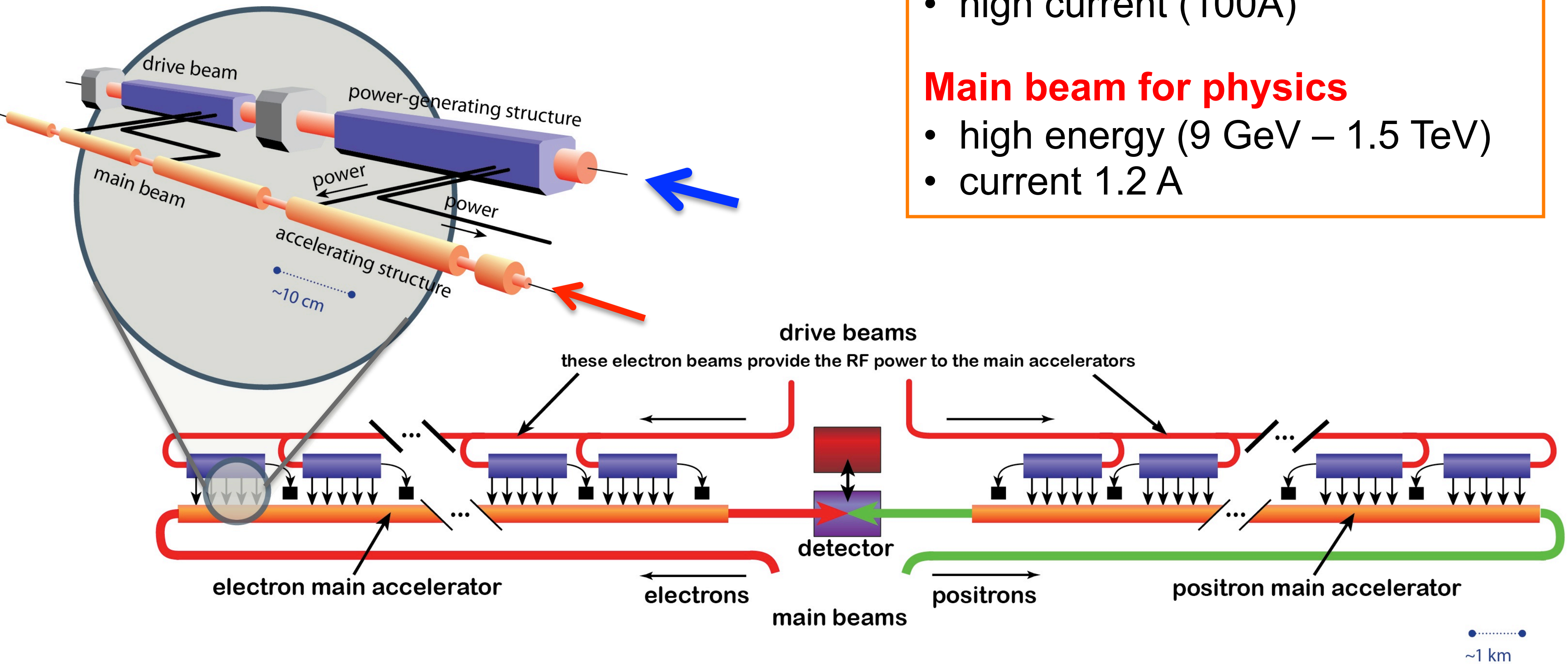
Two Beam Scheme:

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

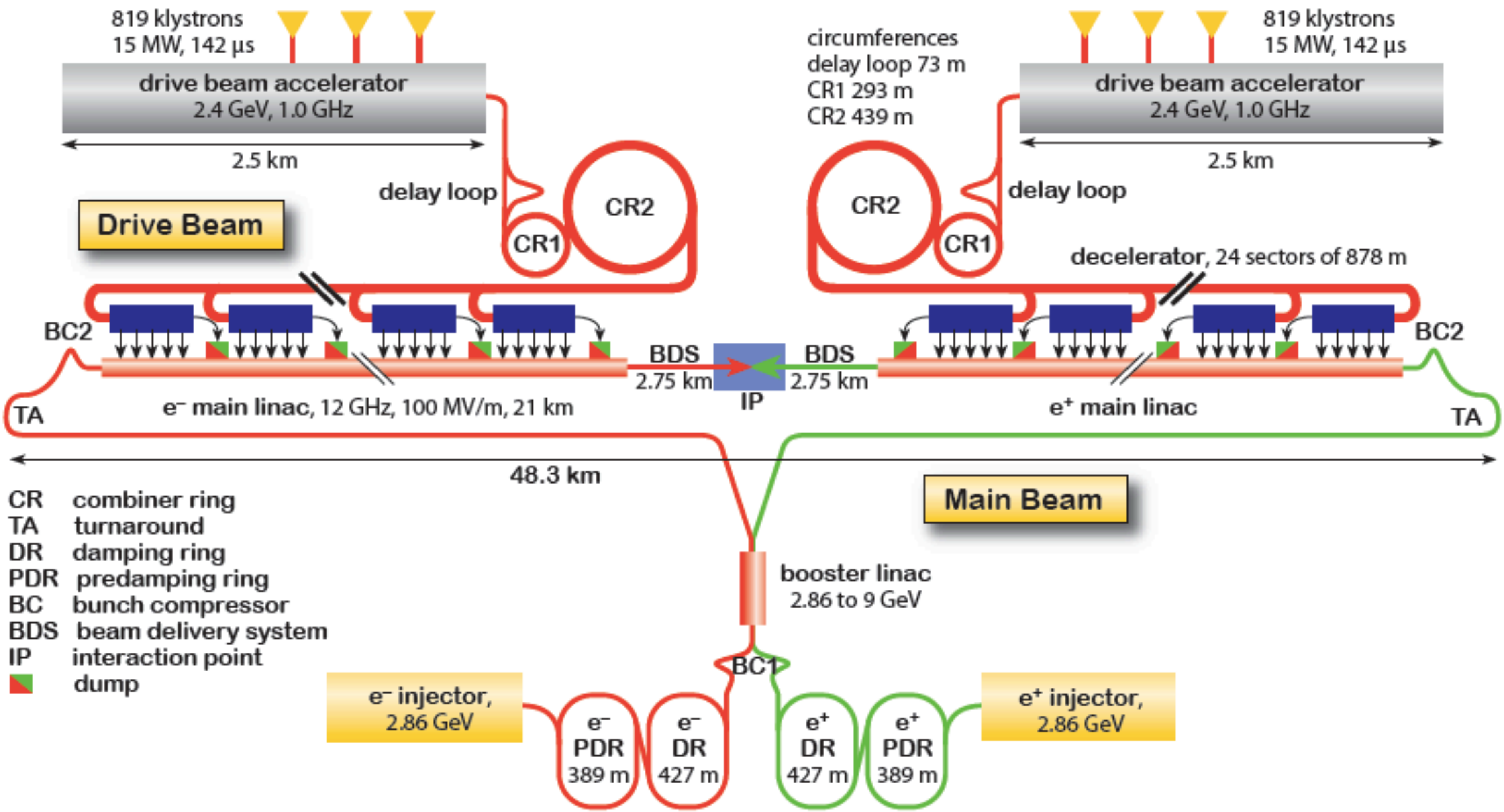
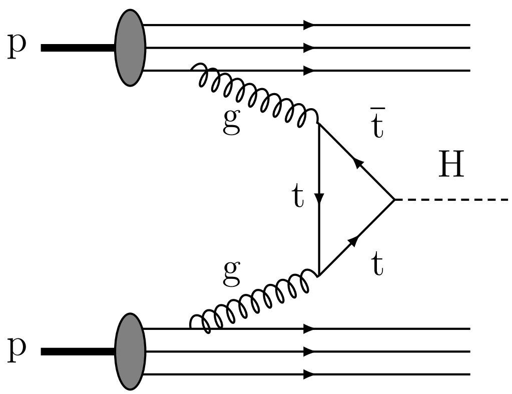
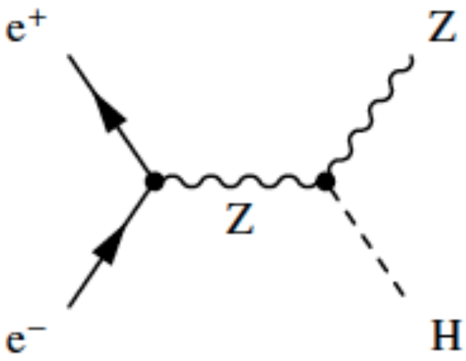


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

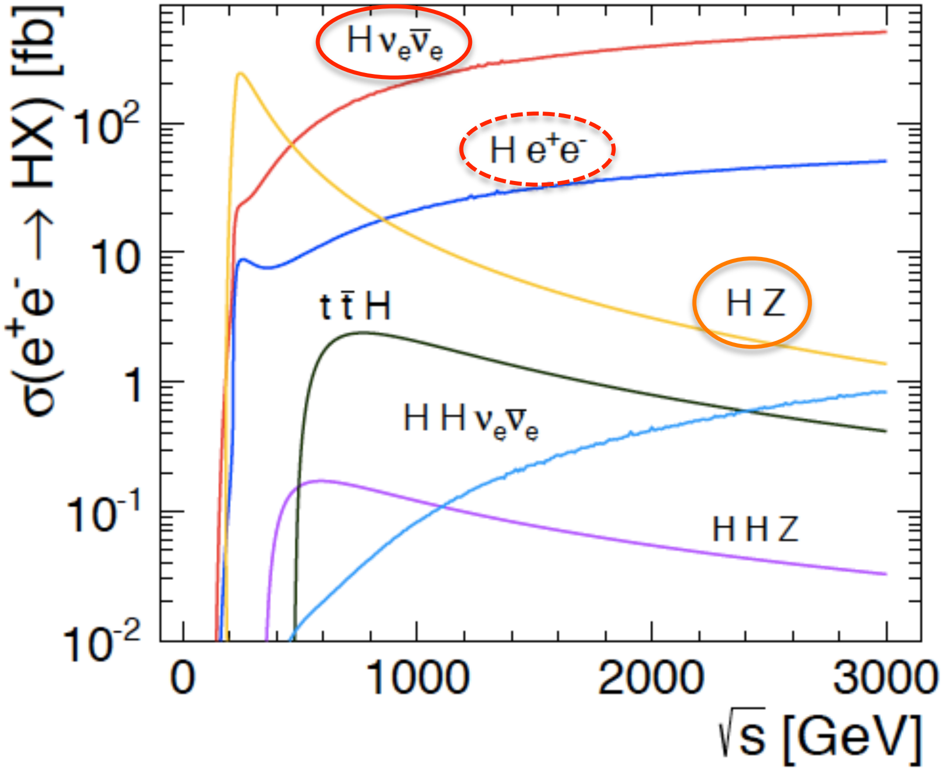
Hadron vs. lepton colliders



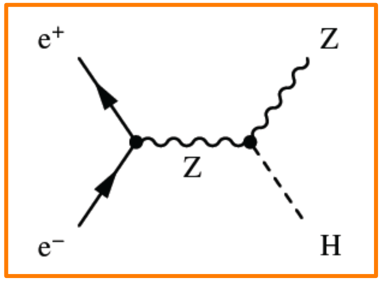


p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	e^+/e^- are point-like → Initial state well defined ($\sqrt{s}$ / polarization) → High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron 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

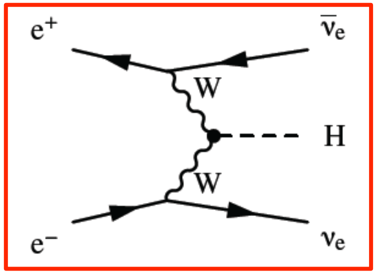
Higgs physics at CLIC



Dominant processes:



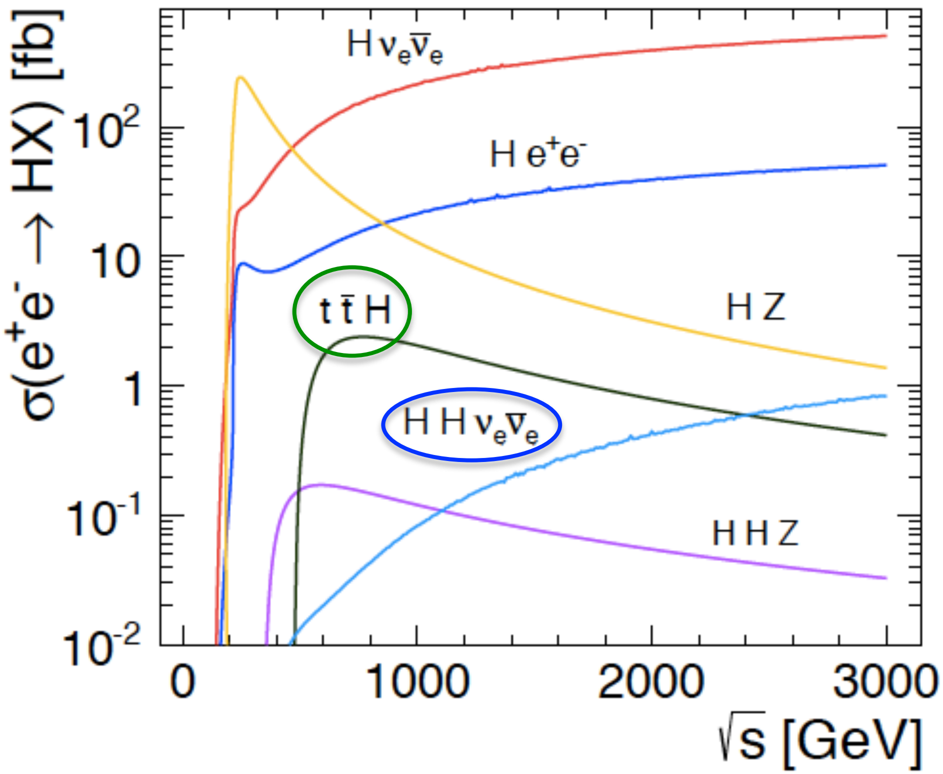
Higgsstrahlung decreases with √s



W(Z) - fusion increases with √s

	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	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

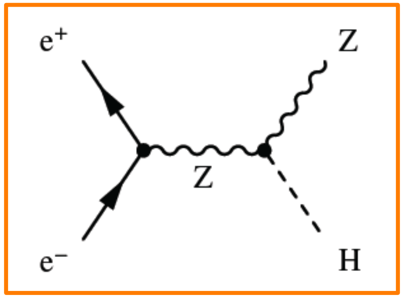


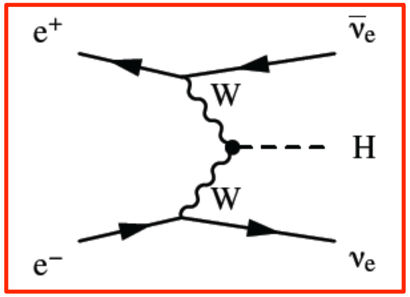
Higgs-Strahlung: $e^+e^- \to ZH$
- Measure H from Z-recoil mass
- Model-independent meas.: m_H, σ
- Yields absolute value of g_{HZZ}

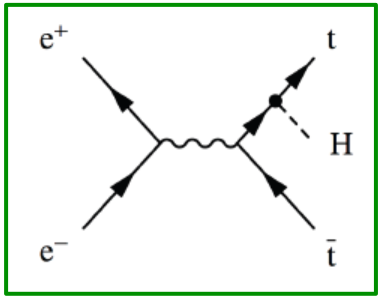
WW fusion: $e^+e^- \to H\nu_e\nu_e$
- Precise cross-section measurements in ττ, μμ, qq, … decay modes
- Profits from higher $\sqrt{s}$ ($\gtrsim$350 GeV)

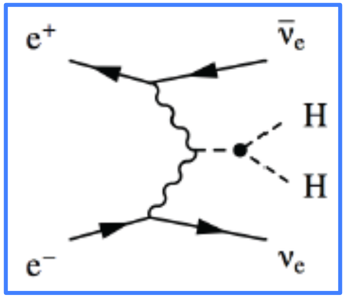
Radiation off top-quarks: $e^+e^- \to ttH$
- Measure top Yukawa coupling
- Needs $\sqrt{s} \gtrsim 700$ GeV

Double-Higgs prod.: $e^+e^- \to HH\nu_e\nu_e$
- Measure tri-linear self coupling
- Needs high $\sqrt{s}$ ($\gtrsim$1.4 TeV)



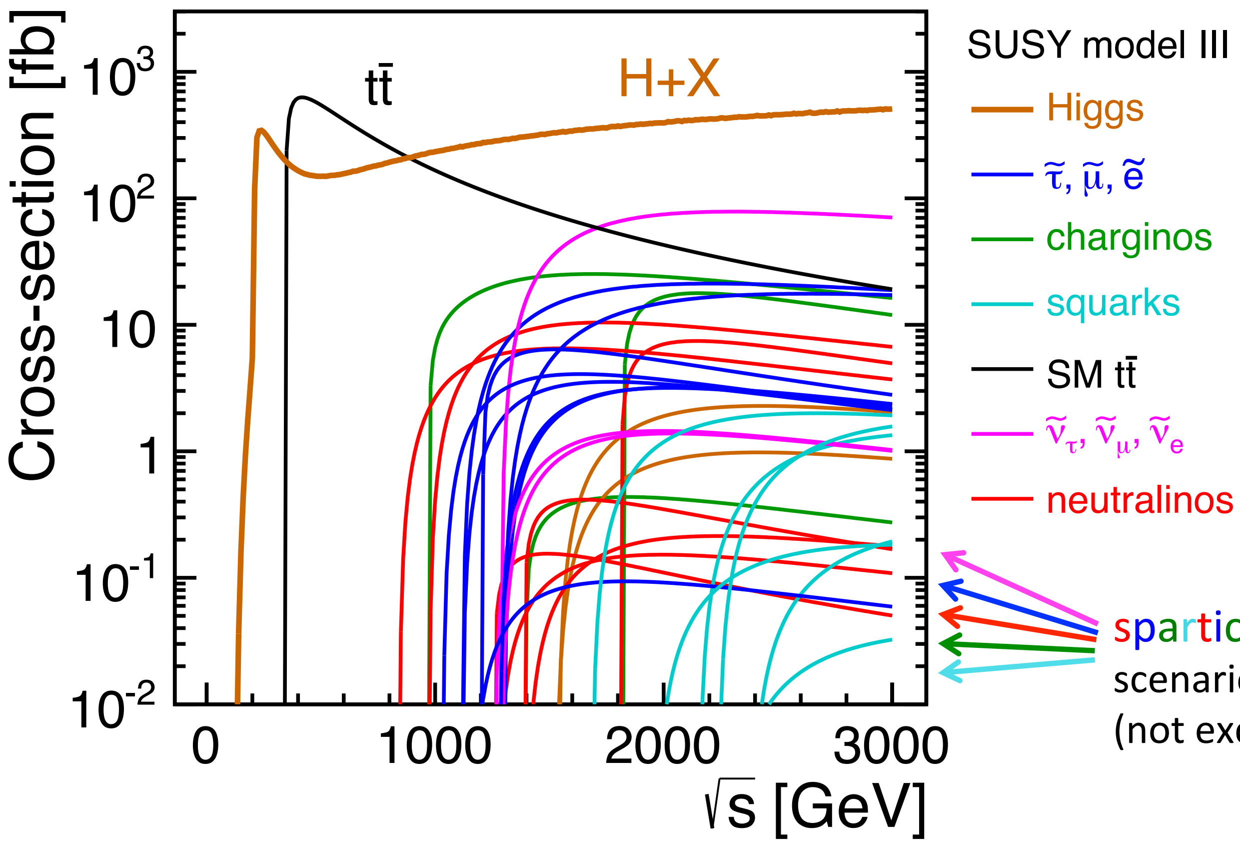






Physics at CLIC

- Precision SM measurements: Higgs, top → √s≲350 GeV, and up to 3 TeV
- Discovery of new physics at TeV scale, unique sensitivity to particles with electroweak charge
- New Physics model discrimination, e.g. SUSY → up to √s ~ 3 TeV



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

Physics at CLIC

- Precision SM measurements: Higgs, top → √s≲350 GeV, and up to 3 TeV
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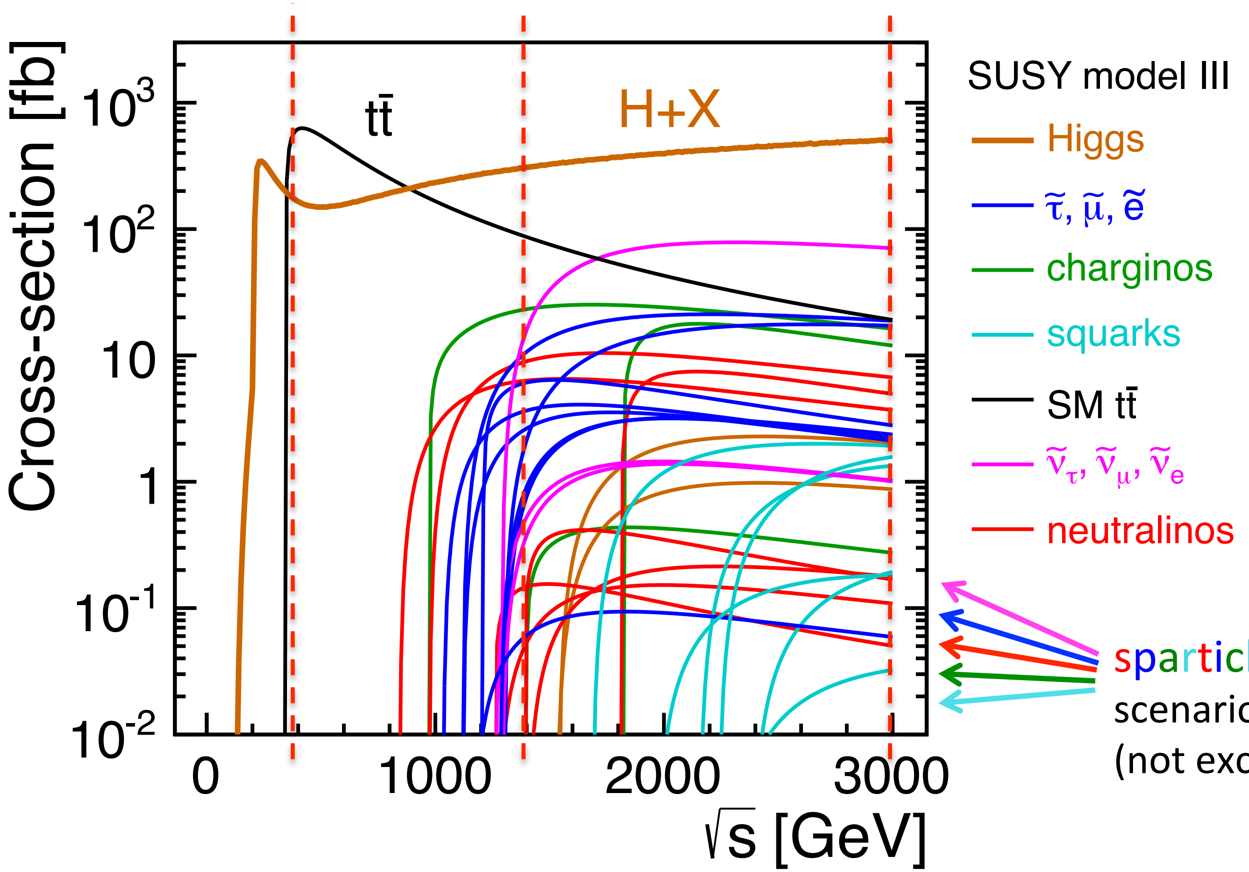


sparticles in **SUSY** example scenario
(not excluded by LHC results)

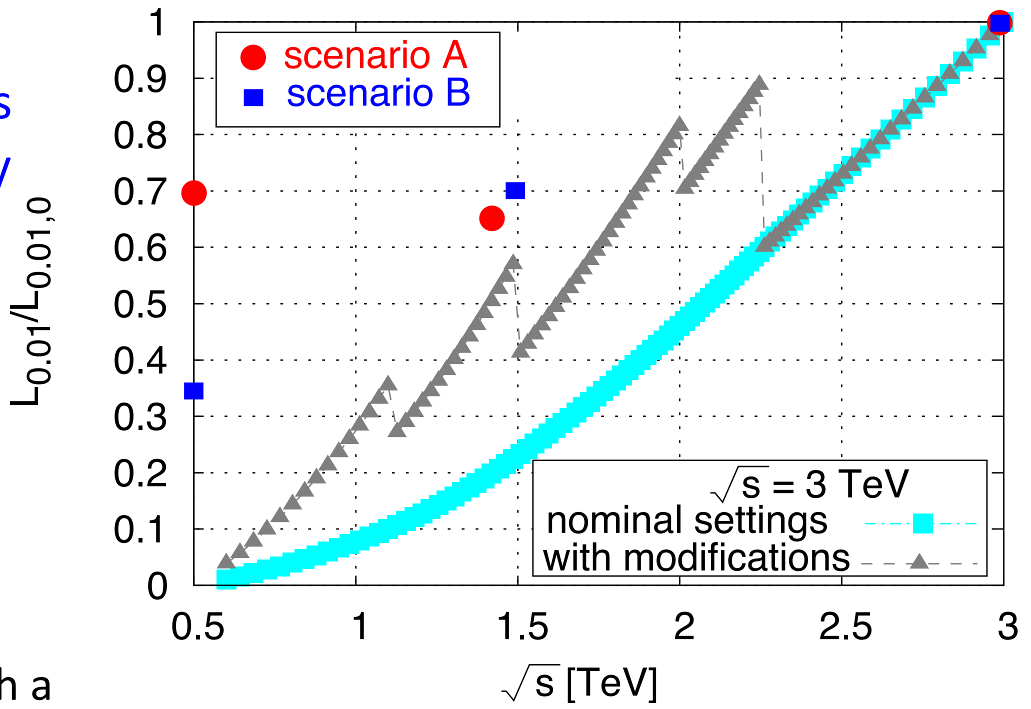
Motivation for energy staging

CLIC physics potential:

- Good physics at various CM energies
- Most studies require high luminosity

At each energy stage, the centre-of-mass energy can be tuned down by a factor ~3 with limited luminosity loss (e.g. for threshold scans)

Making optimal use of the capacities (luminosity) of CLIC, this is best studied with a **collider built in a few successive energy stages**.



The choice of the energy stages will depend on the physics scenario, driven by 8 TeV + 14 TeV LHC results.

CLIC, possible implementation

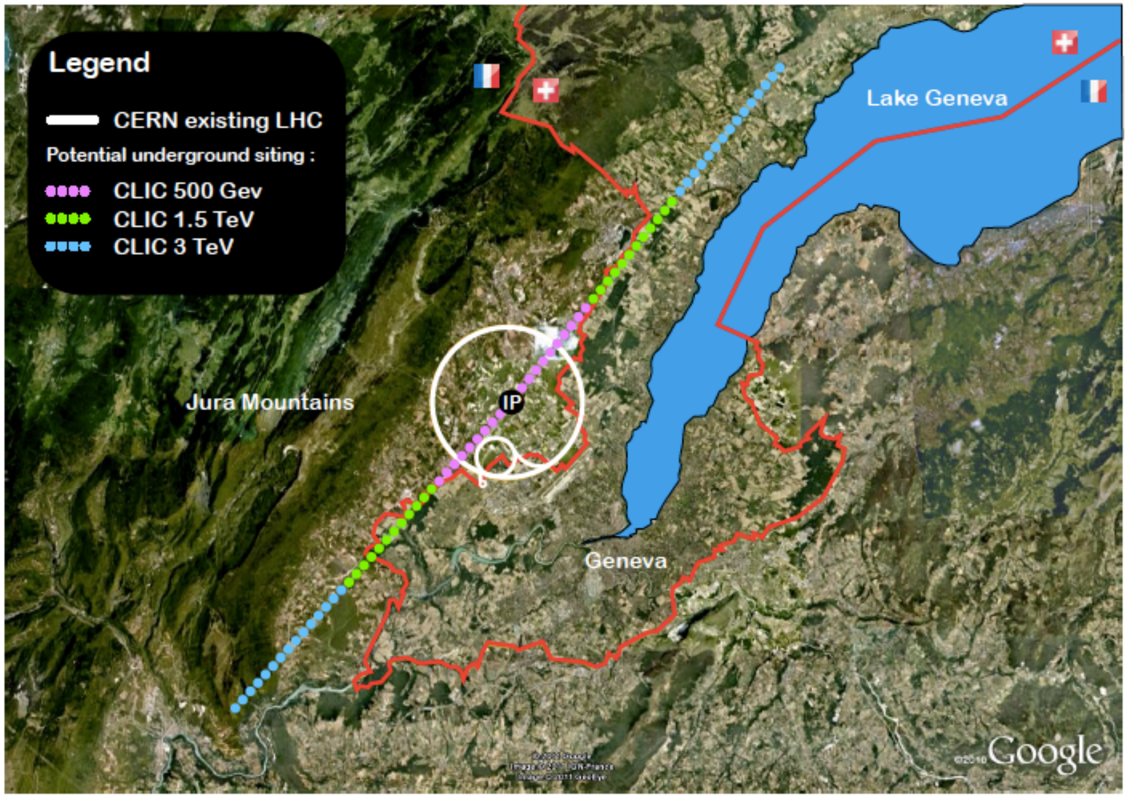


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].

physics aims => detector needs

★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

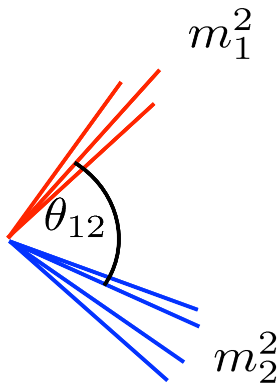
$$\sigma_{p_T}/p_T^2 \sim 2\times10^{-5}\ \mathrm{GeV}^{-1}$$

★ jet energy resolution:

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

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

(for high-E jets)

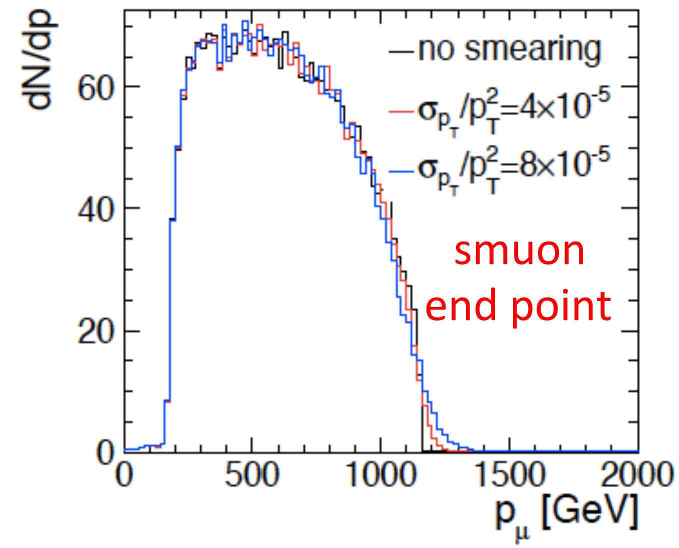


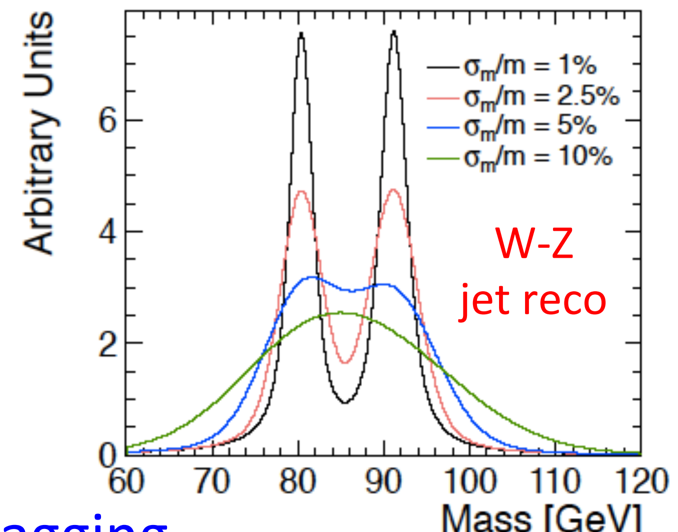
★ impact parameter resolution:

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



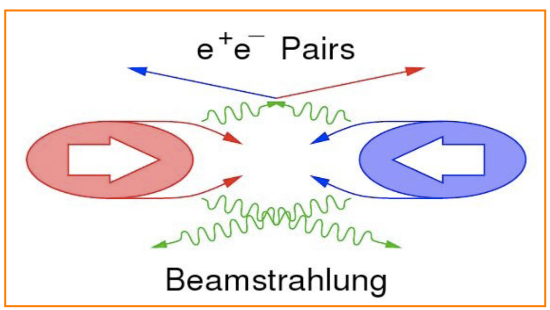


CLIC machine environment (1)

	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

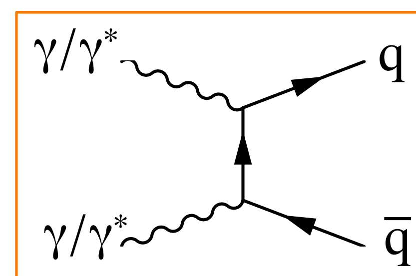
Drives timing requirements for CLIC detector

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 x 10^8 per BX, very forward

Incoherent e^+e^- pairs

- 3 x 10^5 per BX, rather forward

γγ→ 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)

γγ → hadrons

- Impacts on the physics
- Needs suppression in data

Beamstrahlung ➔ important energy losses right at the interaction point

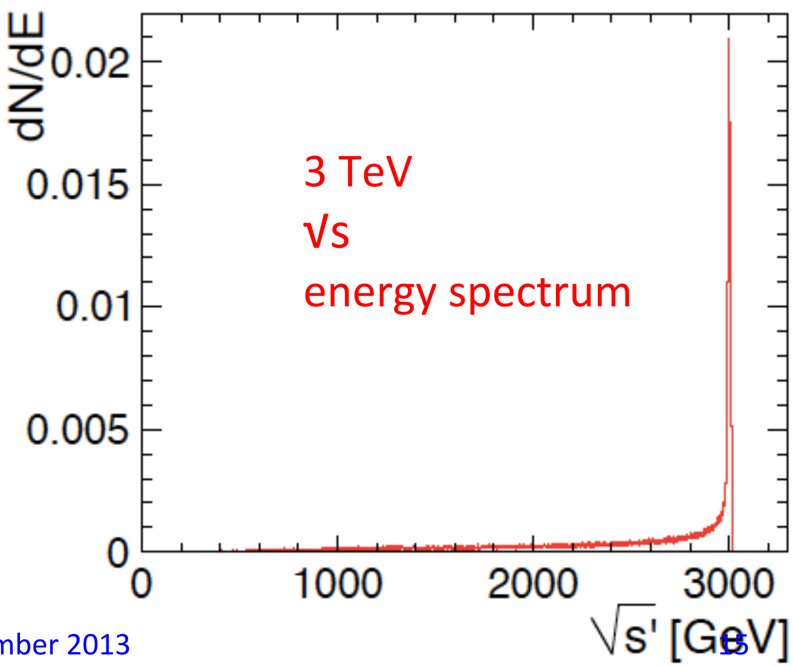
E.g. full luminosity at 3 TeV:

$5.9 \times 10^{34}\ cm^{-2}s^{-1}$

Of which in the 1% most energetic part:

$2.0 \times 10^{34}\ cm^{-2}s^{-1}$

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



challenges in CLIC detector R&D

These requirements lead to the following challenges:

Vertex and tracker

- Very high granularity
- Dense integration of functionalities
  - Including ~10 ns time-stamping
- Super-light materials
- Low-power design + power pulsing
- Air cooling

ultra – light

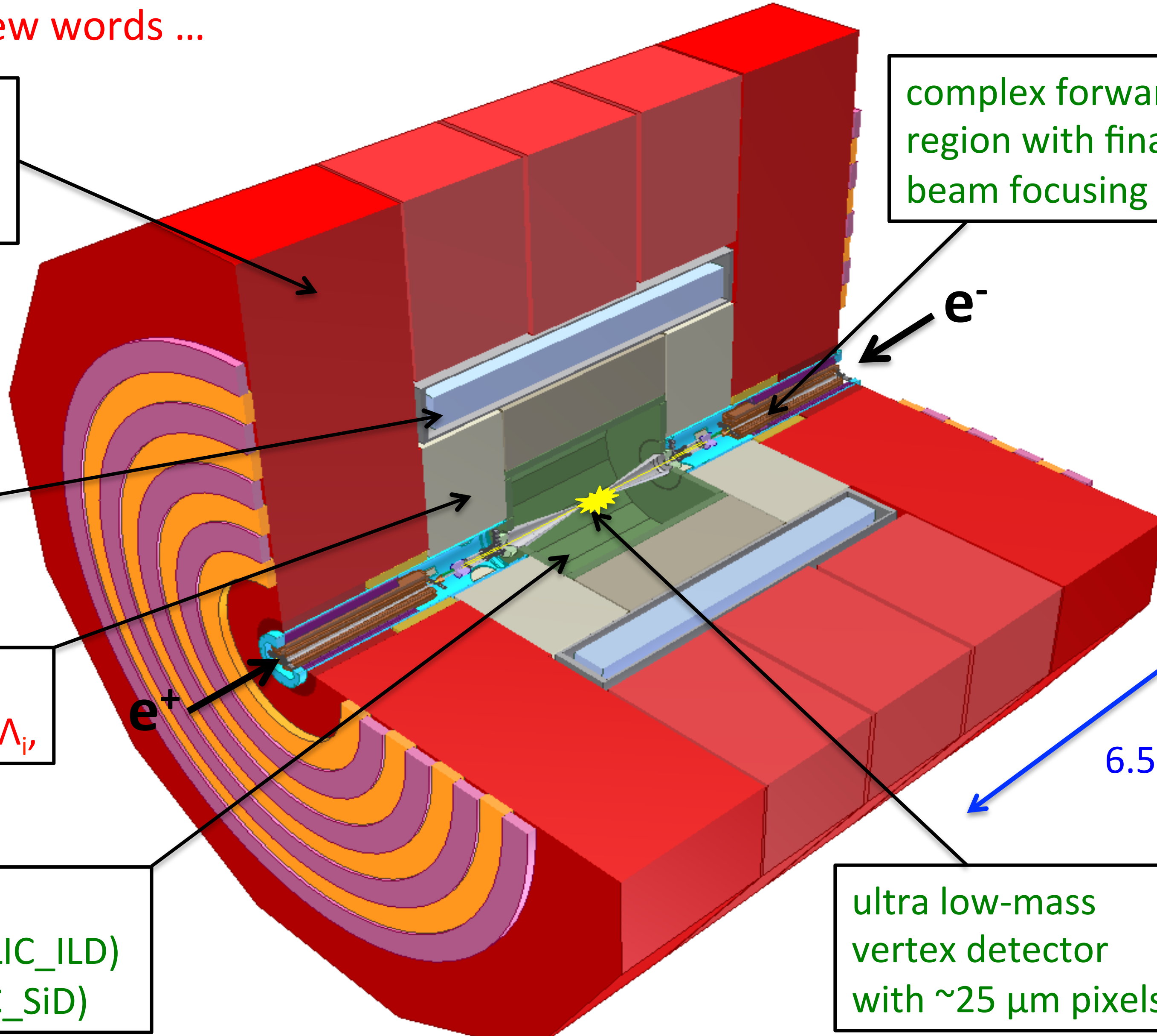
Calorimetry

- Fine segmentation (lateral + longitudinal)
- Time resolution ~1 ns
- Ultra – compact active layers
- Pushing integration to limits
- Power pulsing

ultra – heavy and compact

CLIC detector concepts

… in a few words …



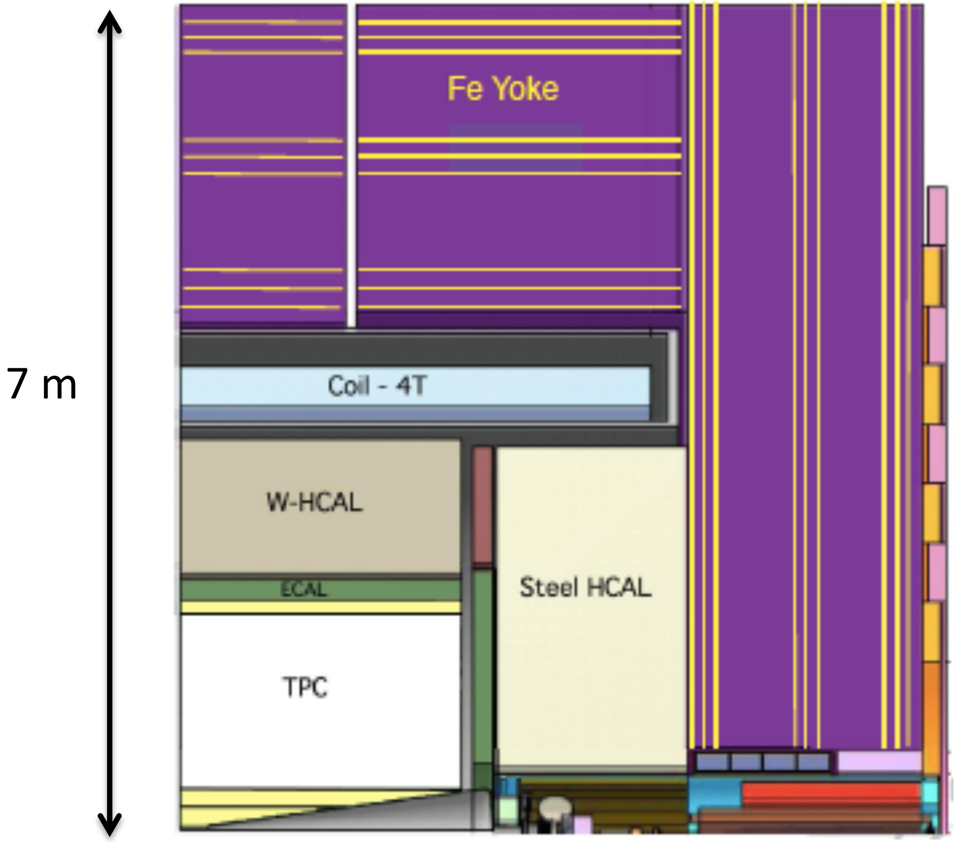
CLIC_ILD and CLIC_SiD

Two general-purpose CLIC detector concepts

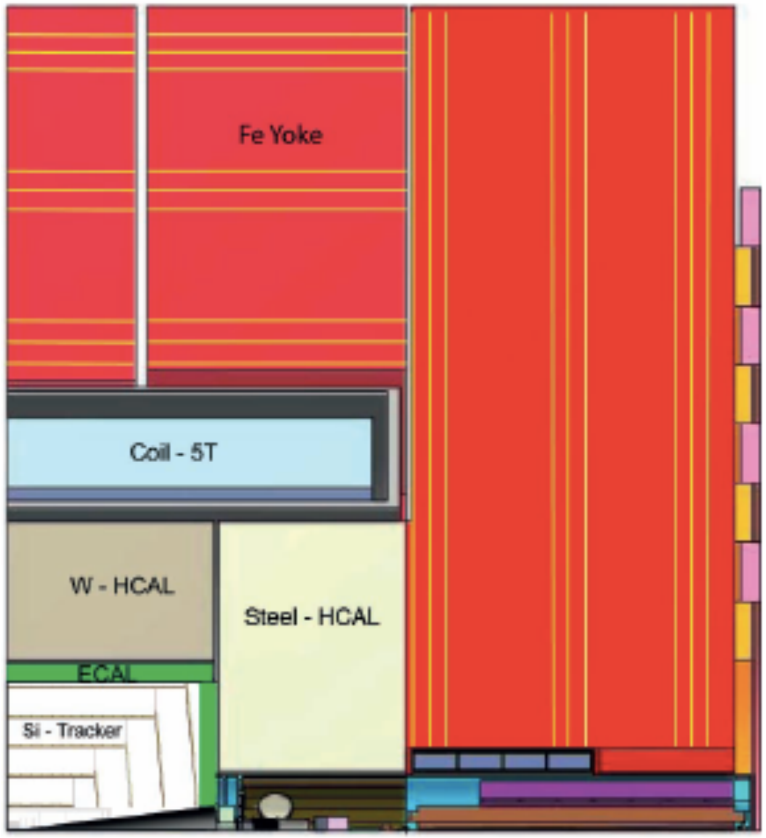
Based on initial ILC concepts (ILD and SiD)

Optimised and adapted to CLIC conditions

CLIC_ILD



CLIC_SiD



Compare experiment CLIC ⇔ LHC

In a nutshell:

CLIC detector:

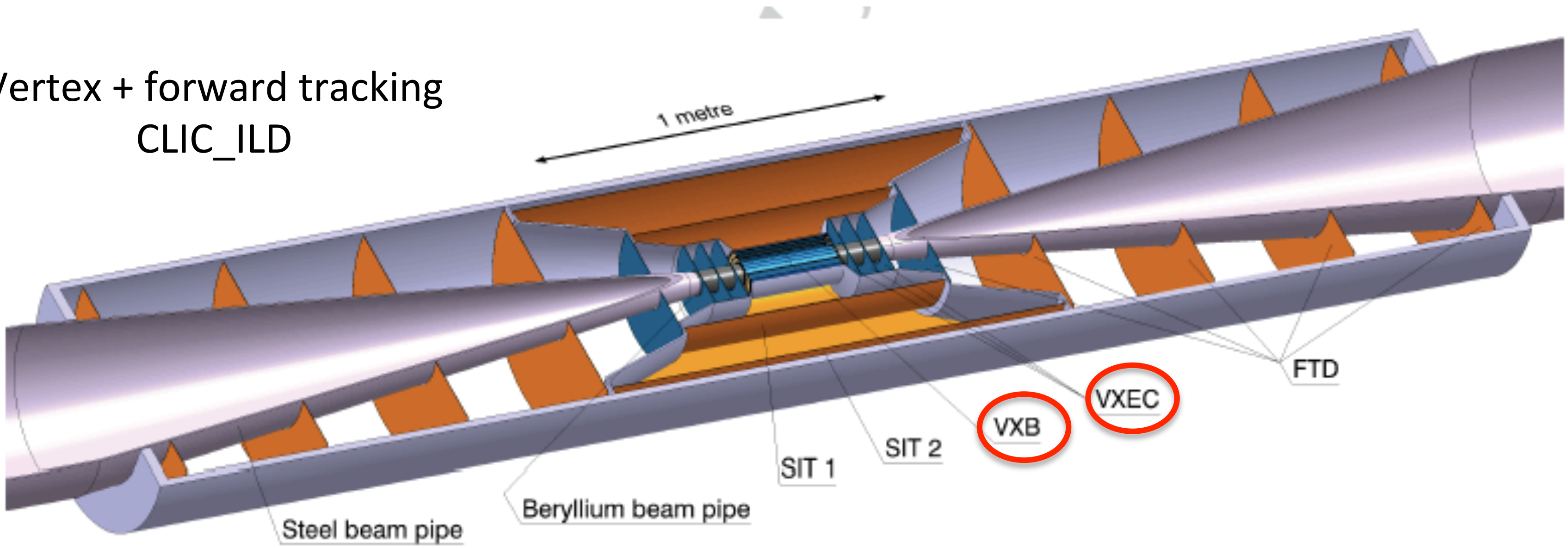
- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (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**

CLIC vertex detector

Vertex + forward tracking
CLIC_ILD



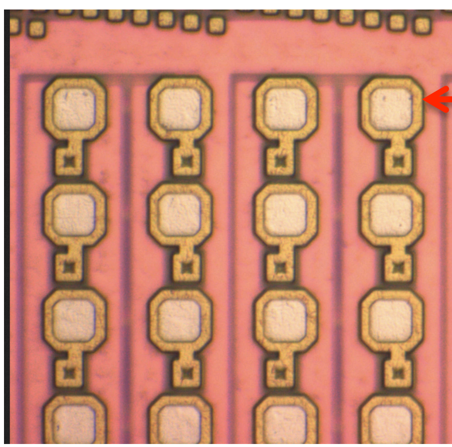
- ~25×25 µm pixel size => ~2 Giga-pixels
- 0.2% X_0 material par layer <= very thin !
  - Very thin materials/sensors
  - Low-power design, power pulsing, air cooling
  - Aim: 50 mW/cm^2
- Time stamping 10 ns
- Radiation level $<10^{11}$ $n_{eq}cm^{-2}year^{-1}$ <= 10^4 lower than LHC

Very challenging R&D project !

CLIC vertex detector R&D

Hybrid approach pursued: (<= other options possible)

- Thin (~50 µm) silicon sensors
- Thinned High density ASIC in very-deep-sub-micron:
  - TimePix3, Smallpix <= R&D steps
  - CLICpix
- Low-mass interconnect
  - Micro-bump-bonding (Cu-pillar option, Advacam)
  - Through-Silicon-Vias (R&D with CEA-Leti)



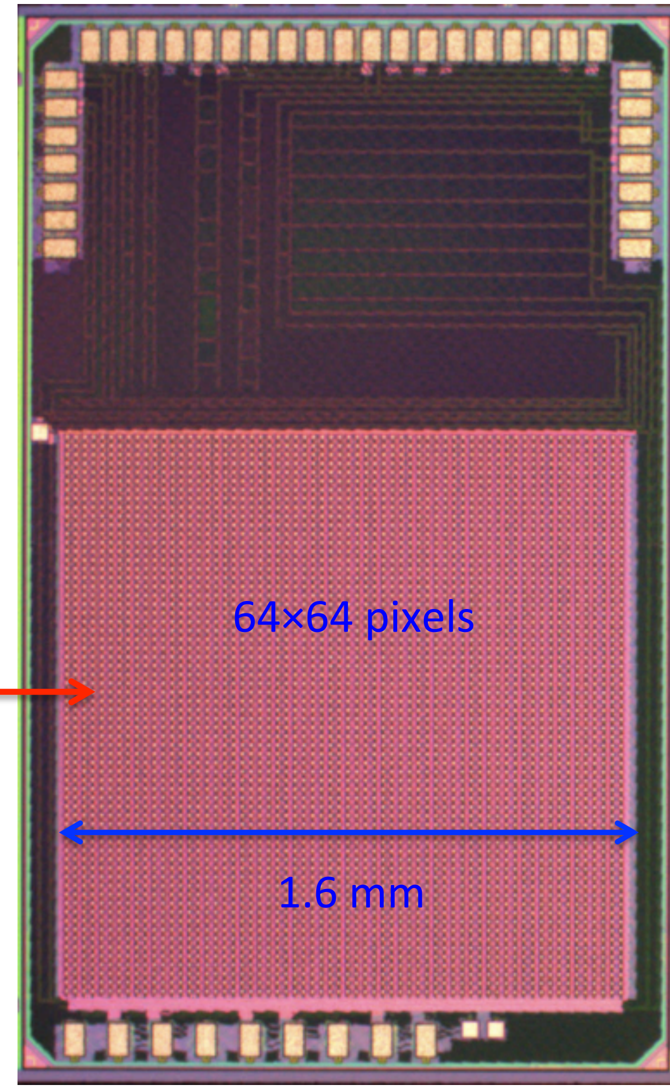
25 µm

CLICpix

64×64 pixel demonstrator

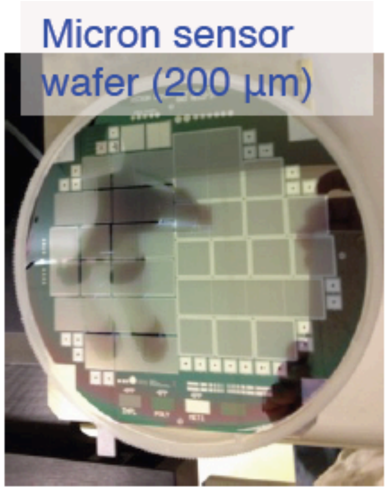
Fully functional

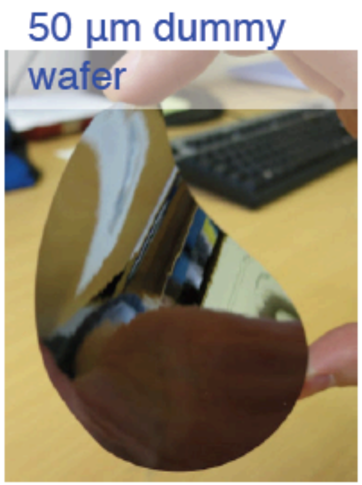
- 65 nm technology
- 25×25 µm^2 pixels
- 4-bit TOA and TOT information
  - 10 nsec time-slicing
- Power 2 W/cm^2 (continuous)
- With sequential power pulsing
  - 50 mW/cm^2

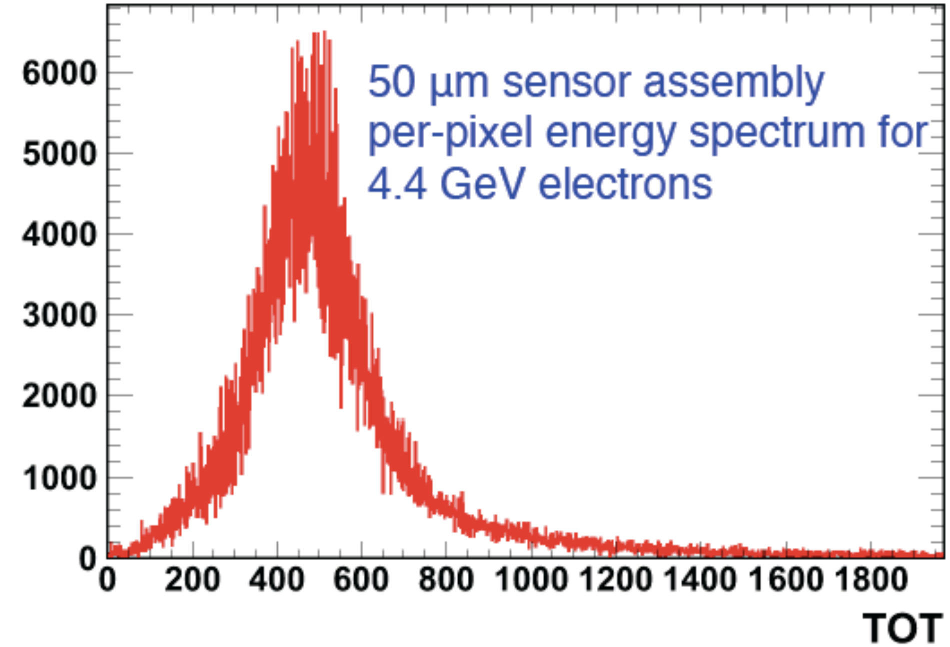


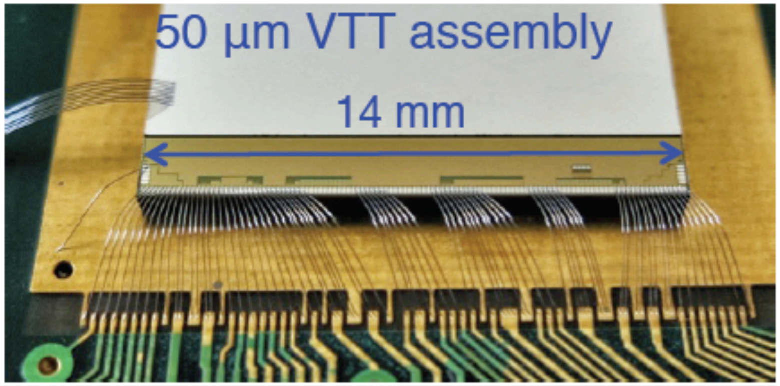
thin pixel sensor assemblies

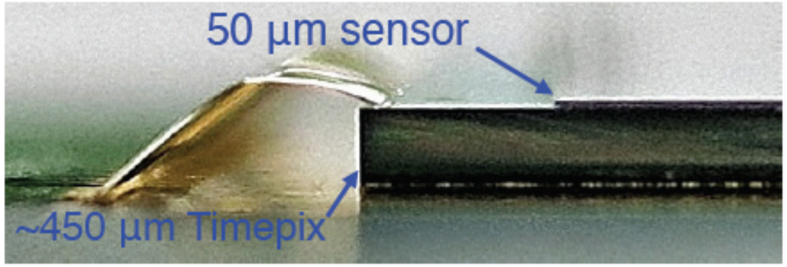
- Micron (UK) + IZM (DE) and VTT/Advacam (FI) Timepix sensor assemblies with 55 µm pitch
  - test feasibility of ultra-thin sensors and assemblies
  - Assemblies delivered: 50-200 µm sensor thickness
  - Sensor calibration (non-linear TOT response)
  - Test beam at DESY in August 2013
- assemblies with thinned (100 µm) Timepix → in the pipeline
- sensors matching 25 µm² CLICpix footprint → end 2013?
- ultimate goal: 50 µm thick sensors + 50 µm thick ASICs



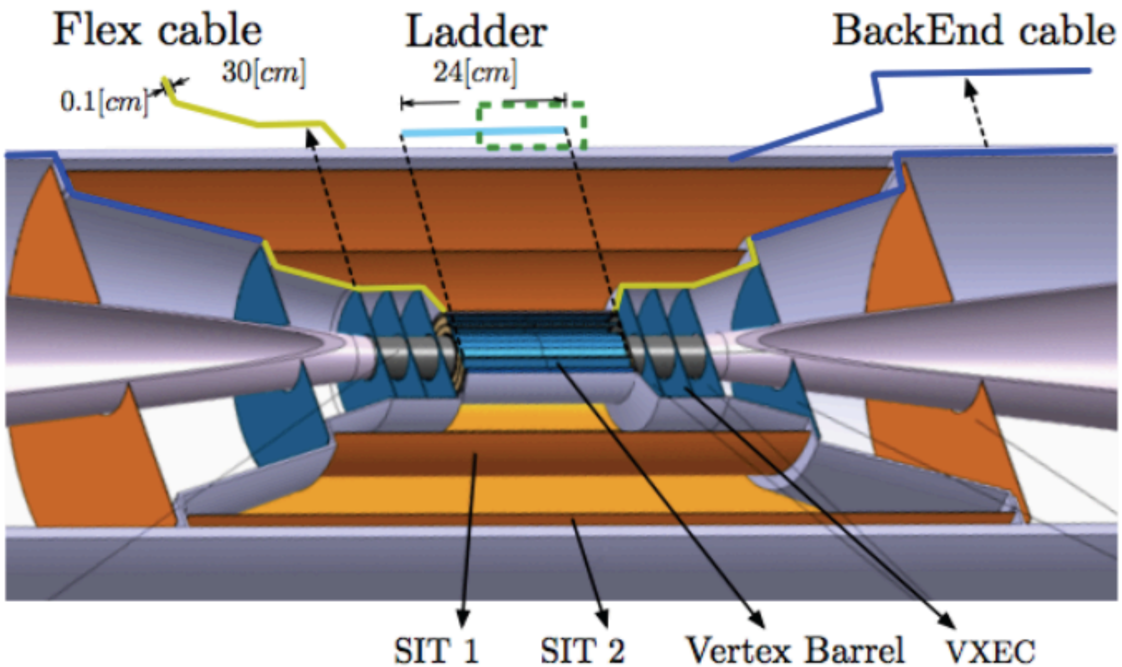








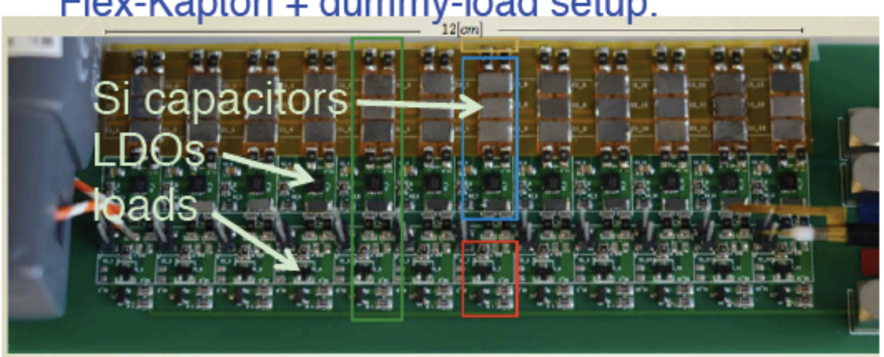
CLIC vertex R&D: power pulsing

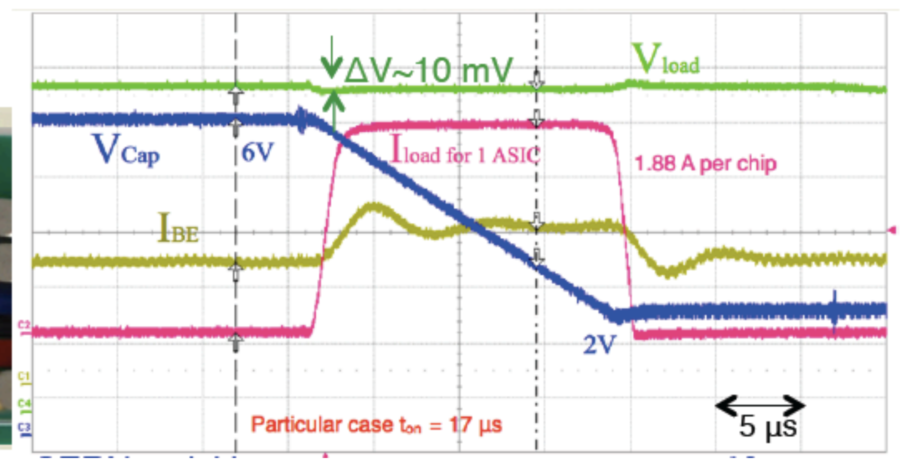


Power-delivery + pulsing

- low-mass Al-Kapton cables
- power pulsing with local energy storage and voltage regulation
- prototype for analog powering of CLICpix ladder:
  - I_{ladder}~20-60 mA; 10 mW/cm^2
  - voltage stability: ΔV~10 mV
  - 0.064% X_0 material contrib.
  - can be reduced to ~0.03% X_0

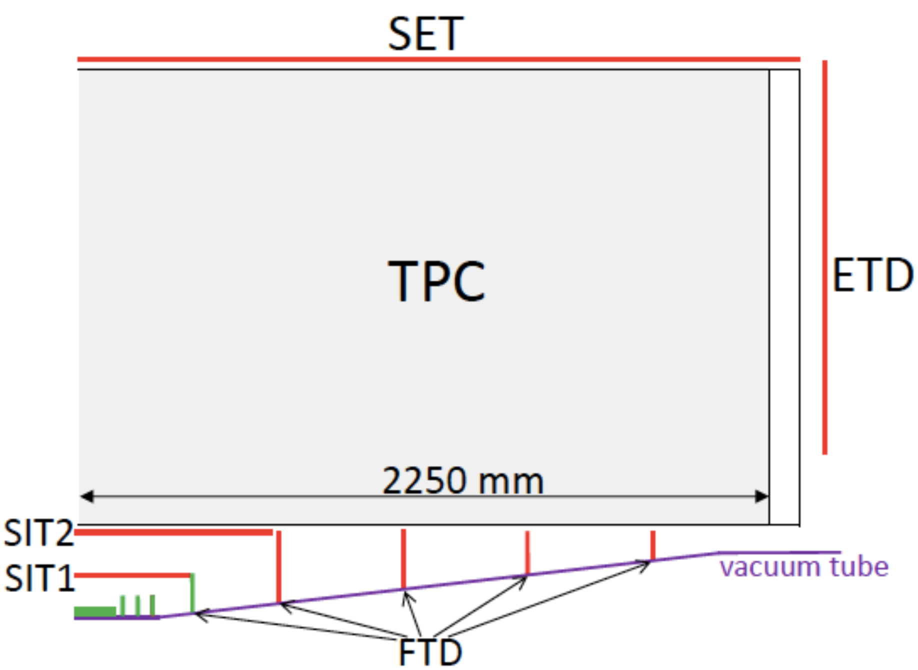
Flex-Kapton + dummy-load setup:

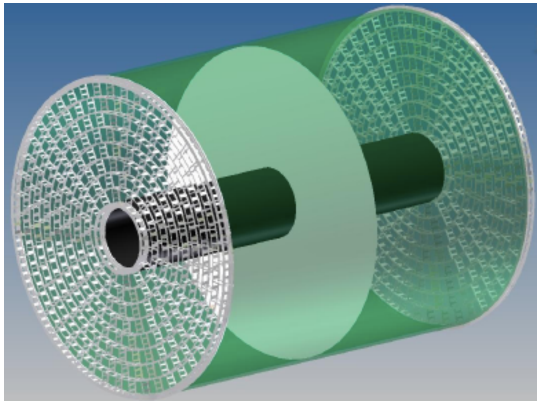




CLIC_ILD ↙ and CLIC_SiD ↘ tracker

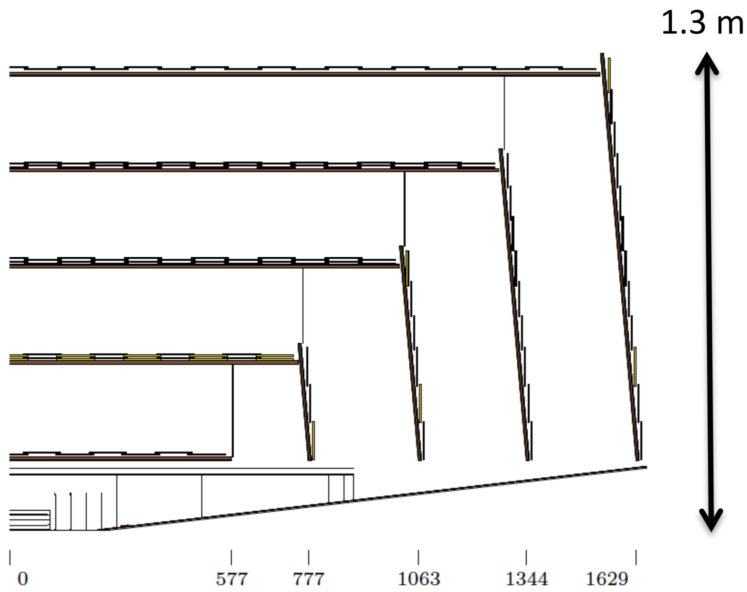
TPC + silicon tracker in 4 Tesla field



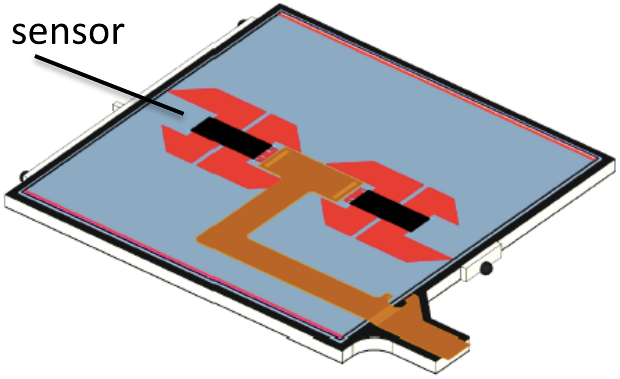


Time Projection Chamber (TPC) with MPGD readout

all-silicon tracker in 5 Tesla field



chip on sensor



calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design

=> => fine-grained calorimetry + Particle Flow Analysis (PFA)

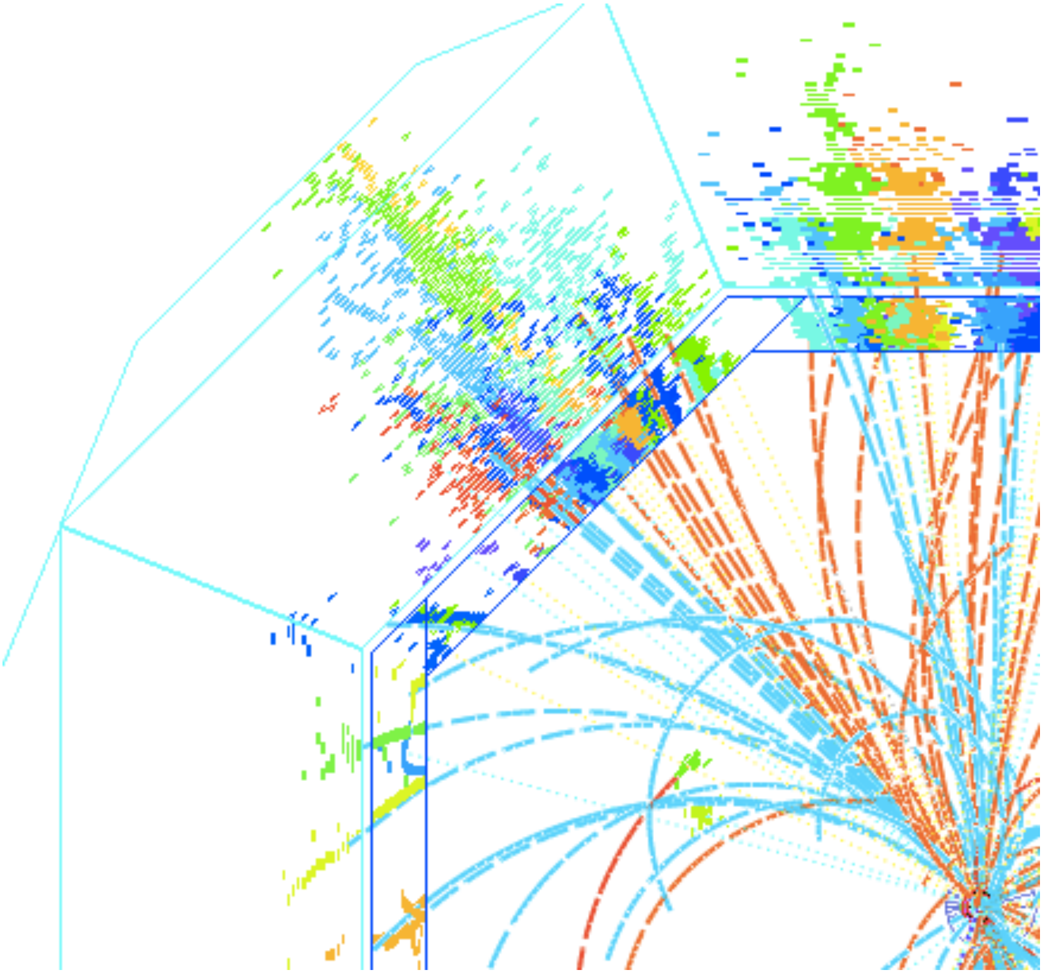
What is PFA?

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutrons

↓

Always use the best info you have:
- 60% => tracker 🙂 🙂
- 30% => ECAL 🙂
- 10% => HCAL 🙁

Hardware + software !



PFA calorimetry at CLIC

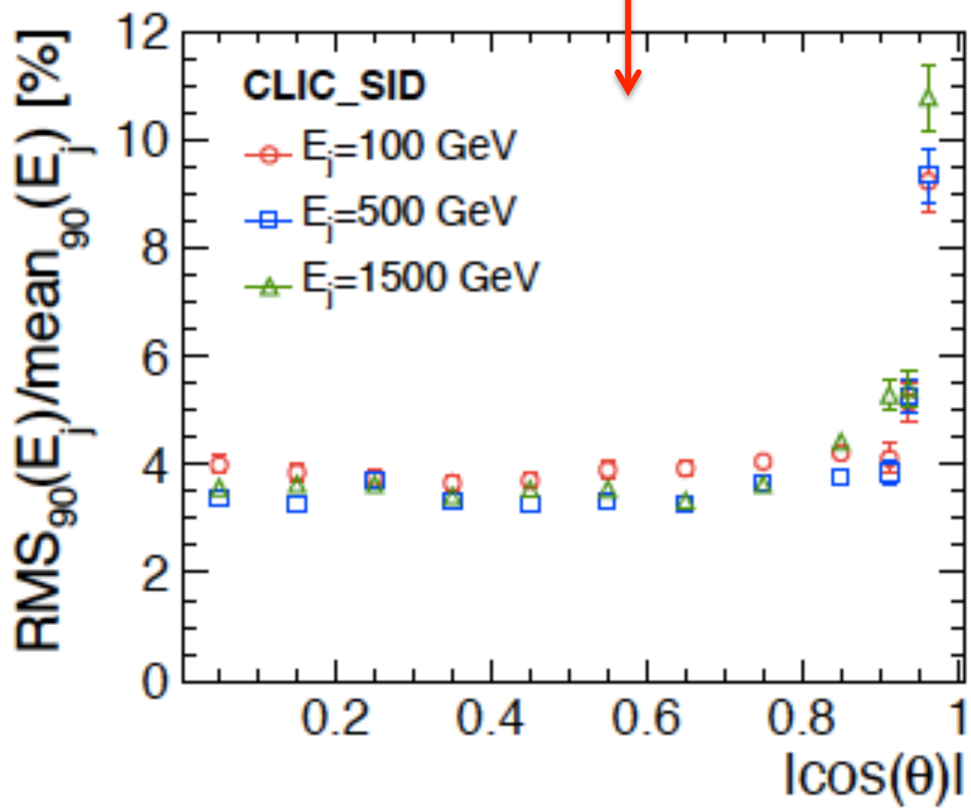
ECAL
Si or Scint. (active) + Tungsten (absorber)
cell sizes 13 mm^2 or 25 mm^2
30 layers in depth

HCAL
Several technology options: scint. + gas
Tungsten (barrel), steel (endcap)
cell sizes 9 cm^2 (analog) or 1 cm^2 (digital)
60-75 layers in depth
Total depth 7.5 Λ_i

← technology

High precision on jets
↓
ECAL +HCAL have to fit inside coil
↓
CLIC needs Tungsten absorber in HCAL
↓
Requires beam tests to validate Geant4

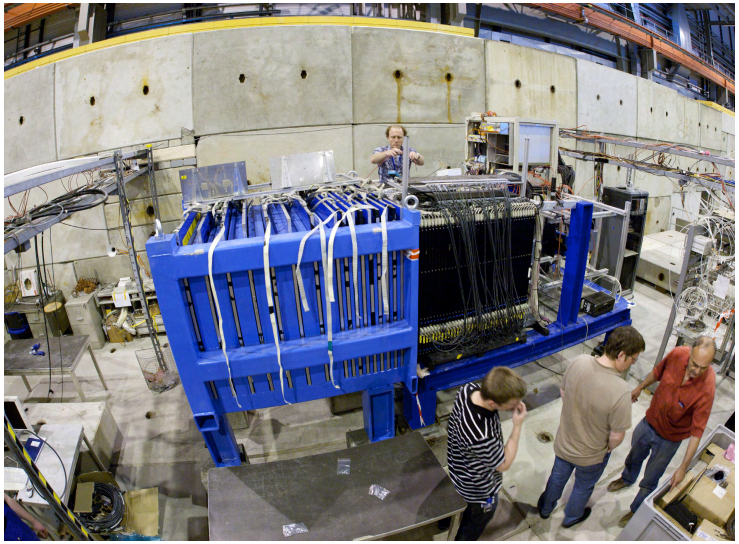
simulated jet energy resolution



(no jet clustering, without background overlay)

Analog HCAL: scintillator/tungsten

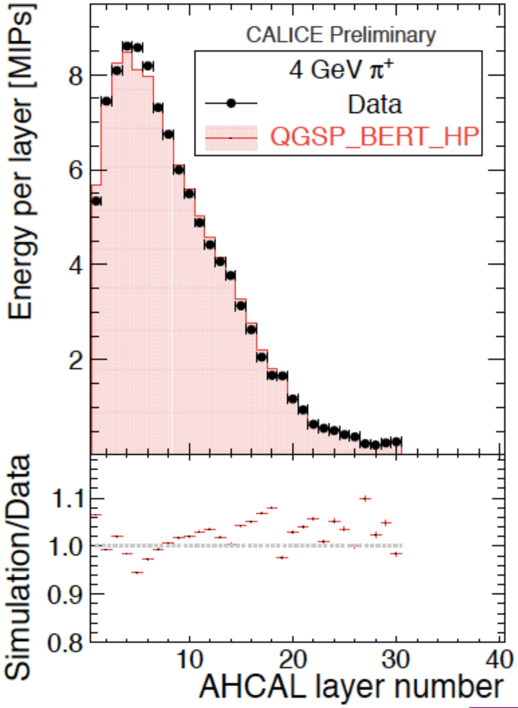
HCAL tests with 10 mm thick **Tungsten absorber** plates,
Tests in 2010+2011 with scintillator active layers, 3×3 cm^2 cells => analog readout



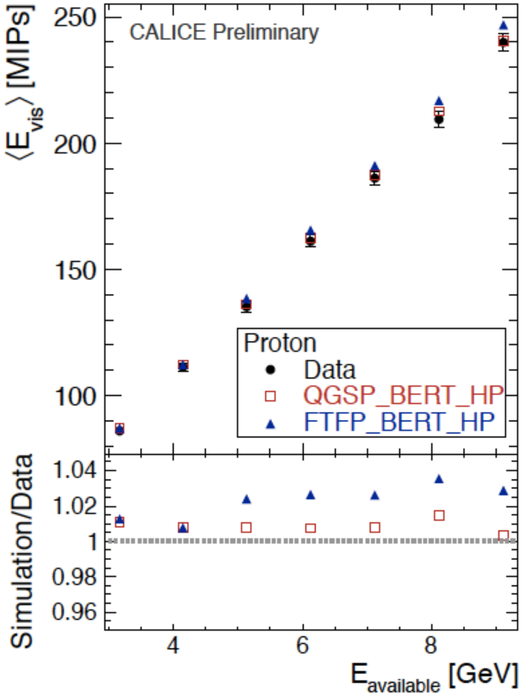
CERN SPS 2011

good agreement with Geant4

longitudinal shower profile, pions

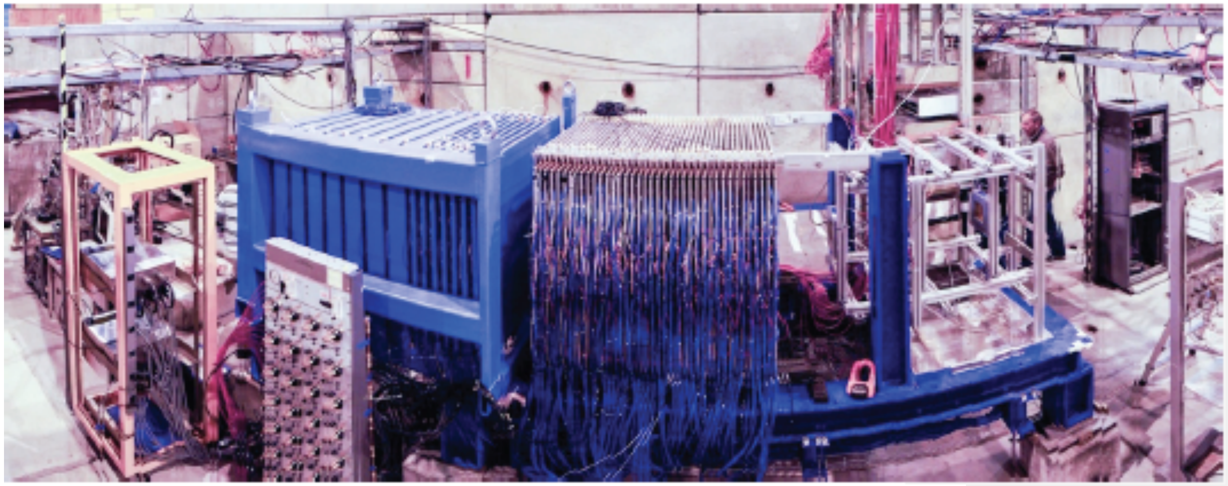


visible Energy protons

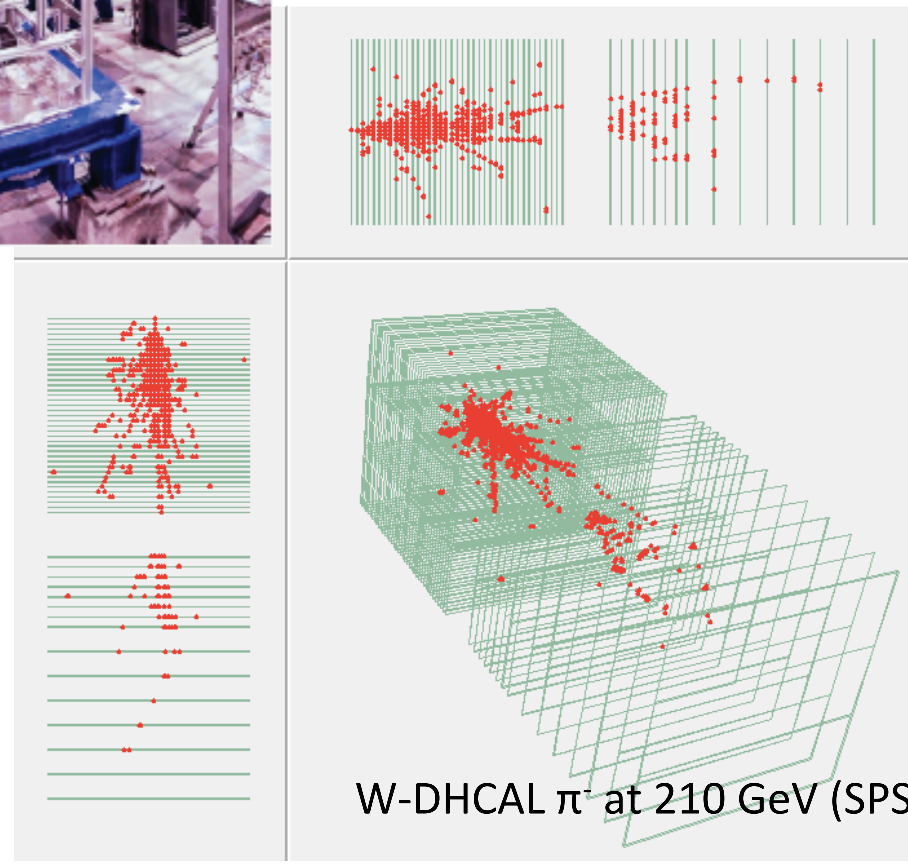


CALICE preliminary

Digital HCAL: scintillator/RPC



Steel DHCAL
Tungsten DHCAL
500’000 readout channels



W-DHCAL π^- at 210 GeV (SPS)

54 glass RPC chambers, 1m^2 each
PAD size 1×1 cm^2
Digital readout (1 threshold)
100 ns time-slicing
Fully integrated electronics
Main DHCAL stack (39) + tail catcher (15)
Total 500’000 readout channels

Successfully tested:
2010+2011 **Fermilab**
Steel absorber
2012 **CERN** PS + SPS
Tungsten absorber

CERN test setup includes **fast readout RPC** after (**T3B**)

Next slides:

Results of physics benchmark studies

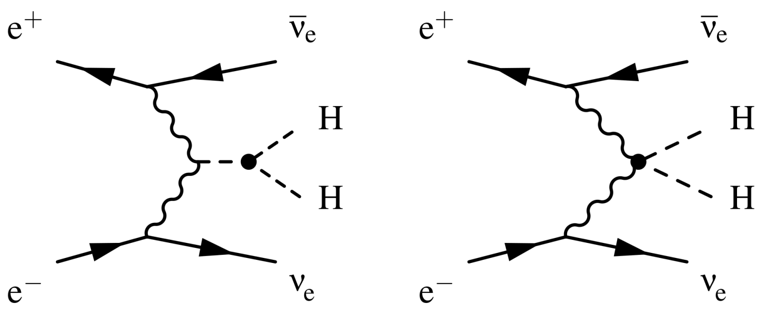
Detailed detector simulations with GEANT4

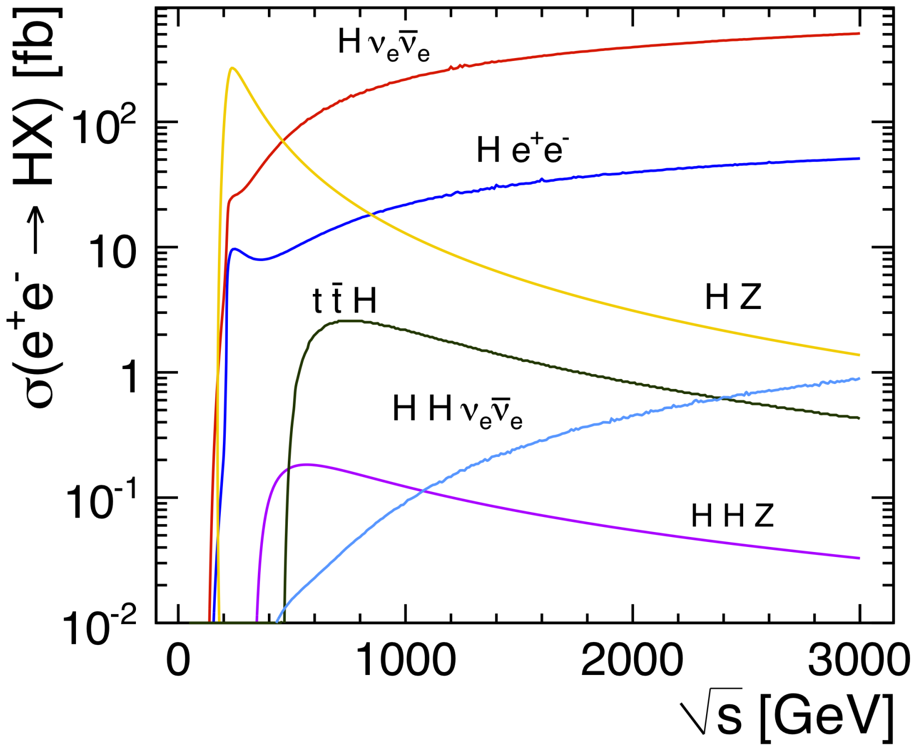
Including overlay of beam-induced backgrounds

Physics signals and physics backgrounds

Reconstruction and analysis

Double Higgs production





- The $HH\nu_e\nu_e$ cross section is sensitive to the Higgs self-coupling, λ, and the quartic g_{HHWW} coupling
- $\sigma(HH\nu_e\nu_e)$ = 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%

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
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu}/\Gamma_H$	–	28%*	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%†	0.7%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ}/\Gamma_H$	–	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

<= work in progress

Global fits to Higgs results

Model-independent global fit to all of the experimental measurements involving the Higgs boson couplings

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 MeV	30 MeV	20 MeV
Γ_H	9.2%	8.5%	8.4%
λ	–	21%	10%
g_{HZZ}	2.1%	2.1%	2.1%
g_{HWW}	2.6%	2.1%	2.1%
g_{Hbb}	2.7%	2.1%	2.1%
g_{Hcc}	3.8%	2.3%	2.2%
$g_{H\tau\tau}$	4.0%	2.5%	tbd
$g_{H\mu\mu}$	–	10.7%	5.6%
g_{Htt}	–	4.5%	tbd

… however precision on couplings is constrained by precision on g_{HZZ}

assumes -80% e- polarisation above 1 TeV

Alternative=> **constrained fit**

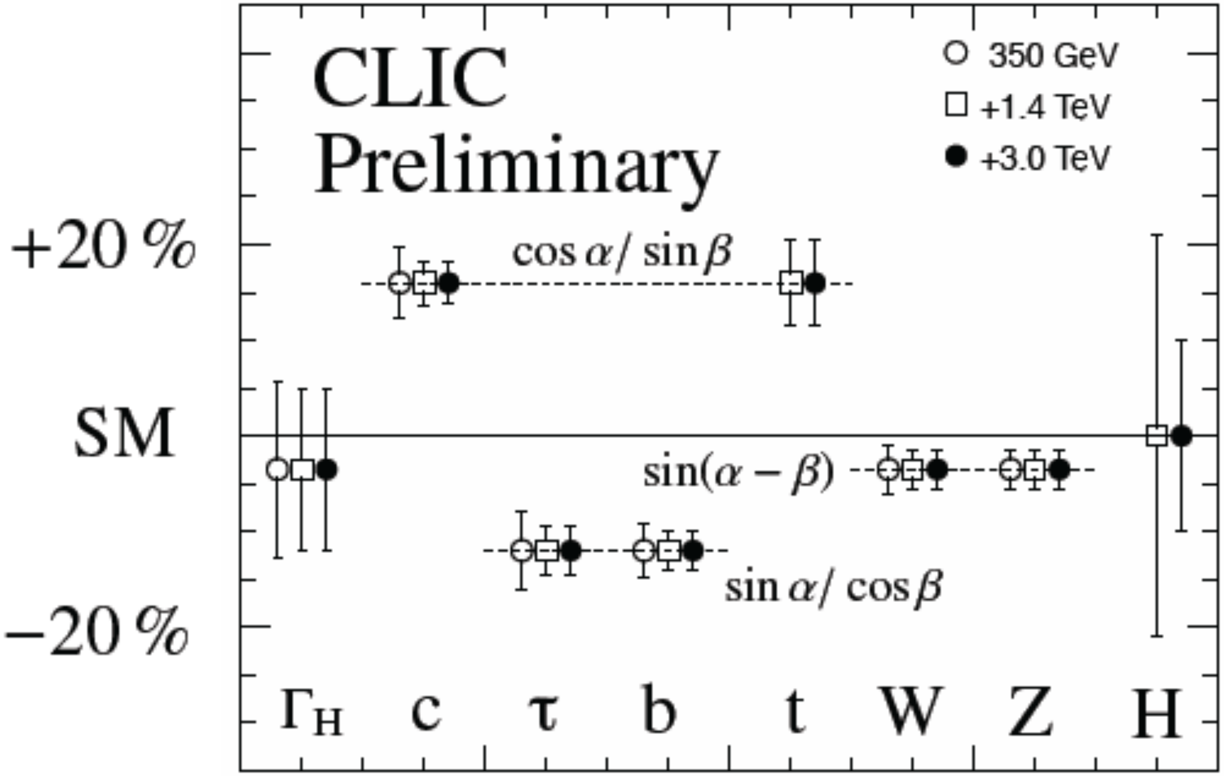
Assuming no invisible Higgs decays, define coupling scaling factors and total width

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}} \qquad \Gamma_{H,md} = \sum_i \kappa_i^2 \, BR_i$$

→ Model-dependent global fit

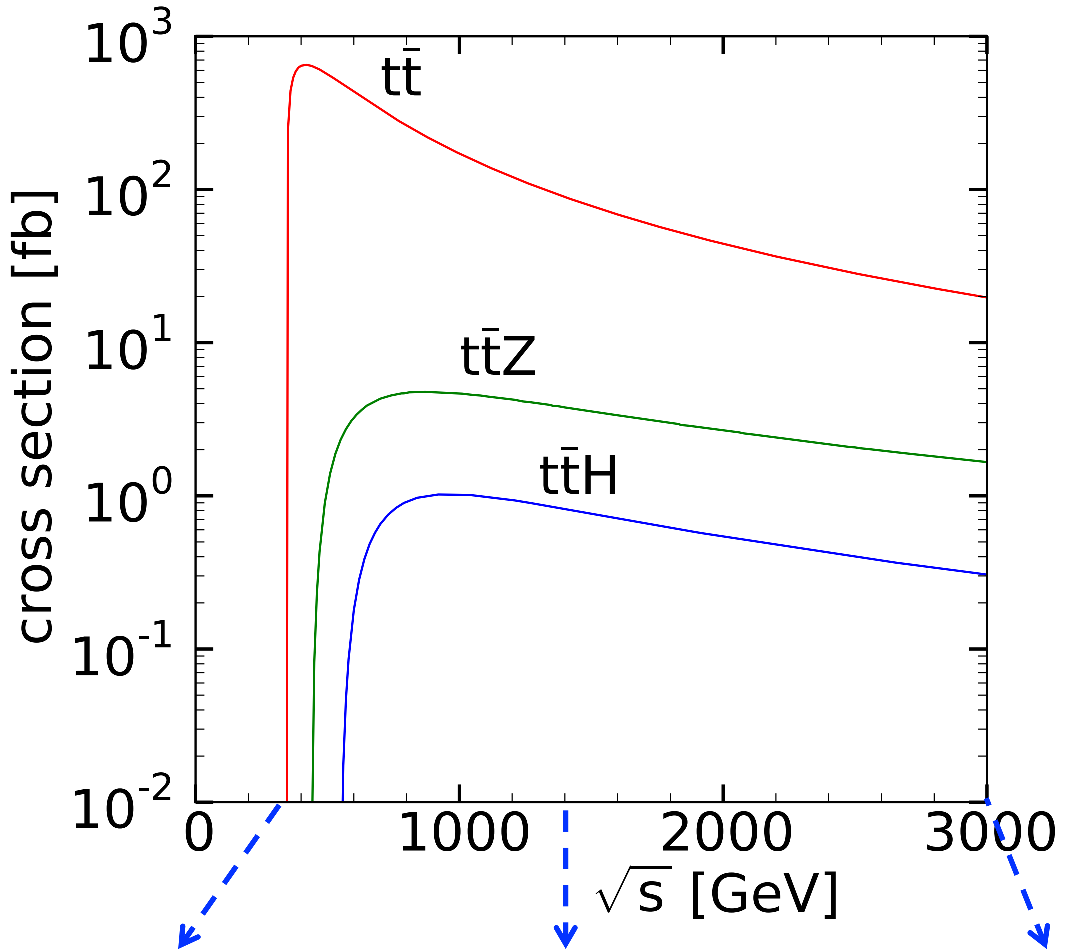
Parameter	Measurement precision		
	350 GeV 500 fb^{-1}	+1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
$\Gamma_{H,model}$	1.6%	0.29%	0.22%
κ_{HZZ}	0.49%	0.33%	0.24%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.32%	0.19%
κ_{Hcc}	3.1%	1.1%	0.75%
$\kappa_{H\tau\tau}$	3.5%	1.4%	tbd
$\kappa_{H\mu\mu}$	–	10.5%	5.2%
κ_{Htt}	–	4.0%	tbd
κ_{Hgg}	3.6%	0.79%	0.56%
$\kappa_{H\gamma\gamma}$	–	5.5%	tbd

Higgs as probe for New Physics



Typical deviations of the Higgs couplings from SM predictions in a 2-Higgs doublet model.

Top physics at CLIC

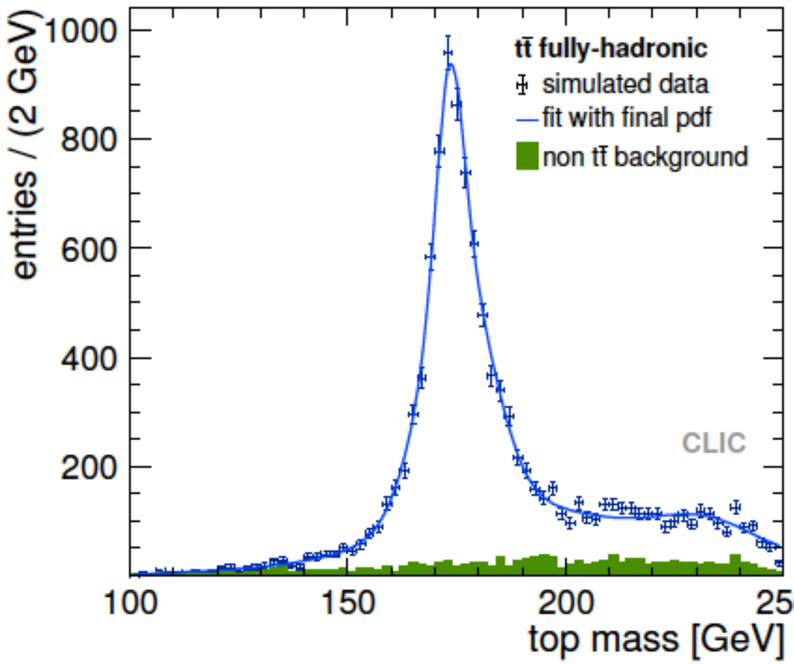


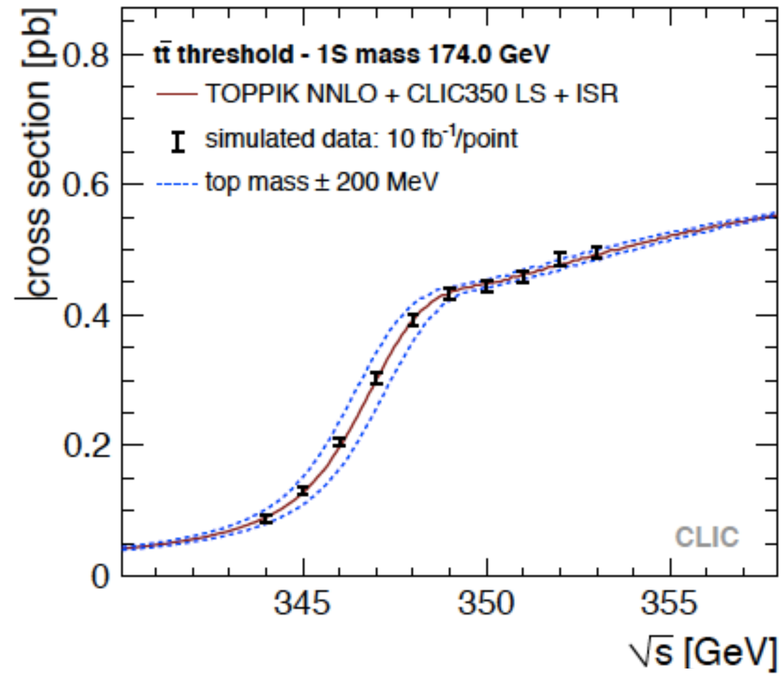
Stage 1: √s = ~375 GeV
Top mass measurement
and threshold scan

Stage 2: √s = 1.4 TeV
Top Yukawa coupling

Stage 3: √s = 3 TeV
Top in combination
with new physics

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	right
500	Invariant mass	Mass	100	GeV	174	0.080	left plot

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

gaugino pair production, 3 TeV

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

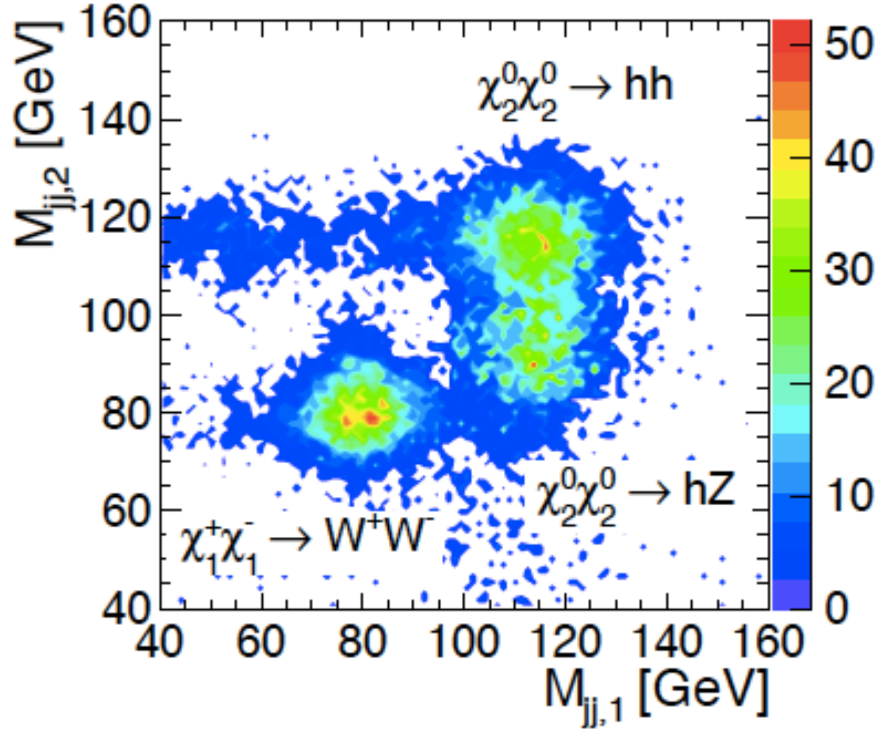
Pair production and decay:

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

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

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

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



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

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

use slepton study result

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

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%

indirect Z' search

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

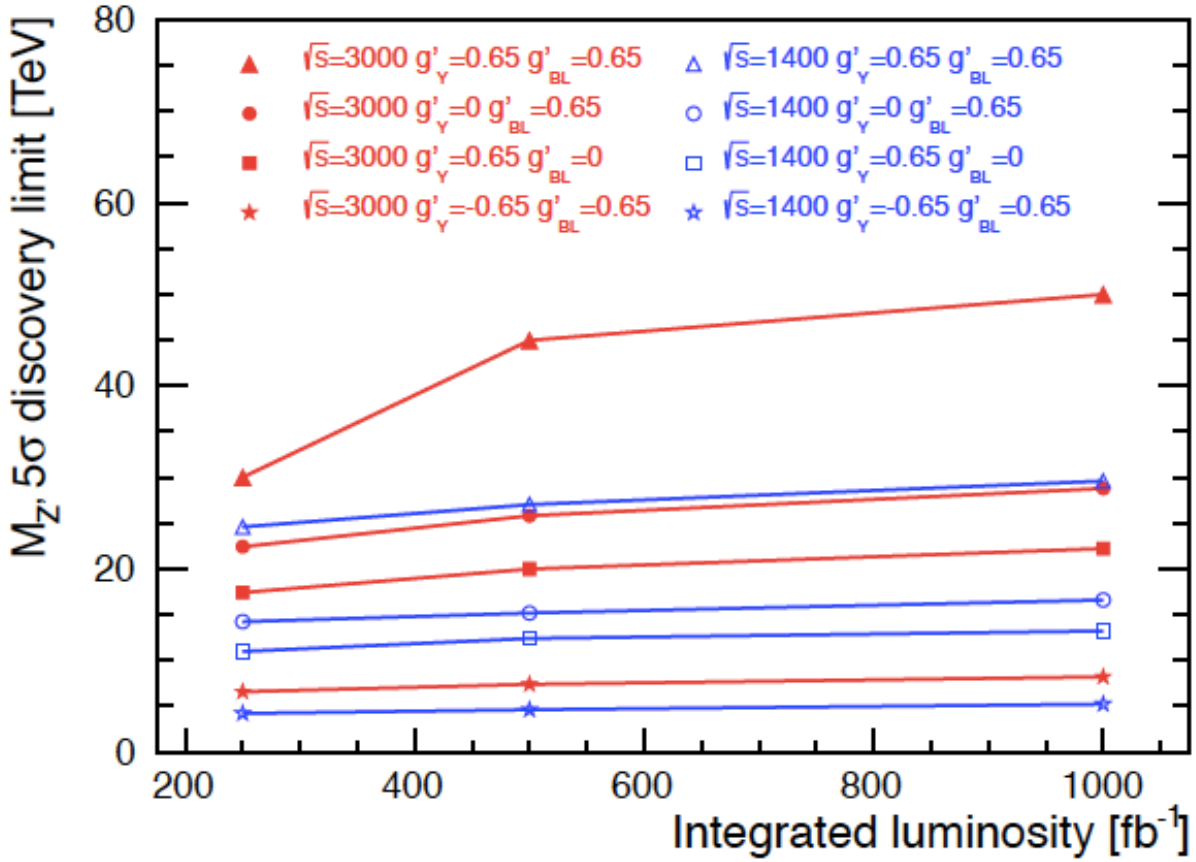


Fig. 14: 5σ limit for a $M_{Z'}$ discovery as function of the integrated luminosity for different values of the couplings g'_{Y} and g'_{BL}. The limits shown are determined from the combined observables σ and A_{FB} at $\sqrt{s} = 3$ TeV and 1.4 TeV.

CLIC reach for New Physics

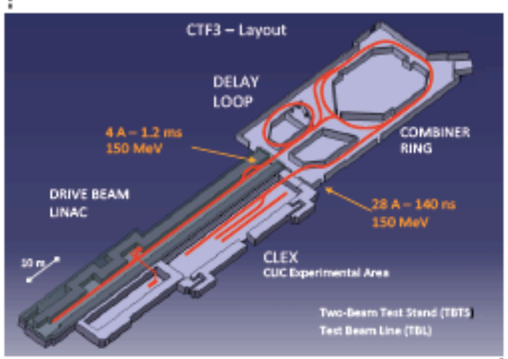
New particle	LHC (14 TeV)	HL-LHC	CLIC3
squarks [TeV]	2.5	3	$\lesssim 1.5$
sleptons [TeV]	0.3	-	$\lesssim 1.5$
Z' (SM couplings) [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0001
μ contact scale [TeV]	15	-	60
Higgs composite scale [TeV]	5–7	9–12	70

Table 9: 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 $g = 1$.

CLIC strategy and objectives

2012-16 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.



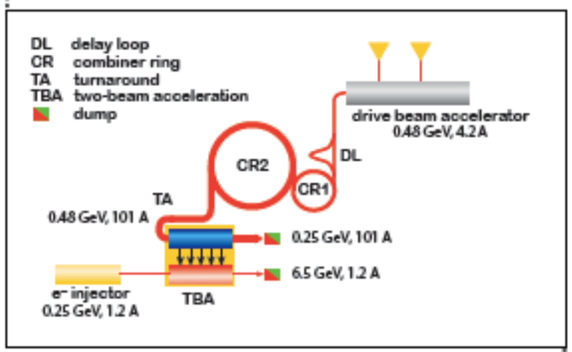
2016-17 Decisions

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.

2017-22 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.



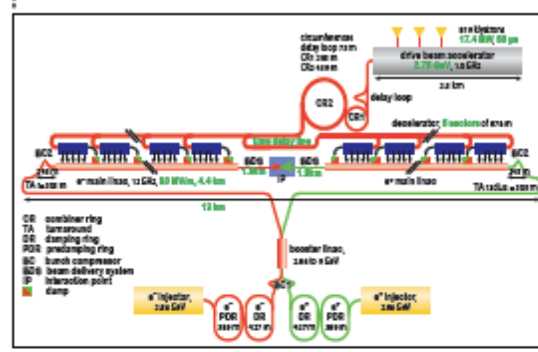
2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

Faster implementation possible, (e.g. for lower-energy Higgs factory): **klystron-based initial stage**

CLIC detector and physics study

- Pre-collaboration structure based on "Memorandum of Cooperation" (MoC): http://lcd.web.cern.ch/lcd/Home/MoC.html
- CERN acts as host laboratory
- At the moment 17 institutes from 14 countries, more contributors most welcome!

[The accelerator R&D is being conducted in collaboration with ~48 institutes]

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

summary

- **CLIC is the only mature option for a multi-TeV e^+e^- collider**
- Very active R&D projects for accelerator and physics/detector technor
- Energy staging will allow for optimal physics exploration, with possible stages at 350 GeV, 1.4, and 3 TeV
- CLIC @ 350 GeV
  - Precision Higgs measurements: mass, branching ratios, absolute coulping…
  - 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
  - As a discovery machine for BSM physics at the energy frontier
    - Direct sensitivity to strong and electroweak particles up to ~ 1.5 TeV (SUSY)
    - Indirect sensitivity up to tens of TeV (ex: heavy Z')

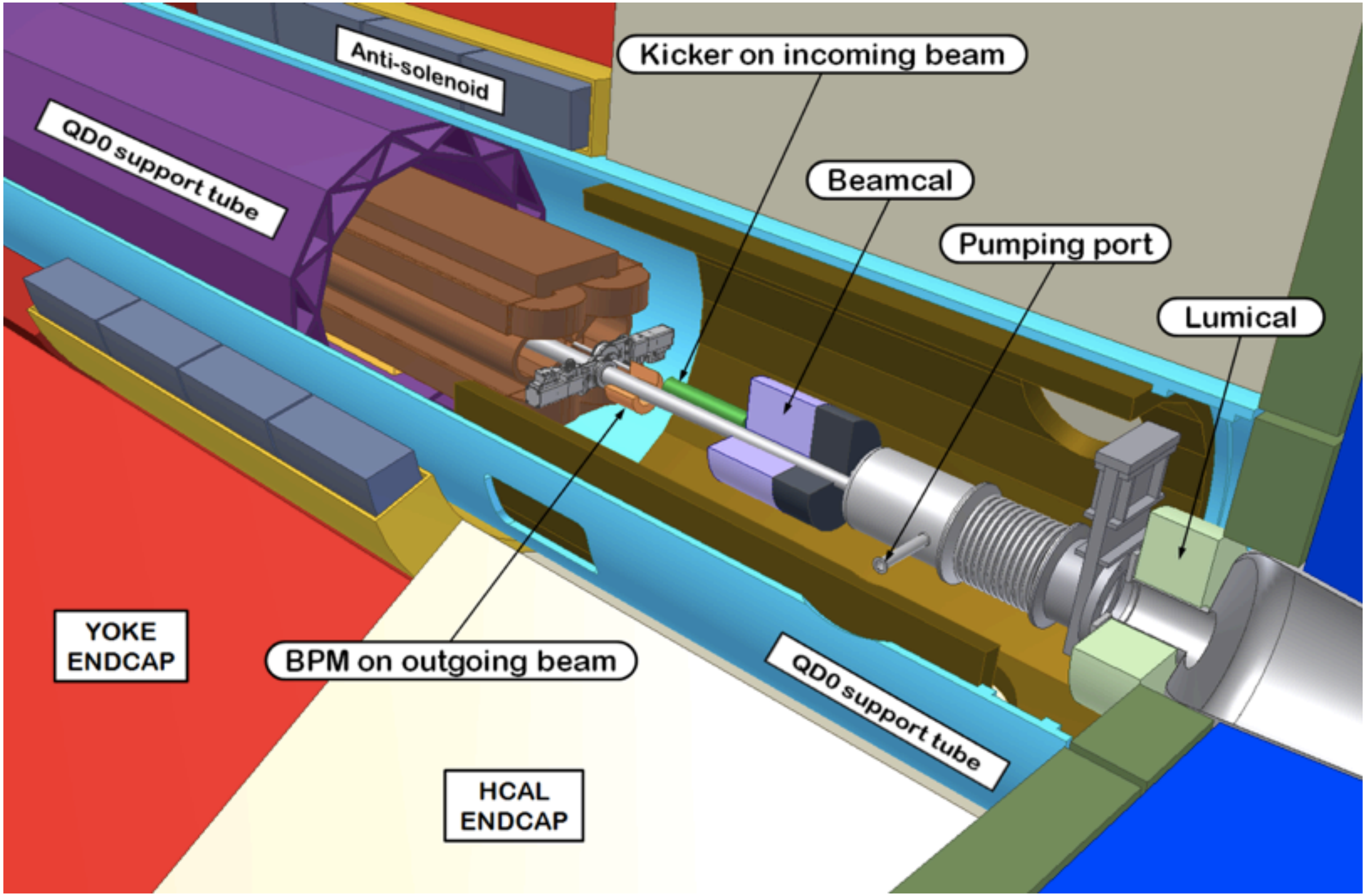
THAT YOU !

Welcome to join !

lcd.web.cern.ch/lcd/

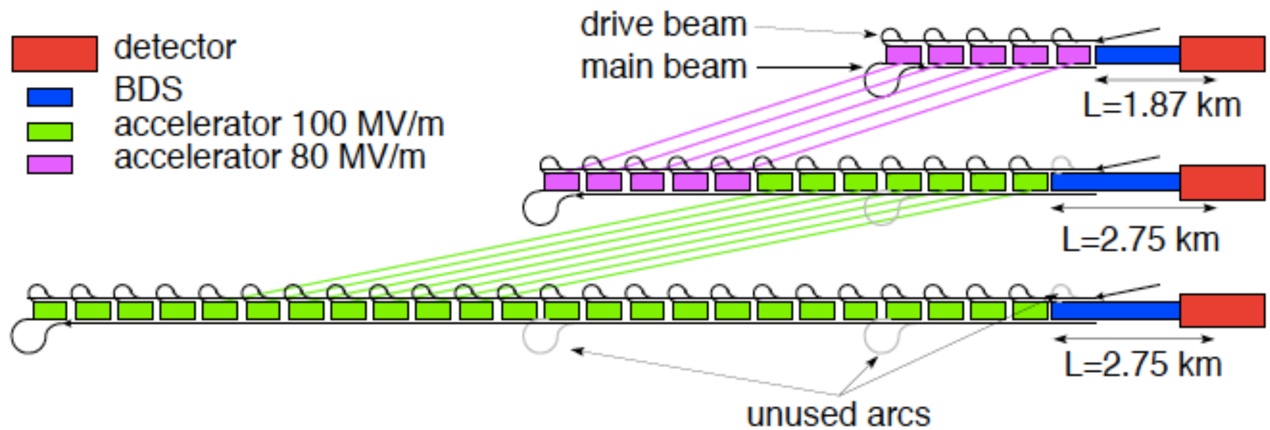
SPARE SLIDES

details of forward detector region



staged approach, scenario A+B

A



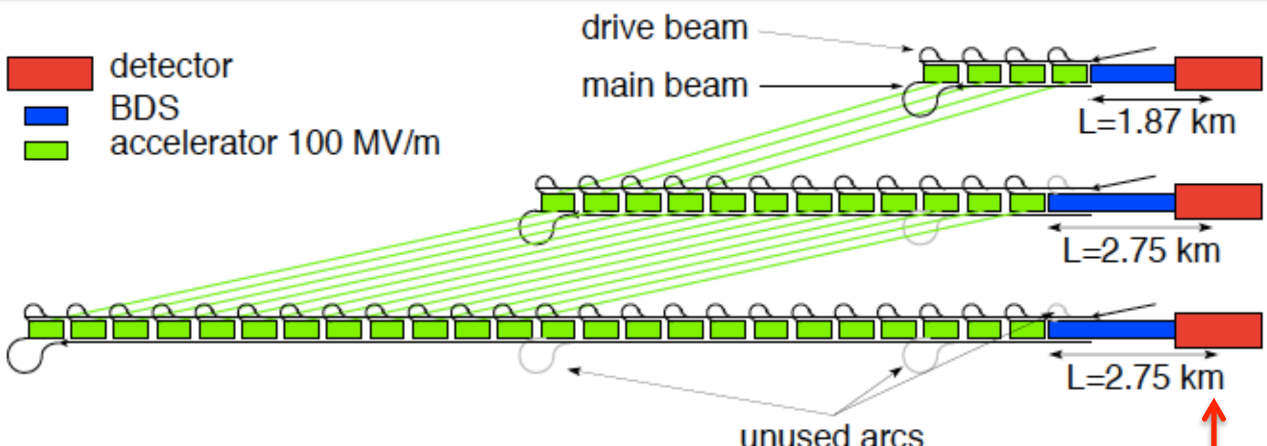
500 GeV

1.4 TeV

3 TeV

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



500 GeV

1.5 TeV

3 TeV

Interaction point

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

CLIC layout at 500 GeV

A

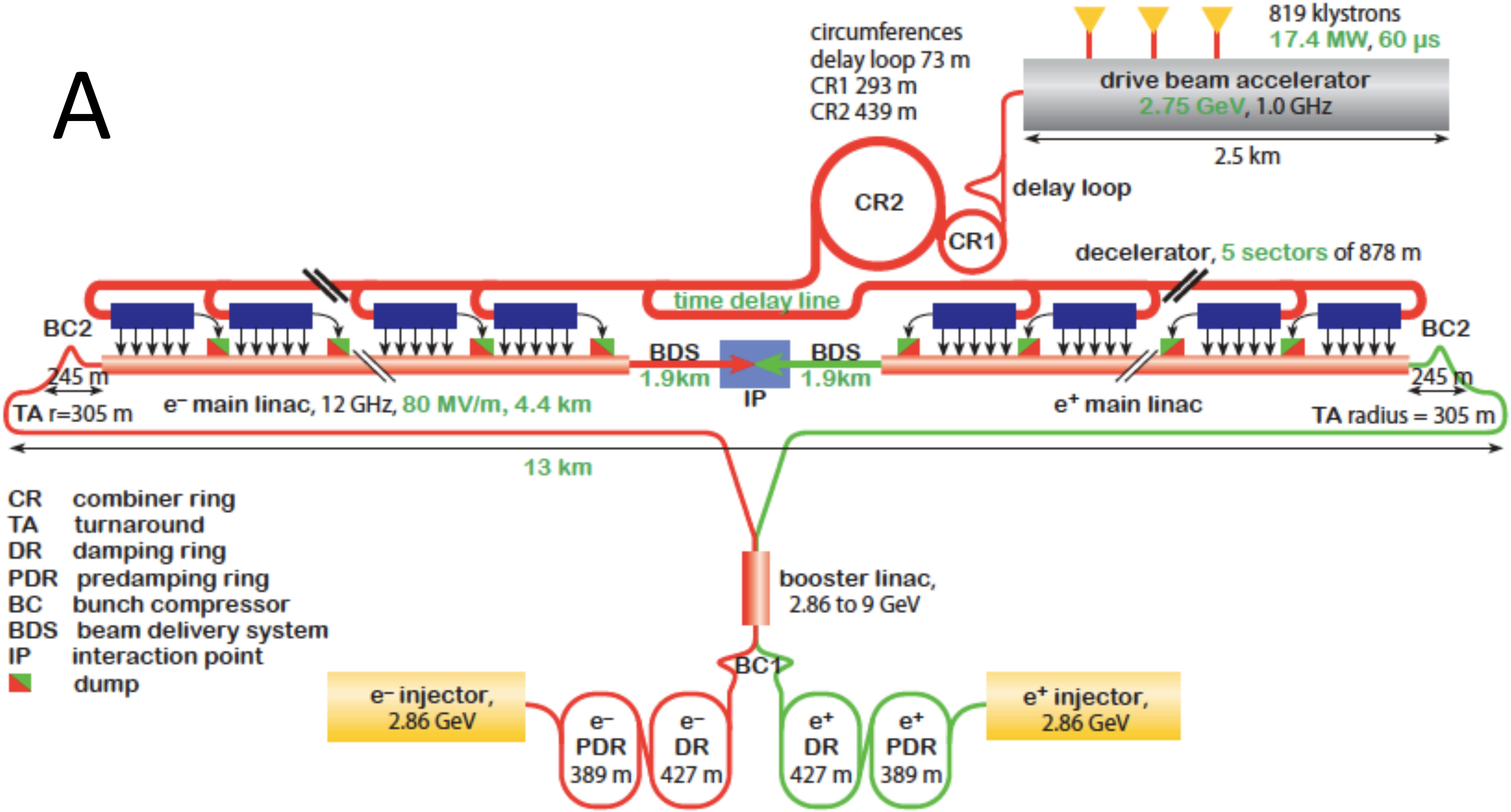


Fig. 3.2: Overview of the CLIC layout at $\sqrt{s}$ =500 GeV. (scenario A)

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	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	2350/20	660/20	660/20
Normalised emittance (IP)	ϵ_x/ϵ_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"**

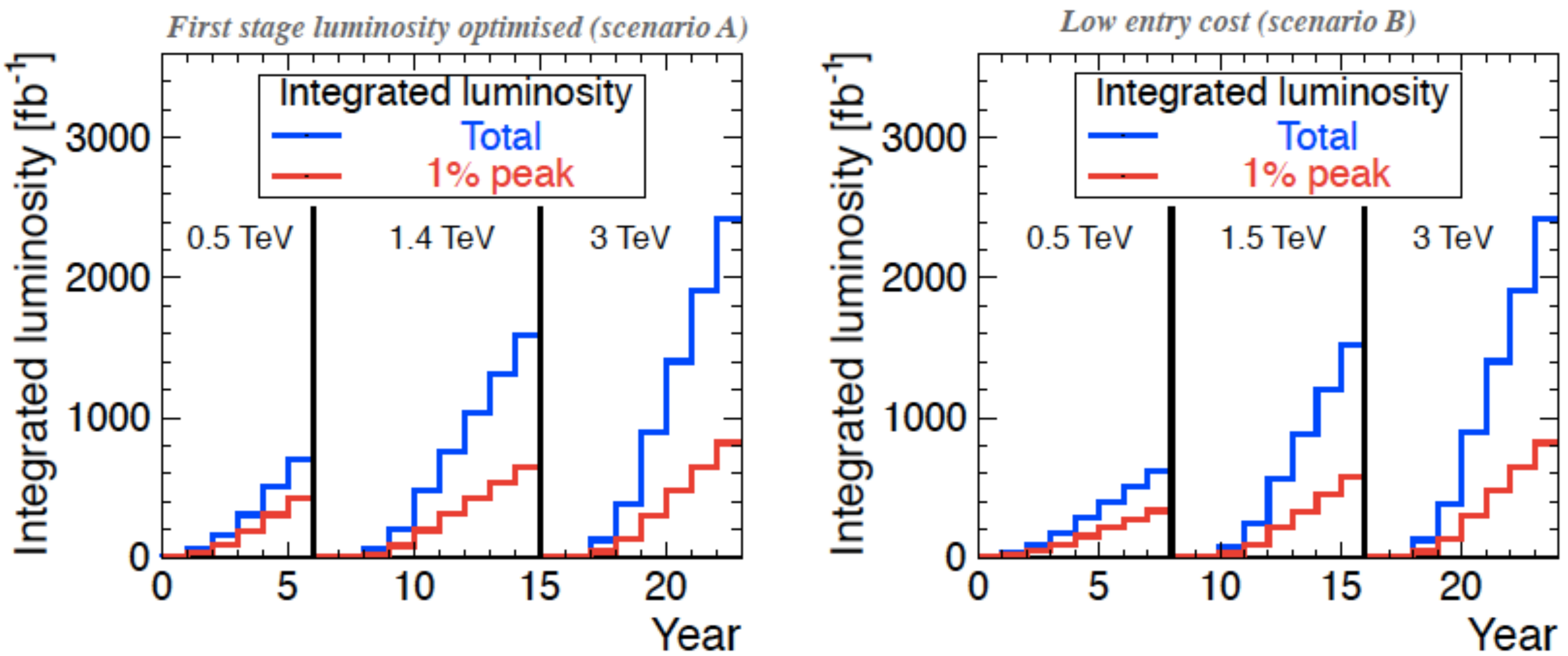


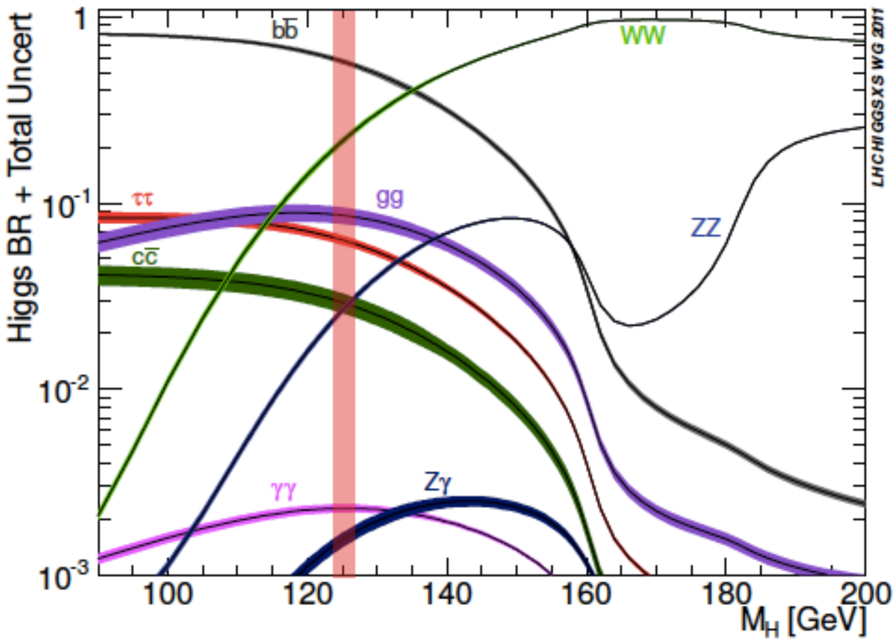
Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two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

Higgs Decay Processes

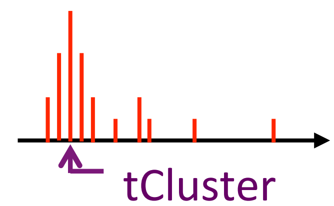
- SM Higgs branching ratios depend only on the Higgs mass
- 125 GeV Higgs has sizable branching ratios to large number of final states
  - $H \to b\bar{b}$: 58%
  - $H \to WW^*$: 22%
  - $H \to gg$: 8.5%
  - $H \to \tau^+\tau^-$: 6.4%
  - $H \to ZZ^*$: 2.7%
  - $H \to c\bar{c}$: 2.7%
  - $H \to \gamma\gamma$: 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



background suppression at CLIC

Triggerless readout of full train

- **Full event reconstruction + PFA analysis with background overlaid**
  - => physics objects with precise p_T and cluster time information
  - Time corrected for shower development and TOF
- **Then apply cluster-based timing cuts**
  - Cuts depend on particle-type, p_T and detector region
  - Allows to protect high-p_T physics objects



+

- **Use well-adapted jet clustering algorithms**
  - Making use of LHC experience (FastJet)

time window / time resolution

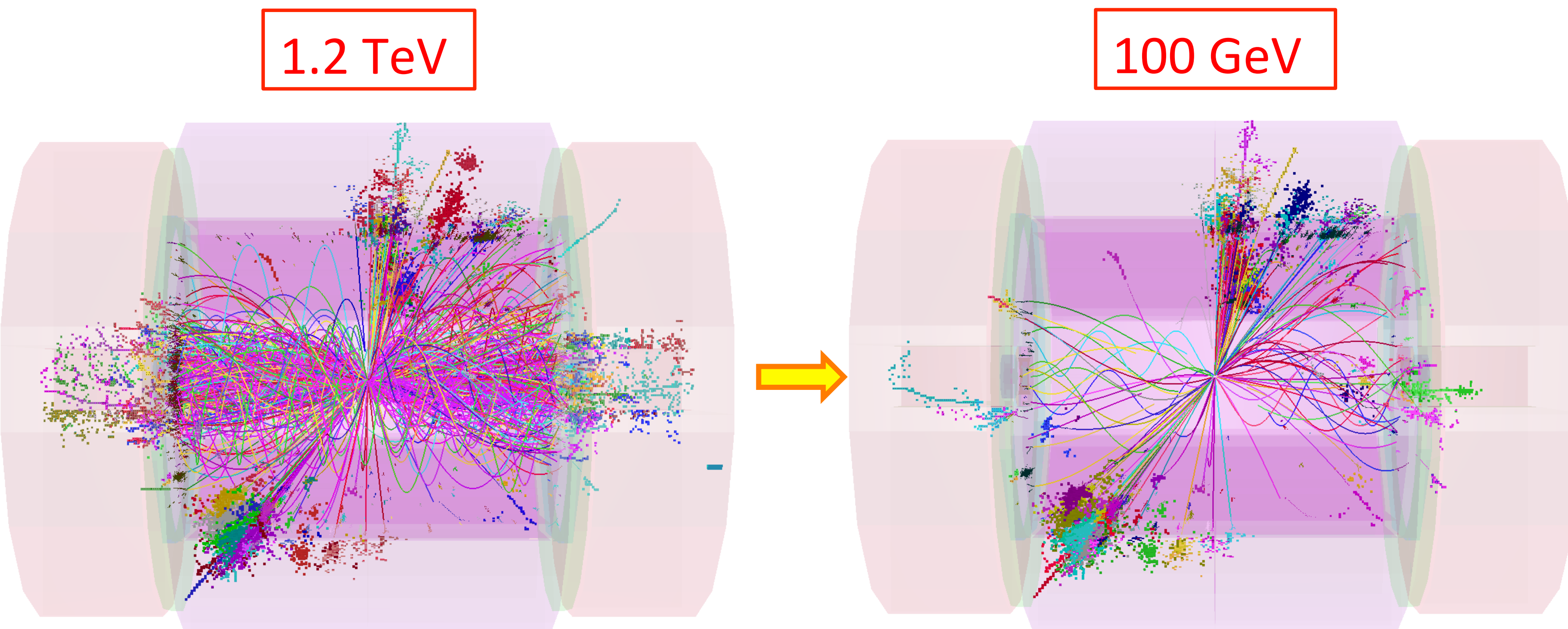
The event reconstruction software uses:

Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

t_0 physics event (offline)

Translates in precise **timing requirements** of the sub-detectors

combined p_T and timing cuts



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

1.2 TeV background in reconstruction time window

100 GeV background after tight cuts

PFO-based timing cuts

Region	p_t *range*	Time cut
Photons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
Neutral hadrons		
central ($\cos\theta \leq 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$	$t < 2.5$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.5$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \text{GeV} \leq p_t < 8.0\ \text{GeV}$	$t < 2.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.0$ nsec
Charged PFOs		
all	$0.75\ \text{GeV} \leq p_t < 4.0\ \text{GeV}$	$t < 3.0$ nsec
	$0\ \text{GeV} \leq p_t < 0.75\ \text{GeV}$	$t < 1.5$ nsec

- Track-only minimum p_t: 0.5 GeV
- Track-only maximum time at ECAL: 10 nsec