CLIC detector challenges
and motivation for energy frontier physics

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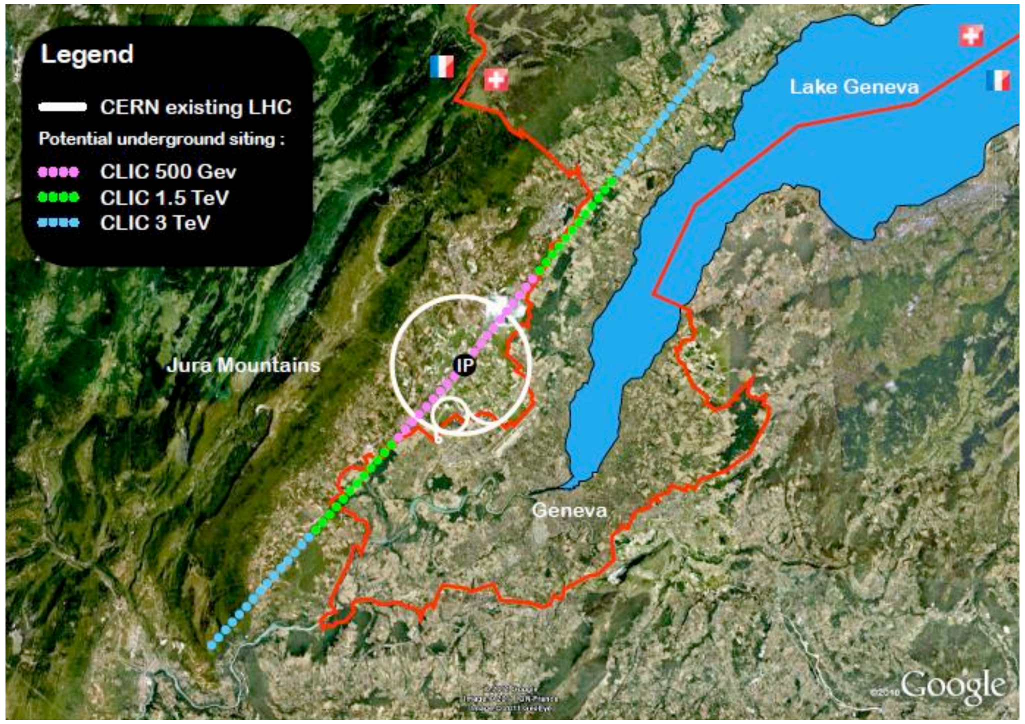
with thanks to the members of CLICdp

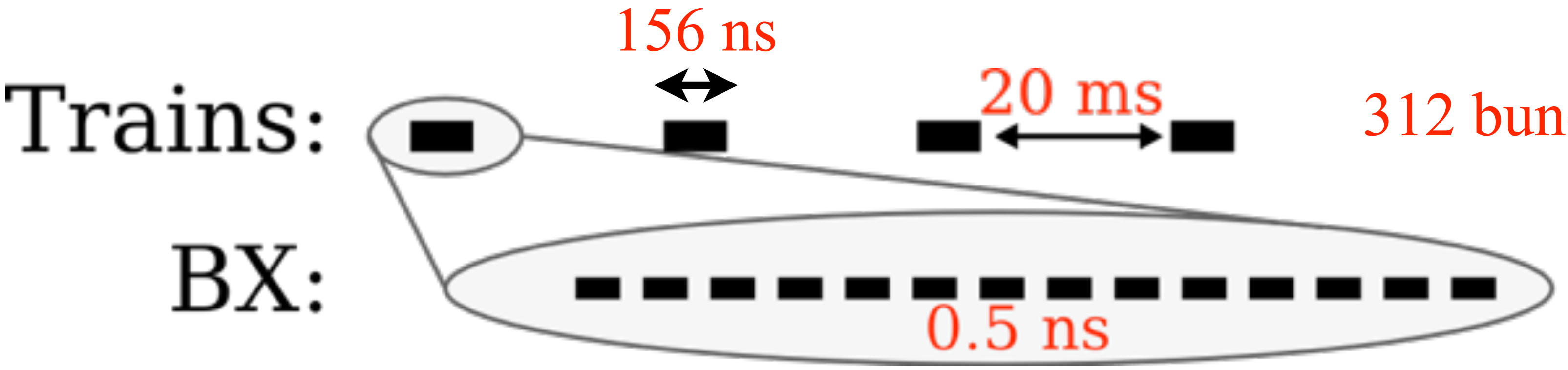
Seminar at 5th INFIERI Workshop - 27th April 2015

CLIC - a collider for the future

CLIC: the Compact Linear Collider

- linear electron-positron collider
- maximum length ~50 km
- $\sqrt{s}$ = 3 TeV (staged construction)
- high luminosity: 6×10^{34} $cm^{-2}s^{-1}$ (at 3 TeV)
- small bunch size: σ_{xyz}(40 nm, 1 nm, 44 μm)
- beam structure:



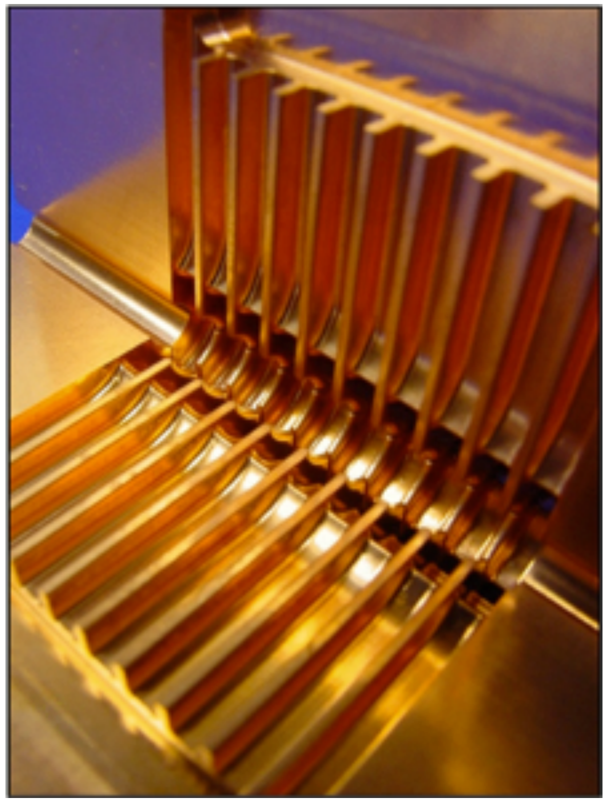


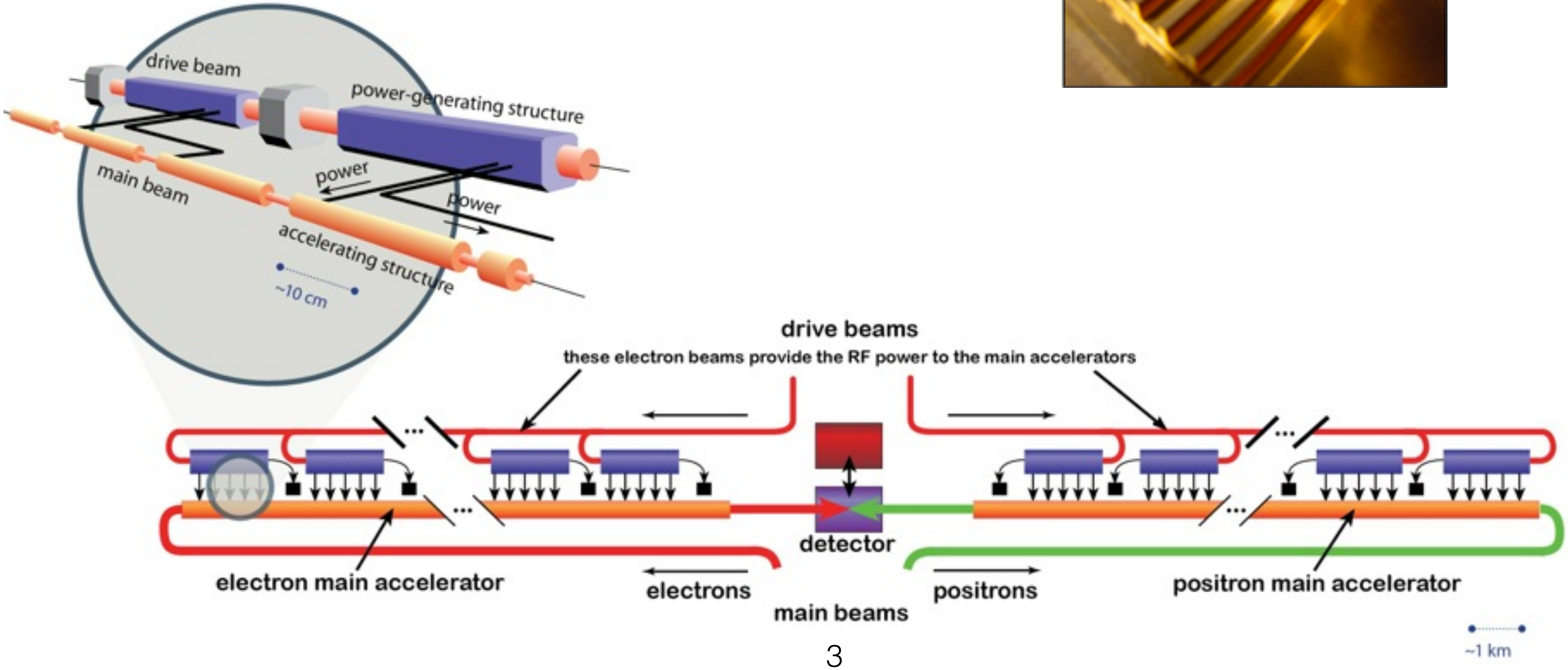
312 bunches per train

Two-beam acceleration

For a ‘compact’ accelerator: 100 MV/m gradient

- high density drive beam
- generates RF in power generating structure
- transferred via wave guides to main beam
- main beams attain maximum √s = 3 TeV

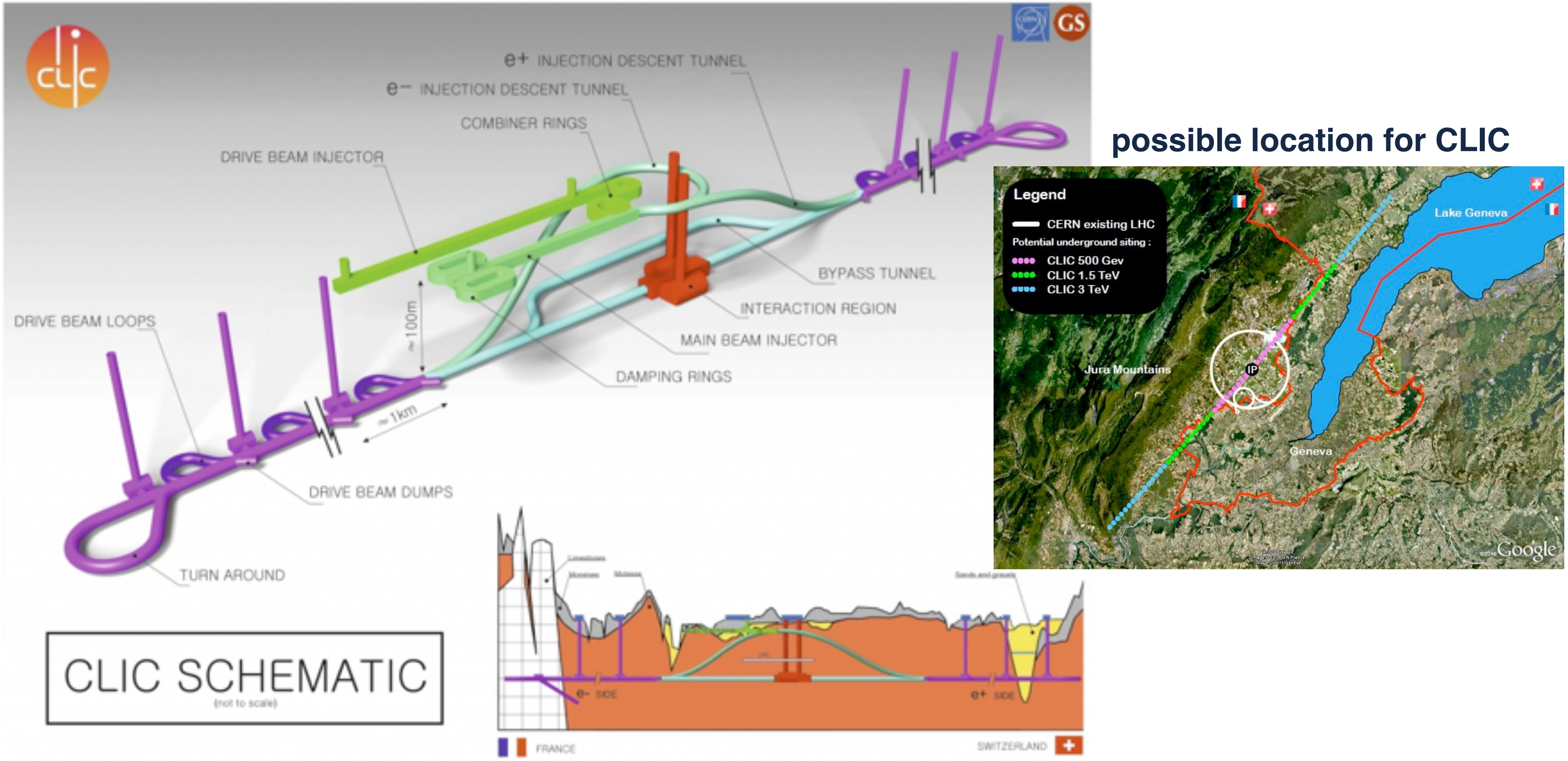




Construction and energy-staging

Construction could be performed in stages, allowing for different √s

1. 500 fb^{-1} at √s = 350 GeV, tunnel ~10 km, Higgs, top physics
2. 1.5 ab^{-1} at √s = 1.4 TeV, tunnel ~30 km, better Higgs, top Yukawa, first BSM searches
3. 2 ab^{-1} at √s = 3 TeV, tunnel ~50 km, double Higgs production, high sensitivity BSM

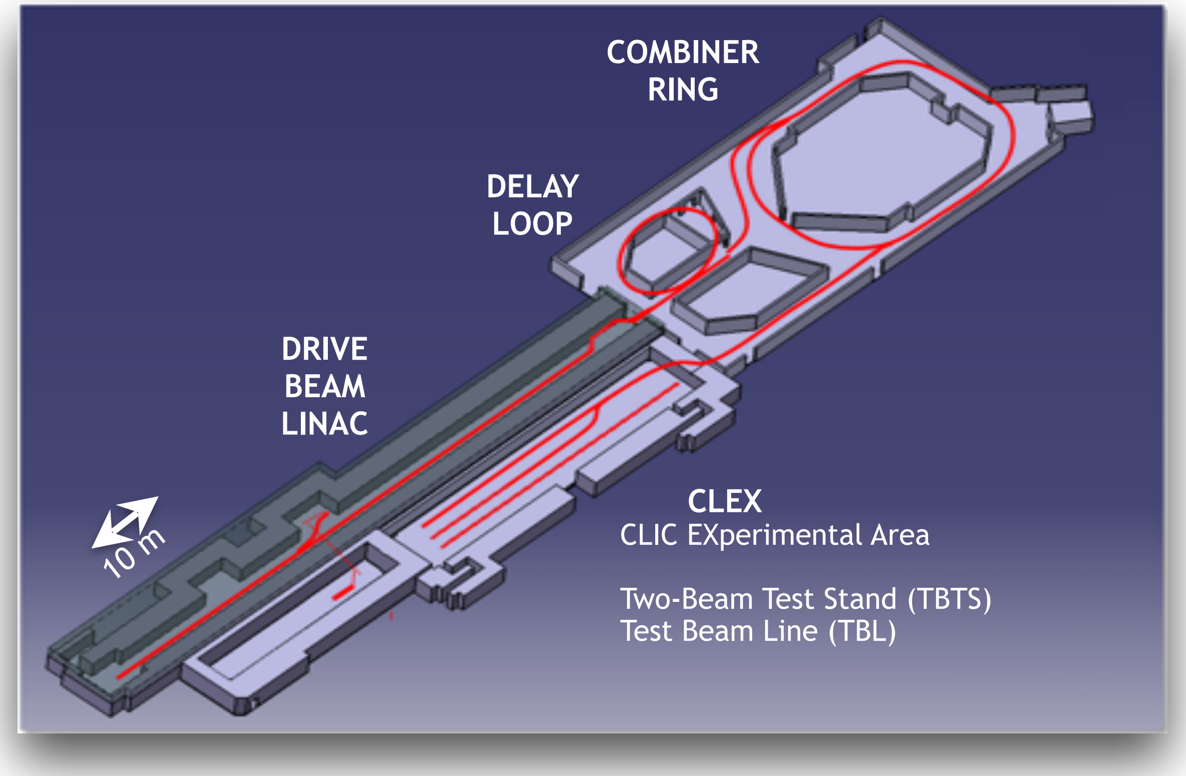


possible location for CLIC

CLIC collaboration and CTF3 status

CLIC is a global, multi-lateral collaboration
of more than 50 institutes
Find out more: http://clic-study.web.cern.ch/

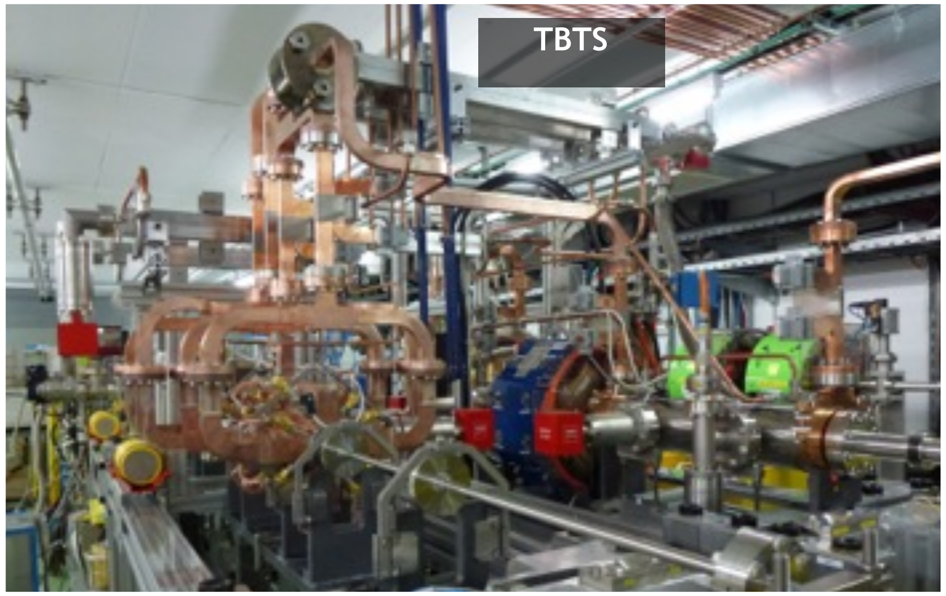
layout of CTF3



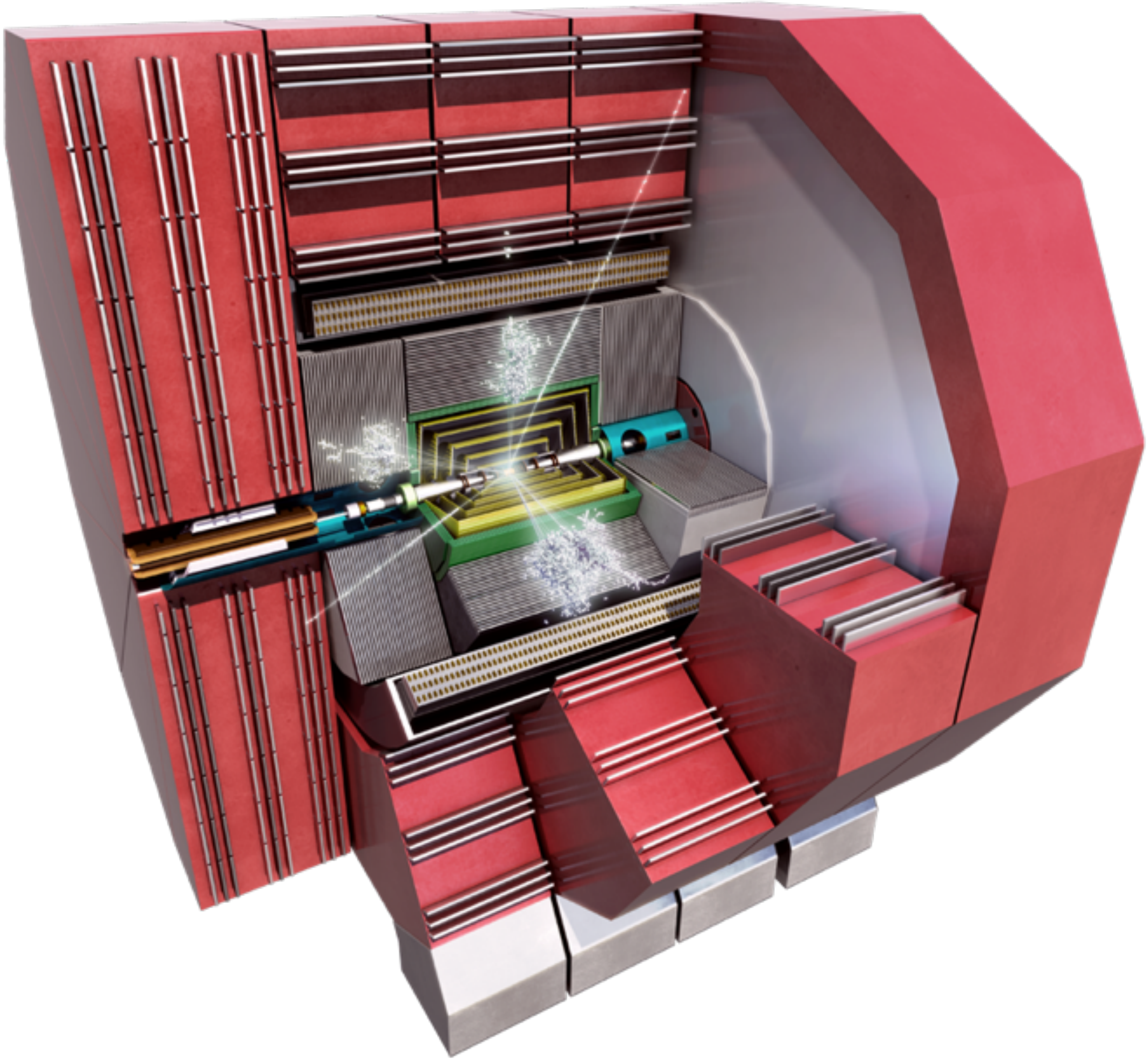
CTF3: The CLIC Test Facility 3 at CERN

- a scaled version of the drive beam complex
- produces a high current drive beam
- generates power for the accelerating structures
- CTF3 has successfully demonstrated drive beam generation, the production of the CLIC RF power, and two-beam acceleration up to a gradient of 145 MeV/m

current tests with two-beam test stand



A detector for CLIC



Precision physics in a challenging environment: broad programme of R&D

Highly granular particle flow calorimetry, using tungsten and steel absorbers

6.8 m inner diameter cryostat for superconducting solenoid, B field 4 T

Instrumented steel return yoke

Complex forward region

More later!

The CLICdp collaboration

From the Memorandum on Cooperation:
"The CLIC Detector and Physics Study [CLICdp] focuses on detector and physics simulations and hardware R&D for experiments at a future high-energy e^+e^- collider based on the CLIC accelerator technology."

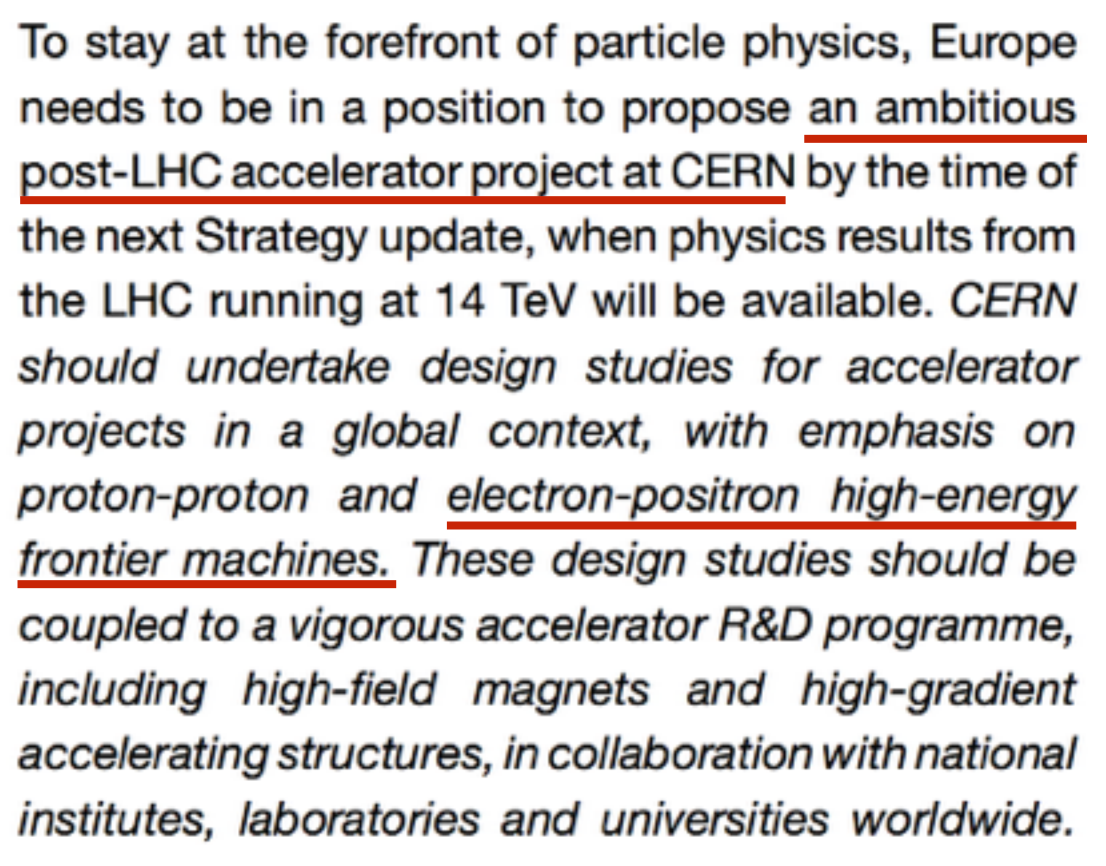
- 25 participating institutes, totalling ~140 members
- CERN as a host laboratory
- Proto-collaboration organisation
- Find out more: http://clicdp.web.cern.ch/

Motivation for CLIC

CERN-2012-003

From the CLIC Conceptual Design Report:
"… the LHC provides a large discovery potential in proton-proton interactions. A high-energy e^+e^- collider is the best option to complement and to extend the LHC physics programme."

European strategy for particle physics, update 2013:



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.*

Motivation for energy frontier physics
and
detector benchmark studies

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

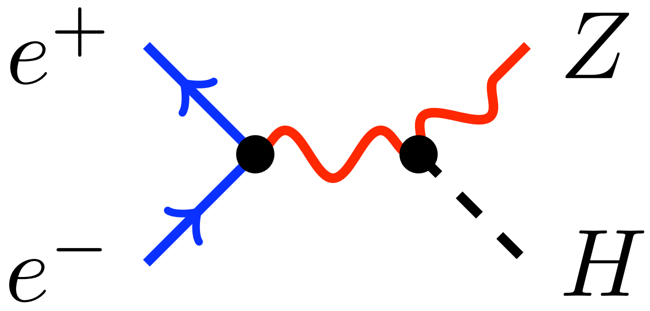
PHYSICS AND DETECTORS AT CLIC

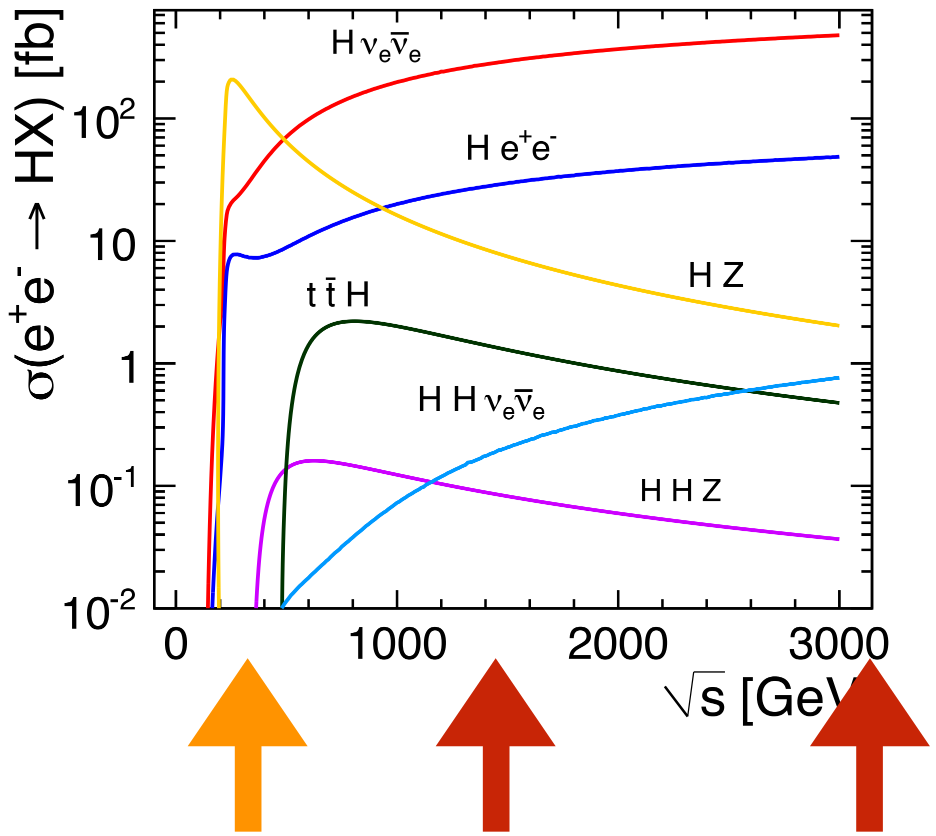
Physics at the CLIC e^+e^- Linear Collider
Input to the Snowmass process 2013

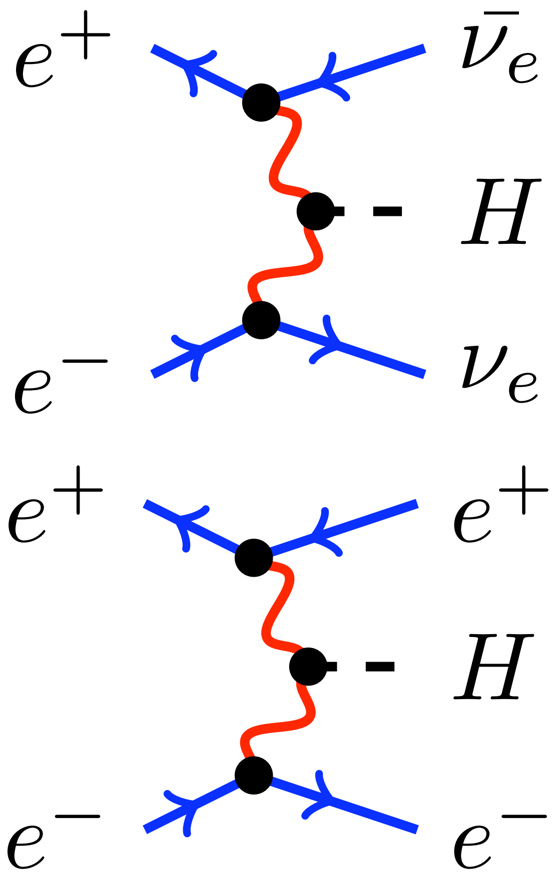
The CLIC Detector and Physics Study

CERN-2012-003   arXiv:1307.5288

Single Higgs production at CLIC







Stage 1: $\sqrt{s}$ = ~375 GeV
Higgsstrahlung

Stage 2&3: $\sqrt{s}$ = 1.4 & 3 TeV
Vector boson fusion

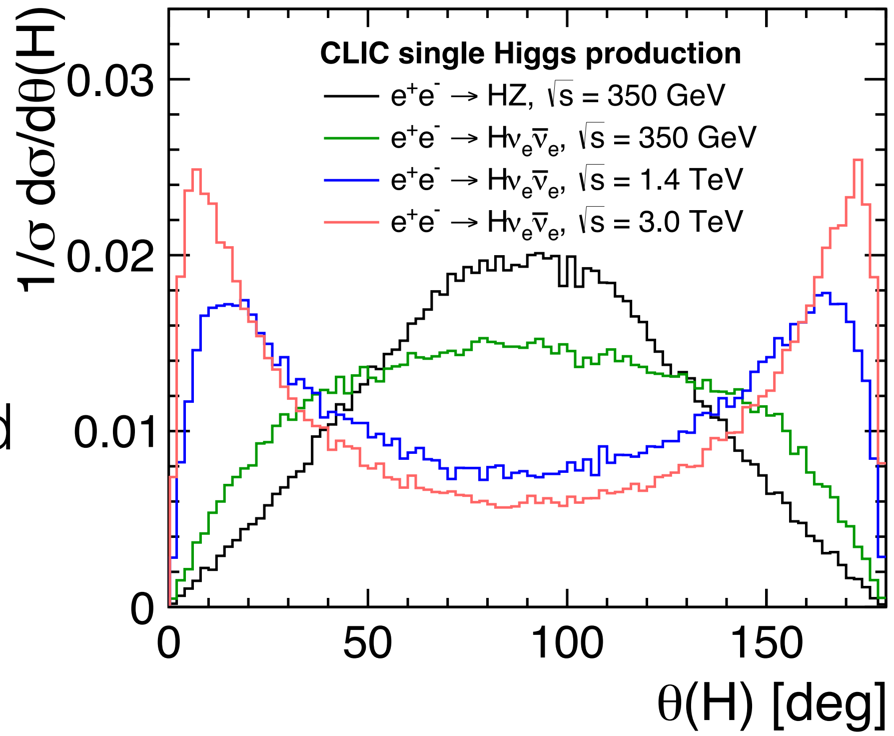
	350 GeV	**1.4 TeV**	**3 TeV**
Int. L	500 fb	1.5 ab	2 ab
#ZH events	**68,000**	20,000	11,000
#Hvv events	17,000	**370,000**	**830,000**
#Hee events	3,700	37,000	84,000

Single Higgs production at CLIC

Higgs polar angle:

- measurements at high energy require good coverage in the forward regions

All benchmark analyses are GEANT4-based full detector and physics simulation studies, with beam-induced background overlaid

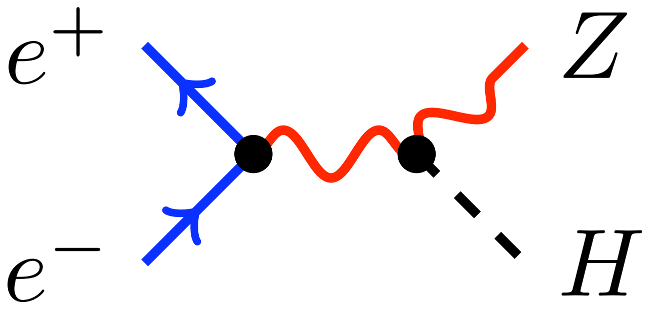


Polarisation:

- benchmark studies assume unpolarised beams
- however, the default accelerator design plans for $P(e^-) = 80\%$
- this brings a significant enhancement at high energy stages

	ZH enhancement	**Hvv enhancement**
unpolarised	1.0	1.0
$P(e^-) = -80\%$	1.18	**1.80**

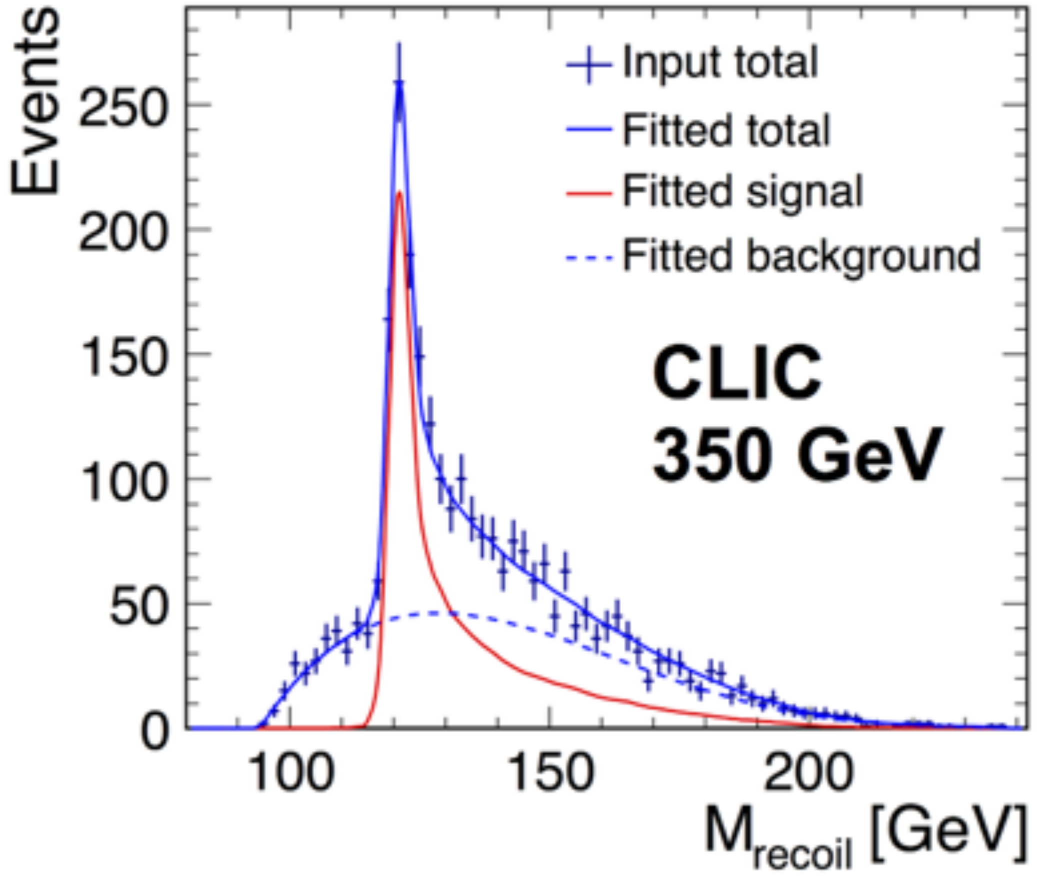
Higgsstrahlung at √s = 350 GeV



Higgsstrahlung process:

- HZ events can be identified from the Z recoil mass only
- no requirement on the H at all
- gives a model independent measurement of g_{HZZ} coupling:
  - $\Delta(g_{HZZ})/g_{HZZ}$ = 2% from $e^\pm$, $\mu^\pm$

$$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- H$$



Using hadronic decays brings extra stats:

- challenge: Z→qq reconstruction may depend on the H decay mode
- but extreme variations in SM H BR lead to bias less that statistical uncertainty
  - $\Delta(g_{HZZ})/g_{HZZ}$ = 0.9% from qq

Combined uncertainty on coupling:

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

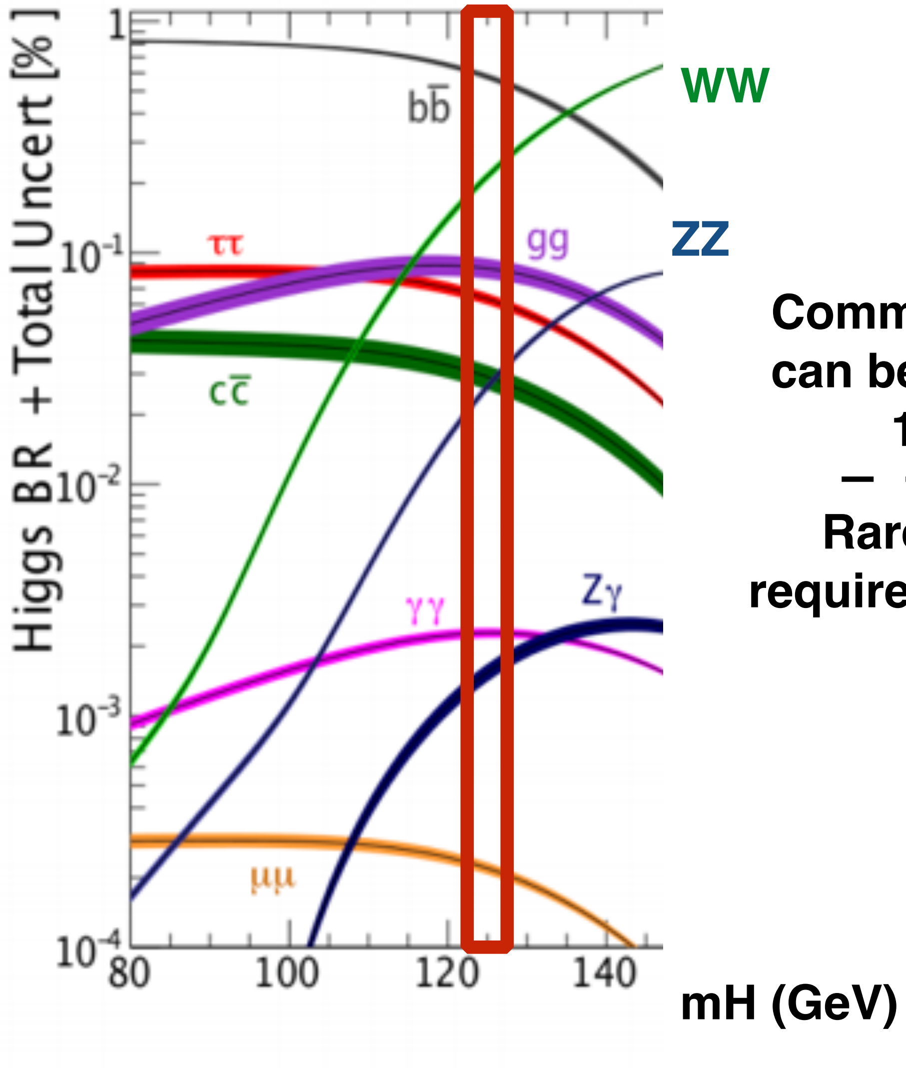
σxBR measurements at √s = 350 GeV

Reconstructing the decay of the Higgs allows σxBR measurements already at the first stage of CLIC

- for those decays with BR > 1%

	Stat. precision
σ(HZ)xBR(H→bb)	1%
σ(HZ)xBR(H→WW)	2%
σ(HZ)xBR(H→gg)	6%
σ(HZ)xBR(H→ττ)	6%
σ(HZ)xBR(H→cc)	5%
σ(Hνν)xBR(H→bb)	3%

← only H in the final state



Common H decays: can be measured at 1st stage

– – – – –

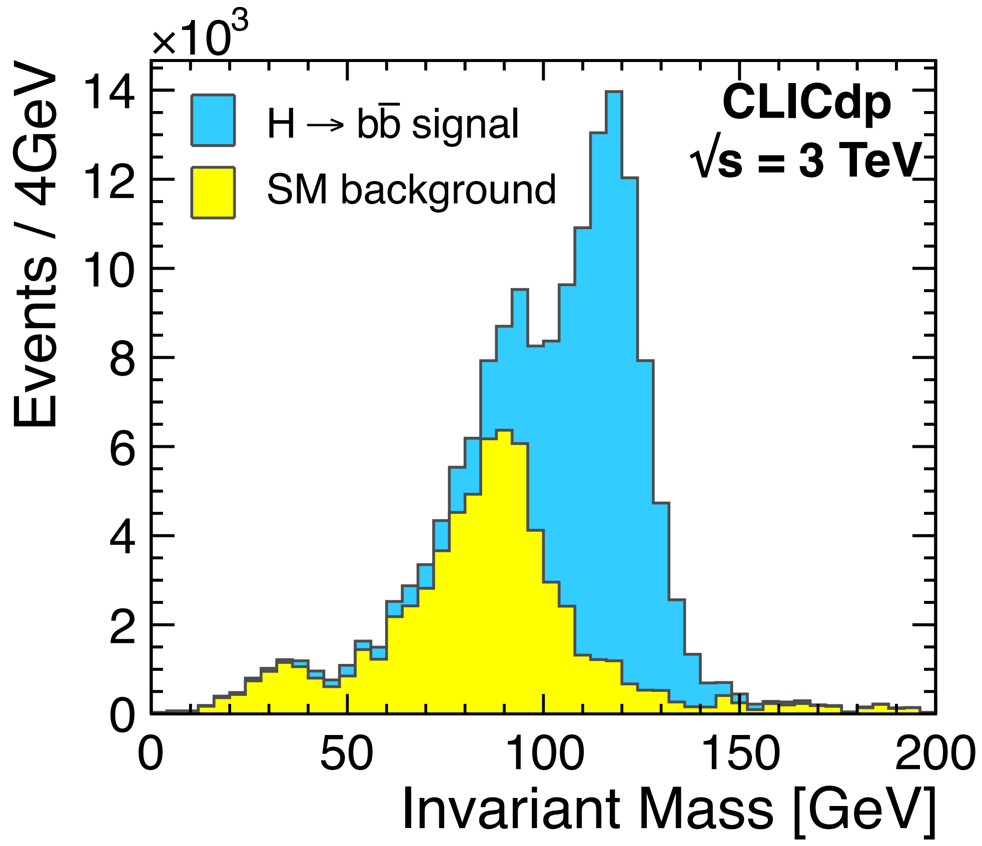
Rare H decays: require higher energy

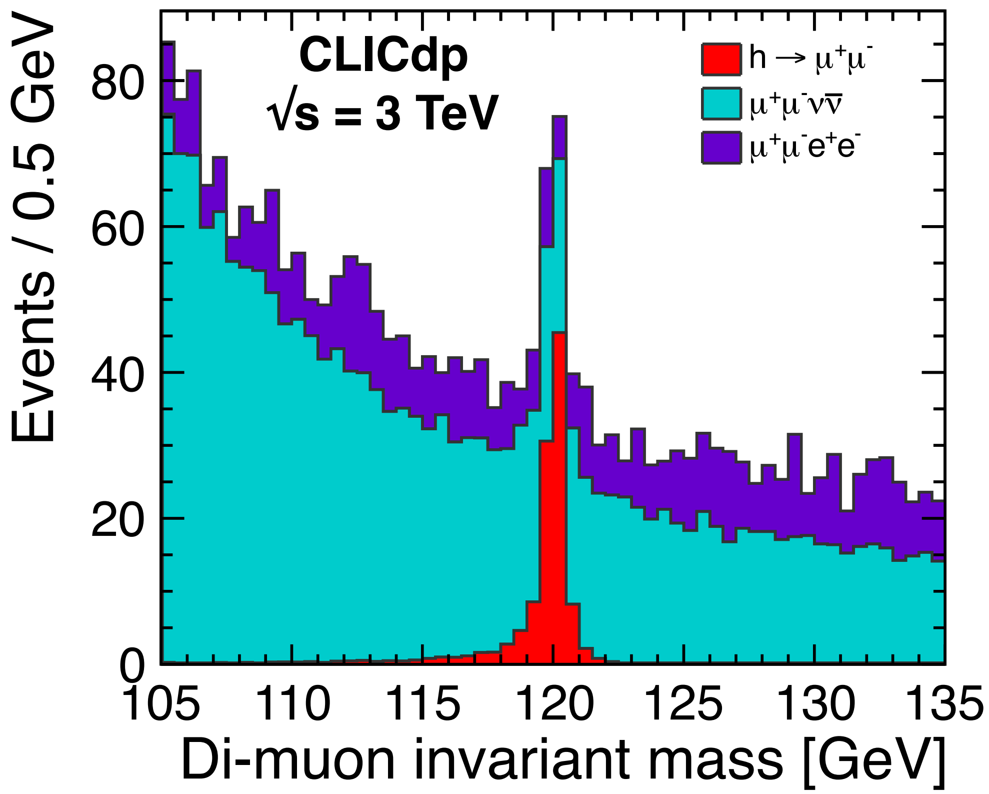
In addition: BR(H→invis.) <0.97% at 90% CL

Measurements with Hvv events at √s = 1.4, 3 TeV

High statistics processes:

- H→bb, cc, gg
- separation via flavour tagging
- H→bb gives H mass ±33 MeV
- σxBR precisions at 3 TeV:
    - Δ(σ(Hvv)xBR(H→bb)) = 0.2%
    - Δ(σ(Hvv)xBR(H→cc)) = 2.7%
    - Δ(σ(Hvv)xBR(H→gg)) = 1.8%





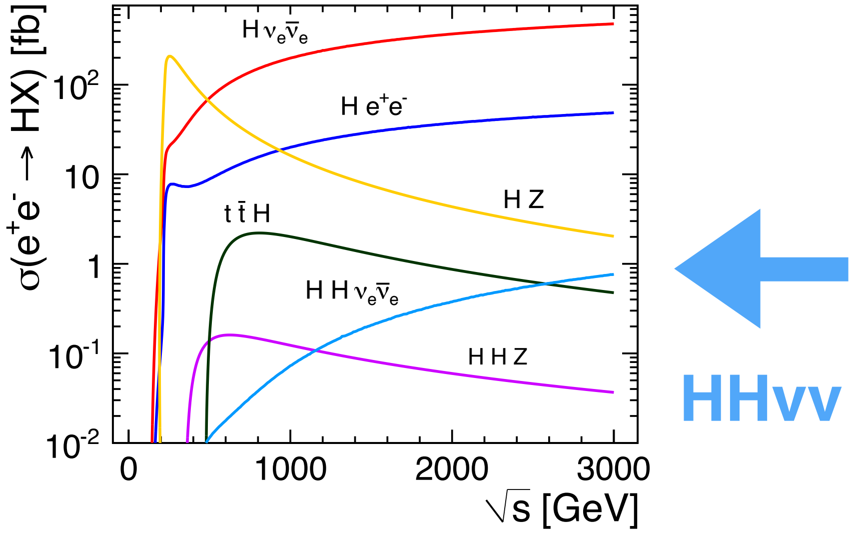
Rare processes:

- H→μμ, H→Zγ, H→γγ
- BRs of the order 0.1% - 0.01%
- precisions on σxBR in the tens of %:
    - Δ(σ(Hvv)xBR(H→μμ)) = 16% (3 TeV)
    - Δ(σ(Hvv)xBR(H→Zγ)) = 15% (1.4 TeV)
    - Δ(σ(Hvv)xBR(H→γγ)) = 42% (1.4 TeV)

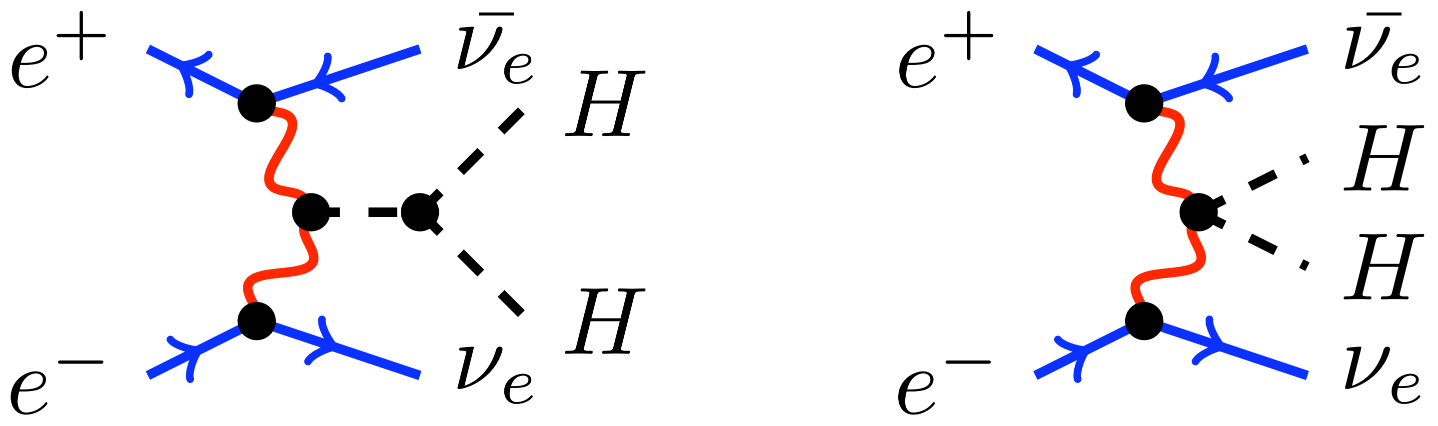
Double Higgs production at √s = 1.4, 3 TeV

The HHvv cross section is sensitive to:

- the Higgs self-coupling λ
- the quartic HHWW coupling g_{HHWW}
- only 225 (1200) HHvv events at 1.4 (3) TeV
  - high energy and high luminosity crucial

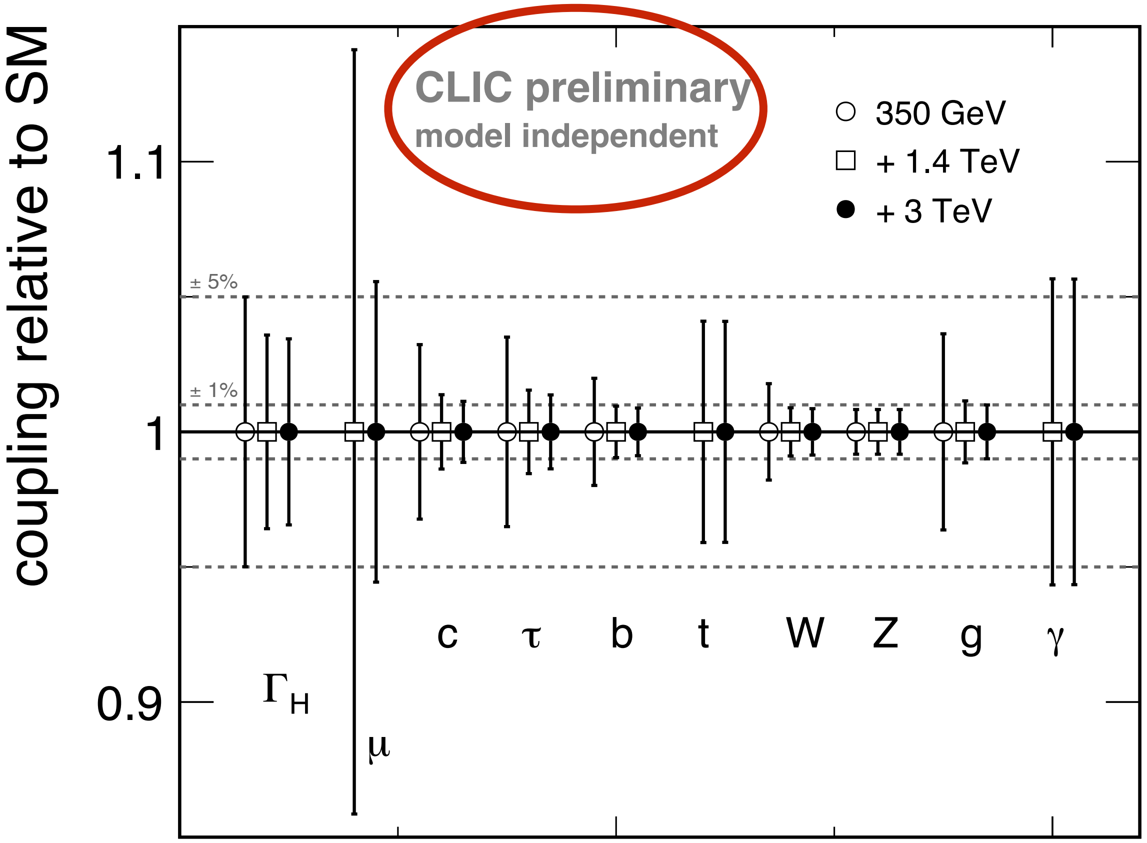


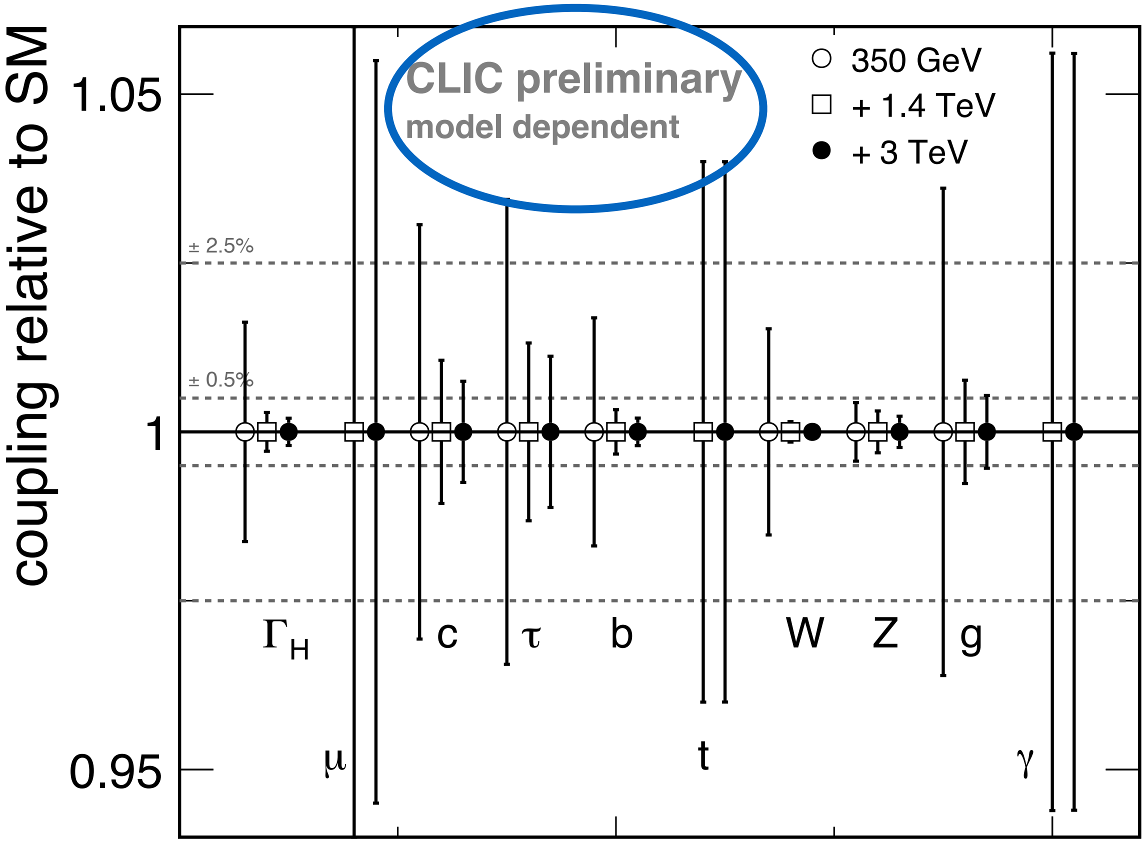
HHvv



	√s = 1.4 TeV	**√s = 3 TeV**
Δ(g_{HHWW})	7% (prelim.)	6% (prelim.)
Δ(λ)	32%	16%
Δ(λ), P(e^-) = -80%	24%	12%

CLIC Higgs combined fit





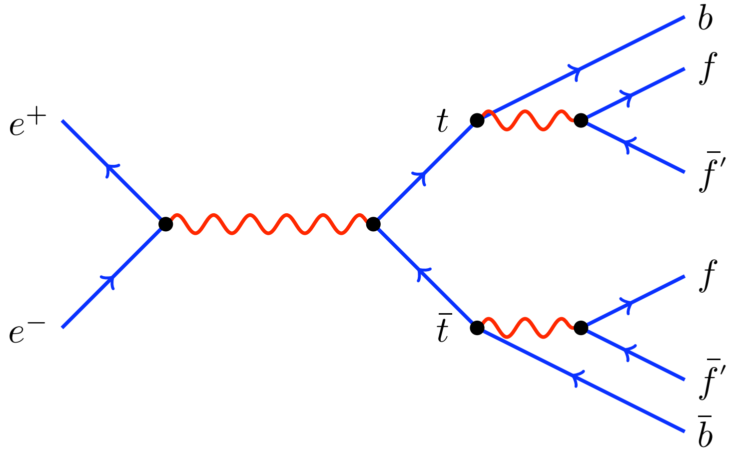
Fully **model independent** fit of Higgs parameters:

- only possible at a lepton collider
- dependent on (and limited by) the model independent g_{HZZ} measurement
- extract Higgs width with 5% precision

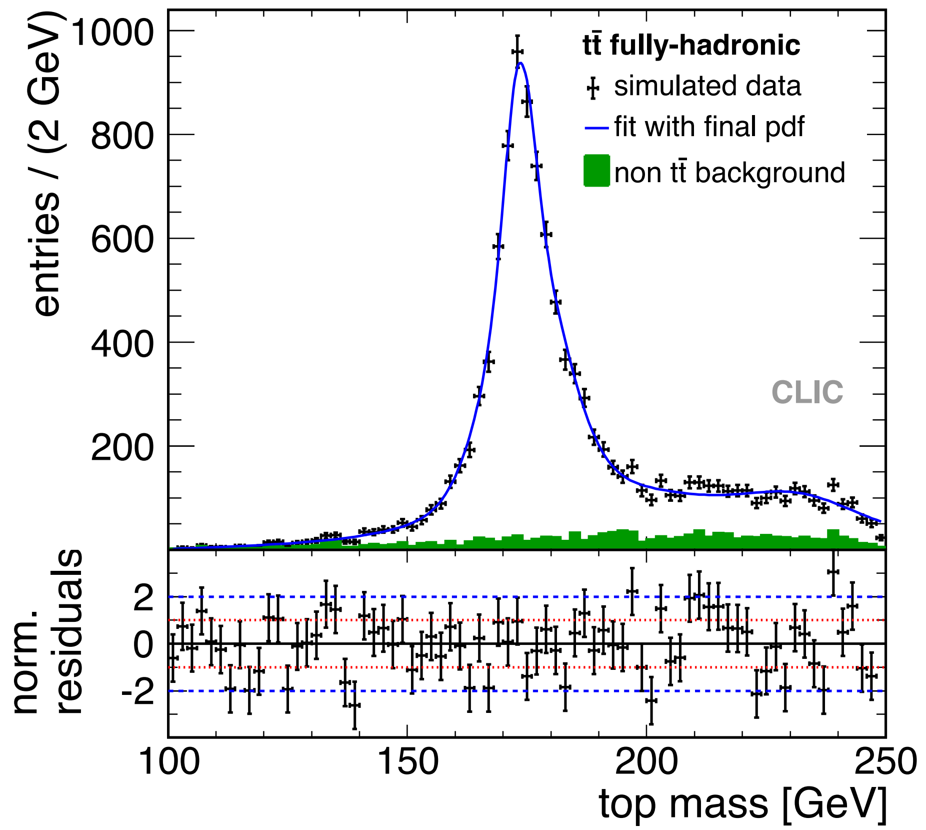
Model dependent: assuming no invisible decays (LHC style analysis)

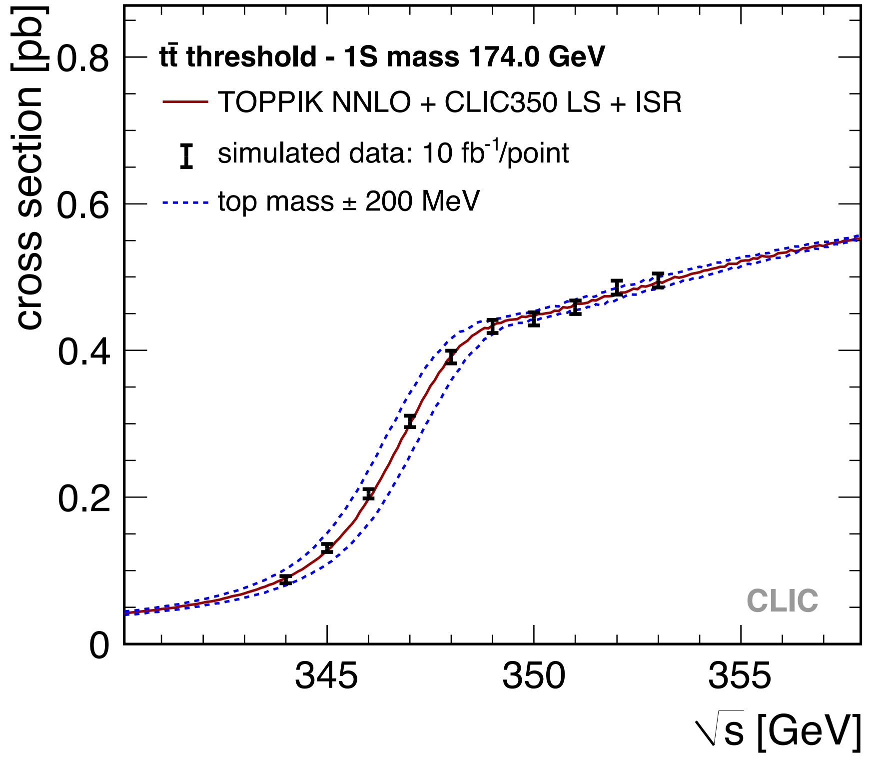
- higher precision: Higgs width with <1% precision
- but results strongly dependent on fit assumptions

Top quark mass at √s = 350 GeV

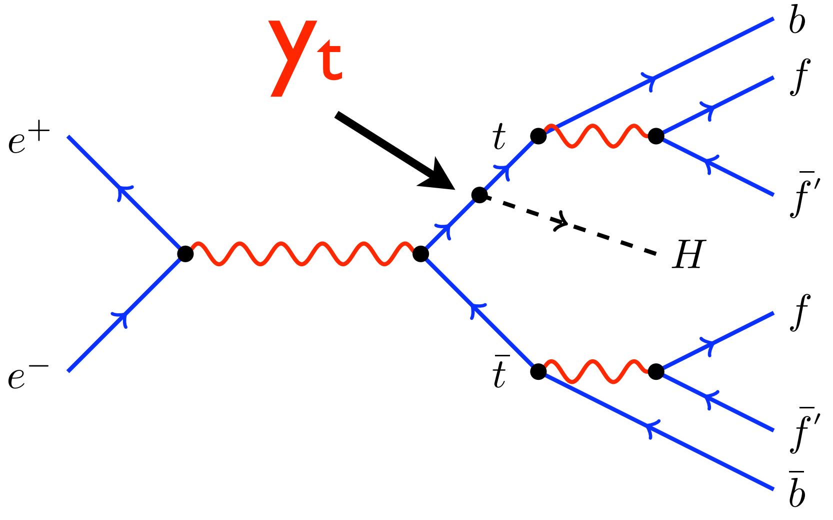


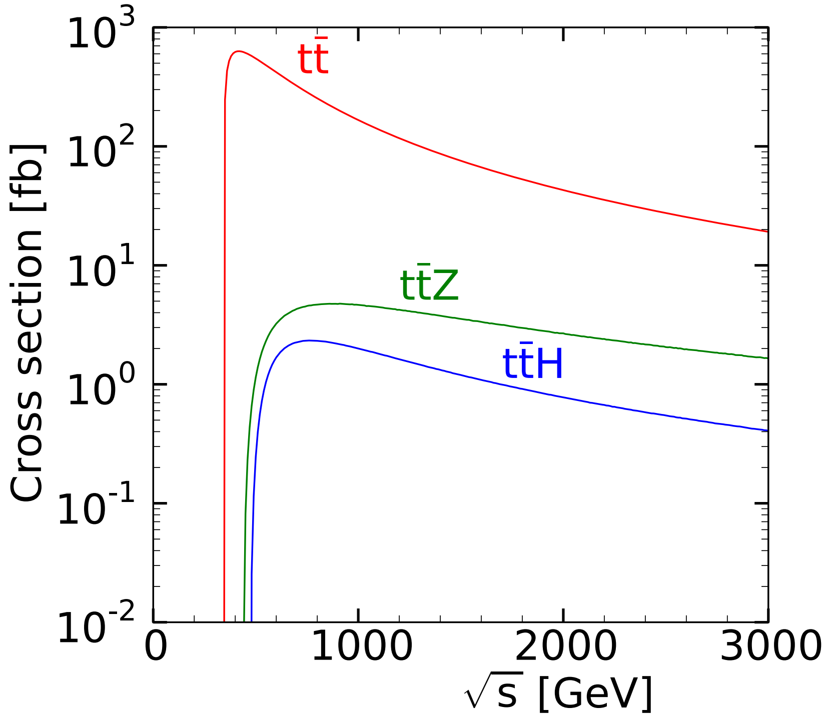
- tt pair production for the first time in e^+e^- collisions
- threshold scan with dedicated operation
  - 10 x 10 fb^{-1} around √s = 2 x top mass
- theoretically clean mass measurement
- statistical precision on top quark mass 34 MeV
- total uncertainty < 100 MeV (including theory and systematics on beam energy and luminosity spectrum)





Top Yukawa coupling at √s = 1.4 TeV





- ttH cross section gives directly sensitivity to the top Yukawa coupling
- higher √s: less signal but also less tt background
- eight fermion final state - excellent detector benchmark
- precision on the top Yukawa coupling of 4.5% (as at 1 TeV)

BSM top physics at √s = 3 TeV:

- top as a probe for new physics, V_{tb}, A_{FB}^{t}
- the focus of future studies

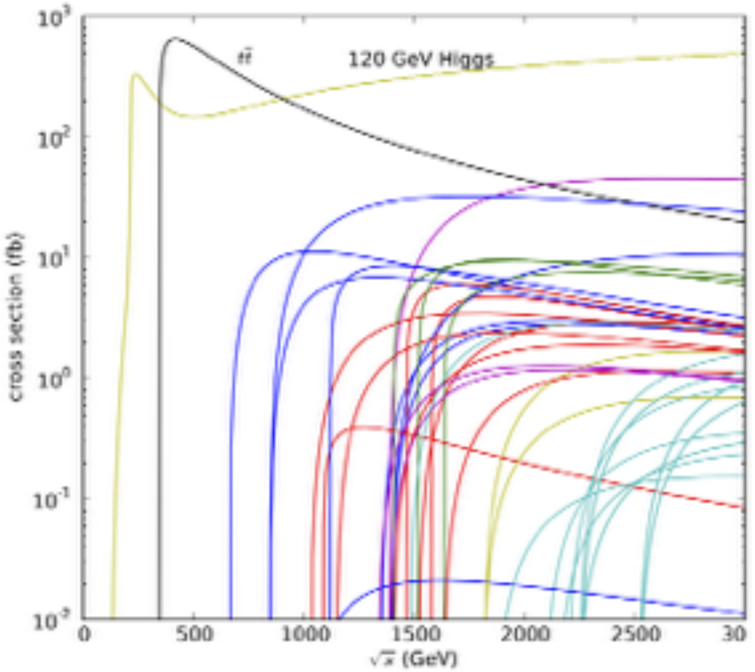
Direct BSM searches at √s = 3 TeV

Direct searches:

- CLIC will pair produce new particles with M < √s / 2
- Analyses using SUSY models:

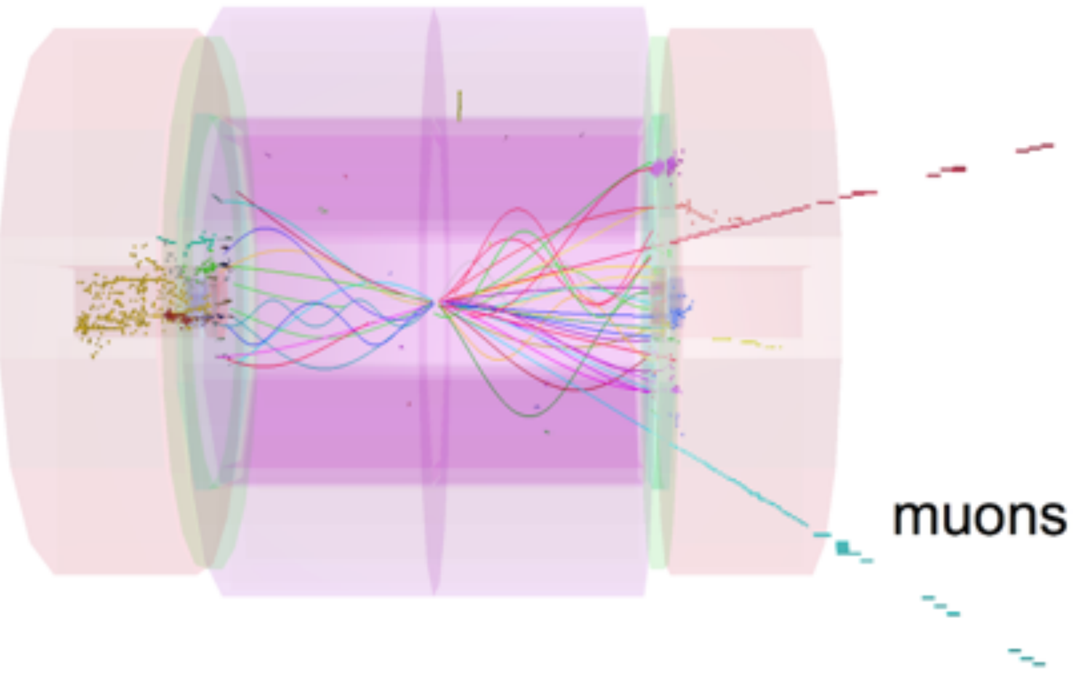
Sleptons

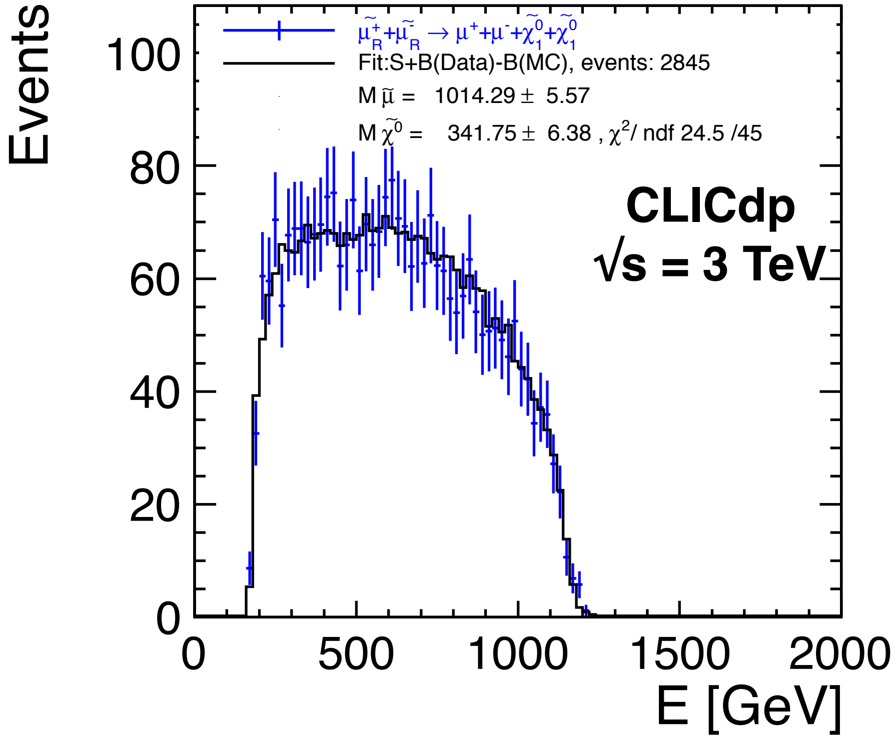
  - leptonic final state with missing energy
  - masses from endpoints of energy spectra
  - precisions of a few GeV possible (M ~ 1 TeV)



CDR Model I

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





Direct BSM searches at √s = 3 TeV

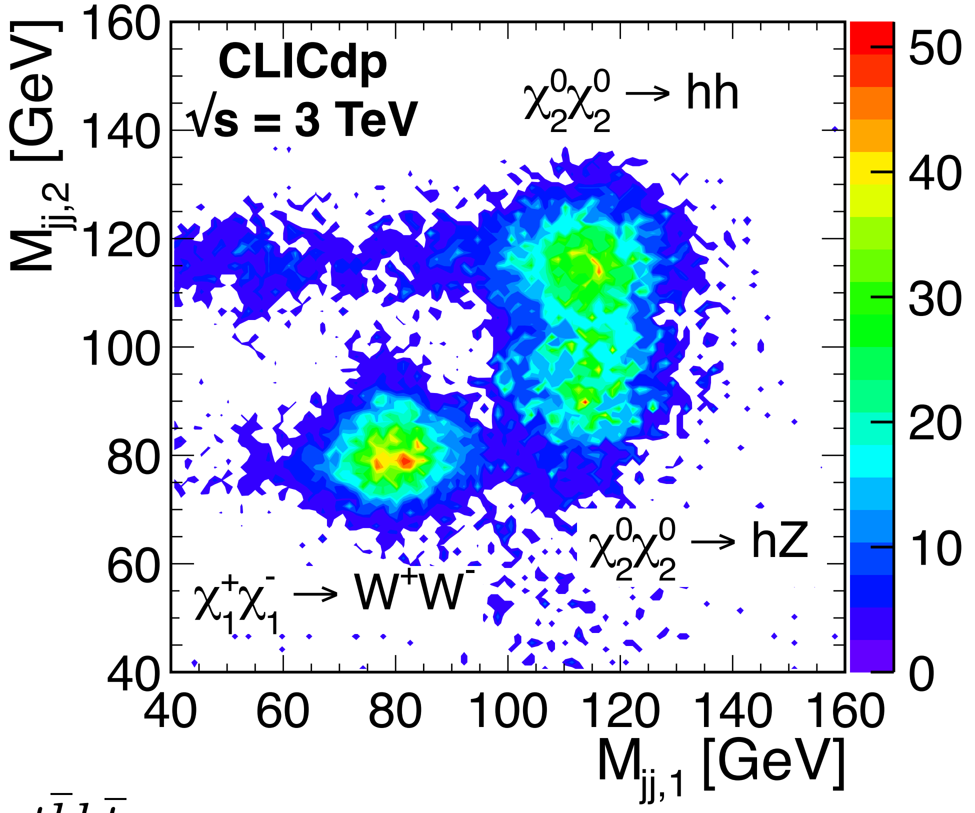
Gauginos

- hadronic final state with missing energy
- precision 1-1.5% (M = 643 GeV)

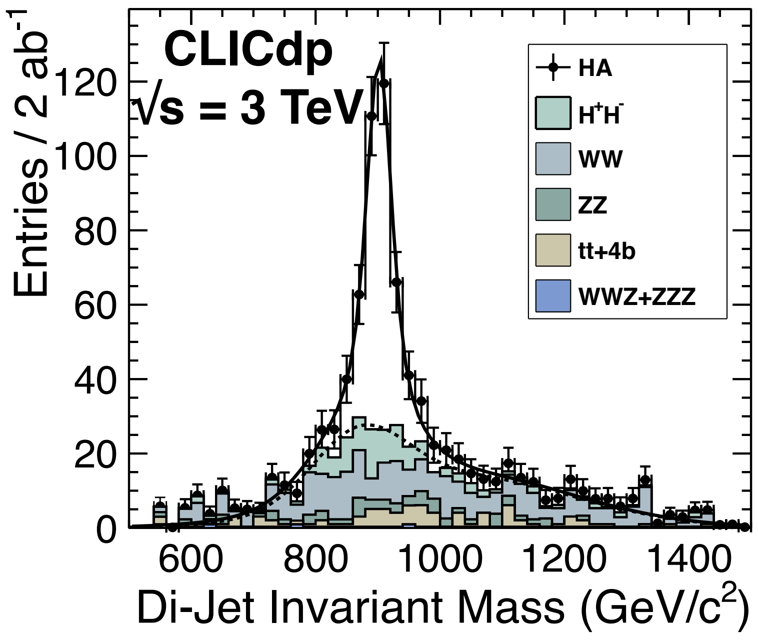
Heavy Higgs bosons

- top, beauty jets in final state
- masses from tagging heavy flavour jets
- precision 0.3% (M ~ 1 TeV)

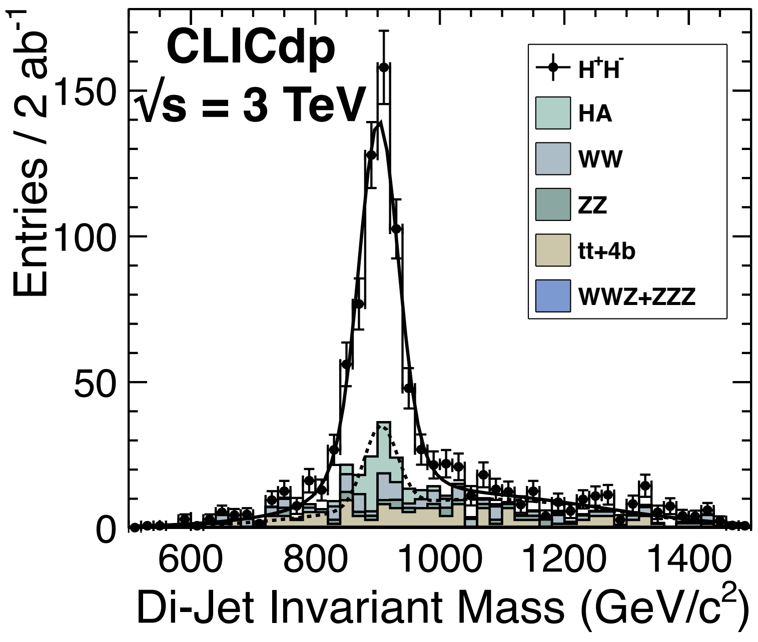
$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$$



$$e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$$



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

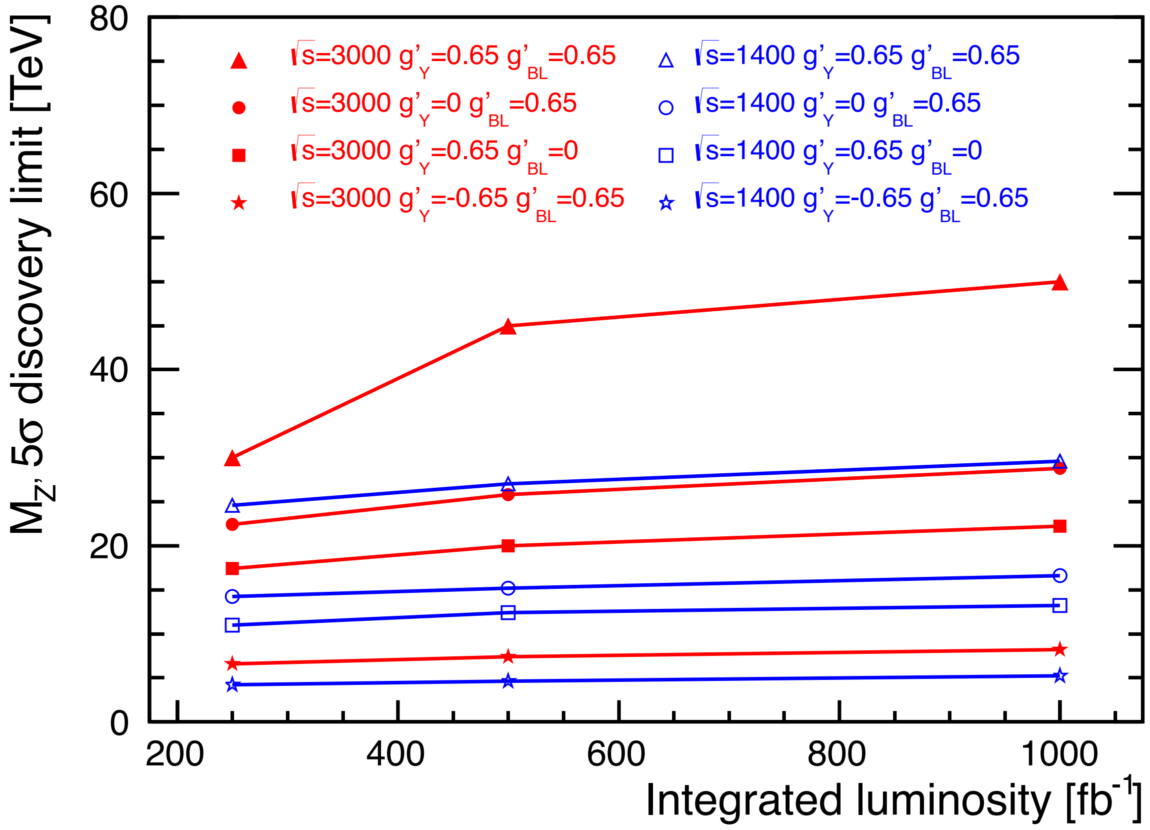


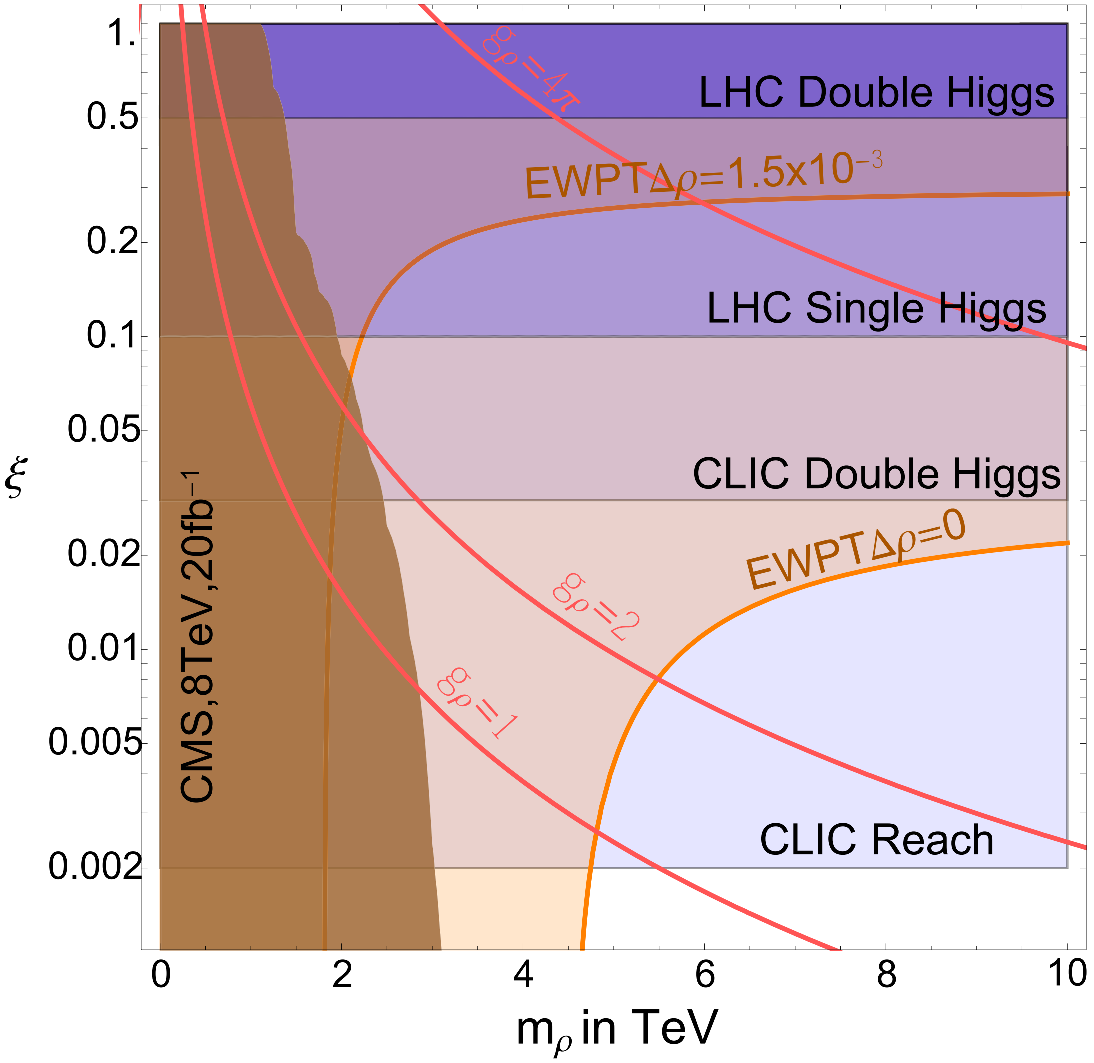
Wider applicability than just SUSY:
Particles classified as states of mass, spin, quantum numbers.

Indirect searches for BSM physics

Indirect searches: reaching higher mass scales through precise measurements of known observables

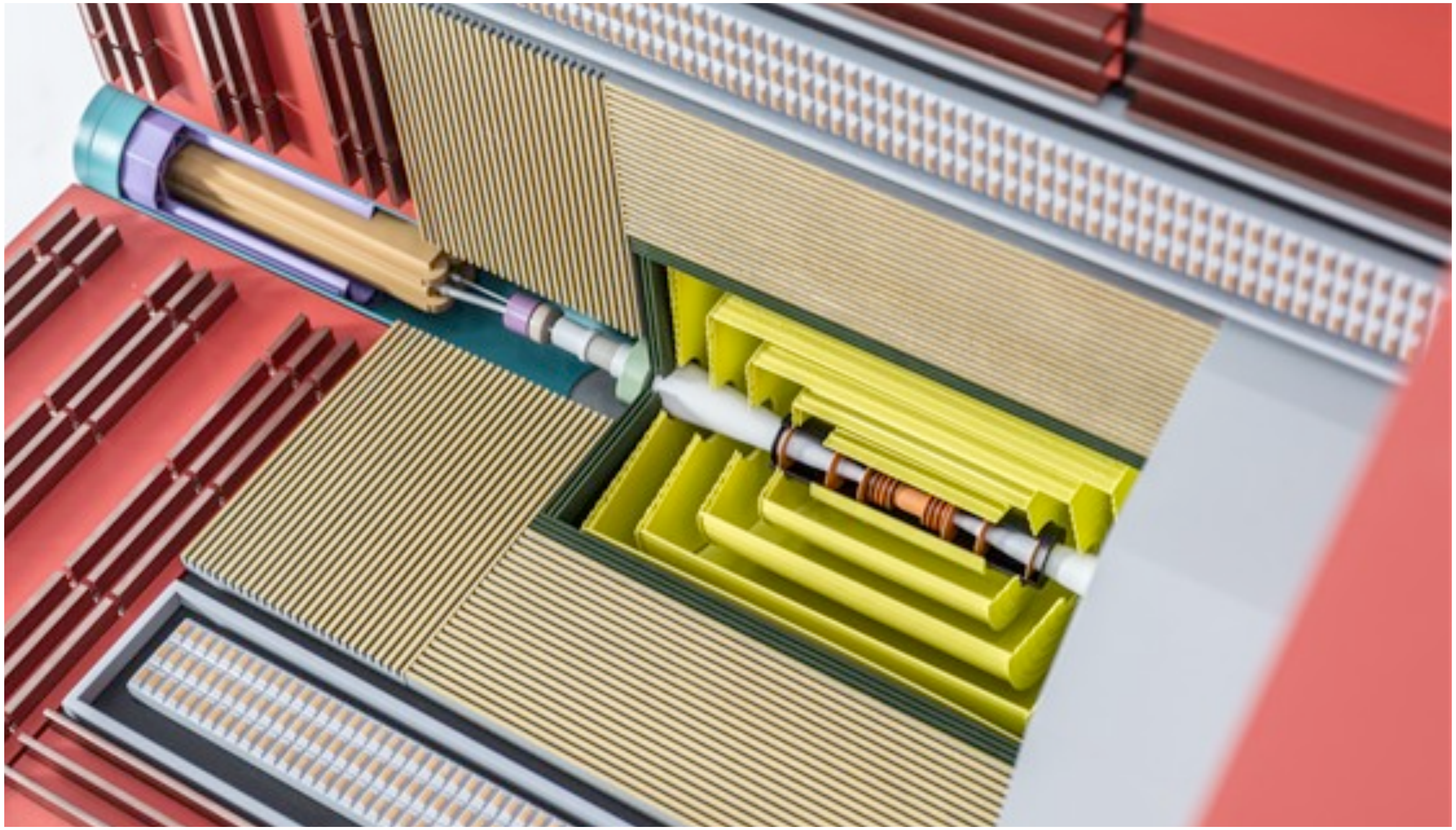
- Z' sensitivity in $e^+e^- \rightarrow \mu^+\mu^-$: observables are cross section, A_{FB}, A_{LR} give CLIC sensitivity up to tens of TeV
- Composite Higgs bosons: using CLIC single and double Higgs measurements to probe compositeness scale up to 70 TeV





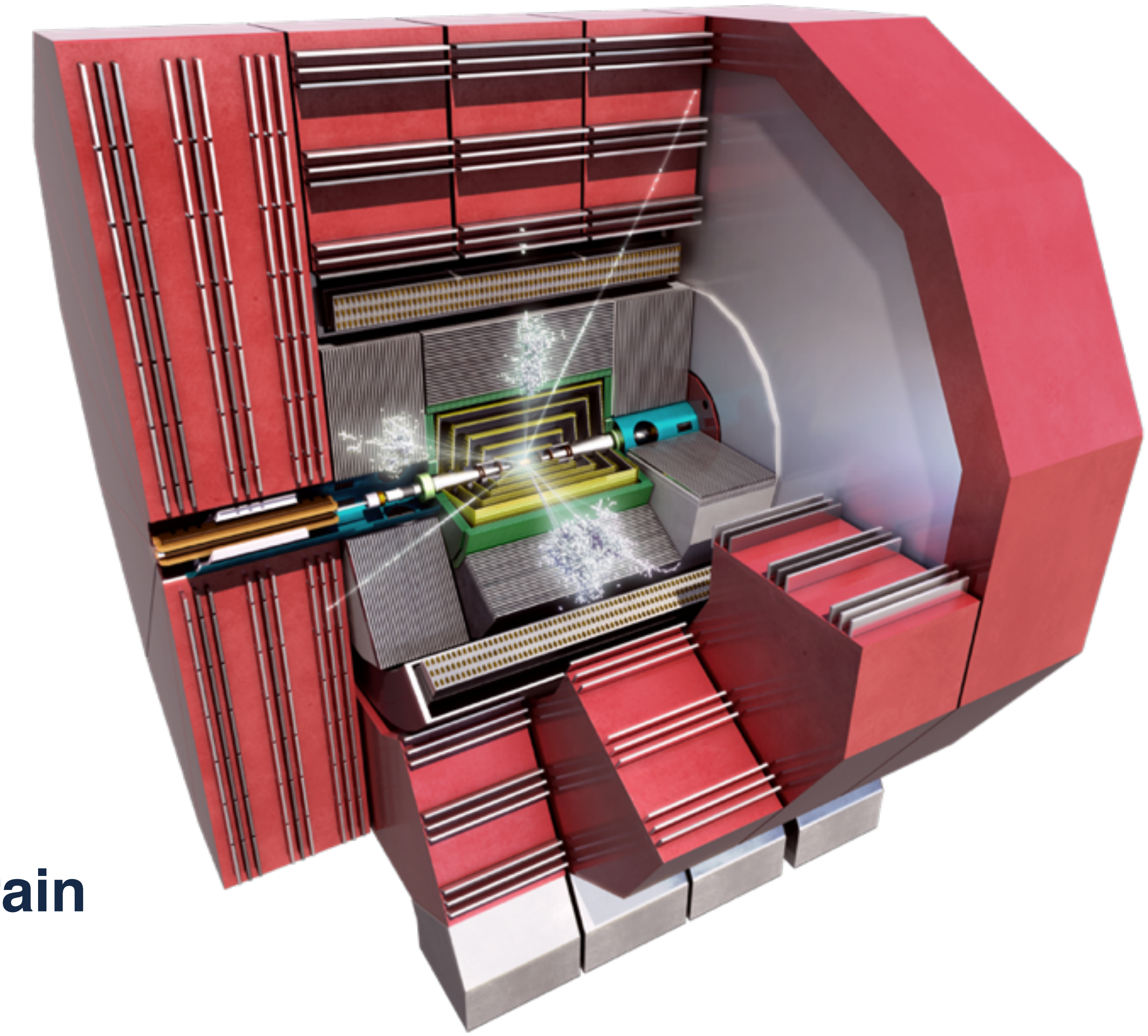
CLIC detector challenges

with a focus on the vertex detector



CLIC in a nutshell

- **High precision:**
  - jet energy resolution - $\sigma_E / E \sim 3.5 - 5\%$
    - fine grained calorimetry - 13 mm^2 ECAL cell size
  - momentum resolution - $\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}$ GeV^{-1}
  - impact parameter resolution - $\sigma_{r\phi} = 5 \oplus 15 / (p \sin^{3/2} \theta)$ µm



- **Overlapping beam-induced background:**
  - high rate - 3 $\gamma\gamma \rightarrow$ hadrons per bunch xing
  - requires precise timing - 1 - 10 ns
  - pixel size 25x25 μm^2

- **'No' issue from radiation damage**
  - 10^{-4} LHC levels
  - except for small forward calorimeters

- **No trigger, full readout of 156 ns bunch train**

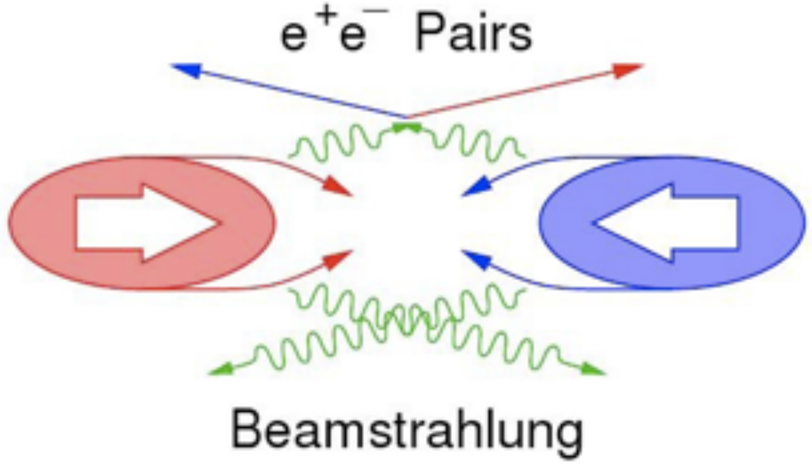
Beam induced backgrounds

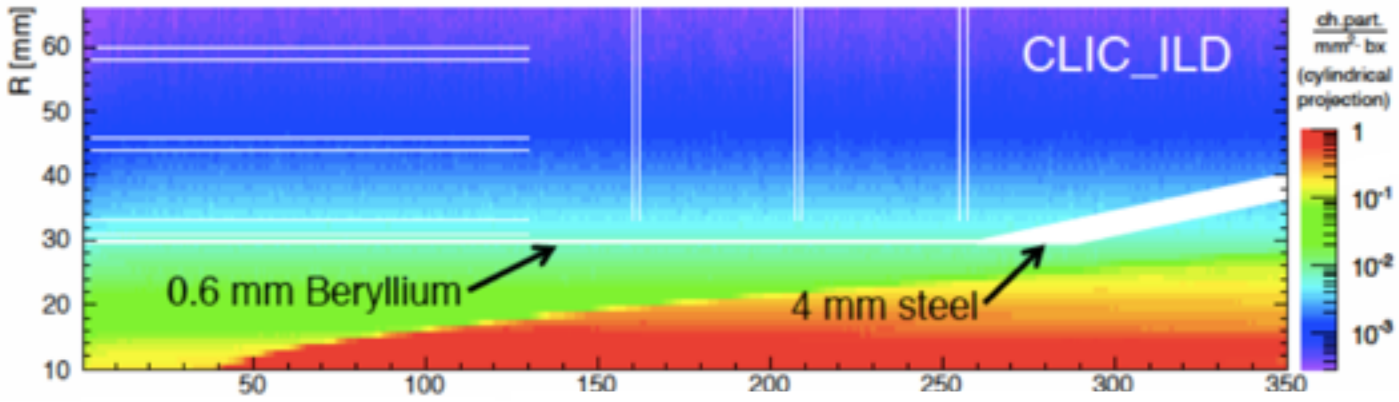
Dense bunches, high energy, small transverse size leads to very high E-field, resulting in beamstrahlung

Consequences:

- reduction in √s
- high occupancies drive small pixel/strip size for tracking
- also geometric requirement on vertex detector inner radius
- bkg energy deposits drive small cell size for calorimetry
- high precision timing: 10 ns in tracking, 1 ns in calorimeters
- reconstruction: particle flow algorithms, followed by hadron-collider-like kT jet clustering (beam jets)

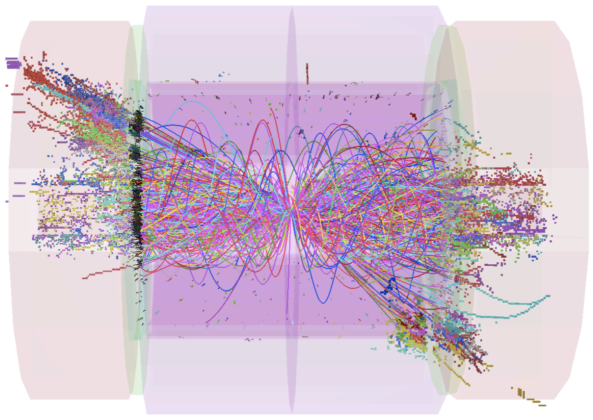
Big challenge!



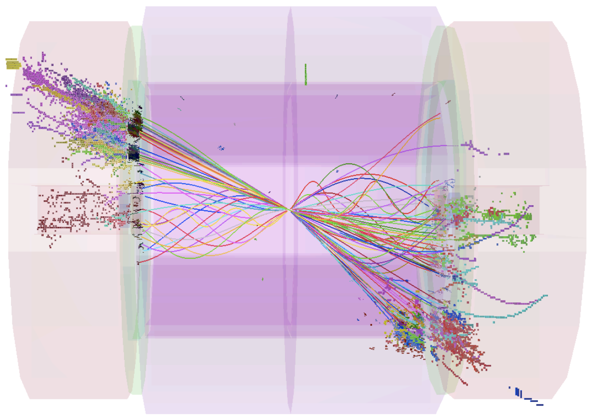


Minimum inner radius = 30mm

Maximum occupancy including safety factor 5:
1.9% per pixel in the barrel layers
2.9% per pixel in the forward layers



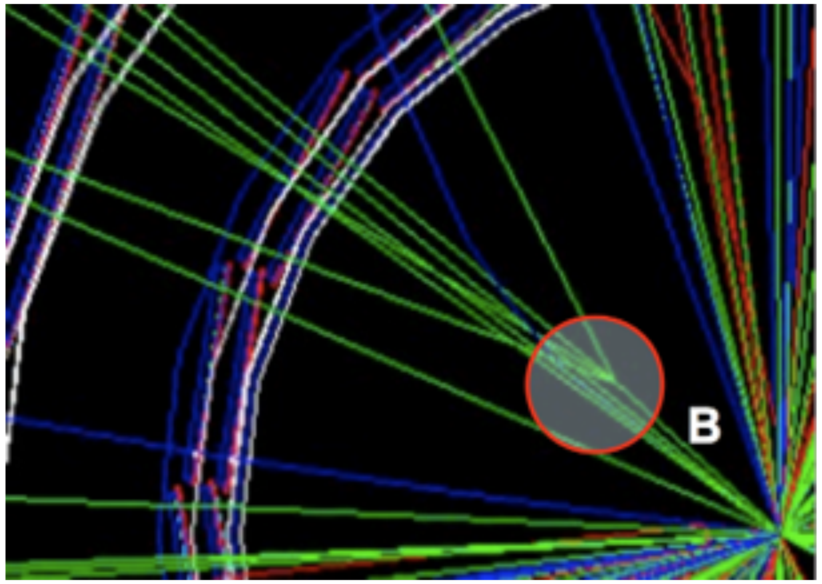
No bkg suppression



After bkg suppression

Vertex detector requirements

Goal: efficient tagging of heavy quarks through a precise determination of displaced vertices



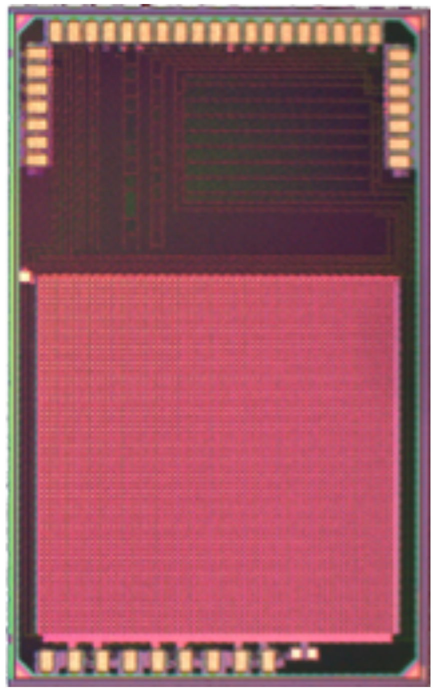
Multi-layer barrel and endcap pixel detectors

- 560 mm in length
- Barrel radius from 30 mm to ~70 mm

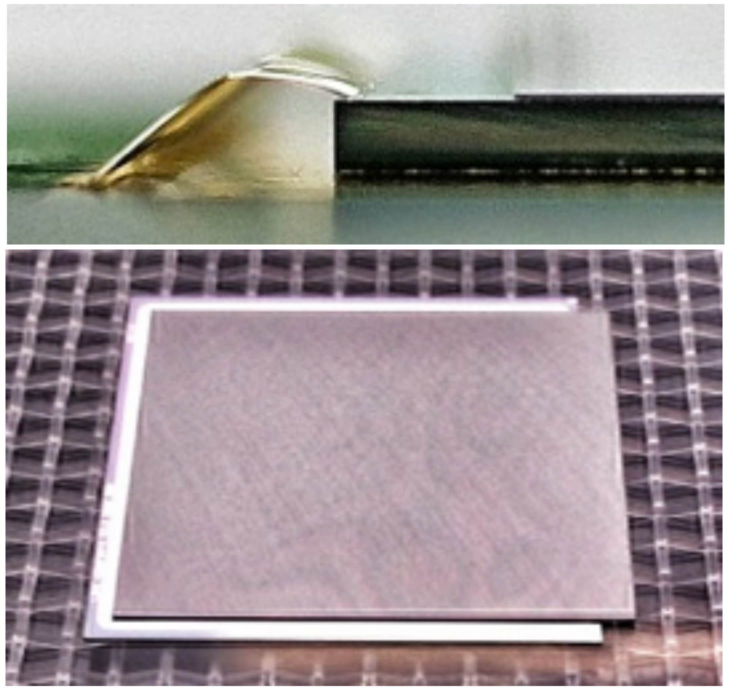
- Single point resolution of 3 μm
- Material budget of < 0.2% of a radiation length per layer
- No active cooling elements - use forced air flow cooling
- Limit the power dissipation to 50 mW/cm^2 in sensor area
- Hit time slicing of 10 ns

Vertex detector R&D programme

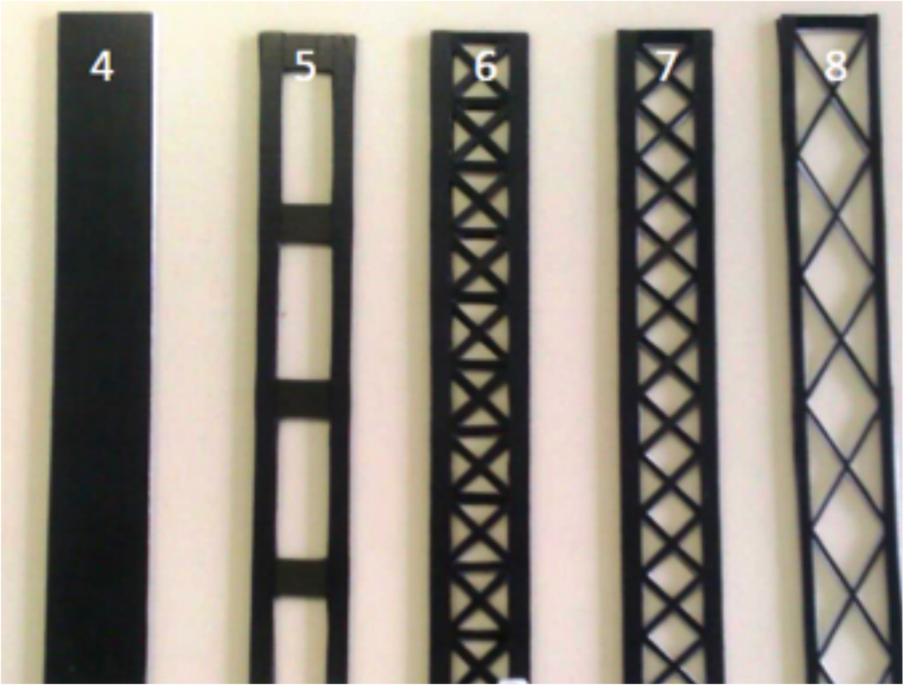
Readout



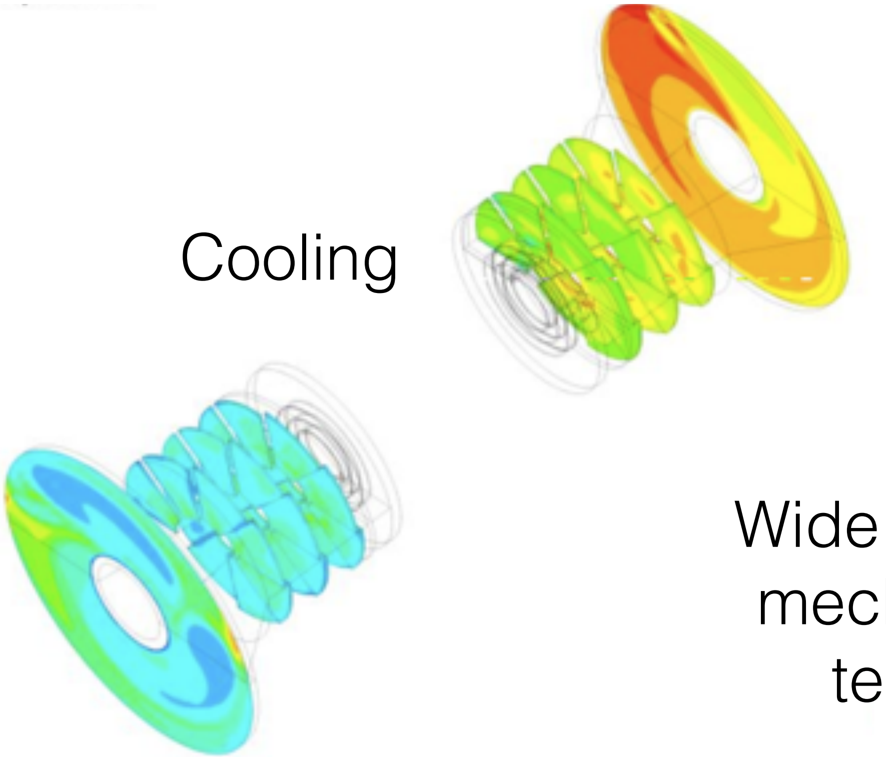
Thin sensor assemblies

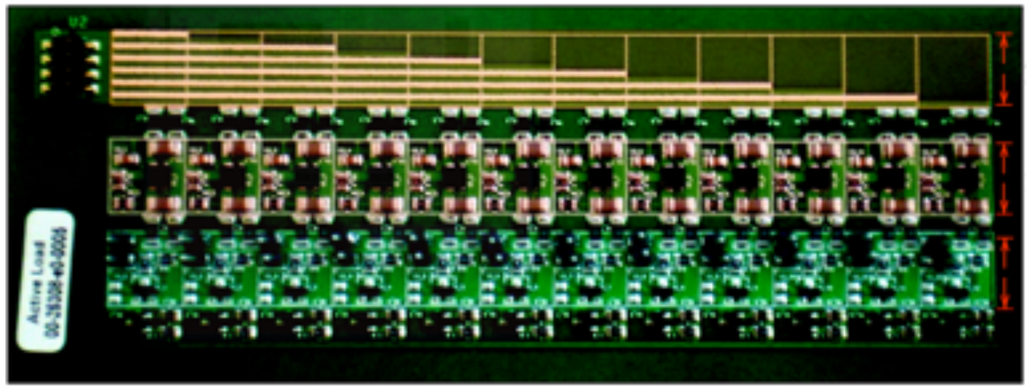


Supports



Cooling



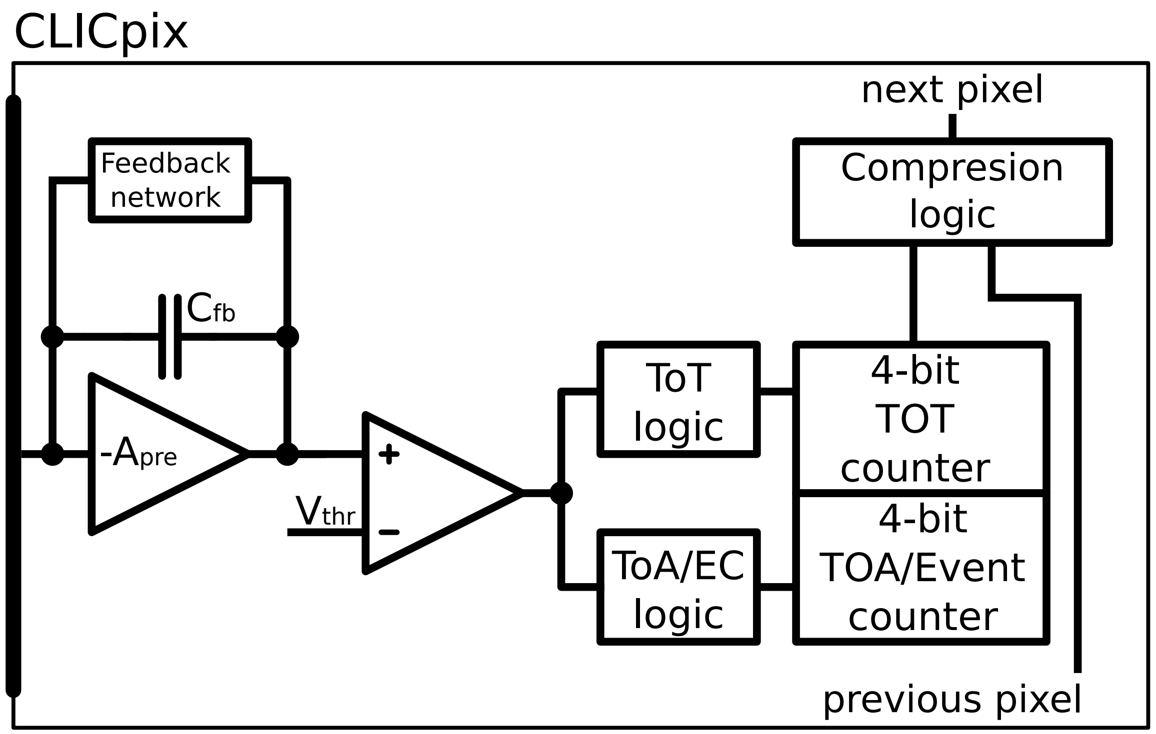


Powering

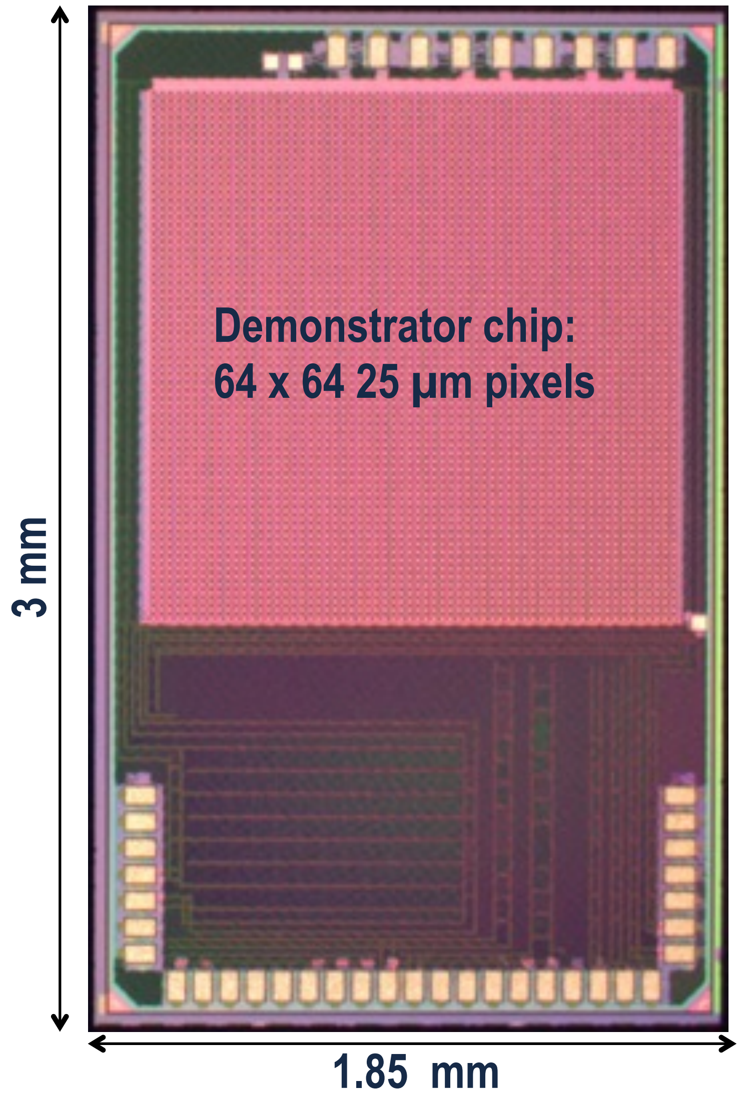
Wide range of expertise required: Electronics, chip design, mechanical engineering, DAQ, silicon sensor technology, test beams, telescopes, pixel data reconstruction …

CLICpix readout

- The CLICpix ASIC: a fast, low power readout chip with 25 µm pitch
- 4-bit TOA and TOT measurements for each pixel
- Supports power-pulsing and data compression
- Implemented in 65 nm CMOS technology

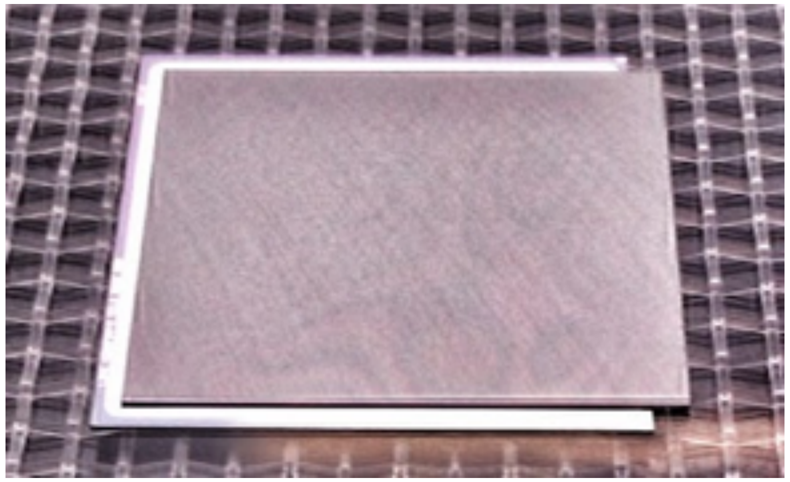


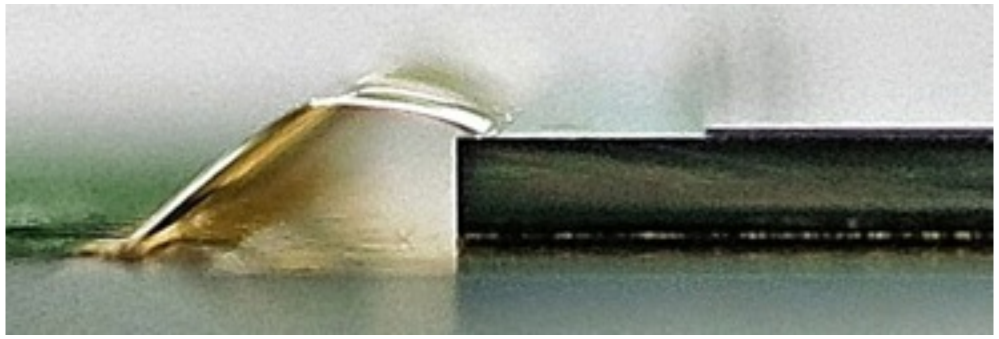
CLICpix schematic

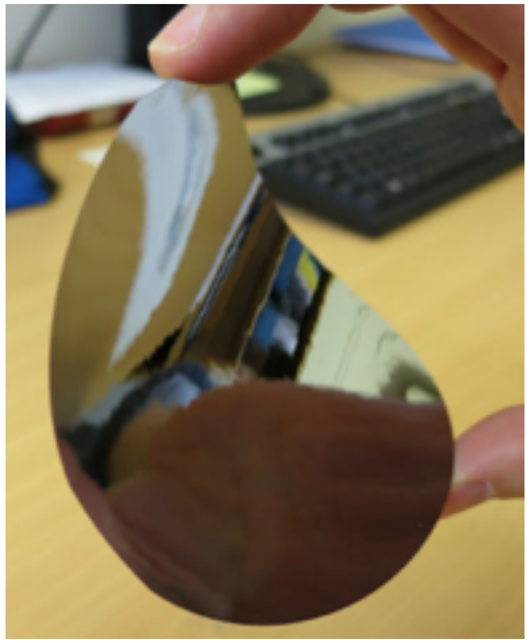


Thin sensor assemblies

- Hybrid planar pixel technology: sensor + read out chip
- Ultimate goal: 50 µm sensor on 50 µm ASIC with 25 µm pitch



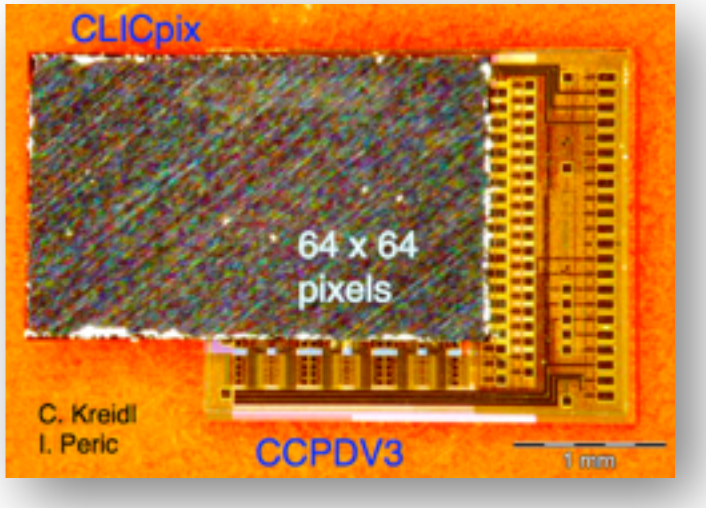




50 µm thick silicon wafer

Two types of assembly so far tested:

- standard or thinned Timepix bump-bonded to 50 - 500 µm silicon wafer, 55 µm pitch
- CCPDv3 active sensor (300 µm) capacitively coupled to CLICpix, 25 µm pitch

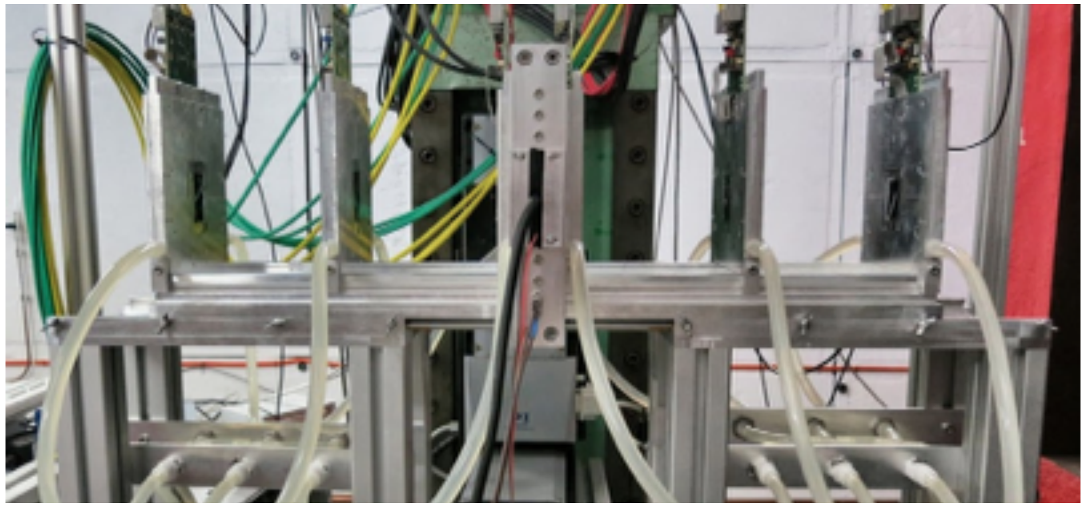


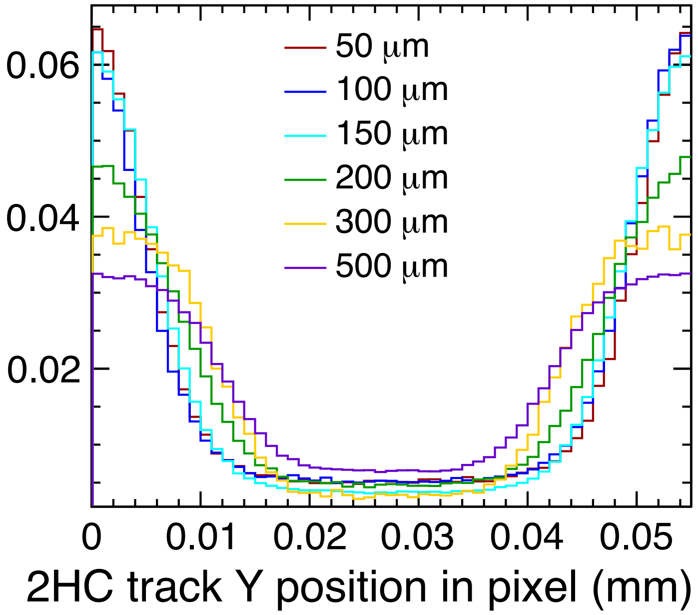
Timepix beam tests

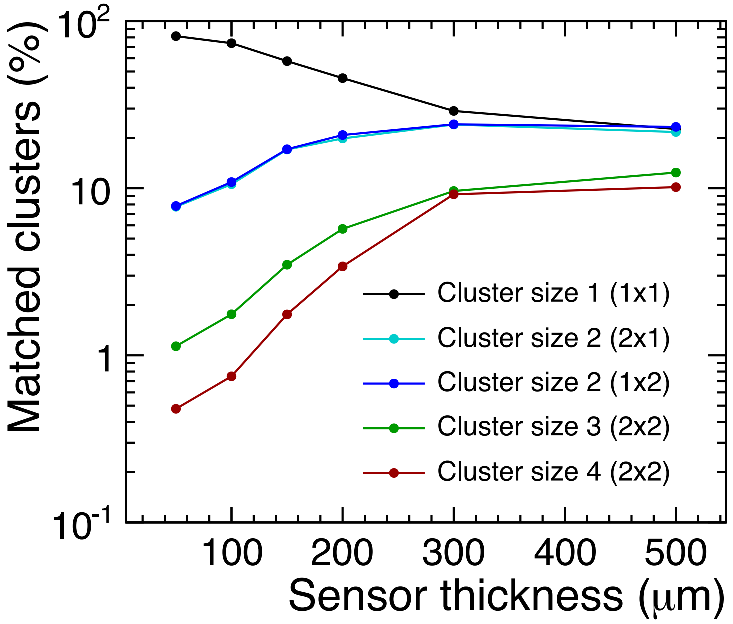
Data recorded at:

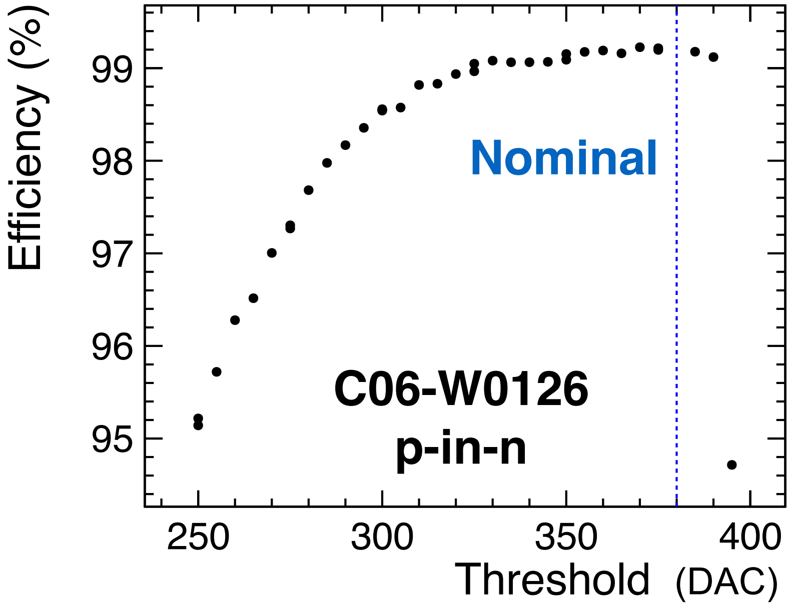
- DESY II: 5.6 GeV electron beam
- CERN PS: 10 GeV mixed beam

Using the EUDET/AIDA telescope

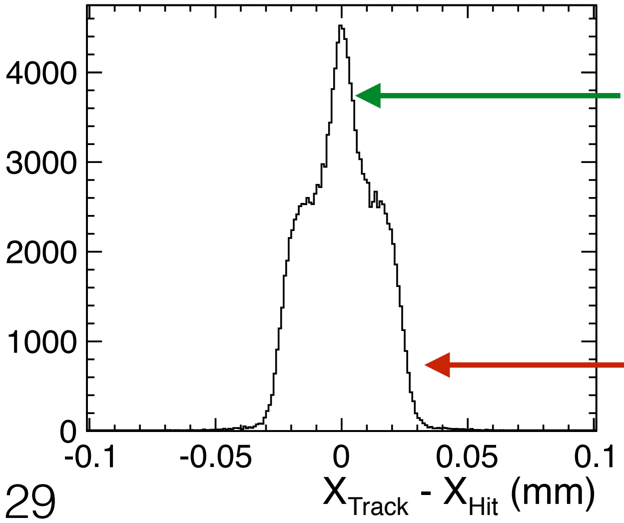








- Charge sharing varies with thickness
- Excellent detection efficiency
- Resolution depends on cluster shape, 2-hit cluster ~4 μm (including tracking)



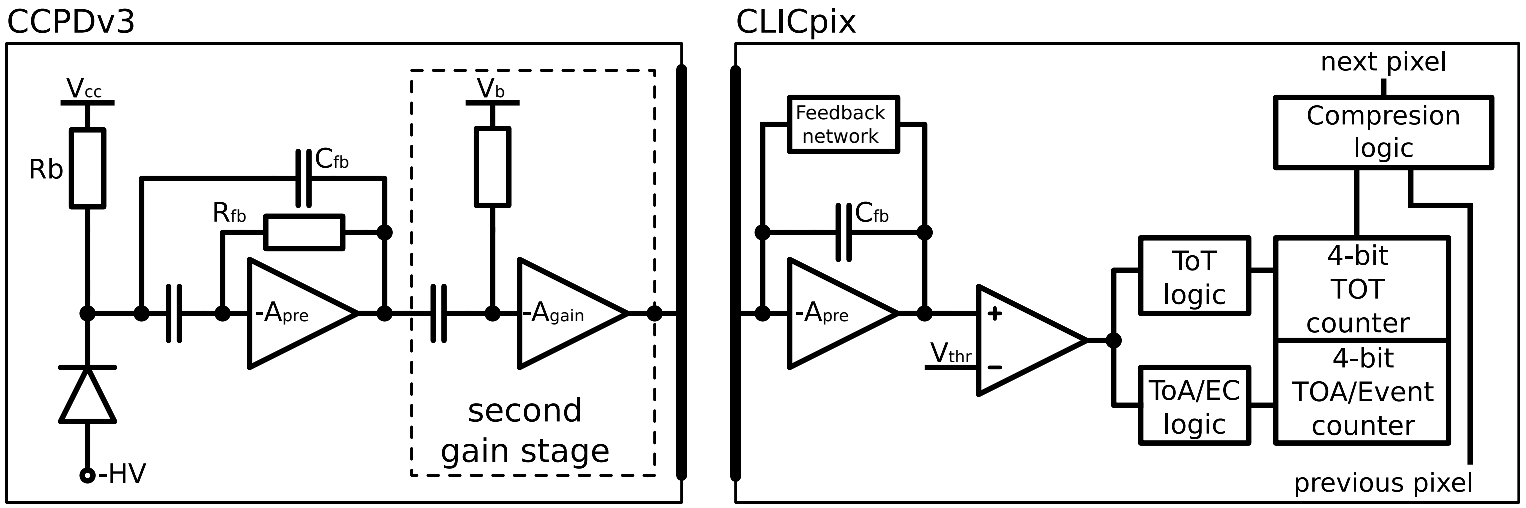
Multi-hit clusters: resolution determined by alignment, charge sharing, hit making method, TOT resolution, noise, efficiency…

Single-hit clusters: resolution determined by pixel size

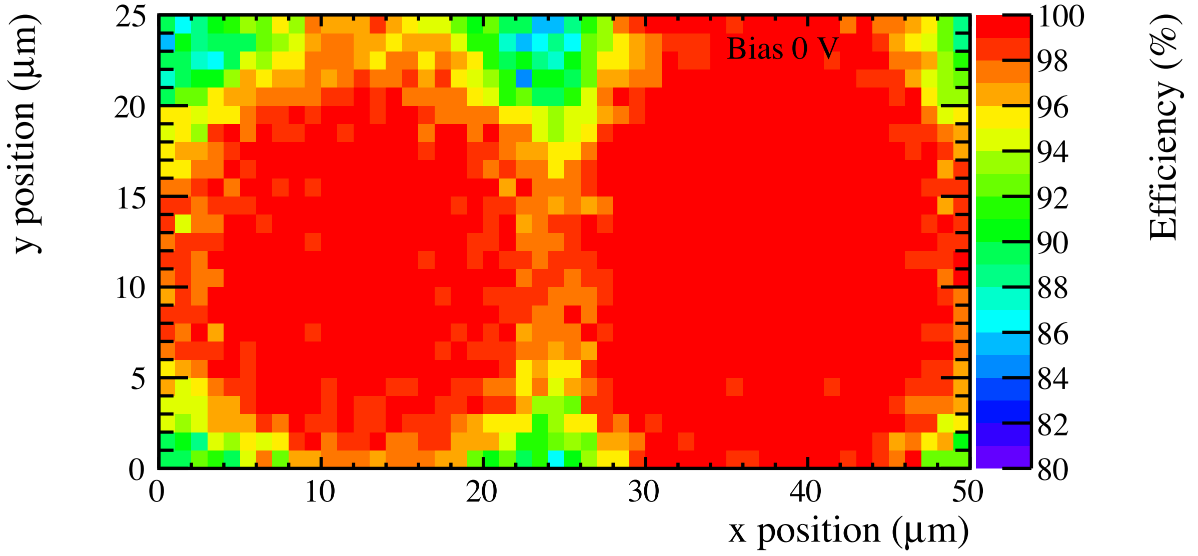
Capacitively coupled HV-CMOS assemblies

Capacitively coupled pixel detector (CCPDv3) as active sensor glued to a CLICpix:

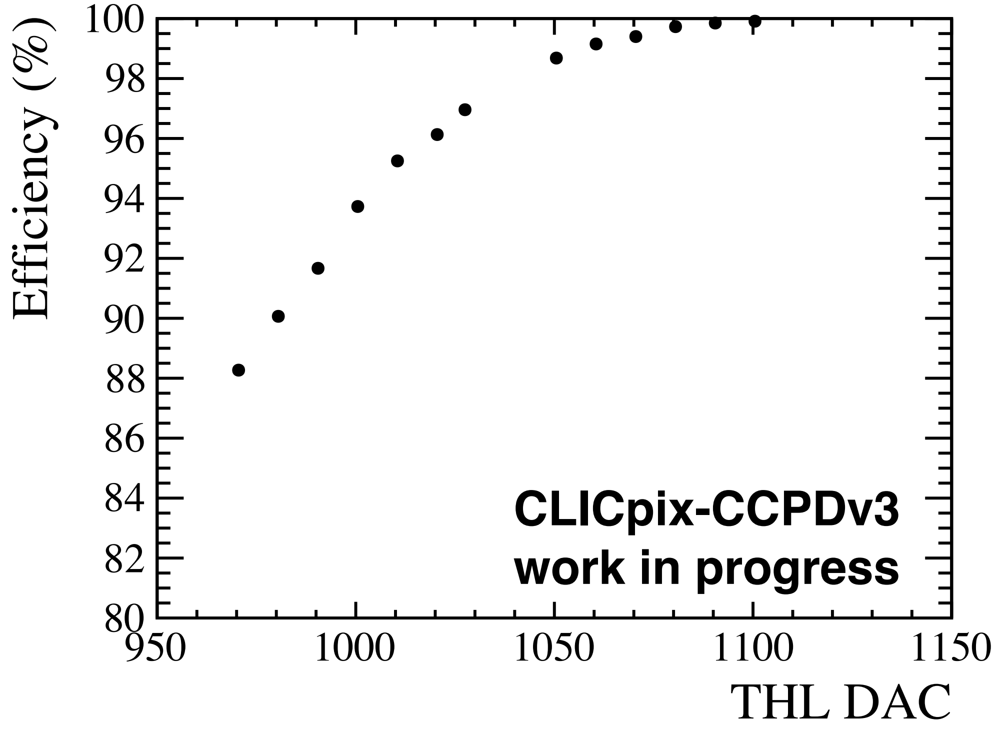
- active sensor has two-stage amplifier in each pixel
- capacitive coupling to CLICpix bond pads through layer of glue



Beam tests show excellent efficiency at operating voltage



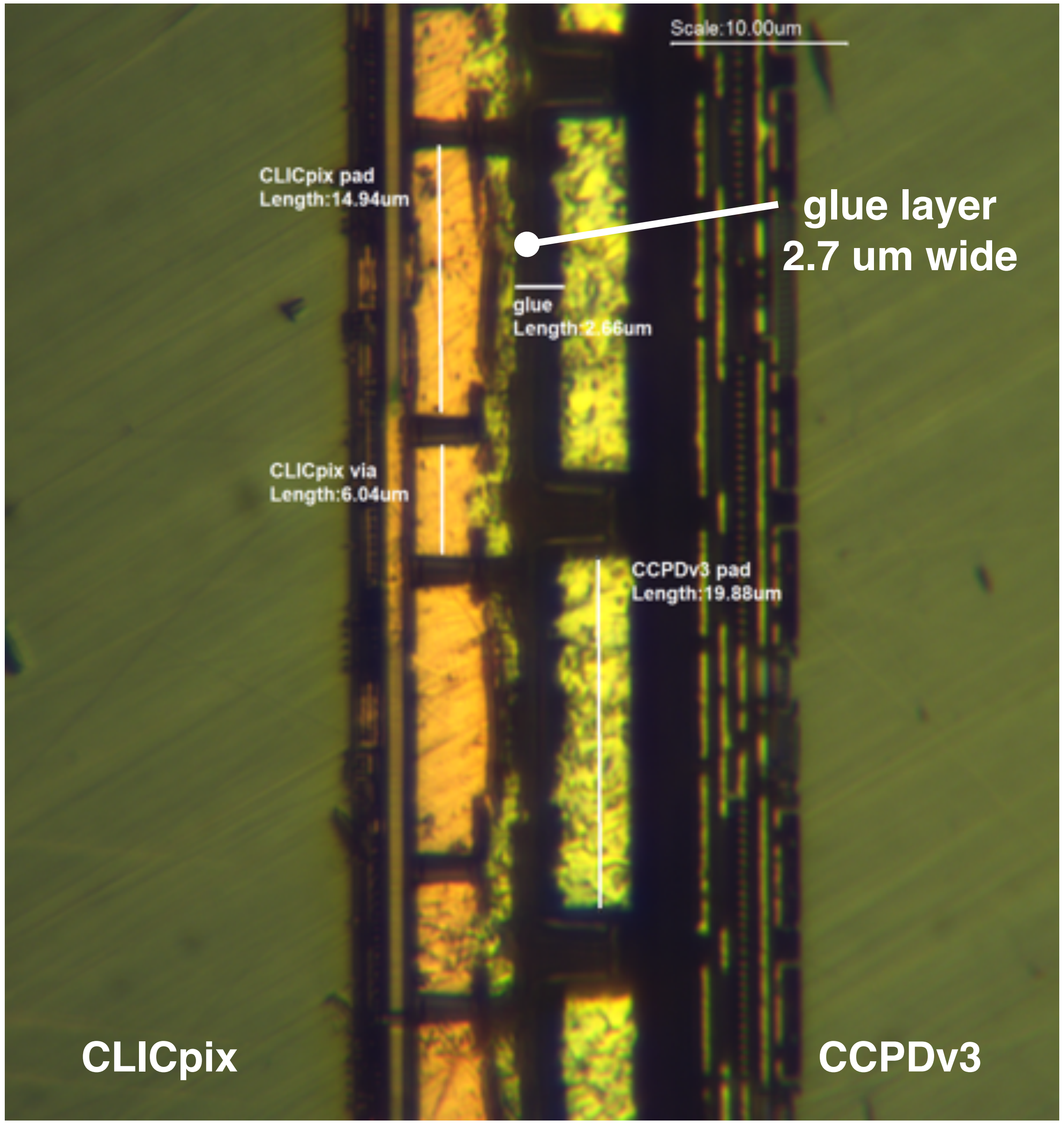
- Lower efficiency due to no bias voltage
- Asymmetry due to odd/even column discriminator differences

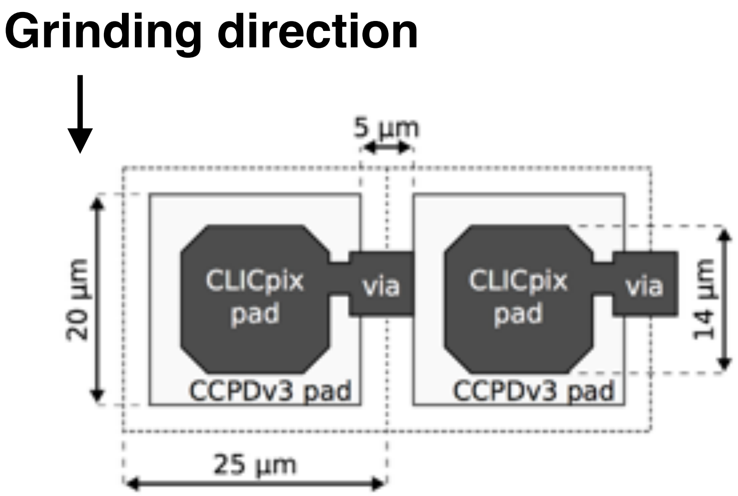


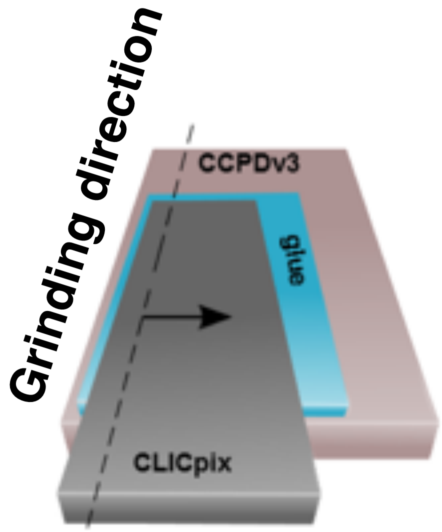
Capacitively coupled HV-CMOS assemblies

Fabrication and glue thickness studies:

- assemblies are fabricated at SET
    - Automated Device Bonder
- assemblies can be characterised in destructive testing
    - embed assembly in resin support
    - grind through cross section
    - measure glue thickness, uniformity
- upcoming beam tests
    - test efficiency, depletion as a function of glue thickness



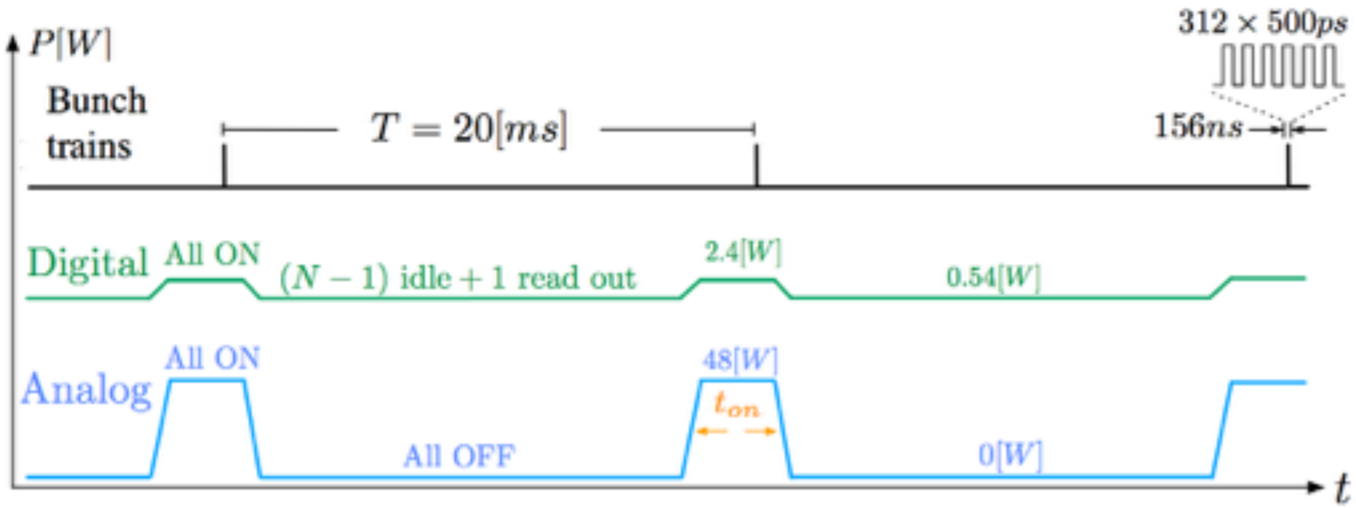


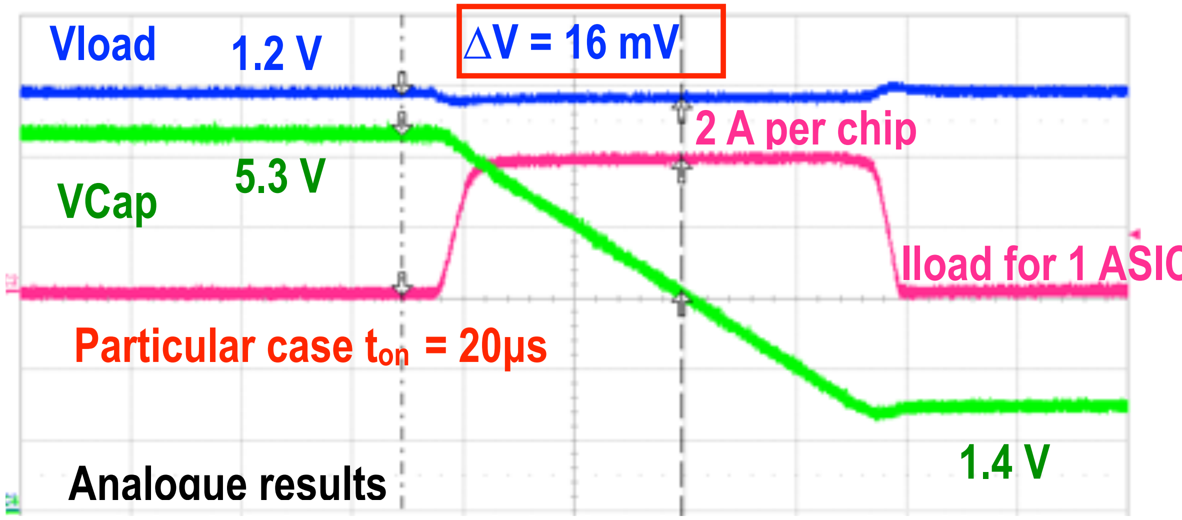


Power pulsing

Power pulse CLICpix ASIC to achieve dissipation < 50 mW/cm^2 in the sensor area

- Analog electronics can be turned off: 2 W/cm^2 → 2 mW/cm^2
- Digital electronics in idle except during readout: 100 mW/cm^2 → 13 mW/cm^2



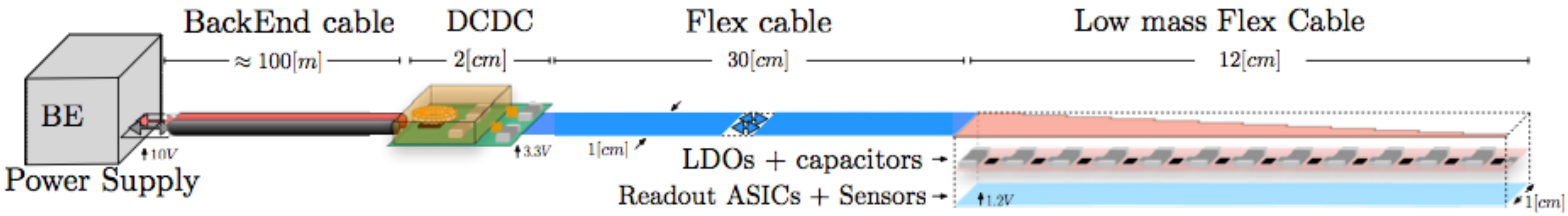


Power delivery:

- small constant current in low mass cables
- local energy storage in silicon capacitors

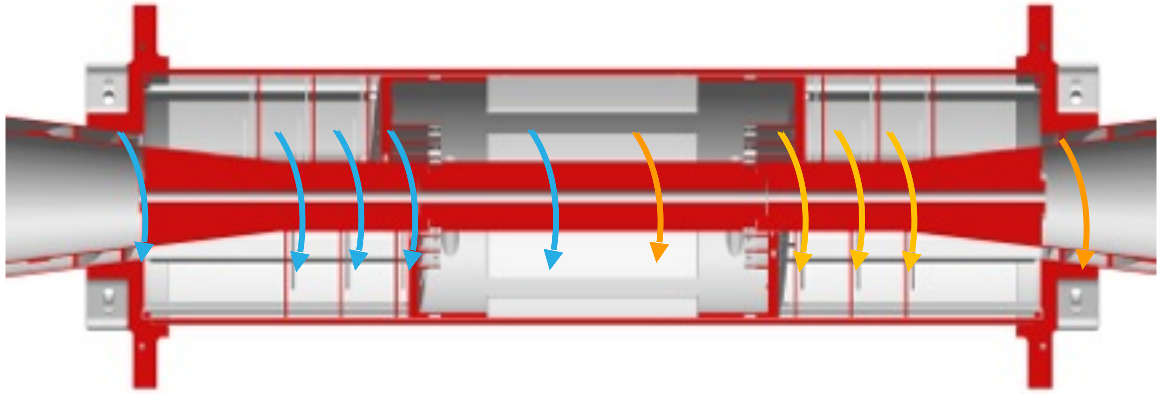
Lab tests of power pulsing:

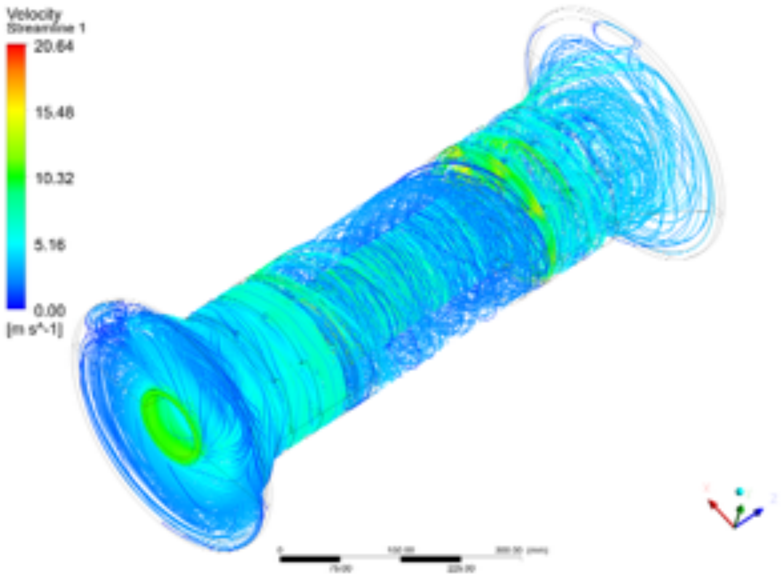
- controlled current source, dummy load
- confirms total dissipation < 50 mW/cm^2



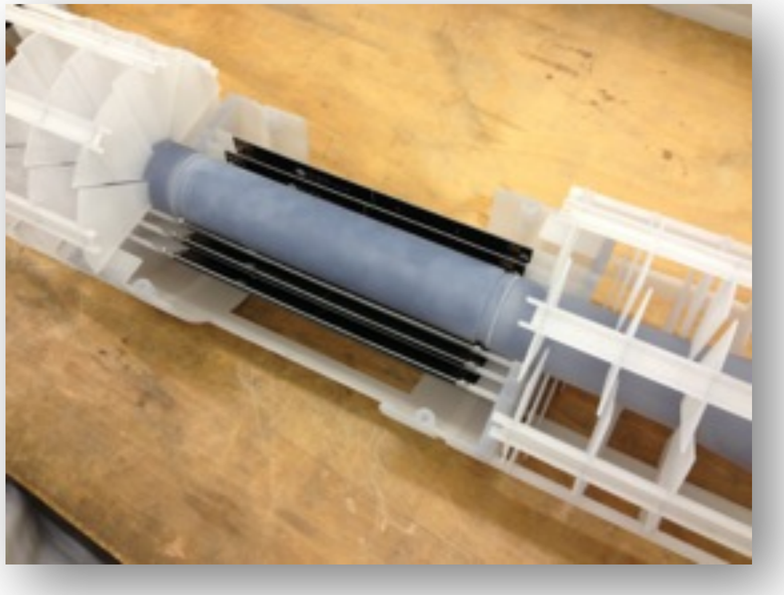
Air flow cooling

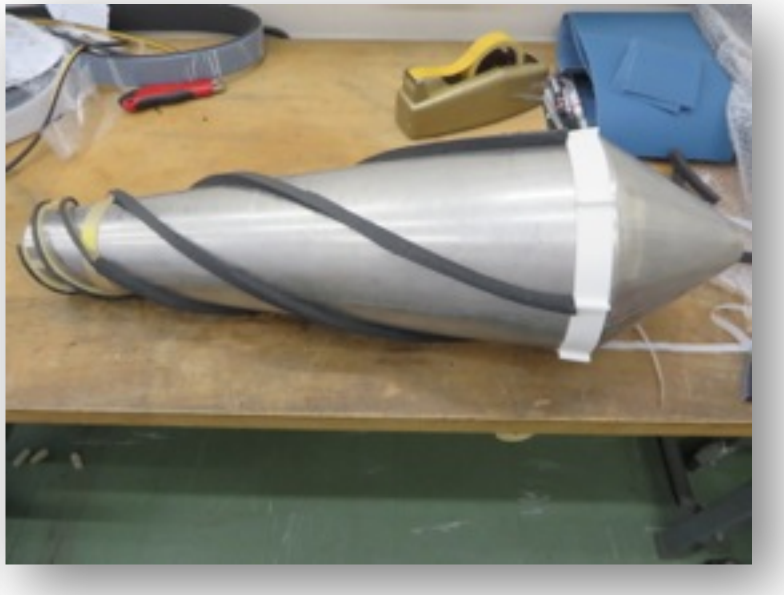
- Total heat load after power-pulsing ~470 W
- Cooling provided by forced air-flow:
  - Dry air cooling at 0°C
  - Low material: radiation length of air ~310m





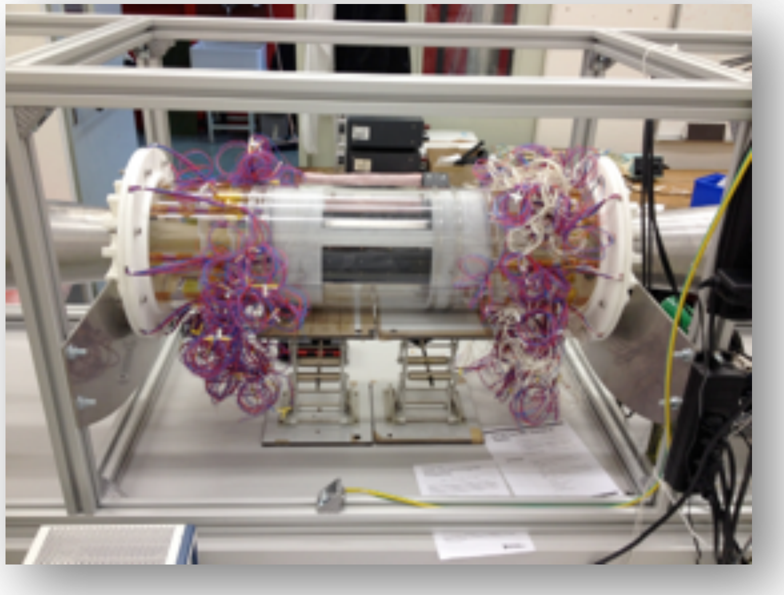
construction of full-scale mock-up





Test bench measurements:

- vibrations < 3 um in transverse plane
- cooling sufficient for single stave at 50 mW/cm^2
- visual confirmation of streamlines
- full temperature and flow measurements under way



Summary

CLIC: a high-energy linear electron-positron collider to go beyond the LHC

Two beam acceleration: 100 MV/m for a compact layout achieving $\sqrt{s} = 3$ TeV

Energy staging gives access to different centre of mass energies

Strong physics programme: Higgs, top, BSM all at high precision

Challenging detector development: many areas of R&D

We welcome new collaborators!

Thanks for your attention!