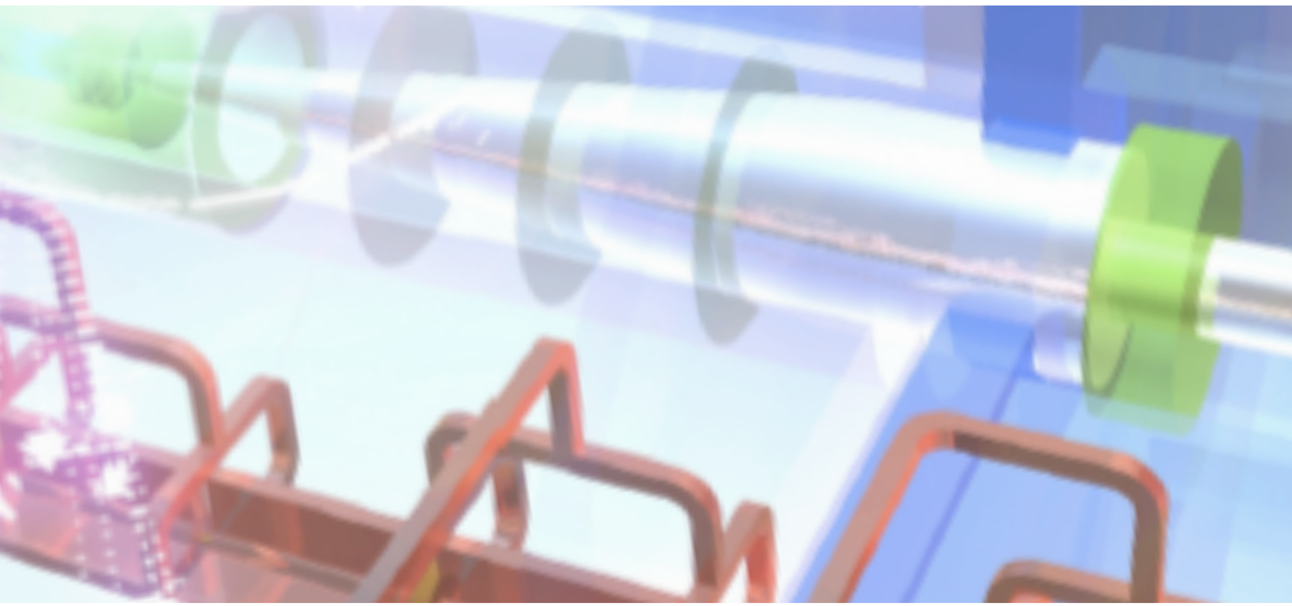
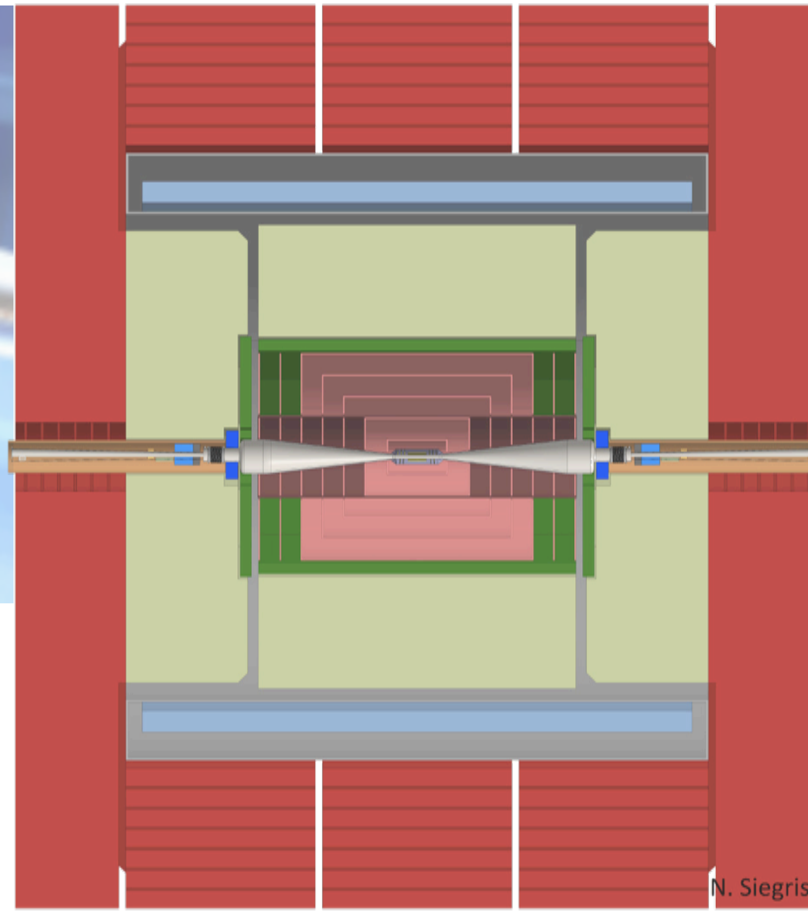
CLIC detector and physics

LCWS, 2 November 2015





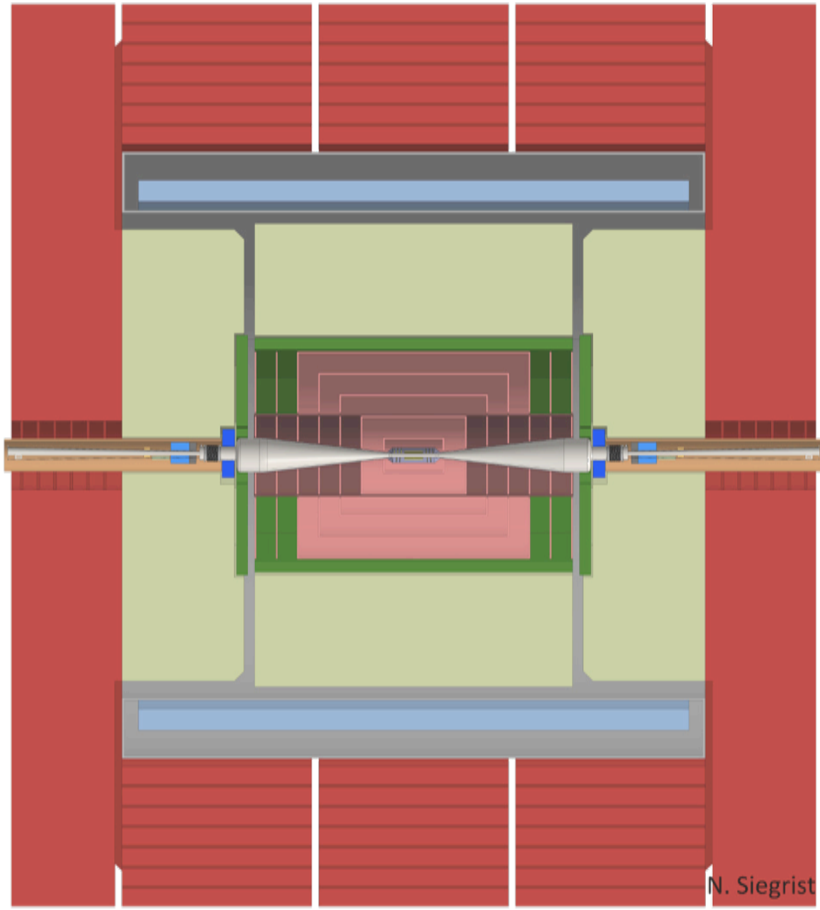
University of Glasgow

Aidan Robson

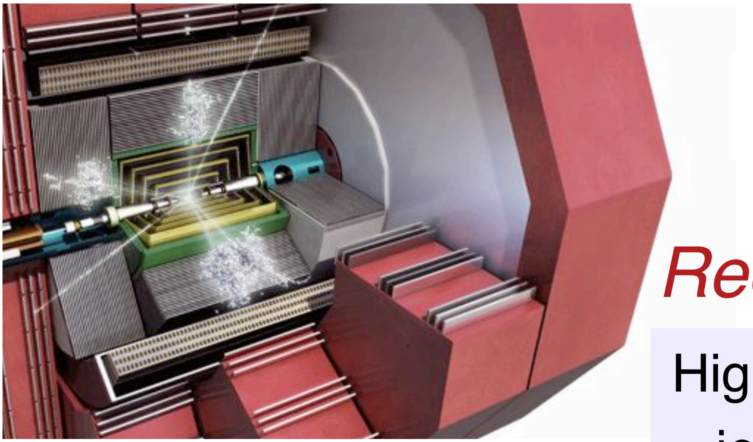
on behalf of the
CLICdp collaboration

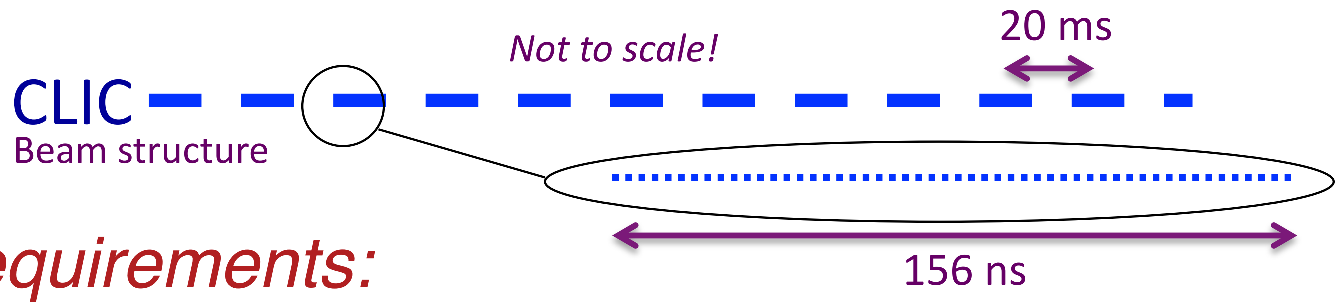
CLIC detector and physics

- Overview
- R&D and optimization developments:
  - vertexing
  - tracking
  - calorimetry
- New detector baseline
- Modelling and software
- Physics analysis
- Outlook



CLIC detector and physics





Requirements:

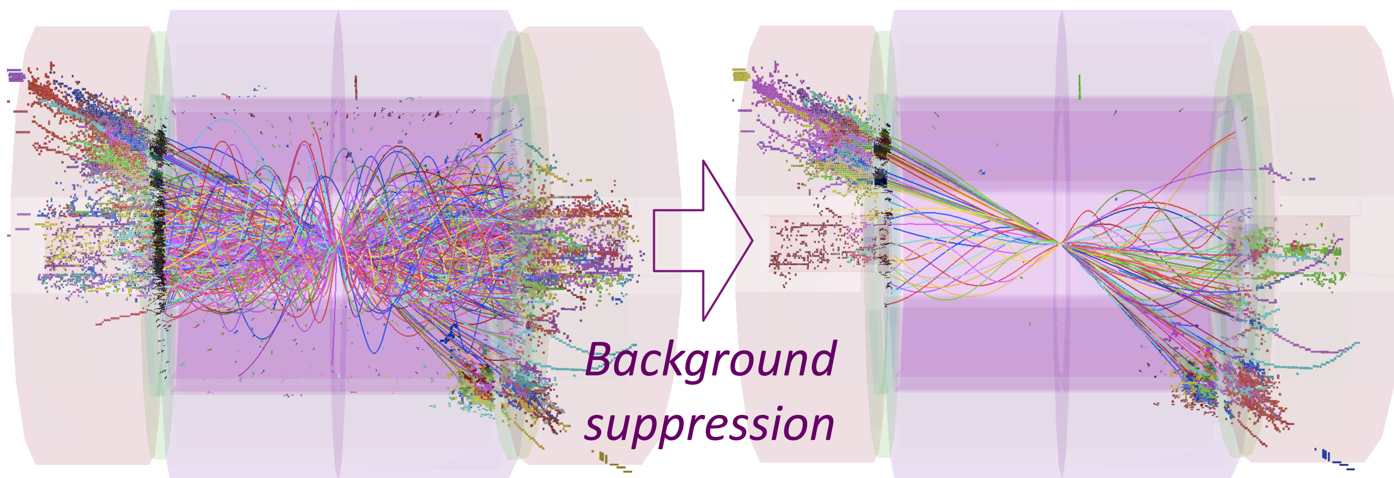
High precision:

- jet energy resolution -> fine-grained calorimetry — $\sigma(E)/(E) \sim 3.5\%$ for $E>100\,\text{GeV}$
- momentum resolution — $\sigma(p_T)/p_T^2 \sim 2\text{x}10^{-5}\ \text{GeV}^{-1}$
- impact parameter resolution — $\sigma_{r\phi} \sim 5 \oplus 15/(p[\text{GeV}]\sin^{3/2}\theta)\ \mu\text{m}$

CALICE / FCAL

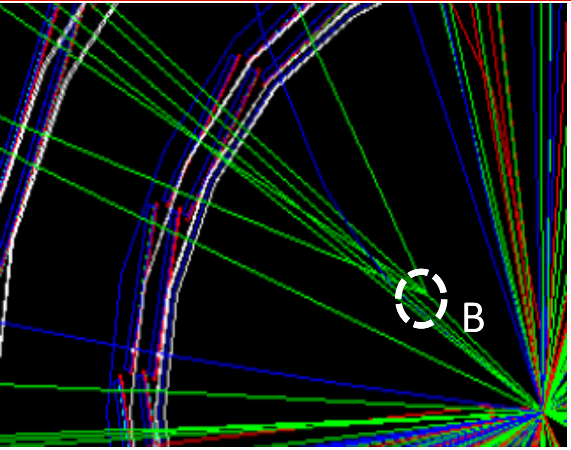
CLICdp vertexing/ tracking programme

High occupancy
-> precise timing
(1ns, 10ns)



- Provide demonstrators for the main technical challenges

Vertex detector



Requirements:

Accurate:

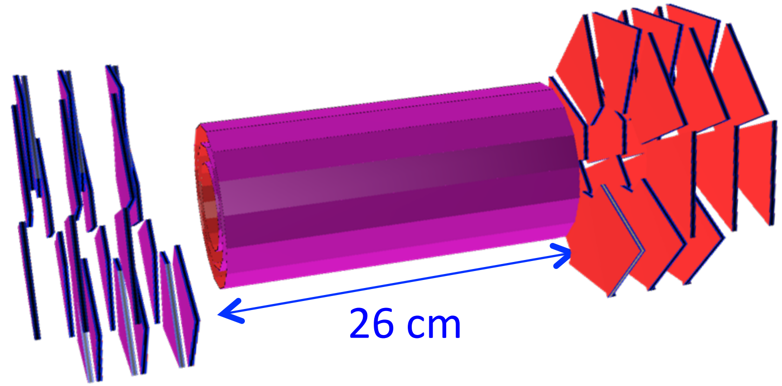
3μm single-point resolution

-> 25 x 25 μm² pixels

Ultra-light:

≤0.2% X_0 per layer

~50 mW/cm²



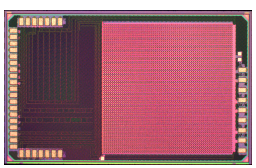
3 double layers in barrel and endcaps

~1m² area, ~2G pixels

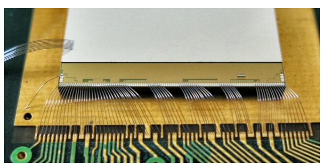
R_i ~31 mm at 3 TeV (background occupancies)

spiral endcap geometry (air flow cooling)

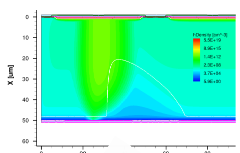
Readout ASICs



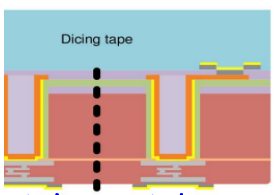
Sensors



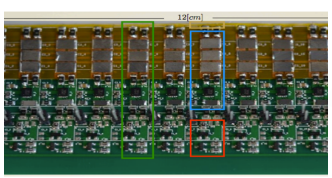
Simulations



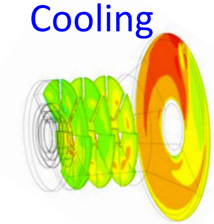
Interconnects



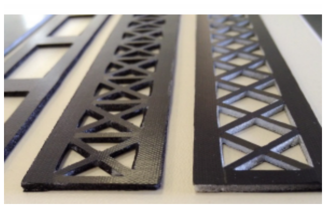
Powering



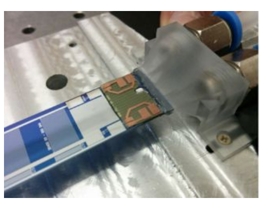
Cooling

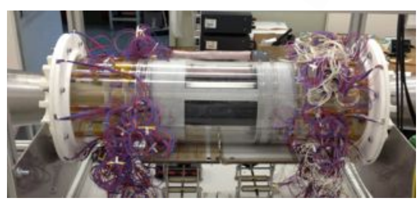


Light-weight supports



Detector integration + assembly





- Integrated R&D effort

Recent highlights:

First test-beam & lab measurements with planar CLICpix assemblies

Systematic studies of capacitively-coupled HV-CMOS assemblies

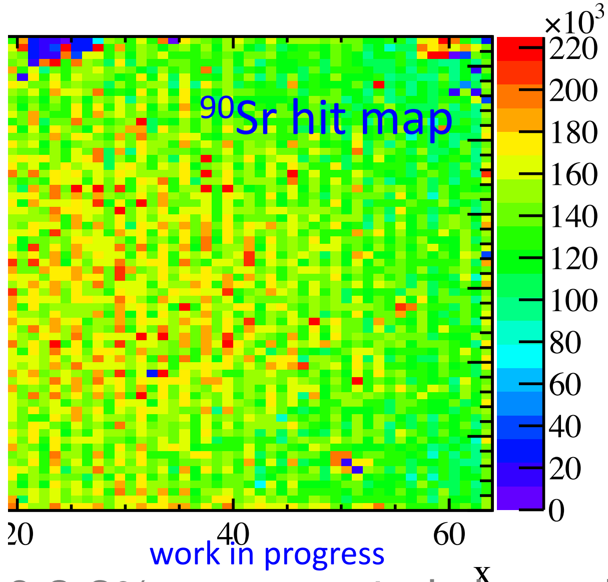
Simulation of HV-CMOS sensors

Planar-sensor CLICpix assemblies

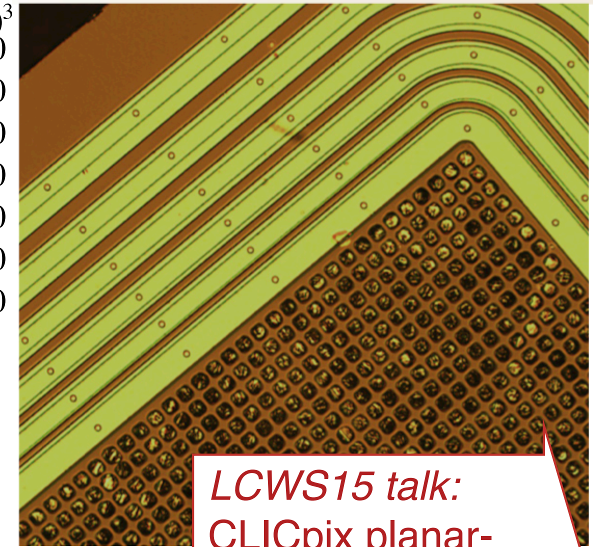
CLICpix: CMOS hybrid readout chip targeted for CLIC vertex detectors, based on Timepix/Medipix chip family

First three bump-bonded pixel assemblies produced using single-chip bump-bonding process at SLAC, 25μm pitch

- Device is small, 3x3mm², but a significant step

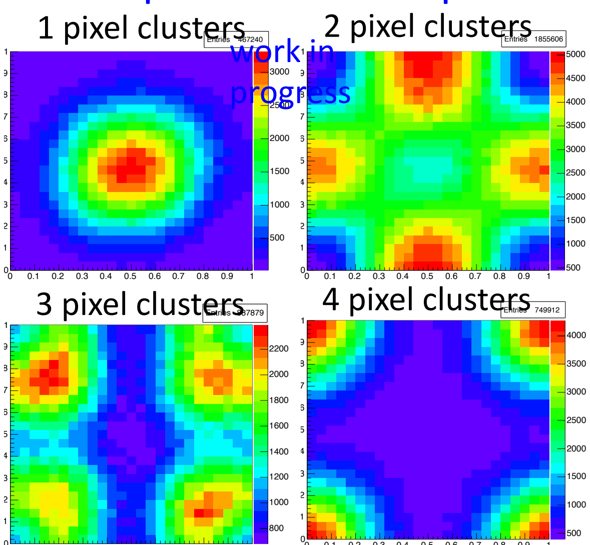


0.2-3% unconnected channels, 1-2% shorted channels



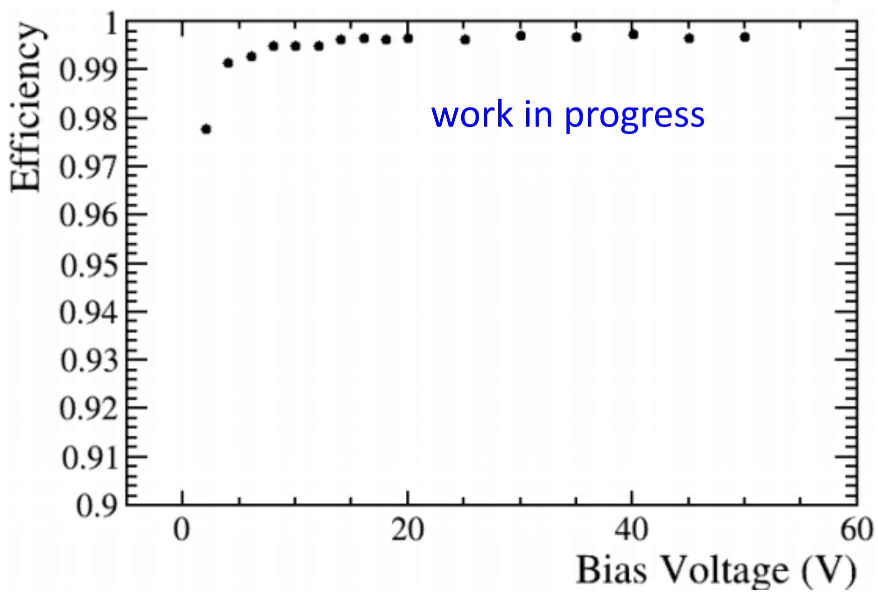
LCWS15 talk:
CLICpix planar-sensor assemblies
Dominik Dannheim

In-pixel cluster maps



CERN SPS test beam with AIDA telescope:

- V_{dep}~35 V
- High detection efficiency (>99.5%)
- ~30% single-pixel clusters at V_{dep}
- ~4μm single-point resolution



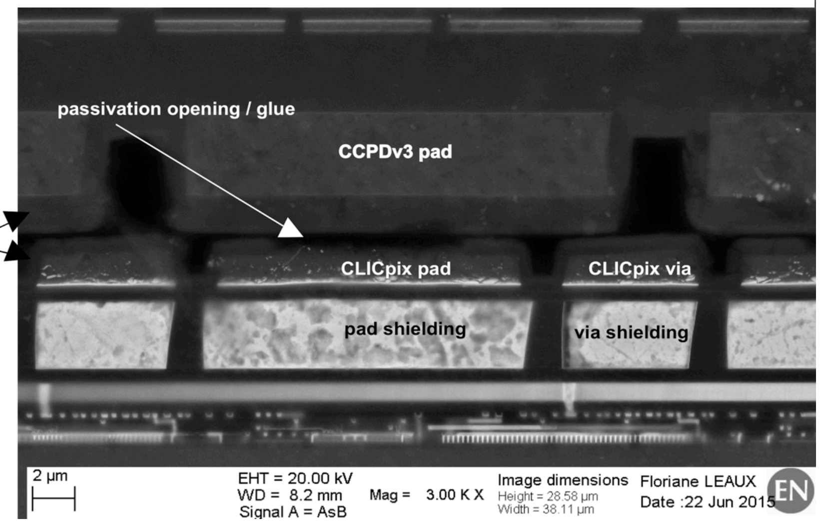
Capacitive coupling

Capacitive Coupled Pixel Detector (CCPD)

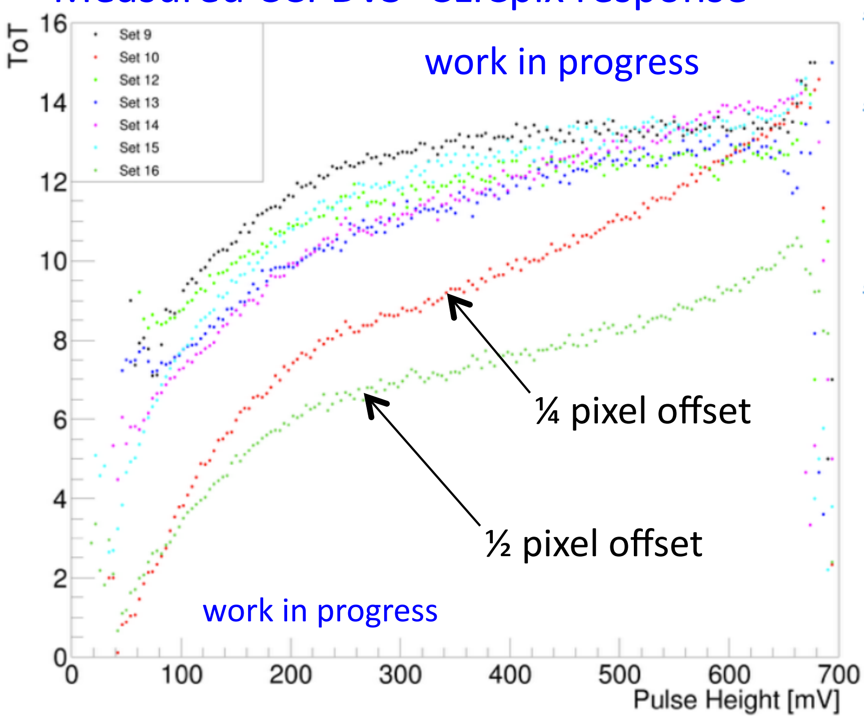
- capacitive coupling of 64x64 matrix (25 μm pitch) to CLICpix readout ASIC through thin glue layer (few μm)

Systematic studies of glue parameters
Achieved ~1μm alignment precision, 0.5μm glue thickness

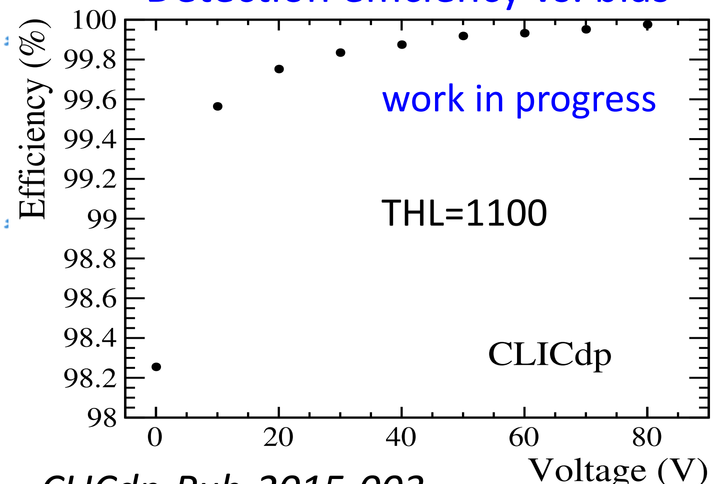
SEM picture CCPDv3-CLICpix assembly



Measured CCPDv3+CLICpix response



Detection efficiency vs. bias



CLICdp-Pub-2015-003

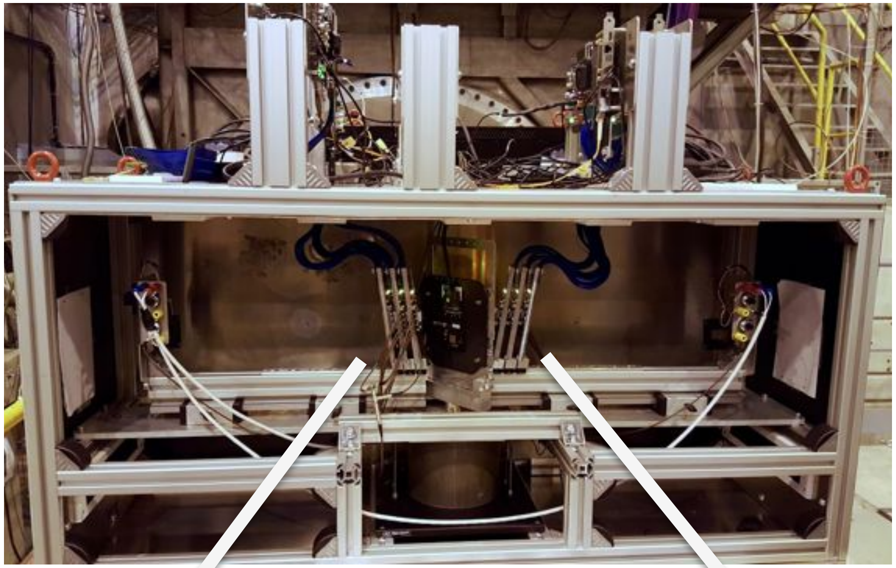
SPS test beam

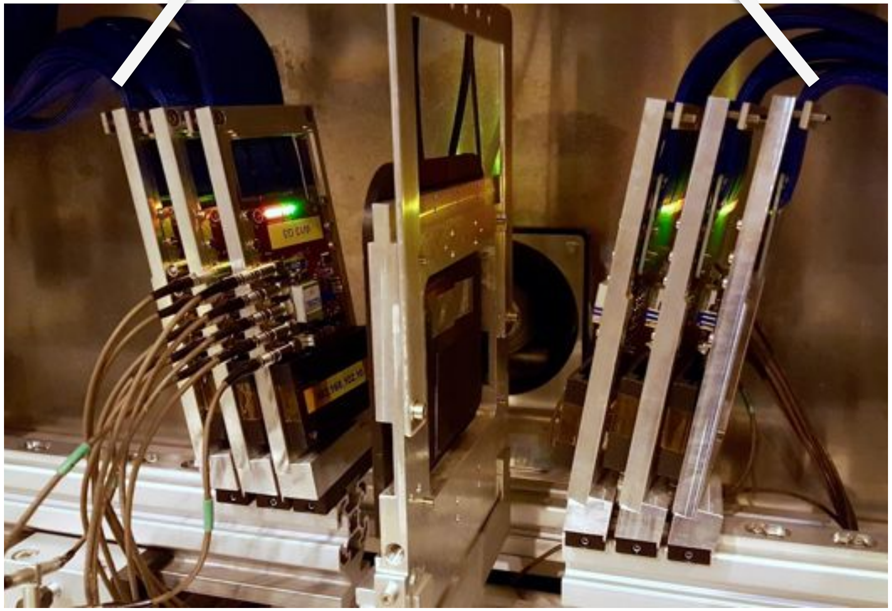
- High detection efficiency
- ~6μm single-point resolution

LCWS15 talk:
Capacitively-coupled pixel detectors for the CLIC vertex detector
Steven Green

◆ Proof of principle achieved, calibration in progress

Timepix3 telescope

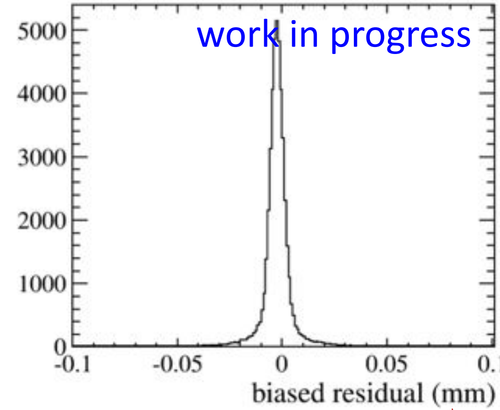




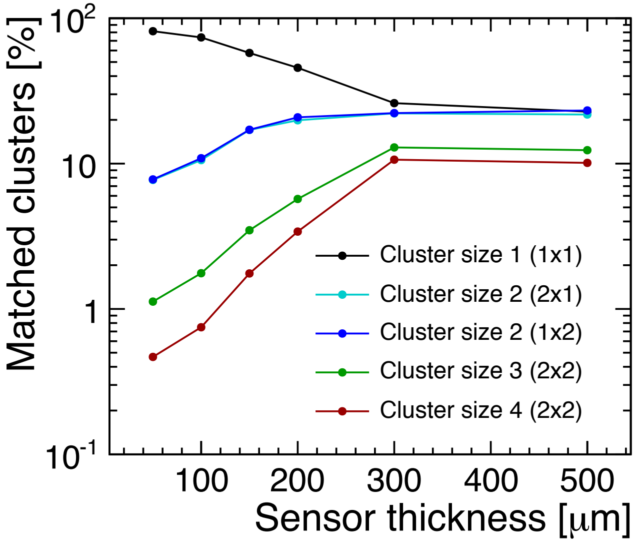
Built, installed and commissioned high-performance beam telescope with Timepix3 readout, at SPS H6 beam

used first to test active edge sensors
power pulsing tests started

- Will allow timing performance characterisation



Ongoing thin sensor characterization



LCWS15 talk:
Recent developments in LC vertex/tracking R&D
Dominik Dannheim

LCWS15 talk:
Thin-sensor studies for the CLIC vertex detector
Sophie Redford

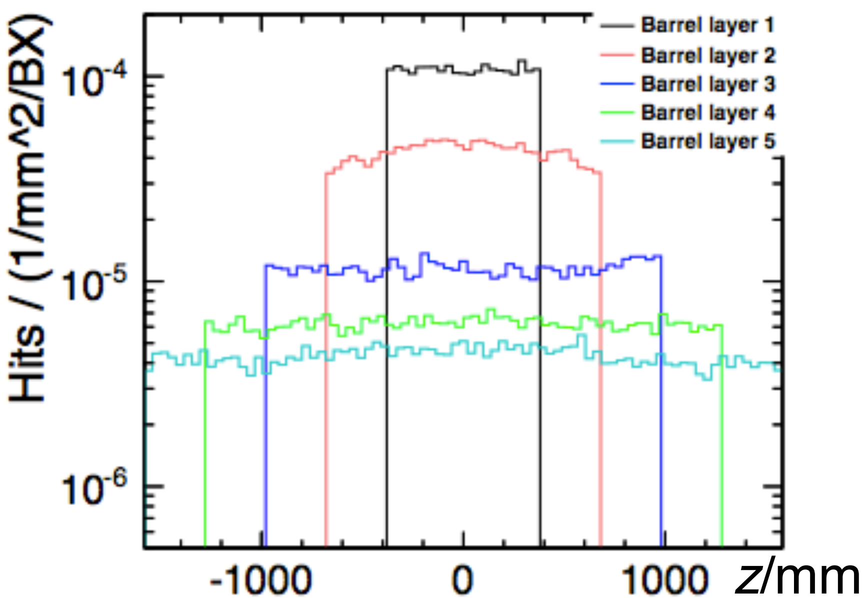
Tracking detector

For CDR used two models: CLIC_ILD with TPC, and CLIC_SiD with Si tracker.
At 3TeV, TPC had ~30% occupancy

-> develop full silicon tracker approach
New CLICdp working group: tracker technology

- Systematic optimization of geometries:
  - background occupancies
  - detector performance

Beam-induced background hits from $\gamma\gamma \rightarrow$hadrons and incoherent pairs:



Requirements:

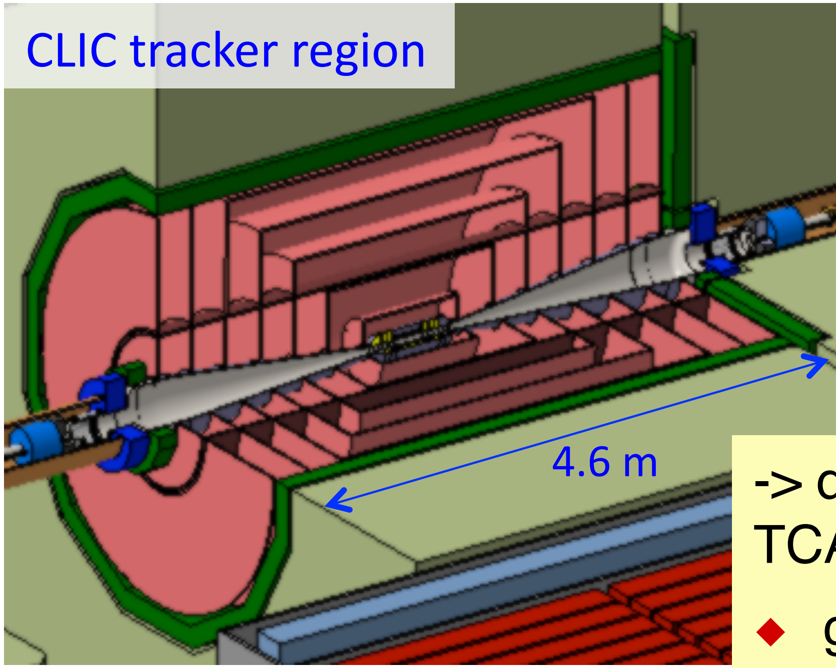
Accurate:
7μm single-point resolution
Light:
~1–2% X_0 per layer
Few % max. occupancy from beam-induced backgrounds

High occupancies in certain regions
-> need large pixels / short strips
Readout granularity ~50μm x 1-10mm

Larger tracker radius benefits:
pt resolution, track angular resolution, jet energy resolution from particle flow
-> increase from 1.3m to 1.5m (with 4T field)

Long tracker extent needed for forward acceptance -> use 2.3m half-length

Tracker technology



Outer tracker:

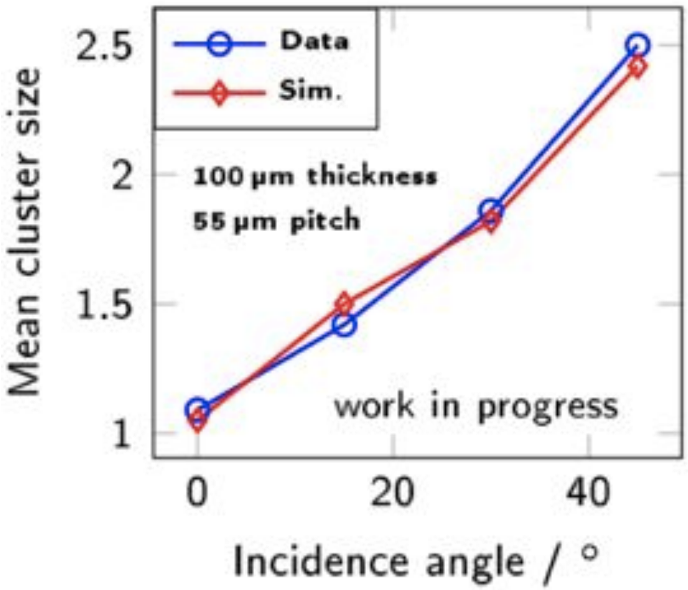
- 5 barrel, 7 forward layers, R~1.5 m, L~4.6 m
- beam pipes with conical sections

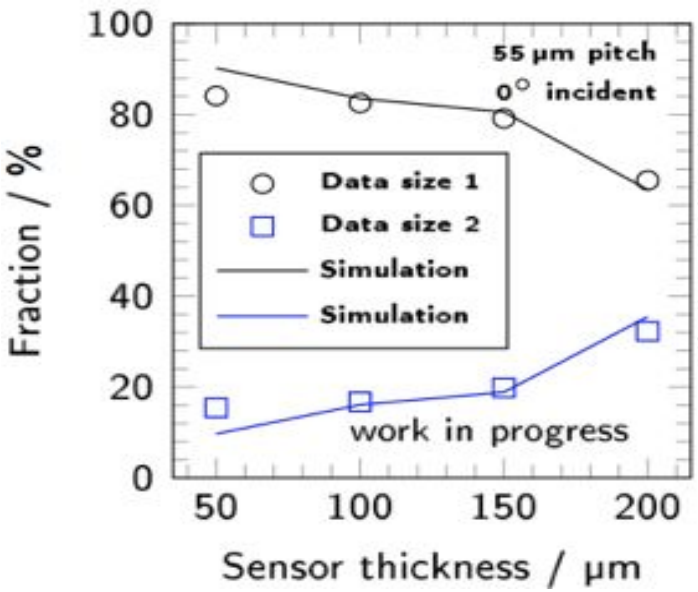
How to achieve 7μm single-point resolution:
sensor technology? readout cell size?
charge sharing? analogue energy information?

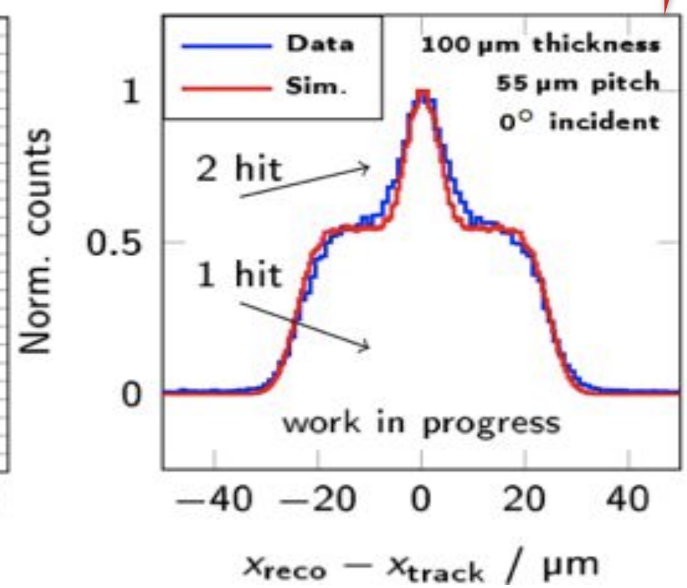
-> developing simulations (Geant + TCAD + parameterised FE-electronics)

◆ good agreement with testbeam data

LCWS15 talk:
Tracker-technology R&D for CLIC
Andreas Nurnberg







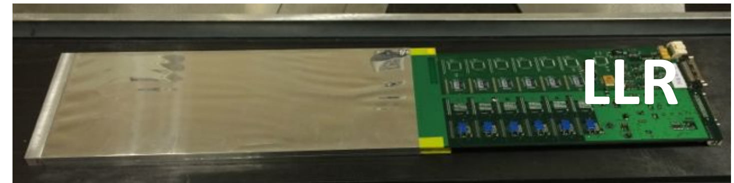
ECAL

Requirements:

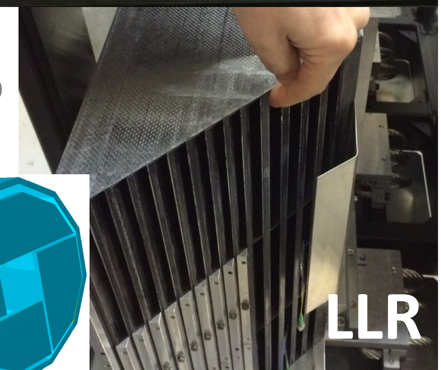
High granularity imaging calorimeters to use with Pandora Particle Flow algorithms

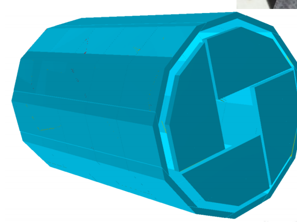
Concept adopted from CALICE SiW development
ECAL is a cost driver
-> post-CDR optimization

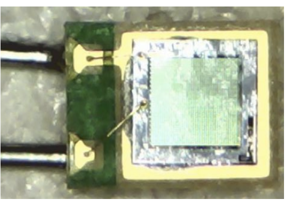
- –inner radius reduced: 1.5m
- –number of layers reduced from 29 to 25 (little change in performance)
- –cell size remains 5x5mm²



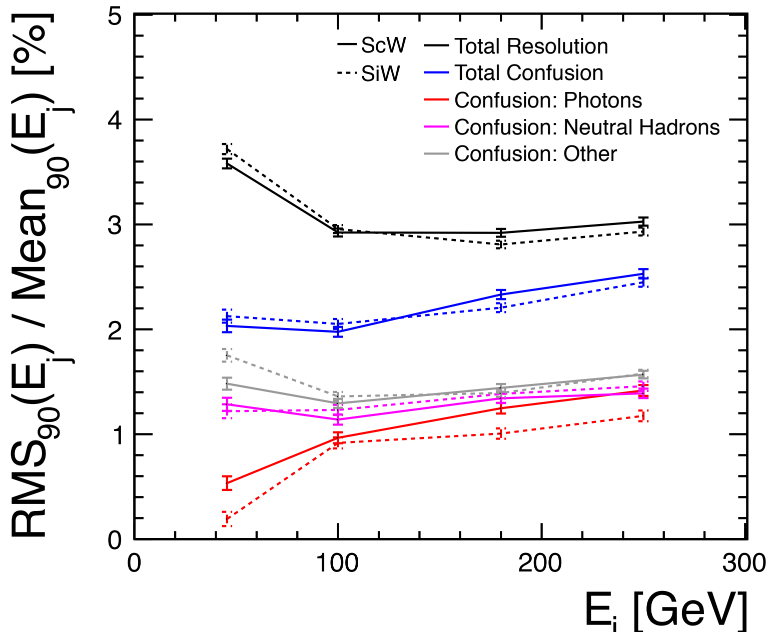
Prototype ECAL slab & module







lab tests with both scintillator tiles & SiPMs



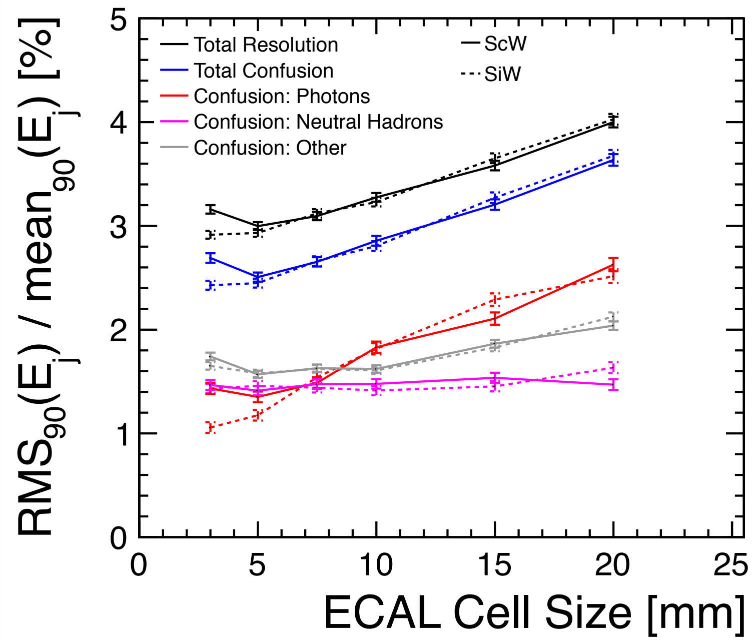
Jet energy resolution:

Total resolution

Total confusion

Photon ↗ ↑ ↖ **Other**

Neutral hadron

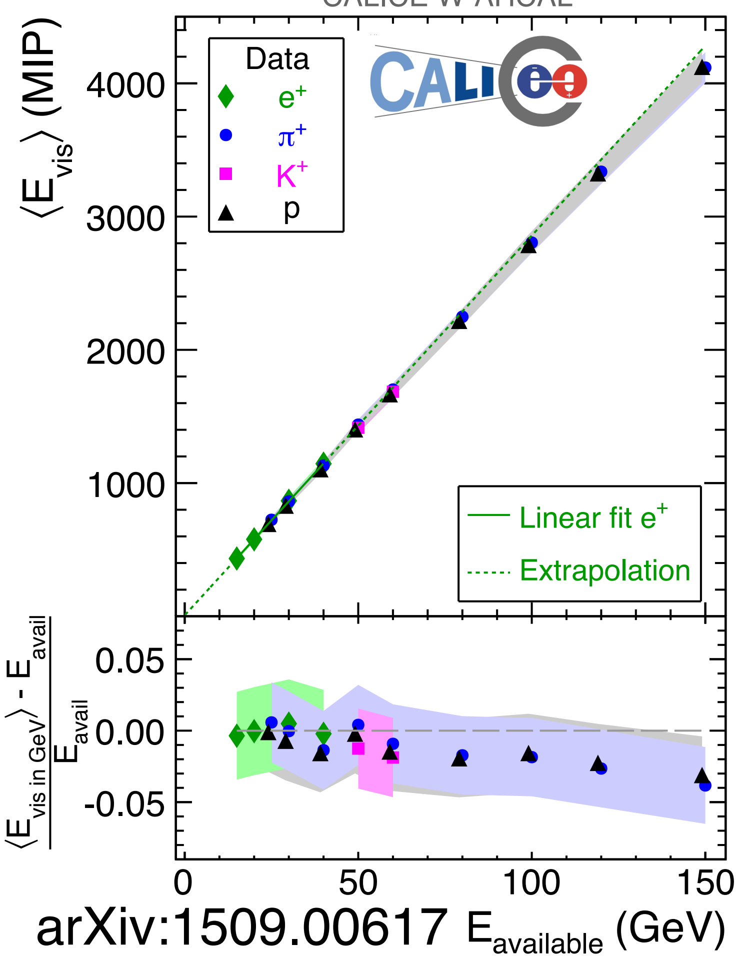


HCAL

Similar optimization for HCAL

number of layers
cell-size
material

Trade-off between:
–depth to contain high-energy showers
–compact size for surrounding solenoid



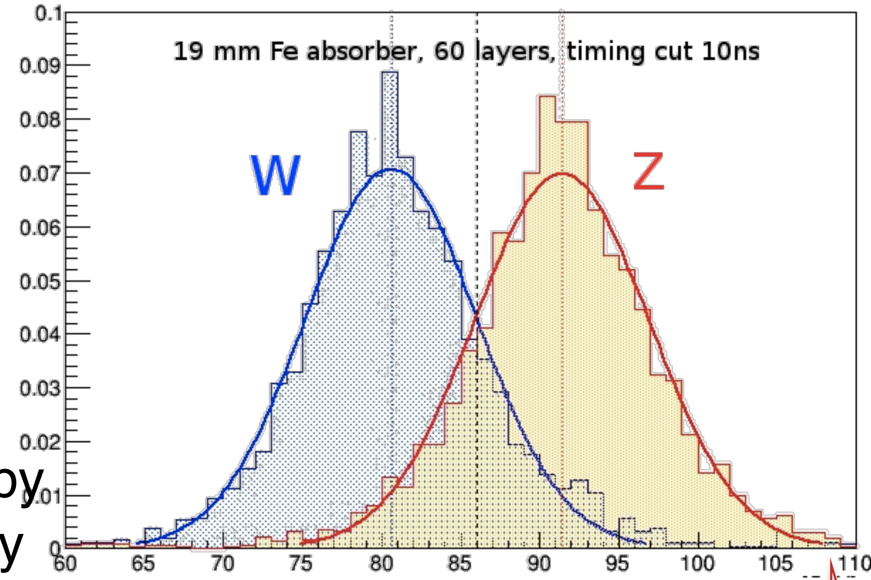
arXiv:1509.00617

Absorber options:
10mm Tungsten (W)
19mm Steel (Fe)

W-HCAL motivated by CLIC and extensively studied (CALICE)

comparison of response for different particle types – agree to ~60GeV
Well-described in simulation

Study m_W (W->ud) and m_Z (Z->dd)



LCWS15 talk:
Shower characteristics… in the CALICE W-AHCAL
Felix Sefkow

Performance for jets found to be similar for W and Fe;
Fe is cheaper and easier to produce

LCWS15 talk:
HCal optimization studies for the ILD
Steven Green

- Steel chosen for HCAL

60 layers, 30x30mm² cell
20mm Fe / 3mm scintillator

New detector concept

Learning from experience with CLIC_ILD and CLIC_SiD, and optimization studies

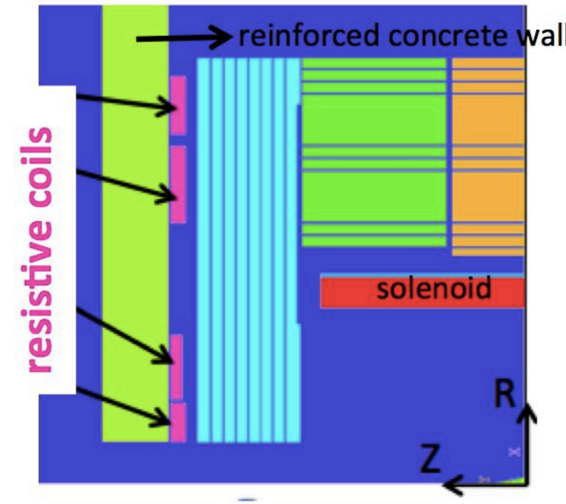
Vertex detector, tracker, ECAL, HCAL

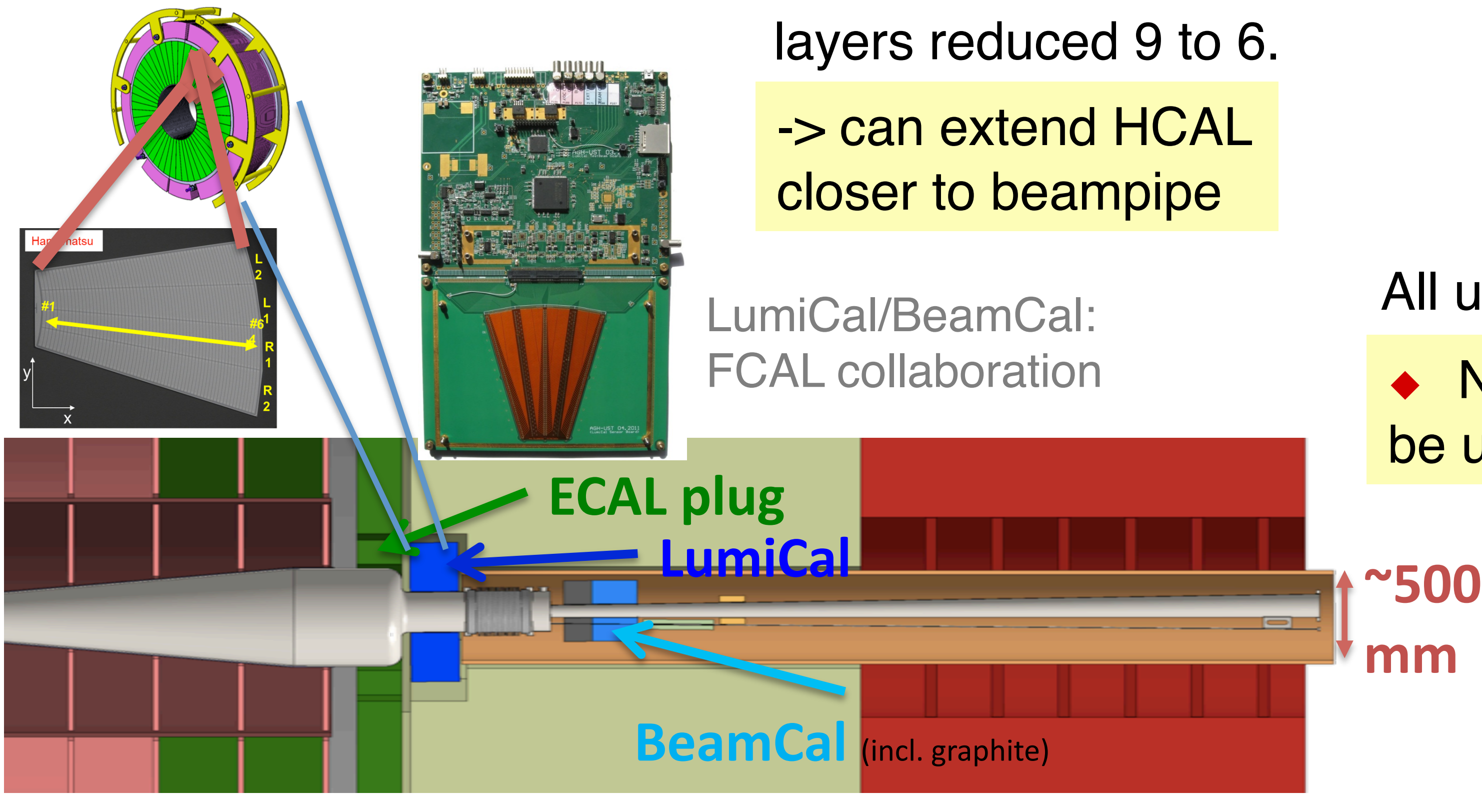
Final quadrupole QD0 was inside detector
-> maximal luminosity but reduced forward coverage.

-> decided to move QD0 to L* = 6m outside detector, by thinning return yoke

-> number of muon layers reduced 9 to 6.

-> can extend HCAL closer to beampipe





LumiCal/BeamCal:
FCAL collaboration

All updates together:

- New detector model to be used for future studies

LCWS15 talk:
CLICdp detector model
Nikiforos Nikiforou

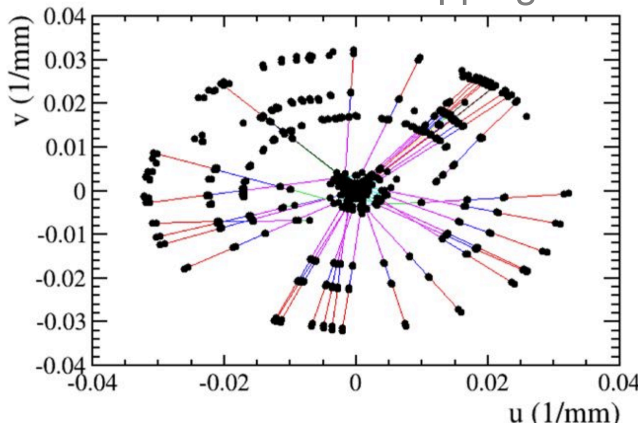
Tracking and software

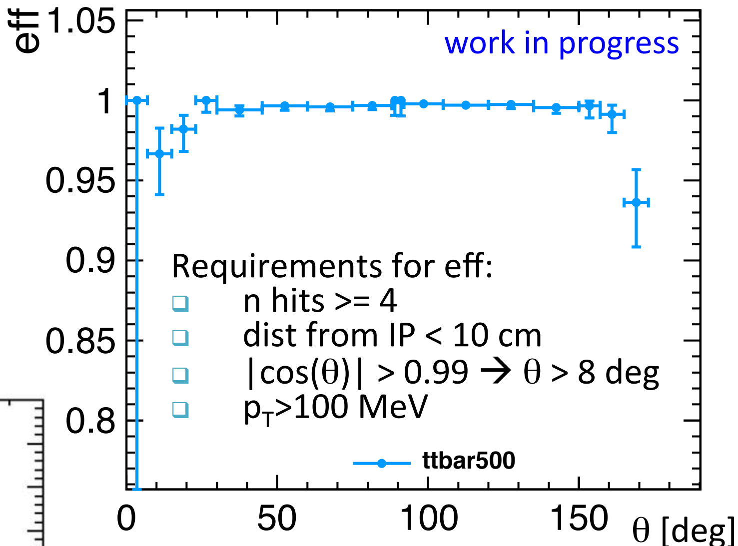
For CDR used SiD tracking, no Kalman filter. -> implement extended ILD vertex tracking software

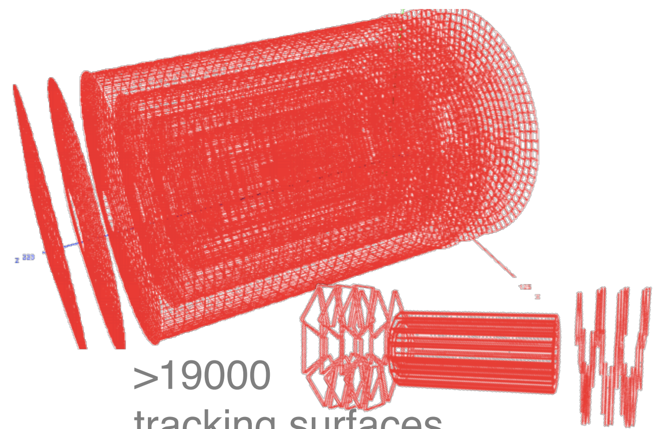
Several cellular automaton pattern-recognition strategies being developed

Validation, improvements ongoing (single muons -> ttbar events)

Conformal mapping







>19000 tracking surfaces

- New detector model being developed entirely in DD4HEP

– common toolkit for detector description for simulation, visualization, reconstruction. Current work is interfacing with established ILCSOFT reconstruction software

- Pandora particle flow algorithm continues to be refined

LCWS15 talks: Track reconstruction for the CLIC full silicon tracker Rosa Simoniello

Track Reconstruction Frank Gaede

DD4HEP-based reconstruction Nikiforos Nikiforou

The CLICdp detector model implementation Marko Petric

ILCDirac: status & plans ; Marko Petric

Status of the Pandora particle flow algorithm John Marshall

Photon reconstruction using Pandora Boruo Xu

CLIC Physics

CLIC foreseen as a staged machine:

Stage 1: precision SM physics

Higgs and top

Energies of subsequent stages motivated by physics

– unique for high-precision

-> considered optimum energy for first stage

HZ production

$\sqrt{s} \sim 250$–450 GeV

Top at threshold

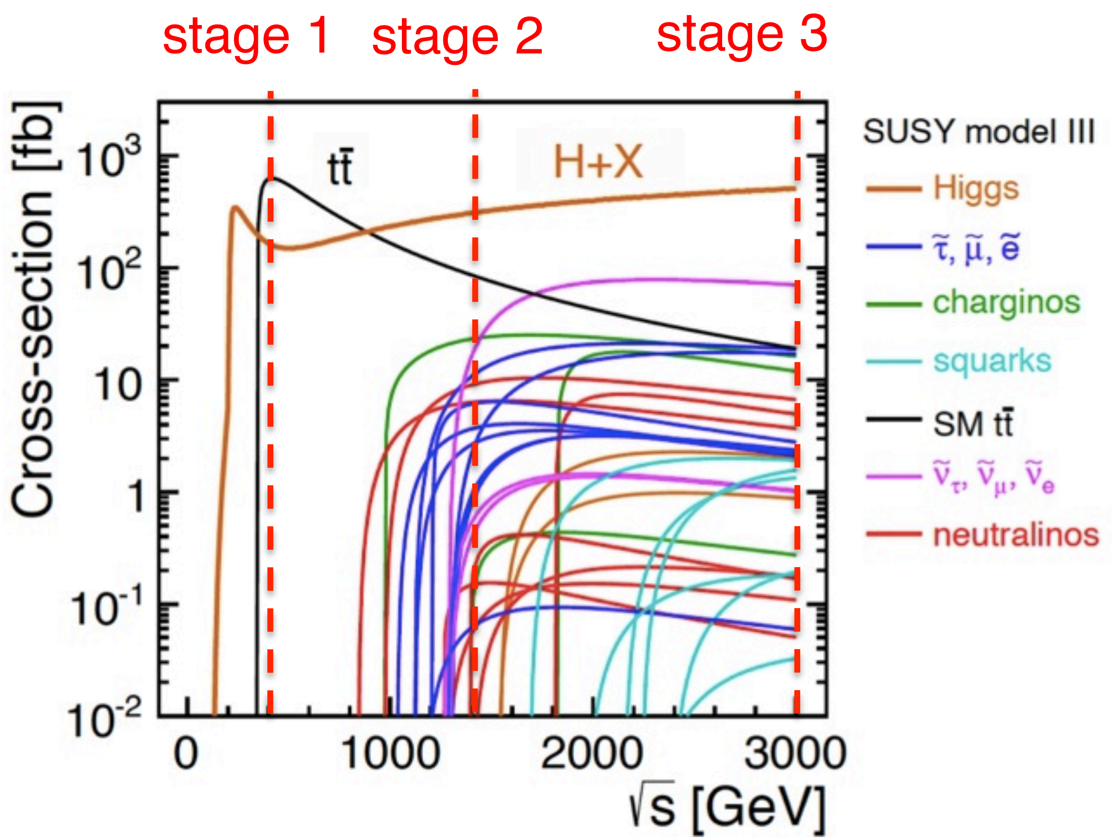
$\sqrt{s} > 350$ GeV

Top pair production

$\sqrt{s} > 360$ GeV

Recoil mass (HZ, Z->qq)

$\sqrt{s} < 400$ GeV



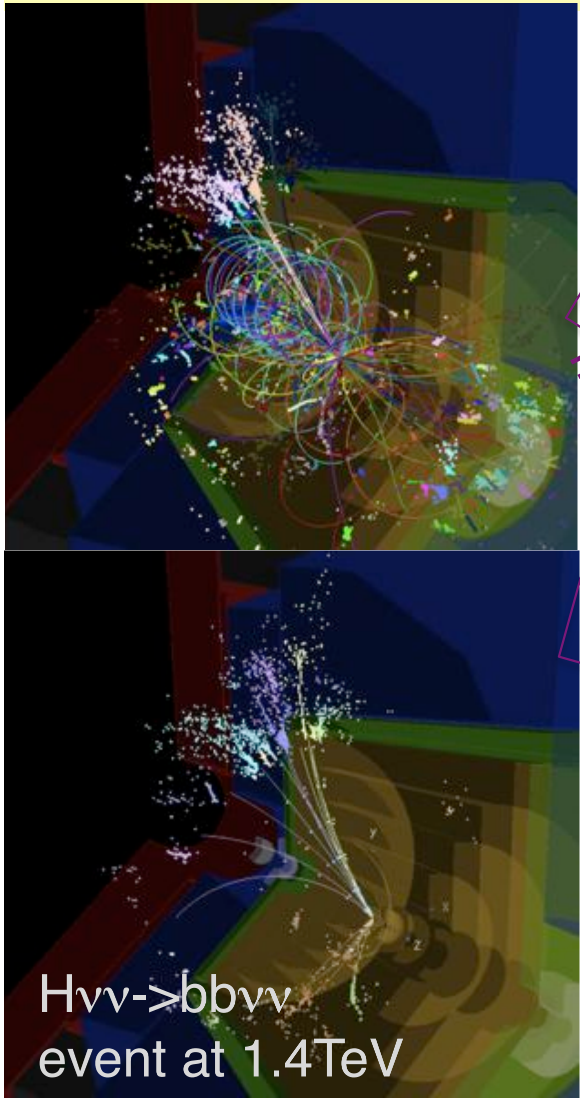
- $\sqrt{s} \sim 380$ GeV

for first stage is good for both HZ and top physics programme

– chosen as new baseline

Higgs -> bb/cc/gg

Separation of bb/cc/gg possible in e+e– final state using excellent detector

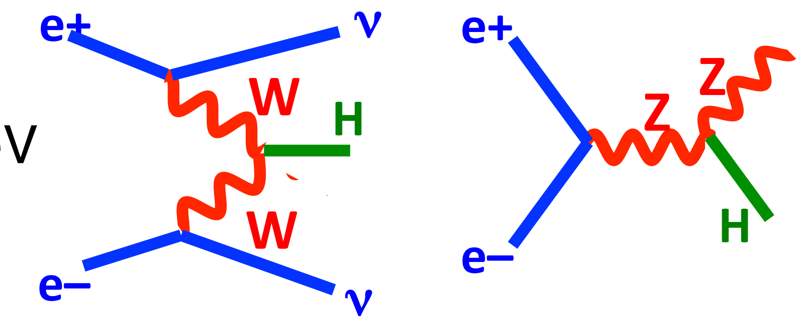


timing/momentum cuts

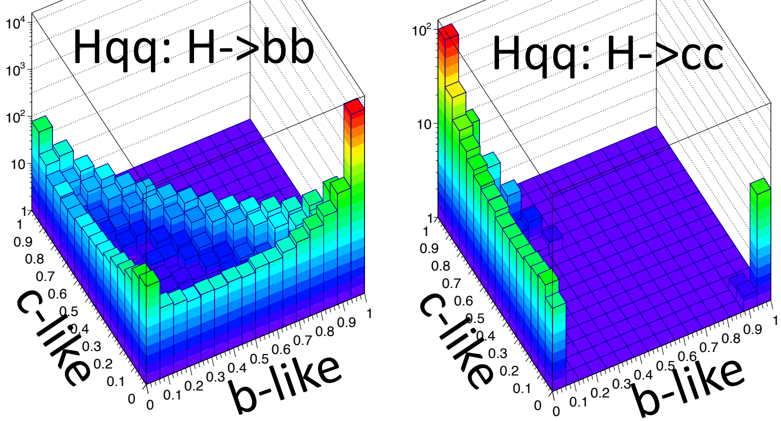
New analyses at 3TeV, 1.4TeV, 350GeV

2jets+missing energy

also 2 jets + 2 leptons, and 4 jets



Train BDTs to classify events then fit templates



LCWS15 talk:
Physics potential for the measurement of hadronic Higgs decays and the Higgs mass at high-energy CLIC
Philipp Roloff

LCWS15 talk:
H->bb/cc/gg at 350GeV at CLIC, Marco Szalay

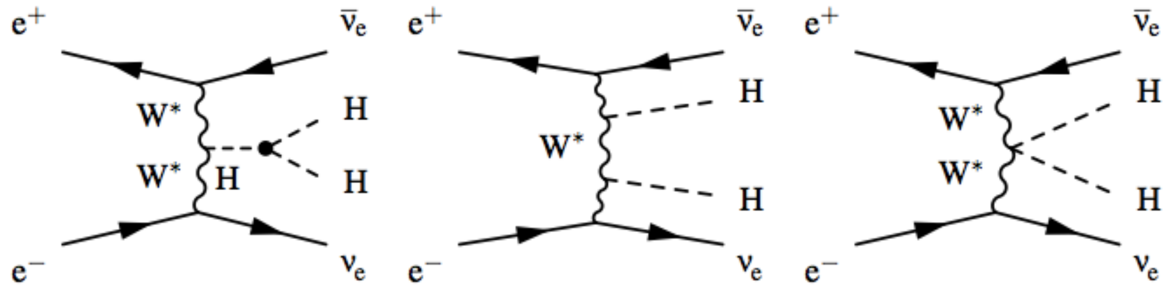
Analyses replace earlier versions that had missing eγ->X , γγ->X backgrounds

work in progress

indicative

Δ(σxBr(H->bb))	<1%
Δ(σxBr(H->cc))	6–10%
Δ(σxBr(H->gg))	4–5%

Higgs self-coupling



Measure Higgs self-coupling g_{HHH} at 3 TeV; simultaneous extraction with g_{HHWW}

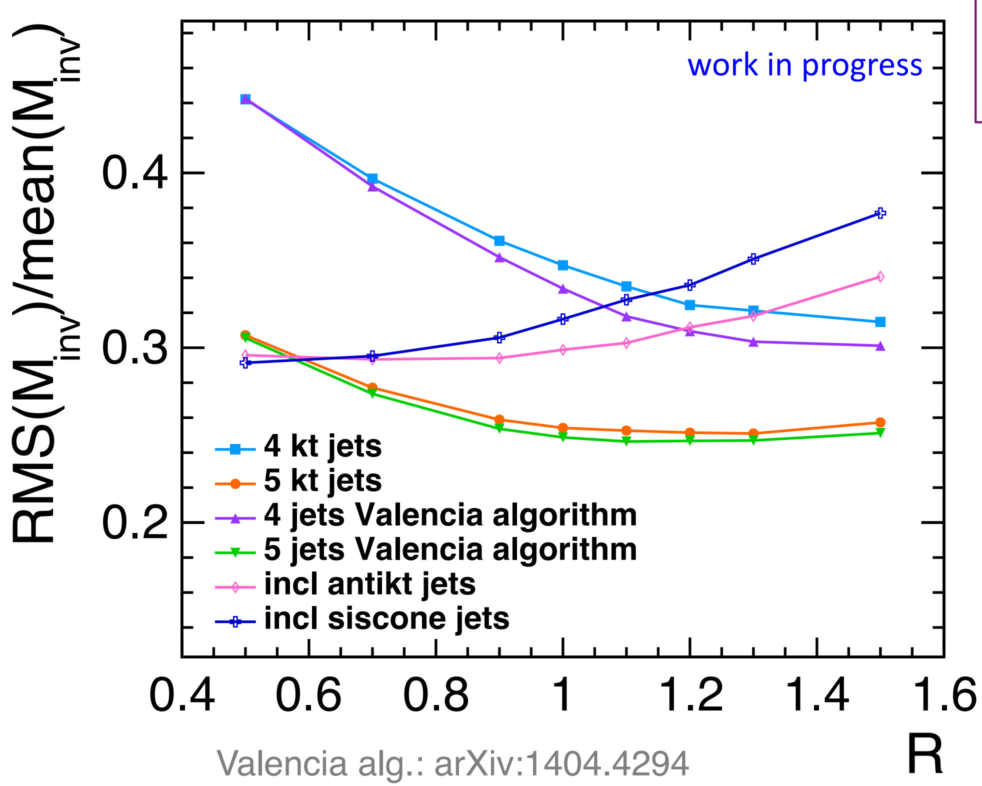
Looking at HHνν -> bbbbνν
4-jet final state,
require 4 b-tag jets

-> systematic studies of clustering and jet algorithm to optimize for energy flow

optimize reconstructed m(bb)

-> use 5-jet reconstruction with k_T or Valencia algorithm, R=1.1

MVA trained on event variables



Valencia alg.: arXiv:1404.4294

indicative
Δ(σ(HH)) ~10–20% (2ab^{-1})

LCWS15 talk:
Measurement of double Higgs production at CLIC
Rosa Simoniello

LCWS15 talk:
Measurement of the Higgs to EW boson decays at CLIC
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Comprehensive Higgs studies

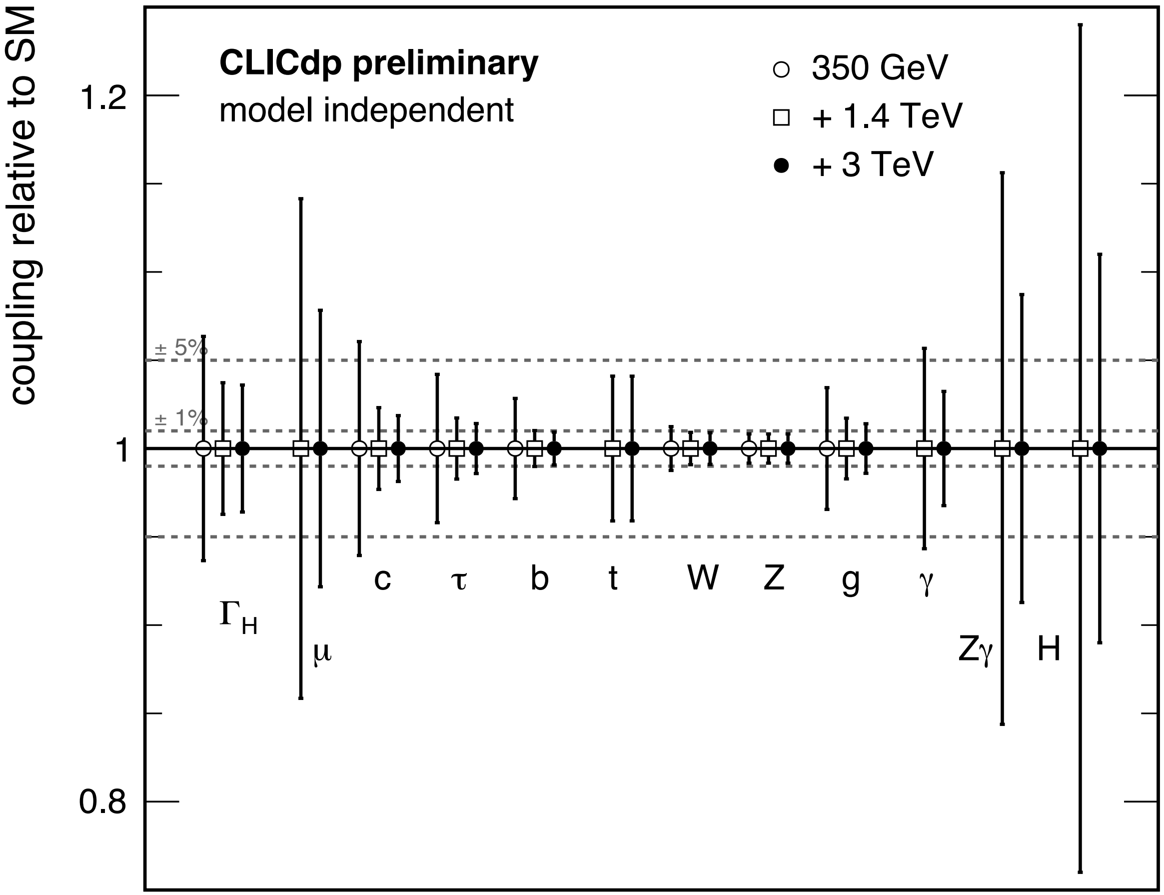
Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}	1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.85%*	–	–
ZH	$\sigma(H+X) \times BR(H \to c\bar{c})$		10.7%*	–	–
ZH	$\sigma(H+X) \times BR(H \to gg)$		4.1%*	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	5.1%*	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.8%*	0.4%*	0.3%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	6.1%*	6.9%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	5.0%*	4.3%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	4.2%	4.4%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	25%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%	10%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	42%	28%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	5.6%	3.7%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1.8%	1.8%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	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	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarization	λ	–	24%	12%

-> measure many processes at all energy stages

- Combined fit of all the measurements -> extract fundamental parameters

analyses all complete for this workshop

Comprehensive Higgs studies



Each stage contributes significantly: first stage provides crucial model-independent Z coupling measurement, and couplings to most fermions and bosons; higher stages improve them, and add t, μ, γ couplings

- Large statistics at high energies allow unique measurements and high precision!

- Comprehensive 'Higgs Physics at CLIC' paper has been in preparation for a while, and final analyses completed for this workshop -> expect to see it imminently!

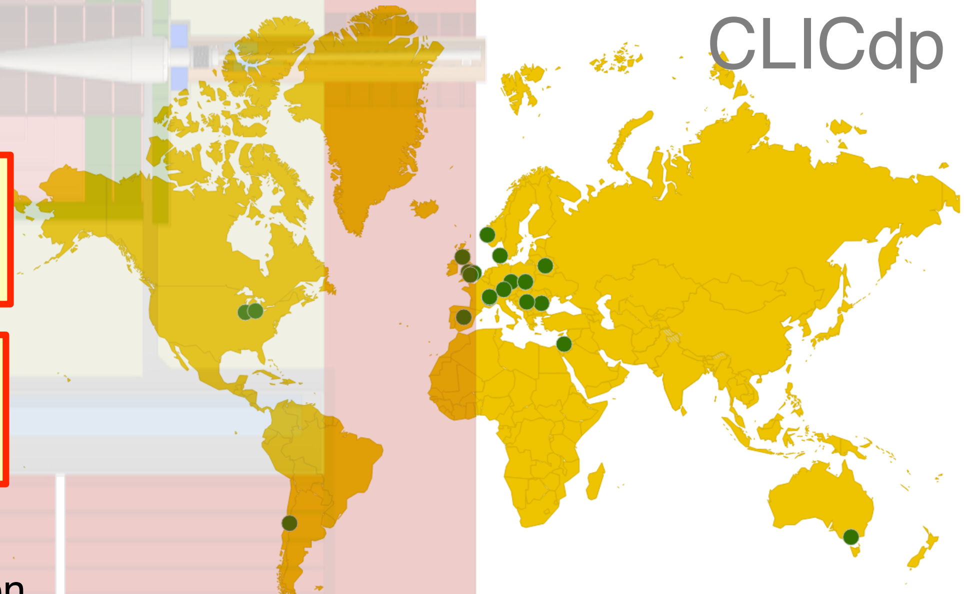
- Planning to focus on BSM and top physics in the next period

Summary

- Many optimization studies -> converging on a new detector concept
- Many advances in detector R&D towards demonstrators for main technical challenges
- Common software tools being developed
- Physics studies ongoing
- New collaborators welcome!

LCWS CLICdp session: Thursday 8.30am – Vertex and tracker design optimization

CLIC workshop: 18–22 Jan 2016 @CERN
https://indico.cern.ch/event/449801/



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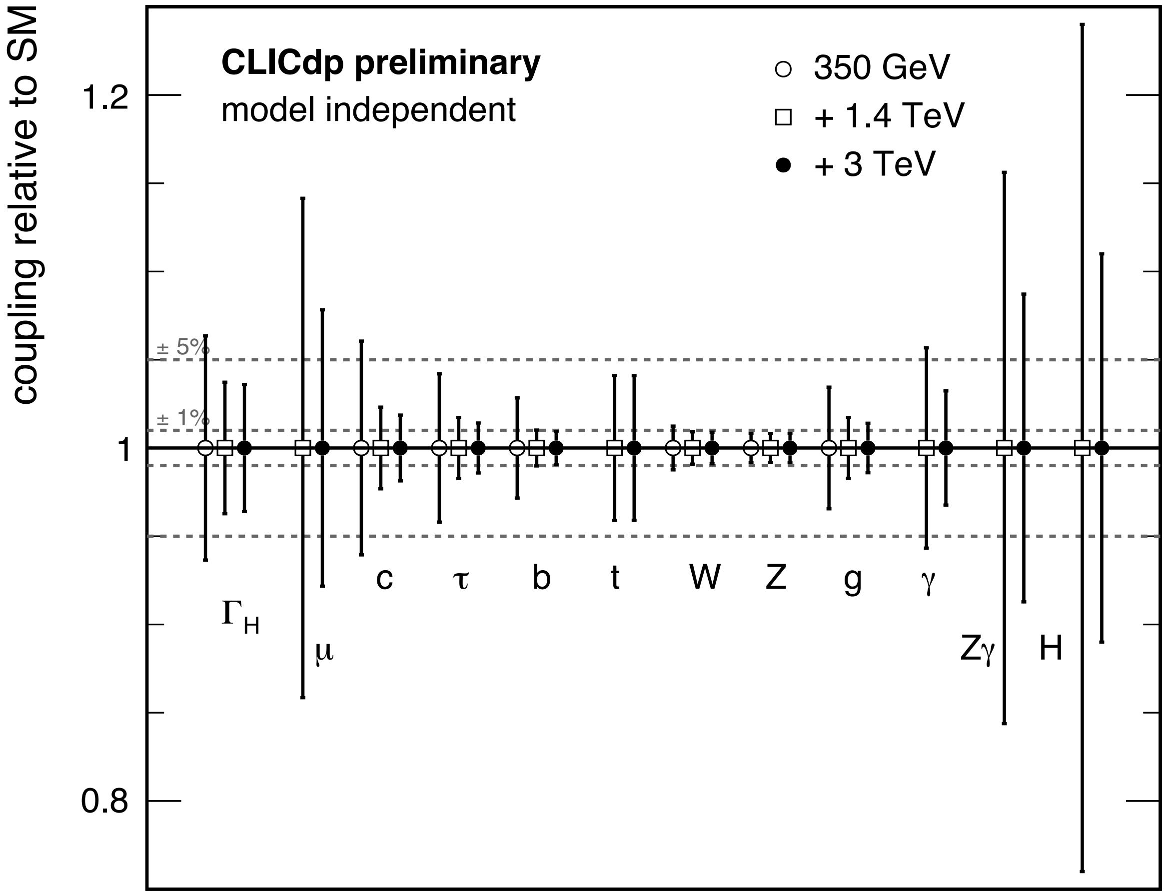
Dominik Dannheim, Daniel Hynds, Aharon Levy, Lucie Linssen, John Marshall, Nikiforos Nikiforou, Andreas Nurnberg, Sophie Redford, Philipp Roloff, Rosa Simoniello, Frank Simon, and others

Backup

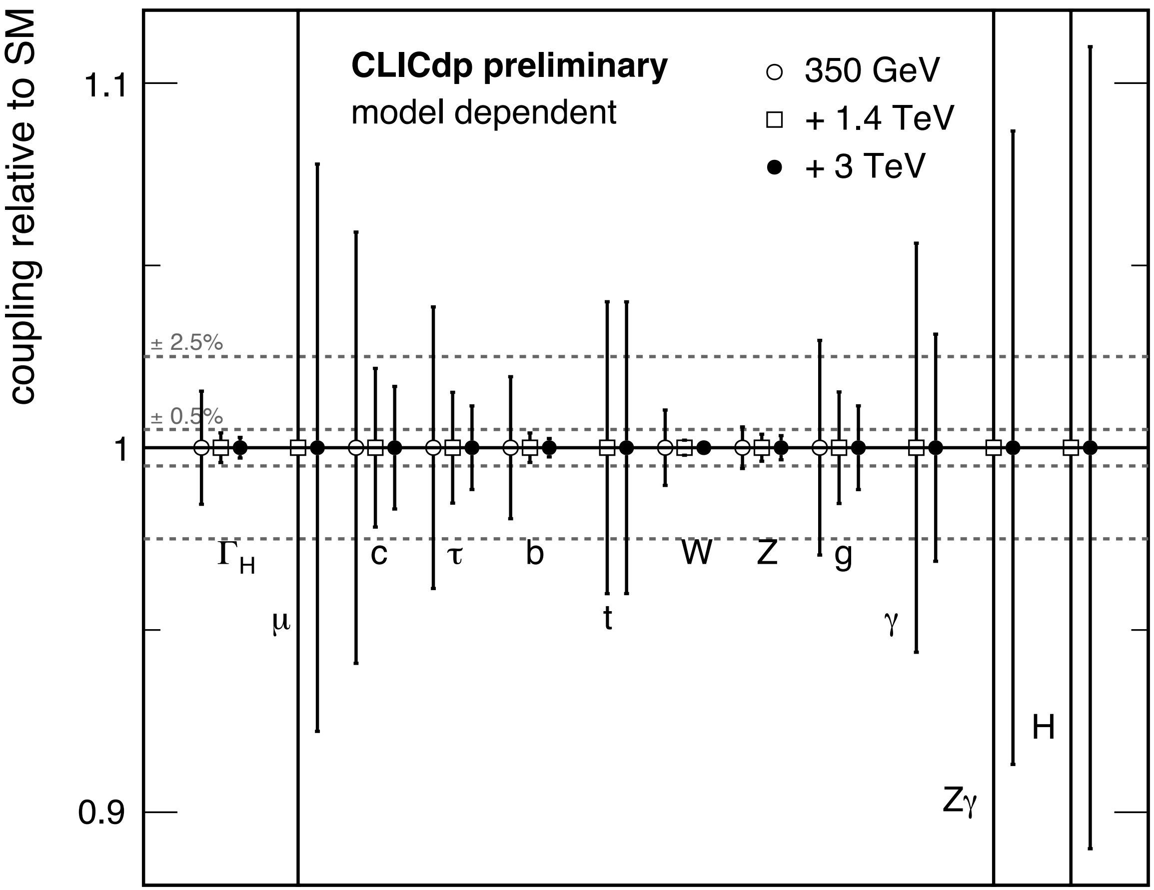
Comprehensive Higgs studies



Preliminary

Parameter	Relative precision		
	$500fb^{-1}$ 350GeV	$+1.5ab^{-1}$ +1.4TeV	$+2ab^{-1}$ +3TeV
g_{HZZ}	0.8%	0.8%	0.8%
g_{HWW}	1.2%	0.9%	0.9%
g_{Hbb}	2.8%	1.0%	0.9%
g_{Hcc}	6.1%	2.3%	1.9%
$g_{H\tau\tau}$	4.2%	1.7%	1.4%
$g_{H\mu\mu}$	–	14.1%	7.8%
g_{Htt}	–	4.1%	<4.1%
g_{Hgg}	3.4%	1.7%	1.4%
$g_{H\gamma\gamma}$	–	5.7%	3.2%
Γ_H	6.3%	3.7%	3.6%

Comprehensive Higgs studies



Preliminary

Parameter	Relative precision		
	500fb^{-1} 350GeV	+1.5ab^{-1} +1.4TeV	+2ab^{-1} +3TeV
κ_{HZZ}	0.6%	0.4%	0.3%
κ_{HWW}	1.0%	0.2%	0.1%
κ_{Hbb}	1.9%	0.4%	0.3%
κ_{Hcc}	5.9%	2.2%	1.7%
$\kappa_{H\tau\tau}$	3.9%	1.5%	1.1%
$\kappa_{H\mu\mu}$	–	14.1%	7.8%
κ_{Htt}	–	4.0%	<4.1%
κ_{Hgg}	2.9%	1.5%	1.1%
$\kappa_{H\gamma\gamma}$	–	5.6%	3.1%
$\Gamma_{H\text{md.derived}}$	1.6%	0.4%	0.3%