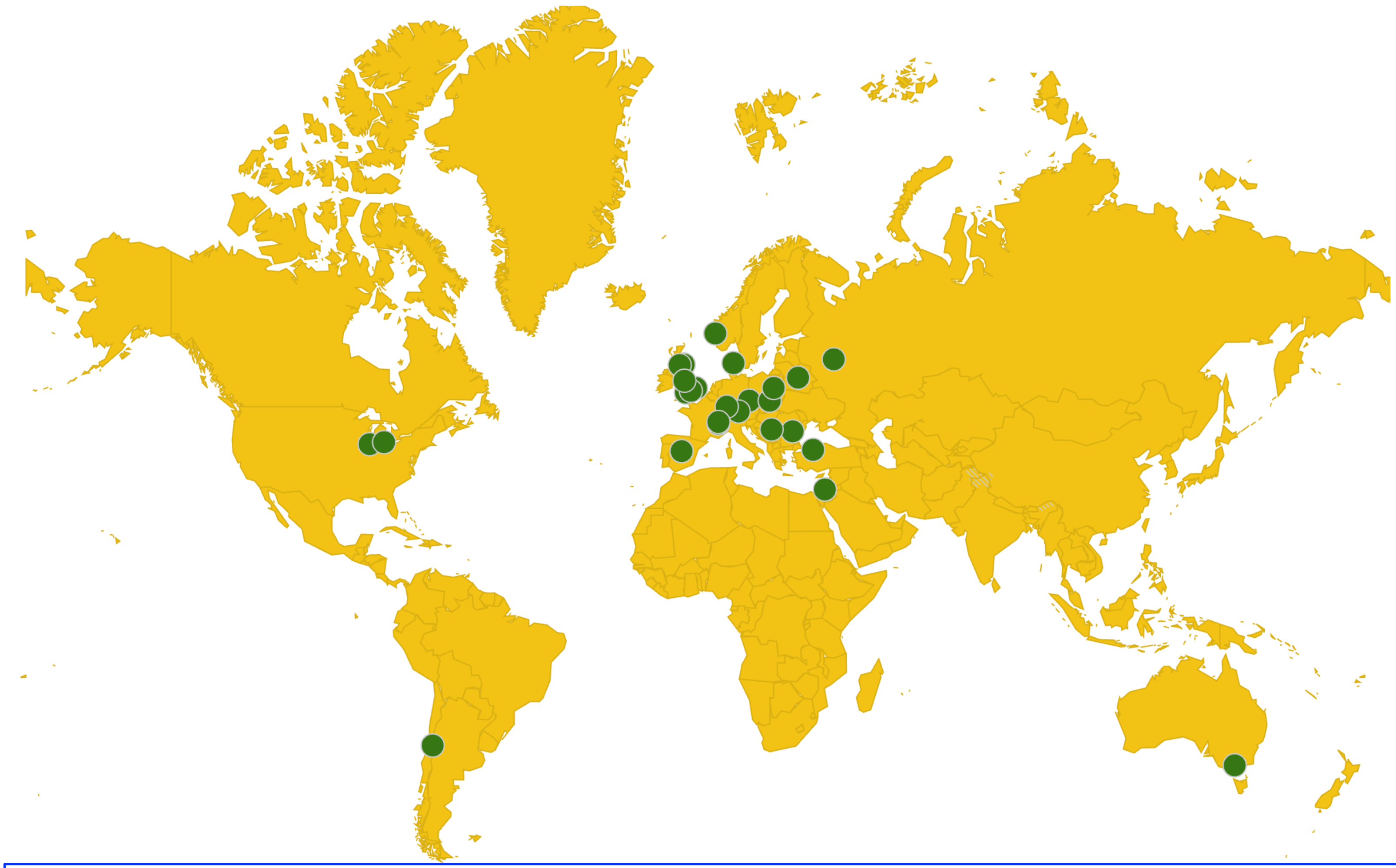
Status and plans of the CLIC detector and physics study

CLIC collaboration meeting
March 8th, 2017

Dominik Dannheim (CERN)
on behalf of the
CLIC detector and physics (CLICdp) collaboration

CLIC detector & physics collaboration



- CLICdp collaboration addresses detector and physics issues for CLIC
- CERN acts as host laboratory
- Currently 29 institutes from 18 countries, ~180 members http://clicdp.web.cern.ch/
- Close connection to ILC detector concepts, CALICE, FCAL, AIDA-2020

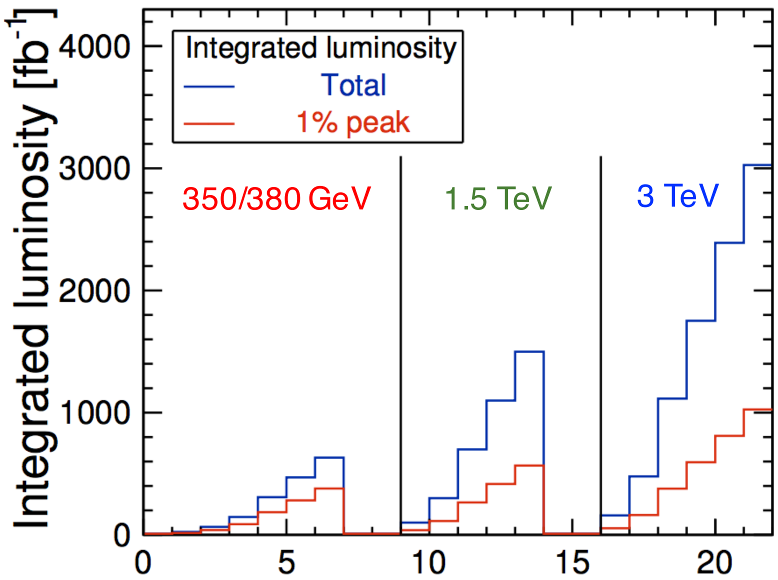
CLIC physics program

- **CLIC staging baseline:**
  - Stage 1: 500 fb^{-1} @ 380 GeV
    + 100 fb^{-1} @ ~350 GeV (top threshold scan)
    Precision SM Higgs and top physics
  - Stage 2: 1.5 ab^{-1} @1.5 TeV
    BSM physics, rare Higgs processes
  - Stage 3: 3 ab^{-1} @ 3 TeV
    BSM physics, rare Higgs processes

Staging baseline document
CERN-2016-004

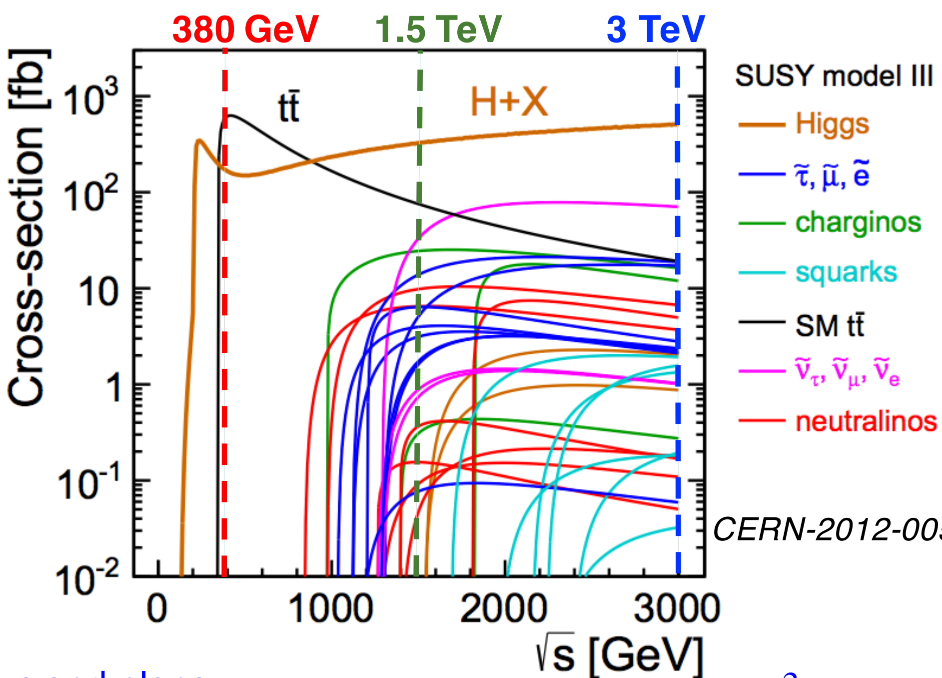
- Physics case for 350/380 GeV
- Optimization of energy stages and running scenario for 22 years of operation

CLIC staging scenario



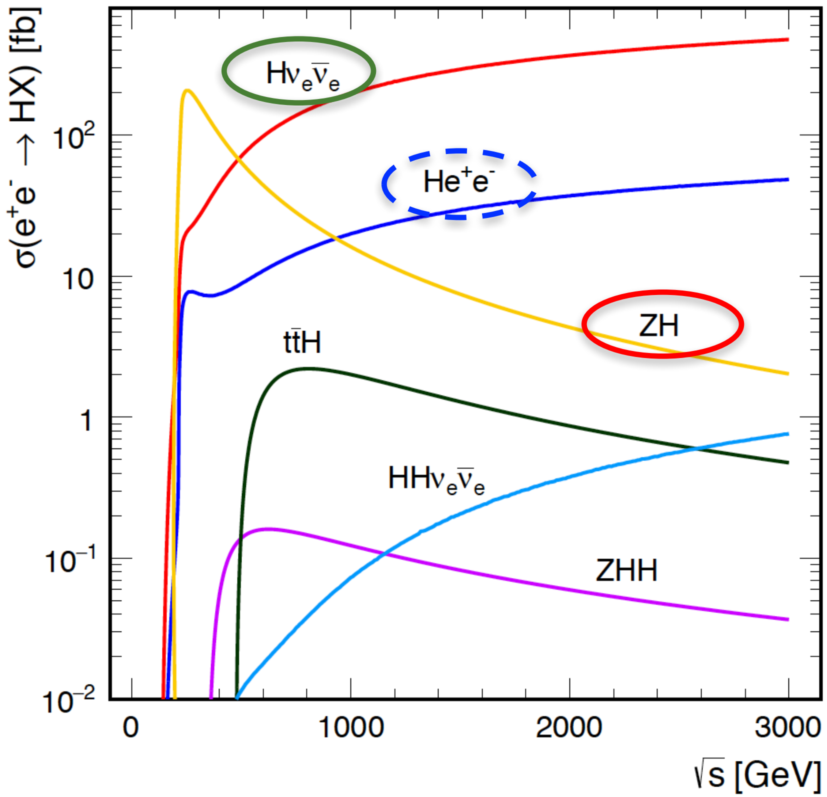
CERN-2016-004

CLIC physics reach: SM + SUSY example

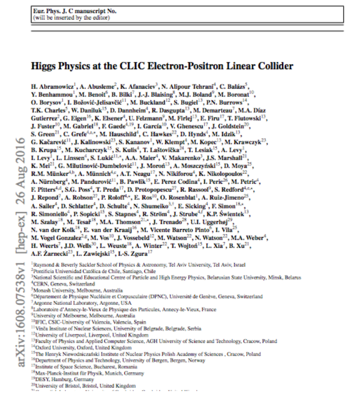


CERN-2012-005

Higgs measurements



- Comprehensive paper on Higgs physics at CLIC: *arXiv:1608.07538*, submitted to EPJC


Eur. Phys. J. C manuscript No.
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Higgs Physics at the CLIC Electron-Positron Linear Collider

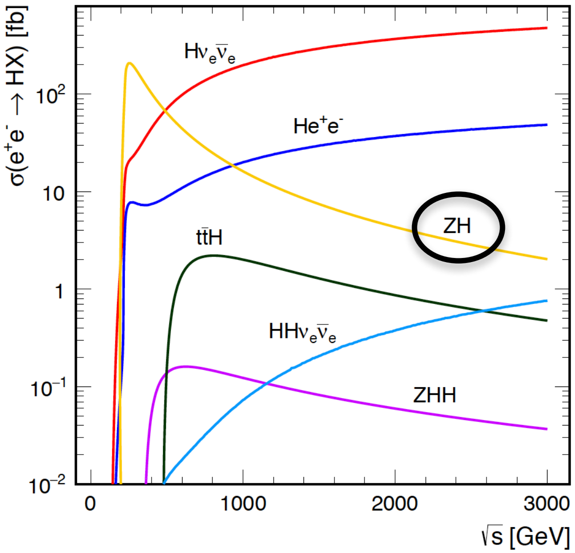
arXiv:1608.07538v1 [hep-ex] 26 Aug 2016

- Production cross sections for different processes cover wide energy range
  → Higgs measurements profit from all stages
- Large event samples for main production mechanisms expected
- Geant4-based full detector simulation studies with background and pile-up overlay for 350 GeV, 1.4 TeV and 3 TeV
- High selection efficiencies in most cases

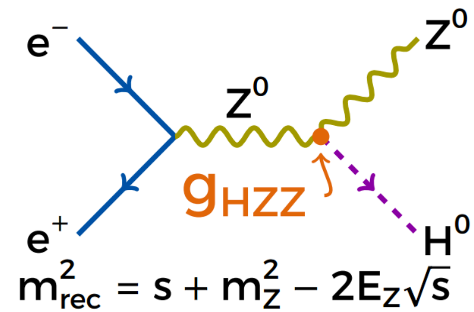
	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# *ZH* events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

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

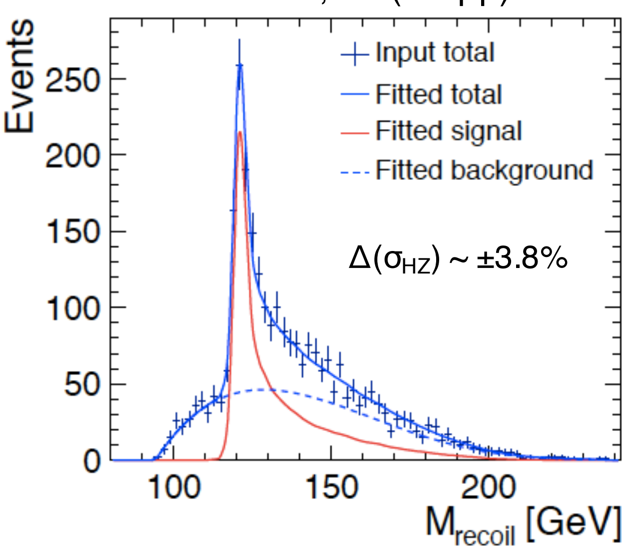
Higgsstrahlung $e^+e^- \to ZH$ @ ~350 GeV



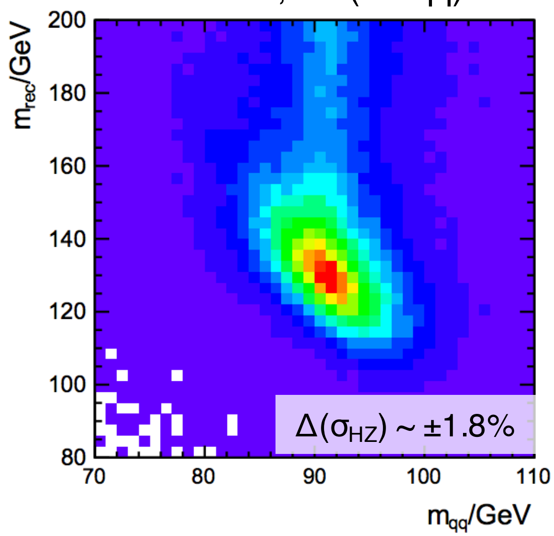
- Benchmark studies for $e^+e^- \to ZH$ @ 350 GeV, 500 fb^{-1}
- Select ZH through recoil mass against Z
  → model-independent measurement: $\Delta\sigma_{HZ} \sim g_{HZZ}^2$
- Combined uncertainty on $\Delta(g_{HZZ}) \sim \pm 0.8\%$
- ZH → Hqq gives access to invisible Higgs decays: BR(H→inv) < 1% @ 90% CL



$\sqrt{s}$=350 GeV; HZ (Z→μμ)

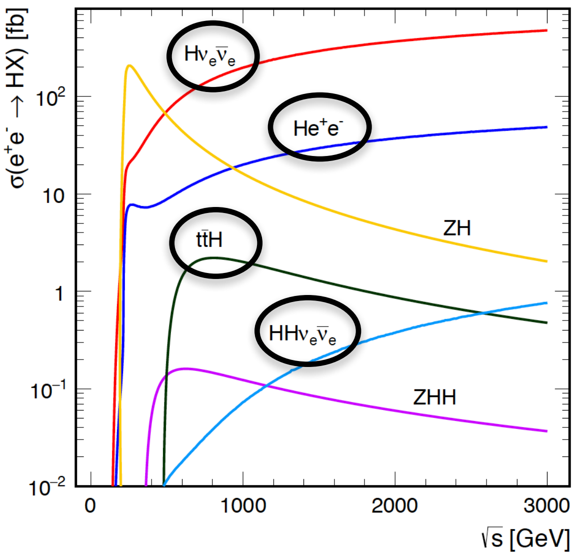


$\sqrt{s}$=350 GeV; HZ (Z→qq)



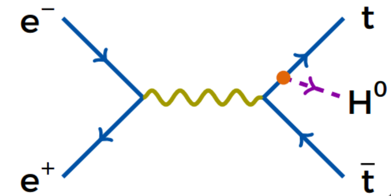
- ZH→Zqq studies for 250, 350, 420 GeV
- Trade-off between jet-energy resolution and signal/background
- Best performance at ~350 GeV
  → drives choice of 380 GeV for first energy stage (together with top physics)

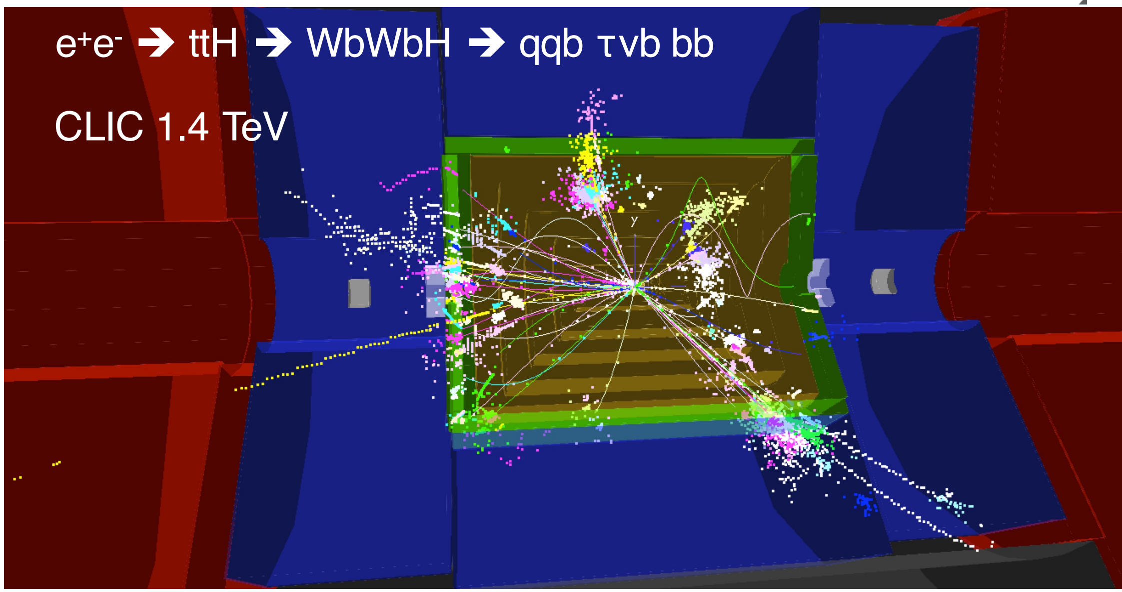
Higgs measurements at higher energies



ttH production: $e^+e^- \to ttH$

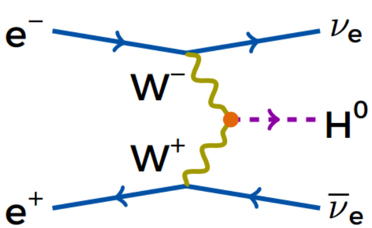
- Sensitive to top-Yukawa coupling
- 2400 events @ 1.4 TeV, 1.5ab^{-1} (1400 @ 3 TeV, 2ab^{-1})





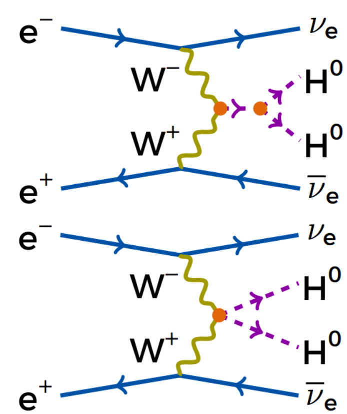
WW fusion: $e^+e^- \to H\nu\nu / He^+e^-$

- σ~log(s), dominant >450 GeV
- Access to H→cc and rare decays like H→μμ

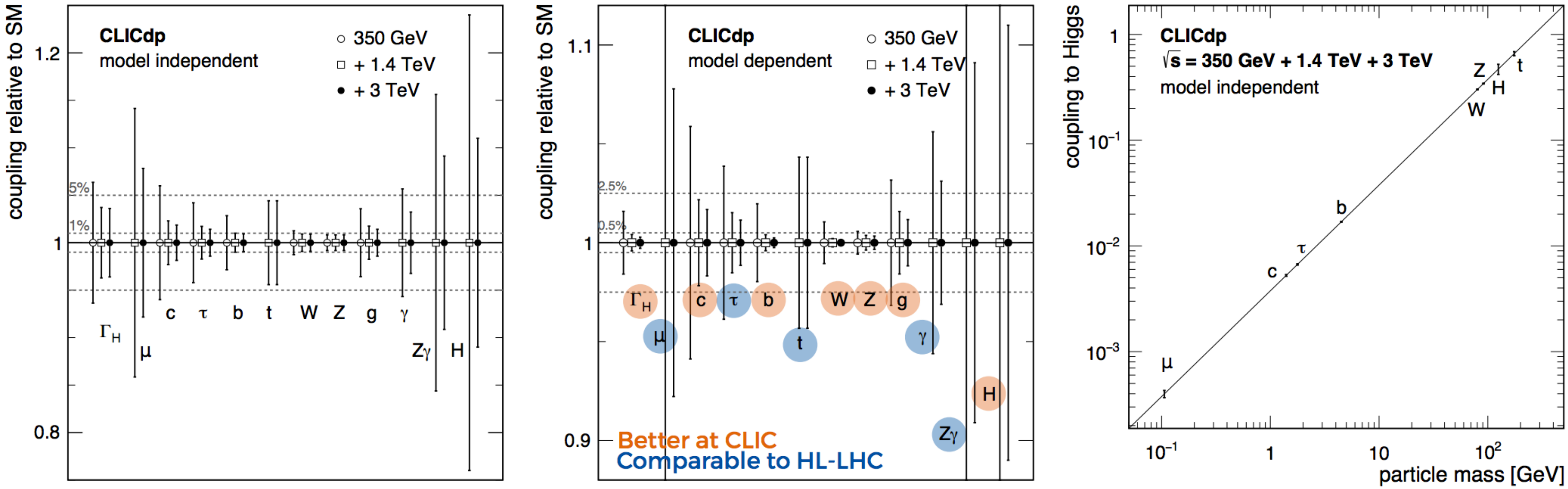


Double-Higgs production: $e^+e^- \to HH\nu\nu$

- Sensitive to trilinear self coupling parameter λ and to quartic coupling g_{HHWW}
- Small cross section: 225 events @ 1.4TeV, 1.5ab-1 (1200 @ 3TeV, 2ab-1) → needs high energy and luminosity

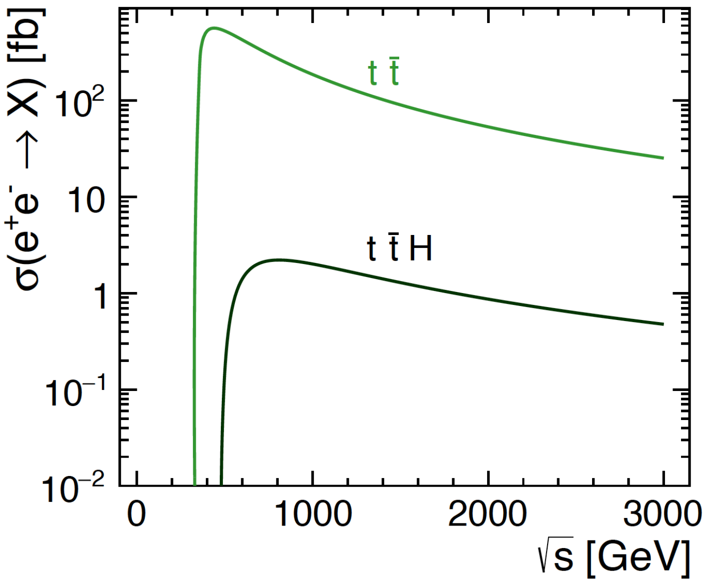


Higgs measurements - summary



- Model independent extraction only at lepton colliders, due to model independent measurement of g_{HZZ}
- Significant improvements from higher energy stages
- Many couplings measured with ~1% precision
- Higgs width extracted with 5-3.5% precision
- Model dependent fits can achieve precision below 1%

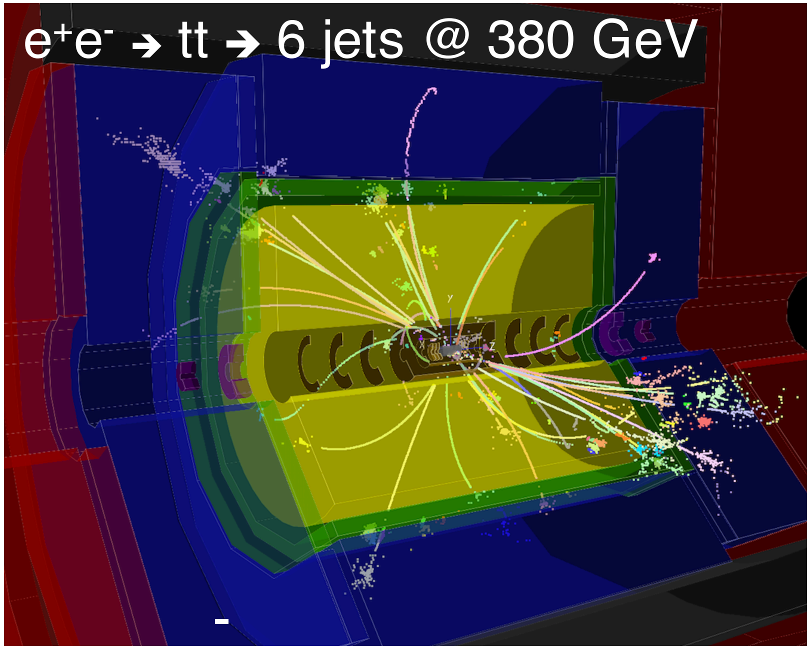
Top quark physics



Motivation:
- Top quark is the heaviest known particle
- Yukawa coupling to Higgs boson y_t~1 → probe of EWSB
- Top quark decays before hadronizing → test of QCD
- Large loop contrib. to many precision measurements
- Sensitive to many BSM scenarios
- So far top quark only measured at hadron colliders

Results from full-simulation studies for CLIC:
- Precision on 1S-mass ~50 MeV (HL-LHC: ~500 MeV)
- ~10x higher precision on most couplings than HL-LHC

Top physics overview paper in preparation:
- mass measurement through tt threshold scan
  → 100 fb^{-1} around $\sqrt{s}$=350 GeV
- mass measurement through reconstruction
- Electroweak couplings @ 380 GeV
- Electroweak couplings above 1 TeV
- Yukawa coupling though ttH production
- Measurement of V_{tb} in single top production
- Rare (CP violating) decays
- ...



BSM

New physics at CLIC:

- Direct searches via pair production up to ~√s/2
- Searches for deviations from SM expectation
- Precision measurements of new particles discovered at HL-LHC

Results from full-simulation studies for CLIC:

- ~1% precision on masses and cross sections
- Measurement of spin and quantum numbers

Ongoing full-simulation BSM studies:

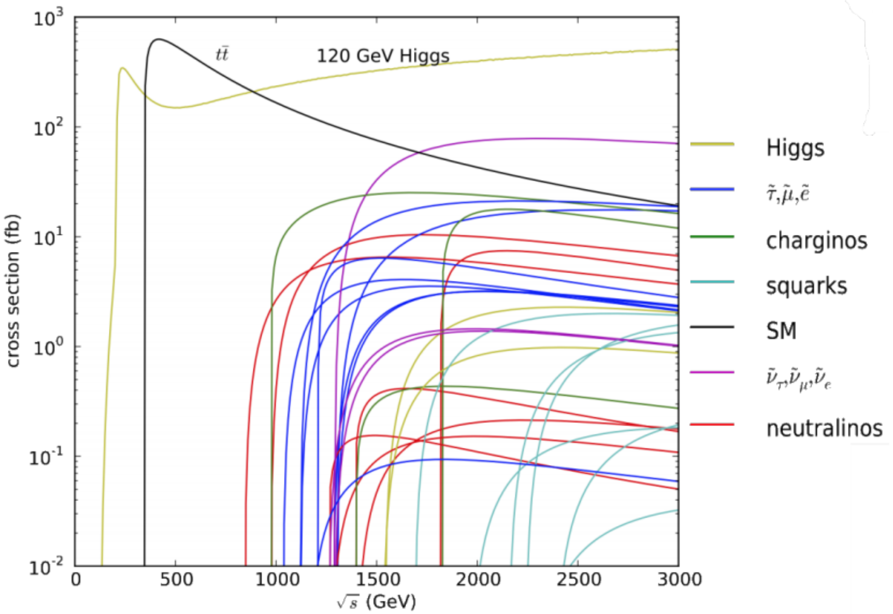
- Anomalous gauge couplings
- Hidden valley search
- FCNC: t→cH, t→cγ
- ...

New phenomenological approaches:

- Effective theories of universal theories
- Clockwork mechanism

More on top and BSM in following talk by P. Roloff and in analysis session contributions

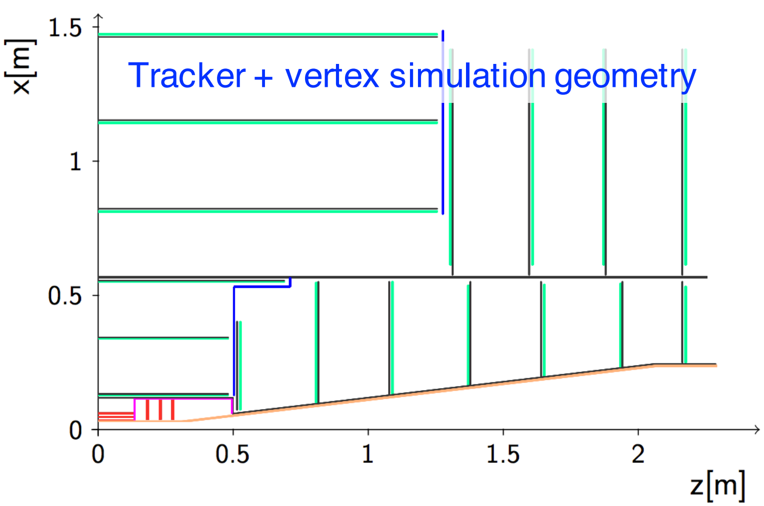
Example SUSY model from CDR for 1.4 TeV

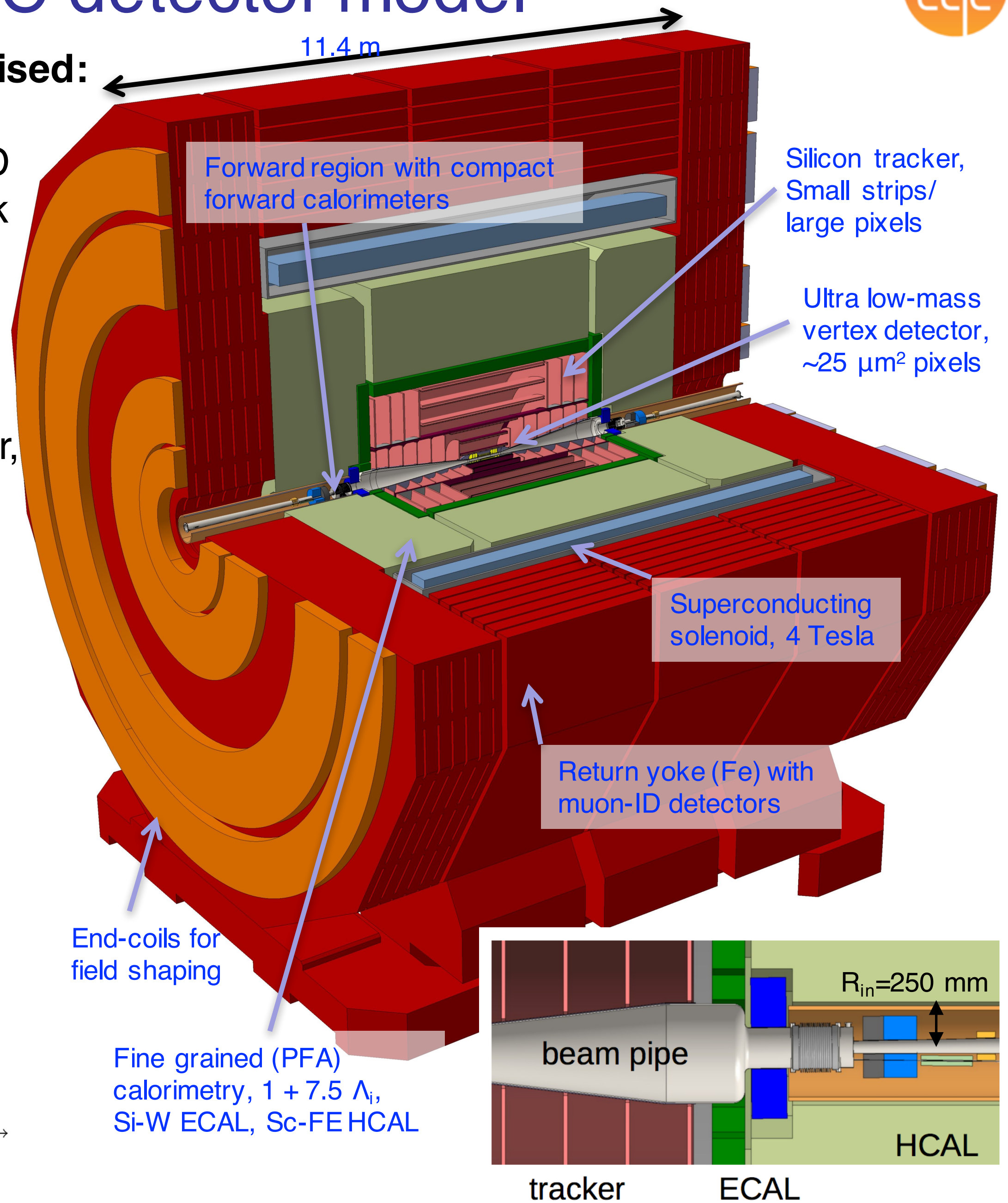


New CLIC detector model

New CLIC detector model CLICdet finalised:
- Optimized layout (simulation studies)
- Incorporates results from hardware R&D
- Implemented in new software framework
- Documented in *CLICdp-Note-2017-001*

Major changes w.r.t. CDR models:
- Only one detector
- Last beam magnet QD0 outside detector, to increase HCAL forward acceptance
  → slight luminosity loss (increased L*)
- Fe absorber for HCAL instead of W
- More layers and more realistic material budget for tracker



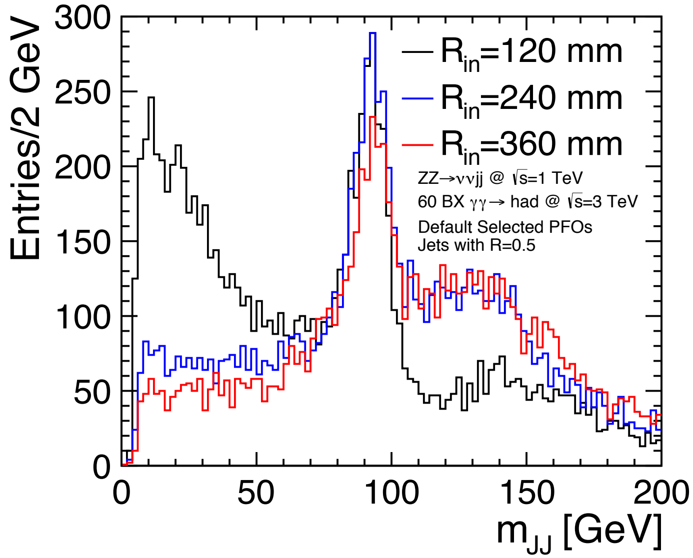


Optimization of CLIC detector model

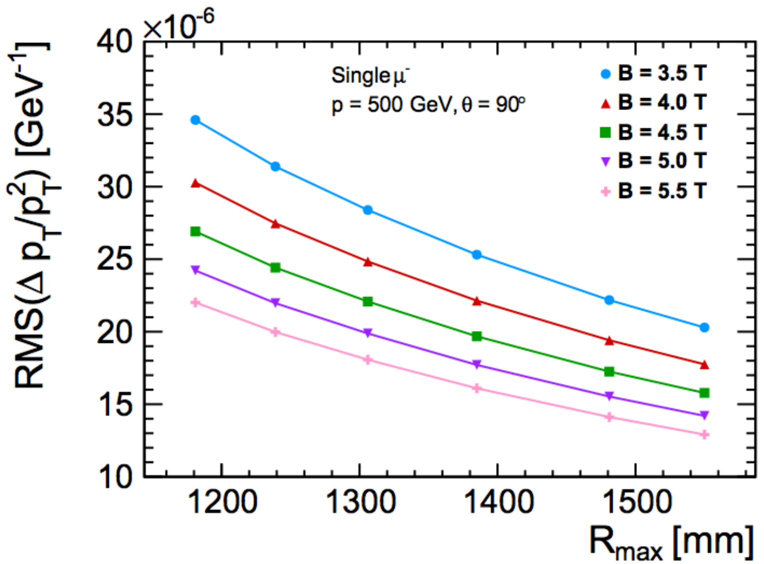
CLICdet design based on optimization studies, e.g.:

- Endcap HCAL inner radius
  - Large impact on jet reconstruction
    → R_{in} reduced from 500 mm to 250 mm,
    implies that QD0 had to move outside detector,
    longer L* of 6 m → reduced luminosity
- ECAL depth and segmentation
  → 40 layers, 22 X_0 needed for good photon resolution
- Tracker radius and B-field
  - Trade-off between achievable coil radius and B-field
    → tracker radius 1.5 m and B=4 T

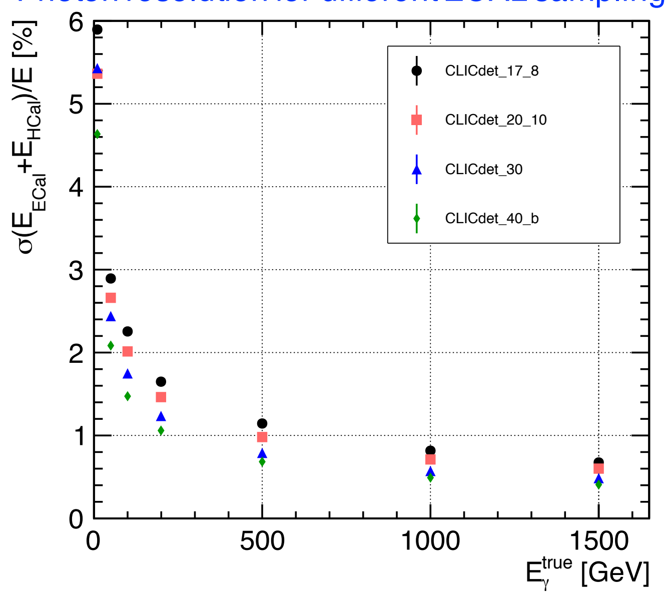
Physics performance for different HCAL EC radii



Tracker performance for different radii and B-fields



Photon resolution for different ECAL samplings



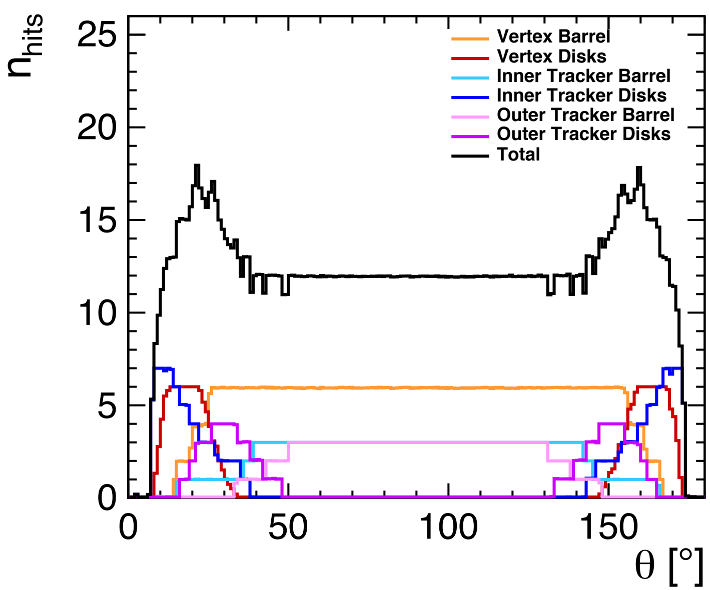
Validation of new CLIC detector model

Ongoing validation studies with CLICdet:
- Implementation of simulation vs. engineering model
- Check background levels
- Validate new reconstruction software
- Ensure that performance meets expectations
  → comparison with CDR performance

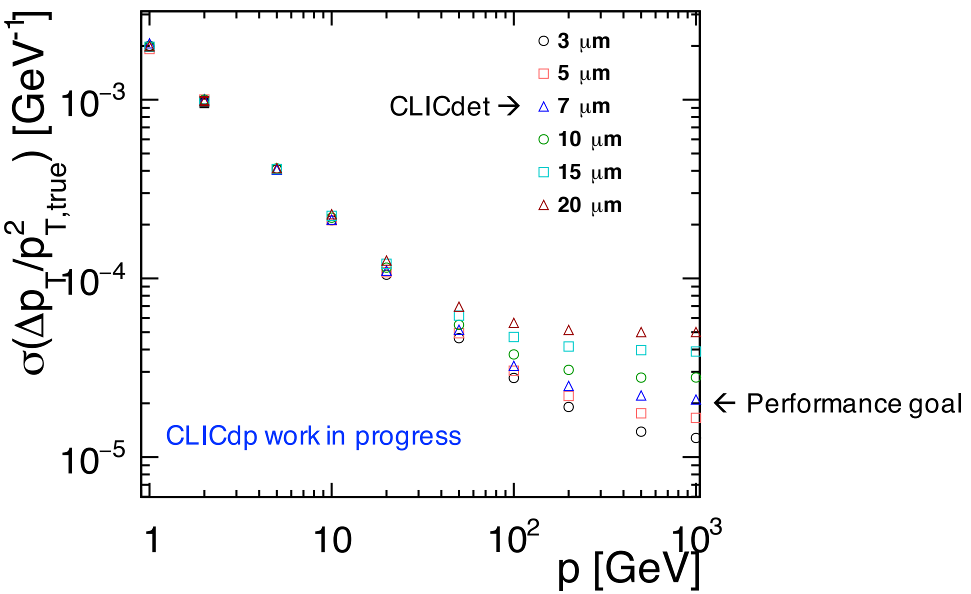
Planned future performance studies:
- Flavour tagging as function of vertex-detector parameters
- Pattern recognition in presence of backgrounds
- …

Take advantage of new flexible software chain → parametric studies

Tracker coverage in CLICdet



p_T resolution for different tracker plane resolutions

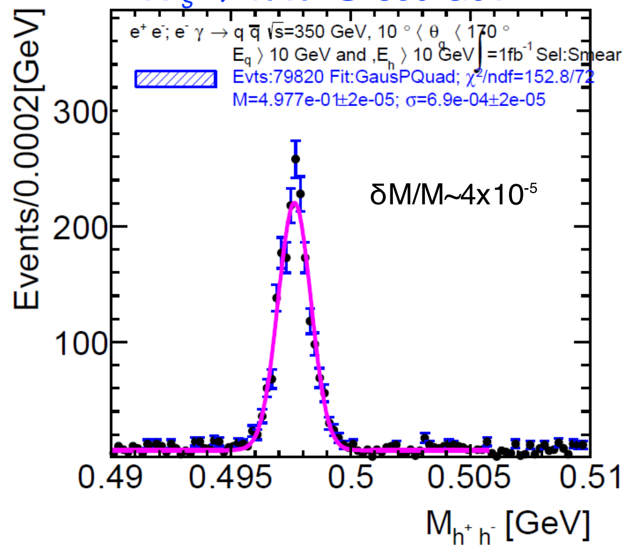


Detector alignment and calibration

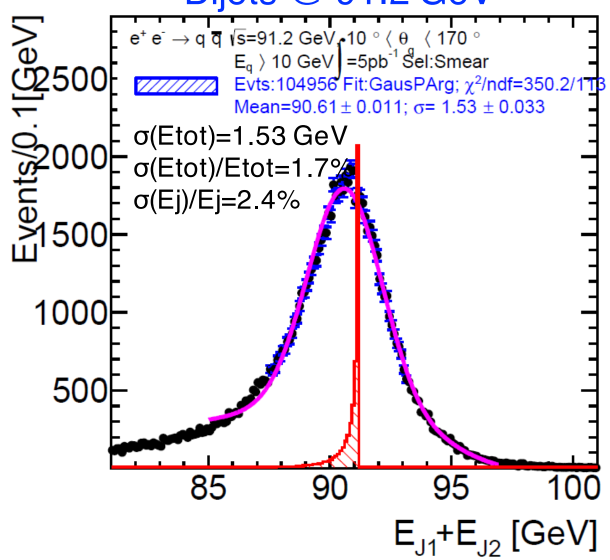
- Detector alignment and calibration are essential to reach good physics performance at each energy stage
- Fast-simulation study performed:
  - Detector alignment using e^+e^-, $e^-\gamma$ and $\gamma\gamma$ interactions with μ final states at $\sqrt{s} = 350$ GeV in 1st year → ~800k useable μ's for 1 fb^{-1}
  - momentum resolution and scale using $Z \rightarrow \mu+\mu-$ and $K^0_s \rightarrow \pi^+\pi^-$ at 350 GeV
  - Flavour-tagging efficiency with $e^+e^- \rightarrow ZZ \rightarrow llqq$ need 2 years @ 350 GeV
  - Di-jet energy resolution and jet-energy scale not precise enough @ 350 GeV (W/Z confusion)
  - Additional few days (~5 pb^{-1}) at $\sqrt{s}$**=91.2 GeV** after 1st year:
    - Accurate momentum resolution and scale for 45.6 GeV with $Z \rightarrow \mu+\mu$
    - Direct measurement of di-jet energy resolution and scale and flavour-tagging efficiency with Z→qq

More in alignment/calibration session tomorrow morning

$K^0_s \rightarrow \pi^+\pi^-$ @ 350 GeV

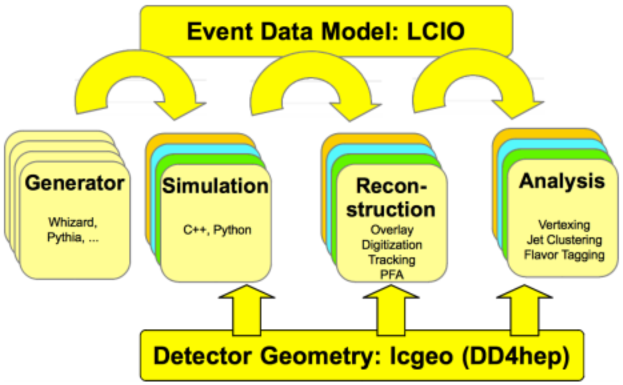


Dijets @ 91.2 GeV

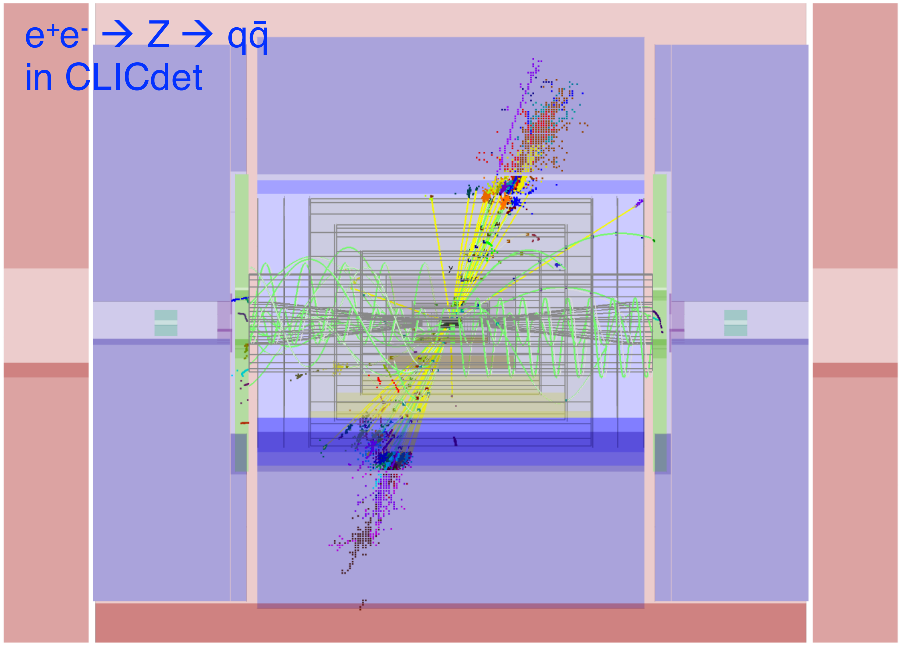


Simulation and reconstruction software

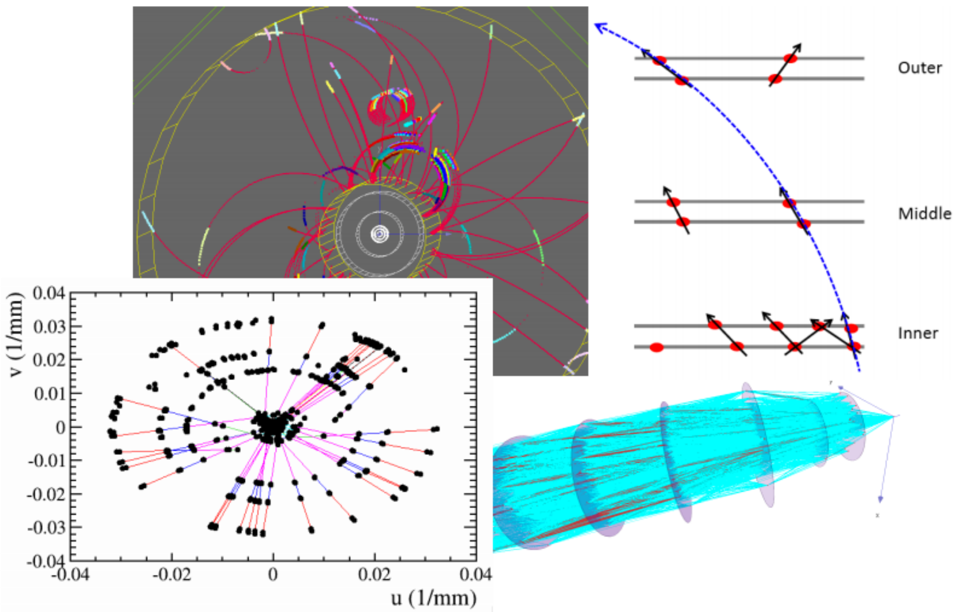
- LC community moved to common iLCsoft tools and new simulation+reconstruction chain:
  - DD4hep unified geometry description for sim.+rec.
    - DDG4/ddsim simulation
    - New reconstruction using DDRec interface
- Strong contributions from CLICdp, in particular for DD4hep, Si tracking, DDMarlinPandora PFlow



- Validation of new software ongoing, large-scale physics productions afterwards
- DD4hep also adopted by FCC, under investigation by LHCb

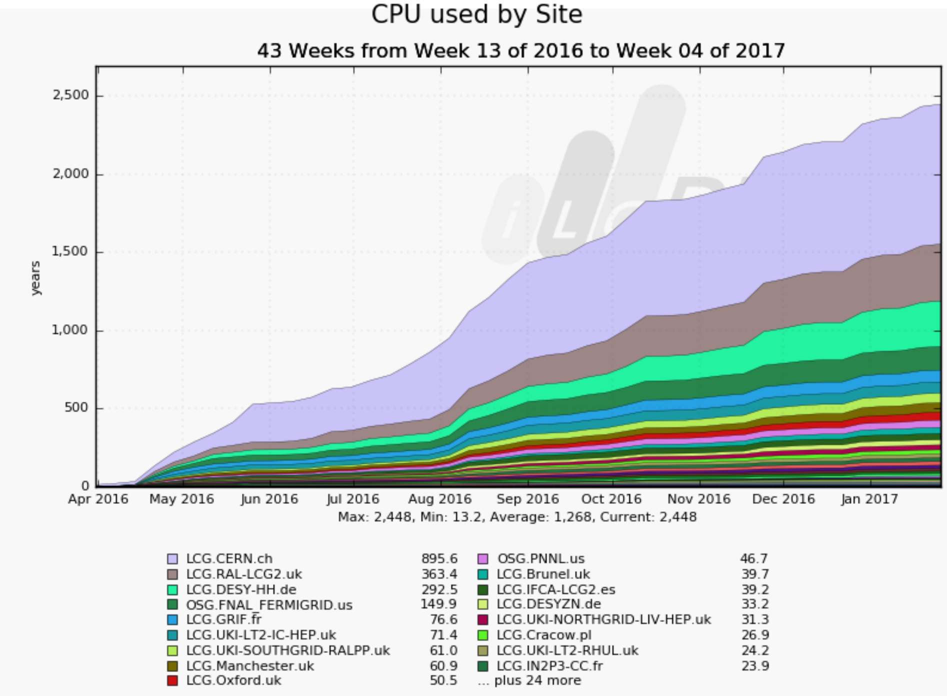


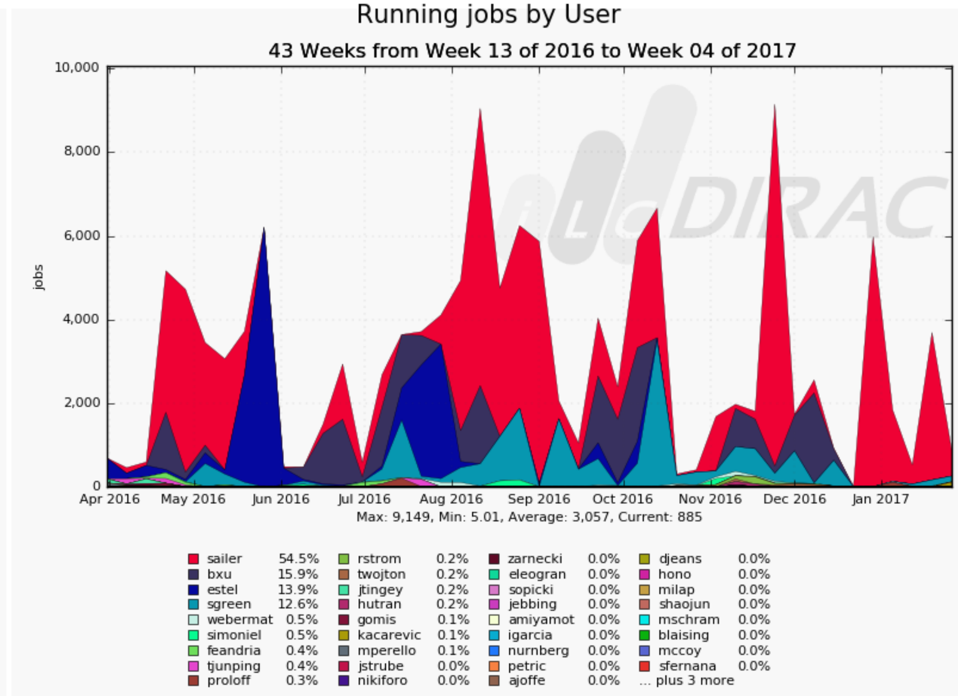
Pattern recognition + track reconstruction



Distributed computing

- Physics simulation and reconstruction for CLICdp performed on the grid
- iLCDirac for managing submissions (both for central productions and end-users)
- OSG Computing Elements (HTCondor-CE, Globus) now fully integrated in Dirac
  → more sites available
- Improvements of maintenance:
  - More (Unit) Tests for Continuous Integration (CI)
  - First Centos 7 site included (Edinburgh) → allows testing of future OS
- New hardware resources: Deep Learning System based on GPUs

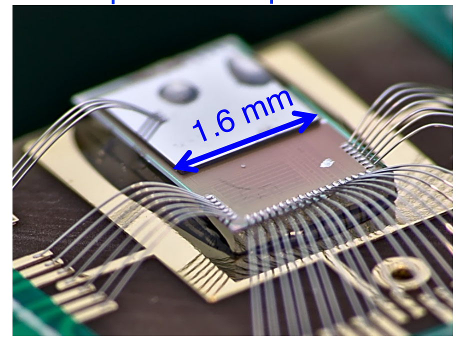




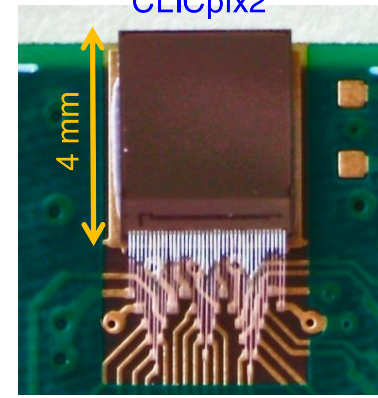
Vertex detector R&D

- **Vertex-detector requirements:**
  - Ultra-thin (50 µm active silicon)
  - High spatial resolution (~3 µm → ~25x25 µm² pitch)
  - Precise timing (~10 ns)
- Broad R&D program on sensors, readout, powering, interconnects, mechanical integration and cooling
- Beam tests of 65 nm readout ASICs with ultra-thin fine-pitch active-edge and HV-CMOS sensors
- Prototypes of Light-weight mechanical supports and air cooling
- Second generation of sensors and r/o ASICs with improved performance currently under test
- Most challenging: position-resolution target

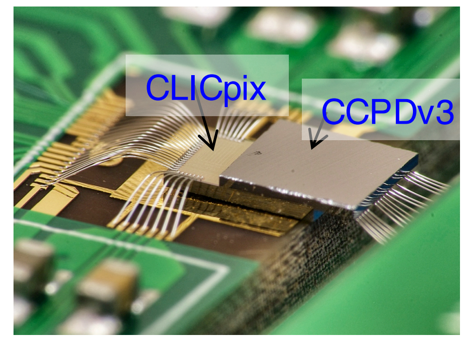
CLICpix with 50 µm sensor



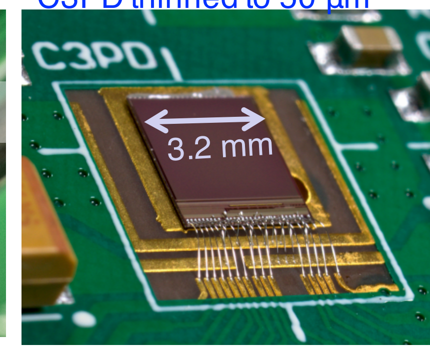
CLICpix2



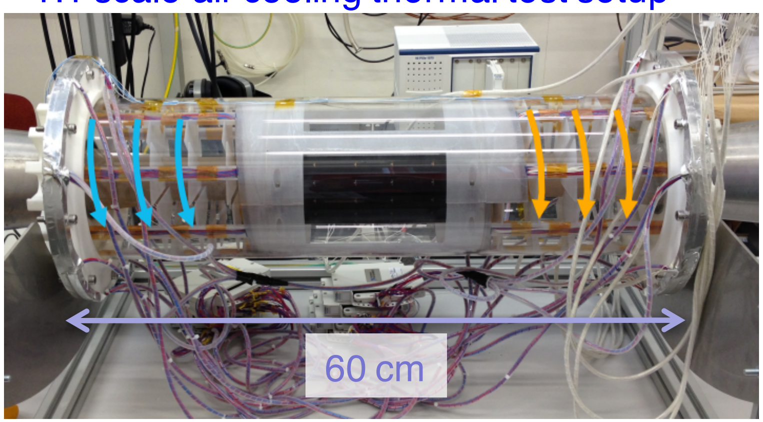
Capacitively coupled assembly



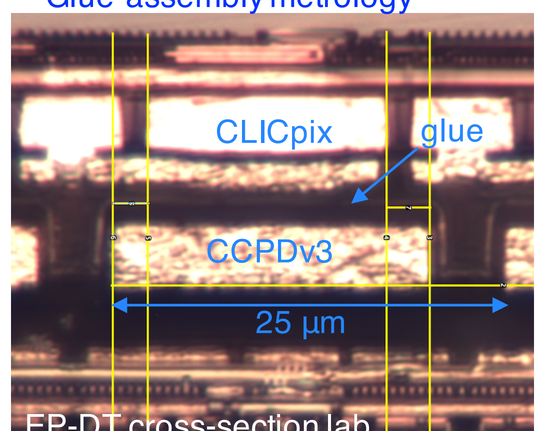
C3PD thinned to 50 µm



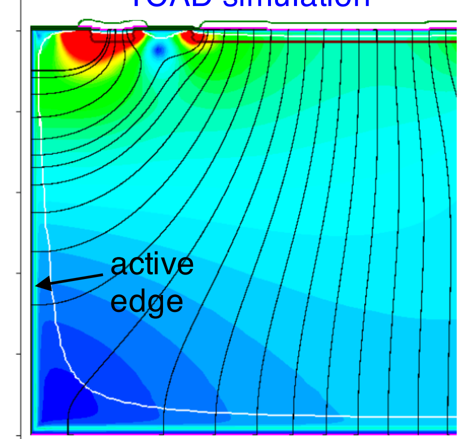
1:1 scale air cooling thermal test setup



Glue-assembly metrology



TCAD simulation



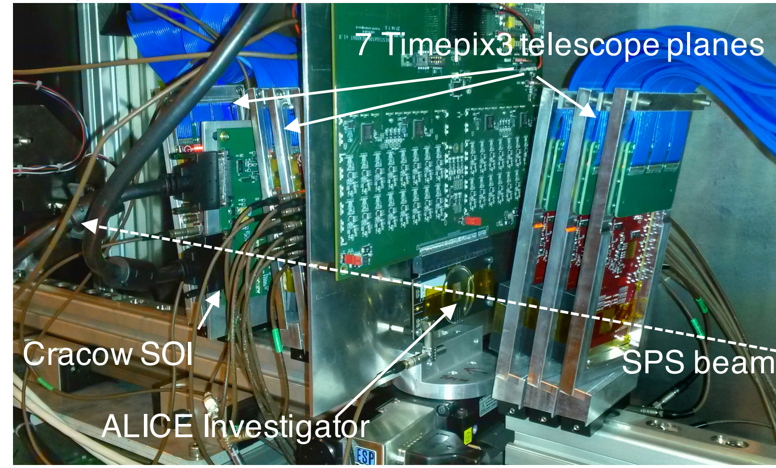
Tracker R&D

- **Tracker requirements:**
  - Material budget 1-1.5% X0 / layer
  - Spatial resolution ~7 µm
  - fast timing (~10 ns)
  - Has to cover ~100 m^2 surface area
    → integrated sensors w. large pixels (≲ 30 µm × 1 mm)

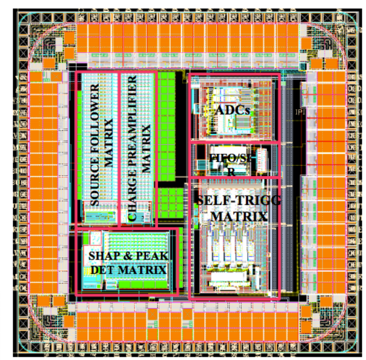
- Evaluating prototypes in different technologies: SOI; depleted monolithic CMOS
- Collaboration with HL-LHC tracker upgrade projects
- Most challenging: maintain efficiency and good timing, despite large pixel area

- Mechanical integration and cooling concept for full tracker
- Prototypes for support frames constructed

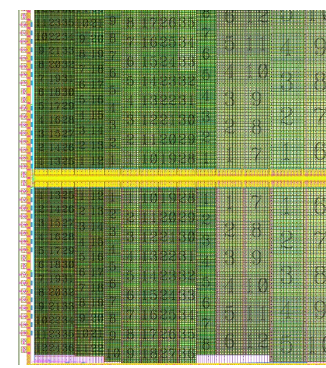
August 2016 test-beam setup in SPS-H6



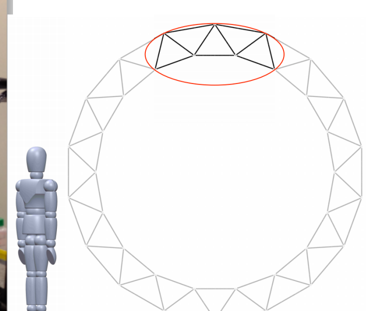
AGH SOI test chip



ALICE Investigator



Prototype of outer barrel tracker support structure

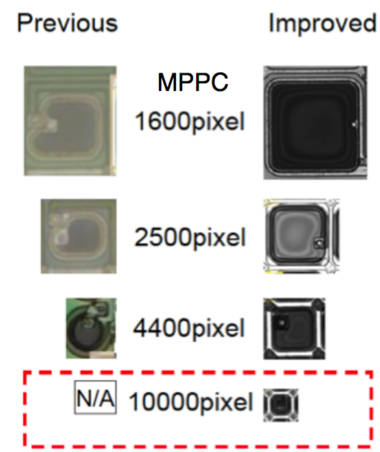


Overview talk on vertex/tracker by D. Hynds later in this session and contributions in tomorrow's vertex+tracker session

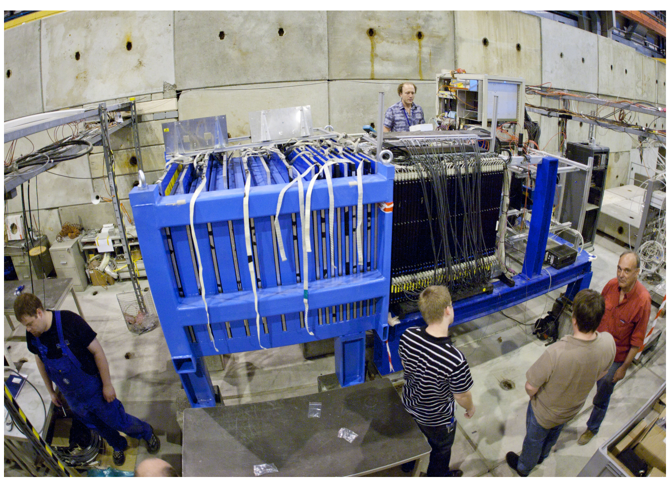
Calorimetry: CALICE

- R&D on HCAL/ECAL technologies for CLIC is performed within the CALICE collaboration for fine-grained particle-flow calorimetry
- Finalizing analyses for data with 1st generation "physics" prototypes → aim for comprehensive comparison of the various technologies
- 2nd generation prototypes under construction:
  - improved r/o technologies
  - establish scalability (embedded electronics)
  - system tests with other sub-detectors
  - first beam tests of full prototypes foreseen in 2017
- CALICE contributions to other detector (upgrade) projects, e.g.:
  - CMS-HGCAL (600m^2 Si sensors, 500 m^2 scintillators)
  - Belle II (CALICE tiles for beam monitoring)

Improved MPPC sensors

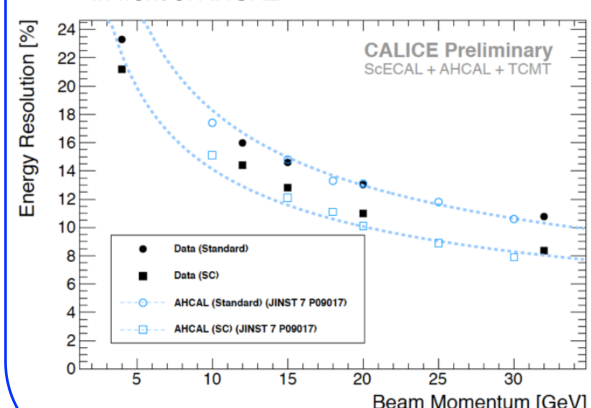


W-A-HCAL beam test in SPS

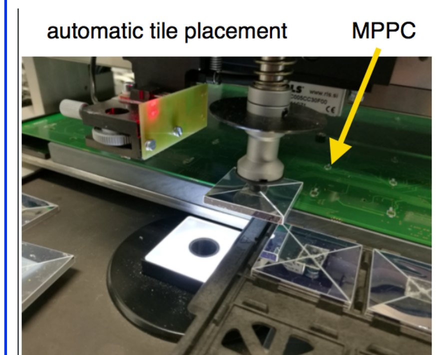


Recent result with physics prototypes

All-scintillator Japanese ECAL in front of AHCAL

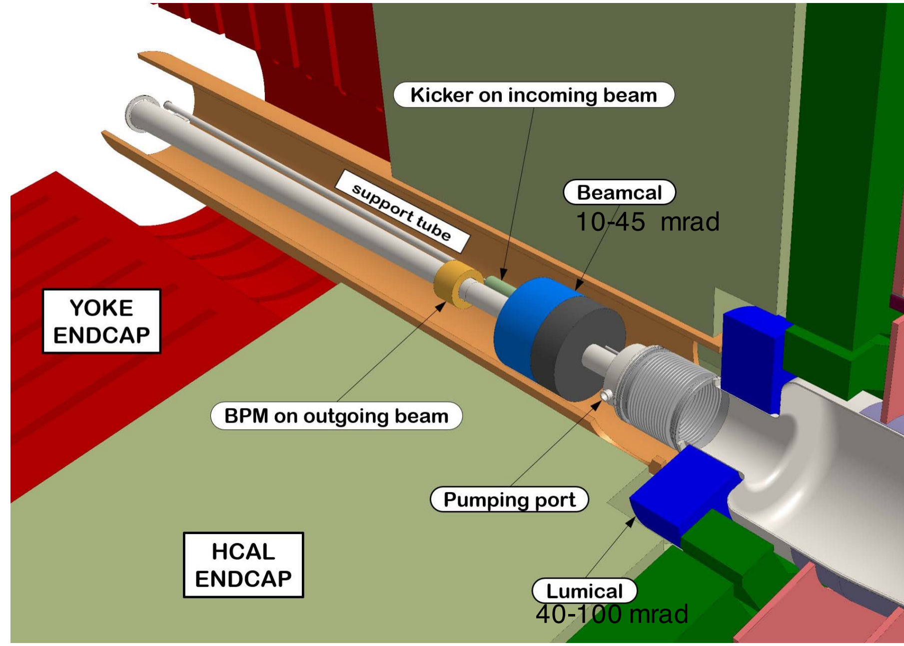


Mass production of AHCAL modules

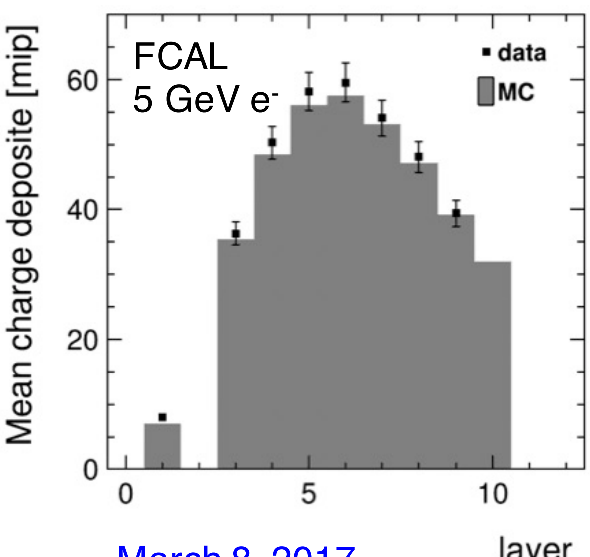


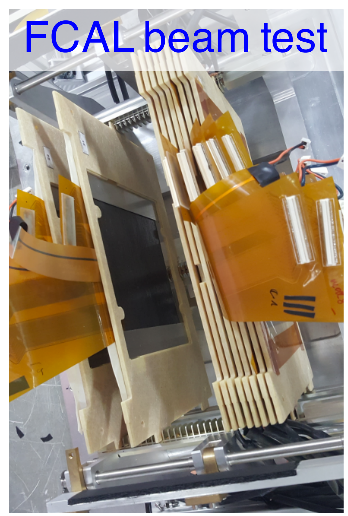
Calorimetry: FCAL

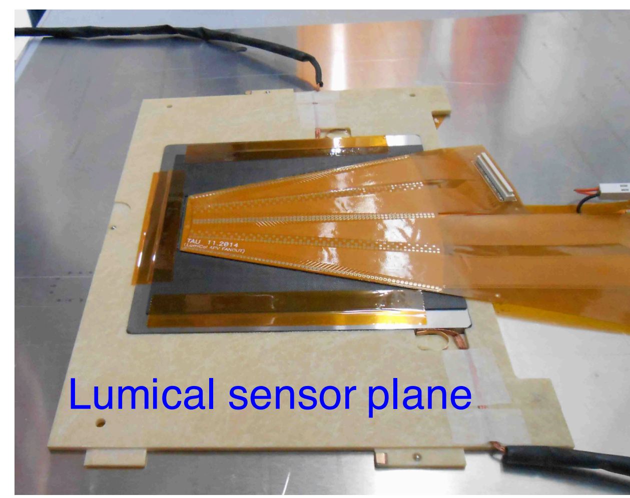
- R&D on compact sampling calorimeters for forward regions is performed within FCAL collaboration
  - LumiCal for luminosity measurement (<±1% accuracy)
  - BeamCal for very forward electron tagging
- Evaluating different r/o technologies
  - Radiation hardness
  - Beam tests



FCAL e- shower depth profile







CLICdp documents for European Strategy

- Preparing for European Strategy Update for HEP in 2019
- CLICdp reports will serve as ingredients for CLIC summary report:

- Updated Baseline for a Staged Compact Linear Collider (380 GeV, 1.5 TeV, 3 TeV) ✔
  - arXiv:1608.07537, CERN-2016-004
- Higgs Physics at the CLIC Electron-Positron Linear Collider ✔
  - arXiv:1608.07538
- The new optimised CLIC detector model CLICdet ✔✔
  - CLICdp note CLICdp-Note-2017-001 (detector/SW validation in progress)
- An overview of CLIC top physics
  - CLIC top physics publication → complete draft before the end of 2017
- Extended BSM studies (hopefully also motivated by LHC discoveries)
  - CLIC BSM overview publication in 2018
- CLIC R&D report → with main CLIC technology demonstrators
  - Summary publication(s) in 2018
- Plan for the period ~2019-2025 in case CLIC would be supported by next strategy

Summary and Conclusions

- Strengthening the Physics case for CLIC:
  - New CLIC staging scenario with optimized Higgs and top physics program
  - Higgs physics overview paper finalized and submitted
  - Top physics overview and BSM physics overview in preparation

- Implemented new single CLIC detector model, now under validation
- Consolidation of simulation, reconstruction and distributed computing software

- Broad and active R&D on vertex and tracking technologies and calorimetry, with CALICE, FCAL, AIDA-2020, and in collaboration with the HL-LHC projects

Thanks to everyone who provided material for this talk!

Additional material

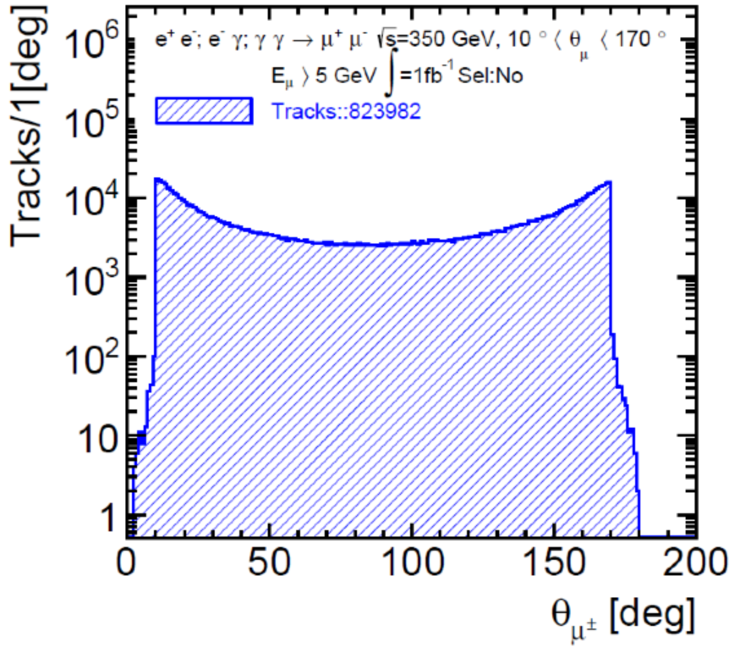
Detector calibration and alignment

Alignment / calibration at √s=350 GeV

- Expect ~65 pb^{-1}/day in first year
- High muon event rates (~$10^6/fb^{-1}$) should allow for good detector alignment
- Jet-energy scale calibration more difficult compared to √s=91 GeV

Most promising: $e^- \gamma \rightarrow e^- q\bar{q}$ (~30k events / pb^{-1})

→ $\sigma(M_Z)/M_Z$~5×10^{-4} achievable for ~3 fb^{-1}



Calibration study for initial run period of 1 pb^{-1} at √s=91 GeV:

- Jet-energy scale calibration:
  $e^+e^- \rightarrow q\bar{q}$ ~30k events
  → $\sigma(M_Z)/M_Z$~2×10^{-4} achievable
- Tracker momentum scale calibration:
  $e^+e^- \rightarrow \mu^+\mu^-$ ~1500 events
  → $\sigma(M_Z)/M_Z$~1×10^{-4} achievable

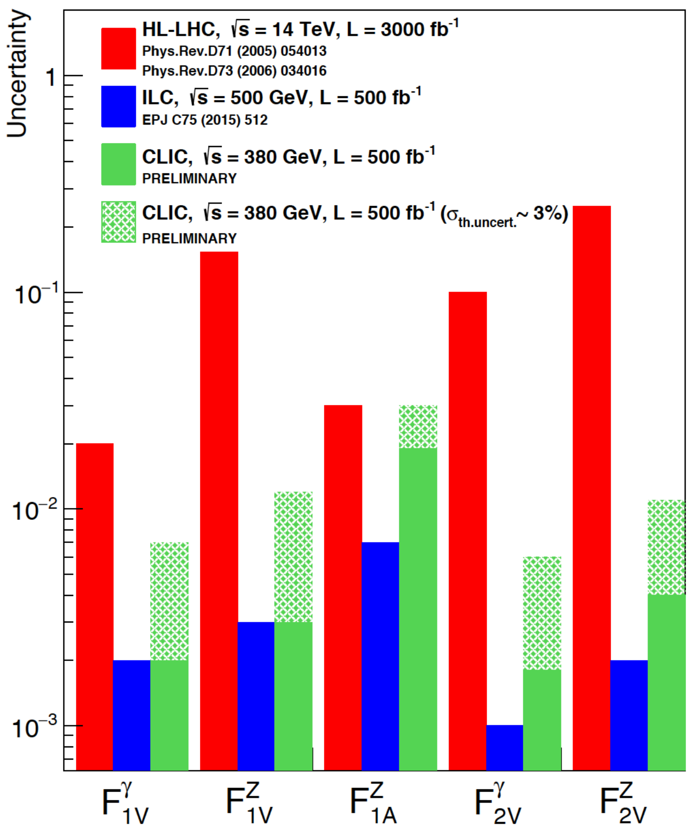
√s Gev	Luminosity $cm^{-2}s^{1}$	Luminosity Per day, pb^{-1}	Luminosity Per day pb^{-1} in year-1	Luminosity Per day pb^{-1} in year-2
350	1.5 10^{34}	1300	65	325
1400	3.7 10^{34}	3200	160	800
3000	5.9 10^{34}	5100	255	1275
91.2	2.3 10^{32}	20	1	5

Expected nominal luminosities at CLIC.
At each centre-of-mass energy for the first three years the luminosity is reduced. The reduction factor is 5%, 25%, 50% for year-1, y-2, y-3.

Top quark couplings to Z/γ

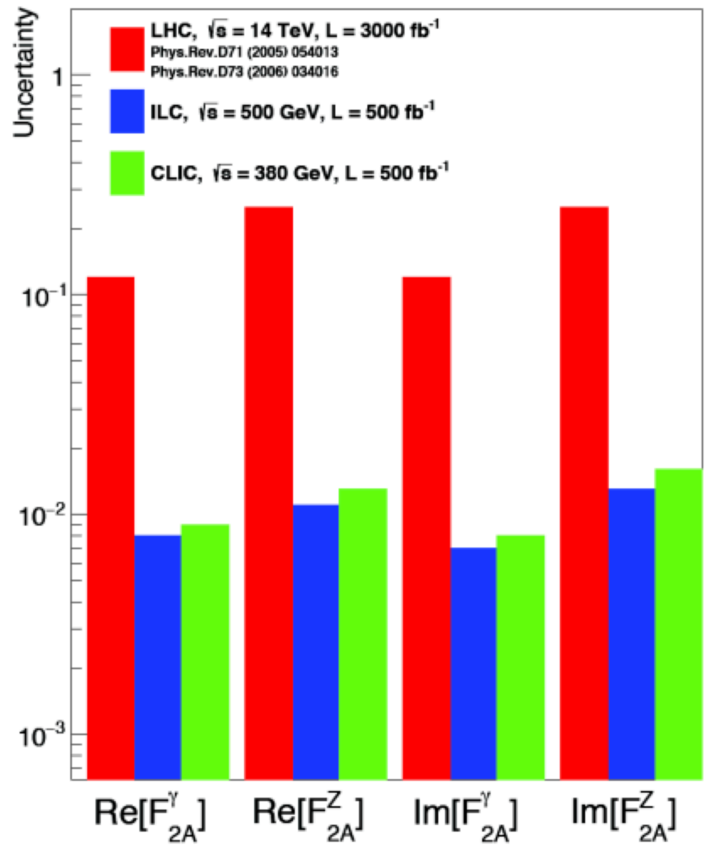
Expected coupling precision at **HL-LHC**, **ILC** (500 GeV) and **CLIC** (380 GeV)

CP-conserving couplings



CERN-2016-004

CP-violating couplings



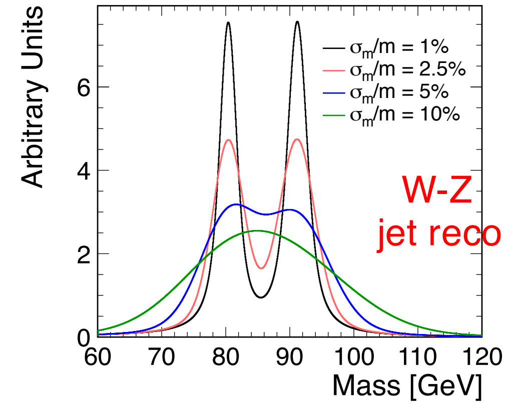
M. Vos at ECFA LC 2016

Detector requirements

→ Jet-energy resolution

e.g. W/Z/H di-jet mass separation, ZH with Z→ qq

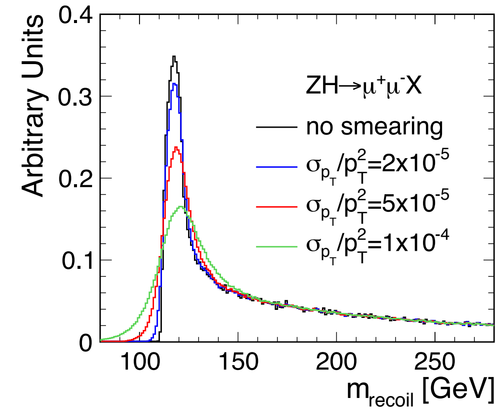
$$\frac{\sigma_E}{E} \sim 3.5 - 5\ \%$$ (for high-E jets, light quarks)



→ momentum resolution:

e.g, $g_{H\mu\mu}$, Smuon endpoint

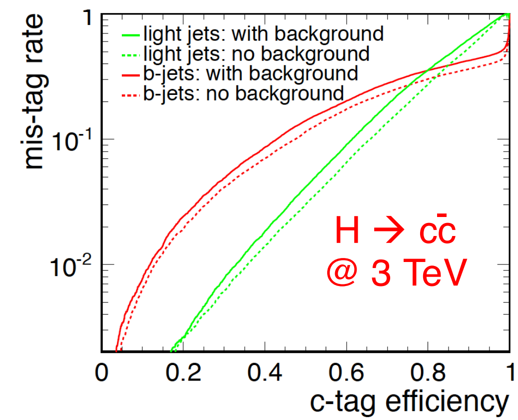
$$\sigma_{p_T} / p_T^2 \sim 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$$



→ 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

+ requirements from CLIC experimental conditions

CLIC strategy and objectives

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion