Detector challenges for future high-energy e^+e^- colliders

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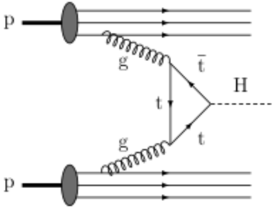
Introduction

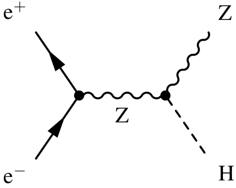
Hadron vs. lepton colliders

Hadron colliders



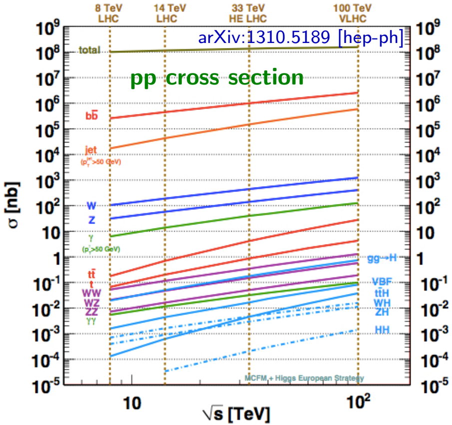
1) Proton is compound object
   - Initial state unknown
   - Limits achievable precision
2) High rates of QCD backgrounds
   - Complex triggers
   - High levels of radiation
3) Very high-energy circular colliders feasible

Lepton colliders

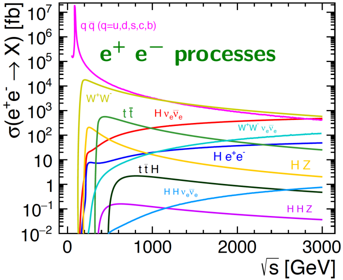


1) e^+e^- are point-like
   - Initial state well-defined (energy, opt.: polarisation)
   - High-precision measurements
2) Clean experimental environment
   - Less/no need for triggers
   - Lower radiation levels
3) Very high energies require linear colliders

pp vs. e^+e^- cross sections



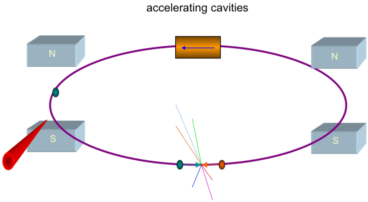
Factor $> 10^8$

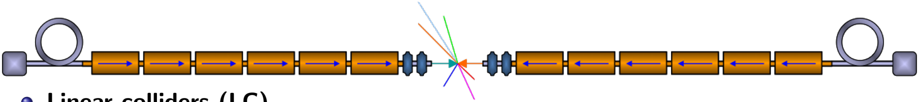


- In pp collisions, interesting events need to be found in huge number of collisions
- $e^+ e^-$ collisions more clean

Circular vs. linear e^+e^- colliders

- **Circular colliders (CC)**
  - Can accelerate beam in many turns
  - Can collide beam many times
  - Possibility of several interaction regions
  - Limited energy due to synchrotron radiation
    - Synchrotron radiation per turn $\sim$ Energy^4/(Mass^4 · Radius)
    - $\text{Mass}_{\text{proton}}/\text{Mass}_{\text{electron}} \approx 2000$
    - E.g. 2.75 GeV/turn lost at LEP for $E = 105$ GeV



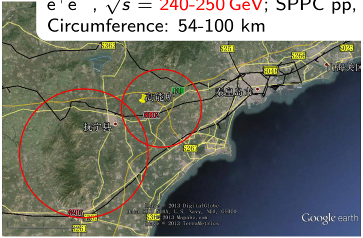


- **Linear colliders (LC)**
  - Very little synchrotron radiation in a linac
  - Can reach high energies
  - Have to achieve energy in a single pass
    $\rightarrow$ High acceleration gradients needed
  - One interaction region
  - Have to achieve luminosity in single pass
    $\rightarrow$ Small beam size and high beam power
    $\rightarrow$ Beamstrahlung, energy spread

High-energy e^+e^- collider proposals

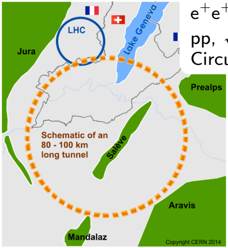
Circular Electron Positron Collider (CEPC)

e^+e^-, $\sqrt{s}$ = 240-250 GeV; SPPC pp,
Circumference: 54-100 km



Future Circular Collider (FCC)

e^+e^+, $\sqrt{s}$ = 90-350 GeV;
pp, $\sqrt{s}$:∼100 TeV
Circumference: 90-100 km



High-energy e$^+$e$^-$ collider proposals

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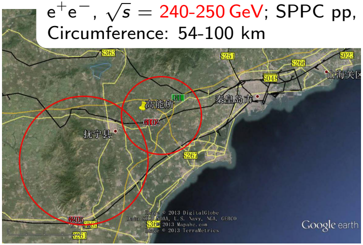

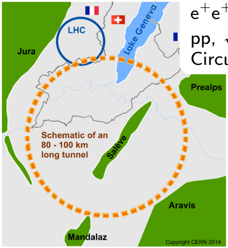

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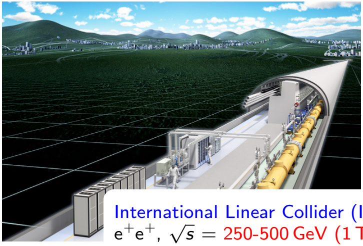
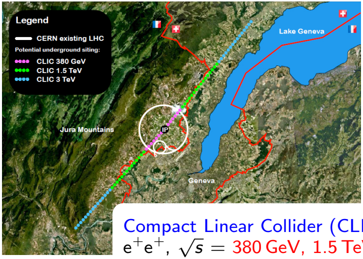


International Linear Collider (ILC)
e$^+$e$^+$, $\sqrt{s}$ = 250-500 GeV (1 TeV)
Length: 31 km (50 km)



Compact Linear Collider (CLIC)
e$^+$e$^+$, $\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km

Status of projects

ILC:
- TDR/DBD in 2013;
- European XFEL in operation using similar accelerator technology;

CLIC:
- CDR in 2012;
- Staging baseline document in 2016;
- Project Implementation Plan planned for 2018;

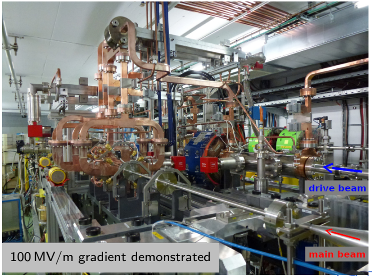
CEPC:
- pre-CDR in 2015;
- CDR planned for 2017;

FCC-ee:
- CDR planned for 2018;

TDR: Technical design report
DBD: Detailed Baseline Design
CDR: Conceptual design report

XFEL operation since Dec. 2016

CLIC two beam test stand



Experimental conditions in linear and circular colliders

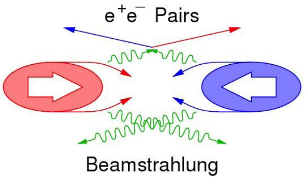
$\rightarrow$ **Impact on detector design**

Difference between pp and e^+e^- environment

- Detectors for hadron colliders
  - Large QCD backgrounds
  - Focus on radiation hardness of many sub-detectors
- Detectors for e^+e^- colliders
  - Cleaner e^+e^- collisions
  - Beam-induced backgrounds dominating source of radiation damage
  - Hadronic radiation damage only relevant in very forward detectors ($\theta \sim 10\,\mathrm{mrad} - 38\,\mathrm{mrad}$)

Beam-induced backgrounds

- Linear collider: Achieve high luminosities by using extremly small beam sizes
  $\rightarrow$ 3 TeV CLIC: Bunch size: $\sigma_{x;y;z} = \{40\,\text{nm}; 1\,\text{nm}; 44\,\mu\text{m}\}$ $\rightarrow$ beam-beam interactions



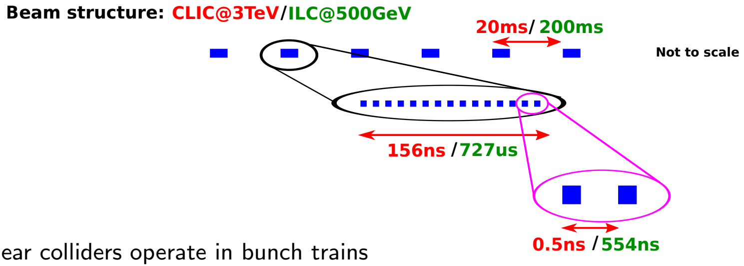
$\gamma\gamma \rightarrow$ hadrons

Main backgrounds ($p_T > 20$ MeV, $\theta > 7.3^\circ$)

- **Incoherent e^+e^- pairs:**
  - 19k particles / bunch train at 3 TeV
  - High occupancies
    $\rightarrow$ **Impact on detector granularity**
- $\gamma\gamma \rightarrow$ hadrons
  - 17k particles / bunch train at 3 TeV
  - Main background in calorimeters and trackers
    $\rightarrow$ **Impact on detector granularity and physics**

- Circular colliders: Same processes + synchroton radiation
- Background yields depend strongly on beam energy $\rightarrow$ currently under study

Duty cycle and bunch separation in linear colliders



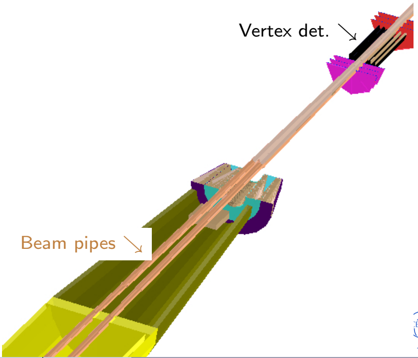
- Linear colliders operate in bunch trains
  → Low duty cycle
  → Possibility of power pulsing of detectors
- Bunch separation impacts on detector design

Property $\sqrt{s}$	ILC 500 GeV	ILC 1 TeV	CLIC 380 GeV	CLIC 3 TeV
Repetition rate	5 Hz	4 Hz	50 Hz	50 Hz
Train duration	727 μs	897 μs	178 ns	156 ns
BX / train	1312	2450	356	312
Bunch separation	554 ns	366 ns	0.5 ns	0.5 ns
Duty cycle	0.36%	0.36%	0.00089%	0.00078%

High luminosities in circular colliders

Property	Unit	FCC-ee (100 km)				CEPC (54km)
Beam energy	GeV	45.6	80	120	175	120
Luminosity/IP	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	90	19	5.1	1.3	2.0
Bunches / beam	91500	5260	780	81	50	
Bunch separation	ns	2.5	50	400	4000	-

FCC-ee beam pipe proposal



- Luminosities of up to $\sim 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Large number of bunches
- **Consequences for detector design**
  - Crossing angle of $\theta_c = 30\,\mathrm{mrad}^\dagger$ to avoid parasitic collisions
  - Bunch separation impacts on detector design
  - No power pulsing of detectors

†CLIC: $\theta_c = 20\,\mathrm{mrad}$

Machine-detector interface in circular colliders

- High luminosities: last focusing quadrupole "QD0" very close to IP:
  - L*≈2.2 m @ FCC-ee
  - L*≈1.5 m @ CEPC
- Protect QD0 from main magnetic field → Screening solenoid around QD0
- Compensating solenoid to prevent emittance blow-up due to non-zero crossing angle

Example: FCC-ee

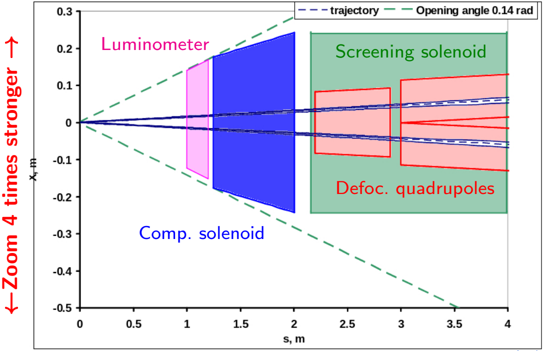
→ Luminometer at only **1 m** from interaction point

  → Limits detector acceptance window to polar angles of ±150 mrad

→ Limits magnetic field of main solenoid to **B=2 T**

  → Need to increase tracker radius to maintain momentum resolution

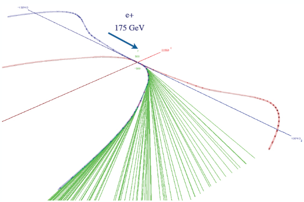
Top view on forward detector region: FCC-ee



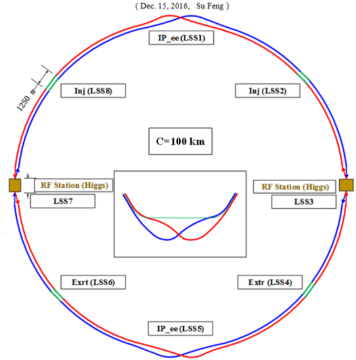
Synchrotron radiation in circular colliders

- Synchrotron radiation from bending high-energy electron beam on circular trajectory
  - Limit synchrotron radiation in interaction region by bending the beams as little as possible upstream to the IP → **"Asymmetric layout"**

FCC-ee simualtions



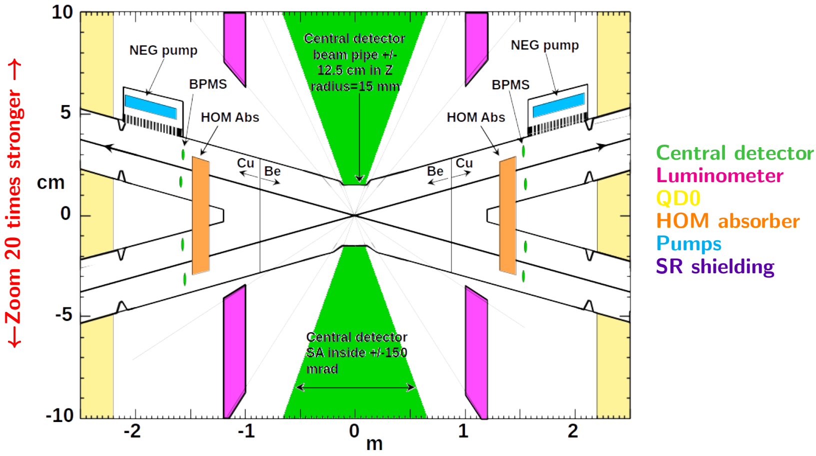
Current CEPC baseline



Property	Unit	FCC-ee (100 km)				CEPC (54 km)
Energy/beam	GeV	45.6	80	120	175	120
Energy loss / turn	GeV	0.03	0.33	1.67	7.55	3.11

Synchrotron radiation in circular colliders: Shielding

- Close to the detector region, additional **shielding** to prevent synchrotron radiation/secondary radiation to enter the detector



- Cooling of beam pipe needed → increased material budget at the IP

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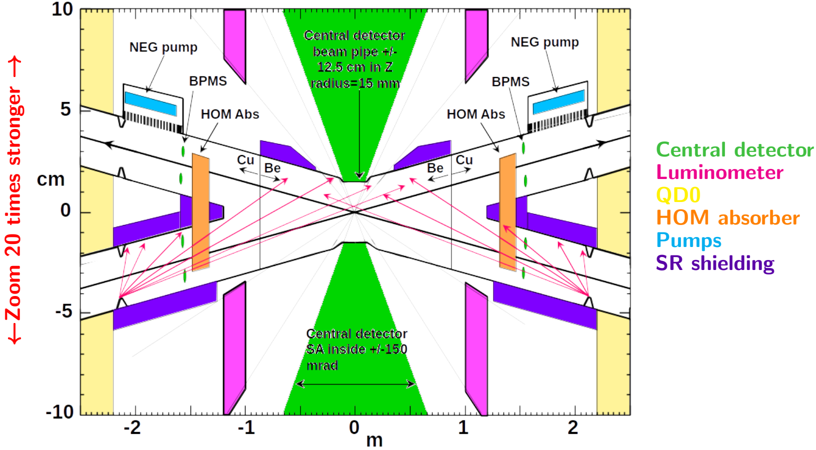

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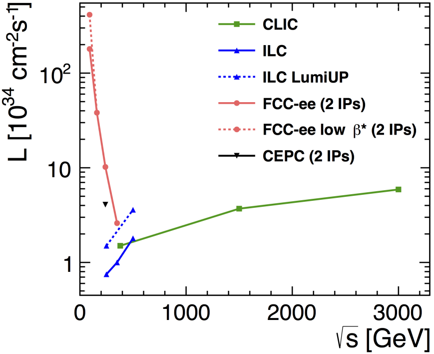
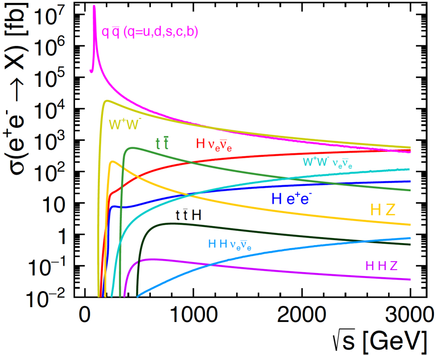
Physics programme

→ **Detector requirements**

Energy reach → physics programmes





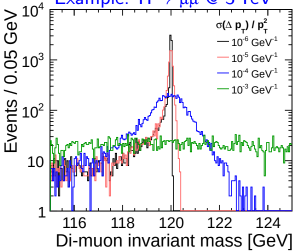
- Physics programmes focus on **precision measurements** of
  - FCC-ee: Z, W, Higgs, top
  - CEPC: Higgs (Z, W under discussion)
  - ILC: Higgs, top, direct high-mass BSM searches
  - CLIC: Higgs, top, direct high-mass BSM searches

Linear collider detector needs

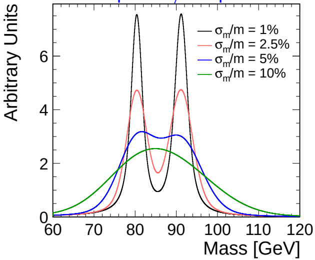
- Momentum resolution
  - Higgs recoil mass, smuon endpoint, Higgs coupling to muons
  - → $\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\mathrm{GeV}^{-1}$ above 100 GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios
  - → $\sigma_{r\varphi} \sim a \oplus b/(p[\mathrm{GeV}] \sin^{\frac{3}{2}} \theta)\mu\mathrm{m}$
  - $a = 5\,\mu\mathrm{m},\ b = 10 - 15\,\mu\mathrm{m}$
- Jet energy resolution
  - Separation of W/Z/H di-jets
  - → $\sigma_E/E \sim 3.5\%$ for jets at 50-1000 GeV
- Angular coverage
  - Very forward electron and photon tagging
  - → Down to $\theta = 10$ mrad ($\eta = 5.3$)
- Requirements from beam structure and beam-induced background

→ Note: Ongoing study to re-define needs for precision measurements

Example: H→ μμ @ 3 TeV



Example: W/Z separation



Circular collider detector needs

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- Impact parameter resolution
  - c/b-tagging, Higgs b

  →
- Jet
  -

  →
- Ang
  - and photon tagging

  → θ = 10 mrad (η = 5.3)
- Requirements from beam structure and beam-induced background

→ Note: Ongoing study to re-define needs for precision measurements

Similar requirements at circular colliders:
Needed for precision measurements

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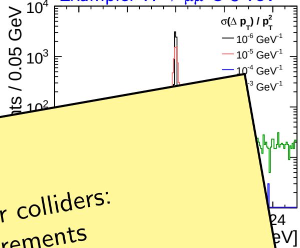
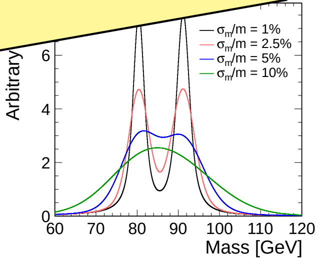




Detector concepts

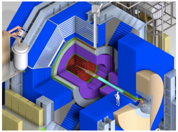
Multi-purpose detectors for e^+e^- colliders

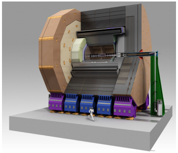
- No large QCD backgrounds in e^+e^- collisions
  - Radiation hardness mainly for very forward direction
- Precision physics programme for e^+e^- colliders
  - Requires excellent flavour tagging and momentum resolution
    - Light-weight vertex and tracker detector, highly granular
  - Requires excellent energy resolution
    - Use excellent calorimeters, for instance based on particle flow

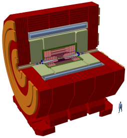
- Multi-purpose detectors

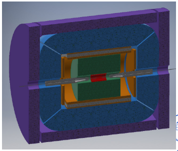
→ Onion-like arrangement of complementary sub-detectors

Vertex detector	→ measure track of charged particles
	→ measure vertex position
	→ measure impact parameter → flavour
Tracking detector	→ measure track of charged particles
El.-mag. calorimeter	→ measure energy of γ, $e^{\pm}$ and hadrons
Hadronic calorimeter	→ measure full energy of hadrons
Magnet system	→ bend charged particles → momentum
Muon system	→ identify muons
Hermiticity	→ measure missing energy (e.g. ν)

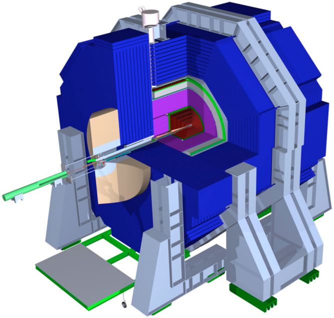


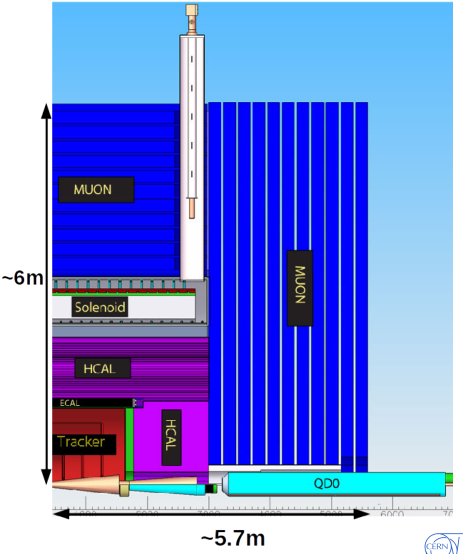






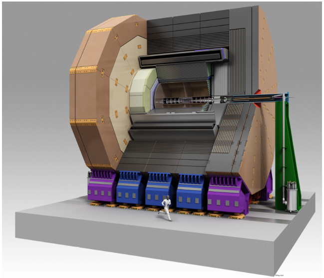
SiD detector @ ILC

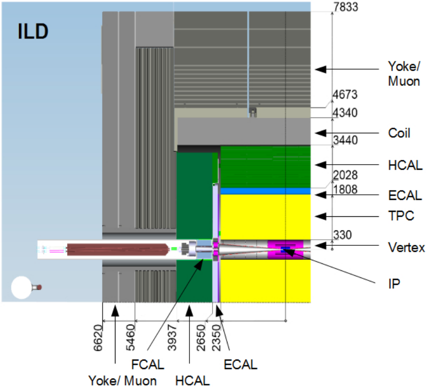




- **SiD**: "Silicon Detector"
- B-field of 5 T
- All-silicon vertex detector + tracker
- Fine-grained calorimetry
  → Particle Flow Analysis
- Compact design (∼ 1.2 m tracker radius)

ILD detector @ ILC

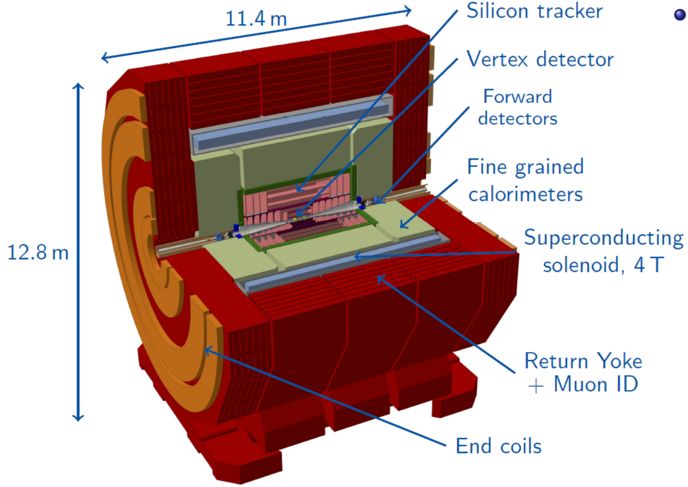




- **ILD**: "International Large Detector"
- Silicon vertex detector
- Time Projection Chamber as tracker surrounded by Silicon Envelope
- Fine-grained calorimetry (PFA)
- Re-optimisation: Large (L) and small (S) options under study

	ILD-L (DBD)	ILD-S
B-field	3.5 T	4 T
TPC outer radius	180 cm	146 cm
Coil inner radius	344 cm	310 cm

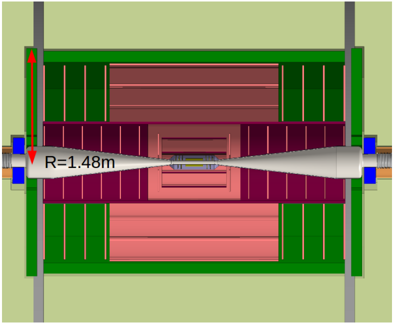
CLIC detector: CLICdet

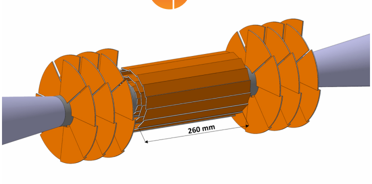


- SiD/ILD-inspired detector concept
  - B-field of 4 T
  - Large silicon tracker R=1.5 m
  - QD0 outside detector
    → increase HCAL forward acceptance

Towards FCC-ee detectors (option I)

- CLICdet-inspired detector concept
  - Complex forward region
    - → smaller magnetic field of B=2 T
    - → larger tracker radius (keep similar momentum resolution)
  - HCAL less deep → lower $\sqrt{s}$
  - Vertex detector endcap without spirals (no air cooling)





- To be further optimised for different
  - Physics goals
  - Backgrounds
  - Detector cooling requirements

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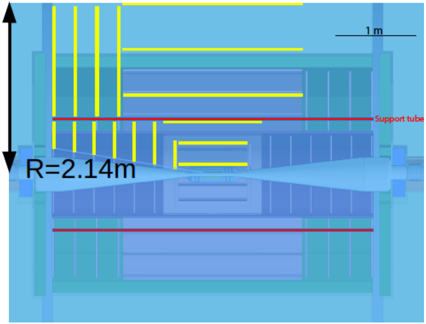

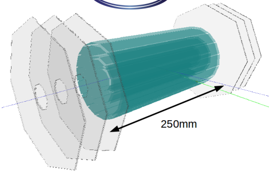

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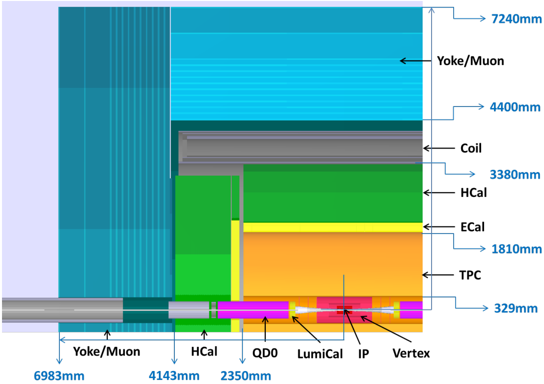
Towards CEPC detectors (option I)

- ILD-L-inspired detector concept studied for pre-CDR



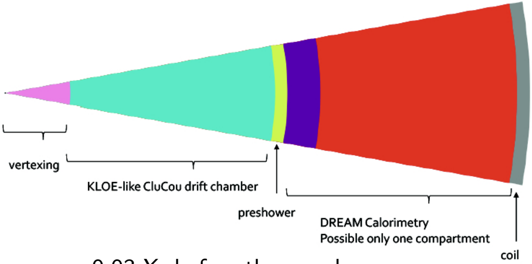
- Shorter L* of 1.5 m
  → QD0 inside tracker
- Increased cooling infrastructure due to continuous operation
- Thickness of return yoke reduced for both barrel and endcap

Towards CDR:

- Study 2+ detector concepts
- ILD-like / SiD-like concepts, novel concept (→ "IDEA")

"IDEA" concept for CEPC/FCC-ee

- IDEA: "International Detector for Electron-positron Accelerator"
- FCC-ee/CEPC detector design from scratch



← DREAM: "Dual READout Module calorimeter"

- Aims
  - Very low mass $\sim 0.03\,X_0$ before the pre-shower
  - Muon momentum resolution of 0.3% at p=100 GeV
  - Acceptance defined at $\sim 2\,\mu$m over few metres
  - E/γ energy resolution $\sim$ 1% at E=100 GeV
  - Jet energy resolution of few % at E=100 GeV
  - Excellent e-μ-h separation
  - More than 3σ π/k separation over a wide momentum range
  - Very good b and c tagging

Detector R&D

Disclaimer:

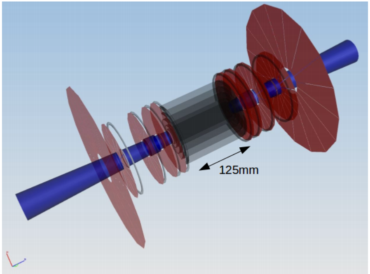
- Showing only examples of recent developments here
- More details and results in parallel session talks

Vertex and tracking detectors

Challenges in vertex detector R&D

- Flavour tagging capabilities drive the design of the vertex detector
  - → Extremely accurate
  - → Extremely light

SiD vertex detector



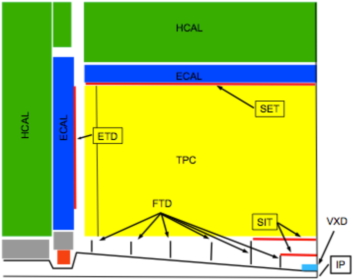
- **LC vertex-detector challenges**
  - $\sim 1\,\mathrm{m}^2$ surface
  - Single point resolution of $\sigma < 3 - 5\,\mu\mathrm{m}$
    - → Pixel pitch $\approx 17 - 25\,\mu\mathrm{m}$
  - Low power dissipation of $\leq 50\,\mathrm{mW/cm}^2$
  - Material budget $< 0.1 - 0.3\,\% X_0$ per layer
    - → Thin sensors and ASICs, low-mass support, power pulsing, air cooling
  - Time stamping
    →$\sim$ 10 ns (CLIC)
    → $\sim$ 300 ns – µs dep. on technology (ILC)

- **CC vertex detectors: Differences**
  - Continuous operation → increased cooling → increased material budget

Challenges in tracking detector R&D

- Very good momentum resolution
- Different concepts, each with large $B \cdot R^2$
  - SiD and CLICdet: all silicon tracker
  - ILD and IDEA: silicon + gaseous tracking

ILD TPC



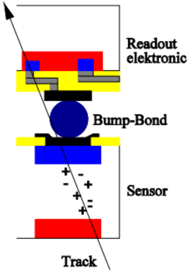
1) Silicon tracker challenges
   - Large surface area of O(100 m^2)
     → Use integrated sensors w. large pixels/strips ($\sim 30\,\mu\text{m} \times 1 - 10\,\text{mm}$)
   - Maintain efficiency and good timing despite large pixel area
   - Mechanical stiffness vs. very little material budget
     → Light-weight support structure and cooling concepts

2) TPC challenges
   - Ion back flow impacts on resolution
     → Gating concepts under study
   - Hit timing and momentum resolution
     → Silicon envelope around TPC
   - Occupancies
     → Meets requirements for ILC
     → Under study for CEPC

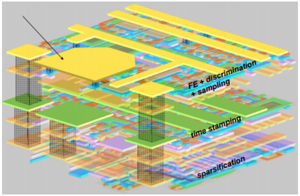
Silicon pixel-detector technologies

Technology	Examples
Hybrid	CLICpix ASIC+planar sensor, HV-CMOS hybrid
Integrated sensor/amplif. + separate r/o	DEPFET, FPCCD
3D integrated	Tezzaron, SOI
Monolithic CMOS	Mimosa CPS, HV-CMOS, HR-CMOS

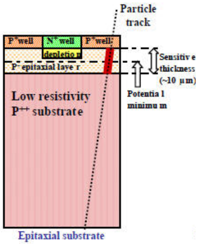
Hybrid



3D integrated

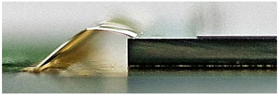


Monolithic



Hybrid: Extremely thin sensors

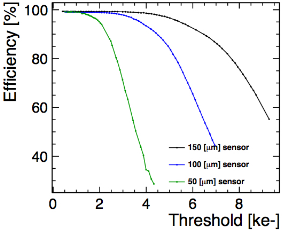
700 µm Timepix ASIC + 50 µm sensor

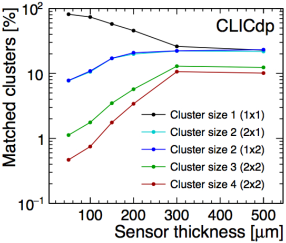


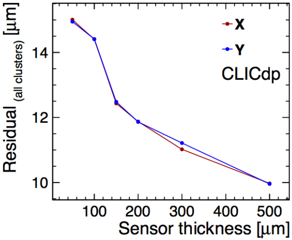
- Classical approach used in LHC pixel detectors
  - Independent optimisation of r/o ASIC and sensor
  - e^+e^- application: Combine ultra-thin sensors with high-performance r/o ASICs
  - Requires bump bonding

- Performance of ultra thin sensors
  - Timepix/Timepix3 ASICs, 55 µm pitch
  - Planar sensors with 50 – 500 µm thickness
  - CLIC Timepix3 telescope for reference, 2 µm track resolution

  - Resolution limited by single-pixel clusters
  - Charge sharing is lower in thin sensors
  - Reduced resolution for thin sensors







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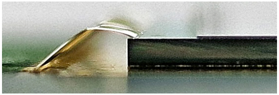

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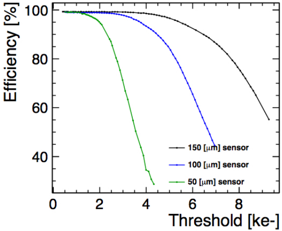
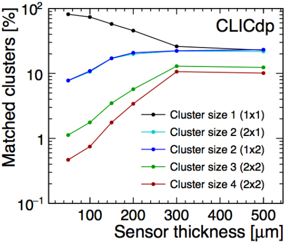
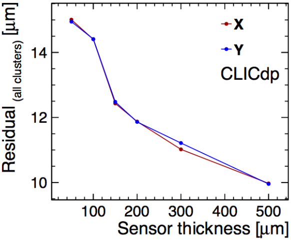
Talk by Andreas Nürnberg (Wed.)

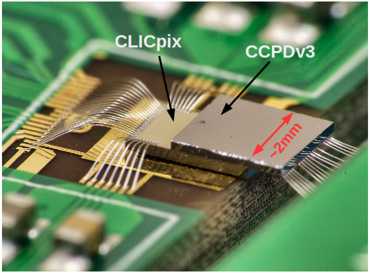




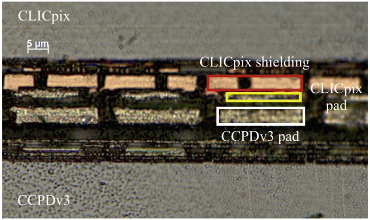


Hybrid: Capacitive Coupled Pixel Detector (CCPD)

CLICpix ASIC + CCPDv3

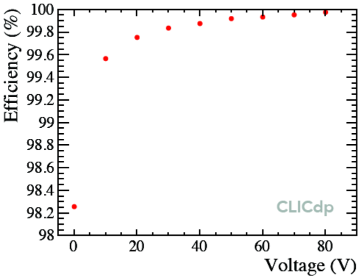


Check alignment



- HV-CMOS chip as integrated sensor+amplifier
- Capacitive coupling to r/o ASIC through layer of glue → no bump bonding
- CCPDv3 test sensor for ATLAS and CLIC
- Proof-of-principle test-beam measurements, e.g. using CLICpix r/o ASIC (25 µm pitch)

Efficiency versus bias voltage



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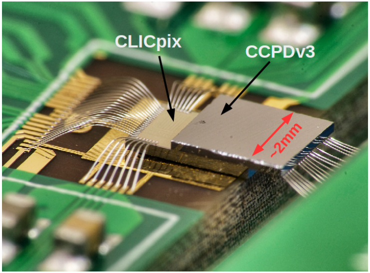

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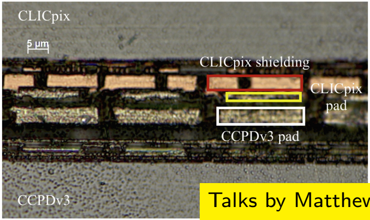

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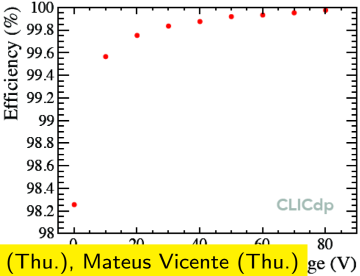
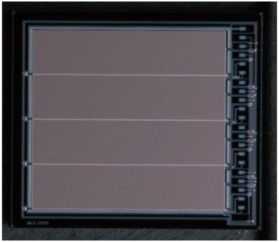


Talks by Matthew Buckland (Thu.), Mateus Vicente (Thu.)

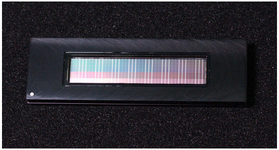
Semi-integrated technology: FPCCD

- "Fine Pixel Charge-Coupled Device" studied for ILD vertex detector
- Semi-integrated technology (separate r/o ASICs)
- Thickness of 50 µm, but material pushed to endcaps
- Trade-off:
  - Pixel pitch down to 5 µm → 1.4 µm res. for single pixel hits
  - Integrate over full ILC bunch trains → no time stamps
  - Background rejection by pattern recognition
- Operation at -40°C in cryostat using CO_2 cooling

FPCCD prototype
Pixel pitch 6, 12, 18, 24 µm
$6 \times 6\,\mathrm{mm}^2$

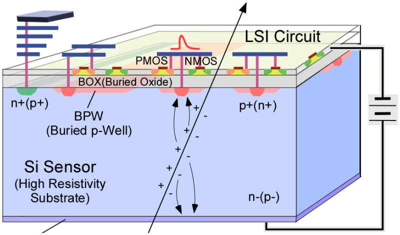


$12 \times 62\,\mathrm{mm}^2$ (real size sensor)

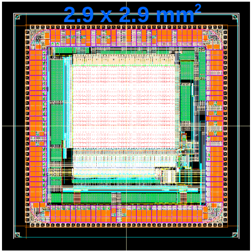


Cryostat design

3D integrated: Silicon on Insulator (SOI)

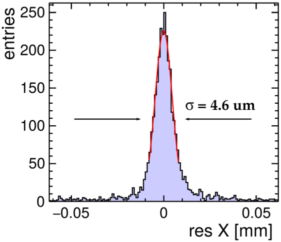


“SOI sens. for Fine meas. of Space & Time”
SOFIST 25 µm-pitch test chip (KEK)



- Monolithic pixel detectors in SOI
- SOI R&D ongoing for CEPC, ILC and CLIC
  - Thin SOI CMOS (200 nm feature size) and thick sensor bulk
  - High-resistive fully depleted sensor $\rightarrow$ Large S/N and high speed
  - Pixel pitch down to 10 µm
  - Thickness down to 50 µm

AGH SOI 30 µm-pitch sensor: resolution



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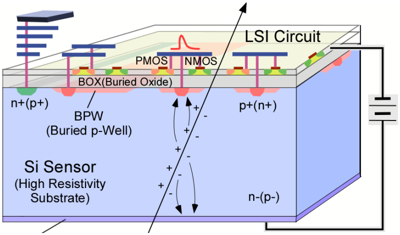

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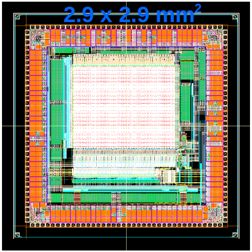

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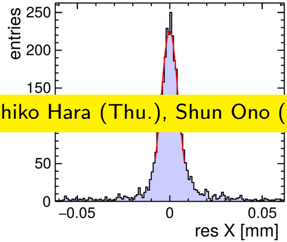
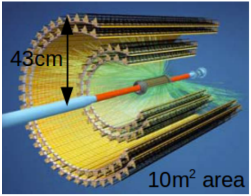


Talks by Marco Meschini (Wed.), Yunpeng Lu (Thu.), Kazuhiko Hara (Thu.), Shun Ono (Thu.)

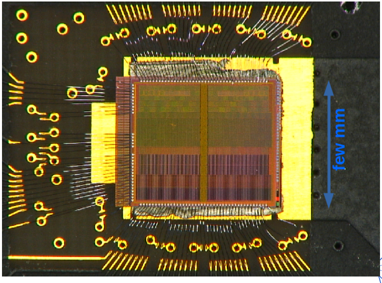
Monolithic Active Pixel Sensor (MAPS)

- Fully integrated CMOS technology
- Early generations
  - Charge collection mainly diffusion, timing limited by rolling-shutter r/o (μs)
- Recent advances
  - Moving towards smaller feature size (180 nm, Tower Jazz) and higher-resistivity substrates (few kOhm cm) → HR-CMOS
  - Promising timing performance
- Successfully deployed in HEP, with increasingly demanding requirements:
  - Test-beam telescopes
  - STAR @ RHIC
  - CBM MVD @ FAIR
  - ALICE ITS upgrade
  - Baseline technology for ILD VTX, under study for CEPC and CLIC

ALICE ITS upgrade



ALICE HR-CMOS investigator



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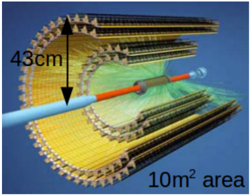

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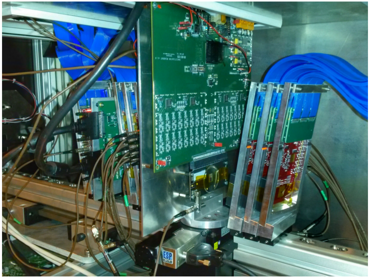

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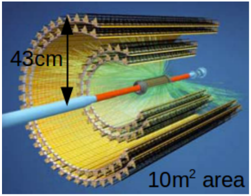


ALICE HR-CMOS investigator

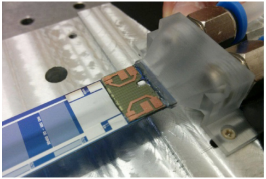
Talk by Magdalena Münker (Thu.)

Example: cooling and power pulsing

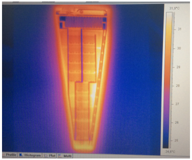
Vertex detector with low material budget

- Micro-channel cooling
  - Low volumetric flow (1 l/h) and low pressure (< 1 bar) enough to dissipate the heat in the front end
- Air cooling
  - Heat load of $13 - 50\,\mathrm{mW/cm^2}$ extractable using air flow
- Power pulsing
  - Small duty cycles $\rightarrow$ turn off front end in gaps between bunch trains

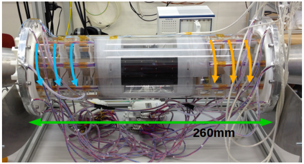
DEPFET Micro-channel cooling



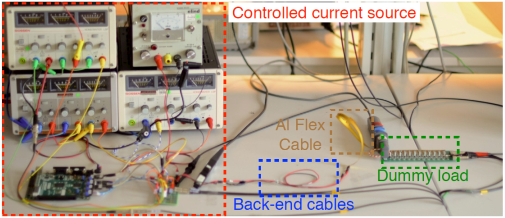
ILD FTD temperature meas. in wind tunnel



Cooling using air flow: 1:1 scale mock-up



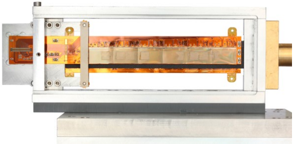
Test setup for power pulsing



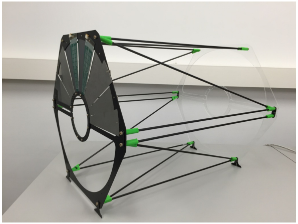
Example: Light support structures

- Low material budget requirements
  → light-weight support
- Synergies with LHC experiment upgrades

Plume ladder equipped with CPS

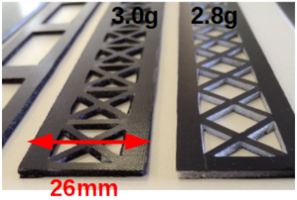


ILD FTD mock-up
carbon-fiber + CF tubes + 3D printed joints

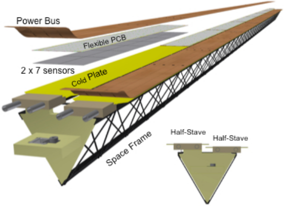


SiD tracker support prototype
based on CFRP box channels

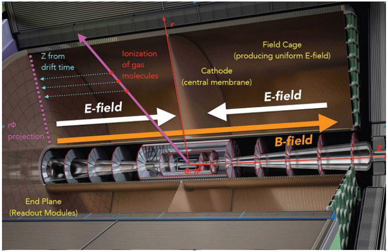
CLIC vertex det. support prototype
carbon fibre + honeycomb core



ALICE ITS outer barrel stave

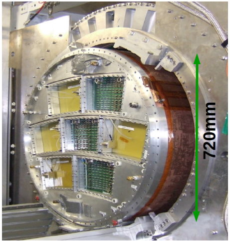


Time projection chamber

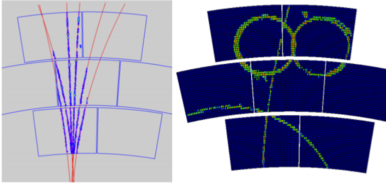


- TPC as tracker studied for ILD, CEPC
- $\sim$ 200 space points along the track
- dE/dx measurement for PID
- Challenges under study
  - Hit timing and momentum resolution, ion back flow, occupancy
- Readout: Micro-pattern gas detectors
  - Double/Triple GEM
  - Resistive micromegas
  - Integrated pixel read-out

Large TPC prototype



GEM and Micromegas readout



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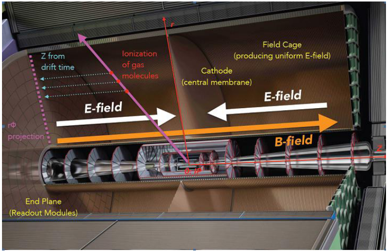

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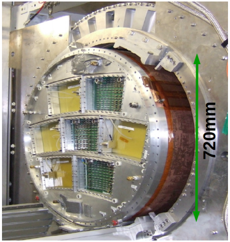

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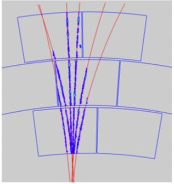

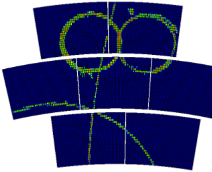

Talk by Huirong Qi (Thu.)

Calorimetry

Particle flow calorimeters

Pursued for ILC, CLIC, CEPC and FCC-ee

3%–4% jet energy resolution reachable with Particle Flow Analysis (PFA)

Idea:

- Average jet composition
  - 60% charged particles
    30% photons
    10% neutral hadrons
- Always use the best information
  - 60% → tracker ☺
    30% → ECAL ☺
    10% → HCAL ☹

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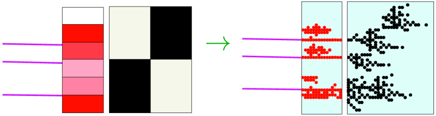
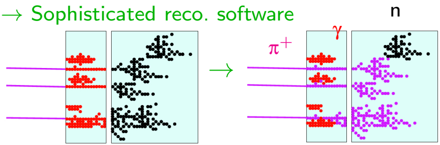
Particle Flow Analysis: Hardware + Software

- Hardware: Resolve energy deposits from different particles
  $\rightarrow$ High granularity calorimeters



$E_{\text{jet}} = E_{\text{ECAL}} + E_{\text{HCAL}}$

- Software: Identify energy deposits from each individual particle
  $\rightarrow$ Sophisticated reco. software



$E_{\text{jet}} = E_{\text{track}} + E_{\gamma} + E_{\text{n}}$

Particle flow calorimeters

Pursued for ILC, CLIC, CEPC and FCC-ee

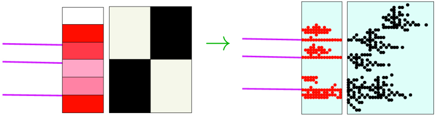
3%–4% jet energy resolution reachable with Particle Flow Analysis (PFA)

Idea:

- Average jet composition
  - 60% charged particles
    30% photons
    10% neutral hadrons
- Always use the best information
  - 60% → tracker ☺
    30% → ECAL ☺

Particle Flow Analysis: Hardware + Software

- Hardware: Resolve energy deposits from different particles
  → High granularity calorimeters



$E_{jet} = E_{ECAL} + E_{HCAL}$

ALICE: Yota Kawamura (Tues.), Hongkai Wang (Tue.)

e: Identify energy deposits

CALICE: Yong Liu (Tue.), Boruo Xu (Tue.), Burak Bilki (Thu.), Imad Laktineh (Thu.)

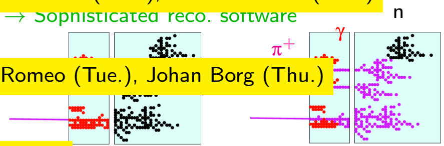
→ Sophisticated reco. software

CEPC: Zhigang Wang (poster)

CMS HGCal: Florian Pitters (Tue.), Francesco Romeo (Tue.), Johan Borg (Thu.)

FCC-hh: Coralie Neubüser (Wed.)

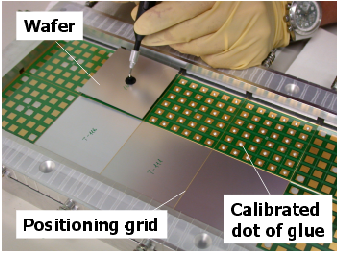
Front-end electronics: Christophe De La Taille (Wed.)



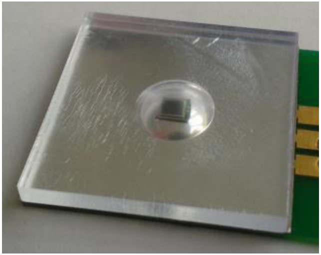
$E_{jet} = E_{track} + E_{\gamma} + E_{n}$

Calorimetry: Active layer technology: Examples

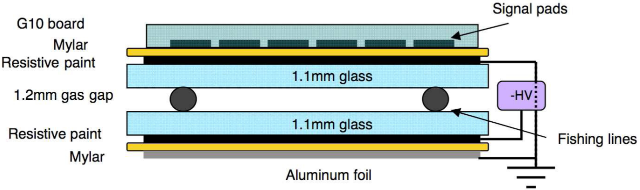
Silicon PIN diodes ($1 \times 1\,\text{cm}^2$ in 6×6 matrices)



Scintillator tiles/strips (here $3 \times 3\,\text{cm}^2$) + SiPMs

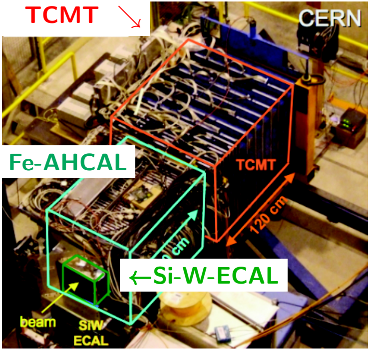


Resistive place chambers ($1 \times 1\,\text{cm}^2$ signal pads)

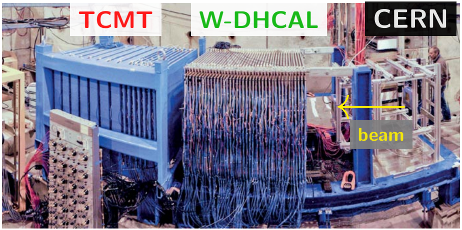


CALICE test beam experiment: Examples

- Test beam experiments in 2006–2015 at DESY, CERN, FNAL
- First physics prototypes of up to $\sim$1 m^3, $\sim$2 m^3 including Tail Catcher Muon Tracker



AHCAL/Si-ECAL: $\sim$ 10 000 readout channels



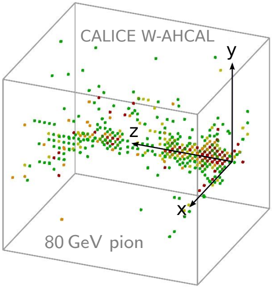
DHCAL: $\sim$ 500 000 readout channels

- Detector challenges:
  - Compact design of calorimeters
  - Calibration of all channels

CALICE event displays

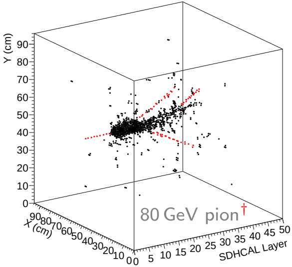
- Trade-off between energy resolution and granularity

Analogue HCAL



- $3 \times 3\,\mathrm{cm}^2$ cells, analogue energy information per cell

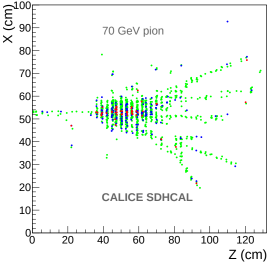
Digital HCAL



- $1 \times 1\,\mathrm{cm}^2$ cells, count cells above one energy threshold

† hits from identified tracks within shower

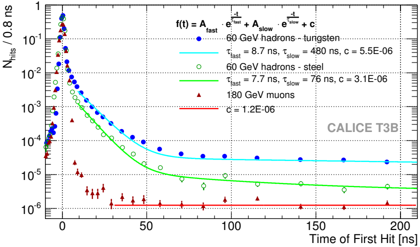
Semi-digital HCAL



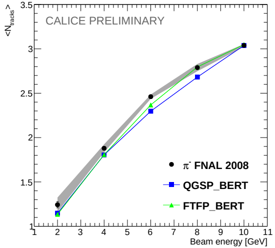
- $1 \times 1\,\mathrm{cm}^2$ cells, count cells above three energy thresholds

CALICE example results

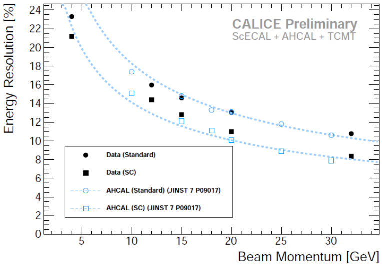
Time structure: W vs. Fe HCAL



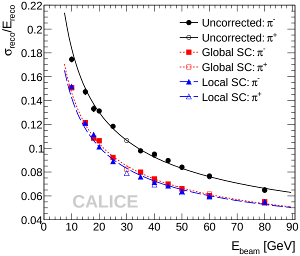
Shower sub-structure: N_{tracks} in Si-W-ECAL



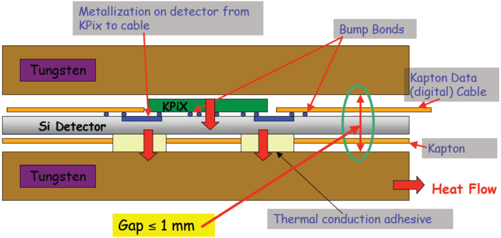
Pion energy resolution: ECAL+HCAL



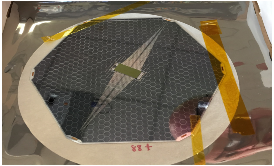
Software compensation



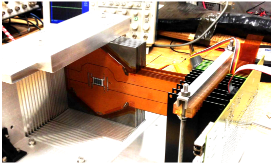
SiD Si-W ECAL



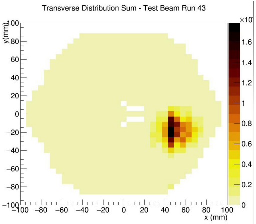
Si-sensor with KPiX



SiD ECAL in test beam



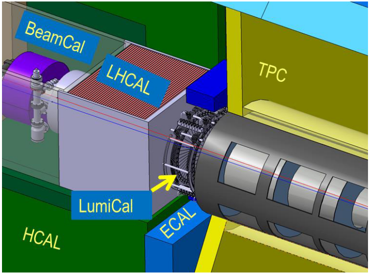
- Highly-granular calorimeter development: Si-W-ECAL for SiD@ILC
- Status: establish scalability
  - Embedded electronics for compact detector: here kPix
  - Demonstrate feasibility of construction of compact calorimeter



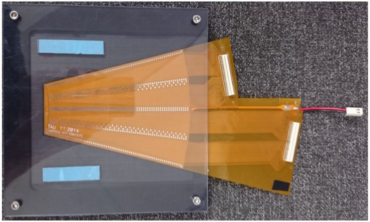
Forward CALorimetry: FCAL

- Very forward e.m. calorimeters
  - LumiCal for luminosity measurement ($< \pm 1\%$ accuracy)
  - BeamCal for very forward electron tagging
- e^- and γ acceptance to small angles
- Very compact design (sensors, read-out, absorber) $\rightarrow$ small Molière radius
- BeamCal: GaAs, LumiCal: silicon

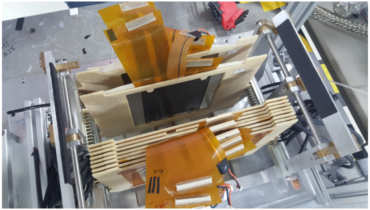
ILD@ILC forward region



LumiCal module with Si sensor (one sector)



Stack used in test beam



Summary

Summary

- e^+e^- colliders are precision machines with a large physics potential
- Existence of many e^+e^- collider studies shows world-wide interest in e^+e^- physics
- Interest increased since Higgs discovery at the LHC

- Detailed studies on e^+e^- detector concepts
  - Demanding requirements and ambitious concepts
  - Requirements depend on physics goals and experimental conditions
  - Large synergies between collider projects and already approved experiments
  - Active detector collaborations and R&D spin-offs

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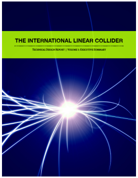
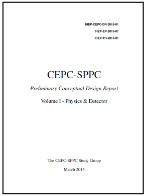
Thanks to all who provided material for this talk:

Sources used in this presentation

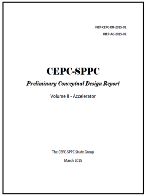
- ILC
  - TDR/DBD ▸ ILC-REPORT-2013-040
- FCC-ee
  - 1st FCC physics workshop ▸ indico
  - FCC-ee MDI workshop ▸ indico
- CLIC
  - CDR ▸ 10.5170/CERN-2012-007 / ▸ 10.5170/CERN-2012-003 / ▸ 10.5170/CERN-2012-005
  - Staging baseline document ▸ DOI: 10.5170/CERN-2016-004
  - CLIC detector note 2017 ▸ CLICdp-Note-2017-001
- CEPC
  - pre-CDR ▸ IHEP-EP-2015-01 / ▸ IHEP-AC-2015-01
- General
  - LCWS'15 ▸ indico, LCWS'16 ▸ indico, LC vertex '17 ▸ indico, CLIC'17 workshop ▸ indico




IHEP-CEPC-DR-2015-01
IHEP-EP-2015-01
IHEP-TH-2015-01

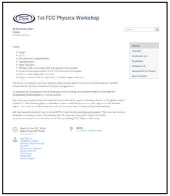
CEPC-SPPC
Preliminary Conceptual Design Report
Volume I - Physics & Detector

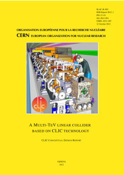
The CEPC-SPPC Study Group
March 2015


IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

CEPC-SPPC
Preliminary Conceptual Design Report
Volume II - Accelerator

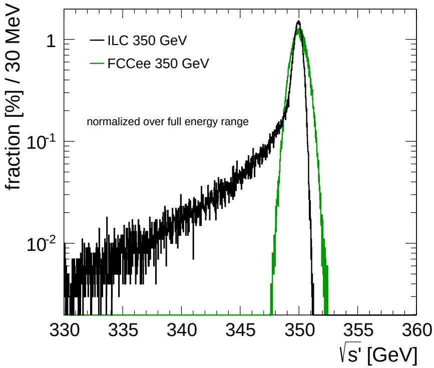
The CEPC-SPPC Study Group
March 2015





Backup

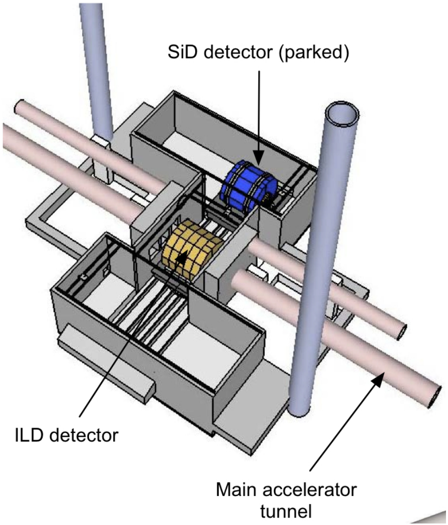
Beam strahlung and luminosity spectrum

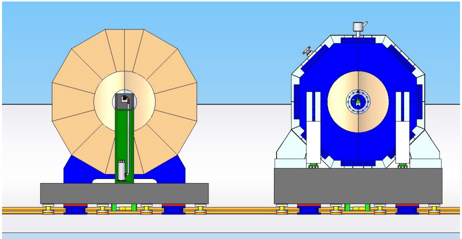


- LCs achieve high luminosity via small beam size → leads to beamstrahlung
- Energy loss reduces collision energy
- 1% most energetic part
  - ∼ 60% at 500 GeV and 1 TeV ILC
  - ∼ 60% at 380 GeV CLIC
  - ∼ 35% at 3TeV CLIC

- Most physics processes are studied well above production threshold
- Can profit from almost full luminosity also at LCs

ILC detectors - Push-pull



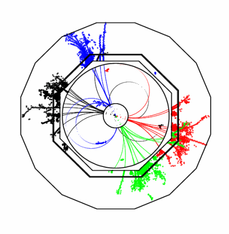


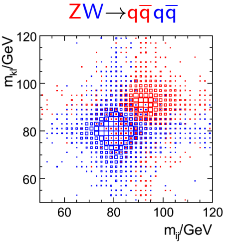
- Only one interaction point at a linear collider
- Plan to exchange ILD and SiD regularly for data taking
- Movable platforms, keeping all services connected
- Fast alignment

Calorimeter optimised for particle flow

Pursued for ILC, CLIC, CEPC and FCC-ee

- Jet energy resolution (JER) requirements depend on physics goals
- Starting point for LC detector design
  - → Ability to separate hadronic W and Z decays





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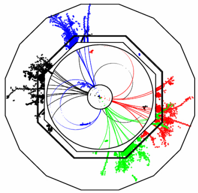
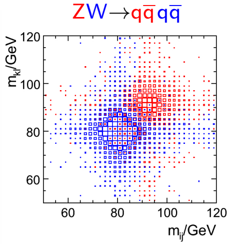
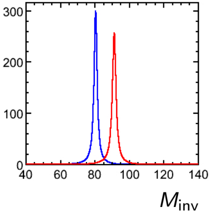
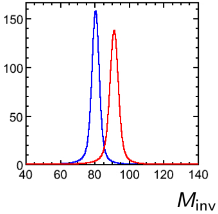




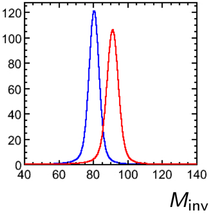
Perfect → 3.1σ W/Z sep.



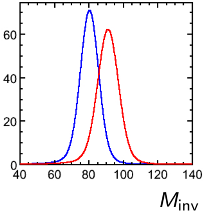
2% JER → 2.9σ sep.



3% JER → 2.6σ sep.



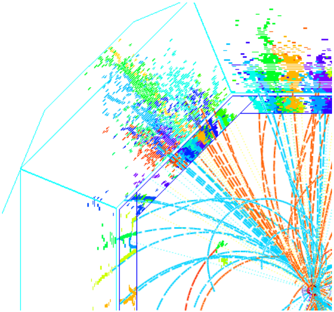
6% JER → 1.8σ sep.

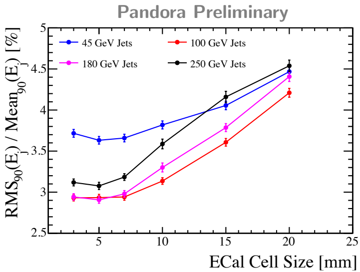


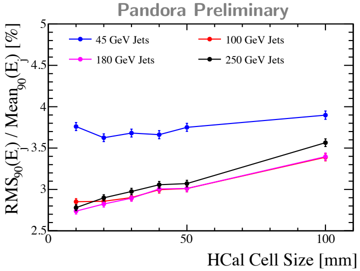
- 3%–4% jet energy resolution gives $\sim 2.6 - 2.3\sigma$ W/Z separation

Optimise calorimeter for particle flow

→ Reco. details next slide







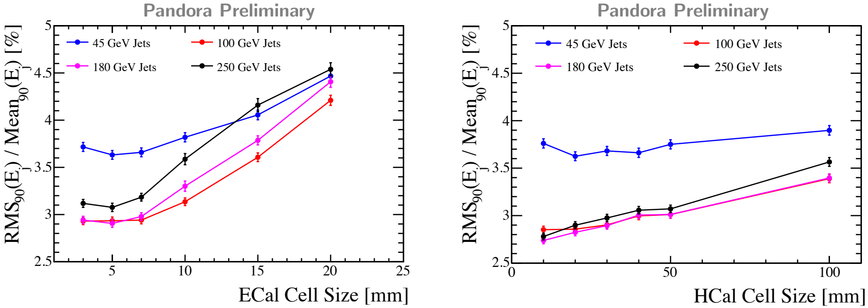
- High granularity of calorimeters
  - → Separate overlapping showers to reduce confusion

$$\sigma_{\text{jet}} = \sqrt{\sigma^2_{\text{track}} + \sigma^2_{\text{el.-m.}} + \sigma^2_{\text{had.}} + \sigma^2_{\text{confusion}}}$$

- JER of 3%–4% when using
  - → ECAL cell size: $\sim 1 \times 1\,\text{cm}^2$
  - → HCAL cell size: $\sim 3 \times 3\,\text{cm}^2$

rms_{90} and mean_{90} $\hat{=}$ rms and mean in smallest range of E_{rec} dist. containing 90% of events

Reconstruction information for cell size optimisation



- HCal timing cuts: 100 ns
- ECal timing cuts: 100 ns
- HCal Hadronic Cell Truncation: Optimised for each detector model
- Software: ilcsoft_v01-17-07, including PandoraPFA v02-00-00
- Digitiser: ILDCaloDigi, realistic ECal and HCal digitisation options enabled
- Calibration: PandoraAnalysis toolkit v01-00-00

More details in LCWS2015 talk by Steven Green