Summer Student Seminar

Detectors for the Compact Linear Collider

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July 26, 2013

Please,
feel free to ask questions at any time!

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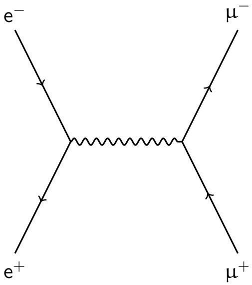
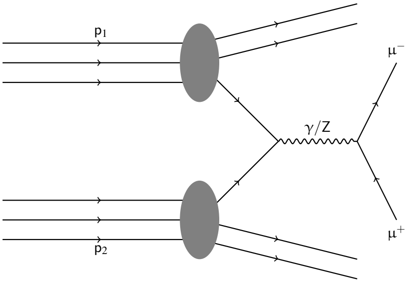
5 Summary

Physics Motivation and Implication for Detector Requirements

Motivation for e^+e^- Collider

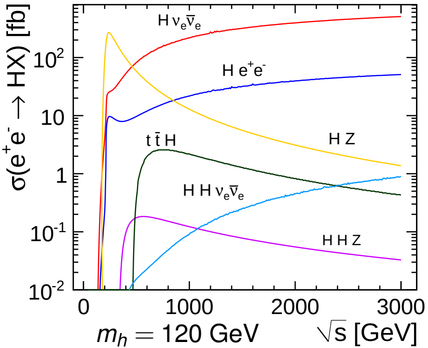
- An electron–positron collider enables precision measurements
- Electrons/Positrons allow precise selection of centre-of-mass energy and polarisation
- Smaller total cross-section; can do trigger-less readout
- No underlying event from proton remnants

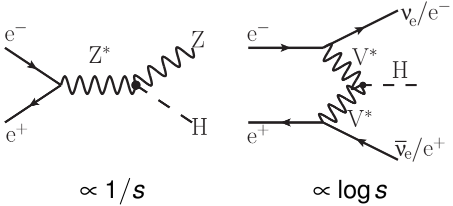




Precision Measurements of SM Higgs Properties

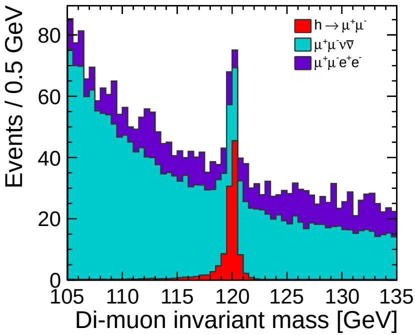
- High energy e^+e^- colliders allows the measurement of fundamental properties of the Higgs boson with high precision
- Vector boson fusion cross-section rising with centre-of-mass energy $\sqrt{s} \to$ large number of higgses produced
- At 3 TeV access to rare Higgs decays, enabling branching ratio measurements: $h \to \mu\mu, h \to c\bar{c}$
- Measurement of tri-linear Higgs coupling possible

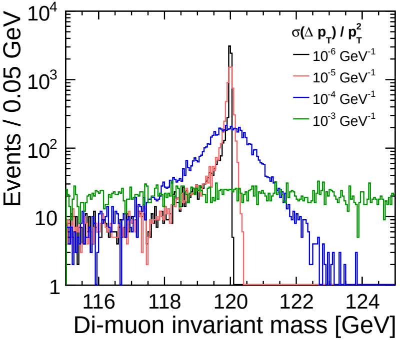




E.g., Branching Ratio of Higgs to Muons

- Higgs couples proportional to particle masses
- Very small probability for decay to muons
- To identify muons from Higgs on top of background an **excellent momentum reconstruction** $\Delta p_\mathrm{T}/p_\mathrm{T}^2 = 10^{-5}$ **required**, as otherwise the invariant mass peak becomes to broad



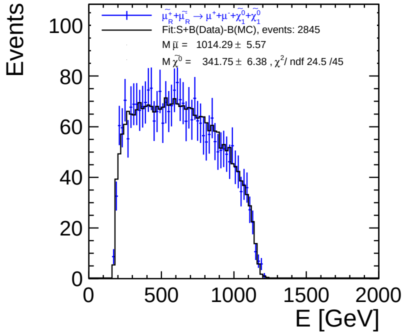


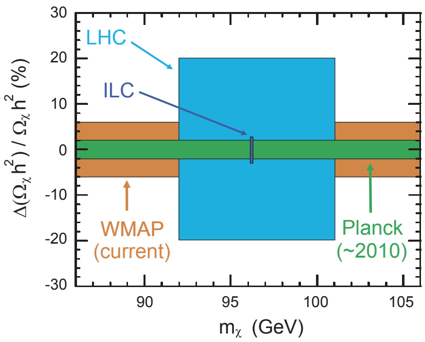
Measuring Dark Matter

- BSM models attractive candidates for dark matter: Neutralinos $\tilde{\chi}^0$
- Measurement of slepton (selectron, smuon) and Neutralino masses from endpoints of lepton energy spectra

$$E_{\mathrm{max,min}} = \frac{\sqrt{s}}{4}\left(1 \pm \sqrt{1 - \frac{4m_{\tilde{\ell}}^2}{s}}\right)\left(1 - \frac{m_{\tilde{\chi}^0}^2}{m_{\tilde{\ell}}^2}\right),$$

- Compared to dark matter relic density from cosmological measurements
- Linear collider will be able to more precisely determine possible DM candidate





Physics Reach

LC physics potential is complementary to the LHC

- Beyond the LHC discovery reach
  - e^+e^- collisions give access to additional physics processes
    - Weakly interacting states (e.g. slepton, chargino, neutralino searches)
    - Cleaner conditions than at the LHC

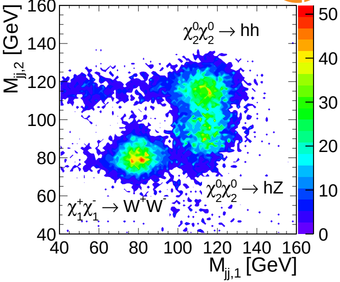
Physics reach at different colliders

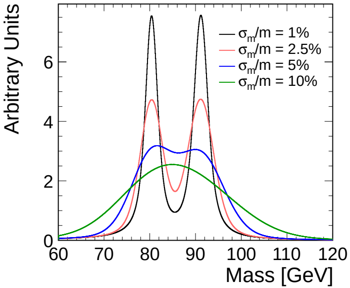
	LHC14 100 fb^{-1}	HL-LHC 1 ab^{-1}	CLIC3 1 ab^{-1}
squarks [TeV]	2.5	3	1.5
sleptons [TeV]	0.3		1.5
$Z'_{\text{(SM couplings)}}$ [TeV]	5	7	20
2 extra dims M_D [TeV]	9	12	20–30
μ contact scale [TeV]	15		60
Higgs compos. scale [TeV]	5–7	9–12	30
TGC (95%) (λ_γ coupling)	0.001	0.0006	0.0001

CERN-2012-003, CERN-TH/2001-023

Jet Energy Reconstruction

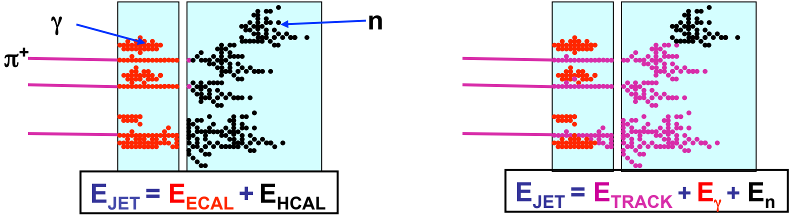
- For some measurements it is necessary to distinguish whether a jet is coming from a W or Z Boson
  - E.g.: Gaugino pair production and their subsequent decay into different bosons
- This requires a **good jet energy (or jet mass) reconstruction**
- Plot on the right shows the energy spectrum of reconstructed jet masses with a given jet mass resolution





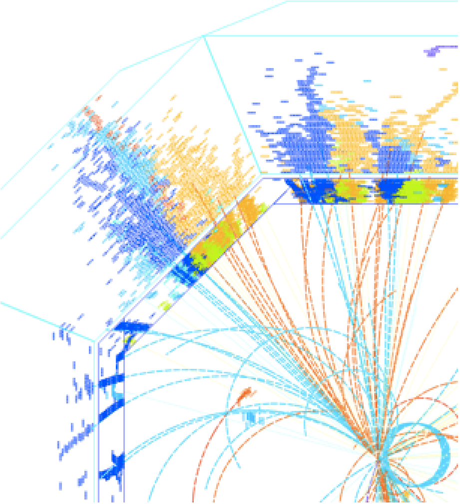
Particle Flow I

- Goal: Improve jet energy reconstruction by reconstructing all visible particles from the collision (esp. in jets)
- Approach: Reconstruct particles with highest resolution detector
  - Charged particles: Tracking detectors (**60%** of jet)
  - Photons: ECal (**30%** of jet, $\pi^0 \rightarrow \gamma\gamma$)
  - Neutral Hadrons: HCal (**10%** of jet, n and K^0_{long})
- Geometrically cluster showers to identify and separate clusters from neutral and charged particles
  - Requires high granularity calorimeters
  - Requires sophisticated clustering algorithms



Particle Flow II

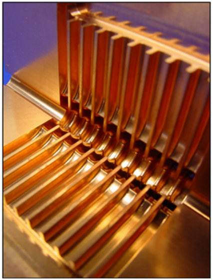
- Dense jets reconstructed with particle flow, different shower clusters are identified by colour



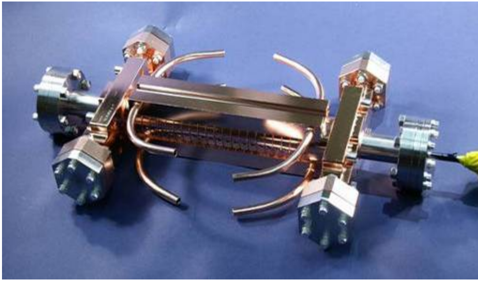
Following are a few slides about the accelerator

For all the details see lectures by D. Schulte on July 25&26

Compact Linear Collider

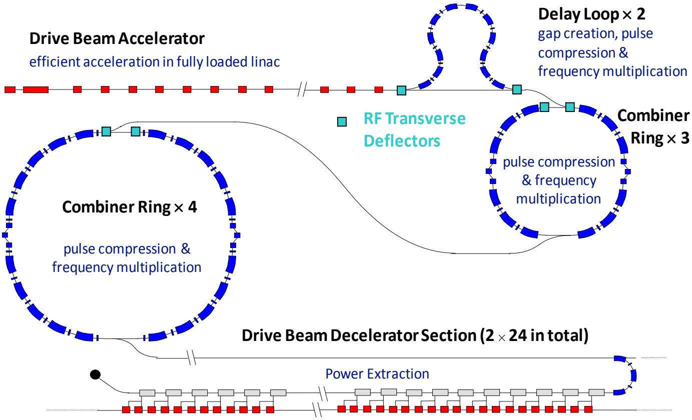


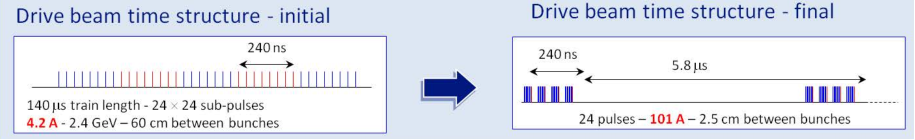
- Accelerator
  - Linear e^+e^- collider with c.m. energy between few hundred GeV and 3 TeV
  - Compact: 100 MV/m acceleration gradient using room-temperature 12 GHz copper cavities
  - Two-beam acceleration scheme: Klystrons used to efficiently accelerate a low energy high current drive-beam which transports the power to the low current main beam



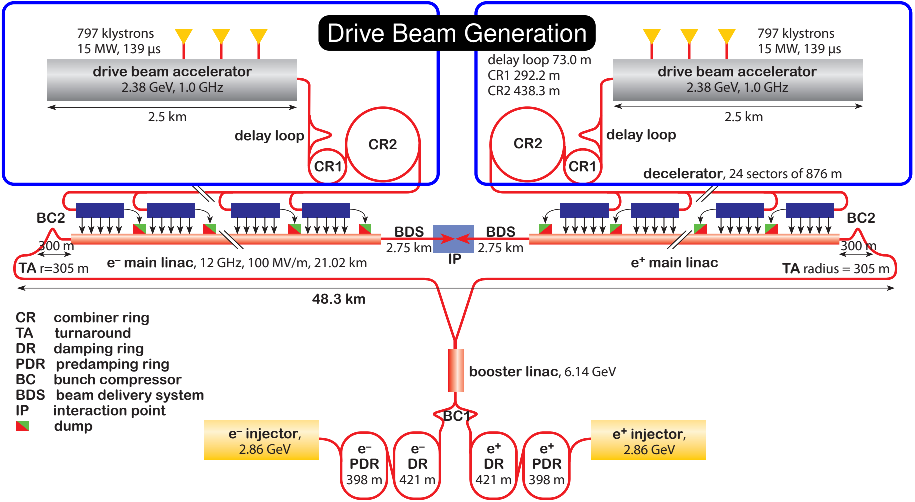
Drive Beam Generation

Full CLIC drive beam complex





CLIC $\sqrt{s} = 3$ TeV Layout



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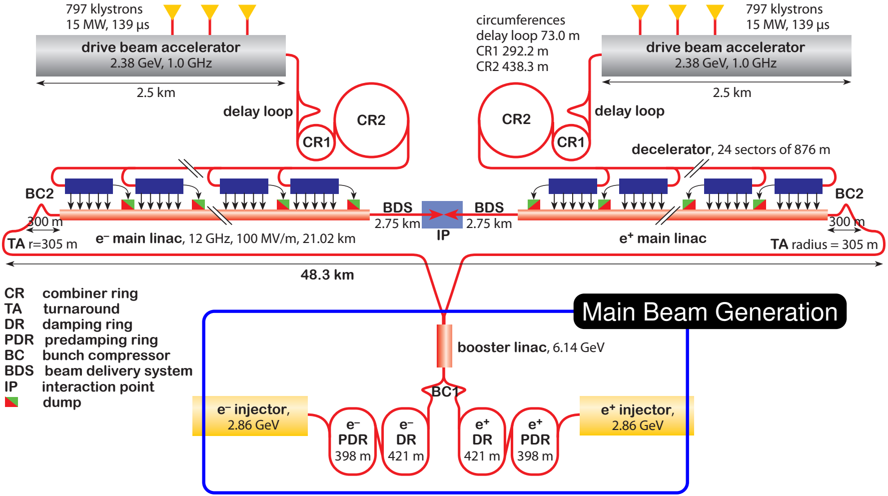
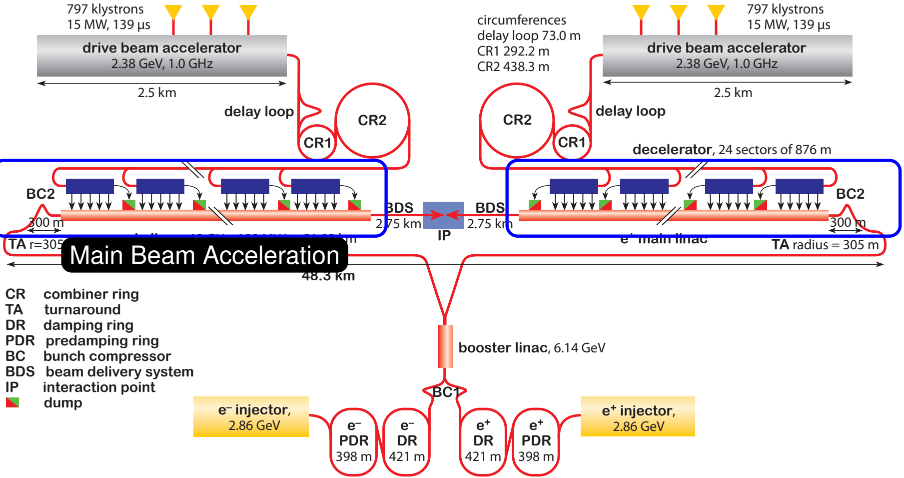


CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
	dump

CLIC $\sqrt{s} = 3$ TeV Layout



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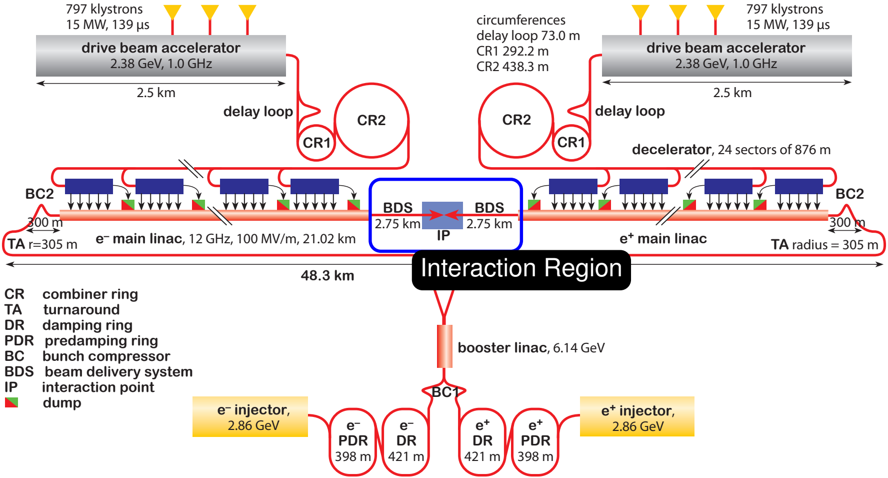
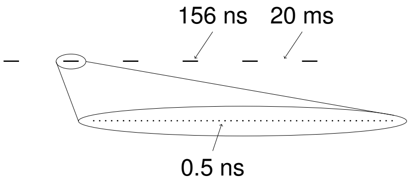


CLIC Accelerator Parameters

- Beam parameters come from global optimisation of parameters
- For high luminosity nanometre beam sizes necessary
- Very short bunch crossing (BX) separation: 0.5 ns
- Has large impact on detector requirements (see later)

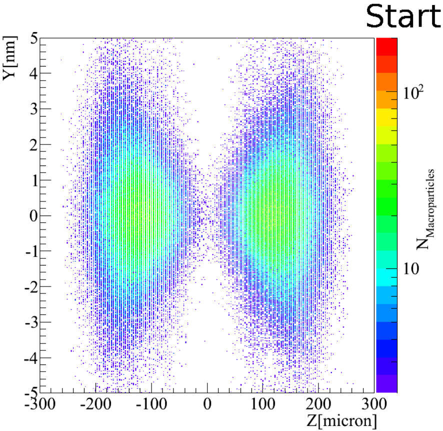


CLIC: trains at 50 Hz, 1 train = 312 bunches

	CLIC 3 TeV	LHC 14 TeV
Luminosity [$10^{34}/\text{cm}^2/\text{s}$]	5.9	1.0
Beam size in $X/\ Y/\ Z$	45 nm/1 nm/44 µm	16.7 µm/16.7 µm/7.55 cm
Bunch charge	$3.72 \cdot 10^9$	$1.15 \cdot 10^{11}$
BX separation	0.5 ns	25 ns
Bunches per train	312	2808
Repetition rate	50 Hz	11.2 kHz

Luminosity, Beam-Beam Effects, and Beam-Induced Backgrounds

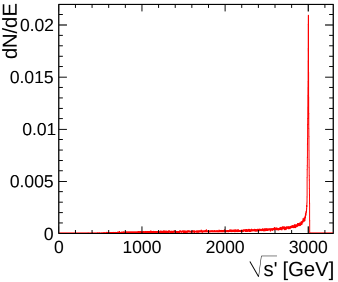
- Large luminosities, necessary to study rare processes, require high bunch charge and small beams (given the other constraints from the accelerator) $L \propto \frac{N^2}{\sigma_x \sigma_y}$
- Which leads to large electromagnetic fields during bunch crossing $B \propto \frac{\gamma N}{\sigma_z(\sigma_x + \sigma_y)}$
  - Also the reason one uses flat beams: $\sigma_y \ll \sigma_x$
- The bunch particles are strongly deflected by the fields

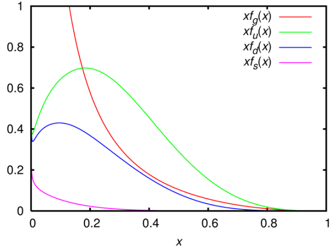


N.b.: Factor 1000 between Y and Z!

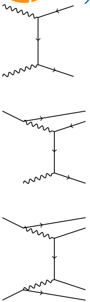
Beamstrahlung, Energy Loss, and Luminosity Spectrum

- The deflection leads to radiation: Beamstrahlung
- Energy loss due to Beamstrahlung results in e^+e^- collisions below the nominal centre-of-mass energy $\sqrt{s'} = 2\sqrt{E_1 E_2}$
  - Only (Still!) 30% of luminosity above 99% of nominal energy, and 76% above 70% of nominal energy
- Compare to parton density functions (right below): x is fraction of momentum carried by proton constituent or sea quarks and gluons
  - At much lower fraction of total momentum and much broader

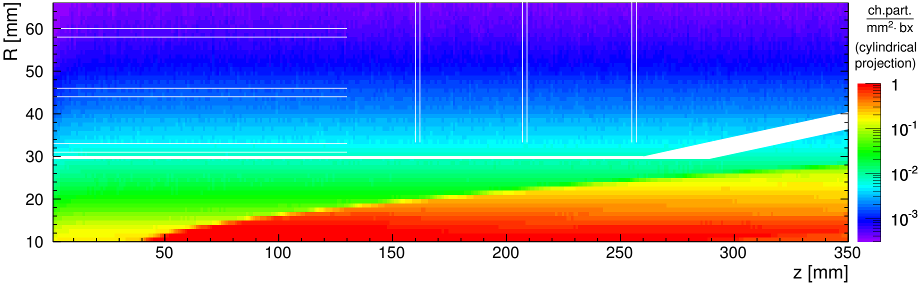




Beam-Induced Backgrounds I



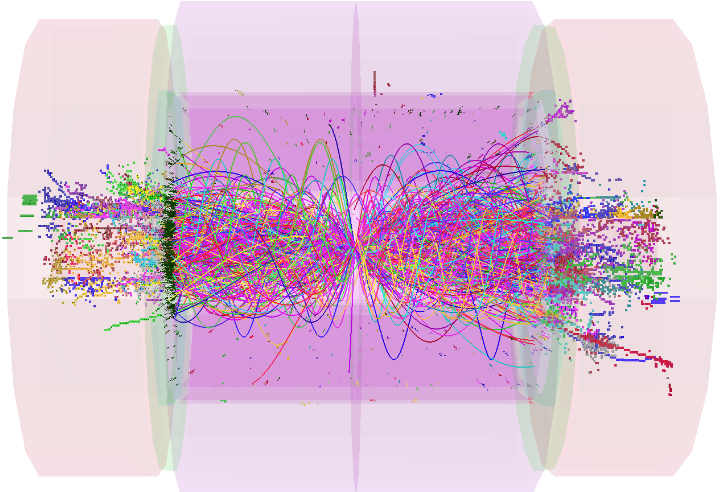
- Large photon flux leads to production of $e^{+}e^{-}$ pairs
  - At 3 TeV each bunch particle emits 2.2 photons on average
- There are 340k electrons/positrons produced per BX
- Only about 60/BX have large enough p_{T} to reach into the vertex detector



Beam-Induced Backgrounds II

- Also to $\gamma\gamma \to$ hadron events, in which photons interact hadronically
- At small angles in the end-cap of the detector
- 20 TeV of reconstructed energy in calorimeters

20 BX of $\gamma\gamma \to$ hadron Background in a Detector



Summarising the Detector Requirements

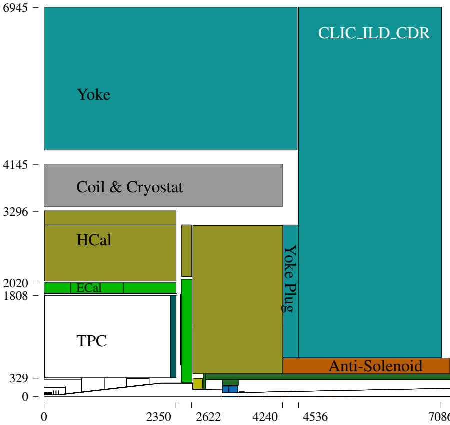
- To perform all possible physics measurements with high precision, the detector has to be able to:
  - reconstruct charged particle momenta with high precision;
  - identify jets from heavy quarks (flavour tagging/vertex reconstruction).
  - separate jets from different gauge bosons;
  - separate background particles from physics events;
  - do fast time-stamping to cope with the small bunch separation;
  - have a low material budget, low power consumption so air cooling is possible, and take advantage of the train structure to do power pulsing.

Detector Requirements Compared to Leading Experiments

Detector feature	Performance compared to leading experiments
Pixel size	20× smaller than LHC
Impact parameter resolution	3× better than SLD
Track momentum resolution	10× better than LEP
Material budget	10× lower than LHC in central region
Jet energy resolution	3× better than CMS 2× better than ZEUS
Calorimeter granularity	200× higher than LHC

CLIC Detector Example

- Precise vertexing and tracking
  - Silicon pixel detectors with very small material budget
  - Main Tracker: time projection chamber or pure silicon-tracking
- High granularity calorimeters inside the coil:
  - optimized for *Particle Flow*
  - 4/5 T Solenoid to separate neutral and charged hadrons
- Very forward region
  - Hermeticity, backgrounds, back-scatters, final focus



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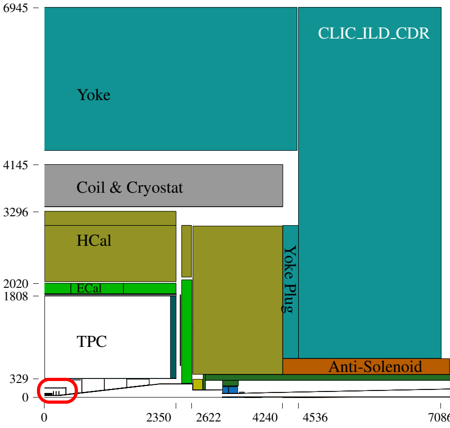

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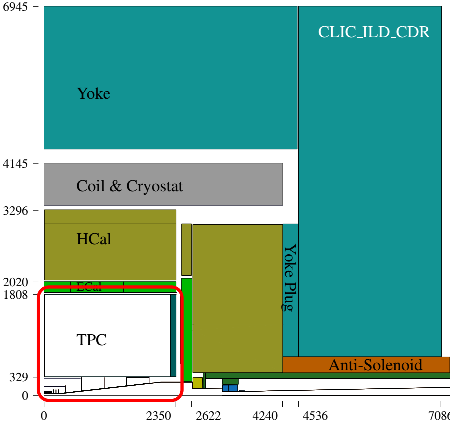

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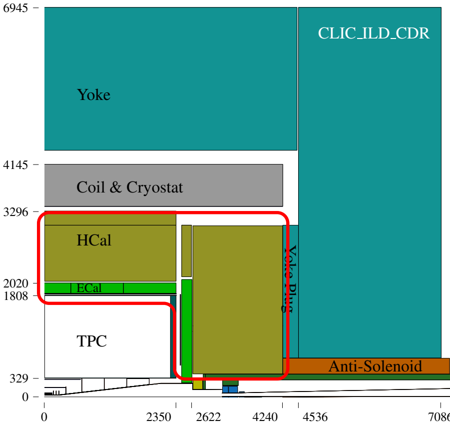

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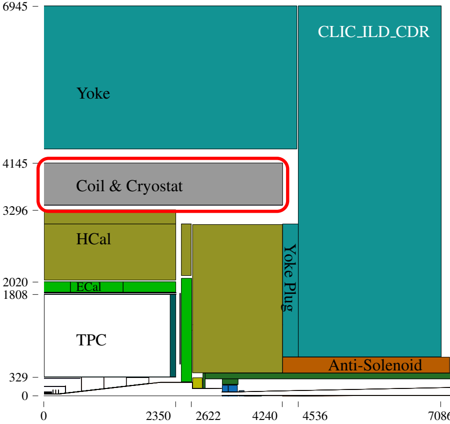

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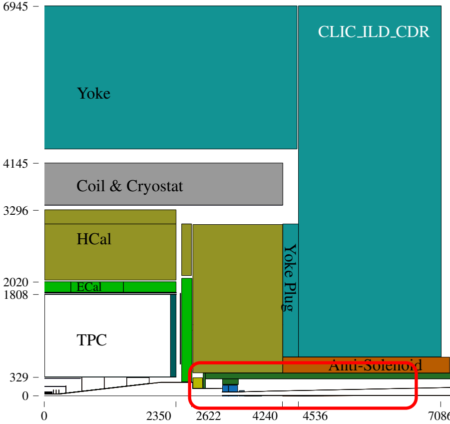
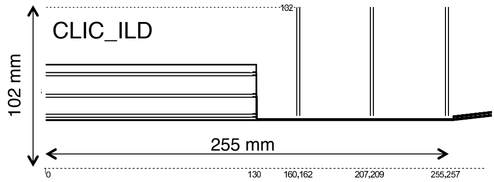
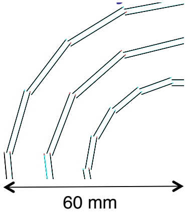
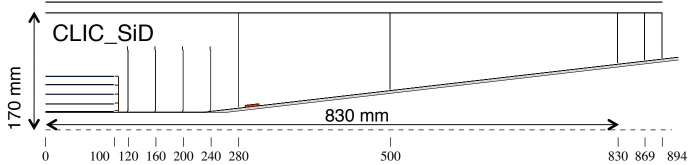
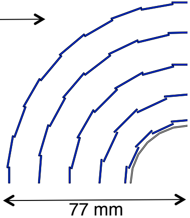


Vertex Detector Layouts









	CLIC_ILD	CLIC_SiD	CMS
Material x/X_0 (at 90°)	0.9% (3 × 2 layer)	1.1% (5 layer)	10% (3 layer)
Pixel size	$20 \times 20\ \mu m^2$	$20 \times 20\ \mu m^2$	$100 \times 150\ \mu m^2$
# pixels	1.84 G	2.76 G	66 M
Time resolution	≈ 10 ns	≈ 10 ns	$\lesssim 25$ ns
Avg. power/pixel	$\lesssim 0.2\ \mu W$	$\lesssim 0.2\ \mu W$	$28\ \mu W$

Tracking

- Momentum p_T reconstruction based on measuring bending radius R of a track in magnetic field B:

$$p_\mathrm{T} = \frac{c}{10^9} BR$$

- The uncertainty is coming from the uncertainty ε for each of N measured points

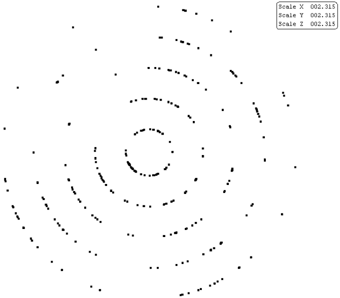
$$\delta_\mathrm{points} \propto \frac{\varepsilon}{L'^2}\sqrt{\frac{720}{N+4}}$$

- And from the multiple scattering in material (radiation length X_0)

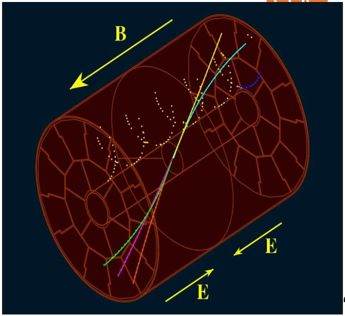
$$\delta_\mathrm{MS} \propto \frac{1}{p_\mathrm{T}\sqrt{LX_0}}$$

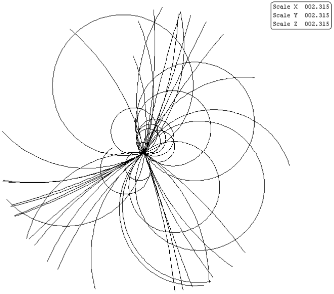
Pure Silicon-Main-Tracker

- Pure silicon-tracking
  - Vertex Detector and Tracker together
  - Small pixels in vertex detector, 10 cm long strips (25 µm pitch)
- A few (10) well measured points: $\sigma_{r\phi} \approx 5\ \mu\mathrm{m}$



Time Projection Chamber



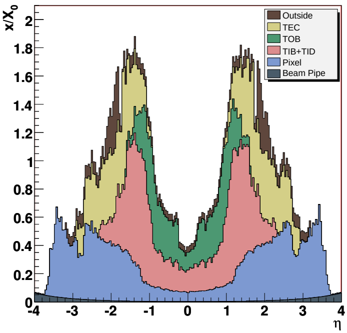


- Very low central material budget
- Many many hits, but somewhat worse resolution: $\sigma_{r\phi} \approx 50\,\mu\text{m}$–$100\,\mu\text{m}$
- Slow readout, because of drift to the end-plate

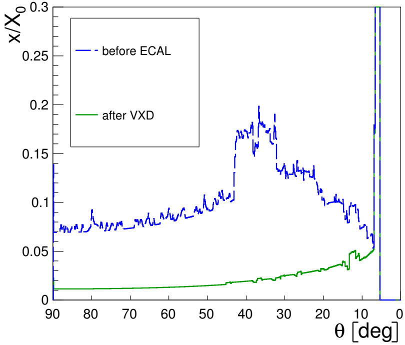
Material Budgets

- Momentum and vertex resolution is reduced by multiple scattering and bremsstrahlung
  - $\rightarrow$ Low material budget tracker

CMS material budget in tracker



CLIC_SiD



$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$ $\eta = 1 \rightarrow \theta = 40^\circ$ $\eta = 2 \rightarrow \theta = 10^\circ$,

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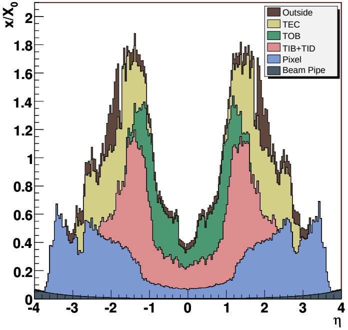
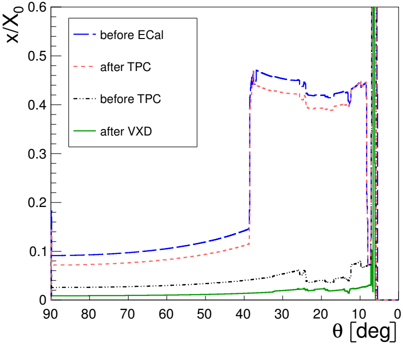
CMS material budget in tracker



CLIC_ILD



$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$ $\eta = 1 \rightarrow \theta = 40^\circ$ $\eta = 2 \rightarrow \theta = 10^\circ$,

Calorimeters

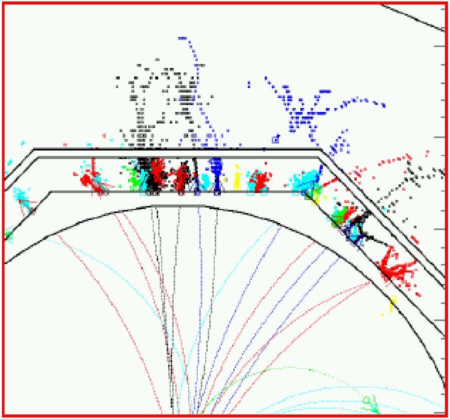
- Particle Flow requires high granularity calorimeters with segmentation in all three dimensions: *Tracking Calorimeters*
- Barrel calorimeter have to be placed inside the solenoid to match showers and tracks
- Energy resolution (ideally):

$$\frac{\sigma_E}{E} \propto \frac{\alpha}{\sqrt{E}},$$

with α as small as possible.

Electromagnetic Calorimeter (ECal)

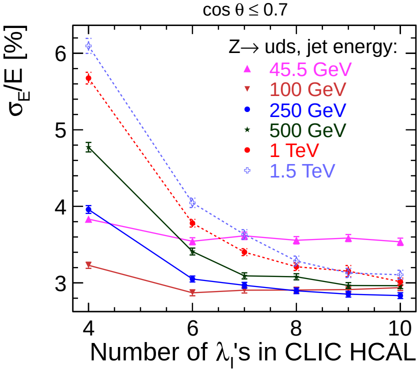
- Silicon-Tungsten sandwich calorimeter, 25 radiation lengths
- Good energy resolution $20\%/\sqrt{E}$
- Small Molière radius* to separate adjacent showers
- Small cells: 13.5 mm^2 to 25 mm^2
- Longitudinal segmentation to separate e.m. and hadronic showers
- CMS/Atlas have better resolution, but only 1 or 3 radial segments, respectively
- Huge area of silicon detectors very expensive, recently started studying scintillator pad alternative



*Radius around shower axis that contains 90% of energy

Hadronic Calorimeter (HCal)

- Typical 3 TeV CLIC jet energies require 7.5 nuclear interaction lengths in HCal
- Coil radius limited, need dense absorber
  - Study the possibility of tungsten as an absorber for hadron calorimeter
  - Tungsten has not been used in HCals before
  - Have to study the performance for hadronic showers in tungsten

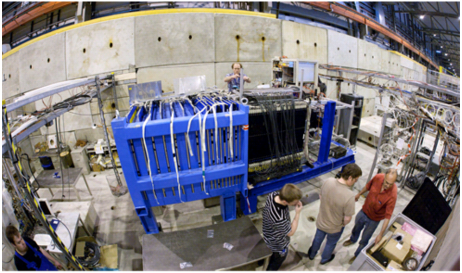


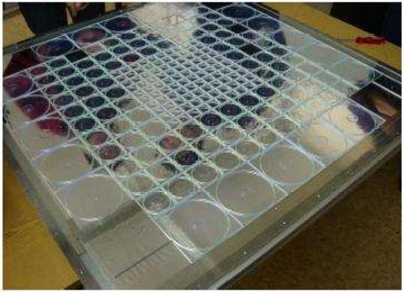
Readout Technologies

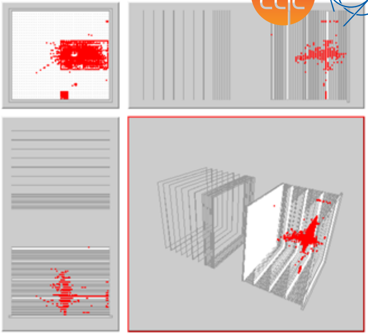
- Primary-particle energy proportional to
  - deposited energy: $E_{\text{part}} \propto E_{\text{dep}}$
  - number of secondary particles or number of hits: $E_{\text{part}} \propto N_{\text{secondary}}$
- Analog HCal (AHcal)
  - Record deposited energy for each pad
  - Pad size (3×3 cm^2)
- Digital HCal (DHcal)
  - Store only single bit: pad on/off
  - Pad sizes: 1×1 cm^2
    - ⋆ cell size has to be smaller than shower size (or saturation effects reduce resolution)

HCal Testbeams

AHcal







DHcal

Summary

- Detector design is a very integrated task
- For Particle Flow all sub-detectors have to be optimised together
- Take into account constraints and requirements from
  - Accelerator
  - Physics
  - Sensors
  - Engineering (did not touch on this)

More Question Time. . .