Physics and detector studies for the CLIC multi-TeV e^+e^- collider

Outline:

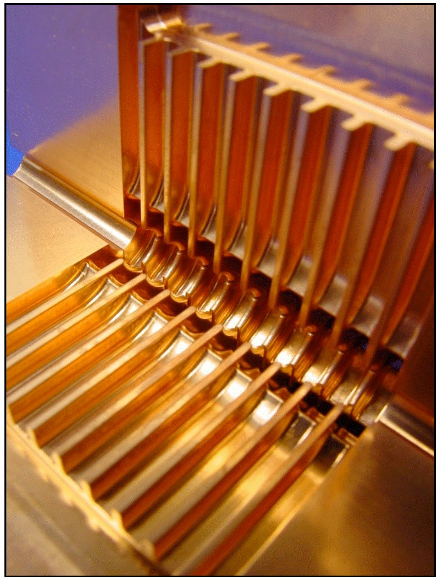
- Introduction
- CLIC physics potential
- CLIC detector requirements
- Current activities and R&D plan
- Summary

Lucie Linssen

CIEMAT 3/12/2009

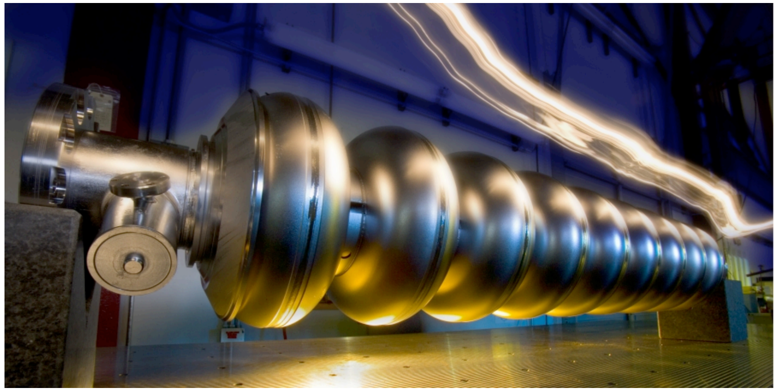
ILC and CLIC in a few words…

linear collider, producing e^+e^- collisions



CLIC

ILC



- Based on superconducting RF cavities
- Gradient 32 MV/m
- Energy: 500 GeV, upgradeable to 1 TeV (~200 GeV ZZ is also considered)
- Detector studies focus mostly on 500 GeV

- Based on 2-beam acceleration scheme
- Gradient 100 MV/m
- Energy: 3 TeV, though will probably start at lower energy (~0.5 TeV)
- Detector study focuses on 3 TeV

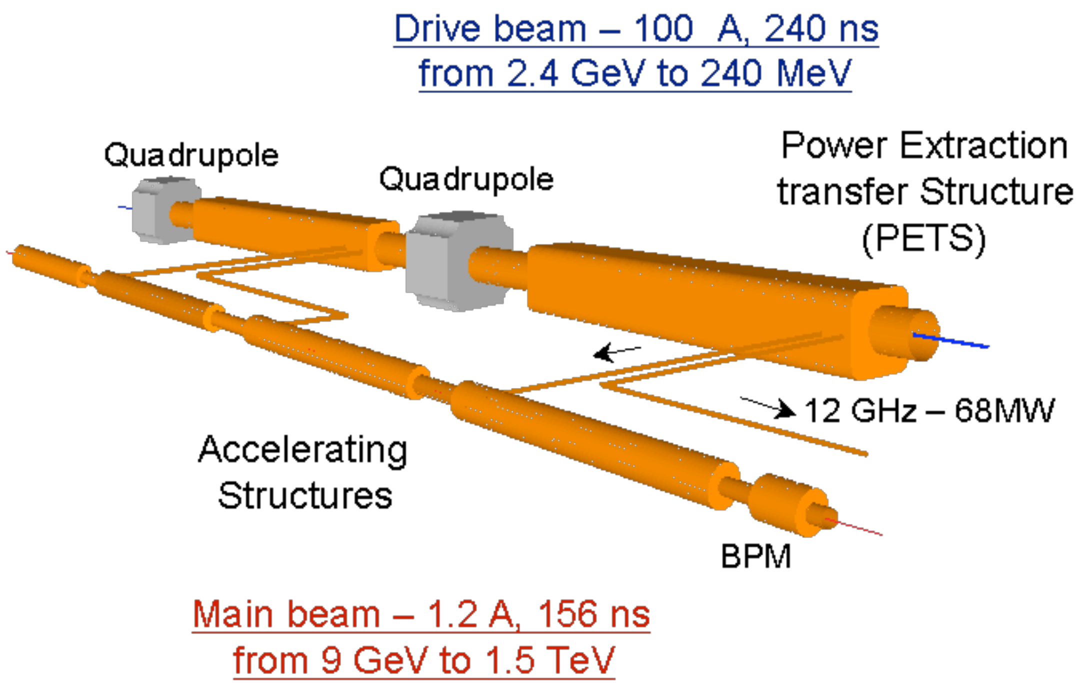
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

The CLIC Two Beam Scheme

Two Beam Scheme:

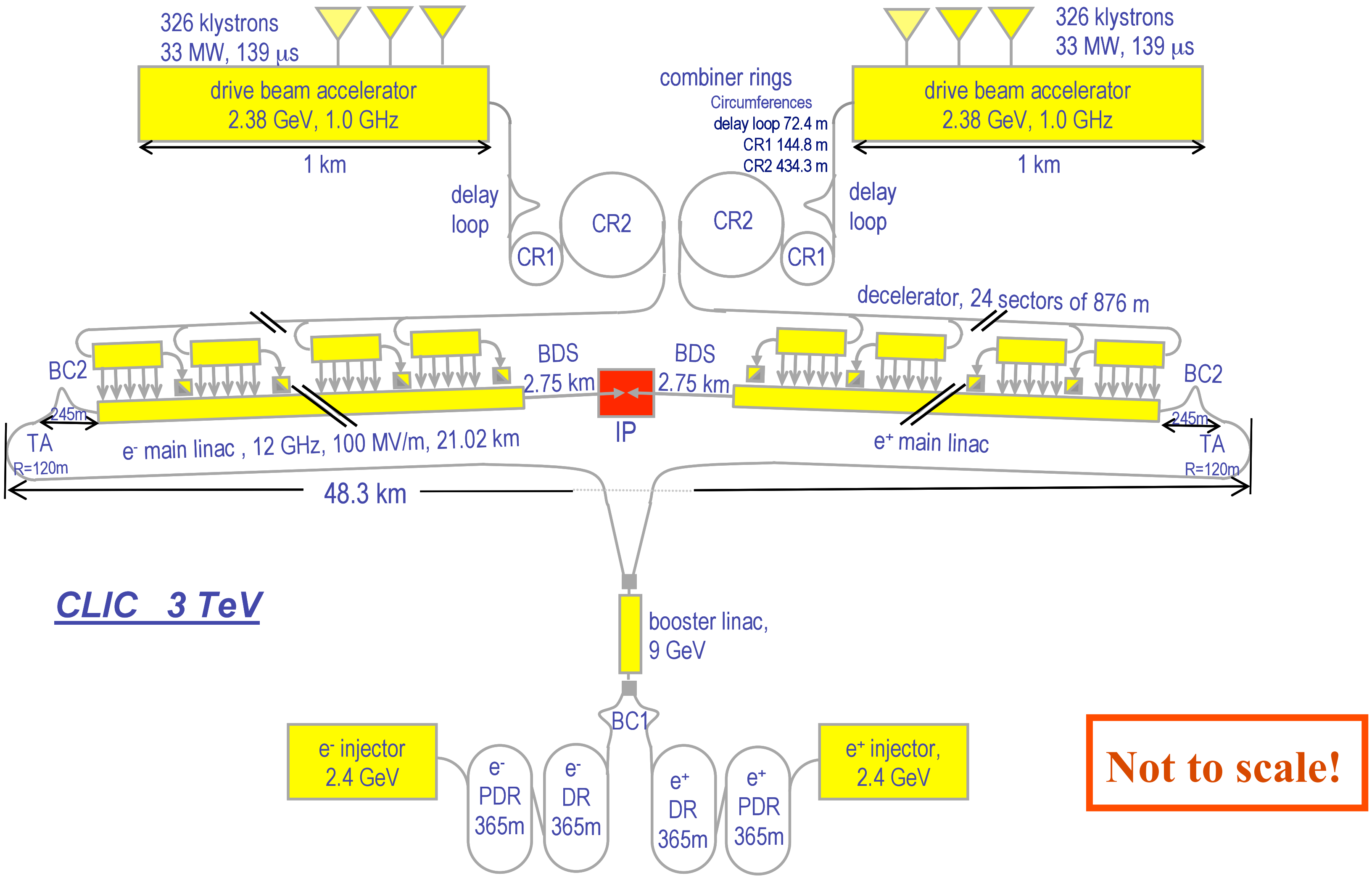
Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



No individual RF power sources

The full CLIC scheme



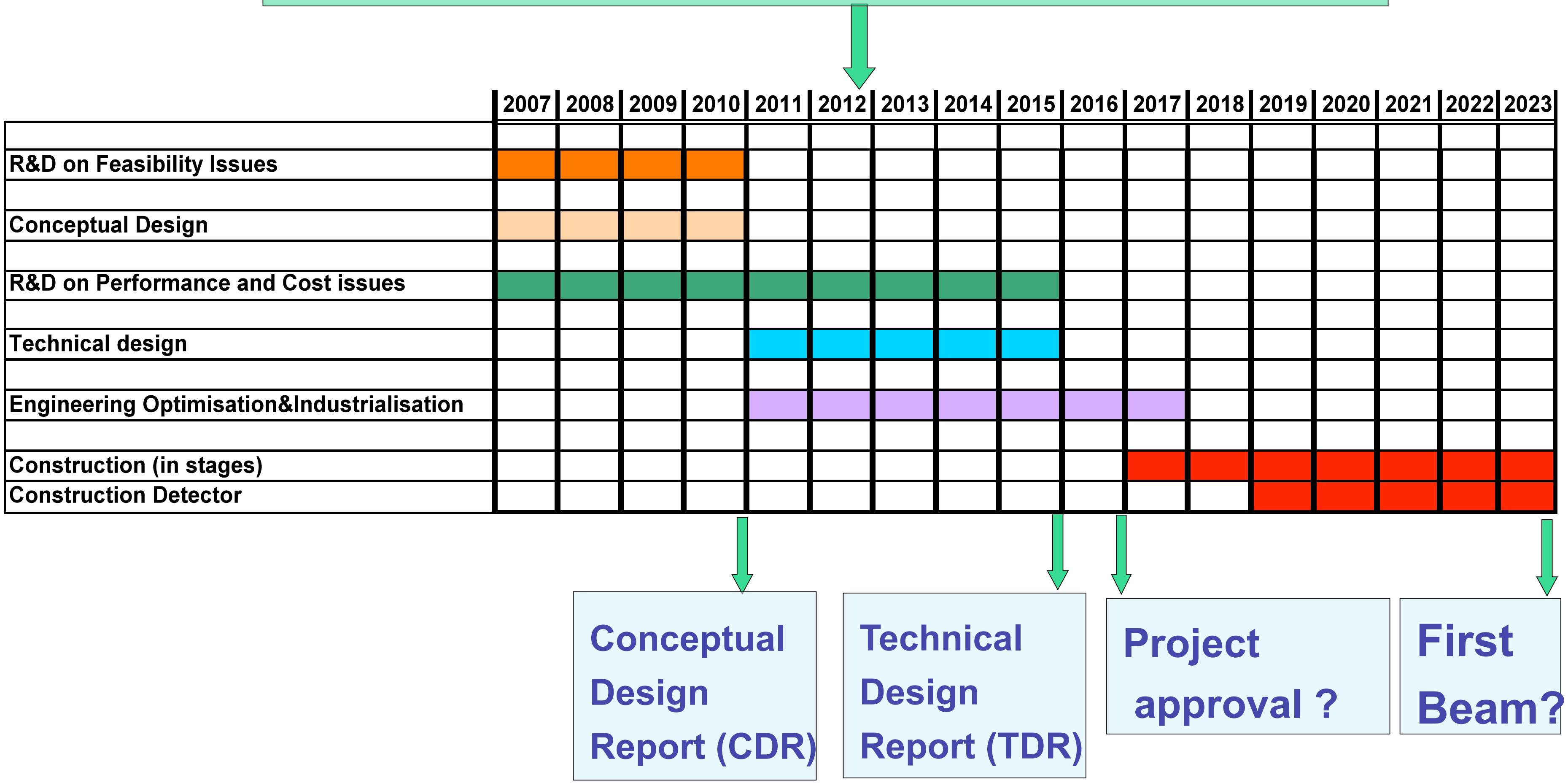
CLIC parameters

Center-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Total (Peak 1%) luminosity [$\cdot 10^{34}$]	2(1.5)	2.3 (1.4)	5.9 (2.0)
Repetition rate (Hz)	5	50	
Loaded accel. gradient MV/m	32	80	100
Main linac RF frequency GHz	1.3	12	
Bunch charge [$\cdot 10^9$]	20	6.8	3.7
Bunch separation (ns)	370	0.5	
Beam pulse duration (ns)	950μs	177	156
Beam power/beam (MWatts)		4.9	14
Hor./vert. IP beam size (nm)	600 / 6	200 / 2.3	40 / 1.0
Hadronic events/crossing at IP	0.12	0.2	2.7
Incoherent pairs at IP	$1 \cdot 10^5$	$1.7 \cdot 10^5$	$3 \cdot 10^5$
BDS length (km)		1.87	2.75
Total site length km	31	13	48
Total power consumption MW	230	130	415

Crossing Angle 20 mrad (ILC 14 mrad)

Tentative long-term CLIC scenario

Technology evaluation and Physics assessment based on LHC results for a possible decision on Linear Collider with staged construction starting with the lowest energy required by Physics



General Physics Context

- New physics expected in TeV energy range
  - E.g. motivated by particle astrophysics (dark matter)
  - Higgs, Supersymmetry, extra dimensions, …?

- LHC will indicate what physics, and at which energy scale (is 500 GeV enough or need for multi TeV?)

- Even if multi-TeV is final goal, most likely CLIC would run over a range of energies (e.g. 0.5 – 3.0 TeV)

CLIC physics up to 3 TeV

What can CLIC provide in the 0.5-3 TeV range?

Higgs physics:

•Complete study of the light standard-model Higgs boson, including rare decay modes (rates factor ~5 higher at 3 TeV than at 500 GeV)

- •Higgs coupling to leptons
- •Study of triple Higgs coupling using double Higgs production

•Study of heavy Higgs bosons (supersymmetry models)

Supersymmetry:

•Extensive reach to measure SUSY particles

And in addition:

•Probe for theories of extra dimensions

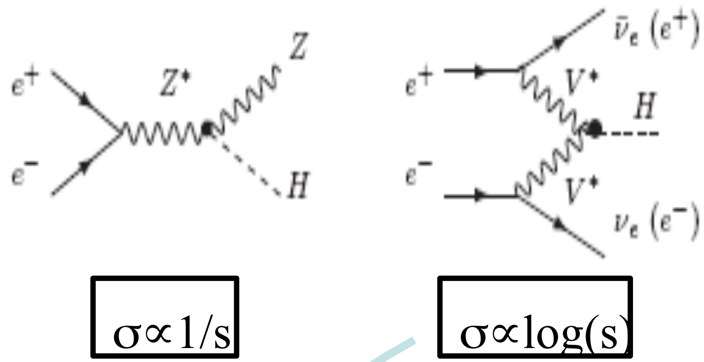
•New heavy gauge bosons (e.g. Z')

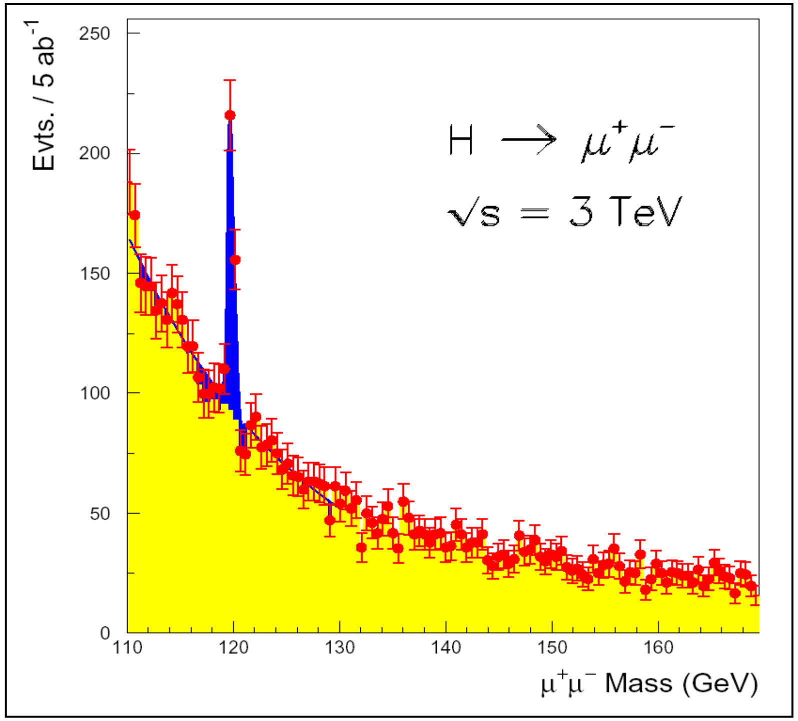
•Excited quarks or leptons

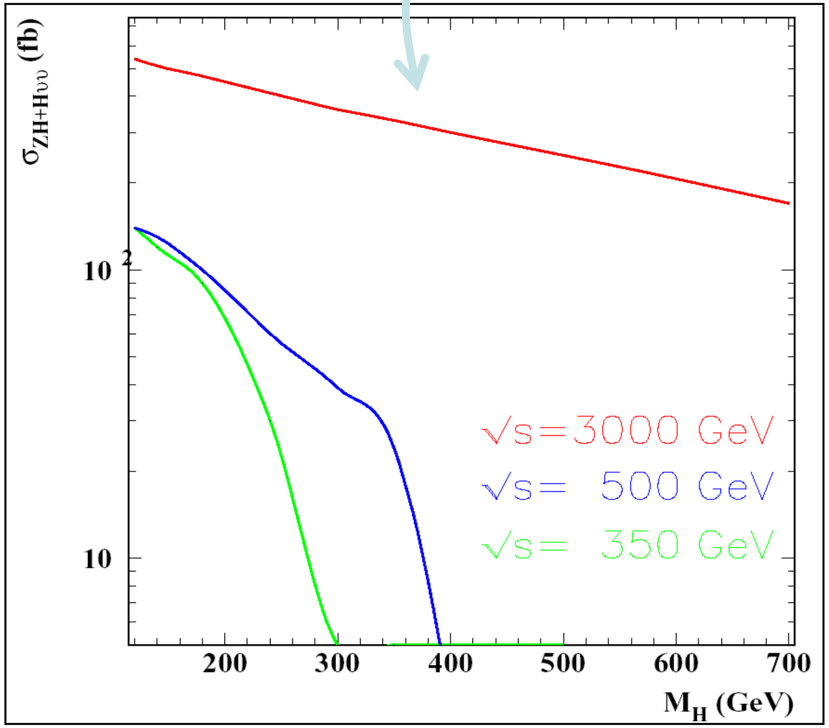
Example:…. light SM-like Higgs

The cross-section at ~3TeV is very large
→ access to very rare decays (BR~10^{-4}).

Measure Higgs couplings to leptons, for instance with 0.5 ab^{-1}, we expect ~70 $H \to \mu^+\mu^-$ decays for M_h=120 GeV/c^2, and measure the couplings with ~4% precision.





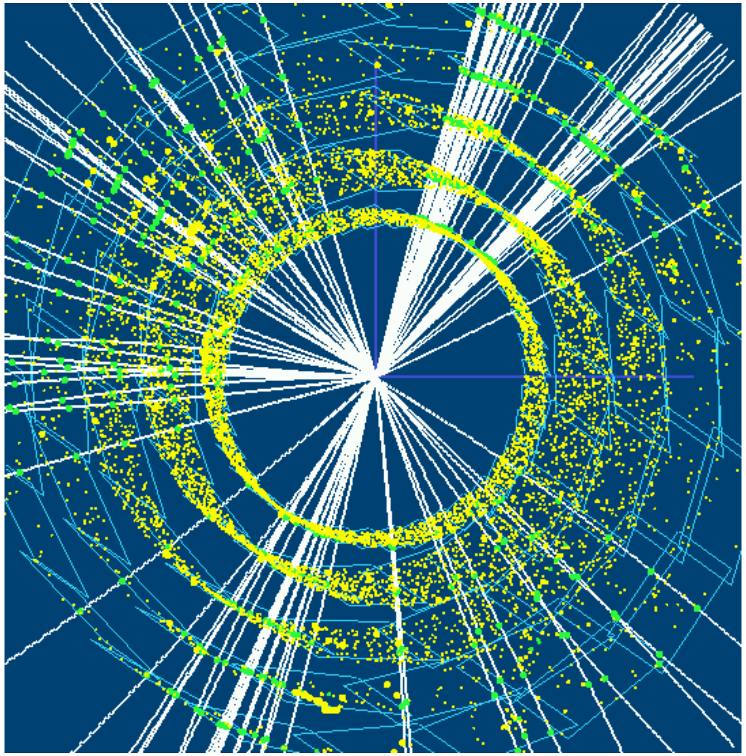


http://www.cern.ch/lcd Lucie Linssen, 3/12/2009

Example: heavy mass SUSY particles

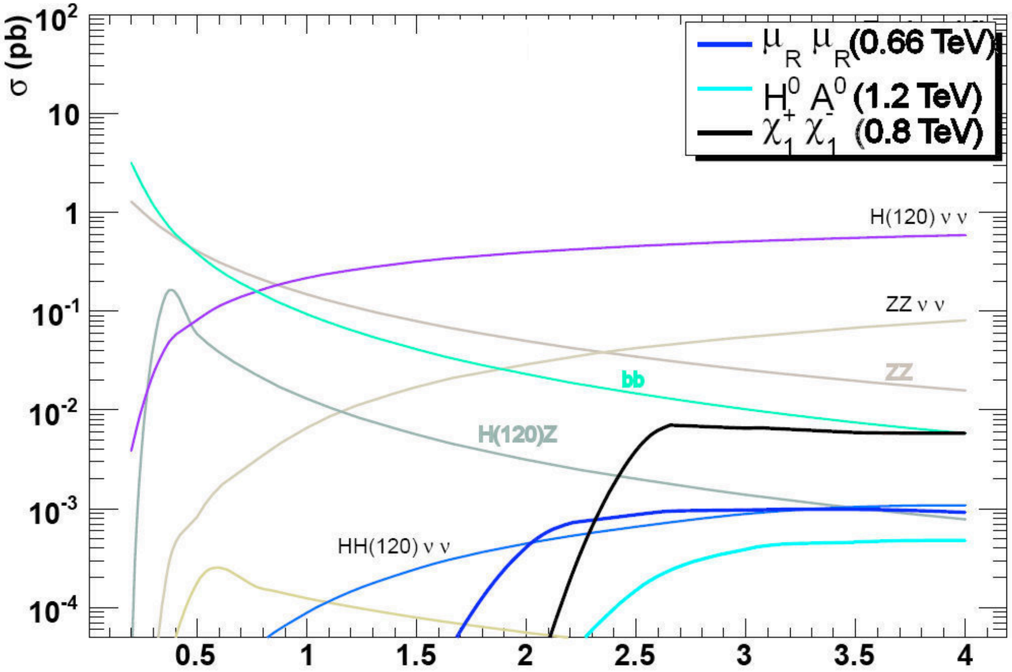
e.g. $e^+e^- \to H^0A^0$ production

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



$m_{H,A} \approx 1$ TeV
Yellow dots mostly from $\gamma\gamma$

s-channel vs t-channel cross sections



√S

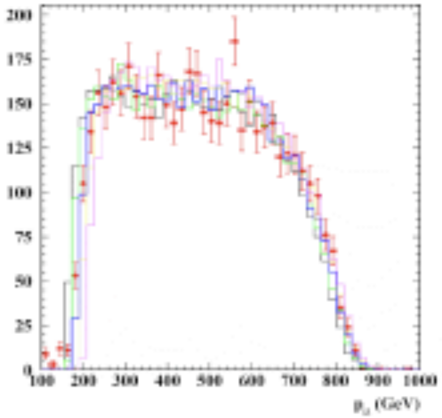
Marco Battaglia

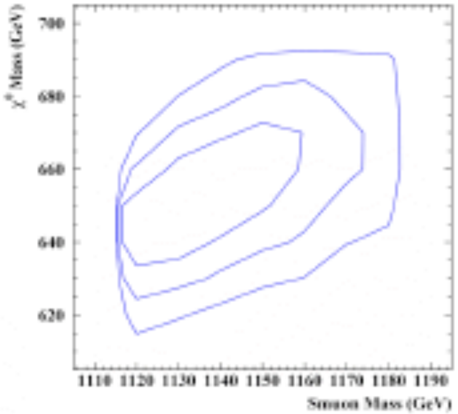
Example: SUSY mass measurement

Mass determinations: $e^+e^- \rightarrow \tilde{\mu}_L^+ \tilde{\mu}_L^- \rightarrow \mu^+ \chi_1^0 \mu^- \chi_1^0$

- If $\sqrt{s} >> 2\tilde{m}_\mu$, μ spectrum end points

$$E_{\min,\max} = \frac{\sqrt{s}}{4}\left(1 - \tilde{m}_\chi^2 / \tilde{m}_\mu^2\right)\left(1 \pm \sqrt{1 - 4\tilde{m}_\mu^2 / s}\right)$$





Two-parameter fit

$\tilde{m}_\mu = (1145 \pm 25)\,\mathrm{GeV}$ 2%

$\tilde{m}_\chi = (652 \pm 22)\,\mathrm{GeV}$ 3%

- Energy scan of cross section close to threshold

$\delta\tilde{m}_\mu = 15$ GeV

LHC mass determinations improve if info from CLIC is included in decay chains

Gian Giudice CLIC09

(S)LHC, ILC, CLIC reach

	LHC 100 fb^{-1}	ILC 800 GeV 500 fb^{-1}	SLHC 1000 fb^{-1}	CLIC 3 TeV 1000 fb^{-1}
Squarks [TeV]	2.5	0.4	3	1.5
Sleptons [TeV]	0.34	0.4		1.5
New gauge boson Z′ [TeV]	5	8	6	22
Excited quark q* [TeV]	6.5	0.8	7.5	3
Excited lepton l* [TeV]	3.4	0.8		3
Two extra space dimensions [TeV]	9	5–8.5	12	20-35
Strong $W_L W_L$ scattering	2σ	-	4σ	70σ
Triple-gauge Coupling (95%)	.0014	0.0004	0.0006	0.00013

Gian Giudice CLIC09

ILC=> CLIC detector requirements

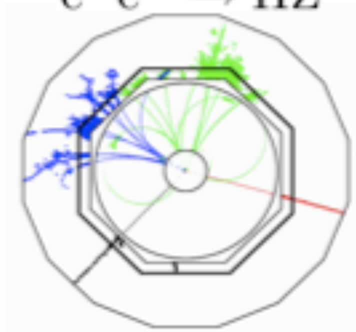
★ **momentum: (1/10 x LEP)**

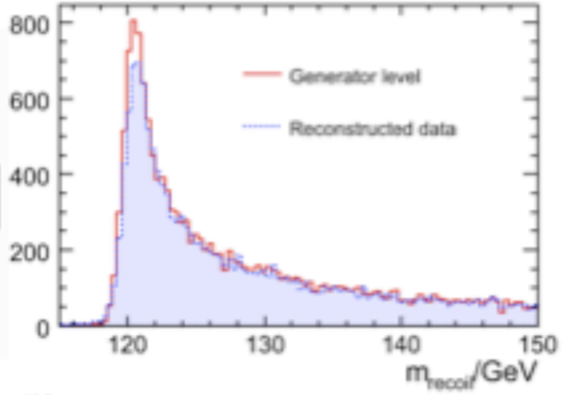
e.g. Muon momentum

Higgs recoil mass

$$\sigma_{1/p} < 5 \times 10^{-5}\,\mathrm{GeV}^{-1}$$

e⁺e⁻ → HZ



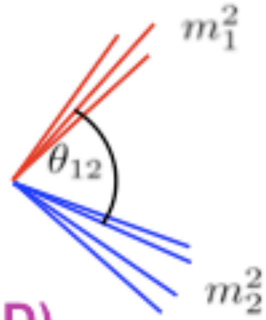


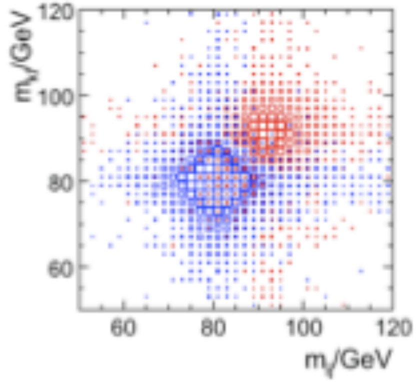
★ **jet energy: (1/3 x LEP/ZEUS)**

e.g. W/Z di-jet mass separation

EWSB signals

$$\frac{\sigma_E}{E} \approx 3-4\,\%$$



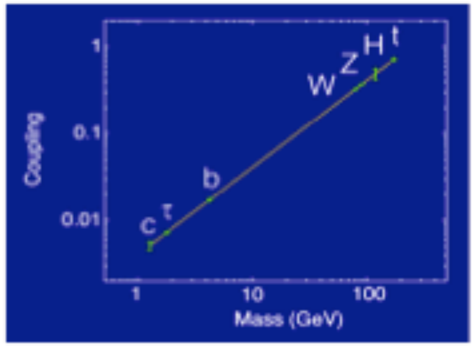


★ **impact parameter: (1/3 x SLD)**

e.g. c/b-tagging

Higgs BR

$$\sigma_{r\phi} = 5 \oplus 10/(p \sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$



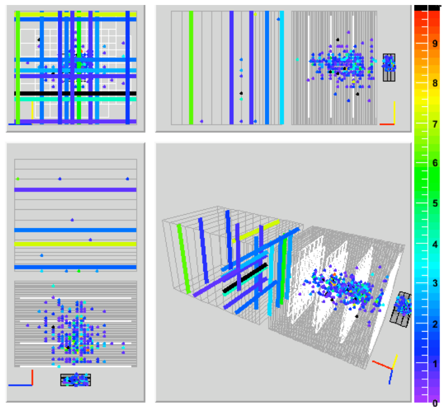
★ **hermetic: down to θ = 5 mrad**

e.g. missing energy signatures in SUSY

CLIC09, CERN, 13/10/2009 Mark Thomson 3

LC technology collaborations

Large international collaborations for Linear Collider detector technology studies:



CALICE

- Fine–grained calorimetry, based on particle flow analysis
- https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

LC-TPC

- Time projection chmber based on MPGD readout
- http://alephwww.mppmu.mpg.de/~settles/tpc/lp/wpmtg/wpmtg.html

SILC

- Silicon-based tracking technologies
- http://lpnhe-lc.in2p3.fr/

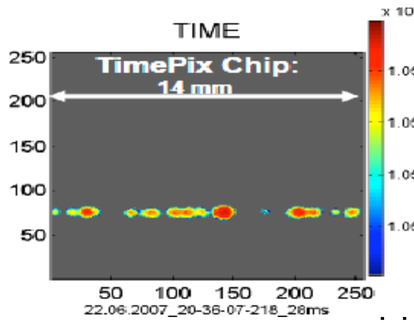
FCAL

- Very forward region: background studies and calorimetry
- http://www-zeuthen.desy.de/ILC/fcal/

EUDET

EU-funded FP6 project on LC detector technologies

http://www.eudet.org/



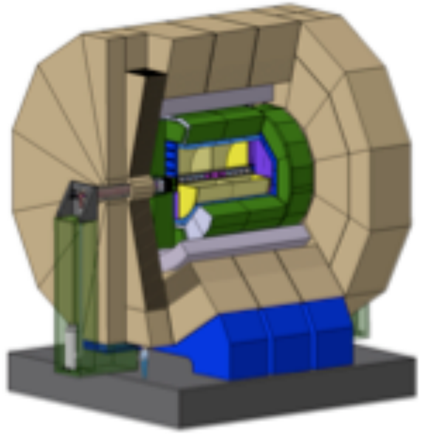
List not fully complete (e.g. vertex detector groups)

Until recently these technology collaborations concentrated on ILC

Validated ILC concepts

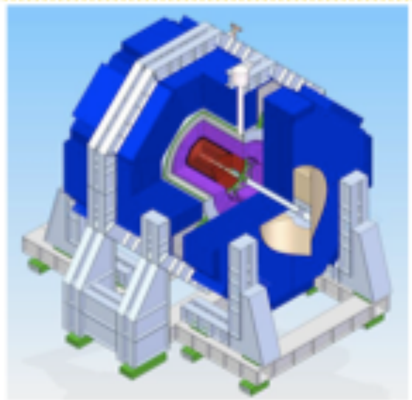
ILD: International Large Detector

"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC + Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



SiD: Silicon Detector

"Small" : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



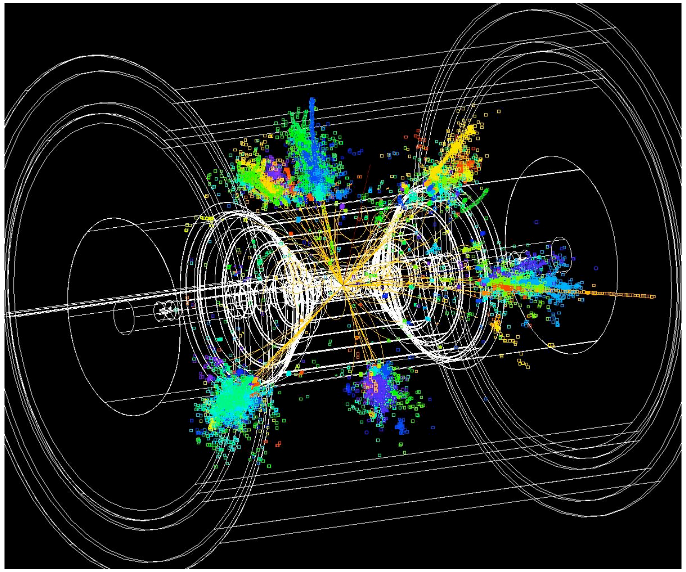
CLIC detector concepts will be based on SiD and ILD.

Modified to meet CLIC requirements

What changes for CLIC?

In several aspects the CLIC detector will be more challenging than ILC case, due to:

- Energy 500 GeV => 3 TeV
- More severe background conditions
  - Due to higher energy
  - Due to smaller beam sizes
- Time structure of the accelerator



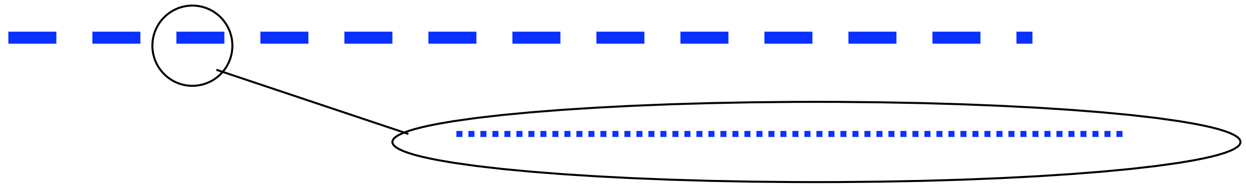
R&D currently carried out for the ILC is most relevant for CLIC.

Many years of investment in ILC e^+e^- physics/detector simulations, hardware R&D and detector concepts. No need to duplicate work.

CLIC time structure

Train repetition rate 50 Hz

CLIC



CLIC: 1 train = 312 bunches 0.5 ns apart 50 Hz

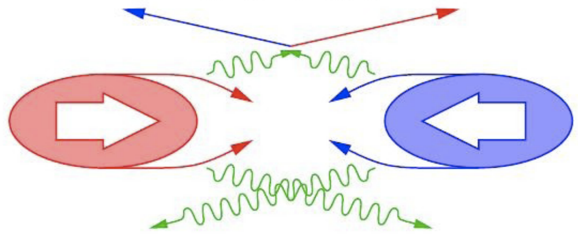
ILC: 1 train = 2820 bunches 308 ns apart 5 Hz

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
L [cm^{-2}s^{-1}]	5×10^{31}	2×10^{34}	2×10^{34}	6×10^{34}
BX/train	4	2670	350	312
BX sep	~22 μs	369 ns	0.5 ns	0.5 ns
Rep. rate	50 kHz	5 Hz	50 Hz	50 Hz
L/BX [cm^{-2}]	2.5×10^{26}	1.5×10^{30}	1.1×10^{30}	3.8×10^{30}
$\gamma\gamma\rightarrow X$ / BX	neg.	0.2	0.2	3.0
σ_x/σ_y	240 / 4 mm	600 / 6 nm	200 / 2 nm	40 / 1 nm

Beam-induced background

Background sources: CLIC and ILC similar

Due to the higher beam energy and small bunch sizes they are significantly more severe at CLIC.

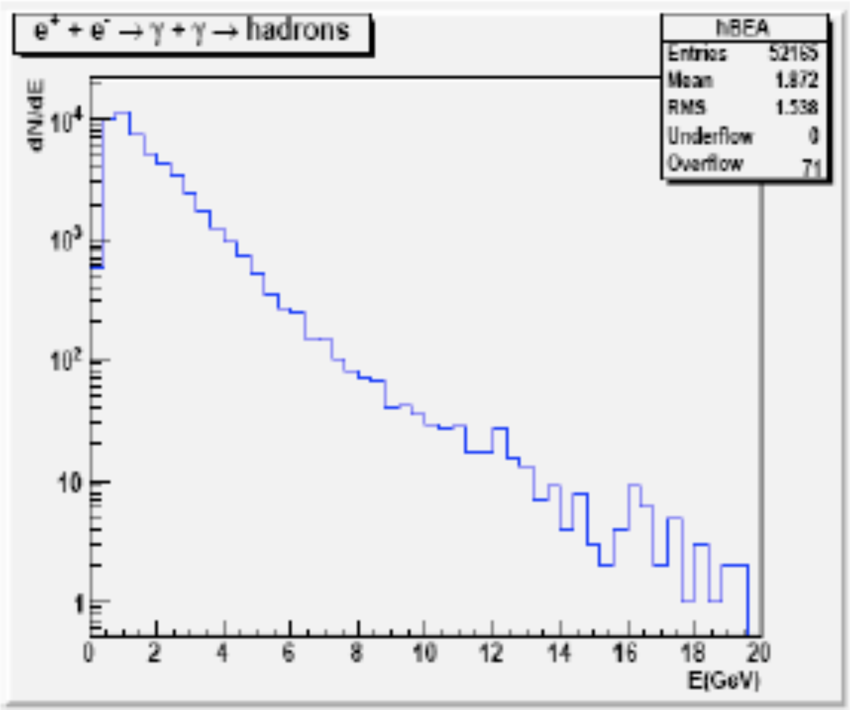


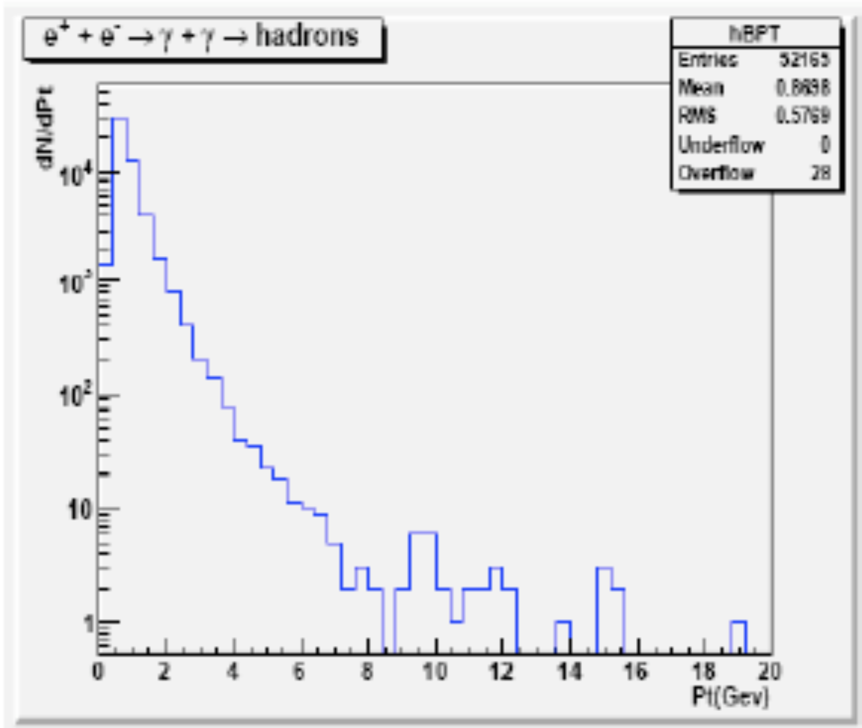
Main backgrounds:

- CLIC 3TeV beamstrahlung $\Delta E/E = 29\%$ ($10\times ILC_{value}$)
  - **Coherent pairs** (3.8×10^{8} per bunch crossing) <= disappear in beam pipe
  - **Incoherent pairs** (3.0×10^{5} per bunch crossing) <= suppressed by strong solenoid-field
  - γγ interactions => hadrons (**3.3 hadron events per bunch crossing**)
- Muon background from upstream linac
  - More difficult to stop due to higher CLIC energy (active muon shield)

Time-stamping requirements (1)

At 3 TeV ~ 3.3 $e^+ + e^- \rightarrow \gamma\,\gamma \rightarrow$ hadrons events / Bx $\rightarrow$ ~ 13 particles/Bx



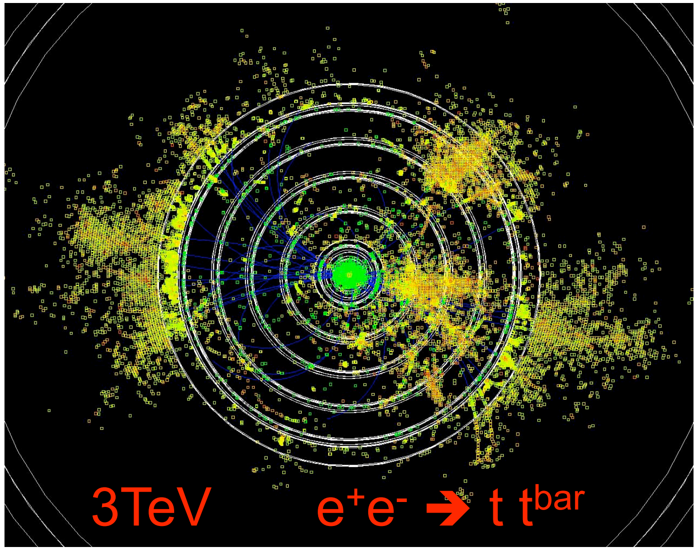


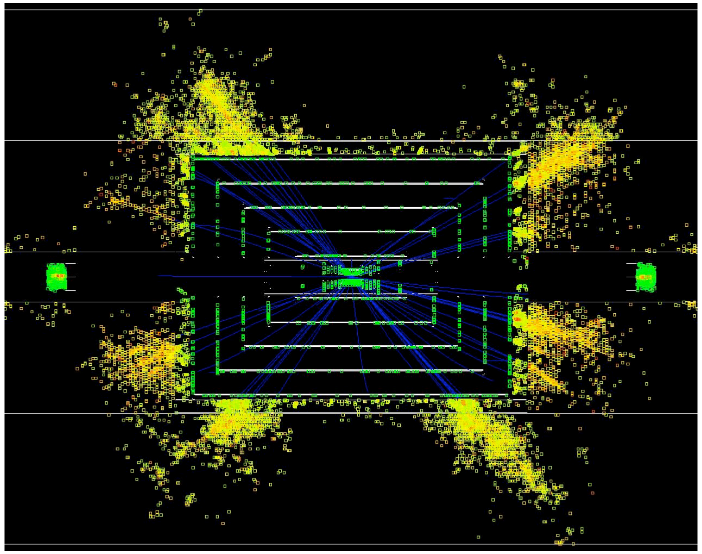
<Eh> ~ 1.9 GeV

<Pt> ~ 0.9 GeV.

CLIC tracking/calorimetry issues

- Due to beam-induced background and short time between bunches:
  - Inner radius of Vertex Detector has to become larger (~30 mm)
  - High occupancy in the inner regions
  - Time-stamping is a must for almost all detectors
- Narrow jets at high energy
  - 2-track separation is an issue
  - Calorimeter has to measure high-energy particles (leakage)





Spatial distance neutral – charged hadrons

Jean-Jacques Blaising, LAPP

Distance, Δ , at the 1. layer of HCAL

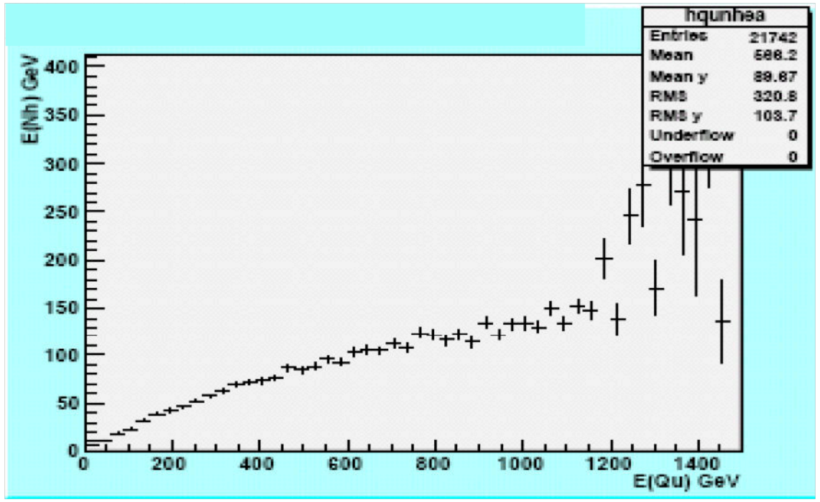
		Njet, Ecm, B	Δ (cm) MPV barrel	Δ (cm) RMS barrel	Δ (cm) MPV endcap	Δ (cm) RMS endcap
ILC	$\nu\nu H^0$	2J, 0.5 GeV,4T	8.0	3.6	9.7	4.4
ILC	$t\bar{t}$	4/6J, 0.5 GeV,4T	6.4	2.8	8.6	6.7
CLIC	$\nu\nu H^0$	2J, 3.0 TeV, 4T	3.8	2.6	2.6	2.4
CLIC	$t\bar{t}$	4/6J, 3.0 TeV, 4T	1.0	1.1	1.7	0.9
CLIC	$t\bar{t}$	4/6J, 3.0 TeV, 5T	1.4	1.2	1.9	1.0

- at 3 TeV neutral - charged particle separation only ~ 1 cm
- cluster of neutral and charged hadrons will overlap in HCAL
- neutral hadron reconstruction (with PFA) only by subtraction

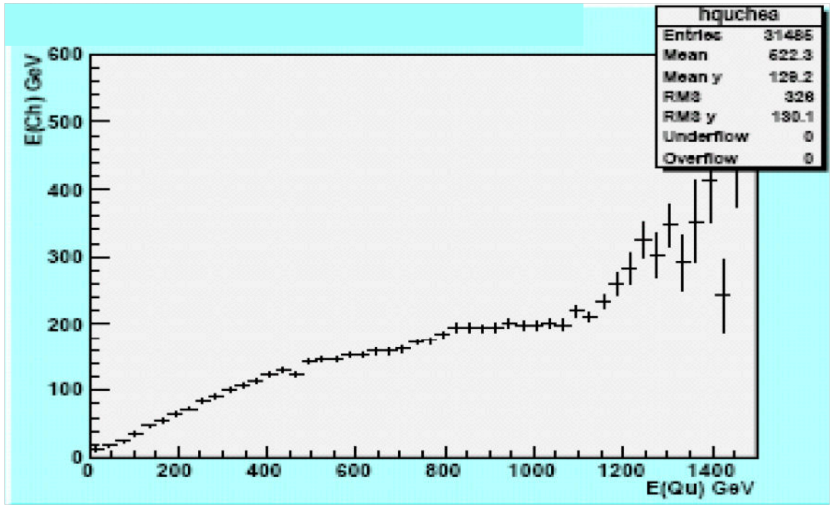
Energy of single hadrons in jets

ttbar events at 3 TeV

Neutral Hadron



Charged Hadron



In jets, even with high quark energies, leading hadron has E < 300 GeV

Jean-Jacques Blaising, LAPP

Jet Energy Resolution

★ Is an ILD-sized detector based on PFA suitable for CLIC ?

★ Defined modified ILD+ model:

- B = 4.0 T (ILD = 3.5 T)
- HCAL = 8 Λ_I (ILD = 6 Λ_I)

★ Jet energy resolution

PFA

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ |cosθ|<0.7	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	28.7 %	2.9 %
180 GeV	37.5 %	2.8 %
250 GeV	44.7 %	2.8 %
375 GeV	71.7 %	3.2 %
500 GeV	78.0 %	3.5 %

Mark Thomson
Cambridge

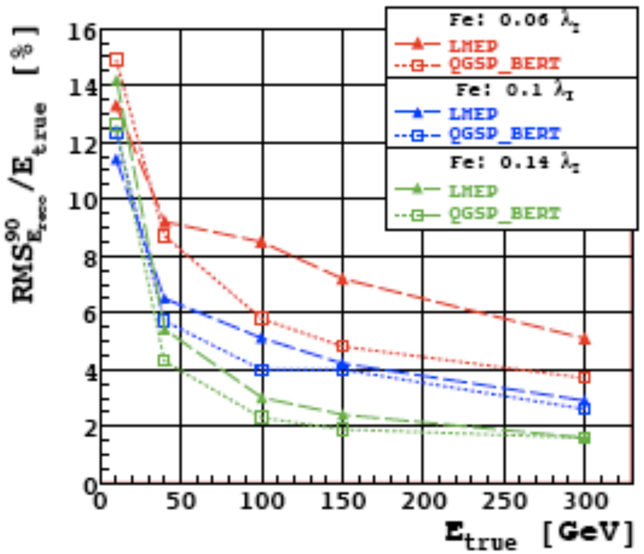
★ Meet "LC jet energy resolution goal [~3.5%]" for 500 GeV ! jets

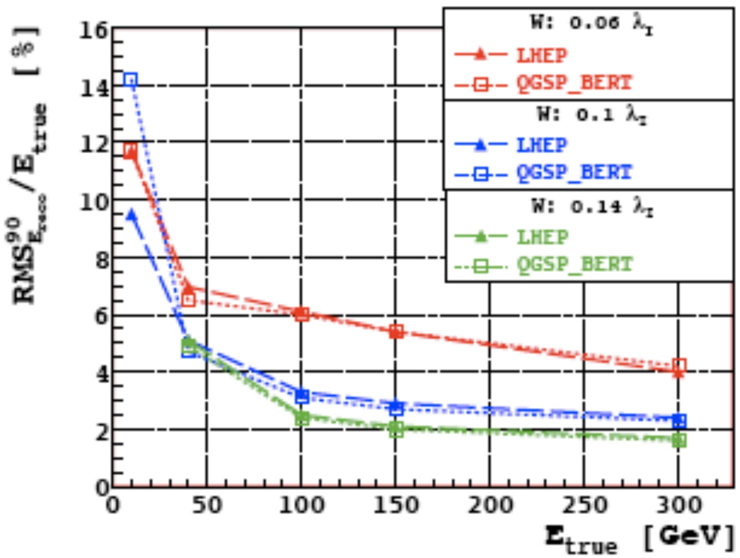
Tungsten HCAL prototype (1)

Motivation:

- To limit longitudinal leakage CLIC HCAL needs ~7Λ_i
- A deeper HCAL pushes the coil/yoke to larger radius (would give a significant cost and risk increase and for the coil/yoke)
- A tungsten HCAL is more compact than Fe-based HCAL, while resolutions are similar (increased cost of tungsten barrel HCAL compensates gain in coil cost)

➔Prototype tungsten HCAL: check simulation in test beam





Fe and W based HCAL resolutions

Angela Lucaci-Timoce DESY)

Tungsten HCAL prototype (2)

Main elements (all still under discussion):

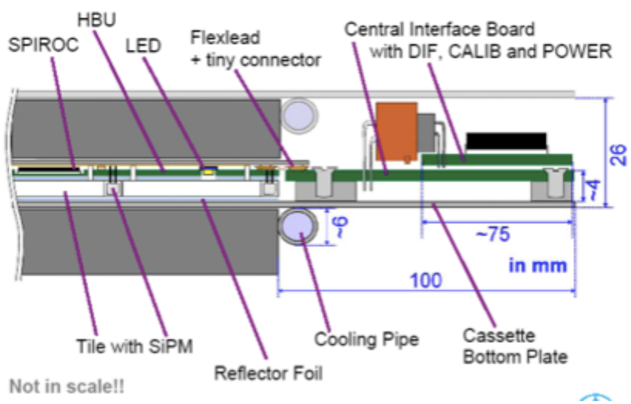
- 40 or more layers of Tungsten absorber ~10×800×800 mm^3
- Phase 1: use existing CALICE HCAL scintillator planes
- Phase 2:
  a) New integrated AHCAL scintillator planes
  b) New DHCAL micromegas or RPC planes

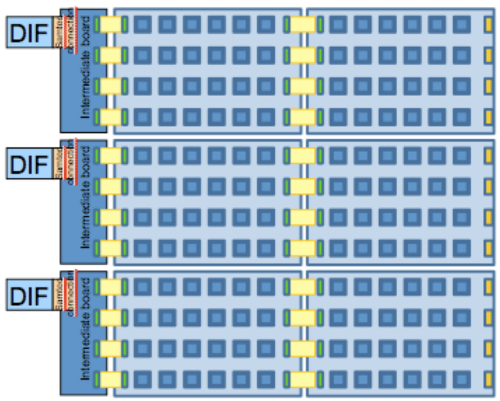
Time scale:

- First (limited) beam tests at CERN in 2010

Integrated scintillator plane

DESY



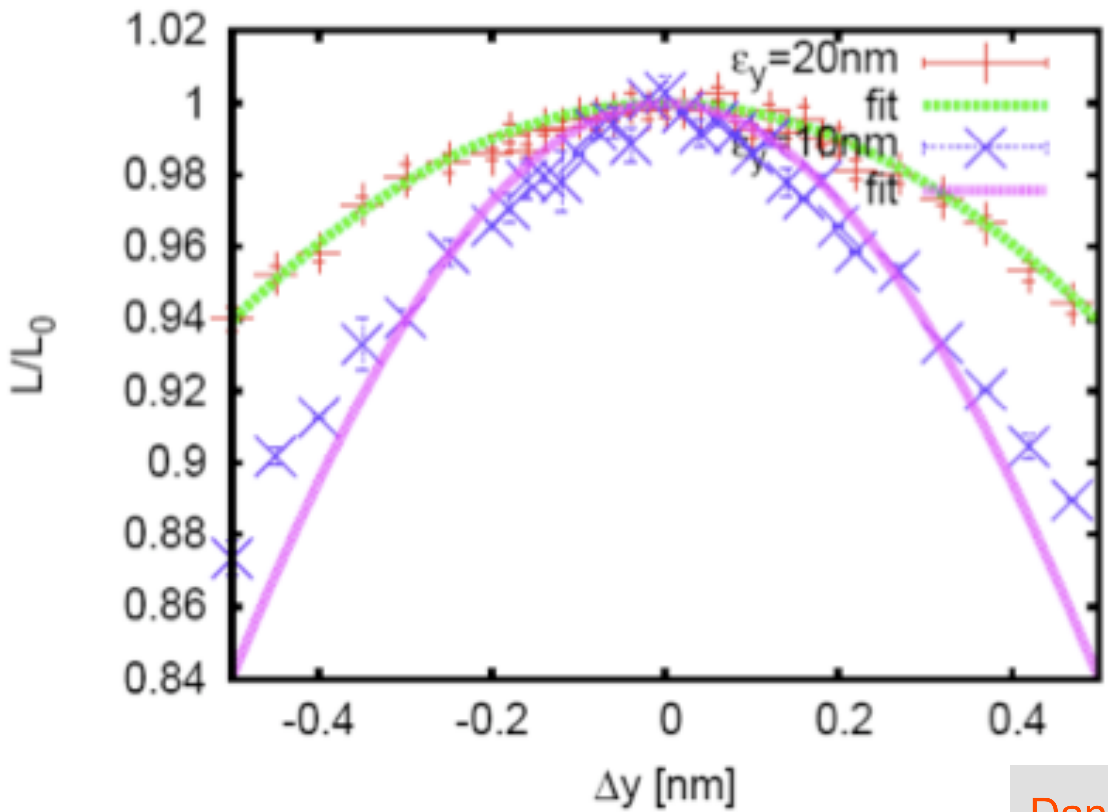


Layout 1 m^2 micromegas

LAPP-Annecy

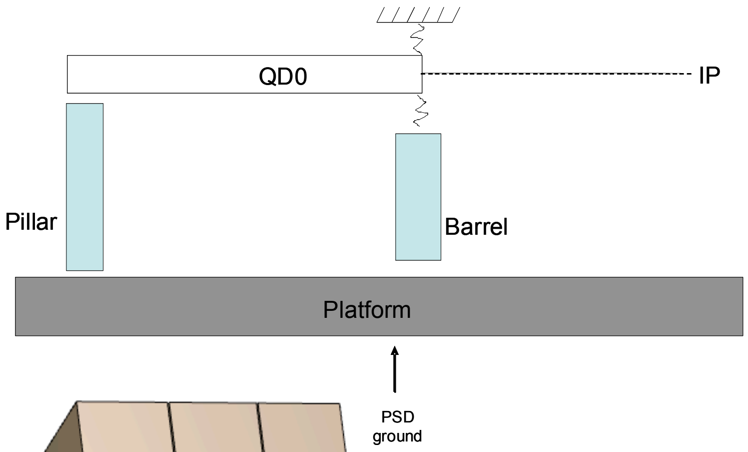
Final focus stability

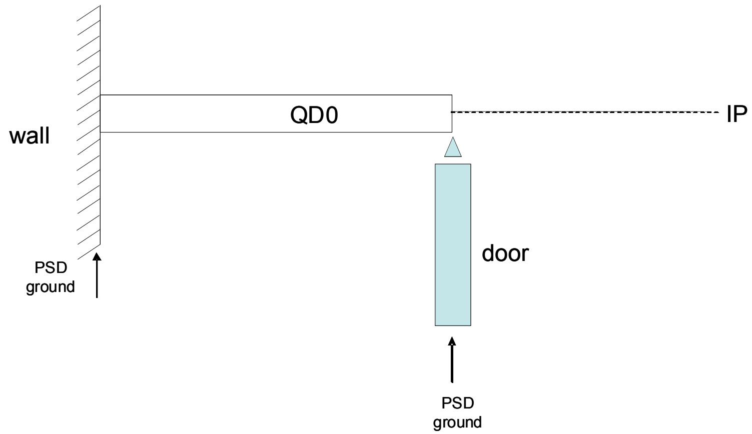
- Final focus quadrupoles inside experiment, L* = ~3.5 m
  - Beam focusing stability required at sub-nm level **!!**

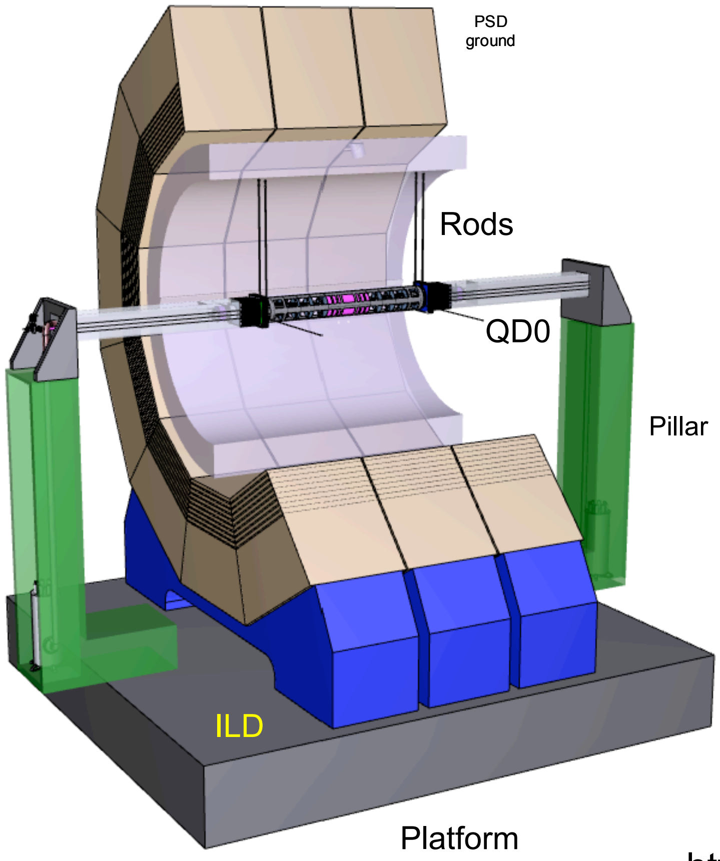


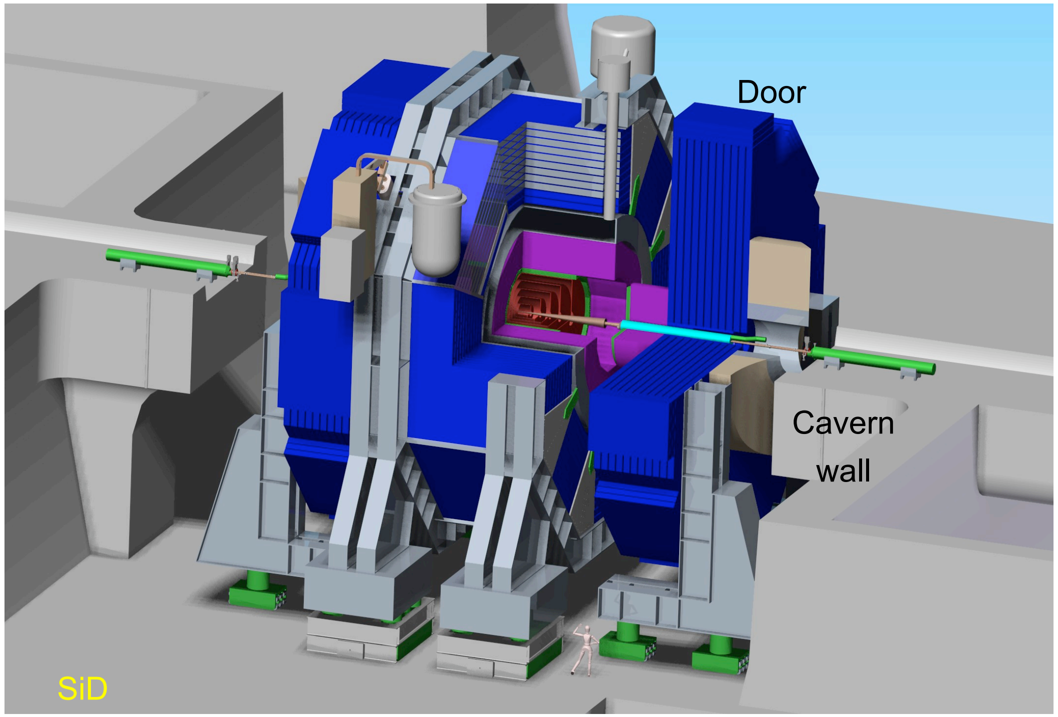
Daniel Schulte CLIC08.

QD0 supports for ILD and SiD in LoIs

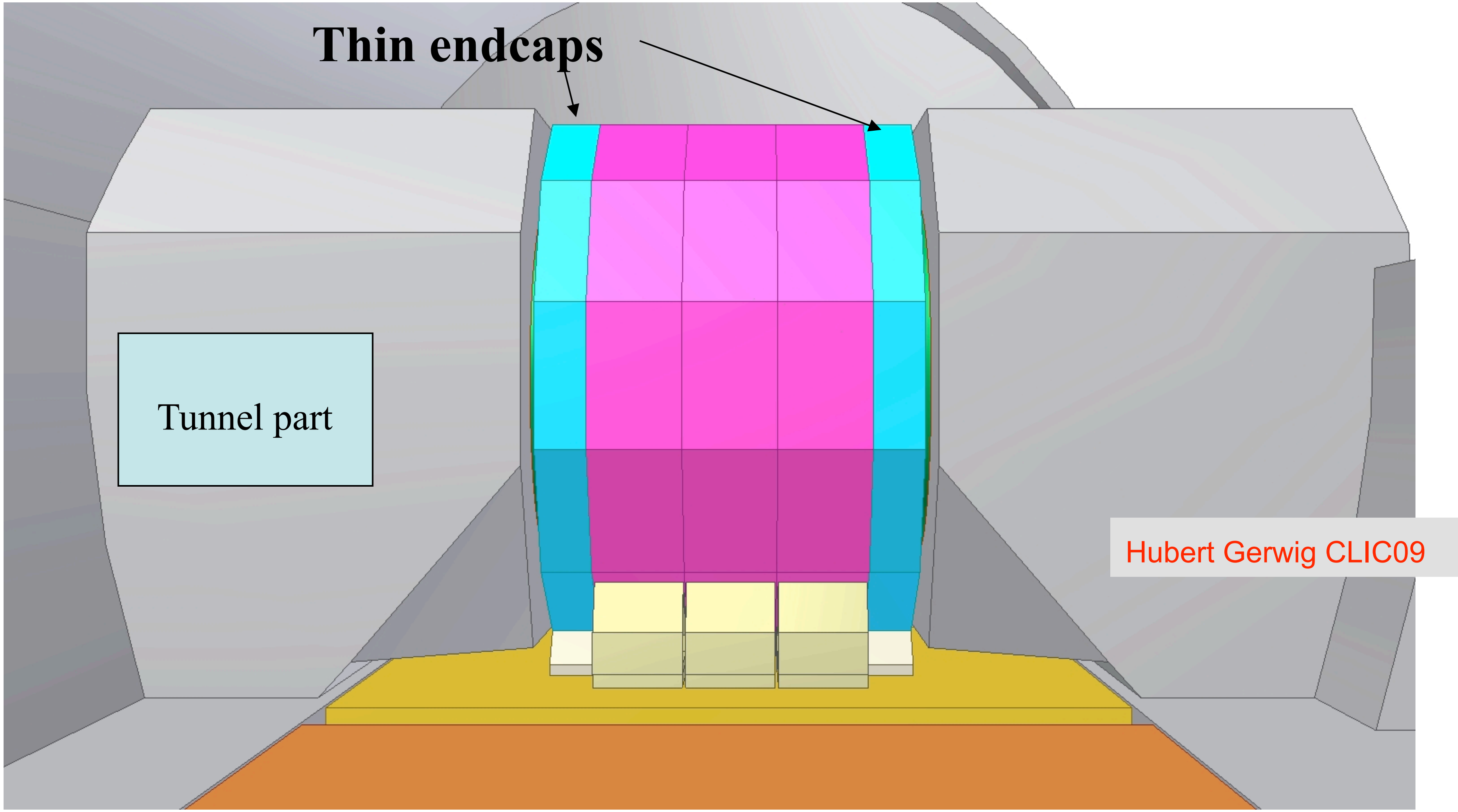




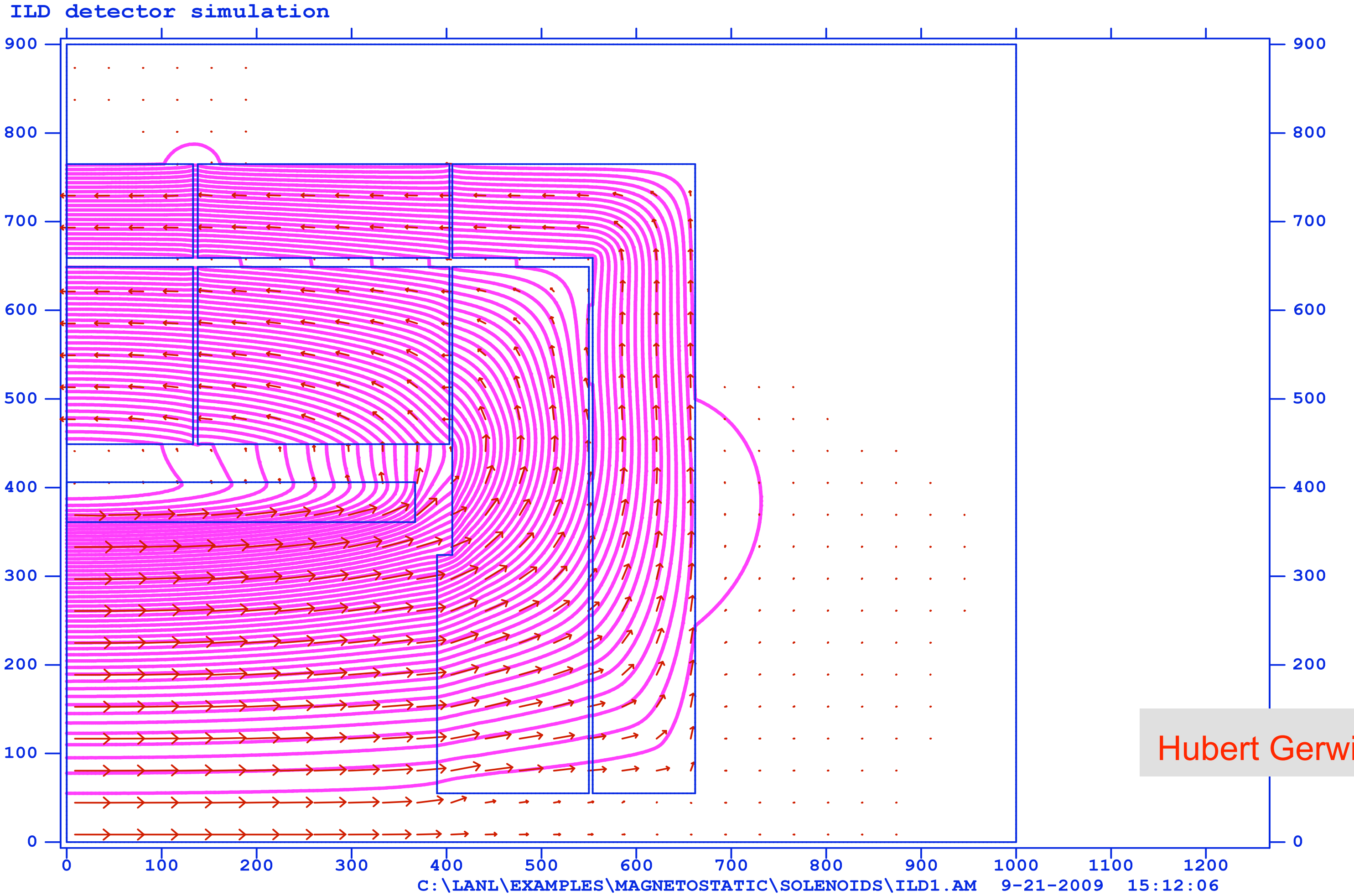




Side View

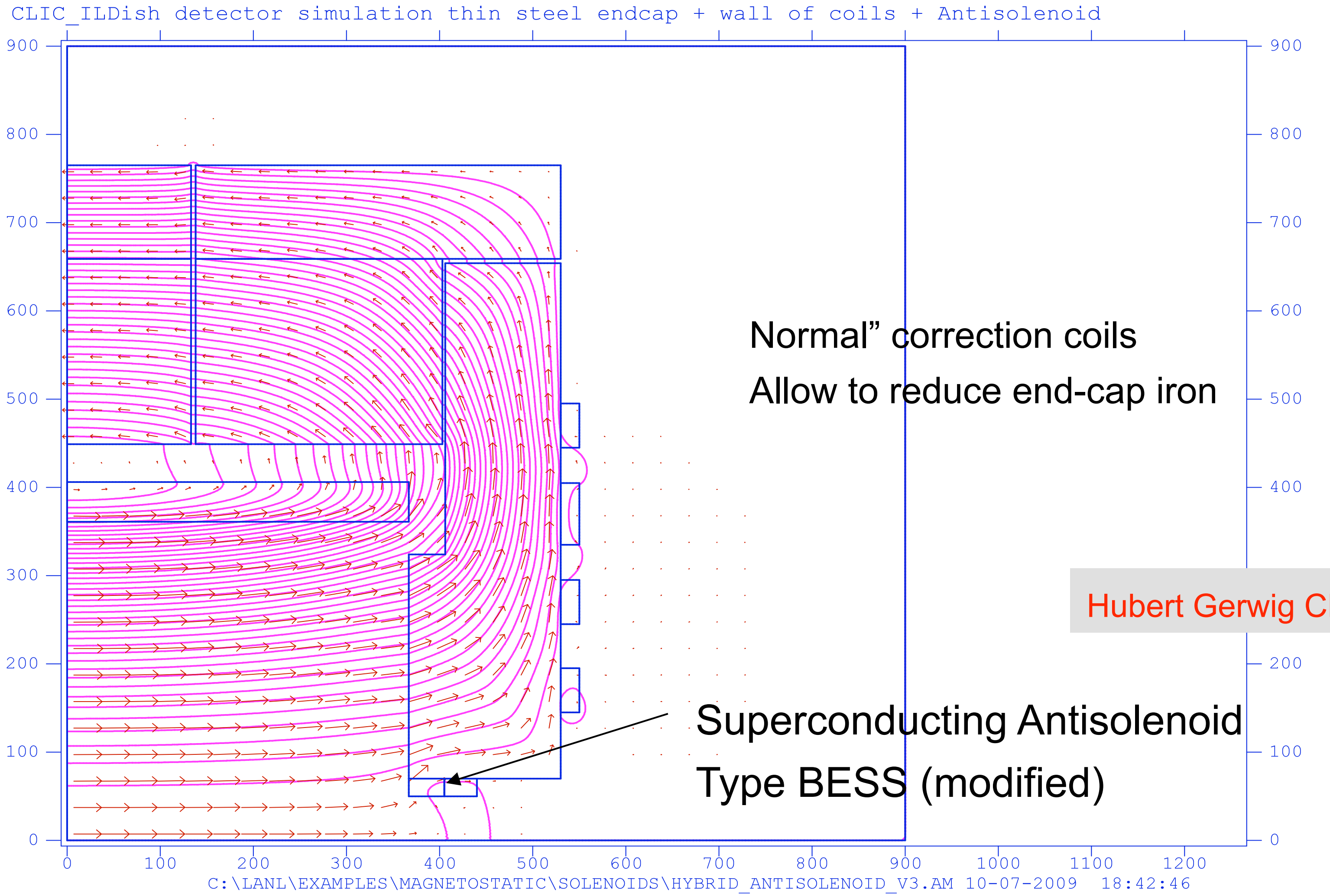


Magnetic field type "ILD"



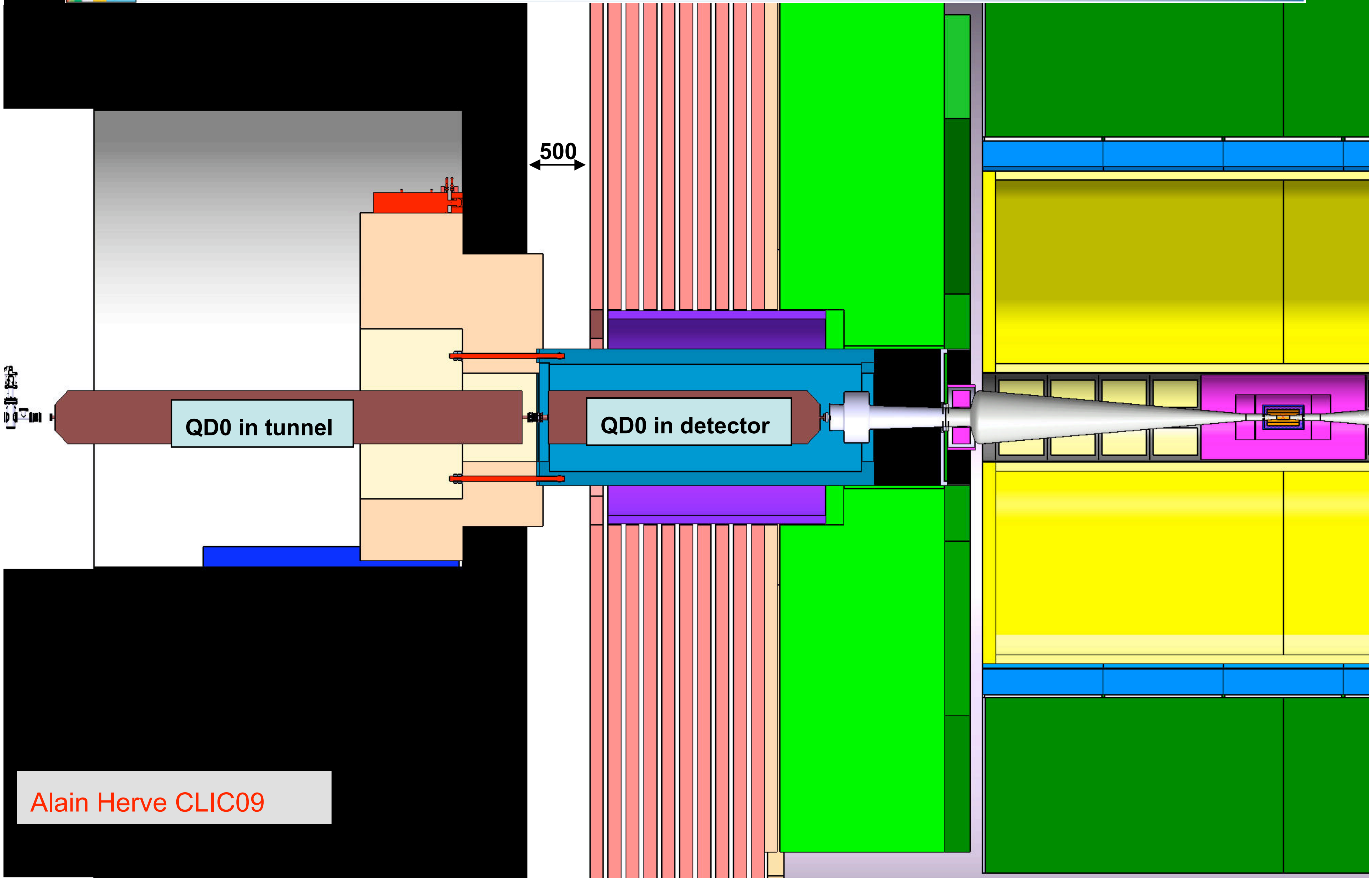
Hubert Gerwig CLIC09

Additional complication Antisolenoid for QD0



Hubert Gerwig CLIC09

With reduced Endcap, part of QD0 in Tunnel!

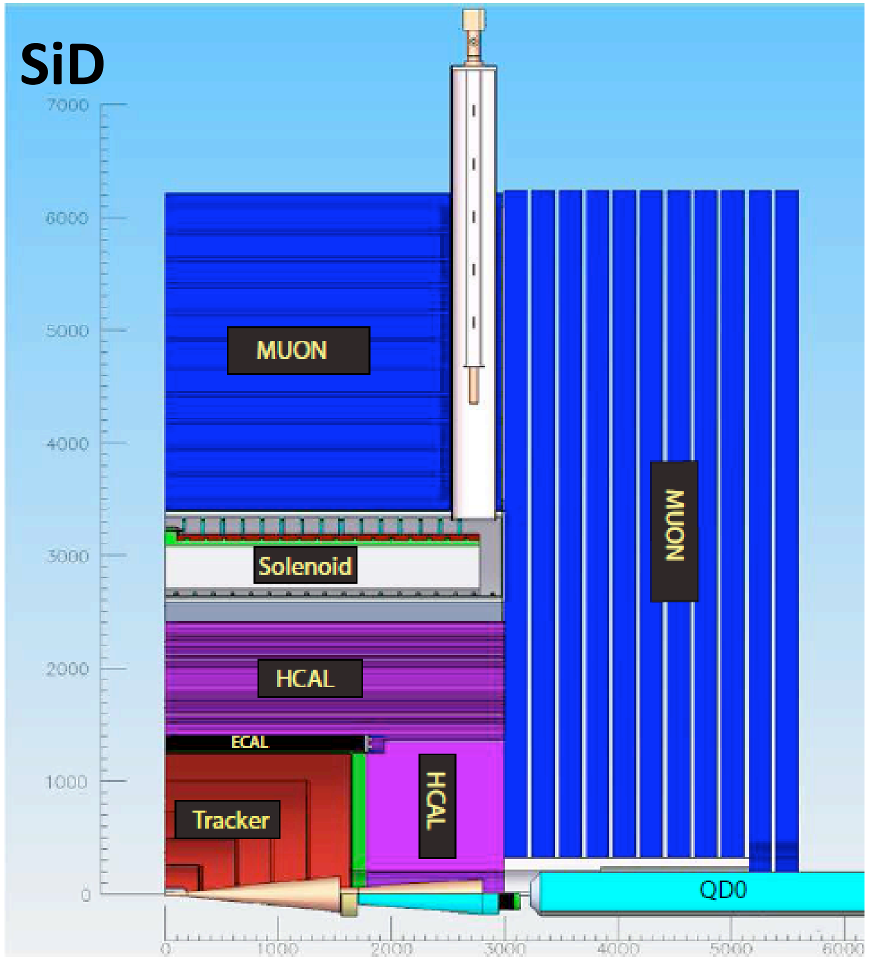


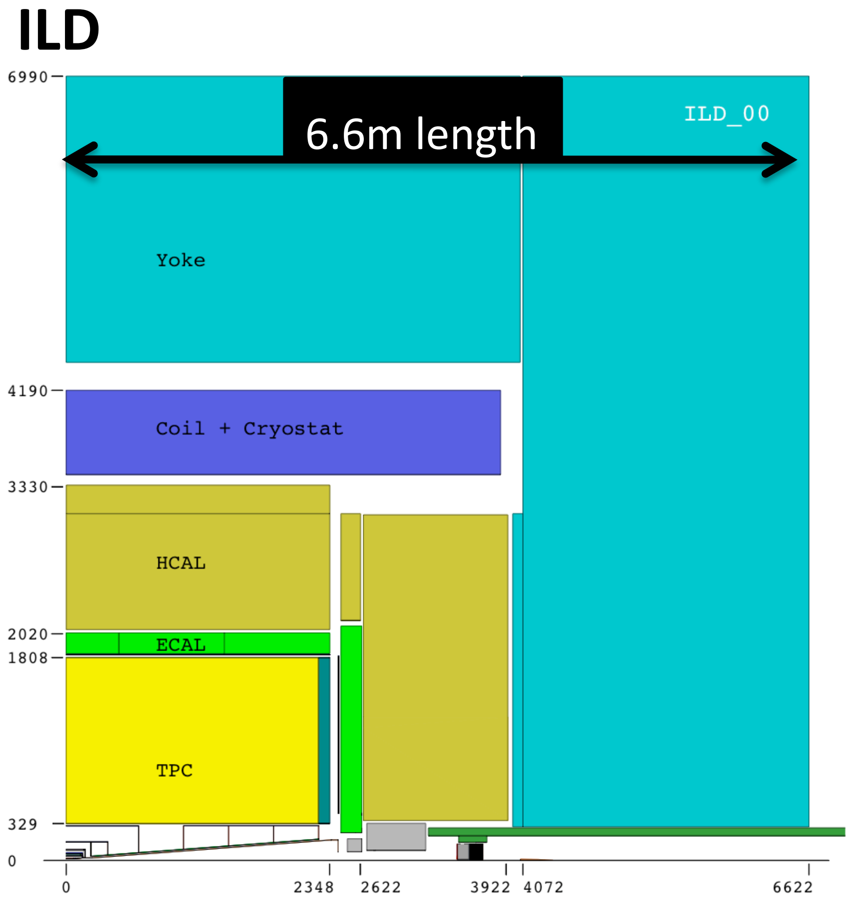
Current activities

Current activities concentrate on preparation for CDR

- Mostly simulation studies:
  - Demonstrate that CLIC physics potential can be extracted from detector
  - Propose ILD-type and SiD-type detectors that can do the job
- Concentrate on critical issues
  - Determine required sub-detector performances to see the physics
    - Adapted to CLIC energies (e.g deeper calorimeter)
    - In the presence of beam/background conditions
    - With particular emphasis on time-stamping needs
  - Redesign of the very forward region
  - Take engineering aspects, cost etc into account
- Small team of theorists is preparing physics scenarios for CDR
- Prepare a targeted hardware R&D plan

ILC Detector Concepts





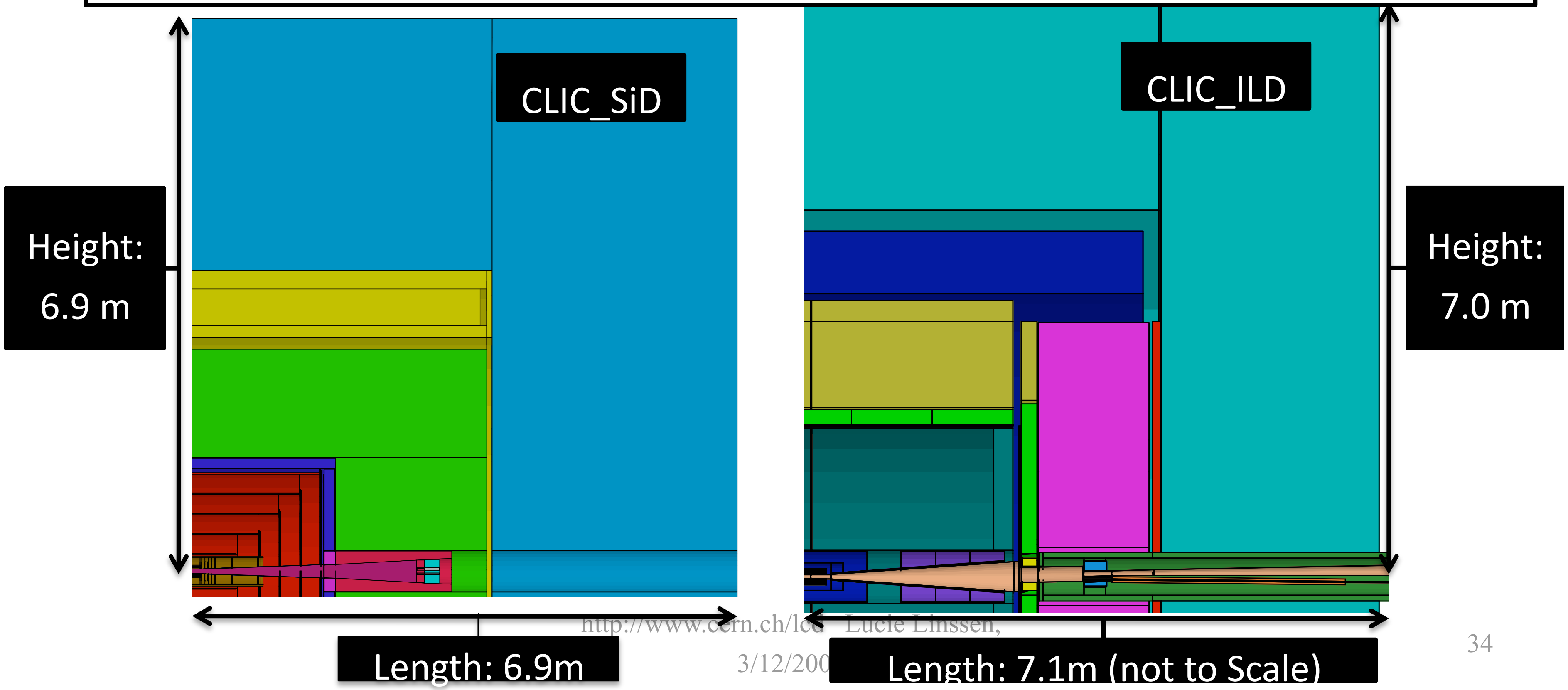
Andre Sailer

From ILC to CLIC Detectors

- Created CLIC 3 TeV detector models using SiD and ILD geometries and software tools

Changes:

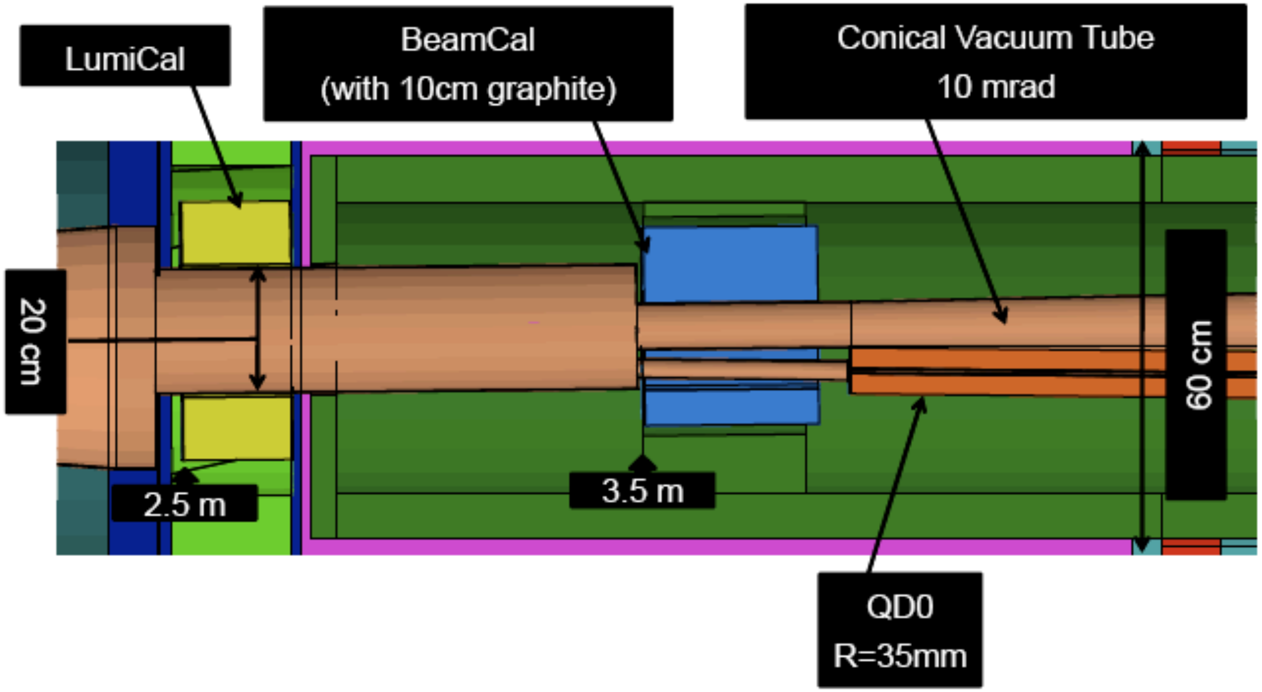
- 20 mrad crossing angle (instead of 14 mrad)
- Vertex Detector to ~30 mm inner radius, due to Beam-Beam Background
- Hadron Calorimeter, more dense and deeper ($7.5\ \lambda_i$) due to higher energetic Jets
- For CLIC_SiD: Moved Coil to 2.9m (CMS Like)



CLIC forward region detectors

Andre Sailer

CLIC01_ILD: LumiCal, BeamCal and QD0



Maintain very forward calorimetry functionalities, adapt to accelerator requirements (stability!), minimise back-scattering of background

Hardware/engineering R&D

Hardware/engineering R&D needed beyond present ILC developments:

- Time stamping
  - Needed for all sub-detectors; challenging in inner tracker/vertex region; trade-off between pixel size, amount of material and timing resolution
- Power pulsing and DAQ developments
  - In view of the CLIC time structure
- Hadron calorimetry
  - Dense HCAL absorbers to limit radial size (PFA calo based on tungsten)
- Solenoid coil
  - Reinforced conductor (building on CMS/ATLAS experience)
  - Large high-field solenoid concept
- Overall engineering design and integration studies
  - For heavier calorimeter, larger overall CLIC detector size etc.
  - In view of sub-nm precision required for FF quadrupoles

In addition: Core software development

Summary

CLIC has big physics potential, complementary to LHC

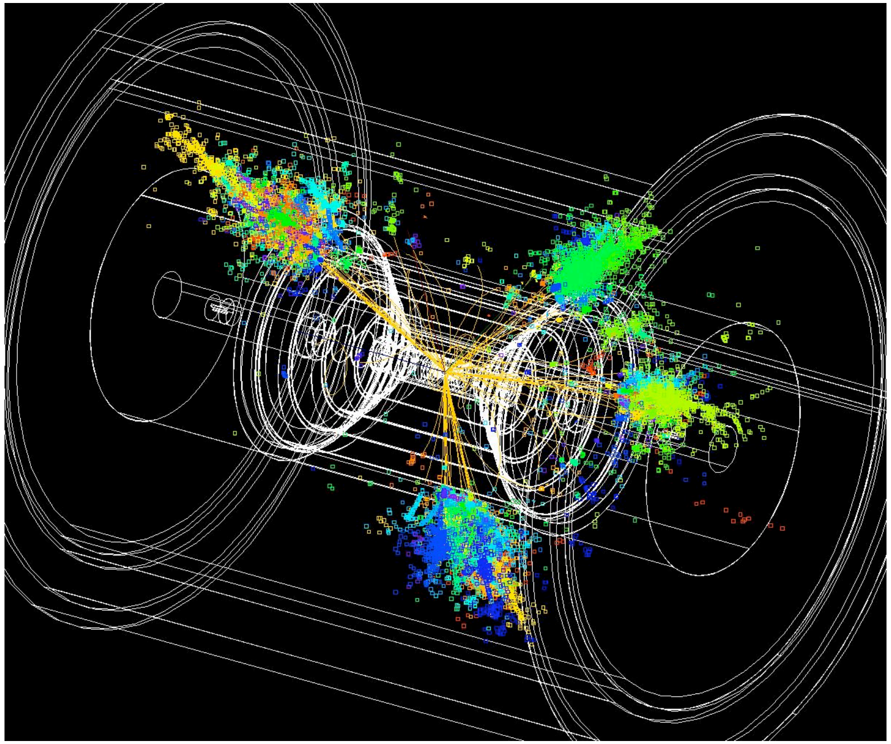
CLIC physics/detector studies in close collaboration with ILC
Growing community both inside and outside CERN

Software tools in place for adapted ILD and SiD detector models
(Further adaptations still required for 3 TeV energy)

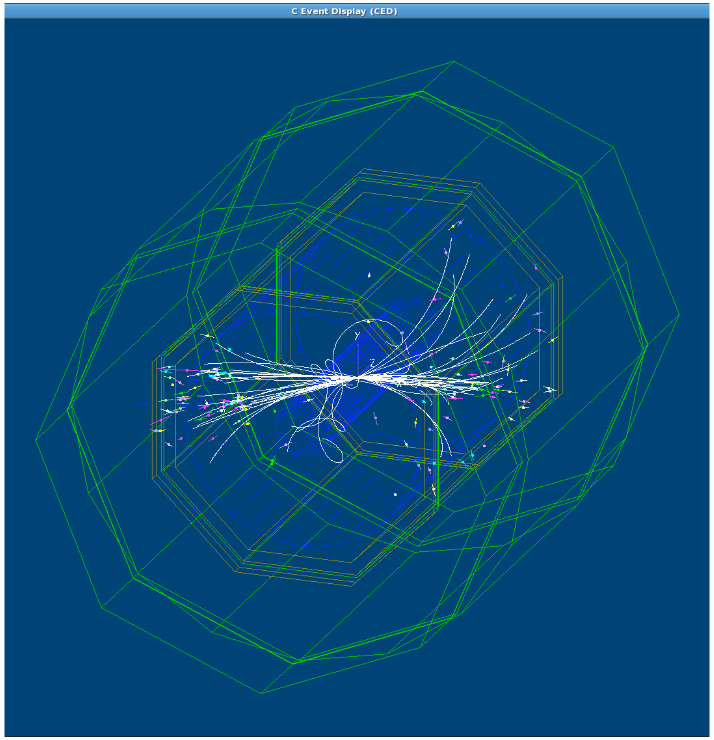
Currently defining CLIC detector requirements
First new results of physics performance studies
R&D plan currently being set up

Welcome to join the study and hardware R&D !

With many thanks to all our ILC physics/detector colleagues!



CLIC_SiD detector



CLIC_ILD detector

Spare Slides

Short summary on the physics

The LHC will determine the future of high-energy physics

- CLIC is one of the best options to complement and extend the LHC research programme
- Detailed investigation of the Higgs sector and discovery of new Higgs bosons
- Extensive reach for possible SUSY particles
- Precise parameter determination (identification of the theory, tests of unification, reconstruction of DM density)
- Indirect probes up to 200-400 TeV

Gian Giudice CLIC09

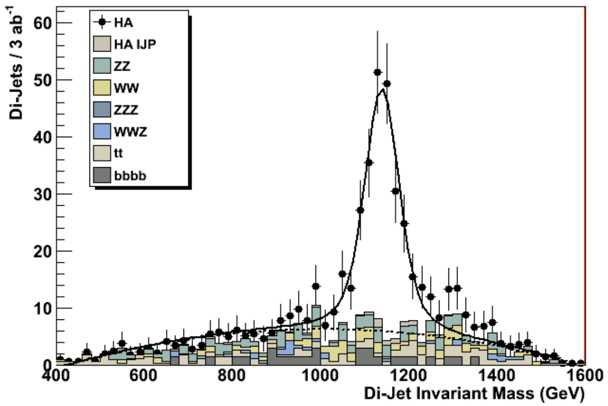
Time stamping requirements (2)

Simulation example of heavy Higgs doublet H^0A^0 at ~1.1 TeV mass (supersymmetry K' point)

e+e- ➔ H^0A^0 ➔ bbbb

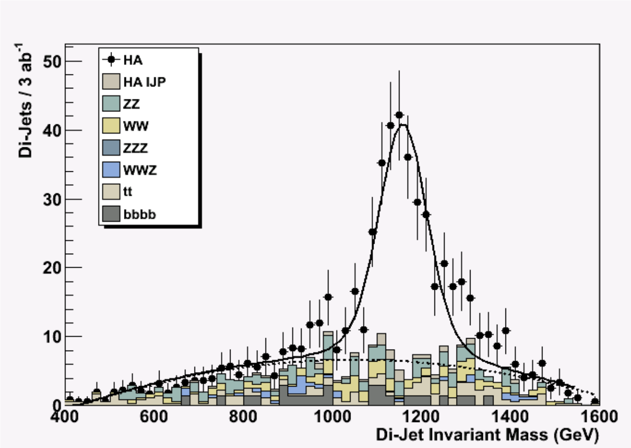
Signal + full standard model background + γγ=>hadron background

CLIC-ILD detector: Mokka+Marlin simulation, reconstruction + kinematic fit.



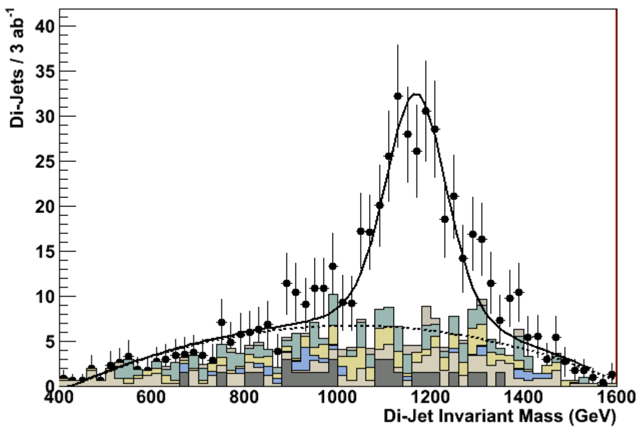
Zero bunch crossings

M_A mass resol. 3.8 GeV



20 bunch crossings

M_A mass resol. 5.6 GeV



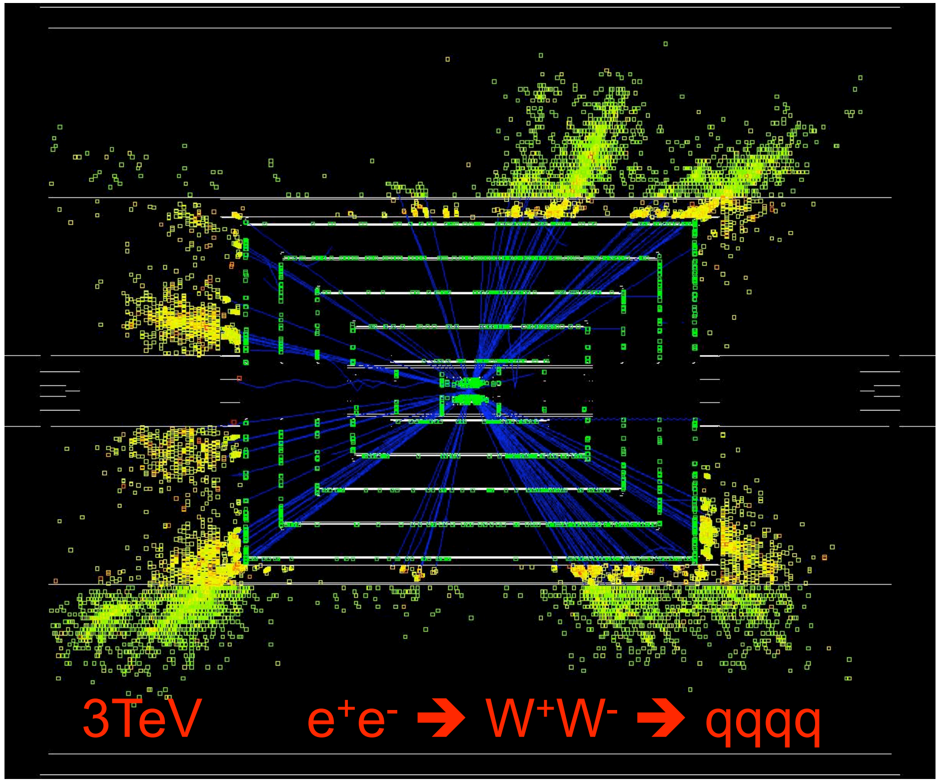
40 bunch crossings

M_A mass resol. 8.2 GeV

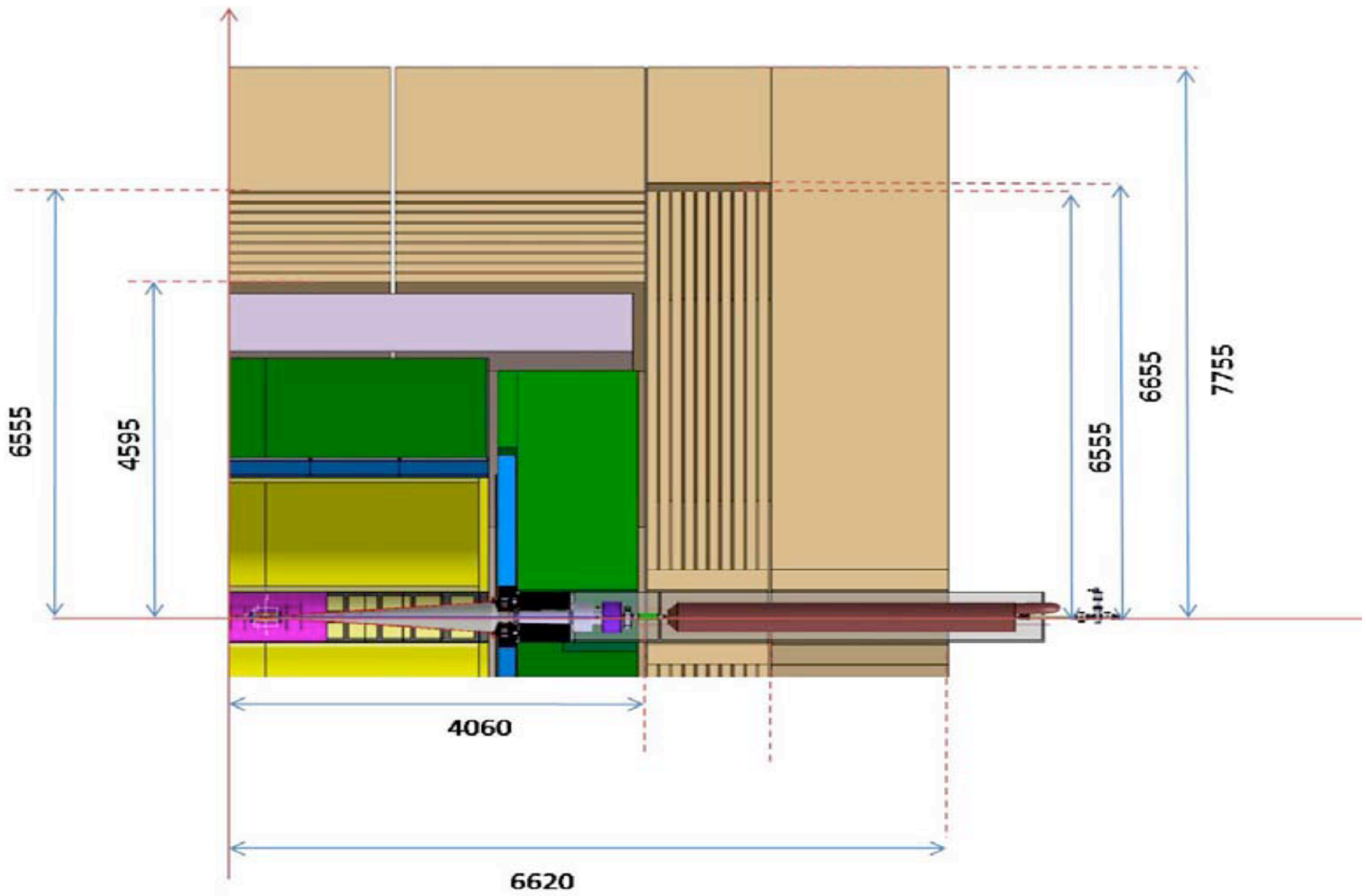
Jet multiplicities

Jet Multiplicity

$\sqrt{s}$ (TeV)	0.09	0.20	0.5	0.8	3.0
$< N_{Jets} >$	2.8	4.2	4.8	5.3	6.4



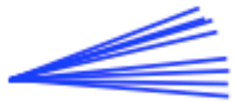
ILD Endcap thickness 2.56 meter!



❷ The Particle Flow Paradigm

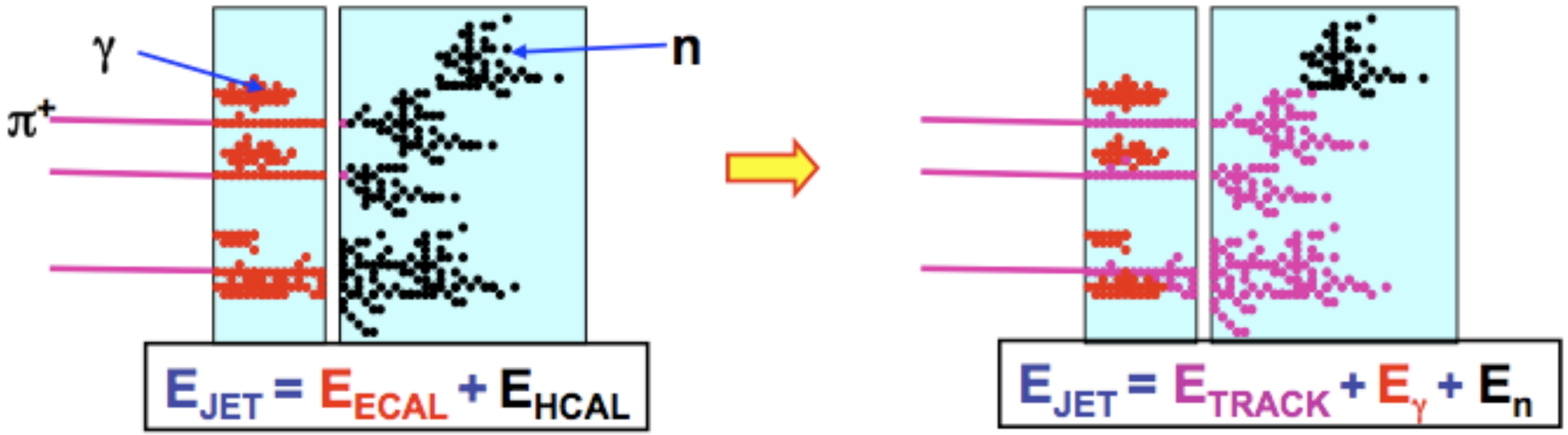
★ **In a typical jet :**

- **60 %** of jet energy in charged hadrons
- **30 %** in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- **10 %** in neutral hadrons (mainly n and K_L)



★ **Traditional calorimetric approach:**

- Measure all components of jet energy in ECAL/HCAL !
- **~70 %** of energy measured in HCAL: $\sigma_E/E \approx 60\%/\sqrt{E(\mathrm{GeV})}$
- Intrinsically "poor" HCAL resolution limits jet energy resolution



★ **Particle Flow Calorimetry paradigm:**

- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20\%/\sqrt{E(\mathrm{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⟹ much improved resolution

Mark Thomson

CLIC CDR

The CLIC CDR is due for end (~December) 2010.

There will be 4 volumes:

1. Executive summary document
2. CLIC accelerator and site facilities
3. CLIC Physics and Detectors

The CDR document for physics/detectors will be some 120-150 pages.

CLIC CDR will be based on required changes for CLIC to the validated ILC detector concepts.

This is a conceptual design report. As the study is very recent, feasibility cannot be demonstrated with hardware proof for all issues.

CLIC CDR layout (1)

Chapter 1-4

1. Introduction
2. CLIC physics potential
   2.1. Higgs physics (light Higgs and accompanying new physics)
   2.2. Supersymmetry
   2.3. Extra dimensions and other possible CLIC physics
3. Strategy for design choices
   3.1. Benchmark processes for detector performance assessment
   3.2. Luminosity and background conditions for a CLIC detector at 0.5 TeV and 3 TeV
   3.3. Beyond the ILC detector concepts
4. Detector performance requirements
   4.1. General optimisation (incl. detector aspect ratio, magnetic field vs. radius, flavour tagging)
   4.2. Calorimetry requirements (incl. e.g. general PFA considerations)
   4.3. Vertexing requirements
   4.4. Tracking requirements
      4.4.1. Central tracking
      4.4.2. Forward tracking
   4.5. Very forward calorimeter requirements

CLIC CDR layout (2)

Chapter 5-11

5. Tracking system
   5.1. Vertex detector
   5.2. Tracking detector
      5.2.1. Central tracker
      5.2.2. Forward tracker
6. Calorimeter system
   6.1. Electromagnetic calorimeter
   6.2. Hadron calorimeter
7. Superconducting Solenoid
8. Muon system
9. Very forward calorimeters
   9.1. Luminosity calorimeter
   9.2. Beam calorimeter
10. Readout electronics and data acquisition
11. Detector integration
   11.1. Mechanical concept, assembly and opening
   11.2. Push-pull operation and alignment

CLIC CDR layout (3)

Chapter 12-17

11. Detector integration
    11.1. Mechanical concept, assembly and opening
    11.2. Push-pull operation and alignment
12. Physics performance for benchmark processes
    12.1. Benchmark studies of an XXX-like detector concept
    12.2. Benchmark studies of an YYY-like detector concept
    12.3. …
13. R&D prospects
14. Costs
15. Conclusion
16. Acknowledgment
17. Bibliography

I) Annex: SW packages used

CLIC physics/detector CDR

Comments:

Some studies will be done with the SiD concept, others with the ILD concept, so the document will have a mix of both.

The CDR will mostly be based on **simulation studies for the CLIC** case and **existing ILC hardware experience**. As CLIC-specific hardware R&D will only start in 2010, its result will come too late for the CDR.

CDR organisation

We are looking for **editors, taking responsibility for the individual chapters** (typically 2 persons per chapter).

Several editors from CERN are available, but ideally would like to have also many editors from outside CERN (members of the concept and technology groups).

Editors will be appointed on an individual basis, following their involvement and interest.

The editors set up a work plan for the subject of their chapter, and help to identify participants (with our LCD help).

Timeline:

- Appointment of editors ~November 2009 (after CLIC'09 workshop)
- Final detailed work plan for the chapters: ~March 2009 (Beijing)