Towards a CLIC detector, opportunities for R&D

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CERN

Outline and useful links

Outline:

- Short introduction to the CLIC accelerator
- CLIC physics
- CLIC detector issues <= difference wit ILC case
- CLIC detector R&D opportunities
- Outlook

Useful links:

- **CLIC website**
- http://clic-study.web.cern.ch/CLIC-Study/

- **CLIC08 workshop, October 14-17 2008**
- http://project-clic08-workshop.web.cern.ch/project-clic08-workshop/

CLIC base-line

CLIC = **C**ompact **L**inear **C**ollider

(length < 50 km)

Electron-Positron Collider

- Centre-of-mass-energy: 0.5 - 3 TeV

Present R&D proceeds with following requirements:

- *Luminosity L* > few **10^{34} cm^{-2} s^{-1}** with acceptable background and energy spread
- Design should be compatible with a maximum l*ength* ~ **50 km**
- Total power consumption < **500 MW**

  (cf LEP@100 GeV => 237 MW)
- Affordable (CHF, €, $,……)

The CLIC Two Beam Scheme

Two Beam Scheme:

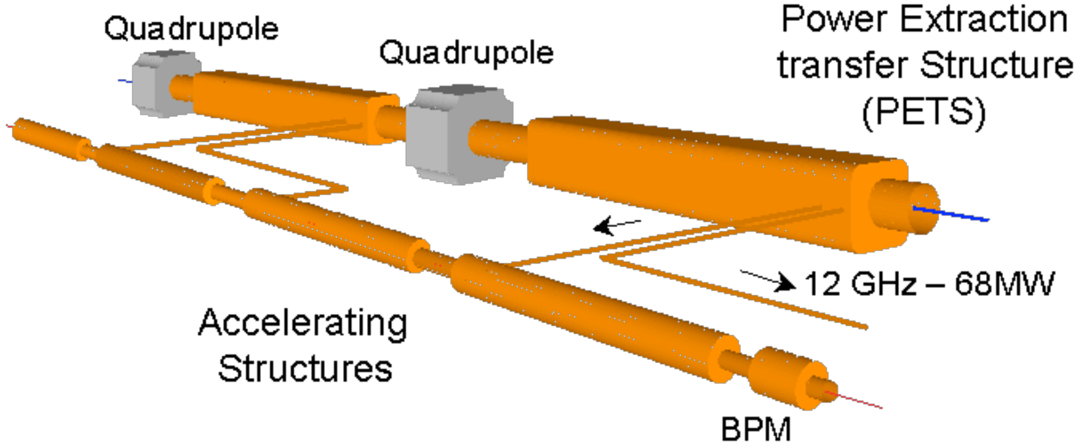
Drive Beam supplies RF power

- 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

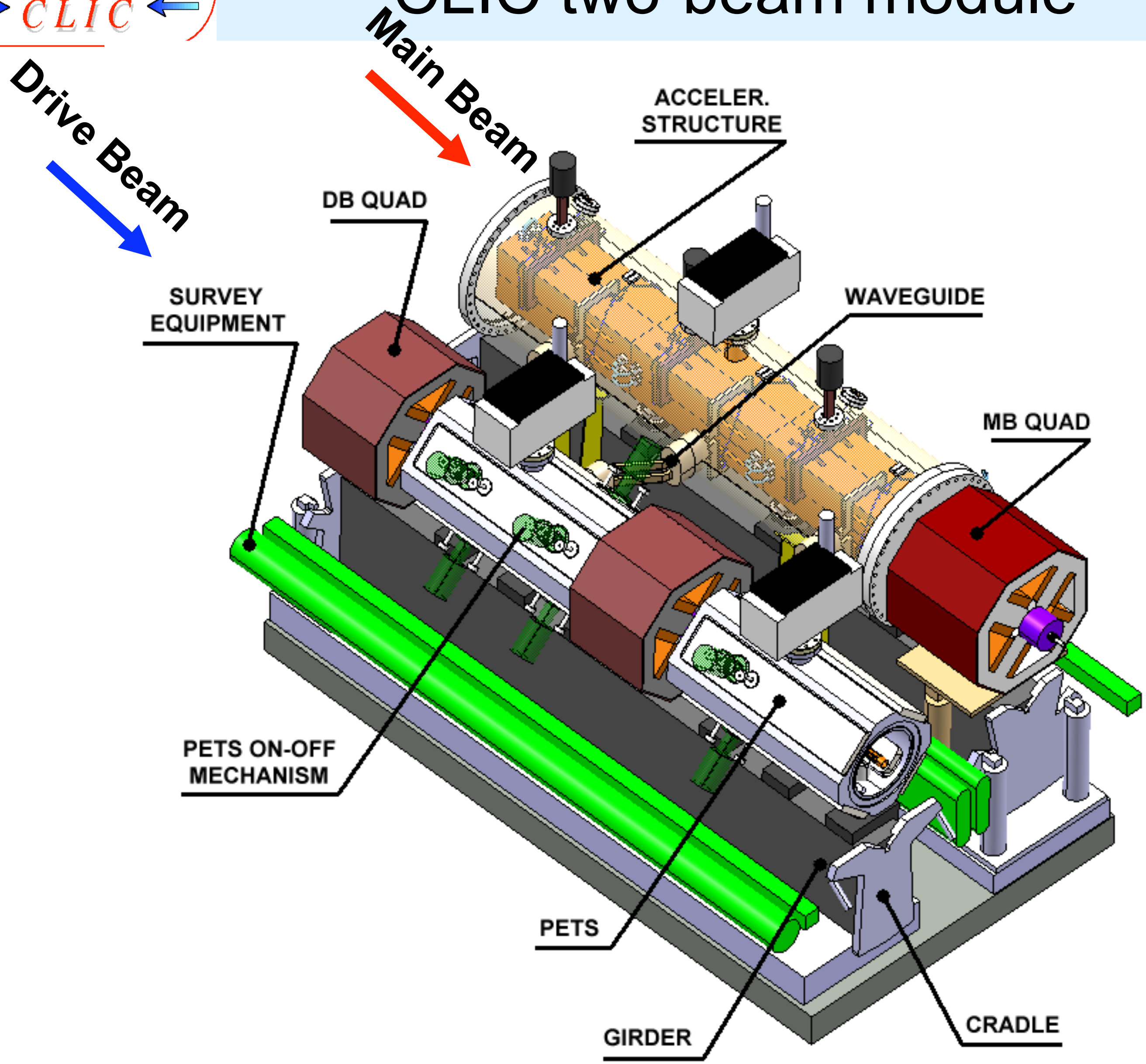
Drive beam – 100 A, 240 ns
from 2.4 GeV to 240 MeV



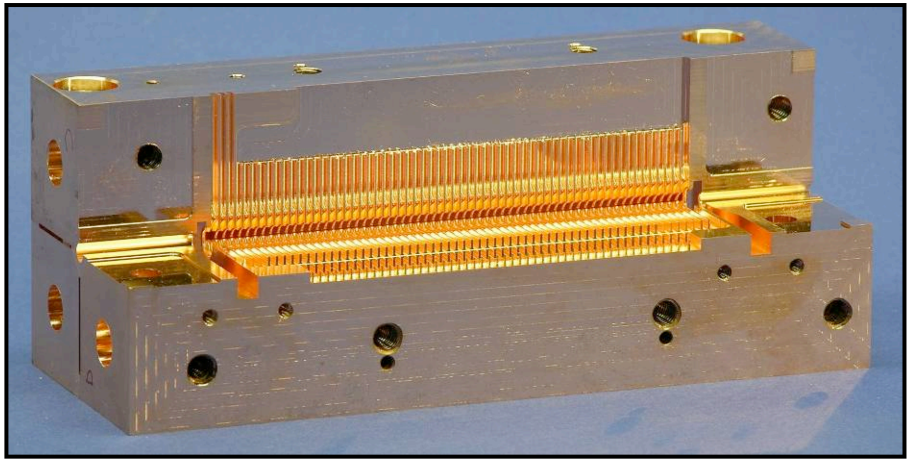
Main beam – 1.2 A, 156 ns
from 9 GeV to 1.5 TeV

No individual RF power sources

CLIC two-beam module



Main beam accelerating structures

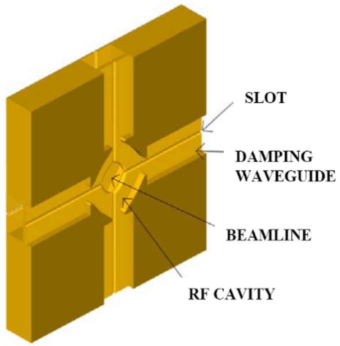


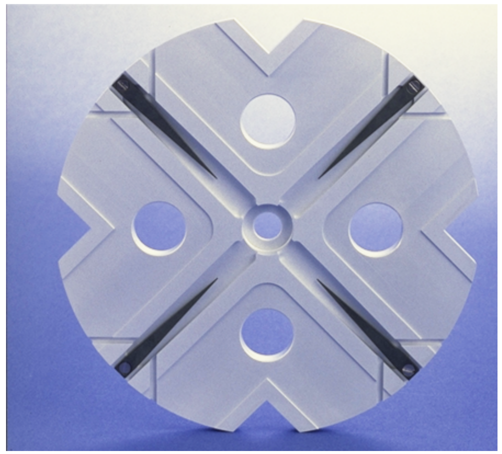
Objective:

- Withstand of 100 MV/m without damage
- breakdown rate < 10^{-7}
- Strong damping of HOMs

Technologies:

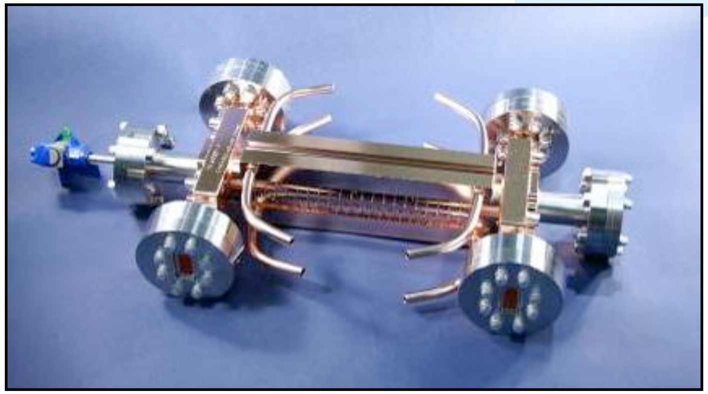
Brazed disks - milled quadrants





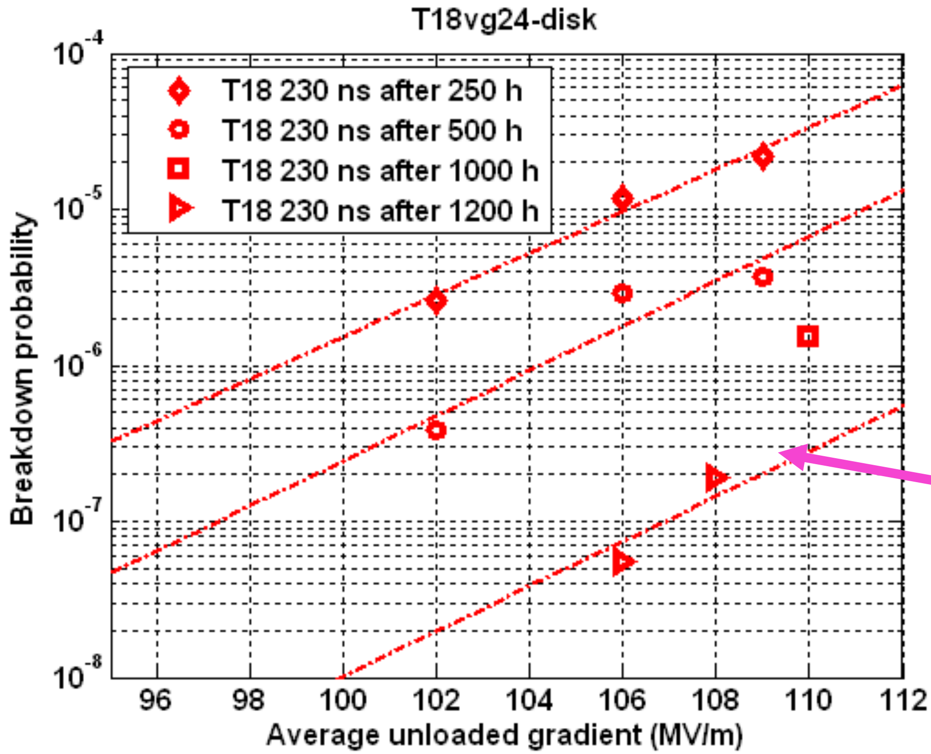
Collaboration: CERN, KEK, SLAC

Best result so far



High Power test of T18_VG2.4_disk (without damping)

- Designed at CERN,
- Machined by KEK,
- Brazed and tested at SLAC

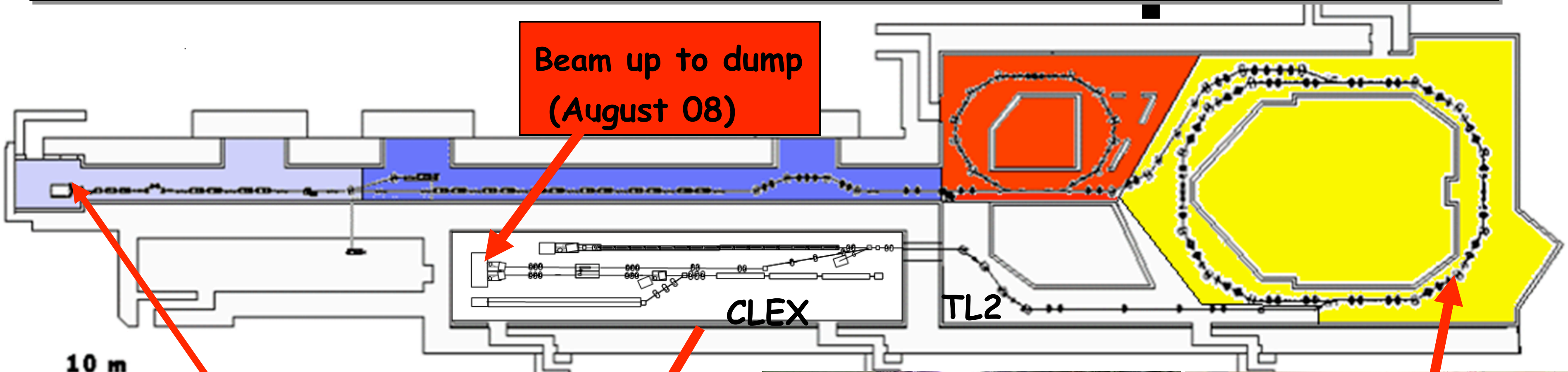


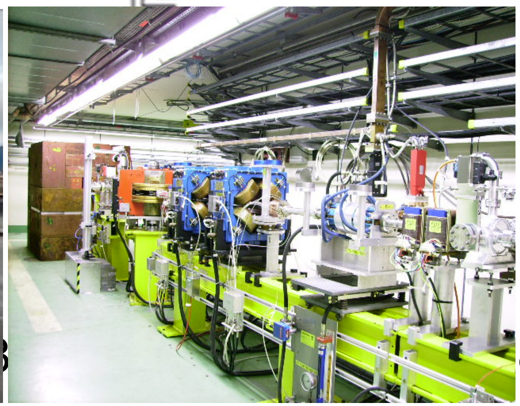
Improvement by RF conditionning

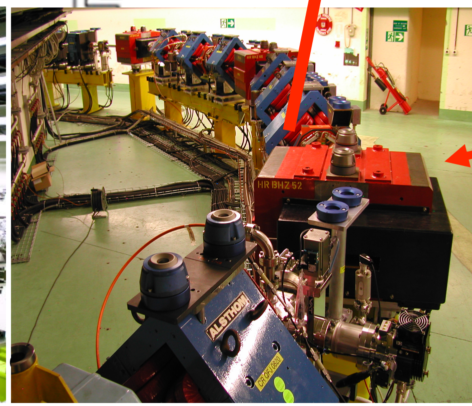
CLIC target

CLIC test facility CTF3

- **Demonstrate Drive Beam generation**
  (fully loaded acceleration, beam intensity and bunch frequency multiplication x8)
- **Demonstrate RF Power Production and test Power Structures**
- **Demonstrate Two Beam Acceleration and test Accelerating Structures**
- **Operational Experience (reliability) by continuous operation (10m/year)**







World-wide CLIC / CTF3 collaboration

http://clic-meeting.web.cern.ch/clic-meeting/CTF3_Coordination_Mtg/Table_MoU.htm

24 members representing 27 institutes involving 17 funding agencies of 15 countries

Ankara University (Turkey)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)

Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
Instituto de Fisica Corpuscular (Spain)
INFN / LNF (Italy)
J.Adams Institute, (UK)

JINR (Russia)
JLAB (USA)
KEK (Japan)
LAL/Orsay (France)
LAPP/ESIA (France)
NCP (Pakistan)

Oslo University (norway)
PSI (Switzerland),
Polytech. University of Catalonia (Spain)
RRCAT-Indore (India)
Royal Holloway, Univ. London, (UK)
SLAC (USA)

Collaboration between ILC and CLIC

Since February 2008: official collaboration between ILC and CLIC

http://clic-study.web.cern.ch/CLIC-Study/CLIC_ILC_Collab_Mtg/Index.htm

Topic	Conveners
Civil Engineering and Conventional Facilities (CFS)	Claude Hauviller (CERN), John Osborne (CERN), Vic Kuchler (FNAL)
Beam Delivery Systems and Machine Detector Interface	Brett Parker (BNL), Daniel Schulte (CERN) , Andrei Seryi (SLAC), Emmanuel Tsesmelis (CERN), Rogelio Tomas Garcia (CERN)
Detectors and Physics	Lucie Linssen (CERN), Francois Richard (LAL), Dieter Schlatter (CERN), Sakue Yamada (KEK)
Cost & Schedule	Hans Braun (CERN), John Carwardine (ANL), Katy Foraz (CERN), Peter Garbincius (FNAL), Tetsuo Shidara (KEK), Sylvain Weisz (CERN)
Beam Dynamics	Andrea Latina (FNAL), Kiyoshi Kubo (KEK), Daniel Schulte (CERN), Nick Walker (DESY)
Damping rings	*** new ***
Positron generation	*** new ***

CLIC parameters

Center-of-mass energy	3 TeV
Peak Luminosity	$6 \cdot 10^{34}$ cm^{-2} s^{-1}
Peak luminosity (in 1% of energy)	$2 \cdot 10^{34}$ cm^{-2} s^{-1}
Repetition rate	50 Hz
Loaded accelerating gradient	100 MV/m
Main linac RF frequency	12 GHz
Overall two-linac length	42 km
Bunch charge	$3.72 \cdot 10^{9}$
Bunch separation	0.5 ns
Beam pulse duration	156 ns
Beam power/beam	14 MWatts
Hor./vert. normalized emittance	660 / 20 nm rad
Hor./vert. IP beam size bef. pinch	40 / ~1 nm
Total site length	48 km
Total power consumption	415 MW

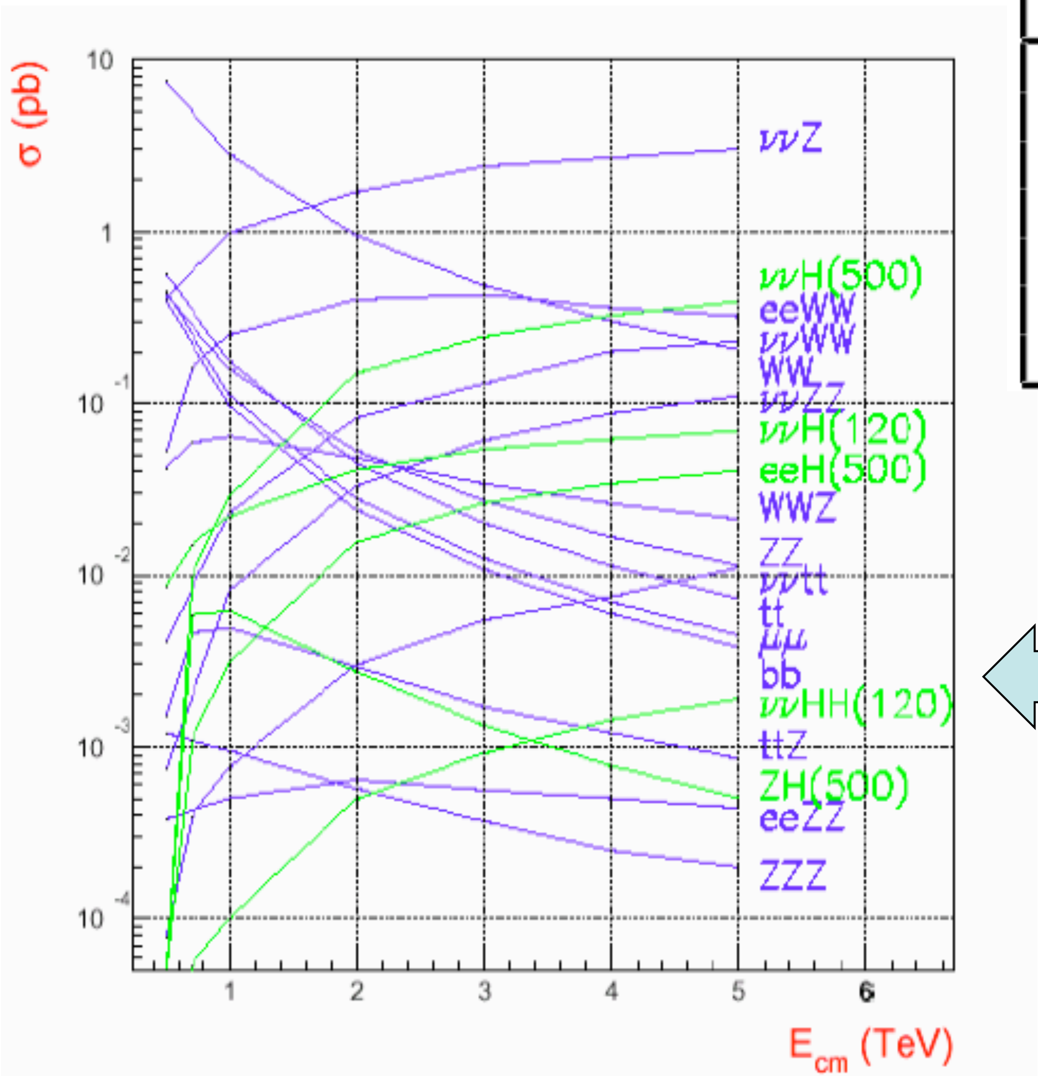
CLIC physics

General Physics Context

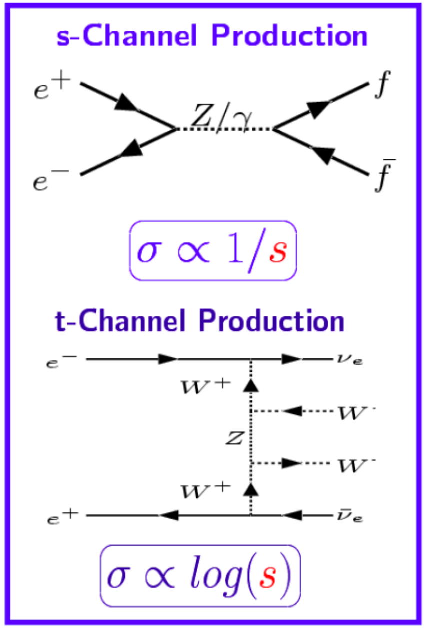
- New physics expected in TeV energy range
  - Higgs, Supersymmetry, extra dimensions, …?
- LHC will indicate what physics, and at which energy scale (is 500 GeV enough or need for multi TeV?)

- However, even if multi-TeV is final goal, most likely CLIC would run over wide range of energies (e.g. 0.5 – 3.0 TeV)
- ILC detector concepts are excellent starting point for high energy detector
- Like for ILC, assume 2 CLIC detectors in pull push mode

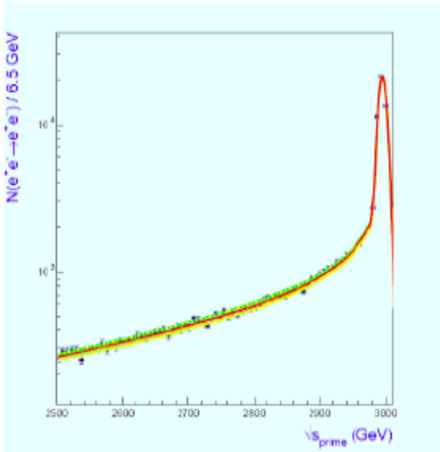
Cross-sections at a few TeV



Event Rates (1000 fb^{-1})	3 TeV 10^3 events
$e^+e^- \to t\bar{t}$	20
$e^+e^- \to b\bar{b}$	11
$e^+e^- \to ZZ$	27
$e^+e^- \to WW$	490
$e^+e^- \to hZ/h\nu\nu$ (120 GeV)	1.4/530
$e^+e^- \to H^+H^-$(1 TeV)	1.5
$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$ (1 TeV)	1.3



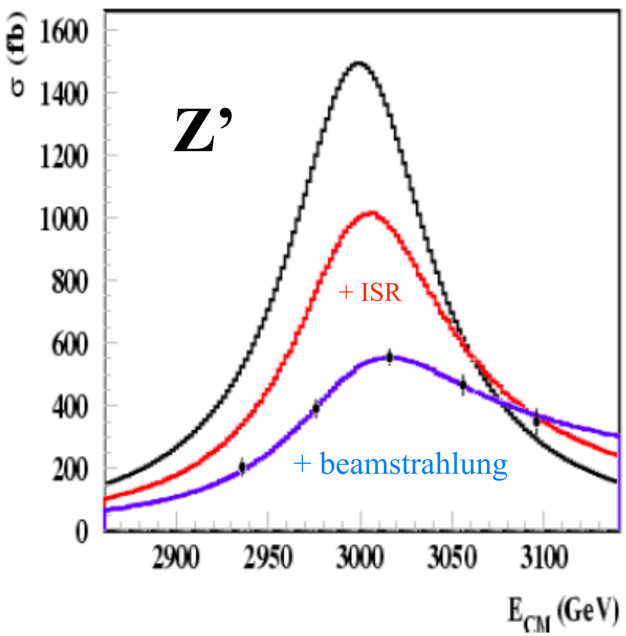
Luminosity spectrum and effect on Resonance Production



@CLIC significant beamstrahlung

→ Luminosity spectrum not as sharply peaked as at lower energy

→ need for luminosity



Resonance scans, e.g. a Z'

FIT ACCURACY

Observable	Breit Wigner	CLIC.01	CLIC.02
$M_{Z'}$ (GeV)	$3000 \pm .12$	$\pm .15$	$\pm .21$
$\Gamma(Z')/\Gamma_{SM}$	$1. \pm .001$	$\pm .003$	$\pm .004$
σ^{eff}_{peak} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

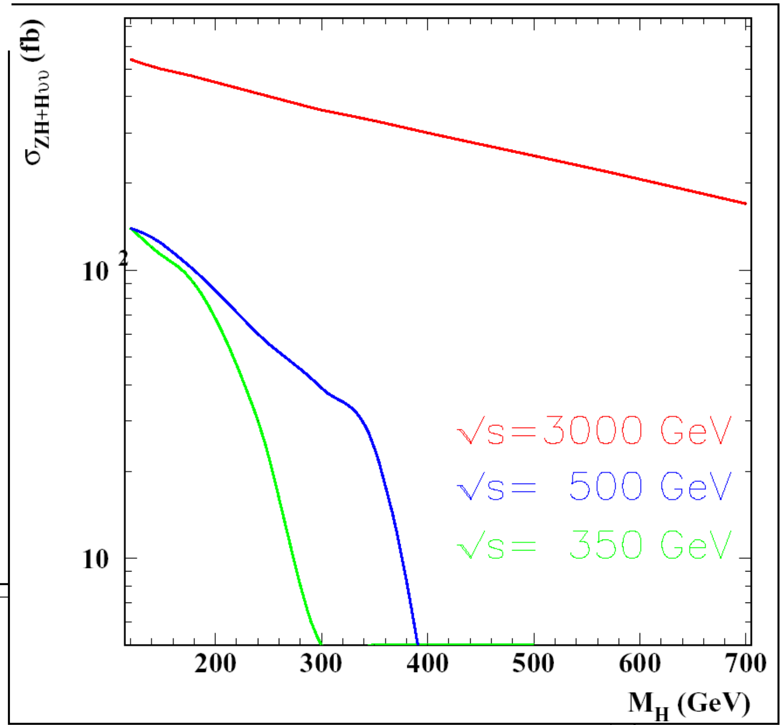
$1\ ab^{-1} \Rightarrow \delta M/M \sim 10^{-4}$ & $\delta\Gamma/\Gamma = 3.10^{-3}$

If there is a light Higgs boson …

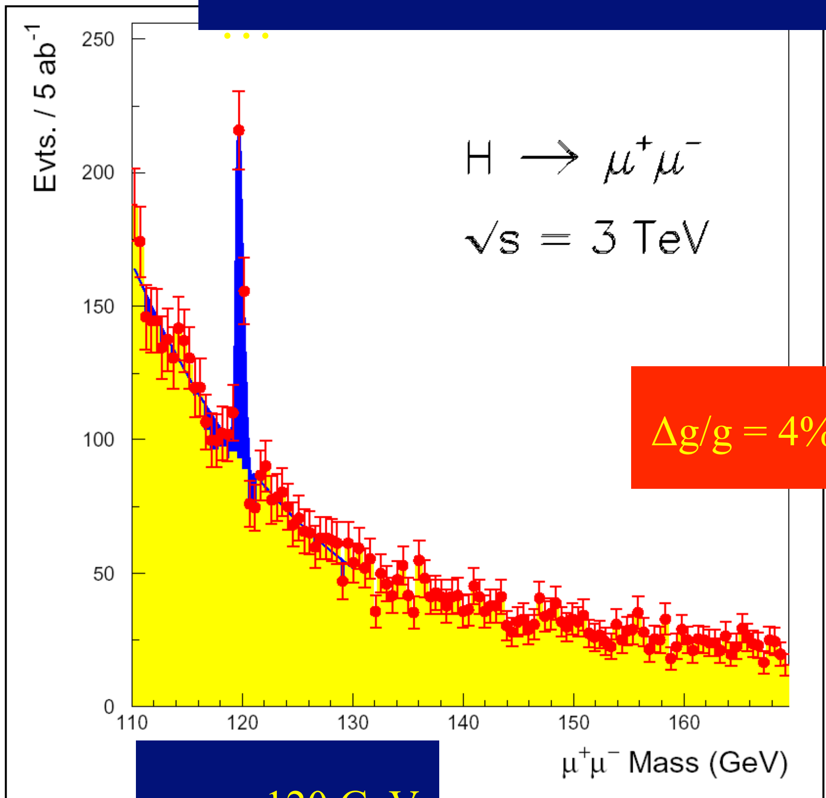
- Large cross section @ CLIC
- Measure rare Higgs decays unobservable at LHC or a lower-energy $e^+ e^-$ collider
- CLIC could measure the effective potential with 10% precision
- CLIC could search indirectly for accompanying new physics up to 100 TeV
- CLIC could identify any heavier partners

John Ellis, CLIC07

Large Cross Section @ CLIC

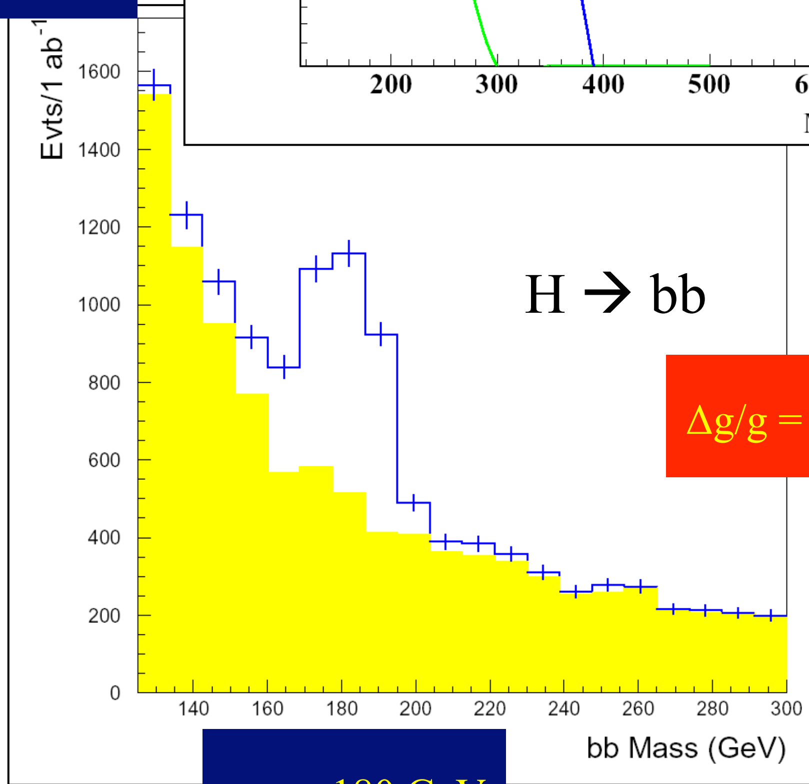


Can measure rare decay modes



$\Delta g/g = 4\%$

$m_H = 120$ GeV

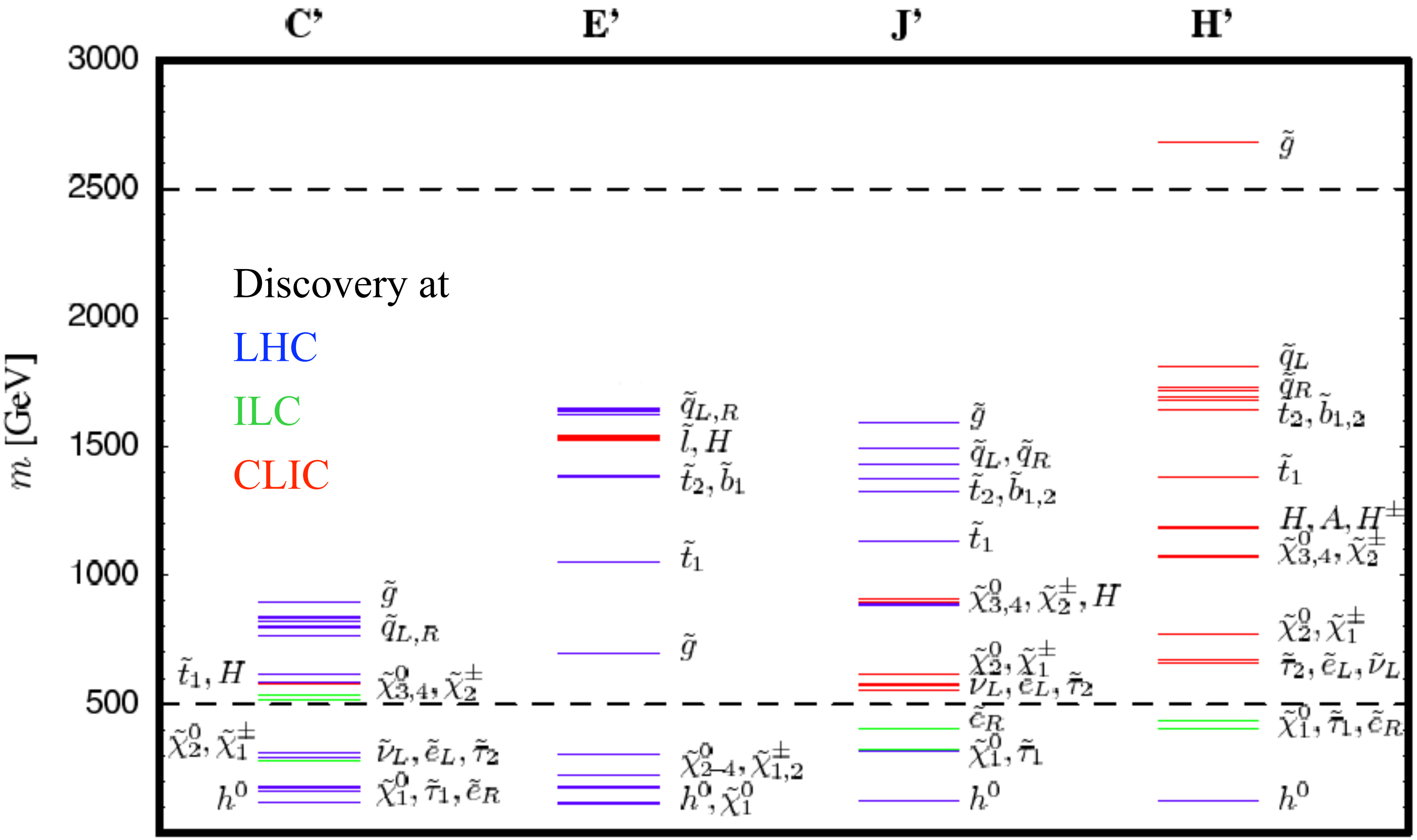


$\Delta g/g = 2\%$

$m_H = 180$ GeV

Physics case: Supersymmetry

Examples of mass spectra for 4 SUSY scenarios (there are many more!)

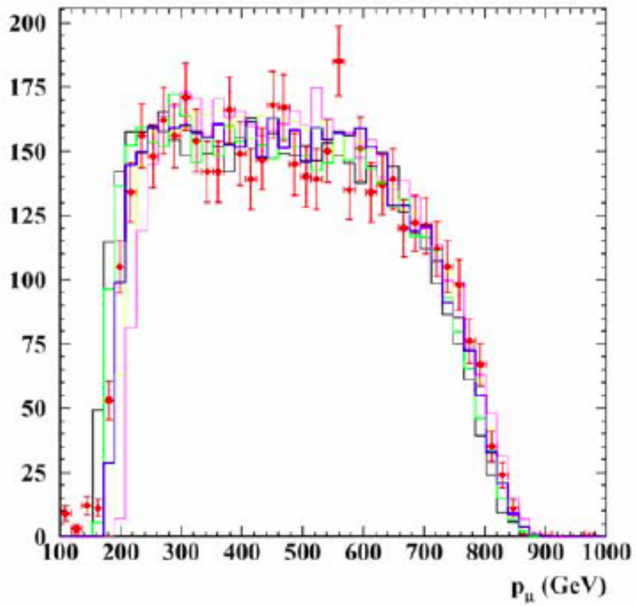


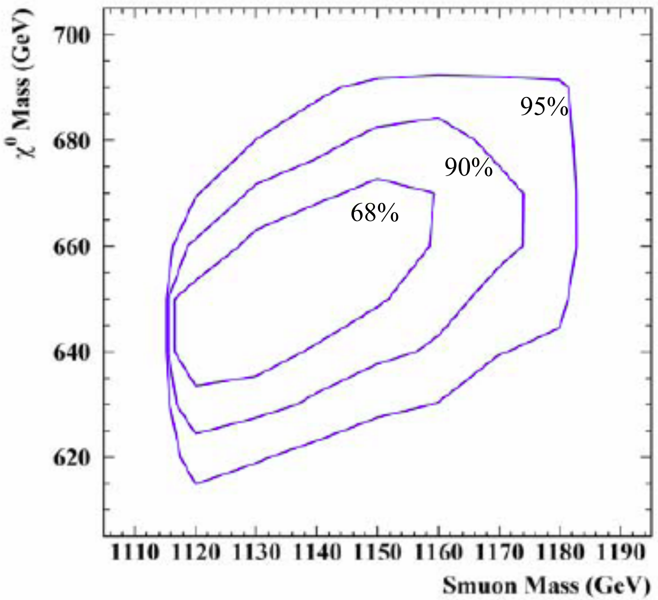
Physics case: Supersymmetry

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

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

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





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

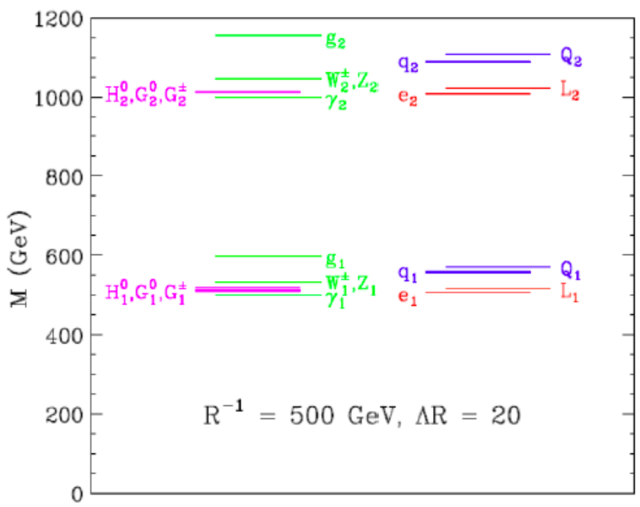
$\tilde{m}_\chi = (652 \pm 22)\,\text{GeV}$ 3%

Physics case: Extra dimensions

Extra-dimension scenario (Randall, Sundrum) predicts production of

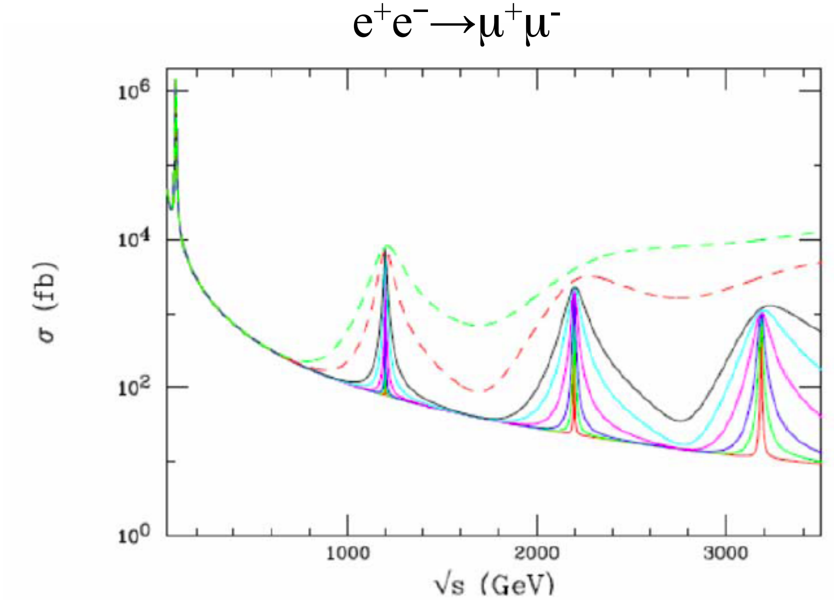
- TeV-scale graviton resonances, decaying into two fermions.
- Cross sections are large, but wide range of parameters.

Examples:



Could be discovered at LHC

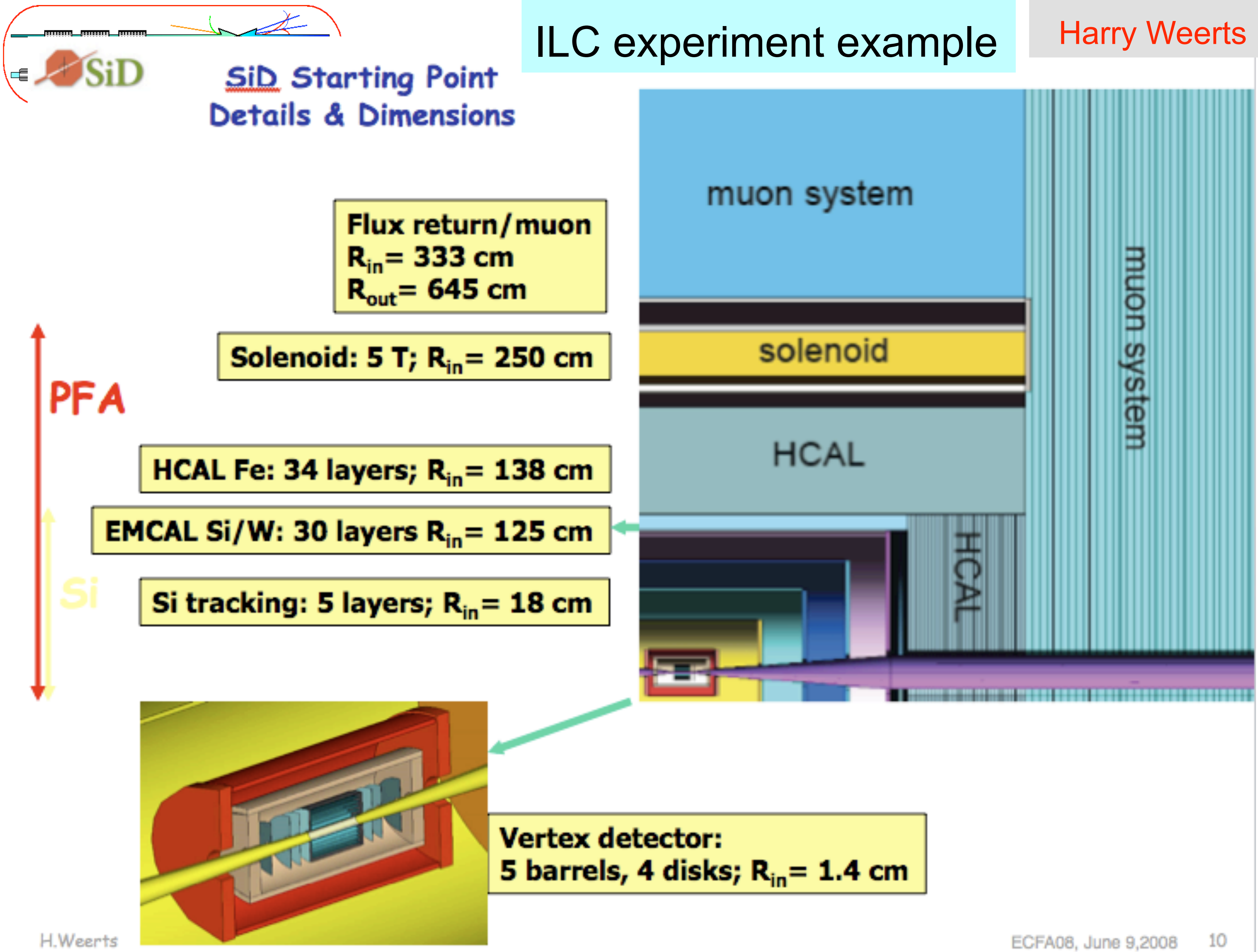
$e^+e^- \rightarrow \mu^+\mu^-$



CLIC detector issues,
and comparison with ILC

ILC experiment example

Harry Weerts



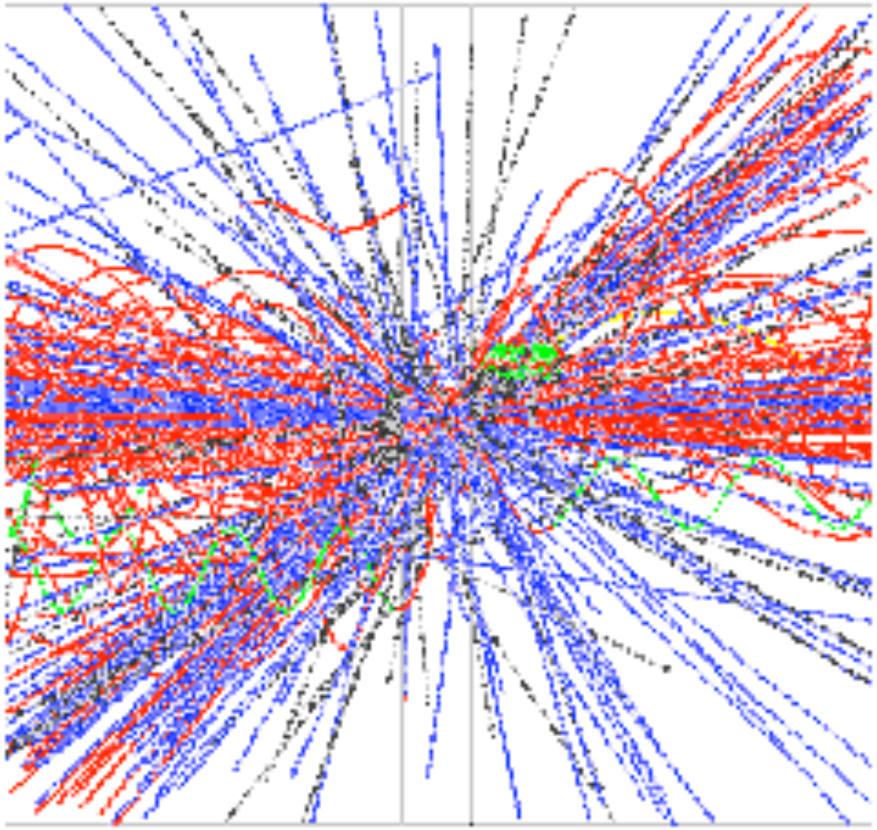
Some Detector Design Criteria

Harry Weerts

Requirement for ILC	Compared to best performance to date
• Impact parameter resolution $$\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$$	• Need factor 3 better than SLD $$\sigma_{r\phi} = 7.7 \oplus 33/(p\sin^{3/2}\vartheta)$$
• Momentum resolution $$\sigma\left(\frac{1}{p_T}\right) = 5\times10^{-5}\ (GeV^{-1})$$	• Need factor 10 (3) better than LEP (CMS)
• Jet energy resolution goal $$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}} \qquad \frac{\sigma_E}{E} = 3-4\%$$	• Need factor 2 better than ZEUS $$\frac{\sigma_E}{E} = \frac{60\%}{\sqrt{E}}$$
• Detector implications:	• Detector implications:
◆ Calorimeter granularity	◆ Need factor ~200 better than LHC
◆ Pixel size	◆ Need factor ~20 smaller than LHC
◆ Material budget, central	◆ Need factor ~10 less than LHC
◆ Material budget, forward	◆ Need factor ~ >100 less than LHC

LHC: staggering increase in scale, but modest extrapolation of performance
ILC: modest increase in scale, but significant push in performance

CLIC detector issues



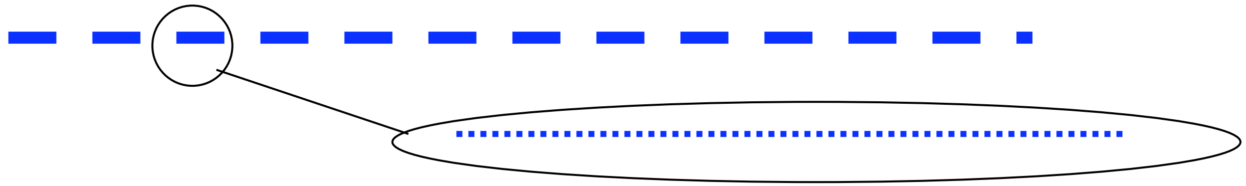
3 main differences with ILC:

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

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	337 ns apart	5 Hz

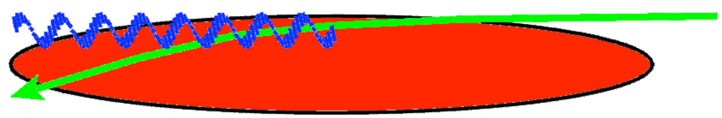
Consequences for CLIC detector:

- Assess need for detection layers with time-stamping
    - Innermost tracker layer with sub-ns resolution
    - Additional time-stamping layers for photons and for neutrons
- Readout electronics will be different from ILC
- Consequences for power pulsing?

Beam-induced background

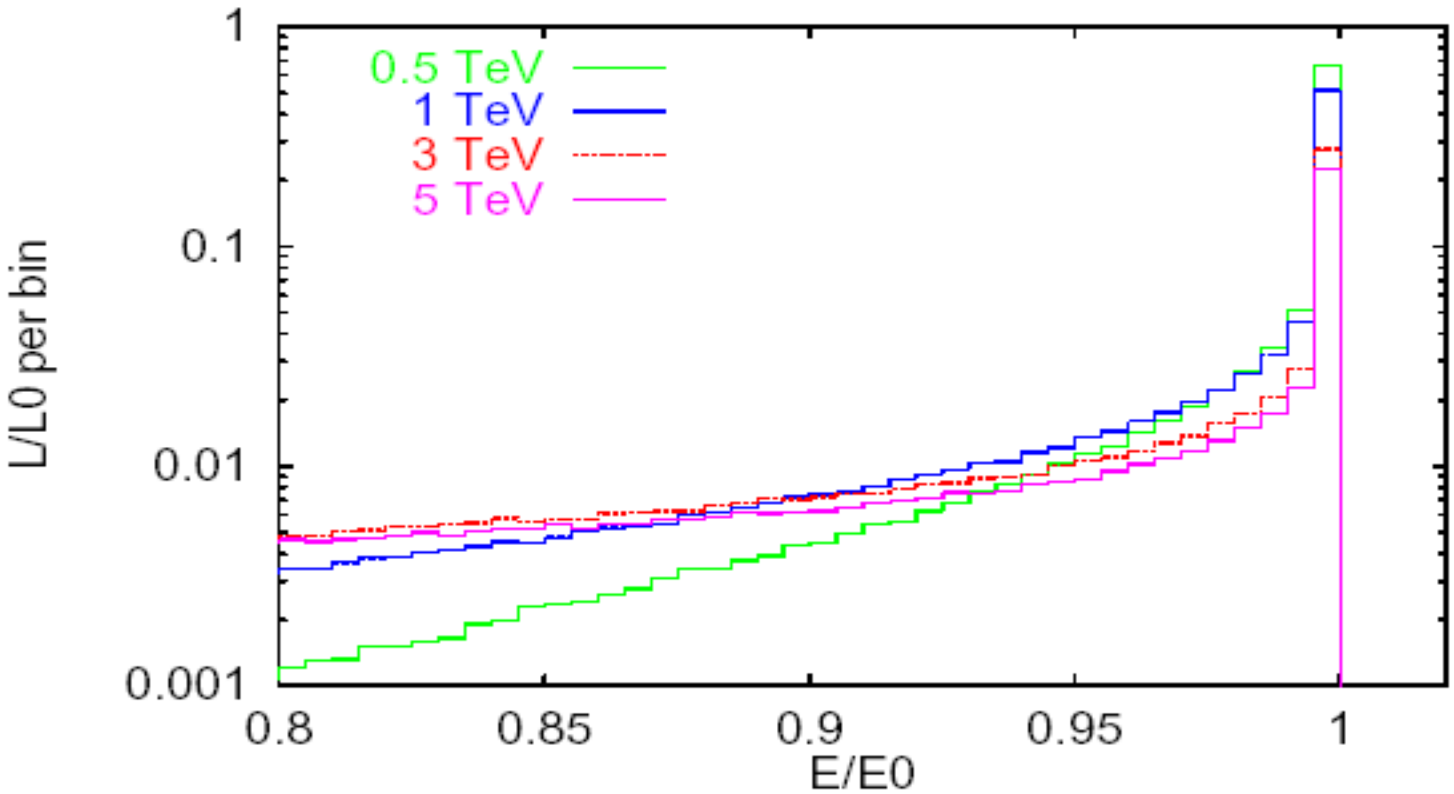
Background sources: CLIC and ILC similar

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



- 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 B-field
  - γγ interactions => hadrons
- Muon background from upstream linac
  - More difficult to stop due to higher CLIC energy (active muon shield)
- Synchrotron radiation
- Beam tails from the linac
- Backscattered particles from the spent beam (neutrons)

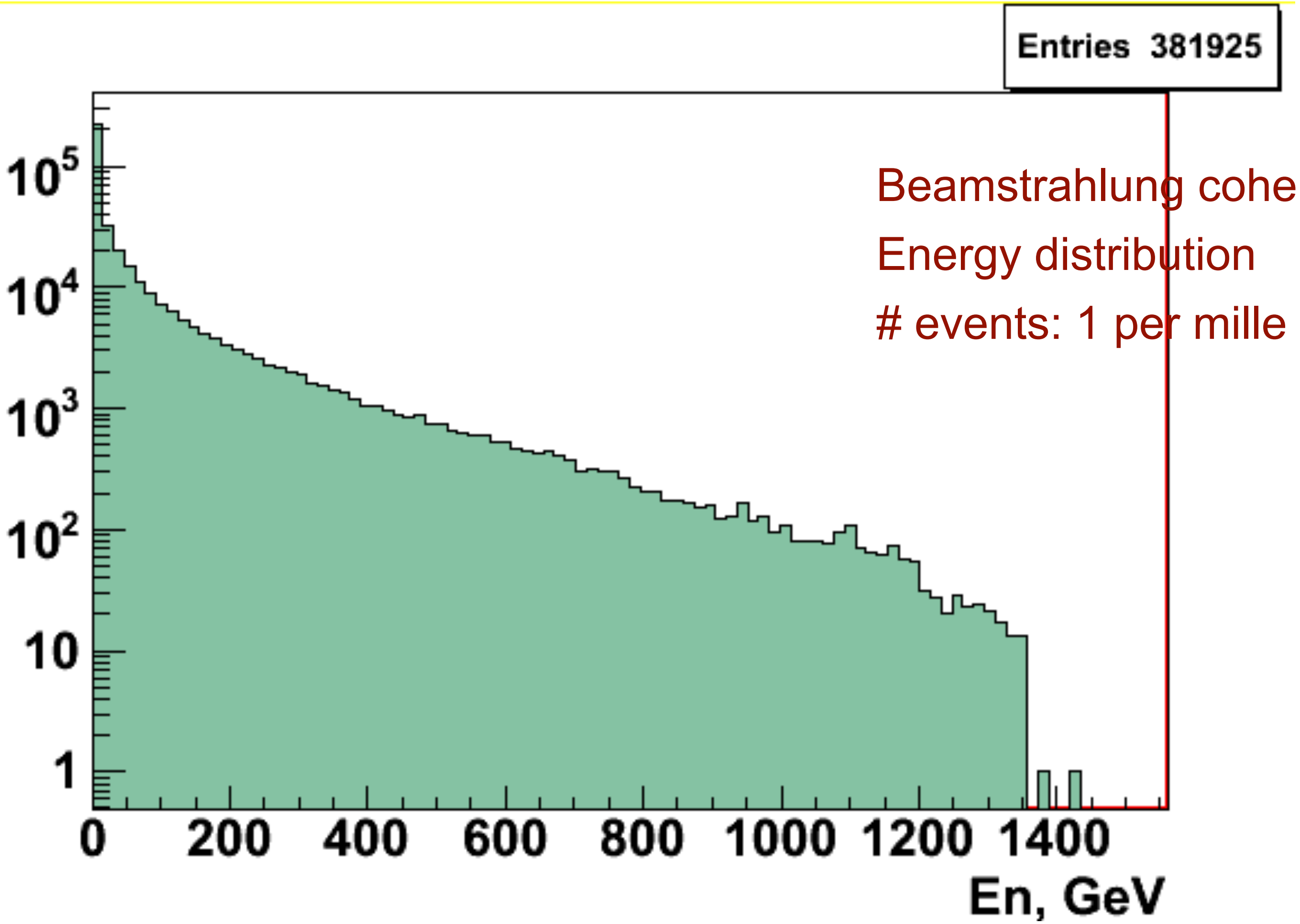
CLIC CM energy spectrum



Due to beamstrahlung:

- At 3 TeV only 1/3 of the luminosity is in the top 1% Centre-of-mass energy bin
- Many events with large forward or backward boost

Beamstrahlung



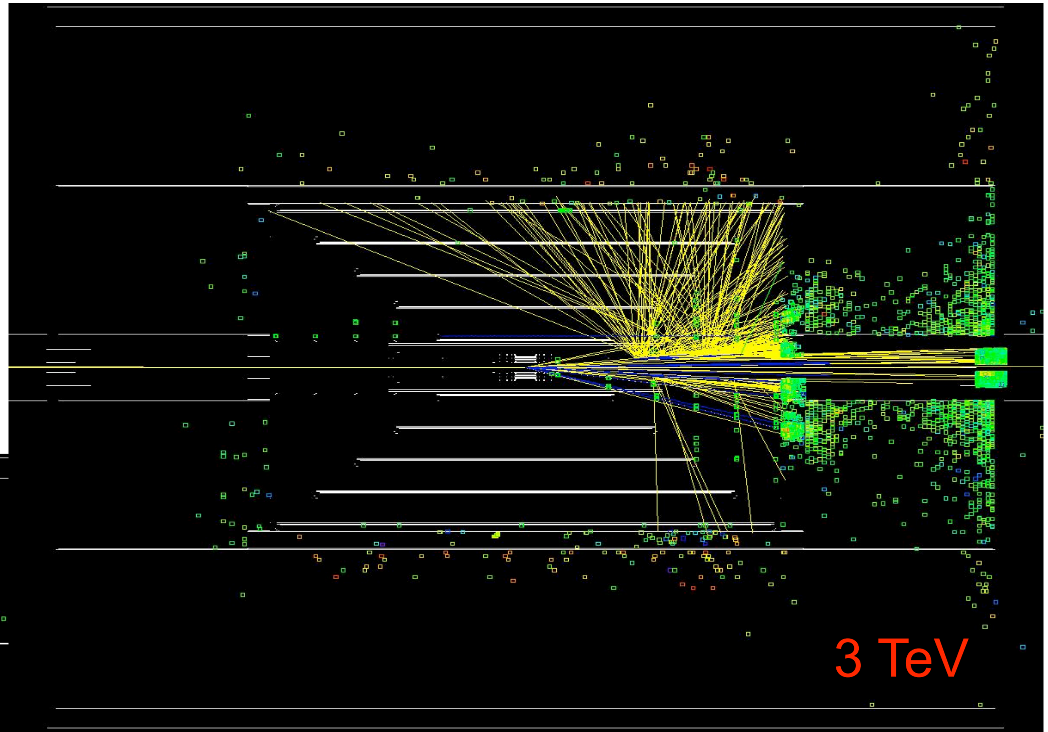
Beamstrahlung coherent pairs

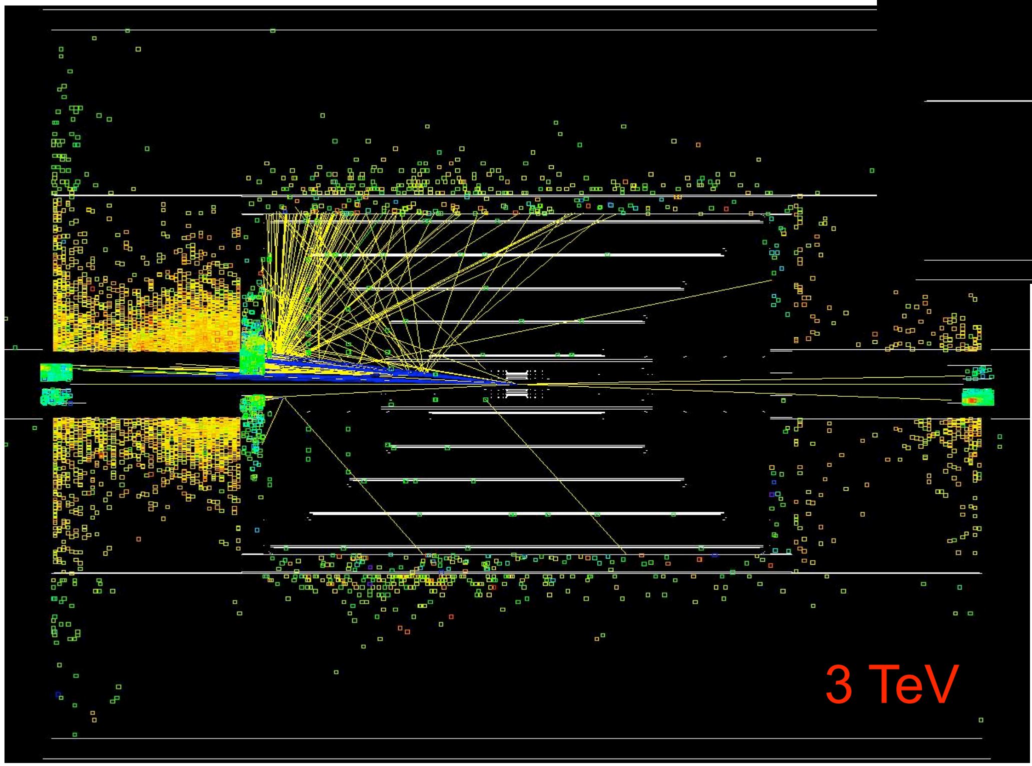
Energy distribution

events: 1 per mille of 1 bunch crossing

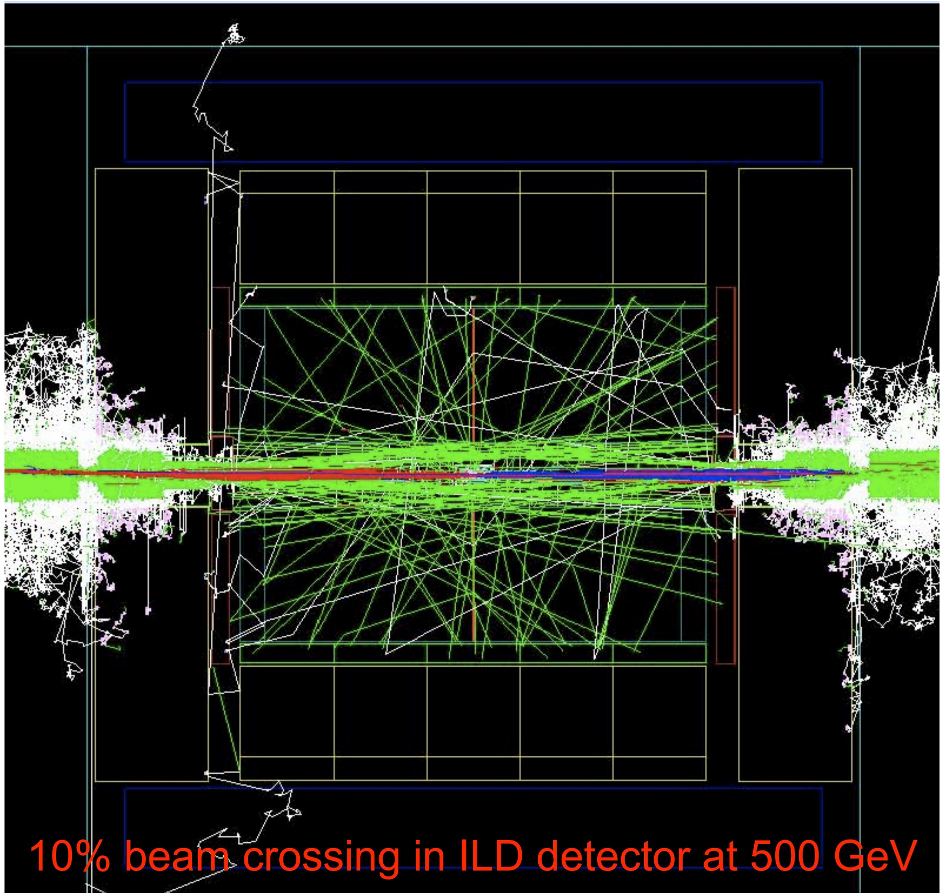
Beamstrahlung, continued…..

At 3 TeV many events have a large forward or backward boost, plus many back-scattered photons/neutrons





Lessons learnt from ILC case



Courtesy: Adrian Vogel, DESY

- Pair production is the dominant background
- Most backgrounds can be controlled by a careful design
- Use full detector simulation to avoid overlooking effects

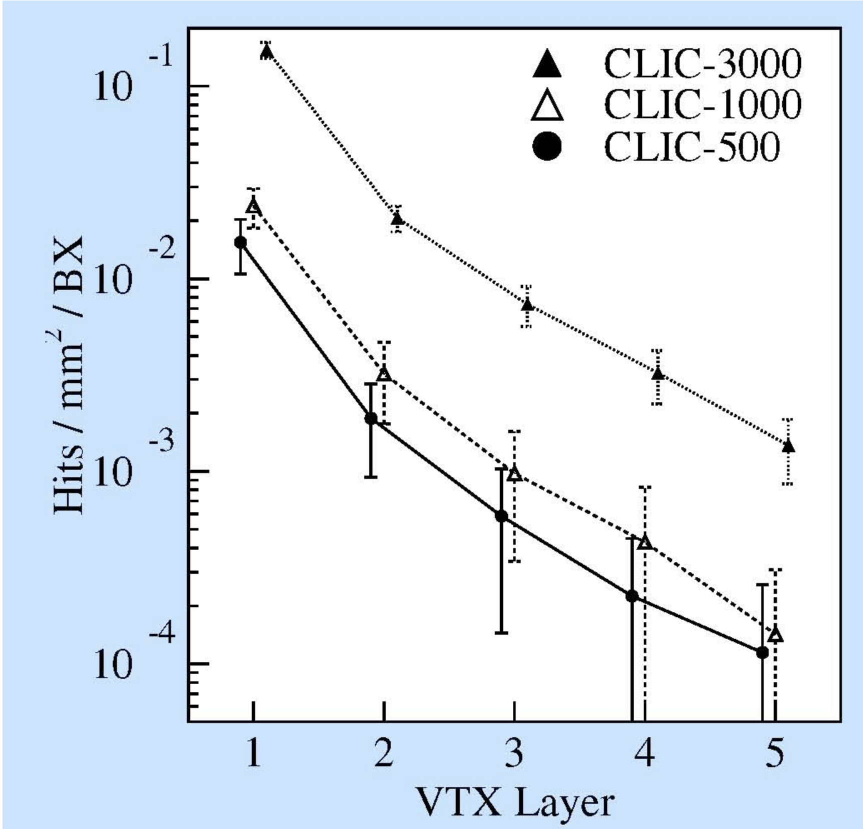
- Innermost Vertex layer (r=1.5 cm) has 0.04 hits/mm^2/BX
- Critical level of neutrons (radiation damage) at small radii of HCAL end-cap

Extrapolation ILC = > CLIC

Full LDC detector simulation at 3 TeV

Simulation of e^+e^- pairs from beamstrahlung origin

Courtesy: Adrian Vogel, DESY

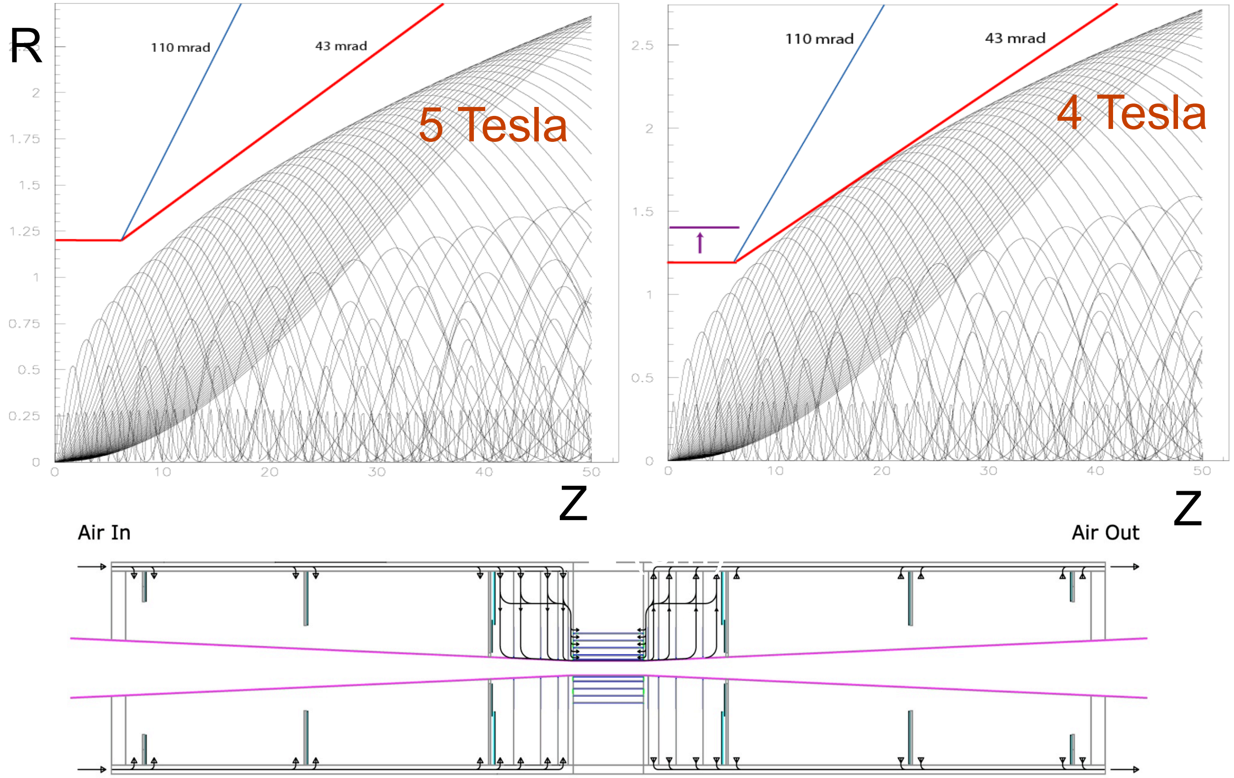


LDC 3 TeV, with forward mask

- **Conclusion of the comparison:**
- ILC, use 100 BX (1/20 bunch train)
- CLIC, use full bunch train (312 BX)

- **CLIC VTX: O(10) times more background**
- **CLIC TPC: O(30) times more background**

Opening angle forward region



SiD plots

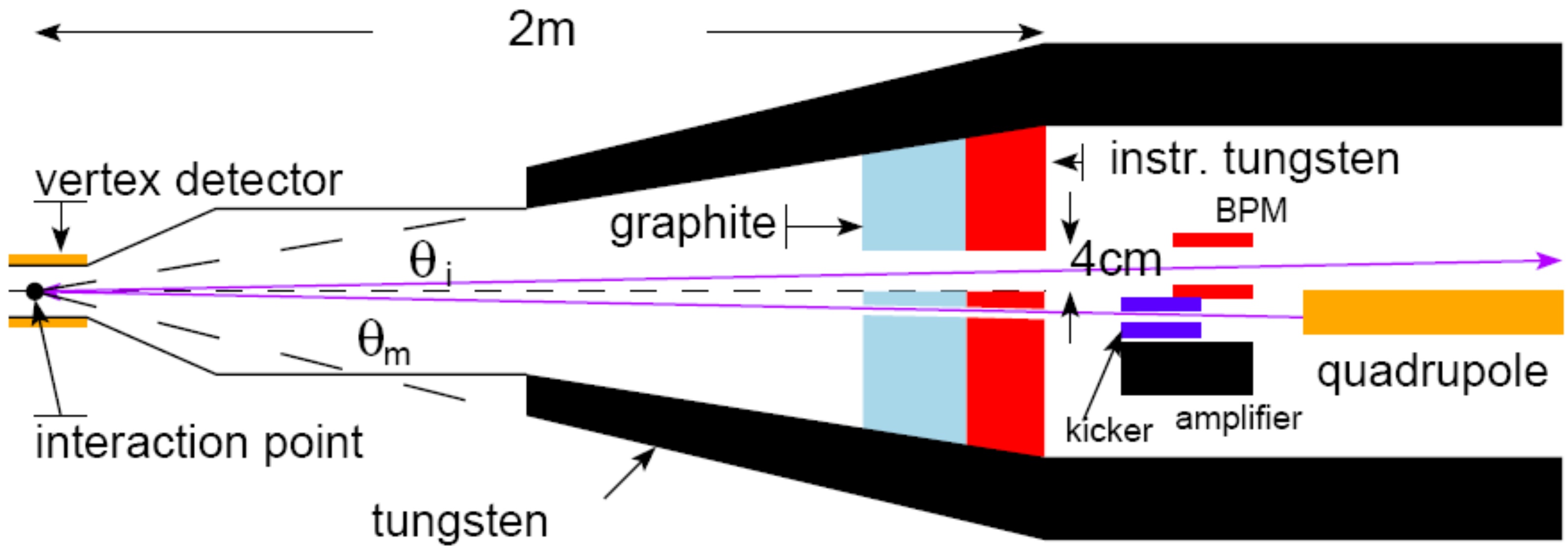
500 GeV

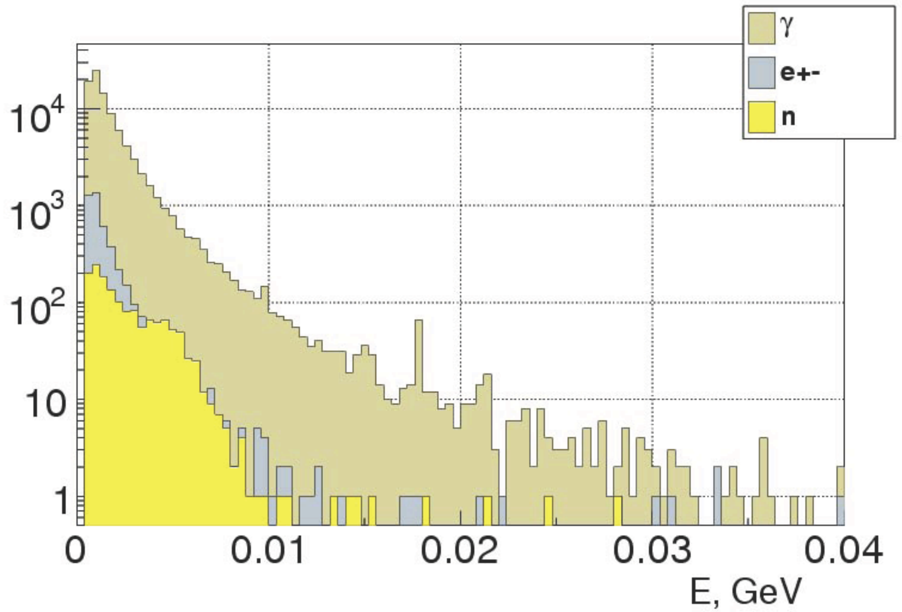
Consequences of machine-induced background for CLIC detector:

Need: **higher magnetic field** and/or **larger tracking/vertex opening angle** and **larger crossing angle** (20 mrad) and **Mask in forward region**

Mask Design

Daniel Schulte, CLIC08





Background energy spectrum (without mask)

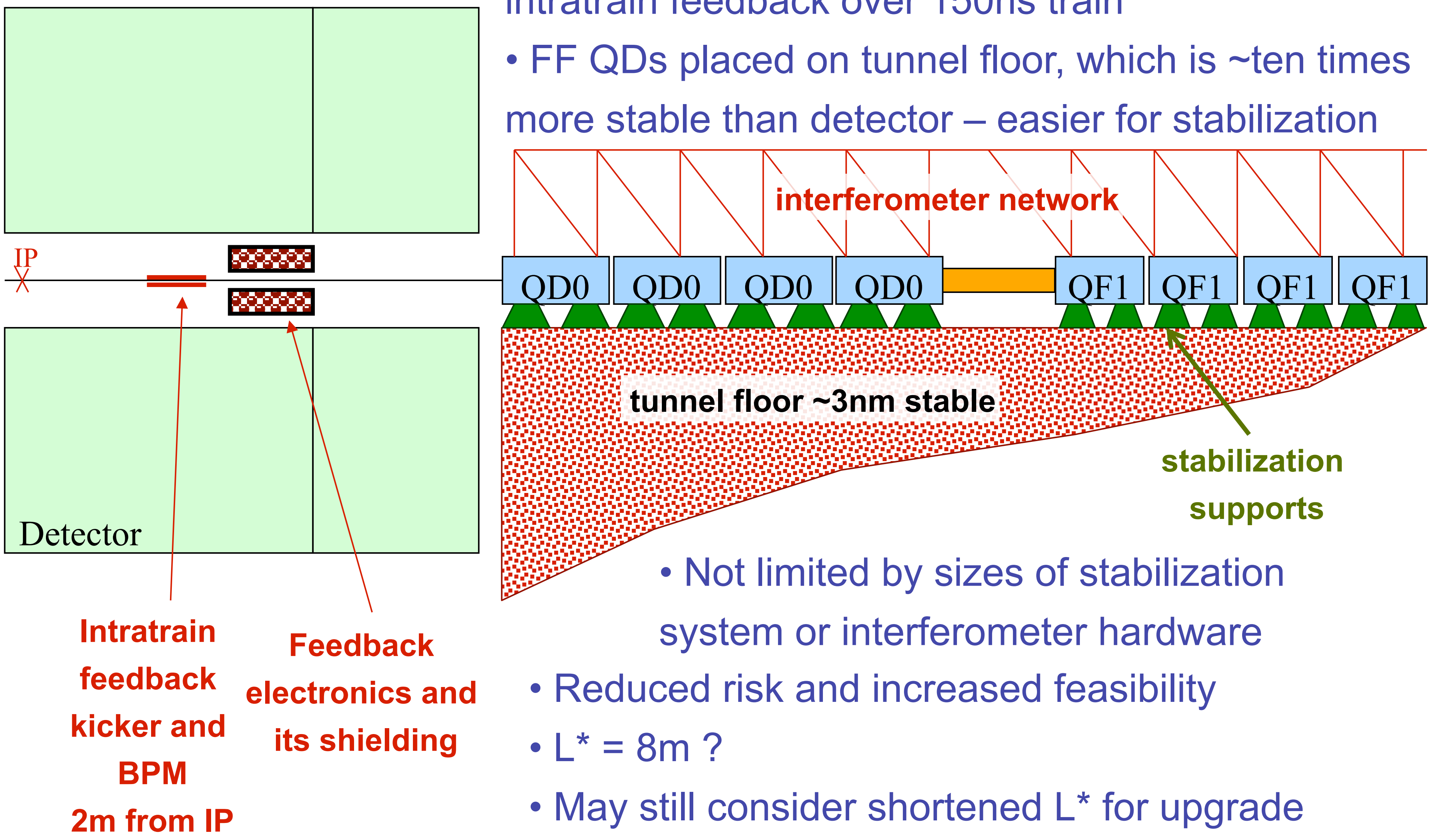
Origin: beamstrahlung => coherent pairs => backscattering γ,e,n

Andrey Sapronov

New CLIC IR

Andrei Seryi, CLIC08

- Reduced feedback latency – several iterations of intratrain feedback over 150ns train
- FF QDs placed on tunnel floor, which is ~ten times more stable than detector – easier for stabilization

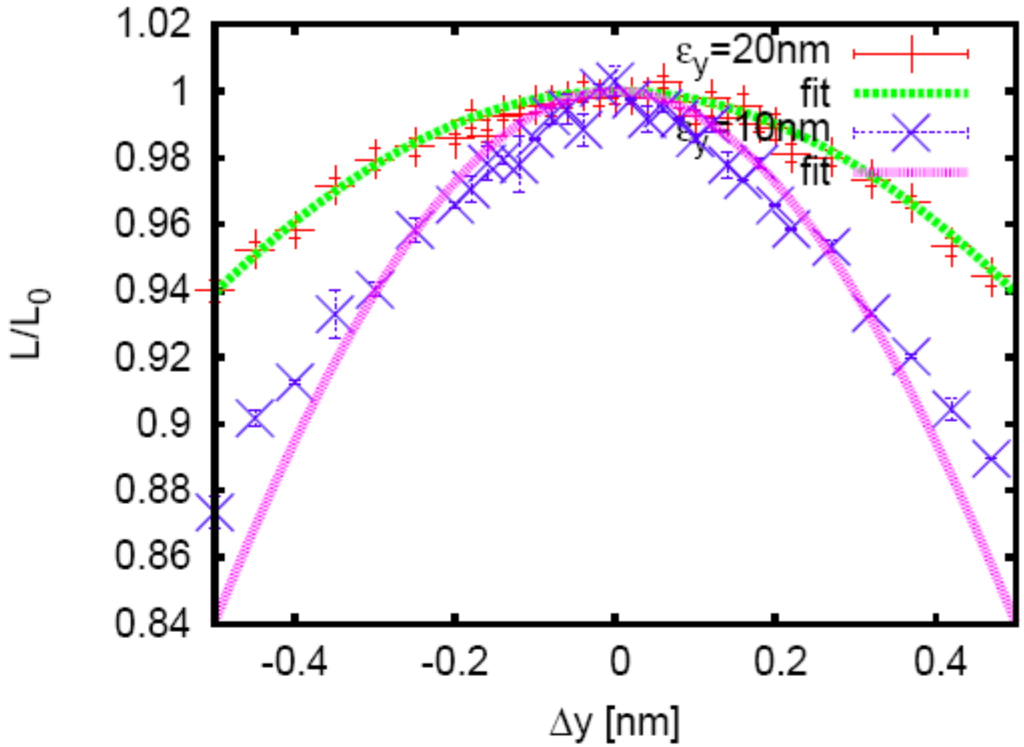


- Not limited by sizes of stabilization system or interferometer hardware
- Reduced risk and increased feasibility
- L* = 8m ?
- May still consider shortened L* for upgrade

Beam-Beam Jitter Tolerance

Daniel Schulte, CLIC08

- At 3 TeV one finds vertical beam-beam jitter tolerance of 0.3 nm
- At 500 GeV $\approx 0.7\,\mathrm{nm}$
  - for conservative parameters $\approx 1.7\,\mathrm{nm}$
- Quadrupole jitter tolerances range from 0.5 to 4 times beam-beam jitter tolerance, depending on configuration
- Can on imagine a support through the detector?
- Beam-beam feedback can give up to about a factor 2



These extremely high stability requirements of the accelerator also impose high stability requirements on the experiment (vibrations, turbulences…)

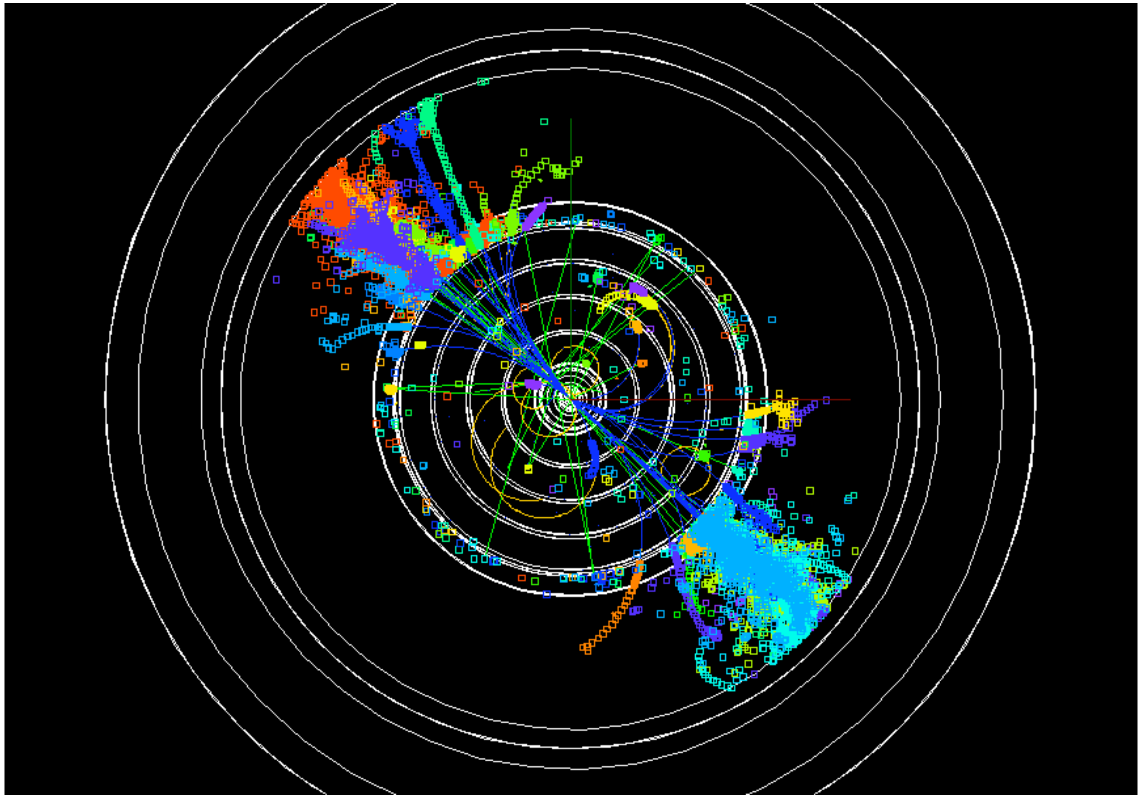
CLIC Calorimetry

Need deep HCAL ($7\Lambda_i$ to $9\Lambda_i$, tbc)

Cannot increase coil radius too much => need heavy absorber

Which HCAL material to use?

- Tradeoff between X_0 and Λ_i for hadron calorimetry



3 TeV e^+e^- event on SiD detector layout, illustrating the need for deeper calorimetry

Which calorimetry at CLIC energies?

To overcome known shortfalls from LEP/LHC experience, new concepts/technologies are chosen for ILC:

- **Based on Particle Flow Algorithm**
  - Highly segmented (13-25 mm^2) ECAL (analog)
  - Very highly segmented ECAL (digital)
  - Highly segmented (1 cm^2) HCAL (digital)
  - Segmented HCAL (analog)
- **Based on Dual (Triple) readout**
  - Sampling calorimeter
    - Plastic fibres
    - Crystal fibres (<= materials studies)
  - Fully active calorimeter (EM part)
    - Crystal-based

Method and Engineering difficult, but conventional

Limited in energy-range to a few hundred GeV

Method and Engineering difficult and non-proven

Not limited in energy range

PFA for high-energy jets

Mark Thomson CLIC08
ILD detector description

★ Traditional calorimetry $\sigma_E/E \approx 60\%/\sqrt{E/\mathrm{GeV}}$

★ Does not degrade significantly with energy (but leakage will be important at CLIC)

★ Particle flow gives much better performance at "low" energies
- very promising for ILC

What about at CLiC ?

★ PFA perf. degrades with energy

★ For 500 GeV jets, current alg. and ILD concept:

$$\sigma_E/E \approx 85\%/\sqrt{E/\mathrm{GeV}}$$

★ Crank up field, HCAL depth…

$$\sigma_E/E \approx 65\%/\sqrt{E/\mathrm{GeV}}$$

★ Algorithm not tuned for very high energy jets, so can probably do significantly better

rms90 PandoraPFA v03-β

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %
500 GeV	84.1 %	3.7 %
500 GeV	64.3 %	3.0 %

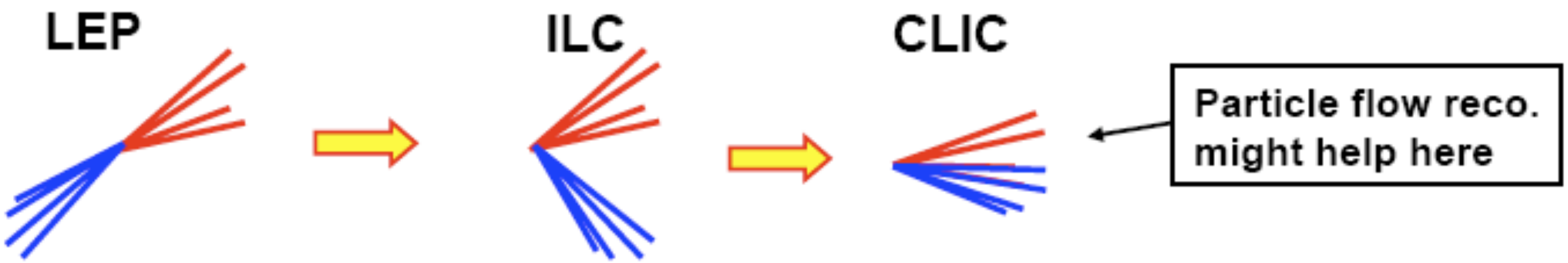
63 layer HCAL (8 λ_I)
B = 5.0 Tesla

Conclude: for 500 GeV jets, PFA reconstruction not ruled out

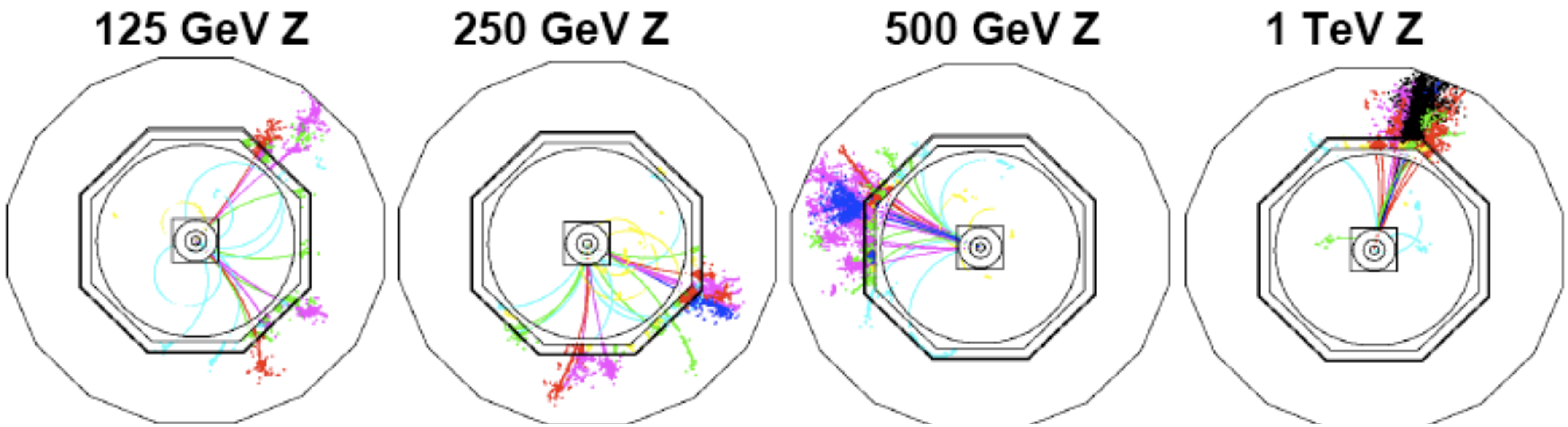
W/Z Separation at high Energies

Mark Thomson CLIC08

- On-shell W/Z decay topology depends on energy:



- A few comments:
  - Particle multiplicity does not change
  - Boost means higher particle density
  - PFA could be better for "mono-jet" mass resolution
- PandoraPFA + ILD performance studied for:

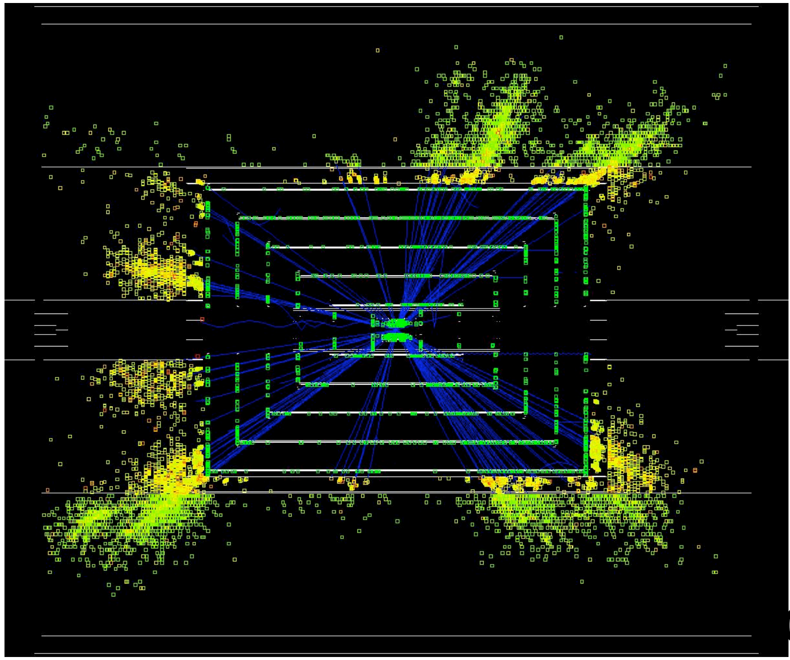


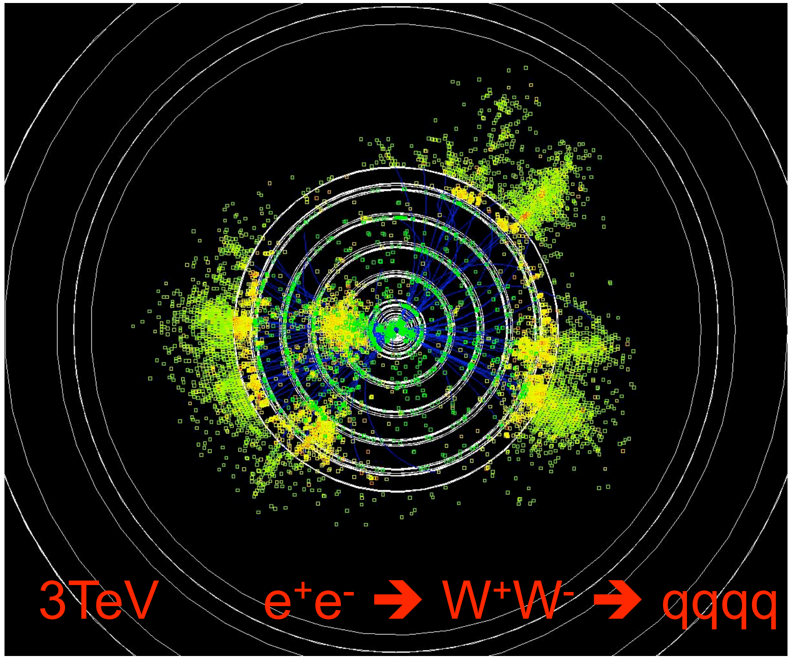
Larger track length beneficial for particle flow

Tracking

Tracking issues:

- Due to beam-induced background and short time between bunches:
  - Inner radius of Vertex Detector has to move out (30-40 mm)
  - High occupancy in the inner regions
- Narrow jets at high energy
  - 2-track separation is an issue for the tracker/vertex detector
  - Track length may have to increase (fan-out of jet constituents)?





Opportunities for Detector R&D and engineering studies

Opportunities for detector R&D

Just a first assessment of which R&D would be needed beyond present ILC developments

- Time stamping
- Alternative to PFA calorimetry
- Mechanical engineering studies
  - Integration studies
  - Heavy calorimeter concept
  - Large high-field solenoid concept
  - Sub-lifting studies
- Precise alignment studies
- Power pulsing and other electronics developments

R&D for Time stamping

0.5 nsec bunch spacing, 312 bunches/train, 50 Hz

Overlapping background for 312 BX will be an issue

Exact needs will come out of detector concept simulations

- **(sub)-ns time stamping in most inner tracking layer**
- Time stamping needed for photons? => preshower
- Time stamping needed for neutron? => layer within HCAL

Critical issue for time-stamping in the inner tracking layer (and preshower)

- Critical analog design involving sensor+electronics for good time resolution
- High granularity (short strips?)
- Power consumption is an issue for high-precision TDC

Alternative to PFA calorimetry

R&D on dual/triple readout calorimetry

Basic principle:

- •Measure EM shower component separately
- •Measure HAD shower component separately
- •Measure Slow Neutron component separately

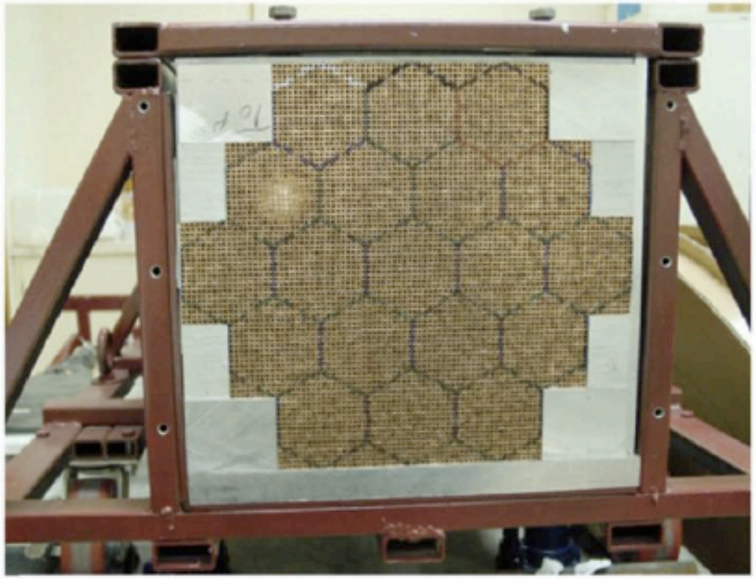
} **Dual** (EM, HAD)

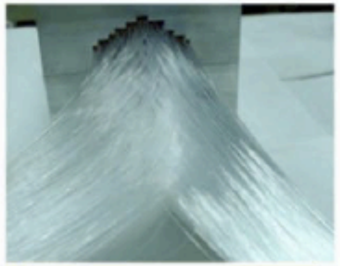
} **Triple** (EM, HAD, Slow Neutron)

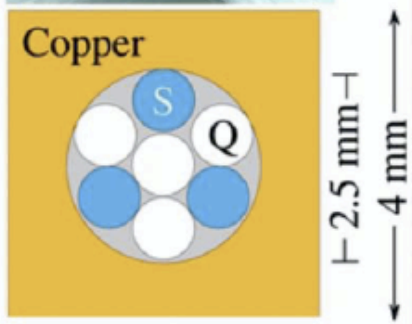
EM-part=> electrons => highly relativistic => Cerenkov light emission

HAD-part=> “less” relativistic => Scintillation signal

Slow neutrons => late fraction of the Scintillation signal







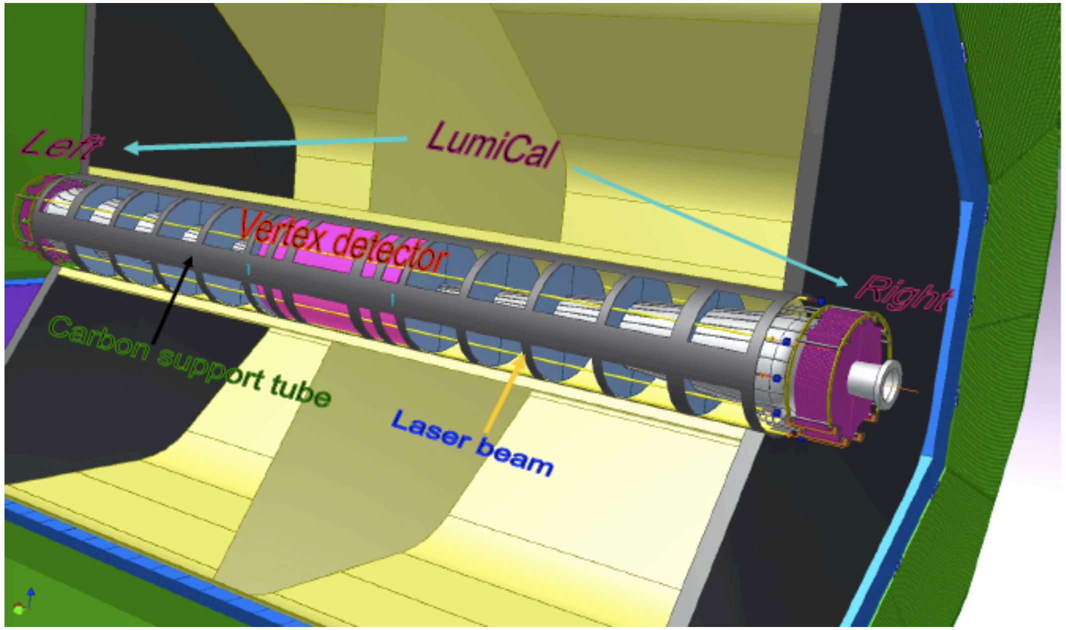
Requires broader collaboration on materials + concept

Mechanical engineering studies

– Integration studies
  - Detailed forward region integration
  - Overall detector integration studies
  - Overall care for precise mechanical stability (decoupling from accelerator!)
– Heavy calorimeter concept (with 7-9 Λ_i)
  - Choice of suitable materials
  - Overall concept design
– Large high-field solenoid concept
  - Extrapolation from CMS solenoid
  - Replacement of Al coil stabiliser by stronger doped alloy (hardware R&D)
  - Welding technique of reinforced conductor cable (hardware R&D)
  - Suspension of heavy barrel calorimeter from coil cryostat
– Sub-lifting studies
  - Smooth/precise displacements without vertical move (e.g. for push-pull)

Precise alignment

- **Precise alignment studies/technologies**
  - How to link left-arm and right-arm?
  - E.g. needed for luminosity measurement using Bhabha scattering
  - ILC requirements => <4 μm (x,y), <100 μm (z)
  - CLIC requirement may be more severe
  - ➔ study requirements
  - ➔ develop technology
  - ➔ solutions for integration



Leszek Zawiejski, FCAL collab.

Power pulsing and other electronics developments

ILC => 5Hz
=> "on"-time 0.5%
CLIC => 50 Hz
=> "on"-time 10^{-5}

- Systematic study of power-pulsing feasibility
  - Needed for ILC and CLIC
  - Leading to recommendations for optimised design
  - Real case implementation
  - (What about influence on wire-bonds?)

- Overall electronics implementation compatible with CLIC time-structure
  - Study of the adaptations required (analog, digital, readout sequence)
  - Implementation of some of the ILC vertex/tracker/calo hardware developments for CLIC

Conclusions

- Work on the CLIC detector/physics has re-started
- **CLIC detector concept studies are based on the ILC work**
  - Basic concepts will be similar
  - ILC hardware developments are most relevant for CLIC
  - Software tools
- A number of areas have been identified, where the CLIC detector at 3 TeV differs from the ILC concepts at 500 GeV
  - The initial CLIC concept simulation studies will concentrate on these areas
  - CLIC-specific R&D will be required in a number of technology domains
- Many thanks to ILC physics community, who helped to get the CLIC detector studies restarted in the framework of the recently established CLIC-ILC collaboration !

Spare slides

Major parameters for Linear Collider

Filling factor — Linac length — Gradient

Energy reach

$$E_{cm} = 2 F_{fill} L_{linac} G_{RF}$$

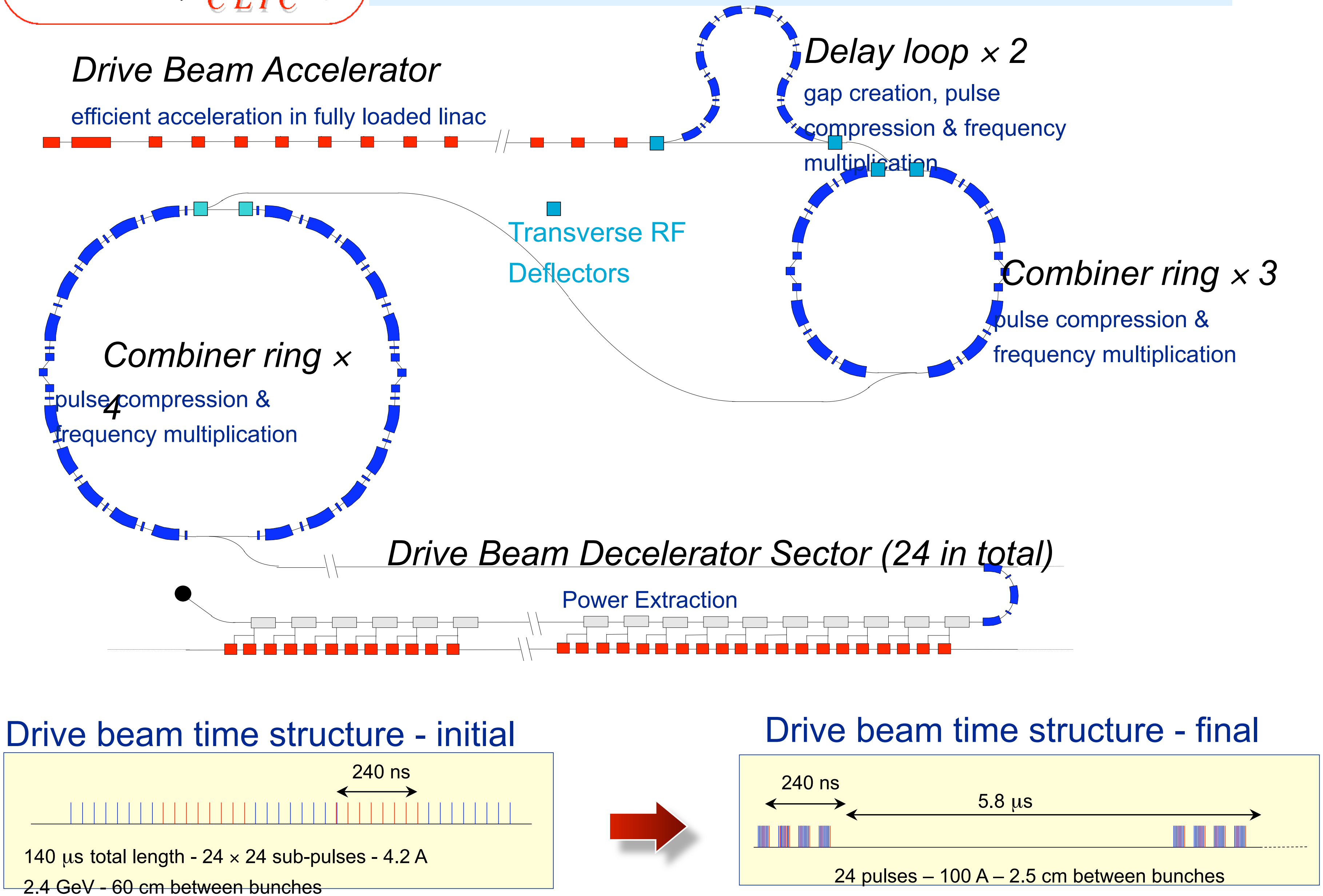
Energy lost by beamstrahlung — Wall-plug power — Wall-plug to beam efficiency

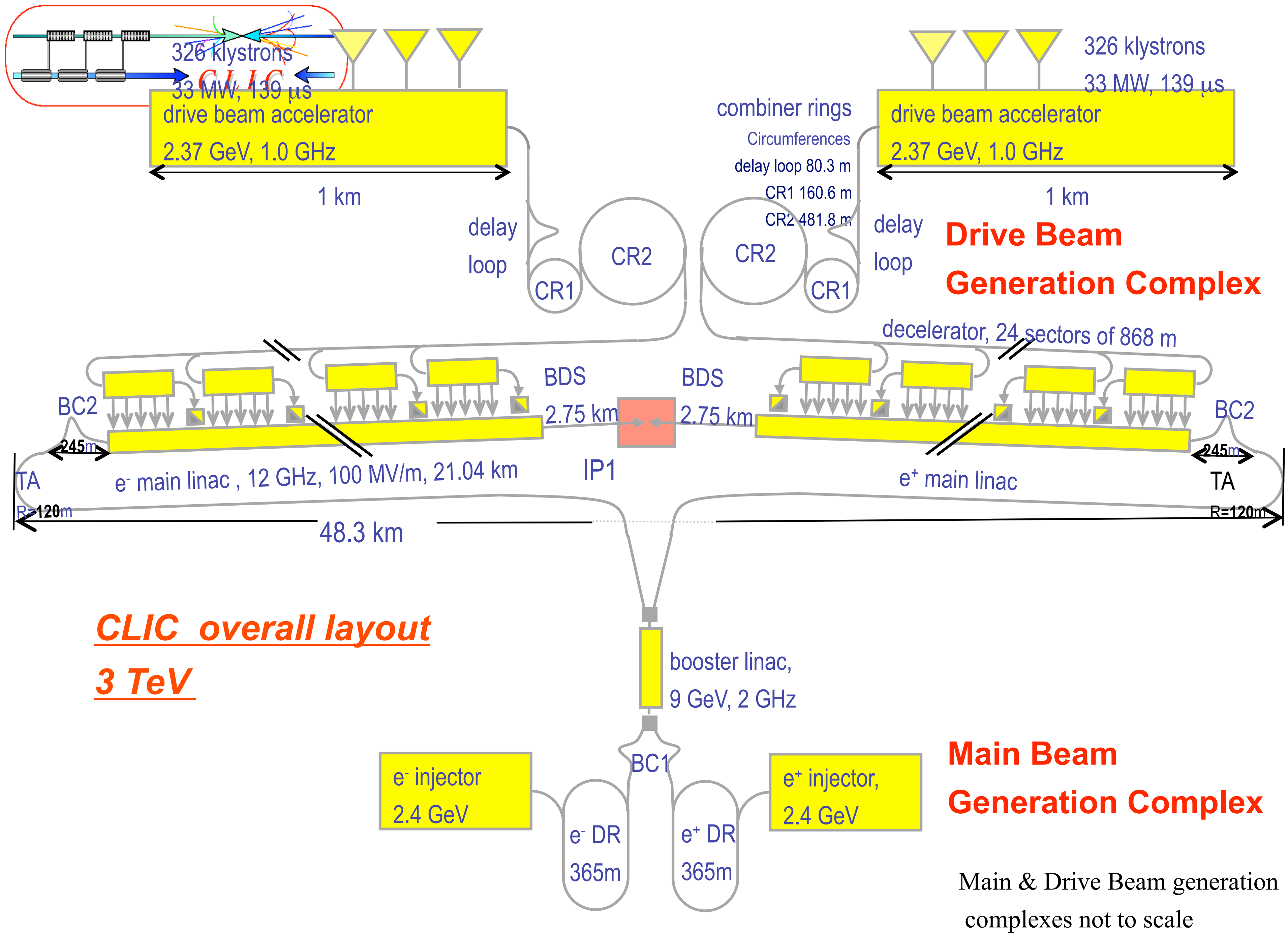
Luminosity

$$L = \frac{k_b N_b^2 f_{rep}}{4\pi \sigma_x^* \sigma_y^*} \quad \alpha \quad \frac{\delta_B^{1/2} P_{AC} \eta_{beam}^{AC}}{E_{cm} \varepsilon_{ny}^{1/2}}$$

Beam size at interaction point — Center-of-mass energy — Vertical emittance

RF power source

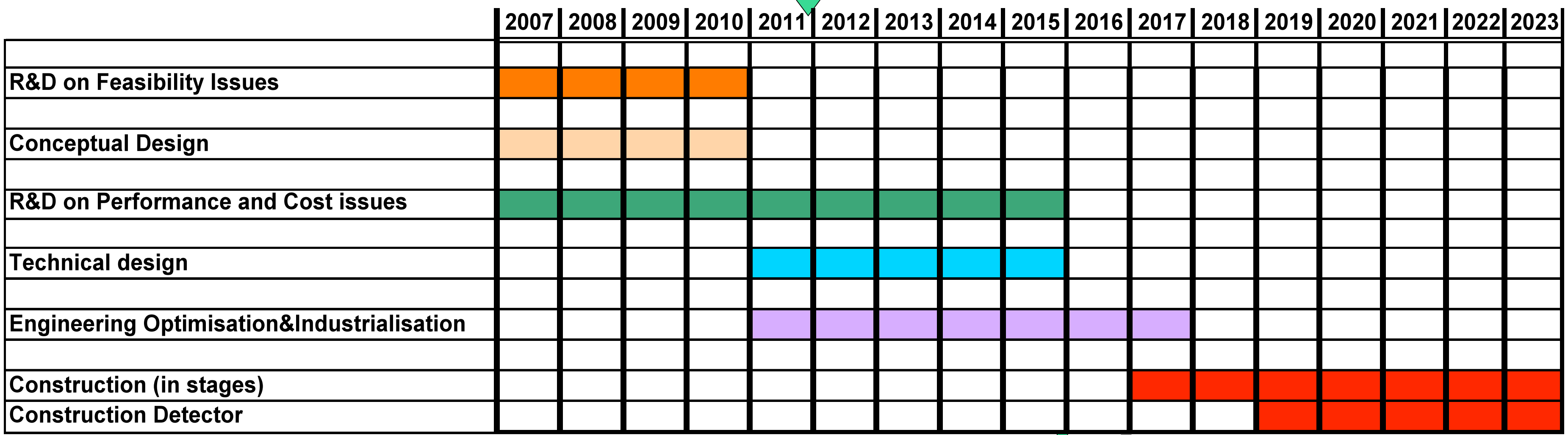




CLIC
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.37 GeV, 1.0 GHz
1 km
delay
loop
CR1
CR2
combiner rings
Circumferences
delay loop 80.3 m
CR1 160.6 m
CR2 481.8 m
Drive Beam
Generation Complex
decelerator, 24 sectors of 868 m
BDS
2.75 km
IP1
BC2
245m
TA
R=120m
e- main linac , 12 GHz, 100 MV/m, 21.04 km
e+ main linac
48.3 km
CLIC overall layout
3 TeV
booster linac,
9 GeV, 2 GHz
BC1
e- injector
2.4 GeV
e+ injector,
2.4 GeV
e- DR
365m
e+ DR
365m
Main Beam
Generation Complex
Main & Drive Beam generation
complexes not to scale

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



Conceptual Design Report (CDR)

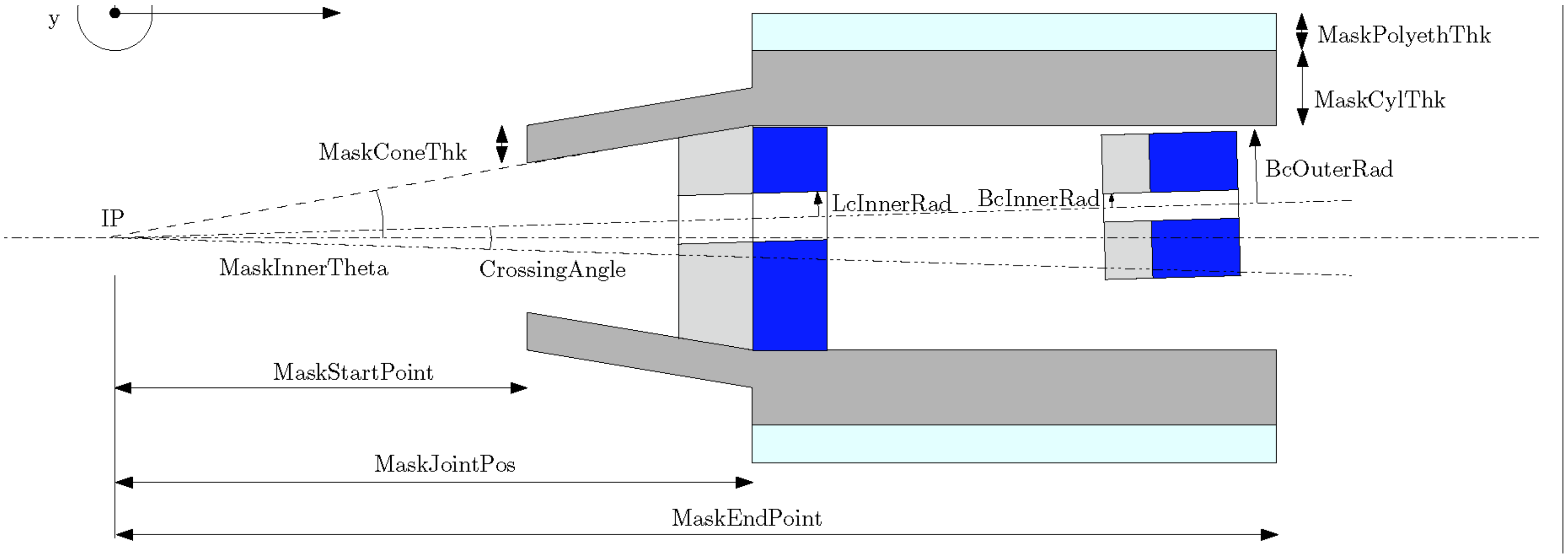
Technical Design Report (TDR)

Project approval ?

First Beam?

Forward region

- Tungsten **Mask** with polyethylene coating to absorb low-energy backscattered relics (e,γ,n) from beamstrahlung. Containing **Lumical** and **BeamCal**



3 TeV centre-of-mass

In a snapshot……

Differences between CLIC and ILC due to higher energy (3 TeV)

(details in following slides)

- Much increased background conditions (beamstrahlung and muons)
  - With several consequences for detector design
- More longitudinal depth of calorimetry
- Is PFA a good option for the higher CLIC energies?
- Cope with higher tracker occupancy and dense jets
- Solenoid size/strength expected to become an issue

Calorimeter depth

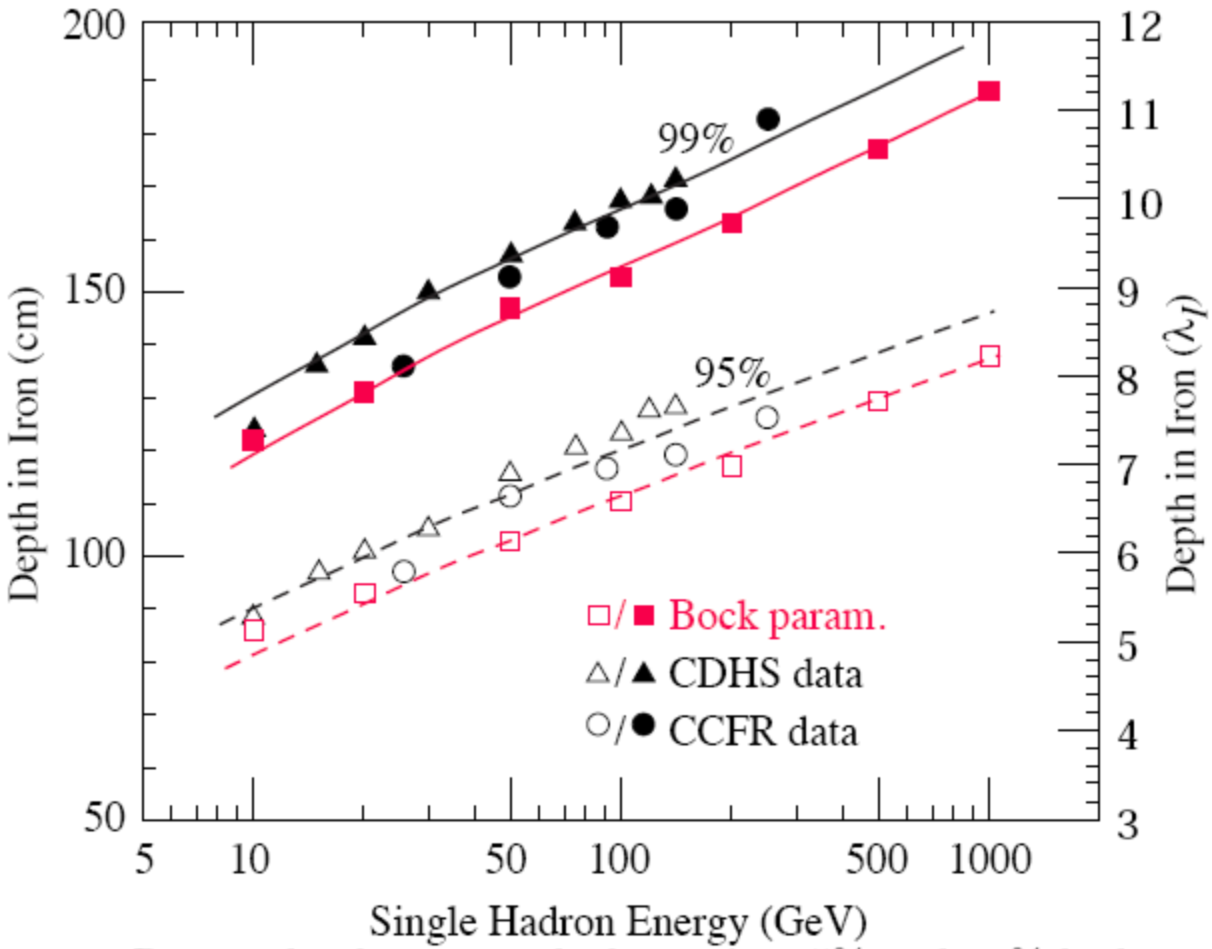


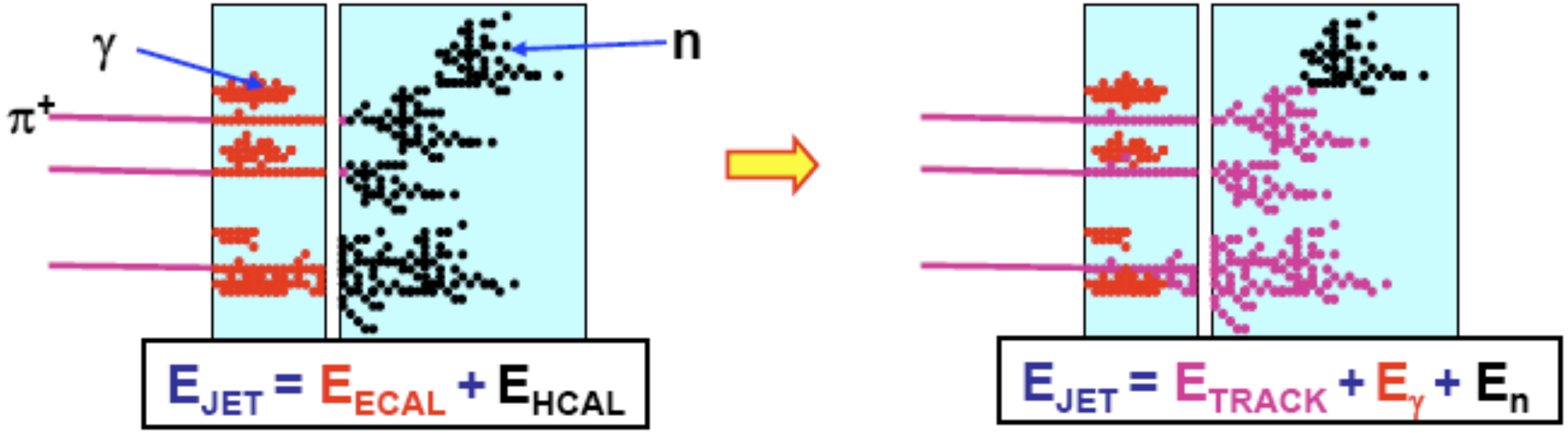
Figure 28.22: Required calorimeter thickness for 95% and 99% hadronic cascade containment in iron, on the basis of data from two large neutrino detectors and Bock's parameterization [143].

❷ The Particle Flow Paradigm

Mark Thomson CLIC08

- 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: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution



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