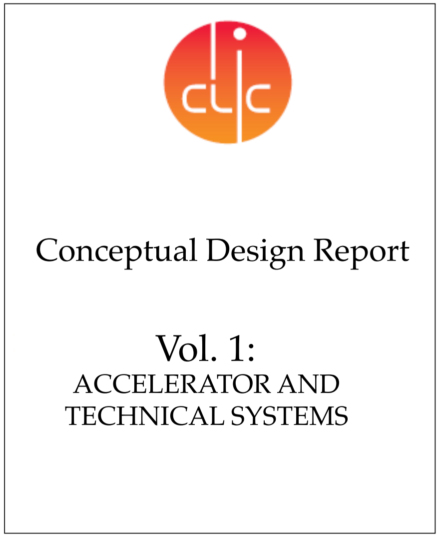
Physics and detectors at CLIC

– a multi-TeV e^+e^- linear collider

Erik van der Kraaij

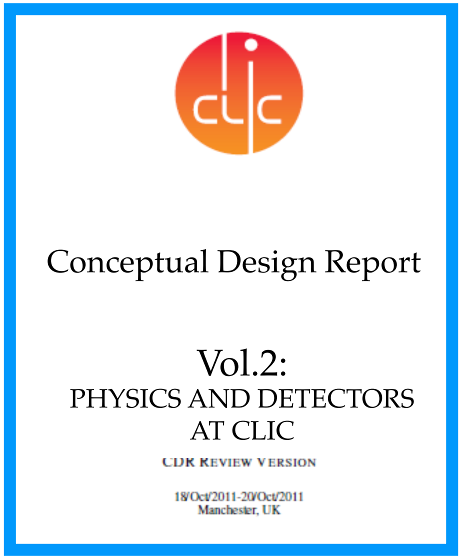
on behalf of

CLIC physics & detectors study group



Conceptual Design Report

Vol. 1:
ACCELERATOR AND
TECHNICAL SYSTEMS

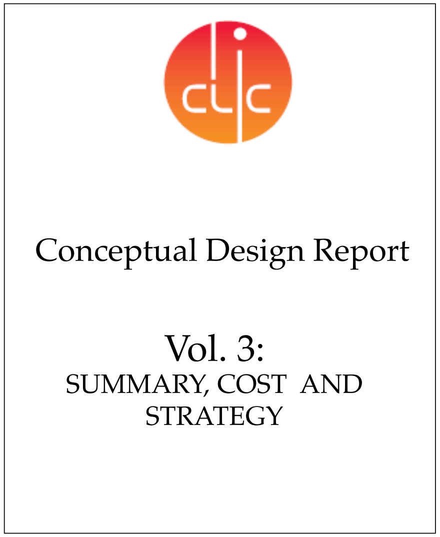


Conceptual Design Report

Vol.2:
PHYSICS AND DETECTORS
AT CLIC

CDR REVIEW VERSION

18/Oct/2011-20/Oct/2011
Manchester, UK



Conceptual Design Report

Vol. 3:
SUMMARY, COST AND
STRATEGY

Outline

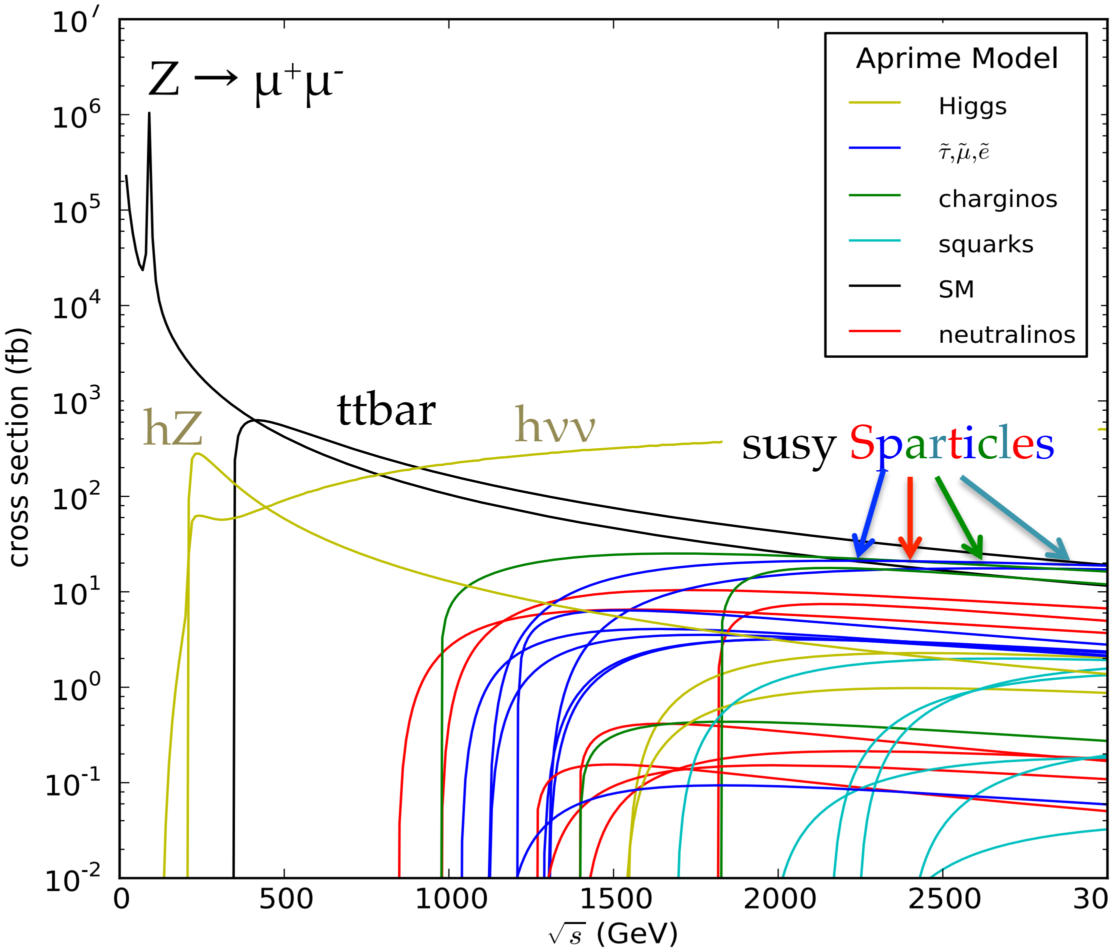
- Physics motivation
- Accelerator design
  - e^+e^- collisions, yet not LEP-like
- Detector designs
  - For unprecedented requirements
- Particle Flow – imaging calorimetry
  - How to cope with background

CLIC physics

Precision measurements of new particles discovered at LHC:

- Higgs, SUSY, …
- Discrimination between competing models

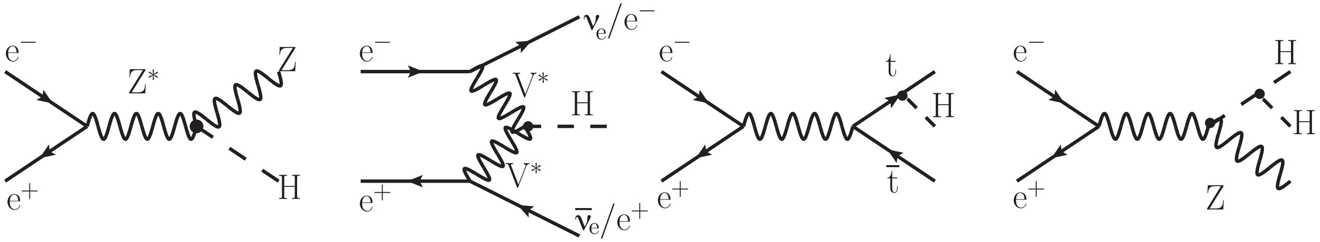
Discovery of new physics at TeV scale



e^+e^- collisions up to $\sqrt{s} = 3$ TeV

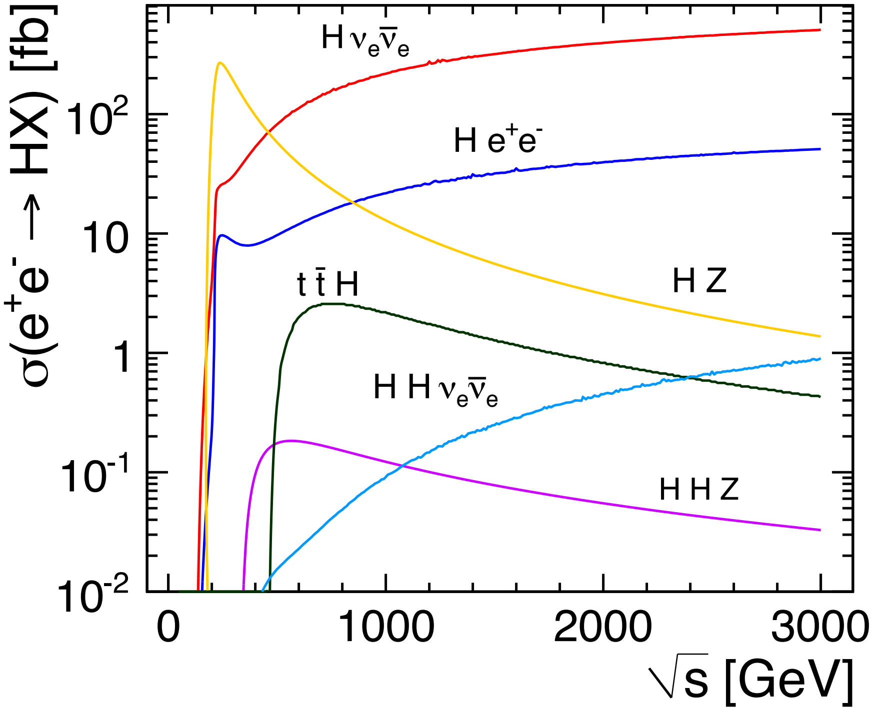
- Must be linear – too much synchroton radiation in storage rings.

Higgs production



s-channel ~ *1/s*

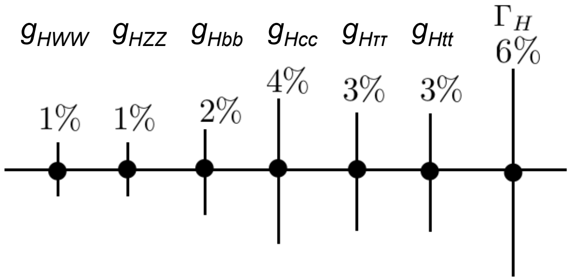
t-channel ~ *log (s)*



$\sqrt{s}$ = 3 TeV: WW fusion crosssection ~2x higher than max of higgsstrahlung

M_h = 120 GeV

Higgs observables ($M_h = 120$ GeV)

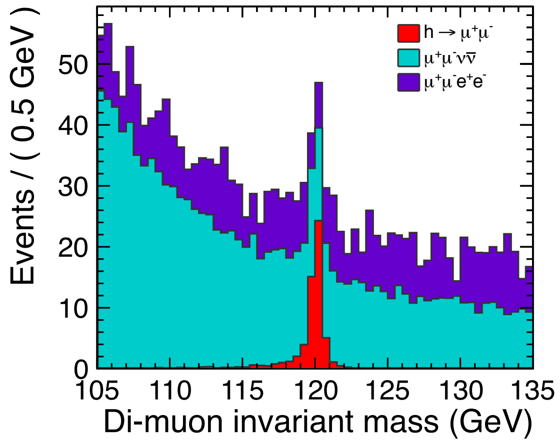


← with 500 fb^{-1} at $\sqrt{s} = 500$ GeV, except g_{Htt} which is at $\sqrt{s} = 800$ GeV with 1 ab^{-1}.

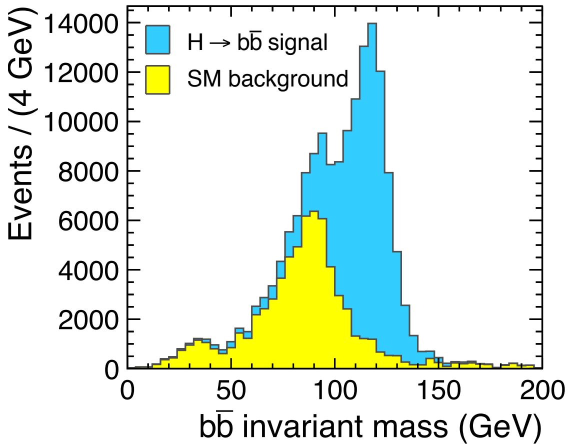
	Stat. Acc.(%)
g_{Hbb}	0.22
$g_{H\mu\mu}$	23

← with 2 ab^{-1} at $\sqrt{s} = 3$ TeV, as shown below. These are pure statistical errors.

$g_{H\mu\mu}$ measurement can be improved



(a) $e^+e^- \to H\nu\bar{\nu}, H \to \mu^+\mu^-$



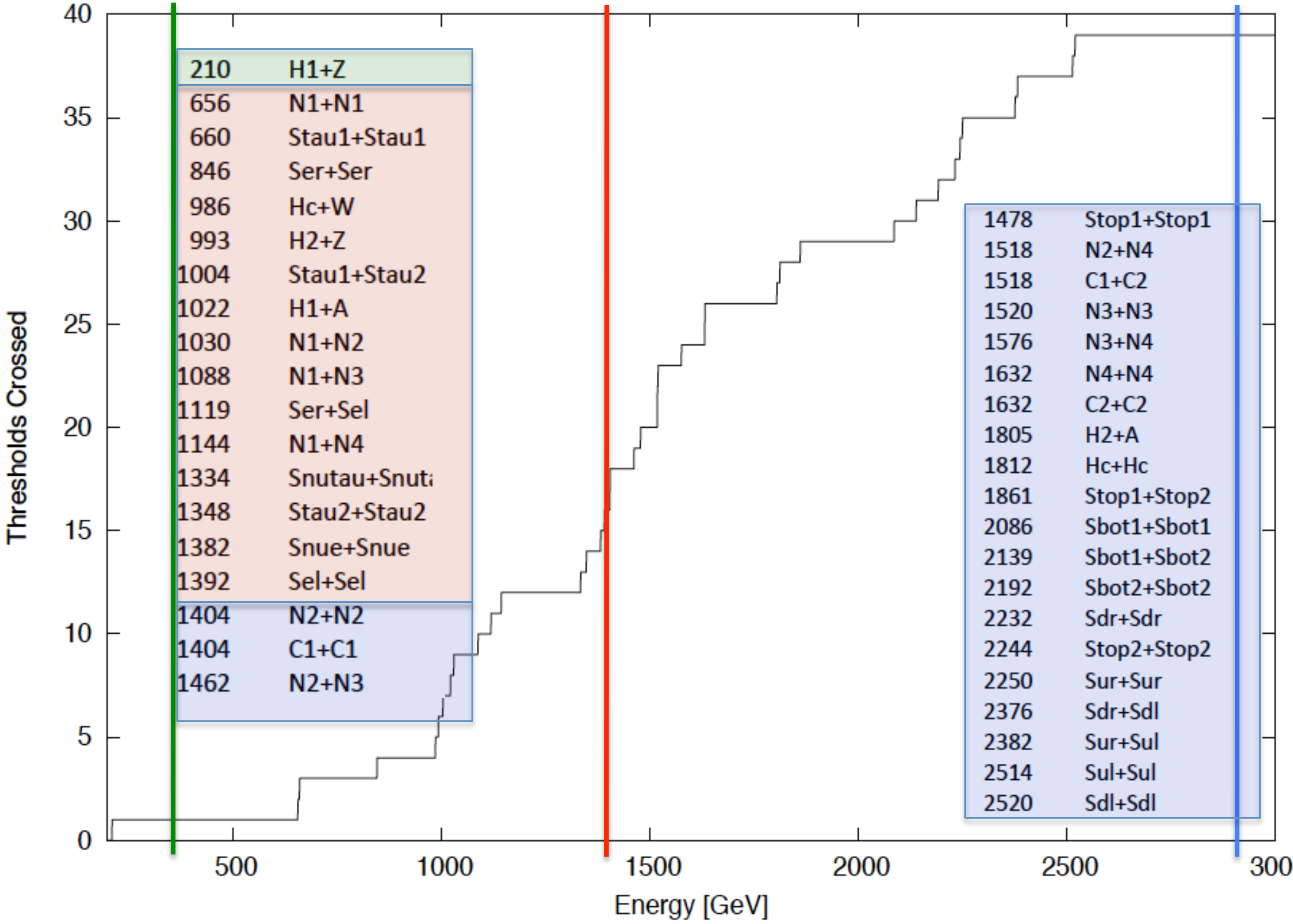
(b) $e^+e^- \to H\nu\bar{\nu}, H \to b\bar{b}$

Example of CDR benchmark channels

Thresholds crossed as a function of energy

Assume LHC is fully explored – Many of the possible particles in the CLIC range will be discovered

→ Design according to expected physics



210	H1+Z
656	N1+N1
660	Stau1+Stau1
846	Ser+Ser
986	Hc+W
993	H2+Z
1004	Stau1+Stau2
1022	H1+A
1030	N1+N2
1088	N1+N3
1119	Ser+Sel
1144	N1+N4
1334	Snutau+Snuta
1348	Stau2+Stau2
1382	Snue+Snue
1392	Sel+Sel
1404	N2+N2
1404	C1+C1
1462	N2+N3

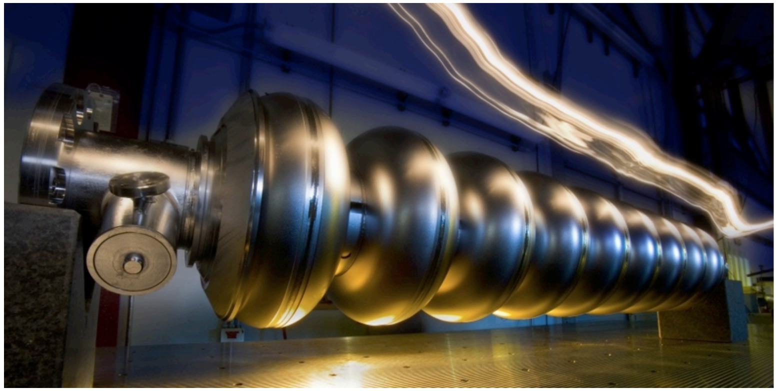
1478	Stop1+Stop1
1518	N2+N4
1518	C1+C2
1520	N3+N3
1576	N3+N4
1632	N4+N4
1632	C2+C2
1805	H2+A
1812	Hc+Hc
1861	Stop1+Stop2
2086	Sbot1+Sbot1
2139	Sbot1+Sbot2
2192	Sbot2+Sbot2
2232	Sdr+Sdr
2244	Stop2+Stop2
2250	Sur+Sur
2376	Sdr+Sdl
2382	Sur+Sul
2514	Sul+Sul
2520	Sdl+Sdl

Outline

- Physics motivation
- Accelerator design
  - e^+e- collisions, yet not LEP-like
- Detector designs
  - For unprecedented requirements
- Particle Flow – imaging calorimetry
  - How to cope with background

ILC and CLIC

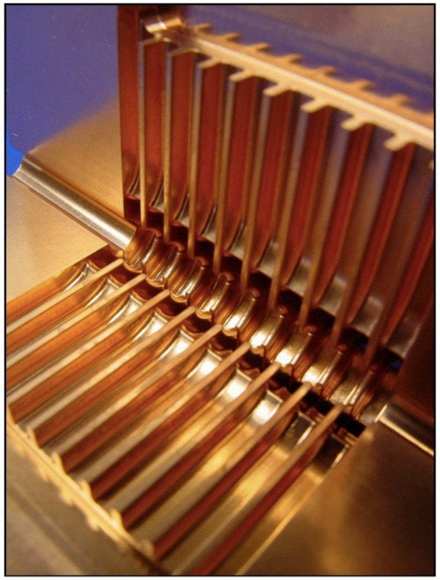
linear colliders producing e^+e^- collisions



ILC

- Based on superconducting RF cavities
- Gradient 32 MV/m
- Energy: 500 GeV, upgradeable to 1 TeV
  (+ lower energies: Higgs, ttbar,…)
- Detector studies 0.5 – 1.0 TeV

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

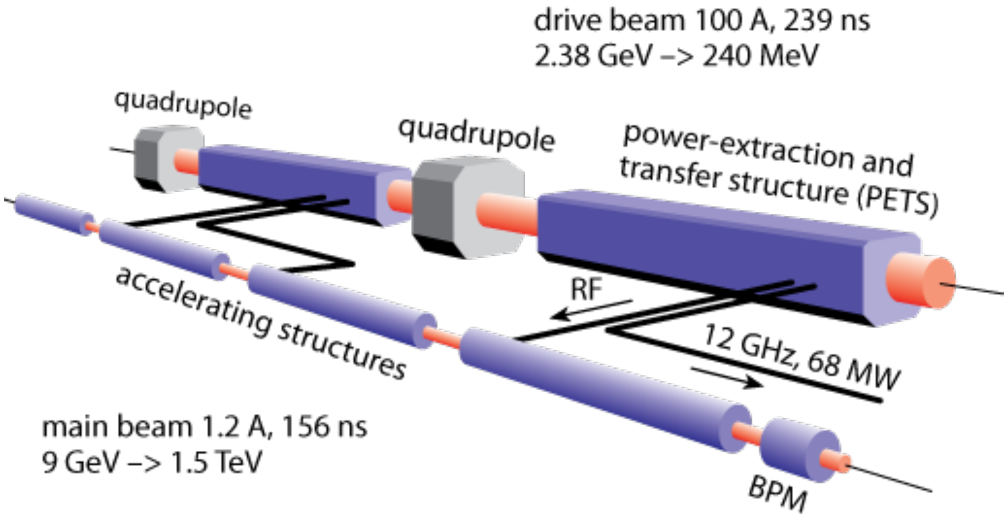


CLIC

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

CLIC acceleration

No individual RF power sources



Two Beam Scheme:

Drive Beam supplies RF power

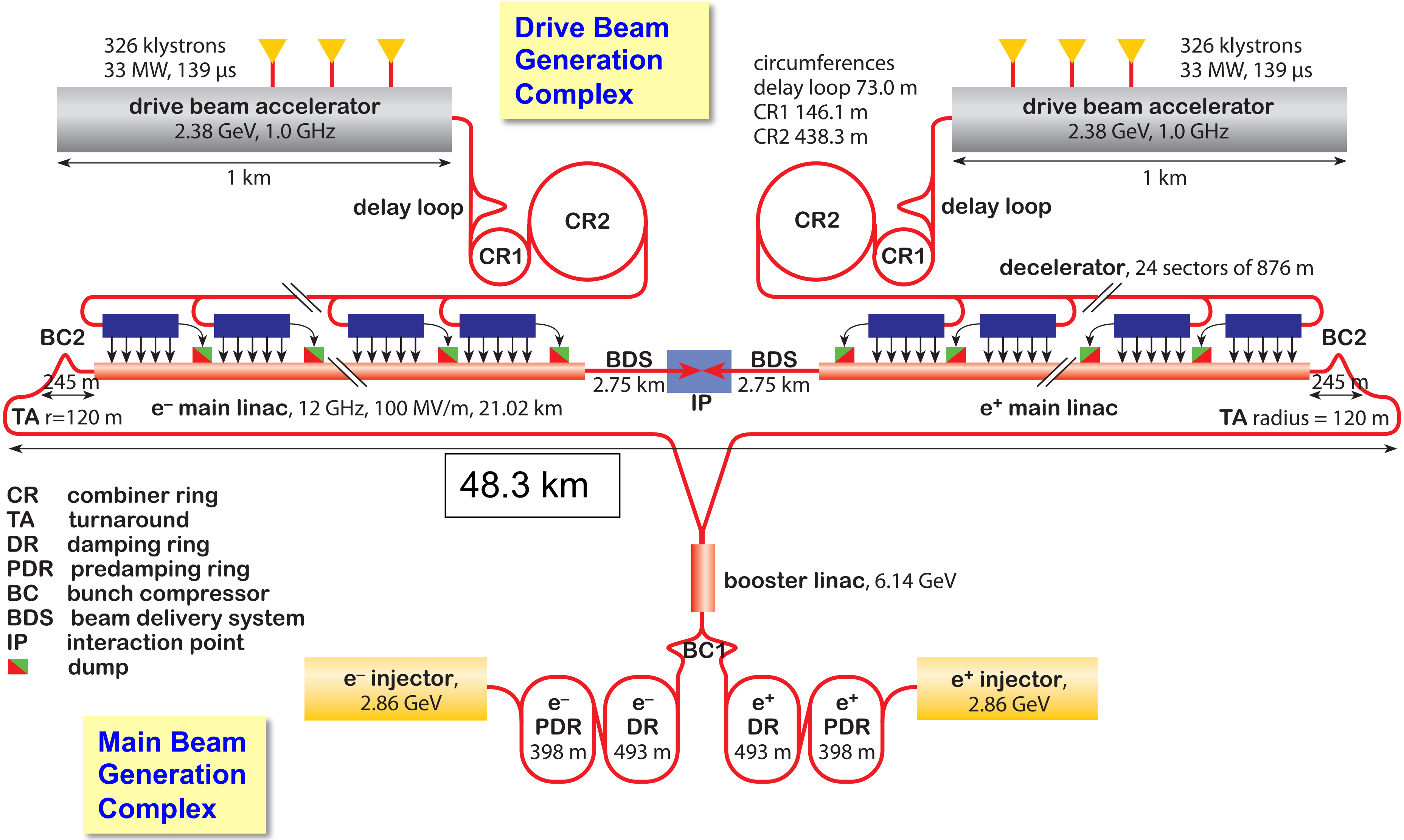
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

- ➢ Like a HV transformer - transformer 'core':
  - ➢ Waveguides with RF waves

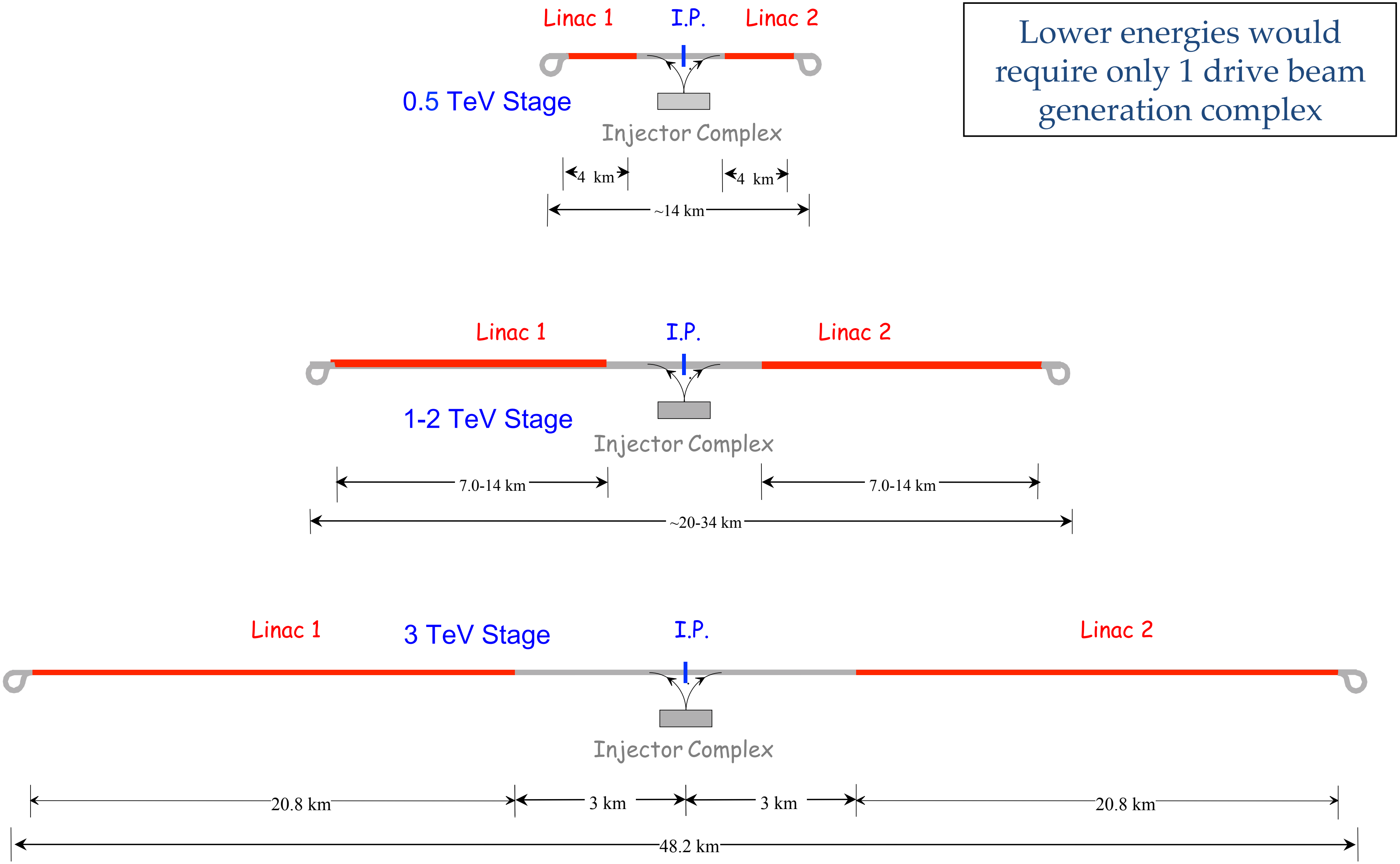
CLIC 3 TeV machine layout



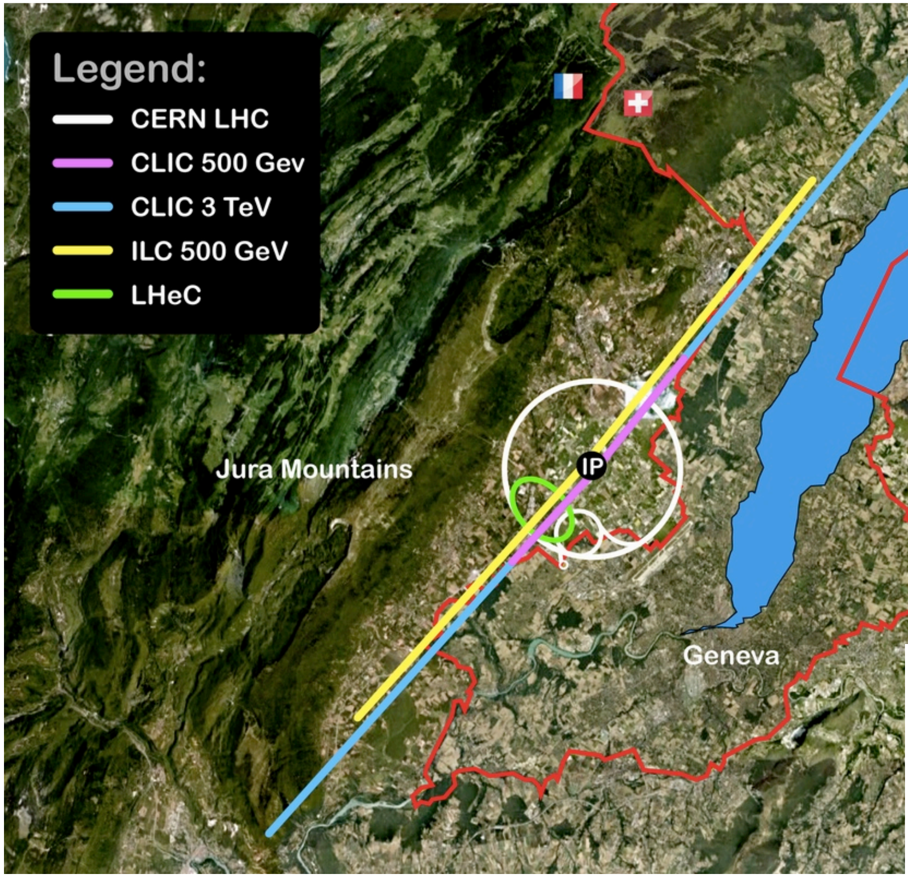
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
◩	dump

CLIC energy staging

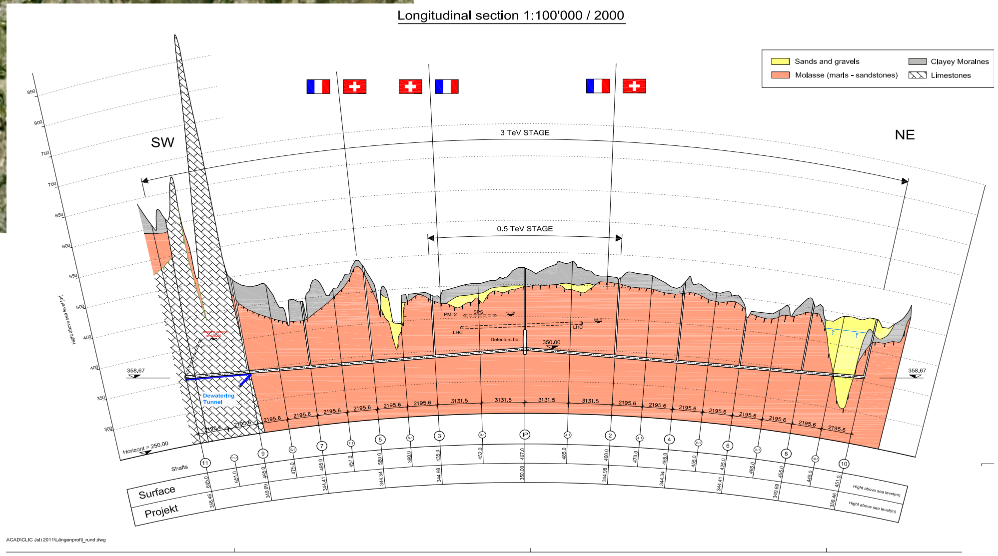
Lower energies would require only 1 drive beam generation complex



Possible construction location

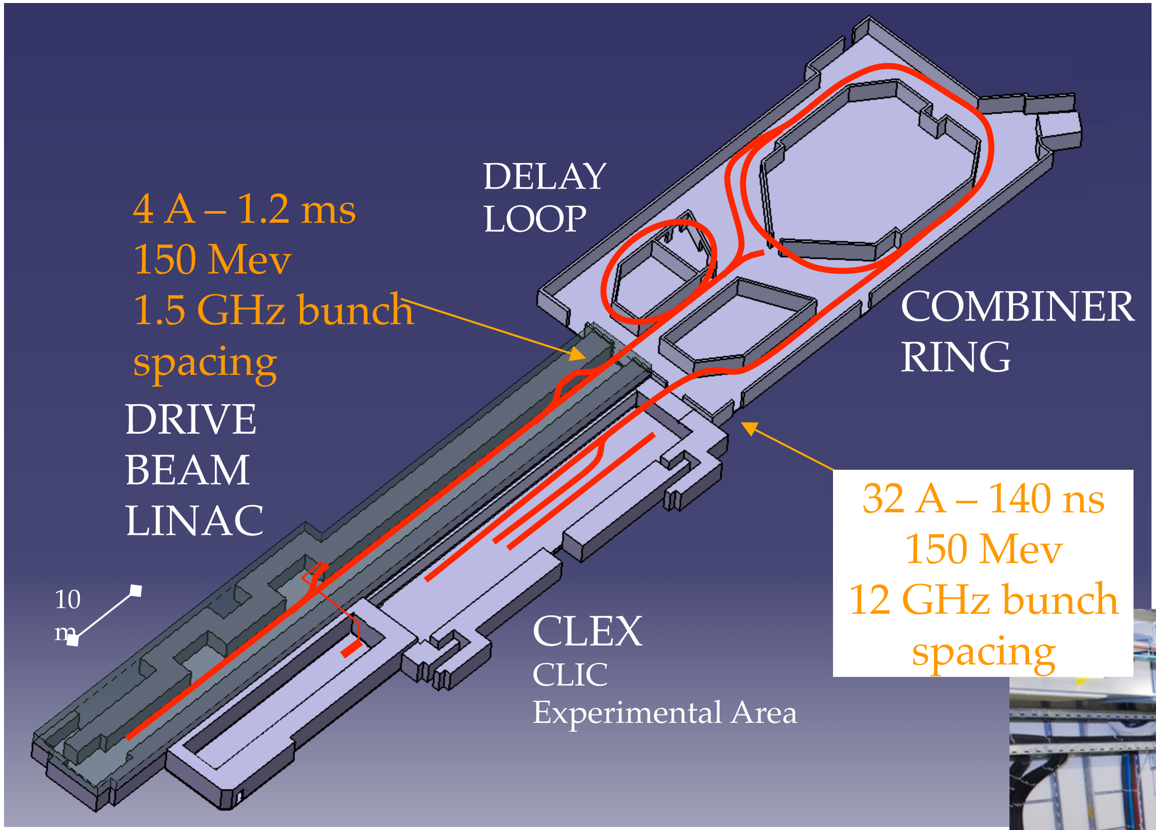


J. Osborne
CERN GS-SE

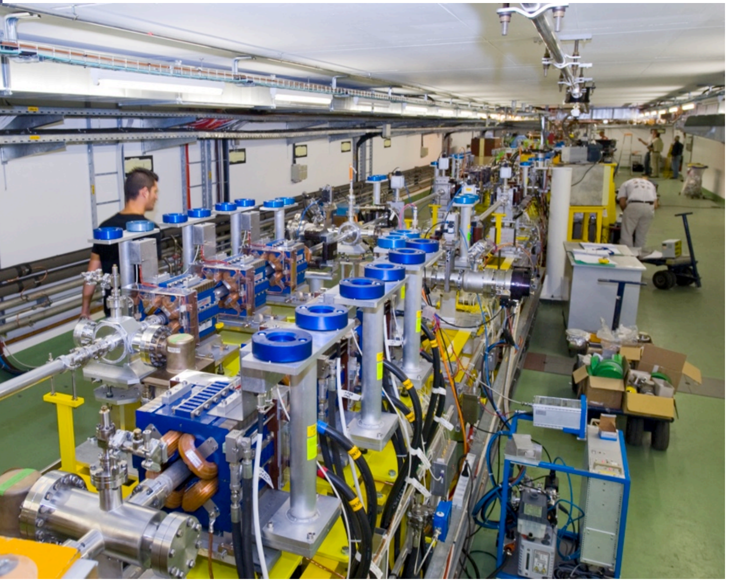


Interaction region, caverns and surface installation, as foreseen in the CDR, at CERN Prevessin

The CLIC Test Facility (CTF3)

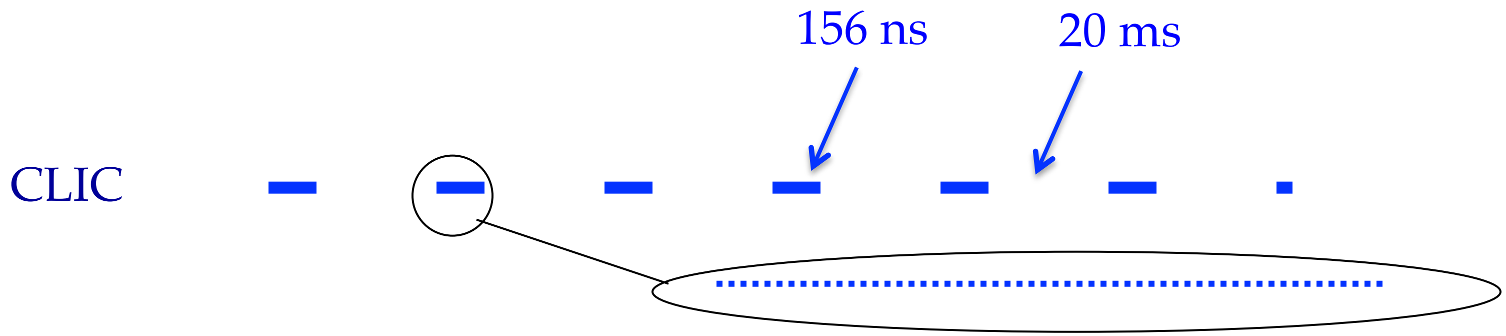


- Drive Beam generation. fully loaded acceleration, beam intensity and bunch frequency multiplication x8
- RF Power Production and test Power Structures



- Demonstrate Two Beam Acceleration and test Accelerating Structures
- Study deceleration

CLIC parameters

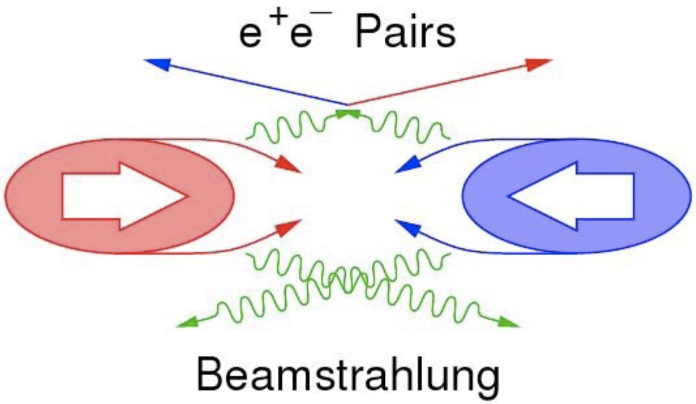


CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart

ILC: trains at 5 Hz, 1 train = 1300 bunches, 700 ns apart

	LEP 2	**ILC 0.5 TeV**	**CLIC 3 TeV**
L [cm^{-2}s^{-1}]]	5×10^{31}	2×10^{34}	6×10^{34}
Crossing angle		14 mrad	20 mrad
BX separation	~22 µs	700 ns	0.5 ns
# ($\gamma\gamma$ → **hadrons) / BX**	negligible	0.2	3.2
# **Incoherent pairs / BX**	negligible	1×10^5	3×10^5

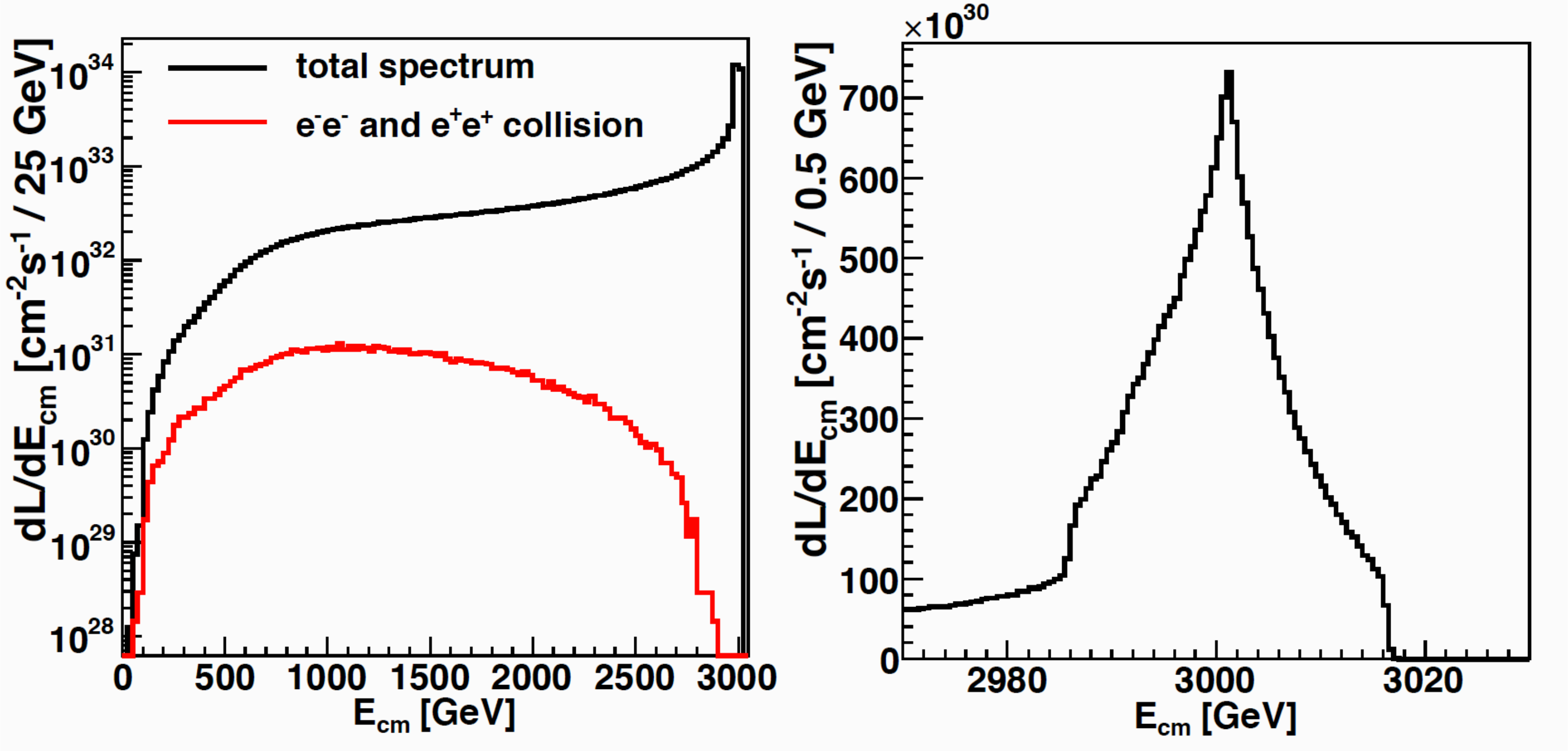
Beam-induced backgrounds



→ Need **pile-up rejection**
→ Need to include background in **simulation**
→ Detector starts at θ>10 mrad

Background	Total	Particles per BX $\theta > 10$ mrad	 $\theta > 7.3^\circ$ and $p_\mathrm{T} > 20$ MeV
Coherent pairs	$6 \cdot 10^8$	≈ 0	0
Incoherent pairs	$3 \cdot 10^5$	$8 \cdot 10^4$	60
$\gamma\gamma \to$ hadrons	102	96 (47 charged)	54 (25 charged)

Luminosity spectrum



Includes beam energy spread and beamstrahlung

$L_{tot} = 6 \cdot 10^{34}$ cm^{-2}s^{-1} ; $L_{0.01} = 2 \cdot 10^{34}$ cm^{-2}s^{-1} (30% in “1% highest energy”)

→ √s is not known per event!
→ Much like the hadronic PDFs, need to fold in luminosity spectrum in simulation

Outline

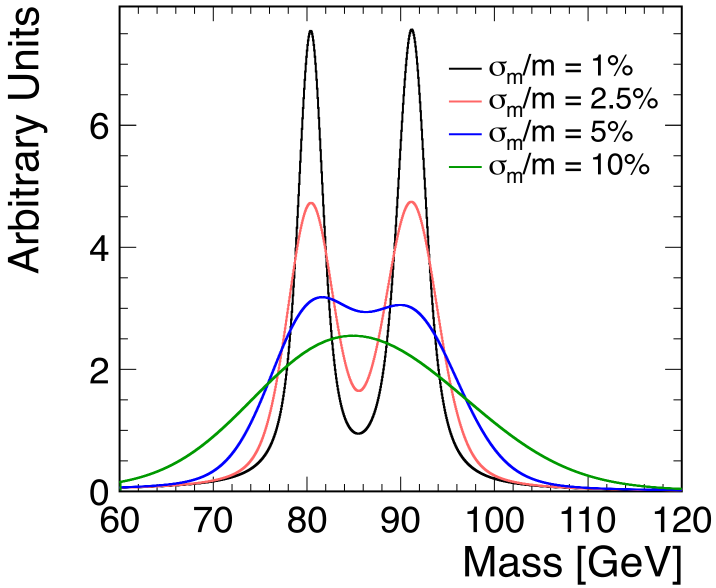
- Physics motivation
- Accelerator design
  - e^+e^- collisions, yet not LEP-like
- Detector designs
  - For unprecedented requirements
- Particle Flow – imaging calorimetry
  - How to cope with background

CLIC Detector Requirements (1/2)

- High-resolution pixel detector to measure displaced vertices
  p = 1 GeV: σ_{d0}~20 μm (CMS: 90 μm)
  p = 100 GeV: σ_{d0}~5 μm (CMS: ~10μm)

- momentum resolution
  p = 1 GeV: $\sigma(p_T)/p_T = 0.1\%$ (CMS: 0.7%)
  p = 100 GeV: $\sigma(p_T)/p_T = 0.2\%$ (CMS: 1.5%)

- Need very good jet-energy resolution



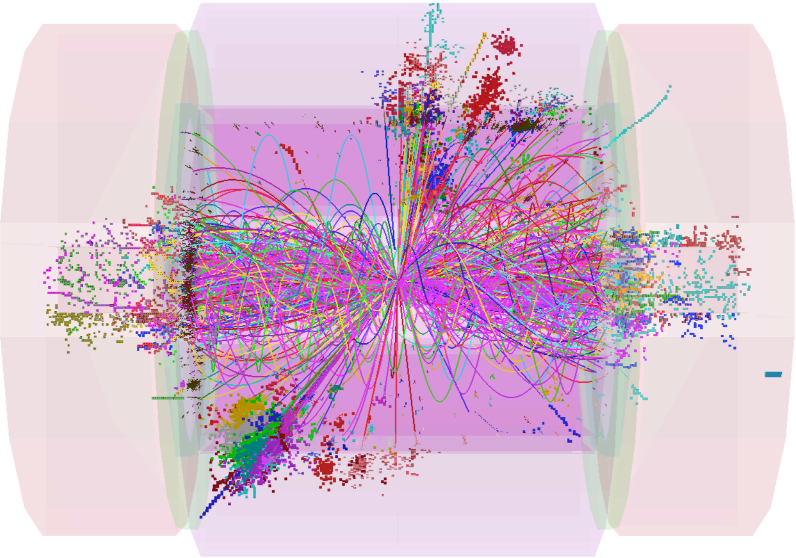
E	=	10^2	–	10^3 GeV:
$\sigma(E_j)/E_j$	~	4.0%	–	3.5%
ATLAS	~	8.0%	–	4.0%

CLIC Detector Requirements (2/2)

Per bunch crossing: 3.2 $\gamma\gamma \rightarrow$ **hadrons** events, 50 GeV visible energy
→ 19 TeV dumped in the calorimeters per 156 ns bunch train.

Will have triggerless readout of full train. Need:

- Detector hit time-stamping
- Multi-hit storage/readout
- filtering algorithms at reconstruction level



8 jet final state

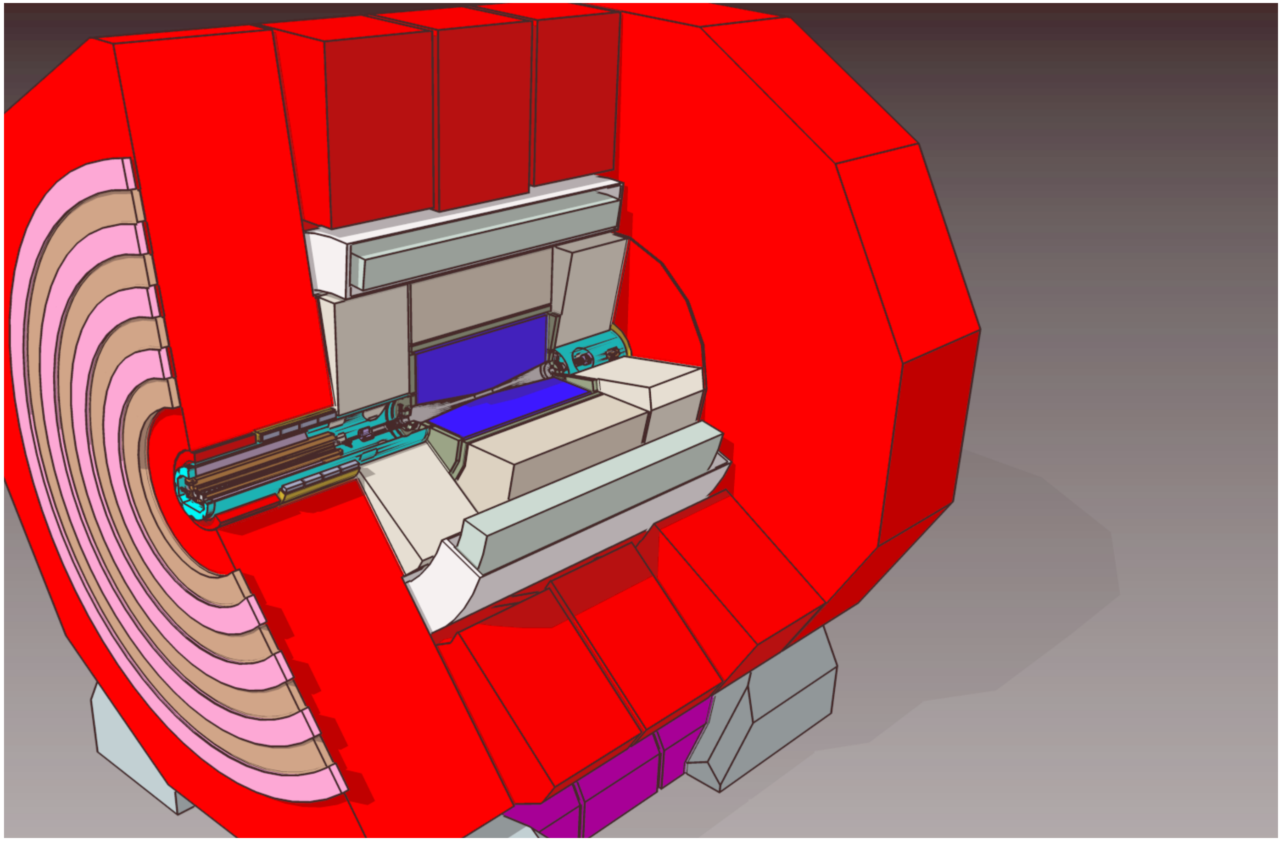
$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{b}b\bar{t}$
$+ 60$ BX $\gamma\gamma \rightarrow$ hadrons

1.4 TeV of background in reconstruction window

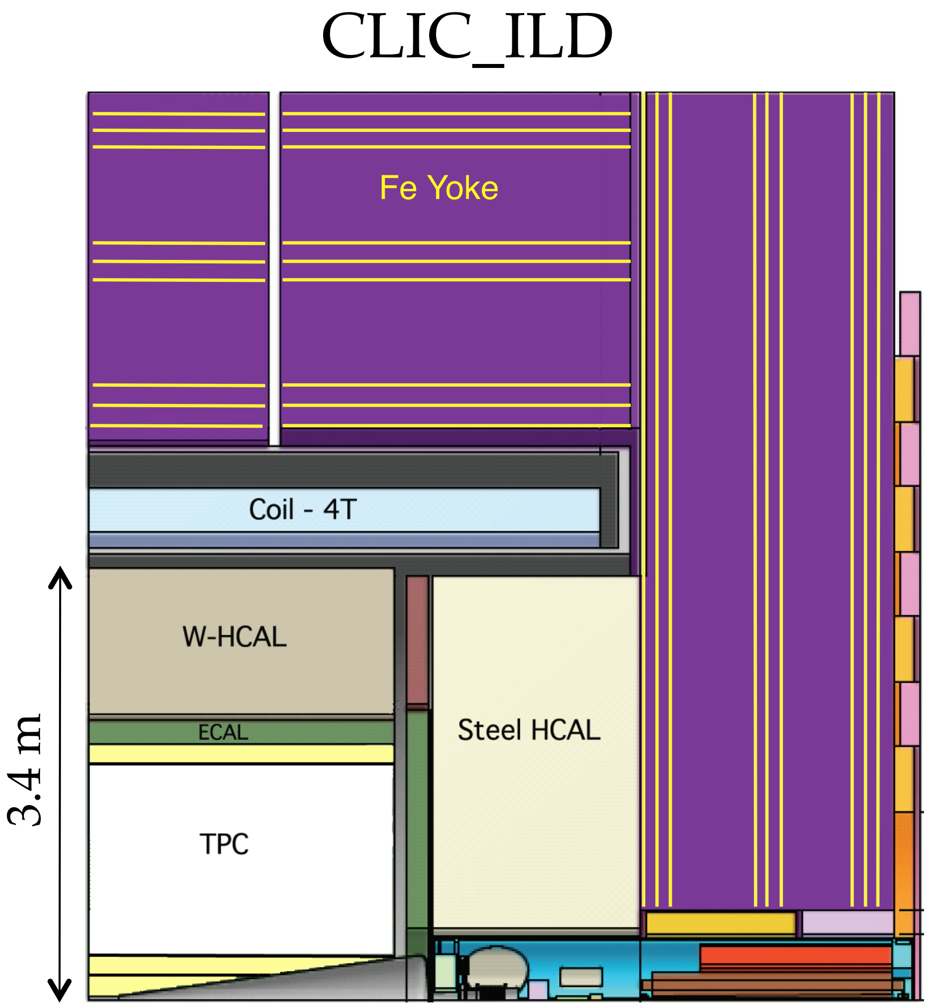
Two general purpose CLIC detector concepts

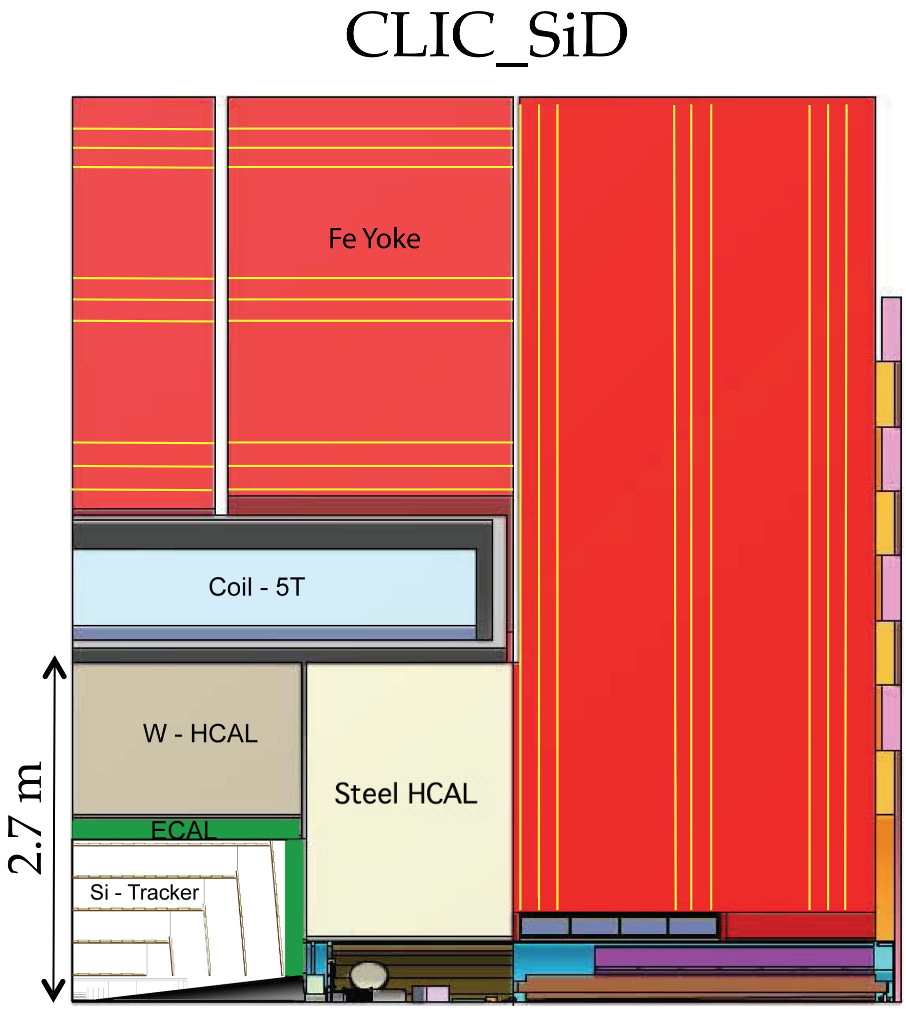
Based on validated ILC designs, adapted to CLIC energy and timing conditions:

- Denser barrel HCAL (Tungsten, 7.5 λ_i)
- Redesign of vertex and forward detector regions (backgrounds)

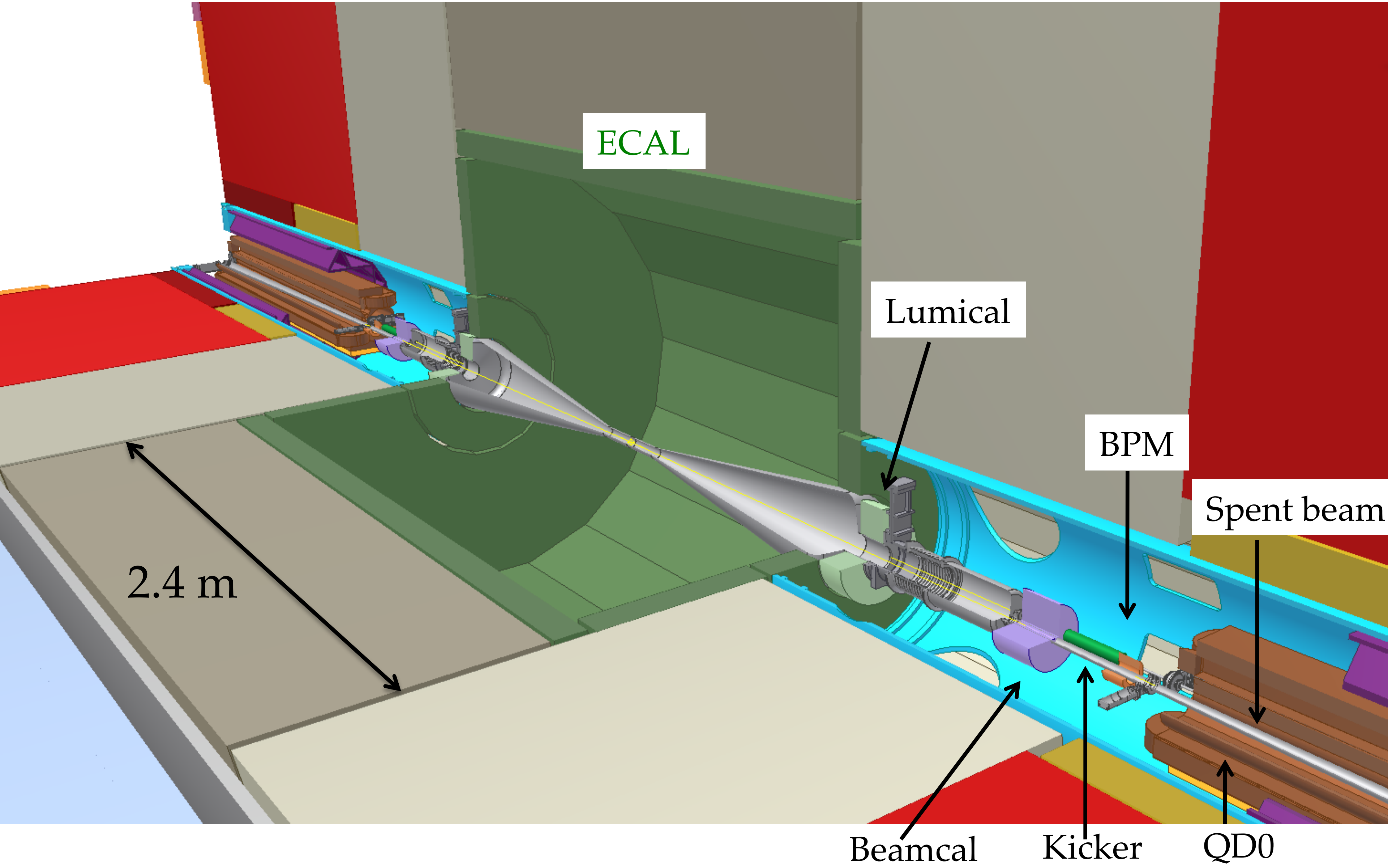


Two general purpose CLIC detector concepts

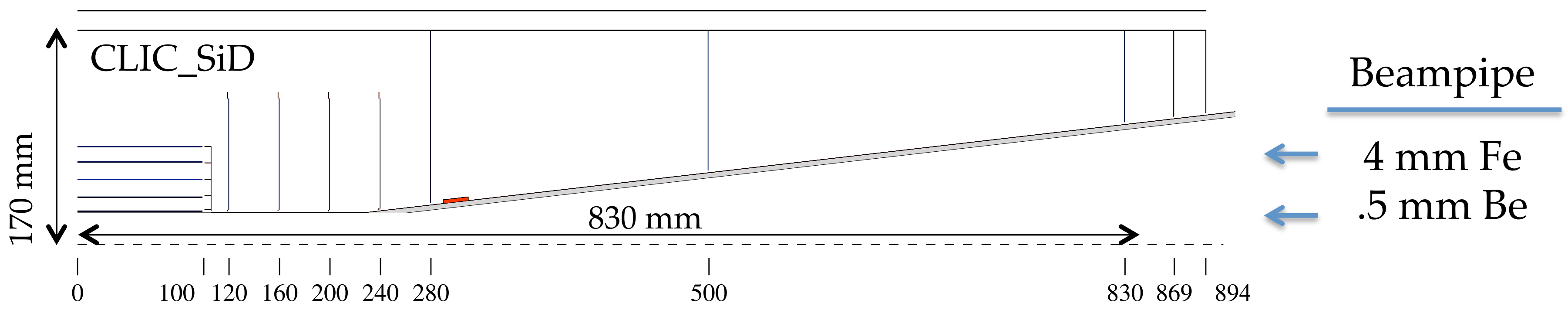




Very Forward Region



CLIC_SiD vertex detectors



	CLIC_SiD	**CMS**
Material X/X_0 (90°)	~1.1% (5 layer)	~10% (3 layer)
Pixel size	20 x 20 μm^2	100 x 150 μm^2
# pixels	2.76 G	66 M
Time resolution	5-10 ns	<~25 ns
Power/pixel	<~0.2 μW	28 μW

Very low duty cycle of CLIC machine: 156 ns train, 20 ms pause

→ All subdetectors will implement power pulsing schemes at 50 Hz, to reduce power consumption and thereby material in cooling systems

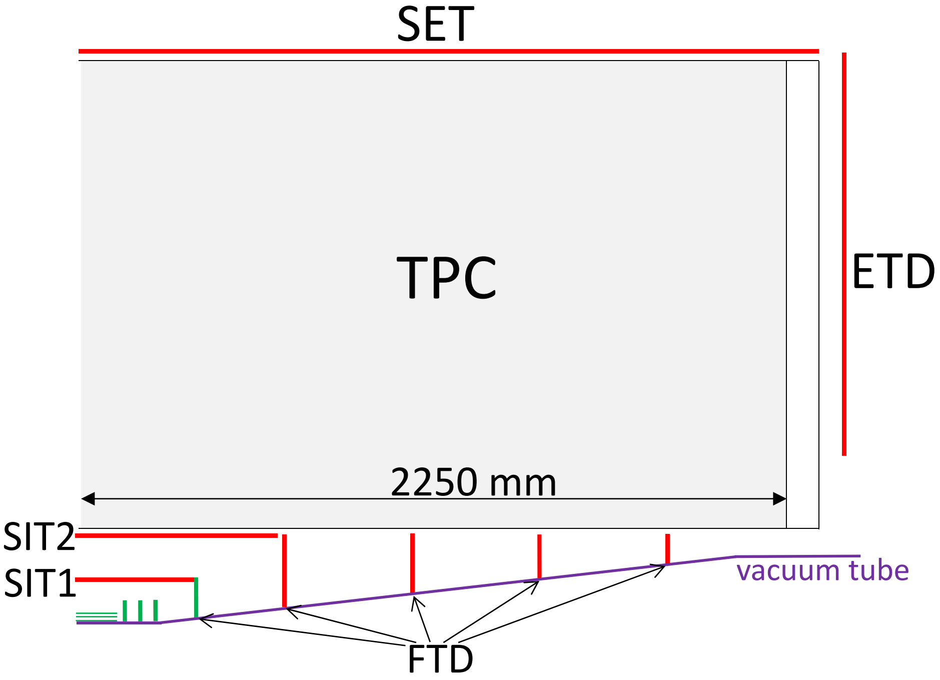
CLIC_ILD: TPC based tracking

Large TPC (329 < R < 1808 mm) for highly redundant continuous tracking (~ 200 measured points)

- Particle ID through dE/dx
- Little material in tracking volume (5% X_0); <25% X_0 in endcap

Complemented by silicon tracking system:

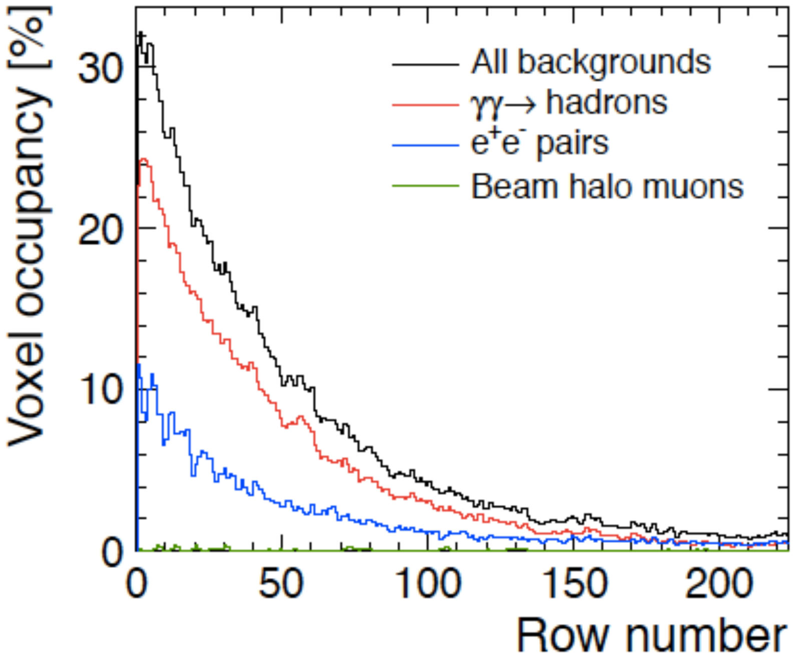
- Independent tracking at low angles (FTD)
- Silicon tracking layers surrounding TPC for timing and precision points (SIT, SET, ETD)



- TPC acceptance down to 12^0 (>10 measurement points)
- SIT acceptance down to 25^0
- FTD acceptance down to 7^0

TPC occupancies

Full detector simulations:



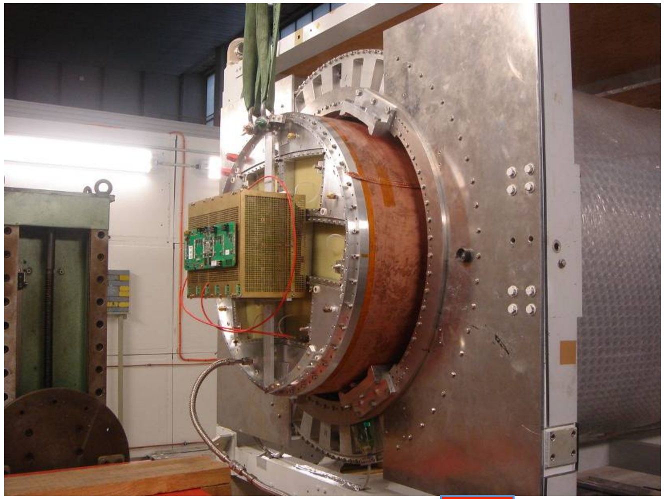
High occupancies in the TPC, mostly due to $\gamma\gamma \rightarrow$ hadrons.

- Consider pixelized readout in this region or suppress the inner pad rows.

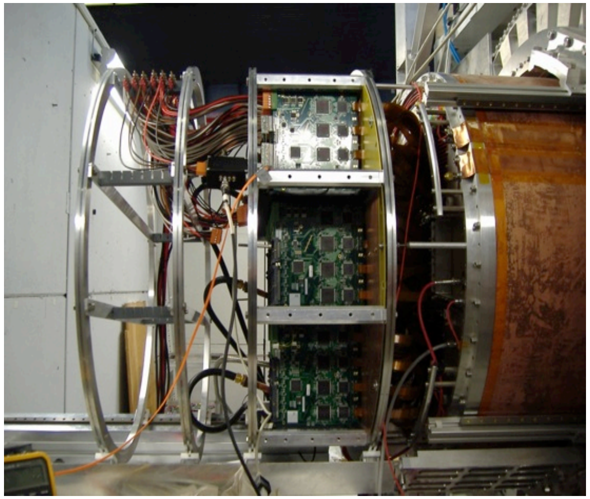
➢ **Requires technology/layout changes**

TPC beam tests at DESY with Large Prototype (2008-2011)

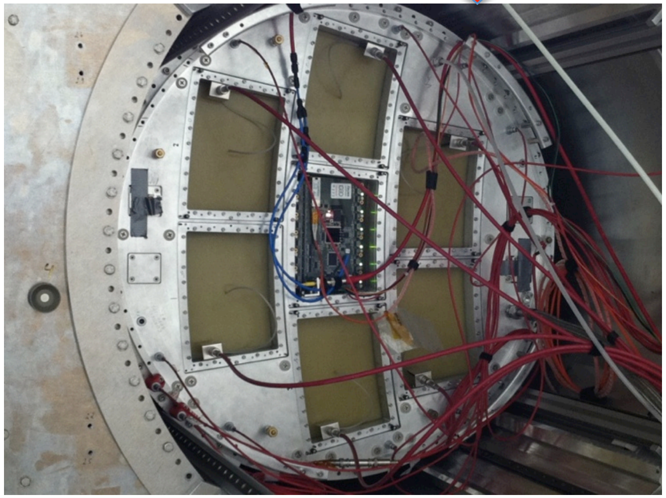
Micromegas (T2K readout)



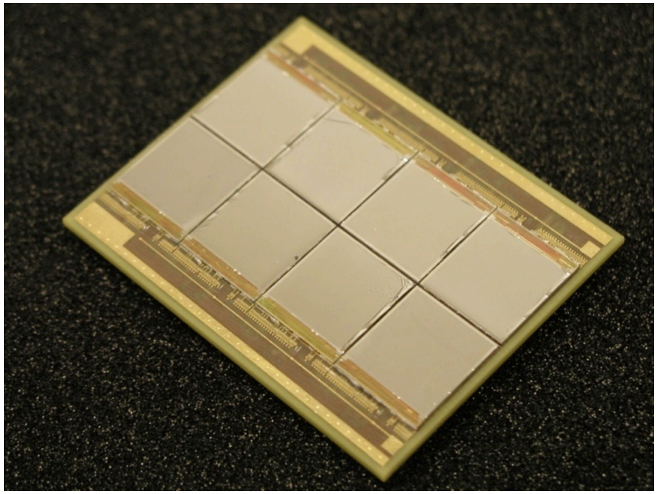
GEMs (Altro readout)



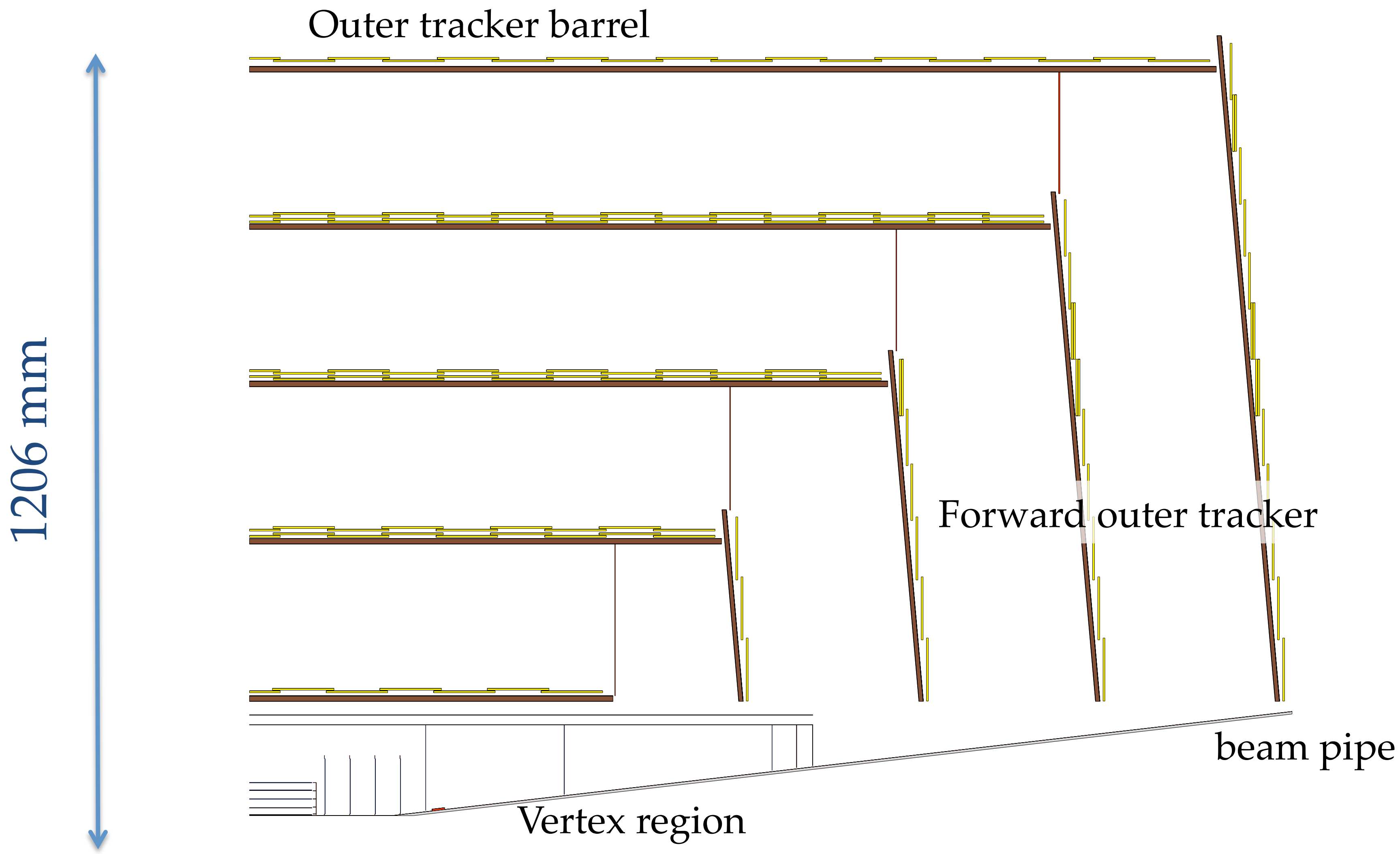
Integrated version



8-chip Ingrid module

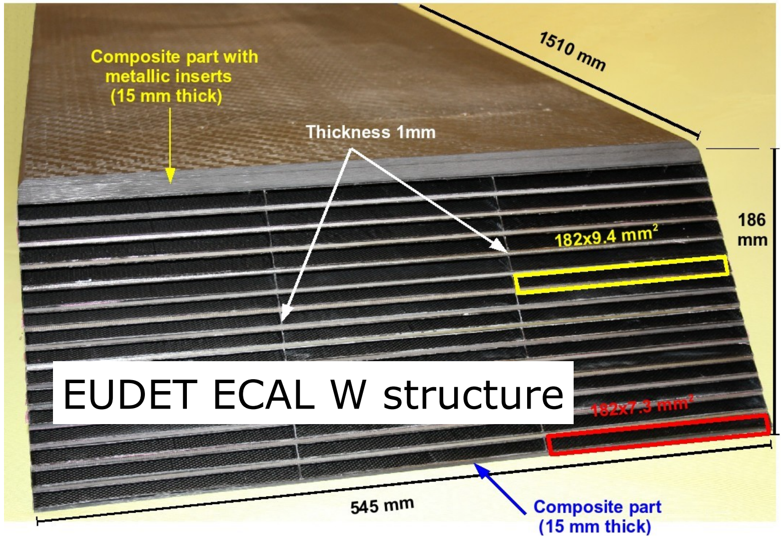


CLIC_SiD: all-silicon tracker

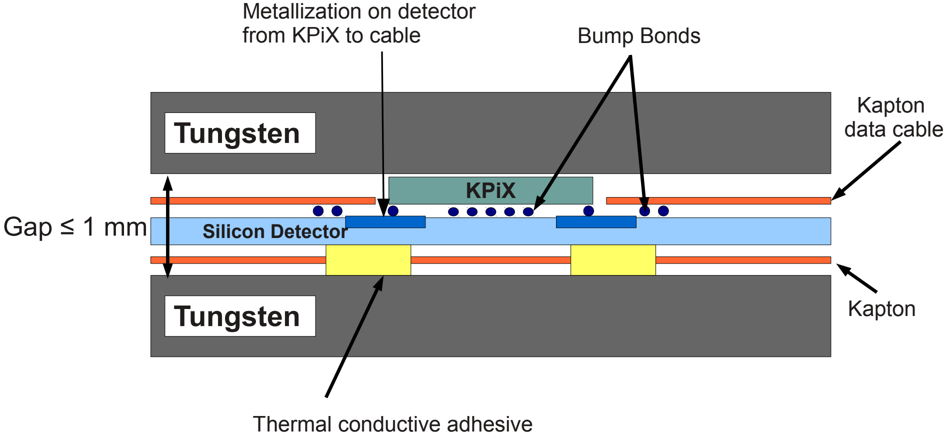


EM calorimetry

ECAL	CLIC_ILD, B = 4 T
Absorber / Active element	Tungsten / Si pads
Sampling layers	20x 2.1 mm, 10x 4.2 mm
Cell size	5.1 × 5.1 mm^2
X_0 and λ_I	23 and 1


EUDET ECAL W structure

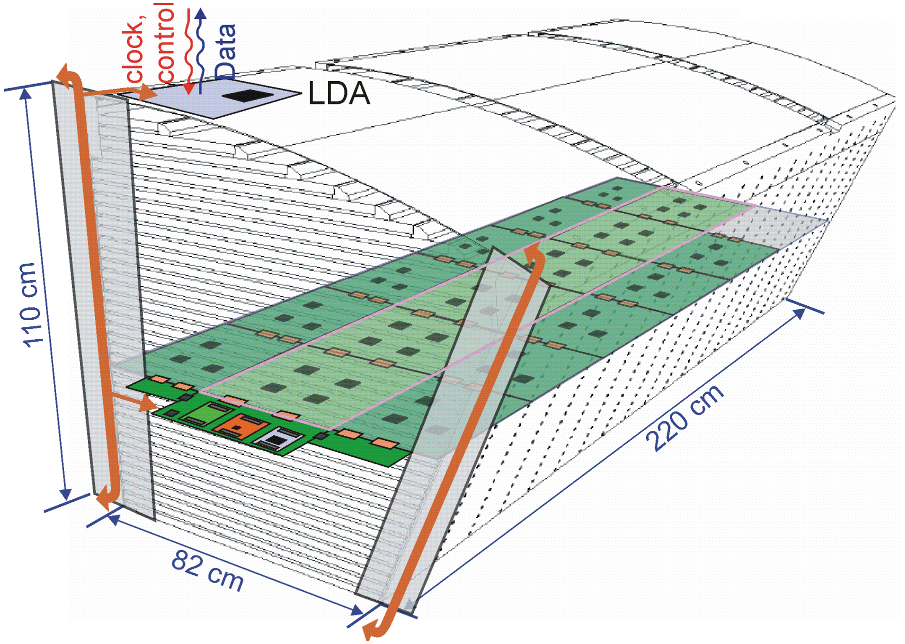
Example – SiD approach:

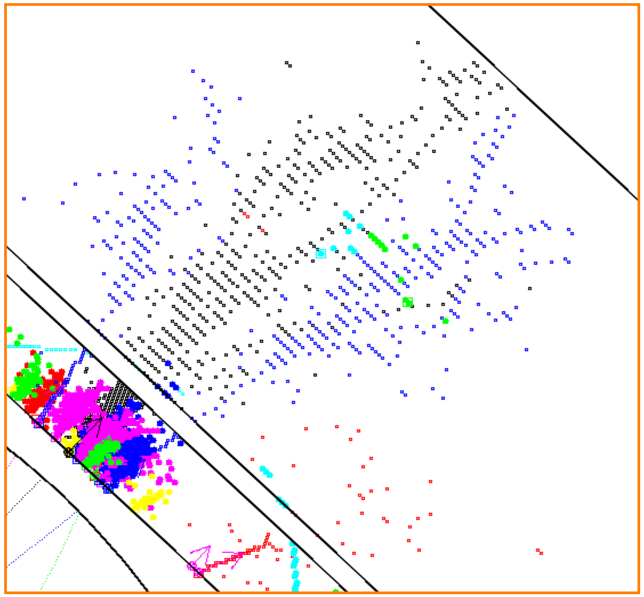


Hadronic calorimetry

HCAL	CLIC_ILD & CLIC_SiD
Absorber (Barrel/F)	Tungsten / Steel
Sampling layers (B/F)	75x10 mm / 60x 20 mm
Cell size	30 × 30 mm^2 (analog, e.g. SiPM)
λ_I	7.5

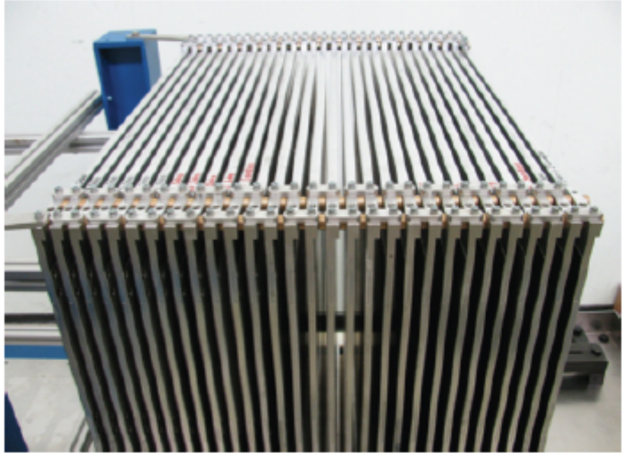
← 10 × 10 mm^2
(digital, e.g. RPC)

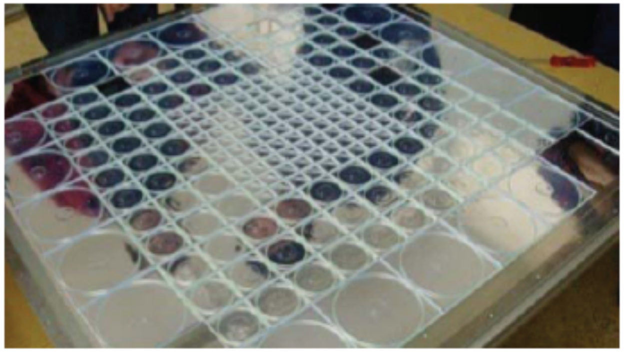




Tungsten HCAL prototype

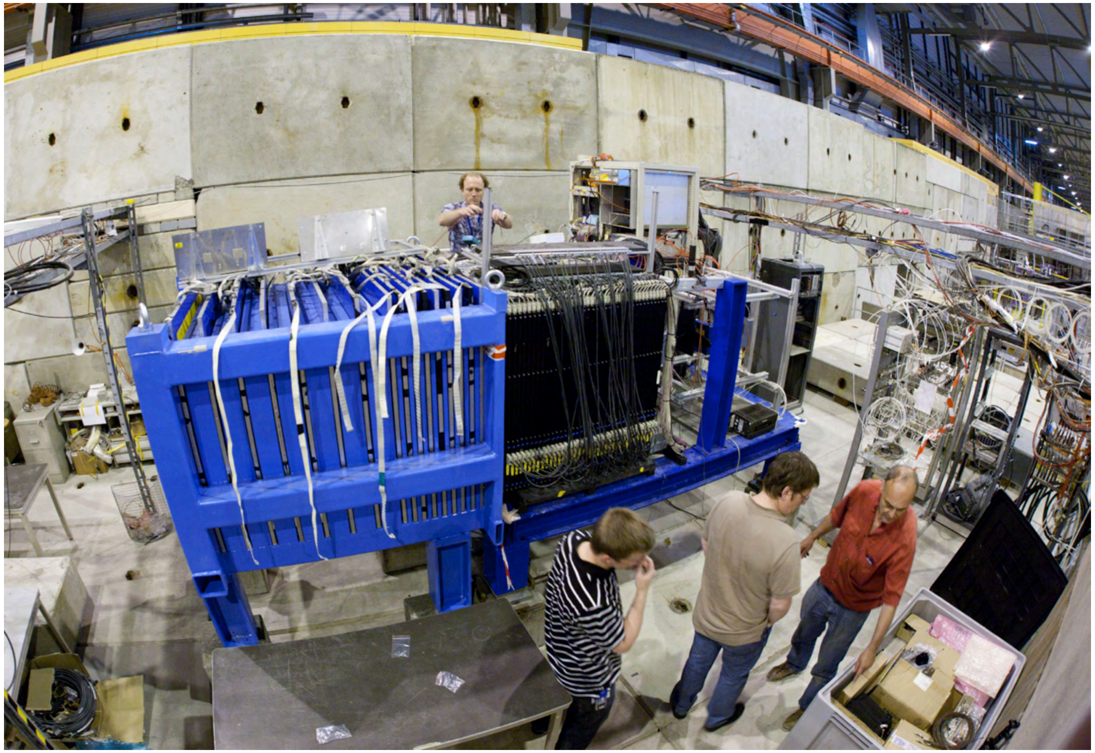
Main purpose: Validation of Geant4 simulation for hadronic showers in tungsten





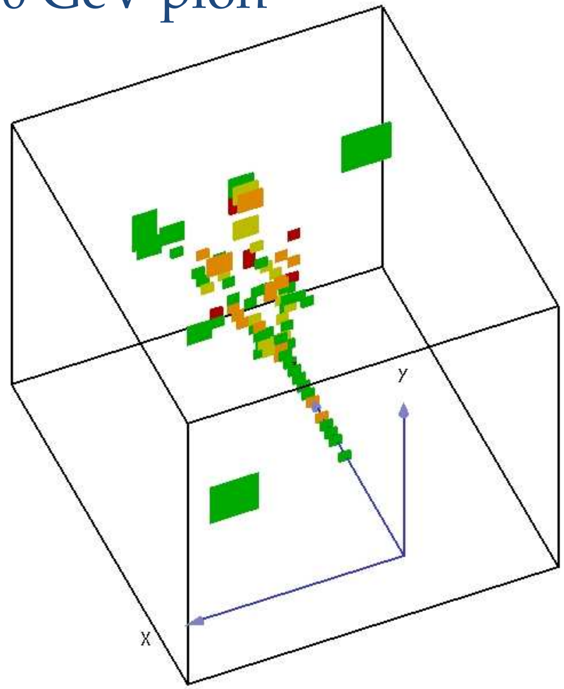
Scintillator tiles 3x3 cm^2 (in centre)
Read out by SiPM

Data taken 2010/11 at CERN-PS/SPS, mixed beams 1 – 300 GeV

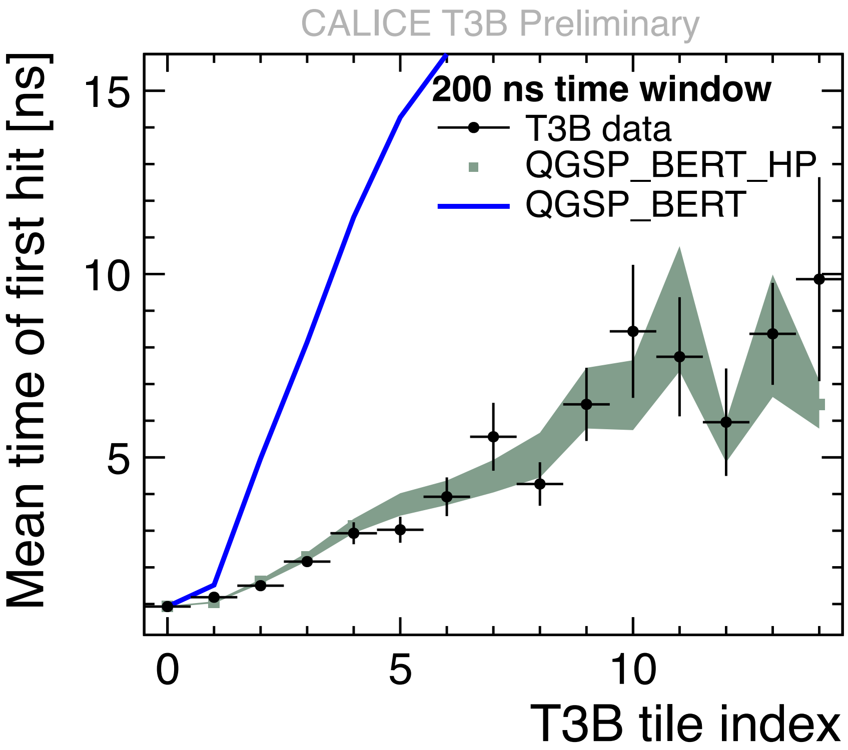


SiPM analog HCAL testbeam

10 GeV pion

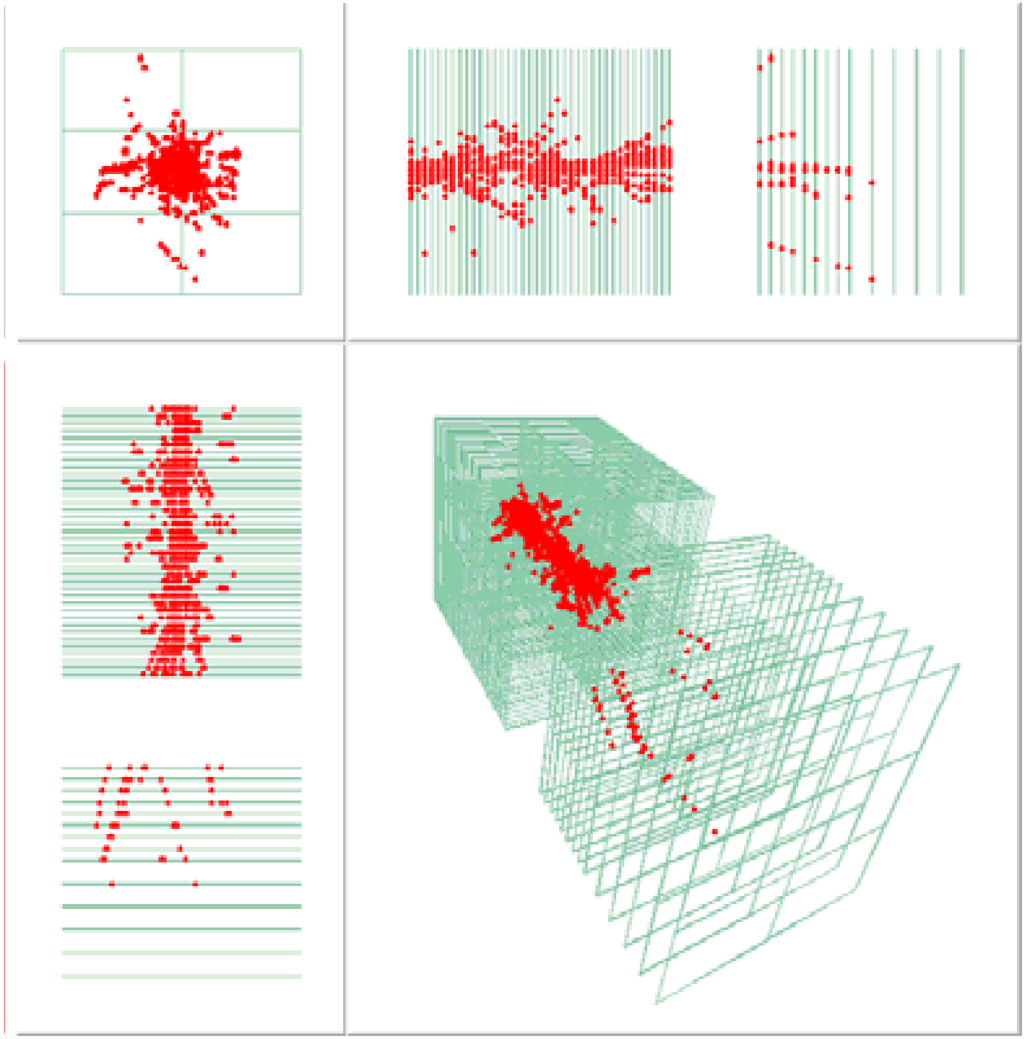


Time structure of shower:



- First results demonstrate the importance of the high precision neutron tracking with QGSP_BERT_HP in Geant4 for the time evolution of hadronic showers in tungsten.

RPC digital HCAL testbeam



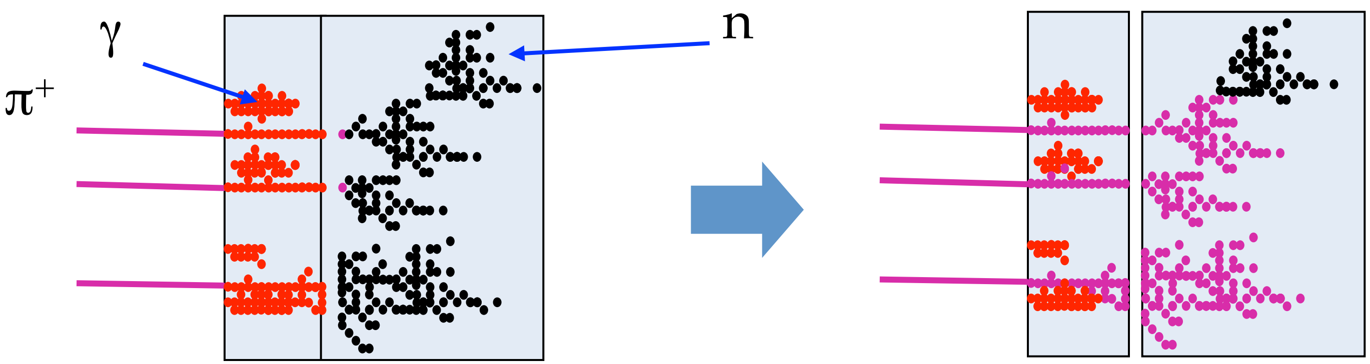
120 GeV proton

With Fe, performed
at Fermilab

Outline

- Physics motivation
- Accelerator design
  - e^+e^- collisions, yet not LEP-like
- Detector designs
  - For unprecedented requirements
- Particle Flow – imaging calorimetry
  - How to cope with background

Particle Flow Calorimetry

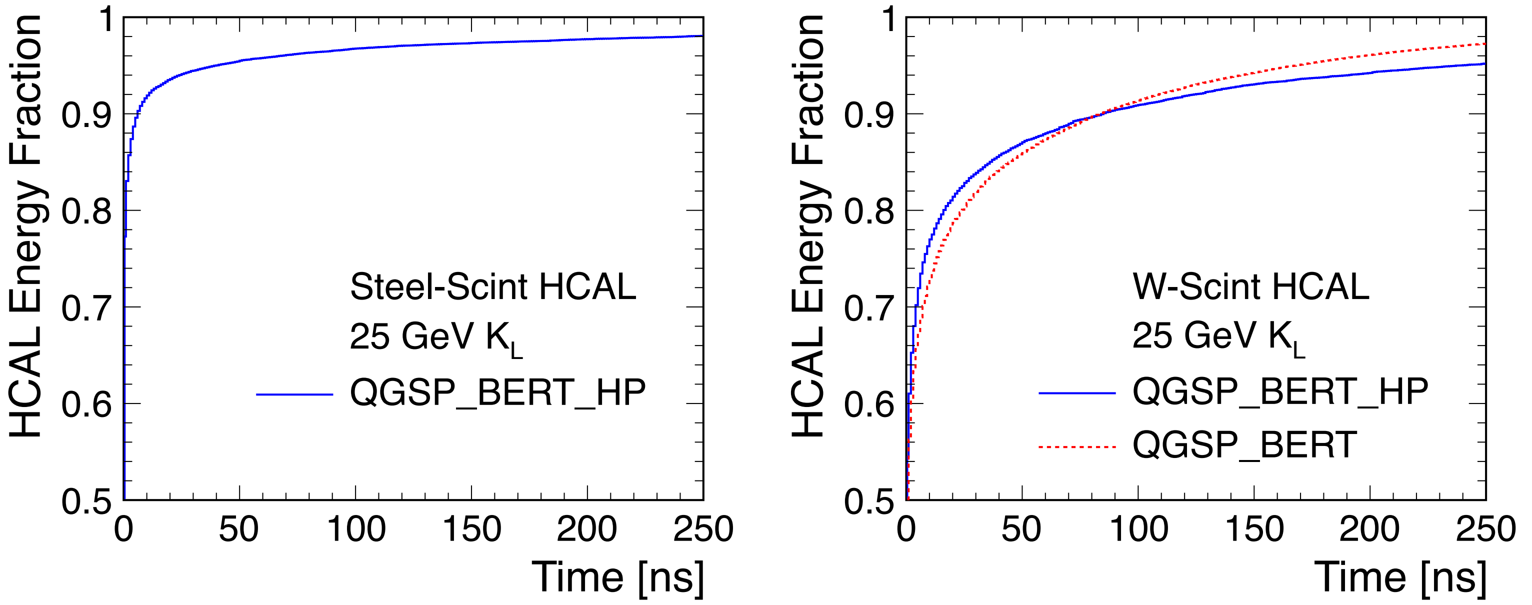


$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- Measure charged particle energies (60% of jet) in tracker.
- Measure photon energies (30%) in ECAL
  $\sigma E / E < 20\% / \sqrt{E(\mathrm{GeV})}$
- Measure only neutral hadron energies (10%) in HCAL.

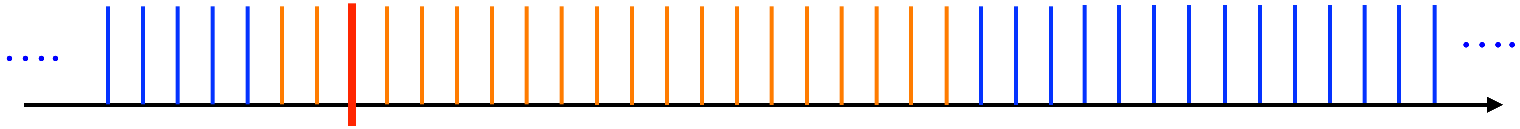
Time development in hadronic showers



- In steel 90% of the energy is recorded within 6 ns (corrected for time-of-flight).
- In tungsten only 82% of the energy is deposited within 25 ns.
  - Response is slower due to the much larger component of the energy in nuclear fragments.

➢ Need to integrate over > 25 ns in the reconstruction, keeping out the pile-up hits…

Reconstruction timing strategy



Assume can identify t_0 of physics event in offline event filter

- define “reconstruction” window around t_0
- All hits and tracks in window are passed to reconstruction.

Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
HCAL Endcap	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$
TPC (CLIC_ILD)	Entire train	n/a

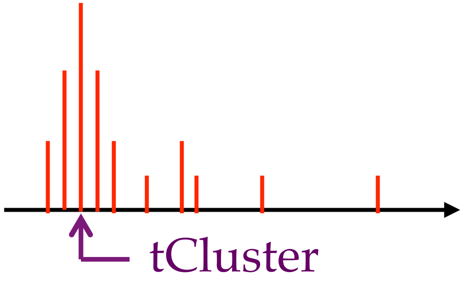
CLIC hardware Requirements

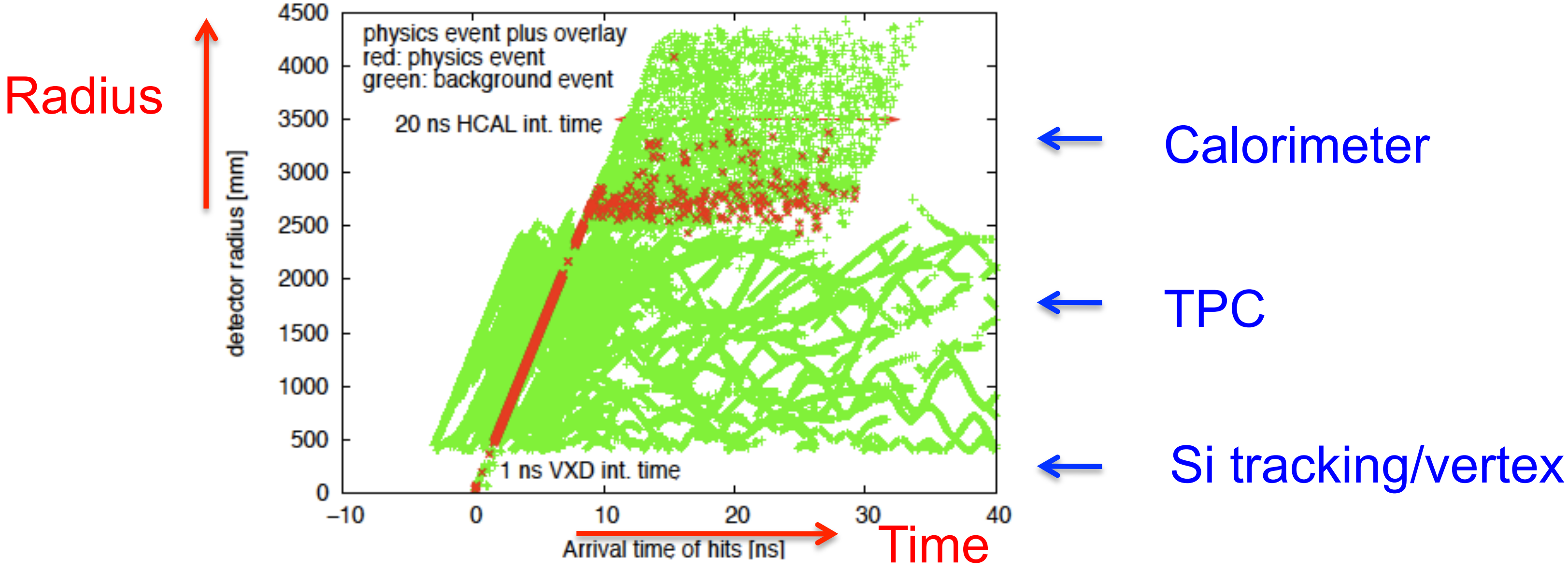
- Achievable in the calorimeters with a sampling each ~25 ns

Reconstruction in time

After reconstruction have a list of Particle Flow Objects (PFOs)

- Calculate energy weighted mean time of each cluster
  - ➢ Obtain sub-ns resolution
  - ➢ Use times to reject clusters and associated tracks



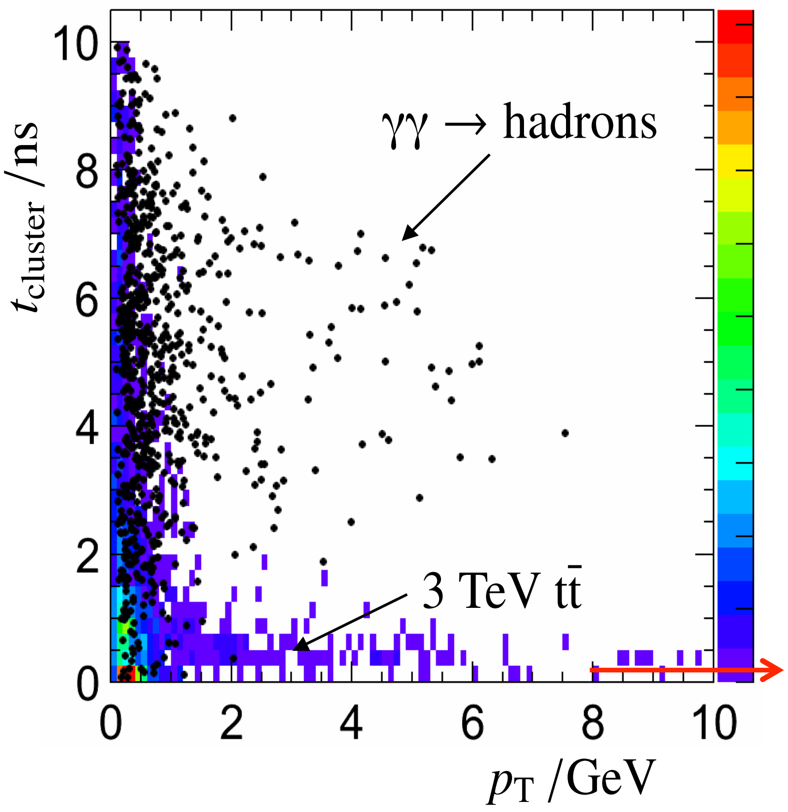


Reconstruction in time

After reconstruction have a list of Particle Flow Objects (PFOs)

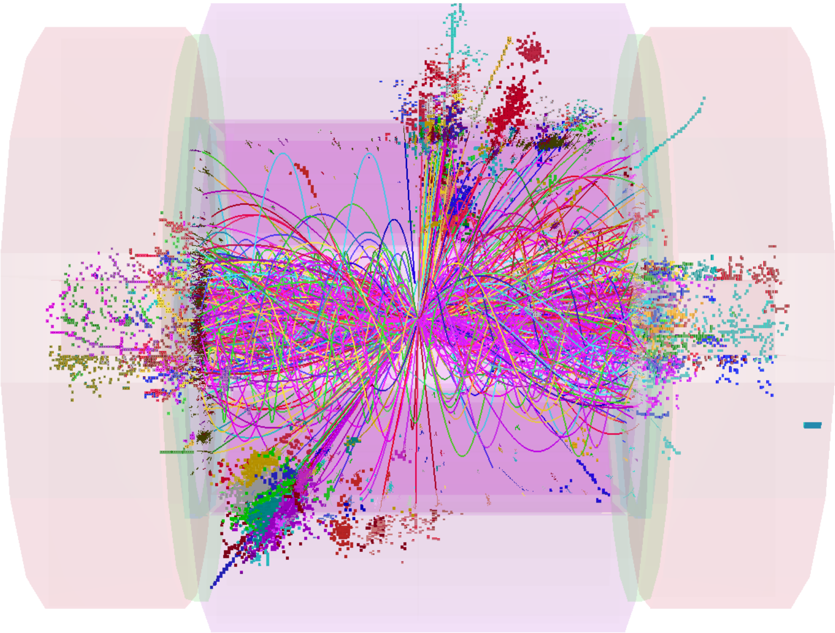
- Calculate energy weighted mean time of each cluster
  - Obtain sub-ns resolution
  - Use times to reject clusters and associated tracks

Neutral hadrons



Impact of Timing Cuts

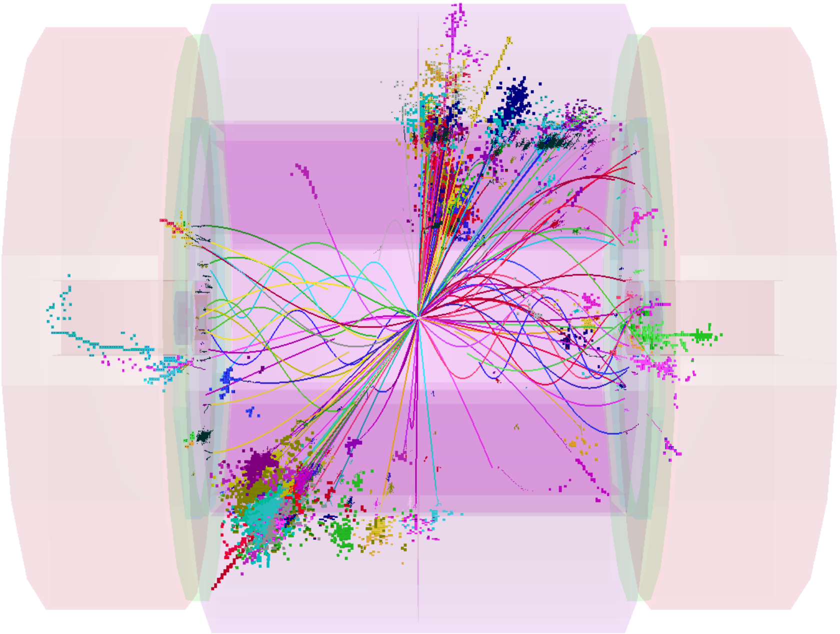
1.2 TeV background



√s = 3 TeV, 500 GeV di-jet event

Impact of Timing Cuts

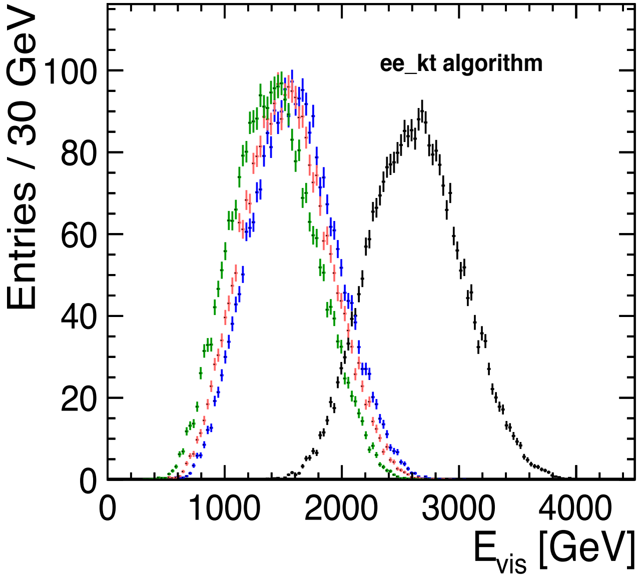
1.2 TeV ⇨ 85 GeV



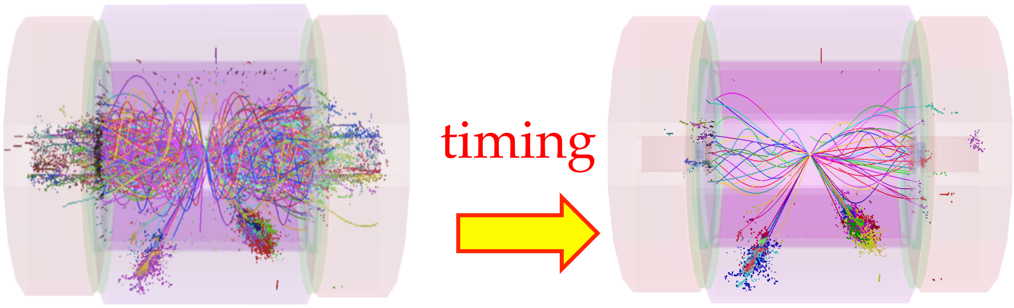
Cut	$\gamma\gamma \to$ hadrons Energy (GeV)	500 GeV di-jet Energy (GeV)	500 GeV di-jet energy loss
`No cut`	1210	500.2	0%
`Loose`	235	498.8	0.3%
`Default`	175	498.0	0.5%
`Tight`	85	496.1	0.8%
$p_T > 3.0$ GeV	160	454.2	9.2%

- Reject 93 % of background energy and < 1% of physics event
  - much more effective than simple p_T cut

Jet Finding at CLIC

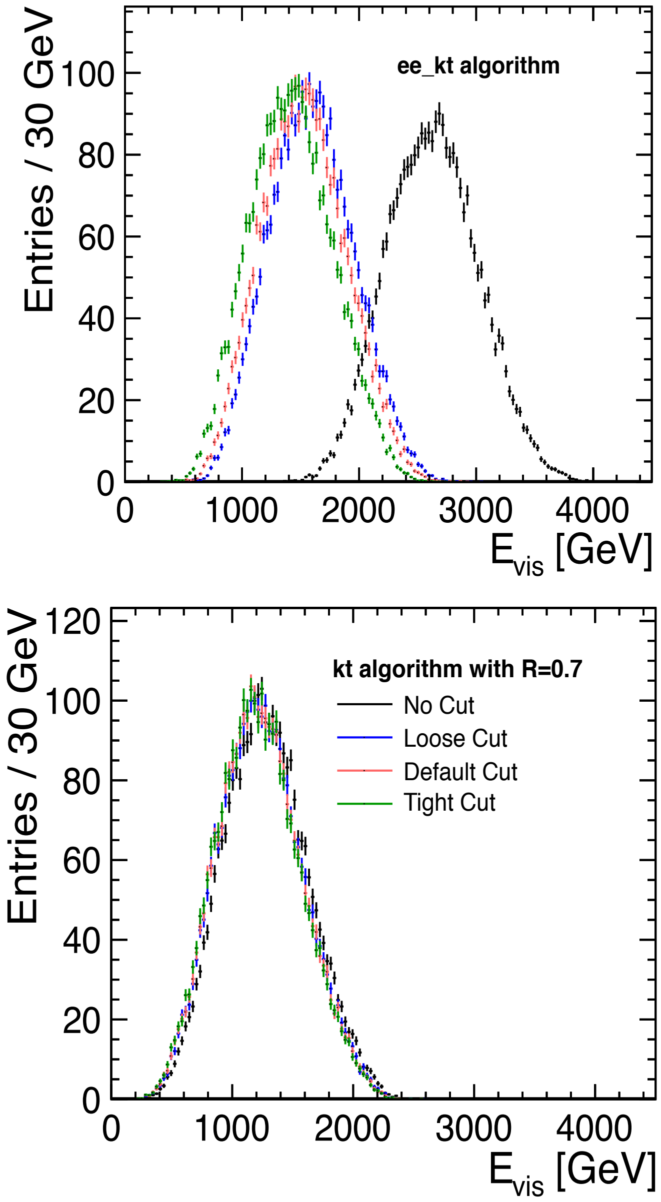


- e.g. $e^+e^- \rightarrow \tilde{q}_R\tilde{q}_R \rightarrow q\bar{q}\,\tilde{\chi}^0_1\,\tilde{\chi}^0_1$

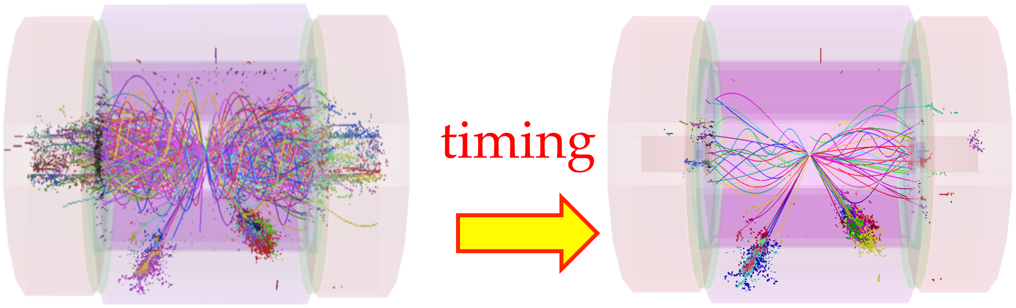


- Using Durham k_T à la LEP
  - Timing cuts are effective, but not sufficient

Jet Finding at CLIC



- e.g. $e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$



- Using Durham k_T à la LEP
  - Timing cuts are effective, but not sufficient
- "hadron collider" k_T : $R = 0.7$
  - Even less background, timing cuts hardly any effect for this topology

➢ To tackle background: timing cuts + jet finding

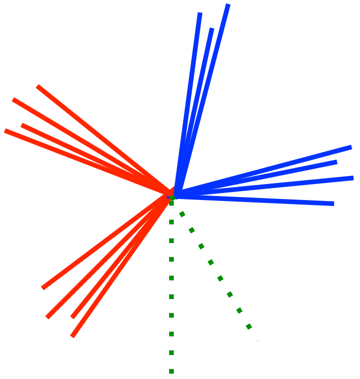
Test of di-jet mass reconstruction

- Clear separation using di-jet invariant masses:

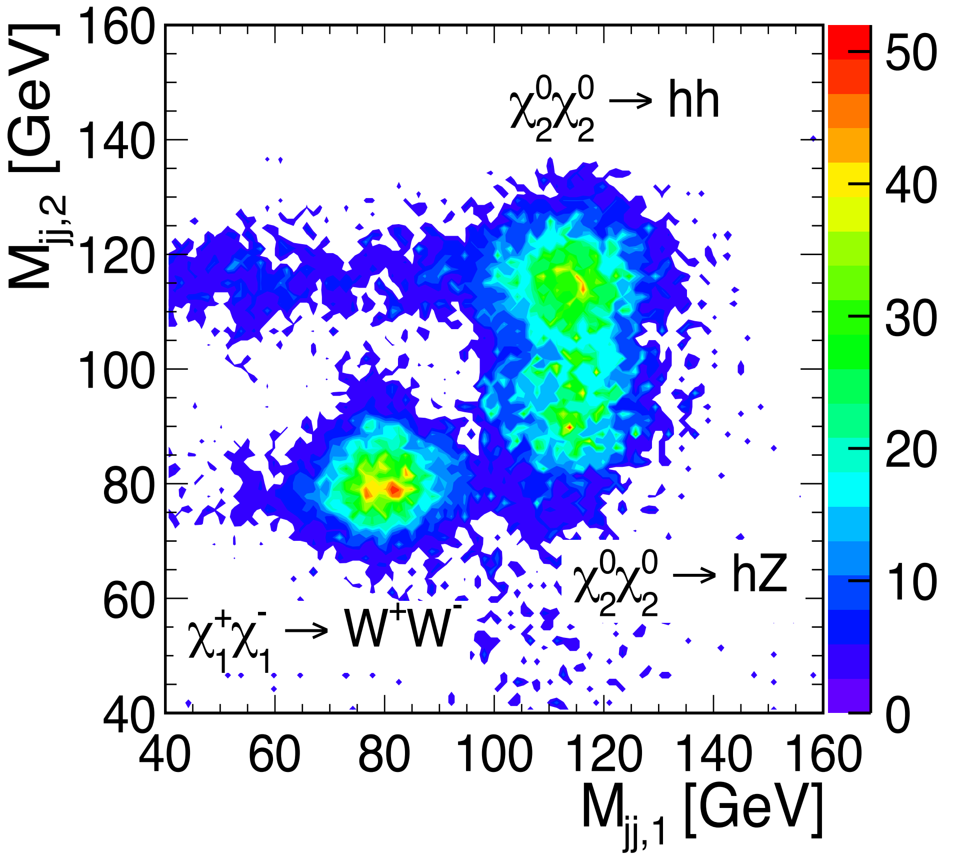
$$e^+e^- \to \tilde{\chi}_1^+\,\tilde{\chi}_1^- \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0 W^+W^-$$

$$e^+e^- \to \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \to hh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \quad 82\ \%$$

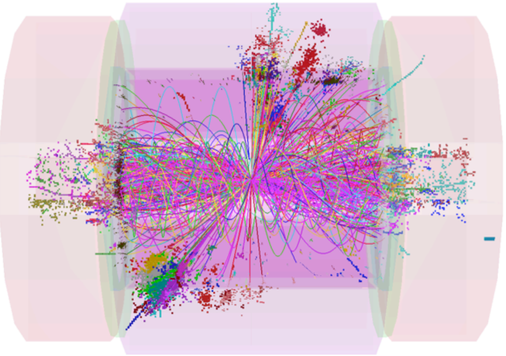
$$e^+e^- \to \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \to Zh\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \quad 17\ \%$$



Full Simulation with background



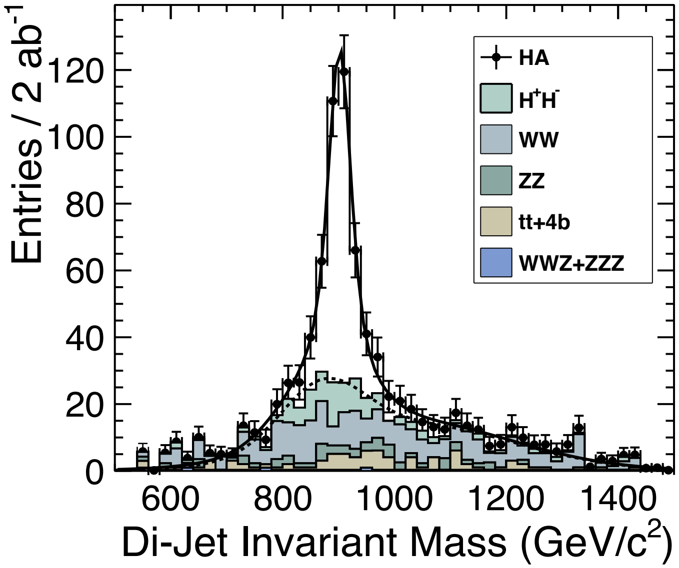
The 8 jet final state



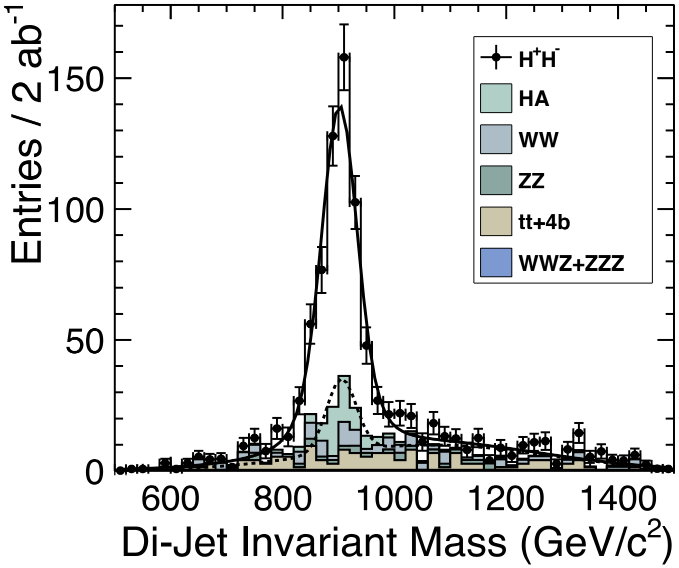
1.4 TeV of background

SUSY model I

M_{MC}	State	Mass (GeV)	Width (GeV)
902.4	A/H	904.5 ± 2.8	20.6 ± 6.3
906.3	$H^{\pm}$	902.6 ± 2.4	20.2 ± 5.4



$e^+e^- \to HA \to b\bar{b}b\bar{b}$

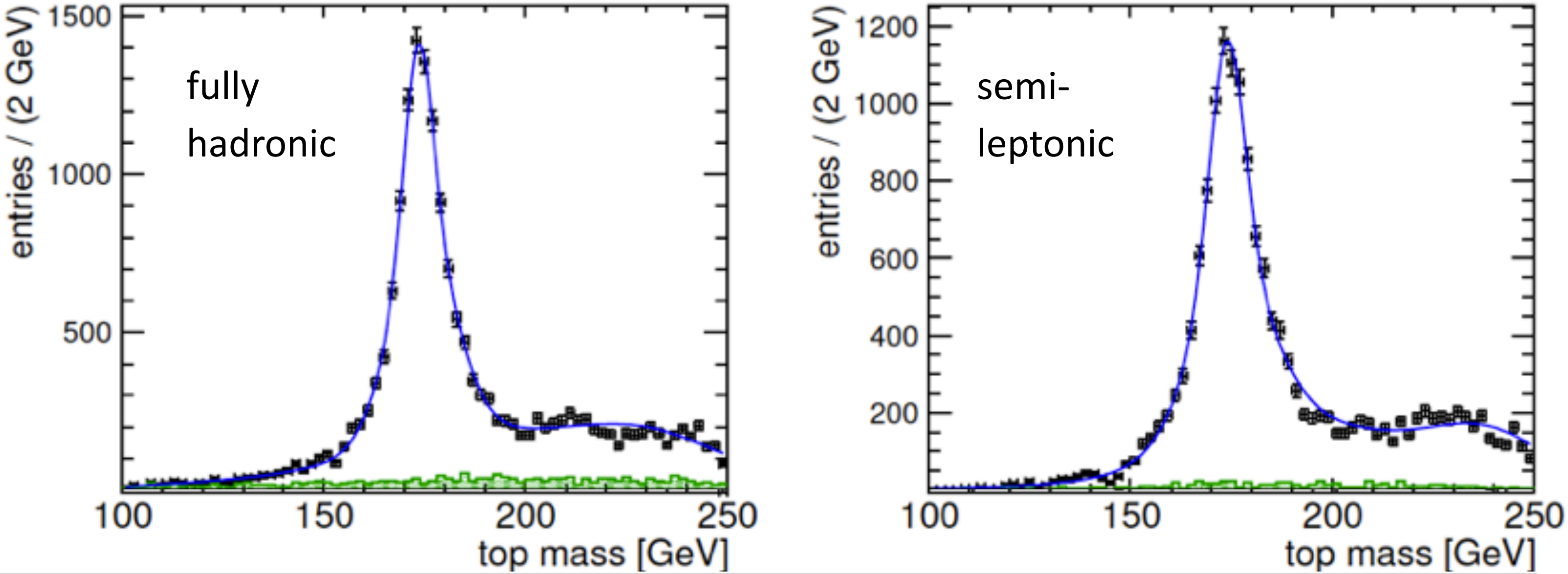


$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t}$

Top pairs at $\sqrt{s}$ = 500 GeV

250 fb^{-1}

Unbinned maximum likelihood fit of mass distributions



Top decay	Top mass (GeV)	Top width (GeV)	Generator value Mass (GeV)	 Width (GeV)
Fully-hadronic	174.08 ± 0.08	1.42 ± 0.22	174	1.37
Semi-leptonic	174.30 ± 0.09	1.45 ± 0.26		

- ➢ Comparable to ILD LOI mass resolution (0.11 GeV in all-hadronic final state)

More **detector** benchmark channels

Summary

- CLIC CDR Volume 2 public and under review:
  https://edms.cern.ch/file/1160419/1/CLIC_CDR_Review_080911.pdf

- Impact of background studied in detail
  - Require high granularity in space and time
  - Defines detector requirements and guides the future of ongoing R&D

- With CDR achieved initial goal:
  - Demonstrated ability to perform high precision physics in the CLIC machine environment

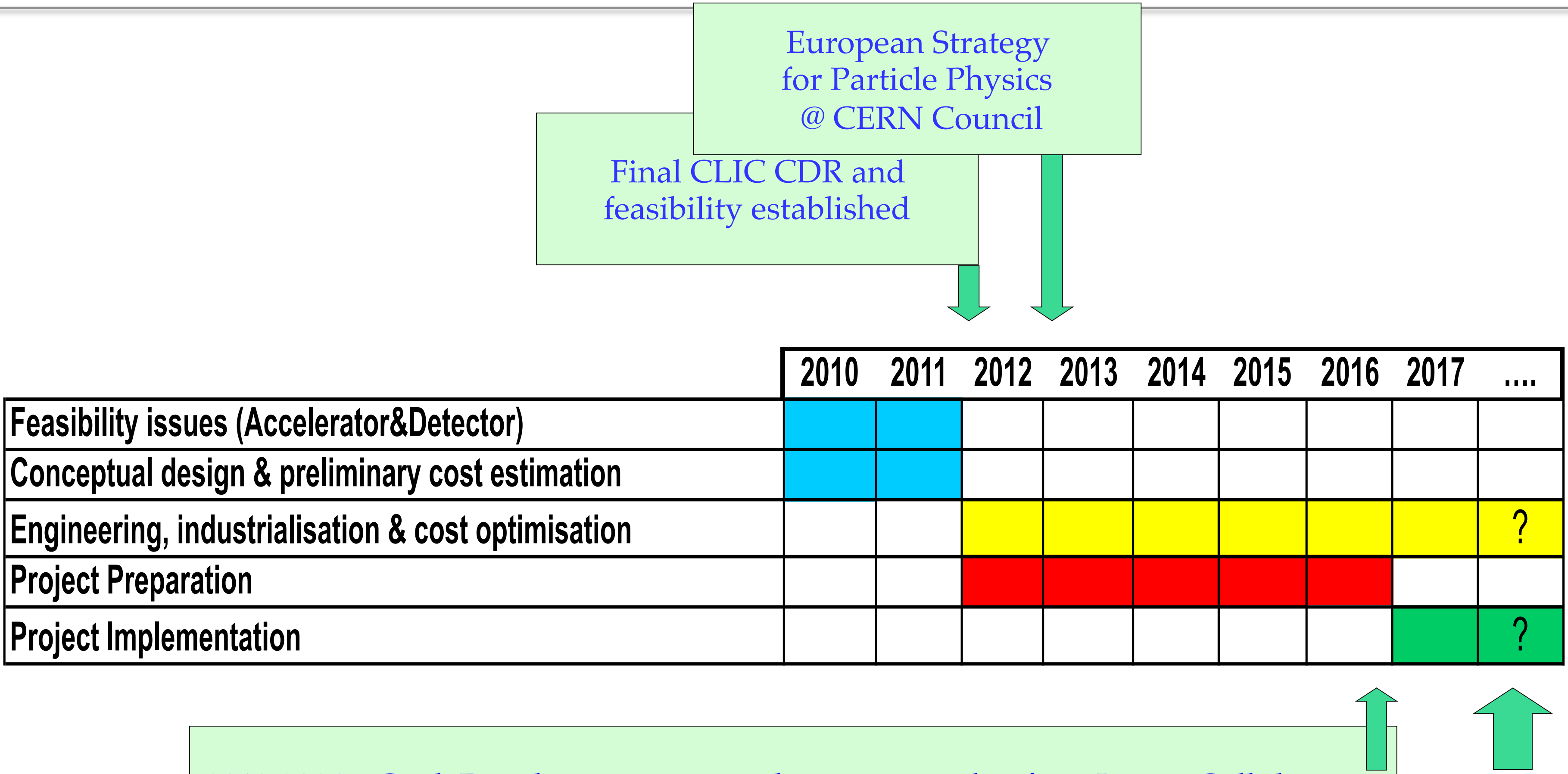
- If you would like to give your support to the physics case and R&D towards a future linear collider based in CLIC technology, you are invited to sign up:
  https://indico.cern.ch/conferenceDisplay.py?confId=136364

  – Does not imply any formal commitment –

Backup slides
- accelerator

More physics potential studies

CLIC next phases



European Strategy for Particle Physics @ CERN Council

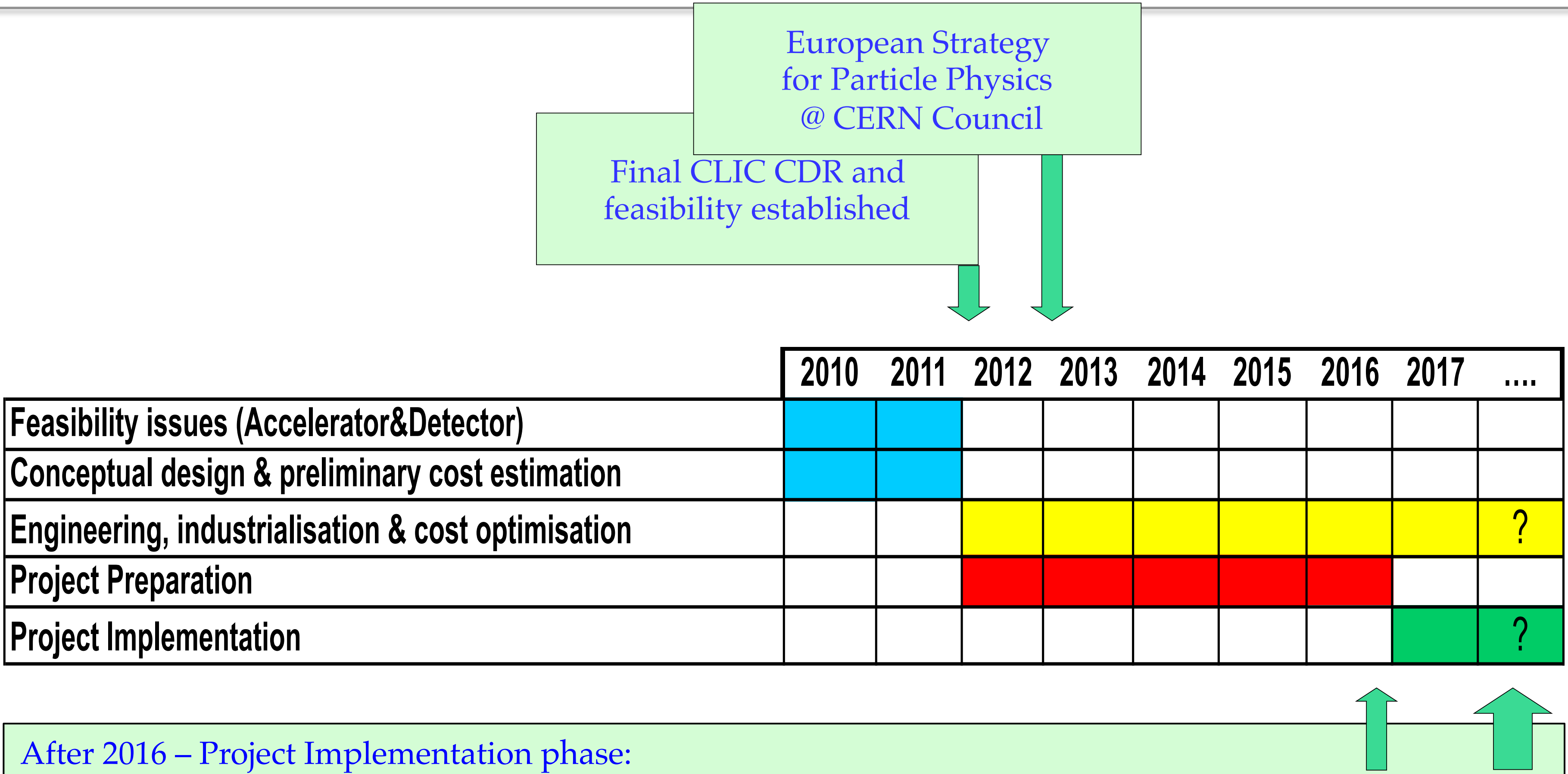
Final CLIC CDR and feasibility established

	2010	2011	2012	2013	2014	2015	2016	2017	....
Feasibility issues (Accelerator&Detector)	🟦	🟦							
Conceptual design & preliminary cost estimation	🟦	🟦							
Engineering, industrialisation & cost optimisation			🟨	🟨	🟨	🟨	🟨	🟨	🟨 ?
Project Preparation			🟥	🟥	🟥	🟥	🟥		
Project Implementation								🟩	🟩 ?

2011-2016 – Goal: Develop a project implementation plan for a Linear Collider :

- Addressing the key physics goals as emerging from the LHC data
- With a well-defined scope (i.e. technical implementation and operation model, energy and luminosity), cost and schedule
- With a solid technical basis for the key elements of the machine and detector
- Including the necessary preparation for siting the machine at CERN
- Within a project governance structure as defined with international partners

CLIC next phases



European Strategy
for Particle Physics
@ CERN Council

Final CLIC CDR and
feasibility established

	2010	2011	2012	2013	2014	2015	2016	2017	....
Feasibility issues (Accelerator&Detector)	🟦	🟦							
Conceptual design & preliminary cost estimation	🟦	🟦							
Engineering, industrialisation & cost optimisation			🟨	🟨	🟨	🟨	🟨	🟨	🟨 ?
Project Preparation			🟥	🟥	🟥	🟥	🟥		
Project Implementation								🟩	🟩 ?

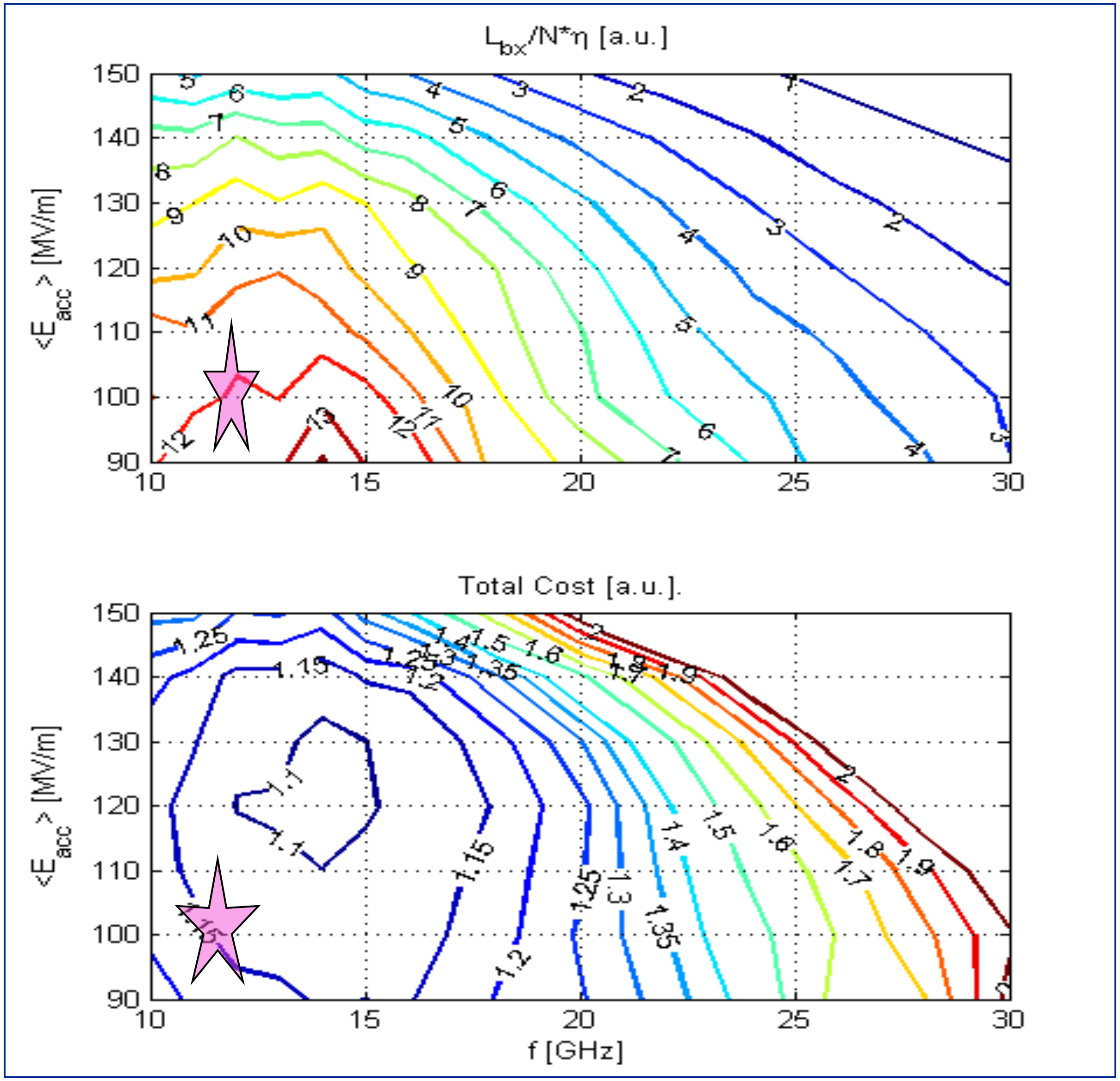
After 2016 – Project Implementation phase:
Including an initial project to lay the grounds for full construction (CLIC 0 – a significant part of the drive beam facility: prototypes of hardware components at real frequency, final validation of drive beam quality / main beam emittance preservation, facility for reception tests – and part of the final project)

- Finalization of the CLIC technical design, taking into account the results of technical studies done in the previous phase, and final energy staging scenario based on the LHC Physics results, which should be fully available by the time
- Further industrialization and pre-series production of large series components with validation facilities

3TeV Parameter Optimisation

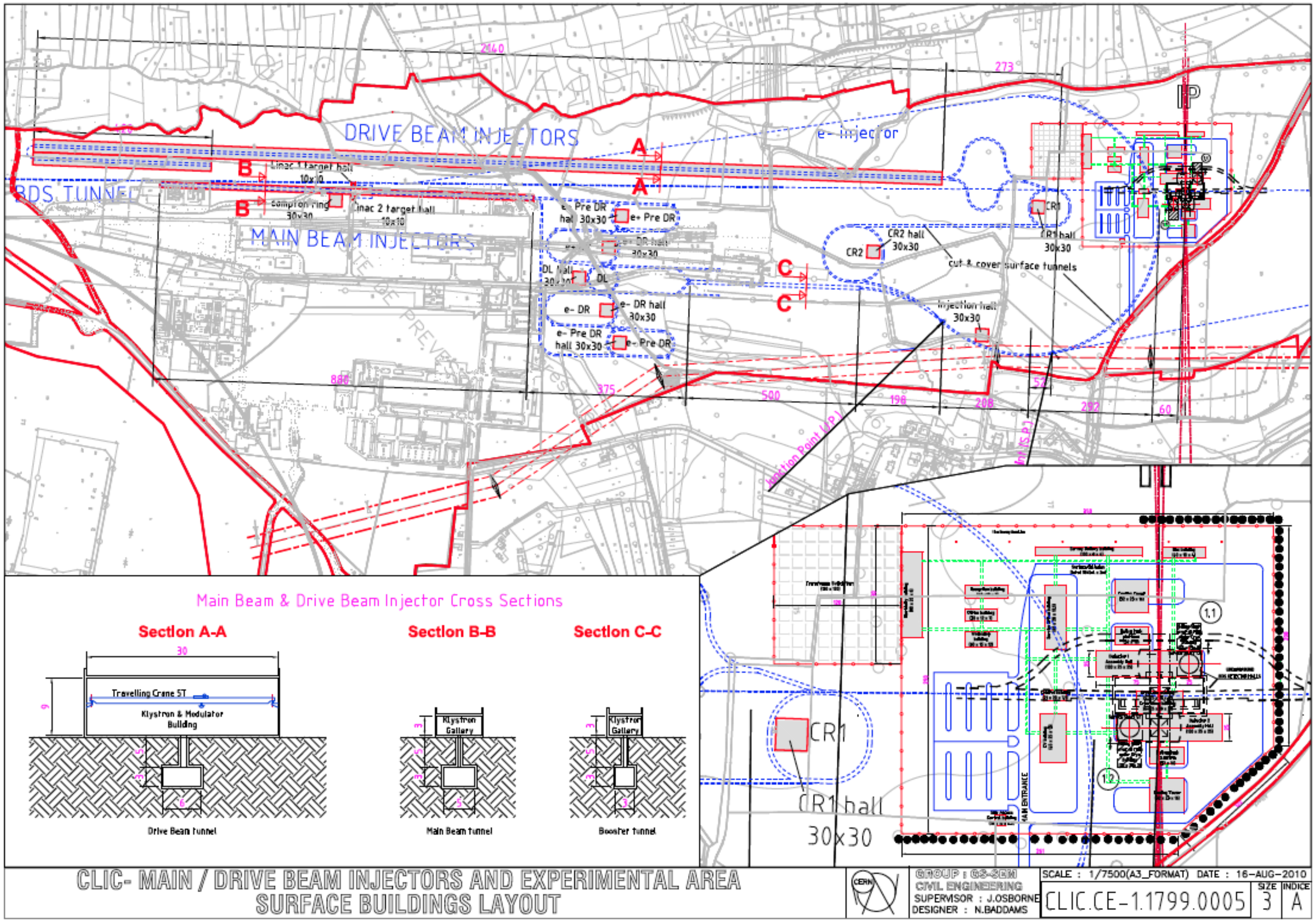
Optimisation:

- Minimise cost for fixed luminosity $L_{0.01}$
- Physics constraint
  - $L_{0.01} > 0.3$ L
- No constraints on background
  - Regarded as perturbation



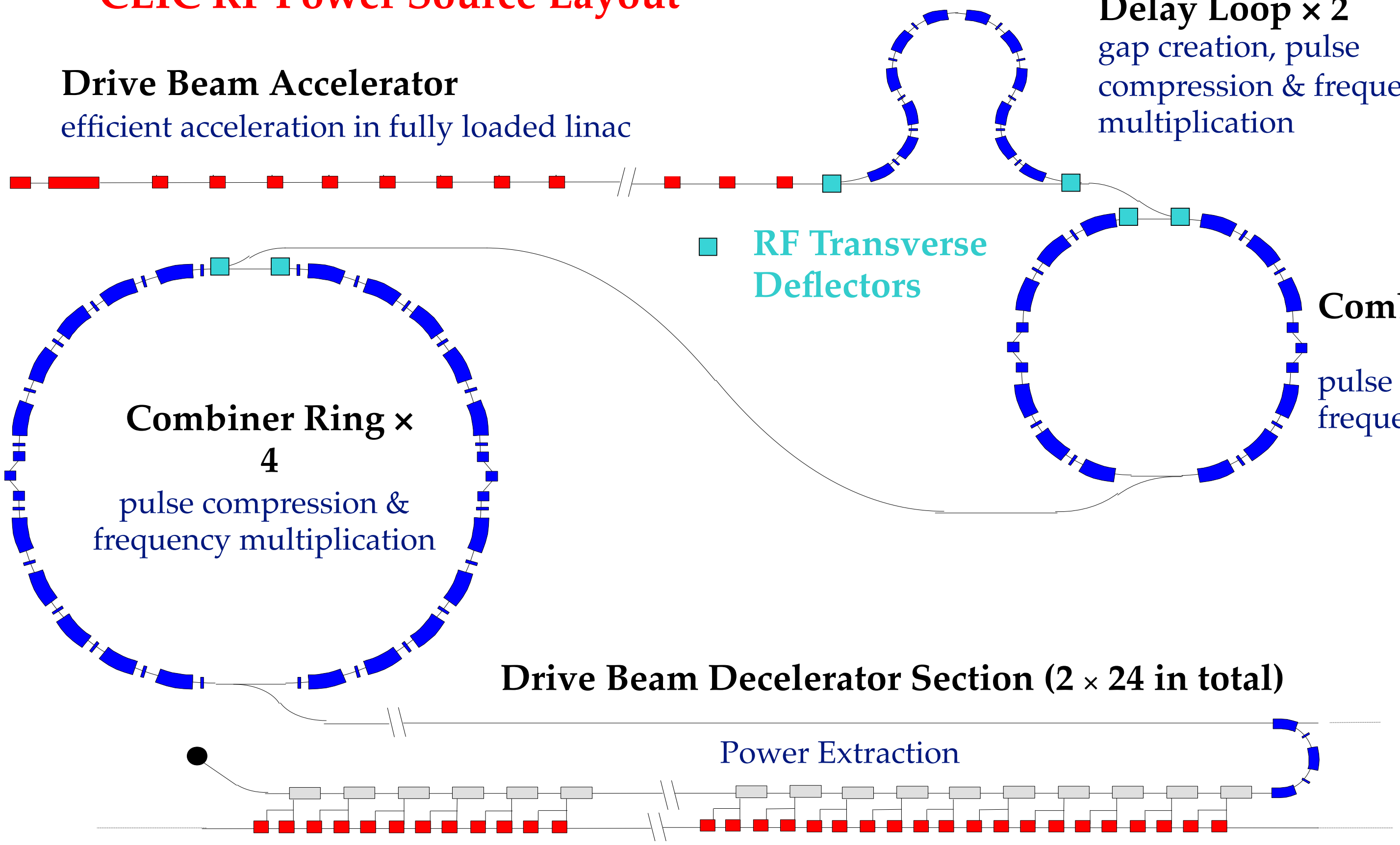
Injector complex & experimental area

Interaction region, caverns and surface installation, as foreseen in the CDR, at CERN Prevessin



Drive beam generation

CLIC RF Power Source Layout



Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

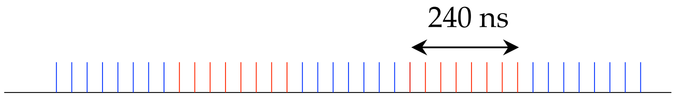
Combiner Ring × 3
pulse compression & frequency multiplication

Combiner Ring × 4
pulse compression & frequency multiplication

Drive Beam Decelerator Section (2 × 24 in total)

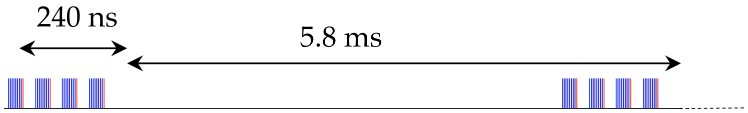
Power Extraction

Drive beam time structure - initial



140 ms train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

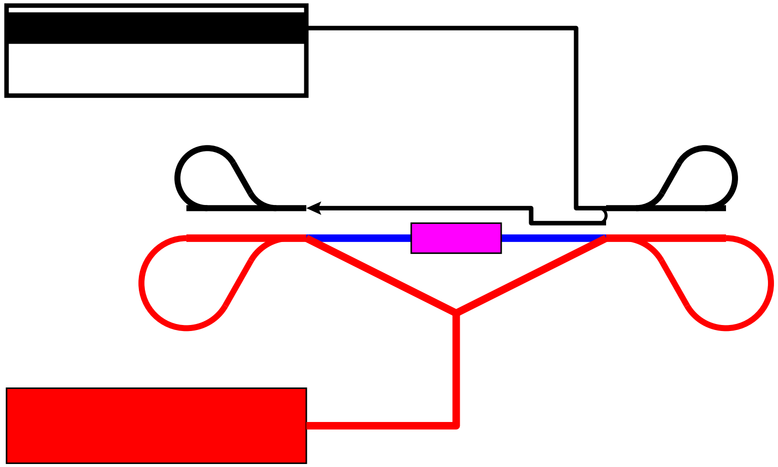


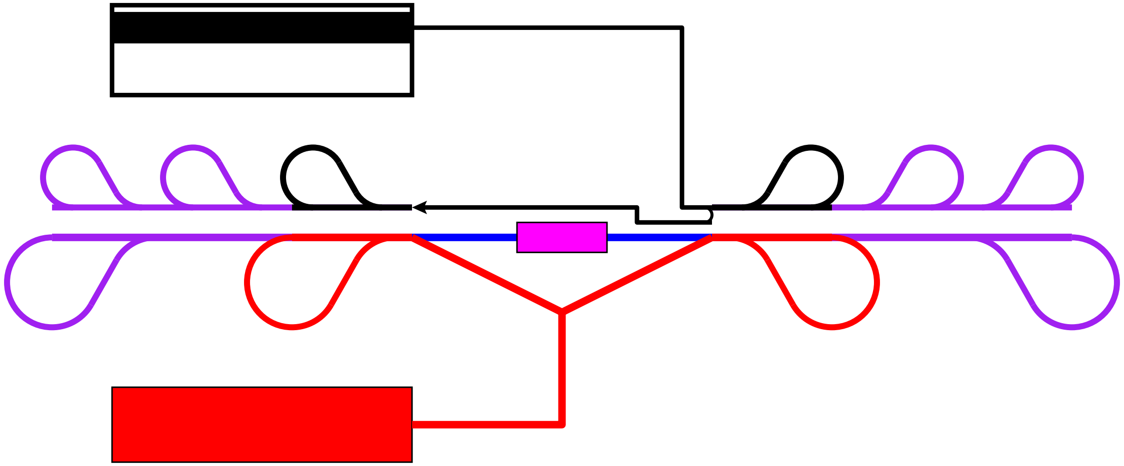
24 pulses – 101 A – 2.5 cm between bunches

Concept of staging

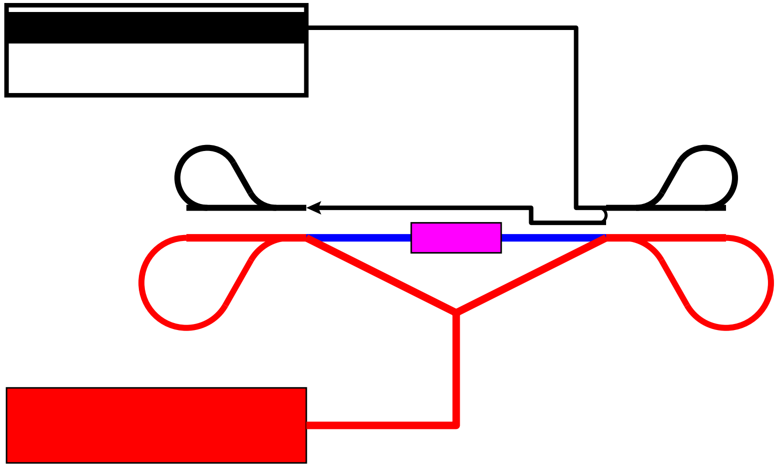
Lower energy can run most of the time during construction of next stage.

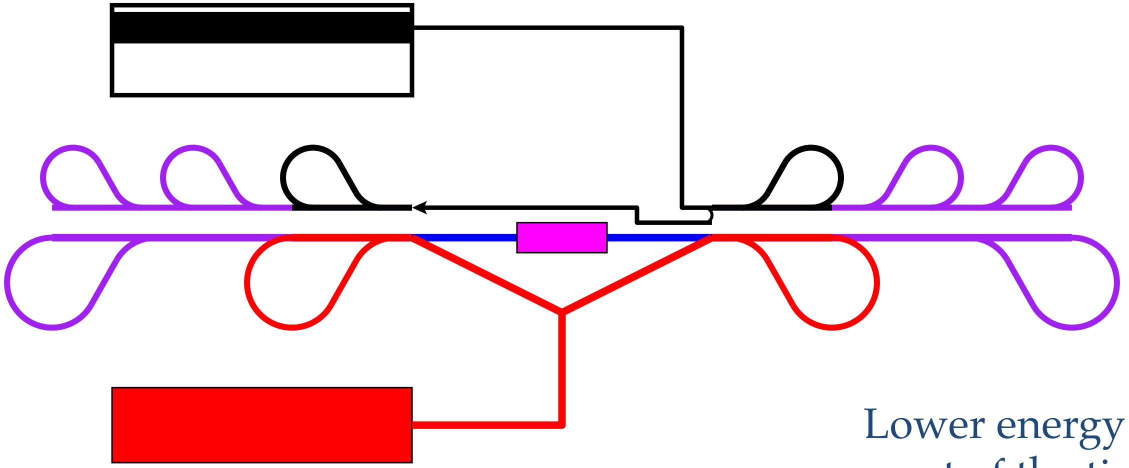
0.5 TeV stage
Tot. length ~14 km





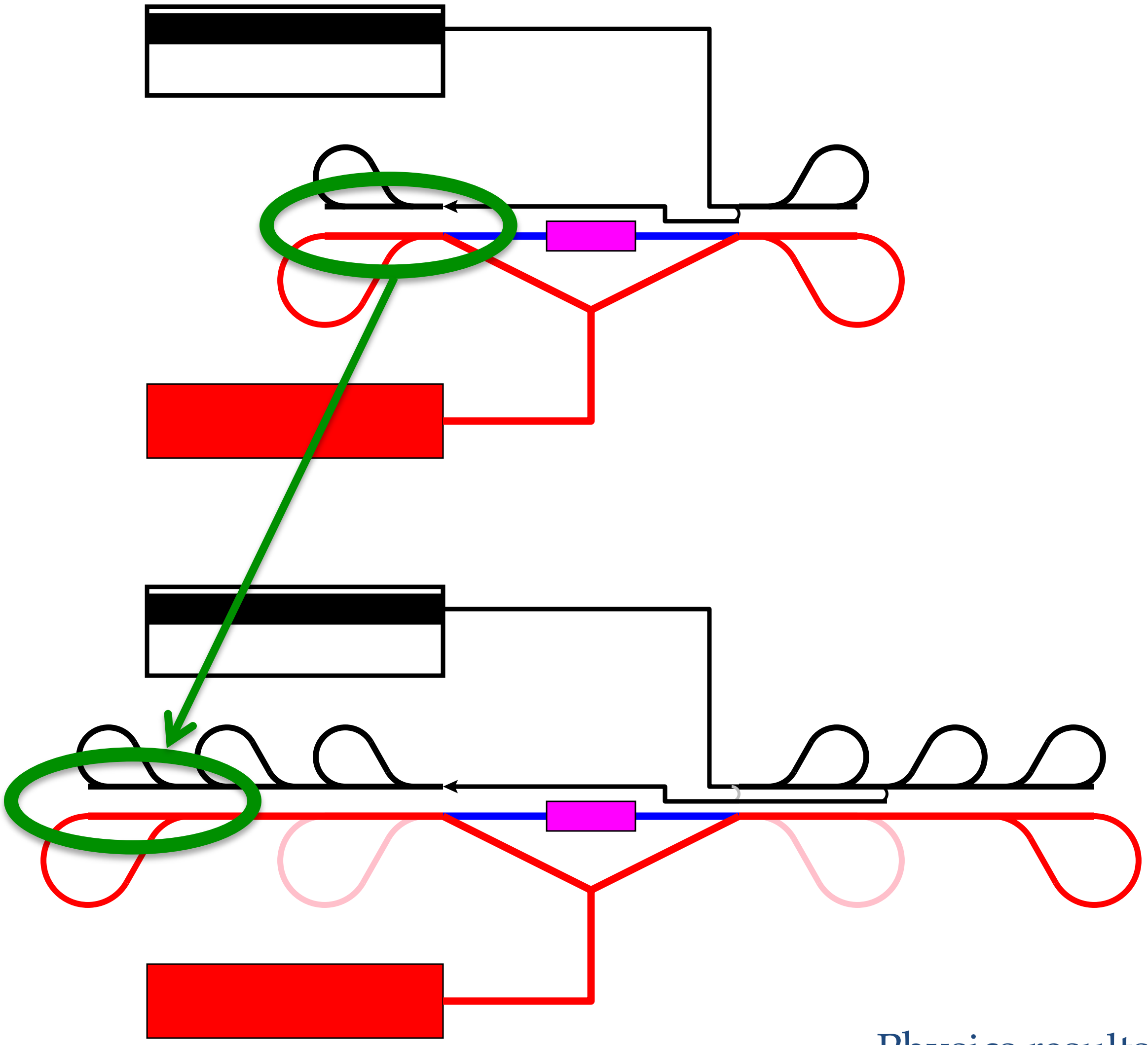
Concept First Stage





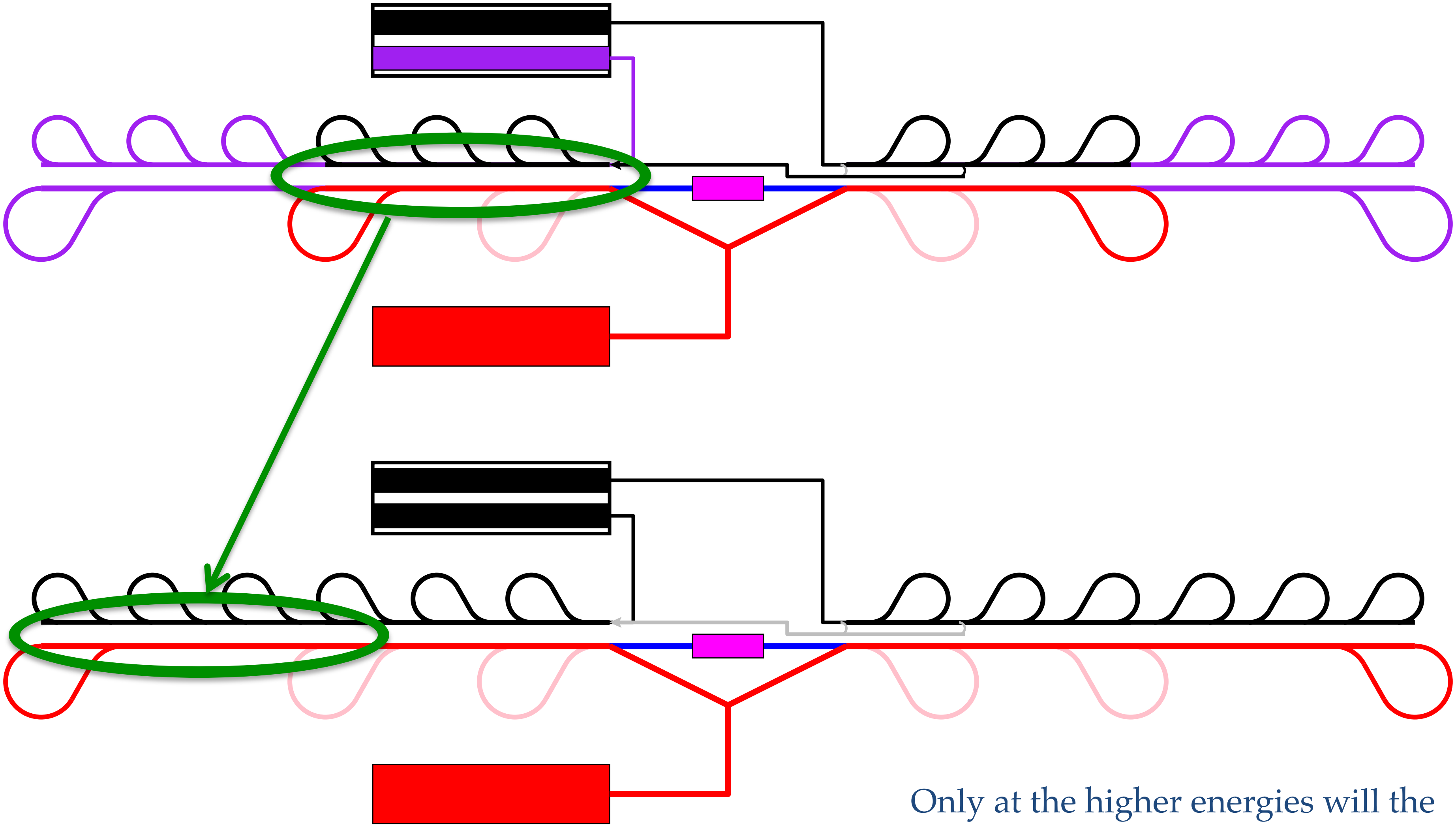
Lower energy machine can run most of the time during the construction of the next stage.

Concept Second Stage



Physics results will determine the energies of the stages

Concept of staging



Only at the higher energies will the second drive beam generation complex be needed.

Potential New CLIC Staged Parameters

parameter	symbol			
centre of mass energy	E_{cm} [GeV]	350	1400	2900
gradient	G [MV/m]	80	80/100	80/100
DB sectors		4	12	24
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	1.54	3.6	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.0	1.5	2
site length	[km]	11	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	70	44	44
IP beam size	σ_x/σ_y [nm]	236/2.7	?/?	41/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
est. power cons.	P_{wall} [MW]	260	360	580

First stage ML structures are re-used

Potential New CLIC Staged Parameters

parameter	symbol			
centre of mass energy	E_{cm} [GeV]	350	1400	2900
gradient	G [MV/m]	80	80/100	80/100
DB sectors		4	12	24
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	1.54	3.6	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.0	1.5	2
gradient	G [MV/m]	80	100	100
site length	[km]	11	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	70	44	44
IP beam size	σ_x/σ_y [nm]	236/2.7	?/?	41/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	260	360	580

First stage ML structures are re-used

Choice of L*

Longer L* would be beneficial

- detector design
  - angular coverage
  - shielding solenoid
- final quadrupole stabilisation

But it reduces luminosity

-> use 3.5m/4.3m as a baseline

-> all studies performed at 3.5m, some at 4.3m

Vol 1, 2.5.3.7

L* [m]	total luminosity [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	peak luminosity [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]
3.5	6.9	2.5
4.3	6.4	2.4
6	5.0	2.1
8	4.0	1.7

Luminosity includes 20% overhead for imperfections

More effort in the future to understand trade-off

Comparison CLIC vs LHC detector

In a nutshell:

CLIC detector:

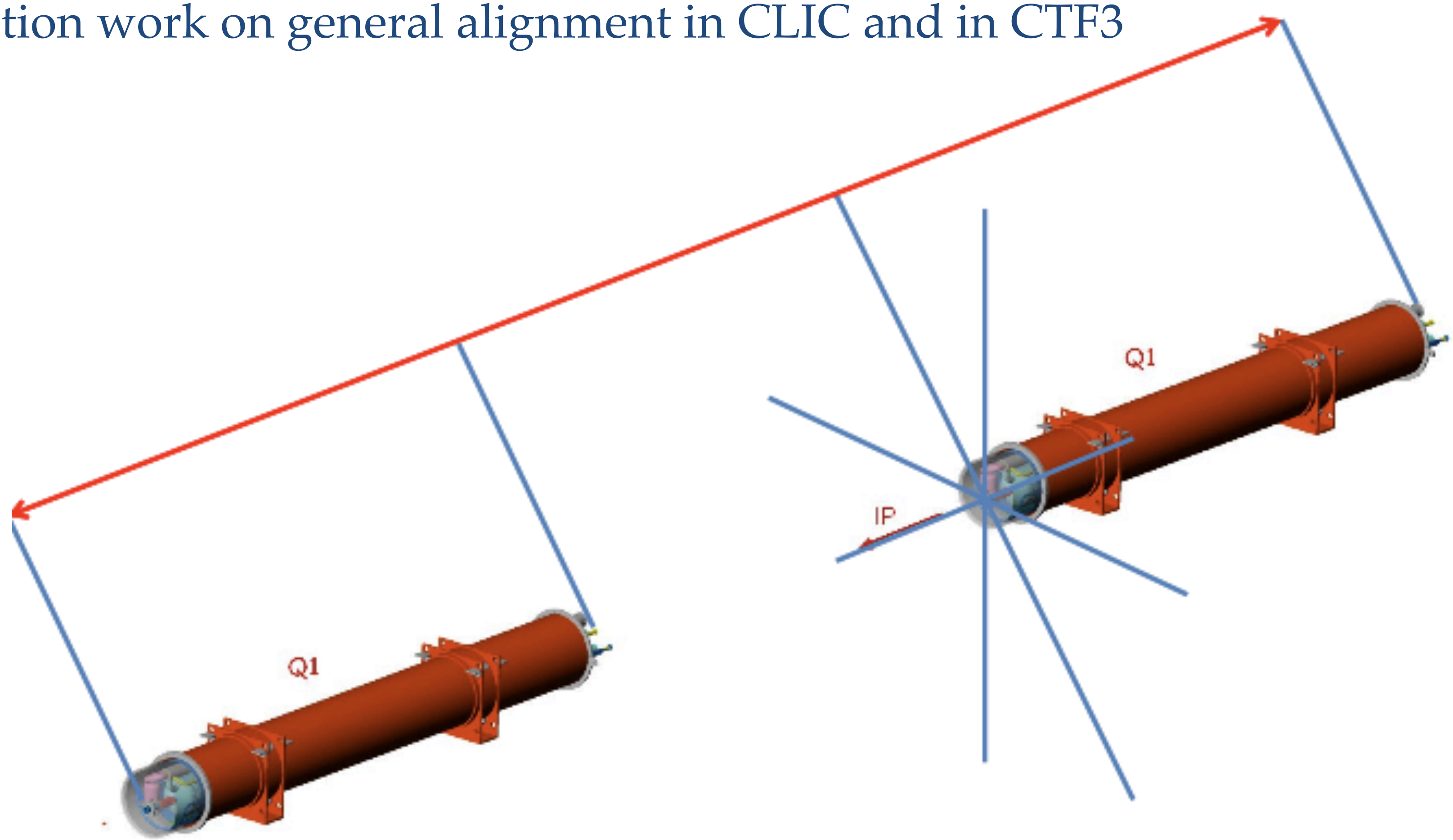
- **High precision:**
  - Jet energy resolution
    - => fine-grained calorimetry
  - Momentum resolution
  - Impact parameter resolution
- **Overlapping beam-induced background:**
  - High background rates, medium energies
  - High occupancies
  - Cannot use vertex separation
  - Need very precise timing (1, 2, 5, 10ns)
- **No issue of radiation damage (10^{-4} LHC)**
- **Beam crossings "sporadic"**
- **No trigger, read-out of full 156 ns train**

LHC detector:

- **Medium-high precision:**
  - Very precise ECAL (CMS)
  - Very precise muon tracking (ATLAS)
- **Overlapping minimum-bias events:**
  - High background rates, high energies
  - High occupancies
  - Can use vertex separation in z
  - Need precise time-stamping (25 ns)
- **Severe challenge of radiation damage**
- **Continuous beam crossings**
- **Trigger has to achieve huge data reduction**

Nikhef: Alignment

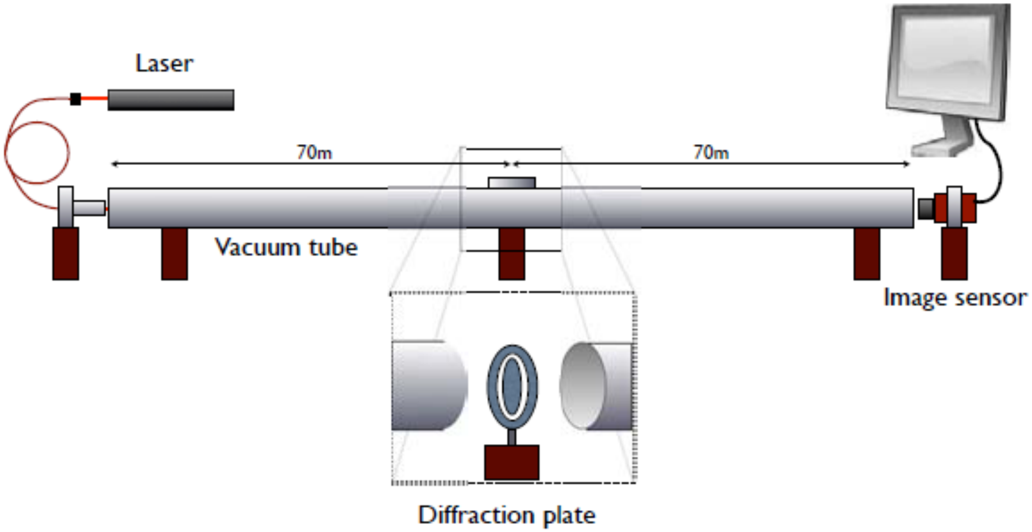
- Alignment of beamlines wrt each other
- Based on RASNIK
- In addition work on general alignment in CLIC and in CTF3



Nikhef collab. on pre-alignment

Objectives: provide transverse positional data on targets distributed over 100 m, with an uncertainty of measurement better than 5 μm

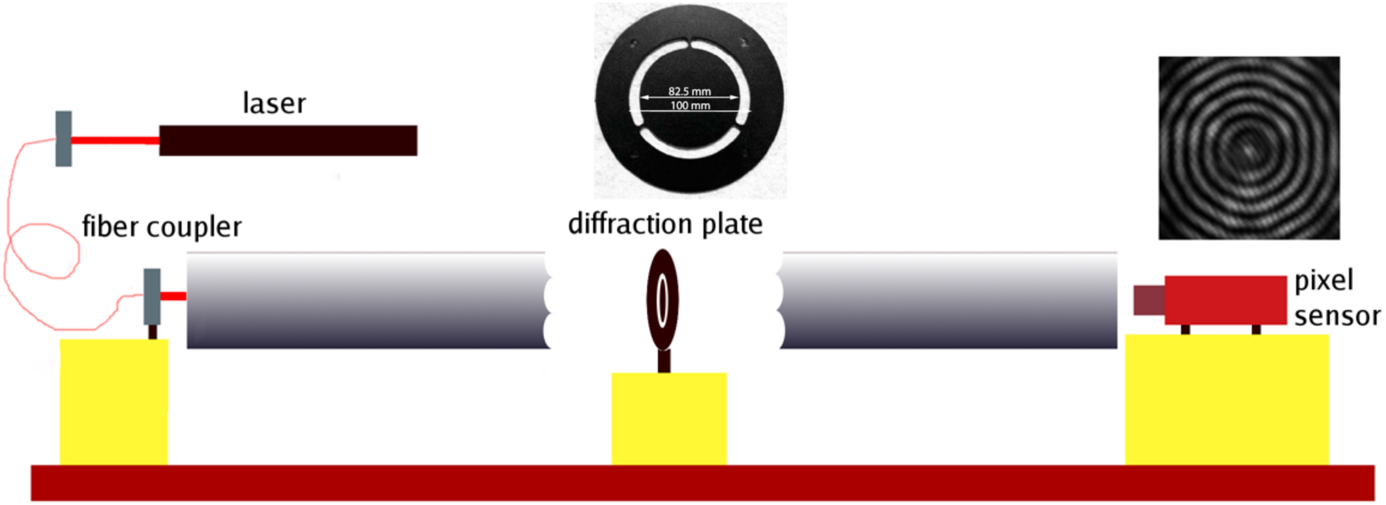
- Concept: RASCLIC is a 3 point alignment, which consists of a monochromatic light source, a diffraction plate and a pixel image sensor.
- The position of a diffraction pattern is monitored on the image sensor, which provides the relative position of the three components.



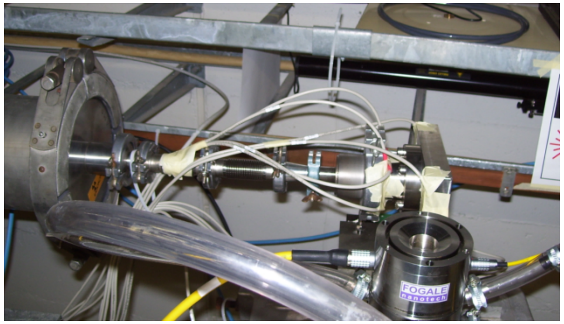
(M. Beker)

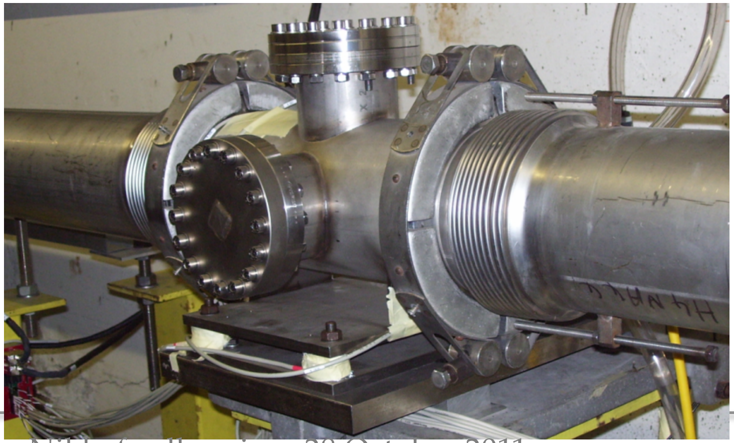
Nikhef collab. on pre-alignment

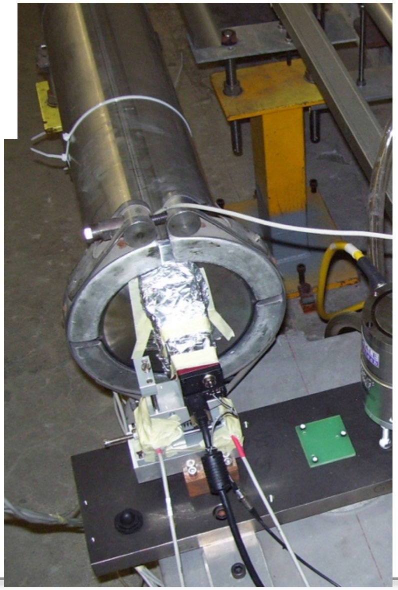
- The concept was validated in an old tunnel named TT1 on 140 m.
- A precision of 20 nm was reached
- New agreement signed for improved and expanded system



(H. van der Graaf)







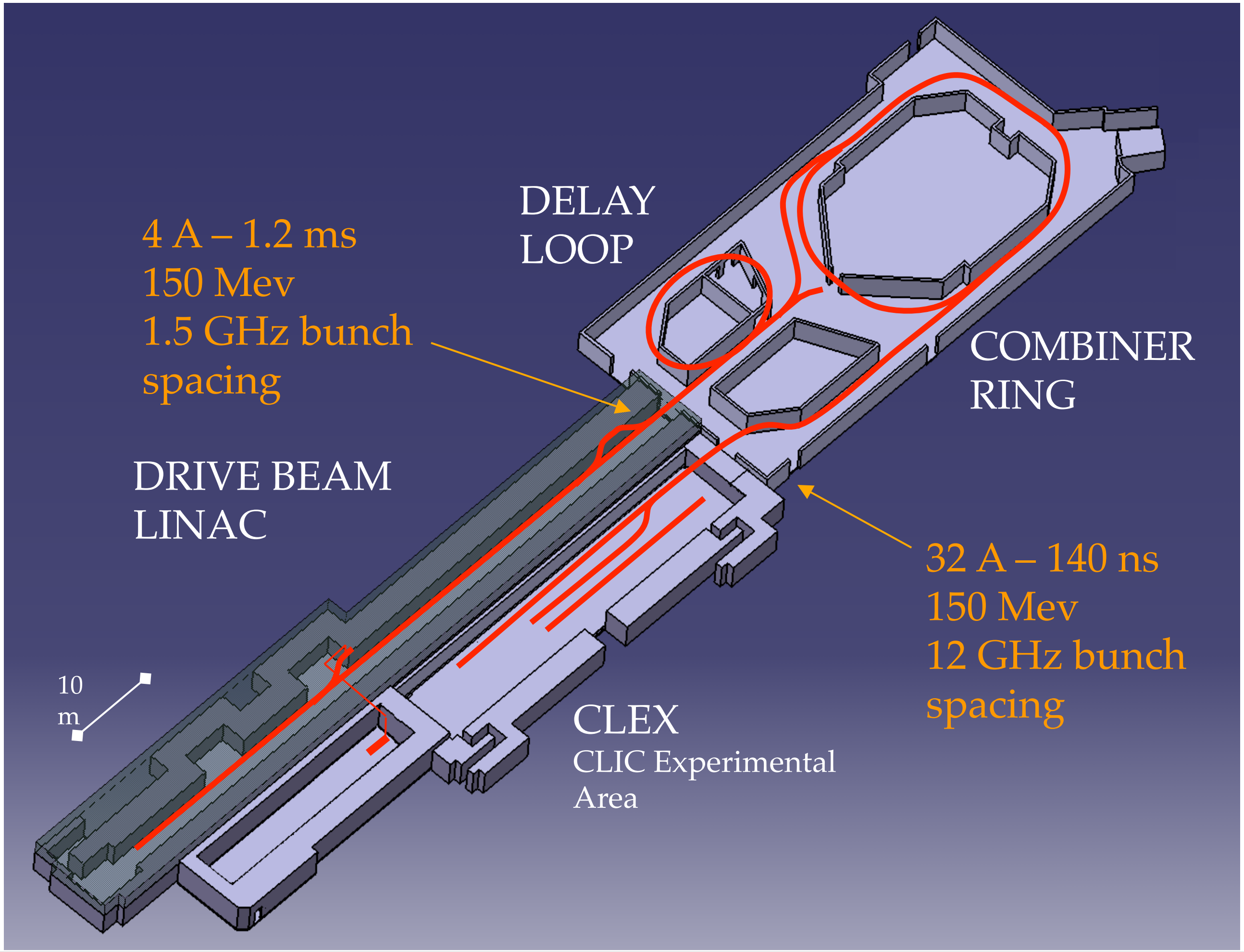
Backup slides
- CTF3

The CLIC Test Facility (CTF3)

Small scale version of the CLIC drive beam complex

Feasibility issues studied:

- Drive beam generation
- Beam driven RF power generation
- Two beam acceleration & accelerating structures
- Ultra low emittances & beam sizes
- Alignment
- Vertical stabilization
- Operation and Machine Protection System

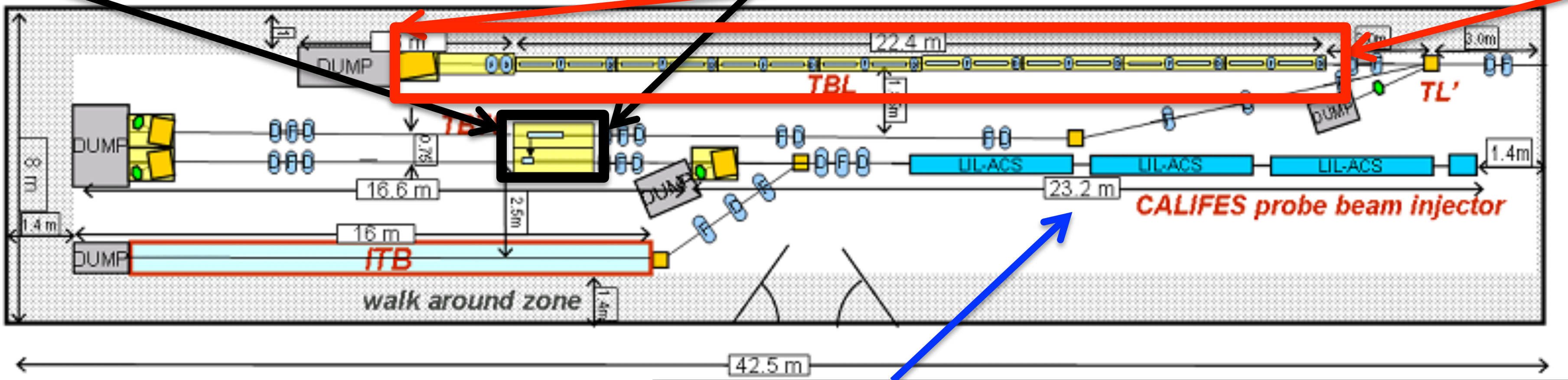


Drive Beam Deceleration and Module: CLEX

- CLIC Decelerator sector: ~ 1 km, 90% of energy extracted

Two-beam Test Stand (TBTS):
- **Single** PETS with beam
- Accelerating structure with beam
  - wake monitor
  - kick on beam from break down
  - Integration

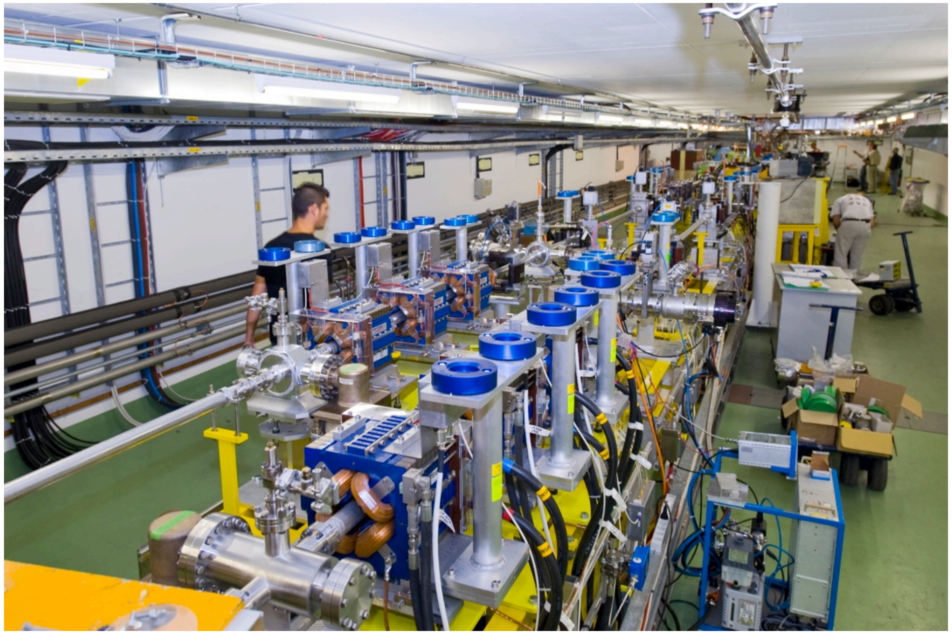
Test Beam Line (TBL):
- **Drive beam transport (16 PETS)**
  - beam energy extraction and dispersion
  - wakefield effects



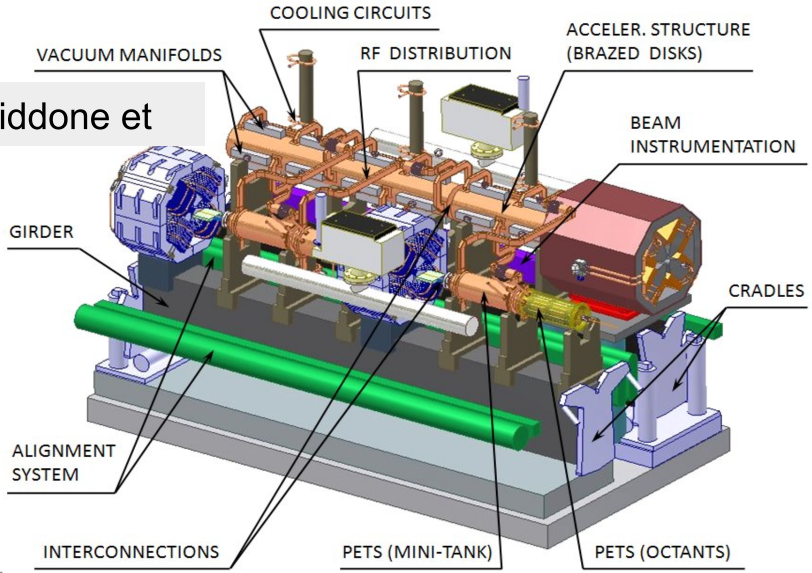
- **Califes**: Probe beam photo-injector
- Beam energy 175 MeV

Two Beam Module

- Integration aspects are important
  - alignment
  - vacuum
  - transport
  - cabling
  - …



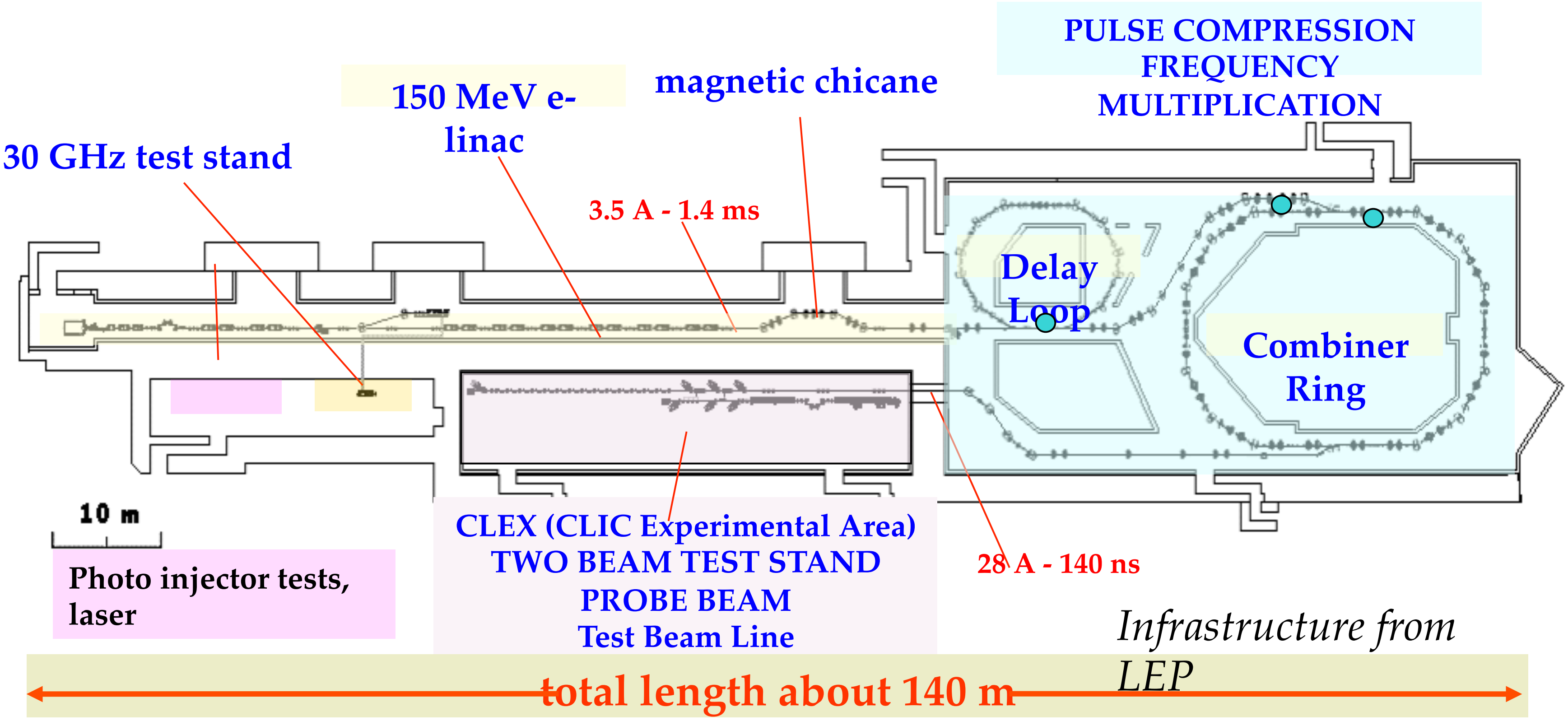
- Beam tests of PETS are ongoing
- accelerating structure installed
- important goal 2010: two-beam acceleration with 100 MV/m
- Some tests after 2010
  e.g. wake monitors, design exists
- Later full modules will be tested



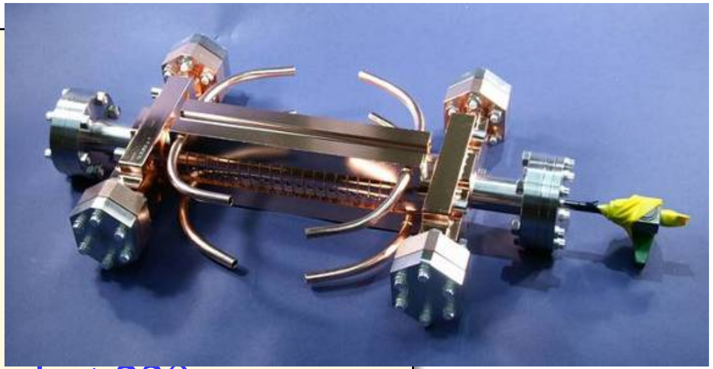
G. Riddone et al.

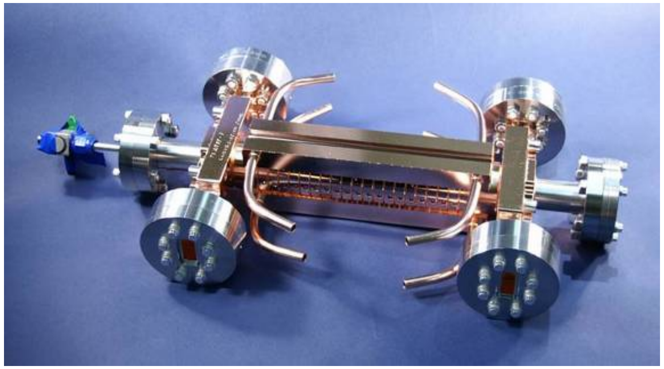
Two-Beam Acceleration: CLIC Test Facility (CTF3)

- 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



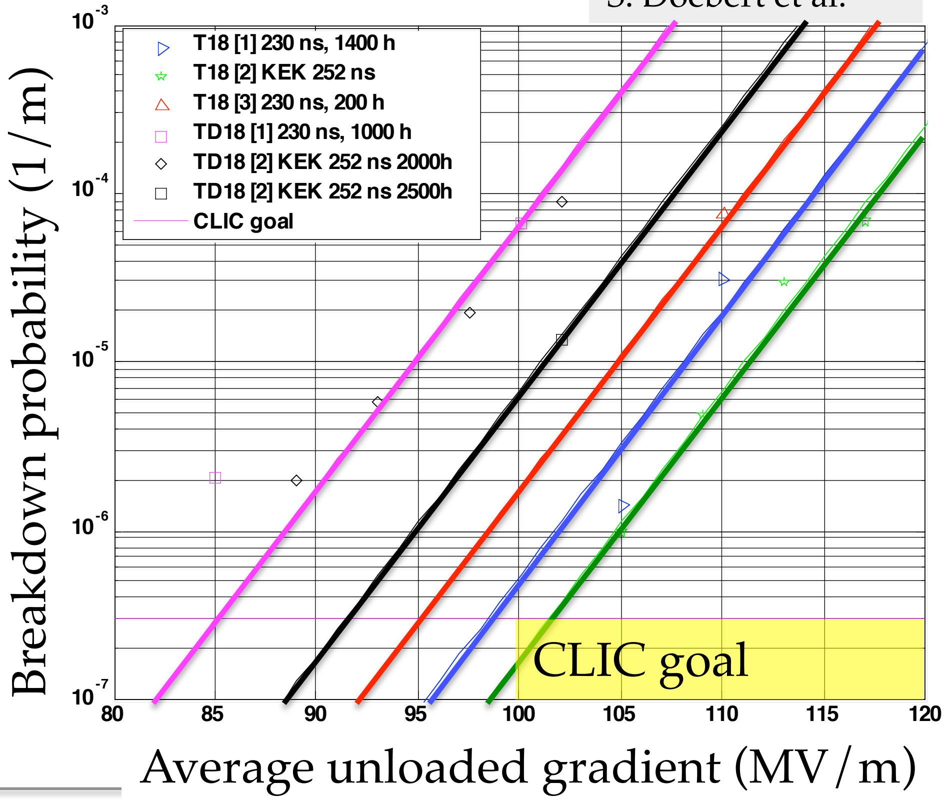
Accelerating Structure Results





- RF breakdowns can occur
  => no acceleration and deflection
- Goal: 3 10^{-7}/m breakdowns
  at 100 MV/m loaded at 230 ns
- T18 and TD18 structures built and tested at SLAC and KEK
- **T18 reached 95-105 MV/m**
- Damped TD18 reaches an extrapolated 85 MV/m
  - Second TD18 under test at KEK
  - Pulsed surface heating expected to be above limit
- CLIC prototypes with improved design (TD24) will be tested this year
  - expect similar or slightly better performances

S. Doebert et al.



Backup slides
- beamsthralung

Incoherent Pairs

GUINEA-PIG used

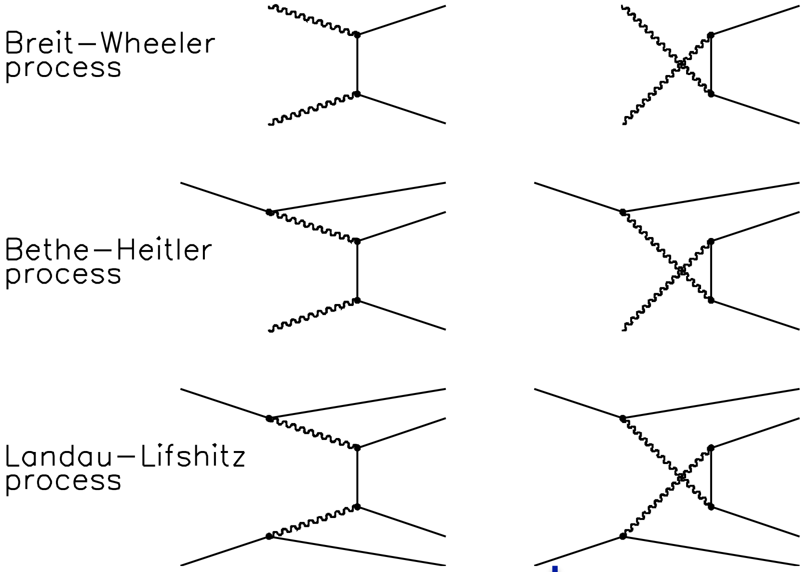
- Calculation with virtual photon approximation (Q^2_{max} choice confirmed by benchmarking Ph. Bambade et al.)

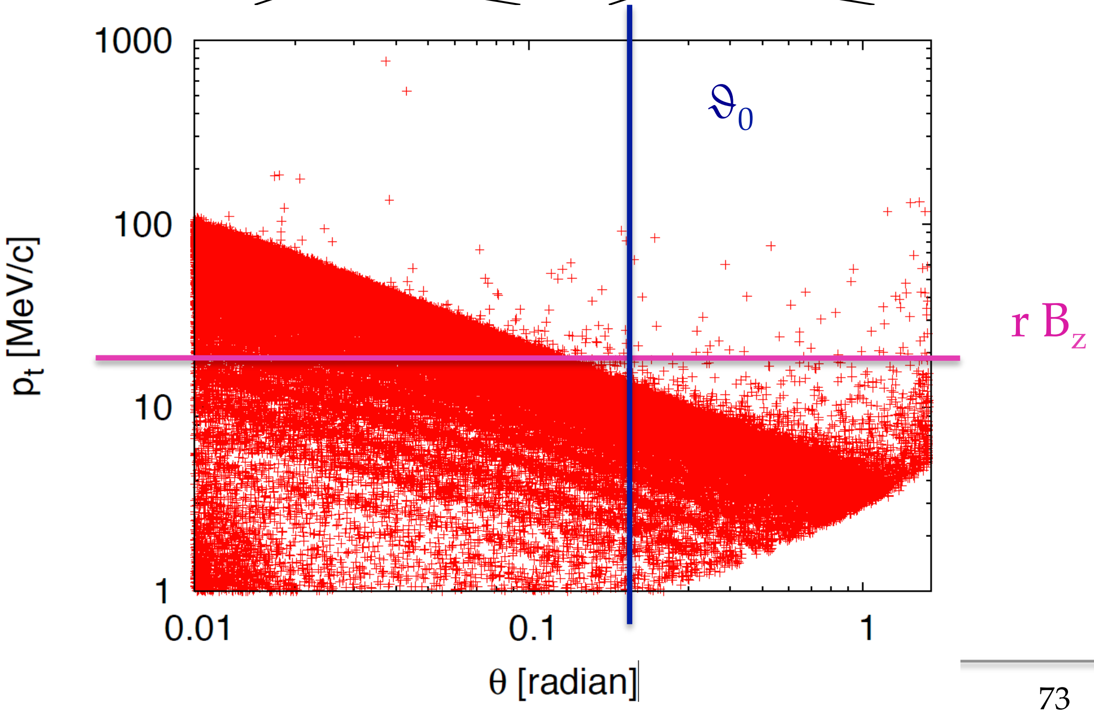
- Beam size effect is included

300,000 particles produced

Average energy is 70 GeV

Strong deflection by the beam
- smaller deflection observed with CAIN, under study





Hadronic Background

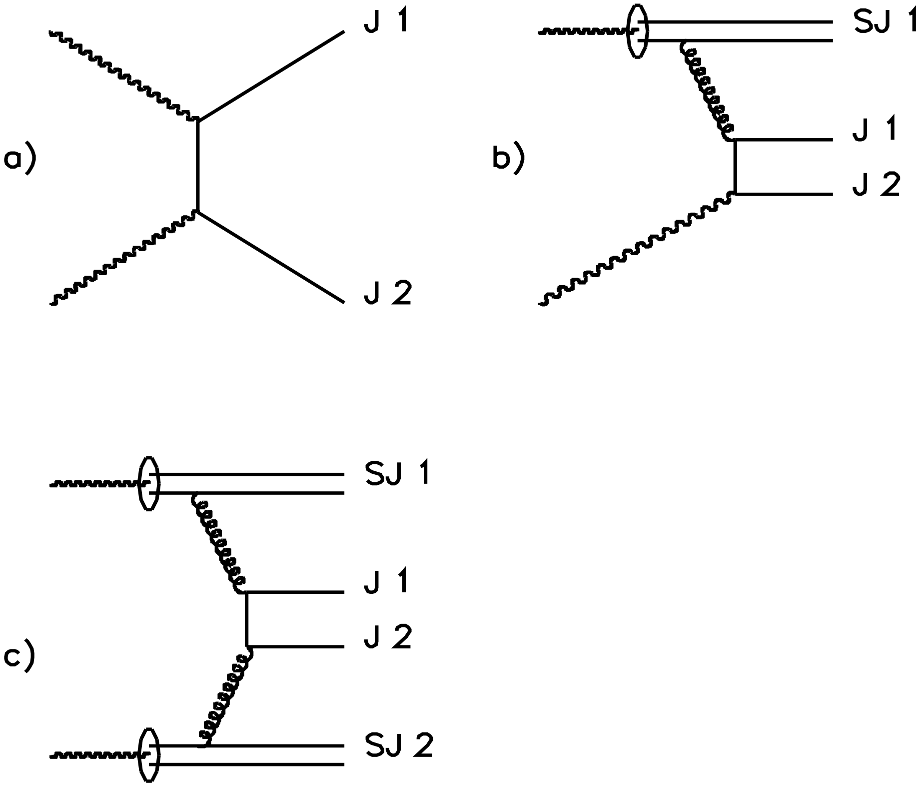
Based on equivalent photon approximation with

$Q^2_{\mathrm{max}} = \max(1\,\mathrm{GeV}^2, (s/100)^{0.43})$

3.2 events per bunch crossing

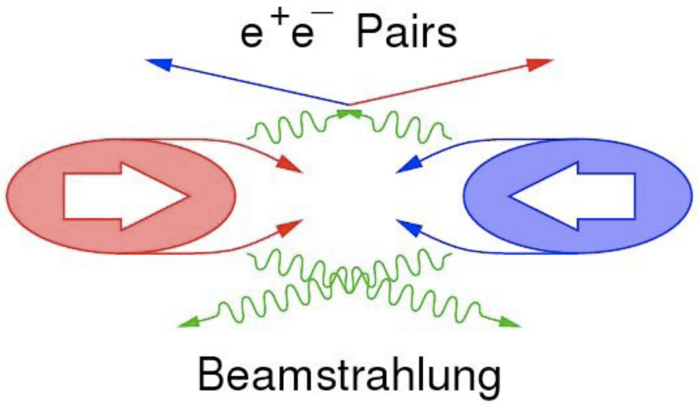
Events are simulated with PYTHIA 6.4.20

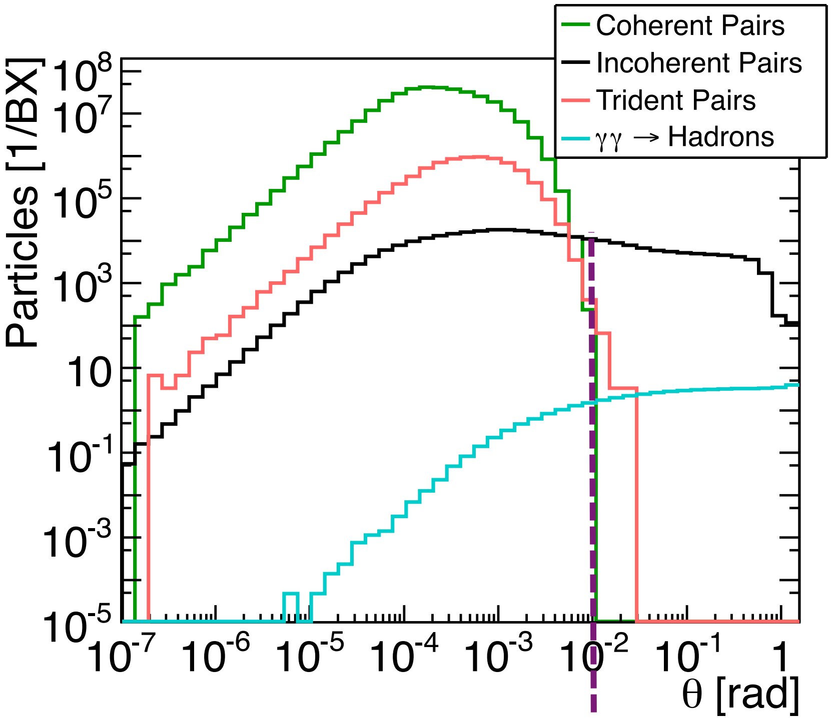
Benchmarked with SLAC generator (T. Barklow et al.)



$$\sigma_{\gamma\gamma}(s_{\gamma\gamma}) = 211\ \mathrm{nb}\left(\frac{s_{\gamma\gamma}}{\mathrm{GeV}^2}\right)^{0.0808} + 215\ \mathrm{nb}\left(\frac{s_{\gamma\gamma}}{\mathrm{GeV}^2}\right)^{-0.4525}$$

Beam-induced backgrounds





Detector starts at θ>10 mrad

- Main backgrounds in detector:

  Incoherent pairs: 60 particles / BX

  γγ → hadrons: 54 particles / BX

→ Need **pile-up rejection**

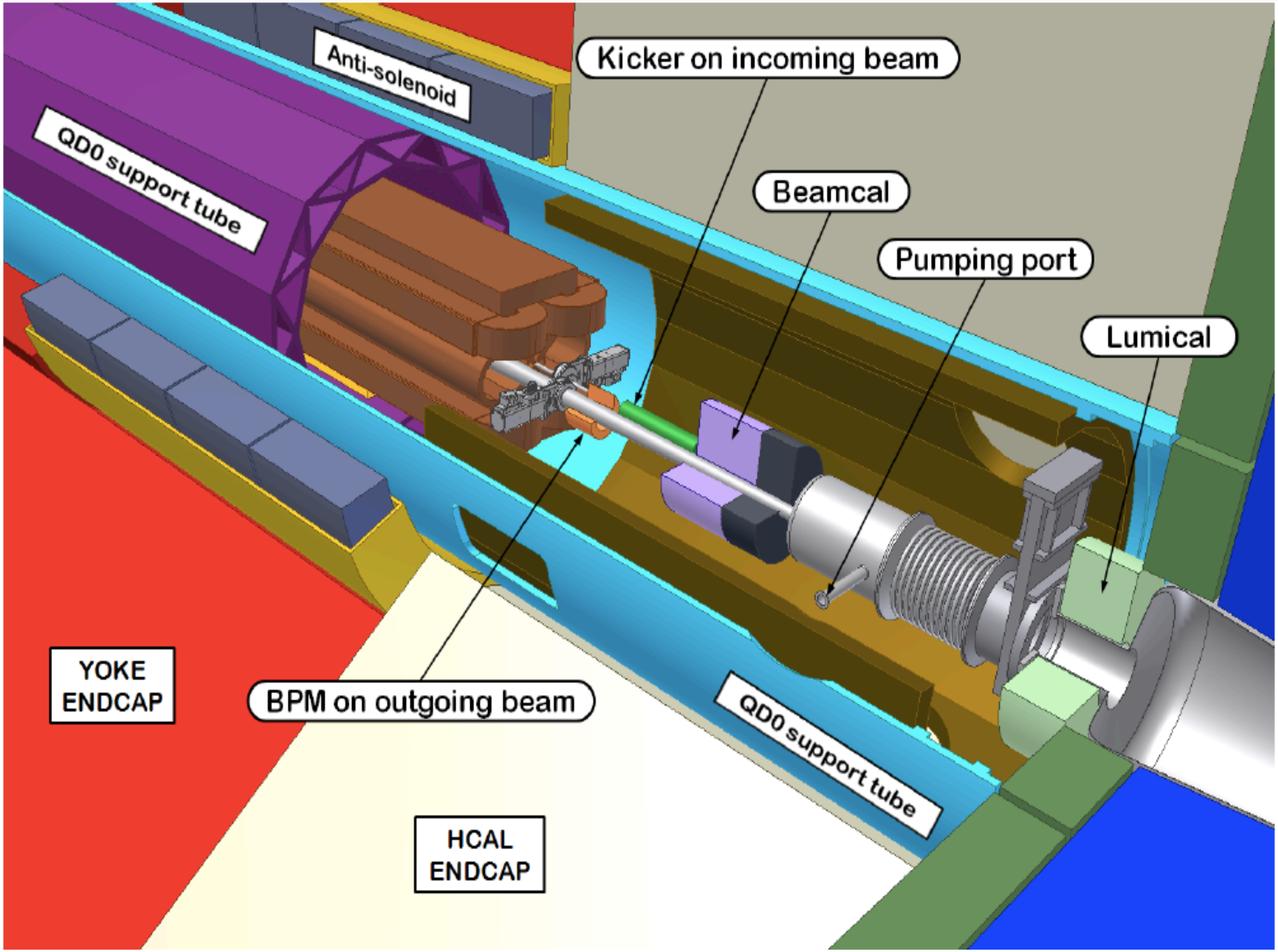
→ Need to include background in **simulation**

Background Summary

parameter	units		
E_{cms}	[TeV]	0.5	3.0
L_{total}	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9
$L_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2.0
n_γ		1.3	2.1
$\Delta E/E$		0.07	0.28
N_{coh}	$[10^5]$	2×10^{-3}	6.8×10^3
E_{coh}	$[10^3\ \mathrm{TeV}]$	0.015	2.1×10^5
N_{incoh}	$[10^6]$	0.08	0.3
E_{incoh}	$[10^6\mathrm{GeV}]$	0.36	22.6
$n_\perp$		20.5	45
$n_{Had}(W_{\gamma\gamma} > 5GeV)$		0.2	2.8
$n_{Had}(W_{\gamma\gamma} > 2GeV)$		0.3	3.2

CLIC detector – very forward region (closely linked to MDI)

Integration of QD0 magnets and IP Feedback systems

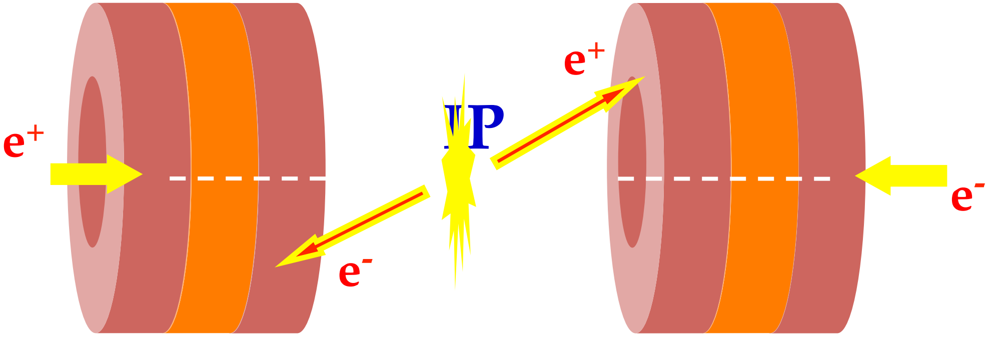


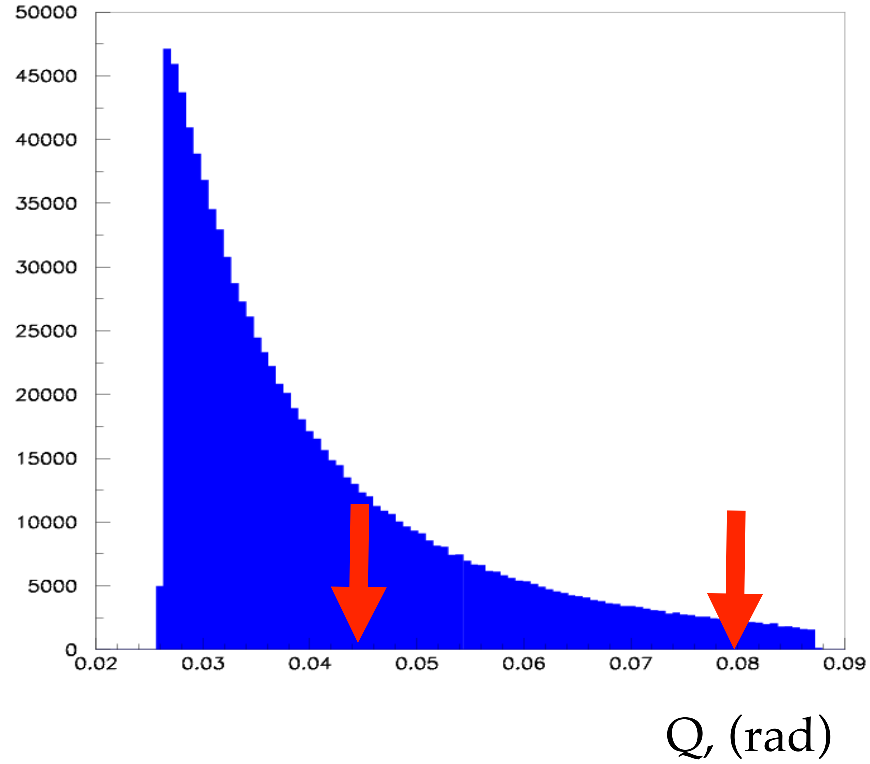
Measure luminosity using Bhabha events

(NB. luminosity spectrum measurement using large-angle Bhabha scattering, not treated here)

- located at z=2.6 m
- geometrical acceptance: 38 – 110 mrad
- fiducial acceptance: 44 – 80 mrad

- 62 pb at 3 TeV
- statistical accuracy
  for 500 fb^{-1}: 1.8x10^{-4}





LumiCal – preliminary design

(FCAL collaboration)

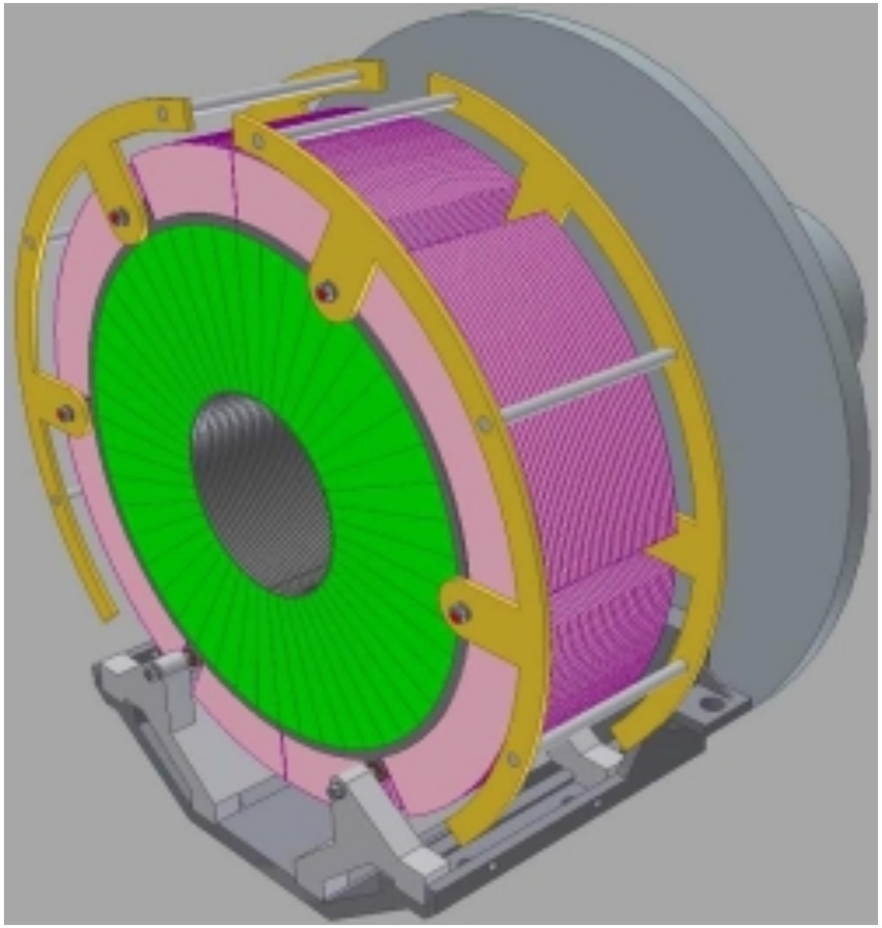
In CLIC_ILD:

- located at z=2.6 m
- total depth: 171 mm
- inner radius: 100 mm
- outer radius: 290 mm

40 layers:

- 3.5 mm W plates
- 320 mm Si sensors
- 550 mm connectivity

readout electronics
at outer radius



LumiCal – accuracy

(systematics!)

- ILC at 500 GeV: requiring 0.1% accuracy
  - high statistics physics channels at 500 GeV
  - e.g. e^+e^- -> WW or f f yield approx. 10^6 events for 500 fb^{-1}
- ➢ Statistical error 10^{-3}
- ➢ LumiCal accuracy should be the same or better

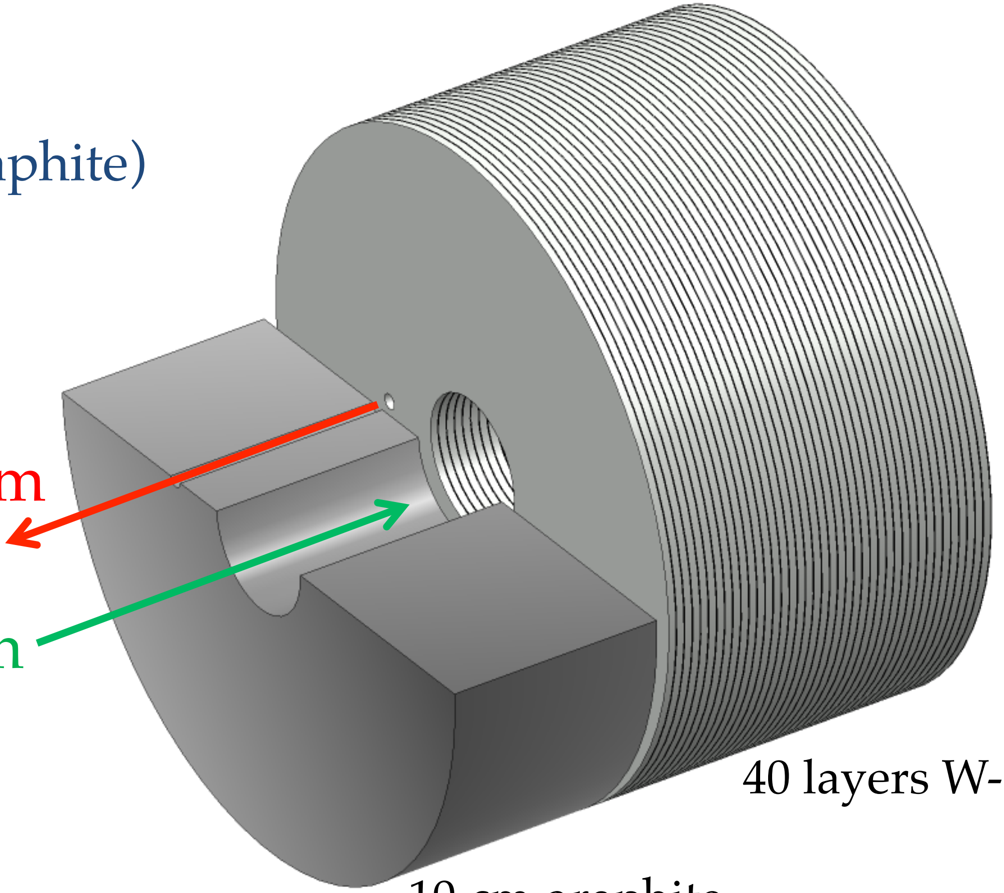
- CLIC at 3 TeV: requiring 1% accuracy
    - (e.g. 0.2 mrad or 0.5 mm accuracy on inner edge of LumiCal)
  - decided in February 2009, at start of first simulations studies
  - considered sufficient (?) w.r.t. statistics in typical physics processes
  - considered realistic for CLIC (higher background!)

BeamCal

Tag h.e. electrons at small angles
(possibly used to give feedback to beam steering – not studied)

In CLIC_ILD:
- located at z=3.1m
- total depth: 260 mm (w/graphite)
- inner radius: 32 mm
- outer radius: 150 mm

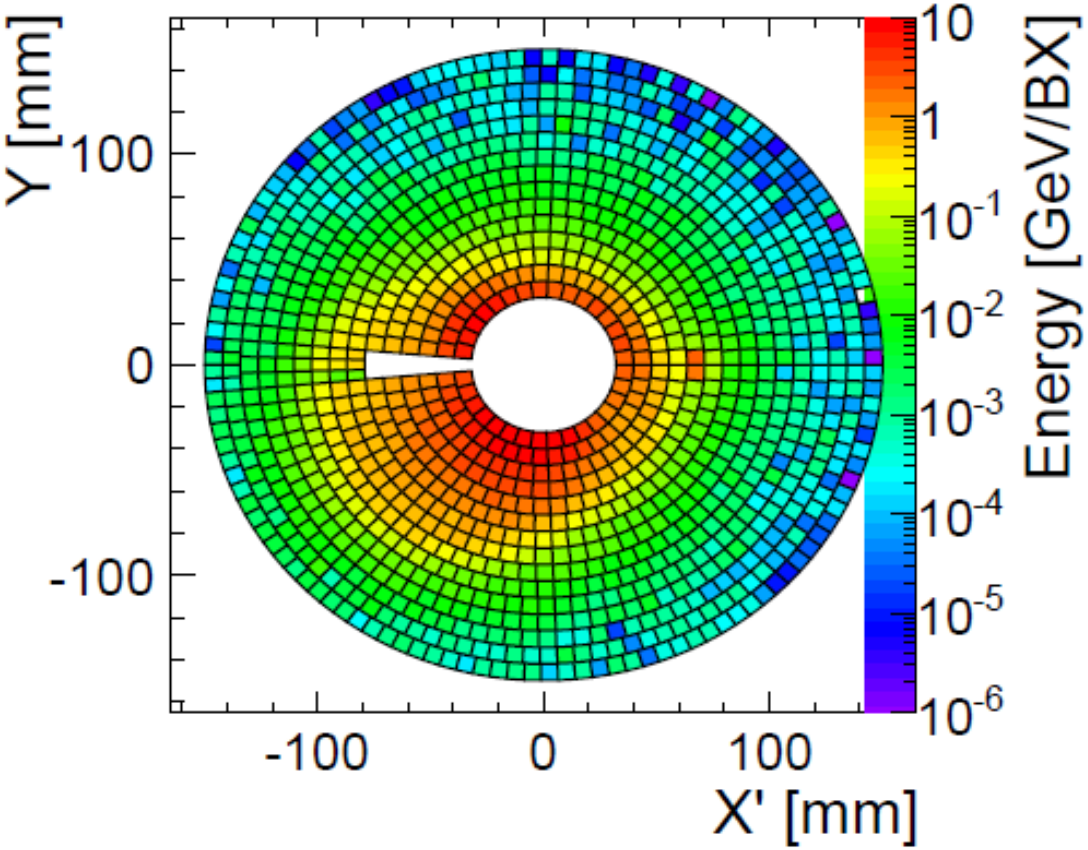
40 layers:
3.5 mm W plates
+ sensors



BeamCal

A single h.e. electron and 10 BX of bg.

- Shown here: energy deposition in the 10th layer



Coil parameters

	Nominal magnetic field (T)	Free bore (mm)	Magnetic length (mm)	Cold mass weight (tons)
CLIC_SiD	5.0	5480	6230	170
CLIC_ILD	4.0	6850	7890	210

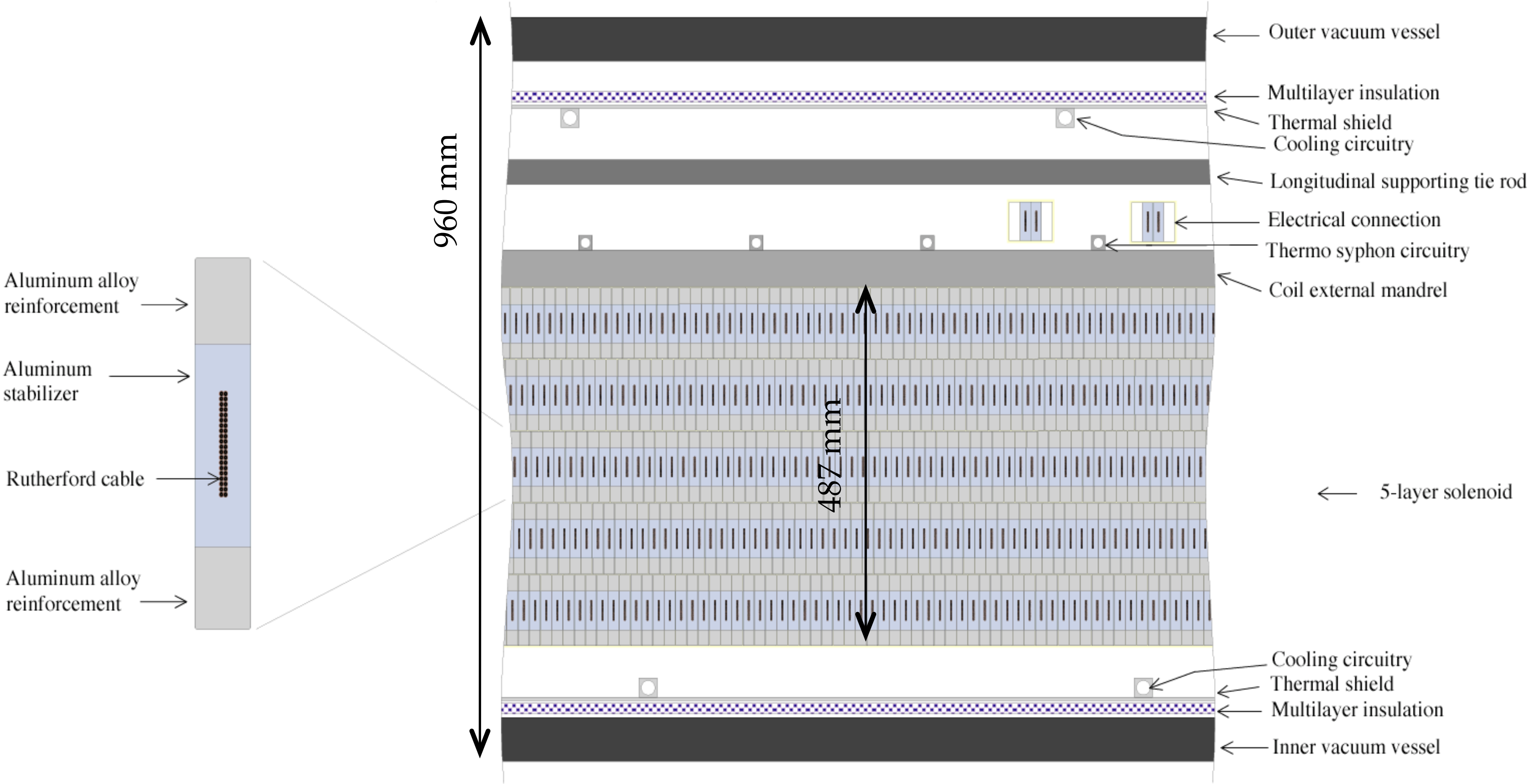
CLIC_SiD magnet parameters:

Nominal magnetic field at the IP	5.0 T
Peak magnetic field on the conductor	5.8 T
Free bore diameter	5.5 m
Magnetic length	6.2 m
Ampere.turns	34 MA.turns
Operating current	18 kA
Stored magnetic energy	2.3 GJ
Energy/Mass ratio	14 kJ/kg
Inductance	14 H

Conductor total length: 38 km

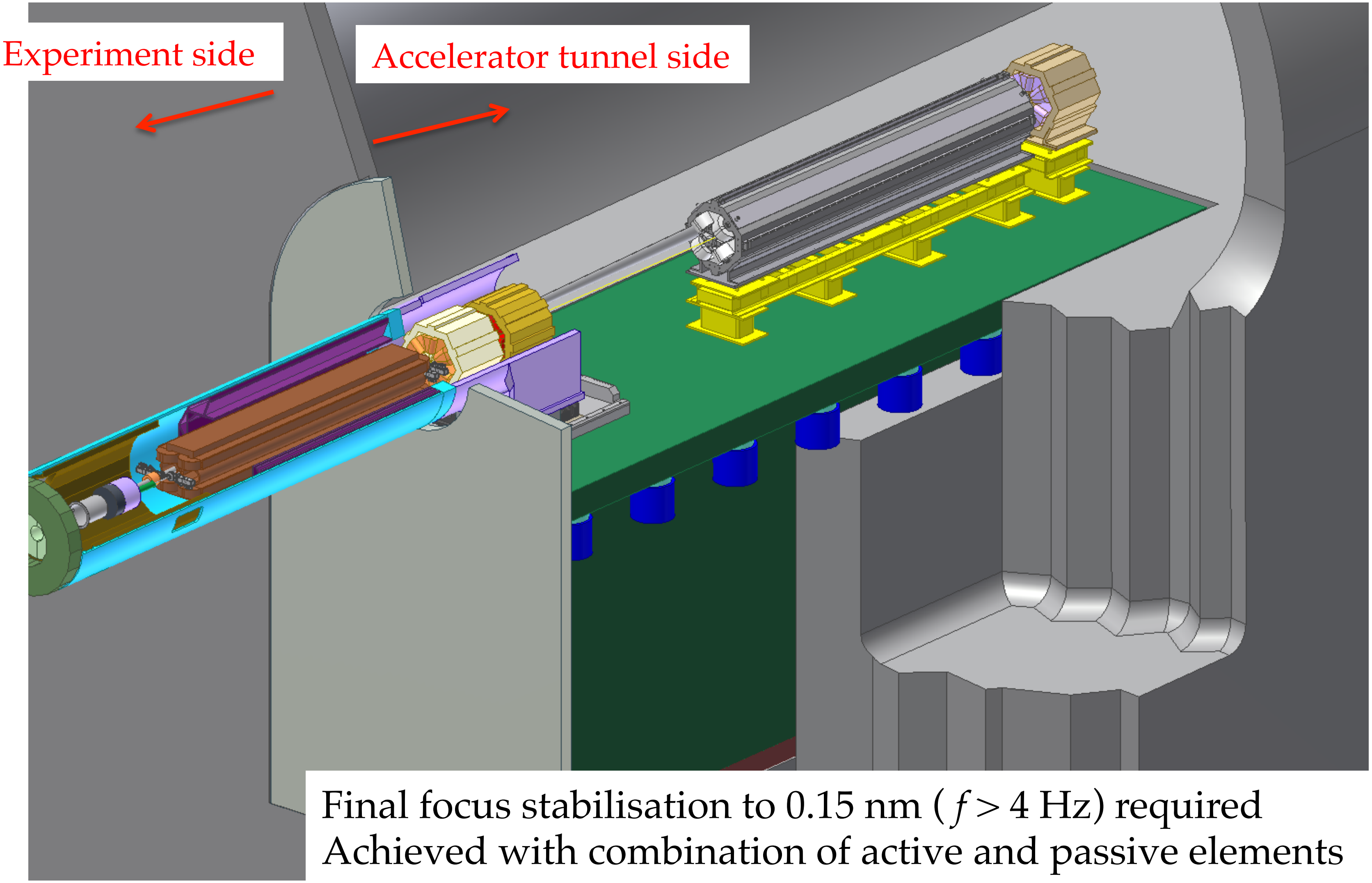
For details about transient behavior of the coil after a quench ->LCD Note 2011-007, B. Curé

Coil & Conductor



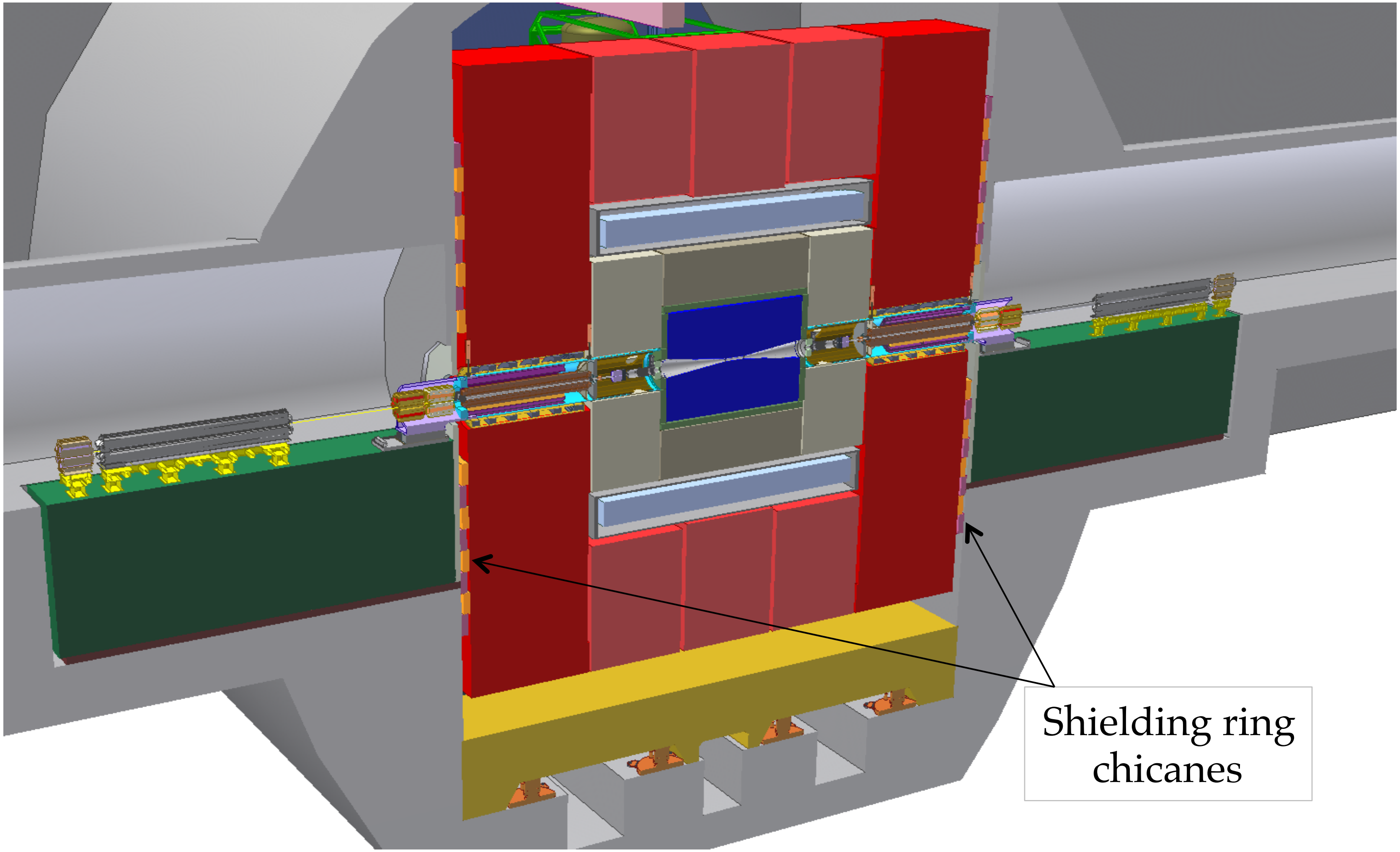
Cross section of the solenoid conductor and cut through the coil assembly

QD0 & Final focus stabilisation



Final focus stabilisation to 0.15 nm ($f > 4$ Hz) required
Achieved with combination of active and passive elements

Detector on IP – between 2 vertical walls

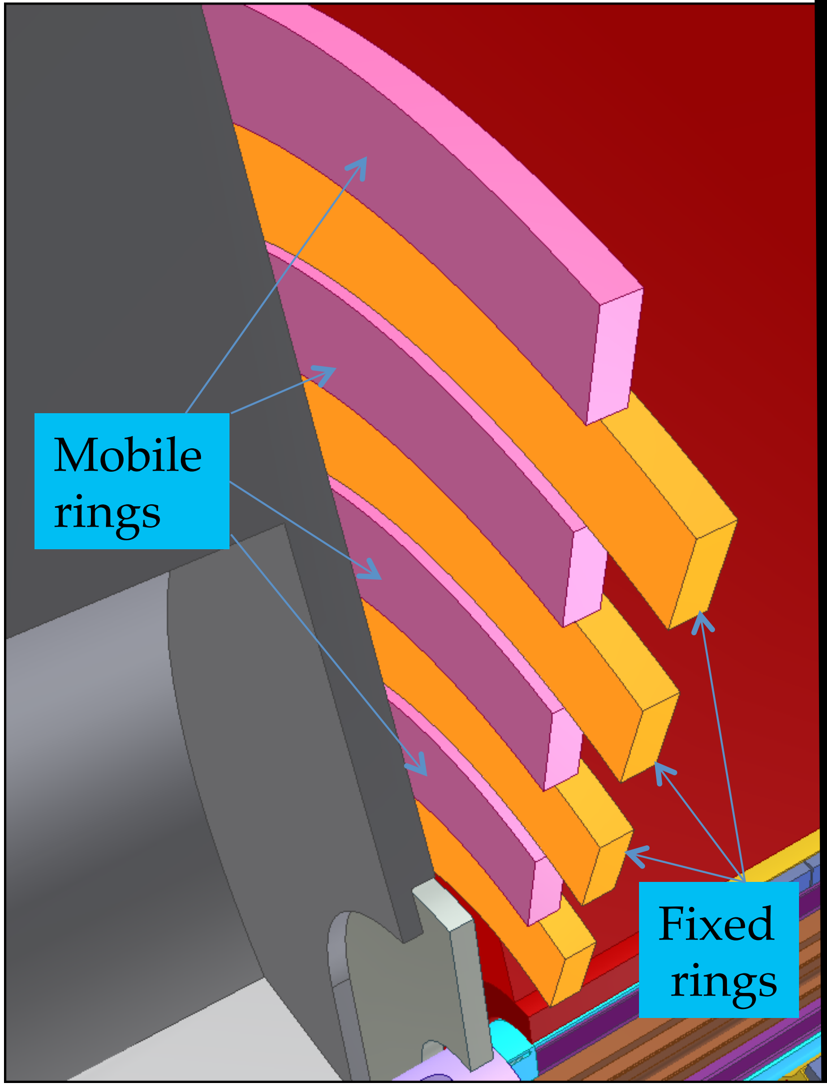


Shielding ring chicanes

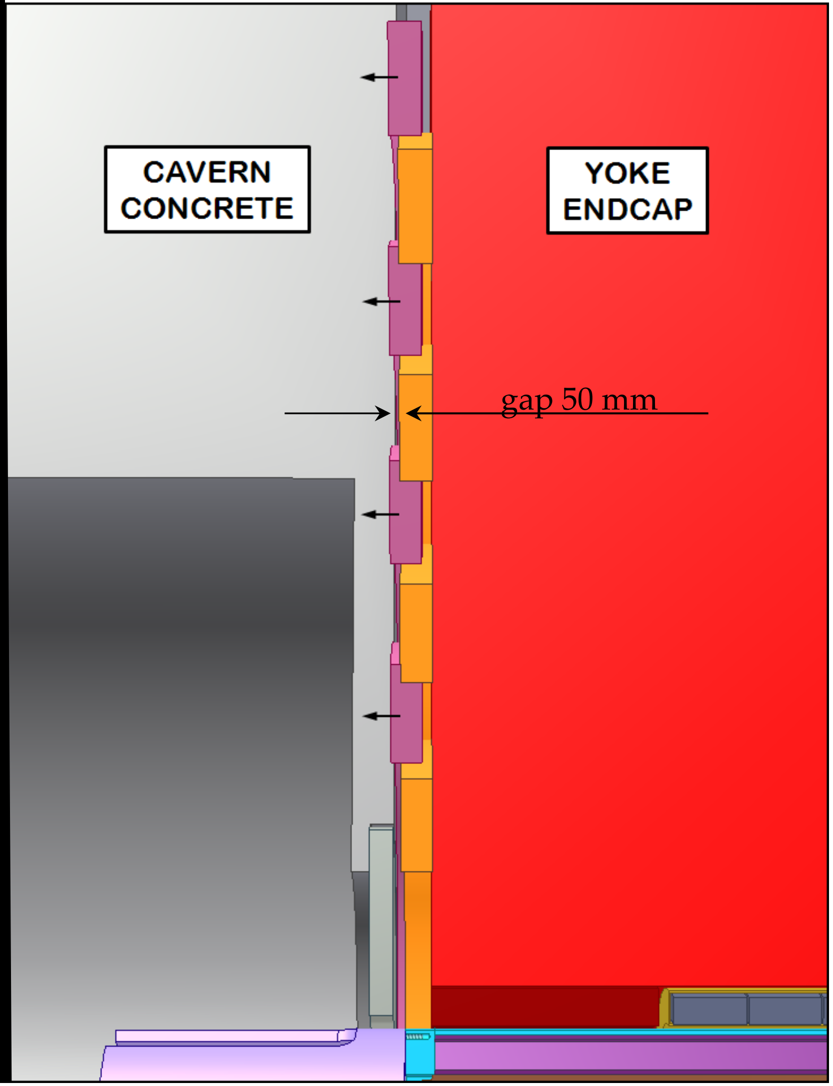
Vertical cut through the experiment

Ring chicane Shielding technique

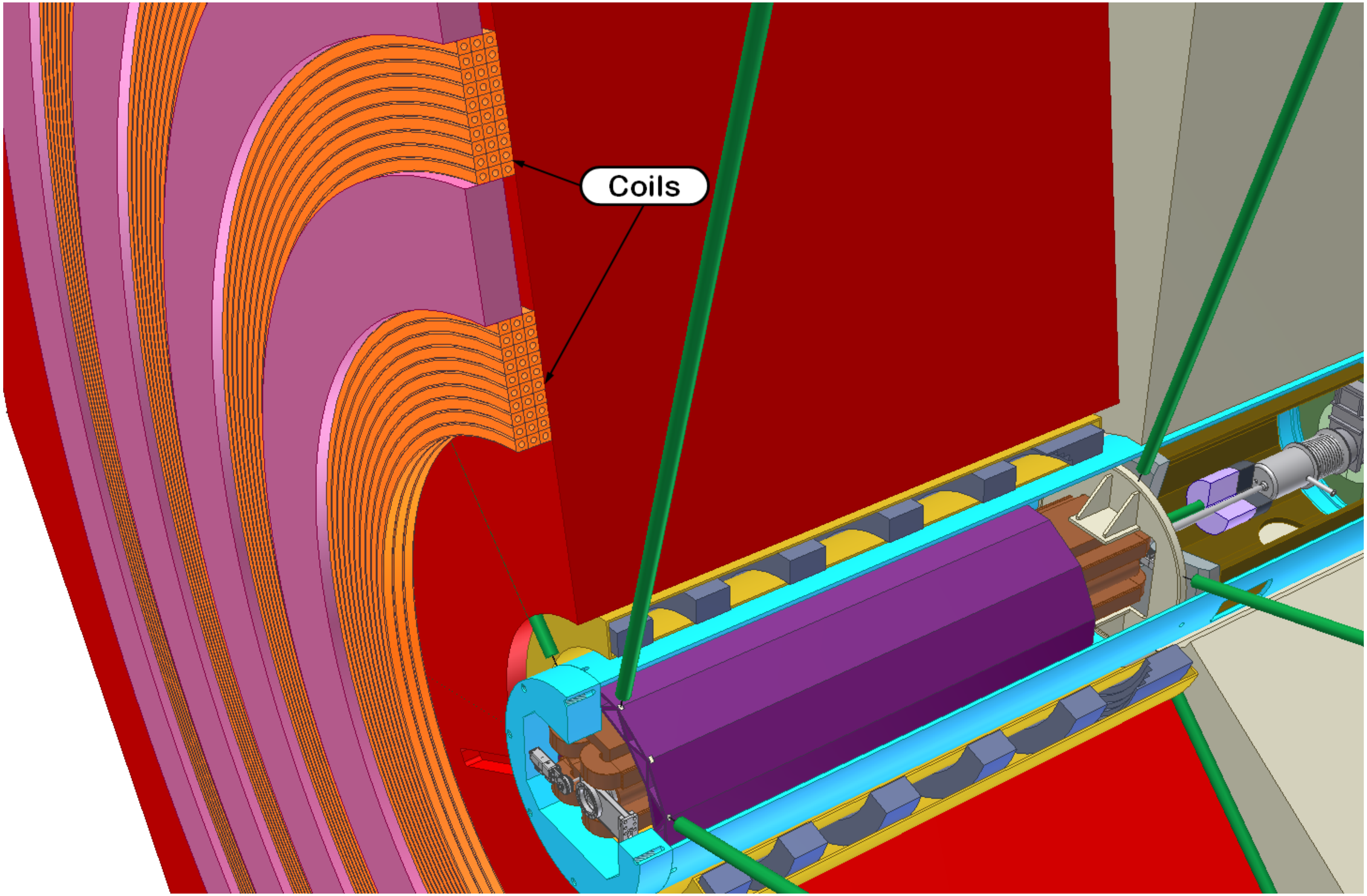
3-D View



Side View

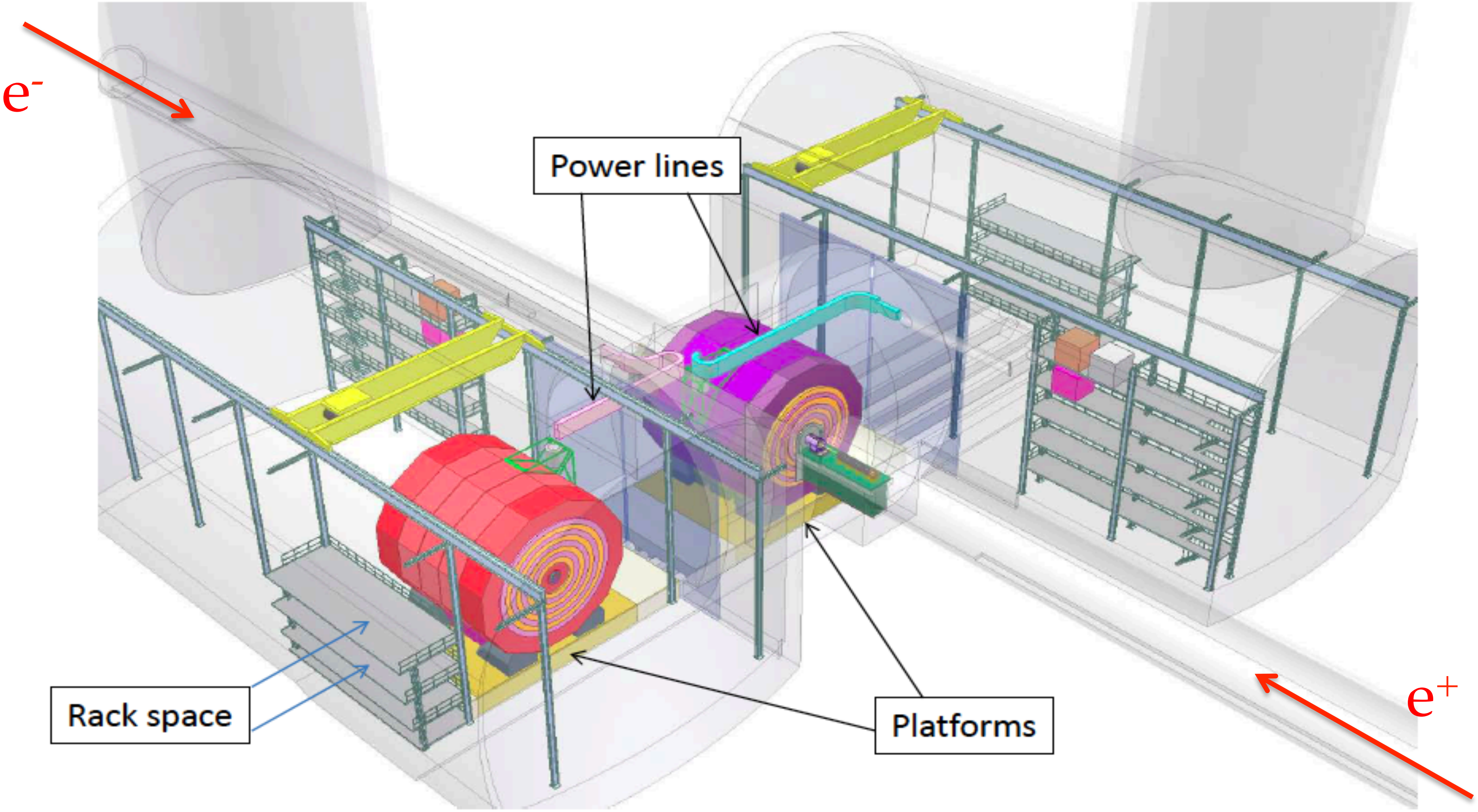


CLIC_ILD: Ring chicane and Coils

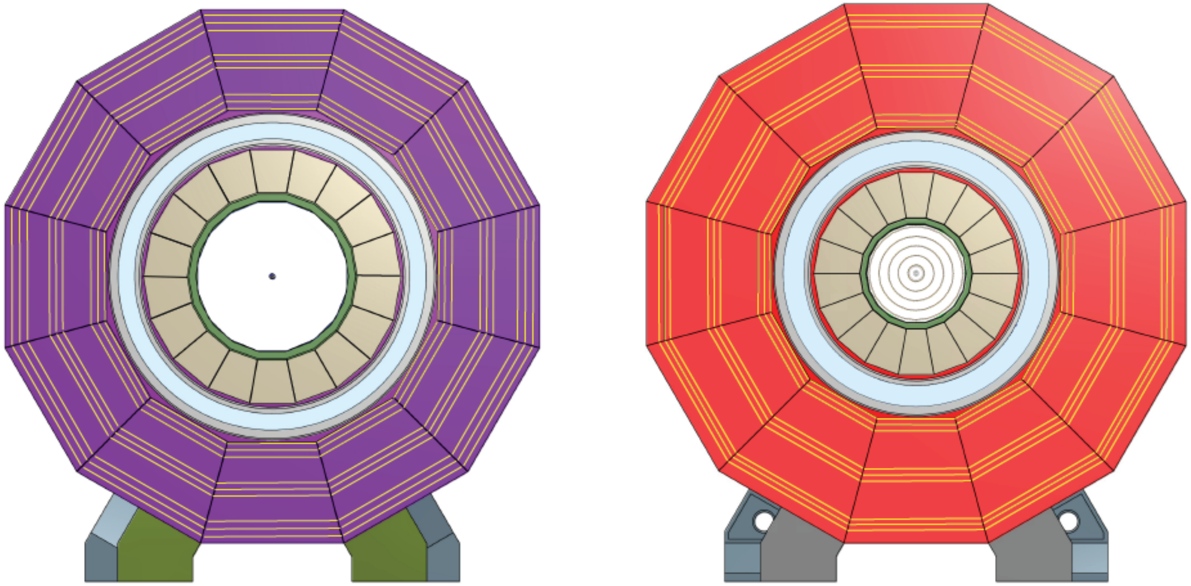


Backup slides
- detectors

Two detectors in Push-Pull

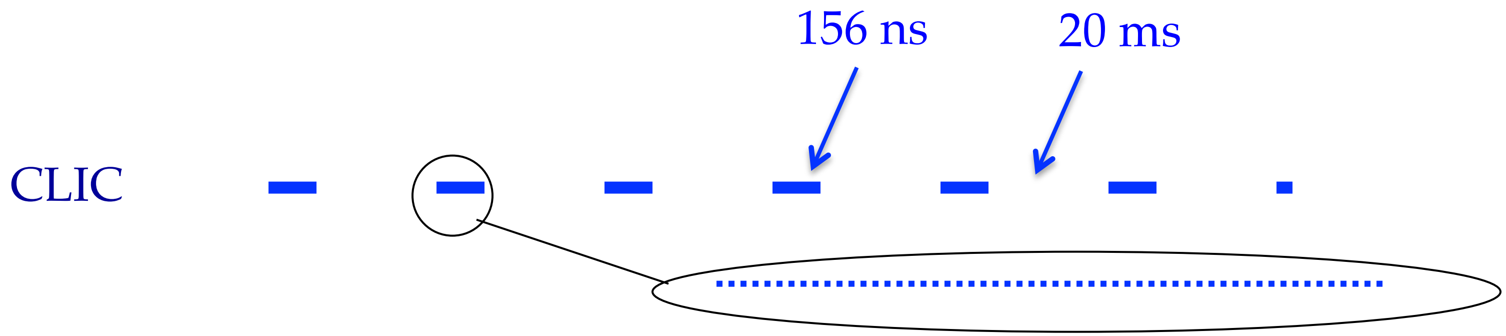


CLIC Detector Concepts Overview



System	CLIC_ILD	CLIC_SID
VTX+Tracker	TPC, Radius=1.8m	Silicon, Radius=1.2m
ECAL	W/Si	W/Si
HCAL Barrel	W/Scint	W/Scint
HCAL Endcap	Steel/scint	Steel/Scint
Solenoid: B-Field	4 T	5 T

CLIC parameters

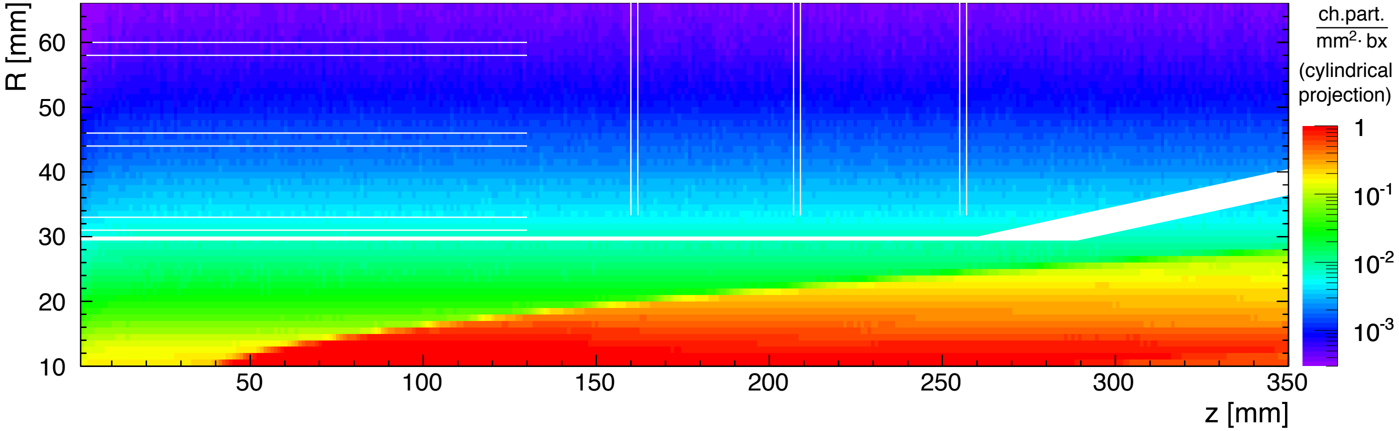


CLIC: 1 train = 312 bunches, 0.5 ns apart trains at 50 Hz

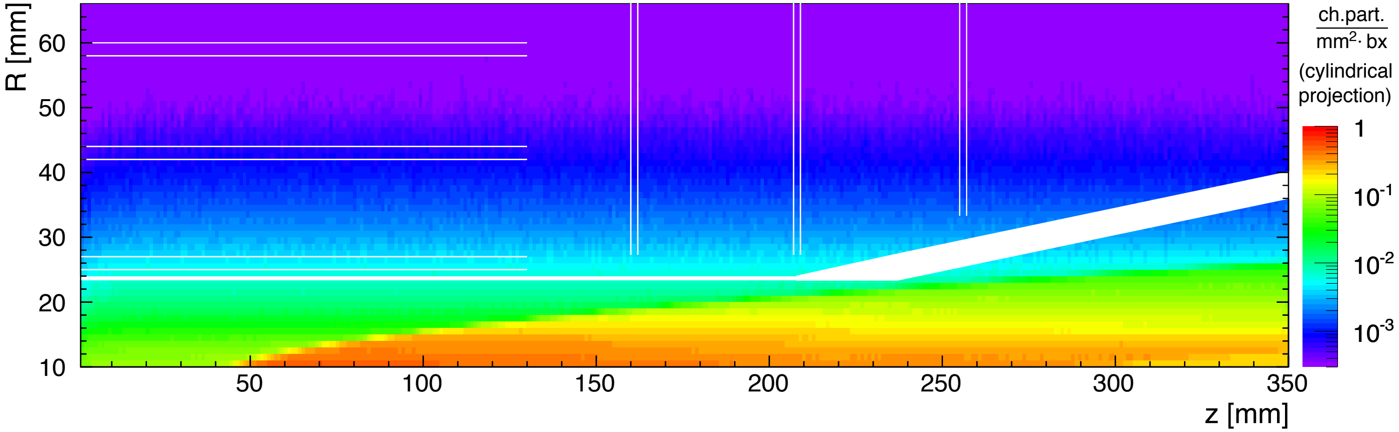
ILC: 1 train = 1300 bunches, 700 ns apart trains at 5 Hz

	LEP 2	ILC 0.5 TeV	CLIC 3 TeV
L [cm^{-2}s^{-1}]]	5×10^{31}	2×10^{34}	6×10^{34}
Crossing angle		14 mrad	20 mrad
BX separation	~22 μs	700 ns	0.5 ns
IP size in x / y / z direction [nm]	250 μm / 5 μm / 10 mm	600nm / 6nm / 10mm	45 nm / 1 nm / 40 μm
# (γγ→**hadrons) / BX**	negligible	0.2	3.0
# **Incoherent pairs / BX**	negligible	1×10^5	3×10^5

Optimization of interaction region



3 TeV



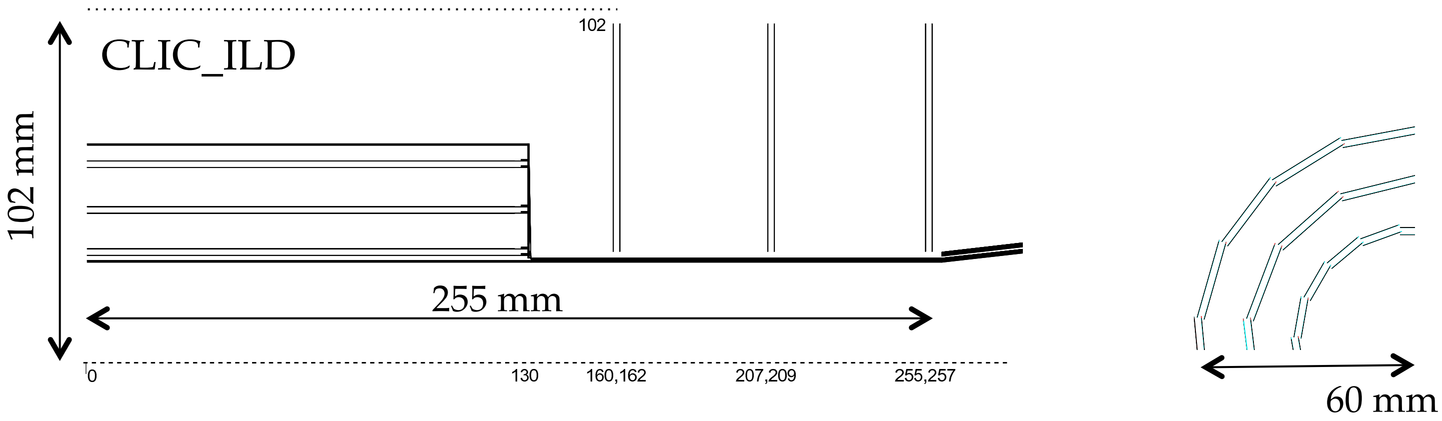
500 GeV

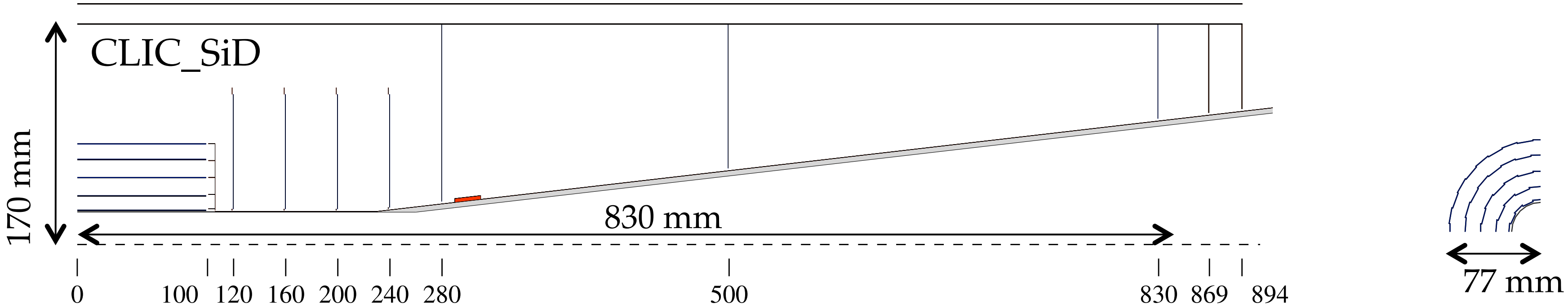
Direct hits from incoh. pairs for CLIC_ILD

- 3 TeV: High occupancy in inner-forward region, cut-off ~parabolic shape
- 500 GeV: situation similar, though lower rates

➢ place beam pipe outside high-occupancy region

Vertex detectors

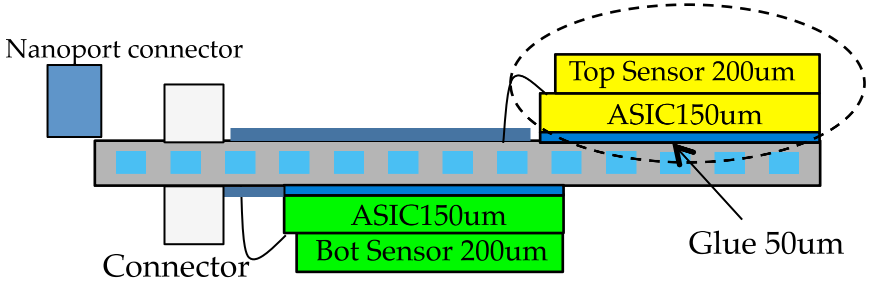




	CLIC_ILD	**CLIC_SiD**	**CMS**
Material X/X_0 (90°)	~0.9% (3x2 layer)	~1.1% (5 layer)	~10% (3 layer)
Pixel size	20 x 20 μm^2	20 x 20 μm^2	100 x 150 μm^2
# pixels	1.84 G	2.76 G	66 M
Time resolution	5-10 ns	5-10 ns	<~25 ns
Power/pixel	<~0.2 μW	<~0.2 μW	28 μW

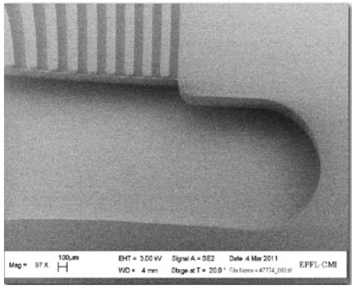
Cooling: P~500 W in vertex detectors

- **Forced air flow** – may work in barrel region
  - no extra material
  - Up to **240 liter/s** flow,
    ~**40 km/h** flow velocity
- **Water cooling** – Sub-atmospheric pressure
  - Can use thin PEEK pipes
  - Need simulations to asses
    impact of material on performance
- **Micro-channel cooling** – Integrate cooling channels in Si
  - Could be solution for forward disks
  - Connectors are major challenge



NA62 GTK

A. Mapelli,
J. Buytaert



Power pulsing and power delivery

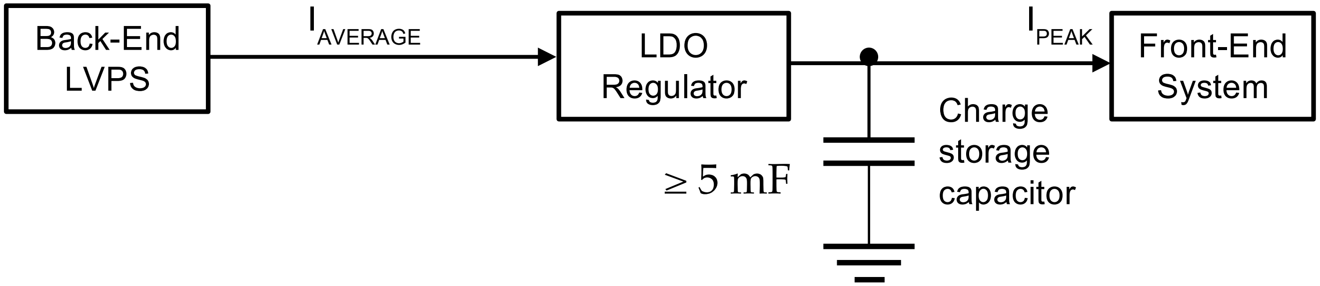
Very low duty cycle of CLIC machine: 156 ns train, 20 ms pause

→ All subdetectors will implement power pulsing schemes at 50 Hz, to reduce power consumption and thereby material in cooling systems

Efficient power delivery to front end → minimize cable volumes

- Example: DC/DC step-down conversion (sLHC upgrades)
- Example: Low drop-out regulators (LDO)

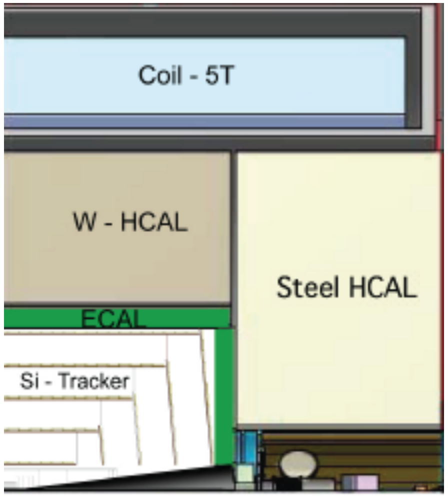
➢ R&D needed to combine power pulsing with DC/DC or LDO and to minimize material + noise

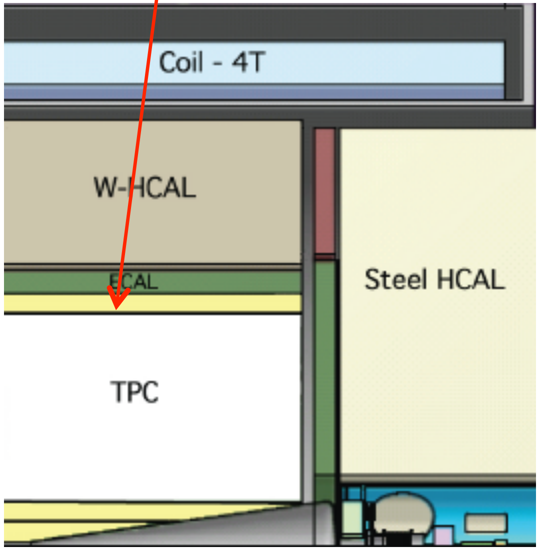


Power pulsing in ASICs

Tracking System

Barrel Tracker	**CLIC_ILD**	**CLIC_SiD**
Technology	TPC+Silicon strips	Silicon strips
Inner radius	329	230
Max. samples	2(Si), 224(TPC), 1(Si)	5
Outer radius	1808	1239
Max. Z	2250	578 to 1536

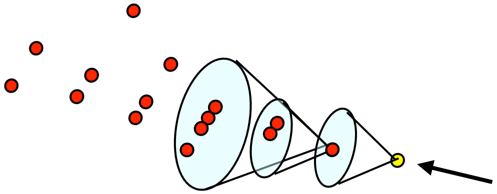




Forward Tracker	**CLIC_ILD**	**CLIC_SiD**
Technology	Silicon strips	Silicon strips
Inner radius	47 to 218	207 to 1162
Max. samples	5	4
Outer radius	320	1252
Max. Z	1868	1556

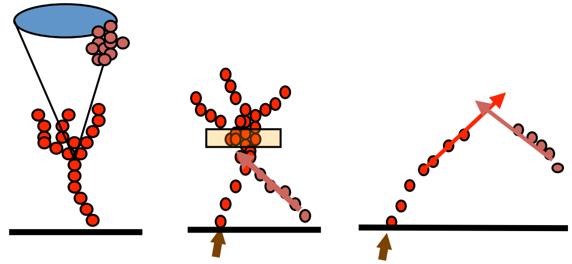
Backup slides
- reconstruction

PandoraPFA



ConeClustering Algorithm

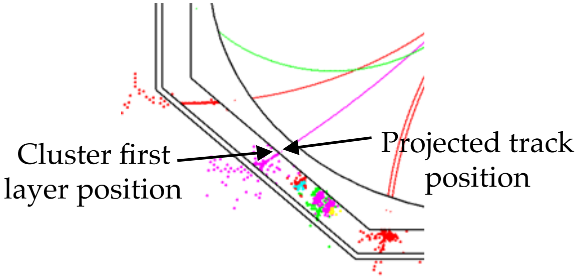
Topological Association Algorithms



Cone associations

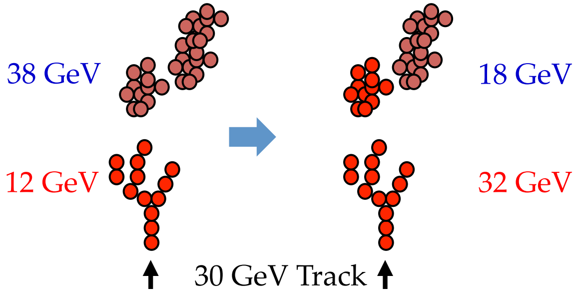
Back-scattered tracks

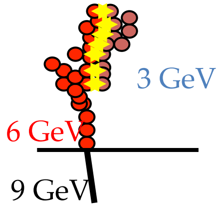
Looping tracks



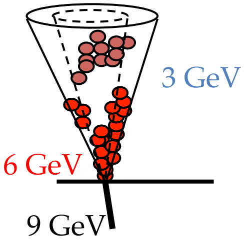
Track-Cluster Association Algorithms

Reclustering Algorithms





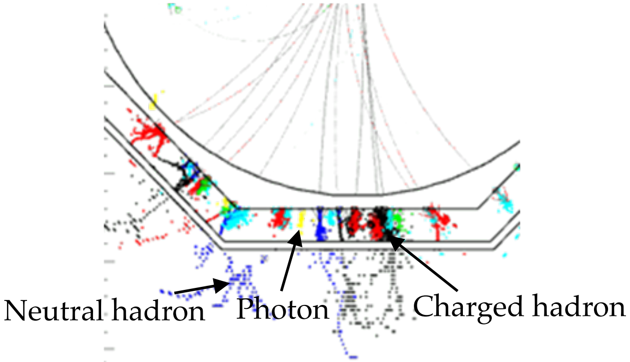
Layers in close contact



Fraction of energy in cone

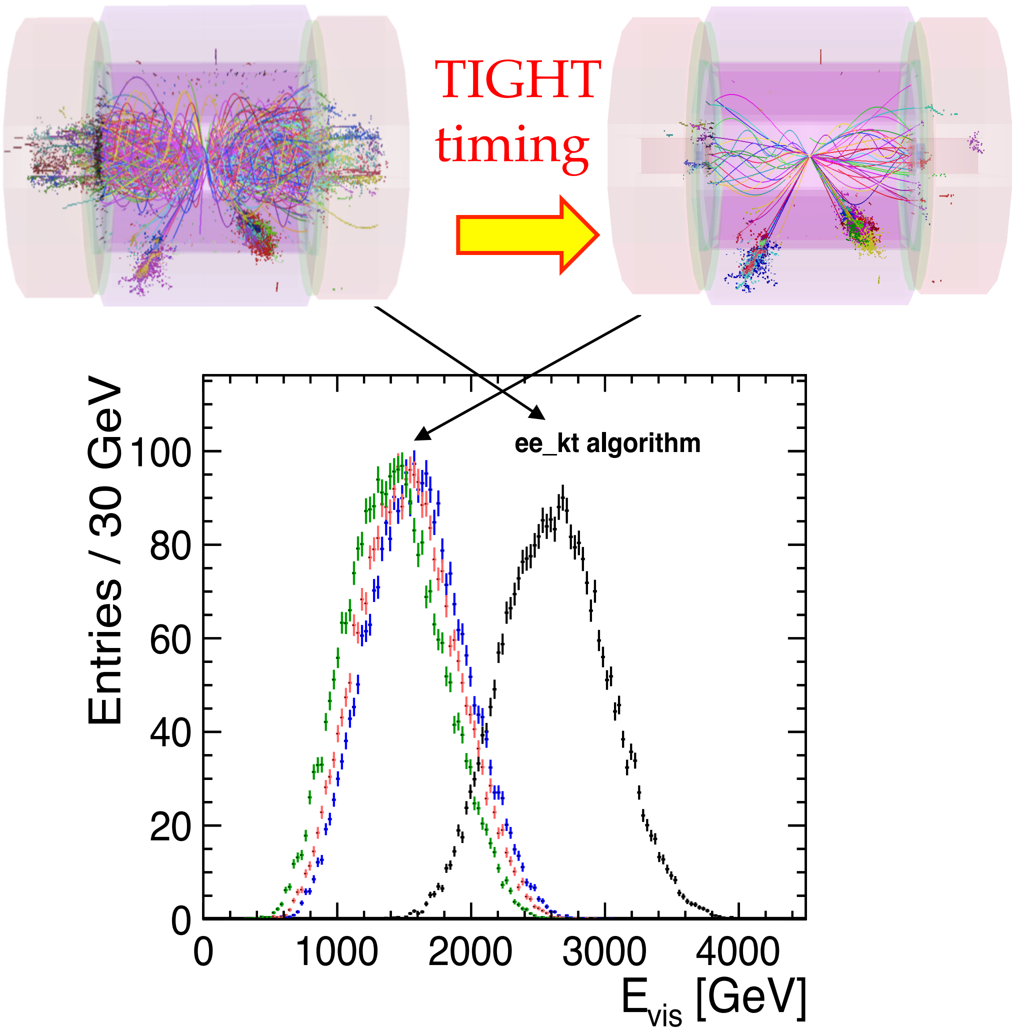
Fragment Removal Algorithms

PFO Construction Algorithms



Jet Finding at CLIC

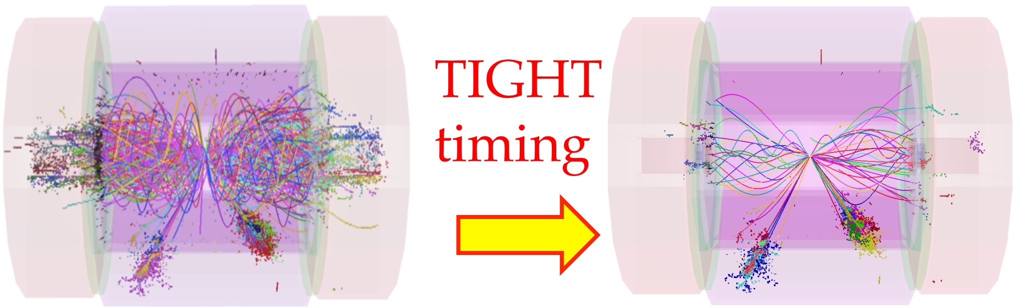
- e.g. $e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
  - two jets + missing energy



- Using Durham k_T à la LEP
  - Timing cuts are effective
  - Yet all particles in event clustered into the jets

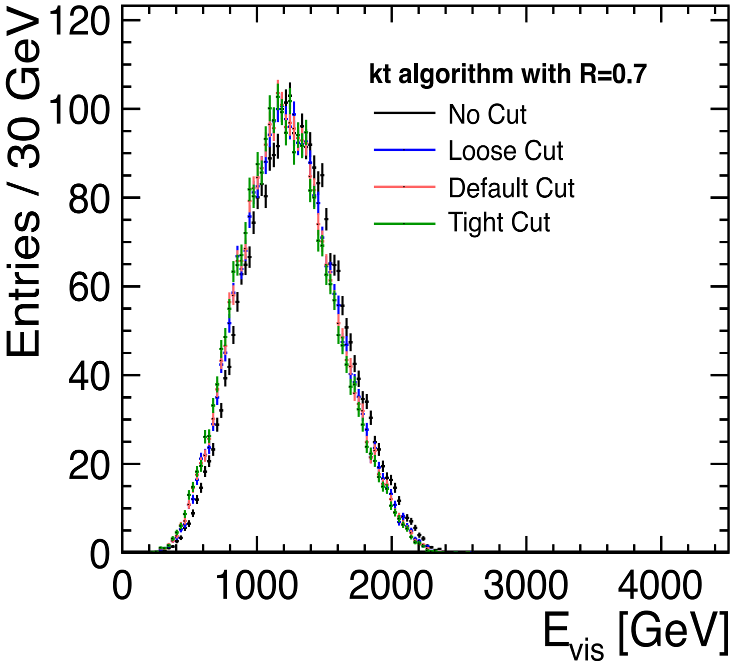
Jet Finding at CLIC

- e.g. $e^+e^- \to \tilde{q}_R\tilde{q}_R \to q\bar{q}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$
  - two jets + missing energy



TIGHT timing

- “hadron collider” k_T : $R = 0.7$
  - much of background clustered with beam axis
  - timing cuts do less work
  - relative impact of timing and jet-finding depends on event topology

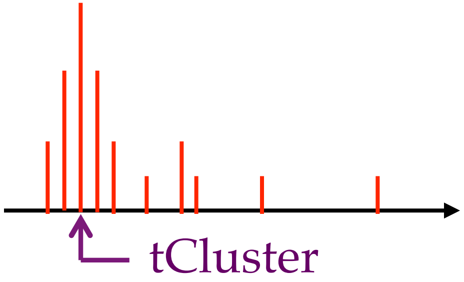


➢ To tackle background: timing cuts + jet finding

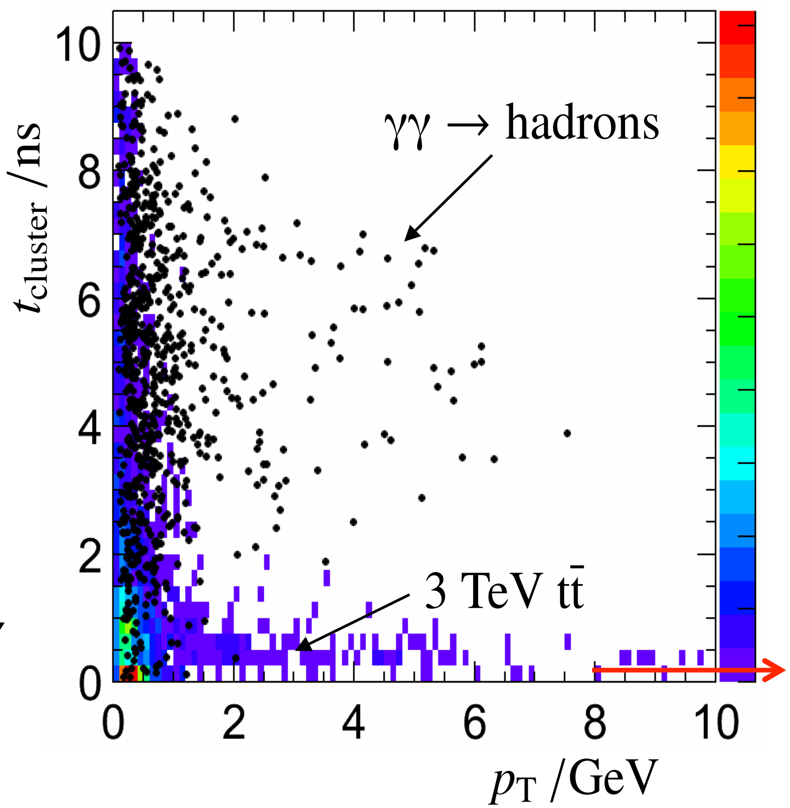
Reconstruction in time

After reconstruction have a list of Particle Flow Objects (PFOs)

- Calculate energy weighted mean time of each cluster
  - ➢ sub-ns resolution



Neutral hadrons

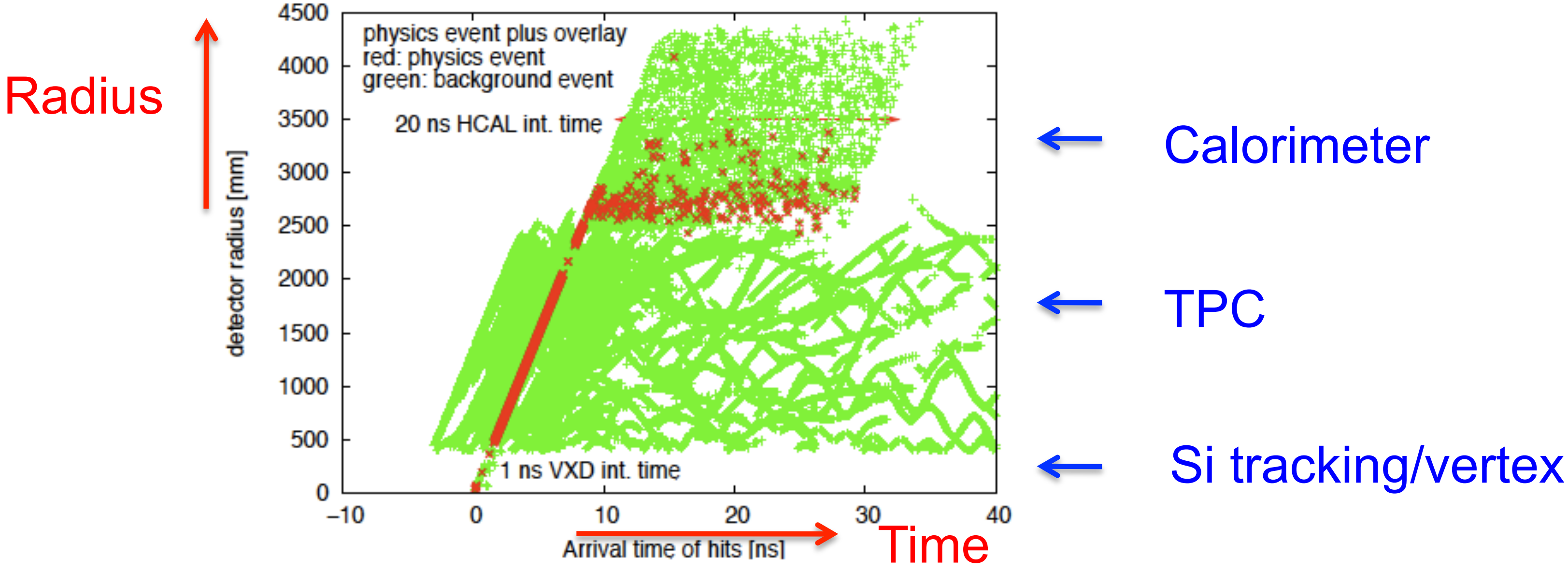


- Use times to reject clusters and associated tracks

- Reject PFOs from background
  - e.g. neutral hadrons in Endcap

Timing requirements in the pile-up

- integrate over > 20 BXs to accumulate calorimetric signals
- integrate over < 5 BXs for acceptable γγ → hadrons backgrounds



Radius

Time

← Calorimeter

← TPC

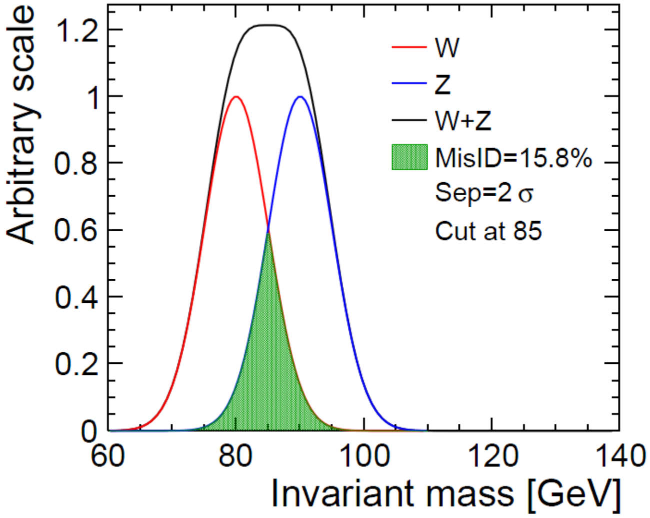
← Si tracking/vertex

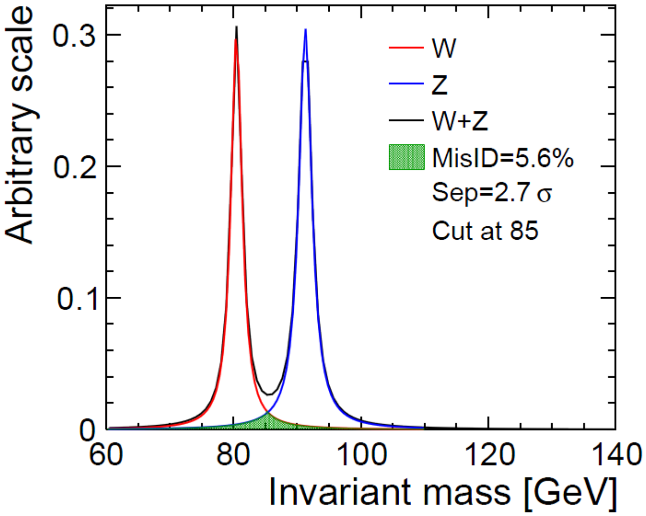
The way out:

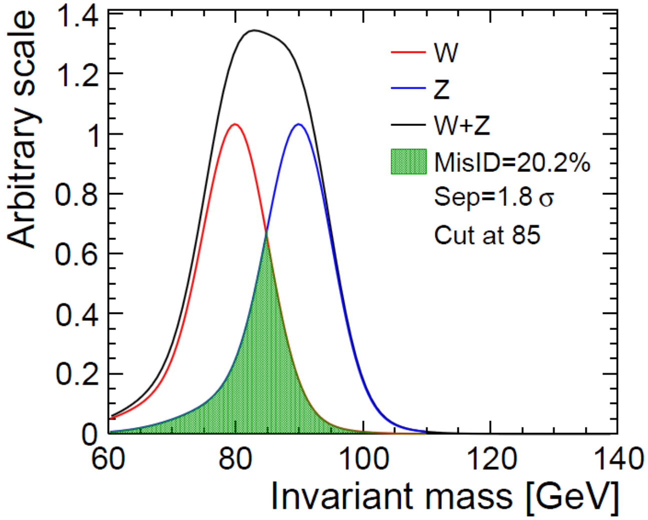
- Excellent time resolution
- High granularity calorimetry
- Sophisticated reconstruction

W / *Z* Separation

- Separation calculated by applying optimal cut, minimising number of misidentified events.
- For ideal Gaussian distributions, misidentification of 15.8% corresponds to 2σ separation.
- If tails present in distribution, separation drops below 2σ even if main peaks remain 2σ apart.
- Obtainable separation limited by natural width of *W* and *Z* to identification efficiency of 94%.

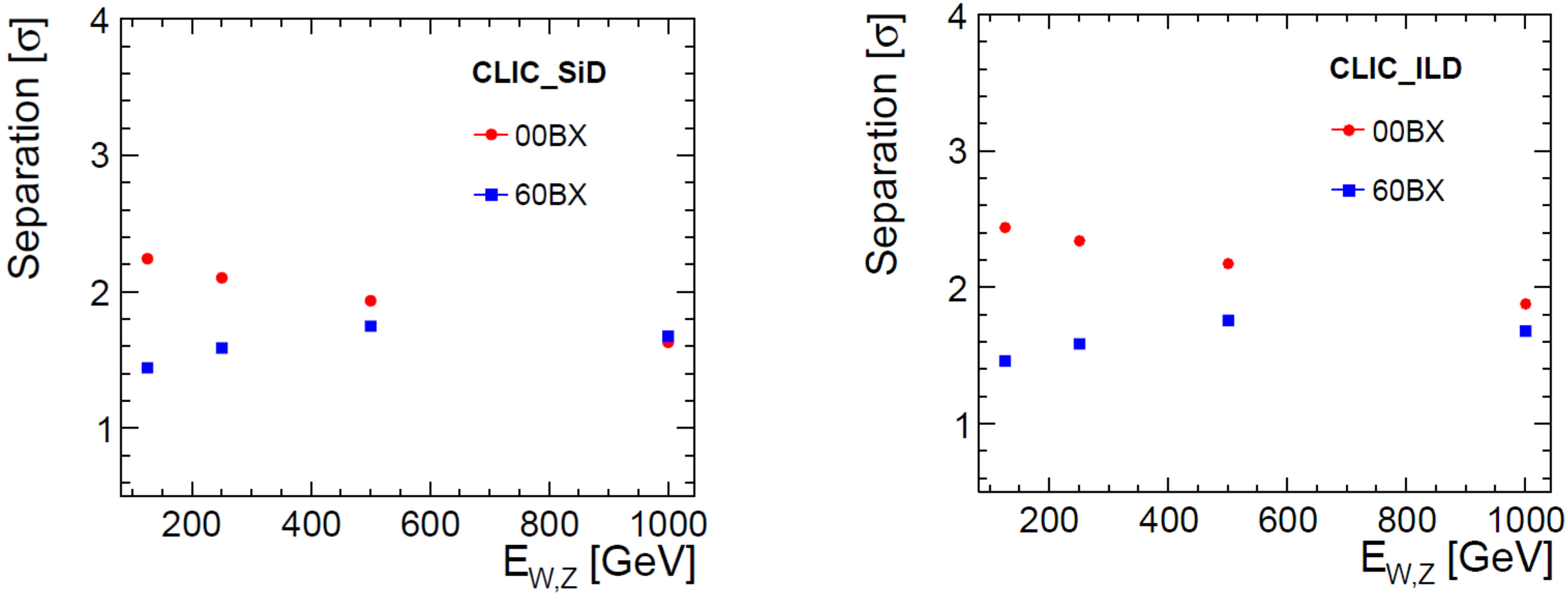




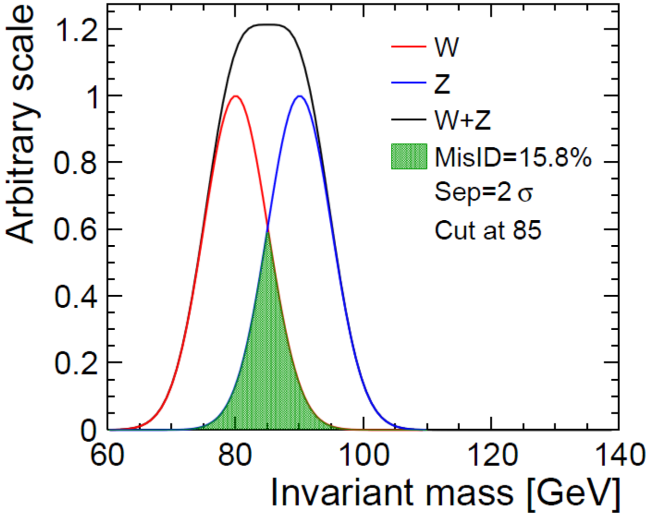


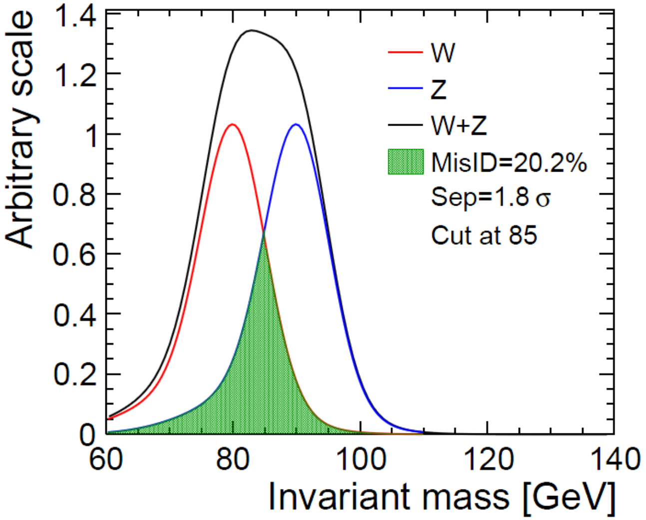
W/ *Z* Separation

- Separation between *W* and *Z* peaks with no background and with 60BX of background:

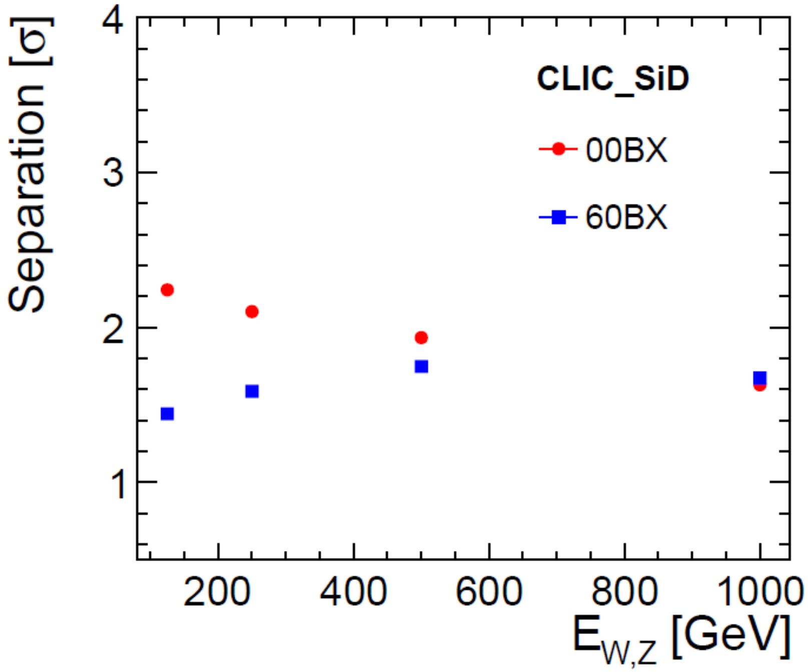


W/Z Separation





- For ideal Gauss, misidentification of 15.8% corresponds to 2σ separation.
- With tails in distribution, separation drops below 2σ even if main peaks remain 2σ apart.
  - ➢ Separation with & without background:



Default PFO Selection

Region	**p_T range**	**Time cut**
	Photons	
Central	$0.75\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
$|\cos(\theta)| \le 0.975$	$0\,\mathrm{GeV} \le p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Forward	$0.75\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
$|\cos(\theta)| > 0.975$	$0\,\mathrm{GeV} \le p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
	Neutral hadrons	
Central	$0.75\,\mathrm{GeV} \le p_\mathrm{T} < 8.0\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$
$|\cos(\theta)| \le 0.975$	$0\,\mathrm{GeV} \le p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
Forward	$0.75\,\mathrm{GeV} \le p_\mathrm{T} < 8.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
$|\cos(\theta)| > 0.975$	$0\,\mathrm{GeV} \le p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
	Charged particles	
All	$0.75\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 3.0\,\mathrm{ns}$
	$0\,\mathrm{GeV} \le p_\mathrm{T} < 0.75\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
	Track only	
	Require $p_\mathrm{T} > 0.5\,\mathrm{GeV}$ and $t_\mathrm{ECAL} < 10\,\mathrm{ns}$	

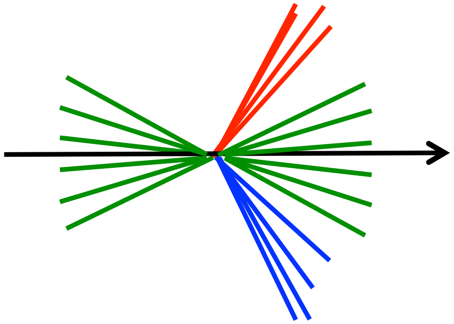
Loose PFO Selection

Region	p_T range	Time cut
Photons		
Central	$0.75\,\text{GeV} \le p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\lvert\cos(\theta)\rvert \le 0.975$	$0\,\text{GeV} \le p_T < 0.75\,\text{GeV}$	$t < 2.0\,\text{ns}$
Forward	$0.75\,\text{GeV} \le p_T < 4.0\,\text{GeV}$	$t < 2.0\,\text{ns}$
$\lvert\cos(\theta)\rvert > 0.975$	$0\,\text{GeV} \le p_T < 0.75\,\text{GeV}$	$t < 1.0\,\text{ns}$
Neutral hadrons		
Central	$0.75\,\text{GeV} \le p_T < 8.0\,\text{GeV}$	$t < 2.5\,\text{ns}$
$\lvert\cos(\theta)\rvert \le 0.975$	$0\,\text{GeV} \le p_T < 0.75\,\text{GeV}$	$t < 1.5\,\text{ns}$
Forward	$0.75\,\text{GeV} \le p_T < 8.0\,\text{GeV}$	$t < 2.5\,\text{ns}$
$\lvert\cos(\theta)\rvert > 0.975$	$0\,\text{GeV} \le p_T < 0.75\,\text{GeV}$	$t < 1.5\,\text{ns}$
Charged particles		
All	$0.75\,\text{GeV} \le p_T < 4.0\,\text{GeV}$	$t < 3.0\,\text{ns}$
	$0\,\text{GeV} \le p_T < 0.75\,\text{GeV}$	$t < 1.5\,\text{ns}$
Track only		
Require $p_T > 0.25\,\text{GeV}$		

Tight PFO Selection

Region	p_T range	Time cut
Photons		
Central	$1.0\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
$\lvert\cos(\theta)\rvert \le 0.95$	$0.2\,\mathrm{GeV} \le p_\mathrm{T} < 1.0\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Forward	$1.0\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
$\lvert\cos(\theta)\rvert > 0.95$	$0.2\,\mathrm{GeV} \le p_\mathrm{T} < 1.0\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Neutral hadrons		
Central	$1.0\,\mathrm{GeV} \le p_\mathrm{T} < 8.0\,\mathrm{GeV}$	$t < 2.5\,\mathrm{ns}$
$\lvert\cos(\theta)\rvert \le 0.95$	$0.5\,\mathrm{GeV} \le p_\mathrm{T} < 1.0\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
Forward	$1.0\,\mathrm{GeV} \le p_\mathrm{T} < 8.0\,\mathrm{GeV}$	$t < 1.5\,\mathrm{ns}$
$\lvert\cos(\theta)\rvert > 0.95$	$0.5\,\mathrm{GeV} \le p_\mathrm{T} < 1.0\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Charged particles		
All	$1.0\,\mathrm{GeV} \le p_\mathrm{T} < 4.0\,\mathrm{GeV}$	$t < 2.0\,\mathrm{ns}$
	$0\,\mathrm{GeV} \le p_\mathrm{T} < 1.0\,\mathrm{GeV}$	$t < 1.0\,\mathrm{ns}$
Track only		
Require $p_\mathrm{T} > 1.0\,\mathrm{GeV}$ and $t_\mathrm{ECAL} < 10\,\mathrm{ns}$		

Jet Finding at CLIC



- At LEP, preferred jet-finding algorithm: Durham k_T
  - All particles in event clustered into the jets
  - not appropriate for CLIC
- Events at CLIC
  - significant background from forward-peaked $\gamma\gamma \rightarrow$ hadrons
  - events are often boosted along beam axis (beamstrahlung)
  - "hadron collider" type algorithms more appropriate
- k_T algorithm at CLIC studied for benchmark physics analyses
  - invariant under longitudinal boosts
  - particles either combined with existing jet or beam axis
    - reduces sensitivity to $\gamma\gamma \rightarrow$ hadrons

➢ To tackle background: timing cuts + jet finding

Backup slides
- reconstruction resolutions

Transverse impact-parameter resolution

d_0: distance of closest approach to interaction point in R-phi plane
→ main benchmark parameter for vertex detector performance
Fast simulation: LiC detector toy tool, used for design optimisation
Full simulation: Geant4-based ILD/SiD frameworks, used for physics studies

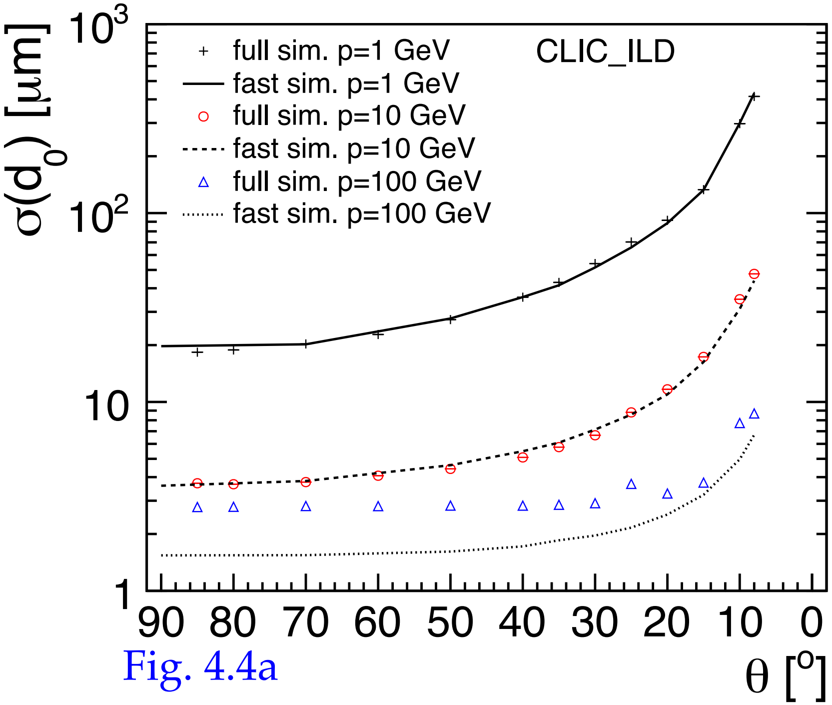


Fig. 4.4a

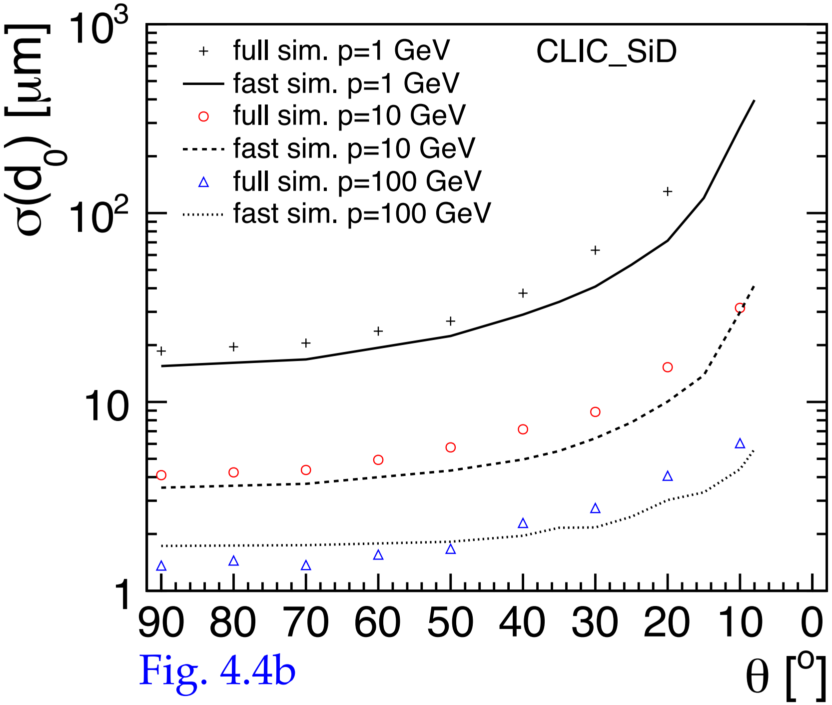


Fig. 4.4b

CLIC_ILD:

- Both full and fast simulation perform simple Gaussian hit smearing
- Full simulation without TPC information
  → Worse resolution for high momenta

CLIC_SiD:

- Full simulation models clustering according to parametrisation of KPiX readout chip
  → added realism leads to worse resolution in full simulation, as expected

Dependence on single-point resolution

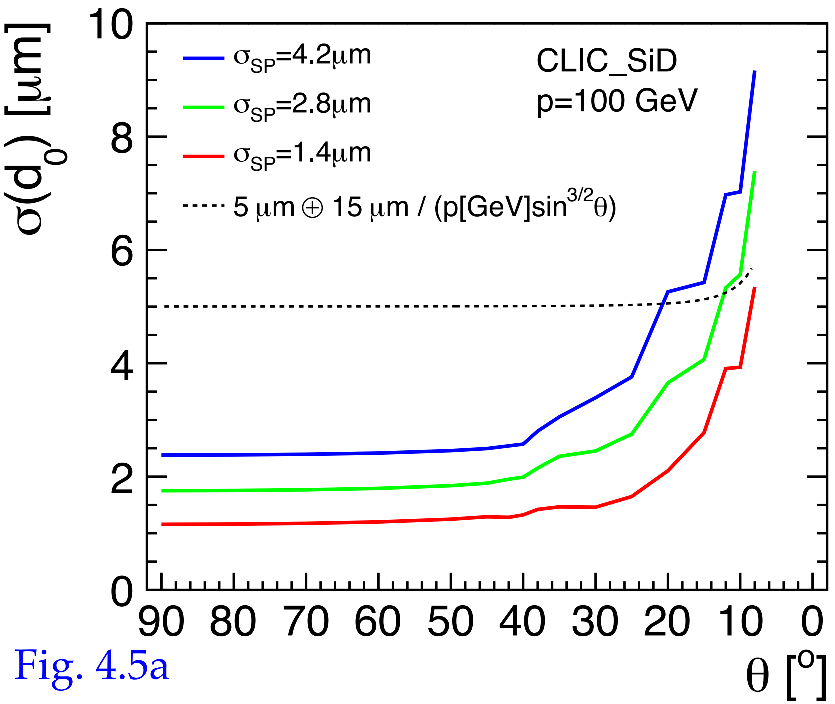


Fig. 4.5a

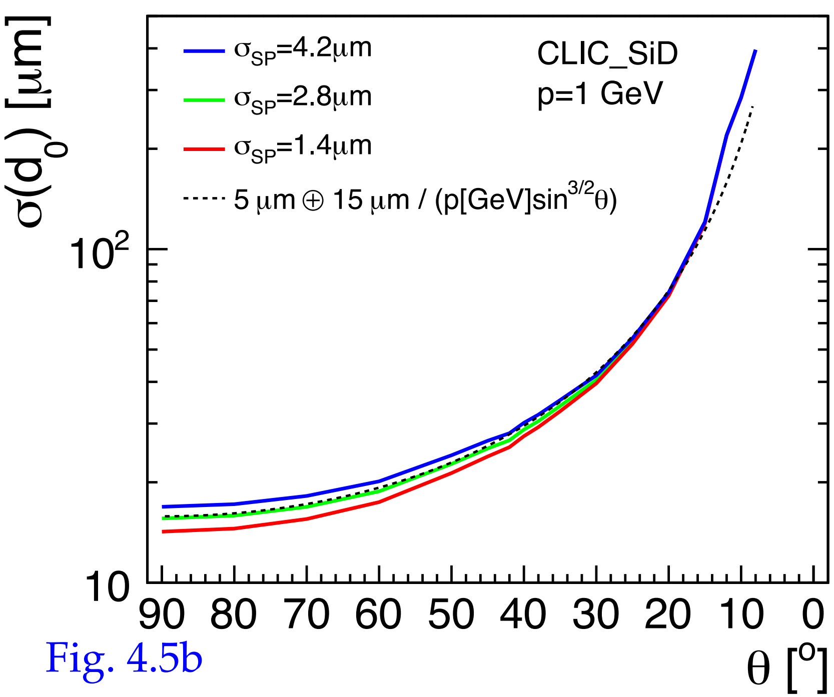
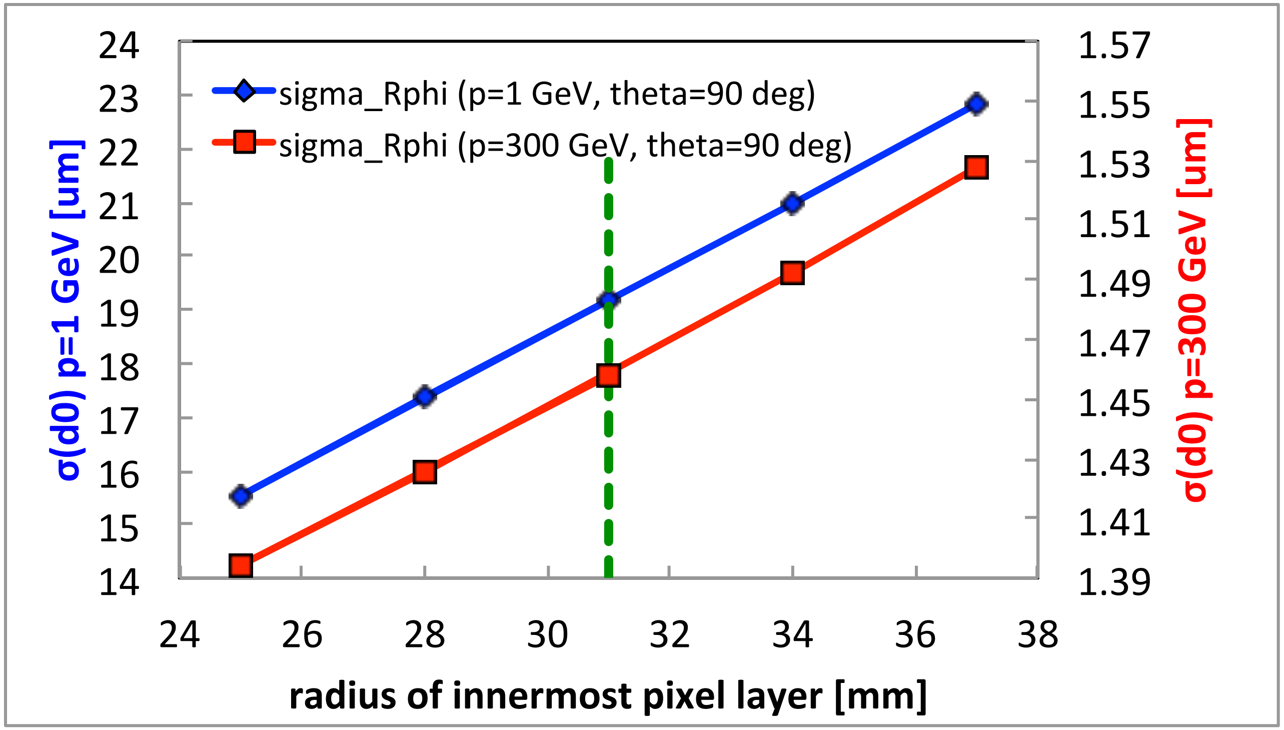


Fig. 4.5b

- Varied single-point resolution by +- 50% (~ pixel sizes 10x10, 20x20, 30x30 μm^2)
- Observed change in d_0-resolution:
  - +- 40% for p = 100 GeV
  - +- 15% for p = 1 GeV
- Resolution close to or better than target values for all cases
- Pixel size is also constrained by:
  - Expected background occupancy
  - Ability to separate adjacent tracks in dense jets

Dependence on distance to IP

Fig. 4.6



- Varied distance to interaction point, by changing radii of beam pipe and barrel vertex layers in CLIC_ILD model
- Observed change in d_0-resolution:
  - 3.2% / mm for high momenta (parameter 'a')
  - 0.8% / mm for low momenta (parameter 'b')
- Distance to interaction point is constrained by direct hits from incoherent pairs (see André Sailer's presentation on backgrounds)

Dependence on material

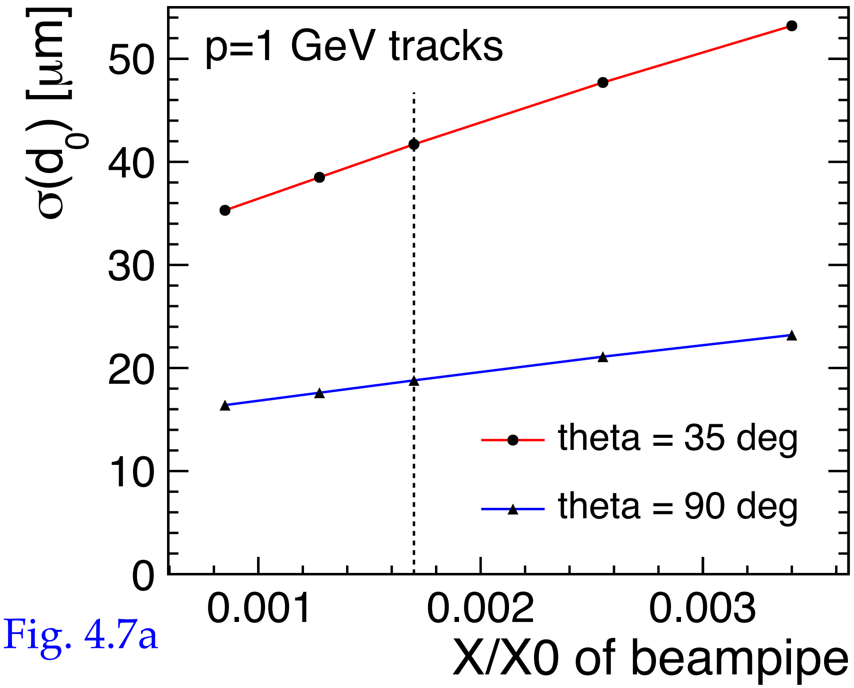


Fig. 4.7a

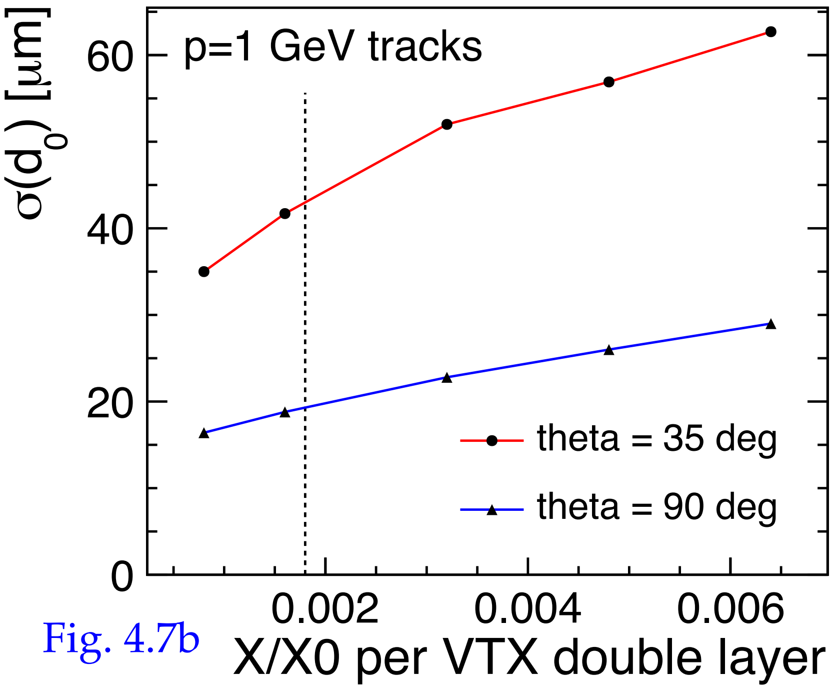
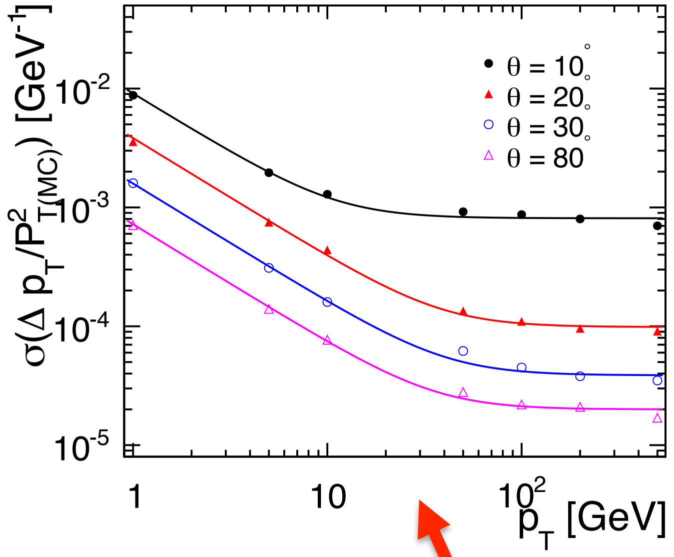
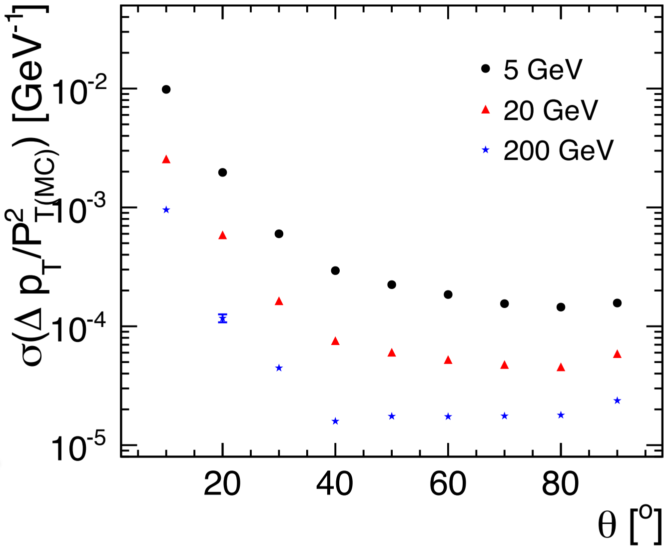


Fig. 4.7b

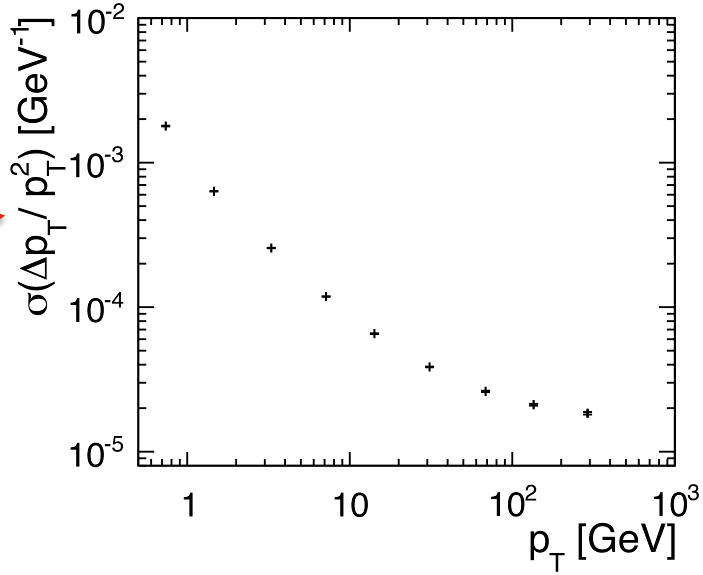
- Very small amount of material in baseline designs
- Realistic models for supports, cabling, cooling not available yet
- Studied sensitivity of d_0 resolution for low momenta on material in beampipe and silicon pixel layers of CLIC_ILD
- Doubling beam-pipe thickness → ~20% worse resolution at 90^o
- Doubling material in silicon layers → ~20% worse resolution at 90^o
- Steeper slope in forward region

Tracking performance CLIC_ILD



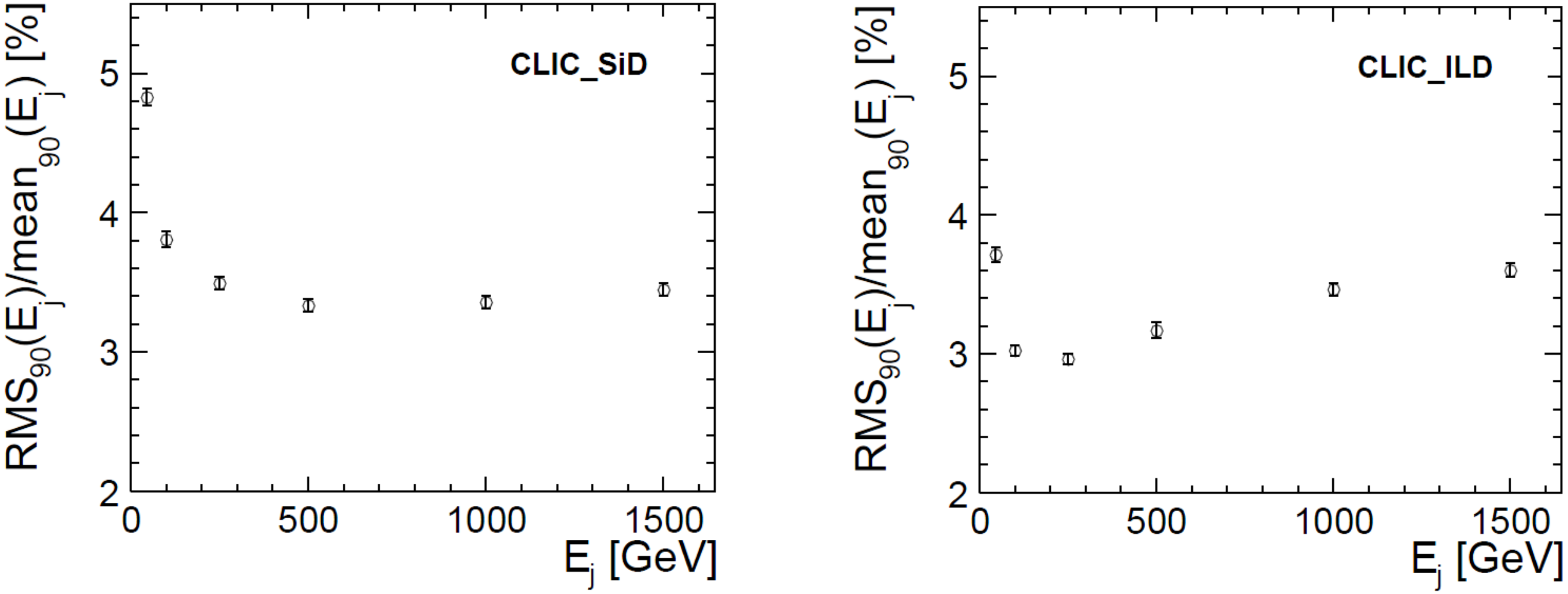


- Single muons:
  - p_T resolution reaches expected asymptotic values
- ttbar events:
  - p_T resolution reaches same asymptotic values for p_T > 100 GeV



Resolution vs. Jet Energy

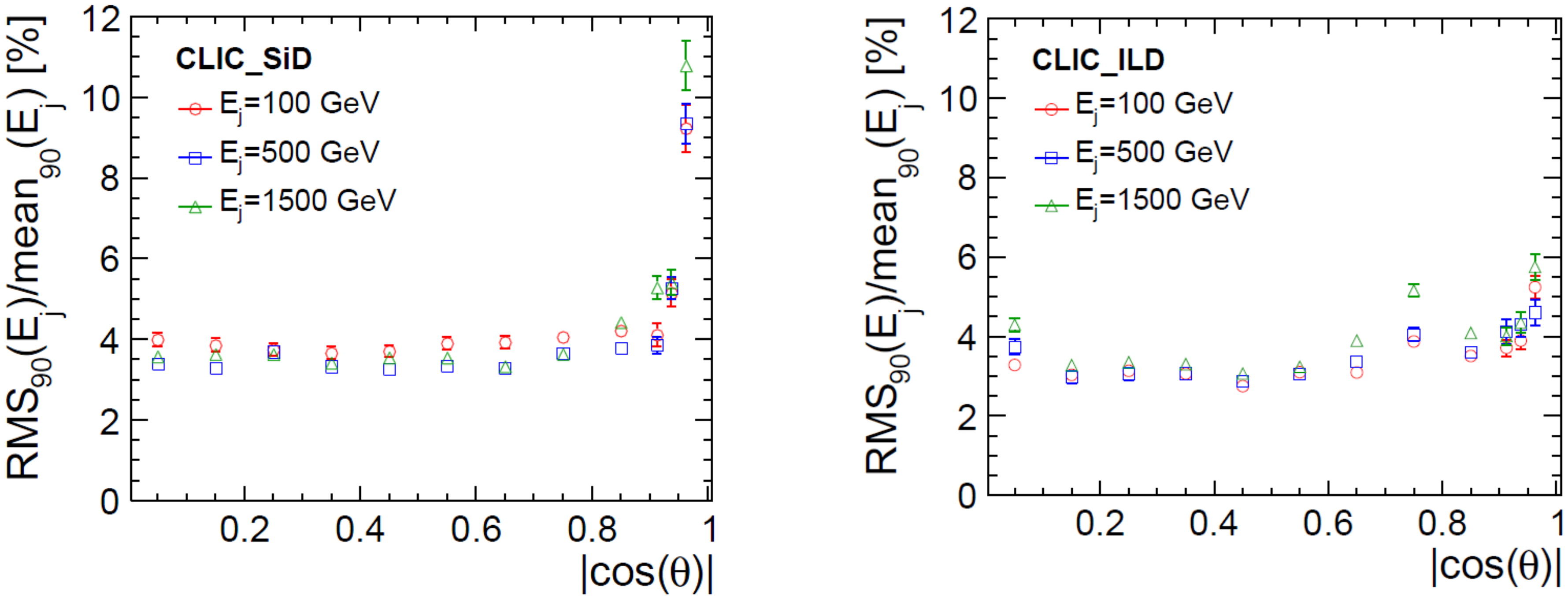
- Barrel region |cos θ| < 0.7, no background, no jet reconstruction:



- At lower energies, CLIC_ILD benefits from its larger radius.
- At higher energies, particle separation becomes more difficult; confusion term dominates energy resolution; particle flow can become energy flow. Both detectors show similar performance.

Resolution vs. Angle

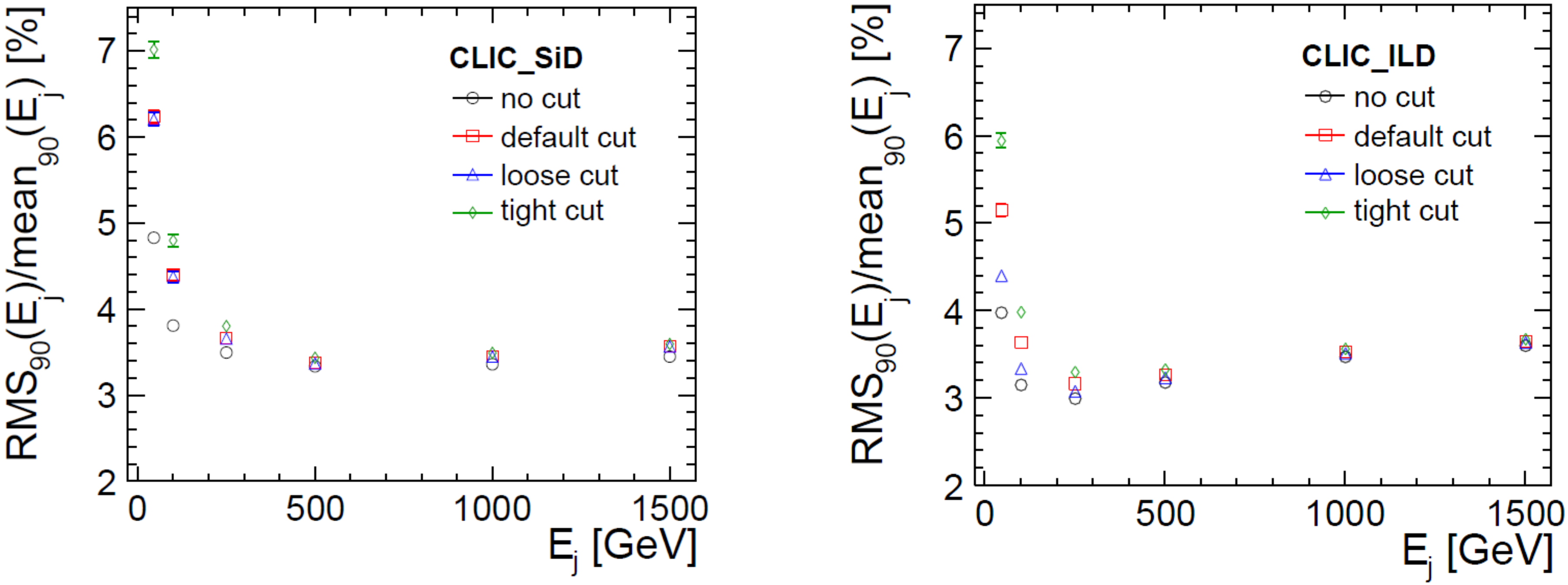
- No background, no jet reconstruction:



- Resolution for CLIC_SiD is worse in the forward region, due to reduced angular coverage. There is no HCAL coverage below $\theta = 15.5°$.
- Resolution for CLIC_ILD dips in barrel/endcap overlap region, due to gap between ECAL barrel and endcap. Leakage effects due to this gap are more pronounced at higher energies.

Timing Cuts

- No background, no jet reconstruction:

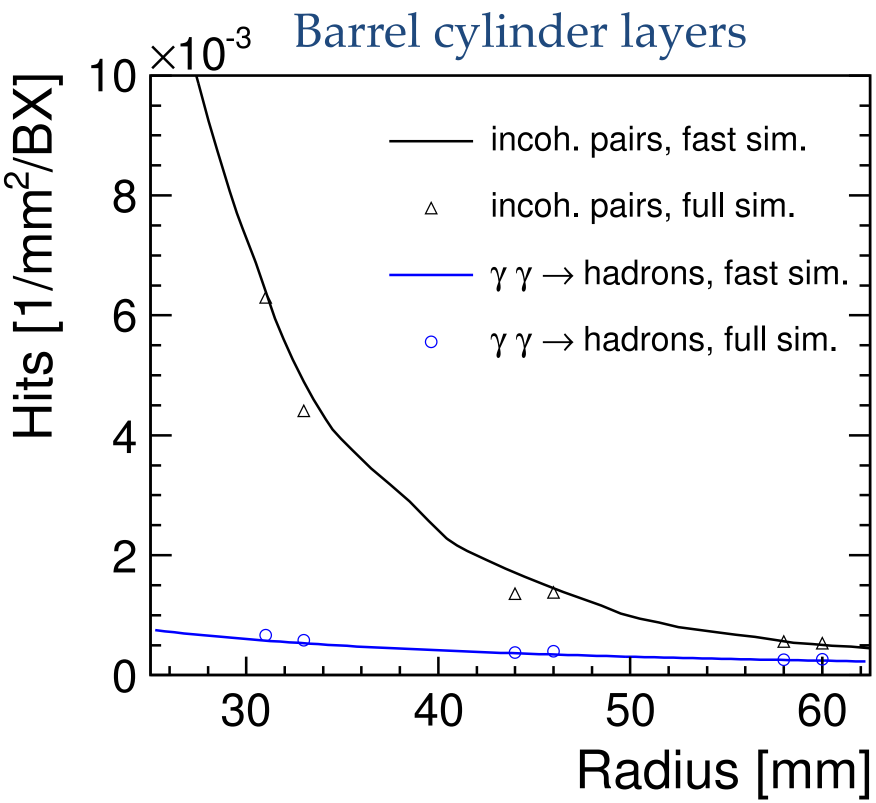


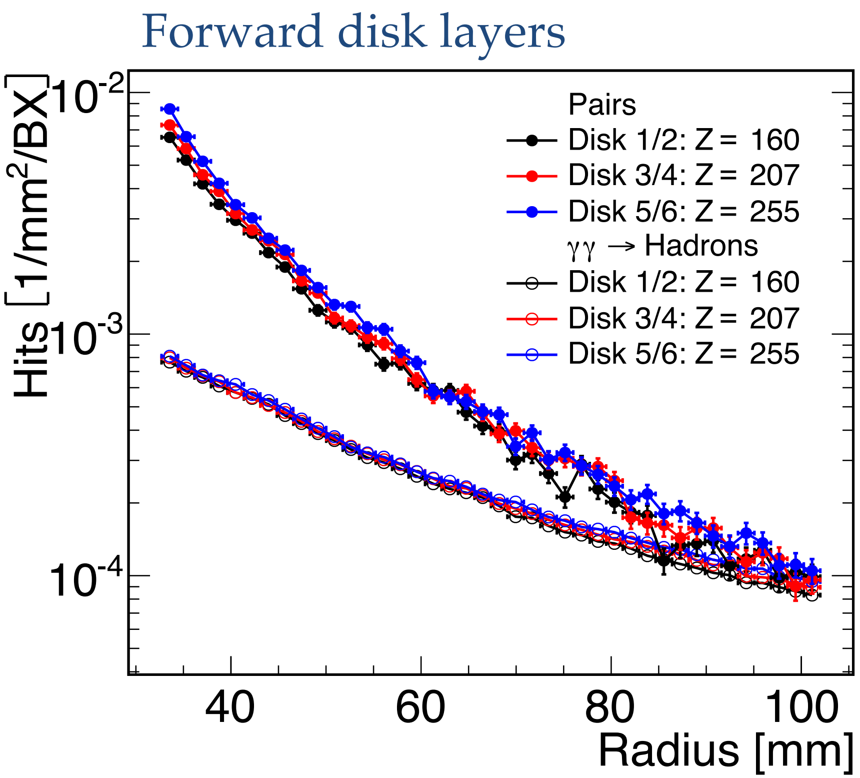
- Impact of **CLICPfoSelector** timing cuts on the physics event is studied by applying the cuts without overlaying any background.
- Whilst timing cuts result in degradation of jet energy resolution for low energy jets, the impact is small for jets above 500GeV.

Backup slides
- occupancies

Occupancies in CLIC_ILD vertex region

Dominik – sep'11


Barrel cylinder layers


Forward disk layers

Direct hits from incoherent e^+e^- pairs dominate

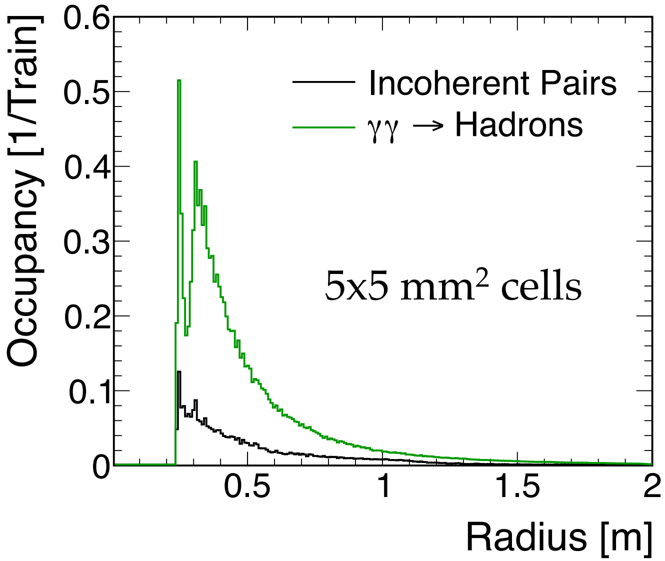
- Up to $3\text{x}10^{-4}$ hits/mm^2/BX in barrel region → 1.9% train occupancy / pixel
- Up to $5\text{x}10^{-4}$ hits/mm^2/BX in forward region → 2.9% train occupancy / pixel
  (including factors for simulation uncertainty and clustering)

for comparison: ATLAS/CMS pixel occupancy ~0.1% / BX

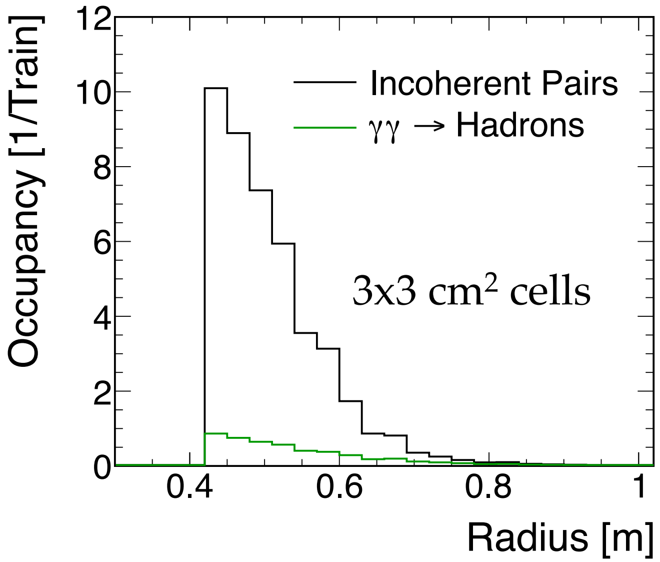
Backgrounds in CLIC_ILD Calorimeters

Dominik – sep'11

ECAL Endcap layer 5-10 train occupancy:



HCAL Endcap layer 35-40 train occupancy:



- Up to 50% train occupancy in **ECAL** Endcap, not including safety factors
- Up to 1000% train occupancy in **HCAL** Endcap, not including safety factors

→ Need several readouts per train

→ May need even higher granularity

37 TeV energy release / train

→ challenge for (jet) reconstruction

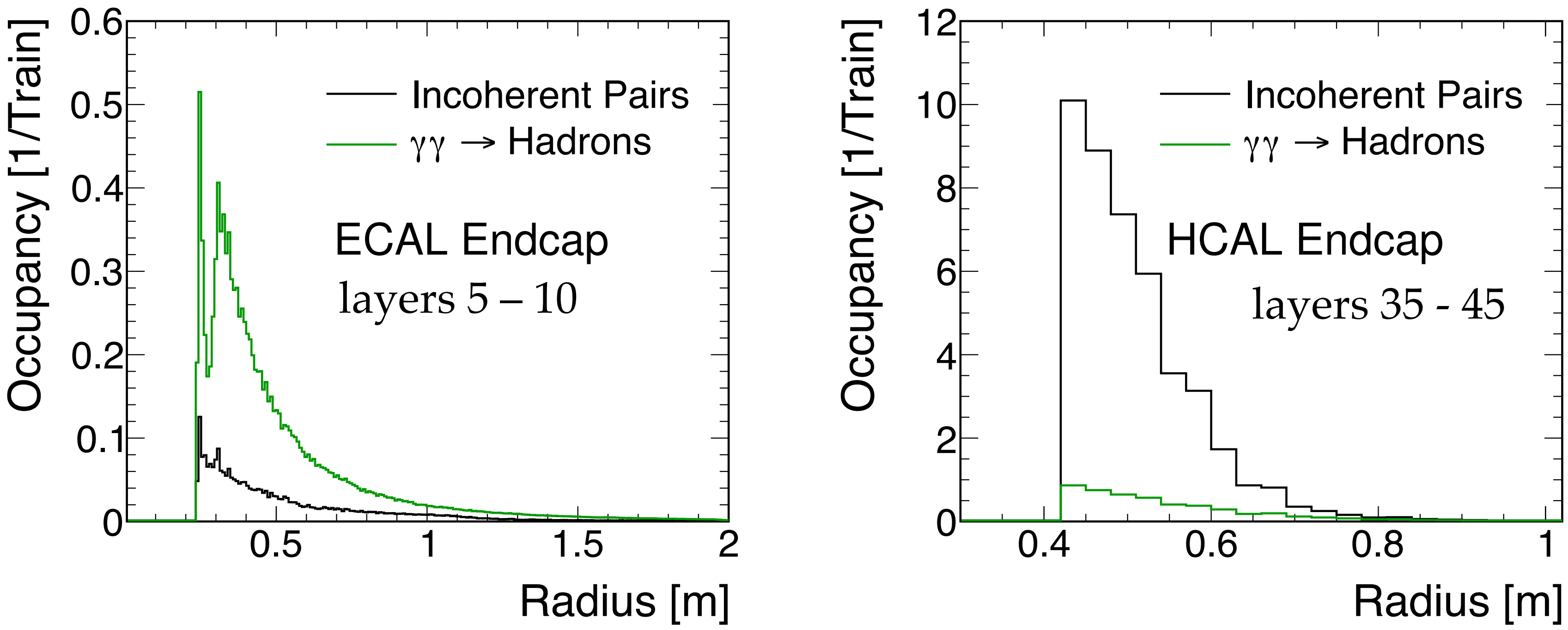
- Note: forward region not yet optimized for backscatters into HCAL

Total energy release / train:

Subdetector	Incoherent Pairs [TeV]	$\gamma\gamma \to$ hadrons [TeV]
ECAL Endcaps	2	11
ECAL Barrel	–	1.5
HCAL Endcaps	16	6
HCAL Barrel	–	0.3
Total Calorimeter	18	19

Calorimeter endcap occupancies

Full detector simulations:



High occupancy due to incoherent pairs in high-z region of HCAL endcap

- Inadequate shielding from the very forward calorimetry region

➢ **Can be solved**

Radiation exposure in silicon layers

Non-Ionizing Energy Loss (NIEL):

- Displacement damage in silicon
- Obtained from hit rates scaled with tabulated damage factors

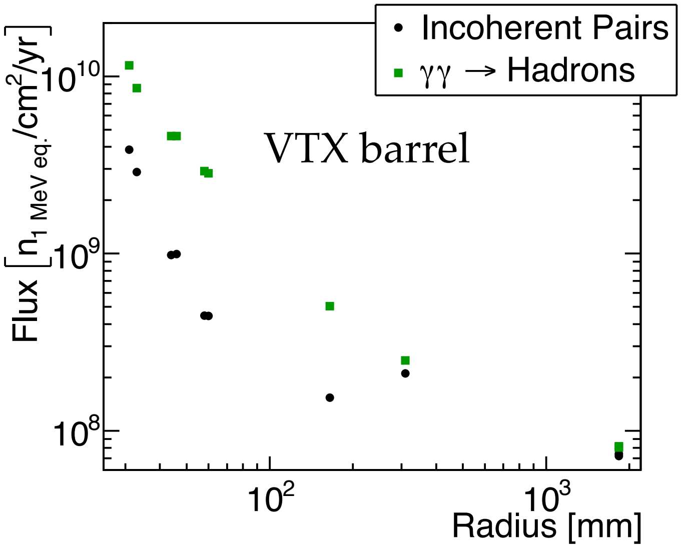
Total Ionizing Dose (TID):

- Obtained from simulated energy loss in silicon layers

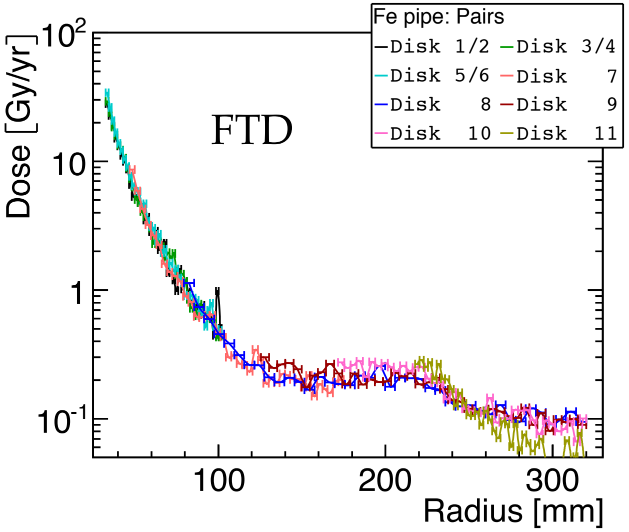
	CLIC_ILD	LHC
NIEL VTX barrel [1-MeV-n_{eq}/yr]	$4x10^{10}$	$>\sim10^{14}$
NIEL FTD [1-MeV-n_{eq}/yr]	$5x10^{10}$	
TID VTX barrel [Gy/yr]	200	$>\sim 10^{5}$
TID FTD [Gy/yr]	180	

→ Small expected radiation exposure, compared to LHC experiments

NIEL:



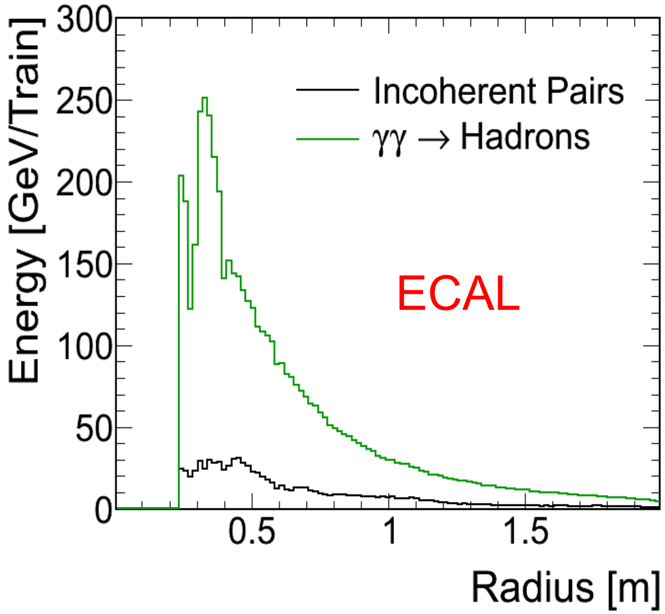
TID:



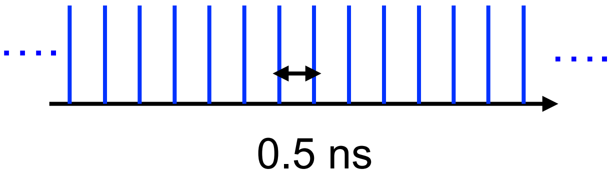
Backgrounds in the calorimeters

- Calorimeter backgrounds per bunch-train (3 TeV)

Detector	**$\gamma\gamma \rightarrow$ hadrons**
ECAL endcaps	**11 TeV**
ECAL barrel	1.5 TeV
HCAL endcaps	**6 TeV**
HCAL barrel	0.3 TeV
Total	**19 TeV**



- Calorimeter backgrounds per bunch-crossing are manageable, ~ 60 GeV
- Hence want to integrate over as few as possible BXs
- Tight timing requirements – *O*(ns) !



CLIC detector
– electronics

5 detector categories with similar readout specifications

- Silicon pixel detectors
  - Arrival time for 1 hit readout per train
  - Zero suppression
- Silicon strip detectors
  - Arrival time for >1 hits per train
  - Sampling of pulse at regular interval
  - No zero suppression due to the large occupancies
- TPC
  - Analog pad readout for 1000 voxels per channel
- Calorimeters
  - Arrival time for >1 hits per train
  - Sampling of pulse at regular interval
  - Pulse heights higher than strip detectors → time resolution
  - No zero suppression
- Muon detectors
  - Digital readout of > 1 hits per train with a multi-hit TDC
  - Zero suppression

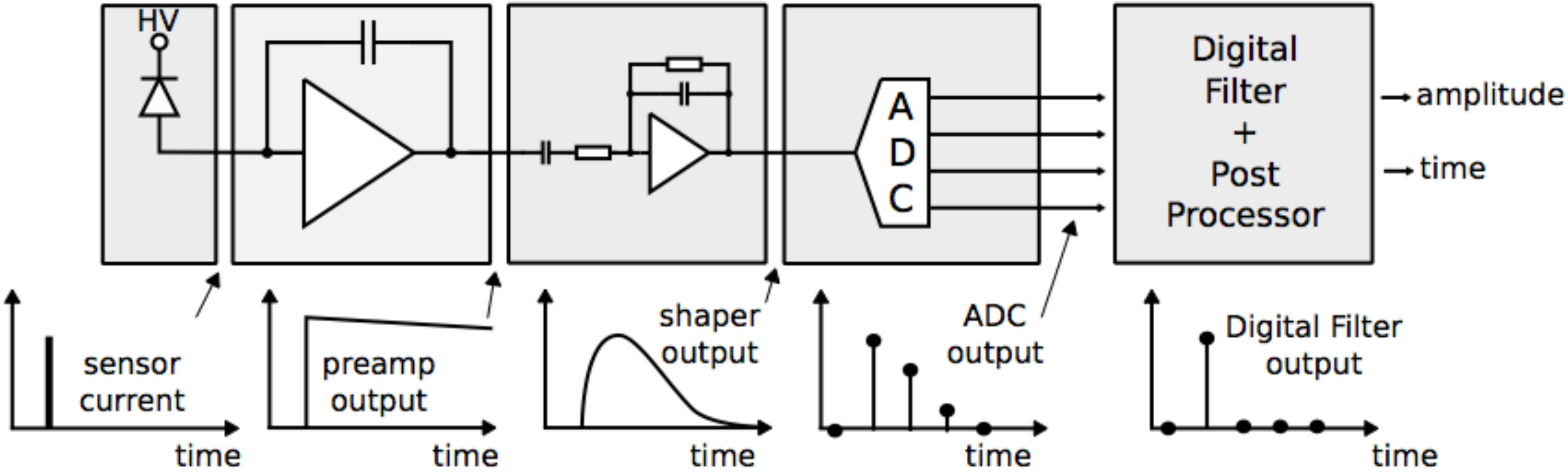
	time stamping resolution [ns]	time sampling period [ns]	cell size [mm^2]	number of channels [10^6]	average to maximum occupancy [%]	number of bits per hit [bit]	data volume [Mbyte]
VTX barrel	~ 5	10	0.02×0.02	945	< 1.5 - 1.9	32	56
VTX endcap	~ 5	10	0.02×0.02	895	< 2.0 - 2.8	32	72
FTD pixels	~ 5	10	0.02×0.02	1570	0.1 - 1.0	32	6.3
FTD strips	~ 5	10 - 25	0.05×100	1.6	160 - 290	16	48
SIT	~ 5	10 - 25	0.05×90	1.0	100 - 174	16	30
SET	~ 5	10 - 25	0.05×438	5.0	17 - 17	16	150
ETD	~ 5	10 - 25	0.05×300	4.0	38 - 77	16	120
TPC	–[a]	25	1×6	3[b]	5 - 32	24	500
ECAL barrel	1	25	5×5	69.5	< 3	16	2090
ECAL endcap	1	25	5×5	43.2	60 - 150	16	1300
HCAL barrel	1	25	30×30	6.9	< 5	16	210
HCAL endcap	1	25	30×30	1.8	120 - 5200	16	54
HCAL rings	1	25	30×30	0.2	< 5	16	6.0
LumiCal	5	25	5×5	0.2	600 - 6000	32	4.6
BeamCal	5	25	8×8	0.1	15600[c]	32	6.0
MUON barrel	1	25	30×30	1.4	0.03 - 0.2	24	< 0.01
MUON endcap	1	25	30×30	2.4	0.2 - 1.0	24	0.01

[a] By combining with different subdetectors in offline reconstruction 2 ns will be achieved.

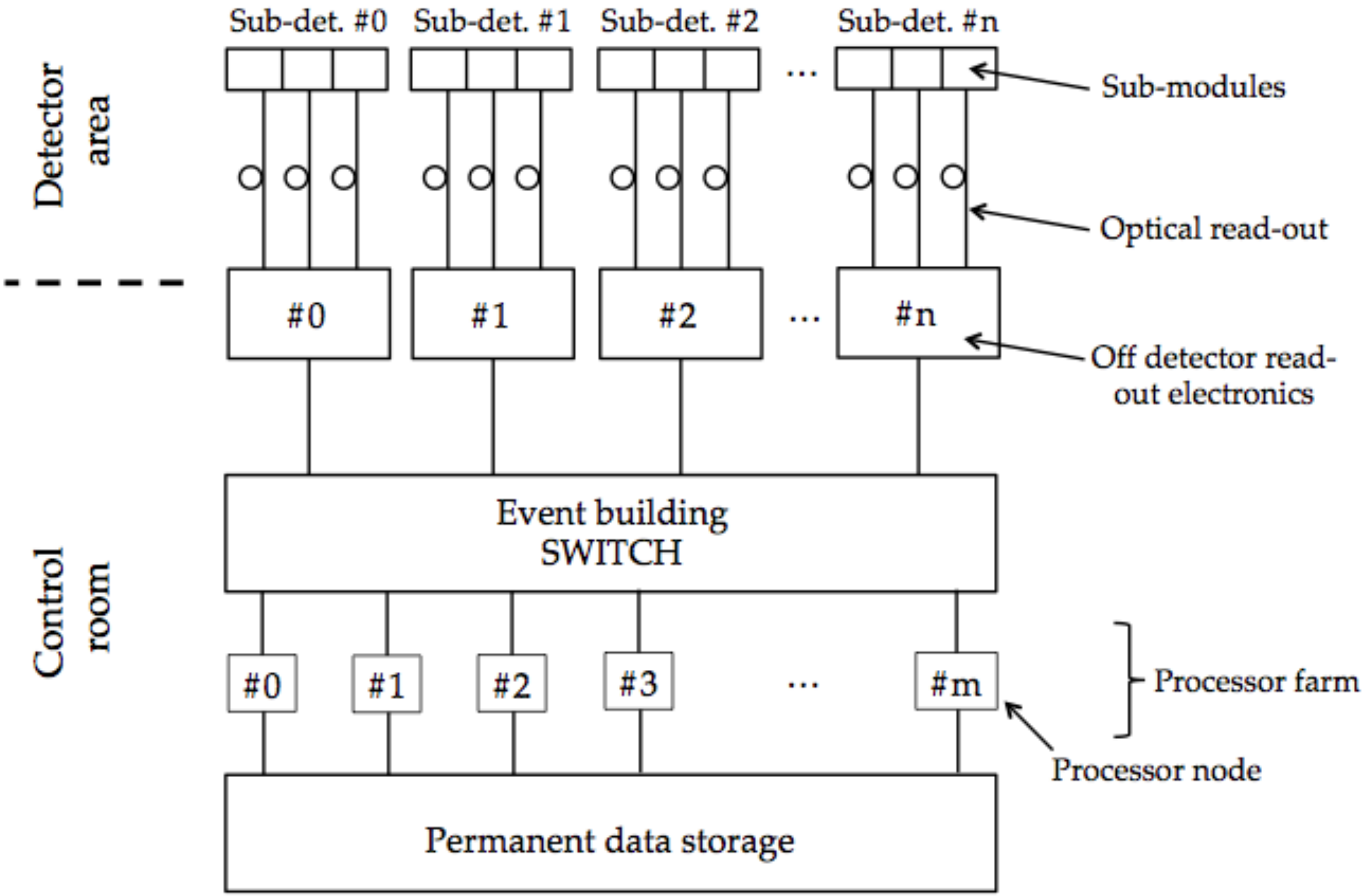
[b] The 3D TPC reads out 1000 voxels per channel for each bunch train.

[c] All cells measure a signal for each bunch crossing.

Implementation Example: Analog Calo Readout



DAQ aspects


Sub-det. #0
Sub-det. #1
Sub-det. #2
Sub-det. #n
...
Sub-modules
Detector area
Optical read-out
#0
#1
#2
...
#n
Off detector read-out electronics
Event building SWITCH
Control room
#0
#1
#2
#3
...
#m
Processor farm
Processor node
Permanent data storage

CLIC detector
– R&D

Hardware/engineering R&D

CERN LCD hardware/engineering R&D
(needed beyond ILC existing developments):

- Vertex detector
  - trade-off between pixel size, amount of material and timing resolution
- Hadron calorimetry
  - Tungsten-based HCAL (PFA calo, within CALICE)
- Electronics
  - Power pulsing for all sub-detectors (50 Hz)
  - Fast readout with pulse-height + time + multi-hit in 156 ns
- Solenoid coil
  - Large high-field solenoid concept, reinforced conductor (CMS/ATLAS experience)
- Overall engineering design and integration studies
  - In view of sub-nm precision required for FF quadrupoles
  - For heavier calorimeter, larger overall CLIC detector size etc.

- In addition at CERN: TPC electronics development (Timepix-2, S-ALTRO)

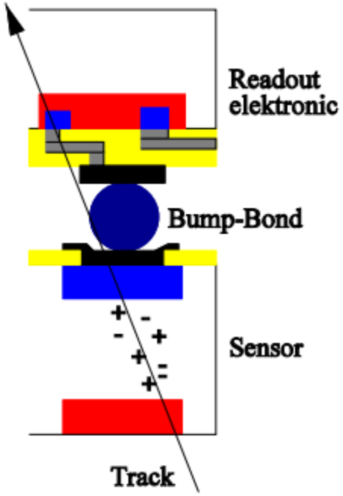
Pixel-detector technology options

- 20x20 μm² pixel sizes → need small feature sizes
- Time-stamping ~5-10 ns → need high-resistivity sensor
- 0.1%-0.2% material/layer → allows for ~50 μm sensor + ~50 μm electronics
- Read out full 156 ns bunch train, no trigger

Technology Options:

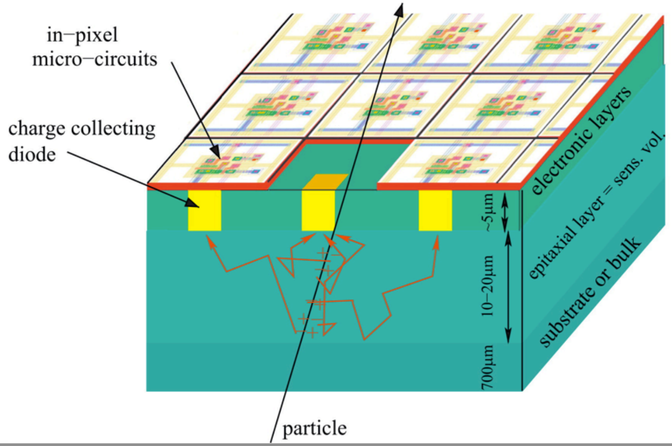
1) Hybrid

- Thinned high-resistivity fully depleted sensors
- Fast, low-power highly integrated readout chip
- Low mass interconnects



2) Integrated technologies

- Sensor and readout combined in one chip
- Charge collection in epitaxial layer



Pixel-detector in hybrid technology

- Thinned depleted high-resistivity sensors, ~50 um active width
  Example: ALICE pixel upgrade → meet CLIC goals
- Fast, low-power, highly integrated readout chips
  Example: Timepix3 (2012) 130 nm IBM CMOS
  - 50x50 μm^2 pixels → needs further reduction (<~90 nm process)
  - 1.5 ns time resolution → exceeds CLIC goals
  - P~350 mW/cm^2 → meets CLIC goals (with power pulsing)
- Low-mass interconnects between sensor+readout
  - cost driver → needs further R&D

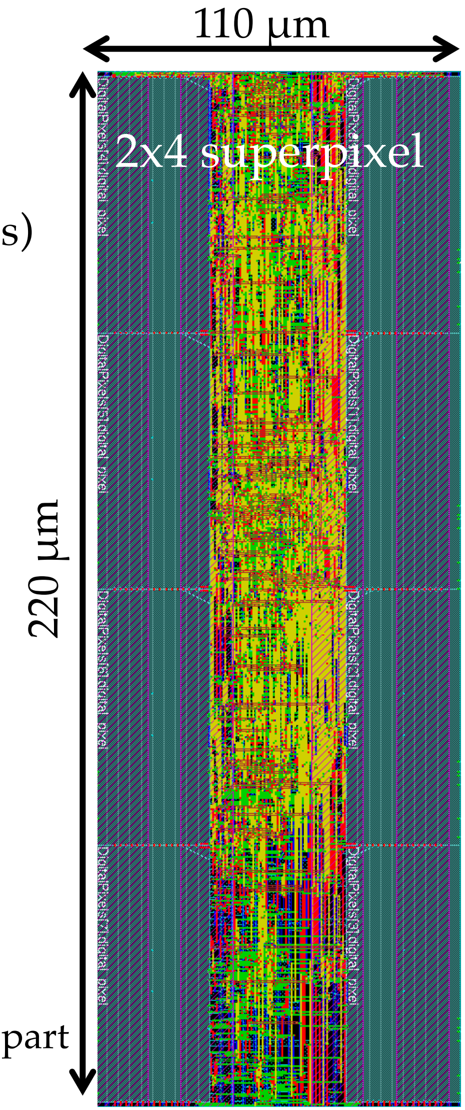
Advantages:

- Use industry-standard processes for readout
- Factorize sensor and readout R&D

Drawbacks:

- Higher material budget than integrated approach
- Interconnects difficult/expensive
- Handling/bonding of thinned structures difficult

Timepix3 design



X. Llopart

Pixel-detector in integrated technology

Integrate sensor and readout in one chip

- Signal collection through electron drift in epitaxial layer

Example: MIMOSA chip family, 0.35 μm CMOS process

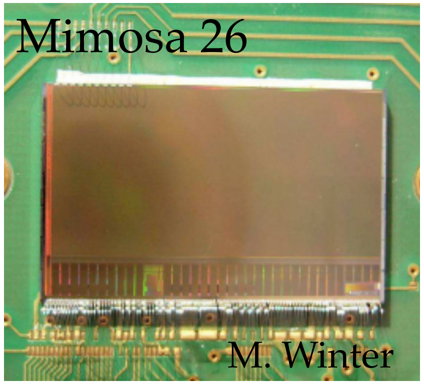
- 50 μm total thickness → meets CLIC goal
- <<1 μm depleted area → need to increase
- 100 μs readout time (rolling shutter) → need single-pixel r/o
- 18.4 μm pitch, σ_{SP}~4 μm → meets CLIC goal
- P~250 mW/cm^2 → meets CLIC goal (with power pulsing)

Advantages:

- Very low material budgets achievable
- Very low power consumption possible

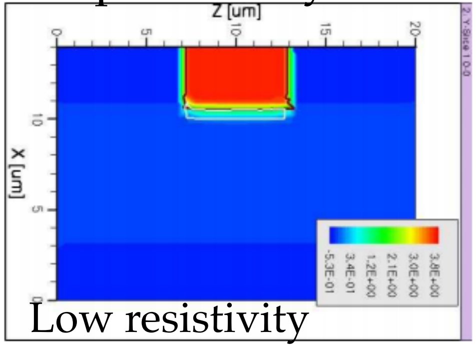
Drawbacks:

- Custom-made processes (availability in 10 years?)
- Difficult to get fast signal collection + good S/N
- Fast readout not yet demonstrated

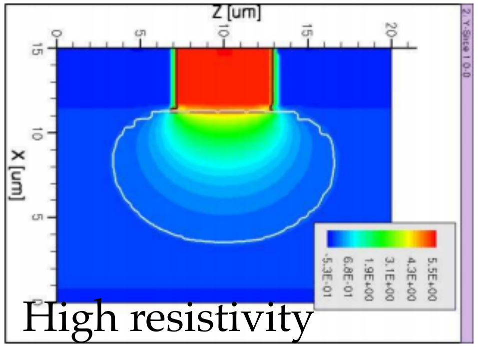

Mimosa 26

M. Winter

Epitaxial layer:

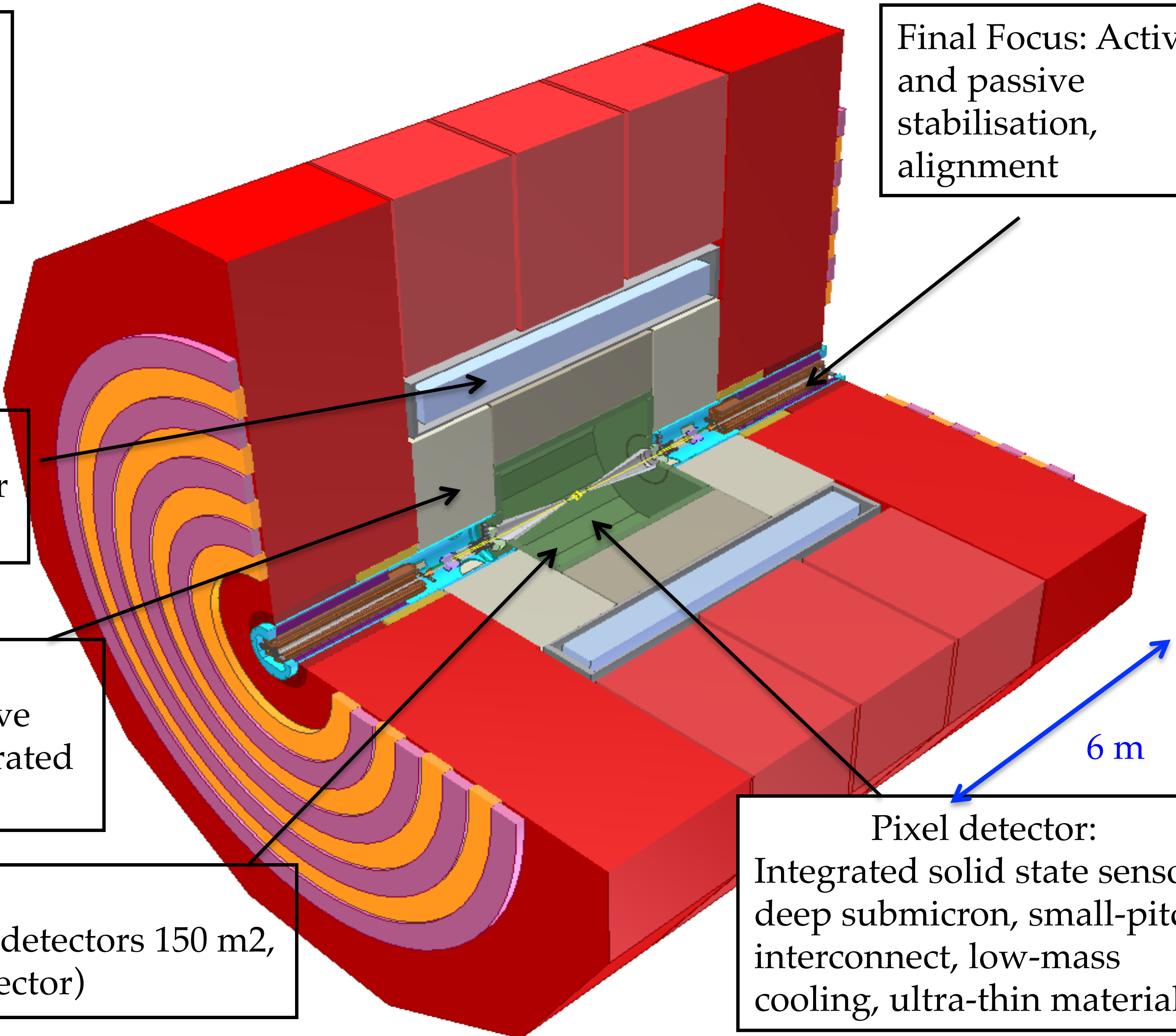


Low resistivity



High resistivity

Hardware R&D on the experiment



Power delivery, on/off at 50Hz, driven by front-end electronics

Final Focus: Active and passive stabilisation, alignment

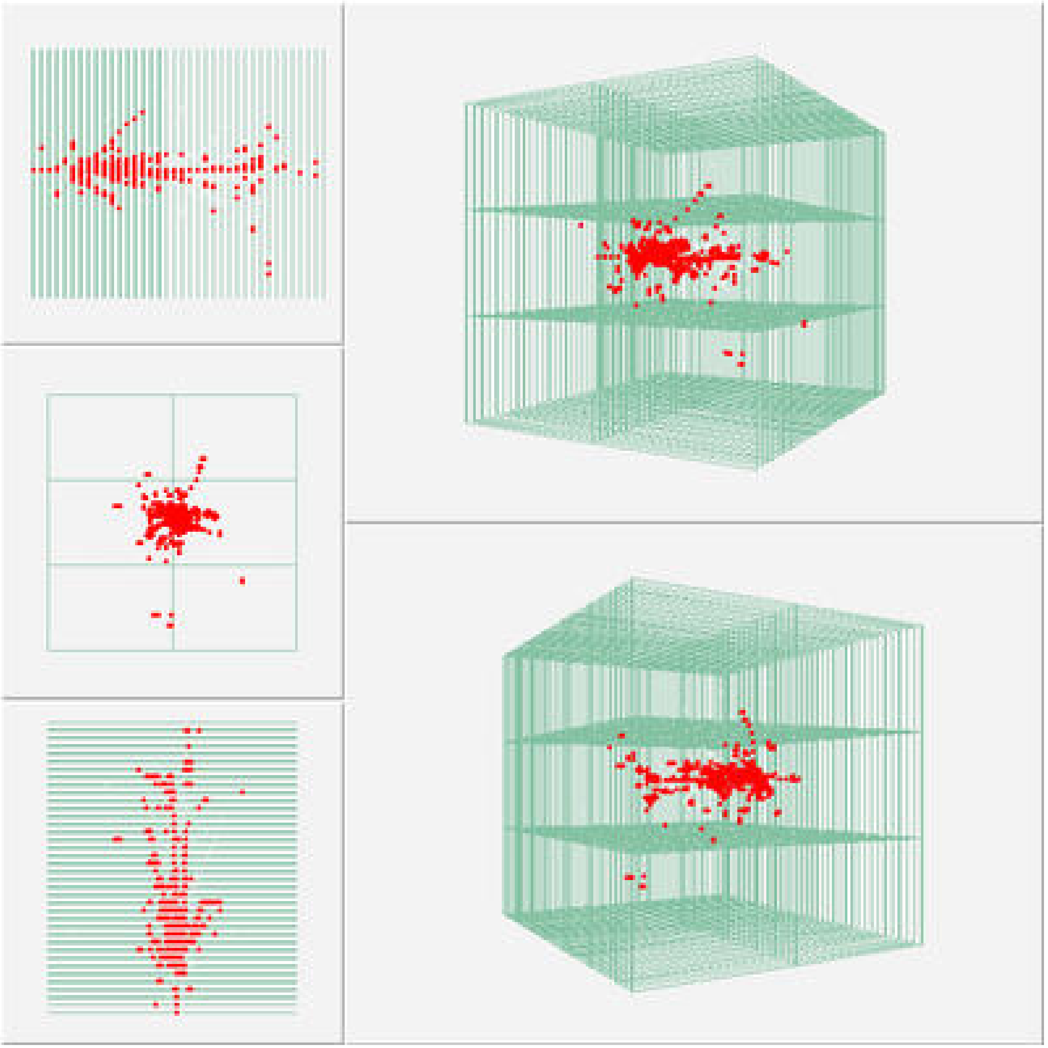
Solenoid coil: Reinforced conductor tests. Materials

Calorimetry: >1000 m2 cost-effective silicon sensors; Integrated HCAL sensor planes

Main tracker (silicon strip detectors 150 m2, TPC gas detector)

Pixel detector: Integrated solid state sensors, deep submicron, small-pitch interconnect, low-mass cooling, ultra-thin materials

RPC digital HCAL testbeam



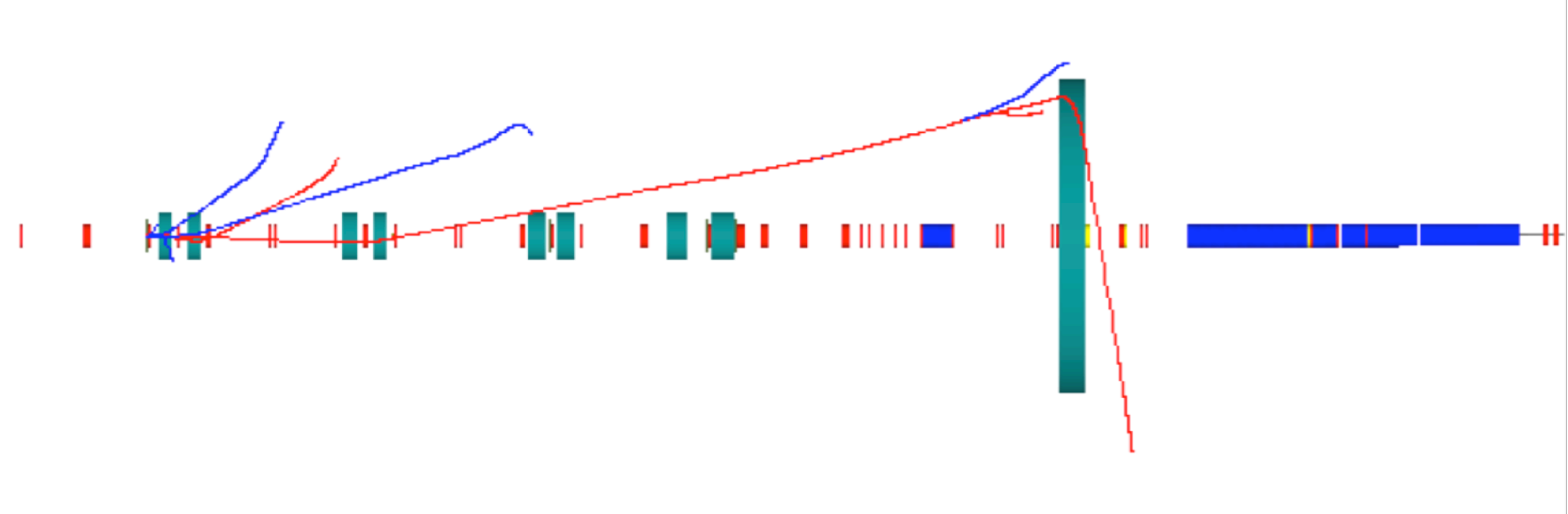
32 GeV pion

With Fe, performed
at Fermilab

Beam Halo Muons

Beam halo muons

- Target muons/bunch crossing < 1
  - muons per lost particle ~ 10^{-4}
  - allowed loss ~10^{-6}
- Muon spoilers gain factor 10, i.e. allowed loss ~10^{-5}
  - further reduction may be possible
- Main halo generation is elastic beam-gas scattering in the BDS
  - expected loss 7 10^{-8}, i.e. 0.05 muons with no spoilers
  - Other sources to be reviewed



Beam Halo muons

- Most work for CDR concentrated on impact of $\gamma\gamma \rightarrow$ hadrons
  - Also looked at beam halo muons
- Simulated events with entire bunch train of beam halo muons
  - For study assumed a bad case: 5 muons/BX through detector

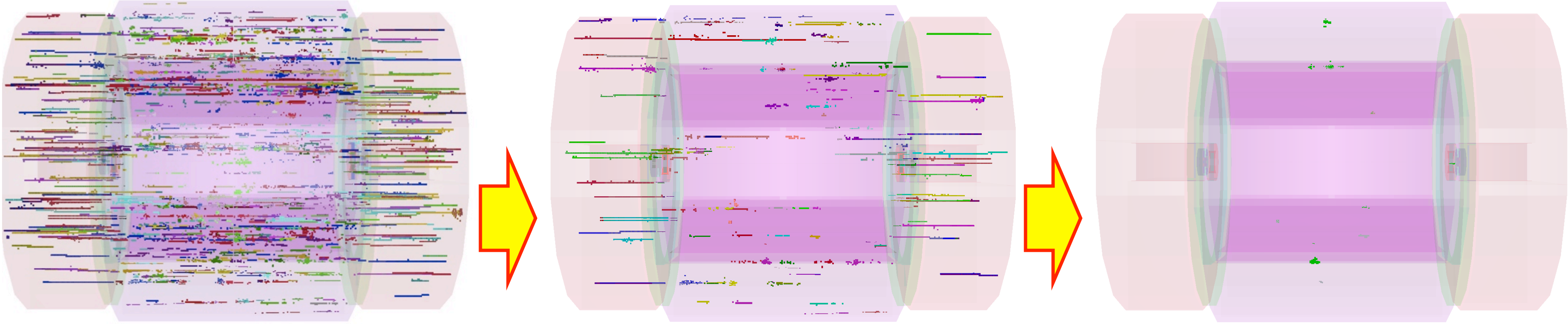
- In 150 ns from start of bunchtrain:
  - ECAL
    - Total = 1.5 TeV (54k hits)
    - Barrel = 0.8 TeV (18k)
    - Endcap = 0.7 TeV (36k)
  - HCAL
    - Total = 10.8 TeV (128k hits)
    - Barrel = 5.3 TeV (32k)
    - Endcap = 5.5 TeV (96k)

For this very conservative level of background:

12 TeV

Software Mitigation

- Three steps of background reduction
  - Initial reconstruction window of 10 ns (50 ns in HCAL barrel)
  - Timing cuts at cluster level (TightPFOSelection)
  - Build in beam halo muon rejection into particle flow reconstruction
- For very conservative assumption of 5 muons per BX



Readout window

TightPFOSelection

+ dedicated reco. Alg.

2.2 TeV

420 GeV

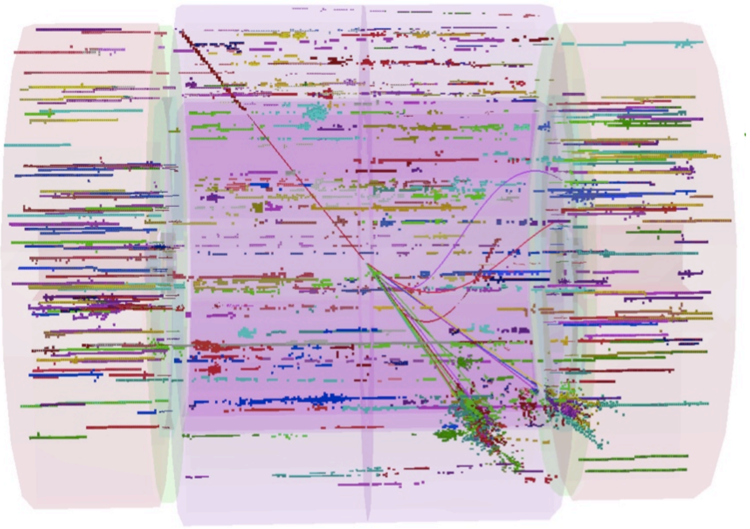
30 GeV

- Background rejection very effective due to high granularity calorimeters

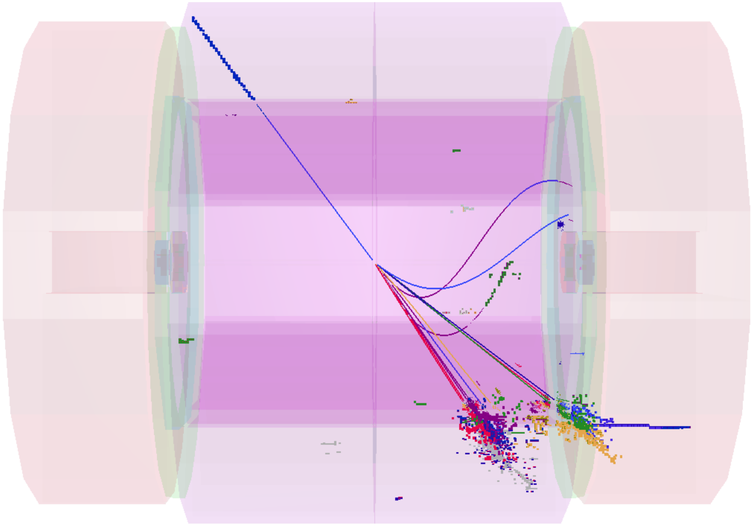
Impact on Physics

- Tested in by looking at W reconstruction in $W^+W^- \rightarrow q\bar{q}\mu\nu$
  - Sample of 500 GeV hadronic W decays
  - Again very conservative assumptions (5 muons/BX)
- Two effects observed
  - Extra energy from clusters from beam halo muons: 30 GeV
  - Energy of reconstructed jets also biased “pick” up hits from muons: 30 GeV

Readout window



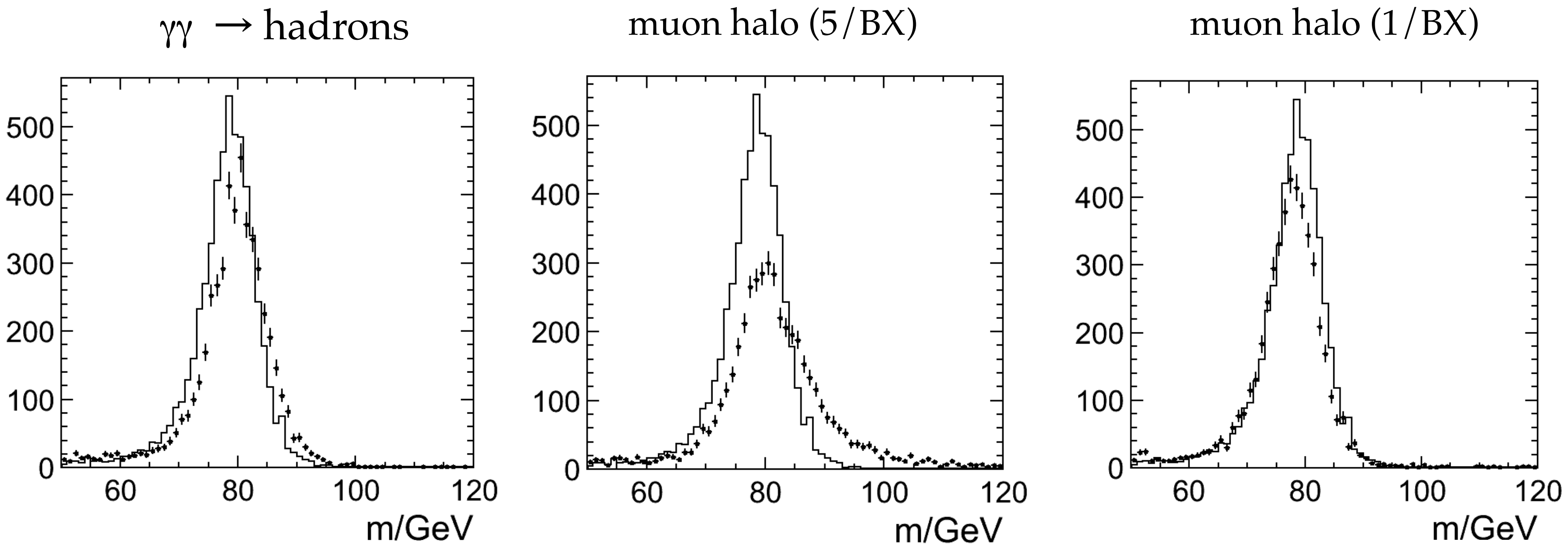
TightPFOSelection + reco. alg.



Impact on W Reconstruction

- Compare W mass reconstruction
  - no background
  - γγ → hadrons
  - 5 muons per BX (very conservative)
  - 1 muon per BX (conservative)

} Worst case as pattern recognition not optimal

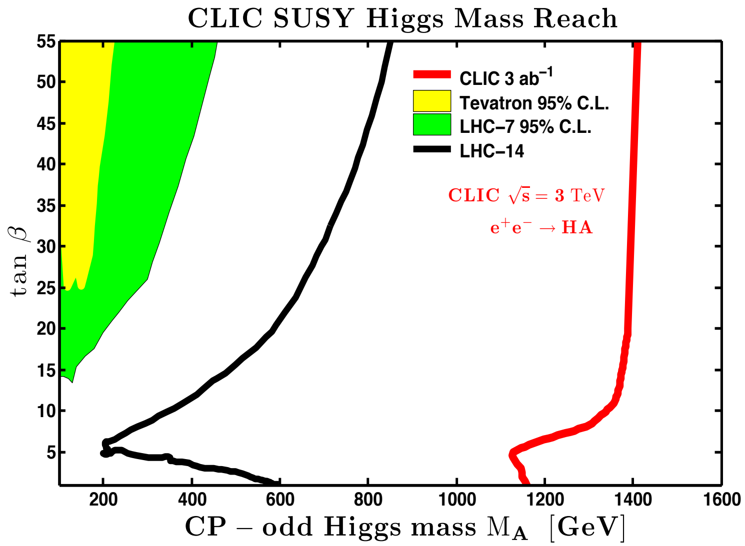


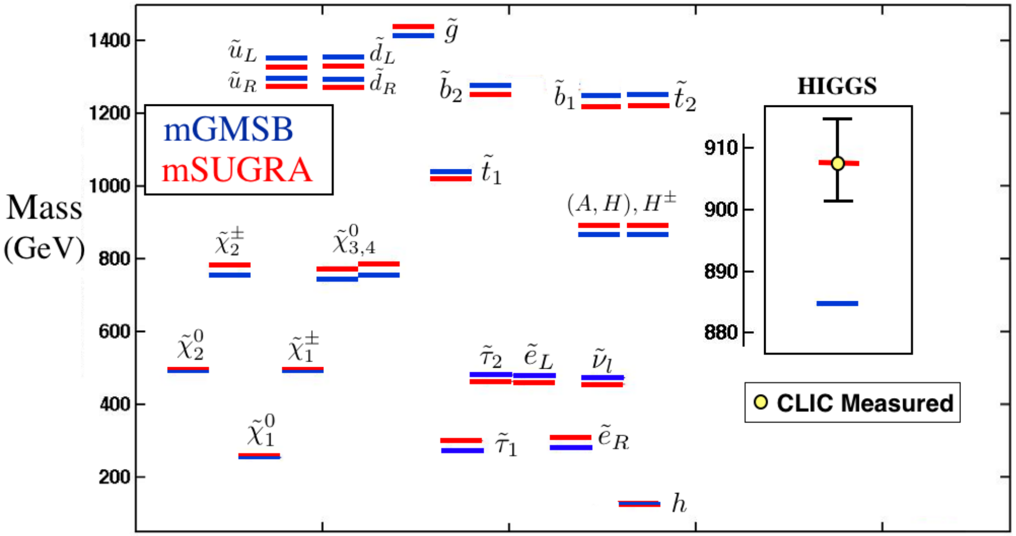
➢ Conclude: a beam halo muon background of 1 muon/BX is acceptable
  - Machine background likely to be much lower than this

Backup slides
- physics examples

Susy

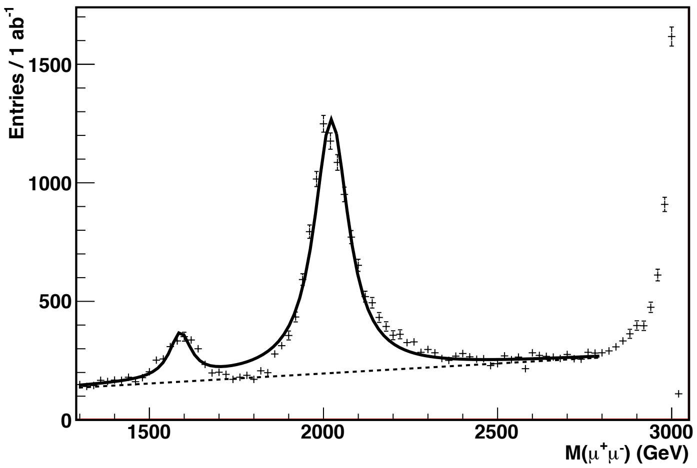
- Search reach in the $m_A - \tan\beta$ plane for LHC and CLIC. The left-most coloured regions are current limits from the Tevatron with ~7.5 fb^{-1} of data at $\sqrt{s} = 1.96$ TeV and from ~1 fb^{-1} of LHC data at $\sqrt{s} = 7$ TeV.
- Black line is projection of search reach at LHC with $\sqrt{s} = 14$ TeV and 300 fb^{-1} of luminosity.
- Right-most red line is search reach of CLIC in the HA mode with $s = 3$ TeV.



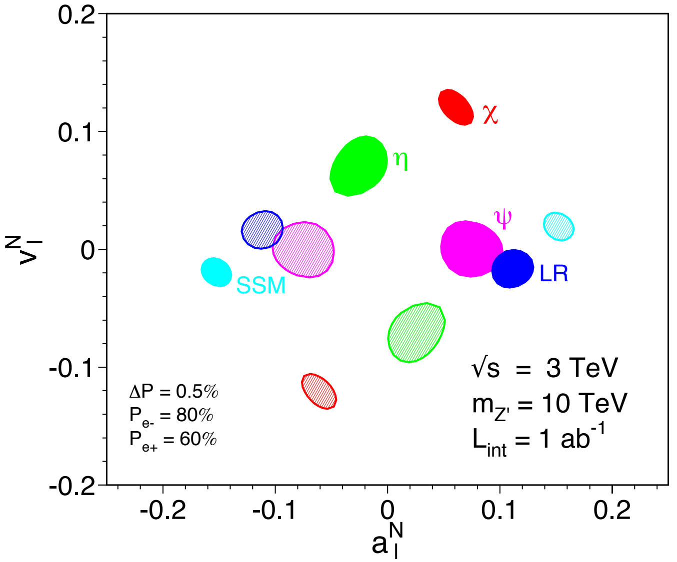


- Resolving SUSY breaking models and masses with CLIC: Shown are the nearly degenerate spectra of a mSUGRA model and a mGMSB model.
- Assuming some of the SUSY masses are measured, with a spectrum of the type above predicted by the different models of Supersymmetry breaking, CLIC would be able to discern not only some of the slepton masses and the heavier charginos within the two models, but also the SUSY Higgs masses.

Heavy gauge boson



Observation of new gauge boson resonances in the $\mu^+\mu^-$ channel by auto-scan at 3 TeV. The two resonances are the $Z_{1,2}$ predicted by the 4-site Higgsless model



Expected resolution with $\sqrt{s} = 3$ TeV and 1 ab^{-1} on the “normalised” leptonic couplings of a 10 TeV Z′ in various models, assuming lepton universality. The couplings can be determined up to a twofold ambiguity.

- Z′ mass is assumed to be unknown.
- χ, η, ϕ refer to various linear combinations of *U(1)* subgroups of *E6;* the SSM has the same couplings as the SM Z; and, LR is *U(1)* surviving in Left-Right model.