the CLIC detector

Lucie Linssen

on behalf of the many contributors
to the CLIC detector study

http://lcd.web.cern.ch/LCD/

Outline

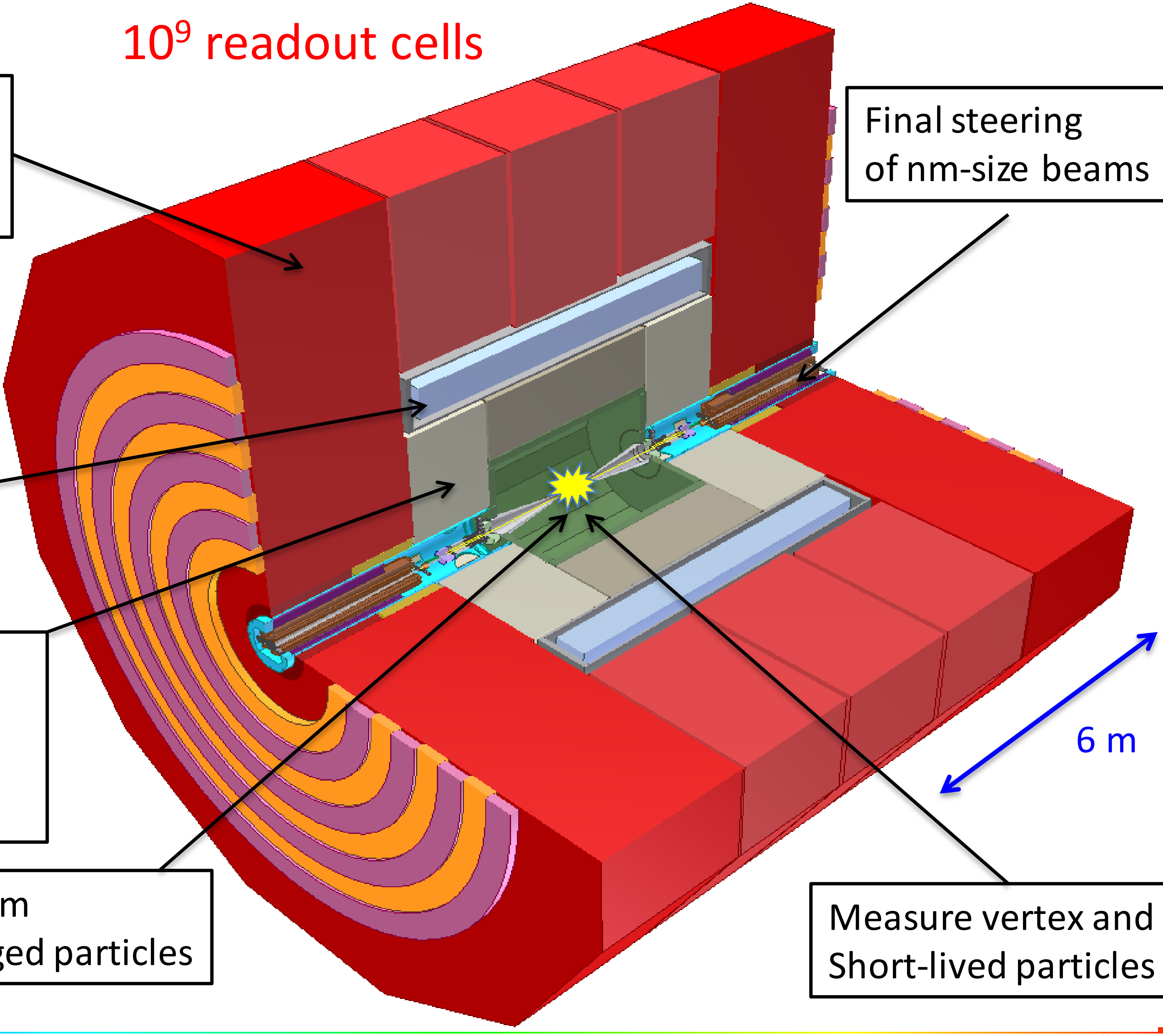
- Detector overview
  - Comparison with CMS
- Detector challenges at CLIC
  - Comparison to LHC
- Detector concepts, overview
- Beam-induced background
- Sub-detectors at CLIC
  - Vertex detector
  - Tracking
  - Hadron Calorimetry and Particle Flow Analysis (PFA)
  - Muon instrumentation
- Background suppression at CLIC
- Detector benchmark studies
- R&D plans

(S)LHC, ILC, CLIC reach

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

Gian Giudici, CERN

Linear Collider experiment



10^9 readout cells

Field return and muon particle identification

Final steering of nm-size beams

B-field for momentum and charge measurement

Energy measurement of (charged and) neutral particles

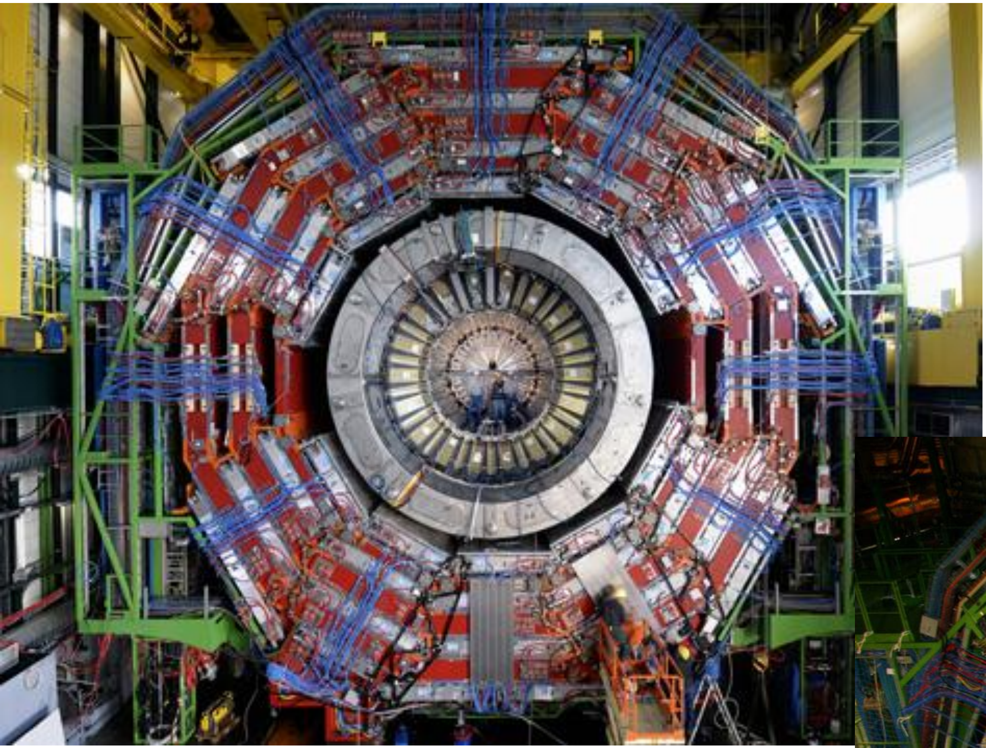
Measure momentum and charge of charged particles

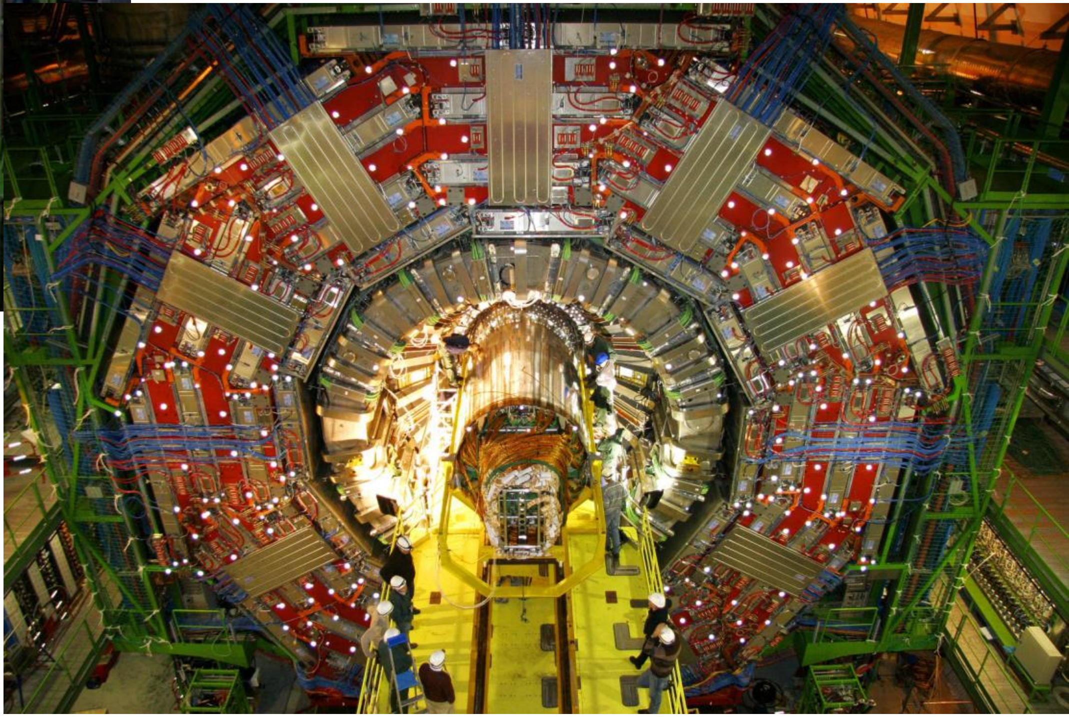
Measure vertex and Short-lived particles

… similar to CMS experiment

https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

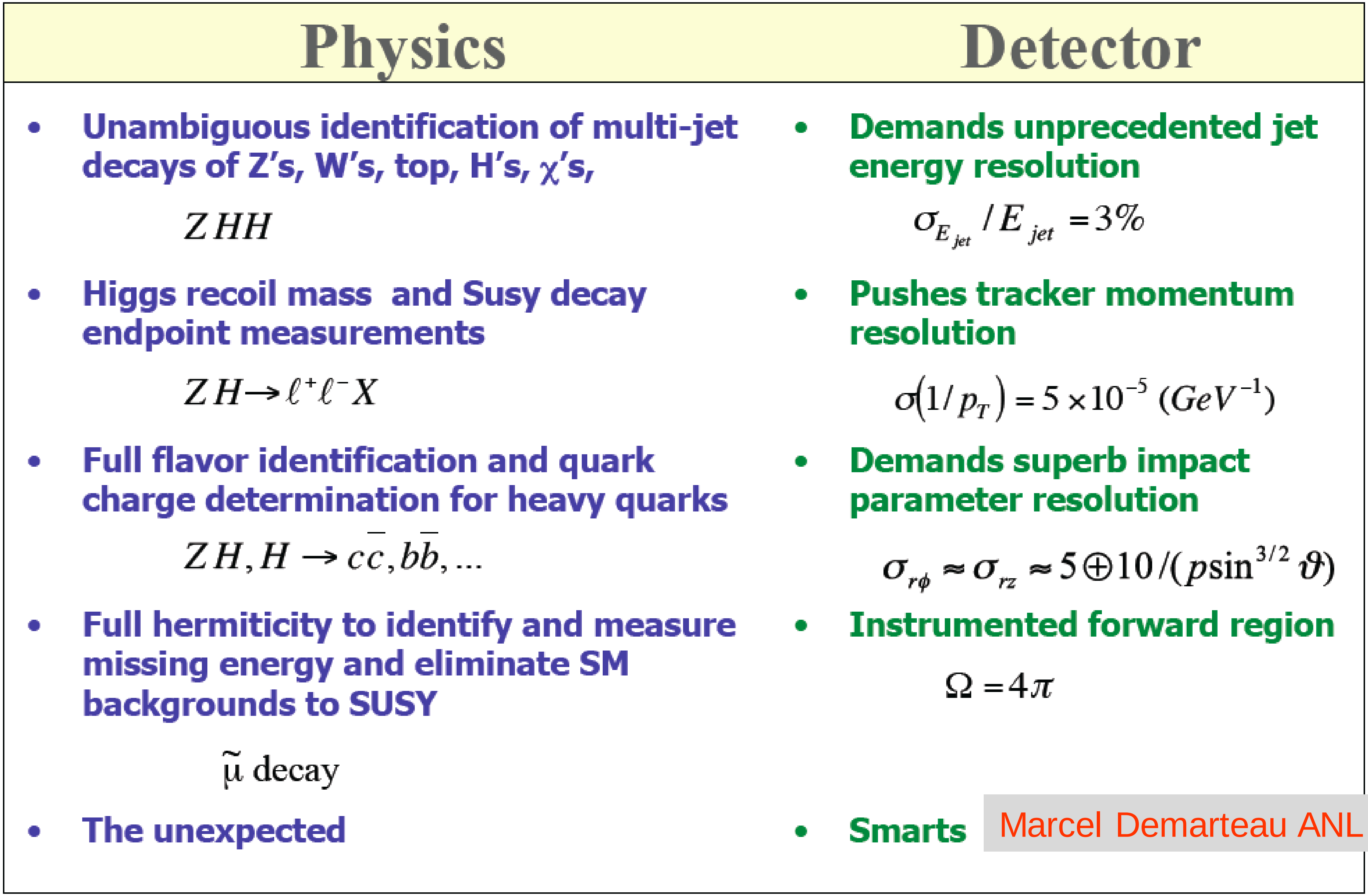
How does it work?





CMS tracker insertion in 2007

LC detector design challenges



Physics	Detector
Unambiguous identification of multi-jet decays of Z's, W's, top, H's, χ's, ZHH	Demands unprecedented jet energy resolution $\sigma_{E_{jet}}/E_{jet} = 3\%$
Higgs recoil mass and Susy decay endpoint measurements $ZH \rightarrow \ell^+\ell^- X$	Pushes tracker momentum resolution $\sigma(1/p_T) = 5 \times 10^{-5}\ (GeV^{-1})$
Full flavor identification and quark charge determination for heavy quarks $ZH, H \rightarrow c\bar{c}, b\bar{b}, \ldots$	Demands superb impact parameter resolution $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p\sin^{3/2}\vartheta)$
Full hermiticity to identify and measure missing energy and eliminate SM backgrounds to SUSY $\tilde{\mu}$ decay	Instrumented forward region $\Omega = 4\pi$
The unexpected	Smarts

Marcel Demarteau ANL

Comparison CLIC ⇔ LHC detector

In a nutshell:

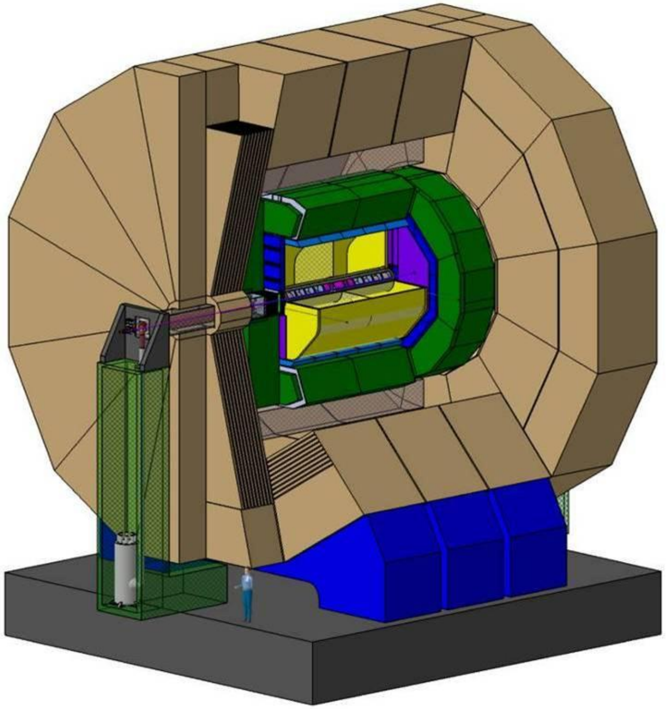
CLIC detector:

- **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**

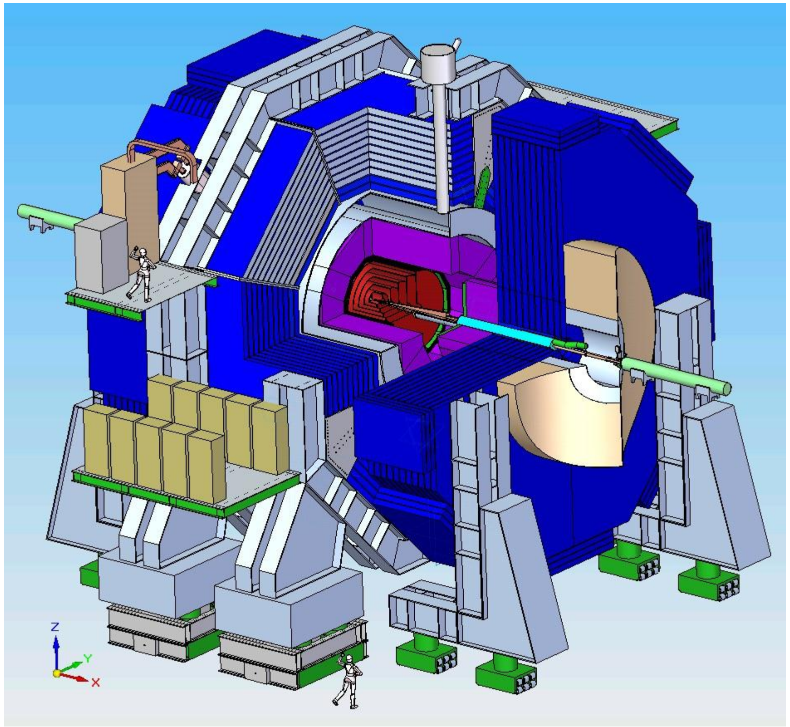
LHC detector:

- **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**

CLIC detector derived from ILC concepts



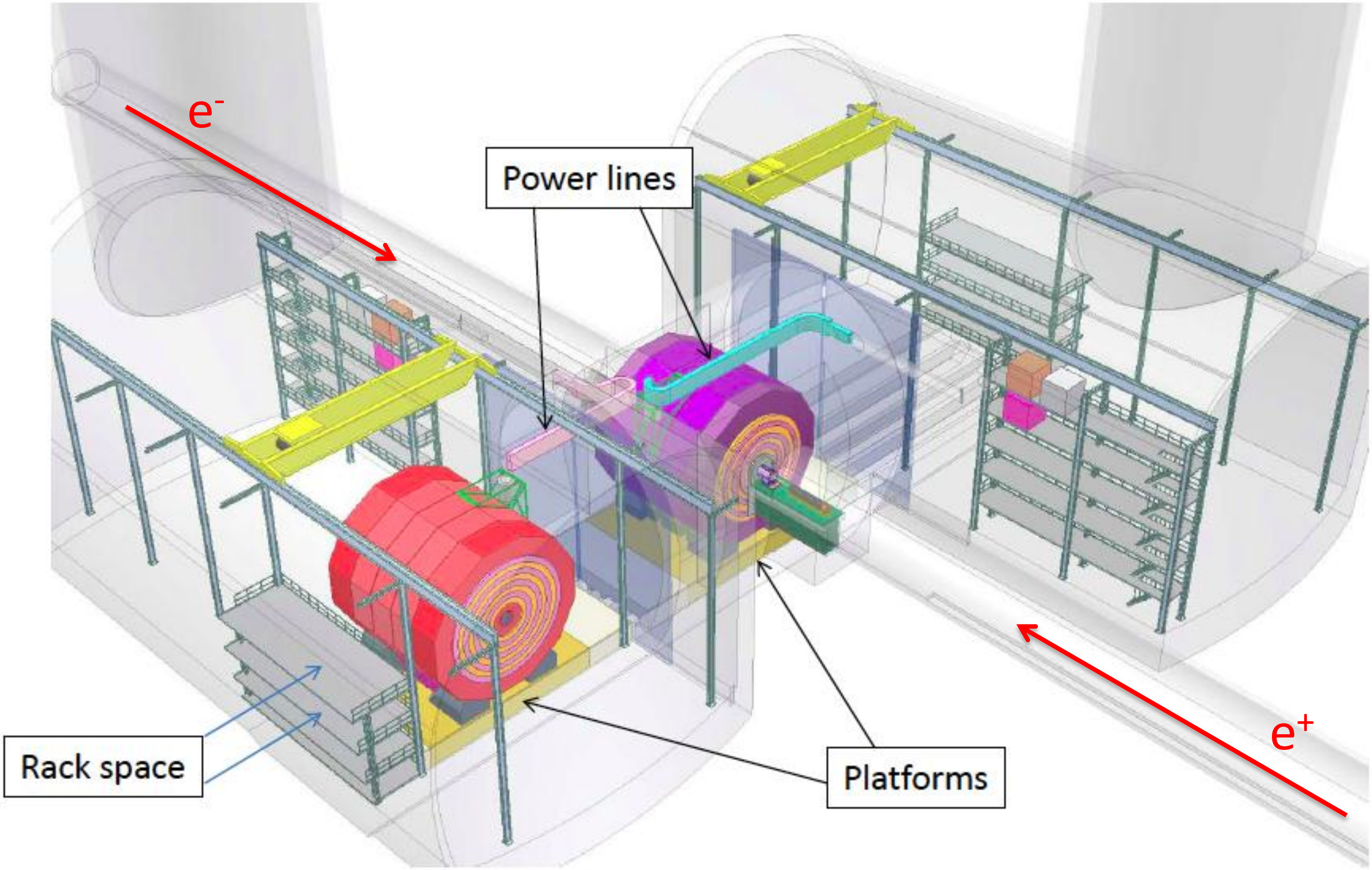
ILD



SiD

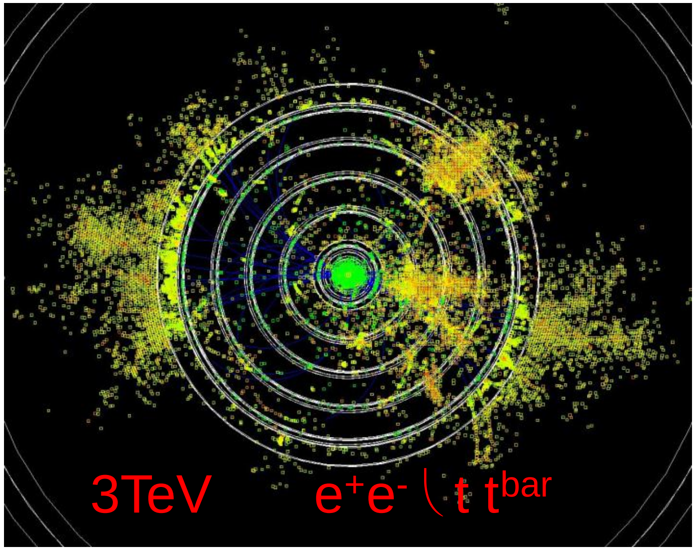
CLIC detector concepts are based on SiD and ILD concepts from ILC.
Modified to meet CLIC requirements

Two experiments in push-pull

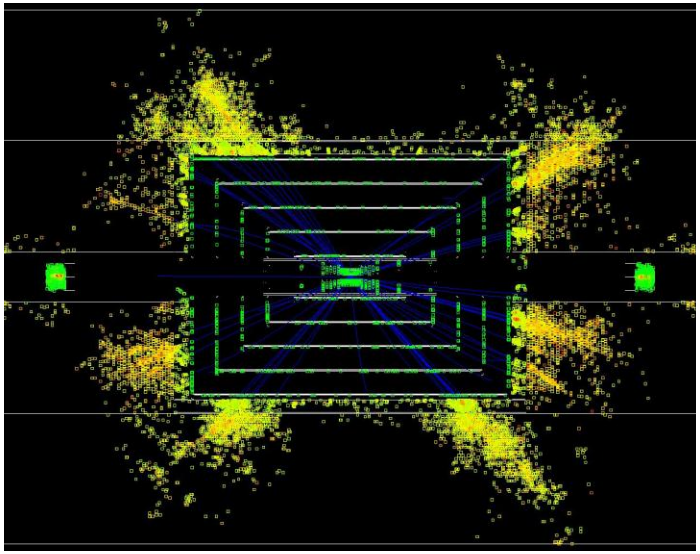


Why ILC concepts need changes for CLIC

- Due to beam-induced background and short time between bunches:
  - High occupancy in the inner regions (incoherent pairs)
  - Jet energy scale and resolution are affected (γγ=>hadrons)
  - => All detectors need precise (few nsec) time-tagging of hits
- Narrow jets at high energy
  - Calorimeter has to measure high-energy particles
  - Calorimeter needs to be deeper, but without increasing coil size

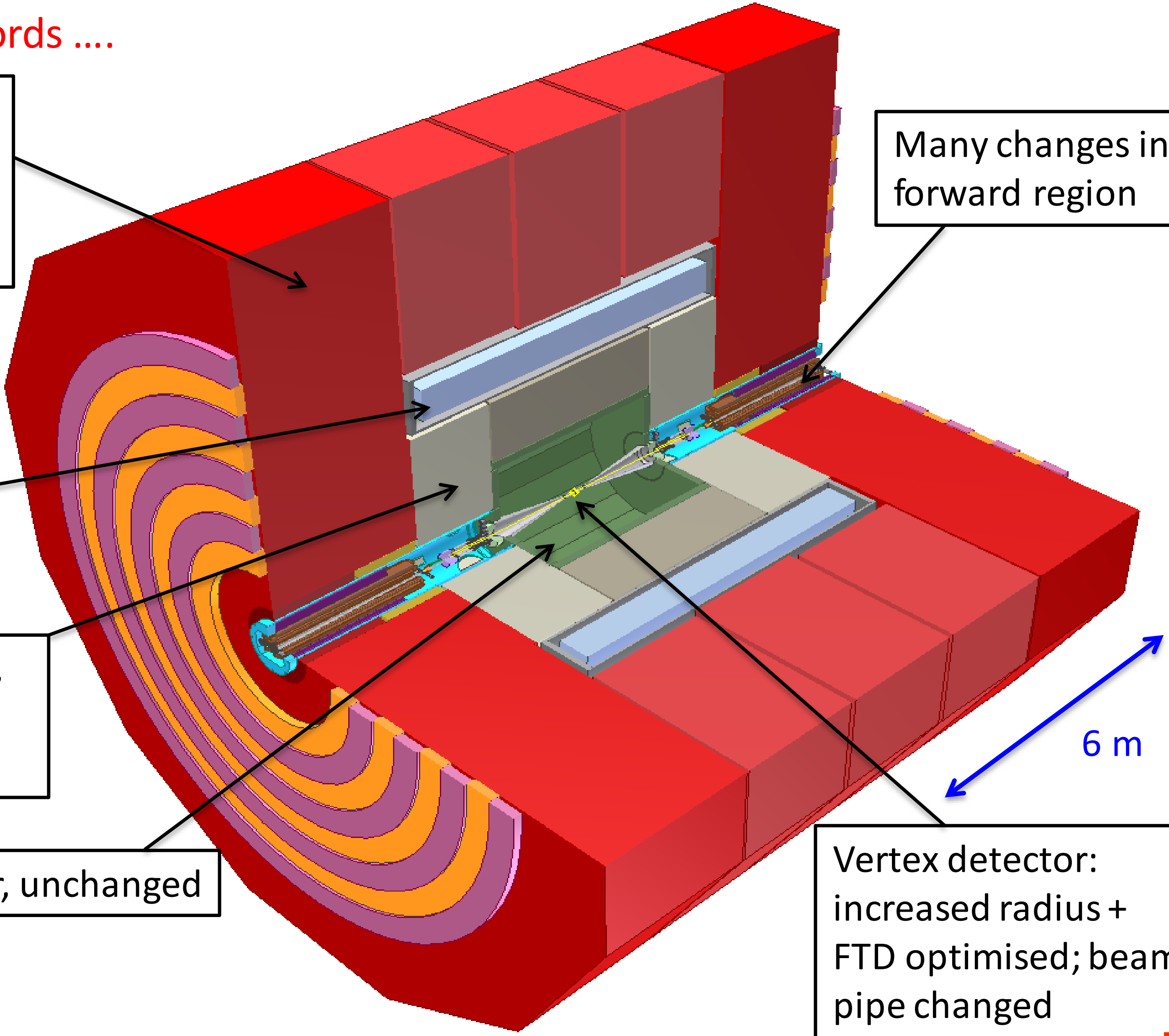


3TeV $e^+e^- \to t\,t^{bar}$



Changes to ILD for CLIC

… in a few words ….



Yoke dimensions and Yoke instrumentation layout changed

Many changes in forward region

Solenoid at 4T, dimensions ~unchanged

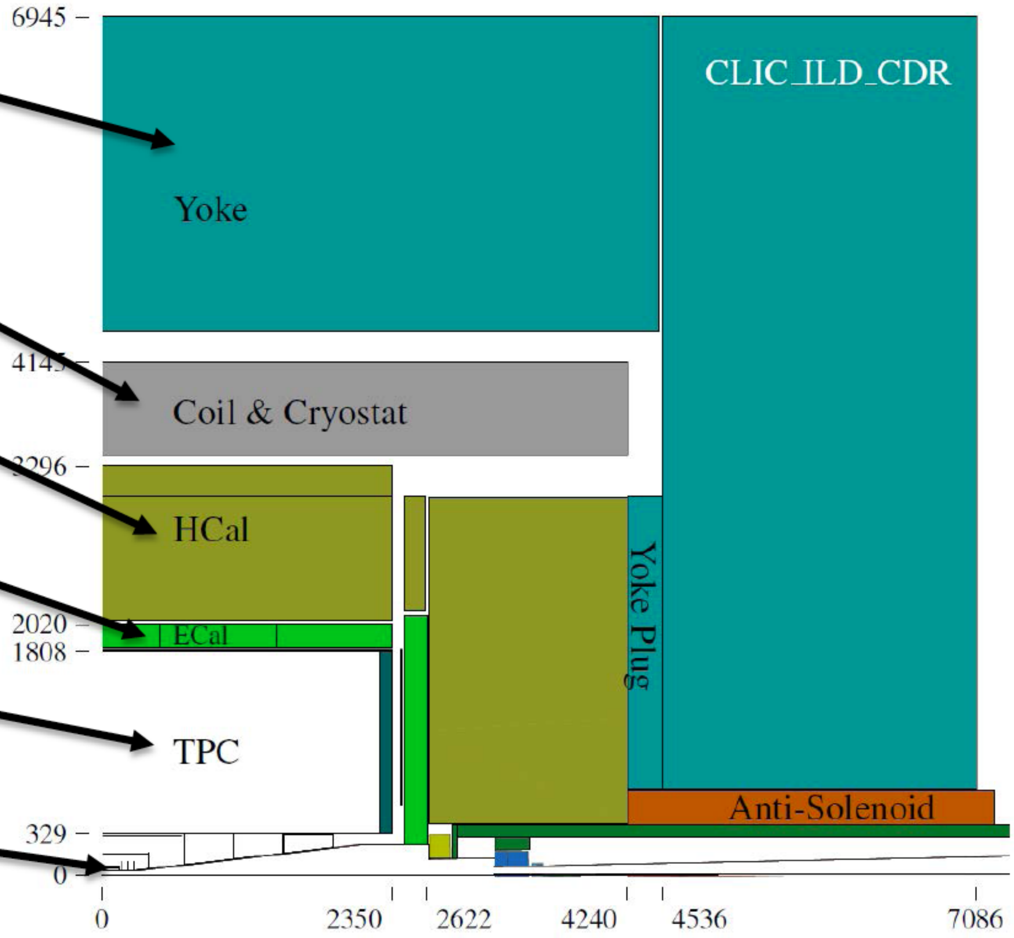
Calorimetry, 7.5 Λ_i, tungsten barrel, steel end-cap

Main tracker, unchanged

Vertex detector: increased radius + FTD optimised; beam pipe changed

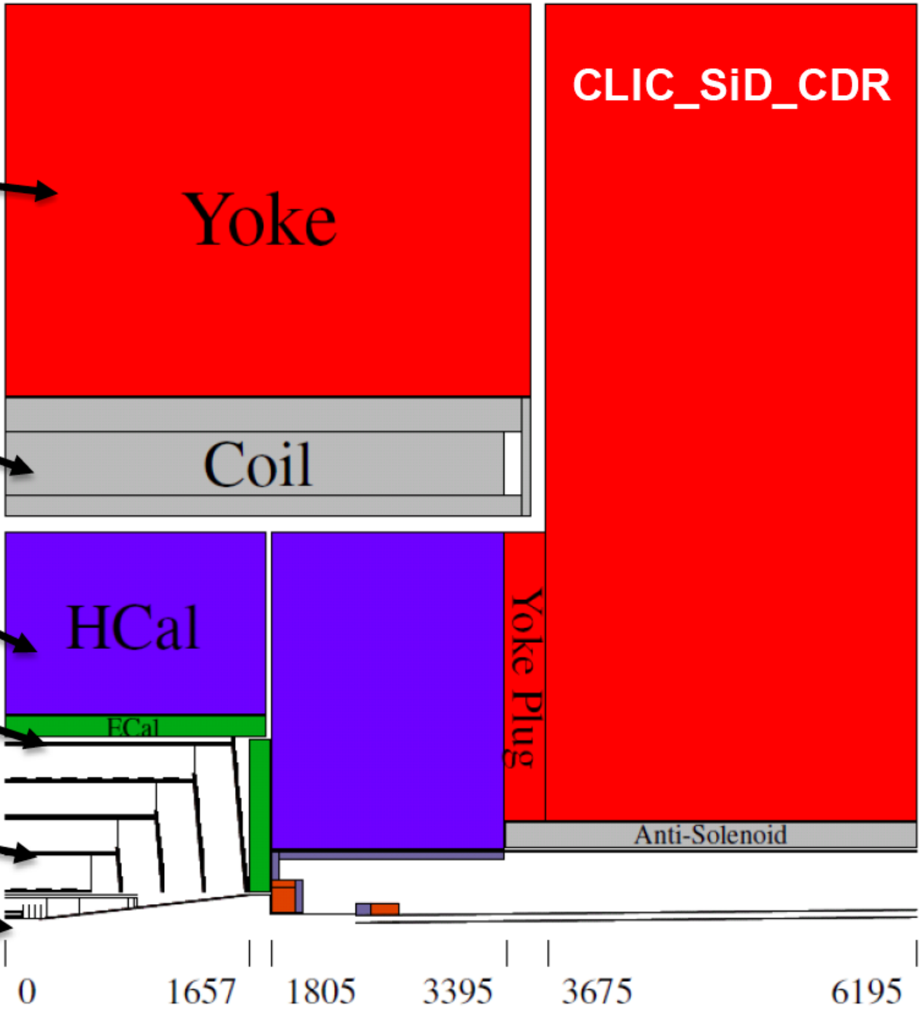
CLIC_ILD

- Instrumented return yoke
- 4T solenoid
- Highly granular HCal
  - Tungsten instead of steel to keep coil size
- Highly granular Si-W ECal
- Large main tracker (r = 1.8 m) Time projection chamber
- Silicon Pixel Vertex Detector
  - Increased inner Radius



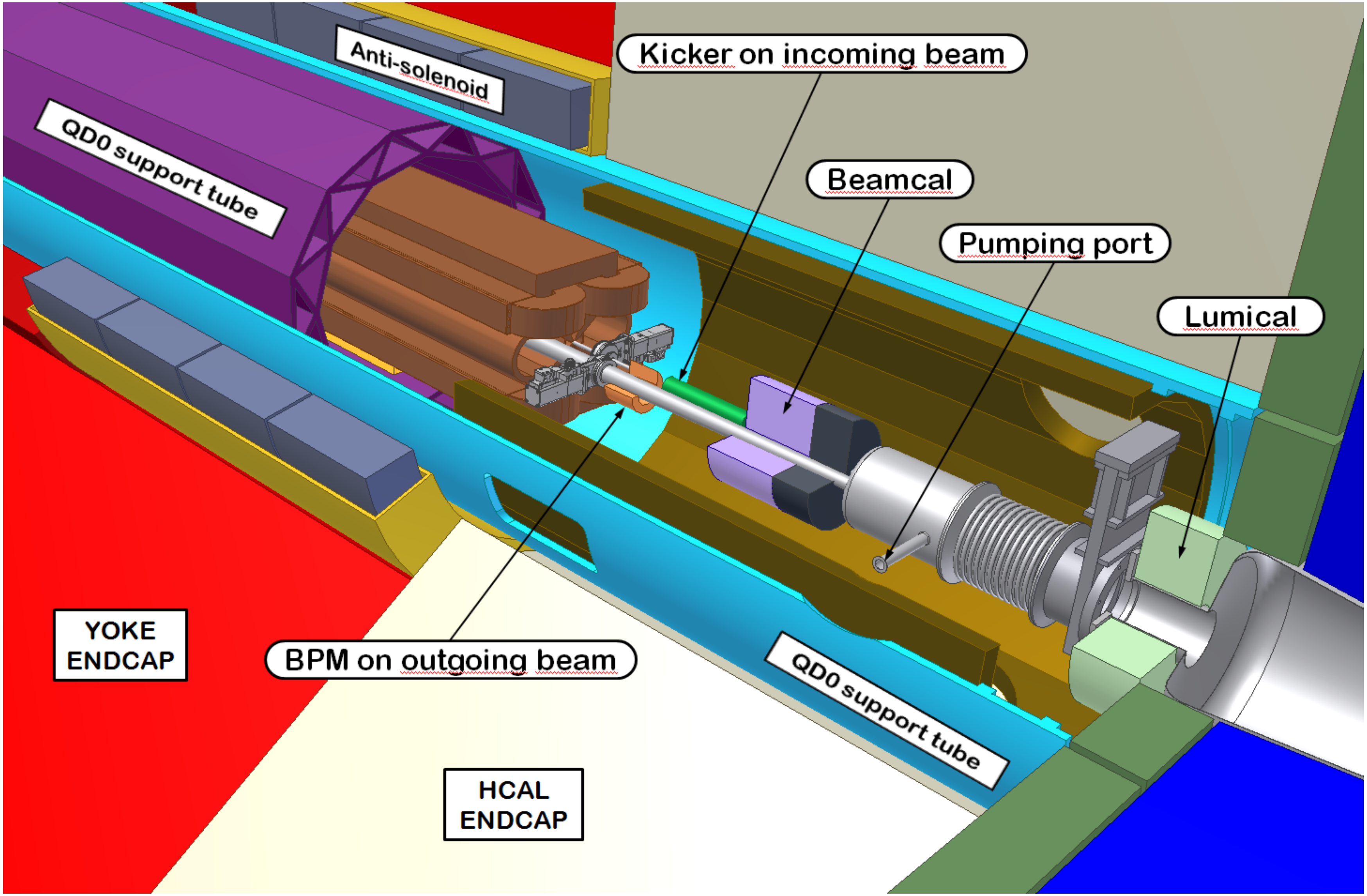
These images are derived from the simulation models for the CDR

CLIC_SiD



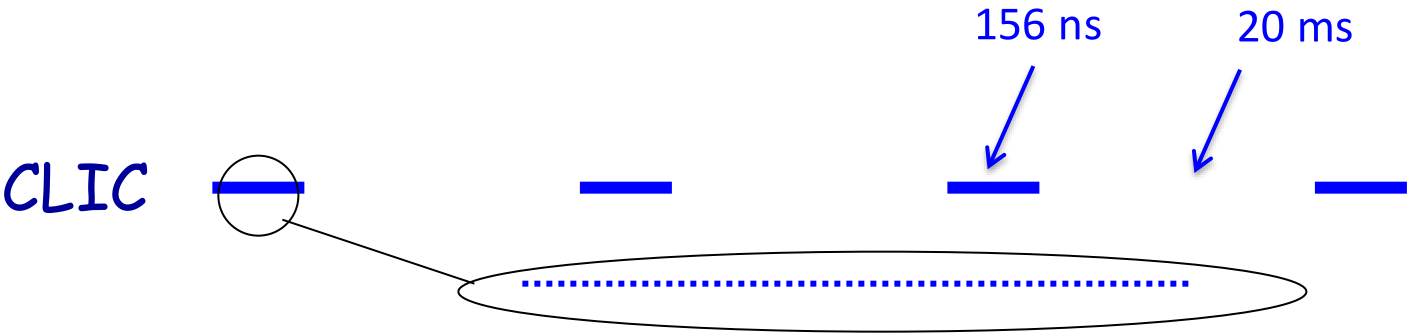
- Instrumented return yoke
- 5T solenoid
- Highly granular HCal
  - ➢ Tungsten instead of steel to keep coil size feasible
- Highly granular Si-W ECal
- Silicon strip tracker (r = 1.2 m)
- Silicon Pixel Vertex Detector
  - ➢ Increased inner Radius

Details of forward detector region



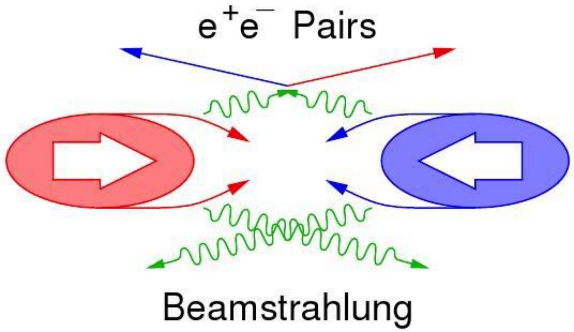
CLIC time structure

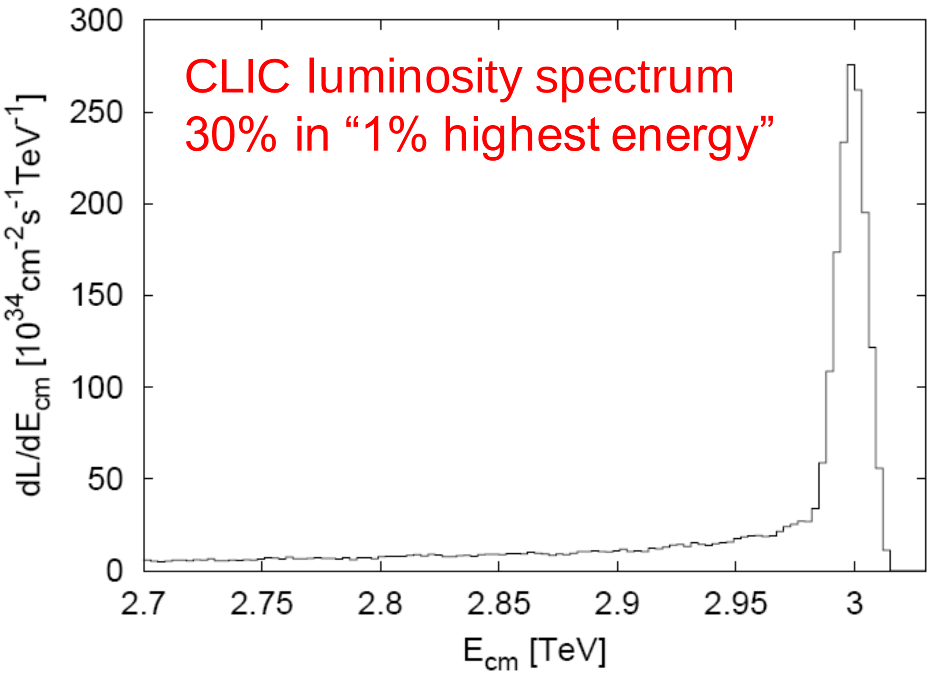
Train repetition rate 50 Hz



CLIC:	1 train = 312 bunches	0.5 ns apart	50 Hz
ILC:	1 train = ~1312 bunches	~738 ns apart	5 Hz

Beam-induced background (1)



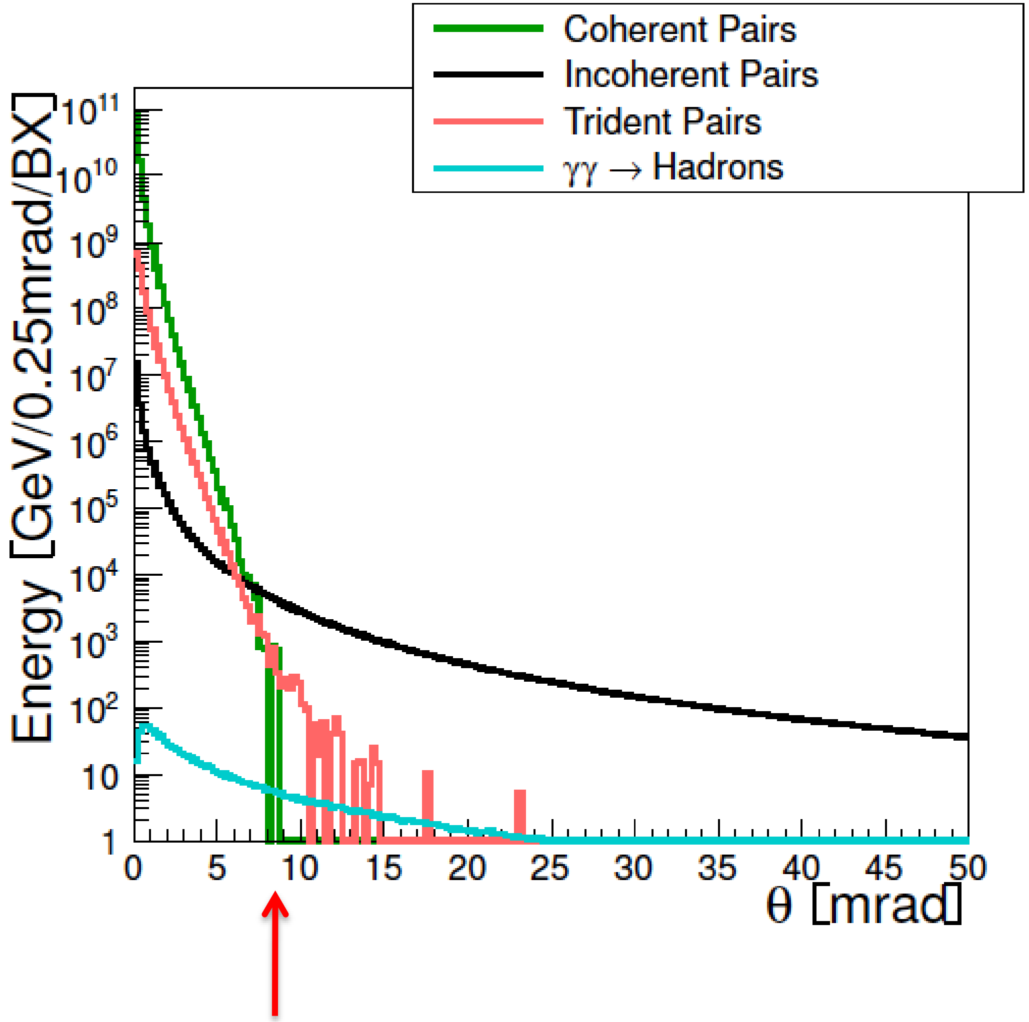


Main backgrounds:

- CLIC 3TeV beamstrahlung ΔE/E = 29% (10×ILC$_{value}$)
  - **Coherent pairs** (3.8×10^8 per bunch crossing) <= disappear in beam pipe
  - **Incoherent pairs** (3.0×10^5 per bunch crossing) <= suppressed by strong solenoid-field
  - γγ interactions => hadrons (**3.2 hadron events per bunch crossing**)

- In addition: Muon background from beam delivery system(~5 muons per bunch crossing) <= spread over detector surface

Beam-induced background (2)



Coherent pairs:

Very numerous at very low angles

Very high total energy

Incoherent pairs:

Extend to larger angles

More difficult for the detector

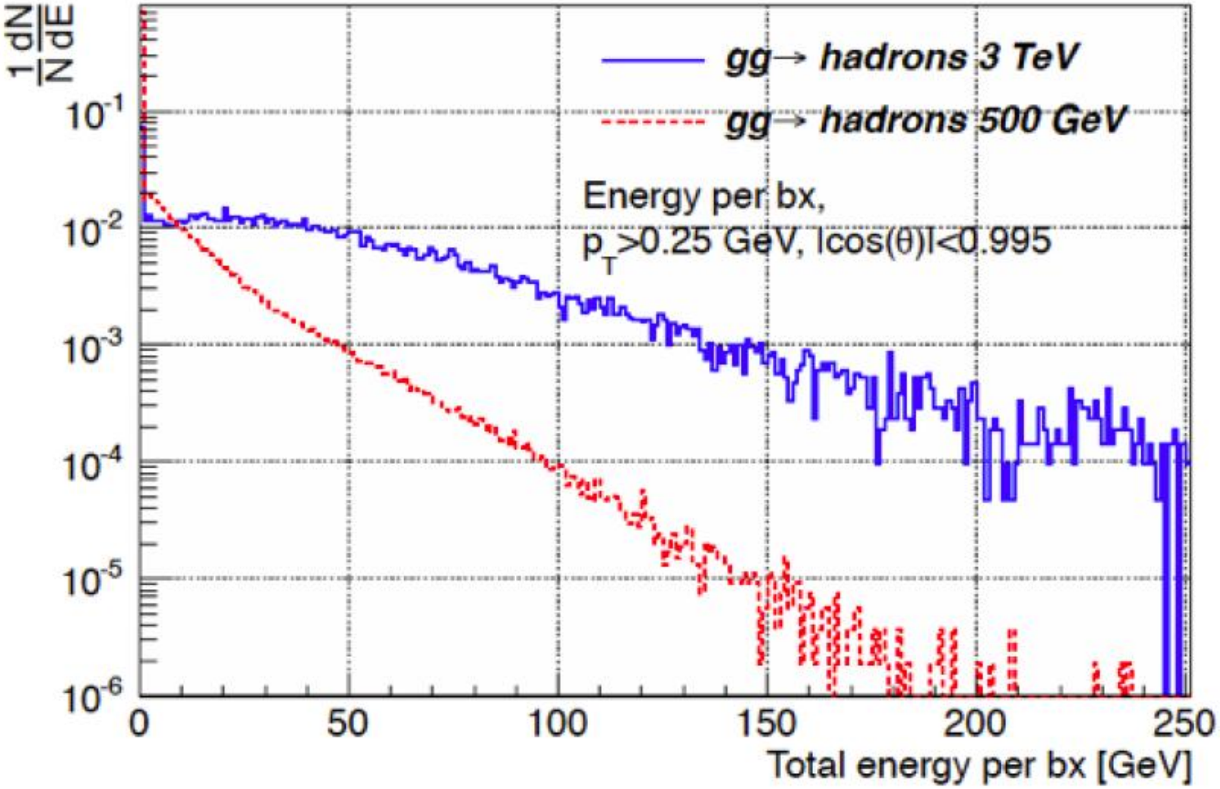
A. Sailer

Determines beam crossing angle (20 mrad)

Determines opening angle of beam pipe for outgoing beam (±10 mrad)

Beam-induced background (3)

CLIC beamstrahlung: γγ ➔ hadrons



Per bunch crossing:

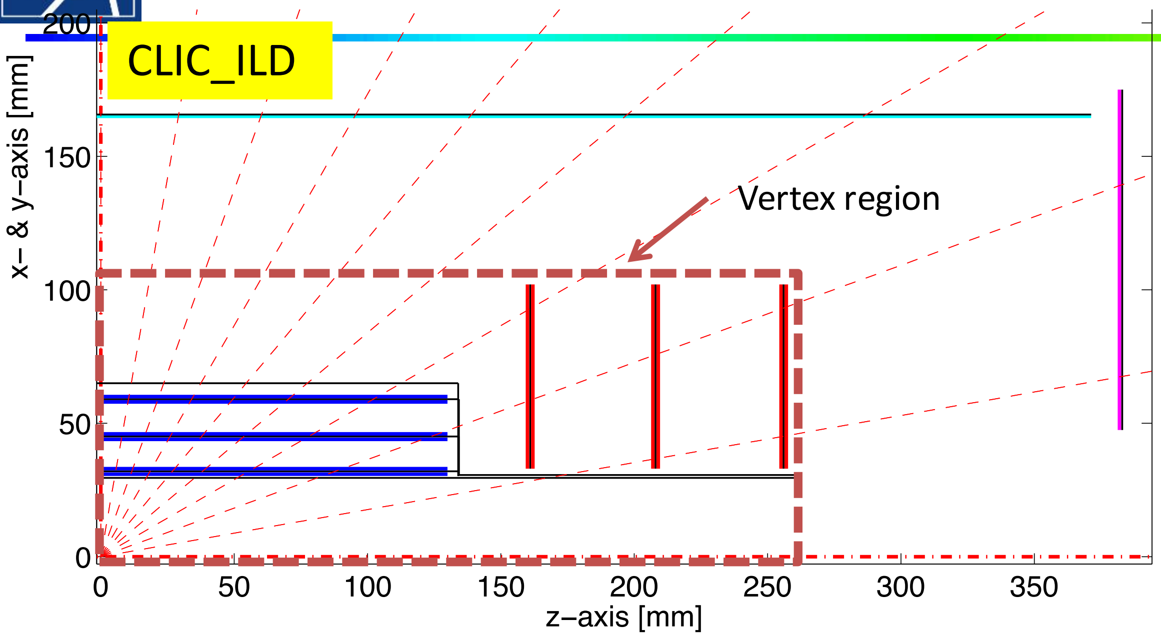
- 3.2 such events
- ~28 particles into the detector
- 50 GeV
- Forward-peaked

15 TeV dumped in the detector per 156 ns bunch train !

we need
TIME STAMPING !
…and play with clever event selections

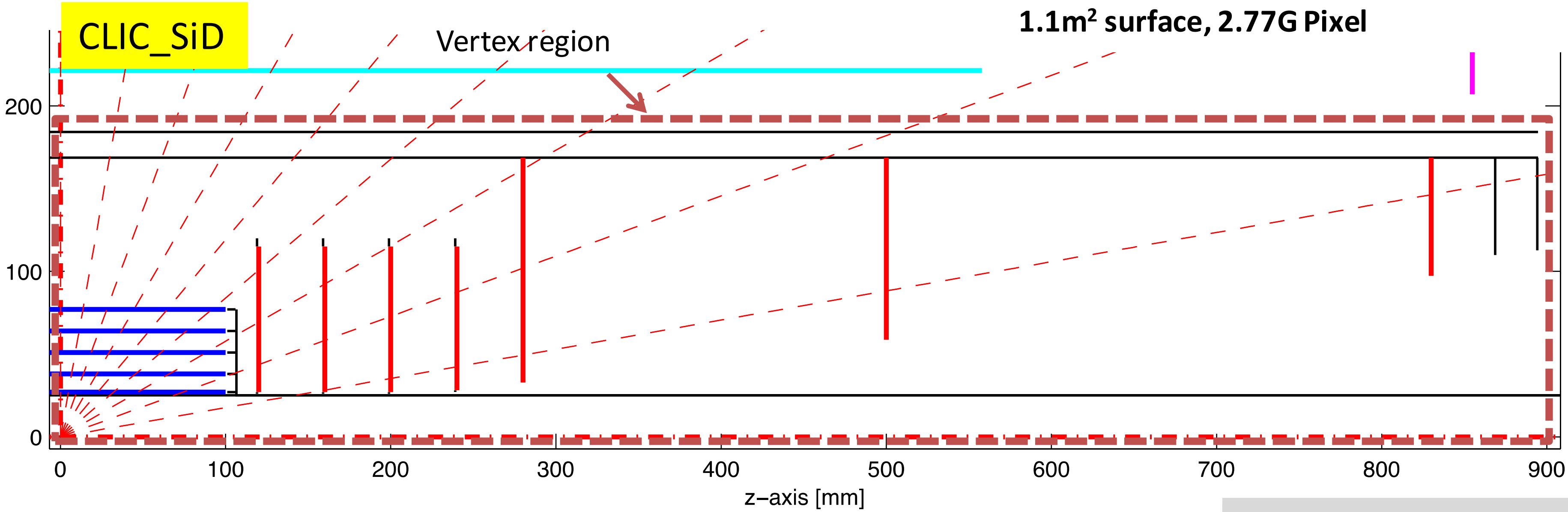
D. Dannheim

CLIC vertex detector region



CLIC_ILD
3 double layers of pixel cylinders
3 double layers of pixel disks
20 µm pixels, analog readout, σ_{sp}=2.8 µm
X=0.18% X0 / double layer
0.74m^2 surface, 1.84G Pixel

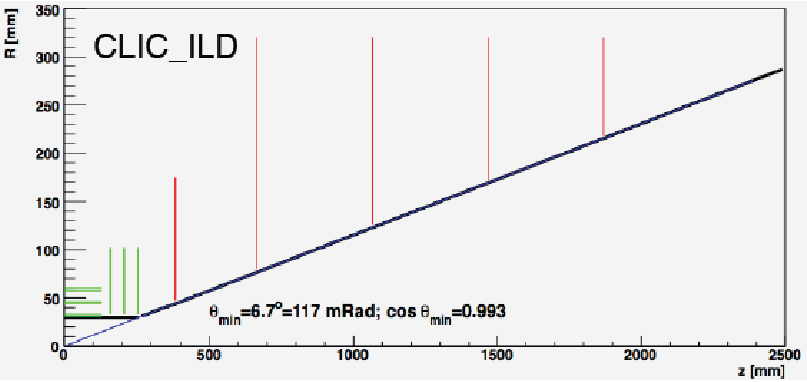
CLIC_SiD
5 single layers of barrel pixel cylinders
7 single layers of forward pixel disks
20 µm pixels, binary (analog) r/o,
σ_{sp}=3-4 µm
X=0.12% X0 / single layer
1.1m^2 surface, 2.77G Pixel

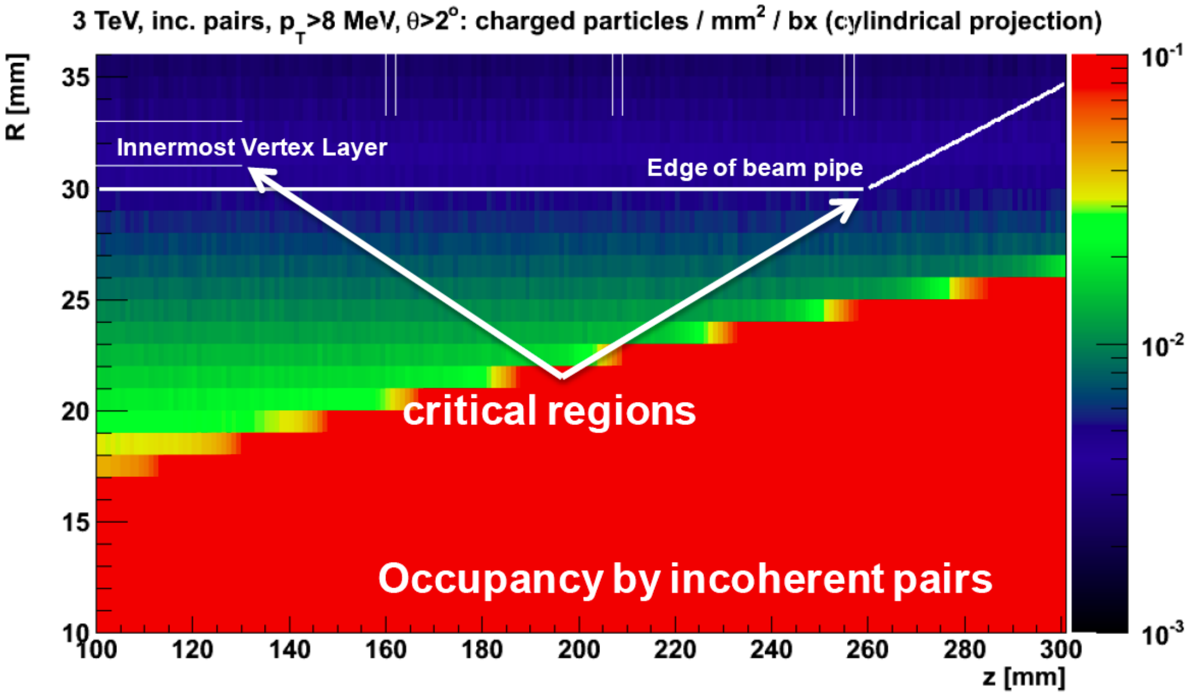


D. Dannheim, CERN

CLIC_ILD vertex detector

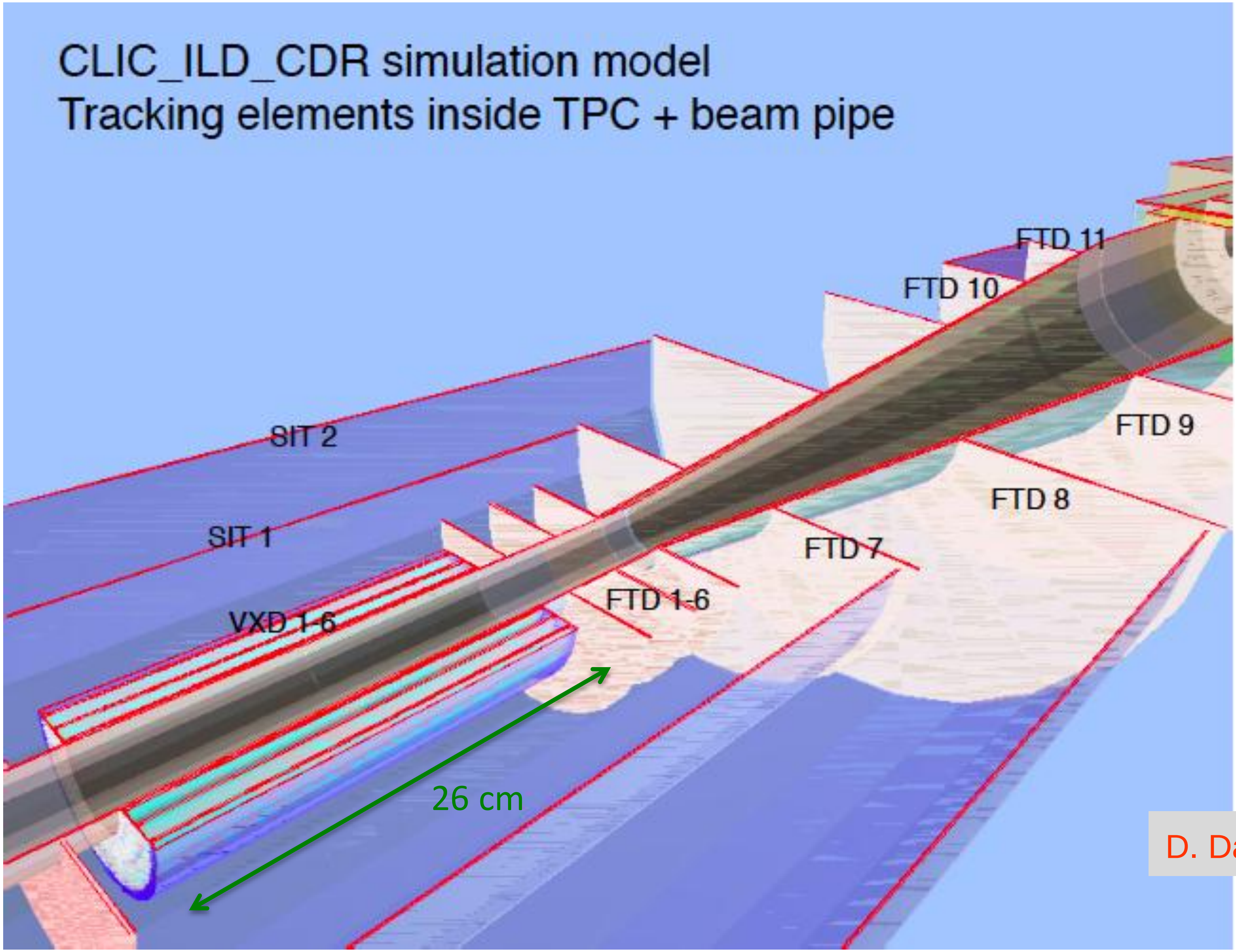
- Vertex detector needs to be as close as possible to the interaction point
- Need to keep occupancy (particle density) as low as possible in critical regions
  - Innermost vertex layer => direct hits
  - Beam pipe => creation of secondary particles





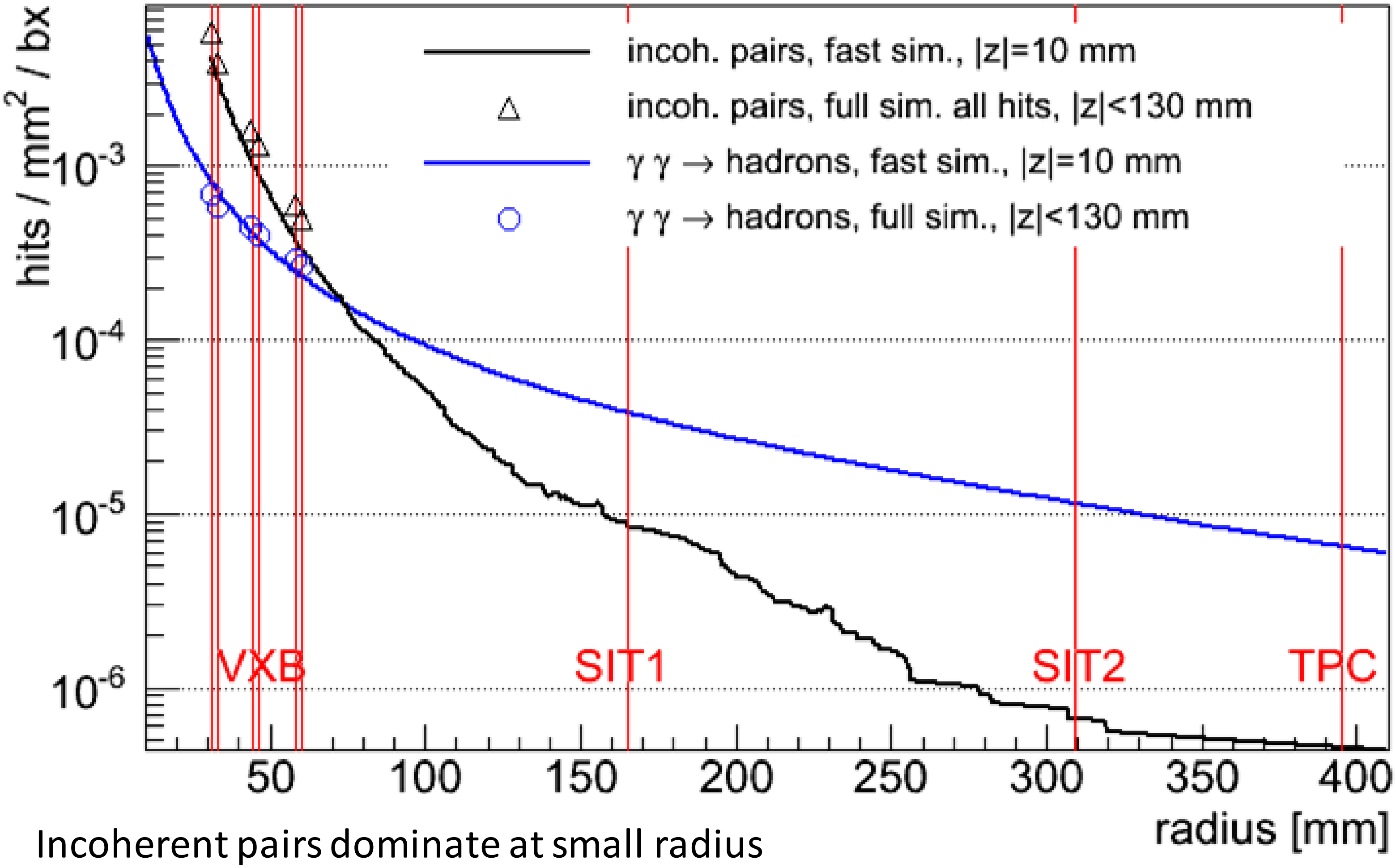
D. Dannheim, A. Sailer

Beam pipe and silicon tracking: VTX / SIT / FTD


CLIC_ILD_CDR simulation model
Tracking elements inside TPC + beam pipe

D. Dannheim

Barrel occupancies in CLIC_ILD_CDR vs. radius

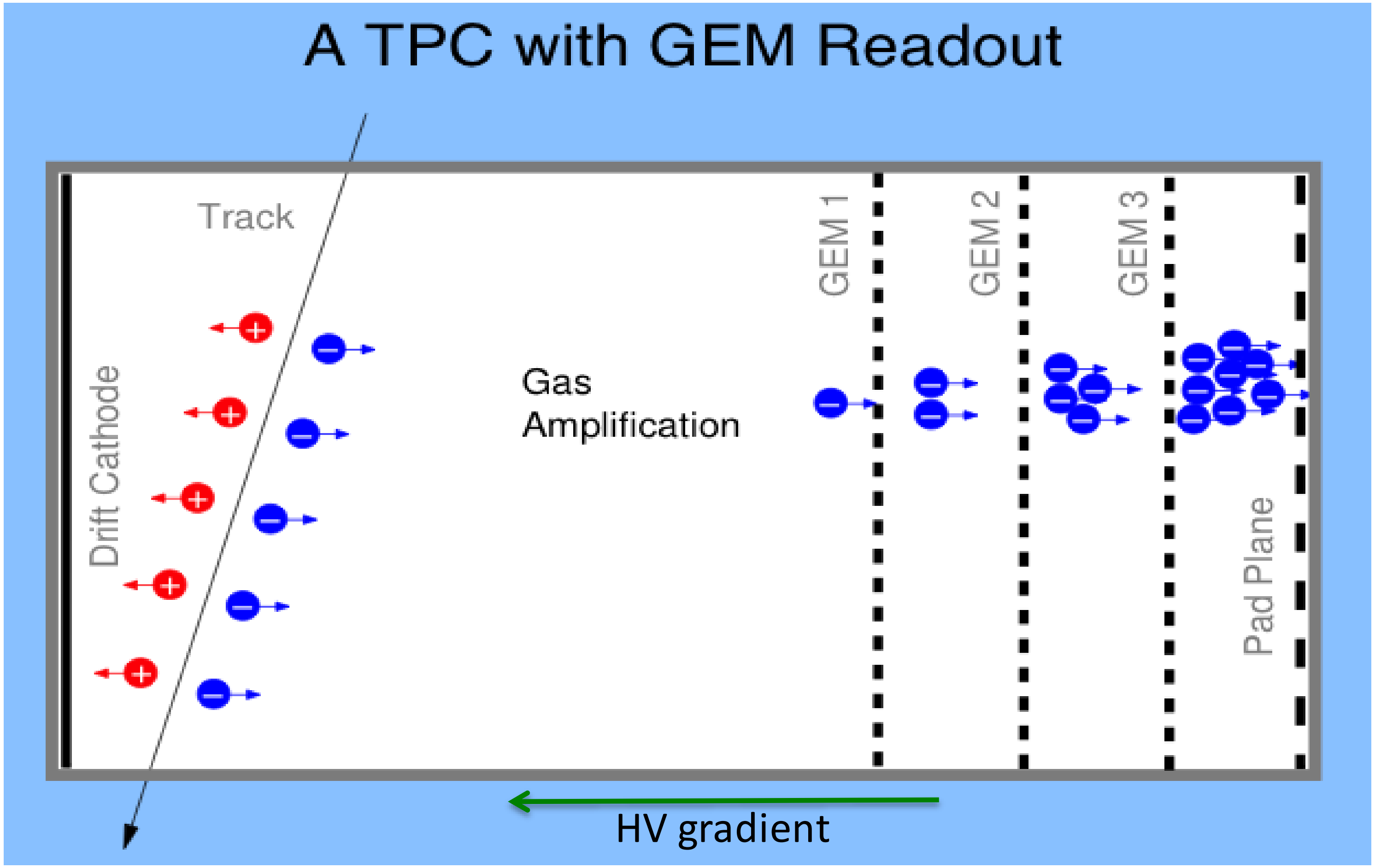


- Incoherent pairs dominate at small radius
- γγ→hadrons dominate at larger radii
- Good agreement between full and fast simulation
- Up to ~1.5 hits / mm^2 / bunch train in innermost vertex layer

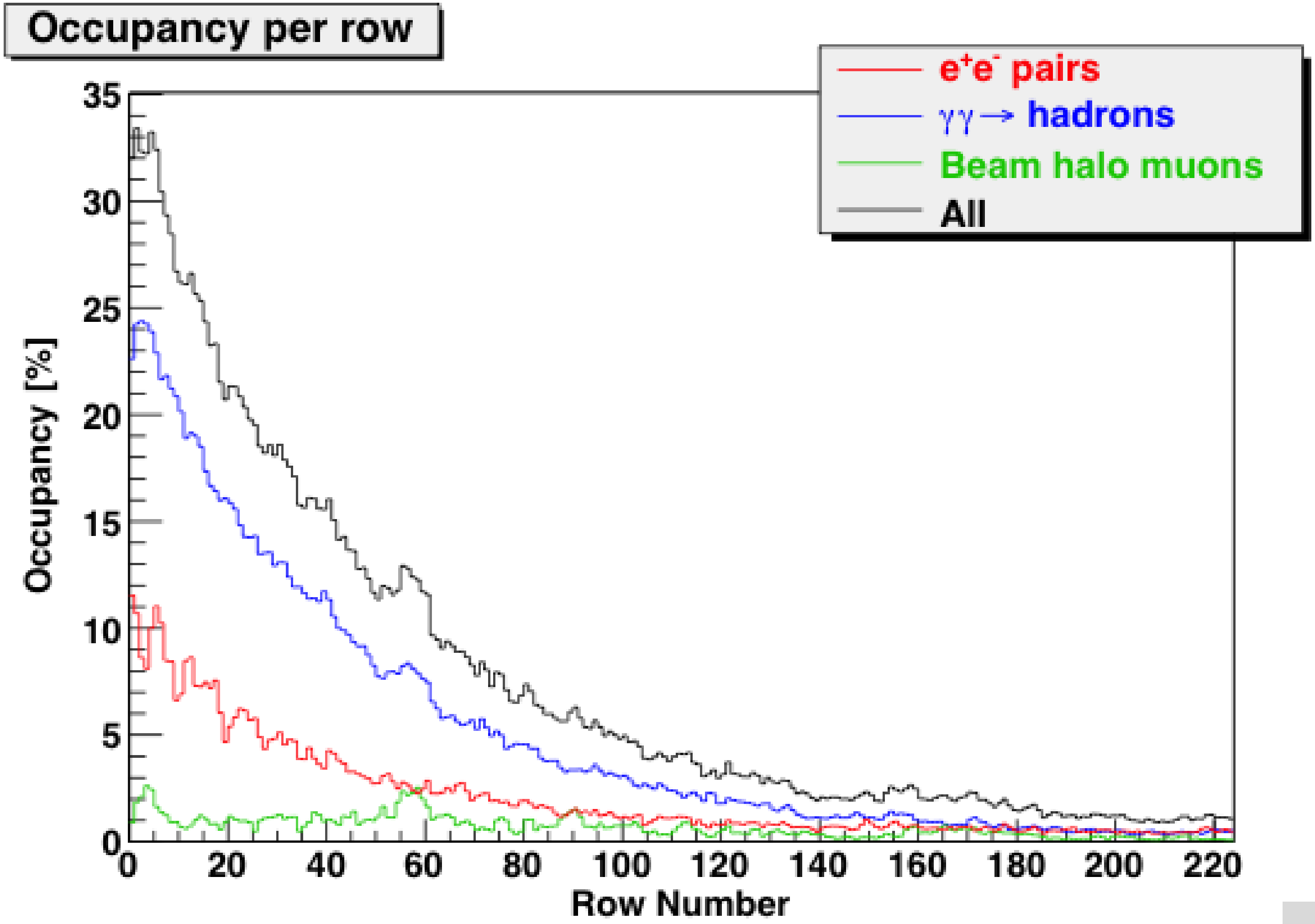
D. Dannheim

TPC detector in CLIC_ILD

TPC = time projection chamber
=> 3D tracking devices, many measurement points, low-mass



TPC tracker occupancies

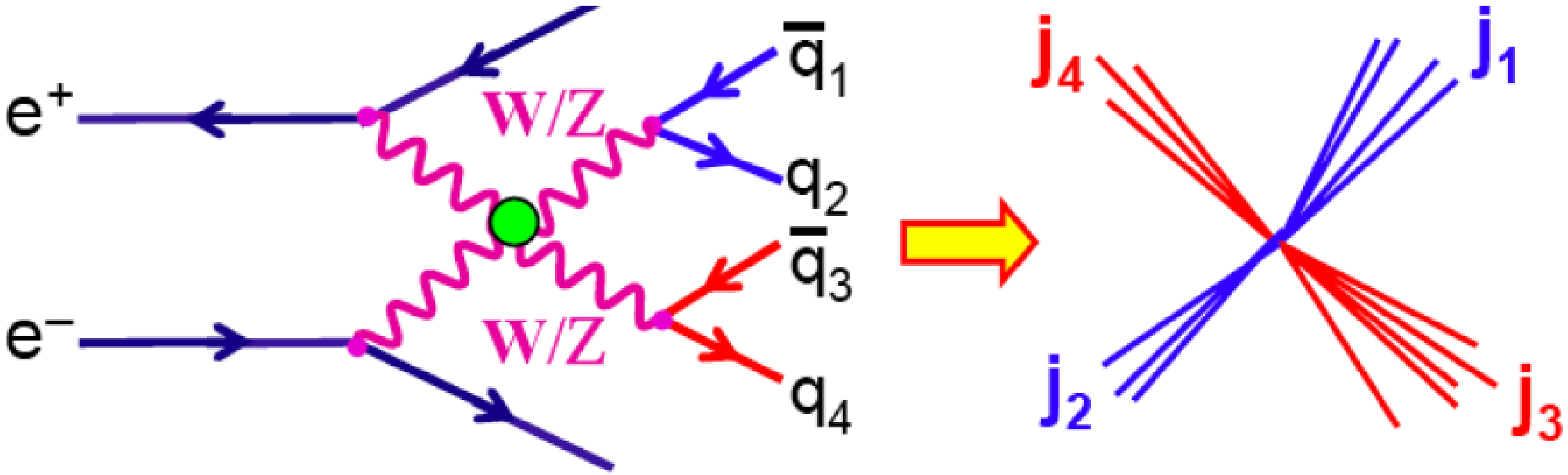


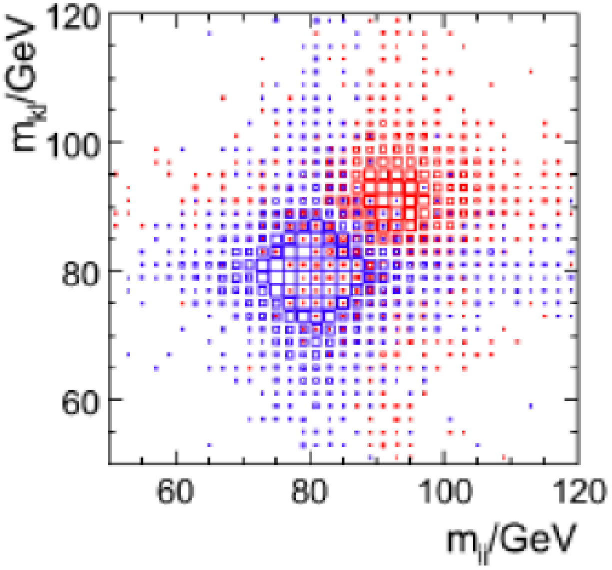
M. Killenberg

Occupancy (percent of time voxels occupied) for full bunch train and 6*1 mm^2 pads at 40 MHz readout

Jet energy resolution

At least: need to separate W/Z hadronic decays





- W and Z widths and the separation between them set the goal for jet energy resolution

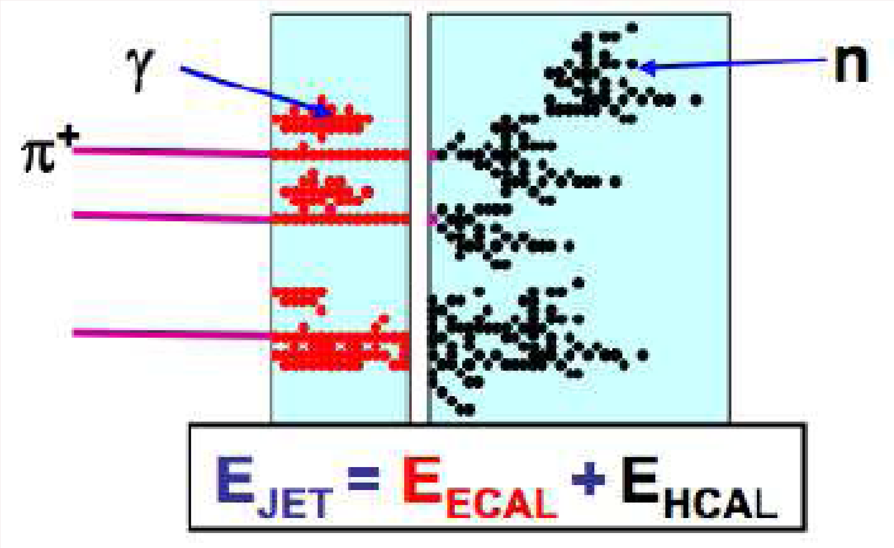
Requires ΔE/E = 3% for jets at high energies
Typical jet energies: up to 0.5-1 TeV

Composition of high-energy jest

- In a typical jet (on average):
  - 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)

How to....

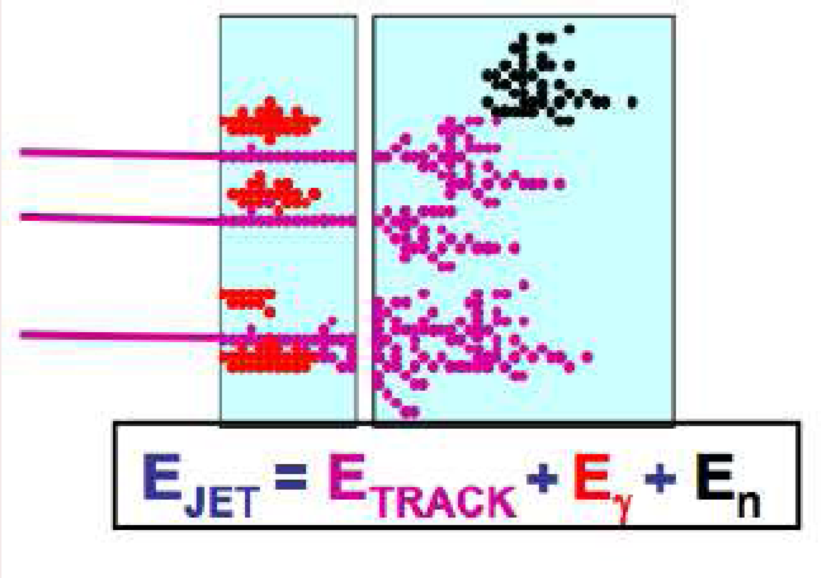
Traditional sandwich calorimetry



- Approximately 70% of energy measured in HCAL with $\sigma_E / E \approx \frac{60\%}{\sqrt{E\ (\mathrm{GeV})}}$

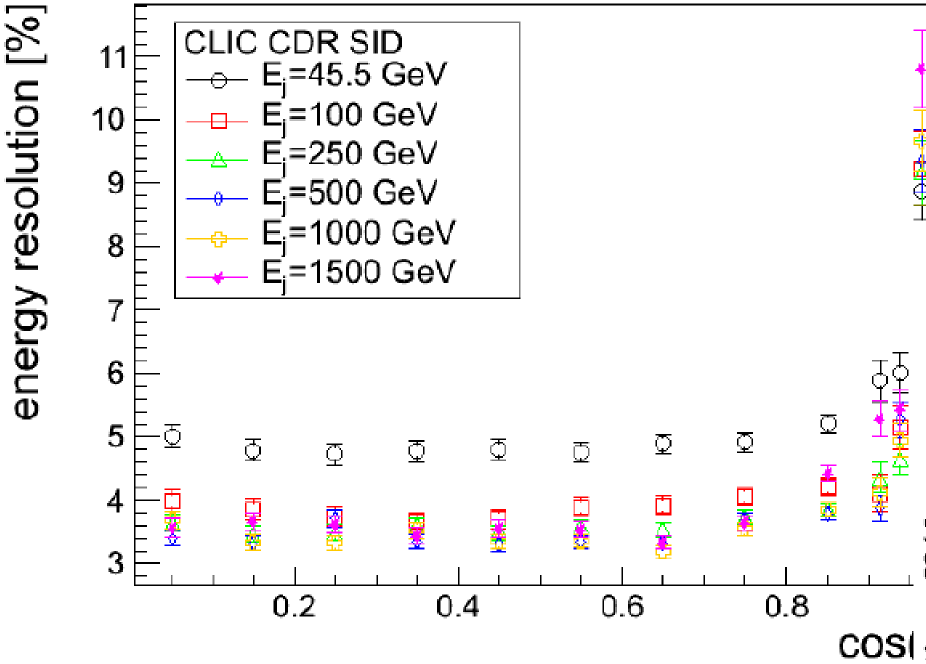
  $\Rightarrow$ Jet energy resolution limited by intrinsically 'poor' HCAL resolution

Particle Flow Calorimetry

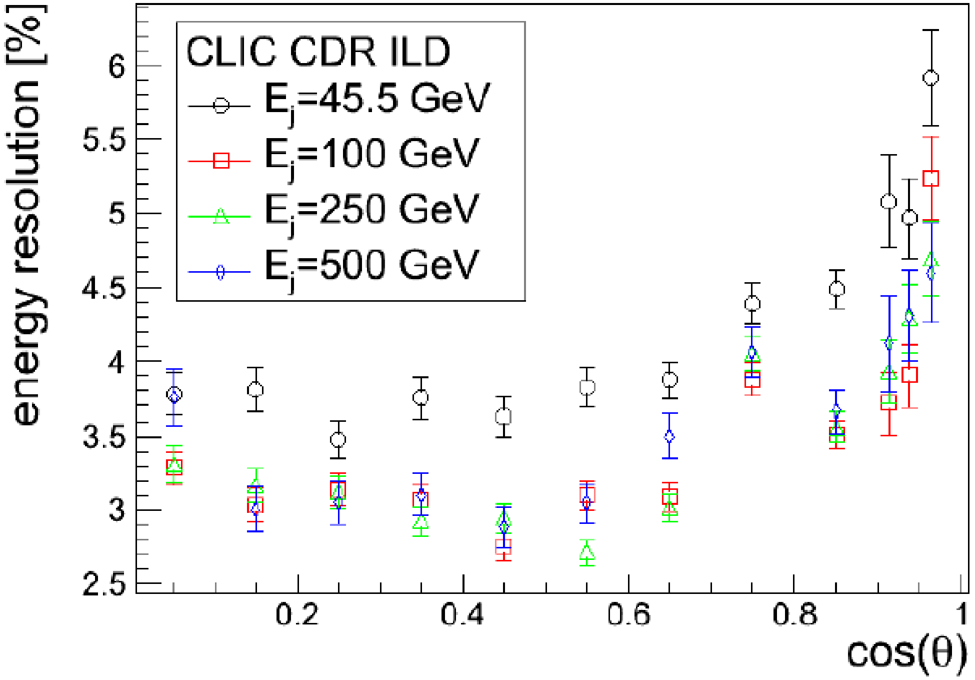


- Charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E / E < 20\% \sqrt{E\ (\mathrm{GeV})}$
- Only 10% of jet energy from HCAL $\Rightarrow$ much improved resolution

PandoraFPA, jet energy resolution



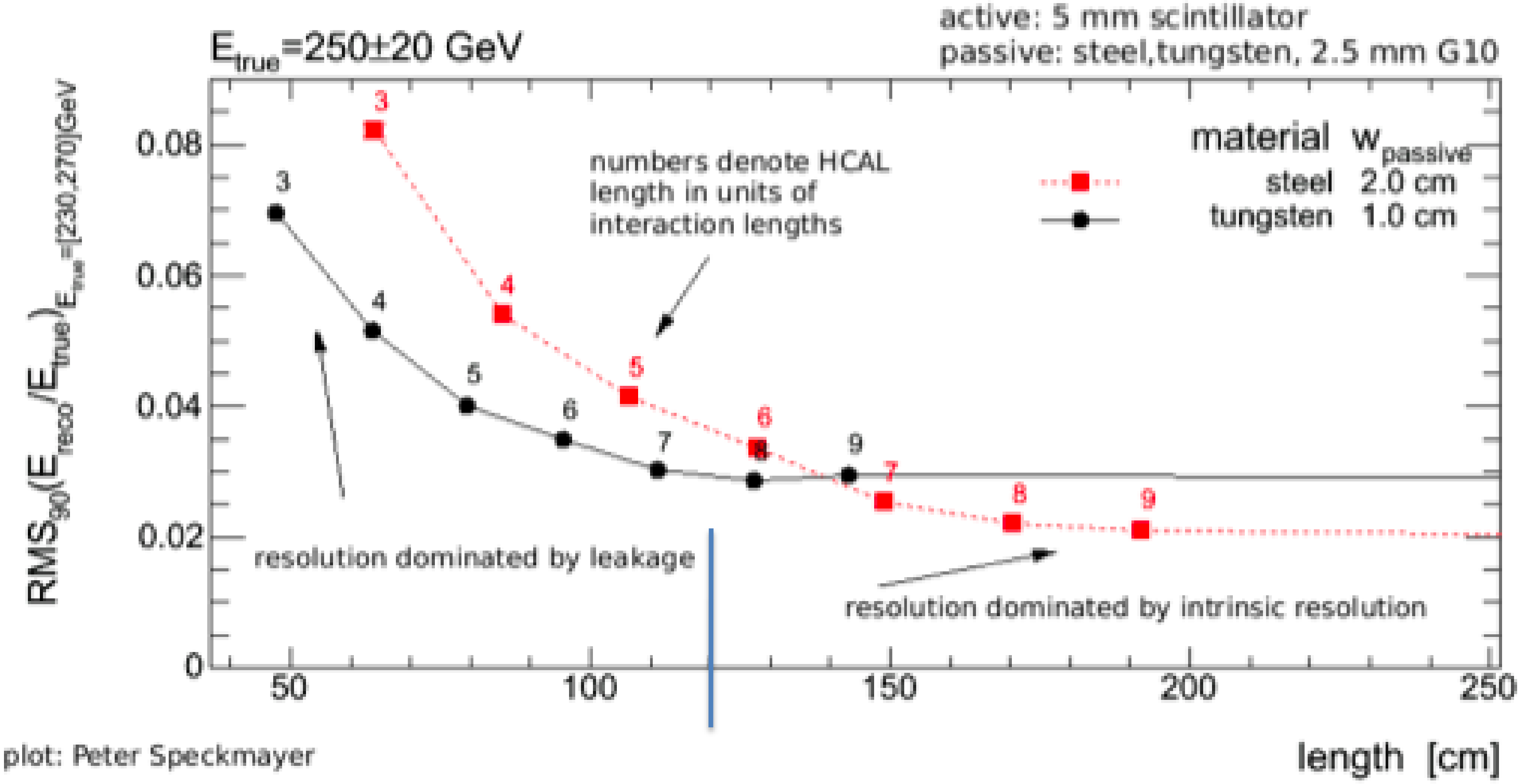
The required jet energy resolution can be achieved, even for high-E jets at CLIC !



M. Thomson, J. Marshall, A. Münnich

High energy => deep calorimeter

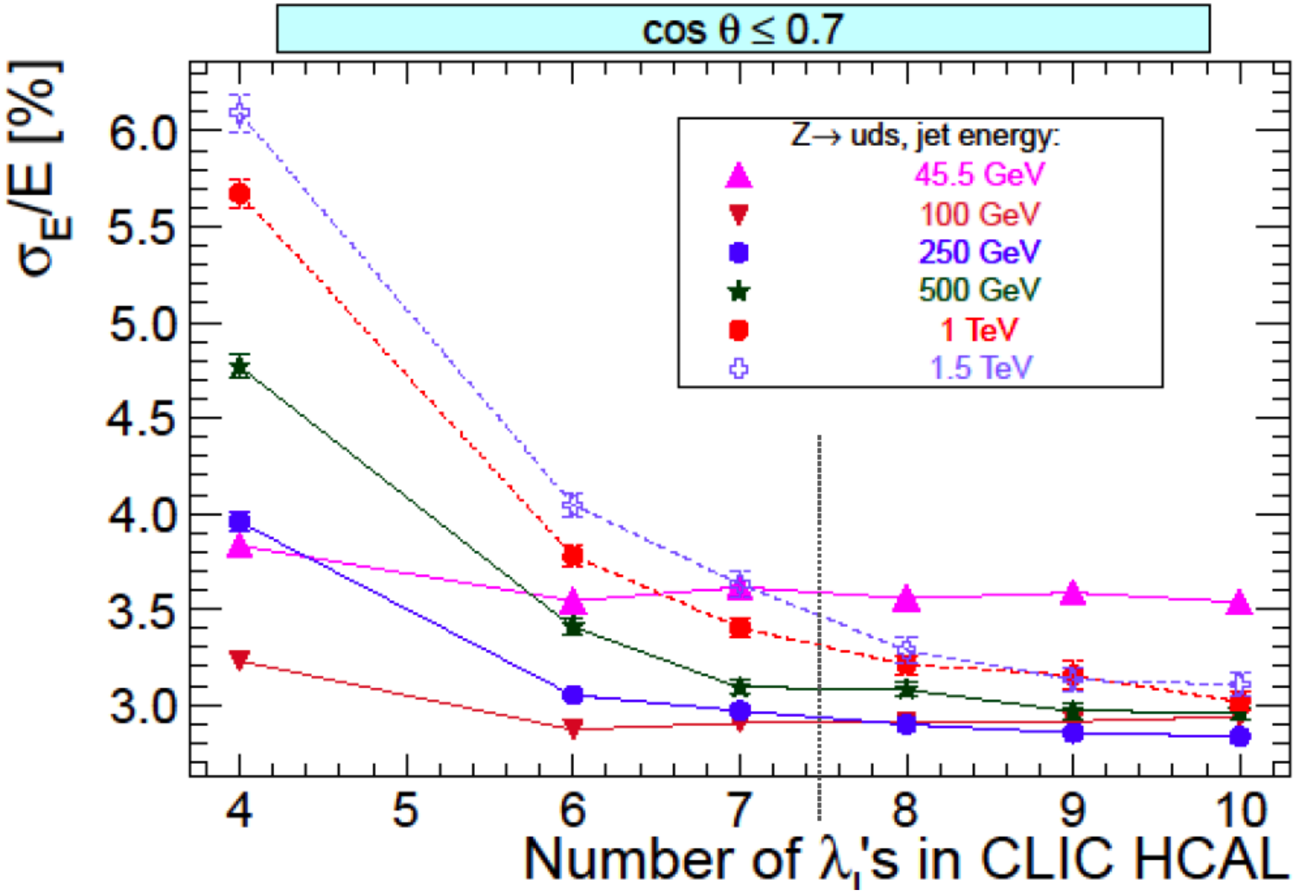
… trying to find a super-dense material for our CLIC hadron calorimeter



plot: Peter Speckmayer

Required resolution reached at smaller HCAL outer radius for **tungsten** than for **steel absorber**

HCAL depth, tail catching and jets



PFA study
Full ILD-type detector
barrel with tungsten
HCAL absorbers

A. Lucaci Timoce

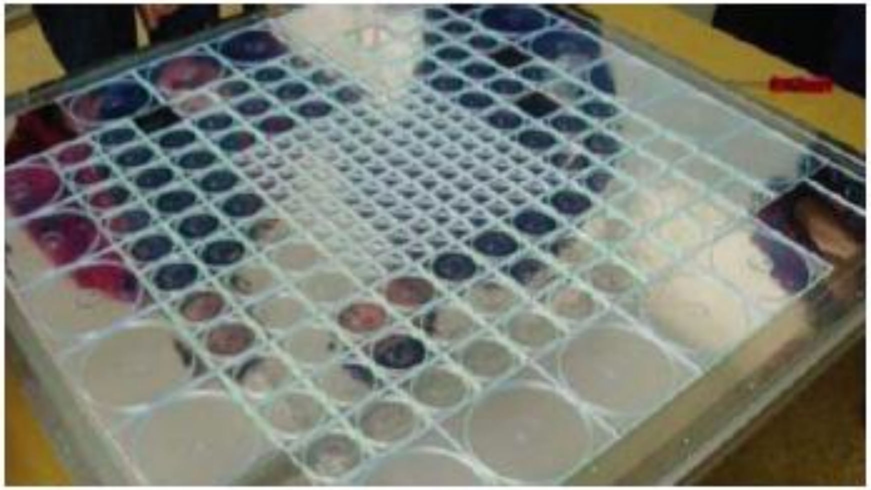
CLIC_ILD has:

- **Barrel: 7.5 Λ_i, with tungsten absorber**
- **End cap: 7.5 Λ_i, with steel absorber**

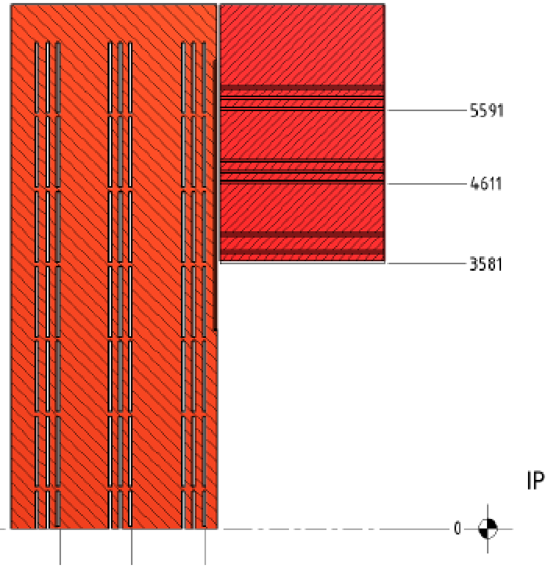
Tungsten HCAL prototype

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

Scintillator tiles
3*3 cm (in the centre)
Read out by SiPM (and wave-length shifting fibre)



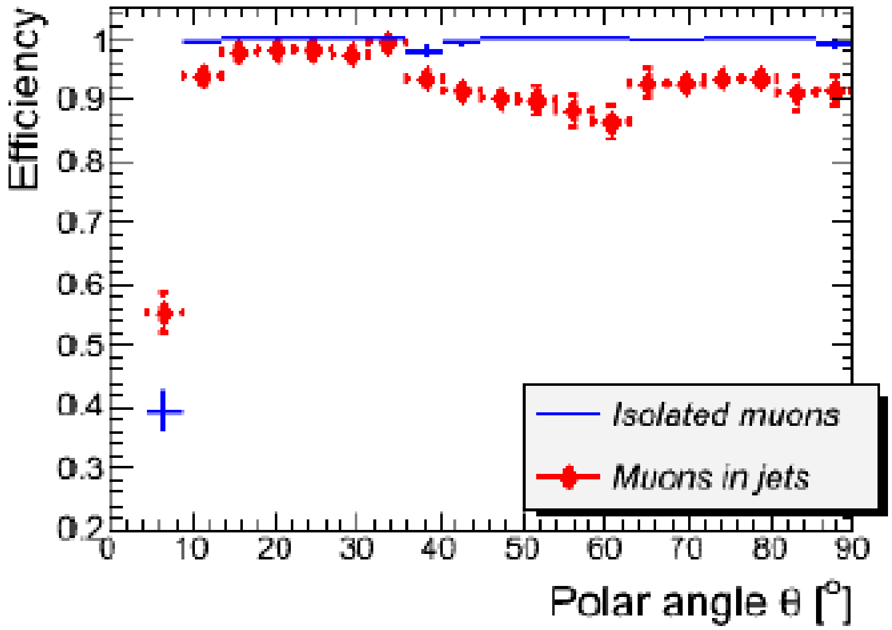
Yoke + Muon instrumentation

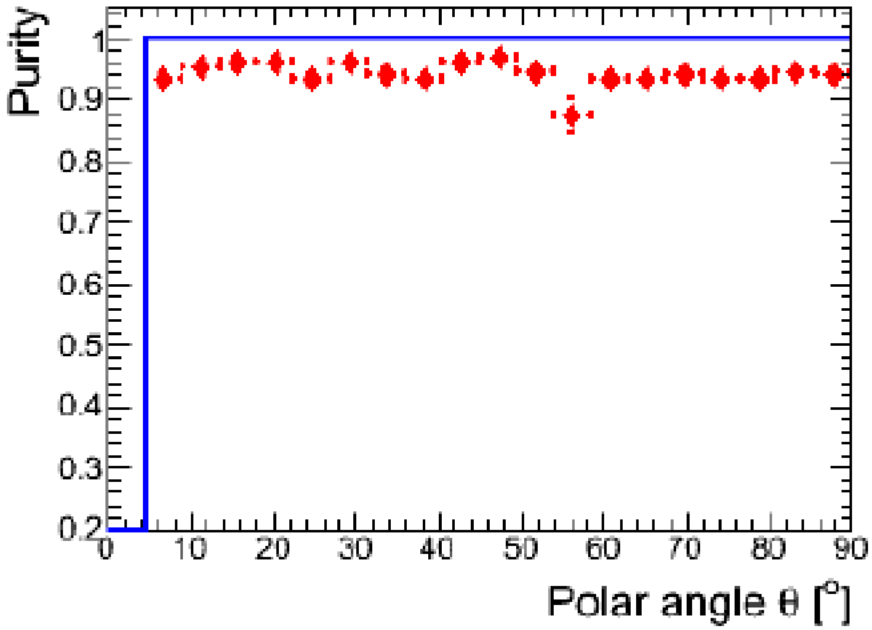


3 times 3 instrumented layers
Barrel starts with an active layer

Functions:
- Tail catcher (small improvement, 3 layers)
- Muon identification (all 3×3 layers)

E. Van der Kraaij, B. Schmidt, H. Gerwig, N. Siegrist, F . Ramos





Background suppression at CLIC

Strategy followed for the suppression of background:

- **Full reconstruction + PFA analysis with background overlay**
  - Taking into account detector integration times and hit timing resolution
  - Provides TOF-corrected timing of clusters
  - Precision on cluster-time is typically better than time-resolution of individual hits

- **Then apply cluster-based timing cuts**
  - These cuts depend on particle-type, p_t and detector region
  - This allows to protect high-p_t physics objects and to act more severely on low-p_t forward-going objects (where background is more severe)

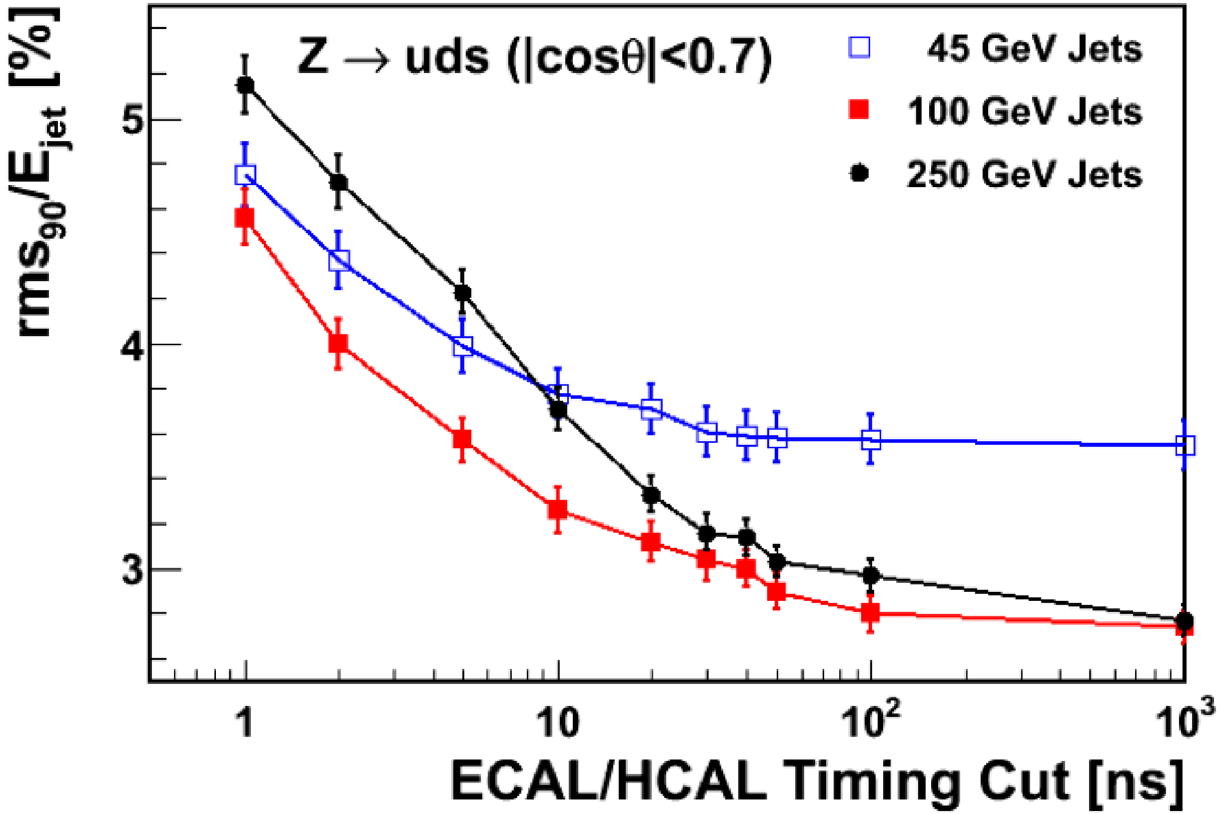
Core Marlin software processors involved:

```
TimingOverlay
LooseSelectedPandoraNewPFAs
SelectedPandoraNewPFAs
TightSelectedPandoraNewPFAs
```

M. Thomson, J. Marshall

Hadron shower timing in tungsten and steel

Hadron shower development in tungsten is slower than in steel



Signal in tungsten HCAL need to be integrated over at least ~50 ns

Detector Assumptions

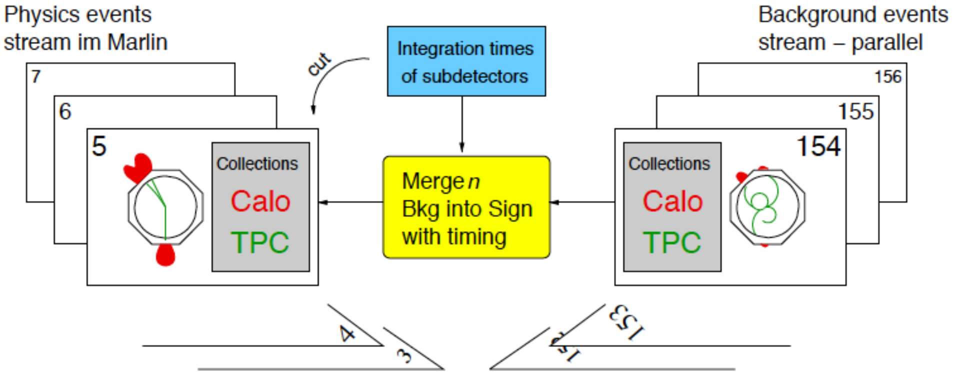
- Calorimeters
  - Assume all hits have a timestamp
    - currently no smearing of hit times, assumed ~ 2 ns
  - Assume two hit separation limited to 20 ns
    - Hits within 20 ns are merged (use time for highest ph hit)
  - For ECAL/HCAL endcap reconstruction integrate over 10 ns
  - For HCAL barrel integrate over 100 ns

- Silicon in trackers
  - Integrate over time window of 10 ns
  - No accounting for multiple hit capability
    - occupancies fairly low

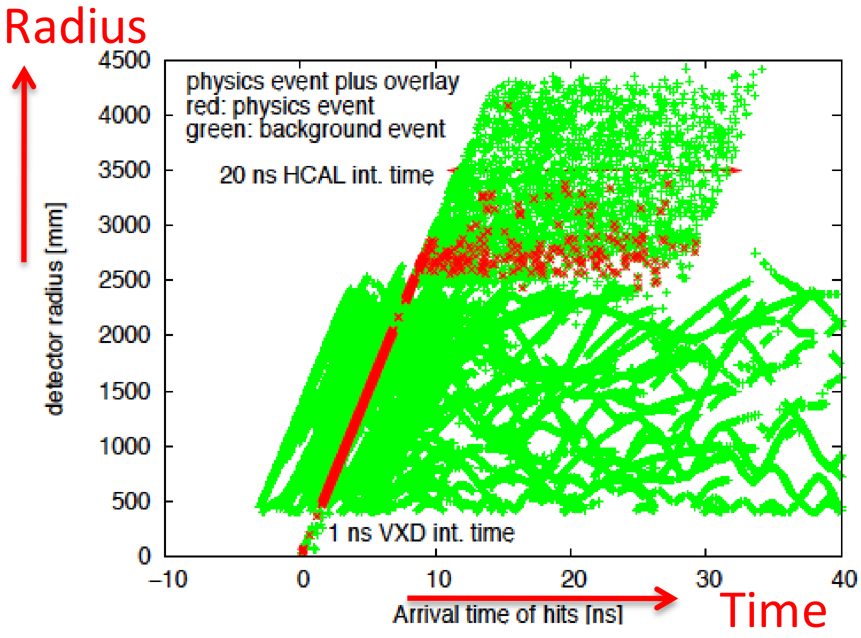
- TPC
  - Integrate over full bunch-train
  - Require a matched Si hit in the above 10 ns window
  - For looping tracks, also require arrival at ECAL within 50 ns

Defines input to event reconstruction

Marlin Processor “OverlayTiming”



- Combining physics and background data streams
- At digitisation stage
- For selected number of bunch crossings
- Taking into account detector integration times



LCD-Note-2011-006 (nearly final)
https://edms.cern.ch/document/1144892

Calorimeter

TPC tracker

Si tracking/vertex

P. Schade, A. Sailer, A. Lucaci

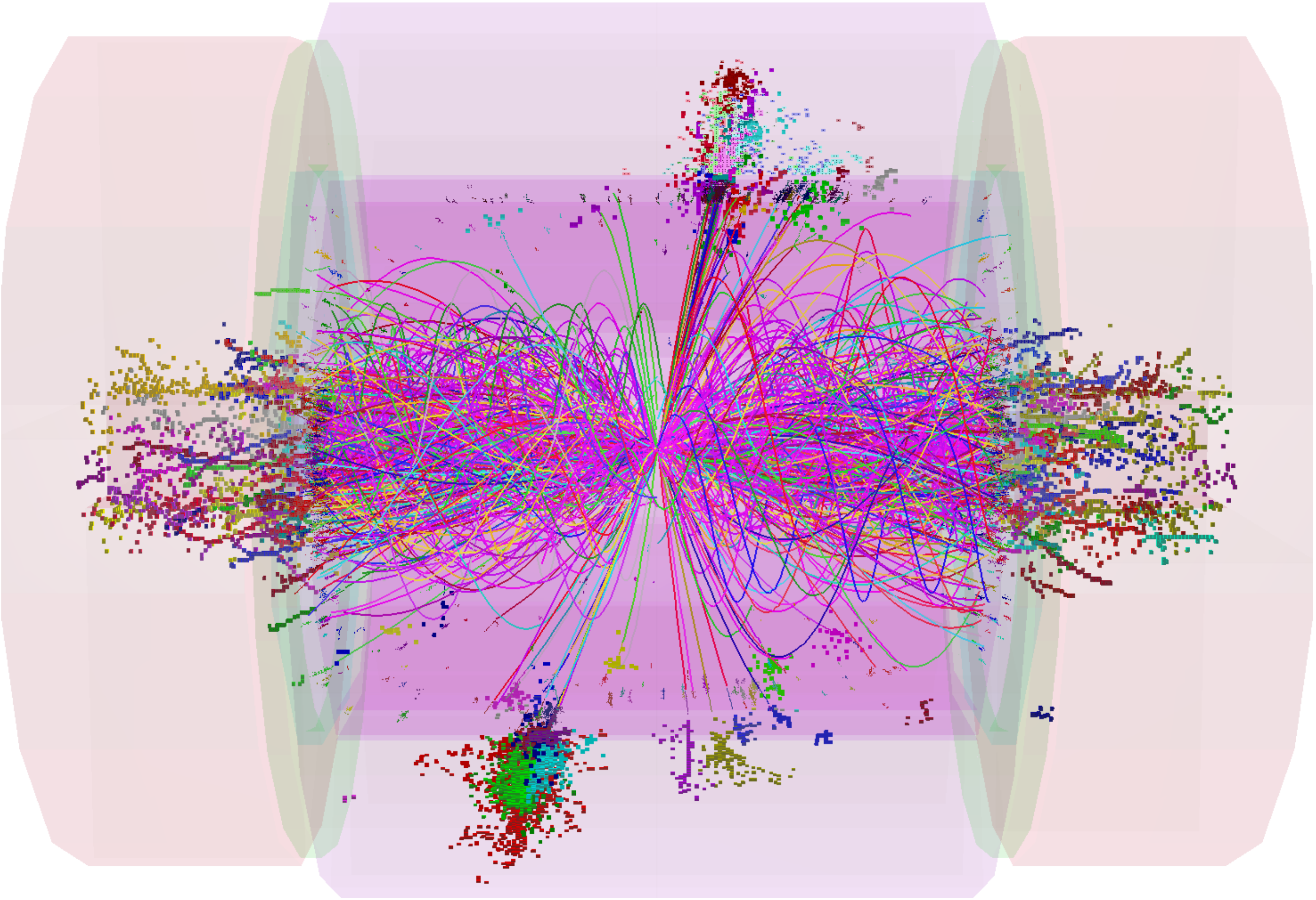
PFO-based timing cuts

Region	p_t *range*	Time cut
Photons		
central ($\cos\theta \leq 0.975$)	$0.75\ \mathrm{GeV} \leq p_t < 4.0\ \mathrm{GeV}$	$t < 2.0$ nsec
	$0\ \mathrm{GeV} \leq p_t < 0.75\ \mathrm{GeV}$	$t < 1.0$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \mathrm{GeV} \leq p_t < 4.0\ \mathrm{GeV}$	$t < 2.0$ nsec
	$0\ \mathrm{GeV} \leq p_t < 0.75\ \mathrm{GeV}$	$t < 1.0$ nsec
Neutral hadrons		
central ($\cos\theta \leq 0.975$)	$0.75\ \mathrm{GeV} \leq p_t < 8.0\ \mathrm{GeV}$	$t < 2.5$ nsec
	$0\ \mathrm{GeV} \leq p_t < 0.75\ \mathrm{GeV}$	$t < 1.5$ nsec
forward ($\cos\theta > 0.975$)	$0.75\ \mathrm{GeV} \leq p_t < 8.0\ \mathrm{GeV}$	$t < 2.0$ nsec
	$0\ \mathrm{GeV} \leq p_t < 0.75\ \mathrm{GeV}$	$t < 1.0$ nsec
Charged PFOs		
all	$0.75\ \mathrm{GeV} \leq p_t < 4.0\ \mathrm{GeV}$	$t < 3.0$ nsec
	$0\ \mathrm{GeV} \leq p_t < 0.75\ \mathrm{GeV}$	$t < 1.5$ nsec

- Track-only minimum p_t: 0.5 GeV
- Track-only maximum time at ECAL: 10 nsec

M. Thomson, J. Marshall

PandoraNewPFAs

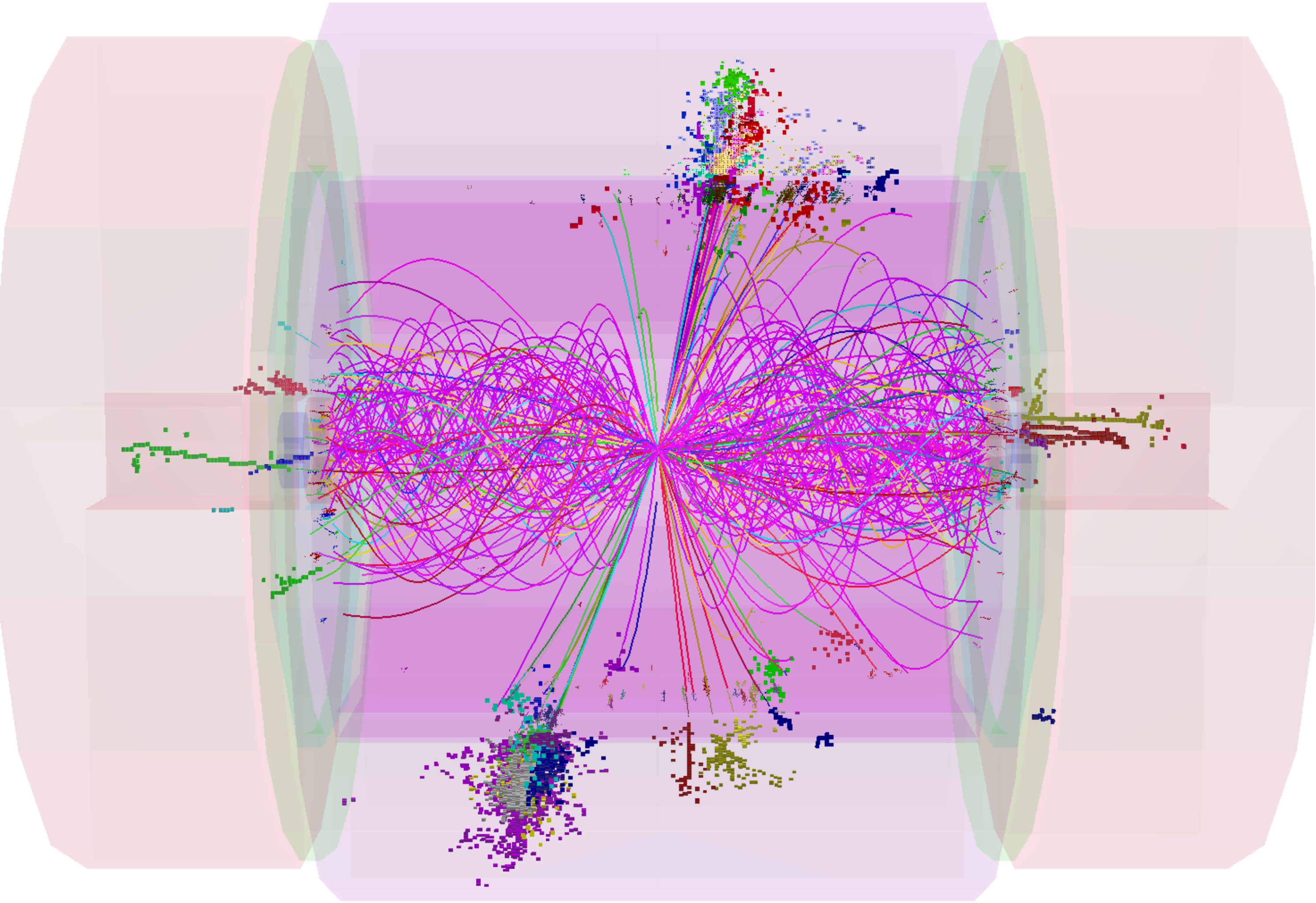


1 TeV Z=>qqbar

1.4 TeV of background !

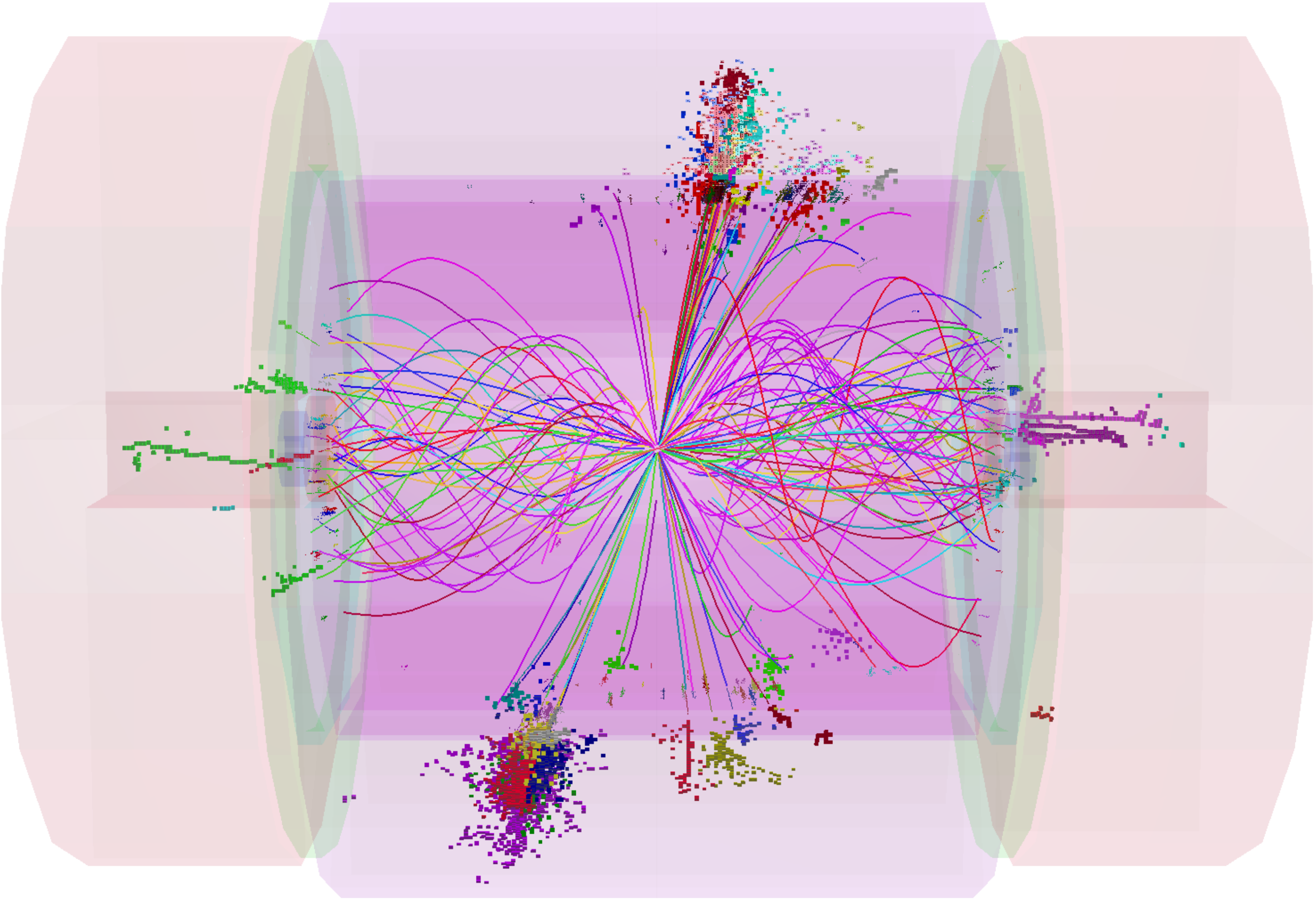
with 60 BX background

LooseSelectedPandoraNewPFAs



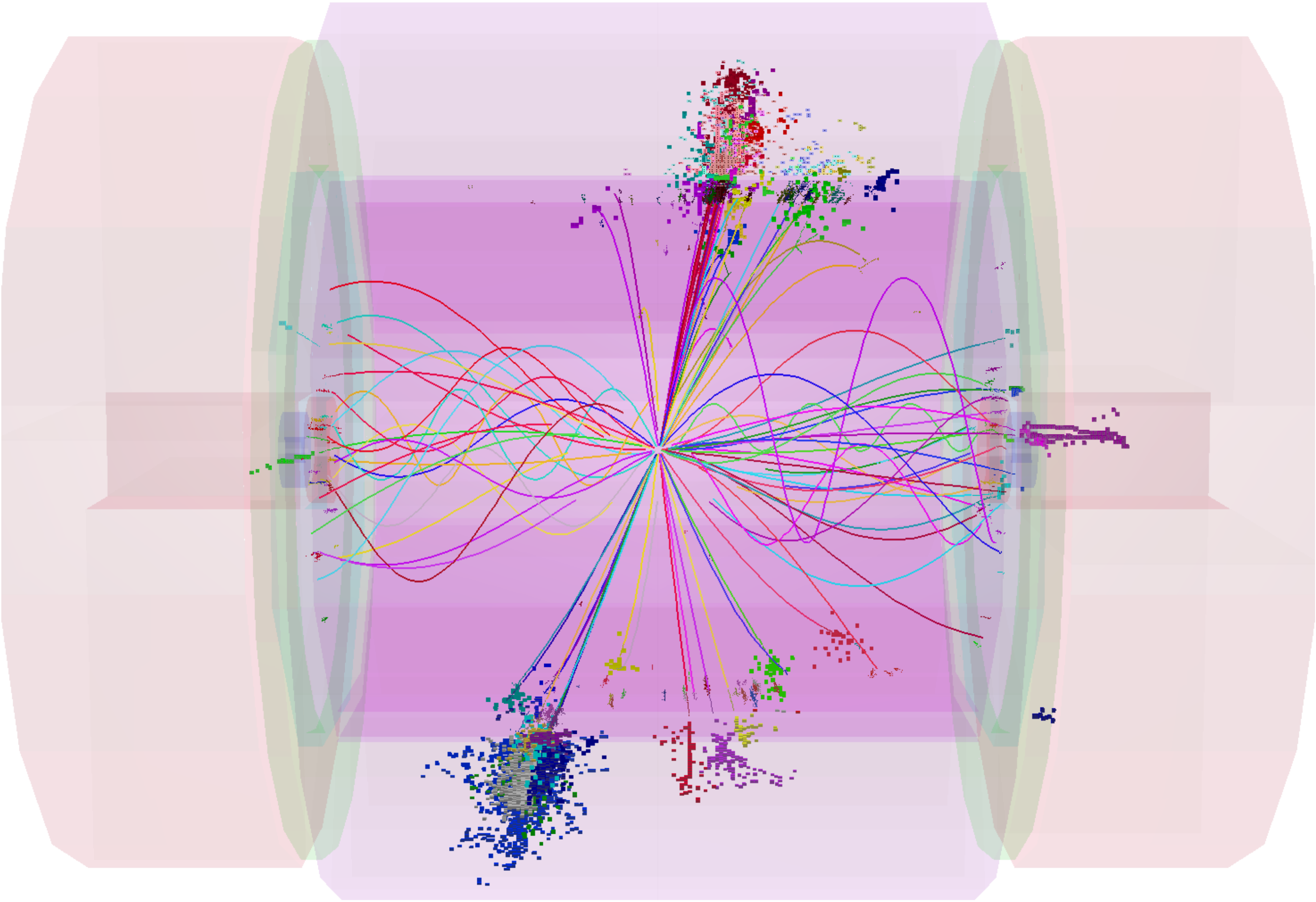
0.3 TeV of background

SelectedPandoraNewPFAs



0.2 TeV of background

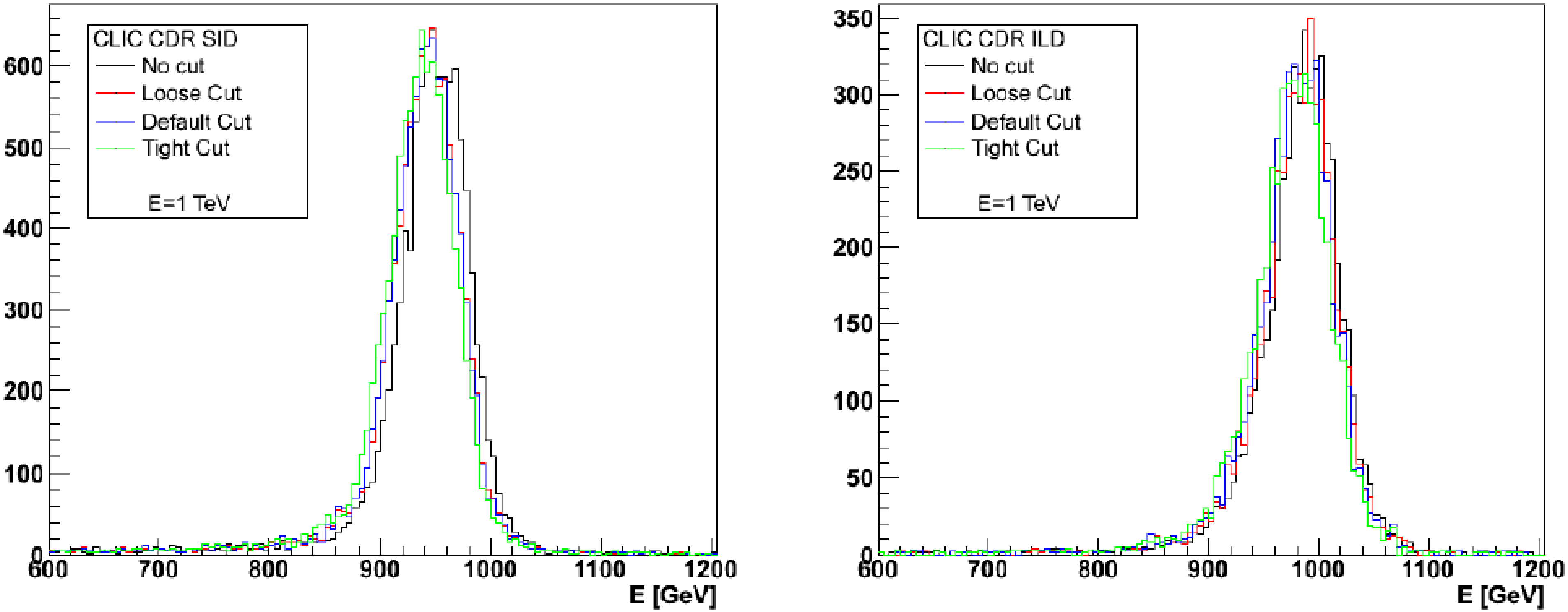
TightSelectedPandoraNewPFAs



0.1 TeV of background

M. Thomson. J. Marshall

Impact of timing cuts on jets



Impact of the PFOSelector timing cuts on the jet energy resolution

E_{jet} [GeV]	45	100	250	500
no cut	3.98 ± 0.05	3.15 ± 0.04	3.00 ± 0.04	3.26 ± 0.06
loose cut	4.40 ± 0.06	3.34 ± 0.04	3.08 ± 0.04	3.29 ± 0.06
default cut	5.15 ± 0.07	3.64 ± 0.05	3.17 ± 0.04	3.33 ± 0.06
tight cut	5.95 ± 0.08	3.99 ± 0.05	3.30 ± 0.04	3.37 ± 0.06

ILD

Detector benchmark studies for CDR

Full physics simulation and analysis studies with beam background overlay ($\gamma\gamma \Rightarrow$ hadrons)

Choose different channels, with emphasis on mapping various crucial aspects of detector performance (jet measurement, missing energy, isolated leptons, flavour tagging etc.)

3 TeV

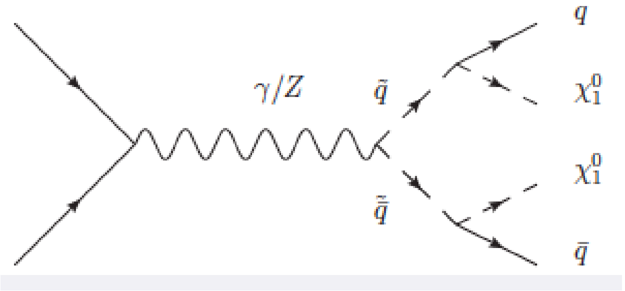
- $e^+e^- \rightarrow h\nu_e\bar{\nu}_e$
- $e^+e^- \rightarrow H^+H^- / H^0A$
- $e^+e^- \rightarrow \tilde{q}_R\bar{\tilde{q}}_R$
- $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$
- $e^+e^- \rightarrow \tilde{\chi}_i^+\tilde{\chi}_i^- / \tilde{\chi}_i^0\tilde{\chi}_i^0$

500 GeV

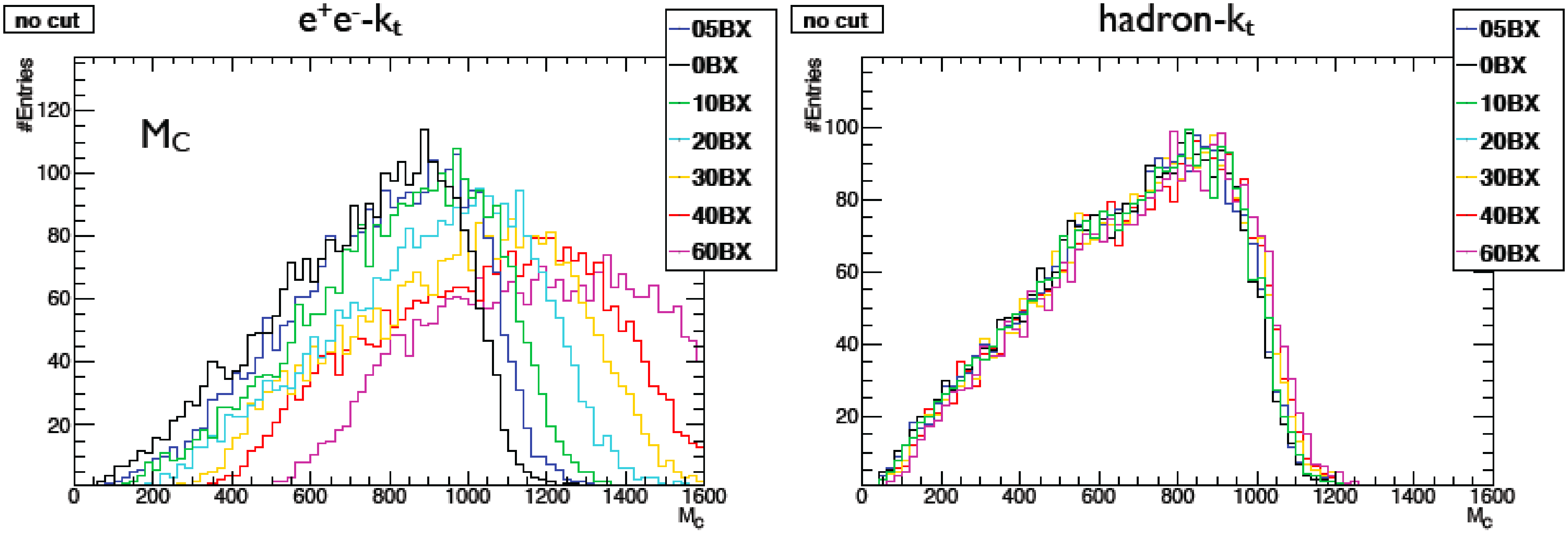
- $e^+e^- \rightarrow t\bar{t}$

Squark study / Jet finding at CLIC (1)

Several jet-finding algorithms are explored



Example: Squark benchmark study,
MC level (no PFO timing cuts)

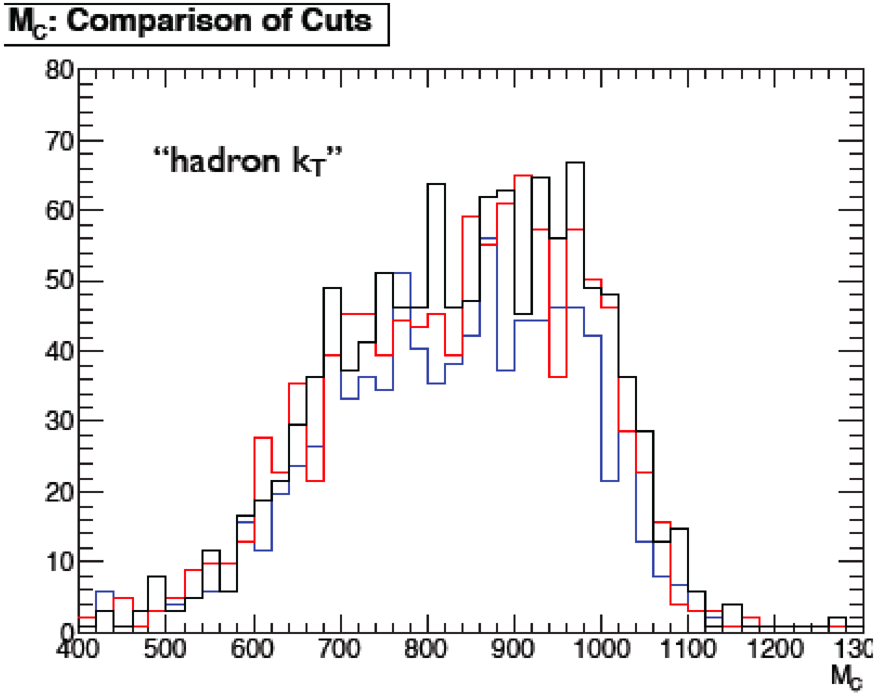


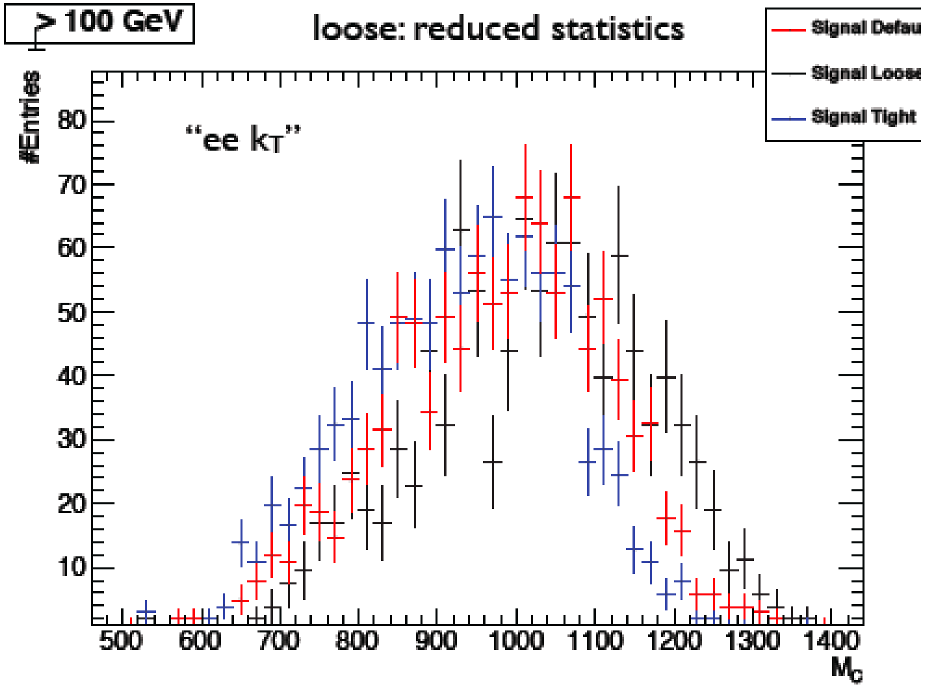
L. Weuste, F. Simon

➩ Jet finder can mitigate impact, provide stable measurements!

Squark study / Jet finding at CLIC (2)

Example: Squark benchmark study,
Full simulation level (including PFO timing cuts)



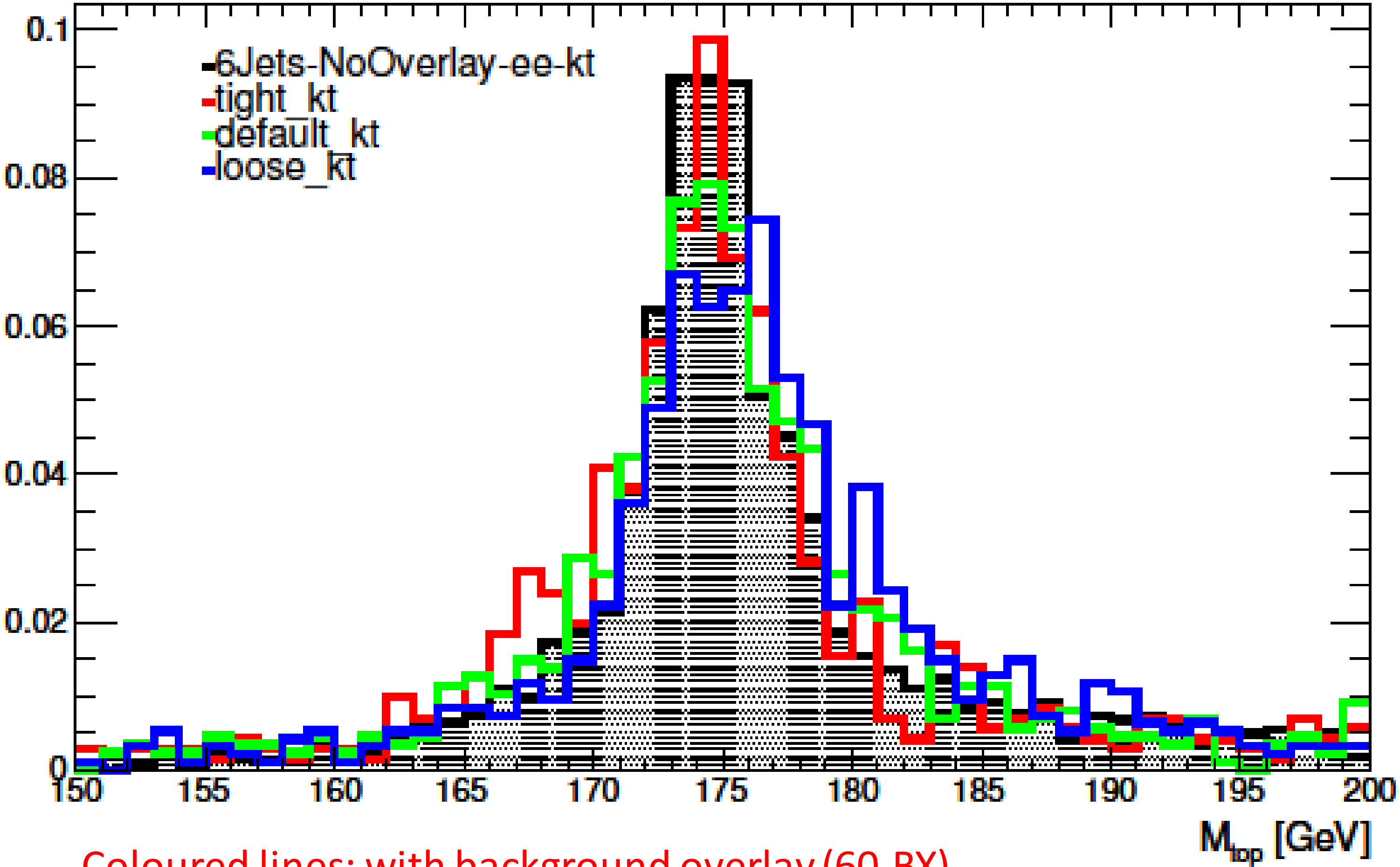


- Hadron k$_T$ algorithm relatively robust agains hadron background
  - still: Effects in particular when going to tight cuts visible
- ee-k$_T$ very sensitive to the choice of PFO cuts - Not a good option!

L. Weuste, F. Simon

Top mass / jet finding / background

Top reconstruction (ttbar, 6 jets) at 3 TeV

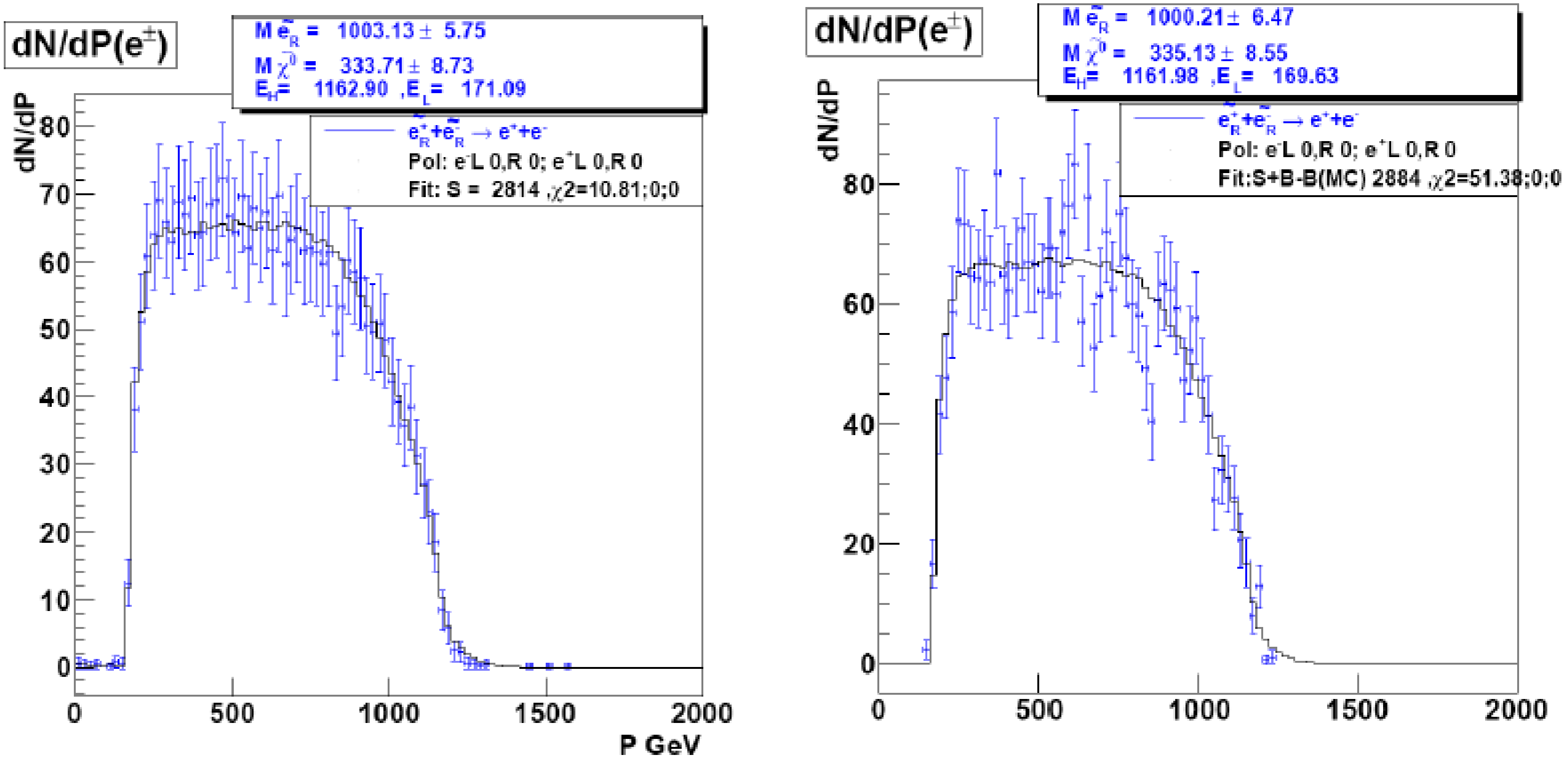


Coloured lines: with background overlay (60 BX)

A. Espargliere, K. Seidel

Slepton benchmark study

ẽ: Fit dN/dP S only, S+B-B(MC)



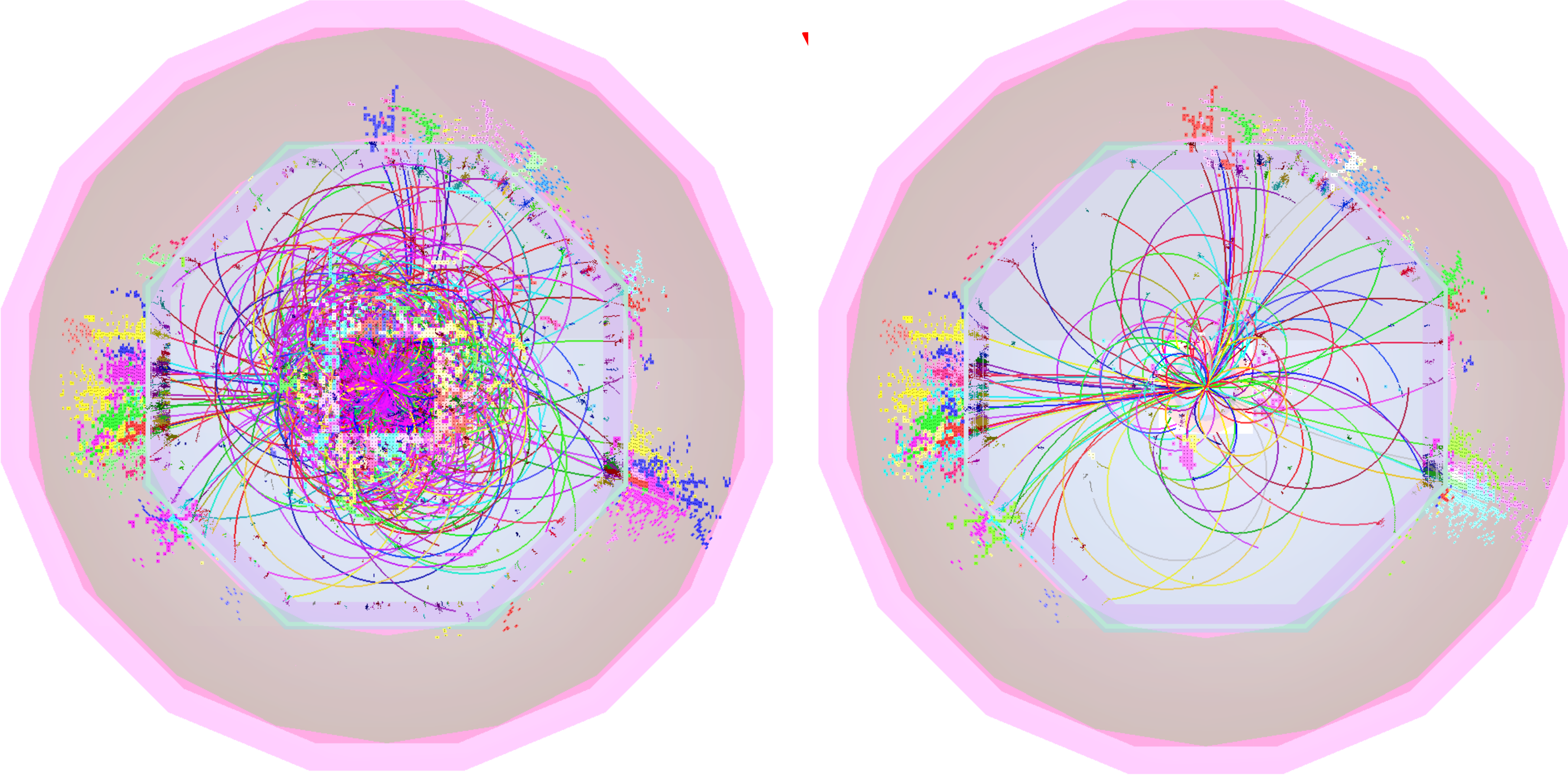
For S only (left); S+B-B(MC) (right)

Δ m/m (ẽ_R) ~ 0.6 % ; Δ m/m (χ̃⁰₁) ~ 3%

JJ. Blaising.
M. Battaglia

The CLIC detector CDR is well on track

This would not have been possible without all prior work done for the ILC



CLIC vertex detector

Requirements for the vertex detector:

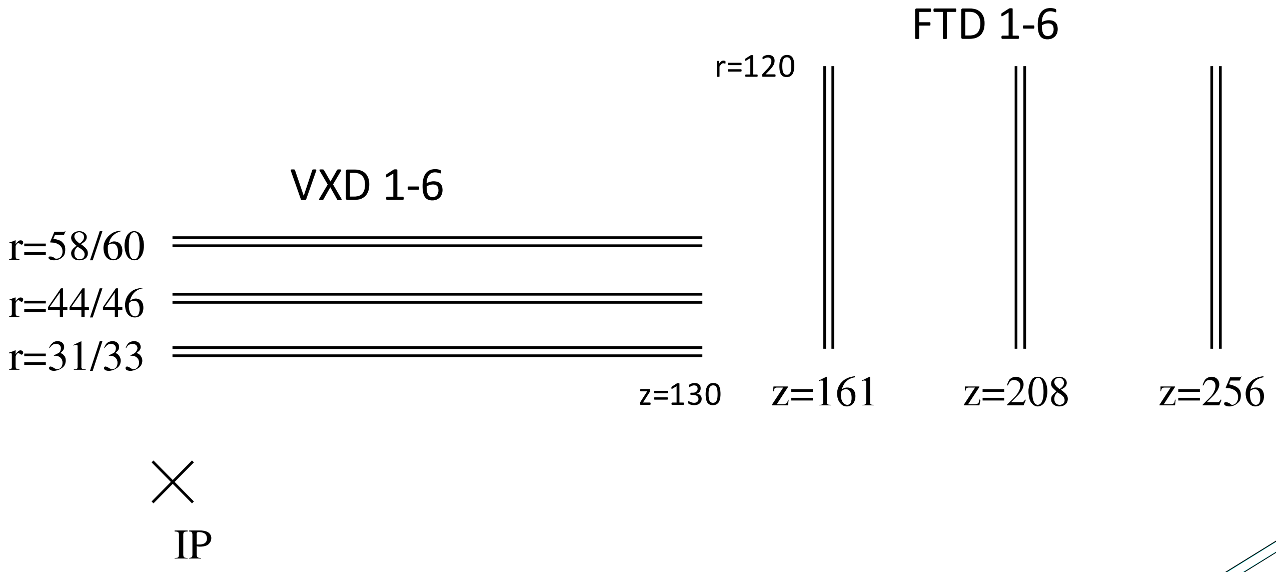
- Single-layer position resolution 3-4μm
  - Typically achieved with 20*20 micron pixels
- Single-layer material thickness 0.1%X_0 – 0.2%X_0
  - Equivalent to 50 μm thick sensor + 50 μm thick readout chip + thin support + connect
  - Very low power dissipation => no liquid cooling (“air flow”)
  - Requires power pulsing (factor ~50 in heat dissipation)
- Time-stamping ~5-10 ns
  - Still needs more study with full simulation
- Occupancy
  - ~1.5% per 20*20 μm2 pixel per bunch train (156 ns) in the innermost layer
- Triggerless readout over the 156 ns bunch-train
  - With full data readout in less than 200-400 μsec to allow power-pulsing

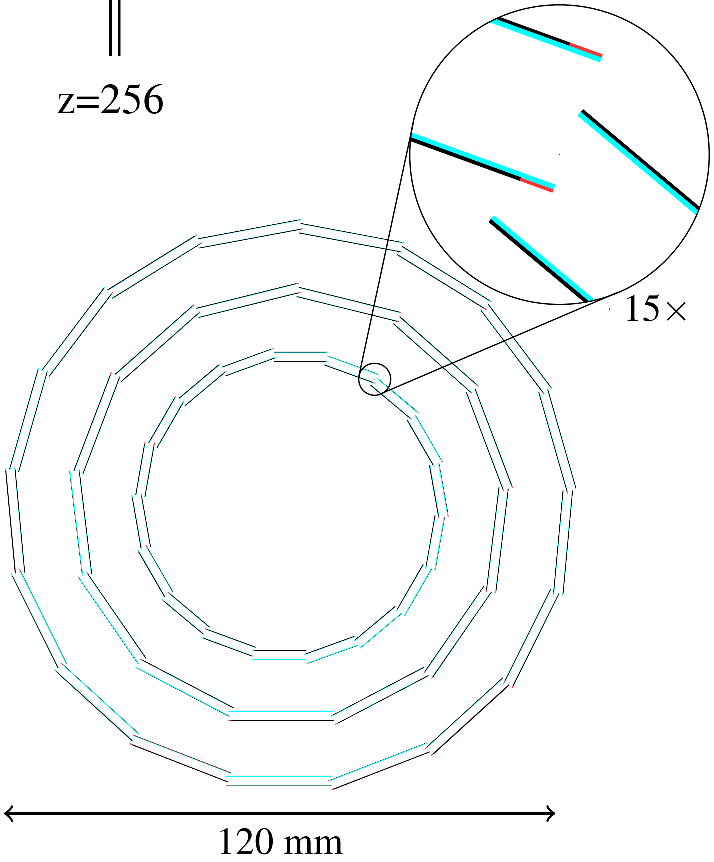
Very challenging hardware project !

CLIC machine parameters

Parameter	Value
Center-of-mass energy √s	3 TeV
Instantaneous peak luminosity	5.9×10^{34} cm^{-2} s^{-1}
Integrated luminosity per year	500 fb^{-1}
Beam crossing angle	20 mrad
Train length	156 ns
$N_{bunches}$ / train	312 (every 0.5 ns)
Train repetition rate	50 Hz
IP size x/y/z	45 nm / 1 nm / 40 µm
# $\gamma\gamma \rightarrow$ hadrons / bx	3.2
# incoherent electron pairs / bx	3×10^5
# halo muons	5 (including safety factor of 5)

Vertex-region layout





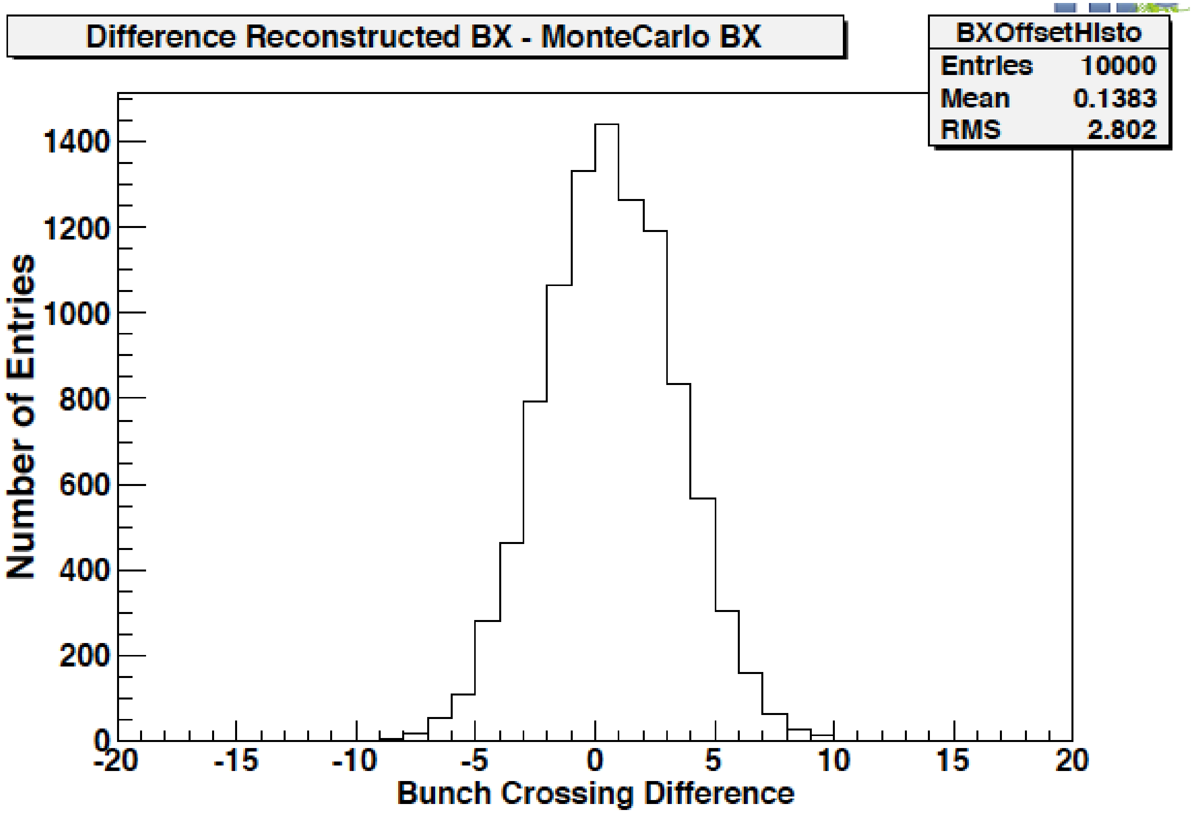
0.6 mm Be beam pipe at R_i=29.4 mm (|z|<260 mm)
VXD 1-6: 3 double layers of pixel cylinders (|z|<130 mm) FTD
1-6: 3 double layers of pixel disks
20 μm pixels, analog readout, σ=2.8 μm
X=0.18% X0 / double layer
(2 x 50 μm Si + 134 μm Carbon Support)

Time-stamping with TPC at CLIC

Approximately 40 micron drift per BX, ~7mm drift for full train

Study mismatch between outer Si tracker (SET) and TPC tracks.

Different muon energies, different angles.

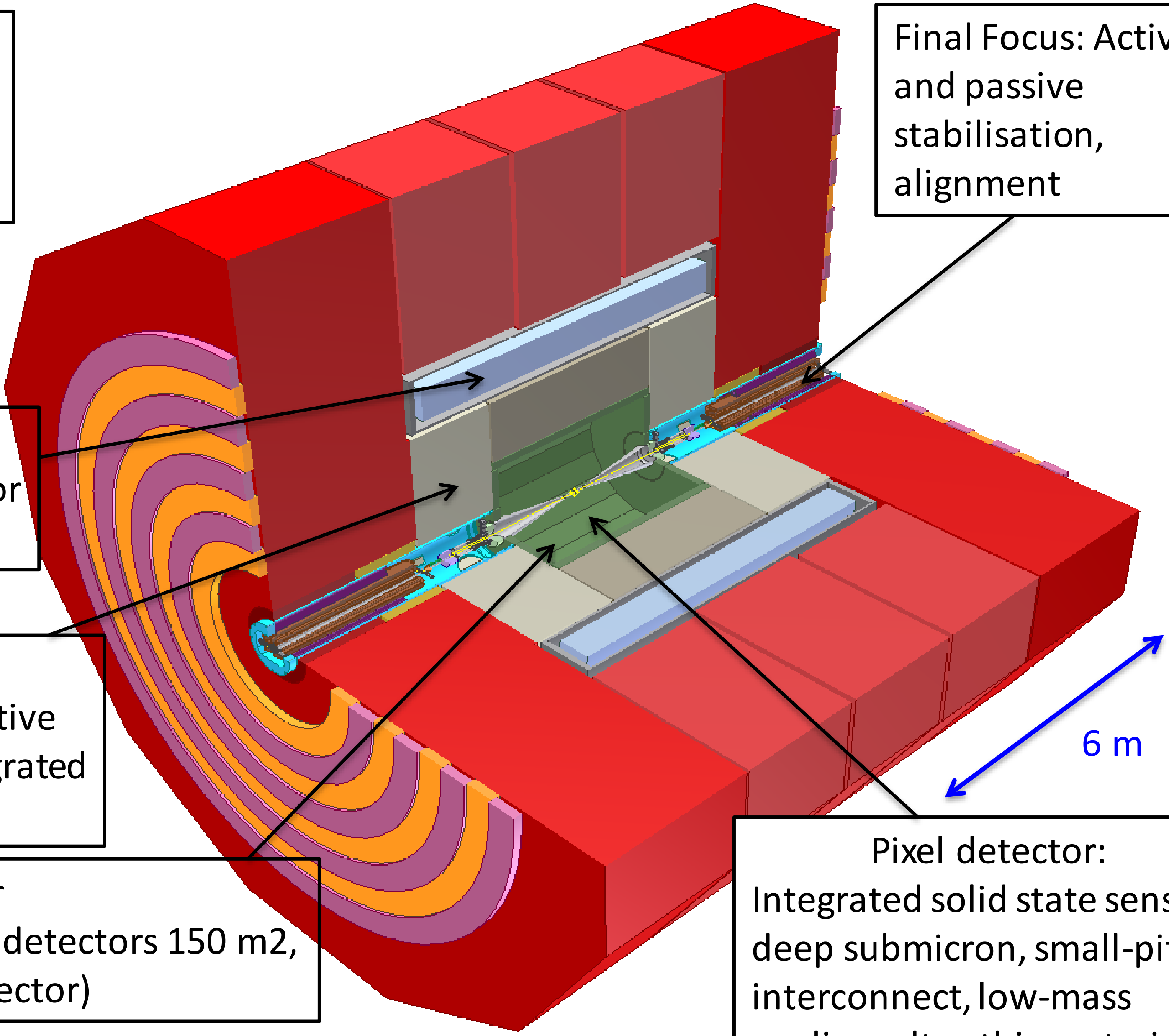


90 % of the muons are assigned correctly to within ± 5 bunch crossings

For: Energy 50 GeV, dip angle 5, SET resolution 50 µm

M. Killenberg

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

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)
- Power pulsing
  - In view of the 50 Hz CLIC time structure => allows for low-mass detectors
- 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)

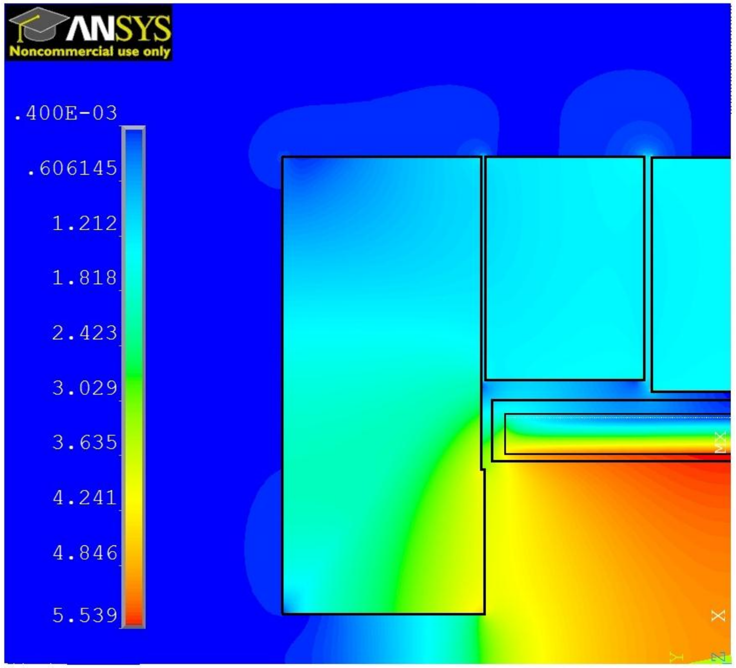
Solenoid studies

Engineering studies of 4-5 T solenoid with 3.4-2.8 m inner bore

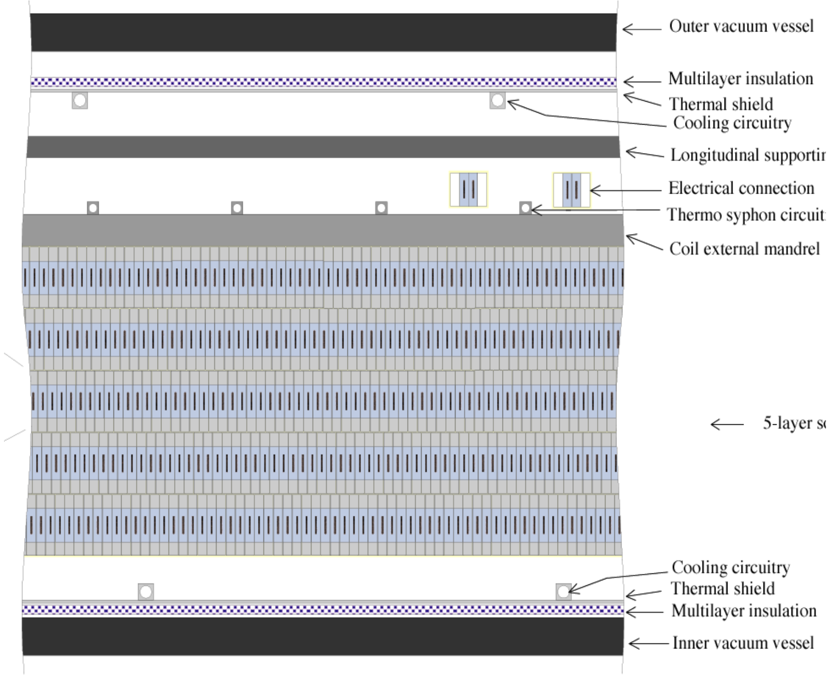
Based on experience of CMS and ATLAS superconducting solenoids

- Engineering calculations
- Coil design
- Reinforced conductor (materials R&D and extrusion test)
- Services, quench protection, etc.

CERN, KEK, SLAC, Genova INFN, CEA, etc



Field map of 5T magnet model



Coil composition for 5T magnet model