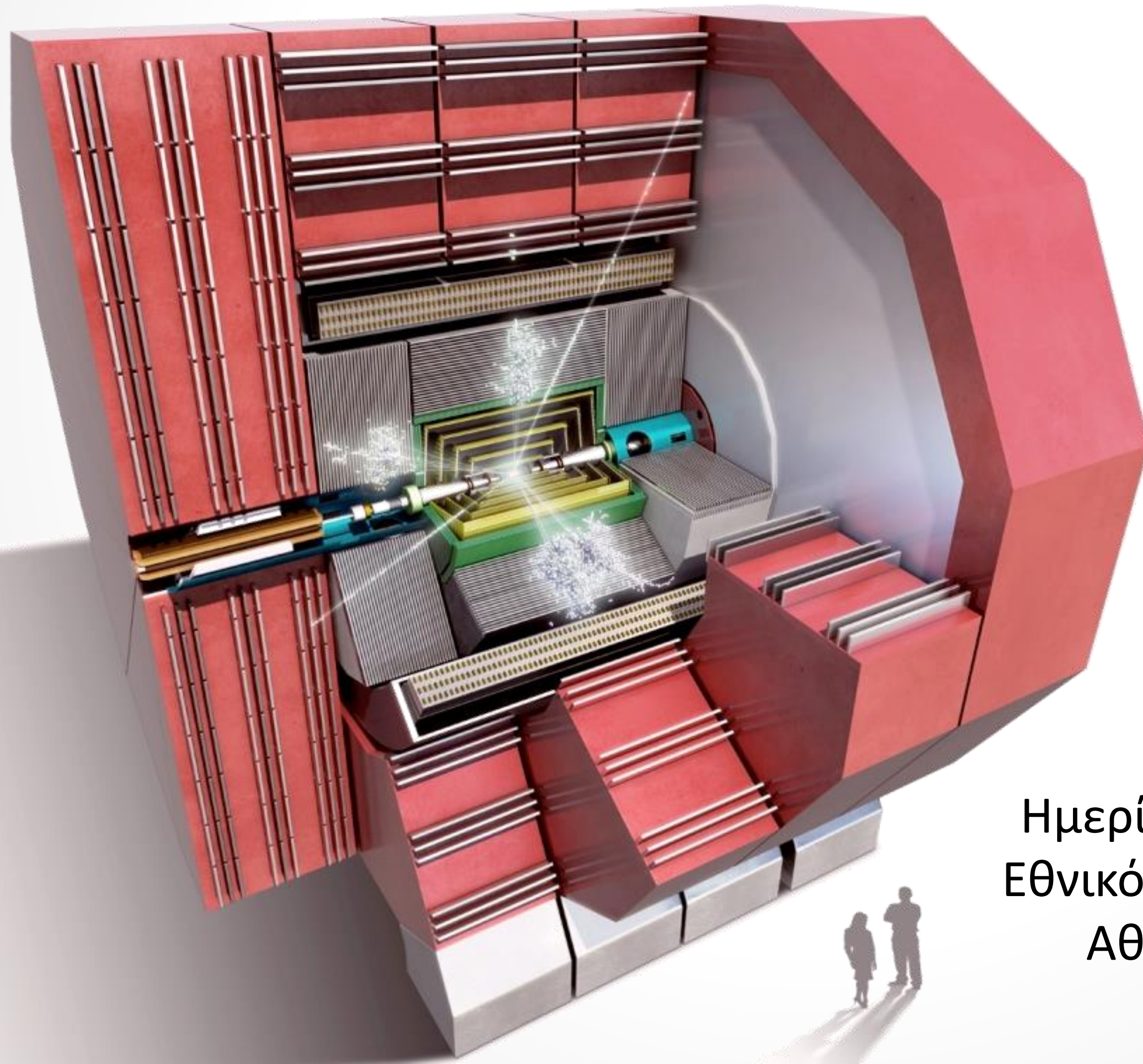
Σχεδιάζοντας ένα ανιχνευτή για τον επιταχυντή CLIC



Νικηφόρος Νικηφόρου
CERN/EP-LCD και
University of Texas at Austin

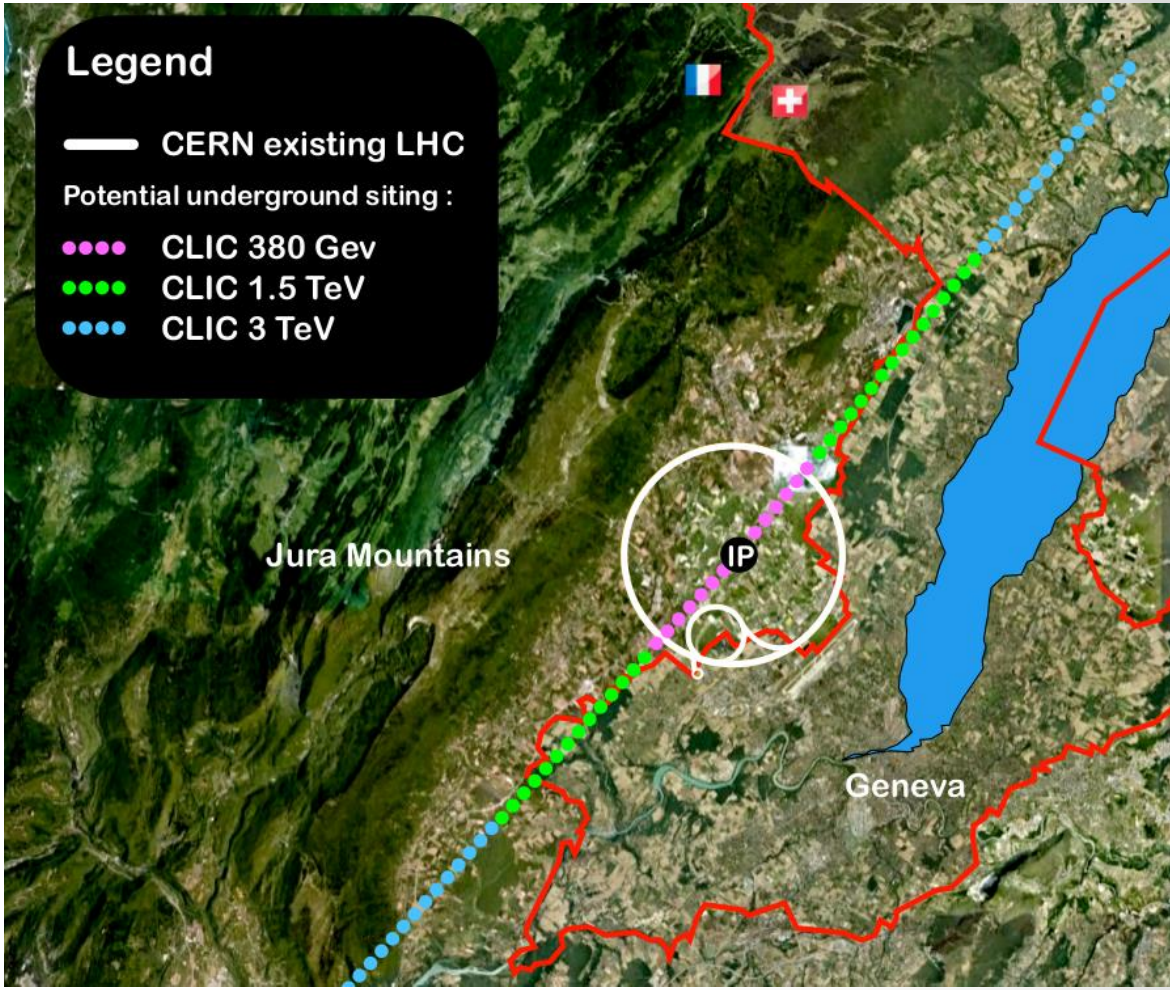
Ημερίδα Αποφοίτων ΣΕΜΦΕ,
Εθνικό Μετσόβιο Πολυτεχνείο,
Αθήνα, 30 Μαΐου 2016

The Compact Linear Collider

- Το CLIC είναι η μόνη ώριμη επιλογή για ένα επιταχυντή e^+e^- για ενέργειες μερικών TeV
- **Compact - συμπαγής:**

  τα σωματίδια μπορούν να επιταχυνθούν σε υψηλότερες ενέργειες με *σχετικά* μικρό μέγεθος διάταξης

  - **CLIC στο CERN: 50 km για 3 TeV**
  - **International Linear Collider στην Ιαπωνία, ILC: 32 km για 500 GeV**
- **Linear - γραμμικός:**
- **Lepton Collider – συγκρουστήρας λεπτονίων:**



Σε αντίθεση με τον LHC (Large Hadron Collider)

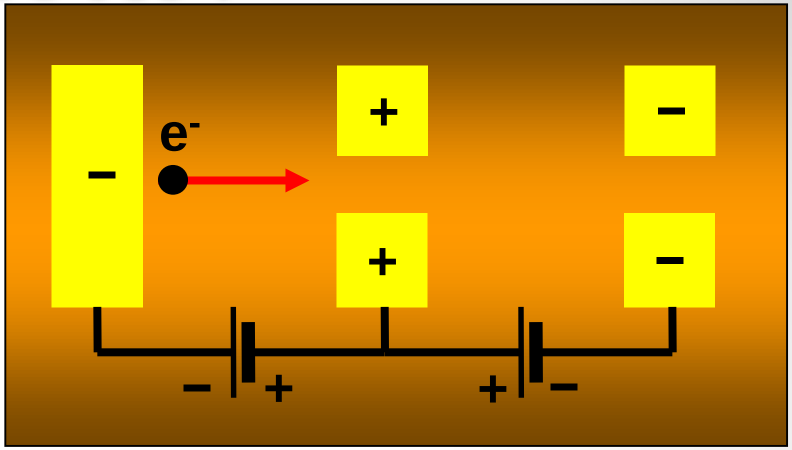
Επιταχυντές Αδρονίων Vs Λεπτονίων

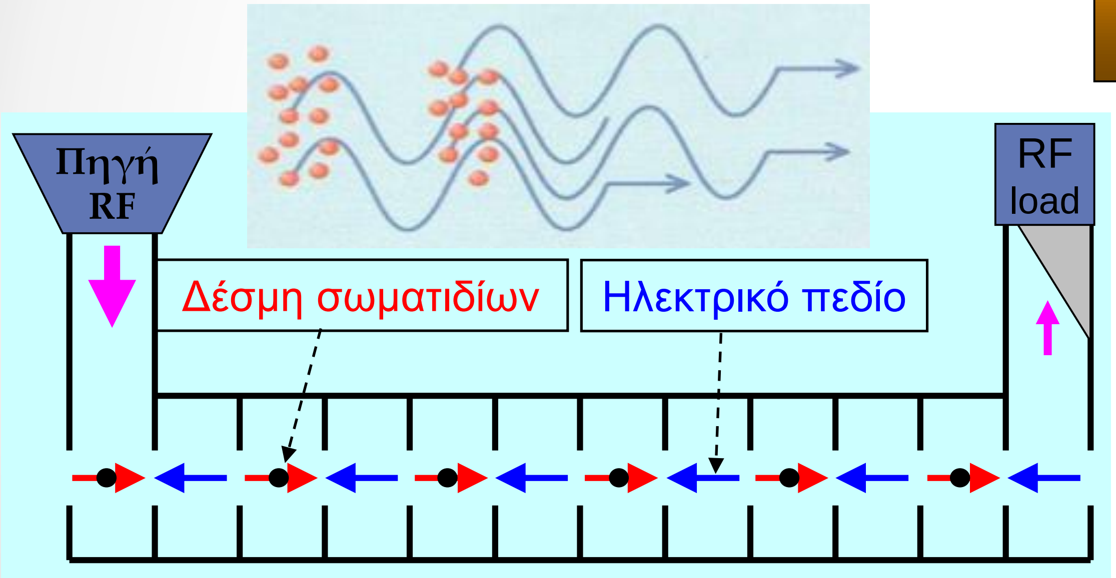
Συγκρούσεις πρωτονίων (p-p)	Συγκρούσεις ποζιτρονίων - ηλεκτρονίων (e^+e^-)
Το πρωτόνιο είναι σύνθετο: • Η αρχική κατάσταση δεν είναι απολύτως γνωστή για κάθε σύγκρουση • Περιορισμός στη μέγιστη ακρίβεια	**Τα e^+/e^- είναι στοιχειώδη:** • Καλά καθορισμένη αρχική κατάστση (√s / πόλωση) • Μετρήσεις υψηλής ακρίβειας
Υψηλοί ρυθμοί υποβάθρου από QCD • Πολύπλοκη επιλογή/απόρριψη γεγονότων (triggering) • Υψηλά επίπεδα ραδιενέργειας	**Καθαρότερο πειραματικό περιβάλλον** • Ανάγνωση χωρίς triggering • Χαμηλά επίπεδα ραδιενέργιας
Μεγάλη μάζα → λιγότερο επιρρεπή στην ακτινοβολία πέδησης/συγχρότρου → επιτάχυνση σε υψηλές ενέργειες με κυκλικούς επιταχυντές	**Η ακτινοβολία συχρότρου αποτρέπει την επιτάχυνση σε πολύ υψηλές ενέργειες σε κυκλικούς επιταχυντές με λογικό μέγεθος → Χρήση γραμμικών επιταχυντών**

Η σωματιδιακή φυσική χρειάζεται και τις δύο προσεγγίσεις!

Επιτάχυνση Σωματιδίων

- Πολύ απλοϊκά: το μεταβαλλόμενο ηλεκτρικό πεδίο επιταχύνει τα φορτισμένα σωματίδια





- Επιταχυντής RF (radio frequency): συγχρονισμός των σωματιδίων με το ηλεκτρομαγνητικό κύμα

Για το CLIC:

- 100 MV/m (100 εκατομ. Volt ανά μέτρο!)
- 12 GHz (συγκ. LHC: 5 MV/m και 400 MHz)

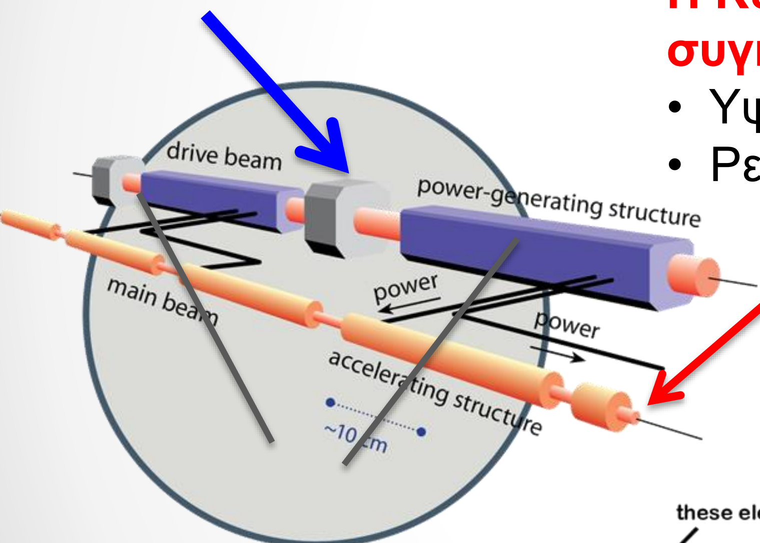
CLIC: Επιτάχυνση με δύο παράλληλες δέσμες σωματιδίων

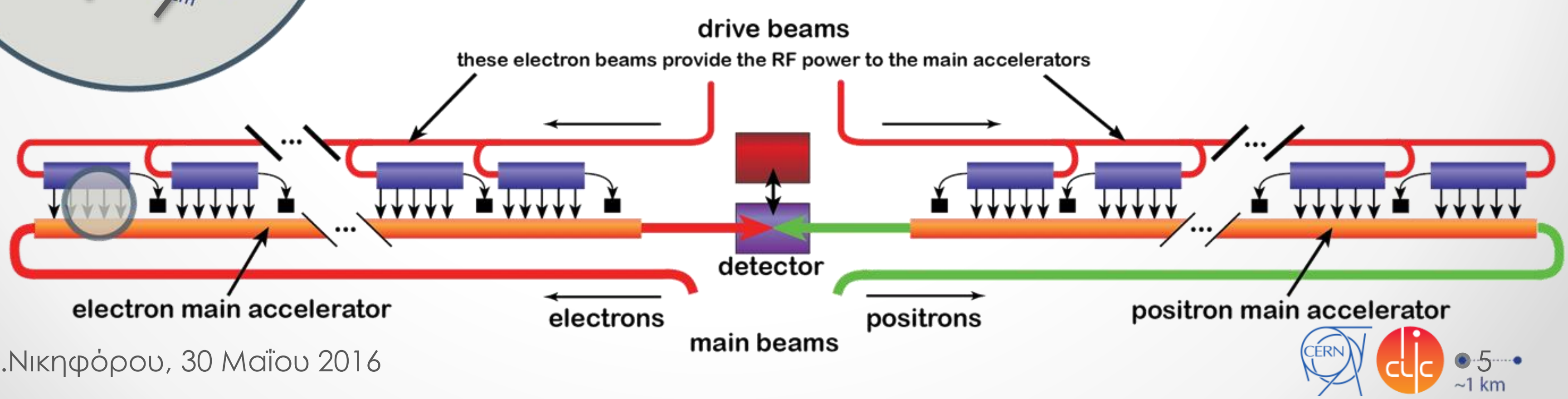
Η Οδηγός Δέσμη (Drive Beam) χαμηλής ενέργειας και υψηλού ρεύματος παρέχει την ακτινοβολία RF για επιτάχυνση

- Δομή δεσμίδων: 12 GHz
- Χαμηλή ενέργεια (2.4 GeV - 240 MeV)
- Υψηλό ρεύμα (100A)

Η Κύρια Δέσμη (Main Beam) επιταχύνεται για να συγκρουστεί για μελέτη στον ανιχνευτή

- Υψηλή ενέργεια (9 GeV – 1.5 TeV)
- Ρεύμα 1.2 A

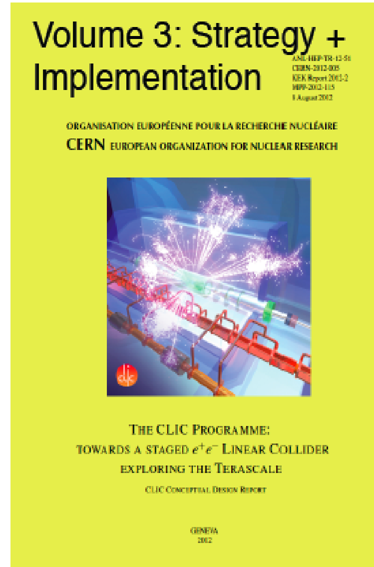




Βιβλιογραφία για το CLIC

[CERN-2012-007]

[CERN-2012-003]



[CERN-2012-005]

Physics at the CLIC e^+e^- Linear Collider
Input to the Snowmass process 2013

October 4, 2013

This paper summarizes the physics potential of the CLIC high-energy e^+e^- linear collider. It provides input to the Snowmass 2013 process for the energy-frontier working groups on The Higgs Boson (HE1), Precision Study of Electroweak Interactions (HE2), Fully Understanding the Top Quark (HE3), as well as The Path Beyond the Standard Model – New Particles, Forces, and Dimensions (HE4). It is accompanied by a paper describing the CLIC accelerator study, submitted to the Frontier Capabilities group of the Snowmass process [1].

The CLIC Detector and Physics Study
H. Abramowicz[1], A. Abusleme[2], K. Afanaciev[3], G. Alexander[1], N. Alipour Tehrani[4], O. Alonso[5,6], K.K. Andersen[7], S. Arfaoui[4], C. Balazs[8,9], T. Barklow[10], M. Battaglia[11], M. Benoit[4], B. Bilki[12], J.-J. Blaising[13], M. Boland[8,14], M. Boronat[5,15], I. Božović Jelisavčić[16], P. Burrows[17], M. Chefdeville[13], R. Contino[18], D. Dannheim[4], M. Demarteau[12], M.A. Diaz Gutierrez[2], A. Diéguez[5,6], J. Duarte Campderros[5,19], G. Eigen[20], K. Elsener[4], D. Feldman[21], U. Felzmann[8,14], M. Firlej[22], E. Firu[23], ...

[arXiv:1307.5288]

+ Higgs Physics at CLIC paper and Updated Staging Baseline paper currently under internal review. Stay tuned!

Παγκόσμια Συνεργασία για το CLIC

CLIC/CTF3 accelerator collaboration
62 institutes from 28 countries

CLIC accelerator studies:
- CLIC accelerator design & development"
- Construction and operation of CTF3"

http://clic-study.org/

CLIC detector and physics (CLICdp)
27 institutes from 17 countries

Focus of CLIC-specific studies on:
- Physics prospects & simulation studies"
- Detector optimization + R&D for CLIC“

http://cern.ch/clicdp

Στόχοι Φυσικής→ Απαιτήσεις για Ανιχνευτή

- Ευκρίνεια στην μέτρηση της ορμής
  - Higgs recoil mass, smuon endpoint, **Higgs coupling to muons**

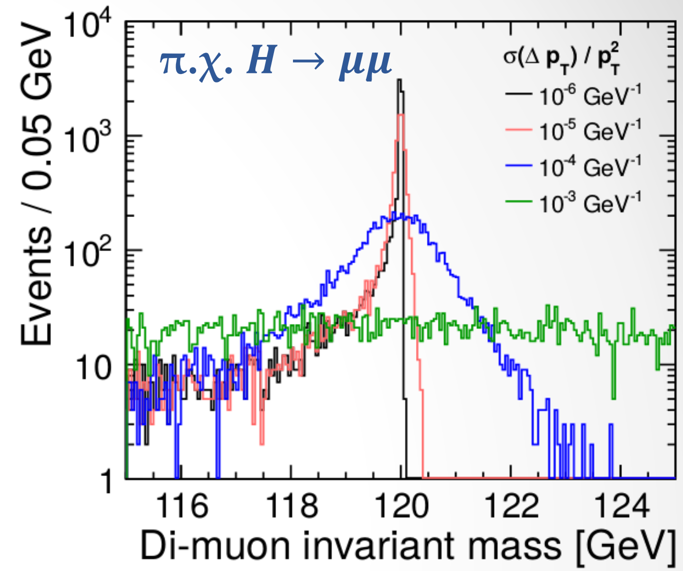
    $\rightarrow \sigma_{P_T}/p_T^2 \sim 2 \times 10^{-5} \mathrm{GeV}^{-1}$
- Ευκρίνεια μέτρησης ενέργειας των Jet
  - **Separation of W/Z/H di-jets**

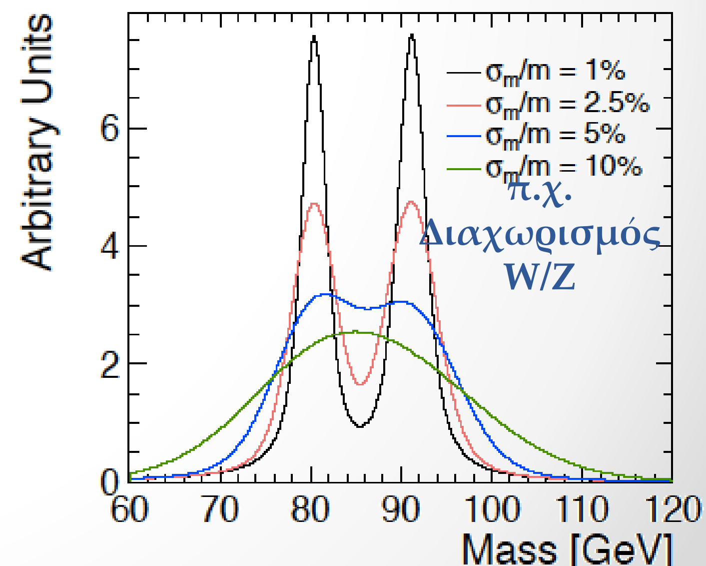
    $\rightarrow \sigma_E/E \sim 3.5\%$ for $\mathrm{E} > 100$ GeV
- Ευκρίνεια παράμετρου πρόσκρουσης
  - c/b-tagging, Higgs branching ratios

    $\rightarrow \sigma_{r\phi} \sim 5 \oplus 15/(p[\mathrm{GeV}] \sin^{\frac{3}{2}} \theta)\mu\mathrm{m}$
- Καλή γωνιακή κάλυψη
  - Αναγνώριση πρόσθιων ηλεκτρονίων

    →Μέχρι και $\theta = 10$ mrad

\+ Ανάγκες λόγω της δομής της δέσμης του CLIC και του υποβάθρου που προκαλείται από τη δέσμη





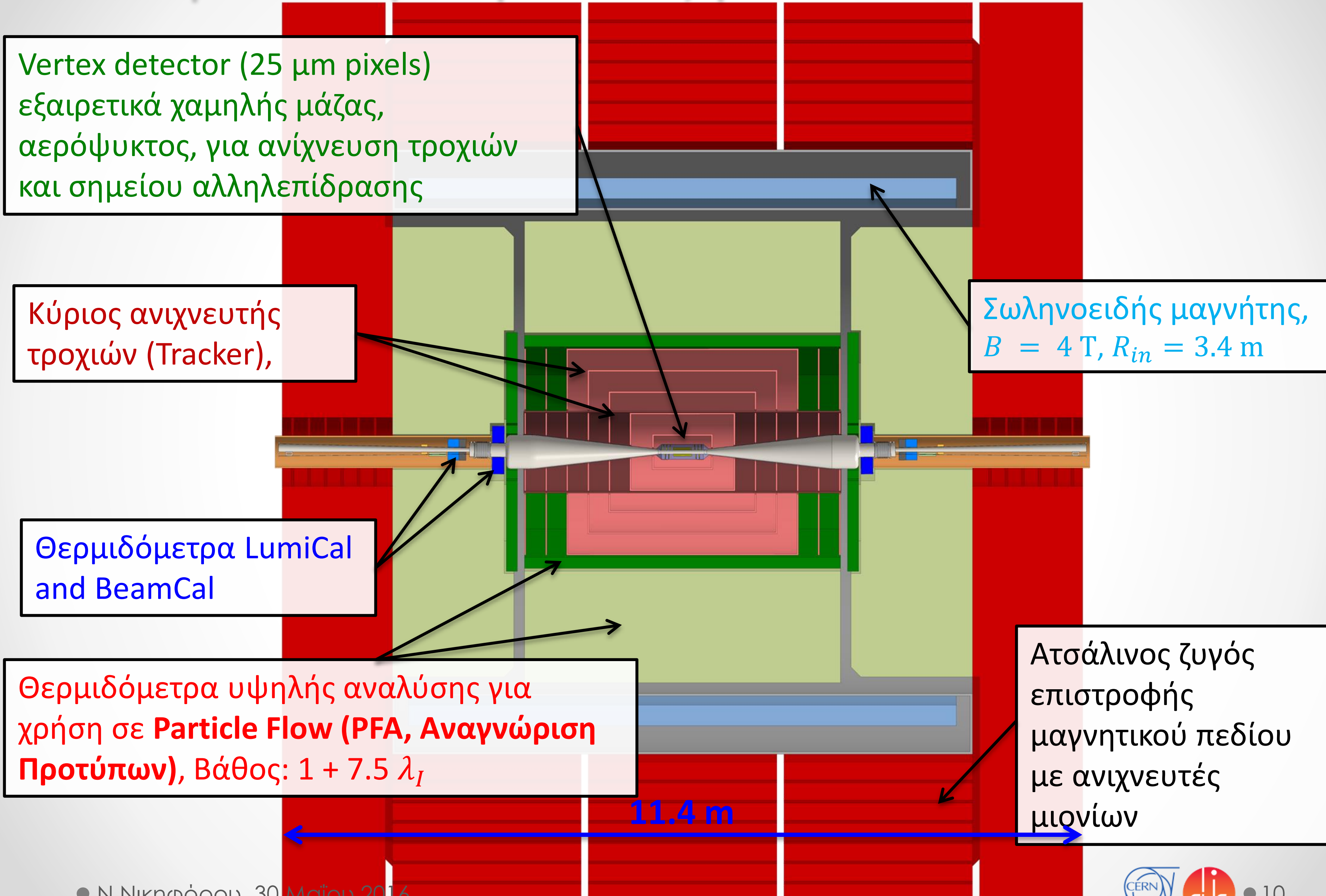
Διαδικασία βελτιστοποίησης των παραμέτρων του ανιχνευτή

- **Αξιοποίηση εμπειρίας από πειράματα του LHC, χρήση των δύο προτάσεων για τον ILC (ILD, SiD) ως εφαλτήρια**
  - Τα μοντέλα ανιχνευτών έχουν ήδη περάσει αρκετά στάδια βελτιστοποίησης
  - Συγκλίνουμε τώρα σε ένα μόνο **“Νέο Μοντέλο” για ανιχνευτή στο CLIC**

- **Χρήση προσομοιώσεων (βασισμένες κυρίως στο πακέτο Geant4)**
  - Αλληλεπίδραση σωματιδιων με τον ανιχνευτή
  - Πλήρης ανακατασκευή και αναλύση ενδιαφέρουσων φυσικών διεργασιών

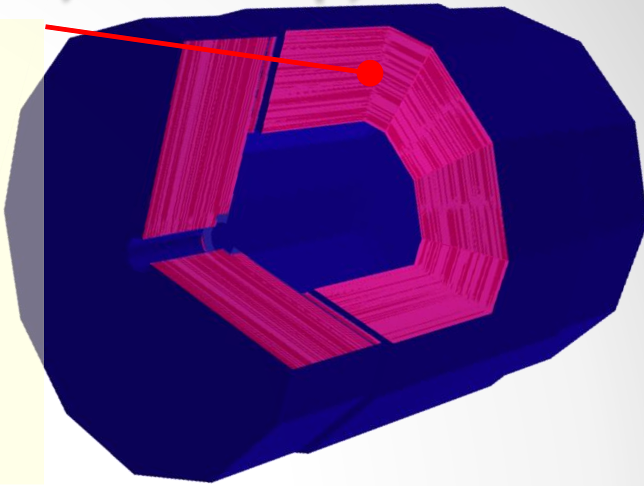
- **Αναπτύξαμε μεγάλο μέρος από το λογισμικό:**
  - Σχεδιασμός και απεικόνιση γεωμετρίας ανιχνευτή και σύνδεση με Geant4 και λογισμικό ανακατασκευής
    - **Πακέτο DD4hep (Detector Description for High Energy Physics)**
  - Λογισμικό ανακατασκευής (τροχιές, αναγνώριση προτύπων, clustering,…)

Προτεινόμενη Διάταξη στο Νέο Μοντέλο

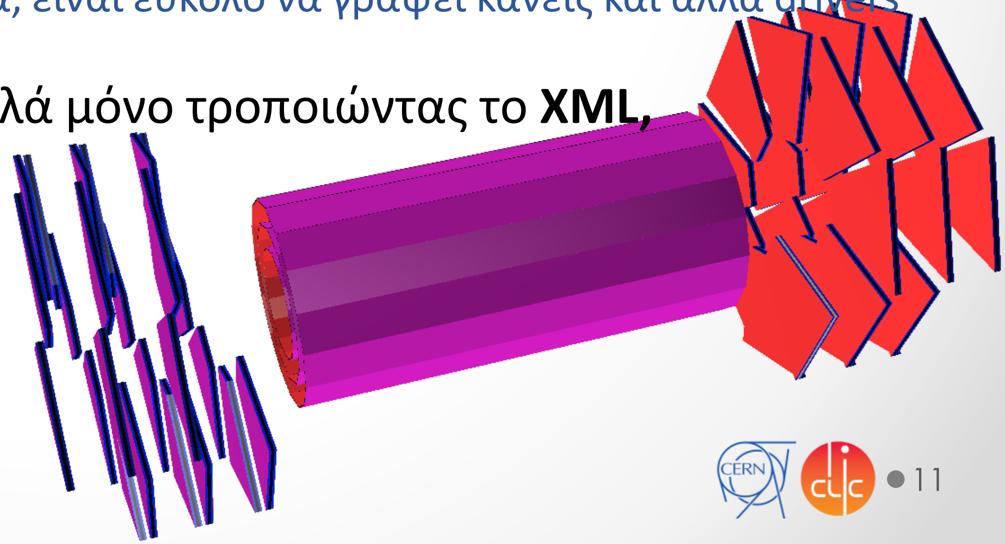


Δημιουργία μοντέλων προσομοίωσης

```
<detector id="DetID_HCAL_Barrel" name="HCalBarrel" type="HCalBarrel_o1_v01"
readout="HCalBarrelHits" vis="HCALVis" >
 <dimensions nsides="HCal_symm" rmin="HCal_Rin" z="HCal_Z" />
 <layer repeat="(int) HCal_layers" vis="HCalLayerVis" >
  <slice material="Steel235" thickness="0.5*mm" vis="AbsVis"/>
  <slice material="Steel235" thickness="19*mm" vis="AbsVis"/>
  <slice material="Polysterene" thickness="3*mm" sensitive="yes"/>
  <slice material="PCB" thickness="0.7*mm"/>
  <slice material="Steel235" thickness="0.5*mm" vis="AbsVis"/>
  <slice material="Air" thickness="2.7*mm"/>
  </layer>
</detector>
```



- **Το λογισμικό DD4hep παρέχει παλέτα γενικευμένων ευέλικτων και κλιμακούμενων μοντέλων για κάθε κομάτι του ανιχνευτή** (C++ drivers)
- Τα μεγέθη, υλικά, τα χρώματα της απεικόνισης ελέγχονται εύκολα μέσω XML
  - Αν χρειάζεται περισσότερη λεπτομέρεια, είναι εύκολο να γραψει κανείς και άλλα drivers
- Συνήθως μπορούμε να κάνουμε πολλά μόνο τροποιώντας το **XML, χωρίς compile**, π.χ.:
  - Αλλαγή μεγέθους ανιχνευτή
  - Δημιουργία διπλών στρωμάτων
  - Σπειροειδής γεωμετρία
  - …

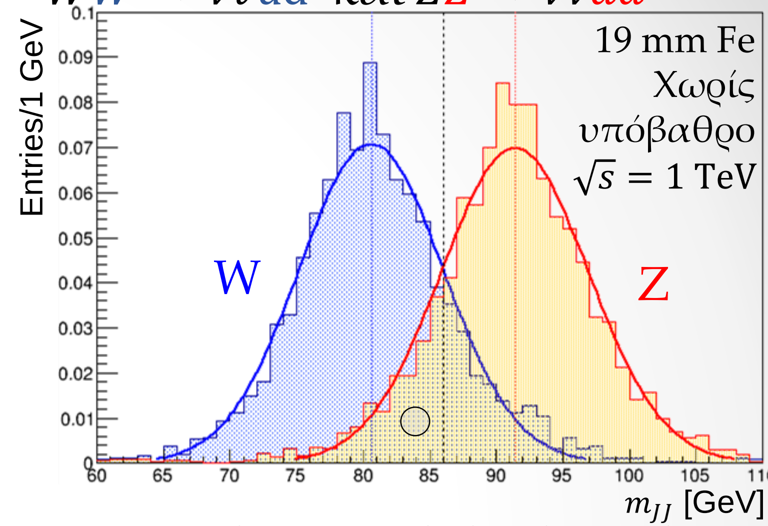


Βελτιστοποίηση HCal

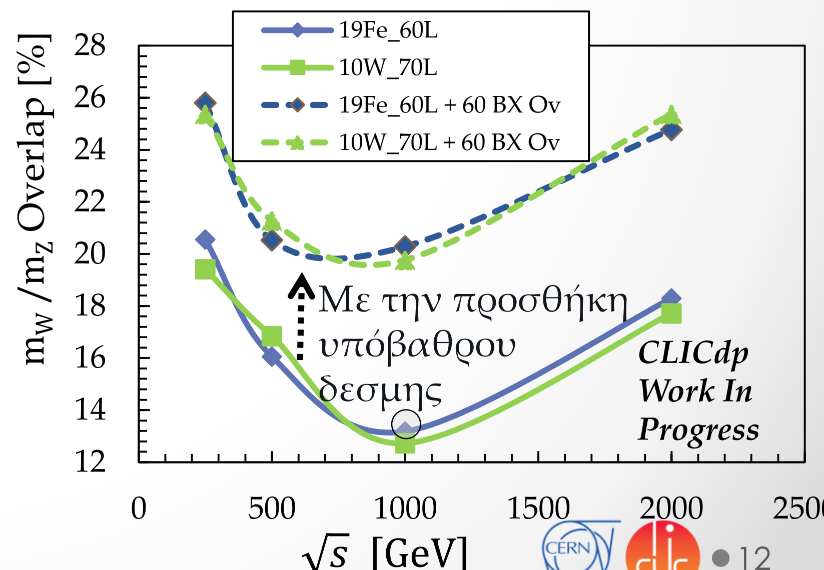
- **Το αδρονικό καλορίμετρο αποτελείται από στρώματα πυκνού απορροφητή και πλαστικού σπινθηριστή**
  - Τα υλικά, ο αριθμός και το πάχος των στρωμάτων, το μέγεθος των κυψελίδων, επιλέγονται με βάση την βελτιστοποίηση της ευκρίνειας της ενέργειας των jets (JER)
- Παράδειγμα: επιλογή απορροφητή
  - 70x10 mm Βολφράμιο (W)
  - 60x19 mm Ατσάλι (Fe)

  Σταθερό συνολικό βάθος $\sim 7.5\ \lambda_I$
- Πλήρης προσομοίωση **Geant4** + **PandoraPFA** + **FastJet**
- Η απόδοση είναι συγκρίσιμη για **βολφράμιο** and **ατσάλι**
  - Το ατσάλι είναι πιο οικονομικό και ευκολότερο στην επεξεργασία

Π.χ. Μελέτη επικάλυψης μετρήσεων m_W και m_Z σε $WW \rightarrow \nu \ell ud$ και $ZZ \rightarrow \nu\nu dd$



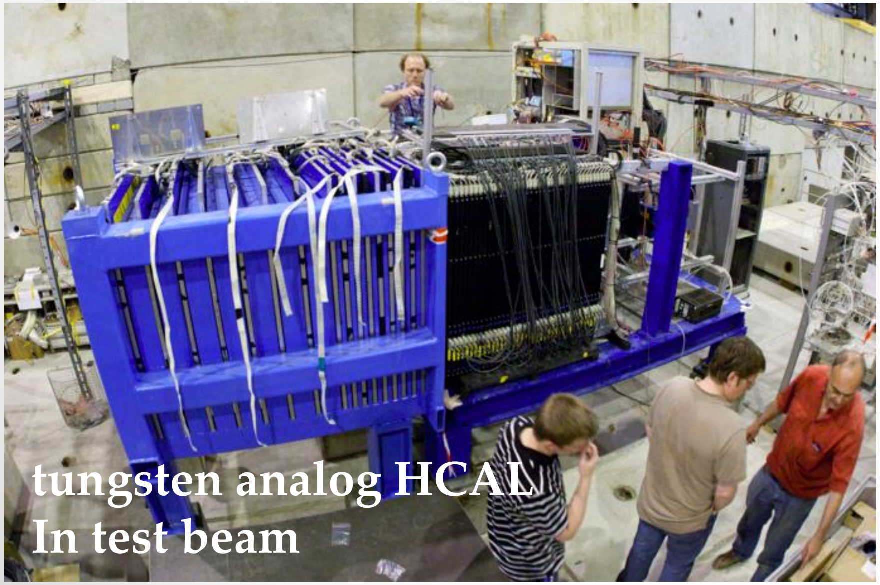
○ Η σκιασμένη περιοχή δίδει ένα από τα σημεία στη πιο κάτω γραφική παράσταση.

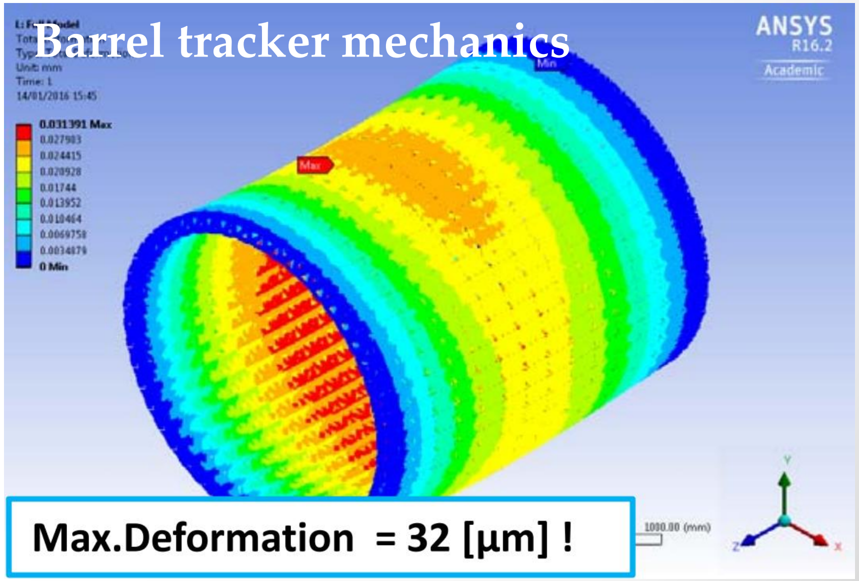


Διαδικασία βελτιστοποίησης των παραμέτρων του ανιχνευτή - II

- **Συνεργασία με μηχανικούς (κόστος, υλοποιησιμότητα, …)**
  - Στατικές/δυναμικές μελέτες (πεπερασμένα στοιχεία, …)

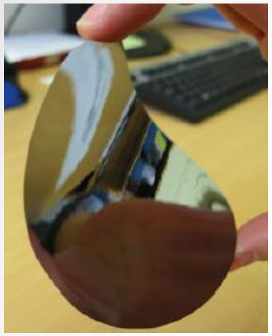
- **Έρευνα και Ανάπτυξη νέων τεχνολογιών (R&D)**
  - Δοκιμές ανιχνευτών σε δέσμες σωματιδίων (Test beams)
  - Προσομοιώσεις απόκρισης ανιχνευτών, …



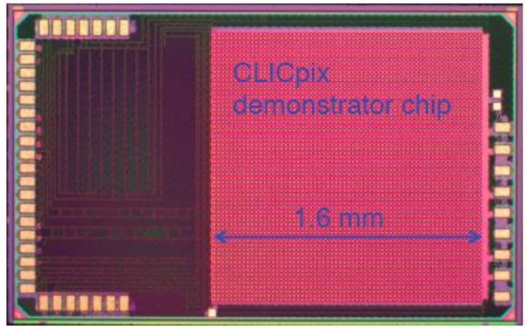


Vertex Detector R&D

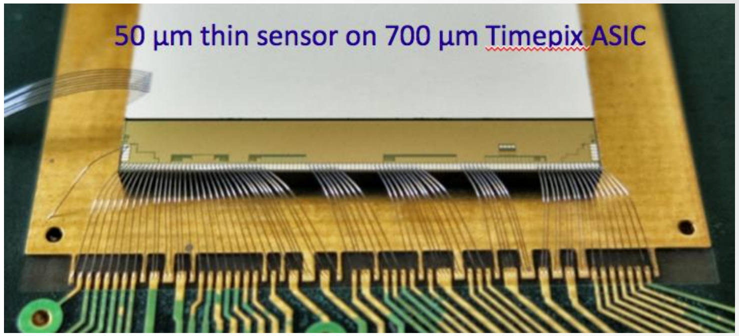
Λεπτοί αισθητήρες πυριτίου



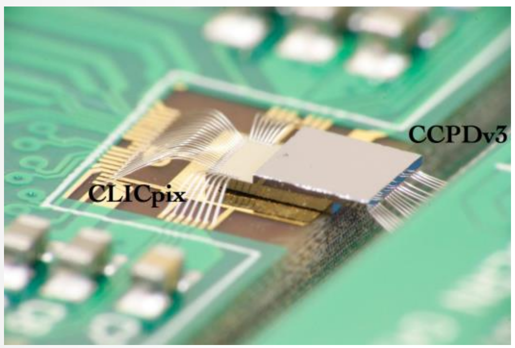
electronics chip (65 nm)



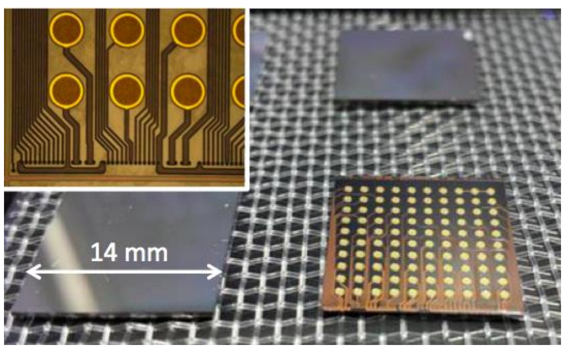
Διάταξη αισθητήρα και ηλεκτρονικών



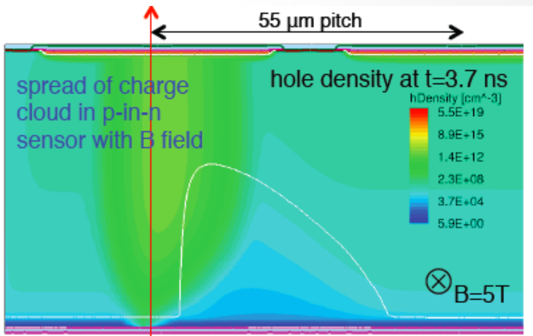
HV-CMOS sensor + CLICpix



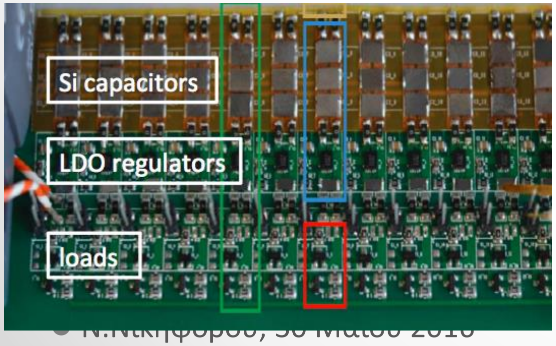
Τεχνολογίες διασύνδεσης



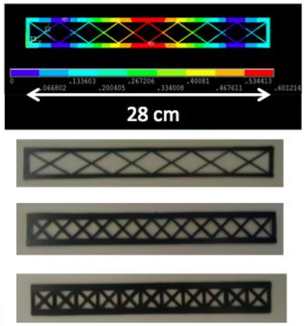
Προσομοιώσεις σήματος



Παλμική παροχή ισχύος



Λεπτά/ελαφριά στηρίγματα



Δοκιμές και προσομοιώσεις για ψύξη με αέρα

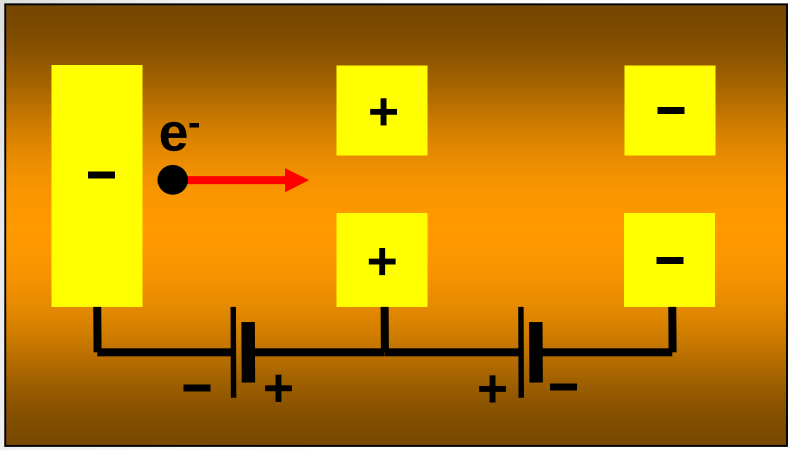
Σύνοψη - συμπεράσματα

- **Το CLIC είναι μια επιλογή για ένα επιταχυντή e^+e^- με ενέργειες μερικών TeV για την μετά-LHC εποχή με εξαιρετικά ενδιαφέρον πρόγραμμα φυσικής και μεγάλες δυνατότητες**
  - **Μεγάλο εύρος ενεργειών με στάδια υλοποίησης βελτιστοποιημένα για φυσική**
  - **Μετρήσεις ακριβείας αλλά και αναζητήσεις νέας φυσικής**
- **Στο CLICdp (detector and physics study) έχουμε ήδη μελετήσει διάφορες επιλογές για ένα ανιχνευτή στο CLIC και συγκλίνουμε σε ένα μοναδικό νέο μοντέλο**
- **Συνεργασία πολλών κλάδων της επιστήμης**
  - **Ανάλυση φυσικής με προσομοιώσεις (benchmark studies, …)**
  - **R&D σε τεχνολογίες αιχμής**
  - **Ανάπτυξη λογισμικού προσομοίωσης, ανακατασκευής, ανάλυσης, …**

Backup Material

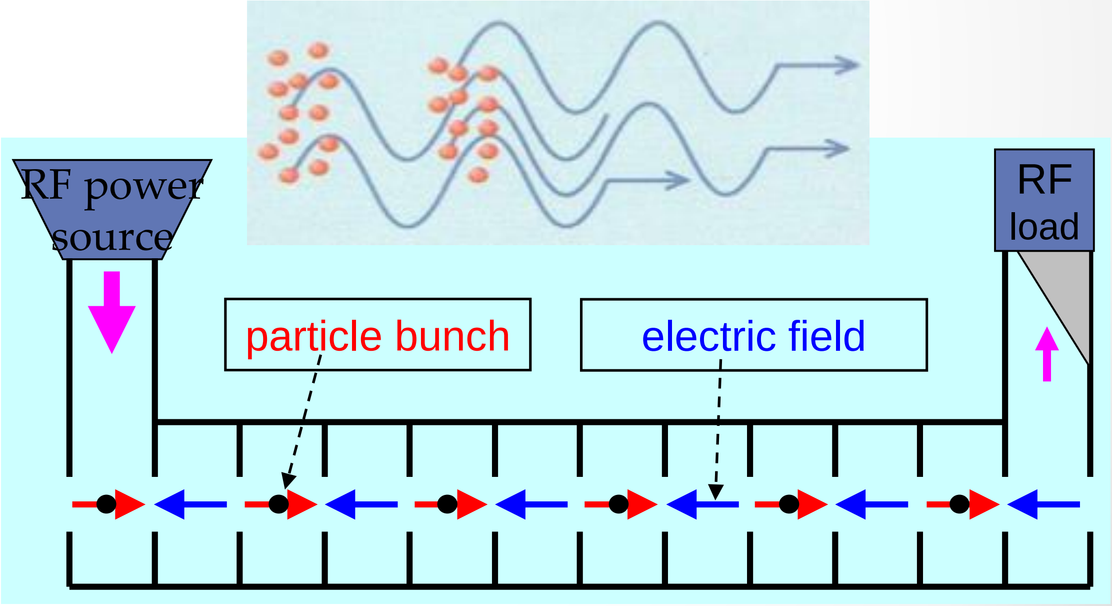
...

Accelerating Particles



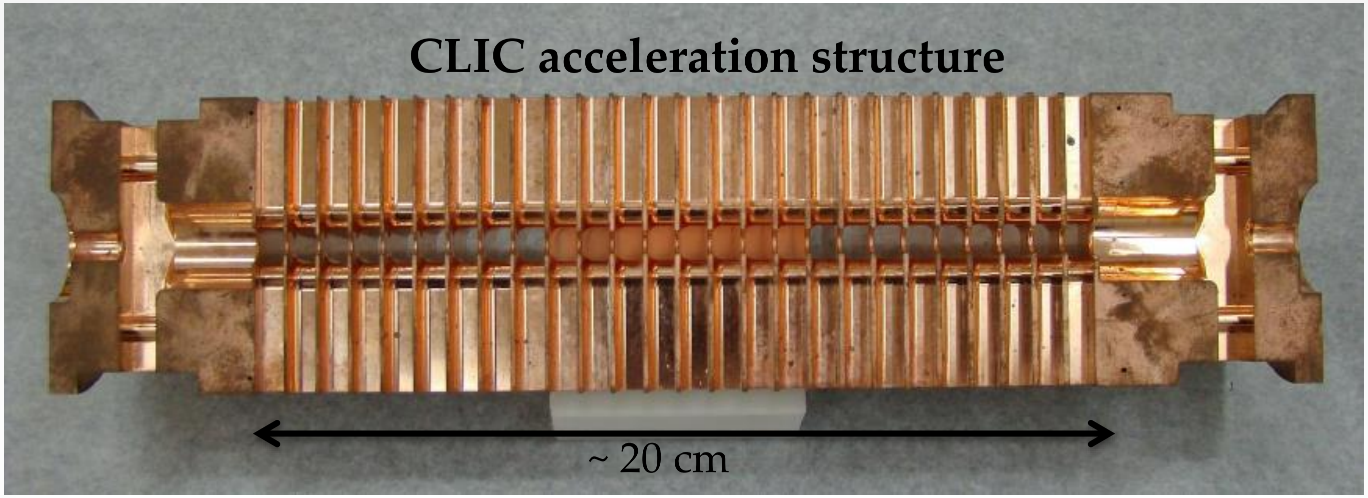
CLIC aims for **high collision energy (3 TeV)**
- need very strong acceleration
- more efficient at high frequency

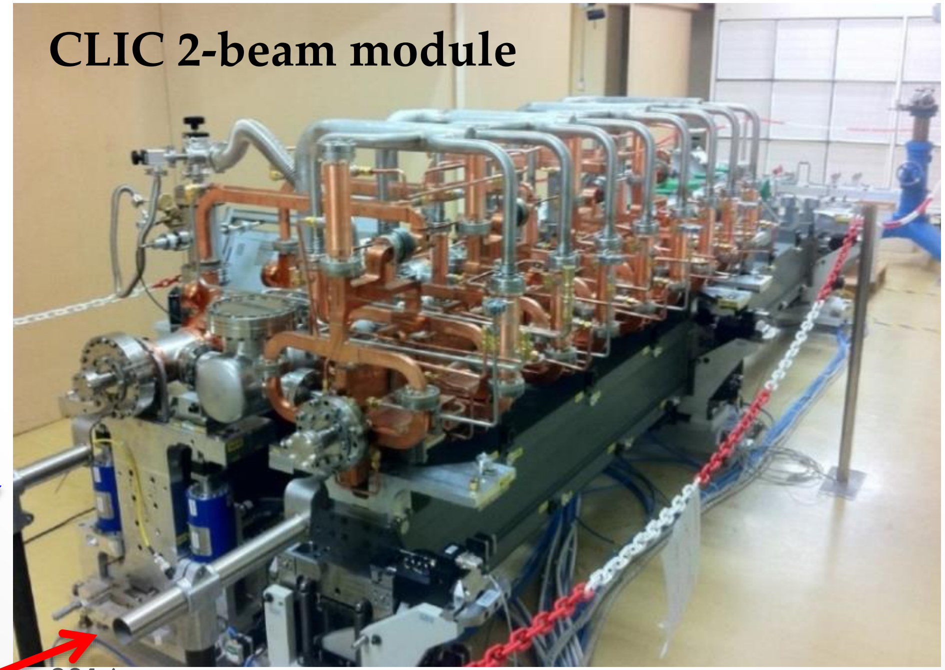
CLIC:
- 100 MV/m (100 million Volts per meter!)
- 12 GHz (at LHC it's 5 MV/m and 400 MHz)



RF (radio frequency) accelerator: synchronise particle with an RF electromagnetic wave

CLIC acceleration modules





CLIC Two-beam Acceleration Scheme

Accelerating gradient: 100 MV/m

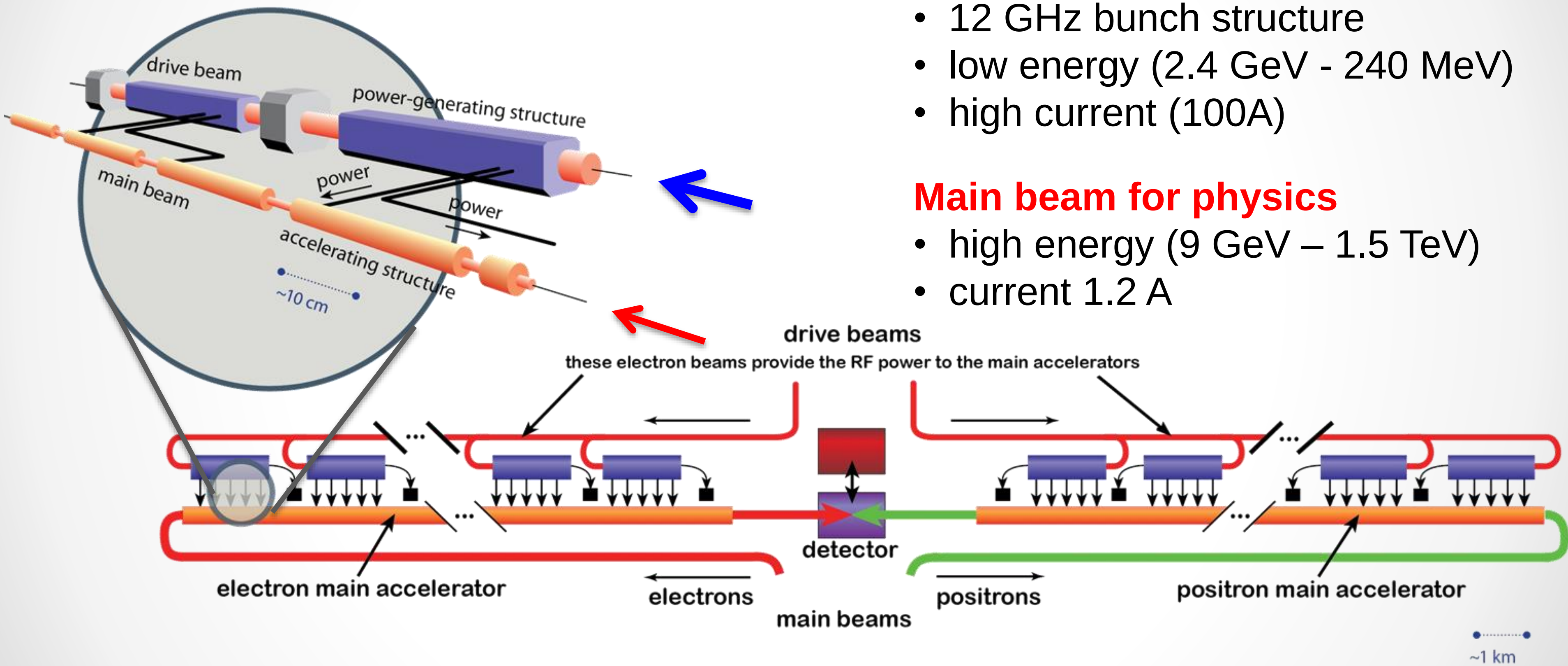
Two Beam Scheme:

Drive Beam supplies RF power

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

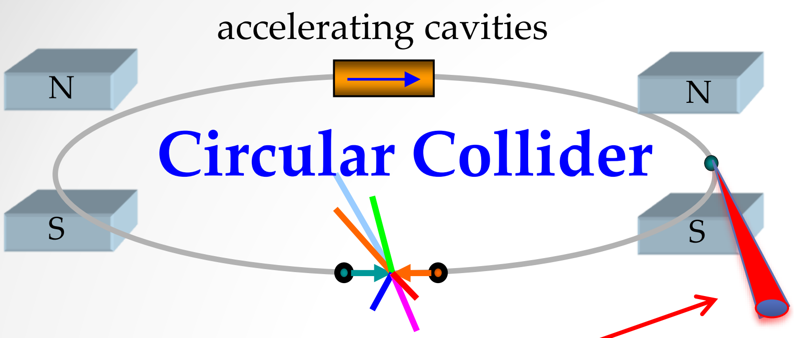
Main beam for physics

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



- Principle of operation already demonstrated successfully at CTF3 at CERN

Why a Linear Collider?



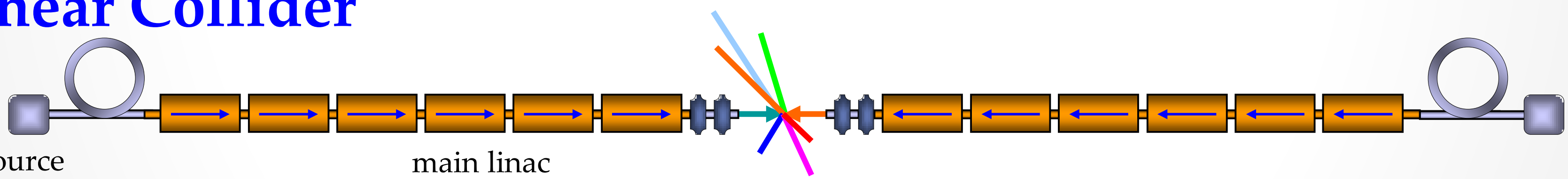
- Few accelerating cavities, many magnets
- Beam circulates for a long time (at 11000 turns/sec in LHC)
- For High energy → <u>strong magnets needed</u> → more synchrotron radiation loss

Synchrotron radiation power: $P \propto \frac{E^2 B^2}{m^4} \propto \frac{E^4}{m^4 R^2}$

Loss of particle energy per turn: $\Delta E \propto \frac{E^4}{m^4 R}$

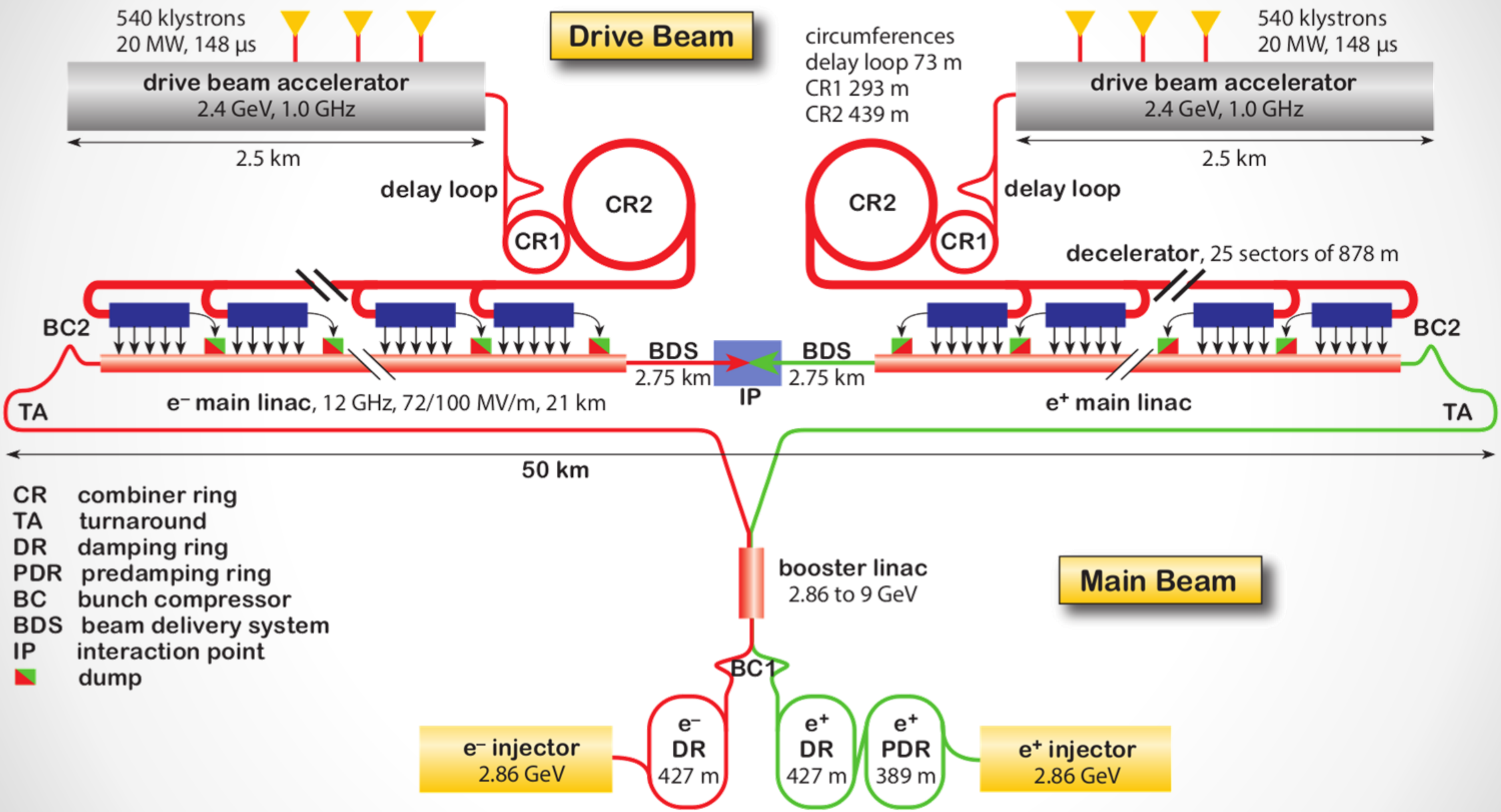
$$\frac{m_{\text{proton}}}{m_{\text{electron}}} \approx 2000$$

Linear Collider



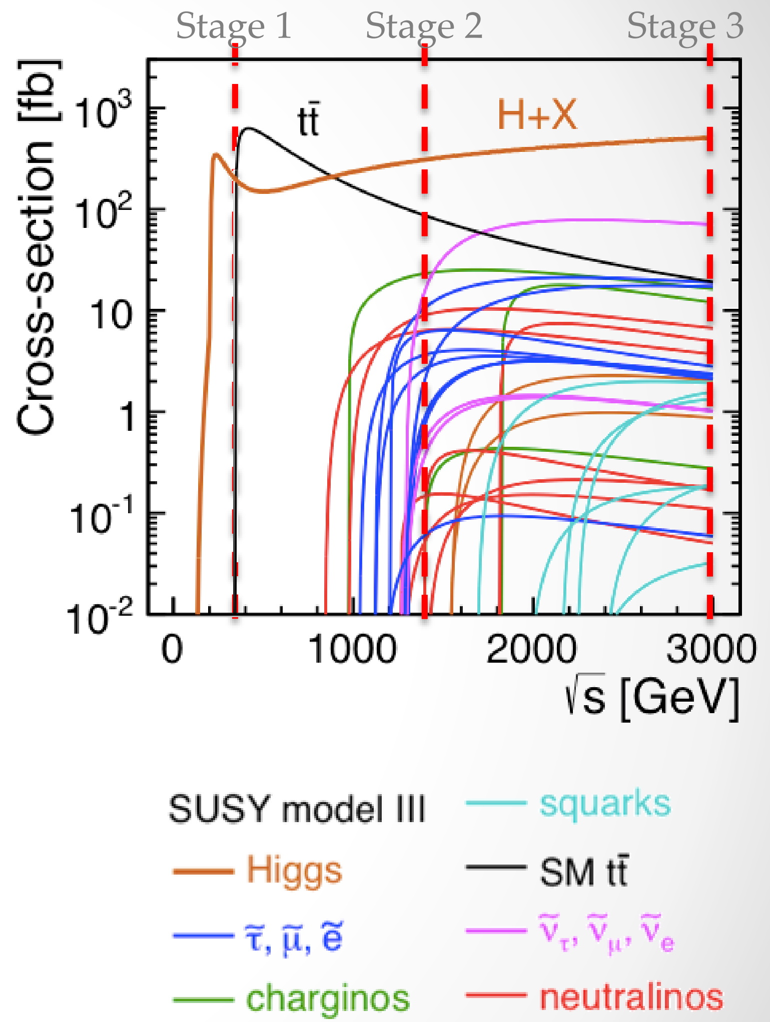
- Few magnets, many accelerating cavities
- Beam passes only once
- For high energy: → <u>high accelerating gradient needed</u>
- For high luminosity → high beam power (high bunch repetition)

CLIC Layout at 3 TeV



CLIC Energy Staging

- **CLIC would be implemented in stages**
  - Wider energy range, optimized running conditions on each stage
  - Driven by Physics **and** technical aspects
- **Exact strategy will depend on LHC results**



Possible staging scenario

(New staging baseline document under collaboration review)

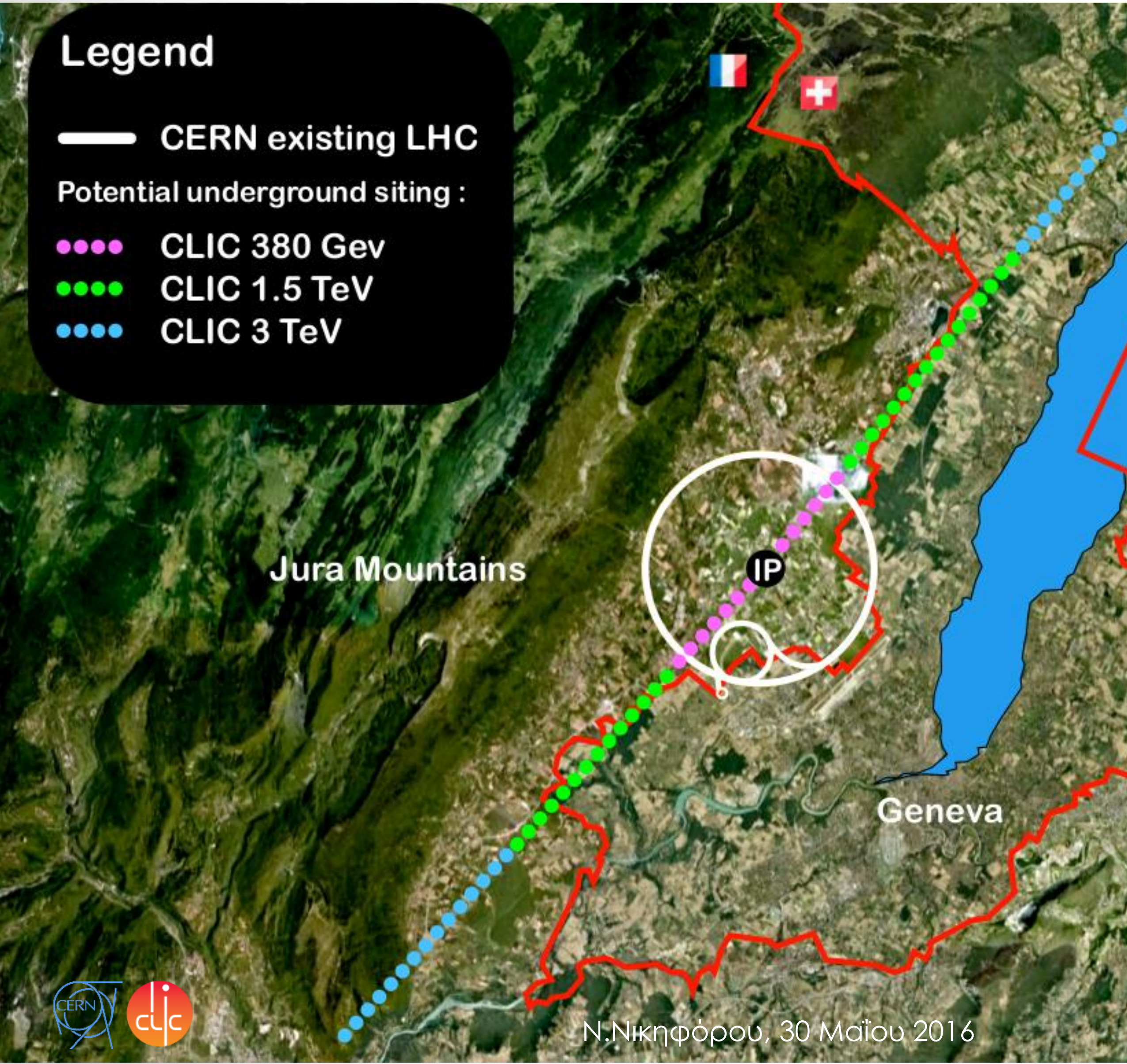
Stage 1: 380 GeV, 500 fb^{-1} , 7 y: precision Higgs and top physics

+ $t\bar{t}$ threshold scan at 350 GeV, 10x10 fb^{-1} points

Stage 2: ~**1.5 TeV, 1.5 ab^{-1}, 5 y:** targeted at BSM physics, precision Higgs

Stage 3: ~**3 TeV, 2 ab^{-1} , 6 y:** targeted at BSM physics, precision Higgs

Proposed CLIC Site and Staging



$\sqrt{s}$ [GeV]	Site length [km]	Inst. Luminosity [$cm^{-2}s^{-1}$]	#Higgs events in ~4 yrs
350	11	1.5×10^{34}	90000
1500	29	3.5×10^{34}	430000
3000	50	6×10^{34}	920000
Higgs event counts ignore any enhancement due to polarization			

Πειραματικές Συνθήκες στο CLIC

	CLIC at 3 TeV
Luminosity	5.9×10^{34} $cm^{-2}s^{-1}$
Bunch separation	**0.5 ns**
#Bunches per train	312
Train duration	**156 ns**
Train repetition rate	**50 Hz**
Particles per bunch	3.72×10^{9}
Crossing angle	20 mrad
σ_x / σ_y [nm]	≈ 45 / 1
σ_z [μm]	44

Drive **timing requirements** for the CLIC detector

Low duty cycle

- Triggerless readout
- Power pulsing (turning power off when not needed)

Very small beam profile at the interaction point

⇒ Very high E-fields ⇒

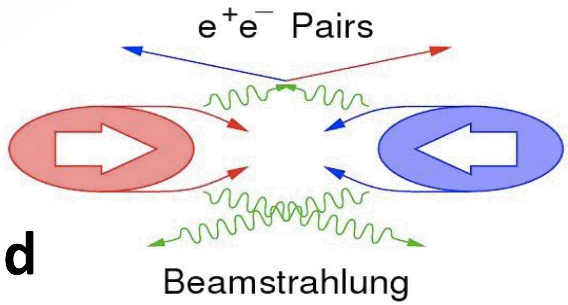
Beam-beam background

CLIC bunch structure

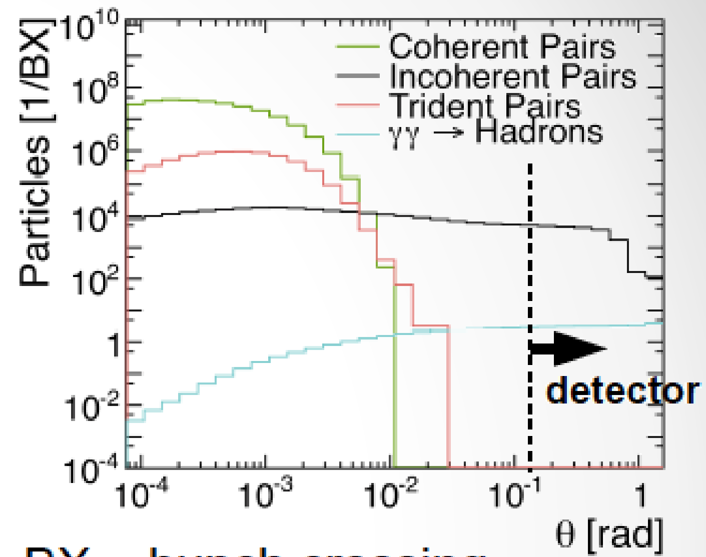
- not to scale -

1 train = 312 bunches, 0.5 ns apart

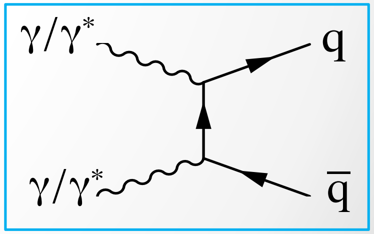
Υπόβαθρο λόγω της δέσμης



- Beamstrahlung:
  - **Pair-background**
    - Coherent e^+e^- pairs: $7 \times 10^8/\mathrm{BX}$
      - Very forward
    - **Incoherent e^+e^- pairs**: $3 \times 10^5/\mathrm{BX}$
      - Rather forward
      - High occupancies influence detector design
  - **γγ to hadrons (3.2 events/BX @ 3 TeV)**
    - Energy deposits (19 TeV/train @ 3 TeV)
    - Main background in calorimeters and trackers



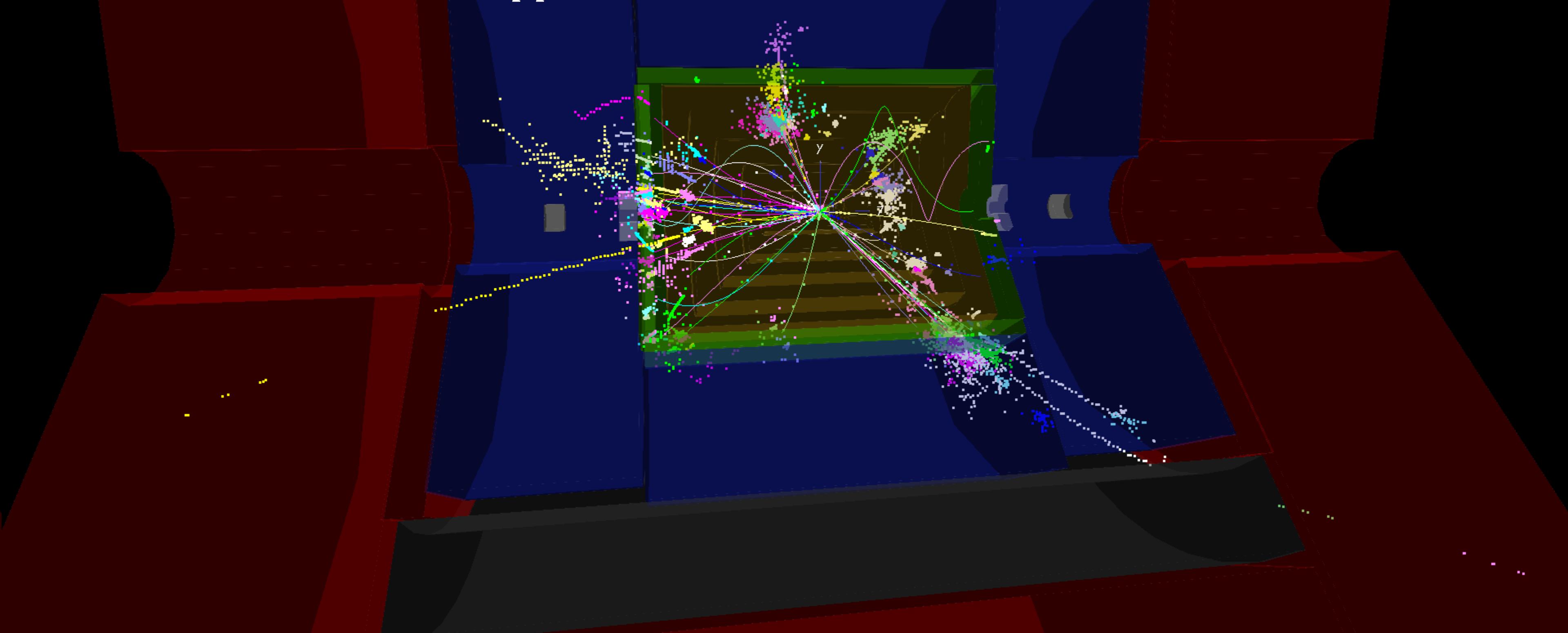
BX = bunch crossing

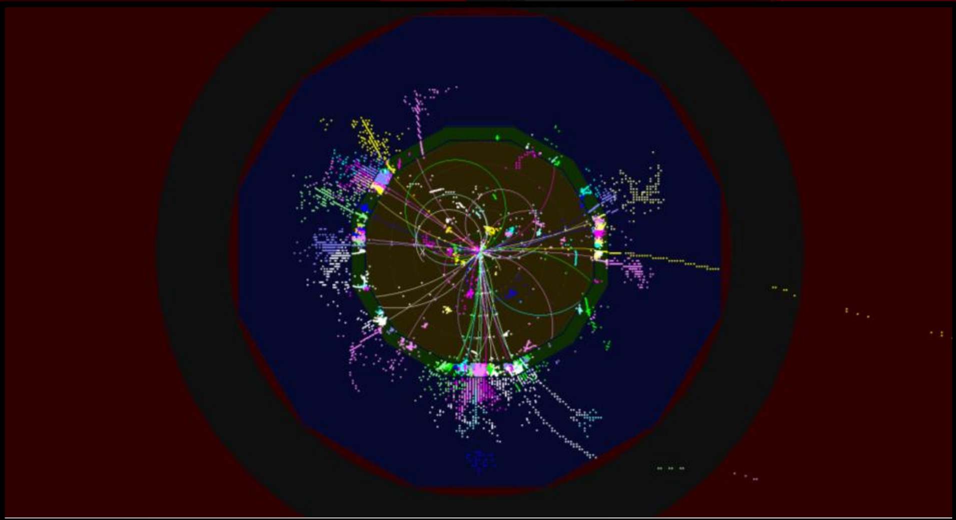


Backgrounds can be mitigated by applying timing and momentum cuts

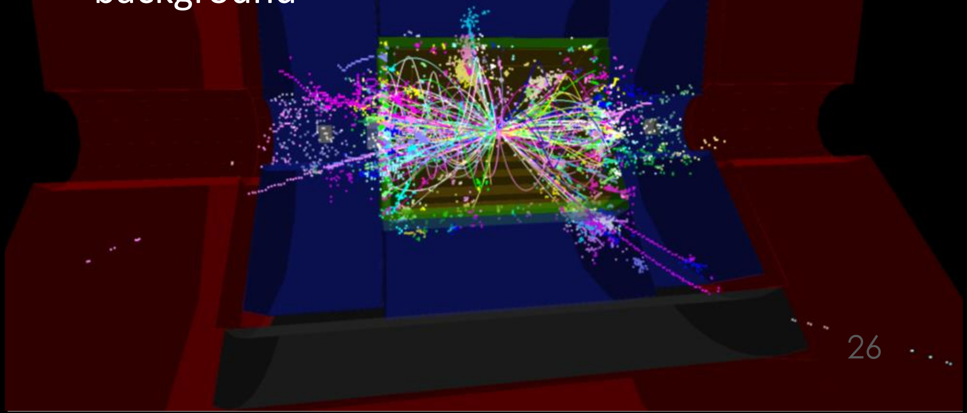
CLIC 1.4 TeV

$$e^+e^- \rightarrow t\bar{t}H \rightarrow WbW\bar{b}H \rightarrow q\bar{q}b\tau\nu\bar{b}\,b\,\bar{b}$$





same event before cuts on beam-induced background



Εξέλιξη των μοντέλων του ανιχνευτή

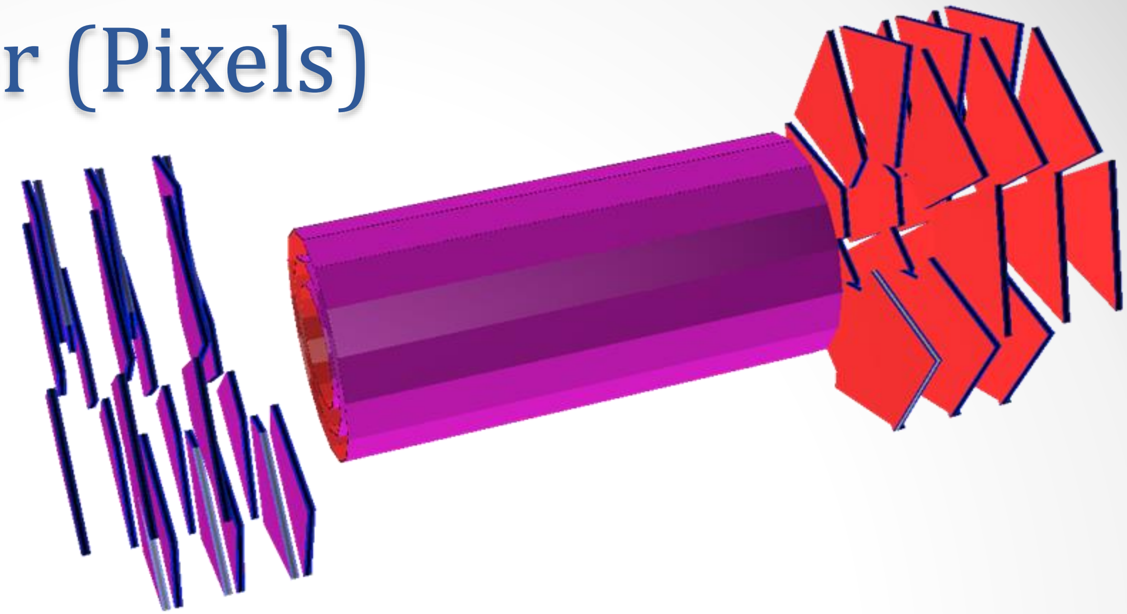
For the CLIC CDR (2012): Two general-purpose CLIC detector concepts

- Based on initial ILC concepts (ILD and SiD) but optimized and adapted to CLIC conditions
- **Now focused on a single detector concept and simulation model**

Concept\Key param.	ILD (ILC)	CLIC_ILD	SiD (ILC)	CLIC_SiD	CLICdet_2015 (3 TeV)	CMS
Tracker	TPC/Silicon	TPC/Silicon	Silicon	Silicon	Silicon	Silicon
Solenoid Field [T]	3.5	4	5	5	4	3.8
Solenoid Free Bore [m]	3.3	3.4	2.6	2.7	3.4	3.0
Solenoid Length [m]	8	8.3	6	6.5	8.3	13
VTX Inner Radius [mm]	16	31*	14	27*	31*	40
ECAL Inner Radius [m]	1.8	1.8	1.3	1.3	1.5	1.3
ECAL ΔR [mm]	172	172	135	135	159	500
HCAL Absorber B / E	Fe	W / Fe	Fe	W / Fe	Fe	Brass
HCAL λ_I	5.5	7.5	4.8	7.5	7.55	5.8 Barrel/10 EC
Overall Height [m]	14	14	12	14	12.8	14.6
Overall Length [m]	13.2	12.8	11.2	12.8	11.4	21.6

* For $\sqrt{s} \lesssim 500$ GeV a variant with a VTX inner radius smaller by 6 mm is foreseen

Vertex Detector (Pixels)



To optimize, flavor tagging was used as a gauge in various tests :

1. **Effect of material (most significant effect on performance)**
2. **Vary inner radius (dictated by background rates ↔ B-field)**
3. Effect of spiral geometry (only small impact)
4. Single vs. double layers (minor impact)

In the new detector model:

- **Double layers (benefits for support)**
- $0.2\% X_0$ **per (single) layer**
- $R_{in} = 31\ \mathrm{mm}$
- **Spiral geometry in the endcaps (better airflow)**
- **Pixel size: 25 μm**
- **3 μm single point resolution**

***High-tech* R&D covering several disciplines**

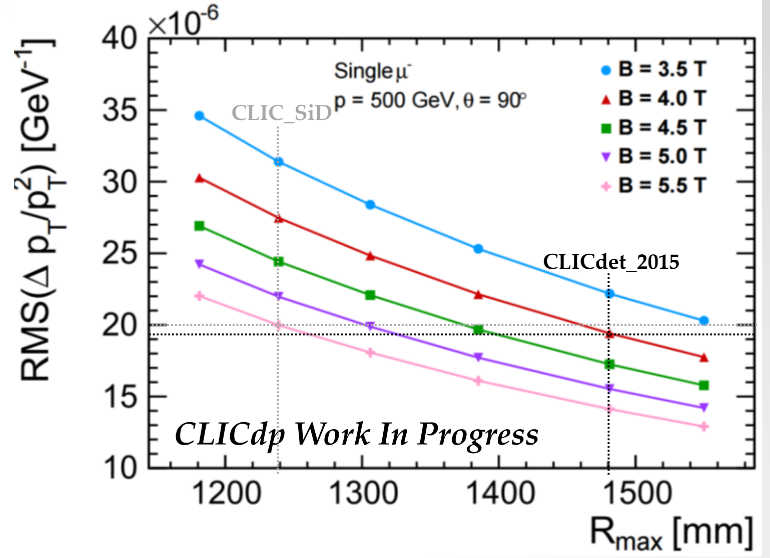
Silicon Tracker

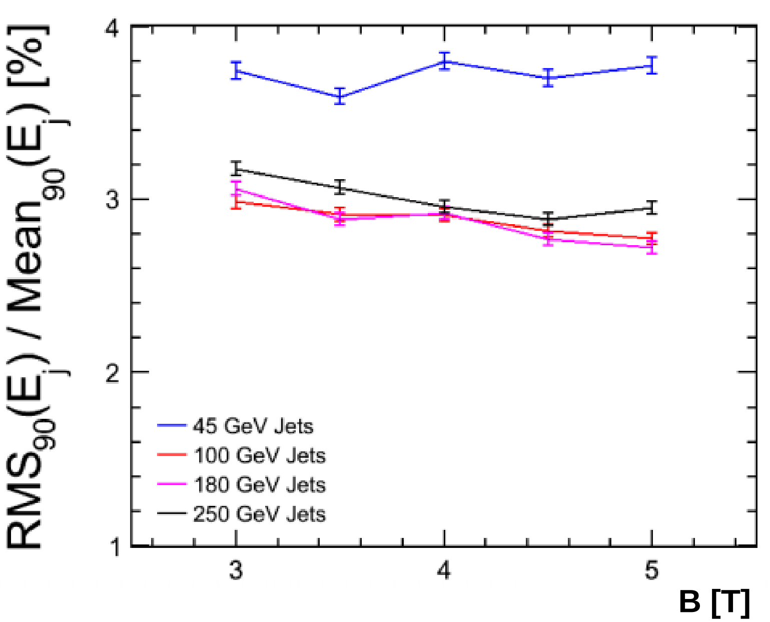
- **We use an All-Silicon Tracker for our new model**
  - A TPC tracker would have very high occupancies (30%) for CLIC @ 3 TeV with 1x6 mm^2 pads (without safety factors)

- **Fast Simulation** (LicToy) studies varying **geometry and layout** (**R**, length, number of layers, etc) as well as **material** (supports, cabling, cooling)
  - Use p_{T} and d_0 resolution to gauge performance
- Key parameters currently implemented:
  - Material Budget: between $1.6\ \%X_0$ and $2.2\%X_0$ per layer
    - Requires very thin materials/sensors
    - Less critical than in Vertex Detector
  - Single point resolution: $\sigma_{R\phi} = 7\ \mathrm{\mu m}$
- **Full simulation studies** ongoing with **new Reconstruction Software**

Silicon Tracker Radius/ B-field

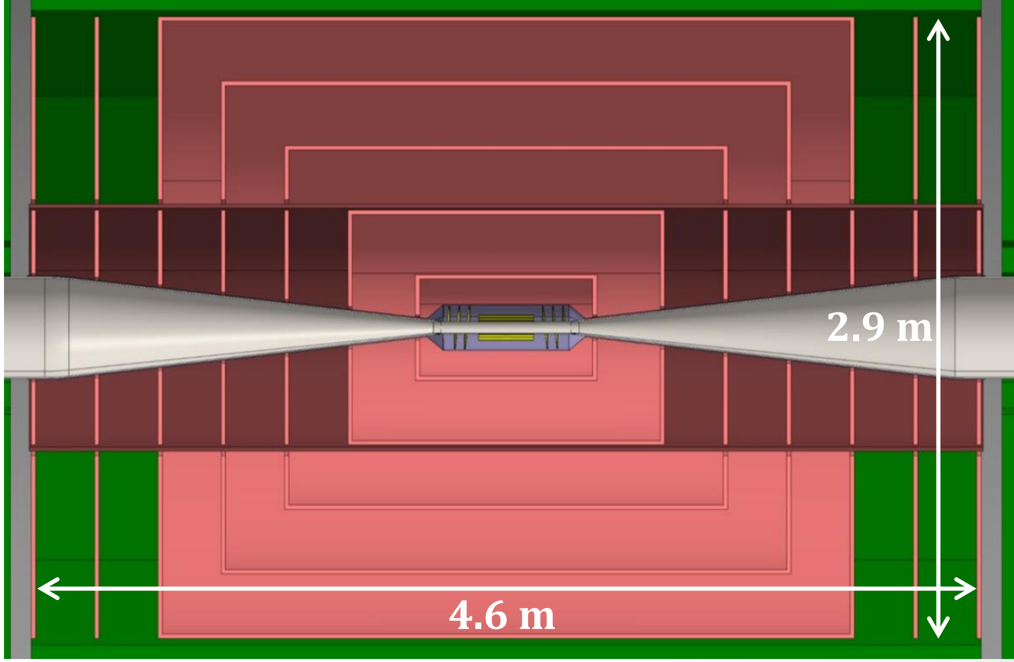
- **Can compensate a change in B by rescaling R by $\sqrt{B_{nom}/B}$**
- **B-Field and R also affect Particle Flow Performance**
  - Previous ILD studies by M. Thomson and J. S. Marshall
- A magnetic field strength of up to 4.5 T should be technically feasible
- **Converged to an outer tracking radius of 1.5 m and field strength of 4 T**
- **Tracker length: at least like CLIC_ILD (4.6 m)**
  - **Motivated by physics in the forward region (e.g. Higgs self-coupling)**
  - Reduce Endcap Yoke thickness by 1.2 m and use end coils

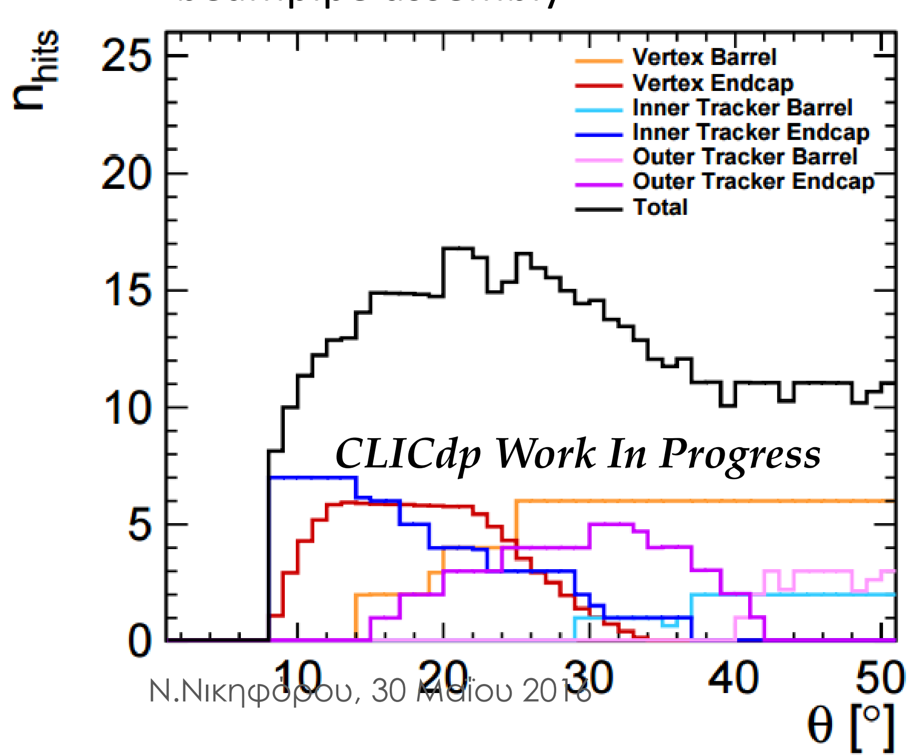




Si Tracker Layout

- **5 "short" Barrel layers**
  - First layer at $R = 230$ mm
- **7 "flat" Endcap disks (full R)**
  - New First disk at $z = 430$ mm
- **Arranged in an *Inner* and *Outer Tracker***
  - Support tube for extraction with beampipe assembly

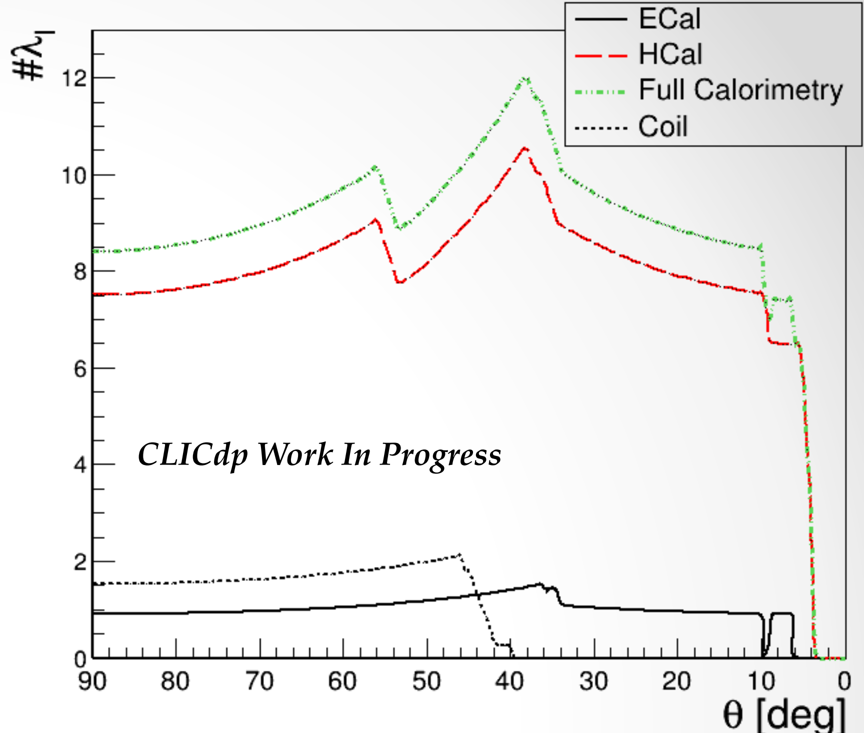


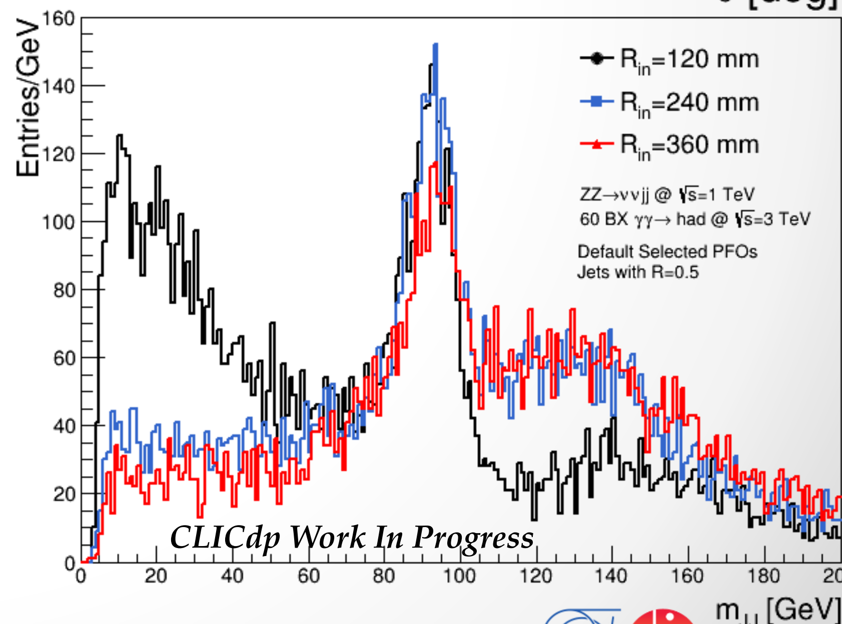


- **At least 8 hits (Vertex + Tracker) for θ> 8º**
- **Module arrangement and overlap still under investigation**
- **Cell size should vary from layer to layer**
  - **Motivated by occupancy (next slide)**

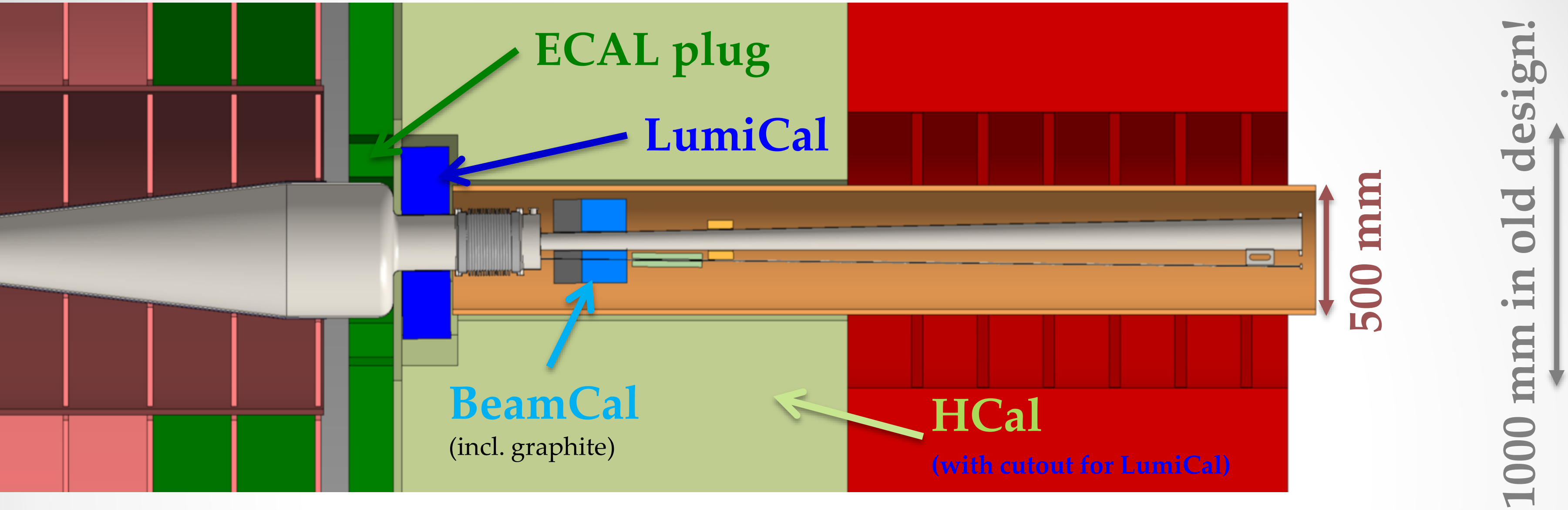
More Calorimetry

- The ECal and HCal combined present at least 8.5 λ_I down to $\theta = 10^o$
  - Does not include BeamCal/LumiCal
- HCal Endcap now **extended** down to $R_{in} = 250$ mm
  - With some cutout for LumiCal
- We found that $\boldsymbol{R_{in} = 240}$ **mm** is a **good compromise** between letting in more background and **increased acceptance**
  - **Studied** m_{JJ} in $ZZ \rightarrow jj\nu\nu$ events with overlay for various HCal Endcap inner radii
- 12-fold inner and outer symmetry for ECal/HCal/Yoke





Forward Region Layout in the New Model



- **HCal Endcap coverage** extended
- Reoptimized for a working hypothesis of an $\boldsymbol{L^* = 6\ \mathrm{m}}$
  → **Final Focusing Quadrupole (QD0) outside detector region**
  - Simplified services, no need for an anti-solenoid
  - No need for rigid support
  - Smaller support outer radius: **250 mm** (was 500 mm)

Tracker: Open Issues

- Probably use gradually longer strips in layers
  - Oriented along z (R) for barrel (endcap)
  - Length $1 - 10$ mm, $\sigma_{z(R)} = 0.3 - 3$ mm
  - Considering large pixels ($\sigma = 5$ μm) for first endcap disk

- Sensor Technology?
- Power pulsing!
- Air cooling not feasible in a large tracker volume
- Use of **liquid cooling** restricts also options for module geometry/layout/overlap!
  - Material budget for cooling and supports already implemented in model

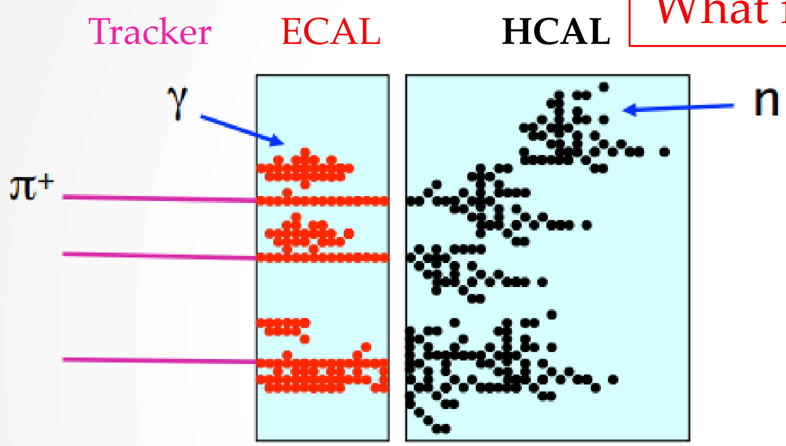
- *Tracker hardware R&D recently started*

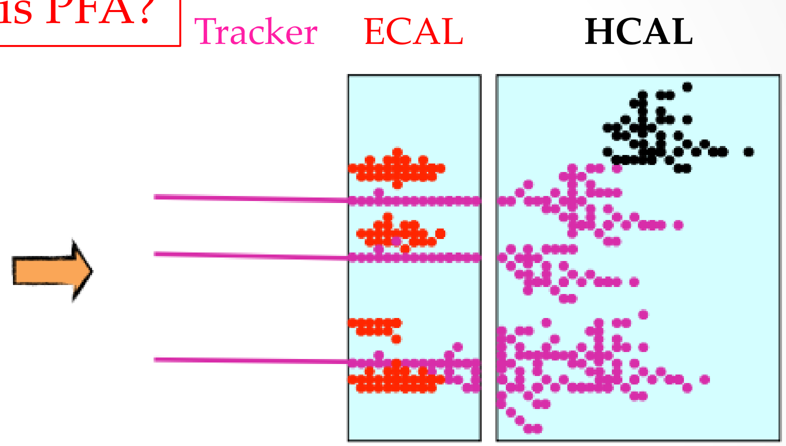
- **Investigating and developing a few track finding and fitting strategies and algorithms**

Calorimetry and PFA

Jet energy resolution and **background rejection** drive the overall detector design
⇒ fine-grained calorimetry + Particle Flow Algorithms (PFA)

What is PFA?





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

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

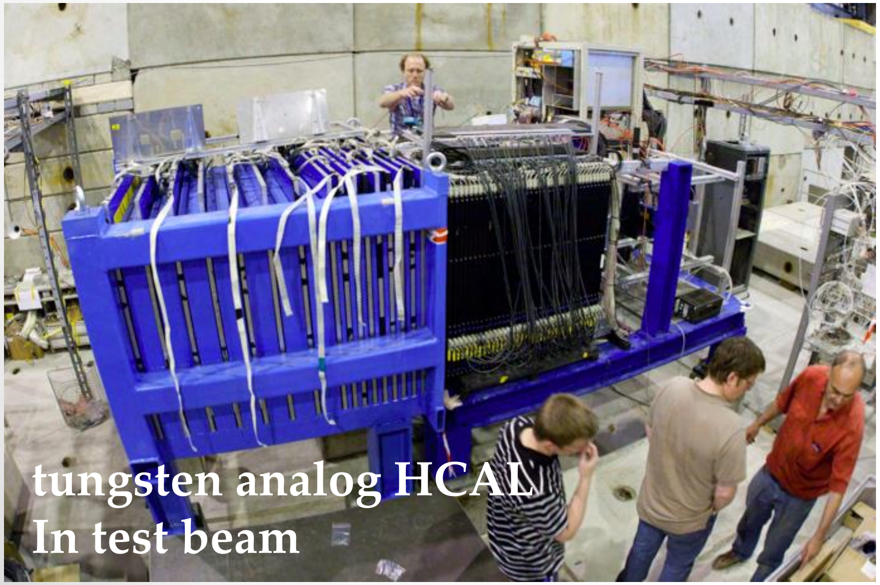
Typical jet composition:
- 60% charged particles
- 30% photons
- 10% neutral hadrons

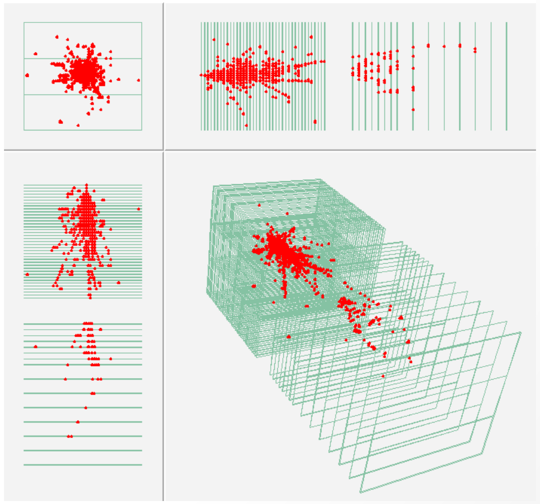
Always use the best info you have:
- 60% ⇒ tracker
- 30% ⇒ ECAL
- 10% ⇒ HCAL

Hardware + software !

Calorimeter R&D

- **Developing high-granularity calorimeters**
  - ~80 million readout channels
  - (400x larger than LHC)
- To be used with Particle Flow Algorithms (mainly **PandoraPFA**)
- R&D in the framework of **CALICE** collaboration
  - Investigating different absorber materials, readout technologies and techniques

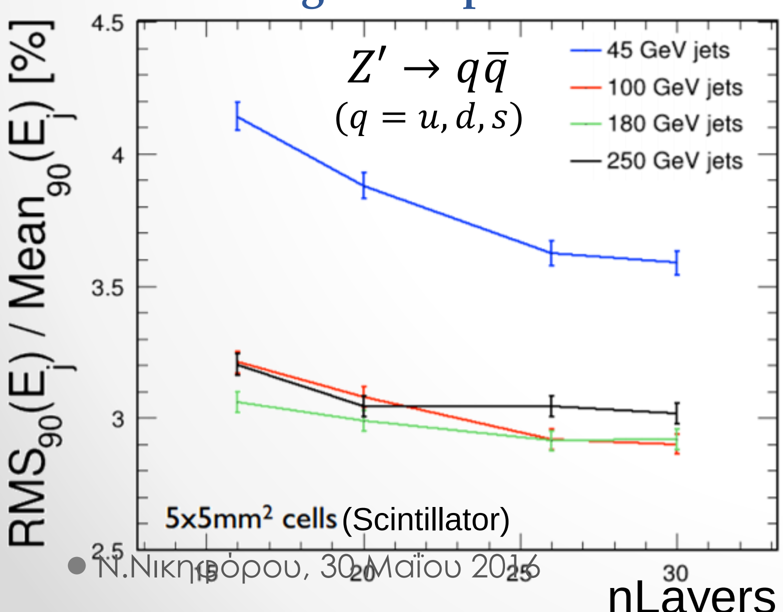


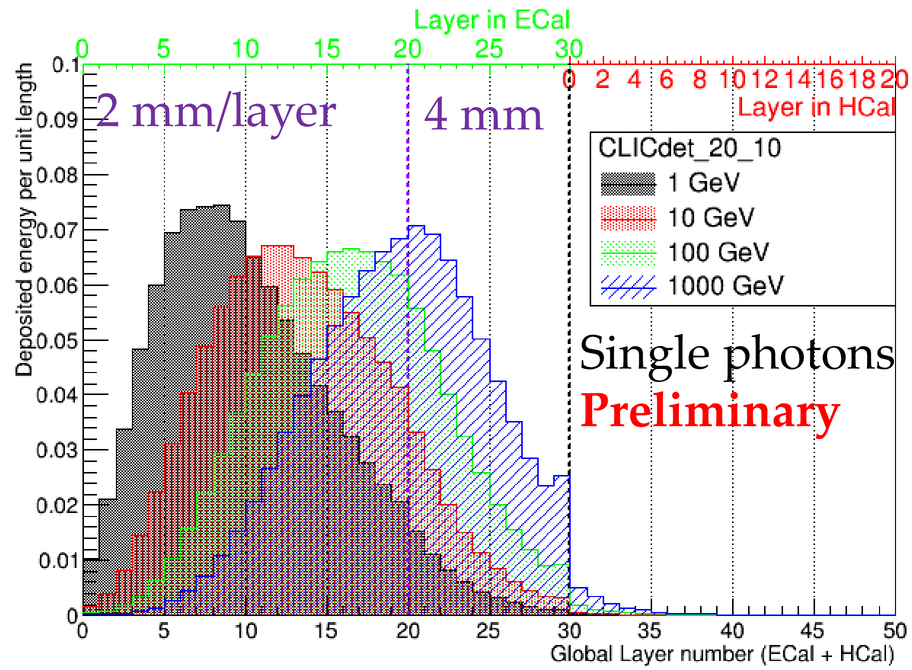


210 GeV π^- in tungsten-DHCAL

ECal Optimization

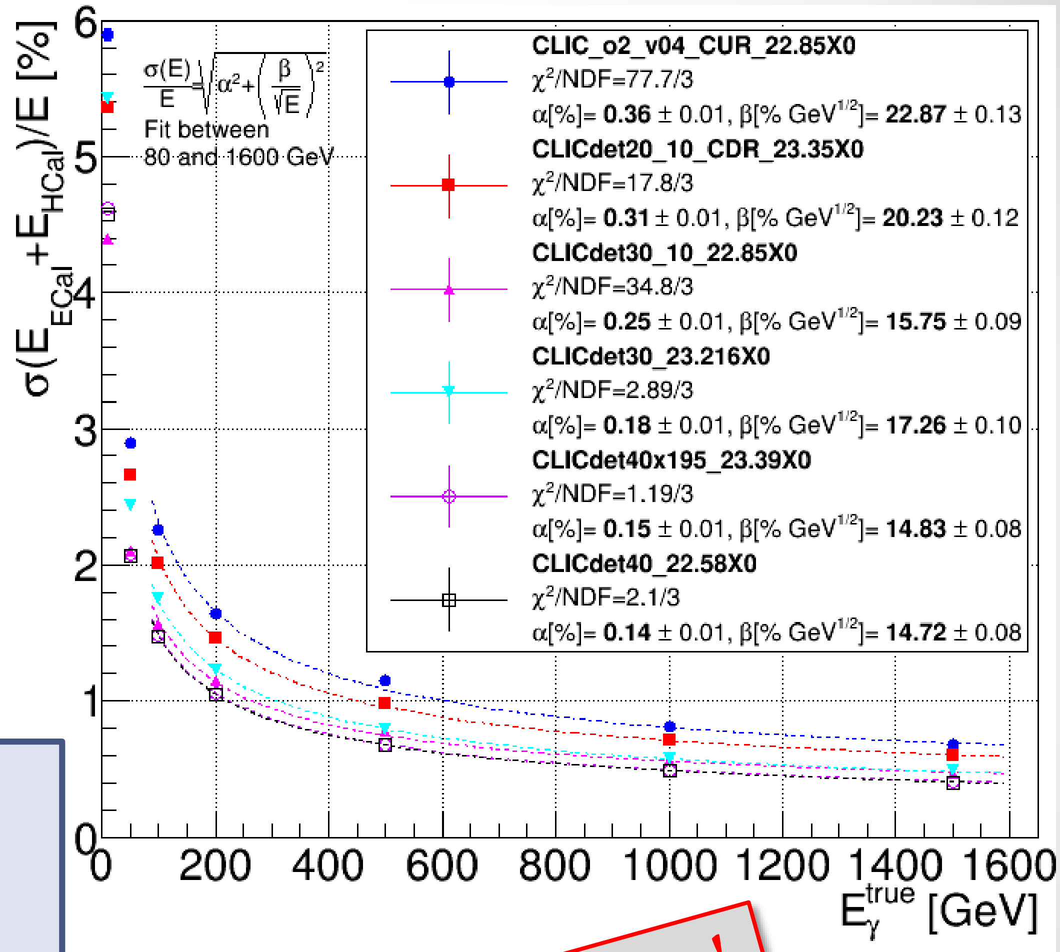
- **Initial optimization performed with Jet Energy Resolution as gauge**
  - **# Layers:** Not very important for higher energy jets (PFA confusion dominates)
  - **Active element (Si vs Sc):** No significant effect on JER
  - **Cell size:** JER **degradation** from 3% to ~3.5% when increasing cell size from 5x5 mm² to 15x15 mm²
  - **Depth: 23 X_0/ 1 λ_I.** The CDR (and ILC) models use Tungsten plates in 30 layers in two sampling groups (say 20x2 mm + 10x 4 mm plate thicknesses)
  - **Suboptimal for high energy photon resolution**
- **High energy photons are becoming more interesting!**
  - **Revisiting ECal optimization**





ECal Optimization (cont'd)

- **Preliminary**
- Single photons
- Higher layer granularity options obviously better but also much more expensive
- CLICdp is considering the option with 40 layers with uniform thickness for the next simulation model(TBD)



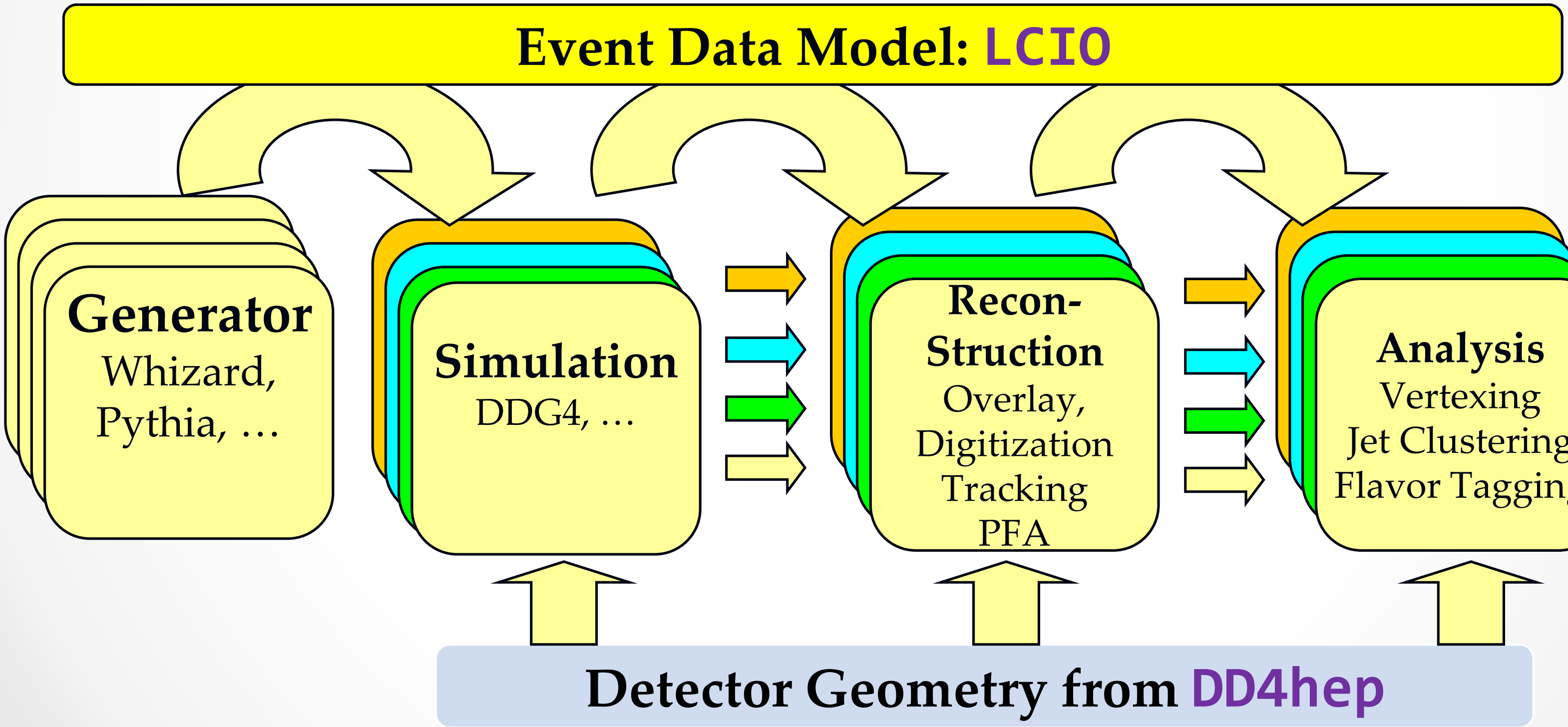
Work in progress !

In new simulation model:

- **40** Layers, 23 X_0/ 1 λ_I
- **1.95 mm Tungsten** plates
- **0.5 mm Silicon** active element
- 5.1x5.1 mm^2 cell size throughout

Linear Collider Software

- Software is shared by the detector concepts of both ILC and CLIC and the hardware R&D groups
  - Common EDM: **LCIO**
  - New **common** Detector Geometry Description and Simulation Framework: **Detector Description 4 HEP (DD4hep)**

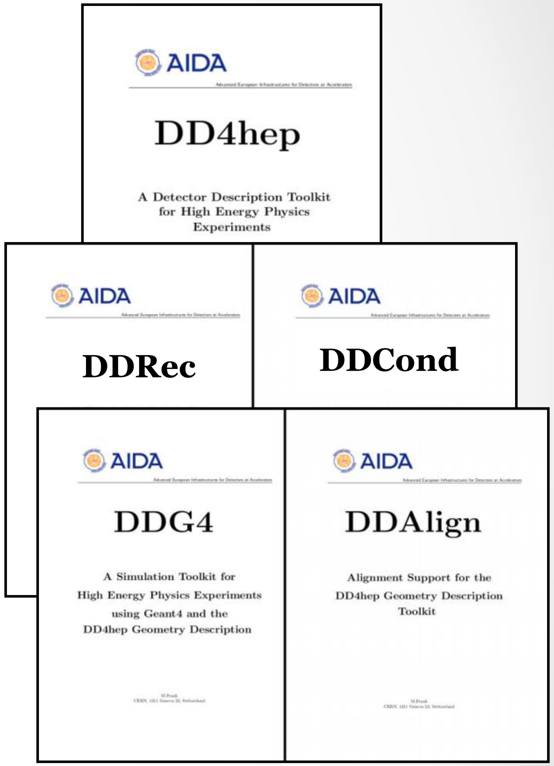


DD4hep motivation and goals

- Complete detector description
  - Includes geometry, materials, visualization, readout, alignment, calibration, etc.
- Support full experiment life cycle
  - Detector concept development, detector optimization, construction, operation
  - Easy transition from one phase to the next
- Consistent description, single source of information
  - Use in simulation, reconstruction, analysis, etc.
- Ease of use
- Few places to enter information
- Minimal dependencies

DD4hep components

- **DD4hep**: basics/core
  - Basically stable
- **DDG4**: Simulation using Geant4
- **DDRec**: Reconstruction support
  - **Driven by LC Community**
- **DDAlign**, **DDCond** : Alignment and Conditions support
  - Being developed


AIDA

DD4hep

A Detector Description Toolkit for High Energy Physics Experiments

AIDA

DDRec

AIDA

DDCond

AIDA

DDG4

A Simulation Toolkit for High Energy Physics Experiments using Geant4 and the DD4hep Geometry Description

AIDA

DDAlign

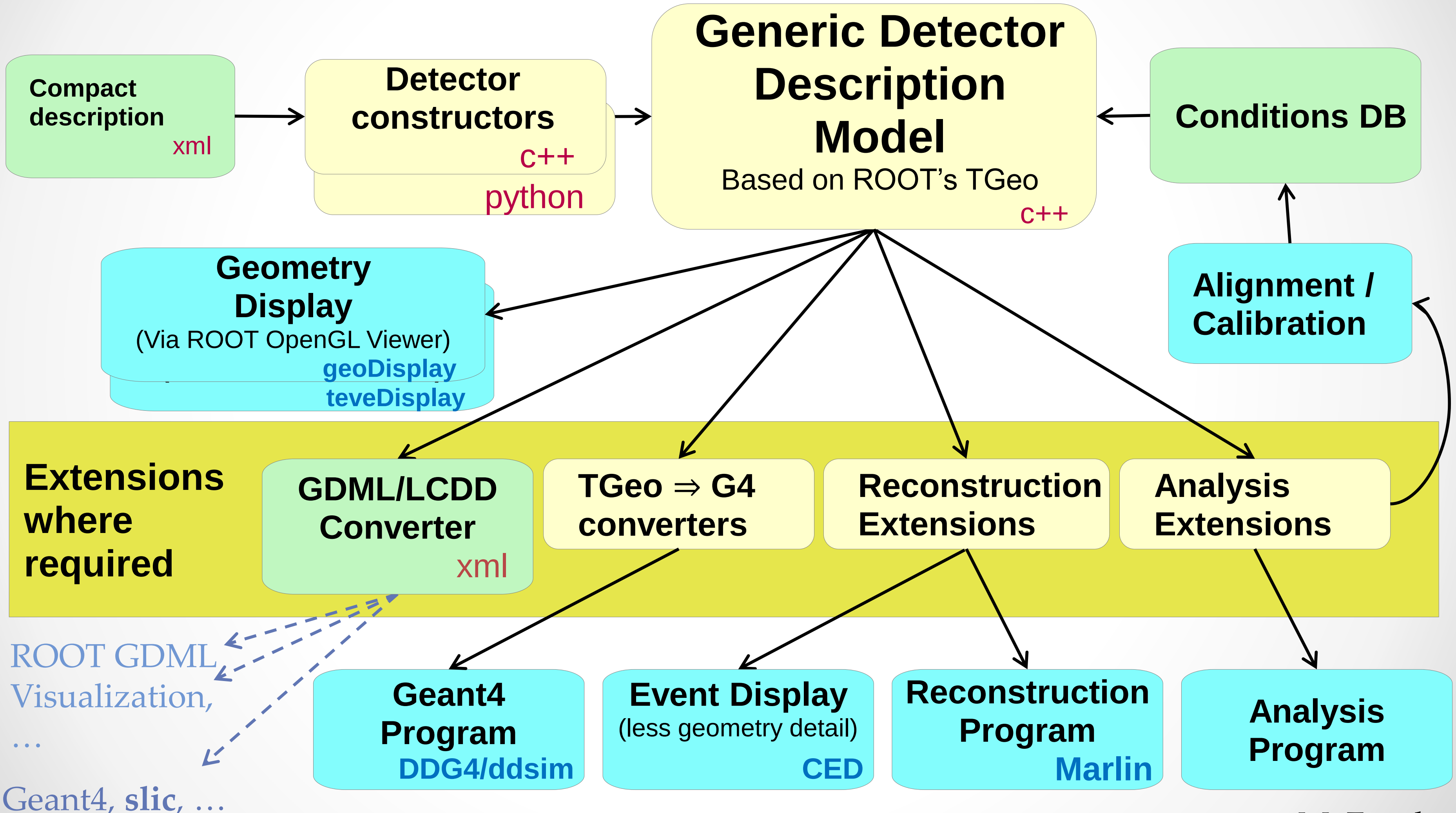
Alignment Support for the DD4hep Geometry Description Toolkit

- **http://aidasoft.web.cern.ch/DD4hep**

Already in use or considered by CLICdp, ILD, SiD, FCC-(ee,eh,hh), LHCb, FCAL, CALICE

- **New CLIC detector simulation model implemented in DD4hep**

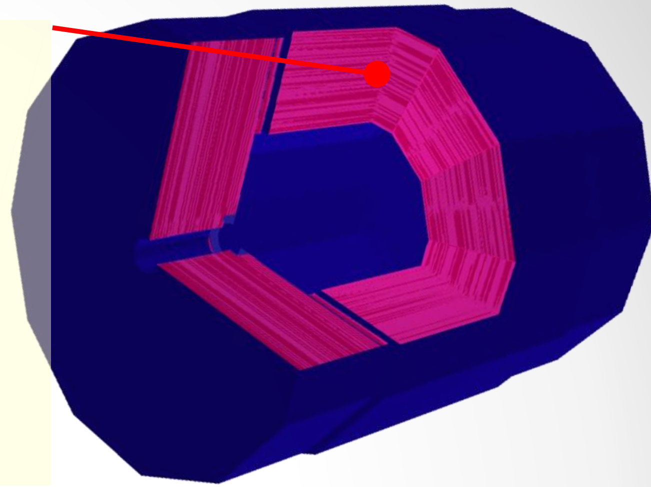
DD4hep – The big picture



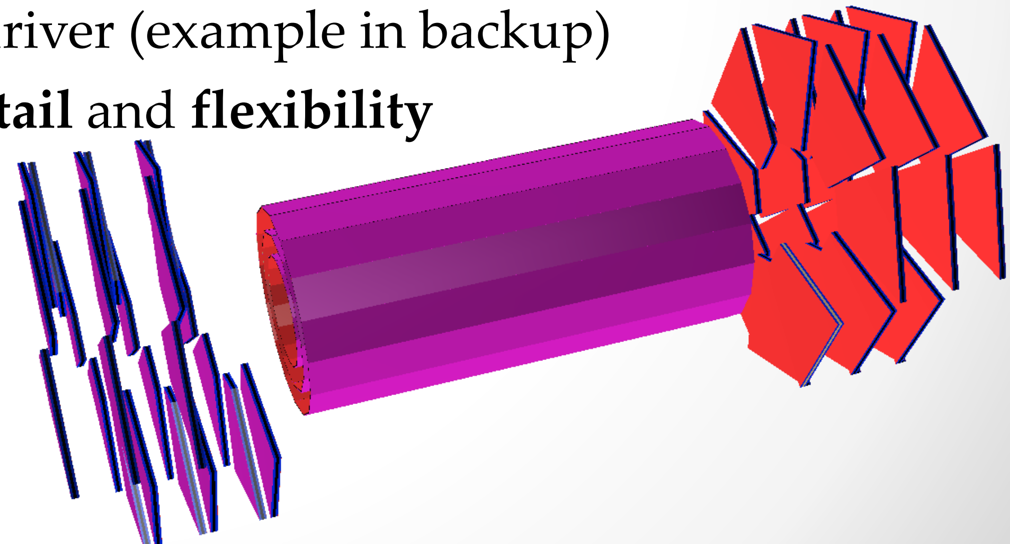
M. Frank

Implementing detectors

```
<detector id="DetID_HCAL_Barrel" name="HCalBarrel" type="HCalBarrel_o1_v01"
readout="HCalBarrelHits" vis="HCALVis" >
 <dimensions nsides="HCal_symm" rmin="HCal_Rin" z="HCal_Z" />
 <layer repeat="(int) HCal_layers" vis="HCalLayerVis" >
  <slice material="Steel235" thickness="0.5*mm" vis="AbsVis"/>
  <slice material="Steel235" thickness="19*mm" vis="AbsVis"/>
  <slice material="Polysterene" thickness="3*mm" sensitive="yes"/>
  <slice material="PCB" thickness="0.7*mm"/>
  <slice material="Steel235" thickness="0.5*mm" vis="AbsVis"/>
  <slice material="Air" thickness="2.7*mm"/>
  </layer>
</detector>
```



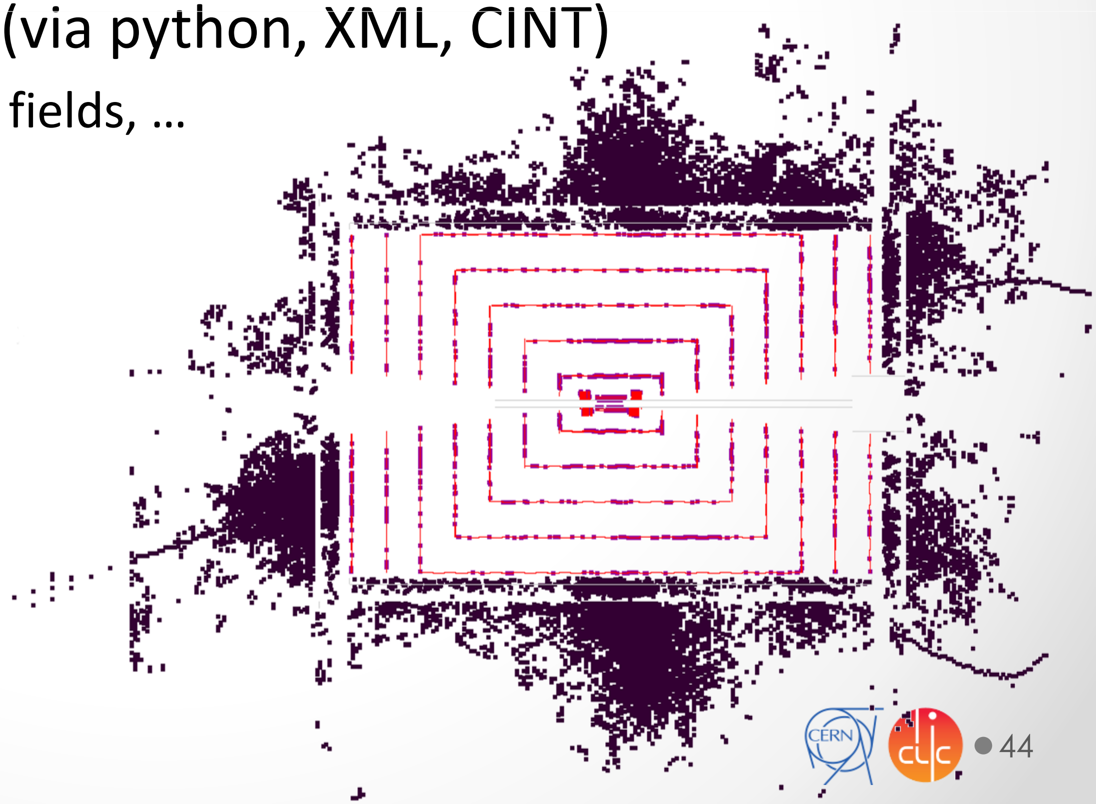
- **Fairly scalable and flexible drivers** (Generic driver palette available)
- Visualization, Radii, Layer/module composition in **compact xml** (snippet above), volume building in C++ driver (example in backup)
- User decides balance between **detail** and **flexibility**
- Usually could do a lot **just by modifying the xml.** For example:
  - Scale detector
  - Create double layers
  - Create "spiral" endcap geometry
  - …



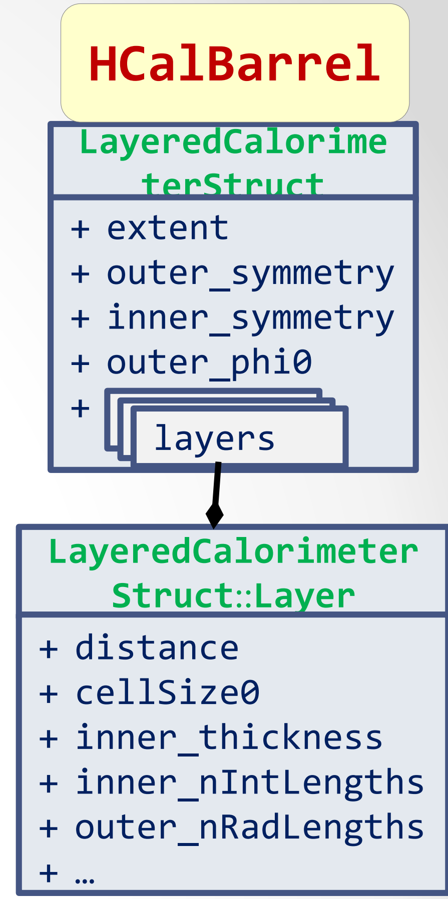
DDG4: Gateway to Geant4

- DD4hep facilitates **in-memory translation of geometry** from **TGeo** to **Geant4**
- Plugin Mechanism -> Highly Modular:
  - Sensitive detectors, segmentations and configurable actions, …
- **All shared with Reconstruction!**
- Configuration mechanism (via python, XML, CINT)
  - Physics lists, regions, limits, fields, …

A $t\bar{t}$ event at 500 GeV simulated in a CLIC detector model using **DDG4**. **Black** points are hits, **Red** lines are measurement surfaces, **Gray lines are auxiliary surfaces** **both** used in reconstruction



DDRec Extensions

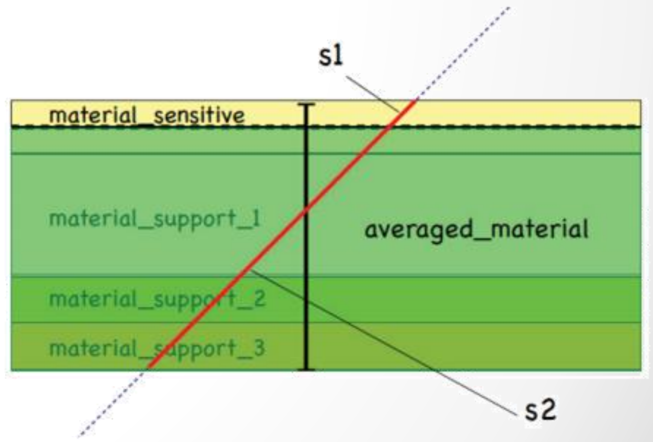


- **The generic DDRec API decouples the reconstruction code the from the specific implementation of the detailed sub-detector geometry**
- e.g: attach a `LayeredCalorimeterStruct` to the `DetElement` for `HCalBarrel` (itself usually a collection of several `DetElement`s)
- Developed with needs of **Pandora** in mind
- Fill all the dimension, symmetry and other info (almost definitely known to the driver)
- Fill a vector of substructures with info on the layers
  - Sum/average material properties from each slice:

```
nRadLengths += slice_thickness/(2*slice_material.radLength());
…
```

Measurement surfaces

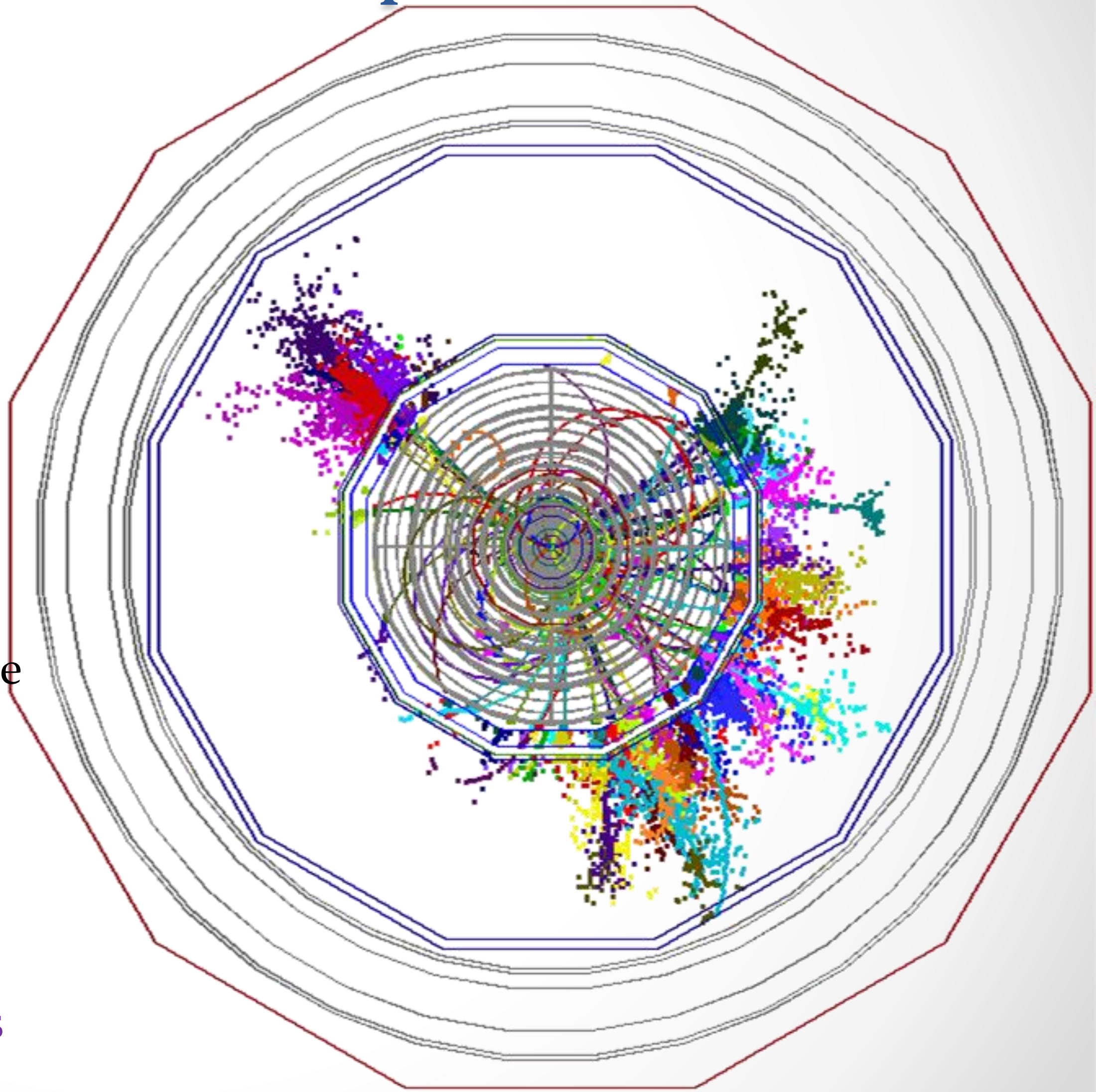
- Special type of extension, used primarily in **tracking**
  - Did not find an implementation in **TGeo**
  - `DDSurfaces` Implemented within `DDRec`
- Attached to `DetElements` and `Volumes` (defining their boundaries), e.g. the sensitive silicon **wafer** in a tracker module
  - Can be added to drivers via **plugins** without modifying detector constructor
- They hold **u**,**v**,**n**ormal and **o**rigin vectors and **inner/outer thicknesses**
- Material properties **averaged automatically**
- Could also be used for **fast simulation**



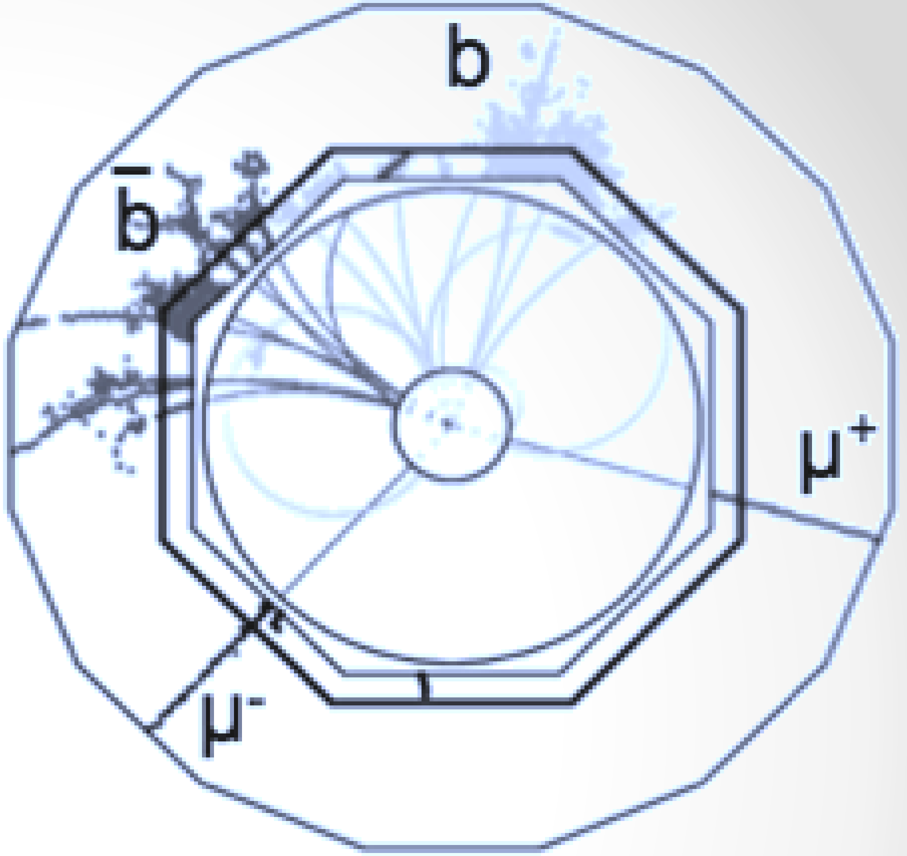
- Outlines of surfaces drawn in `teveDisplay` for CLICdp Vertex Barrel and Spiral Endcaps

Event simulated, reconstructed and visualized fully with DD4hep

- **New CLIC detector** model implemented in **DD4hep**
- $Z \rightarrow uds$ event at $\sqrt{s} = 1$ TeV simulated with **DDG4**
- Tracks reconstructed using **DDSurfaces**
- Particle Flow Objects from **Pandora** interfaced with **DD4hep** and using the **DDRec** data structures
- Event display from the **CED** viewer interfaced with **DD4hep**
  - Also uses **DDRec** and **DDSurfaces**



CLIC Physics Program Highlights …



(extremely) brief summary and elements of the CLIC physics program

CLIC Physics Program Highlights

- Many benchmark studies, performed with Geant4 full detector simulations
  - with overlay of γγ background, SM physics backgrounds

- Comprehensive Higgs studies: ~20 analyses covering all three energy stages
  - 1^{st} stage (380 GeV) : **g_{HZZ} coupling to 0.8%** and couplings to other major decay channels, m_H at the ≈ 100 MeV level
  - Then at Higher energy stages (1.5 TeV and 3 TeV): Higgs boson couplings at the **O(1%) level** (limited by **g_{HZZ}** precision), **g_{HHH} at 10%, top yukawa coupling at 4.5%**

- Top threshold scan: top mass at ≈ 50 MeV level, $t\bar{t}$ kinematic properties

- BSM: e.g. SUSY benchmark models, direct searches up to 1.5 TeV kinematic limit for pair production with O(1%) mass measurement precision

… and much more

Either being investigated or planned:

- More Higgs channels, CP properties, …
- Precision studies with $e^+e^- \to \mu^+\mu^-$
  - e.g. search for Z' or precision coupling measurements if found at LHC
- Higgs boson compositeness
- More SUSY signatures
  - Gauginos/Higgsinos with small mass splittings
  - Top squark production
- Model independent searches for Dark Matter
  - γ +missing energy
- Diphoton resonance (depending on LHC results)
- …

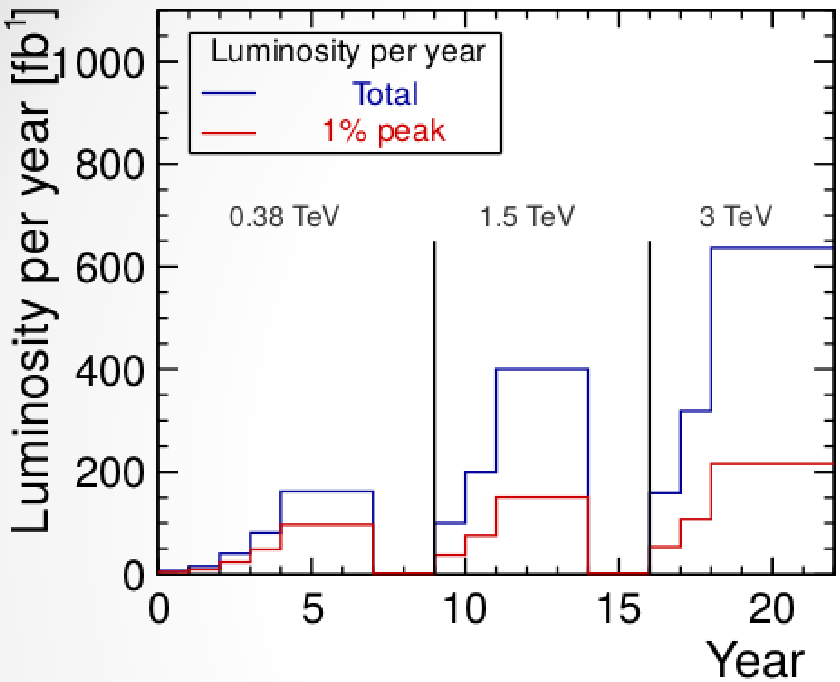
Summary and Conclusions

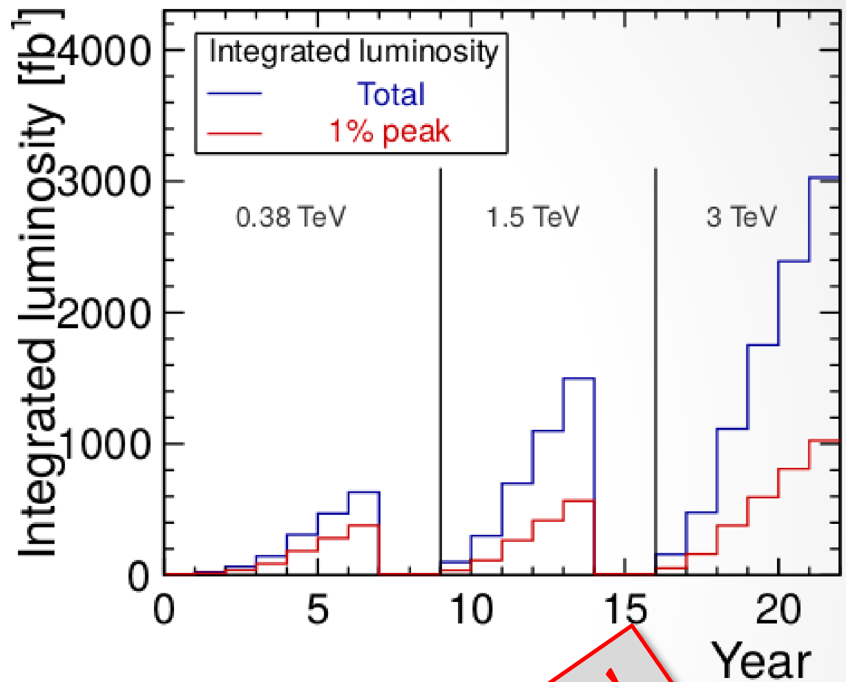
- **CLIC is currently the only option to offer multi-TeV e^+e^- collisions**
  - **Technology demonstrated to work**
  - A feasible option for CERN after LHC
- Very active in **challenging R&D projects for both accelerator and physics/detector**
  - Covers a broad array of disciplines
  - Simulation and reconstruction software development
  - Collaborations and synergies with several other projects
- CLIC has an **exciting physics program** and potential
  - Wide energy range with stages optimized for physics
  - Precision measurements as well as searches

Updated CLIC parameter table: Stage 1–3

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{pulse}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathcal{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

Updated Luminosity Development
(E. Sicking, from re-baselining document)





- CLIC programme of 22 years:
  7 years (380 GeV), 5 years (1.5 TeV), 6 years (3 TeV)
  interleaved by 2-years upgrade periods

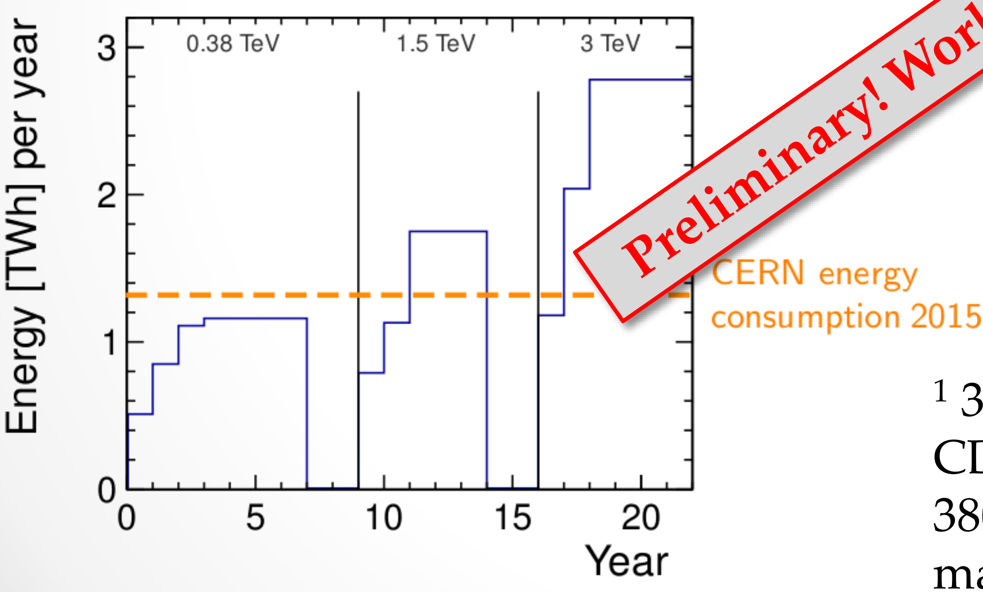
- Luminosity ramp up of 4 years / 2 years
  (5%, 10%,) 25%, 50%, 100%

Preliminary! Work in Progress!

CLIC power and energy consumption
(E. Sicking, from re-baselining document)

- Current estimates of power consumption[1]

$\sqrt{s}$ [TeV]	$P_{nominal}$[MW]	$P_{waiting\ for\ beam}$[MW]	P_{stop}[MW]
0.38	252	168	30
1.5	364	190	42
3.0	589	268	58



[1] 380 GeV values scaled from 500 GeV CDR design. To be re-calculated once 380 GeV stage parameters and machine details are known

Cost Estimate at 380 GeV

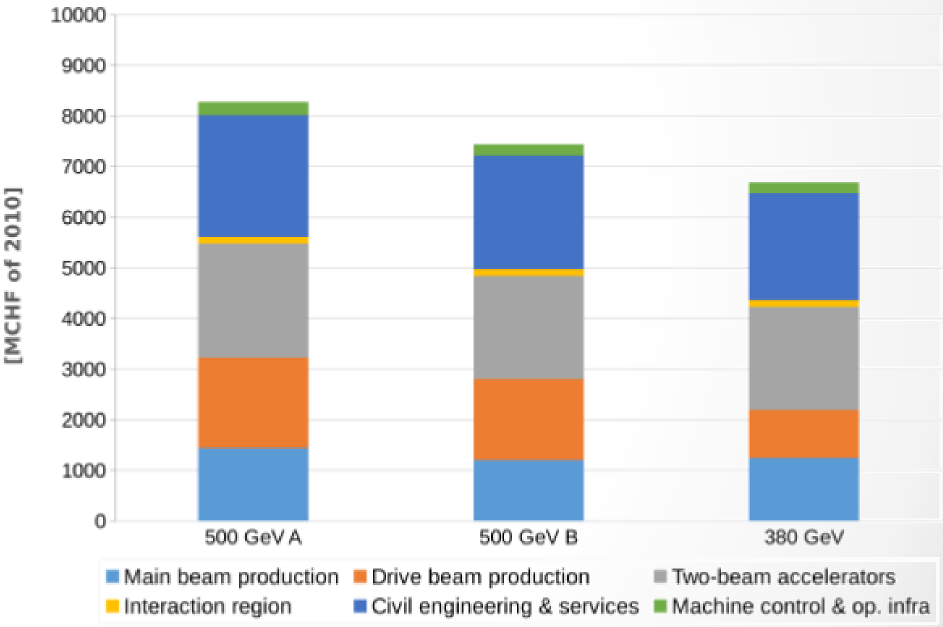
(E. Sicking, from re-baselining document)

- Full CLIC cost estimation including all contributions
- Use 2010 CHF for direct comparison to CDR estimates

	Value [MCHF (2010)]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Machine control & operational infrastructure	216
Total	6690

Preliminary! Work in Progress!

Comparison to CDR values

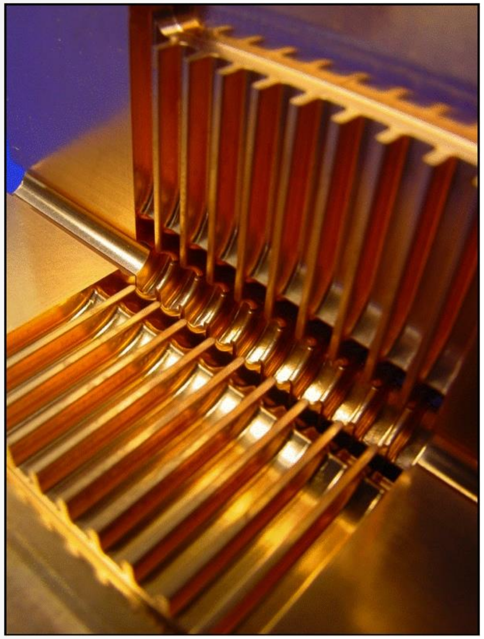


- Full 380 GeV CLIC machine: $\sim$ 6.7 BCHF (2010)$_{\text{preliminary}}$ (+ 4 MCHF/GeV up to 1.5 TeV)

(Note → Numbers scaled from CDR design at 500 GeV
→ To be repeated with detailed tech. description of 380 GeV CLIC)

ILC and CLIC in Just a Few Words

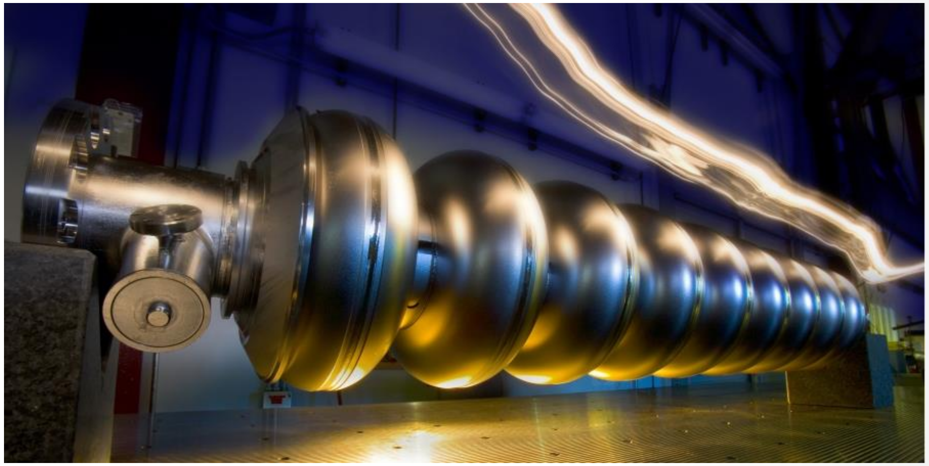
CLIC



•2-beam acceleration scheme, at room temperature
•Gradient 100 MV/m
•$\sqrt{s}$ up to 3 TeV
•Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC



•Superconducting RF cavities
•Gradient 32 MV/m
•$\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
•Focus on ≤ 500 GeV, physics studies also for 1 TeV

More on Beam-Beam Effects

Beamstrahlung can cause important energy losses right at the interaction point

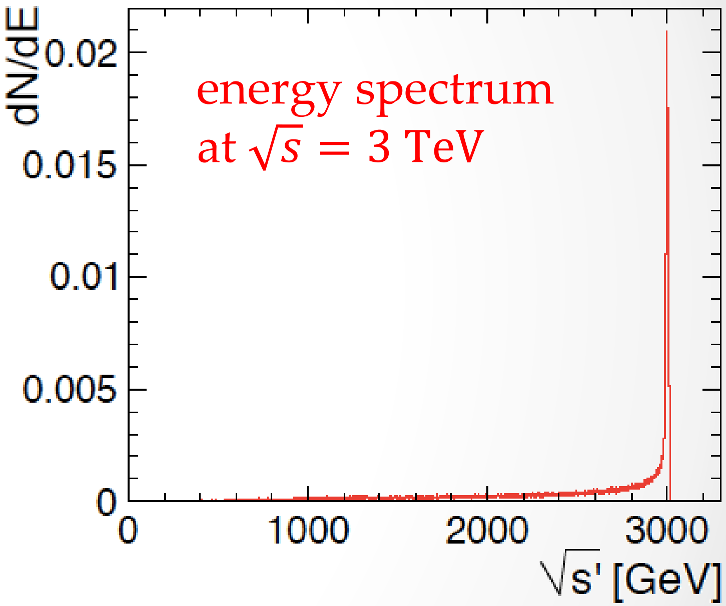
E.g. full luminosity at 3 TeV:

5.9×10^{34} cm^{-2}s^{-1}

Of which in the 1% most energetic part:

2.0×10^{34} cm^{-2}s^{-1}

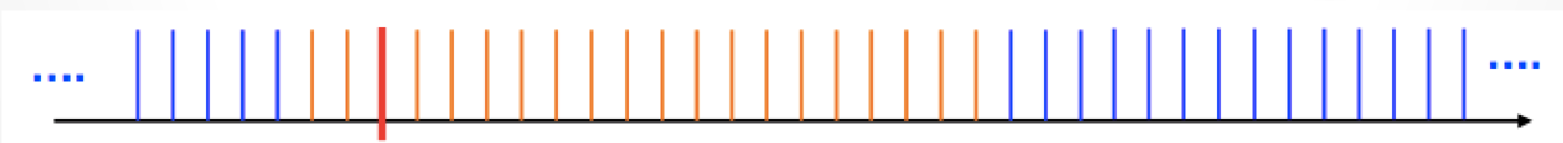
Most physics processes are studied well above production threshold => profit from full luminosity



Time window / time resolution

The event reconstruction software uses:

Subdetector	Reconstruction window	hit resolution
ECAL	10 ns	1 ns
HCAL Endcaps	10 ns	1 ns
HCAL Barrel	100 ns	1 ns
Silicon Detectors	10 ns	$10/\sqrt{12}$ ns
TPC	entire bunch train	n/a

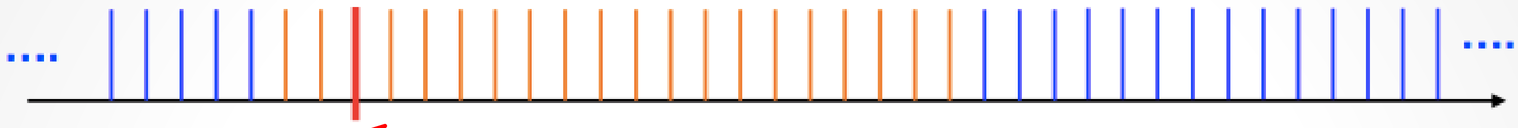


t_0 physics event (offline)

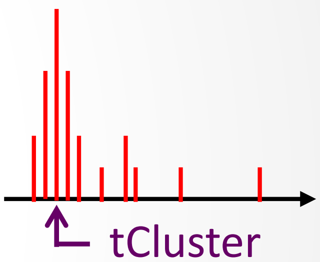
Translates in precise **timing requirements** of the sub-detectors

Background Suppression

Triggerless readout of entire train:



- Identify t_0 of physics event offline
  - Correct for shower development and TOF, define reconstruction window around t_0
  - Pass all calorimeter hits and tracks within window to reconstruction



→ Obtain physics objects with precise p_T and cluster time information

- Then apply cluster-based timing cuts
  - Cuts depend on particle type, p_T and detector region

→Protects high-p_T physics objects

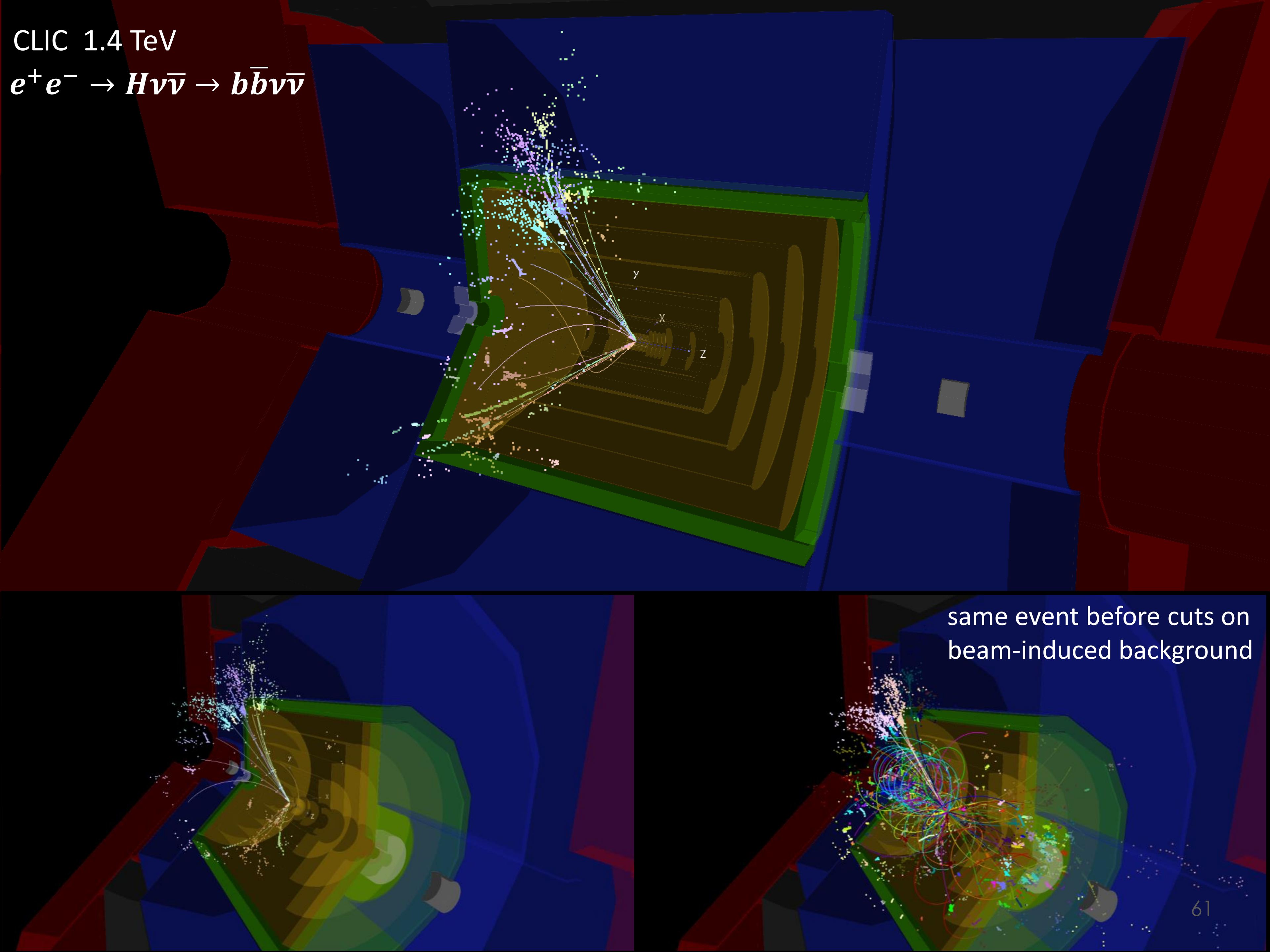
- **Also**: use hadron collider-type jet algorithms (*FastJet*)

PFO-based Timing Cuts

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

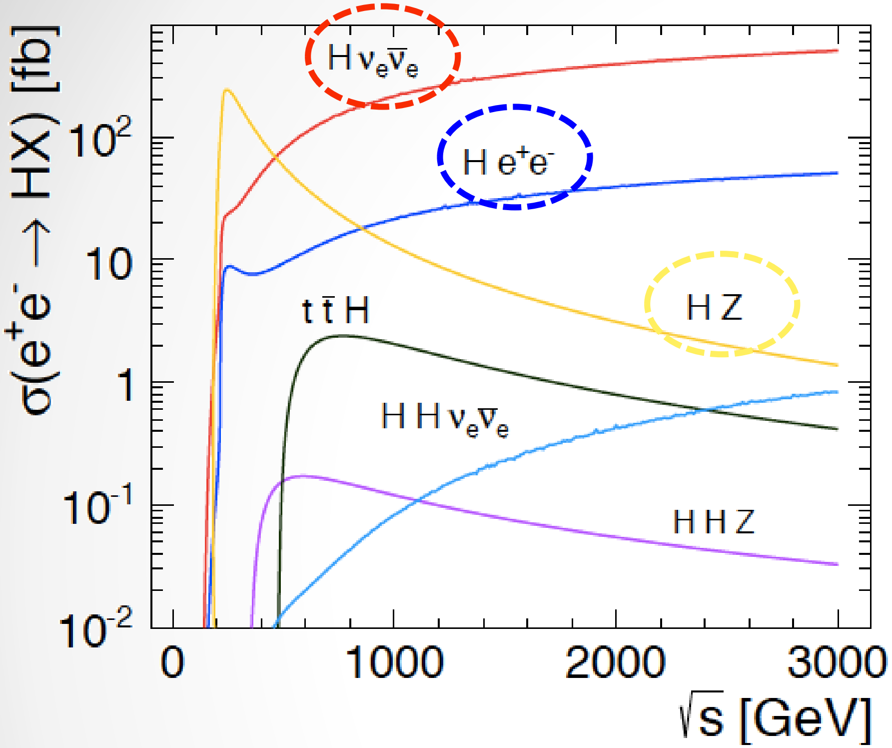
CLIC 1.4 TeV

$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$

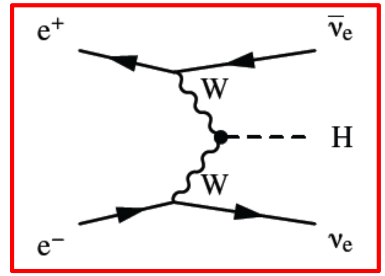


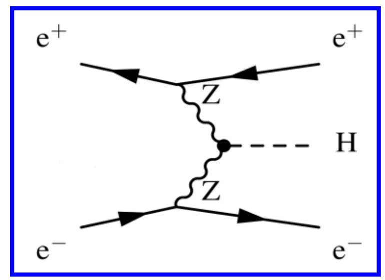
same event before cuts on beam-induced background

Dominant Higgs Processes at CLIC

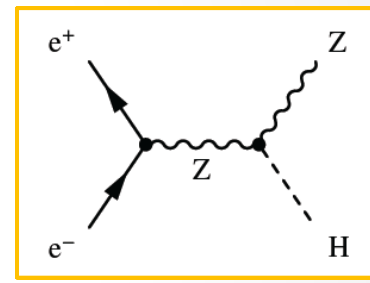


WW/ZZ Fusion: σ increases with $\sqrt{s}$





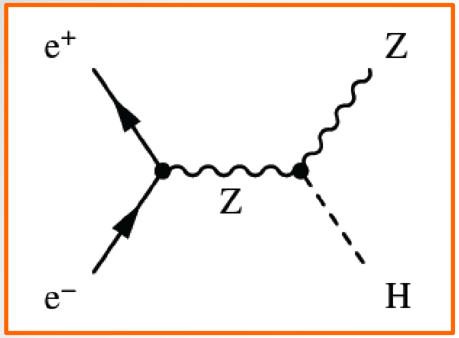
Higgsstrahlung: σ decreases with $\sqrt{s}$



	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
$\#ZH$ events	68 000	20 000	11 000
$\#H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
$\#He^+e^-$ events	3 700	37 000	84 000
Note: Unpolarized beams assumed for benchmark studies			

- **Large samples of Higgs bosons produced at CLIC even without polarization**
- **x1.8 enhancement for $H\nu_e\overline{\nu_e}$ with -80% e^- polarization**

Higgsstrahlung at $\sqrt{s} = 350$ GeV

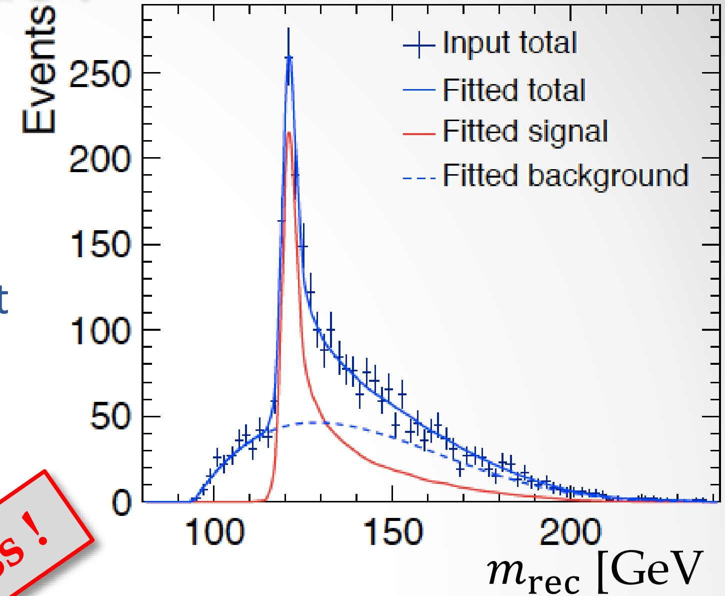


Consider events where $Z \to e^+e^-$, $Z \to \mu^+\mu^-$, $Z \to q\bar{q}$

Define $m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}$

Model-independent measurement of m_H, σ

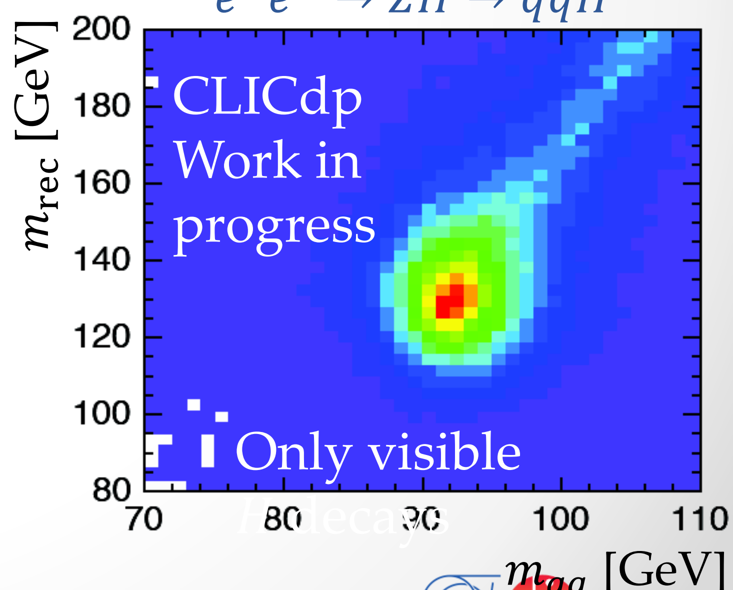
$e^+e^- \to ZH \to \mu^+\mu^- H$



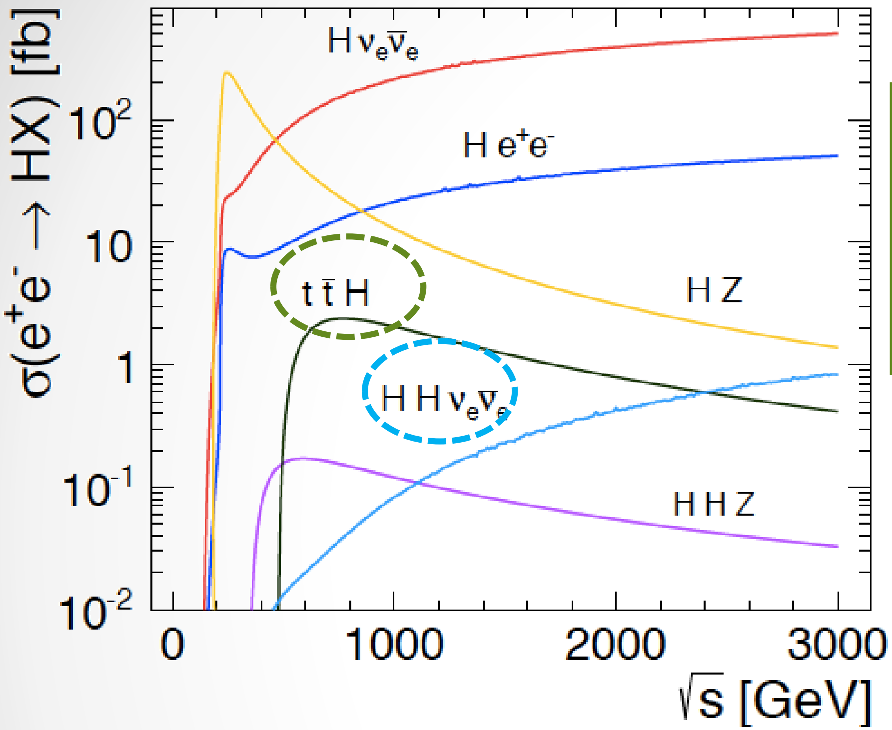
- Identify HZ events from Z recoil
- Includes invisible Higgs decays
- Measurement of g_{HZZ} coupling
- $Z \to e^+e^-/\mu^+\mu^-$ cases:
  - $BR(Z \to ee/\mu\mu) \approx 7\%$
  - Fully model independent
  - $\Delta(g_{HZZ})/g_{HZZ} \approx 2.1\%$
- $Z \to q\bar{q}$ case:
  - $BR(Z \to q\bar{q}) \approx 70\%$
  - Z reconstruction could depend on H decay mode
  - $\Delta(g_{HZZ})/g_{HZZ} \approx 0.9\%$

Work in progress !

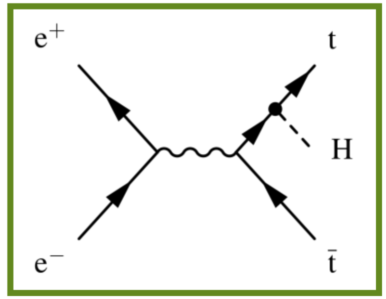
$e^+e^- \to ZH \to q\bar{q}H$



More Higgs Physics at CLIC



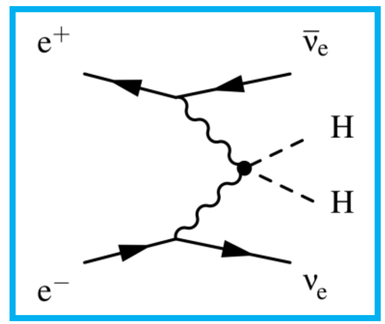
$t\bar{t}H$: Obtain top Yukawa coupling g_{ttH}



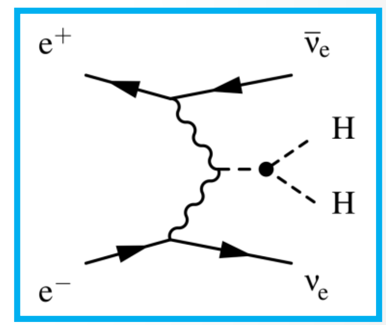
- 2 400 events at 1.4 TeV
- Analysis of events with 6 and 8 jets in final state

→ Δg_{ttH} / g_{ttH} = 4.5%

Quartic coupling



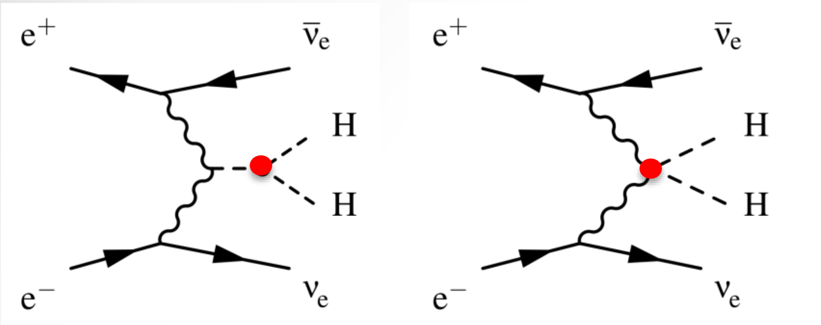
Trilinear self-coupling

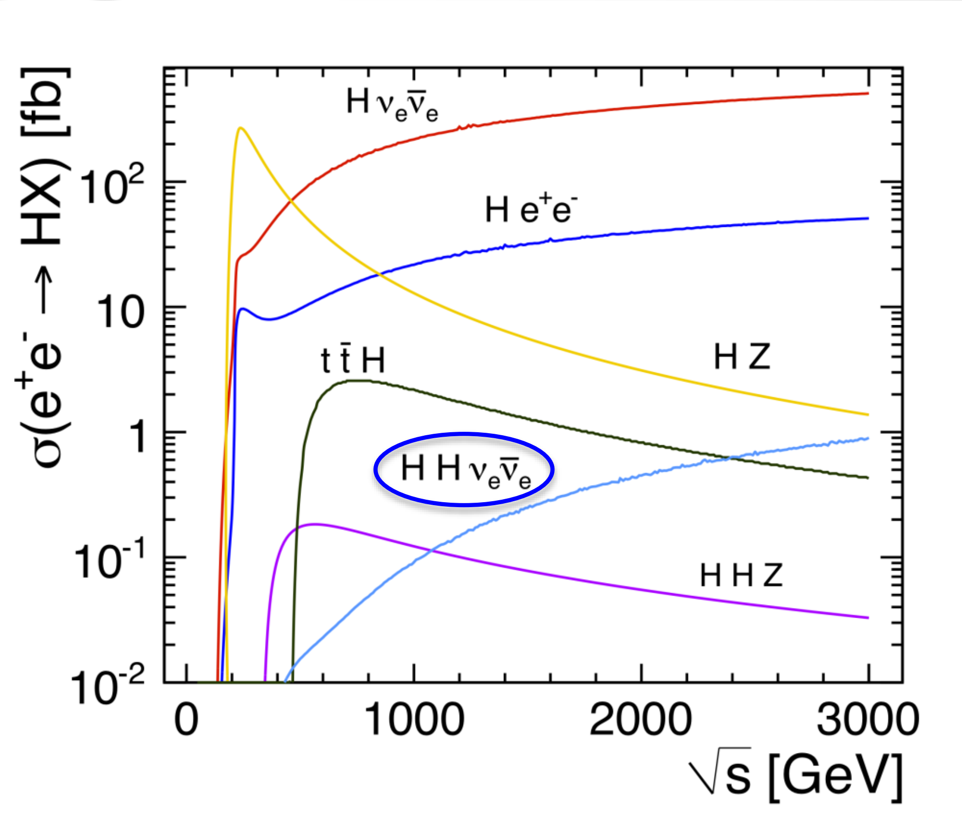


Double Higgs Production

- **Self coupling (g_{HHH})** measurement gives access to understanding the Higgs field
  - Only possible at high energies: to 24% at 1.4 TeV, 10% adding 3 TeV result

double Higgs production





- The $HH\nu_e\nu_e$ cross section is sensitive to the Higgs self-coupling, λ, and the quartic g_{HHWW} coupling

- $\sigma(HH\nu_e\nu_e)$ = 0.15 (0.59) fb at 1.4 (3) TeV
- only 225 (1200) events at 1.4 (3) TeV
  → high energy and luminosity crucial

	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
$\Delta(\lambda)$	32%	16%
$\Delta(\lambda)$ for $p(e^-)$ = 80%	24%	12%

Work in progress !

Summary of Higgs measurements

Channel	Measurement	Observable	Statistical precision: 350 GeV, 500 fb^{-1}	1.4 TeV, 1.5 ab^{-1}	3.0 TeV, 2.0 ab^{-1}
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6%	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	6.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	4.2%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	38%	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	42%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.4%	0.9%†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	32%	16%
$HH\nu_e\bar{\nu}_e$	with -80% e^- polarization	λ	–	24%	12%

Summary of CLIC Higgs benchmark simulations

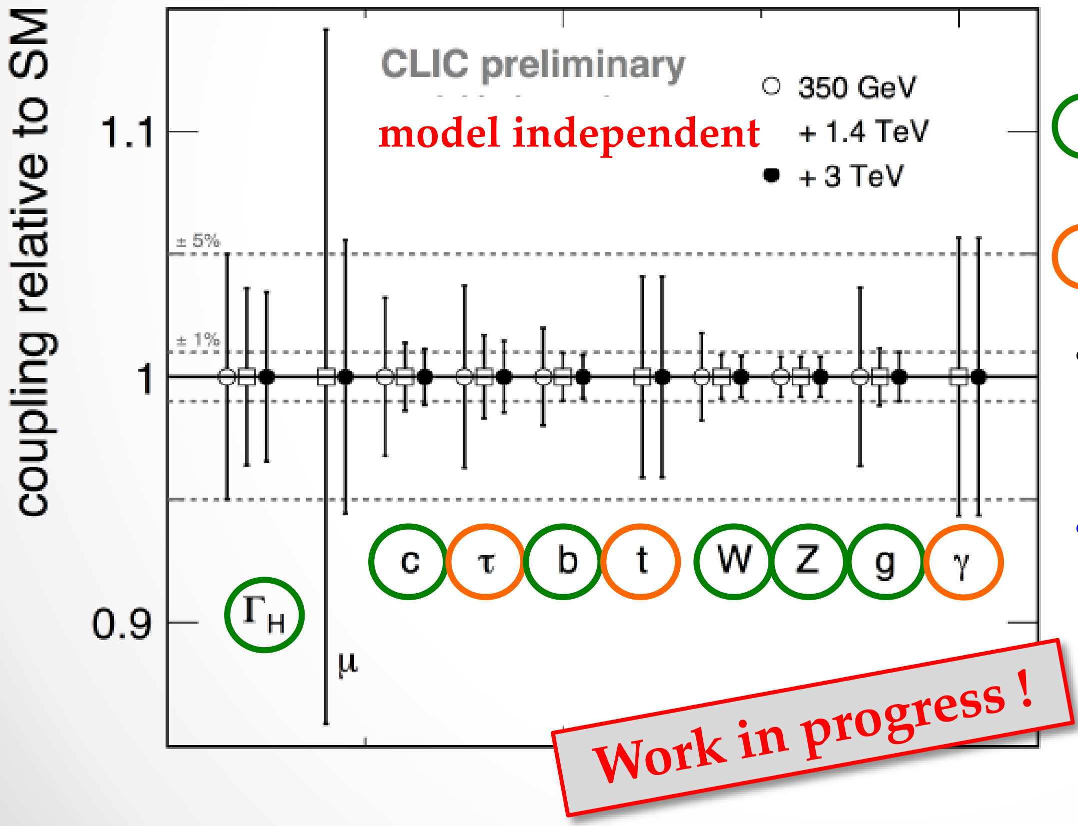
for more info:
http://arxiv.org/abs/1307.5288

Work in progress !

* Preliminary
\+ Estimate

Higgs coupling to mass

- Combine results of studied Higgs production and decay channels in global fit → extract couplings and Higgs width



much more accurate than HL-LHC

similar accuracy as HL-LHC

- Contrary to (HL-)LHC, CLIC results are model-independent
- 80% electron polarization assumed above 1 TeV

CLIC Higgs Global Fits

80% electron polarisation assumed above 1 TeV

- **Model-independent global fits**

Parameter	Measurement precision		
	350 GeV $500\ \mathrm{fb}^{-1}$	+ 1.4 TeV $+1.5\ \mathrm{ab}^{-1}$	+3.0 TeV $+2.0\ \mathrm{ab}^{-1}$
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.8 %	0.9 %	0.9 %
g_{Hbb}	2.0 %	1.0 %	0.9 %
g_{Hcc}	3.2 %	1.4 %	1.1 %
$g_{H\tau\tau}$	3.7 %	1.7 %	1.5 %
$g_{H\mu\mu}$	–	14.1 %	5.6 %
g_{Htt}	–	4.1 %	$\leq$ 4.1 %
$g^{\dagger}_{Hgg}$	3.6 %	1.2 %	1.0 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	< 5.7 %
Γ_H	5.0 %	3.6 %	3.4 %

- ~1 % precision on many couplings
  - limited by g_{HZZ} precision

Work in progress !

- Constrained "LHC-style" fits
  - Assuming no invisible Higgs decays (model-dependent):

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i|_{SM}}$$

$$\Gamma_{H,md} = \sum_i \kappa_i^2 BR_i$$

Parameter	Measurement precision		
	350 GeV $500\ \mathrm{fb}^{-1}$	+ 1.4 TeV $+1.5\ \mathrm{ab}^{-1}$	+3.0 TeV $+2.0\ \mathrm{ab}^{-1}$
κ_{HZZ}	0.44 %	0.31 %	0.23 %
κ_{HWW}	1.5 %	0.17 %	0.11 %
κ_{Hbb}	1.7 %	0.37 %	0.22 %
κ_{Hcc}	3.1 %	1.1 %	0.75 %
$\kappa_{H\tau\tau}$	3.7 %	1.5 %	1.2 %
$\kappa_{H\mu\mu}$	–	14.1 %	5.5 %
κ_{Htt}	–	4.0 %	$\leq$ 4.0 %
κ_{Hgg}	3.6 %	0.79 %	0.55 %
$\kappa_{H\gamma\gamma}$	–	5.6 %	< 5.6 %
$\Gamma_{H,md,derived}$	1.6 %	0.32 %	0.22 %

- sub-% precision for most couplings

Higgs Cross-Sections, Polarization Enhancement Factors

Table 2: The leading-order Higgs unpolarised cross sections for the Higgsstrahlung, WW-fusion, and ZZ-fusion processes at the three centre-of-mass energies of the example CLIC staging scenario. The quoted cross sections include the effects of ISR but do not include the effects of beamstrahlung. Also listed are the numbers of expected events including the effects of the CLIC beamstrahlung spectrum and ISR. The cross sections and expected numbers do not account for the possible enhancements from polarised beams.

$\sqrt{s} =$	350 GeV	1.4 TeV	3 TeV
$\mathscr{L}_{\text{int}}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
$\sigma(e^+e^- \to ZH)$	133 fb	8 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	34 fb	276 fb	477 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	48 fb
# HZ events	68,000	20,000	11,000
# $H\nu_e\bar{\nu}_e$ events	17,000	370,000	830,000
# He^+e^- events	3,700	37,000	84,000

Table 3: The dependence of the event rates for the s-channel $e^+e^- \to ZH$ process and the pure t-channel $e^+e^- \to H\nu_e\bar{\nu}_e$ and $e^+e^- \to He^+e^-$ processes for three example beam polarisations. The numbers are only approximate as they do not account for interference between $e^+e^- \to HZ \to H\nu_e\bar{\nu}_e$ and $e^+e^- \to H\nu_e\bar{\nu}_e$.

Polarisation	Enhancement factor		
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
−80% : 0%	1.12	1.80	1.12
+80% : 0%	0.88	0.20	0.88

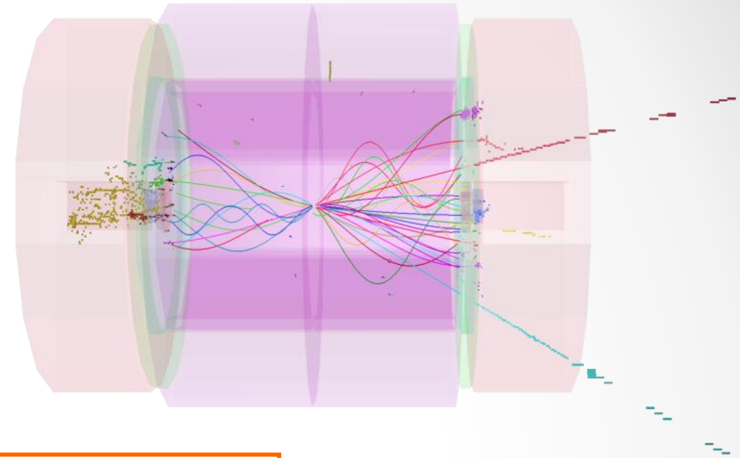
The Simplest Case: Slepton at 3 TeV

Slepton production at CLIC very clean

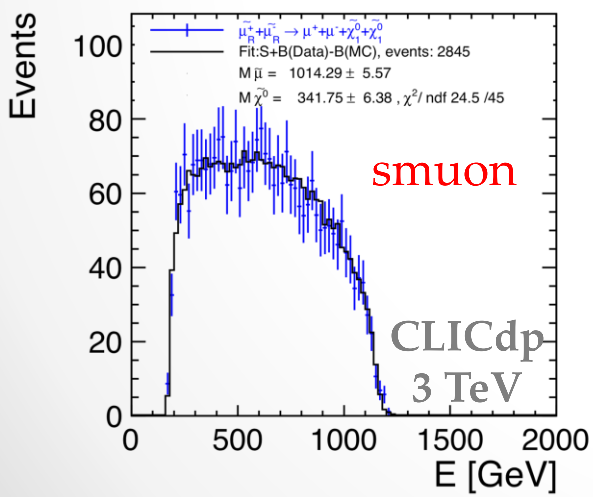
slepton masses ~ 1 TeV

Investigated channels include

- $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^- W^+W^-\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$



- Leptons and missing energy
- Masses from analysis of endpoints of energy spectra



stat. error,
all channels
combined

result: $\Delta m/m \leq 1\%$

$m(\tilde{\mu}_R)\ :\ \pm 5.6\,\text{GeV}$

$m(\tilde{e}_R)\ :\ \pm 2.8\,\text{GeV}$

$m(\tilde{\nu}_e)\ :\ \pm 3.9\,\text{GeV}$

$m(\tilde{\chi}_1^0)\ :\ \pm 3.0\,\text{GeV}$

$m(\tilde{\chi}_1^\pm)\ :\ \pm 3.7\,\text{GeV}$

Di-jet Masses: Gauginos at 3 TeV

$m(\tilde{\chi}_1^0) = 340\,\text{GeV}$

$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\text{GeV}$

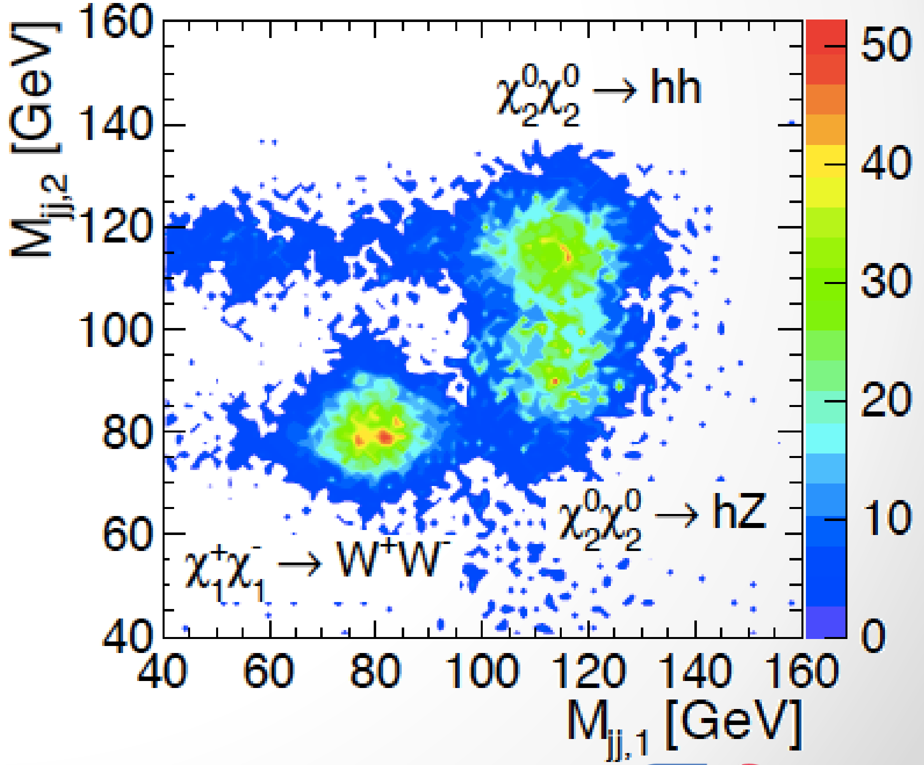
Chargino and neutralino pair production

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

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

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

- separation using di-jet invariant masses (test of PFA)



$m(\tilde{\chi}_1^\pm)$: $\pm 7\,\text{GeV}$

$m(\tilde{\chi}_2^0)$: $\pm 10\,\text{GeV}$

use slepton study result

$m(\tilde{\chi}_1^0)$: $\pm 3\,\text{GeV}$

result: $\Delta m/m \leq 1\%$

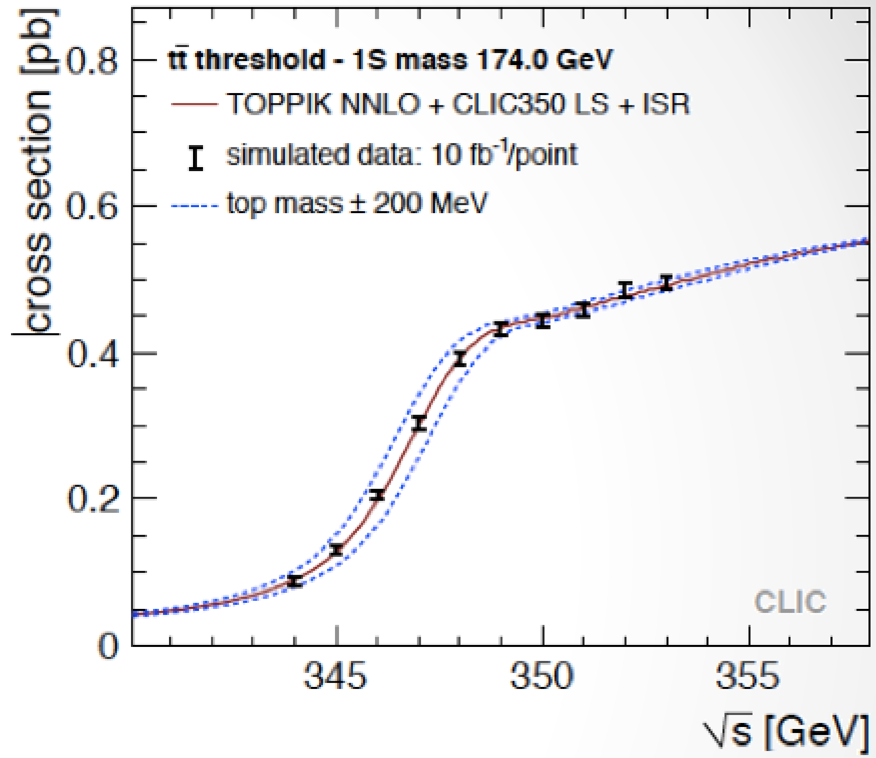
Top Physics

$t\bar{t}$ threshold scan

- **Accurate top mass measurement**
- 10 center-of-mass points, 10 fb^{-1} each

$$\Delta_{stat}(m_t) = 34\ \text{MeV}$$
$$\Delta_{stat}(\alpha_s) = 0.0009$$

- Theoretical uncertainty O(100 MeV) when transforming measured 1S mass to $\overline{MS}$ scheme



Other top physics subjects:

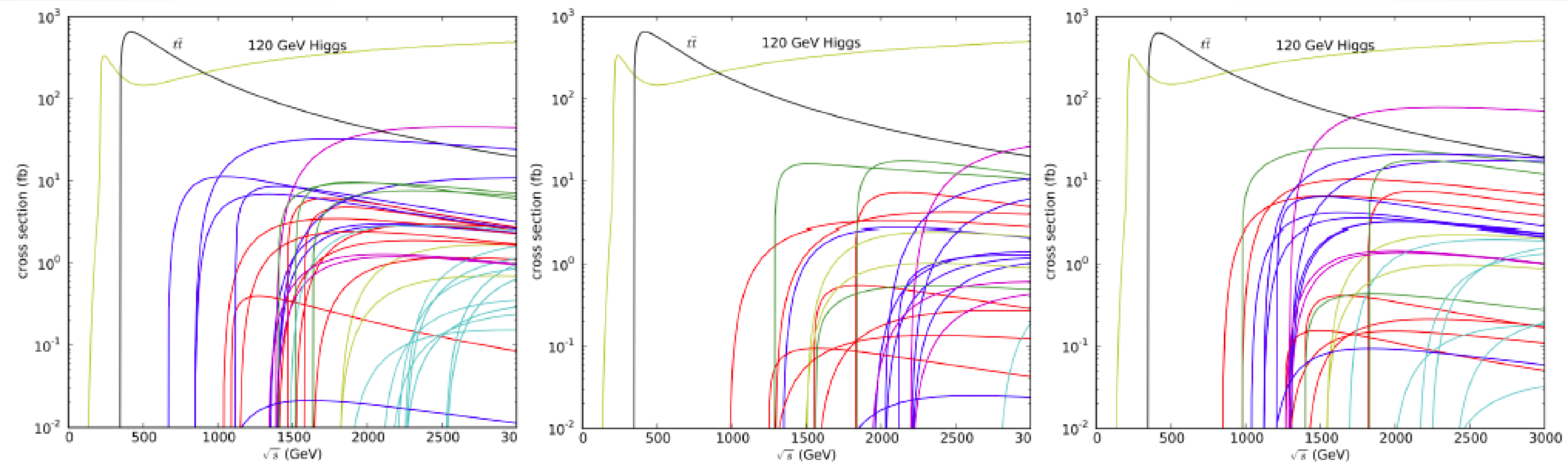
Explore potential of $t\bar{t}$ events as a probe for new physics, examples:

- A^t_{FB} (and A^b_{FB})
- $\sin^2\theta_W$
- top quark couplings to γ, W and Z

At high energy and possibly for the first stage

BSM Physics: SUSY

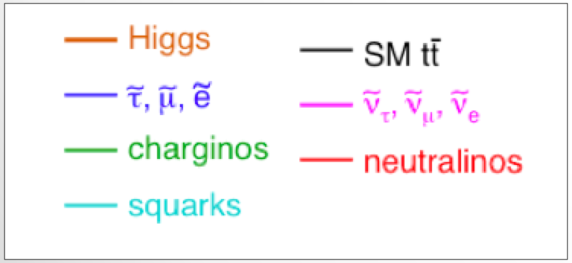
Investigated SUSY models:



CDR model I, 3 TeV:
- Squarks
- Heavy Higgs

CDR model II, 3 TeV:
- Smuons, selectrons
- Gauginos

CDR model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos



Wider capability than only SUSY: reconstructed particles can be interpreted as "states of given mass, spin and quantum numbers"

Results of SUSY Benchmarks

Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	II	$\tilde{\chi}_1^\pm$ mass	643.2	1.1%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	643.1	1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$	I	H^0/A^0 mass	902.4/902.6	0.3%
		$H^+H^- \to t\bar{b}b\bar{t}$		$H^\pm$ mass	906.3	0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	487	0.2%
		$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	487	0.1%

Large part of the SUSY spectrum measured at <1% level

Sensitivity to Higgs Partners

Higgs partners BSM ➔ **accessible up to √s/2**

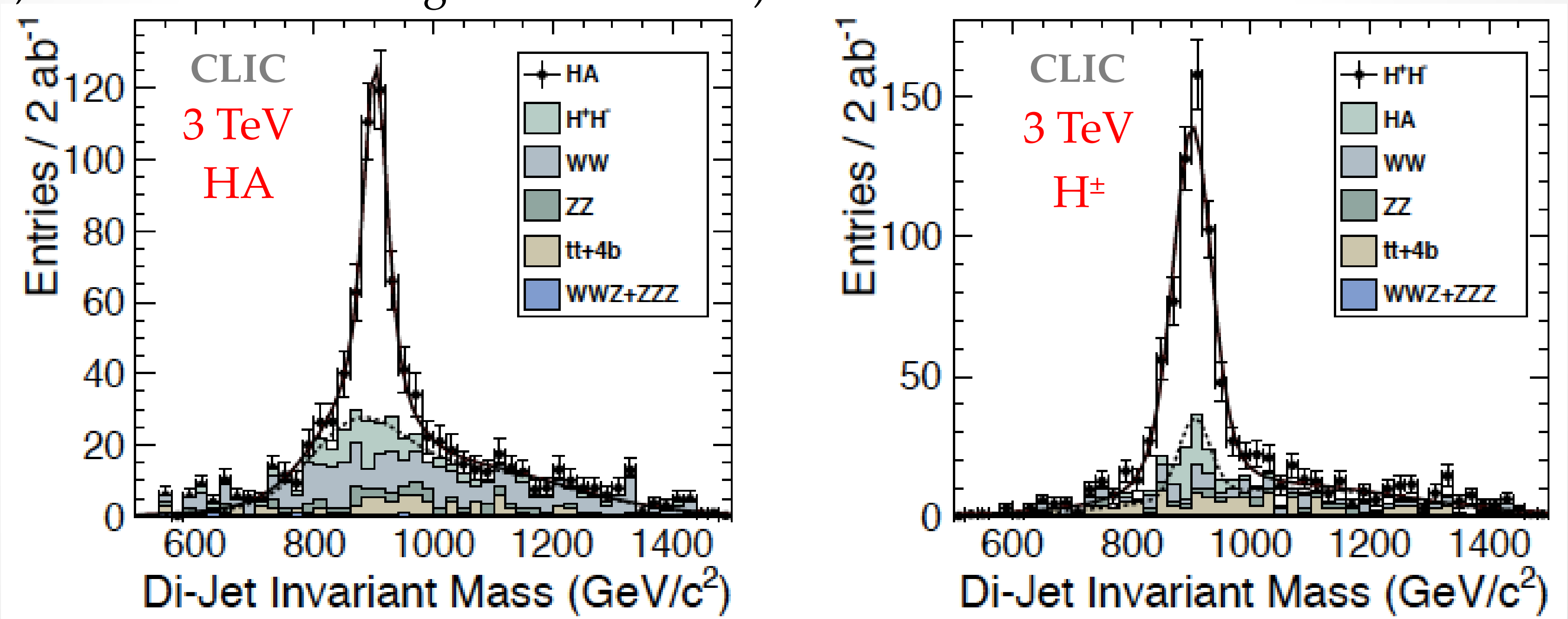
Example MSSM benchmark study at 3 TeV, 2 ab^{-1}

- e^+e^- ➔HA ➔$b\bar{b}b\bar{b}$
- e^+e^- ➔H^+H^- ➔tbbt

(H, A and H^+ almost degenerate in mass)

- Complex final states

$M_1 = 780$ GeV, $M_2 = 940$ GeV, $M_3 = 540$ GeV
$A_0 = -750$ GeV, $m_0 = 303$ GeV, $\tan\beta = 24$, $\mu > 0$
$m_t = 173.3$ GeV, $M_b(M_b) = 4.25$ GeV, $\alpha_S(M_Z) = 0.118$

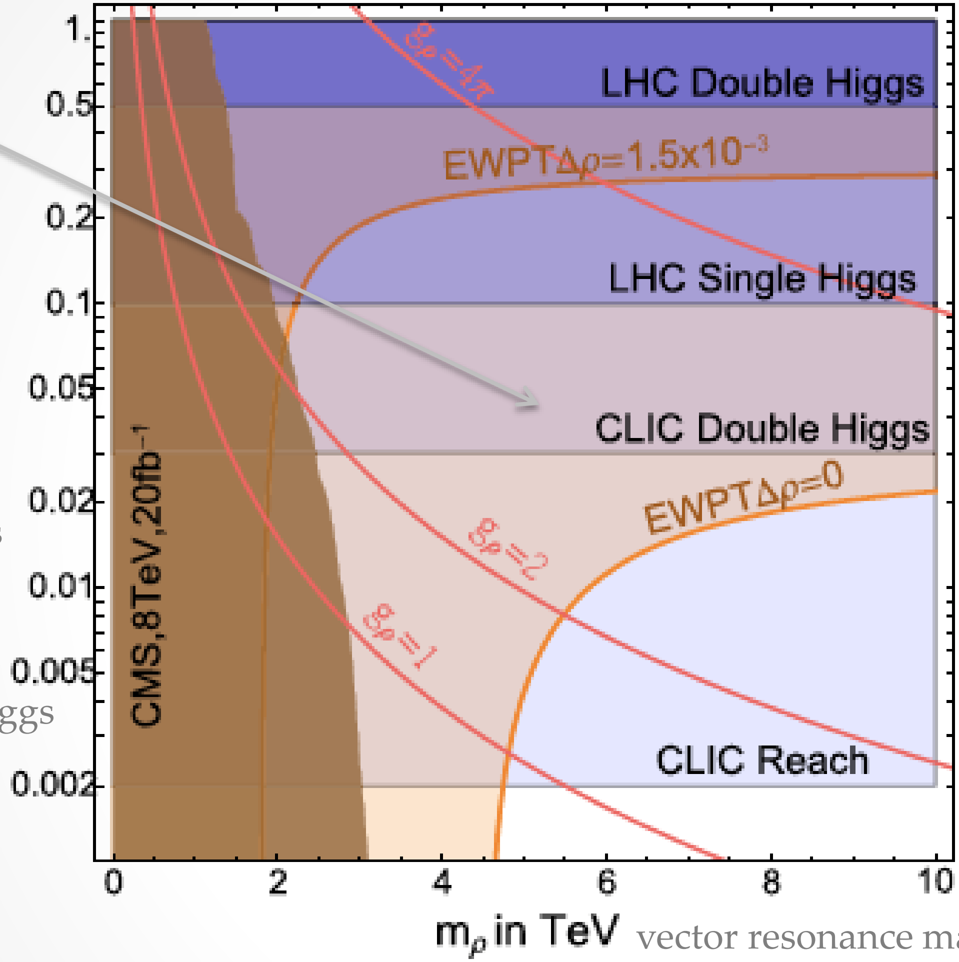


result: $\Delta m/m = 0.3\%$

Composite Higgs Bosons

allowed region EW precision tests

dimensionless scale parameter, measures strength of Higgs interactions

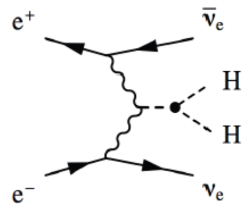


vector resonance mass of the composite theory

LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search WZ =>3 leptons

Allows to probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV

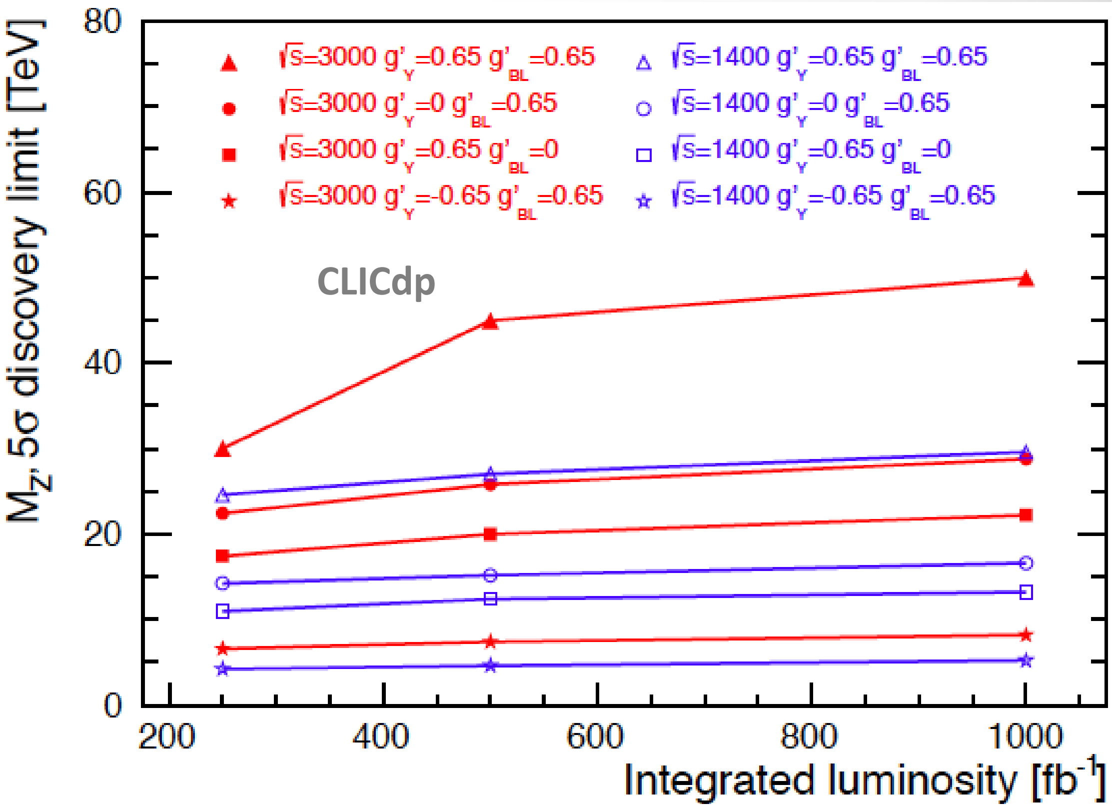
(70 TeV scale if combined with single Higgs production)

Precision Studies of $e^+e^- \to \mu^+\mu^-$

Minimal anomaly-free Z' model

$Q_f = g_Y'(Y_f) + g'_{BL}(B\text{-}L)_f$

(charge of SM fermions under U(1)' symmetry)



Observables:

- Total $e^+e^- \to \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

  (with ±80% e^- polarisation)

If LHC discovers Z'

(e.g. for $M_{Z'} = 5$ TeV)

Precision measurement of effective couplings

Otherwise:

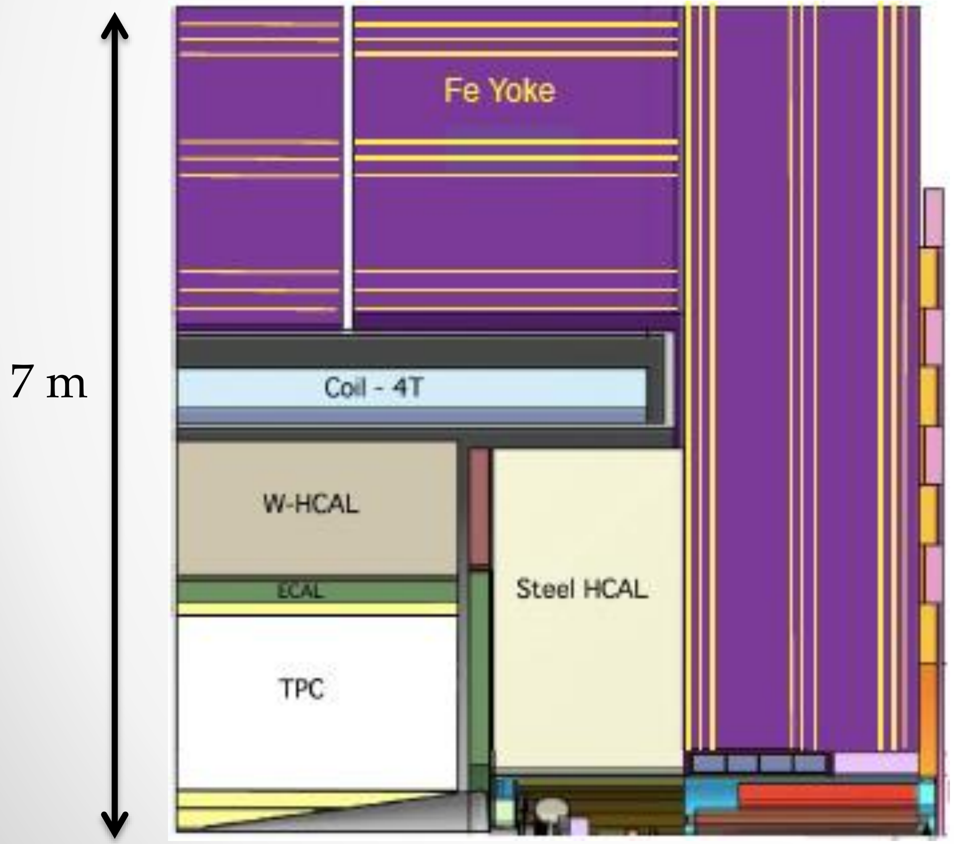
Discovery reach up to tens of TeV (depending on the couplings)

CLIC_ILD and CLIC_SiD

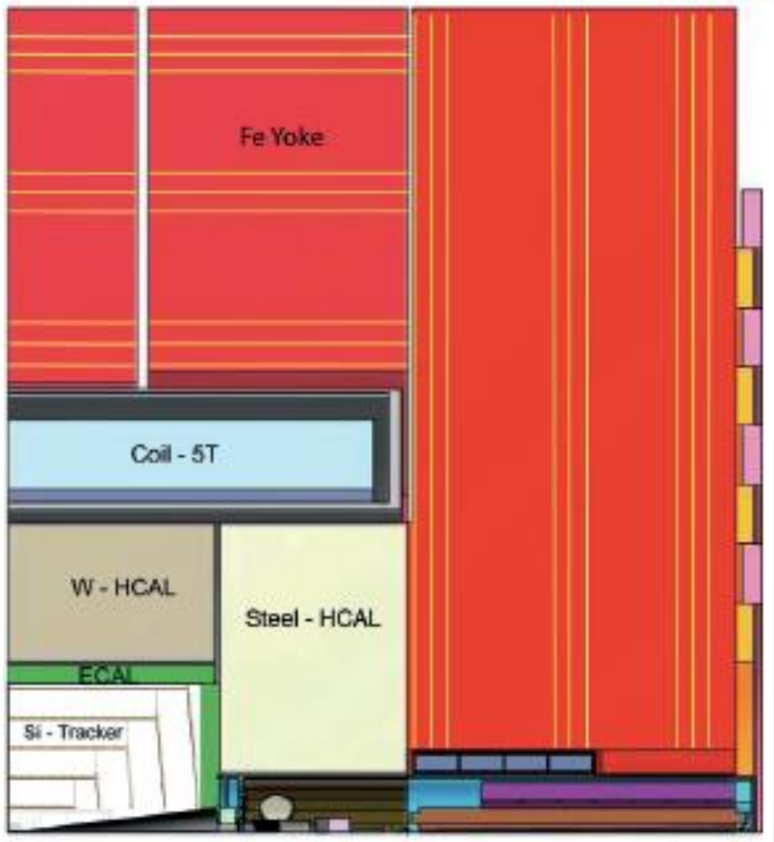
For the CLIC CDR (2012):

Two general-purpose CLIC detector concepts
Based on initial ILC concepts (ILD and SiD)
Optimized and adapted to CLIC conditions

CLIC_ILD



CLIC_SiD



Cost Estimate of the CDR Models

Table 5.4: Value estimate of the CLIC detectors.

	CLIC_ILD (MCHF)	CLIC_SiD (MCHF)
Vertex	13	15
Tracker	51	17
Electromagnetic calorimeter	197	89
Hadronic calorimeter	144	86
Muon system	28	22
Coil and yoke	117	123
Other	11	12
Total (rounded)	560	360

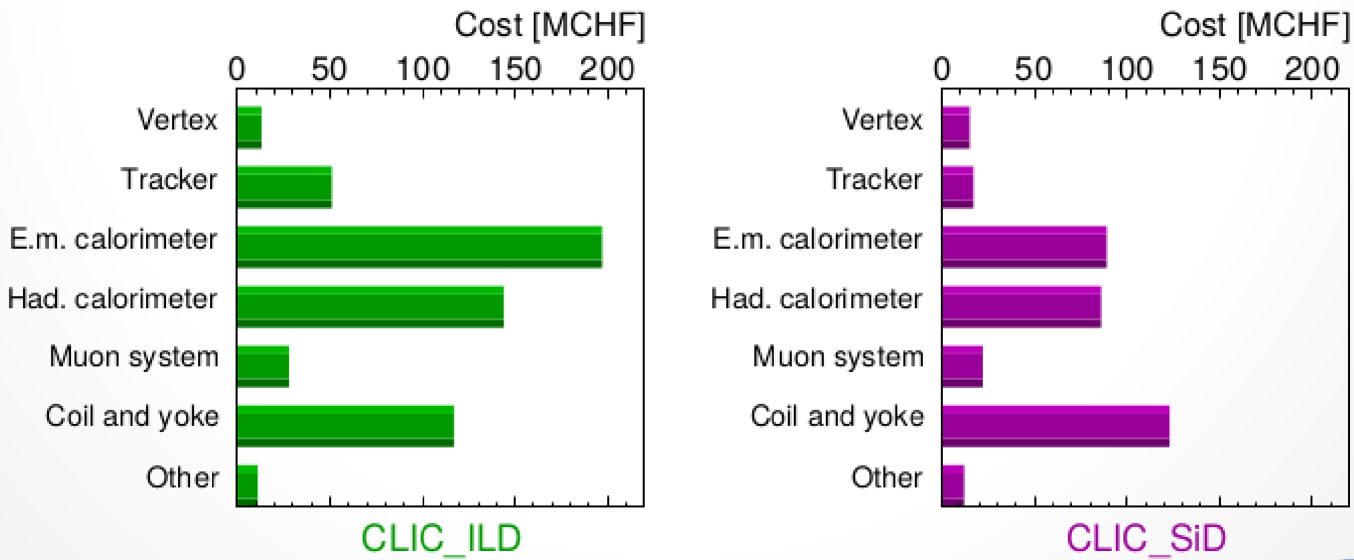


Fig. 5.9: Cost structure of the CLIC detectors.

General Requirements on Detector Technologies

- **CLIC conditions ⇒ impact on detector technologies**:
  - High tracker occupancies ⇒ **need small cell sizes** (beyond what is needed for resolution)
    - Small vertex pixels
    - Large pixels / short strips in the tracker
  - Background suppression
    - Need **high-granularity calorimetry**
    - $\mathbf{1\ ns}$ accuracy for calorimeter hits
    - $\sim\mathbf{10\ ns}$ hit time-stamping in tracking
  - Low duty cycle
    - Triggerless readout
    - Allows for **power pulsing**
      - less mass and high precision in tracking
      - high density for calorimetry

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 (1ns, 10ns)
- **"No" issue of radiation damage (10^{-4} LHC)**
  - Except small forward calorimeters
- **Beam crossings "sporadic"**
- **No trigger, read-out of full 156 ns train**

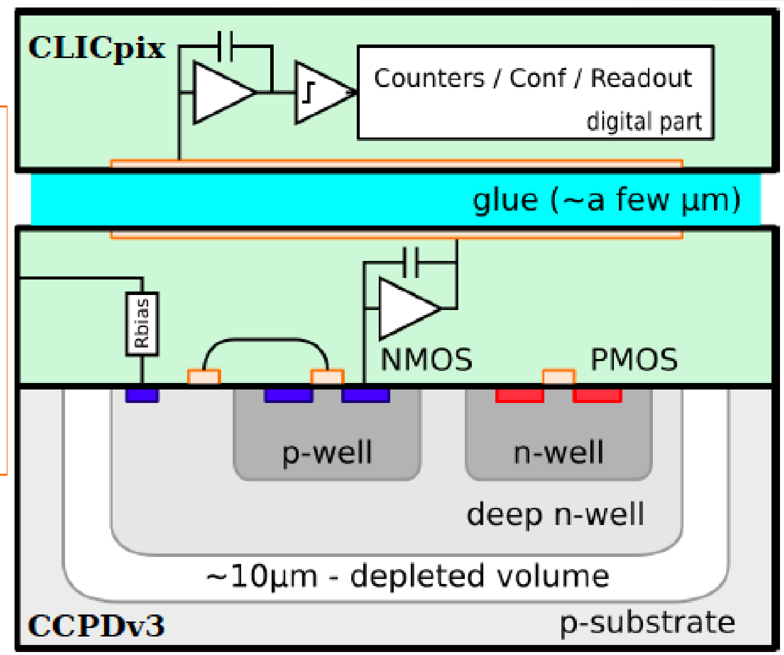
LHC detector:

- **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**

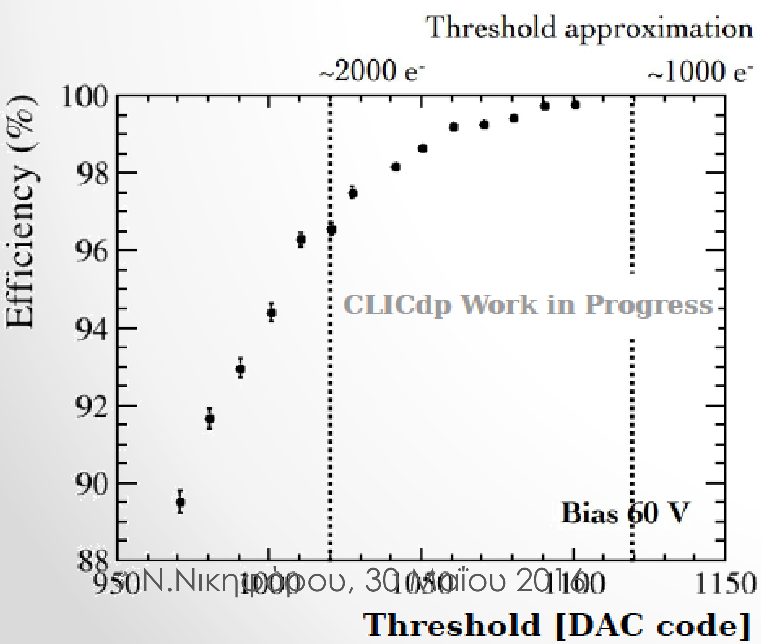
Hybrid Vertex Detector with HV-CMOS

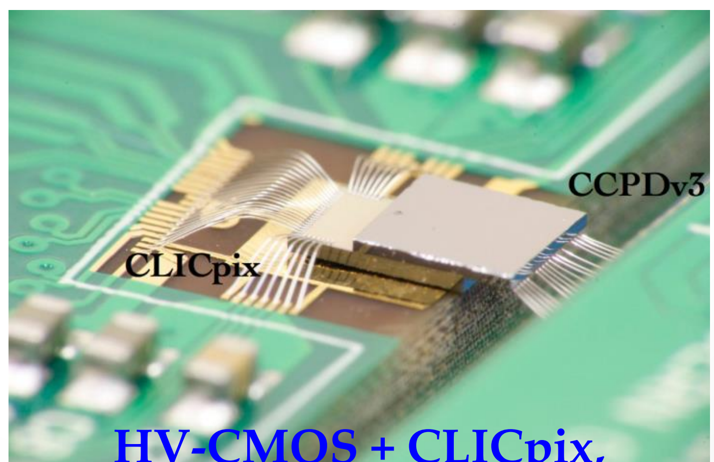
Pursuing an alternative readout option

Hybrid option with High Voltage-CMOS:
Capacitive Coupled Pixel Detector (CCPD)
- HV-CMOS chip as integrated sensor + amplifier
- Capacitive coupling to CLICpix readout chip through layer of glue ⇒no bump bonding

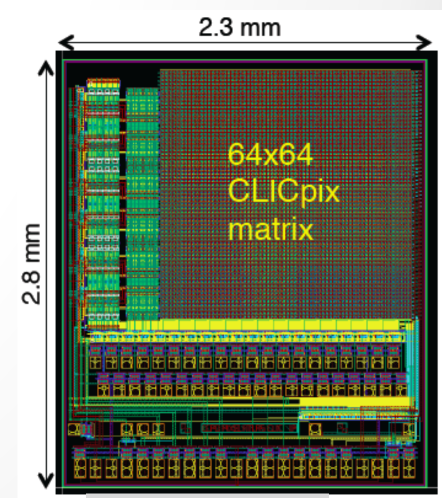


Status: successful initial beam tests in 2014
Further beam tests in 2015 and 2016





HV-CMOS + CLICpix, AC coupled

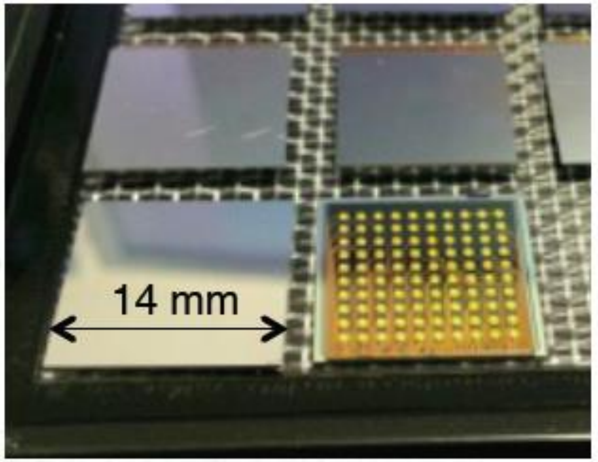


CCPDV3

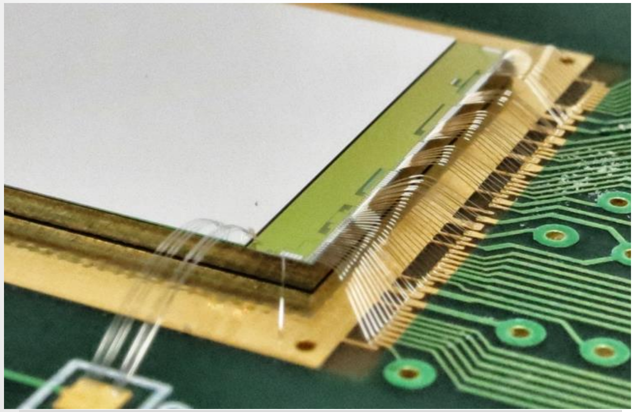
CLIC vertex detector: thin assemblies

Ultimate aim:

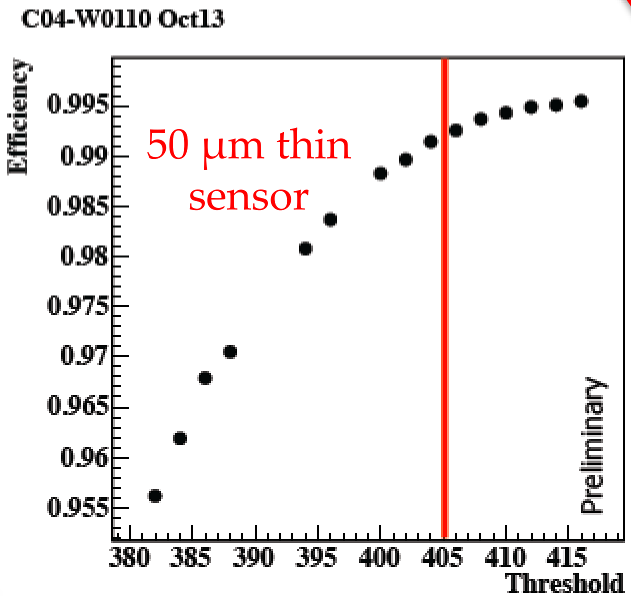
- 50 μm sensor on 50 μm ASIC
- Slim-edge sensors
- Through-Silicon Vias (TSV)
    - eliminates need for wire bonds
    - 4-side buttable chip/sensor assemblies
    - large active surfaces => less material



Medipix3RX with TSV



50 μm thin sensor on Timepix tested at test beam !



99.2% eff. at operating threshold

First successful picture using Medipix3RX with TSV

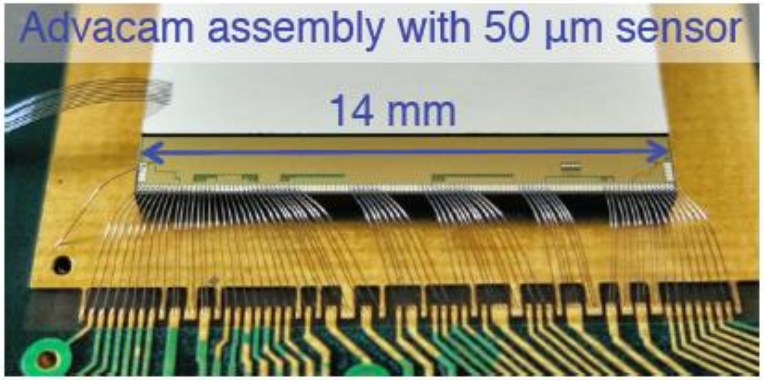
CLIC Vertex Detector R&D Roadmap

Hybrid approach pursued: (<= other options possible)
- Thin (~50 μm) silicon sensors
- Thinned high-density readout ASIC (50 μm)
  - R&D within Medipix/Timepix effort
- Low-mass interconnect
- Power pulsing
- Air cooling

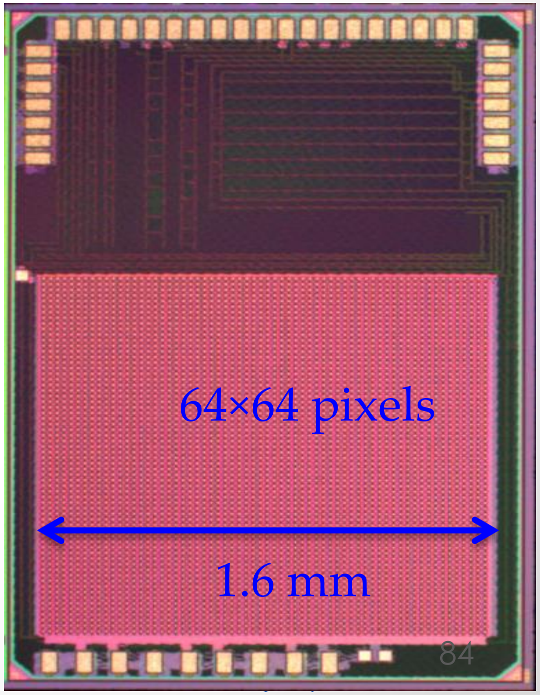
CLICpix demonstrator ASIC

64×64 pixels, fully functional
- 65 nm technology
- 25×25 μm^2 pixels
- 4-bit ToA and ToT info
- Data compression
- Pulsed power: 50 mW/cm^2

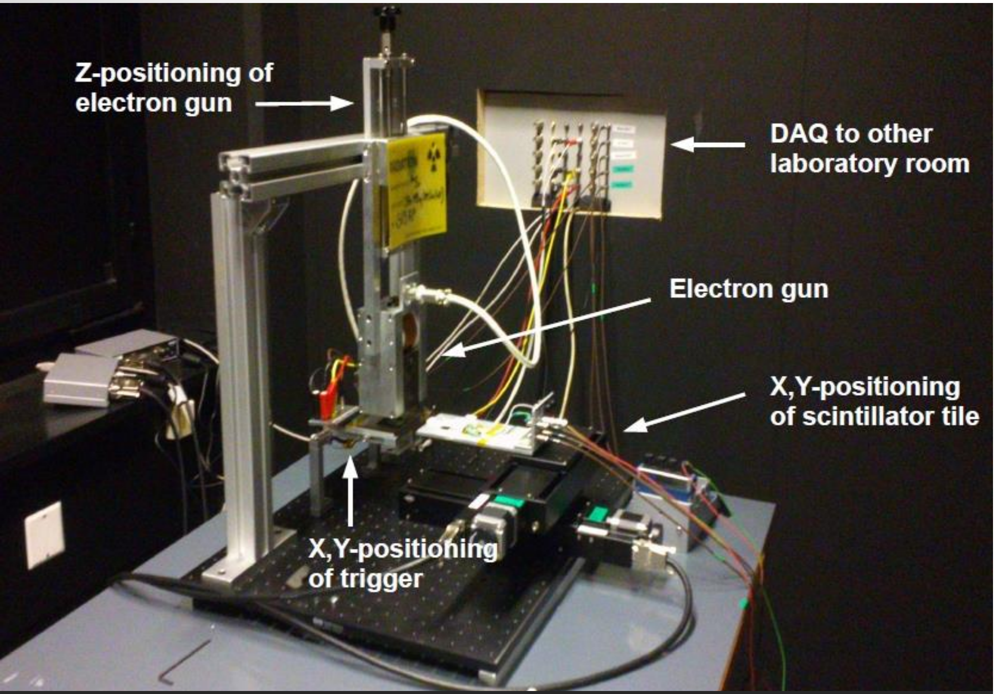
⇩



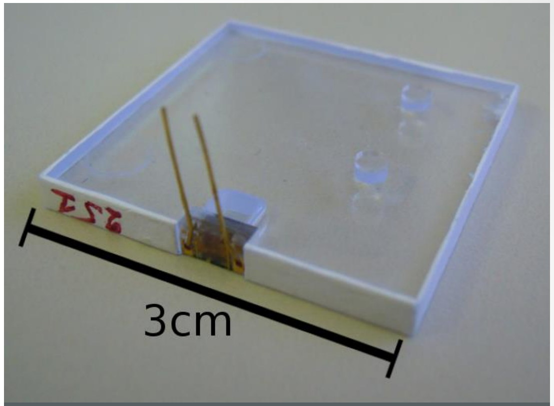
Very thin sensors !
Successfully tested at DESY test beam
(with existing Timepix ASIC)



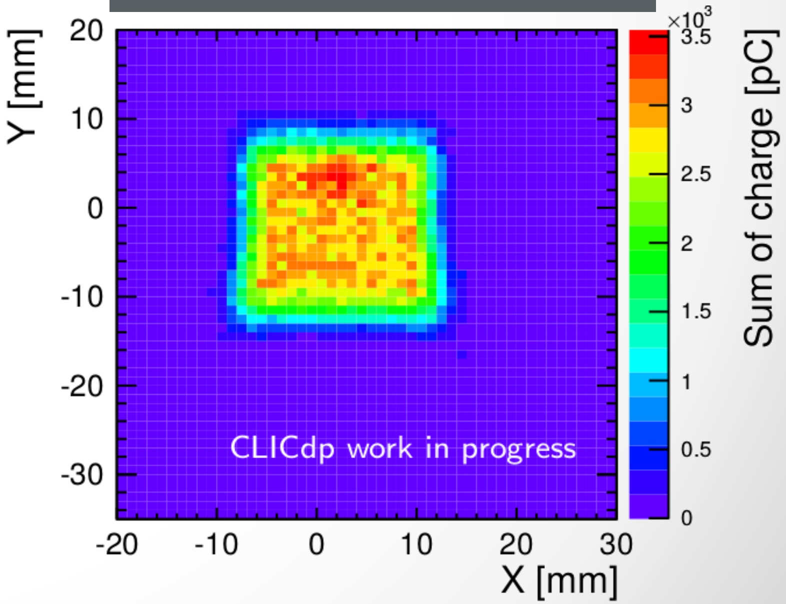
R&D on Scintillator+SiPM



Electron gun in AC-regulated dark room



Scintillator Tile with mounted SiPM



- Also have a dedicated lab at CERN for Scintillator + **Si**licon **P**hoto**M**ultiplier testing
- Test bench: **electron gun**, **D**evice **U**nder **T**est on movable table, trigger scintillators, read-out electronics
- Study response, uniformity, noise, cross-talk, ...

Forward Calorimetry

R&D performed within the FCAL collaboration

2 forward calorimeters:

- **LumiCal + BeamCal**
- **Electron / photo**n acceptance to small angles
- Luminosity measurement
- Beam feedback

Absorbers: tungsten, 40 layers of 1 X_0

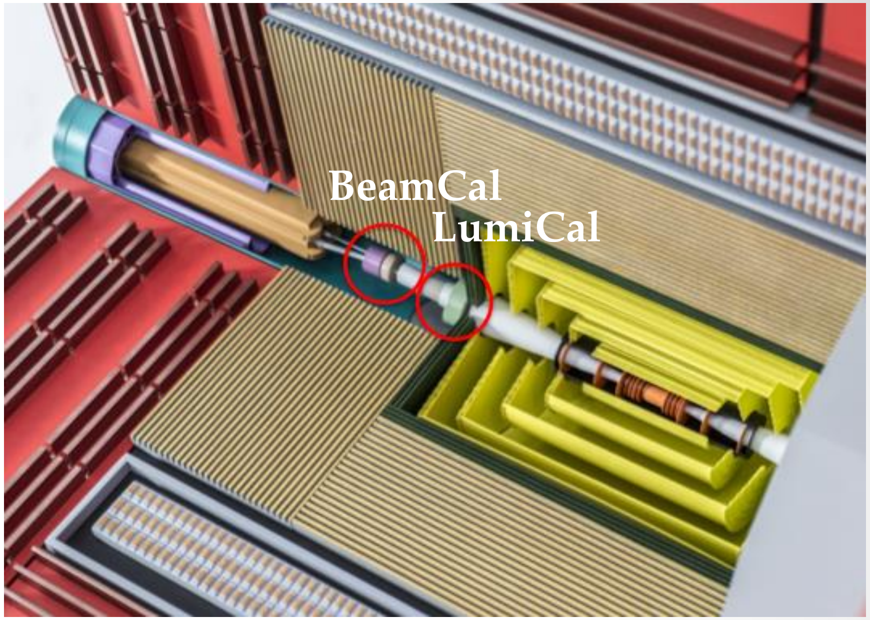
Sensors: BeamCal GaAs, LumiCal silicon

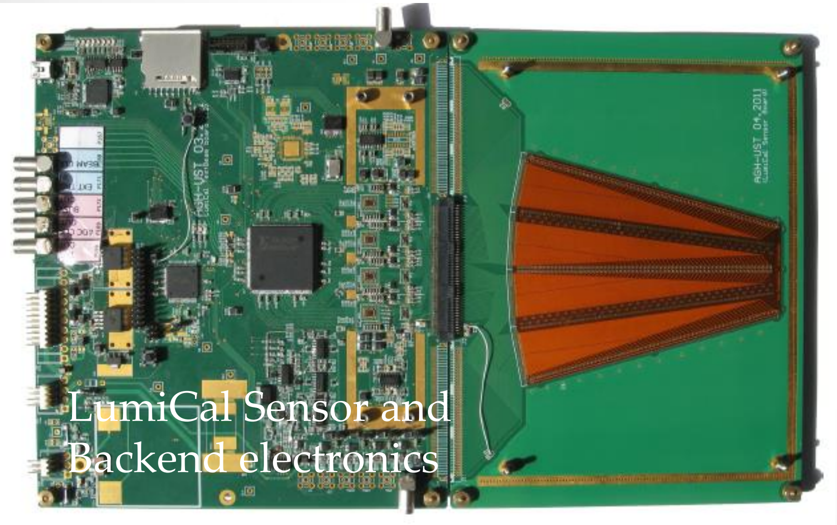
Angular coverage:

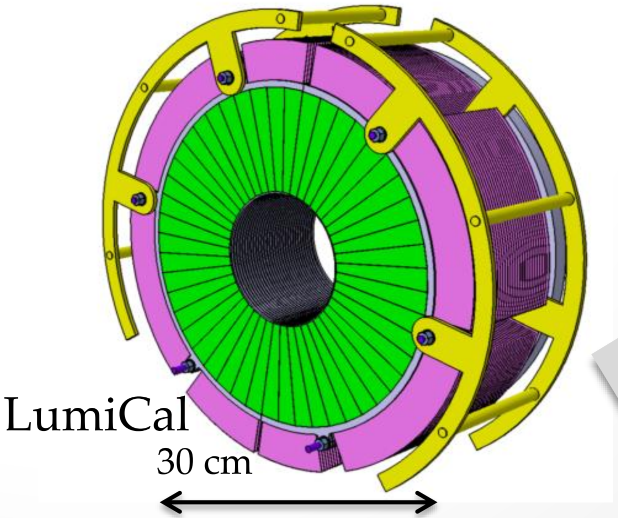
BeamCal 10 - 40 mrad, LumiCal 38 – 110 mrad

Doses up to 1 MGy

Neutron fluxes of up to 10^{14} per year



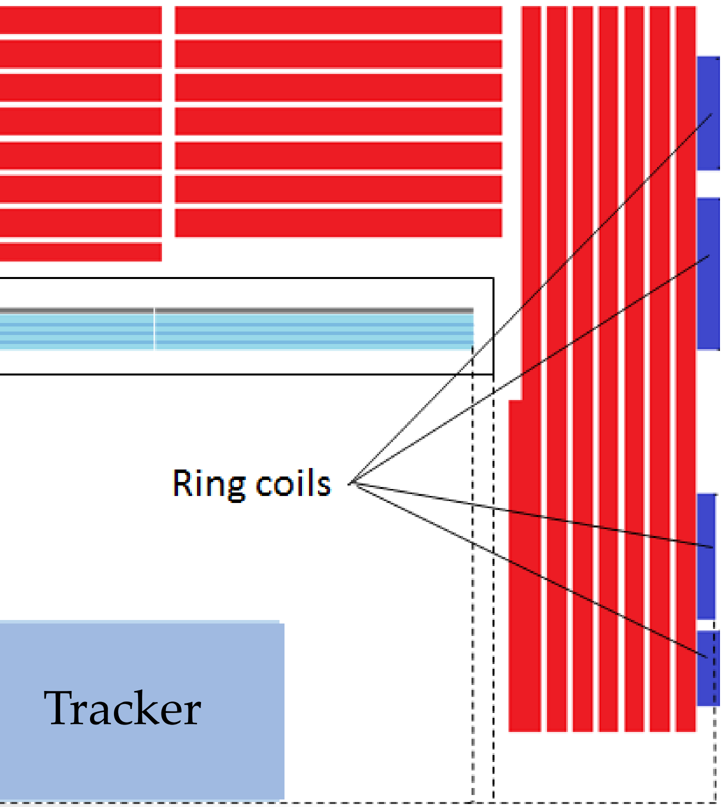


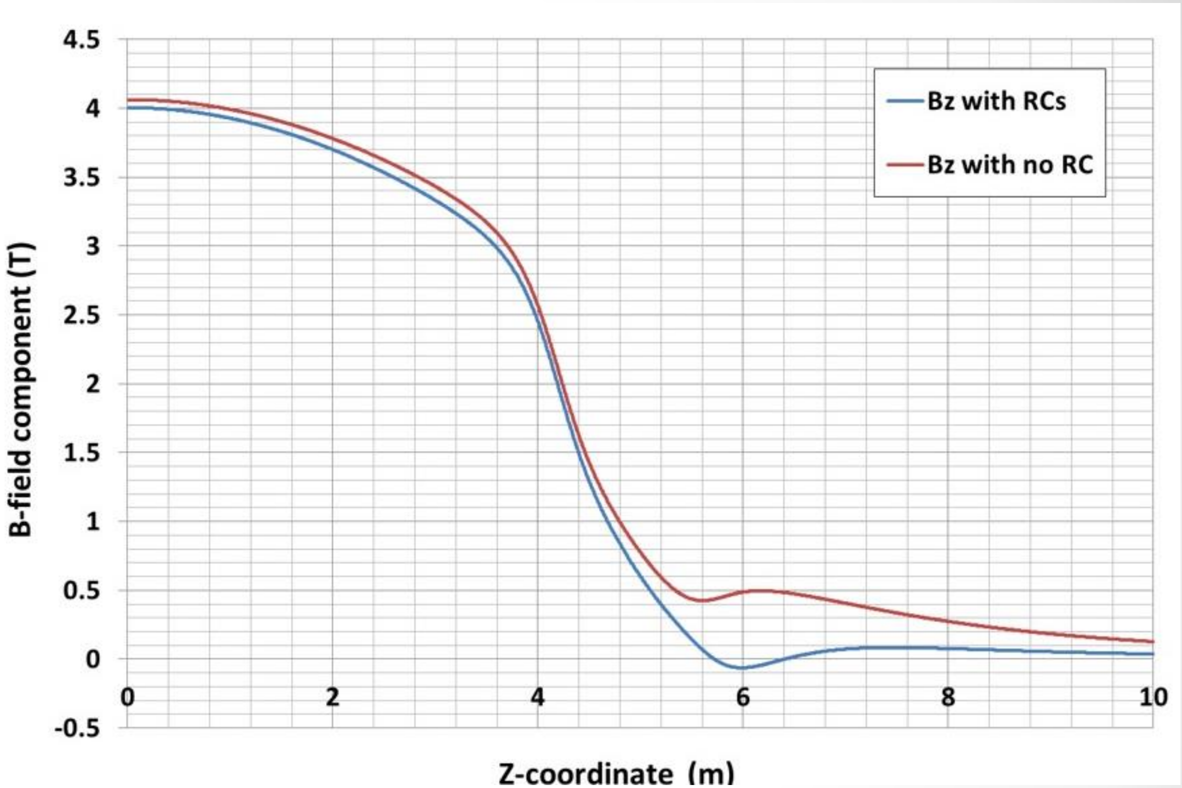


Very compact !

FCAL collaboration
http://fcal.desy.de/

Magnet System Layout





Quarter view of the magnet system with "thin" yoke Endcaps

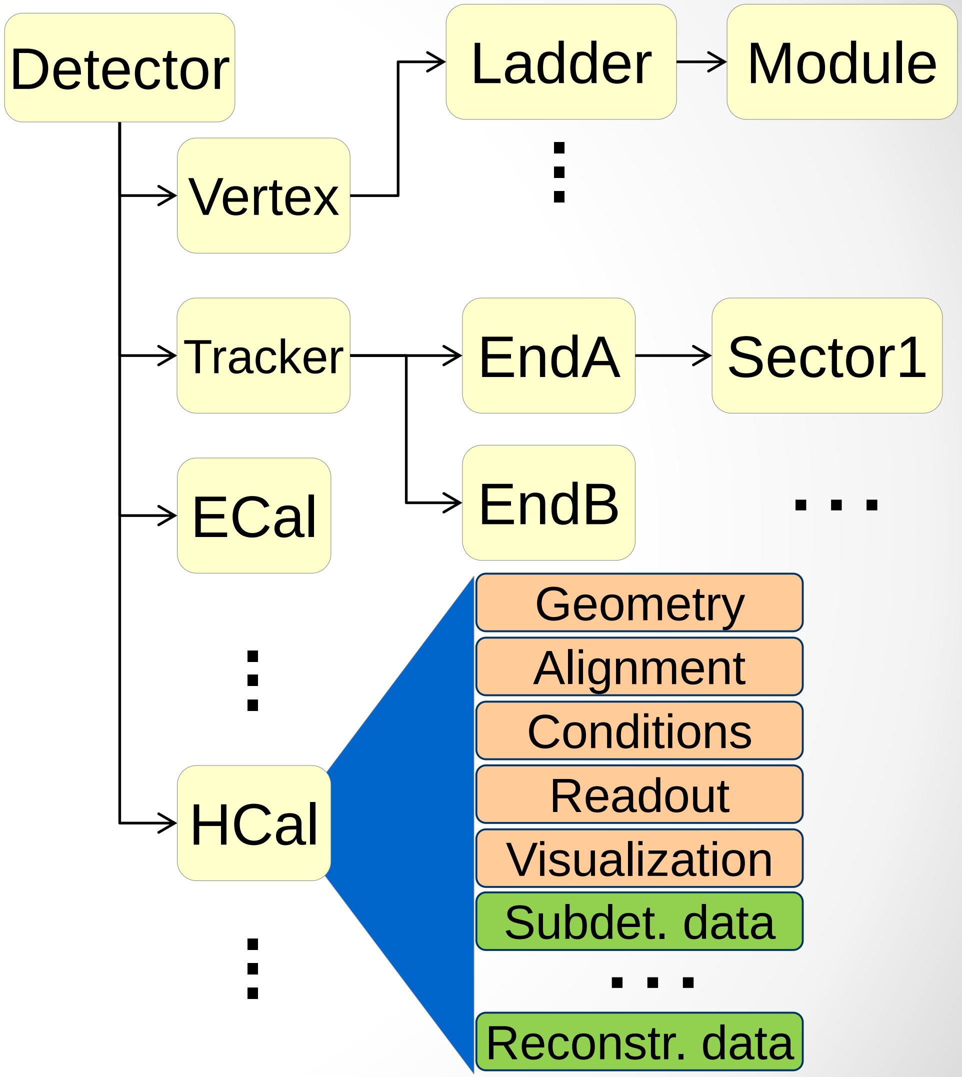
B-field axial component **with** and **without** end coils as function of z

Note 4 concentric ring end coils in blue

Use the end coils to compensate for thin endcaps

What is detector description

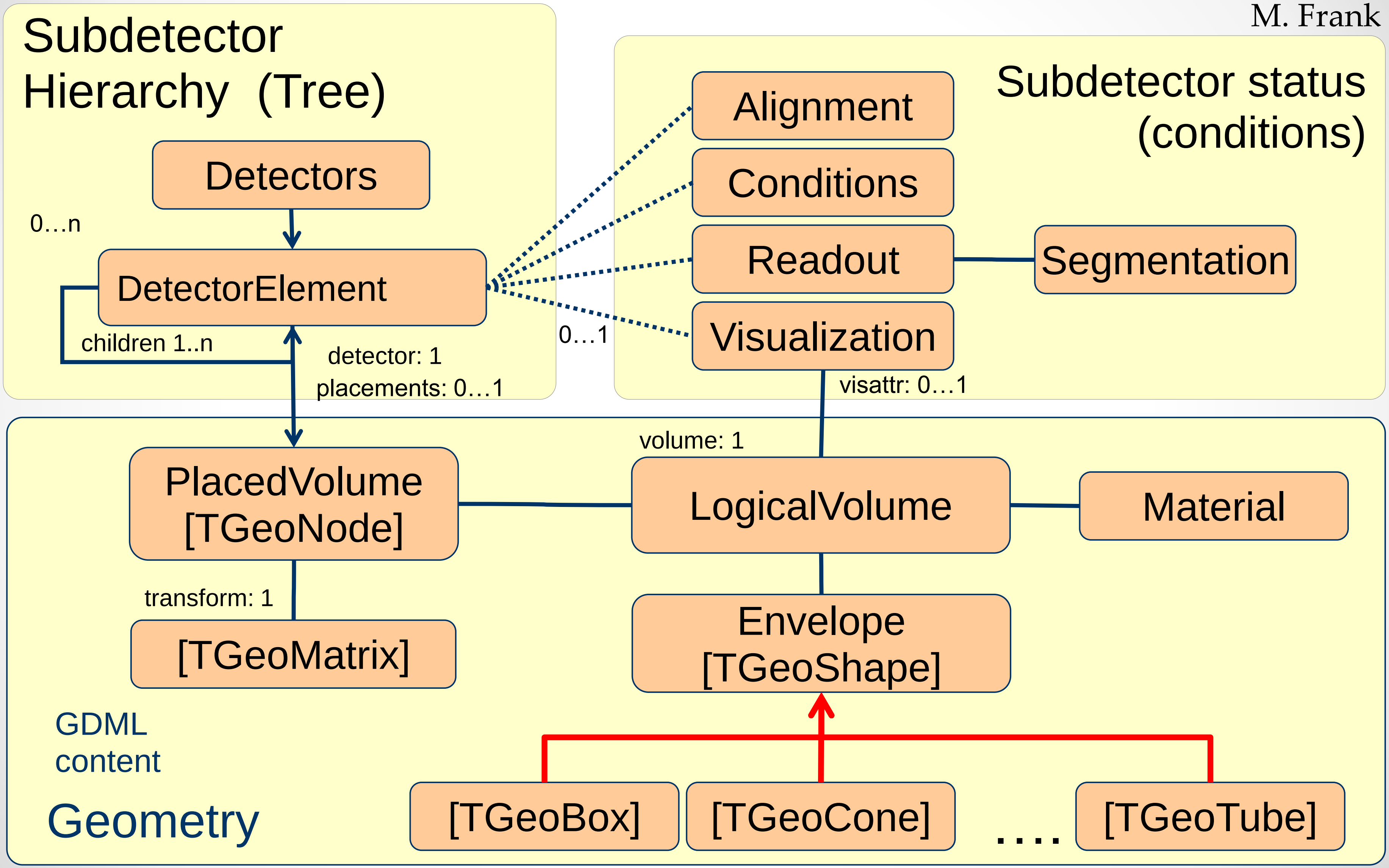
- Description of a tree-like hierarchy of **"detector elements"**
  - Subdetectors or parts of subdetectors
- Detector Element describes
  - Geometry
  - Environmental conditions
  - Properties required to process event data
  - Extensions (optionally): experiment, sub-detector or activity specific data, measurement surfaces, …



M. Frank

Geometry Implementation

M. Frank



Current DD4hep toolkit users

		DD4hep	DDG4
ILD	F. Gaede et al., ported complete model ILD_o1_v05 from previous simulation framework (Mokka)	✓	✓
CLICdp	New detector model being implemented after CDR, geometry under optimization	✓	✓
FCAL	Testbeam simulation	✓	✓
FCC-eh	P. Kostka et al.	✓	✓
FCC-hh	A. Salzburger et al.	✓	
FCC-ee	Interest expressed, already used in studies		
SiD	Decision to use DD4hep taken at LCWS 2015		
CALICE	Started		
LHCb	Investigations started for LHCb upgrade		

Feedback from users is invaluable and helps shaping DD4hep!

```
for (xml_coll_t c(x_det, _U(layer)); c; ++c) {
  xml_comp_t x_layer = c;
  int repeat = x_layer.repeat();            // Get number of times to repeat this layer.
  const Layer* lay = layering.layer(layer_num - 1); // Get the layer from the layering engine.
  // Loop over repeats for this layer.
  for (int j = 0; j < repeat; j++) {
    string layer_name = _toString(layer_num, "layer%d");
    double layer_thickness = lay->thickness();
    DetElement layer(stave, layer_name, layer_num);
    DDRec::LayeredCalorimeterData::Layer caloLayer ;
     // Layer position in Z within the stave.
    layer_pos_z += layer_thickness / 2;
    // Layer box & volume
    Volume layer_vol(layer_name, Box(layer_dim_x, detZ / 2, layer_thickness / 2), air);

    // Create the slices (sublayers) within the layer.
    double slice_pos_z = -(layer_thickness / 2);
    int slice_number = 1;
    double totalAbsorberThickness=0.;

    for (xml_coll_t k(x_layer, _U(slice)); k; ++k) {
      xml_comp_t x_slice = k;
      string slice_name = _toString(slice_number, "slice%d");
      double slice_thickness = x_slice.thickness();
      Material slice_material = lcdd.material(x_slice.materialStr());
      DetElement slice(layer, slice_name, slice_number);

      slice_pos_z += slice_thickness / 2;
      // Slice volume & box
      Volume slice_vol(slice_name, Box(layer_dim_x, detZ / 2, slice_thickness / 2), slice_material);
       if (x_slice.isSensitive()) {
        sens.setType("calorimeter");
        slice_vol.setSensitiveDetector(sens);
      }
      // Set region, limitset, and vis.
      slice_vol.setAttributes(lcdd, x_slice.regionStr(), x_slice.limitsStr(), x_slice.visStr());
      // slice PlacedVolume
      PlacedVolume slice_phv = layer_vol.placeVolume(slice_vol, Position(0, 0, slice_pos_z));

      slice.setPlacement(slice_phv);
      // Increment Z position for next slice.
      slice_pos_z += slice_thickness / 2;
      // Increment slice number.
      ++slice_number;
    }
```

Example HCal Barrel Driver

- Always within a function called

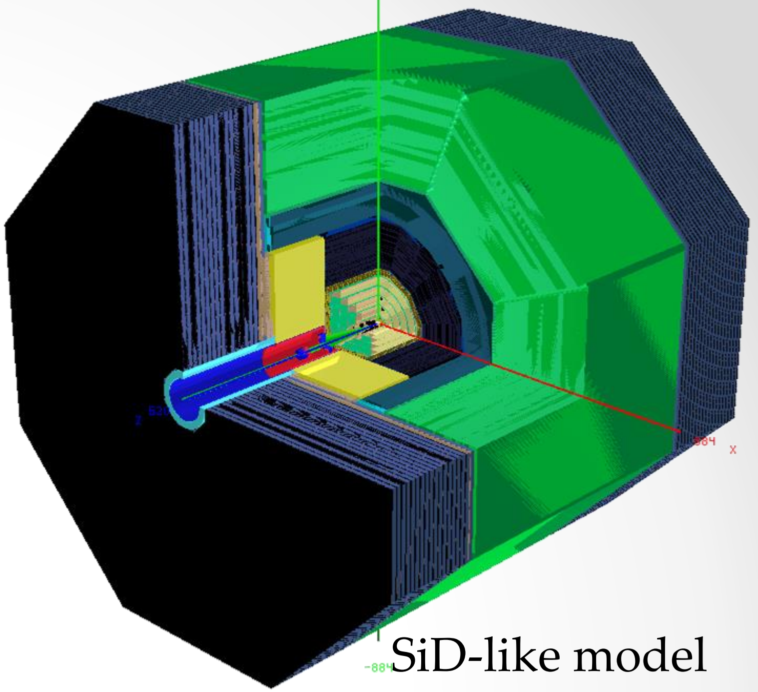
```
static Ref_t create_detector(LCDD& lcdd, xml_h e, SensitiveDetector sens) {
…
return sdet;
}
```

- Macro to declare detector constructor at the end:

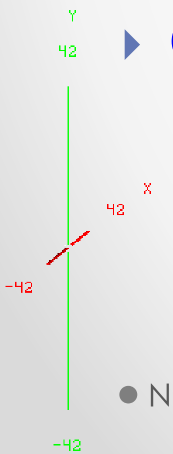
```
DECLARE_DETELEMENT(HCalBarrel_o1_v01, create_detector)
```

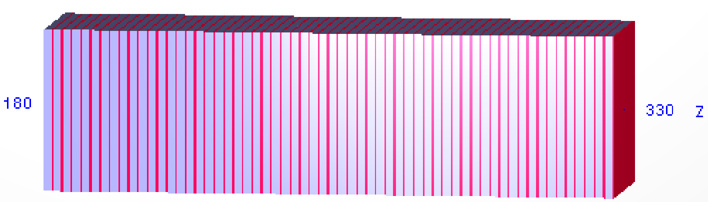
Driver flexibility

- **SiD model** example part of **DD4hep** package (right)
- Quick-n-dirty HCal stack below created from driver above in **1 min!**
  - **No code recompilation**
  - **Just modified compact xml file**
  - **Comment out includes of all other subdetectors**
  - **Leave just HCal Endcap for which I change symmetry from 8 to 4, set "outer radius" to 30 cm, "inner radius" to 0 and turn off reflection about the IP**
  - **Obtain a simplified model to use for material response studies**



SiD-like model





HCal stack along z-axis (60 layers of steel interleaved with scinitllator)

DDG4 configuration

- DDG4 is highly modular
- Easy to configure, especially if one uses the python dictionaries
- Configure actions, filters, sequences, cuts, …

```
...
part = DDG4.GeneratorAction(kernel,
                    "Geant4ParticleHandler/ParticleHandler")
kernel.generatorAction().adopt(part)
part.SaveProcesses = ['Decay']
part.MinimalKineticEnergy = 1*MeV
part.KeepAllParticles = False
...
user = DDG4.GeneratorAction(kernel,
          "Geant4TCUserParticleHandler/UserParticleHandler")
user.TrackingVolume_Zmax = DDG4.tracker_region_zmax
user.TrackingVolume_Rmax = DDG4.tracker_region_rmax
...
```

`ddsim` executable

- Python executable with many command-line argument configuration options
  - Configure most useful and common user options in the command line
  - Even supports tab-completion of arguments and their options! (A. Sailer)

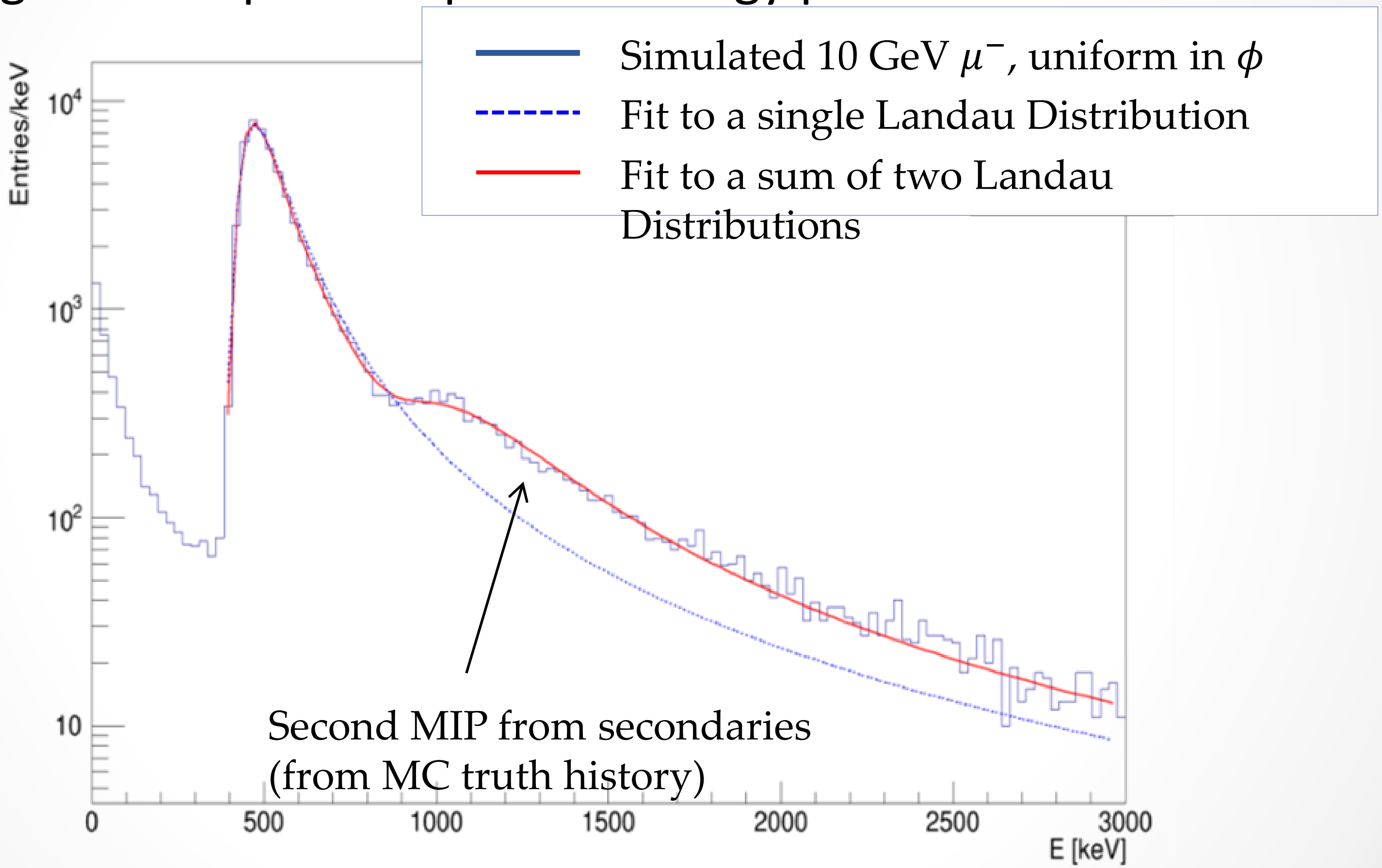
```
ddsim –h
usage: Running DD4hep Simulations: [-h] [--steeringFile STEERINGFILE]
[--compactFile COMPACTFILE] [--runType {batch,vis,run,shell}]
[--inputFiles INPUTFILES [INPUTFILES ...]] [--outputFile OUTPUTFILE] [-v PRINTLEVEL]
[--numberOfEvents NUMBEROFEVENTS] [--skipNEvents SKIPNEVENTS]
[--physicsList PHYSICSLIST] [--crossingAngleBoost CROSSINGANGLEBOOST]
[--vertexSigma VERTEXSIGMA VERTEXSIGMA VERTEXSIGMA VERTEXSIGMA]
[--vertexOffset VERTEXOFFSET VERTEXOFFSET VERTEXOFFSET VERTEXOFFSET]
[--macroFile MACROFILE] [--enableGun]
[--enableDetailedShowerMode]
```

Continuously implementing more options!

- Calls Python library which is also modular and even more configurable (more advanced)
  - Users can write applications using DDG4

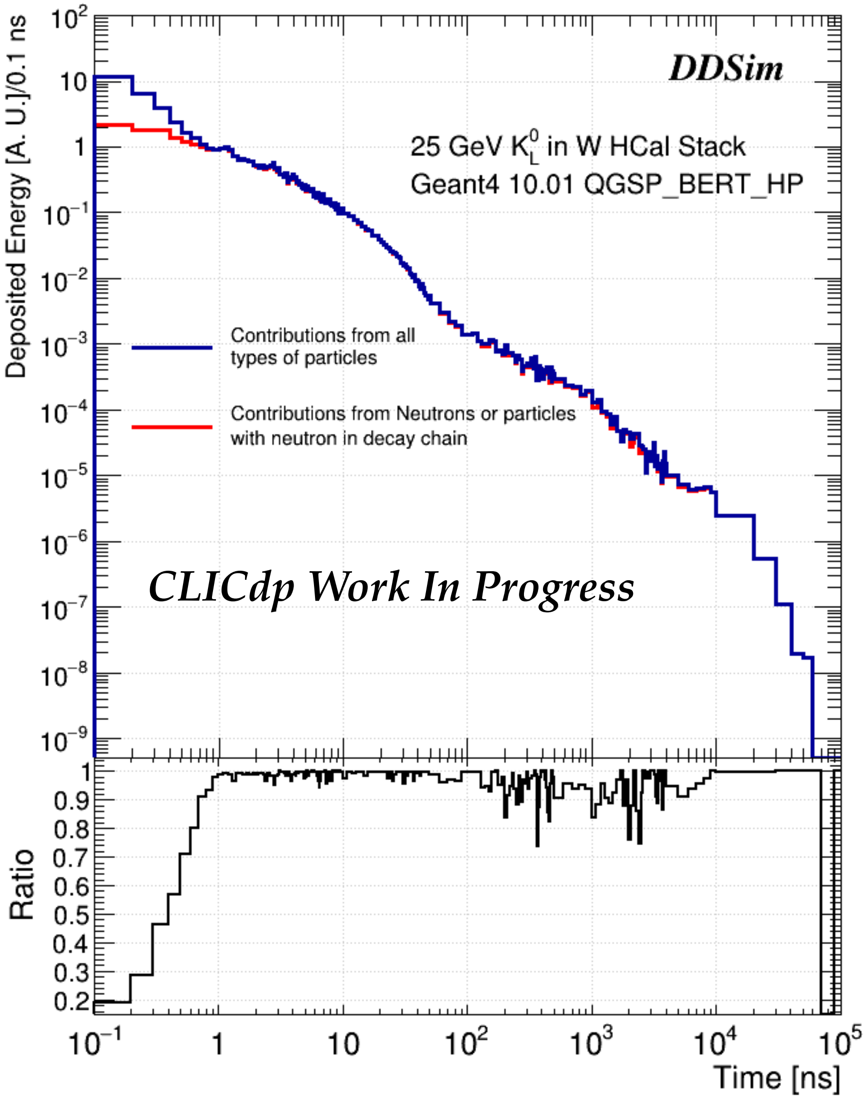
Simulating single muons with DDSim

- We can validate the tool by using single particles
- Looking for example at deposited energy per hit in the HCal



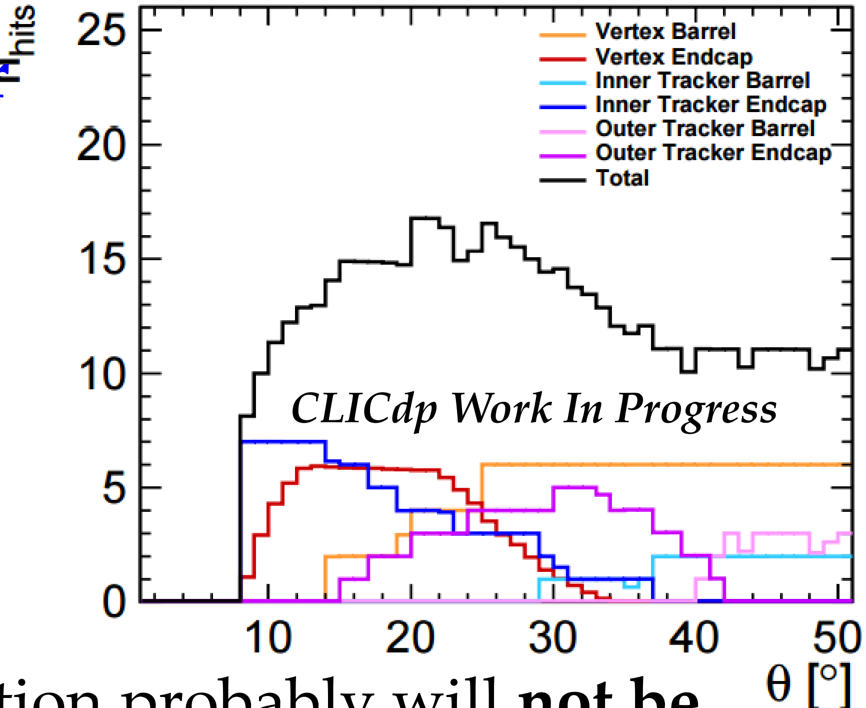
Detector optimization with DDSim

- Can have a larger more detailed MC Particle Truth Record by increasing "Tracking Region", lowering energy cuts
- E.g. expanded region to include calorimeters
  - Track provenance of every hit contribution in the hadronic shower
  - Try to understand timing in Fe/W



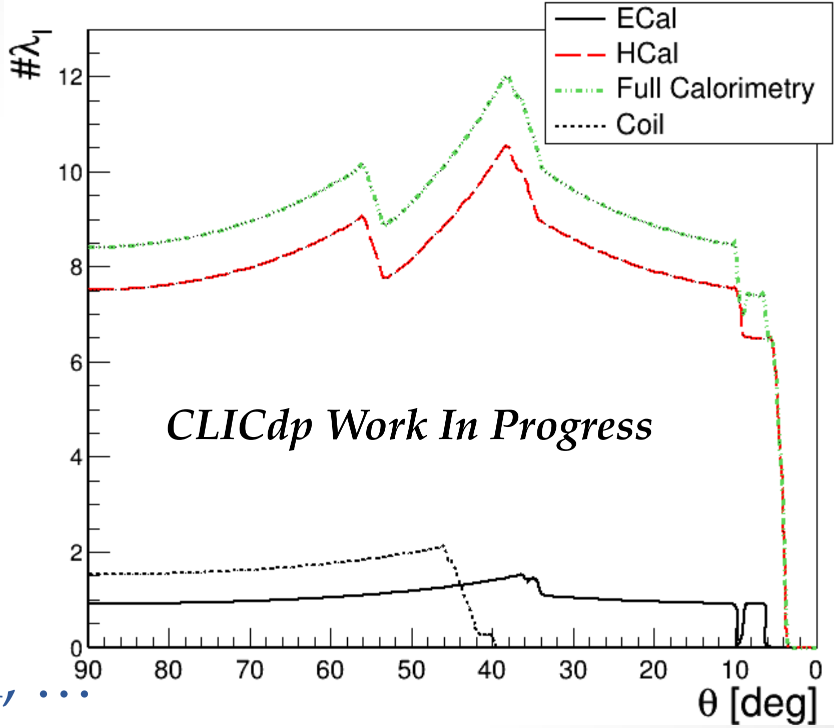
Detector optimization with DDSim

R. Simoniello



- **Control over sensitive detector actions**
- E.g. Use a tracker action that combines all interactions in the Silicon as one `SimTrackerHit`
  - Use **muon** tracks to count hit coverage w.r.t. angle
- **NB:** For physics events reconstruction probably will **not be** combining the hits in simulation [this will probably stay as the default tracker action]
  - Combine hits in the Digitization stage
  - Already simulating $Z \rightarrow uds$ and $t\bar{t}$ events up to 3 TeV to aid with Det. Optimization and Reconstruction software development

Geant4 material scan

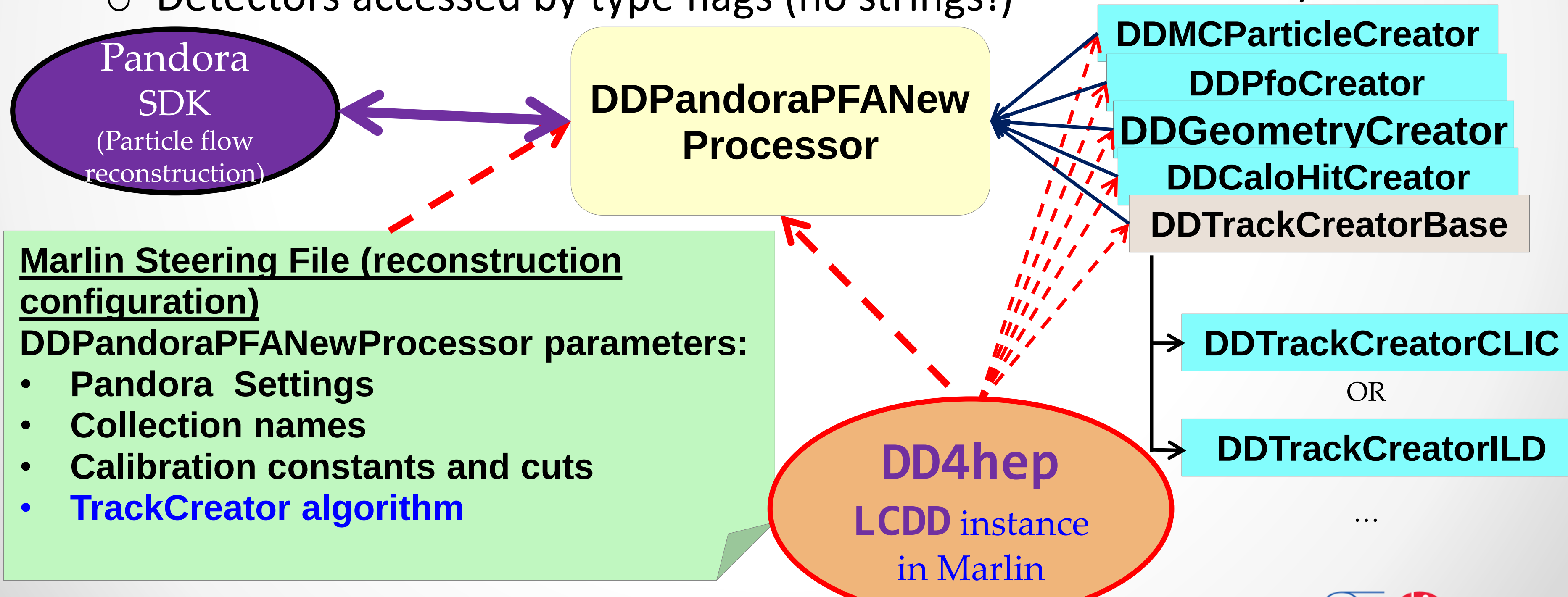


- Can request a Geant4 UI to **interact with G4 Kernel**
  - csh-like, or Qt-based GUI
- Access to whatever Geant4 modules are loaded
  - E.g. material scan, visualization, …
- G4 Material scan can be restricted to regions
  - /control/matScan/region CalorimeterRegion
- It's nice that in DD4hep regions can be defined and assigned to detectors trivially in the xml regardless of their shape

```
<detector id="DetID_HCAL_Barrel" name="HCalBarrel" type="HCalBarrel_o1_v01“ readout="HCalBarrelHits" vis="HCALVis" region="CalorimeterRegion" >
. . .
</detector>
```

DDMarlinPandora

- Developed a package to interface geometry with Particle flow reconstruction (provided by **PandoraPFA**)
- **DD4hep** (with **DDRec**) as single source of information
  - No material or other geometry info in processor parameters
- Not tied to specific detector geometry
  - Detectors accessed by type flags (no strings!)



Event Simulated, Reconstructed and Visualized Fully with DD4hep

S. Lu

- **ILD_o1_v05** model implemented in **DD4hep**
- $Z \rightarrow uds$ event at $\sqrt{s} = 500$ GeV simulated in **DDSim**
- Tracks reconstructed using **DDSurfaces**
- PFOs from **DDMarlinPandora** using the **DDRec** data structures
- Event display from the **CED** viewer interfaced with **DD4hep**
  - Also uses **DDRec** and **DDSurfaces**