The New CLIC Detector Simulation Model

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CLIC Physics Goals → Detector Requirements

- Momentum resolution
  - e.g., **Higgs coupling to muons**

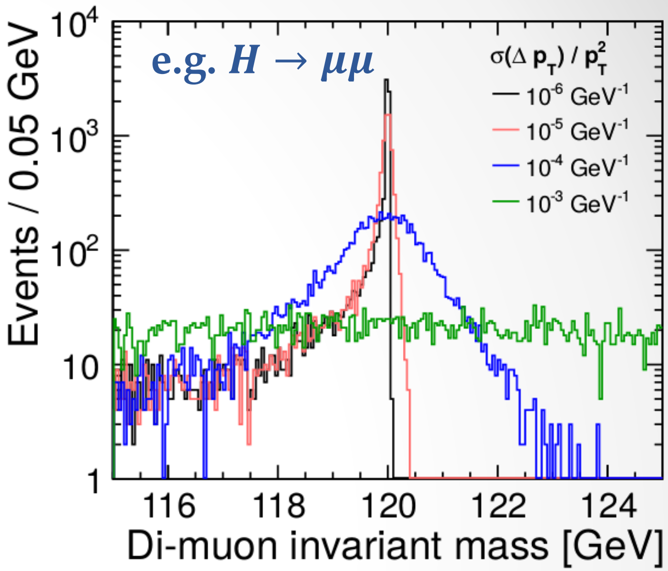
    $\rightarrow \sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5}\text{GeV}^{-1}$
- Jet energy resolution
  - e.g. **Separation of W/Z measurement in di-jet events**

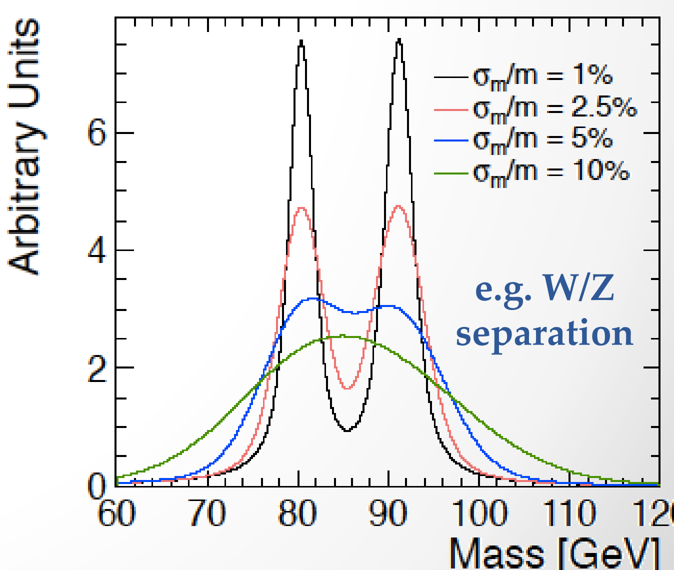
    $\rightarrow \sigma_E/E \sim 3.5\%$ for $E > 100$ GeV
- Impact parameter resolution
  - c/b-tagging, Higgs branching ratios

    $\rightarrow \sigma_{R\phi} \sim 5 \oplus 15/(p[\text{GeV}]\sin^{\frac{3}{2}}\theta)\mu\text{m}$
- Angular coverage
  - Very forward electron tagging

    $\rightarrow$down to $\theta = 10$ mrad

\+ **Requirements due to CLIC beam structure and beam-induced backgrounds**





Evolution of Detector Designs

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

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

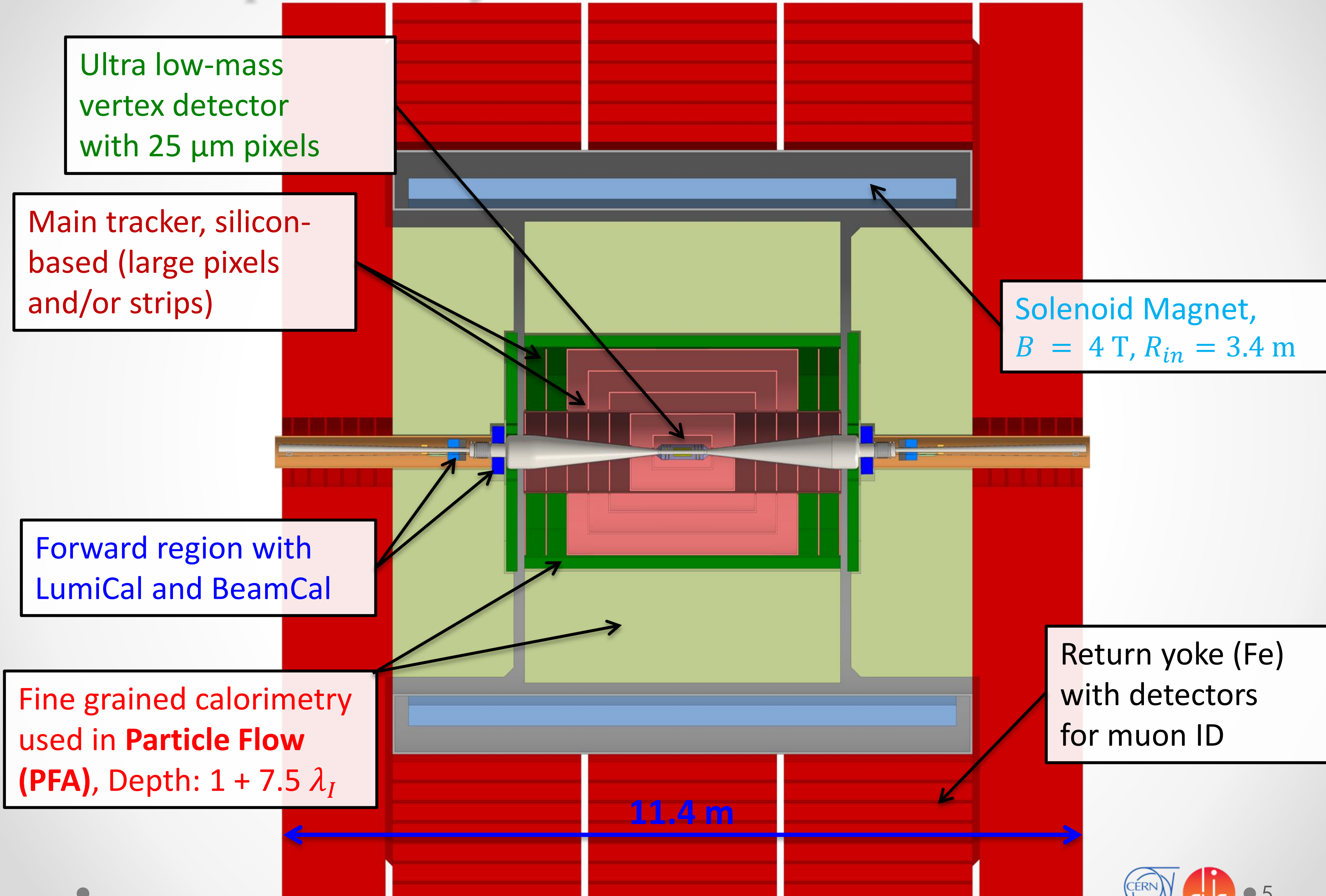
Simulation Model in Software

- New detector model implemented and being refined in DD4hep with relative **flexibility/scalability**
  - **New package LCgeo holds model implementation**

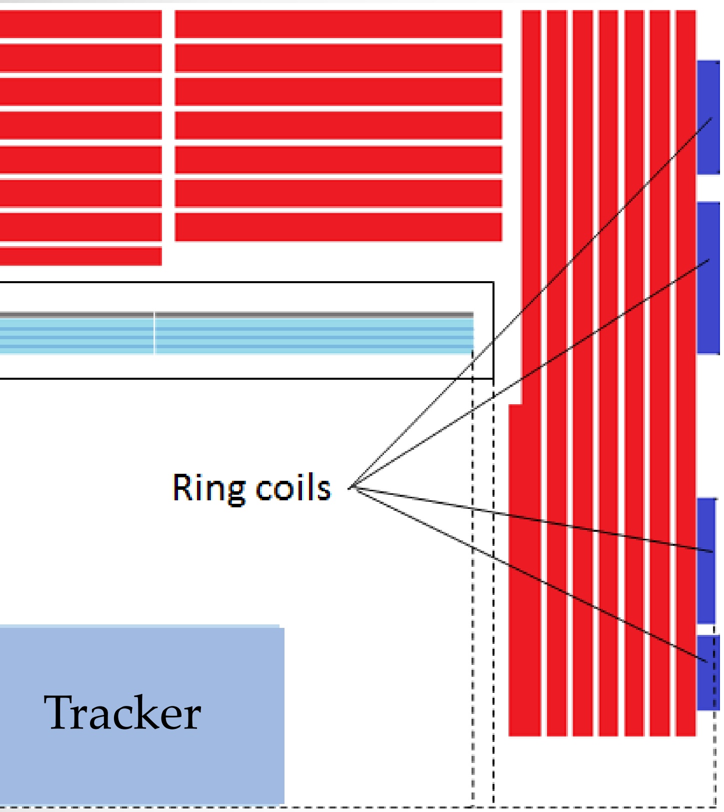
See talk by M. Petric (Thursday morning)

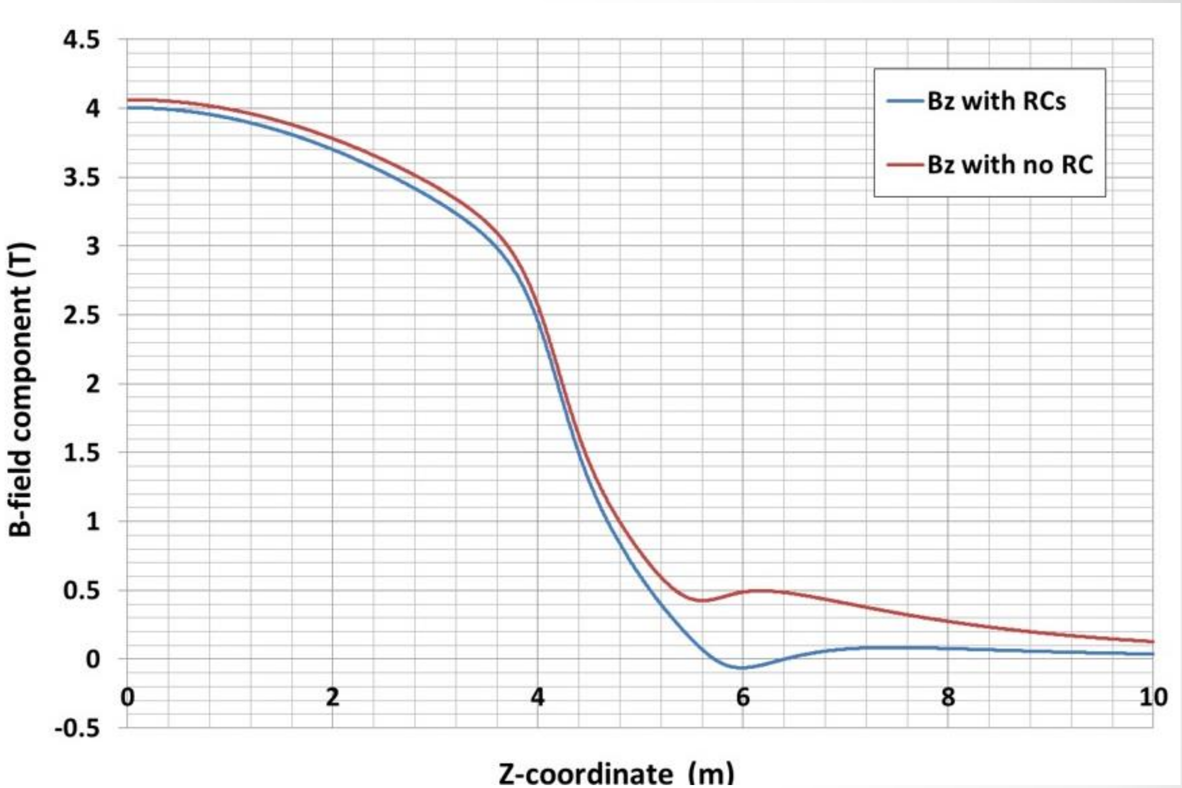
- Developing **simulation** and **reconstruction** software based on **DD4hep** in collaboration with ILD
  - Other relevant talks:
    - Joint ILD/ SiD/CLICdp session on simulation tools and reconstruction algorithms: **Tuesday afternoon**
    - Simulation/Performance/Reconstruction sessions: **Tuesday morning**
    - Vertex/tracking joint session with Simulation/Performance/Reco: **Thursday afternoon**

Proposed Layout in New Detector Model



Magnet System Layout





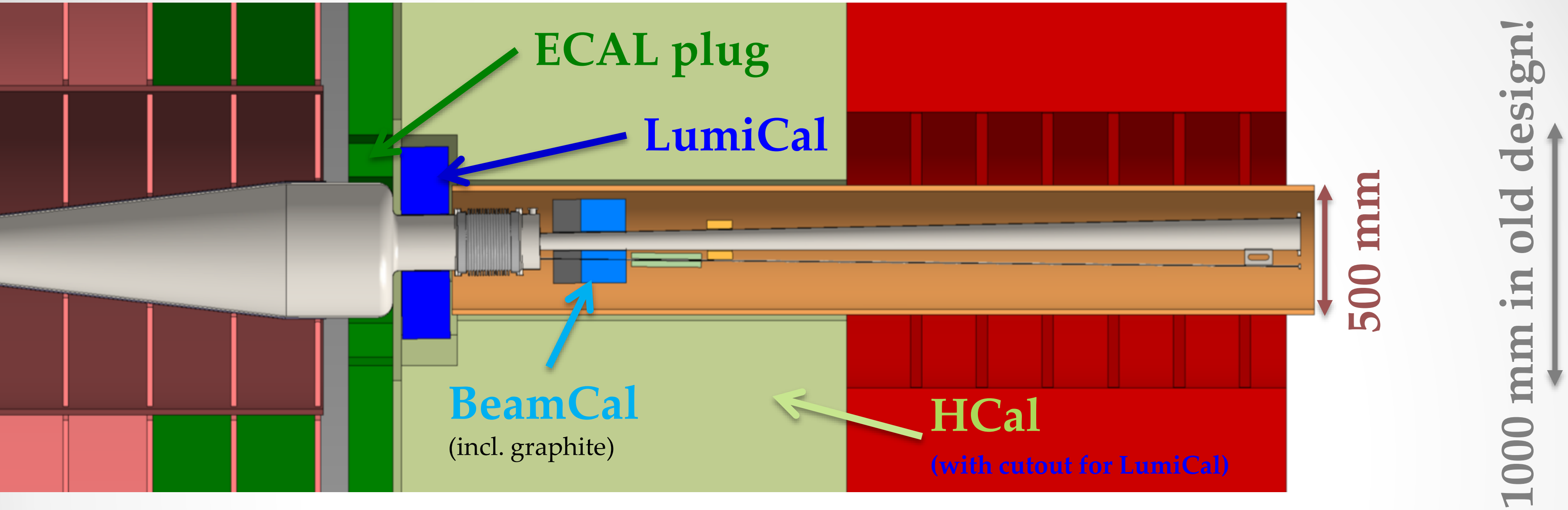
Quarter view of the magnet system with "thin" yoke Endcaps

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

Note 4 concentric ring end coils in blue

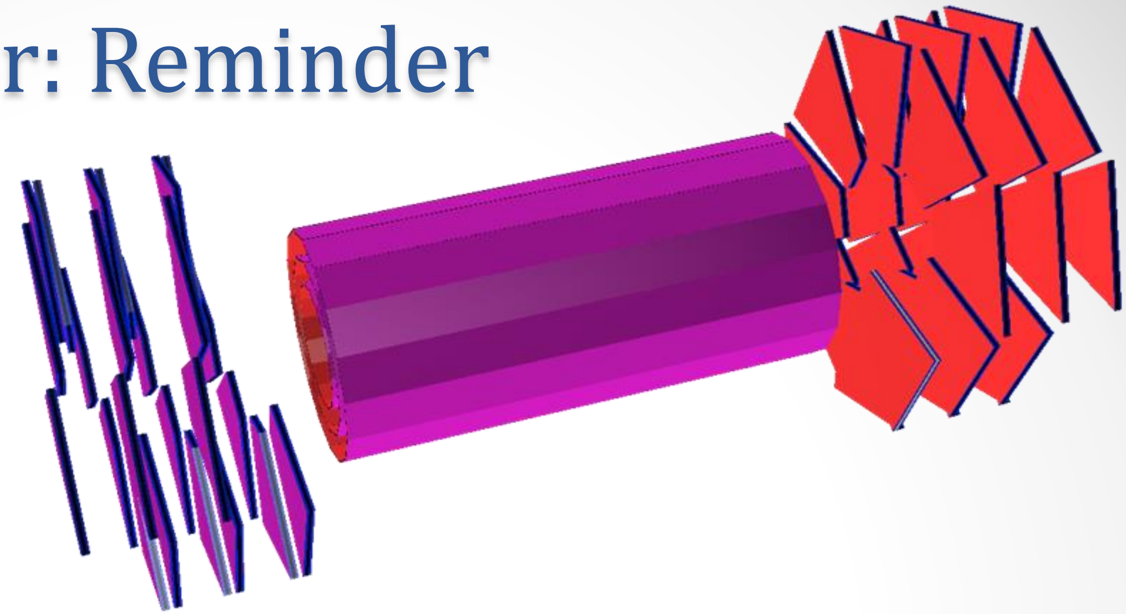
Use the end coils to compensate for thin endcaps

Forward Region Layout in the New Model



- Wanted to **extend HCal Endcap coverage** closer to beampipe
- Reoptimized for a working hypothesis of an $L^* = 6$ m
  → **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)

Vertex Detector: Reminder



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)

See talks during CLICdp meeting with emphasis on Vertex/Tracking (Thursday morning)

In the new detector model:

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

Silicon Tracker

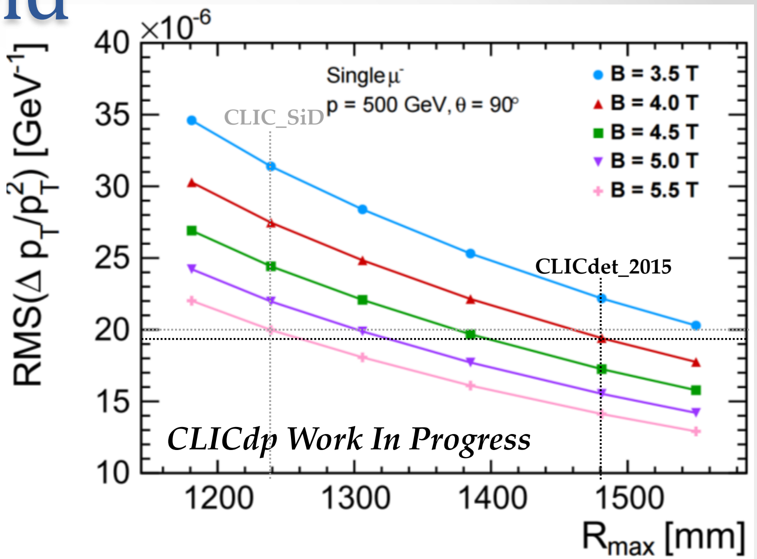
- **We use an All-Silicon Tracker for our new model**
  - A TPC tracker would have very high occupancies (30%) for CLIC @ 3 TeV with 1x6 mm^2 pads (without safety factors)

- **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**

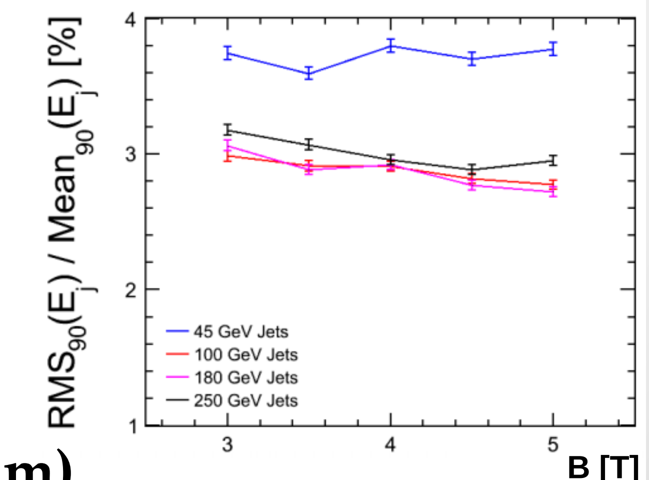
See talk by R. Simoniello (Thursday afternoon)

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 [4,5]



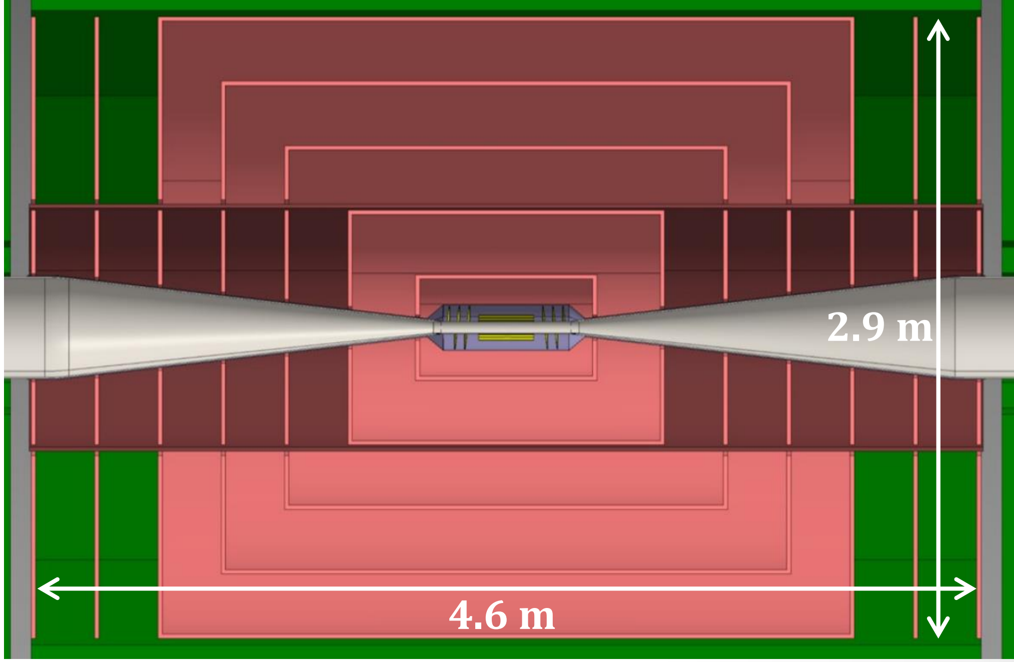
- A magnetic field strength of up to 4.5 T should be technically feasible
- **Converged to an outer tracking radius of 1.5 m and field strength of 4 T**

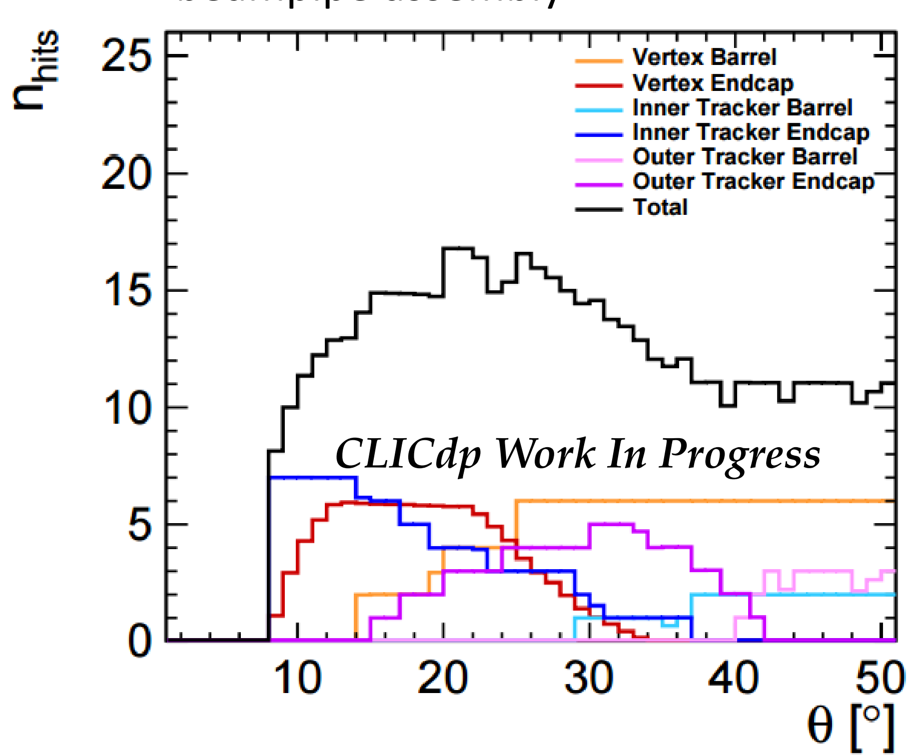


- **Tracker length: at least like CLIC_ILD (4.6 m)**
  - **Motivated by physics in the forward region (e.g. Higgs self-coupling)**
  - Reduce Endcap Yoke thickness by 1.2 m and use end coils

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> 8°**
- **Module arrangement and overlap still under investigation**
- **Cell size should vary from layer to layer**
  - **Motivated by occupancy (next slide)**

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

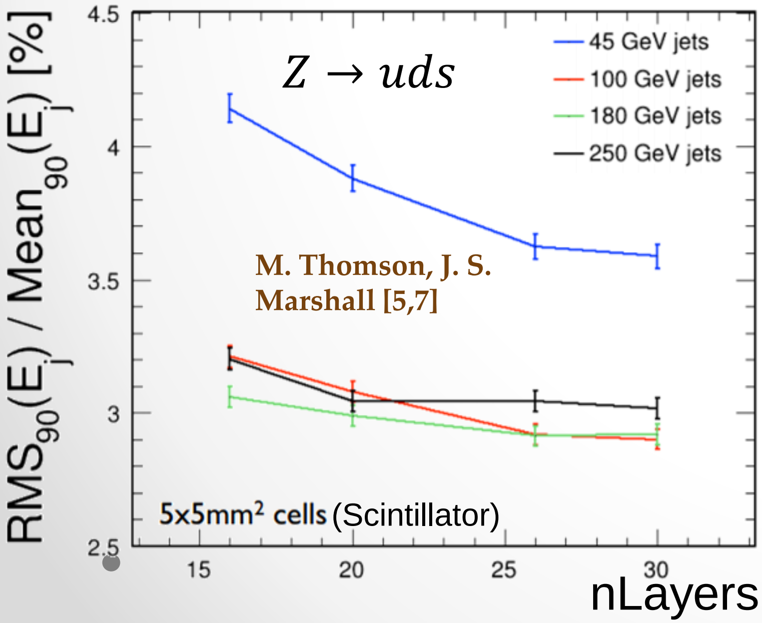
- Sensor Technology?
- Power pulsing!
- Air cooling not feasible in a large tracker volume
- Use of **liquid cooling** restricts also options for module geometry/layout/overlap!
  - Material budget for cooling and supports already implemented in model

- ***Tracker hardware R&D recently started***

See talk by A. Nurnberg (Thursday afternoon) and talks in the CLICdp meeting (Thursday morning)

ECal Optimization

- # **Layers:** Not very important for higher energy jets (PFA confusion dominates): **Not much more improvement from 25 to 30 layers**
  - Keeping 23 X_0
- **Si vs Sc:** No significant effect on JER
- **Cell size:** JER **degradation** from 3% to ~3.5% when increasing cell size from 5x5 mm^2 to 15x15 mm^2
  - Combinations of different granularities in layers considered
    - No significant gain for the extra complexity



In new simulation model:
- **Tungsten** absorber, **Silicon** active material
- **25** Layers, 23 X_0/ 1 λ_I
  - 17×2.4 mm + 8×4.8 mm
- Use **5.1x5.1 mm²** cells throughout

HCal Optimization

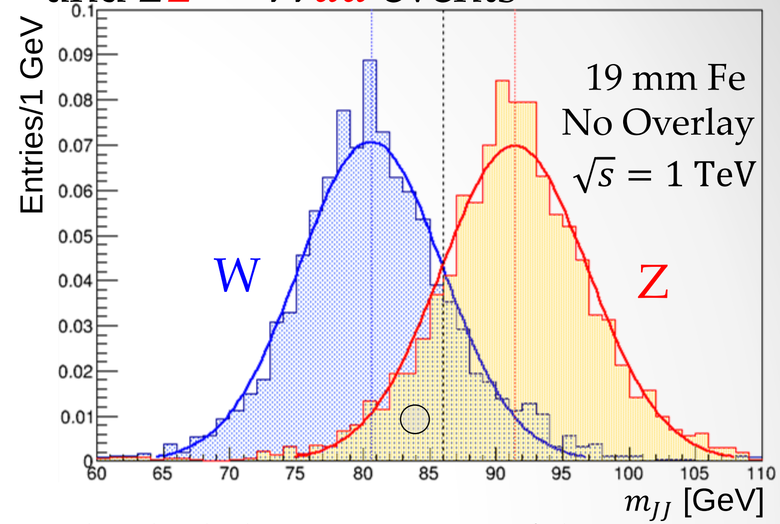
- Example: HCal Barrel Absorber
  - 10 mm Tungsten (W)
  - 19 mm Steel (Fe)

  Keep same Depth at $\sim 7.5\ \lambda_I$
- Full **Geant4** detector simulation + **PandoraPFA** + **FastJet**
- JER Performance shown to be **similar** for **tungsten** and **steel**
  - Steel is cheaper and easier to process

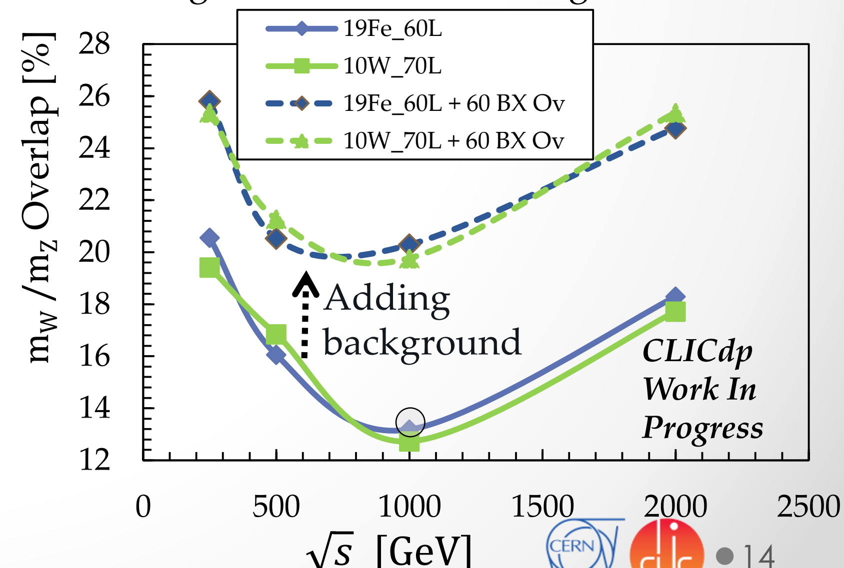
⇒ Use Steel as an absorber for the entire HCal

- **60 layers**
- **20 mm Steel** (1 mm in cassette)
- **3 mm Scintillator**
- **30x30 mm² Cell size**

E.g. study overlap of m_W and m_Z measurement in $WW \to \nu\ell ud$ and $ZZ \to \nu\nu dd$ events

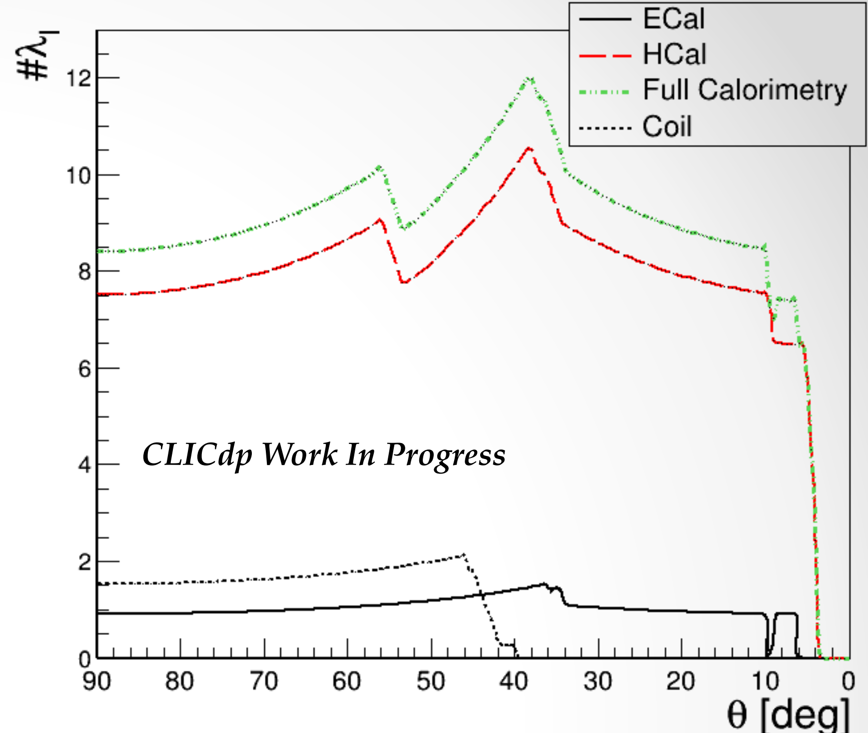


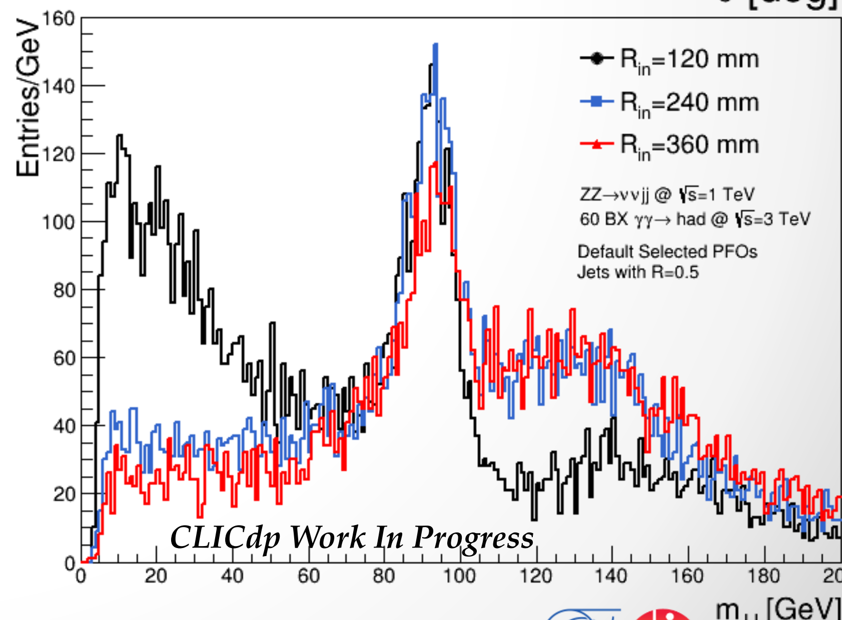
The shaded area gives one of the points on the plot below. Repeat for both models, all energies. Do also with background.



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





Summary

- **New simulation model** for a detector at CLIC evolving from previous CDR models based on modified ILC designs
  - Longer **All Silicon** Tracker, $B = 4\ \mathrm{T}$, $R_{in}^{ECal} = 1.5\ \mathrm{m}$, thinner endcap yoke with end coils
  - **25** layer **W+Si ECal**, **60** layer **Fe HCal**, 12-fold symmetry
- Optimization result of a big effort from many people and still ongoing
  - **Important R&D efforts also ongoing (not covered in this talk)**
- **Model implementation in DD4hep up to date**
  - **Reconstruction software developed in parallel**
- **Full simulation physics studies with the new software chain will start soon**

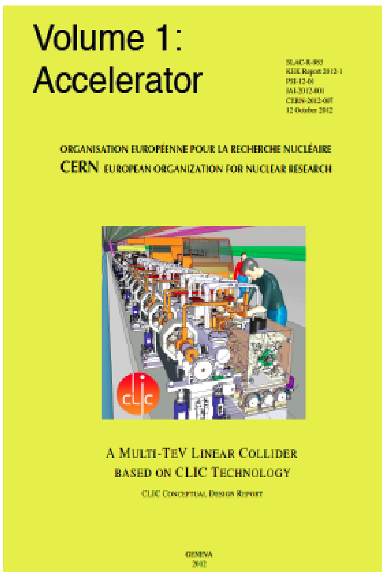
Backup Material

References

1. *L. Linssen et al.*, ***Physics and Detectors at CLIC : CLIC Conceptual Design Report***, CERN-2012-003
2. *N.Alipour Tehrani and P. Roloff*, ***Optimisation Studies for the CLIC Vertex-Detector Geometry***, CLICdp-Note-2014-002
3. *D. Dannheim et al.*, Slides at https://indico.cern.ch/event/309925/contribution/2/material/slides/0.pdf
4. *M. Thomson, Nucl.Instrum.Meth. A611 (2009)*
5. *J. Marshall*, Slides at http://indico.cern.ch/event/309926/contribution/1/material/slides/0.pdf
6. *B. Cure*, Slides at https://indico.cern.ch/event/314325/contribution/1/material/slides/1.pdf
7. *M. Thomson*, Slides at http://indico.cern.ch/event/309926/contribution/1/material/slides/0.pdf
8. M. Valentan et al, LiC Detector Toy Fast Simulation
9. R. Simoniello, Slides at https://indico.cern.ch/event/376800/session/3/contribution/5/material/slides/0.pdf
10. A. Nurnberg, Slides at https://indico.cern.ch/event/376800/session/2/contribution/28/material/slides/0.pdf
11. M. Killenberg, LCD-Note-2011-029
12. J. S. Marshall, Slides at https://indico.cern.ch/event/336335/session/6/contribution/5/material/slides/0.pdf
13. F. Gaede, Slides at https://indico.cern.ch/event/376800/session/0/contribution/12/material/slides/0.pdf
14. M. Petric, Slides at https://indico.cern.ch/event/376800/session/0/contribution/11/material/slides/0.pdf
15. D. Dannheim, A. Sailer, Beam-Induced Backgrounds in the CLIC detectors, LCD-Note-2011-021
16. E. van Der Kraaij, Detector challenges at CLIC, contrasted with the LHC case, slides at http://indico.cern.ch/event/210720/

CLIC and Detector Documentation

- 2012: **CLIC Conceptual Design Report** published
- 2012: CLIC detector and physics collaboration (**CLICdp**) was set up
- 2012/2013: CLIC input to the European strategy and the Snowmass Process in the US



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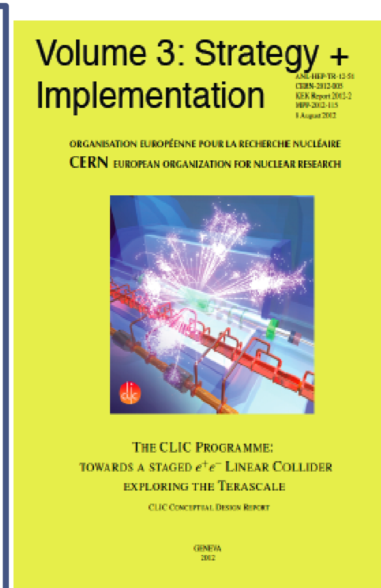

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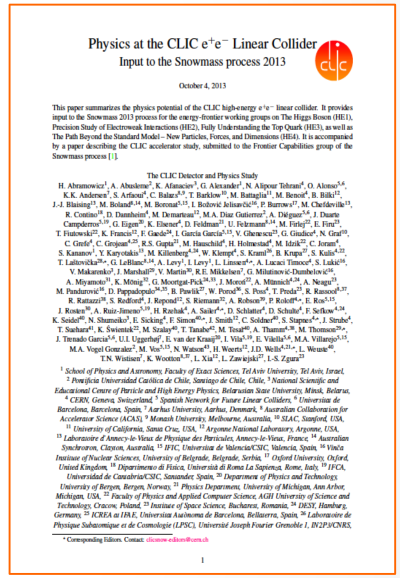


arXiv:1307.5288

The CLIC Experimental Environment

	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]	$\approx 45 / 1$
σ_z [μm]	44

Drive **timing requirements** for the CLIC detector

Low duty cycle

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

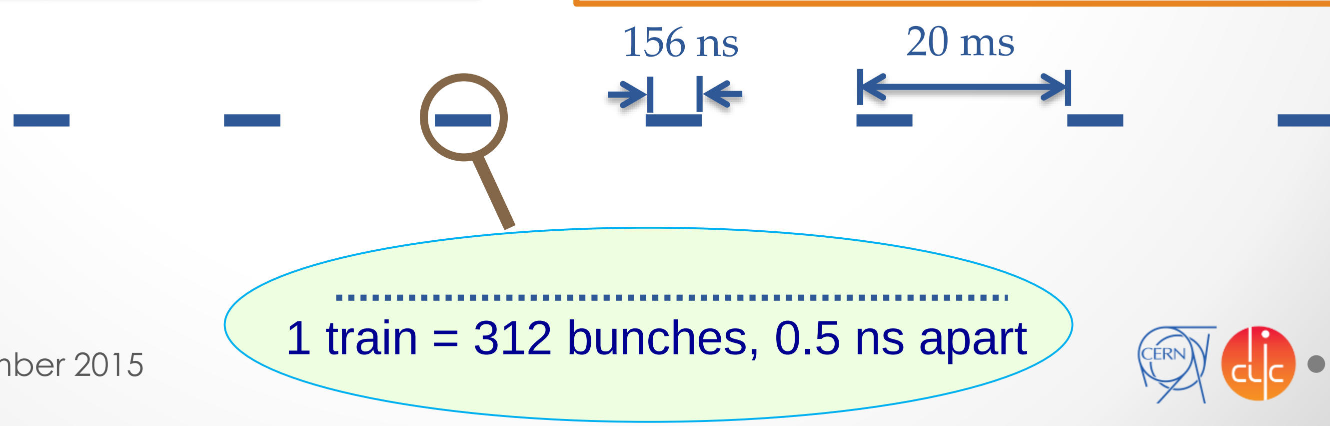
Very small beam profile at the interaction point

⇒ Very high E-fields ⇒

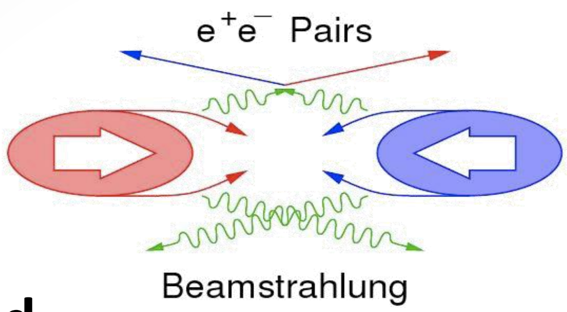
Beam-beam background

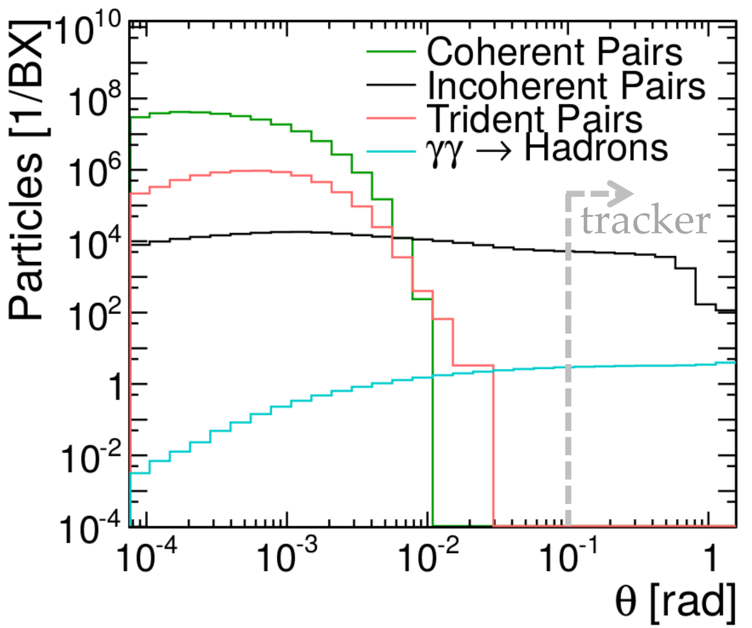
CLIC bunch structure

- not to scale -

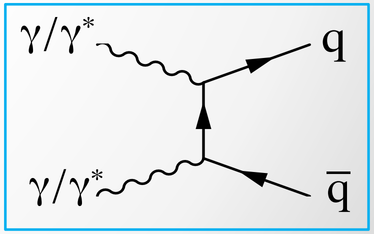


Beam-Induced Backgrounds





- 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



More on Beam-Beam Effects

Beamstrahlung can cause important energy losses right at the interaction point

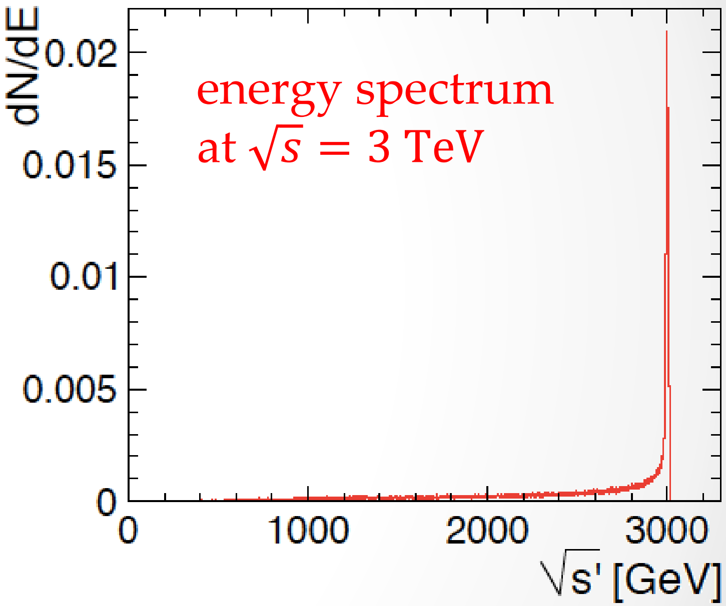
E.g. full luminosity at 3 TeV:

$5.9 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

Of which in the 1% most energetic part:

$2.0 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

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



CLIC power and energy

Table 5.1: Nominal power and efficiency for staging scenarios A and B, where $W_{main\ beam}$ is for the two main beams.

Staging scenario	$\sqrt{s}$ (TeV)	$\mathscr{L}_{1\%}$ ($cm^{-2}s^{-1}$)	$W_{main\ beam}$ (MW)	$P_{electric}$ (MW)	Efficiency (%)
A	0.5	$1.4 \cdot 10^{34}$	9.6	272	3.6
	1.4	$1.3 \cdot 10^{34}$	12.9	364	3.6
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7
B	0.5	$7.0 \cdot 10^{33}$	4.6	235	2.0
	1.5	$1.4 \cdot 10^{34}$	13.9	364	3.8
	3.0	$2.0 \cdot 10^{34}$	27.7	589	4.7

Table 5.2: Residual power without beams for staging scenarios A and B.

Staging scenario	$\sqrt{s}$ (TeV)	$P_{waiting\ for\ beam}$ (MW)	$P_{shut\ down}$ (MW)
A	0.5	168	37
	1.4	190	42
	3.0	268	58
B	0.5	167	35
	1.5	190	42
	3.0	268	58

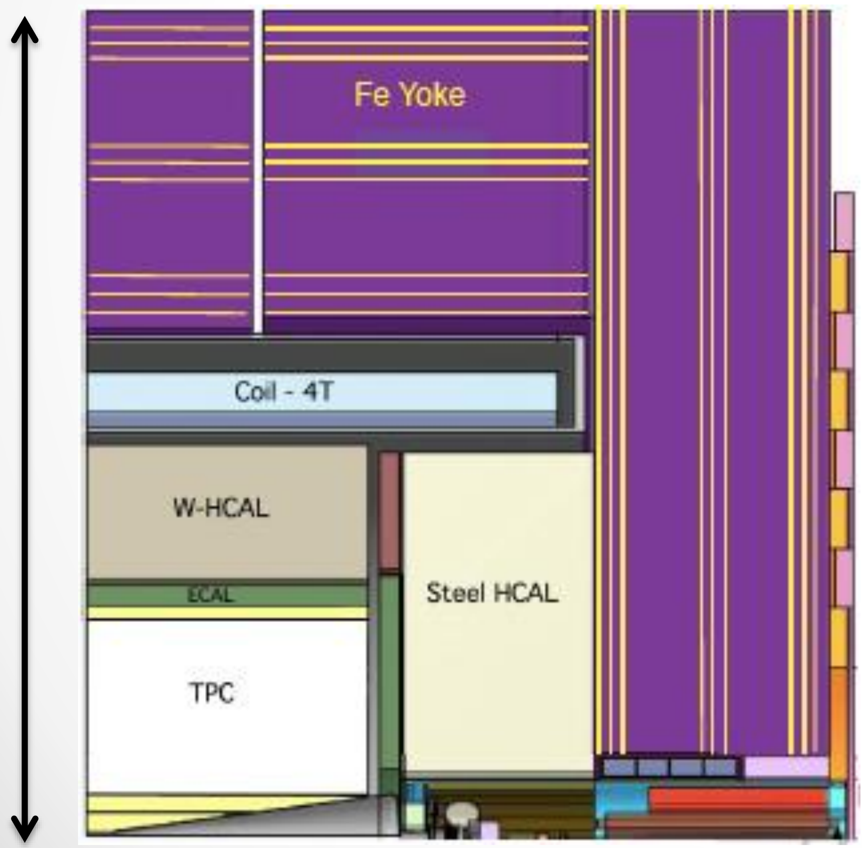
CLIC_ILD and CLIC_SiD

For the CLIC CDR (2012):

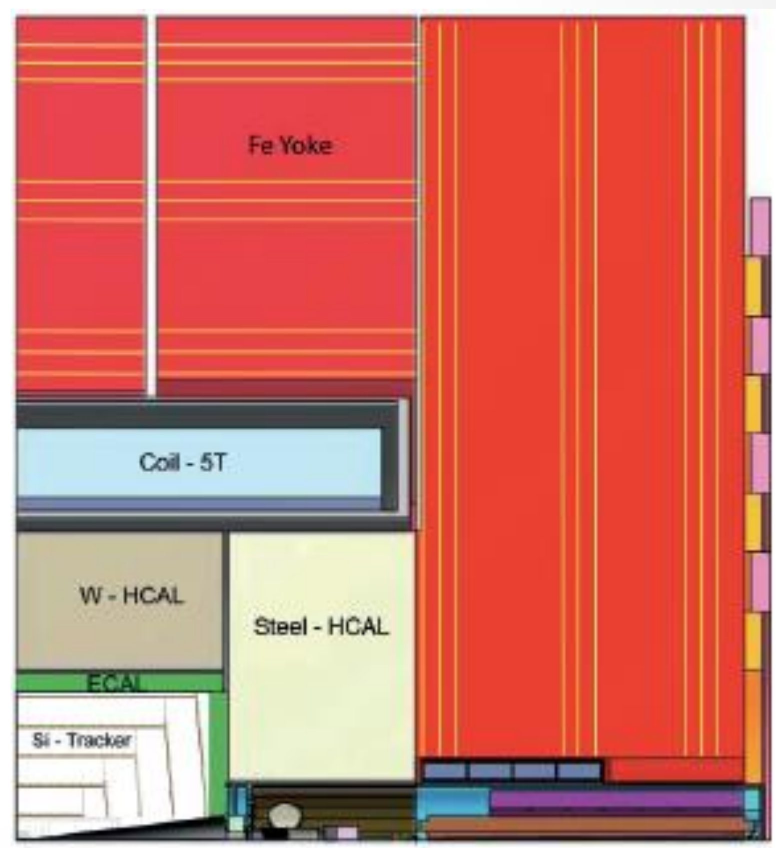
- Two general-purpose CLIC detector concepts
- Based on initial ILC concepts (ILD and SiD)
- Optimized and adapted to CLIC conditions

CLIC_ILD

7 m

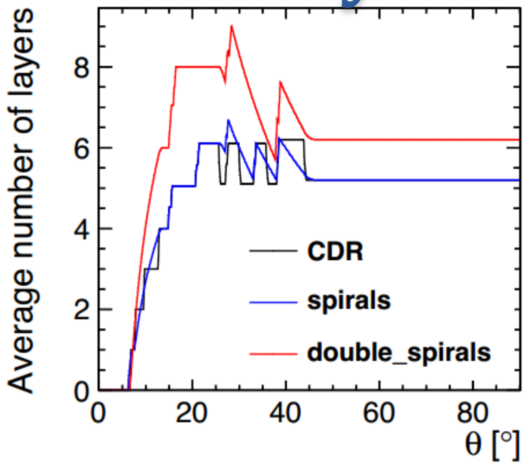


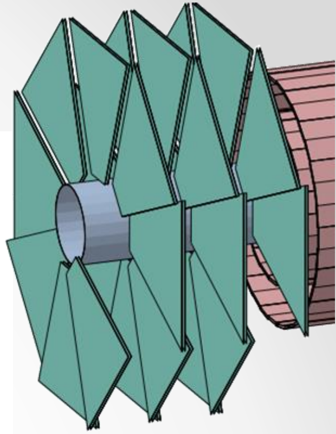
CLIC_SiD



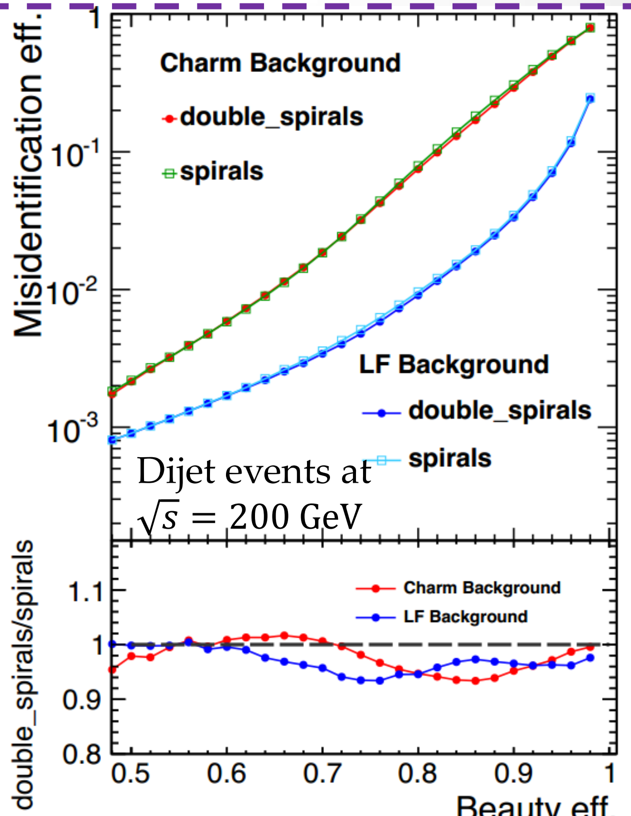
Vertex Detector: double layers

- 0.18% X_0 per double-layer in simulation
- Spiral Geometry (better airflow)
- Barrel: 5 single-layers ⇒ 3 double-layers
- Endcap: 4 single-layers ⇒ 3 double-layers

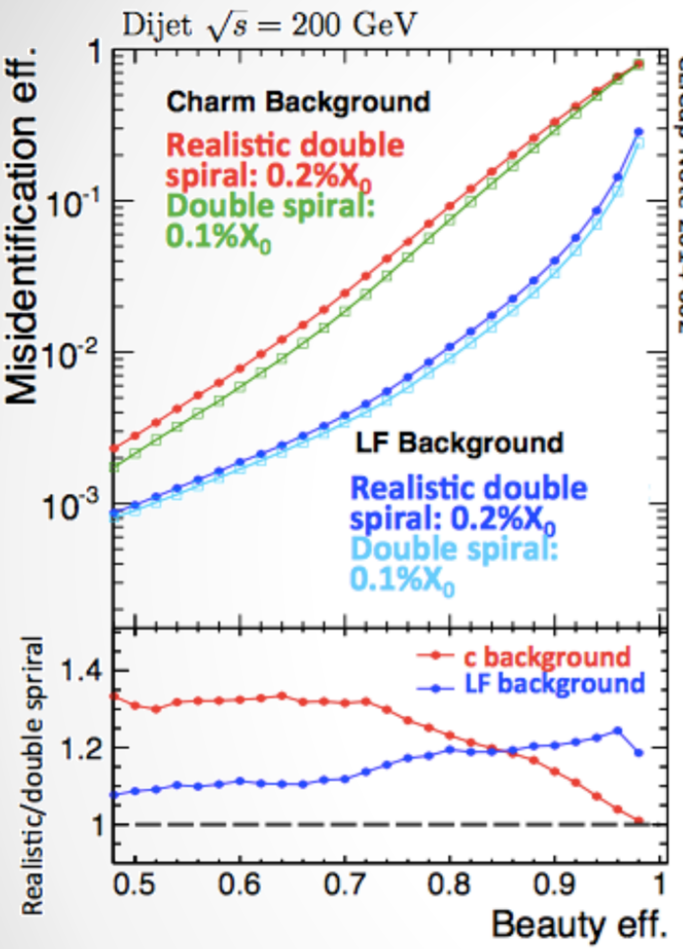




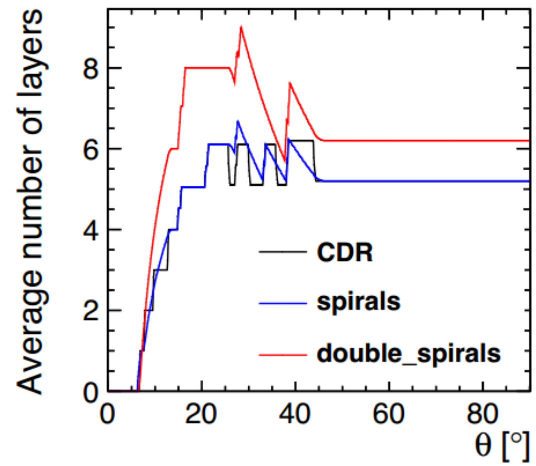
- Estimate changes in performance due to layout by studying the **flavor-tagging performance** (N. Alipour Tehrani, P. Roloff [2])
- *b*-quark misidentification as a function of *b*-quark Identification efficiency with a background rich in *c*-quarks (Top lines) or **L**ight-**F**lavored quarks (bottom lines). Similar study performed for *c*-tagging
- Lower panel shows ratio of double-layer over the single-layer geometries
  - **Almost the same as single-layer layout**

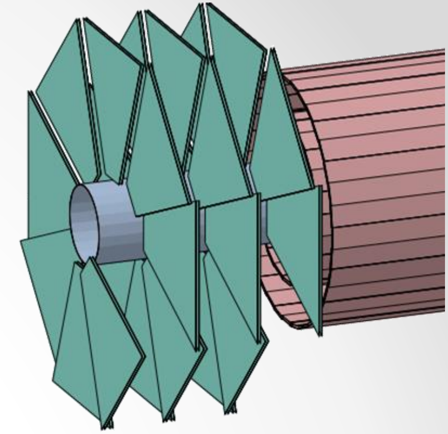


Vertex Detector Optimization



Effect of extra material:
Ratio > 1 means worse performance for more material





Spiral Geometry
(better airflow)

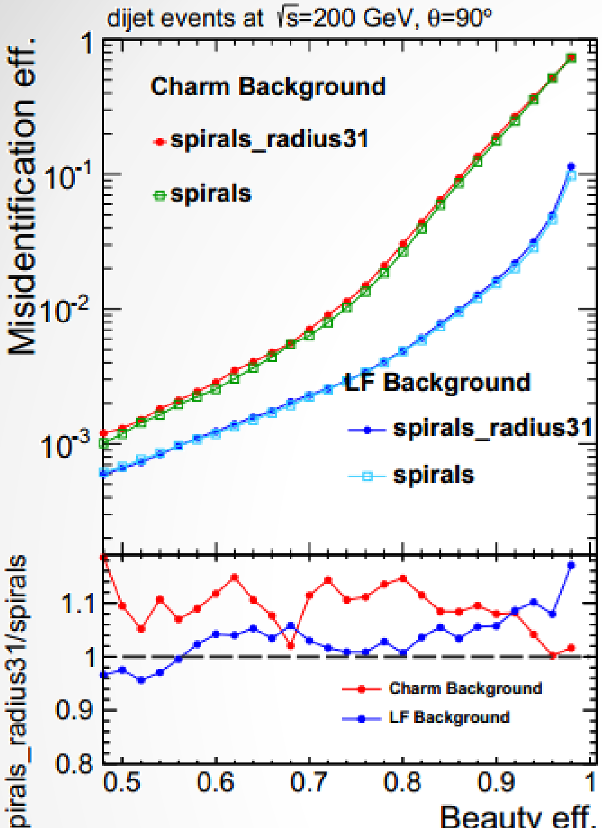
Use flavor tagging as a gauge in various tests:

1. **Effect of material (most significant effect on performance)**
2. Test single vs. double layers
3. Vary inner radius (for 4 T or 5 T B-field)

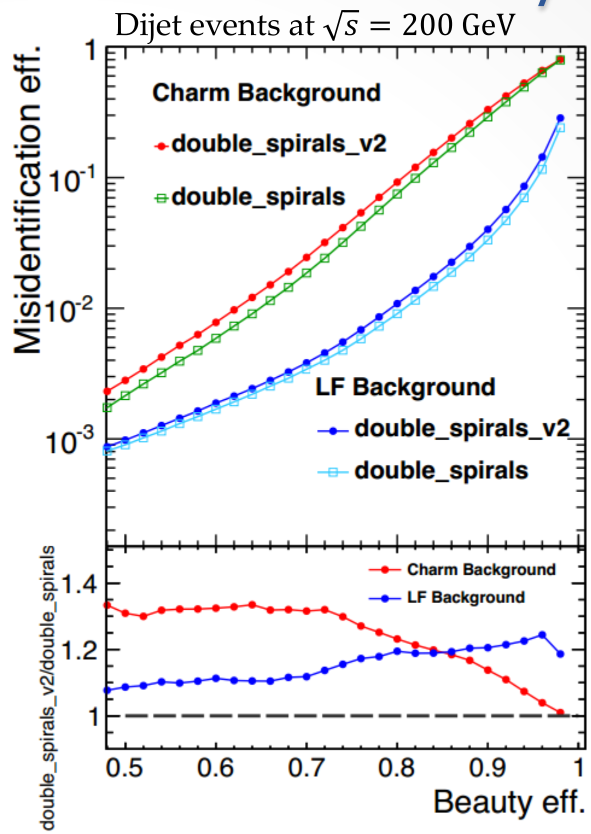
In the new detector model: Use double layers with spirals and modules with $0.2\%X_0$ per (single) layer, $R_{in} = 31$ mm

(N.Alipour Tehrani, P. Roloff [2])

Vertex Detector : Effect of Inner Radius /Material



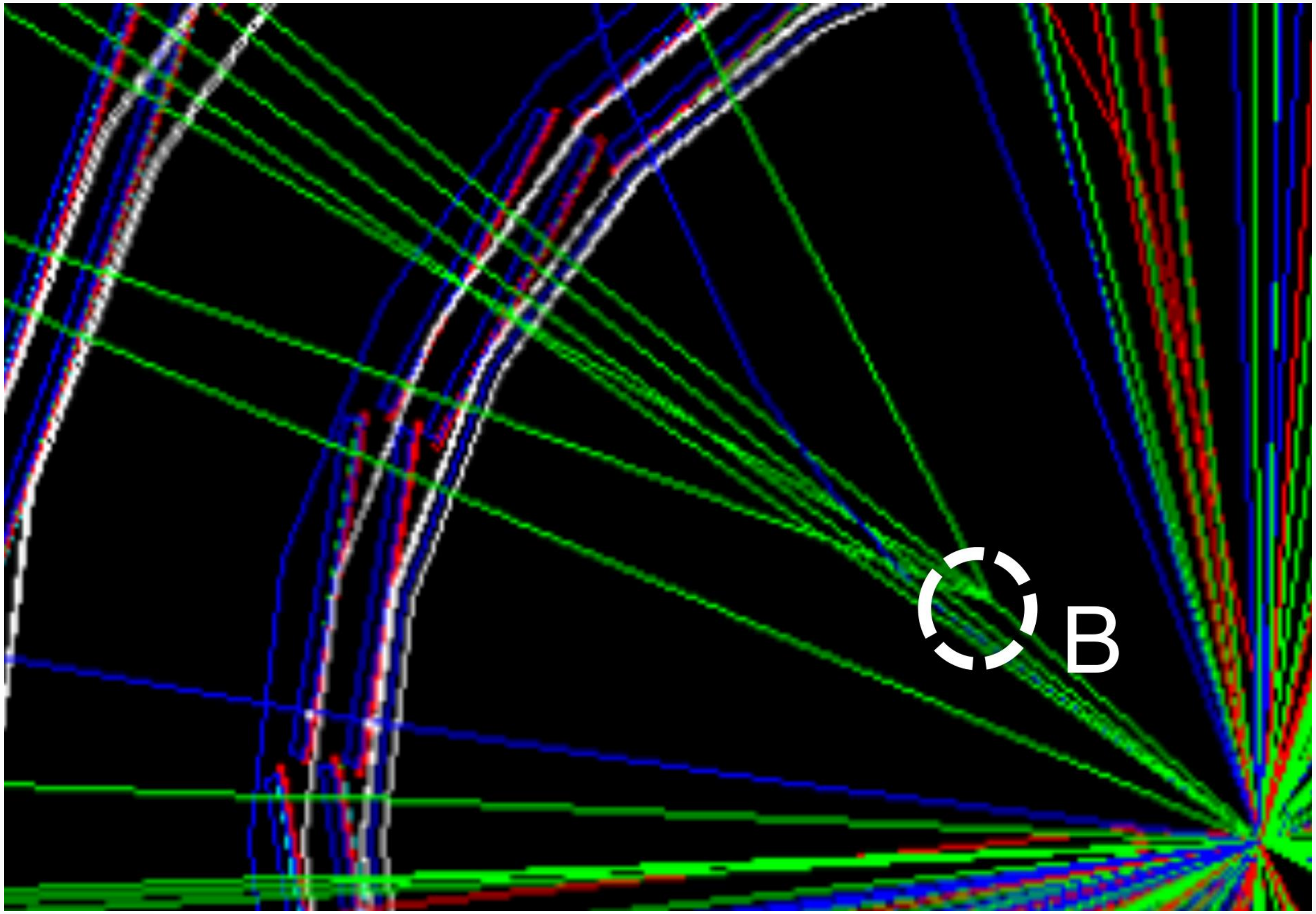
(N.Alipour Tehrani, P. Roloff [2])



- Inner Radius from 27 mm to **31 mm**
- Compensates for increase in the rate of Incoherent e-pair background if B-field is reduced
- **Small effect in flavor-tagging performance**

- Double-layer modules were simulated with twice as much material
- Extra material leads to undesirable increase of fake rate

In the new detector model: Use double layers with spirals and modules with $0.2\%X_0$ per (single) layer

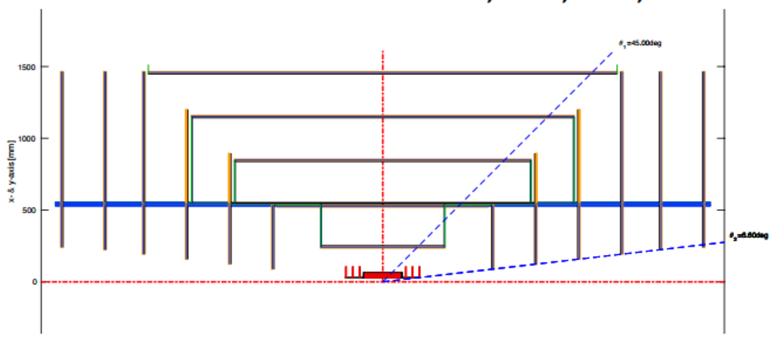

B

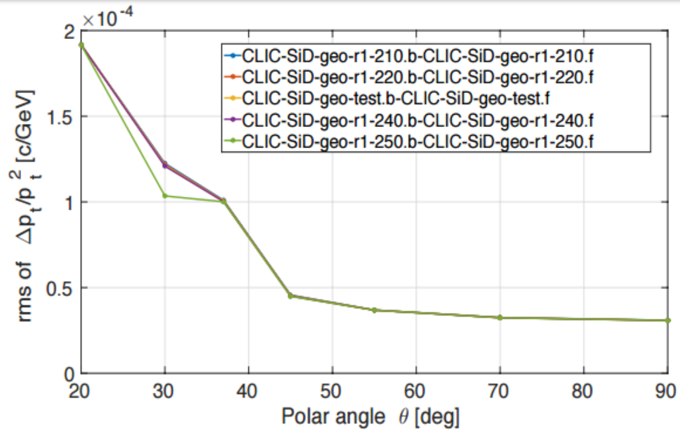
More Tracker Optimization (R. Simoniello[9])

- **Fast Simulation** (LicToy) Study 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
- **Full simulation studies** also ongoing with **new Reconstruction Software**

Move r position of the first barrel layer

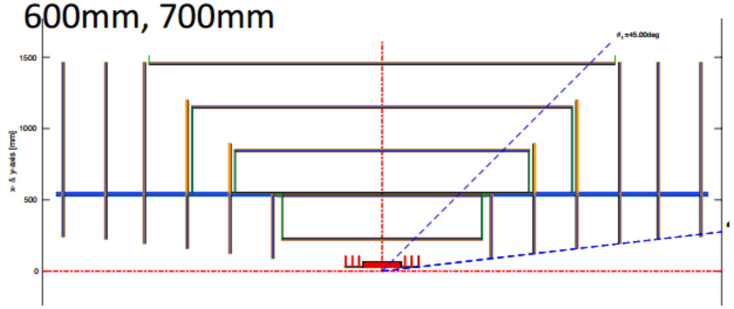
Scan of r1 from 230mm to 210, 220, 240, 250mm





Change length of the first barrel layer

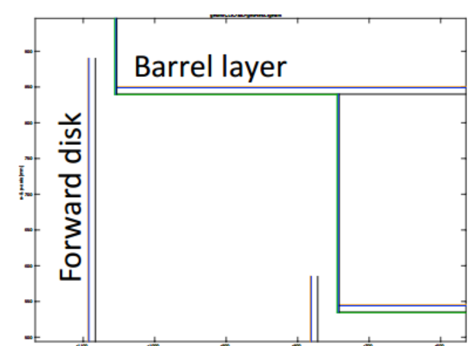
z1 varied from 430mm to 450mm, 500mm, 600mm, 700mm



Optimise gap between barrel/forward and the outer radius of the forward disk

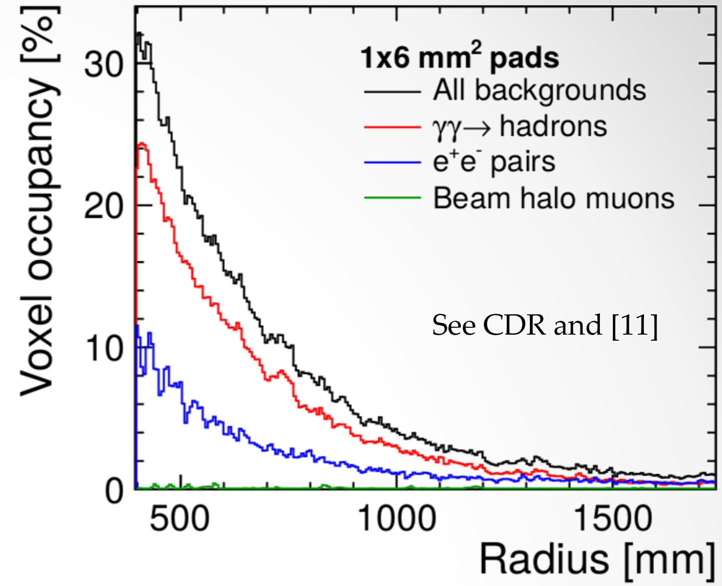
- Δr = 40 mm
- Gap = 30 mm

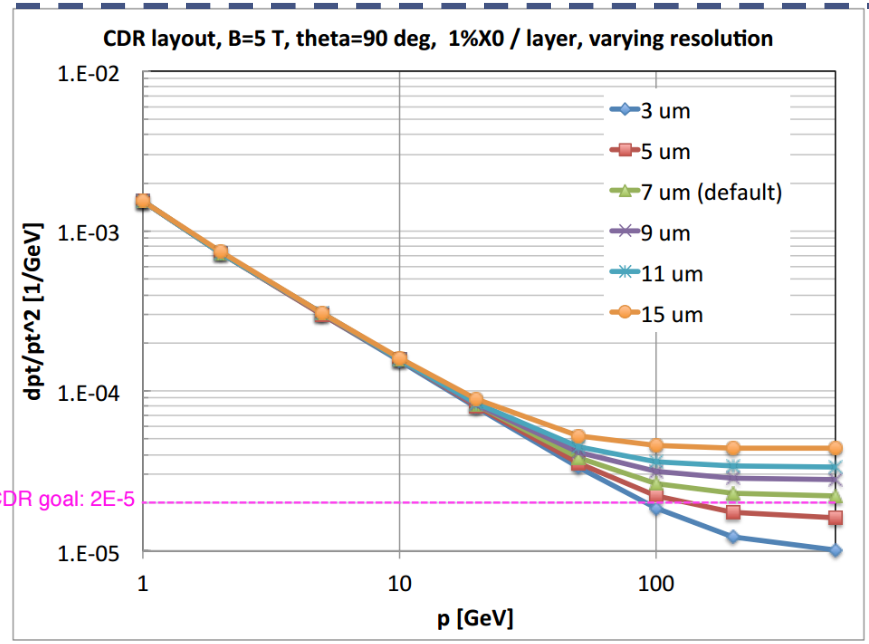
- Not full scan performed yet
- Gaps are not pointing to IP



Silicon Tracker

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



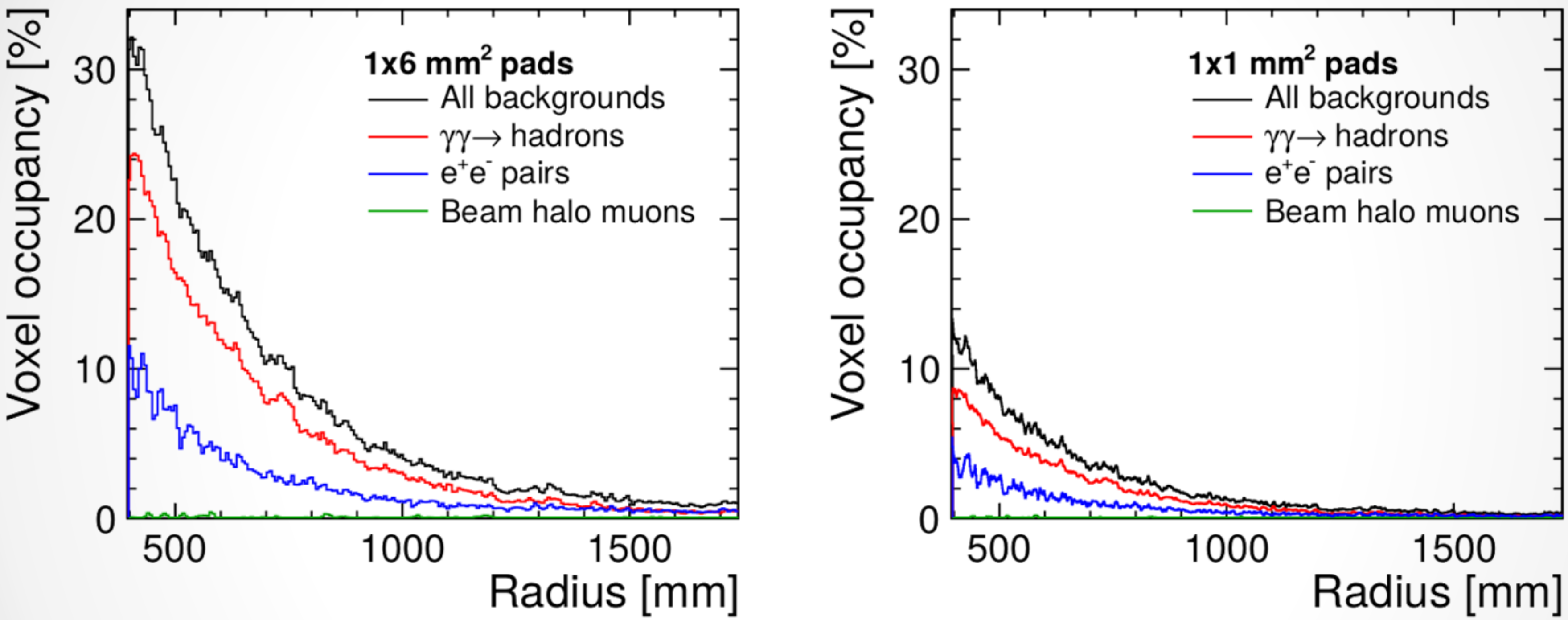


Fast simulation studies (LicToy) with CLIC_SID_CDR geometry (D. Dannheim et al. [3])

- Fast Simulation studies (LicToy) to determine optimal parameters
- Material Budget→ $\sim 1\% X_0$ per layer
  - Requires very thin materials/sensors
  - Less critical than in Vertex Detector
- Single point resolution: ~7 μm
  - Critical for high-momentum tracks

TPC Occupancy in CLIC_ILD

From CDR. See also LCD-Note-2011-029 [11]



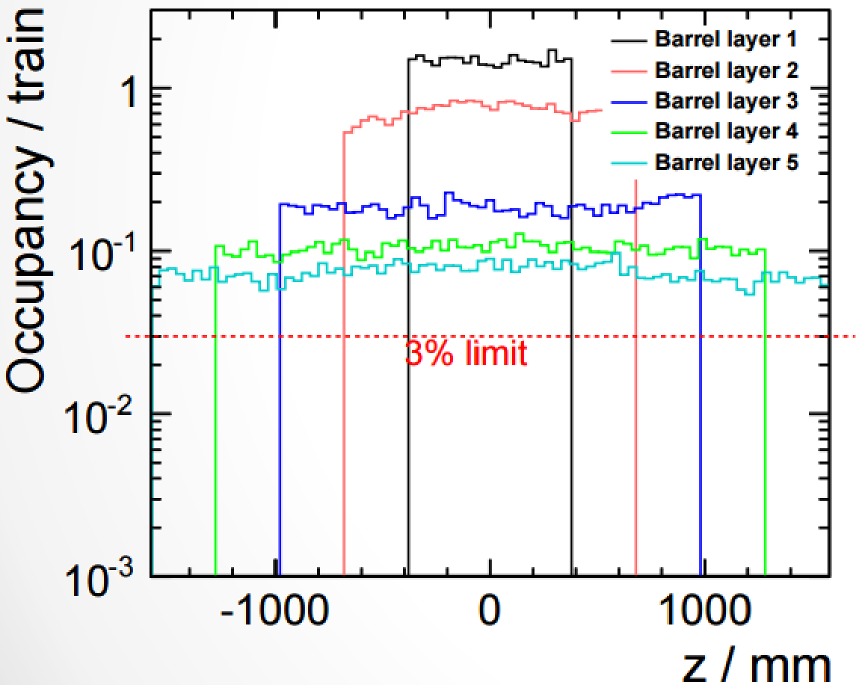
(a) Voxel occupancies for 1×6 mm^2 pads (b) Voxel occupancies for 1×1 mm^2 pads

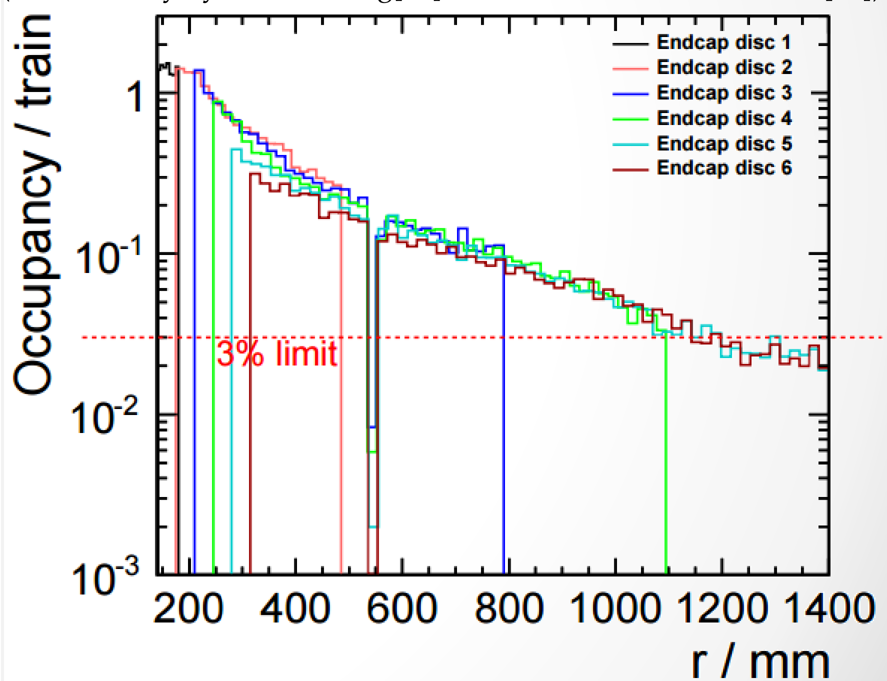
Fig. 5.11: Voxel occupancies for different pad sizes, averaged per pad row in the TPC for particles originating from $\gamma\gamma \rightarrow$ hadrons, incoherent pairs and beam-halo muons. The data correspond to one complete bunch train and do not include safety factors.

Occupancy in the Main Tracker

- High occupancies in certain regions
- Full Mokka-based (Geant4) simulation using a modified CLIC_ILD detector driver (TPC replaced with Si Layers) – **DDSim-based study ongoing**
- Assume 100 mm × 50 μm strips, avg. cluster size 2.6 , **safety factors** 5 (pairs) and 2 ($\gamma\gamma \rightarrow had$)

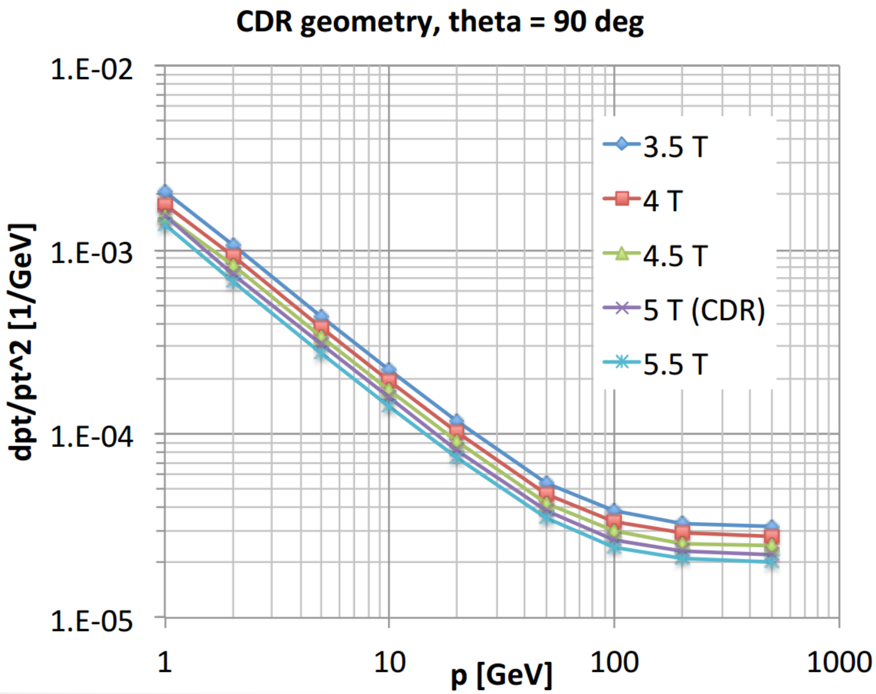
(Recent study by A. Nurnberg[10]. See also LCD-Note-2011-021[15])

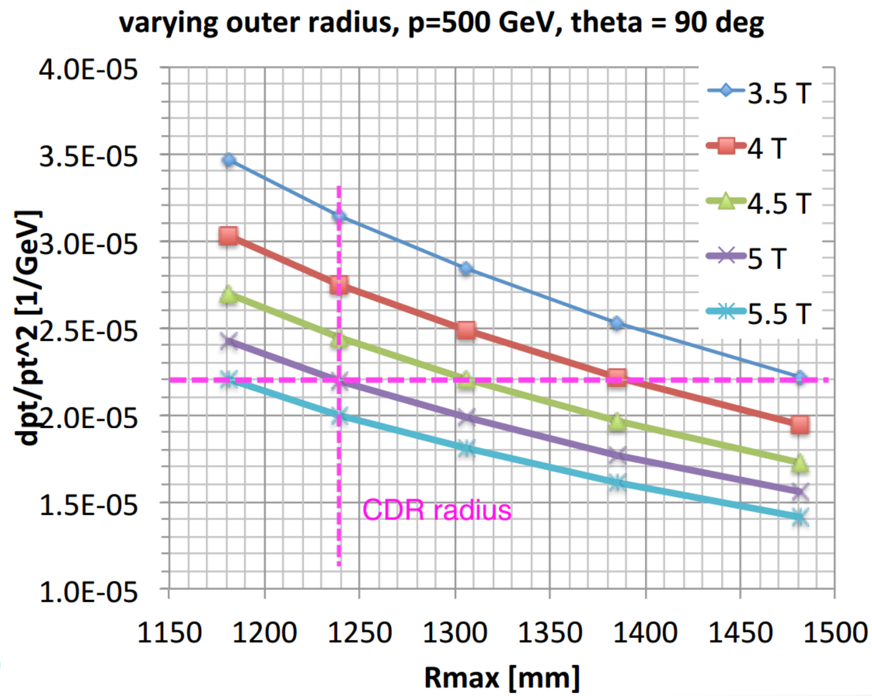




- **Need for large pixels and/or short-strips**
- Maximal strip length to be below 3% limit depends on layer (2 – 50 mm in barrel)

Silicon Tracker Radius/ B-field





Fast simulation studies (LicToy) with CLIC_SID_CDR geometry (D. Dannheim et al. [3])

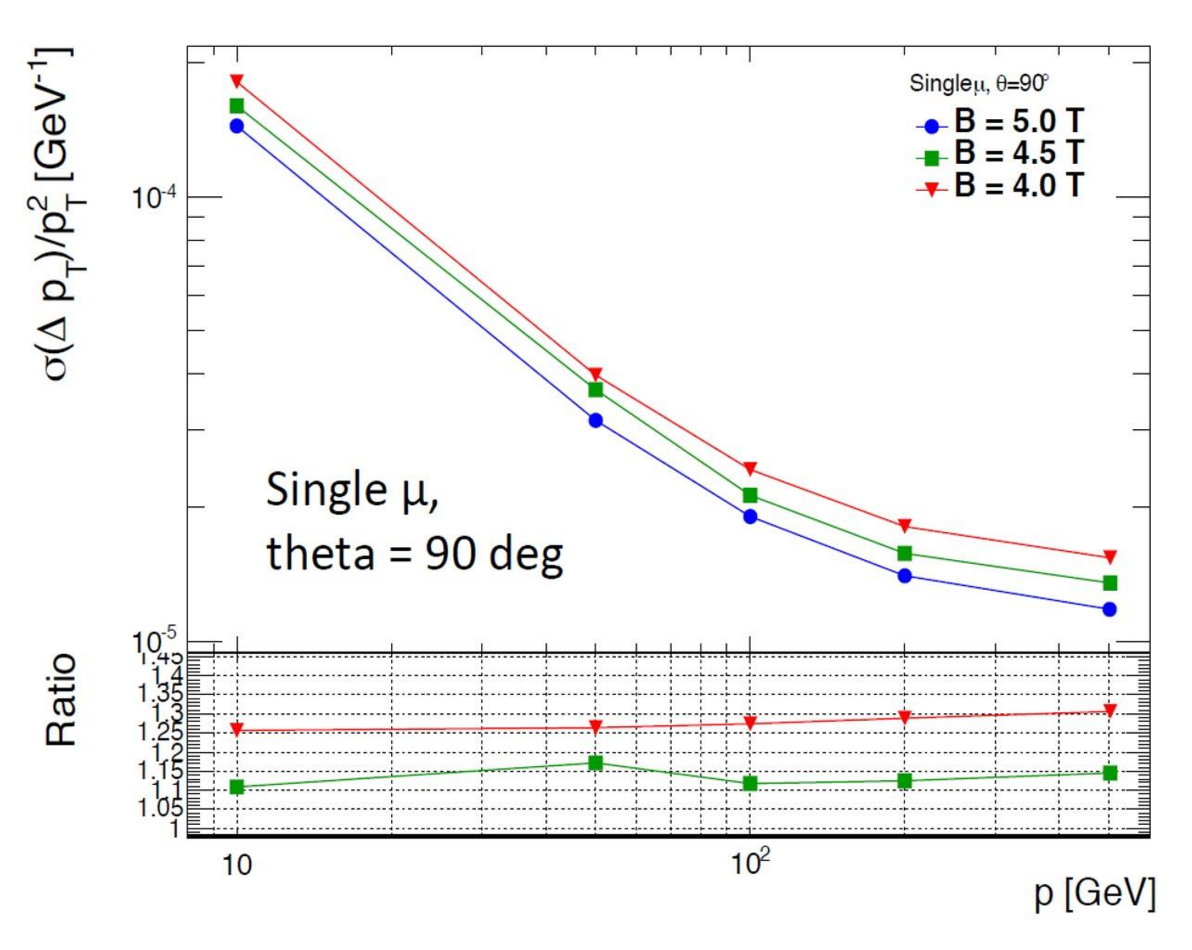
- Tracking performance depends on tracker **radius** and **magnetic** field

$$\frac{\sigma(p_T)}{p_T^2} \propto \frac{\sigma^{meas}}{\sqrt{N}\boldsymbol{B}\cdot\boldsymbol{R^2}}$$

Stronger dependence on *R*

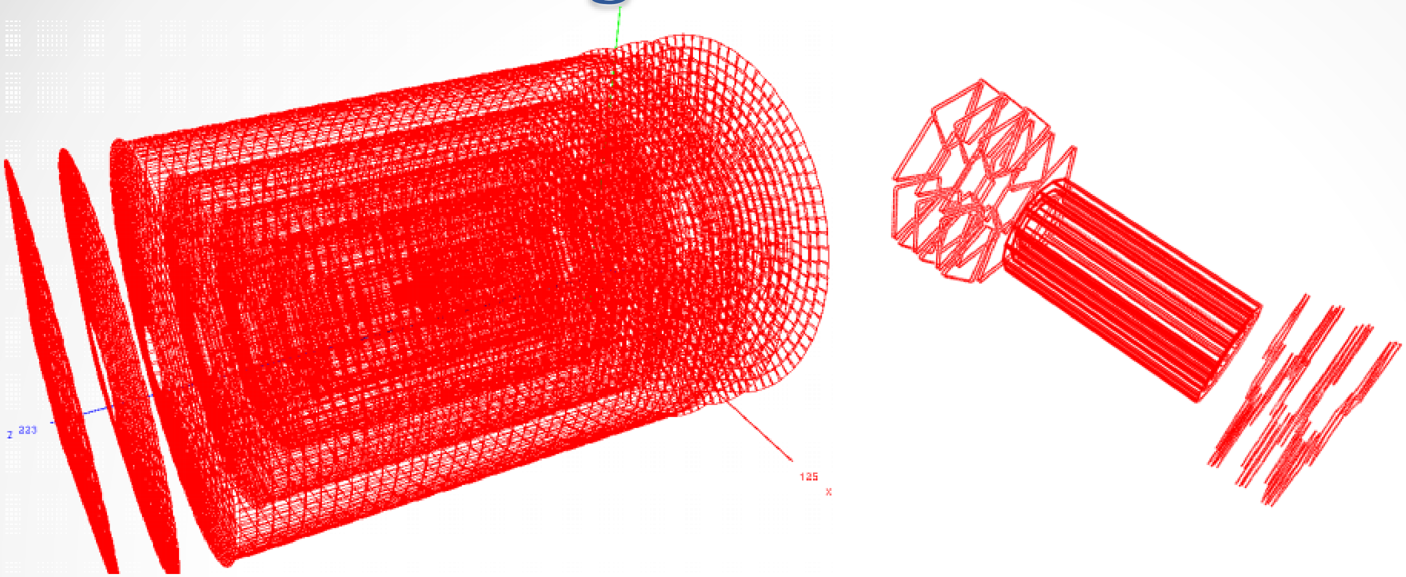
- **Can compensate reduction of $\boldsymbol{B}$ in new detector by rescaling $\boldsymbol{R}$ by $\sqrt{\boldsymbol{B_{nom}}/\boldsymbol{B}}$**
- Increase from 1.3 m (CLIC_SID) but not much gain by going to 1.8 m (CLIC_ILD) -> **Converged to 1.5 m for new model**

Extended Tracker: Momentum Resolution Vs B-Field



Tracking in an All Si-Tracker

F. Gaede [13]
R. Simoniello [9]

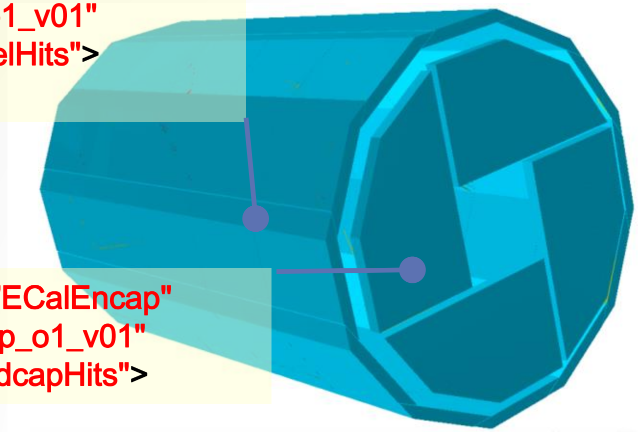


The (>19000) tracking surfaces in the CLIC model

- **Based on DD4hep/DDRec**
- **Track Fitting Strategy:**
  - Fit inside-out starting with vertex pixel hits
    - 1D hits in main tracker (strips) provide no constraint in z so cannot be used to initialize tracks
  - Finally smooth back to third hit and fit inside from there
- Current pattern recognition being developed from ILD Celloular Automaton-based Vertex patt. Rec.

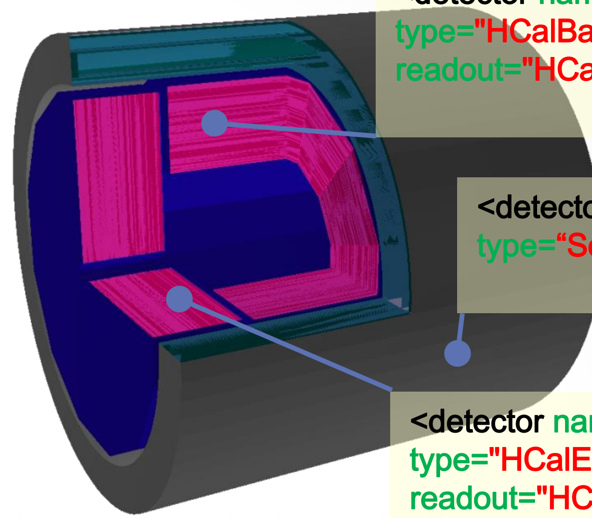
Calorimeters

```
<detector name="ECalBarrel"
type="ECalBarrel_o1_v01"
readout="ECalBarrelHits">
```



```
<detector name="ECalEncap"
type="ECalEndcap_o1_v01"
readout="ECalEndcapHits">
```

```
<detector name="HCalBarrel"
type="HCalBarrel_o1_v01"
readout="HCalBarrelHits">
```

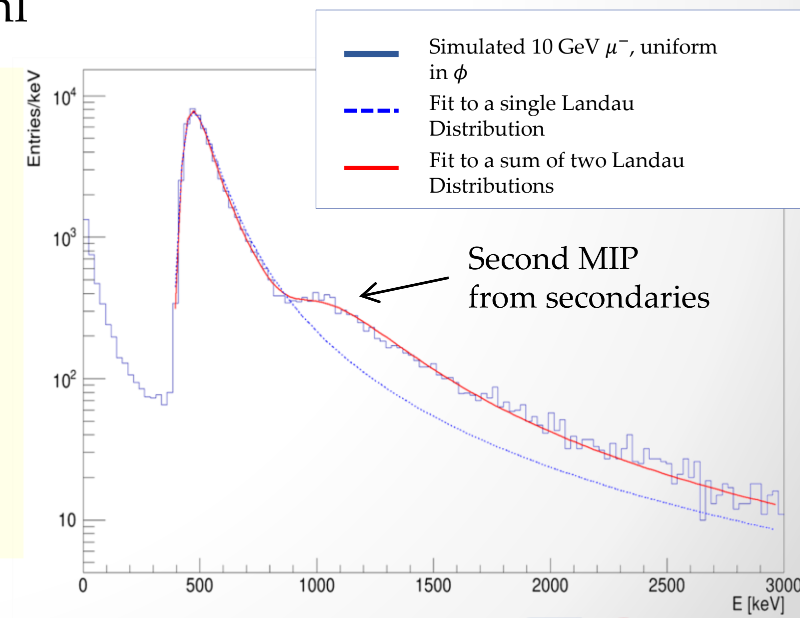


```
<detector name="Solenoid"
type="Solenoid_o1_v01"
```

```
<detector name="HCalEncap"
type="HCalEndcap_o1_v01"
readout="HCalEndcapHits">
```

- Fairly scalable drivers
- Radii, Layer/module composition in compact xml

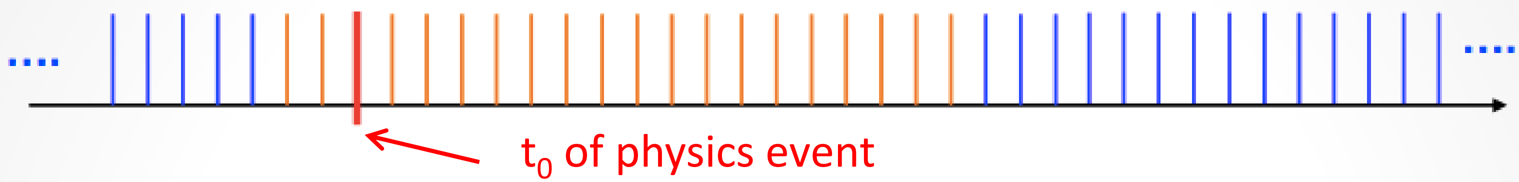
```
<detector ...>
...
 <dimensions numsides="HCal_symmetry" rmin="HCal_inner_R" z="HCal_half_L*2" />
 <layer repeat="(int) HCal_layers" >
  <slice material="Steel235" thickness="0.5*mm"/>
  <slice material="Steel235" thickness="19*mm"/>
  <slice material="Polystyrene" thickness="3*mm" sensitive="yes"/>
  <slice material="PCB" thickness="0.7*mm"/>
  <slice material="Steel235" thickness="0.5*mm"/>
  <slice material="Air" thickness="2.7*mm"/>
  </layer>
</detector>
```



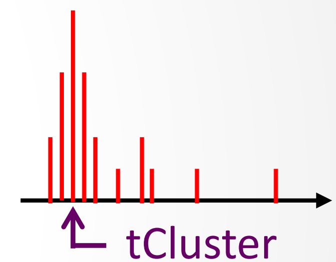
- Simulation and reconstruction under validation

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*)

General Requirements on Detector Technologies

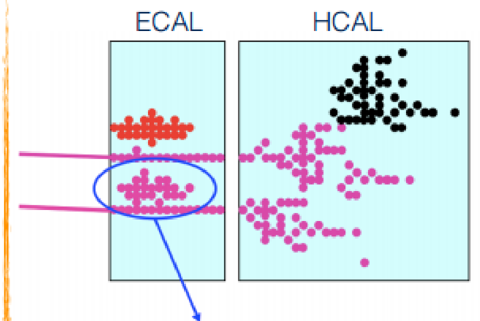
- **CLIC conditions ⇒ impact on detector technologies**:
  - High tracker occupancies ⇒ **need small cell sizes** (beyond what is needed for resolution)
    - Small vertex pixels
    - Large pixels / short strips in the tracker
  - Background suppression
    - Need **high-granularity calorimetry**
    - $\mathbf{1\ ns}$ 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

Calorimeter Optimization

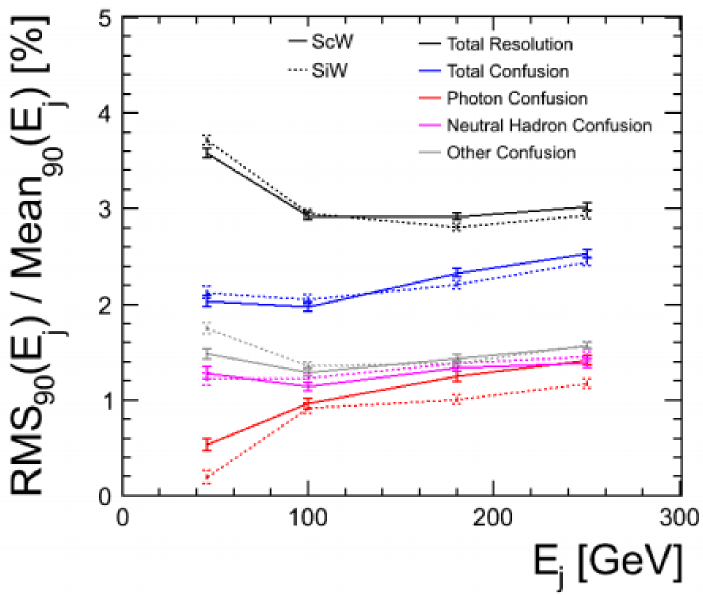
- High granularity imaging calorimeters to use with **Pandora Particle Flow Algorithms**
- Variations on **Number and Layout of Layers**, **Cell size**, **absorber material and thickness**, **active material and thickness**, **total depth, …**
- Optimization performed also in collaboration with ILD
  - Used mainly ILD-based Mokka drivers and ILD software chain
- **Need to recalibrate detector response with each variation**
  - Developed a quasi-automatic calibration procedure
- Gauge model performance using:
  - Single particle response
  - **Jet Energy Resolution** ($Z \rightarrow uds, WW \rightarrow \nu\ell ud, ZZ \rightarrow \nu\nu dd$)

ECal Optimization (J.S. Marshall [12])

- **Starting point: 29 layers W absorber ($23X_0, 1\lambda_I$), 30 layers Si active medium (1 pre-sampler), divided into 5x5mm^2 pixels.**
- Particle flow means performance depends critically on pattern-recognition, not just intrinsic ECAL energy resolution.
- Granularity requirements and use of Si make ECAL expensive: consider scintillator (Sc) with SiPM readout as active medium.
- Examined wide range of ECAL models, developing detailed understanding of resulting **jet energy resolutions.**



Failure to separate photons from nearby charged hadrons: **"photon confusion"**



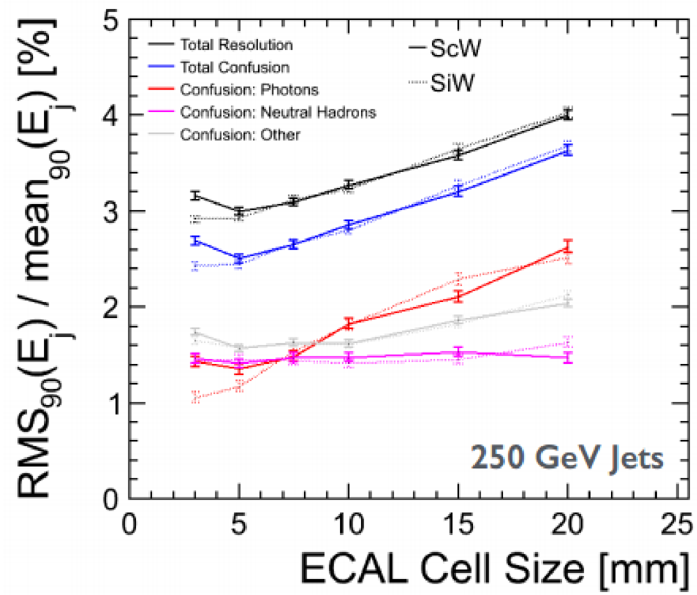
Jet energy resolution:

Total resolution

Total confusion

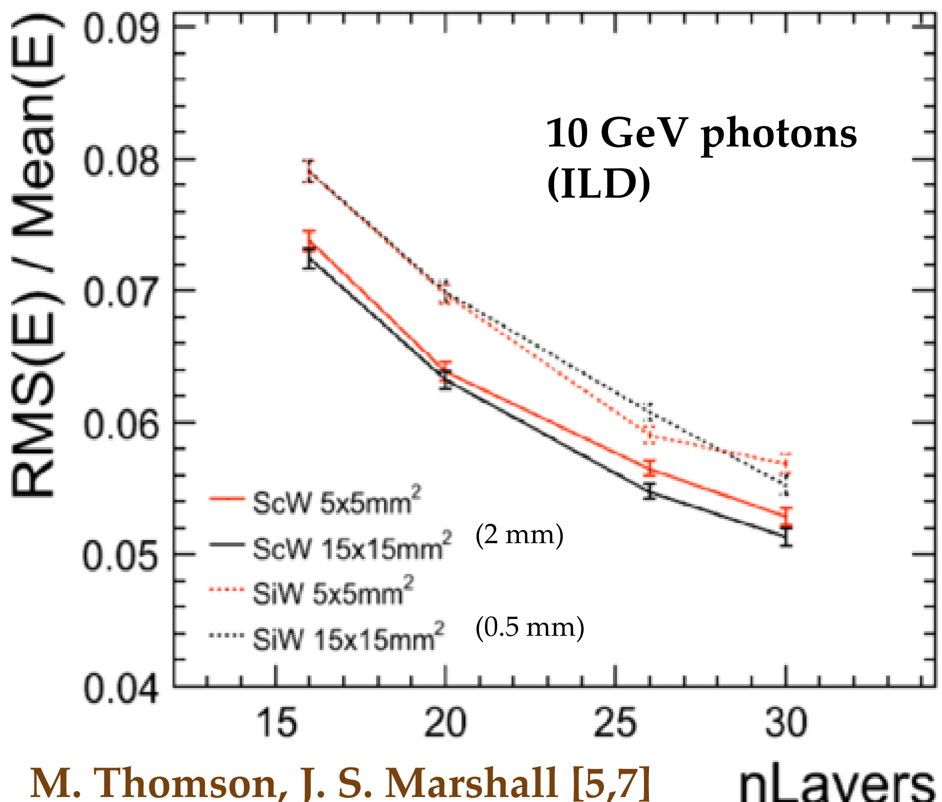
Photon **Neutral hadron** **Other**

[40]



ECal Optimization: Active Material, Number of Layers, Granularity

ILD-based baseline model: **SiW ECal with 29 layers** (23 X_0 / 1 λ_I):
- Tungsten absorber: **20x2.1 mm + 9x 4.2 mm**
- Silicon Active material, **500 μm** thickness, **5x5 mm²** cells

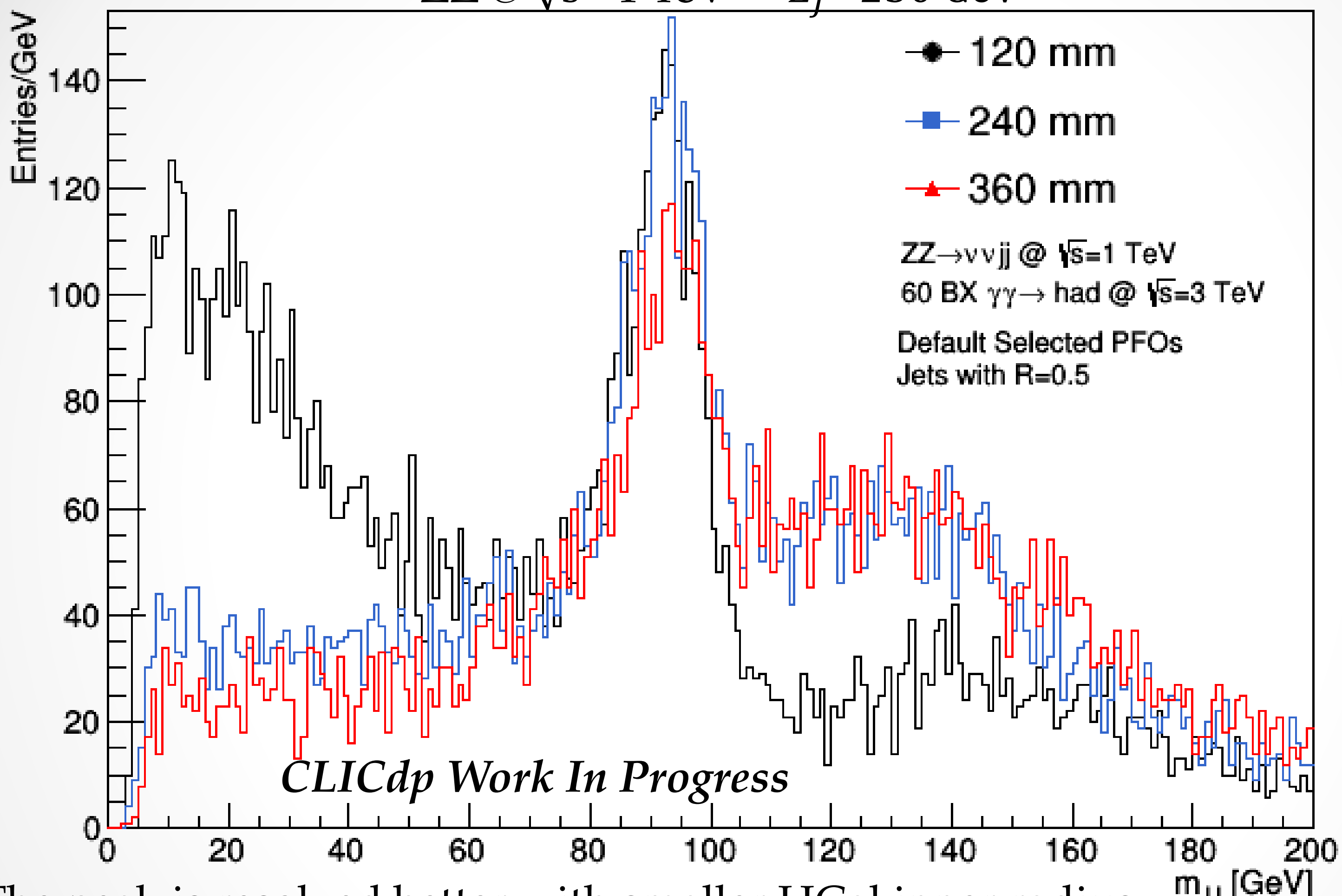


M. Thomson, J. S. Marshall [5,7]

- Scintillator instead of silicon may give a slightly better resolution
  - Depends on active element thickness
  - Also considered Si/Sc combinations
- **Stronger dependence on number of layers ($\sim 1/\sqrt{N}$)**

Extending the HCal coverage: m_{JJ}

ZZ @ $\sqrt{s}$= 1 TeV -> E_j~250 GeV



- The peak is resolved better with smaller HCal inner radius
- However, at 120 mm probably the increased background spoils the efficiency
  - Investigated more the peak below $m_{JJ} < 50$ GeV