Detector Requirements and R&D Status for Future Linear High Energy e+e- Machines

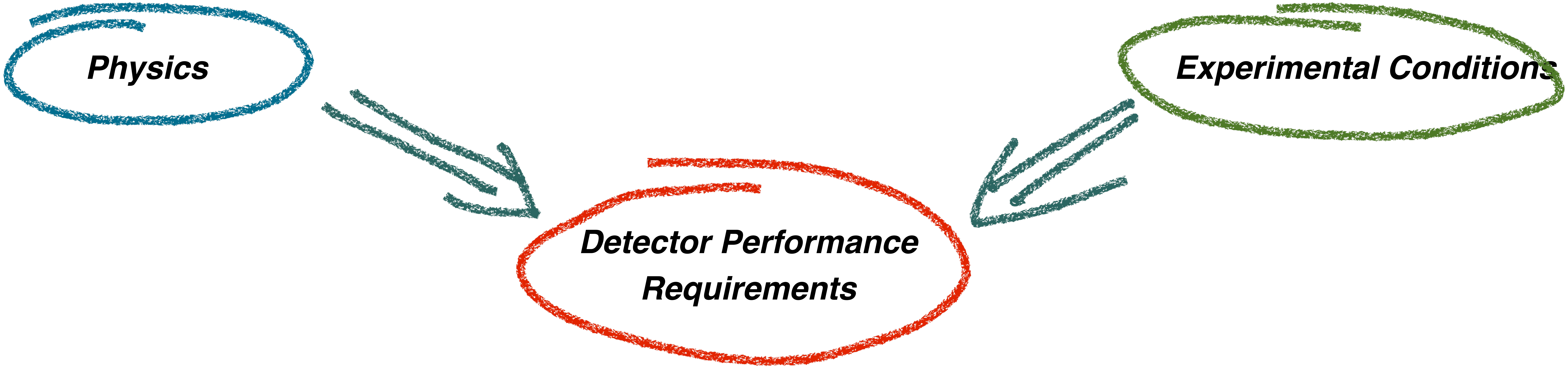
Frank Simon & Jenny List

@ Snowmass e+e- Collider Forum

April 5, 2022

Outline

Physics and Experimental Conditions



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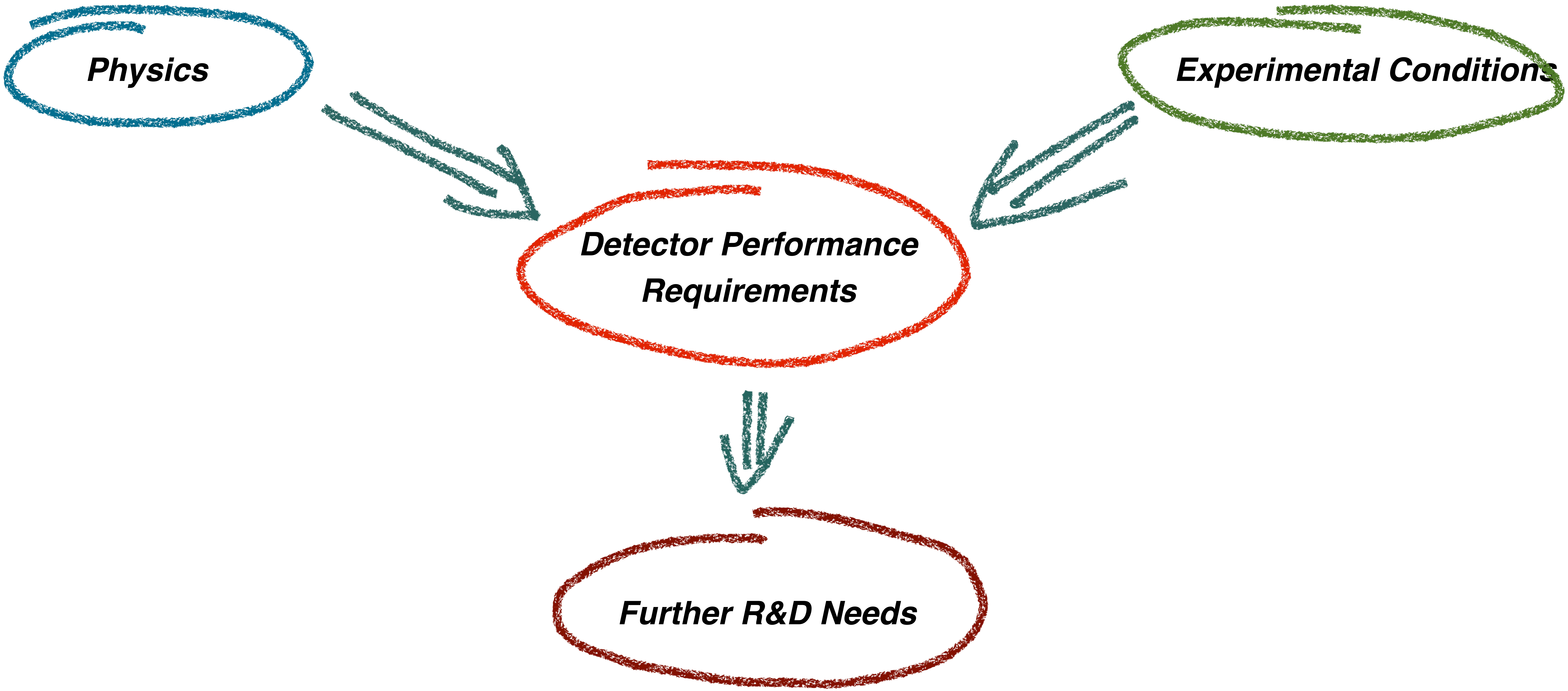


Physics

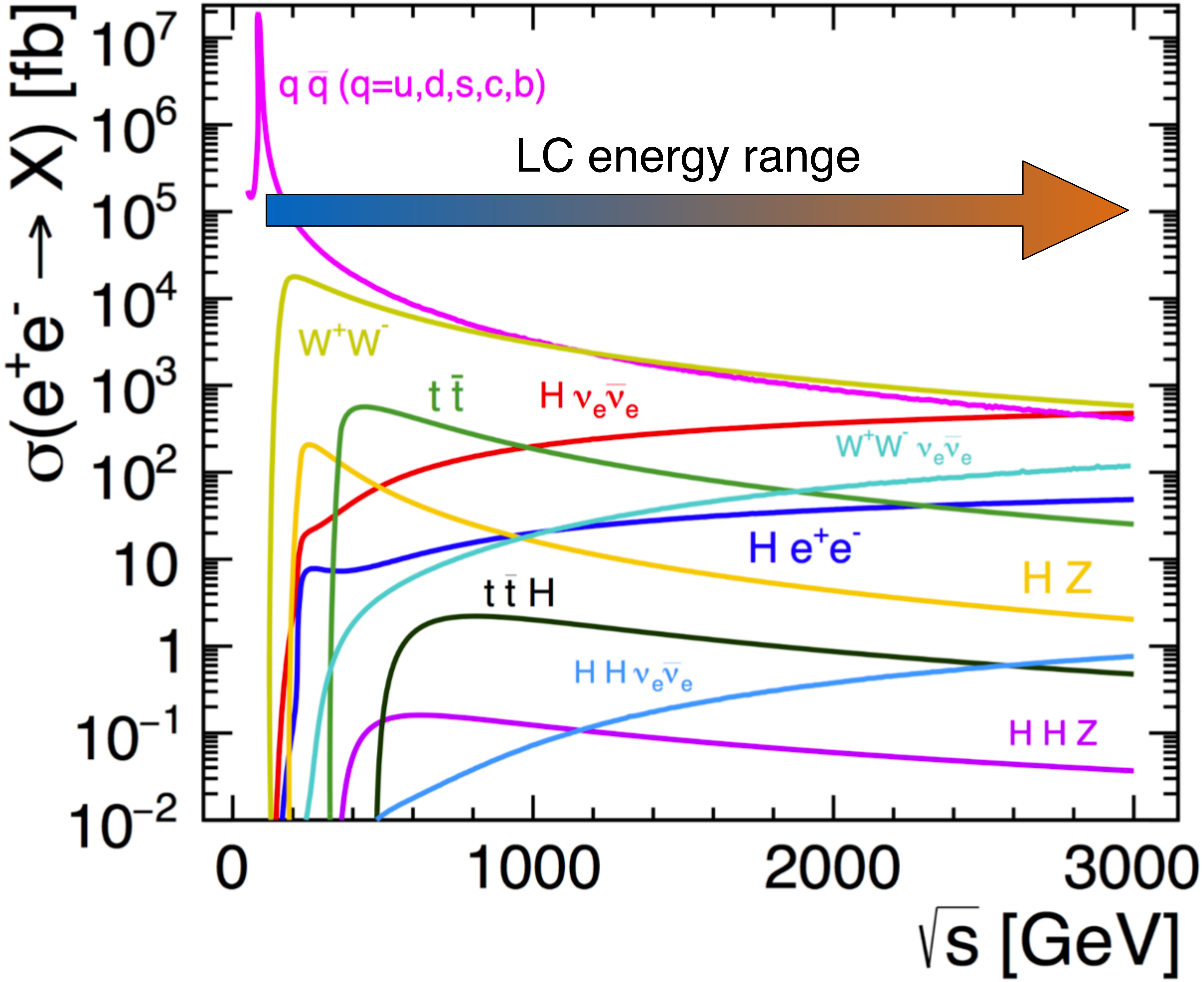
Experimental Conditions

Detector Performance Requirements

Further R&D Needs

Physics Cross Sections & Signatures

General drivers



Collision Energy

- ILC: 250 GeV - 500 GeV - 1+ TeV, option 91 GeV
- CLIC: 380 GeV - 1.5 TeV - 3 TeV, option 91 GeV
  - ➯ Leptons, jets, from a few 10 to many 100 GeV, heavy bosons / complex final states

Physics Drivers

- Physics cross sections low: rates, radiation damage moderate in most regions of the detector
  - ➯ Statistics is precious: Excellent reconstruction of all final states
  - ➯ Requires high luminosity - achievable with very small beams: Beamstrahlung (Luminosity spectrum, backgrounds)

Detector Performance Goals - Tracking

Motivated by key physics signatures

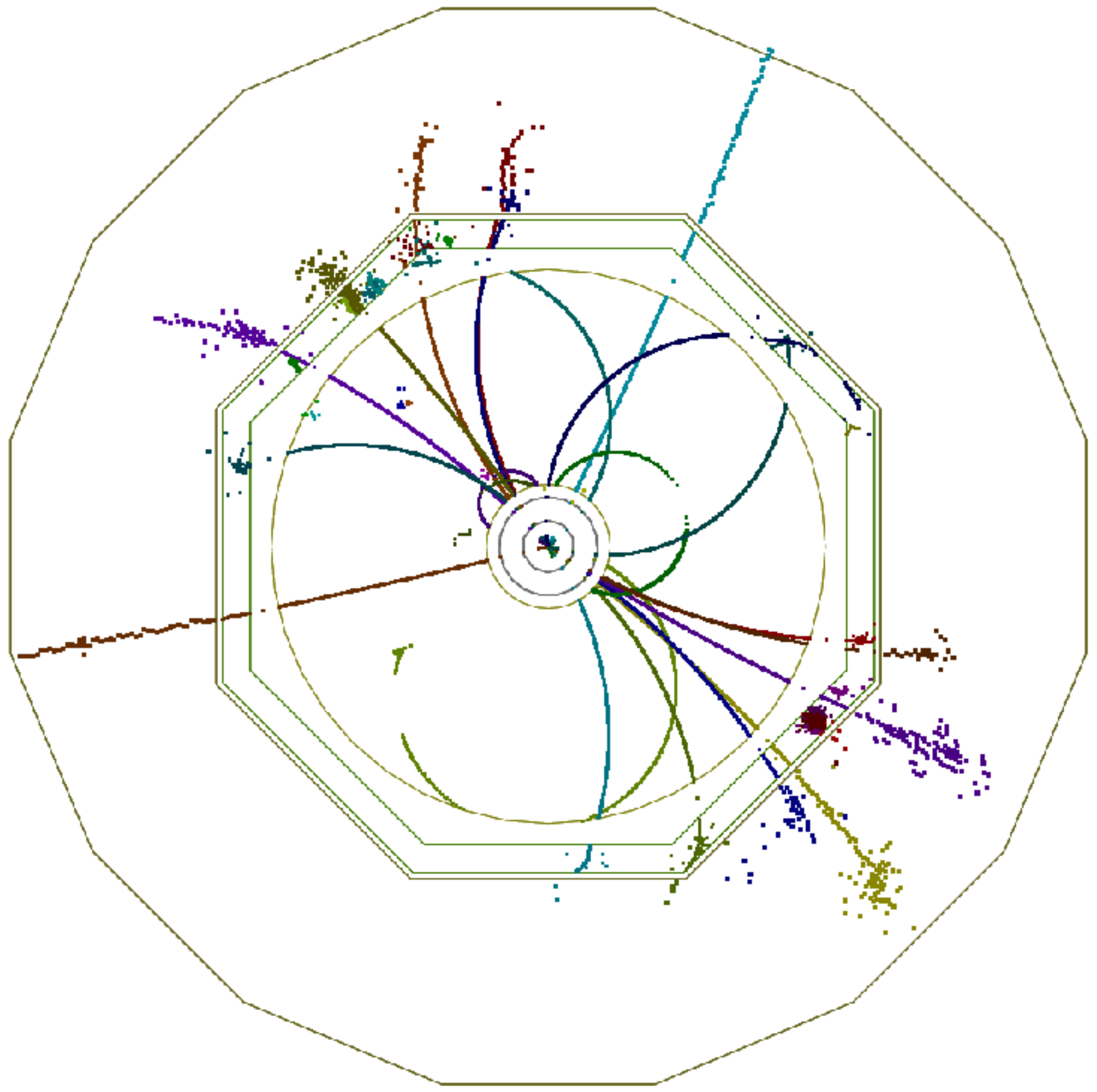
- ***Momentum resolution***

  Higgs recoil measurement, H -> $\mu\mu$,
  BSM decays with leptons

  $\sigma(p_T) / p_T^2 \sim 2 \times 10^{-5}$ / GeV

  precise and highly efficient tracking,
  extending to 100+ GeV

low mass, good resolution:
for Si tracker ~ 1-2% X_0 per layer, 7 μm point resolution



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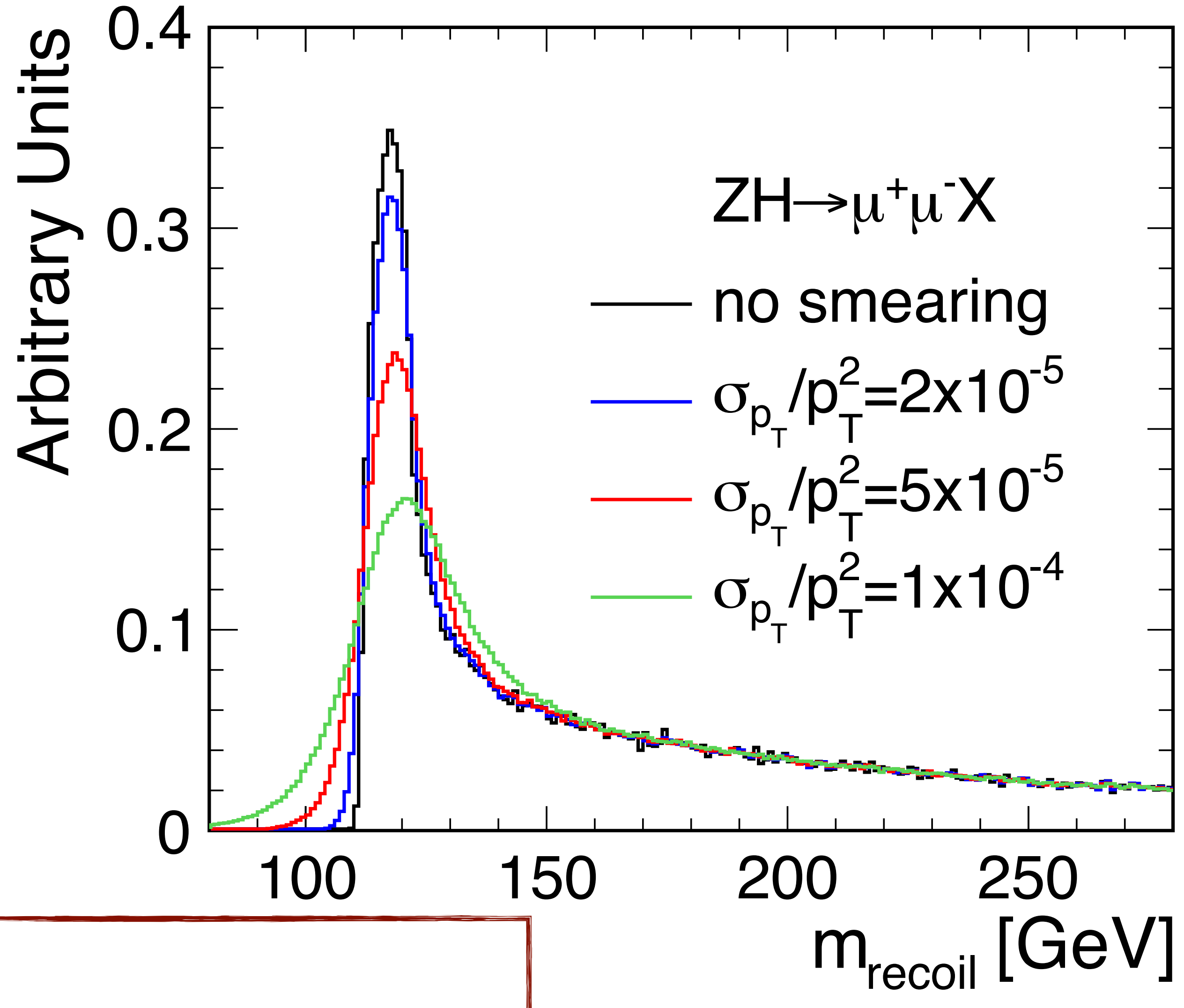

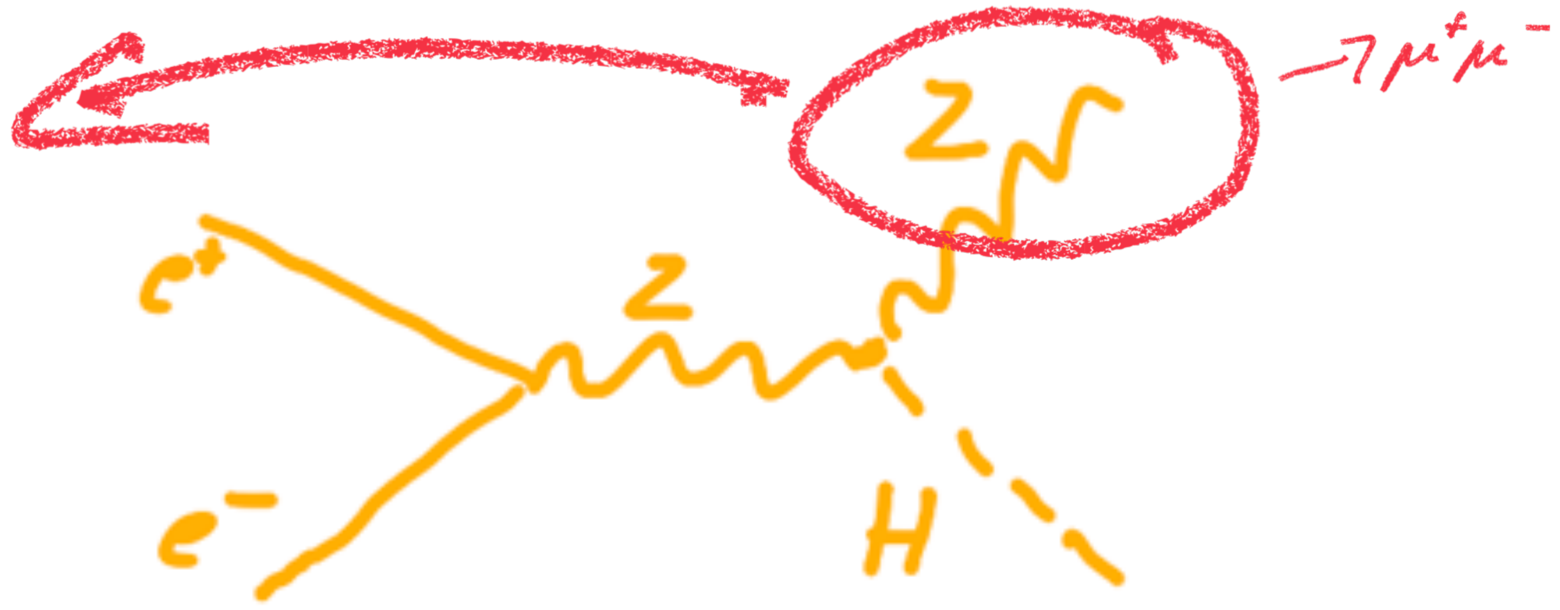

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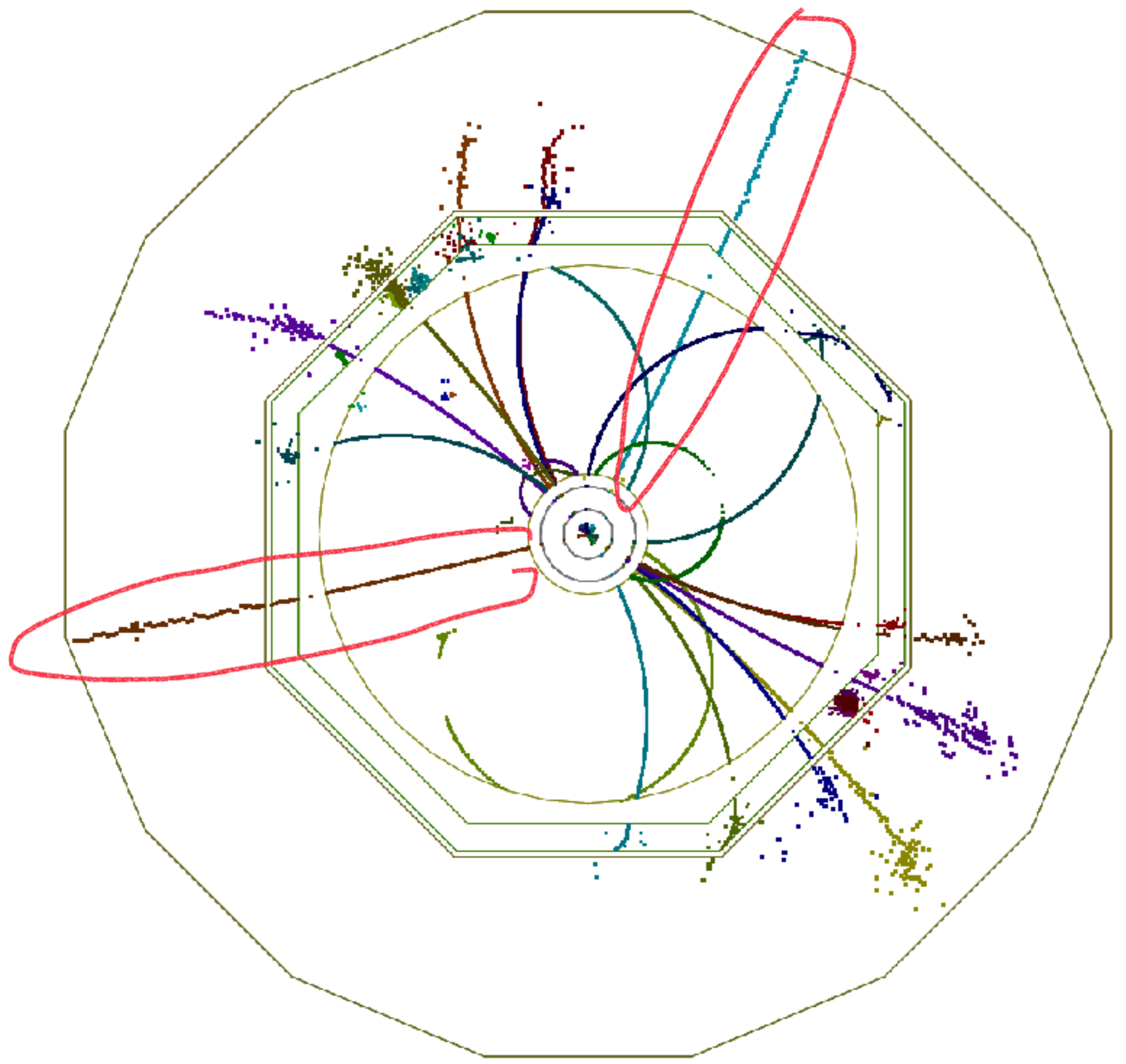

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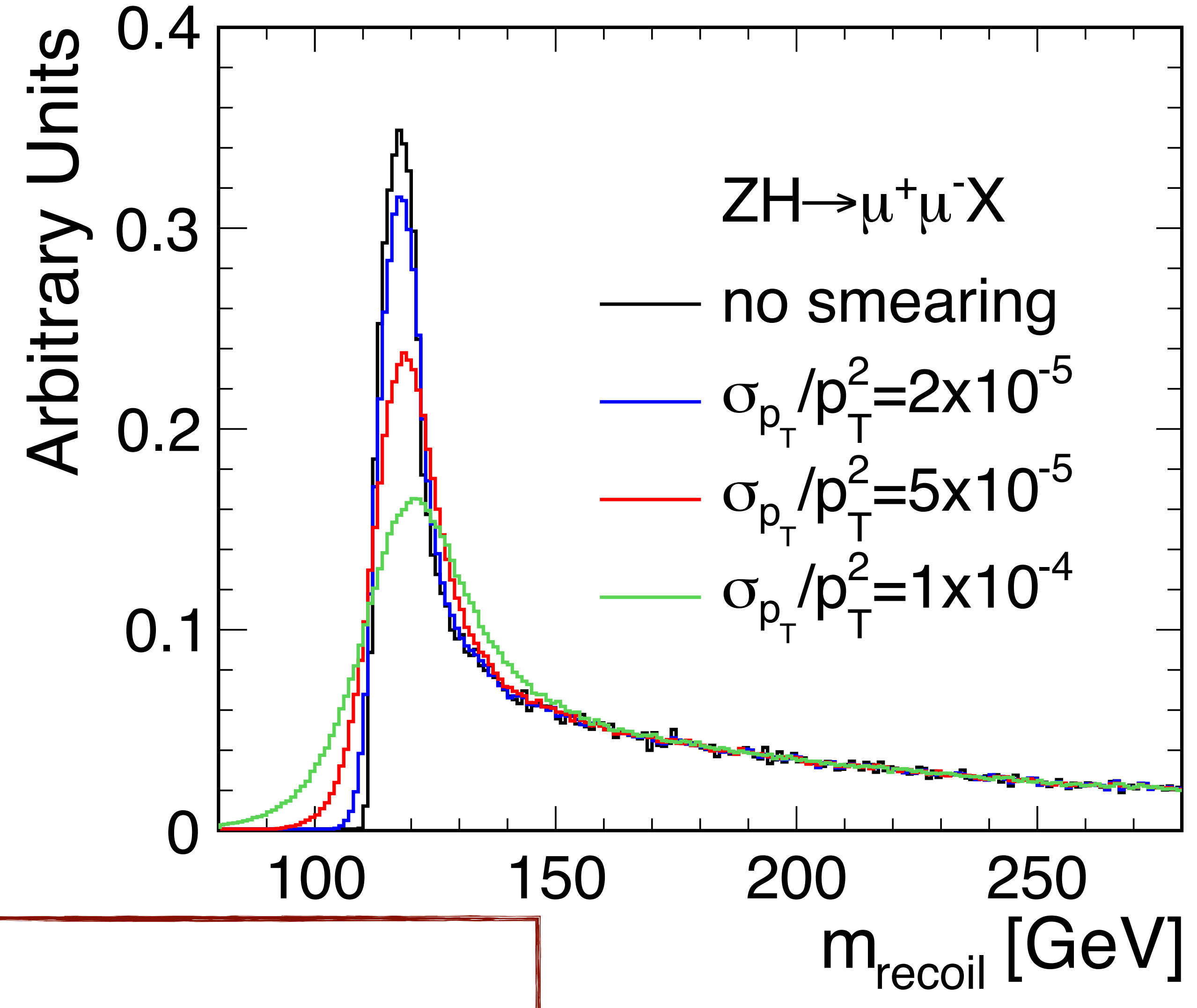

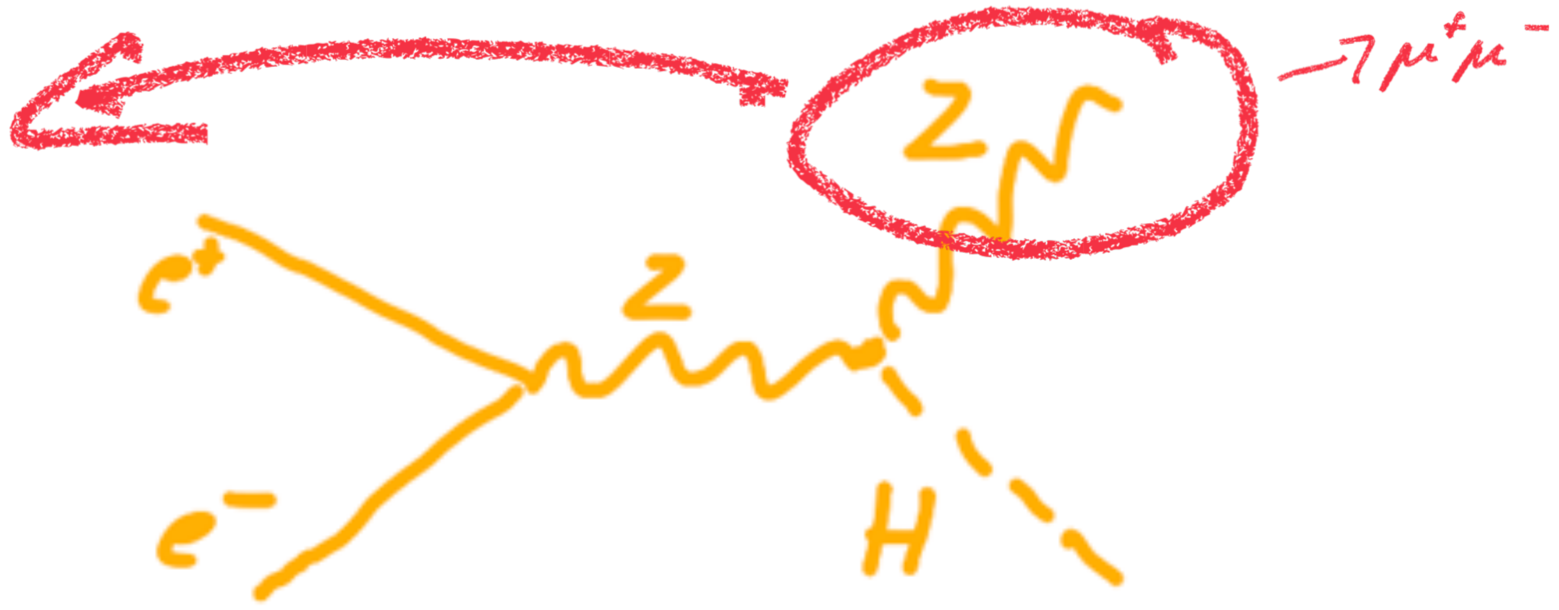

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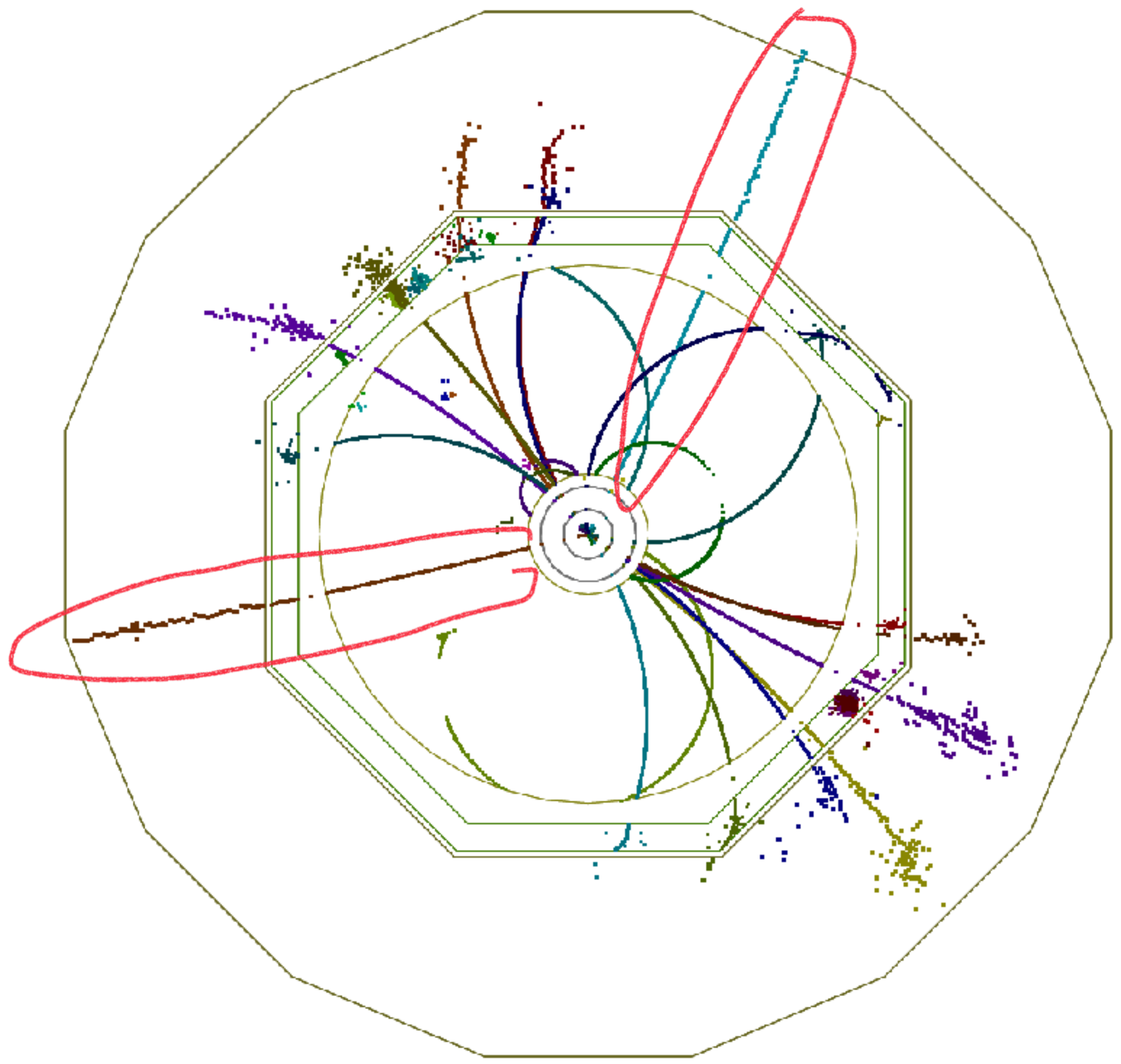
- ***Impact parameter resolution,*** *vertex charge*

  Flavour tagging: b/c/light tagging in Higgs decays, top physics, …

$$\sigma(d_0) \sim [5 \oplus (10 - 15)/p\sin^{3/2}\theta]\ \mu\text{m}$$

single point resolution in vertex detector ~3 μm
< 0.2 X_0 per layer



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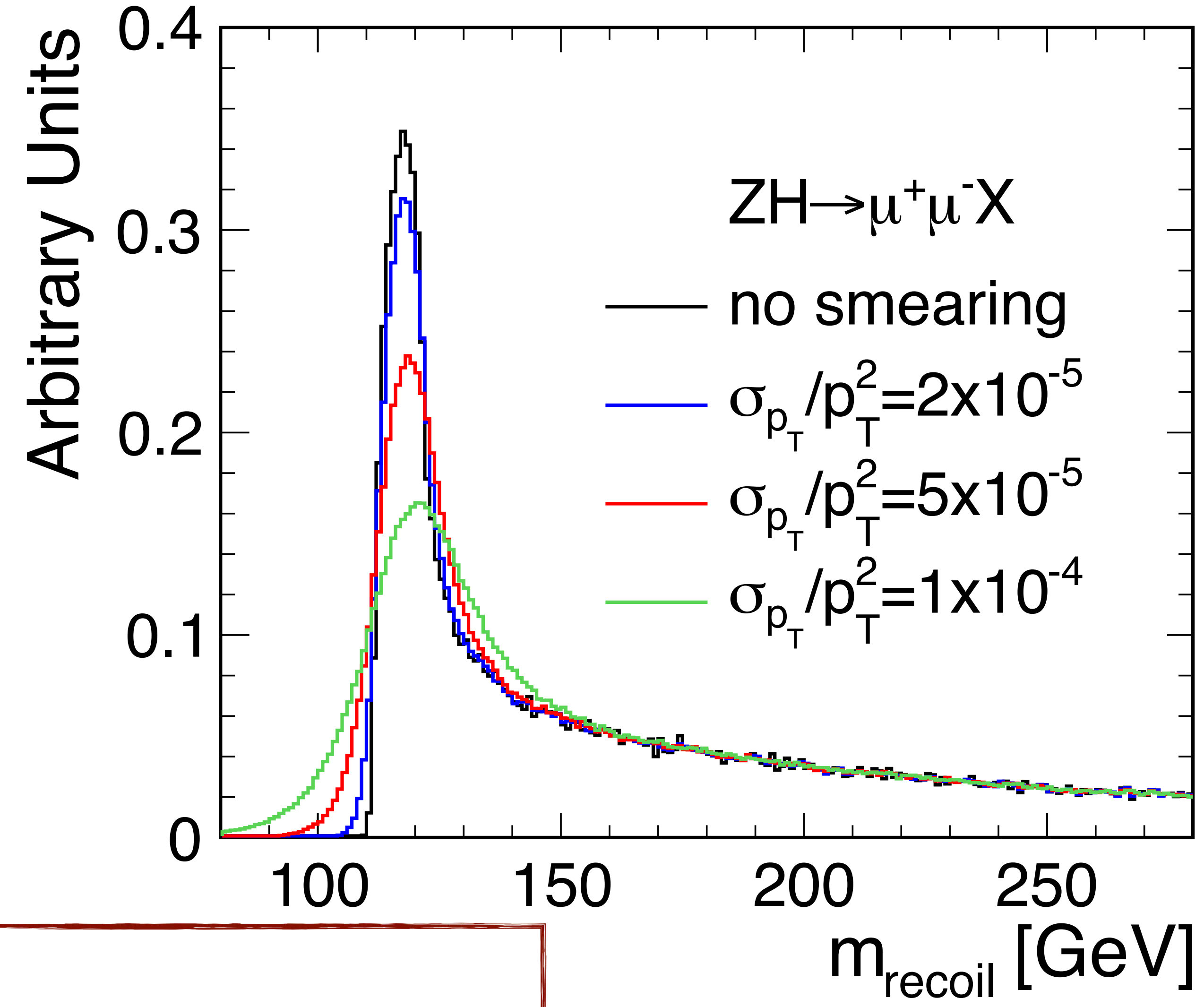

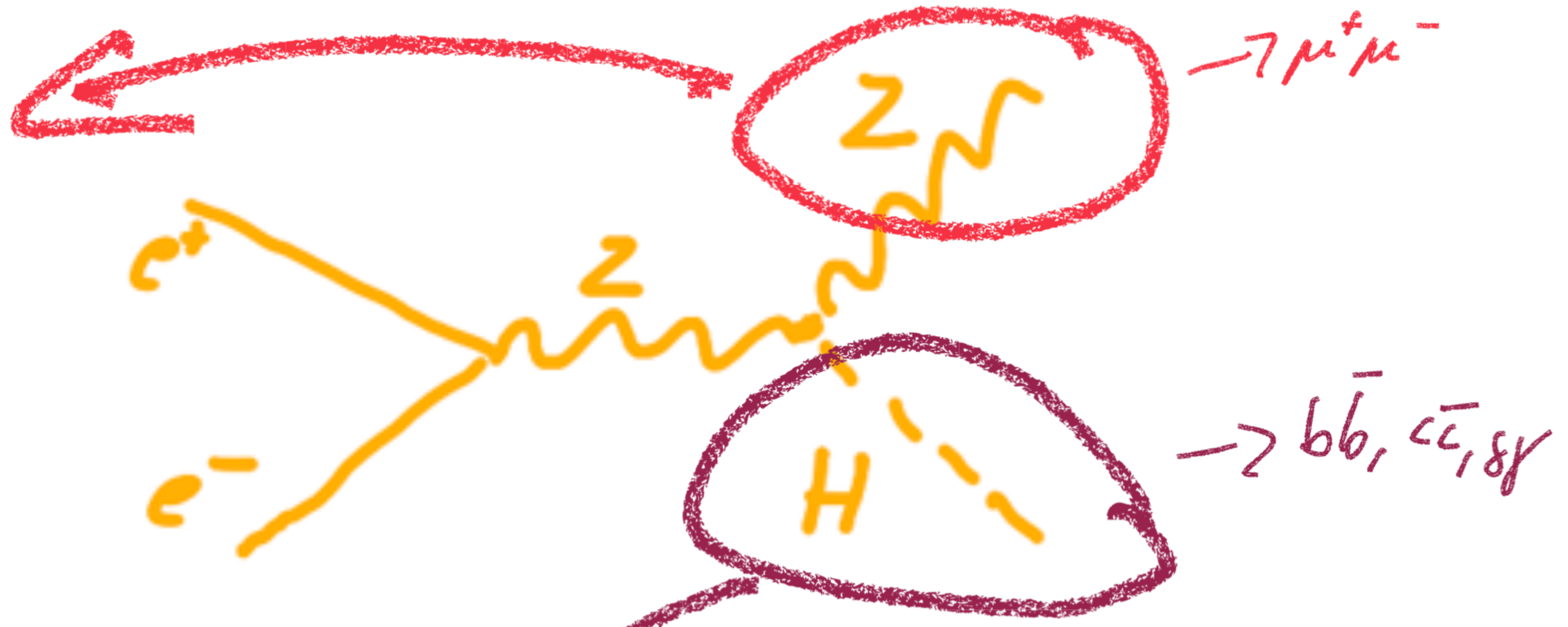

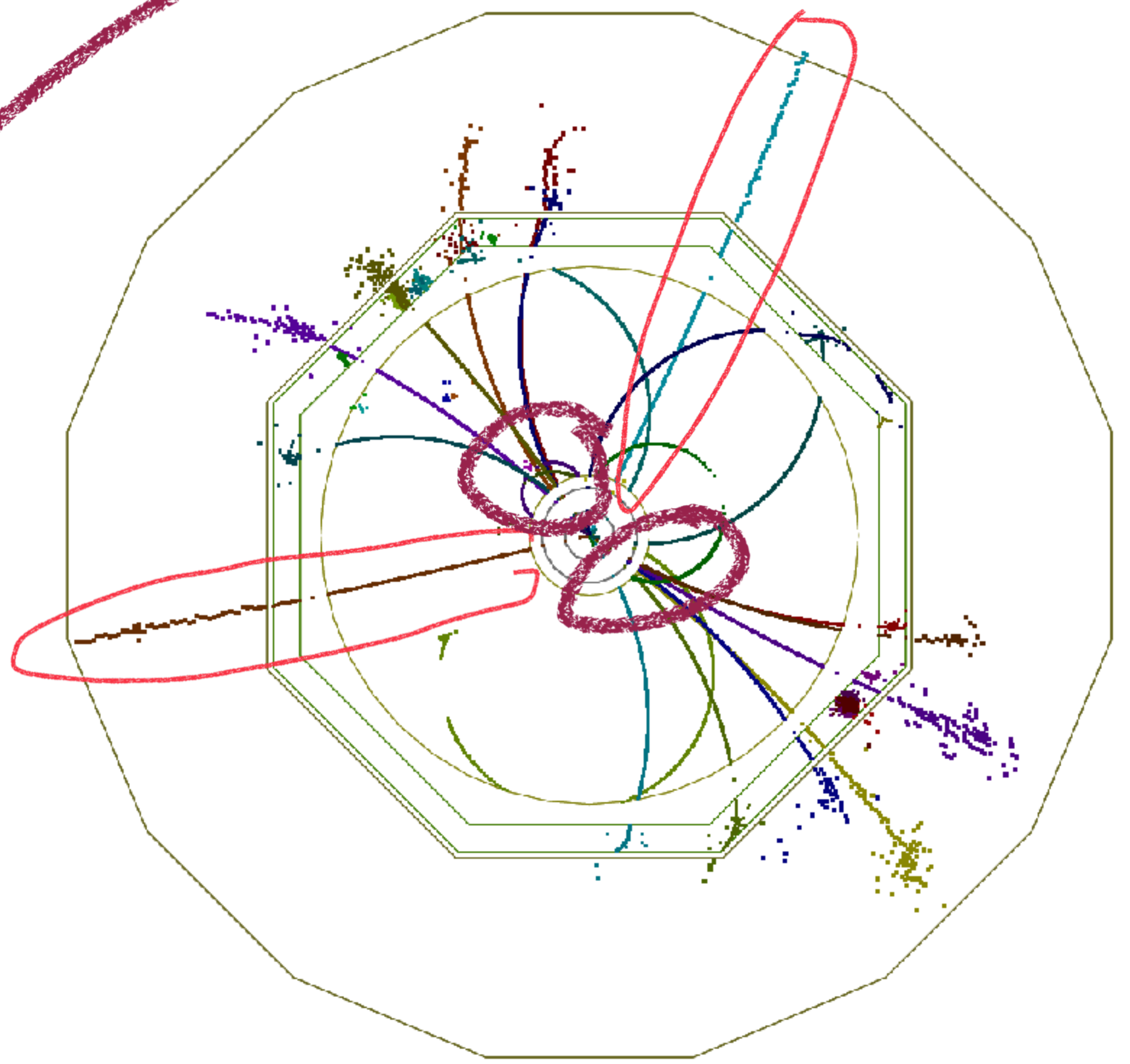

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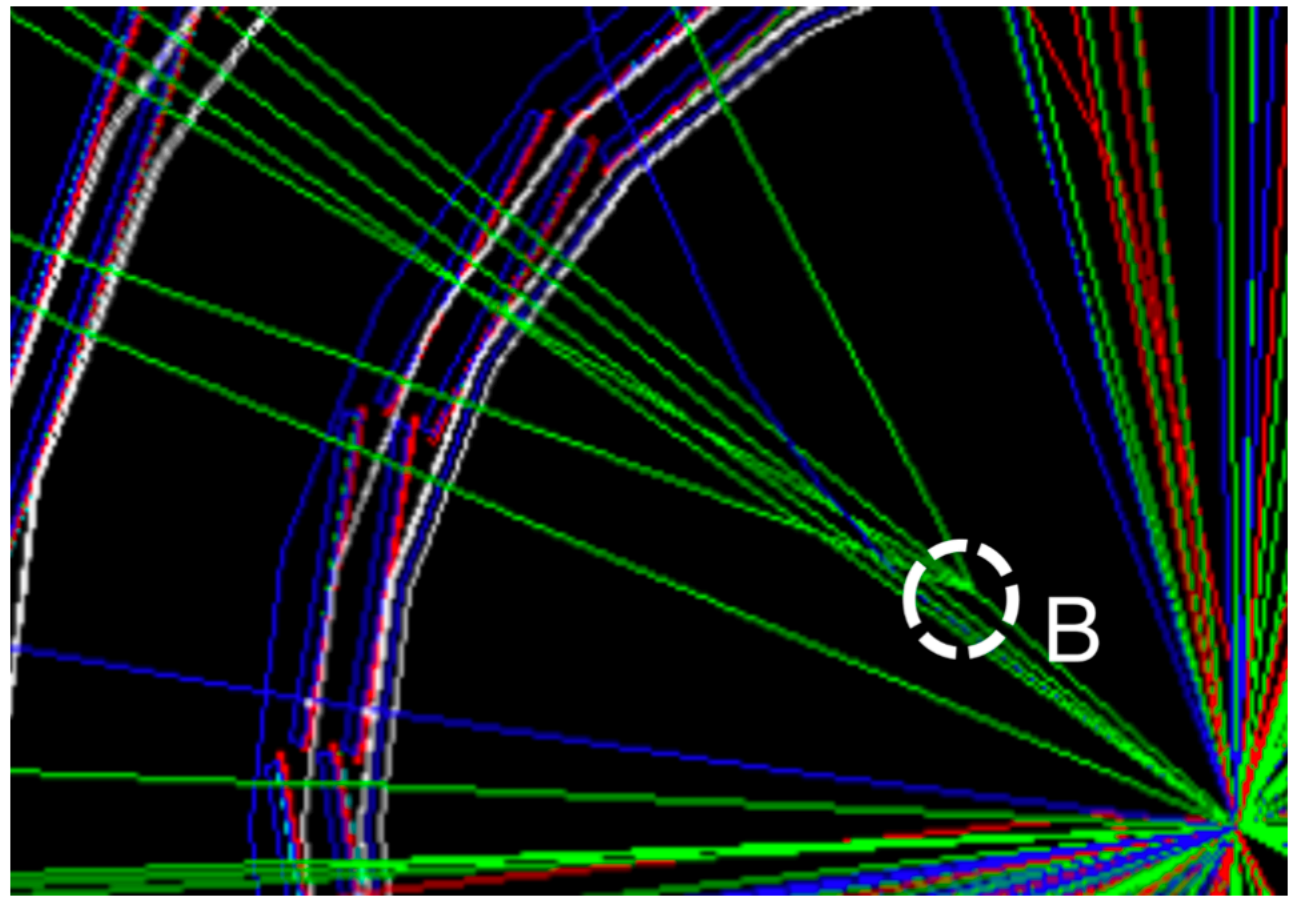


Detector Performance Goals - Jets, Photons, PID

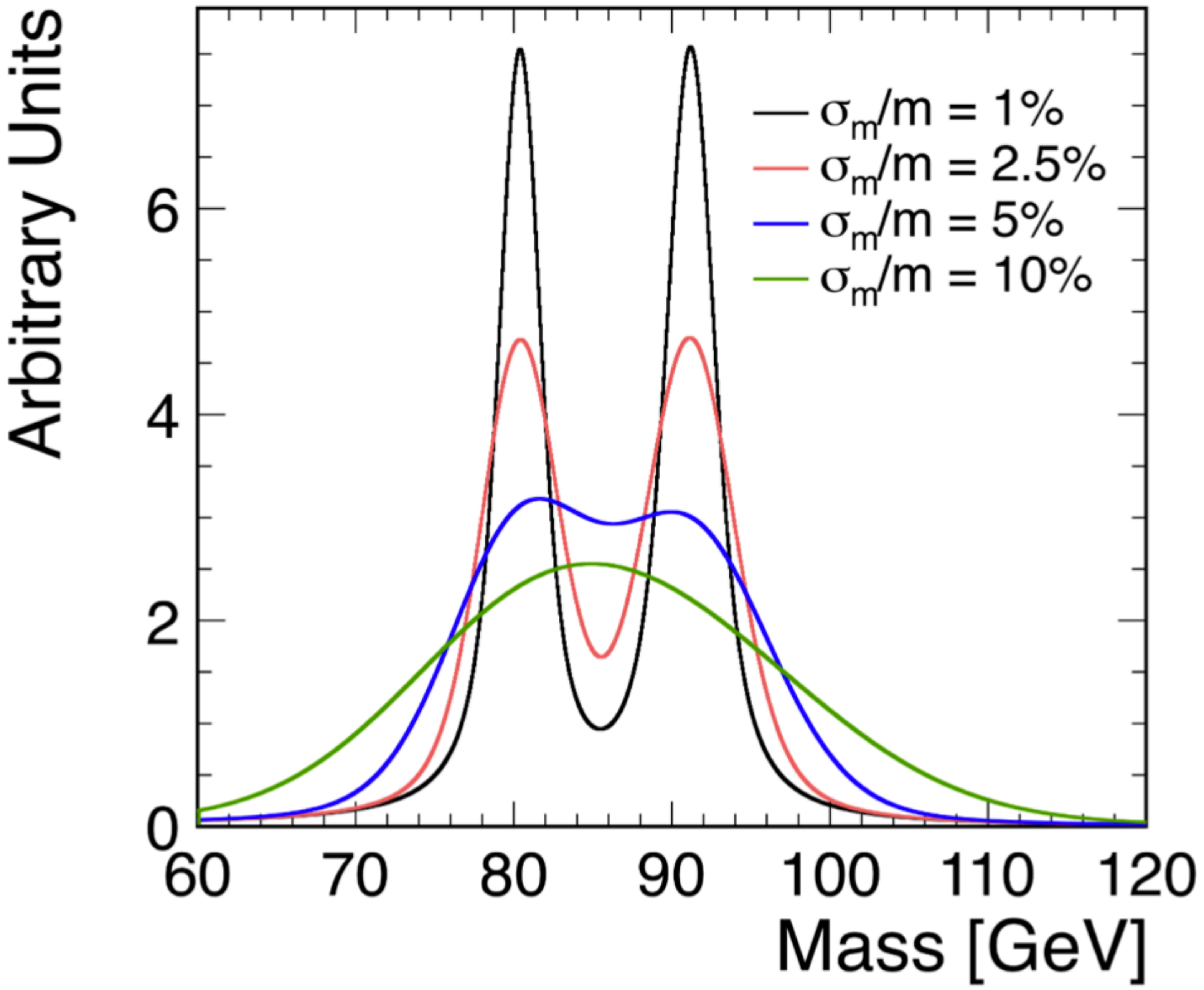
Motivated by key physics signatures

- ***Jet energy resolution***
  Recoil measurements with hadronic Z decays, separation of W, Z, H bosons, …

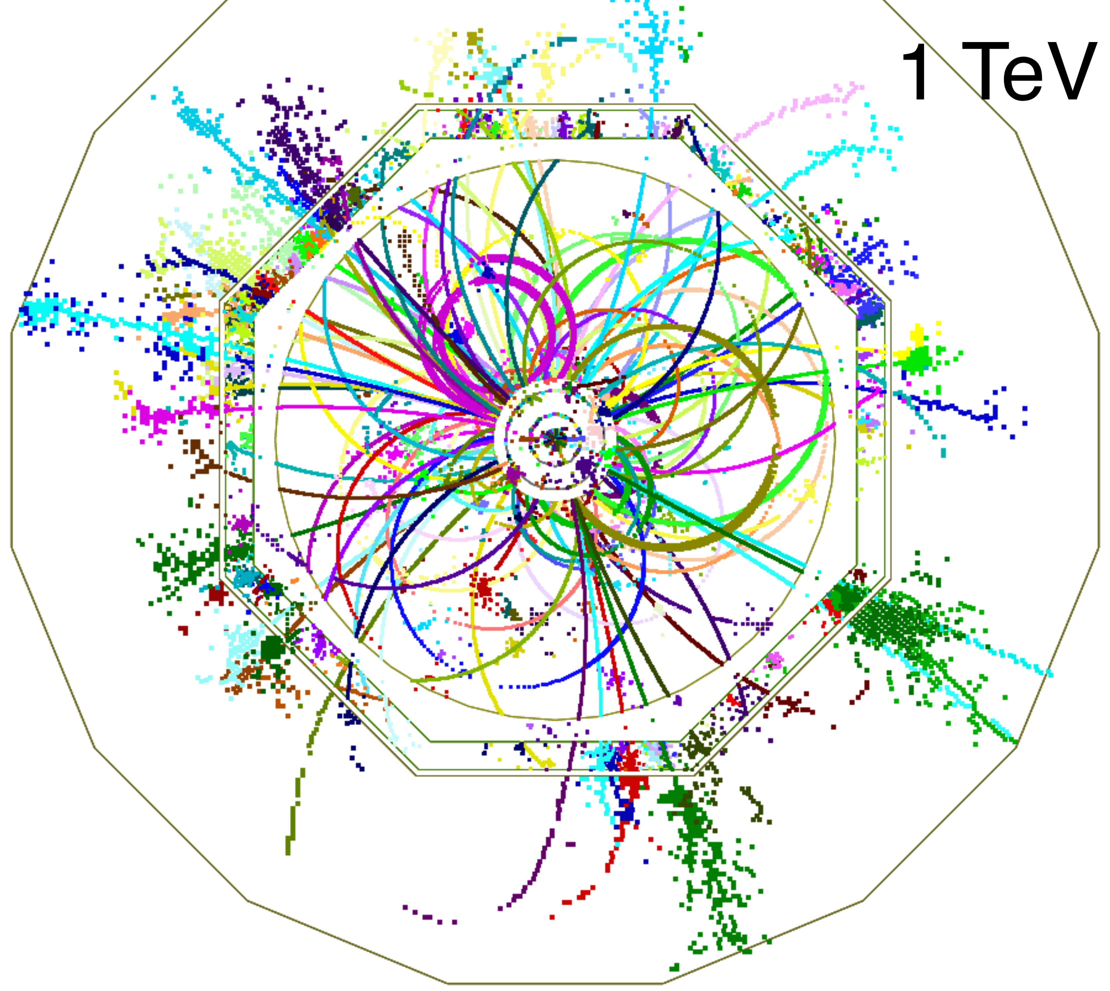
  $\sigma(E_{jet}) / E_{jet}$ ~ 3% - 5% **for E_{jet} > 45 GeV**

  reconstruction of complex multi-jet final states.

- ***Photons***
  Resolution not in the focus: ~ 15 - 20%/√E
  Worth another look ?
  Coverage to 100s of GeV important



$e^+e^- \to ttH \to q\bar{q}b\, q\bar{q}\bar{b}\, b\bar{b}$



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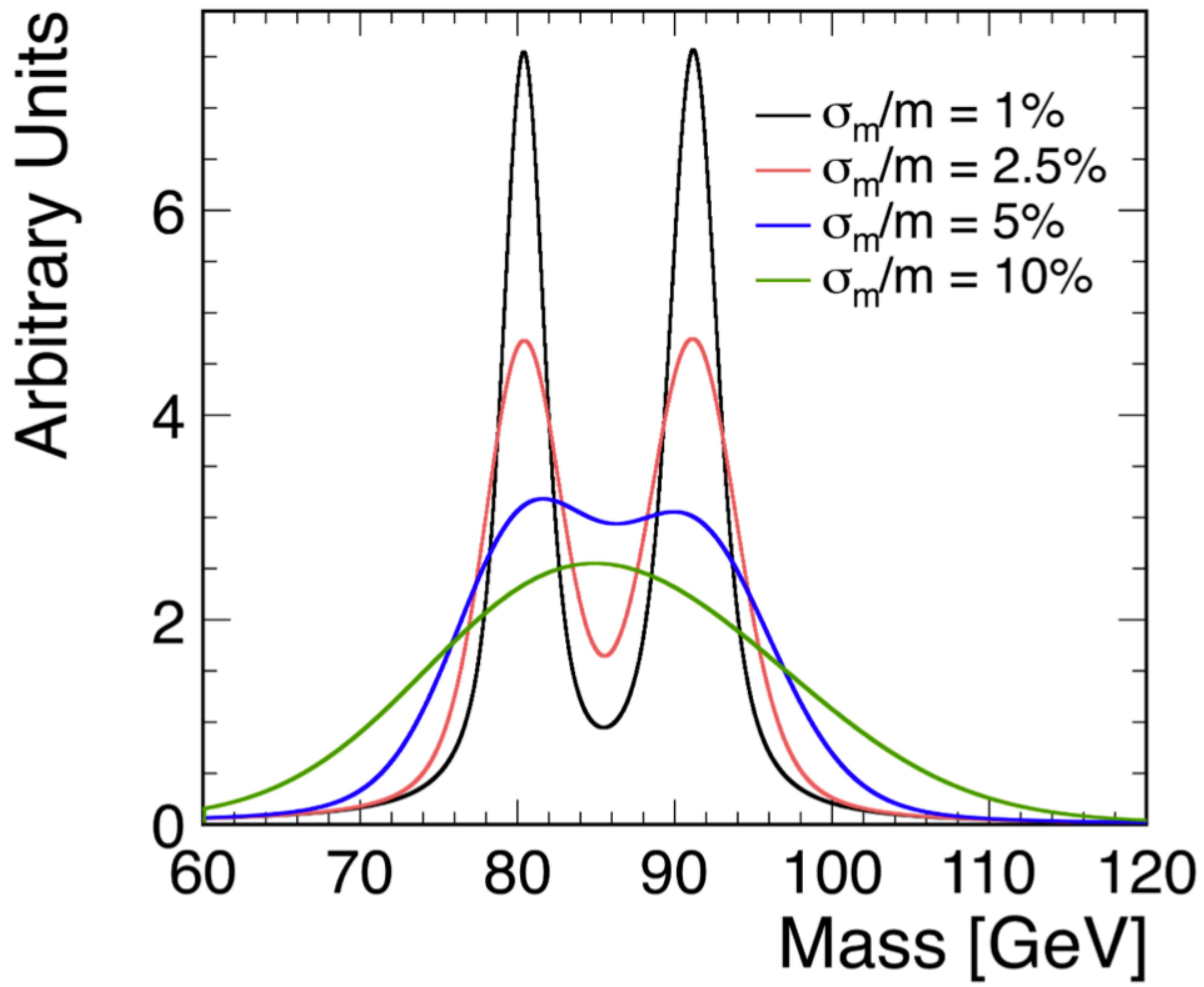
  Clean identification of e, μ up to highest energies
- PID of hadrons to improve tagging, jets,…



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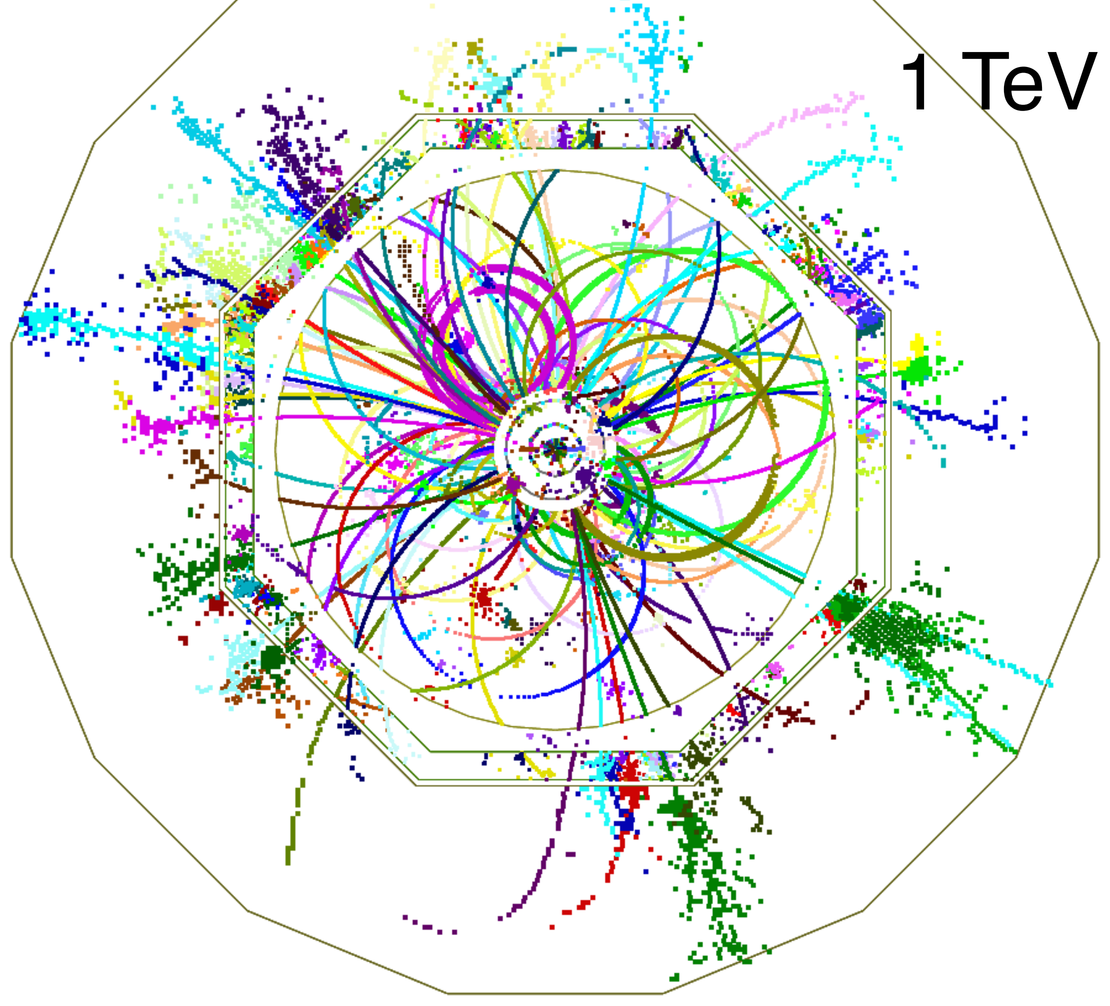

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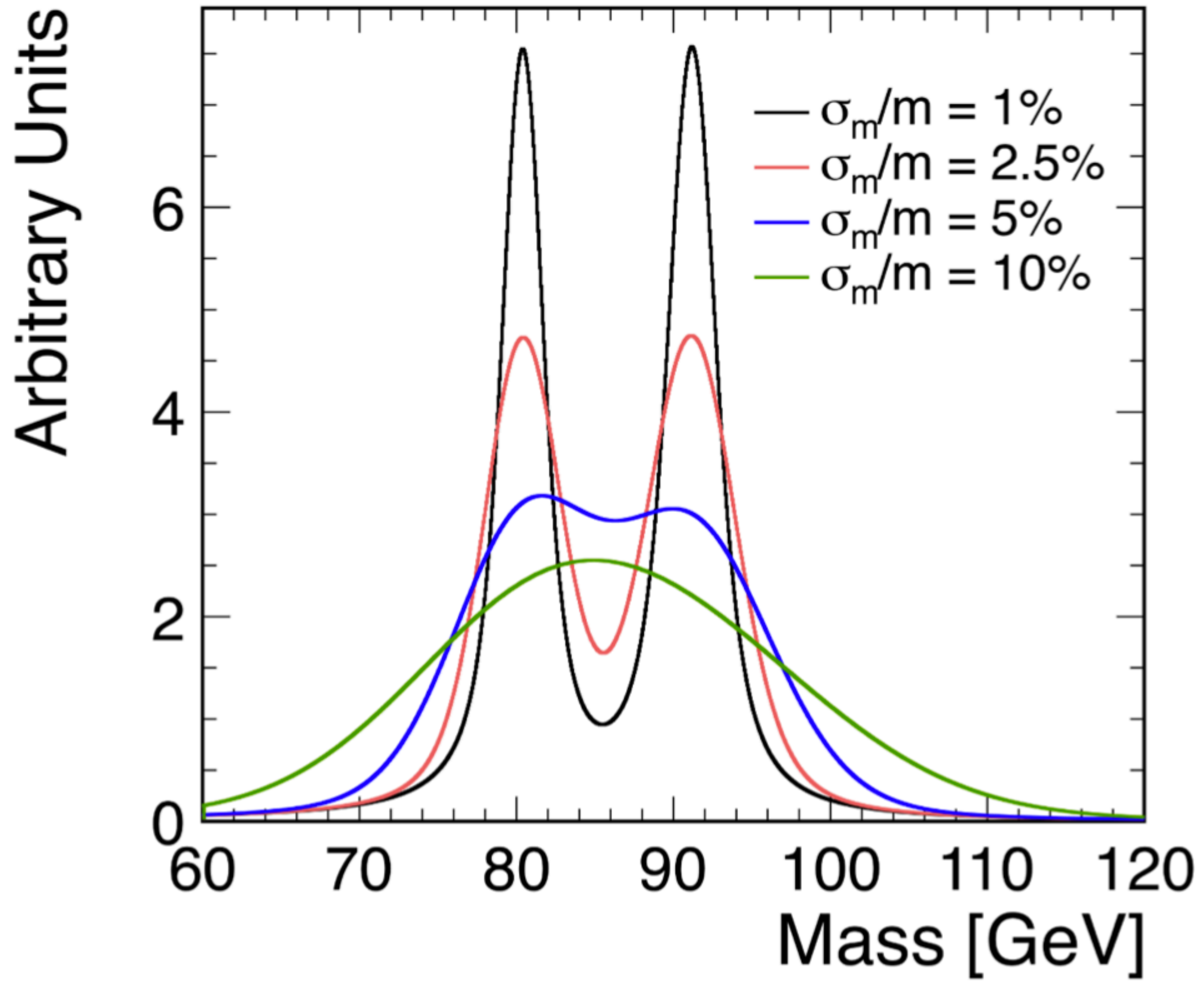
- ***Hermetic coverage***
  Dark matter searches in mono-photon events, …

  N.B.: Achievable limits do not depend strongly on $\sigma(E_\gamma)$



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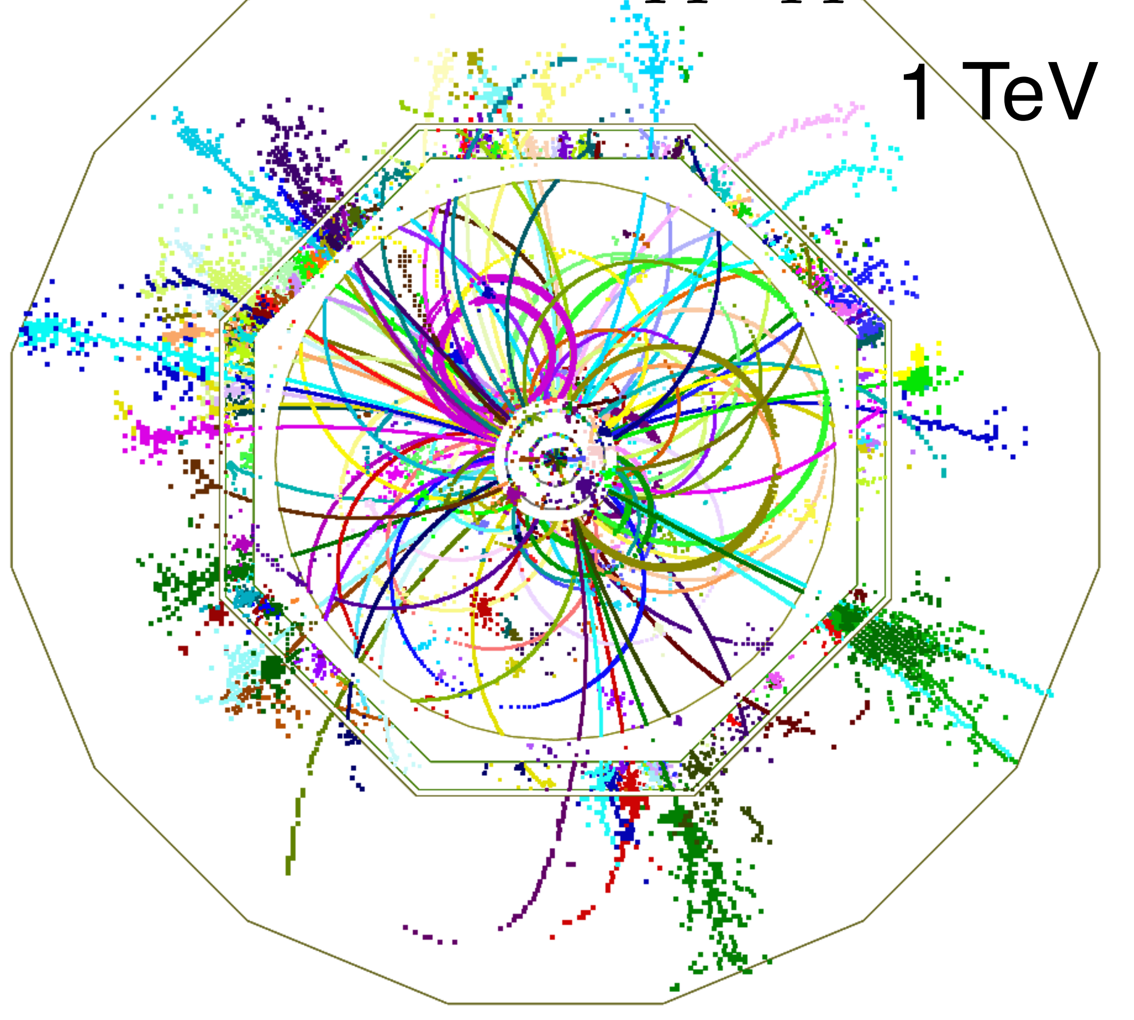
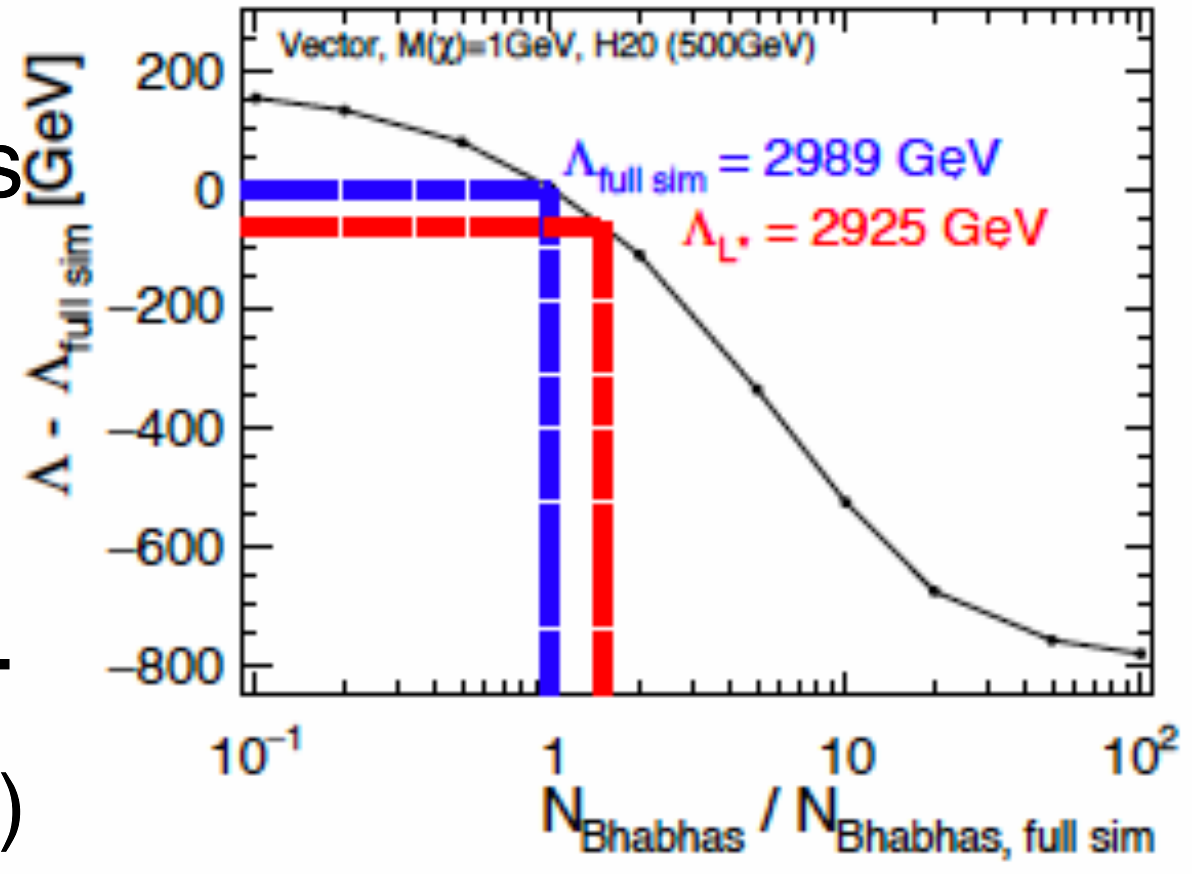
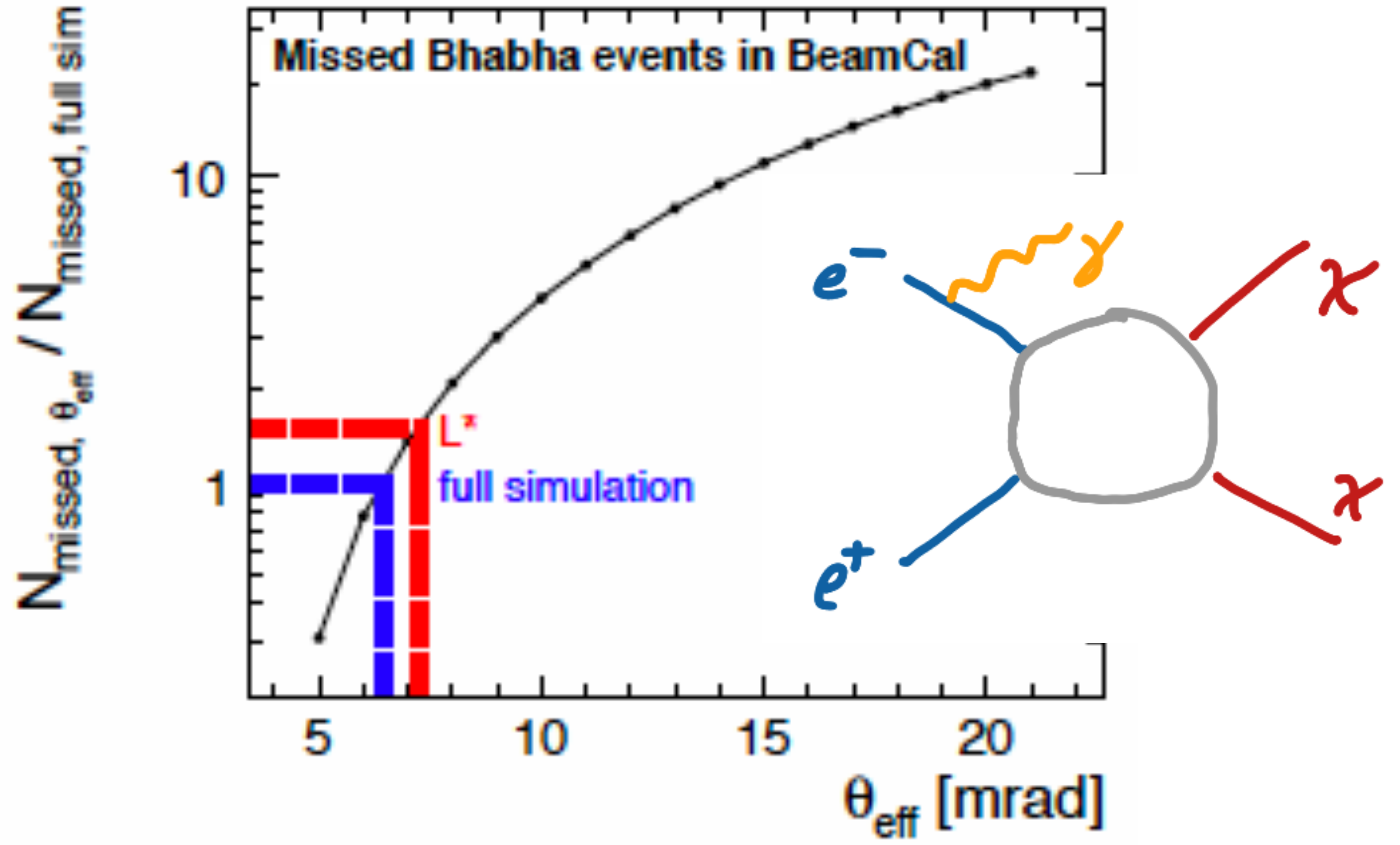
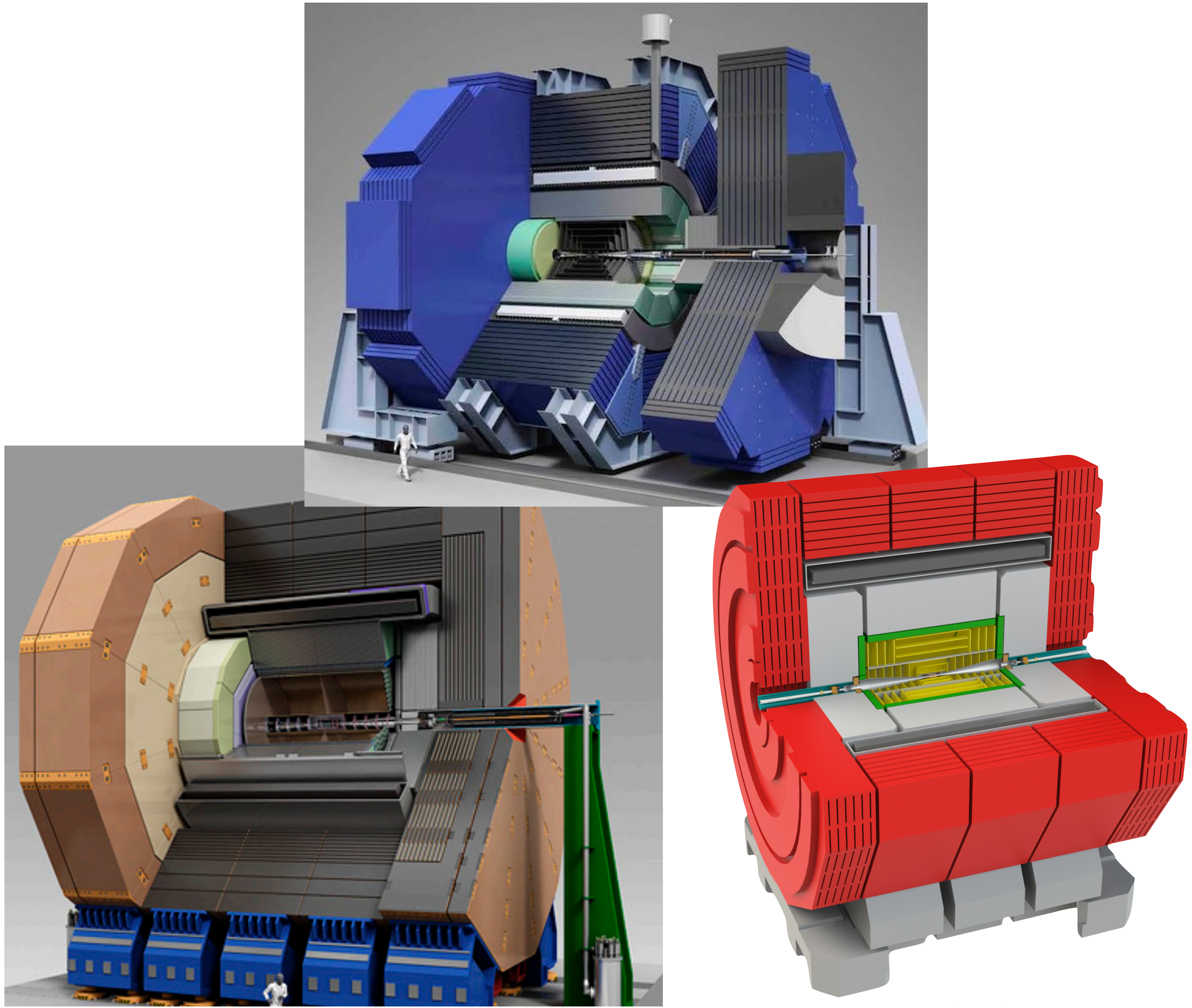






The Linear Collider Detector Design - Main Features

Focusing on general aspects



- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

Detector Optimisation

some scaling laws

- Cell lateral size
  - Shower separation (EM~2×cell size)
  - Cell time resolution (1 cm/c ~ 30 ps)
    - Time performance for showers
      - ParticleID, easier reconstruction
- Longitudinal segmentation
  - sampling fraction
    - E resolution (ECAL ~15%/√E)
  - shower separation/start

Number of cells ↗ ⇒ Cost ↗ (1/size^2)
Cell density ↗ ⇒ Power consumption ↗
Time resolution ↘ ⇒ Power ↗

threshold, passive vs active cooling
dead-zones ↗

NEED TO BE FULLY RE-EVALUATED for EW region

- ECAL inner radius; Barrel Z_{Start}
- ECAL–HCAL distance
- Barrel–Endcap distance
- Dead-zones sizes (from Mechanics, Cooling)

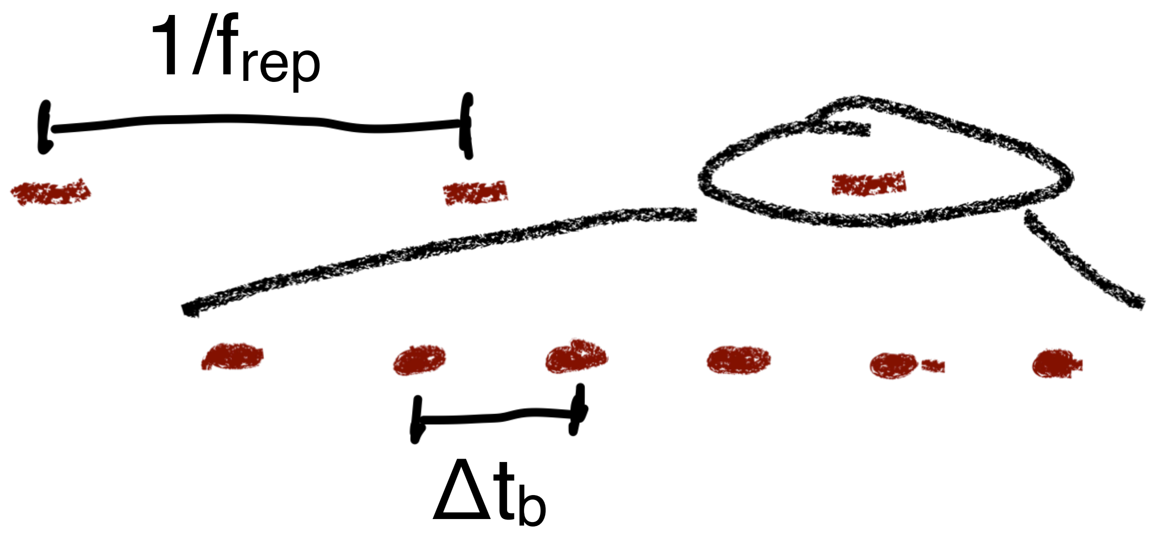
Inner Radius ↗ ⇒ Tracking performance ↗
Cost $\nearrow^2$ (⊃ Magnet, Iron)
Gaps ↗ ⇒ PFlow performances ↘

Vincent Boudry

Linear Collider Conditions…

… and the consequences for the detector design

- Linear Colliders operate in bunch trains:



  - at CLIC: **Δt_b = 0.5 ns**; f_{rep} = 50 Hz
  - at ILC: Δt_b = 554 ns; f_{rep} = 5 -10 Hz
  - at C3: Δt_b = 3…5 ns; **f_{rep} = 120 Hz**

⇰ Enables power pulsing of front-end electronics, resulting in dramatically reduced power consumption

  ⇰ Eliminates need for active cooling in many areas of the detectors: Reduced material, increased compactness

Jenny List (jenny.list@desy.de)

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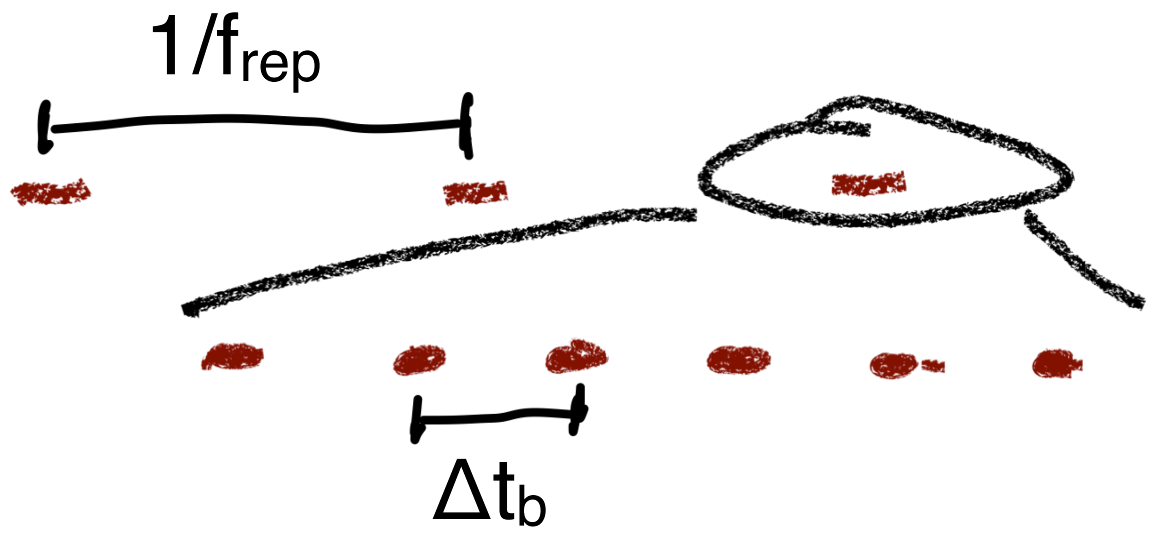

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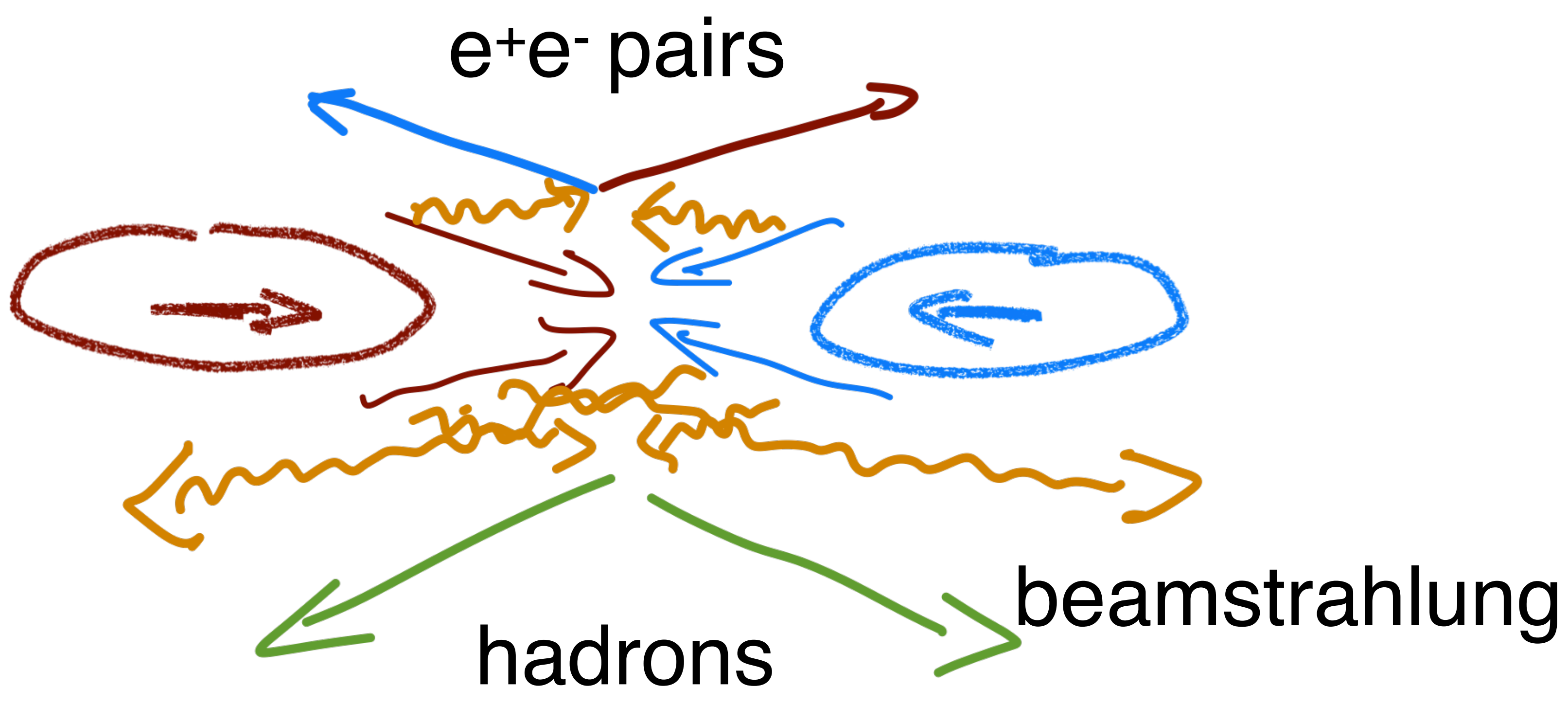

⇨ Significant beam-induced backgrounds

- ⇨ Constraints on beam pipe geometry, crossing angle and vertex detector radius
- ⇨ In-time pile-up of hadronic background: **sufficient granularity for topological rejection**
- ⇨ At CLIC: small Δt_b also results in out-of-time pile-up: **ns-level timing** in many detector systems

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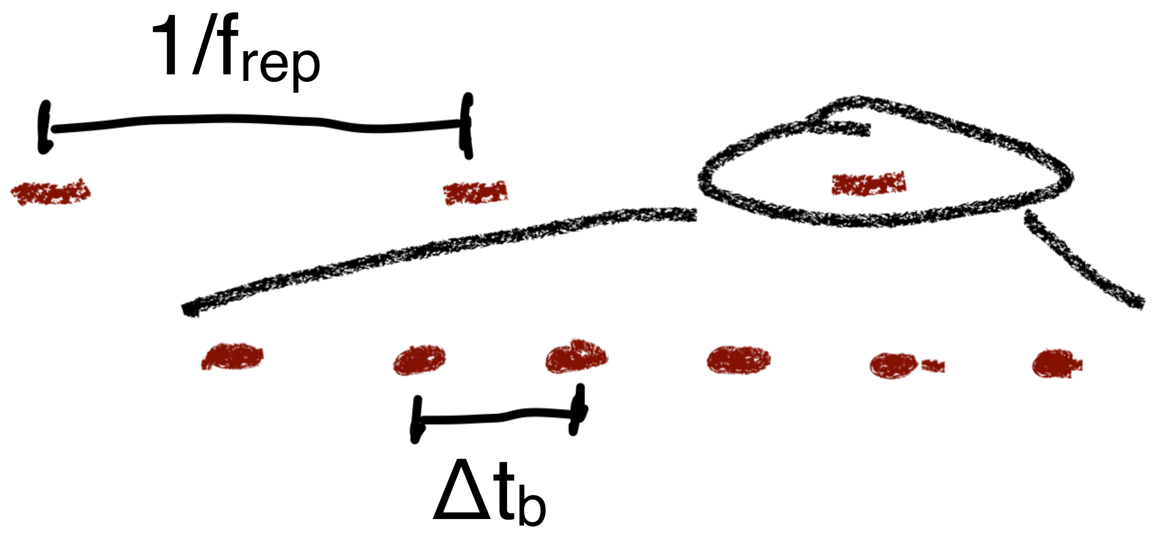

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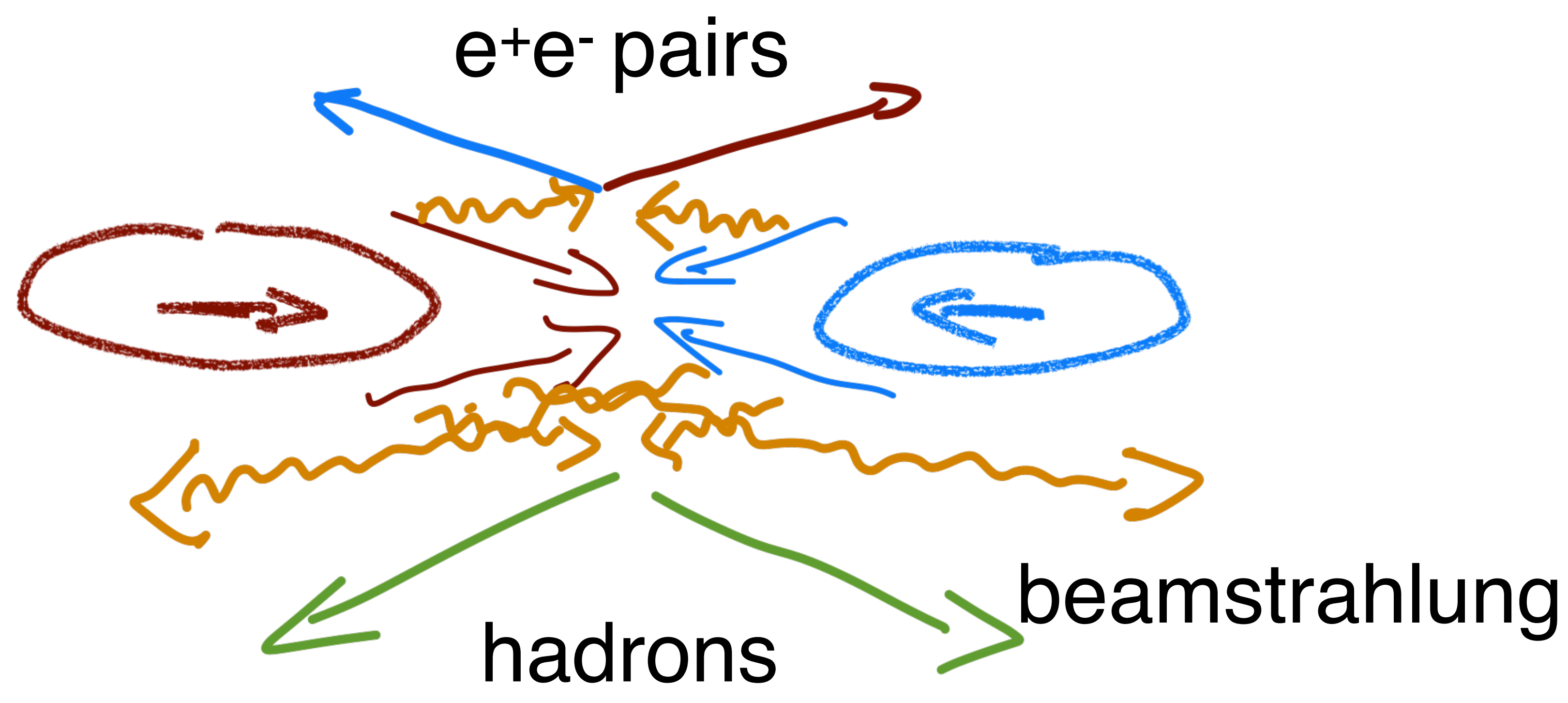

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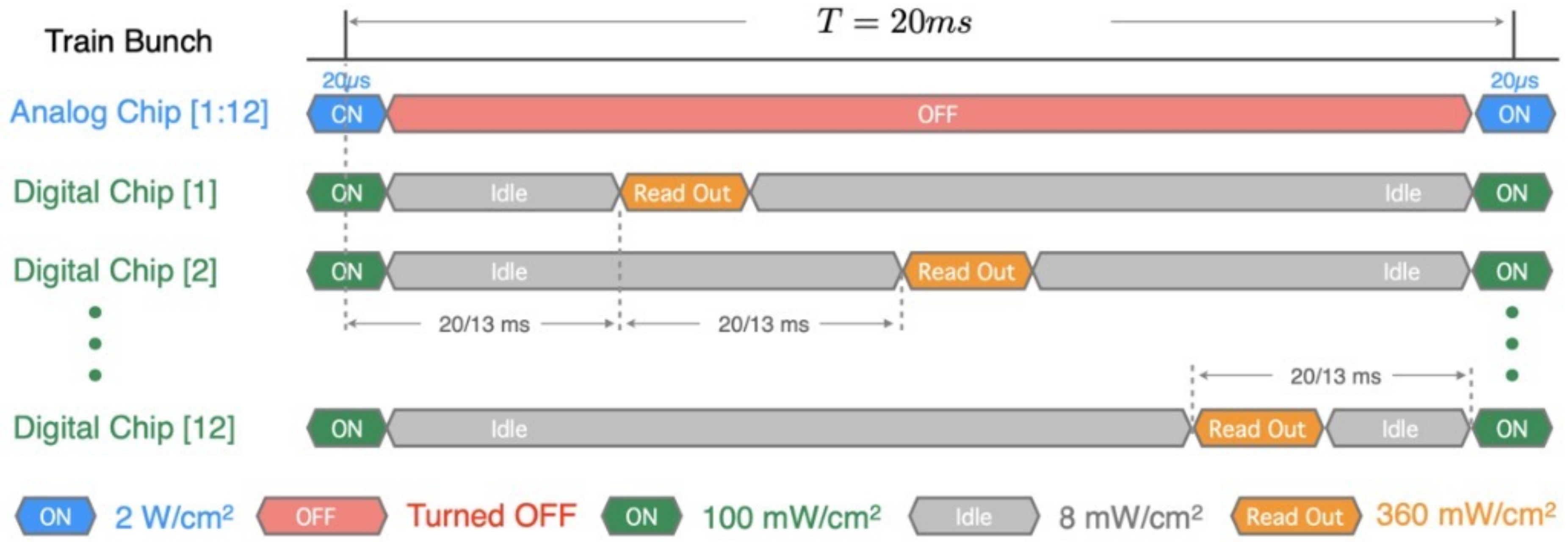
C3 as well?

Power Pulsing - CLIC example

R&D Status

Power-pulsing concept developed for CLIC vertex detector, to match accelerator bunch structure. Analogue peak power needed only during short acquisition time of around 20μs around collisions and can be switched off during 20ms gaps between bunch trains.

Most power-consuming digital parts are disabled between bunch trains, while ladder readout is spread over the 20ms.

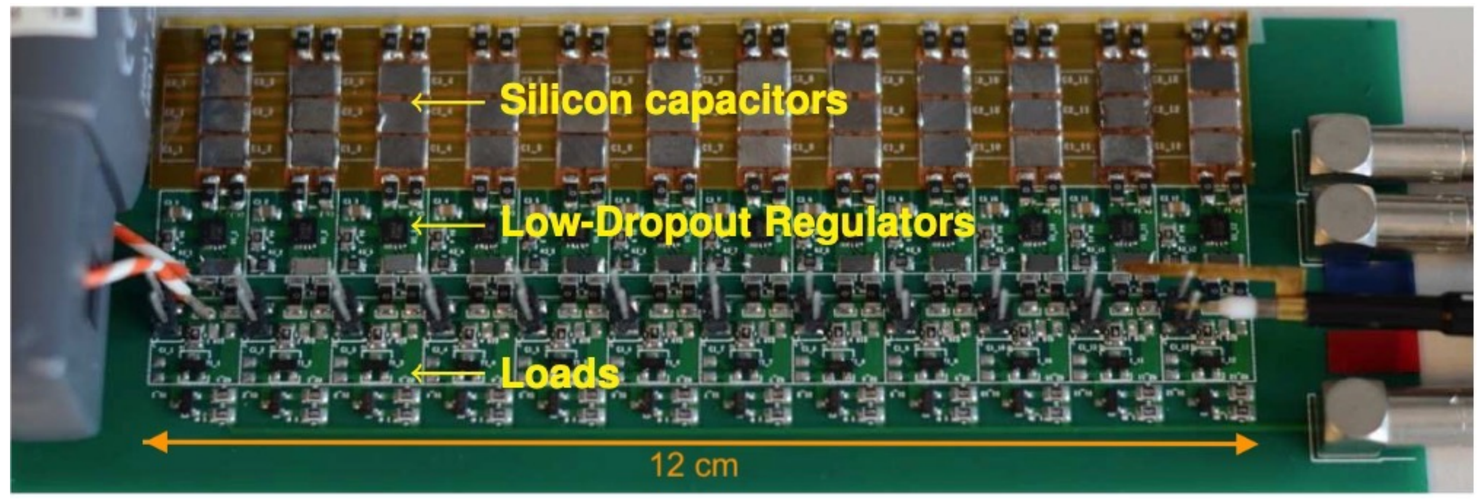


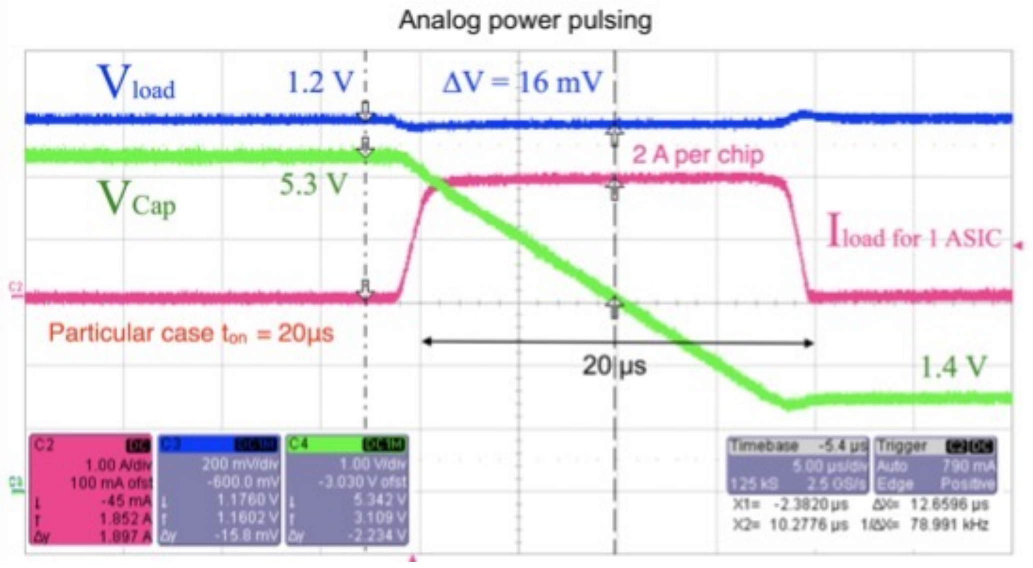
Experimental setup tested with FPGA-controlled current source and on-detector silicon capacitors at each ASIC.

Combined power dissipation stays below 50mW/cm² target

Cables/regulators/capacitors contributions to material budget at 0.1%X_0

Operated in magnetic field up to 1.5T without performance loss





Detector Technologies for CLIC: https://arxiv.org/abs/1905.02520

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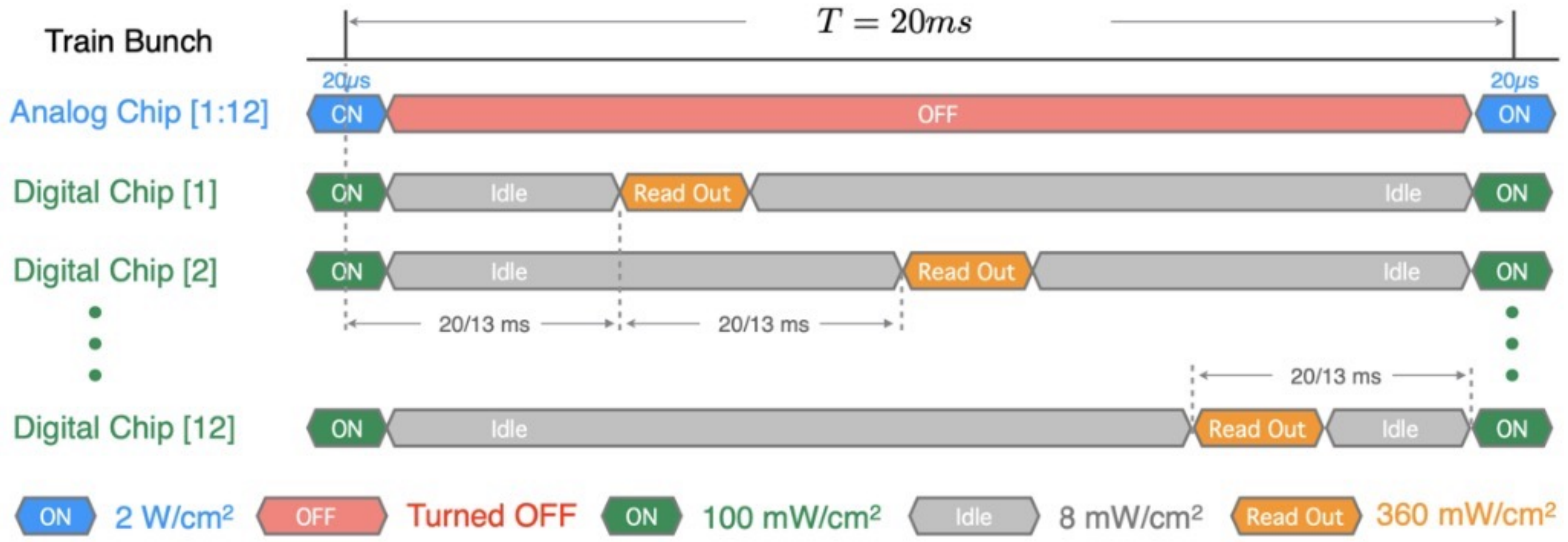

ILC: few ms for acquisition, switch off after read-out
C3: few µs for power on/off.
EMI effects? Pulsing in 5T field?

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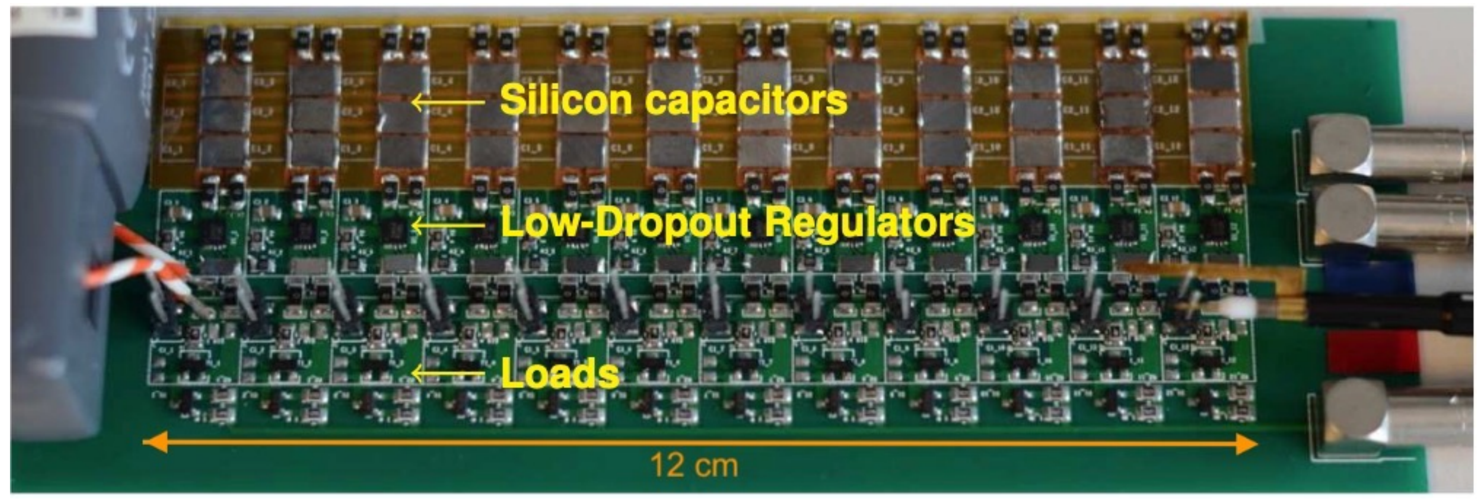

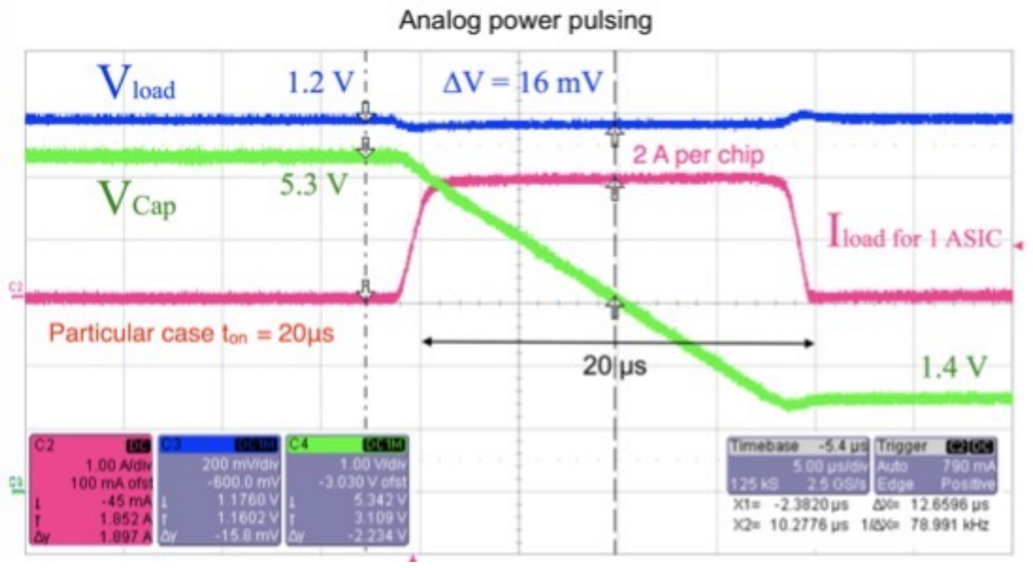

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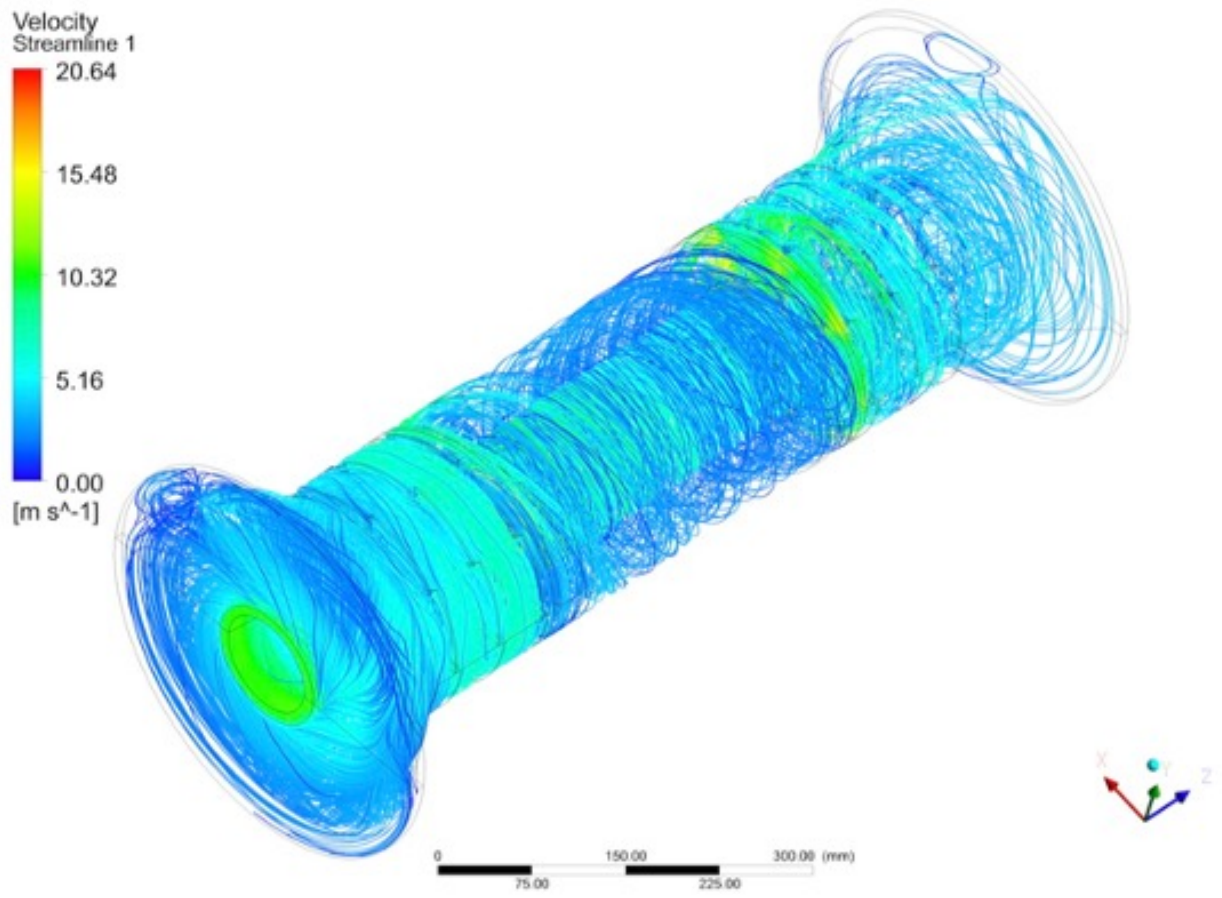
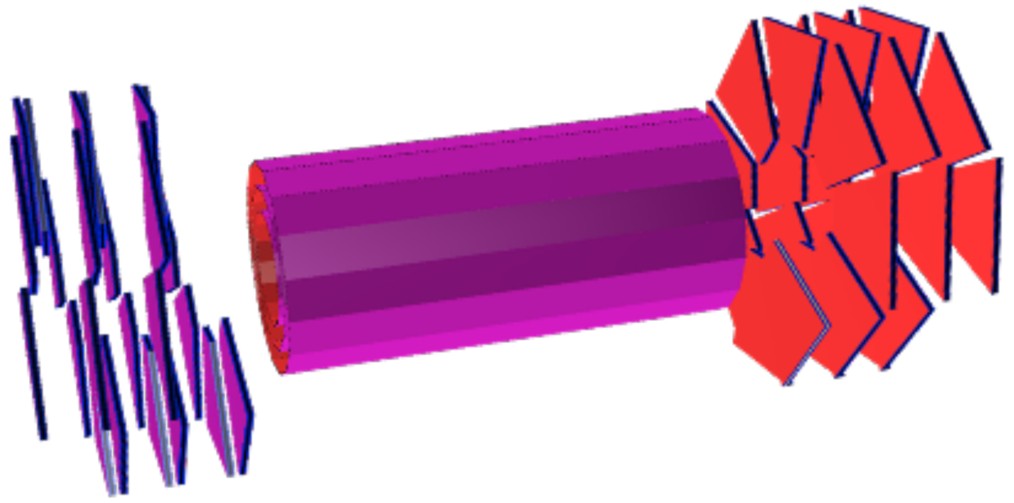
CLIC Vertex Detector

Air cooling tests

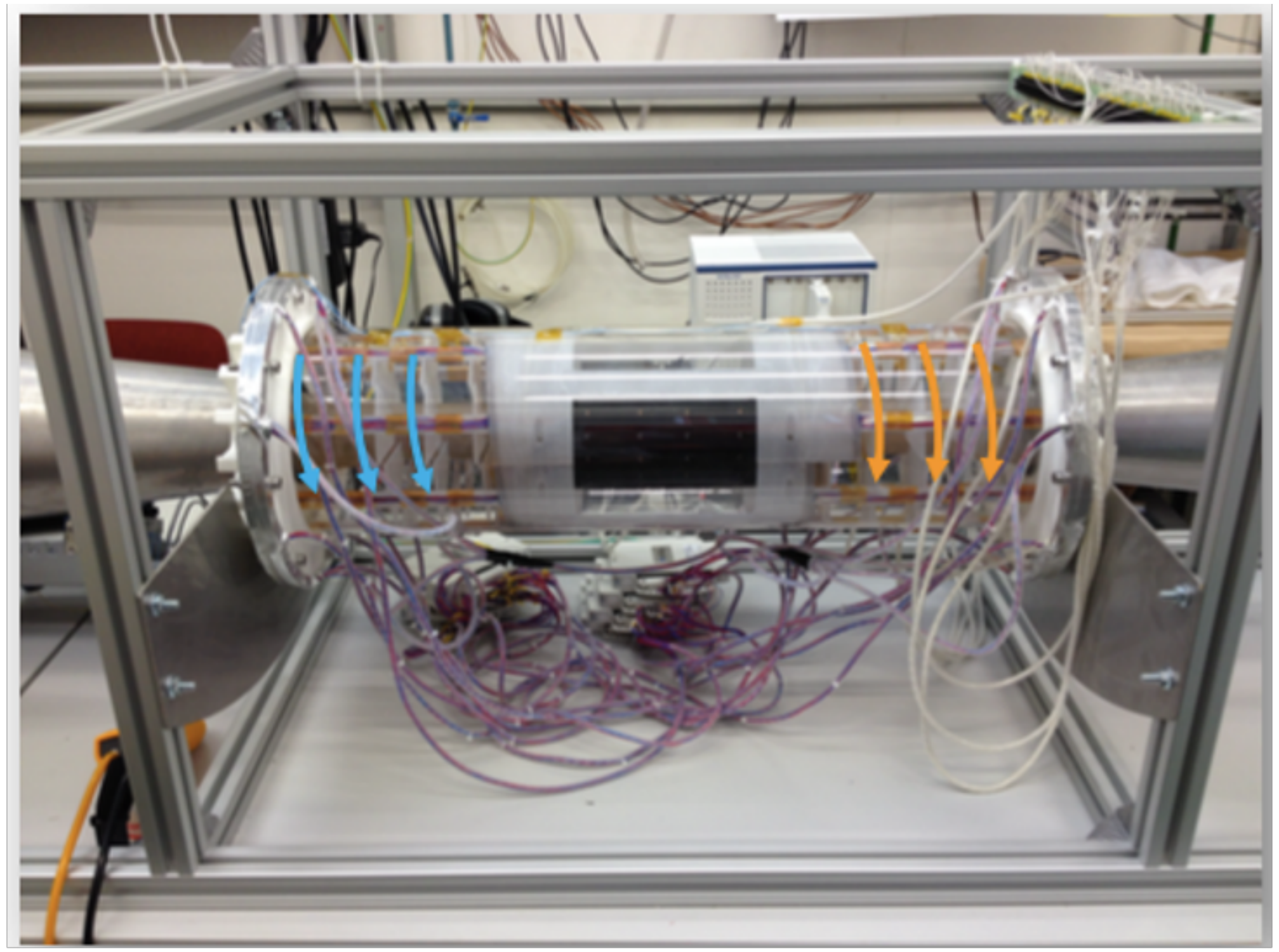
CLIC vertex detector proposed to be air-cooled to reduce material budget
Spiral endcap design with forced air flow
Feasibility studied using computational fluid dynamics, validated by experimental studies
1:1 scale mock-up of vertex detector performance in wind tunnel measured
Thermal simulations reproduce measured data within a few degrees.



fluid dynamics simulation:
velocity streamlines of forced air flow



vertex detector spiral endcap geometry



1:1 scale mock-up studied in wind tunnel

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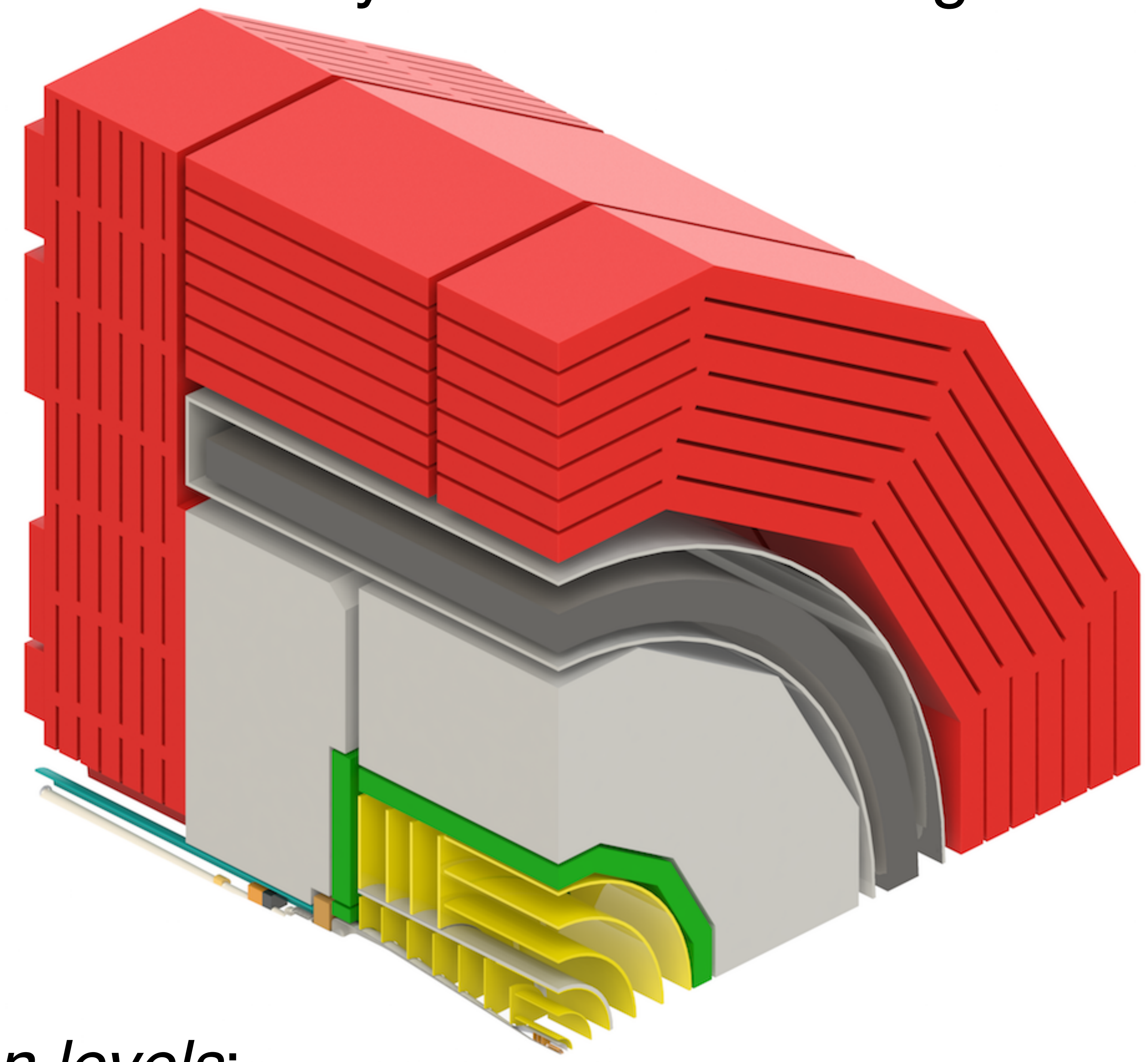
Occupancies and Radiation

Higher for CLIC - Put in Focus here

- In general the radiation environment and the particle density at Linear Colliders is benign compared to HL-LHC - but not fully free from challenges. The most stringent requirements are imposed by CLIC 3 TeV



Hit rates

Energy stage	380 GeV		3 TeV	
Subdetector	Minimum Hits[1/mm^2/train]	Maximum Hits[1/mm^2/train]	Minimum Hits[1/mm^2/train]	Maximum Hits[1/mm^2/train]
Vertex barrel	0.2	3.2	0.6	8.8
Vertex endcaps	0.1	2.7	0.2	8.8
Tracker barrel	0.0003	0.03	0.002	0.1
Tracker endcaps	0.0004	0.1	0.002	0.6

Background energy

Energy stage	380 GeV		3 TeV	
Subdetector	Incoherent pairs [GeV/train]	$\gamma\gamma \rightarrow$ hadrons [GeV/train]	Incoherent pairs [GeV/train]	$\gamma\gamma \rightarrow$ hadrons [GeV/train]
ECAL barrel	3.6	2.1	14	52
ECAL endcaps + plugs	11.1	9.4	39	252
HCAL barrel	0.05	0.18	0.22	5.0
HCAL endcaps	2874	7.0	11 790	312
Total ECAL+HCAL	2889	19	11 840	621
LumiCal	68.5	4.5	283	193
BeamCal	54 730	5.6	270 600	540

Radiation levels:

- inner vertex: 6 x 10^{10} n_{eq}/cm^2/year; 300 Gy/year
- ECAL endcaps: 2 x 10^{11} n_{eq}/cm^2/year; ~ 10 Gy/year
- BeamCal: 1.4 x 10^{14} n_{eq}/cm^2/year; ~ 7 MGy/year

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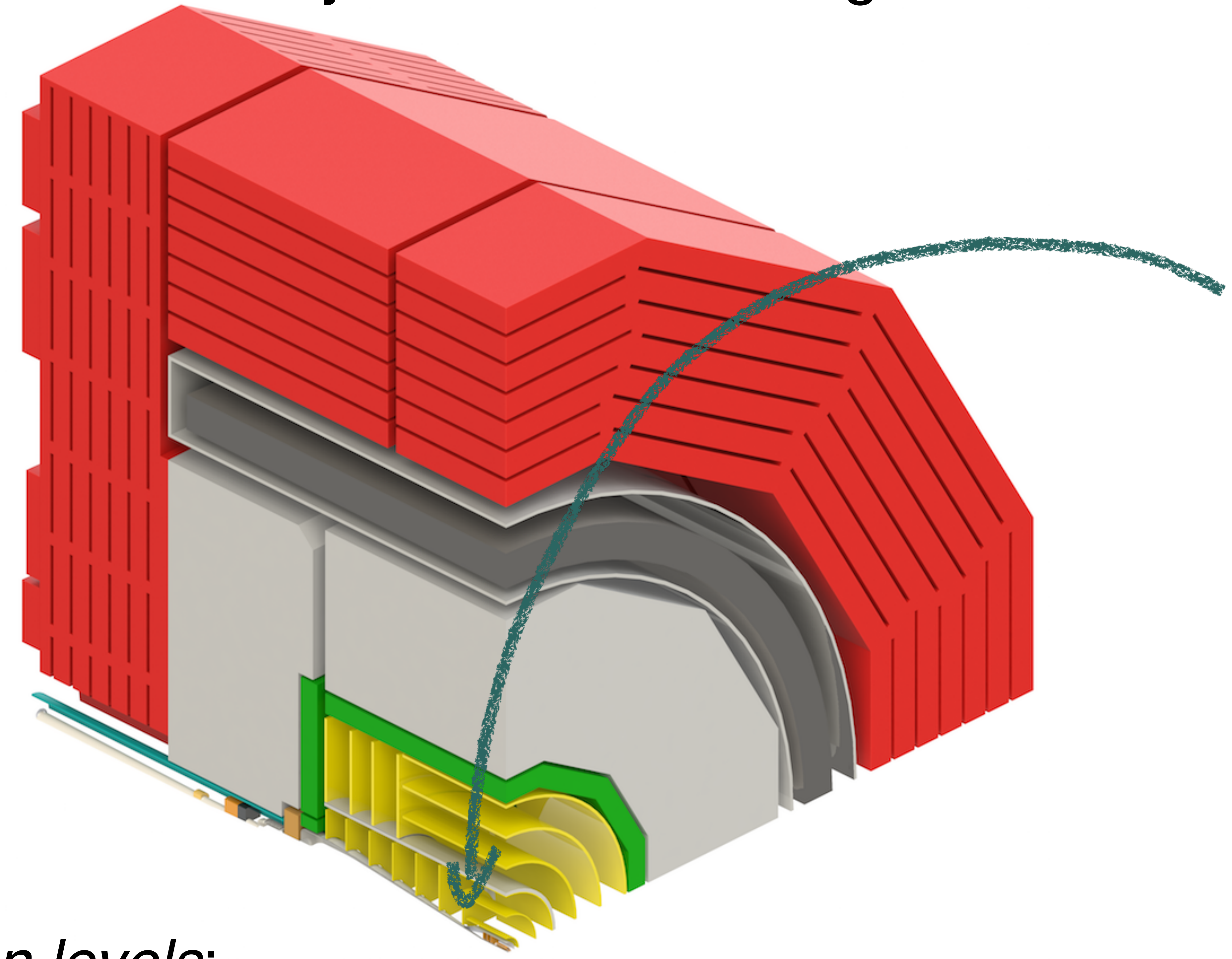

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Subdetector	Incoherent pairs [GeV/train]	$\gamma\gamma \to$ hadrons [GeV/train]	Incoherent pairs [GeV/train]	$\gamma\gamma \to$ hadrons [GeV/train]
ECAL barrel	3.6	2.1	14	52
ECAL endcaps + plugs	11.1	9.4	39	252
HCAL barrel	0.05	0.18	0.22	5.0
HCAL endcaps	2874	7.0	11 790	312
Total ECAL+HCAL	2889	19	11 840	621
LumiCal	68.5	4.5	283	193
BeamCal	54 730	5.6	270 600	540

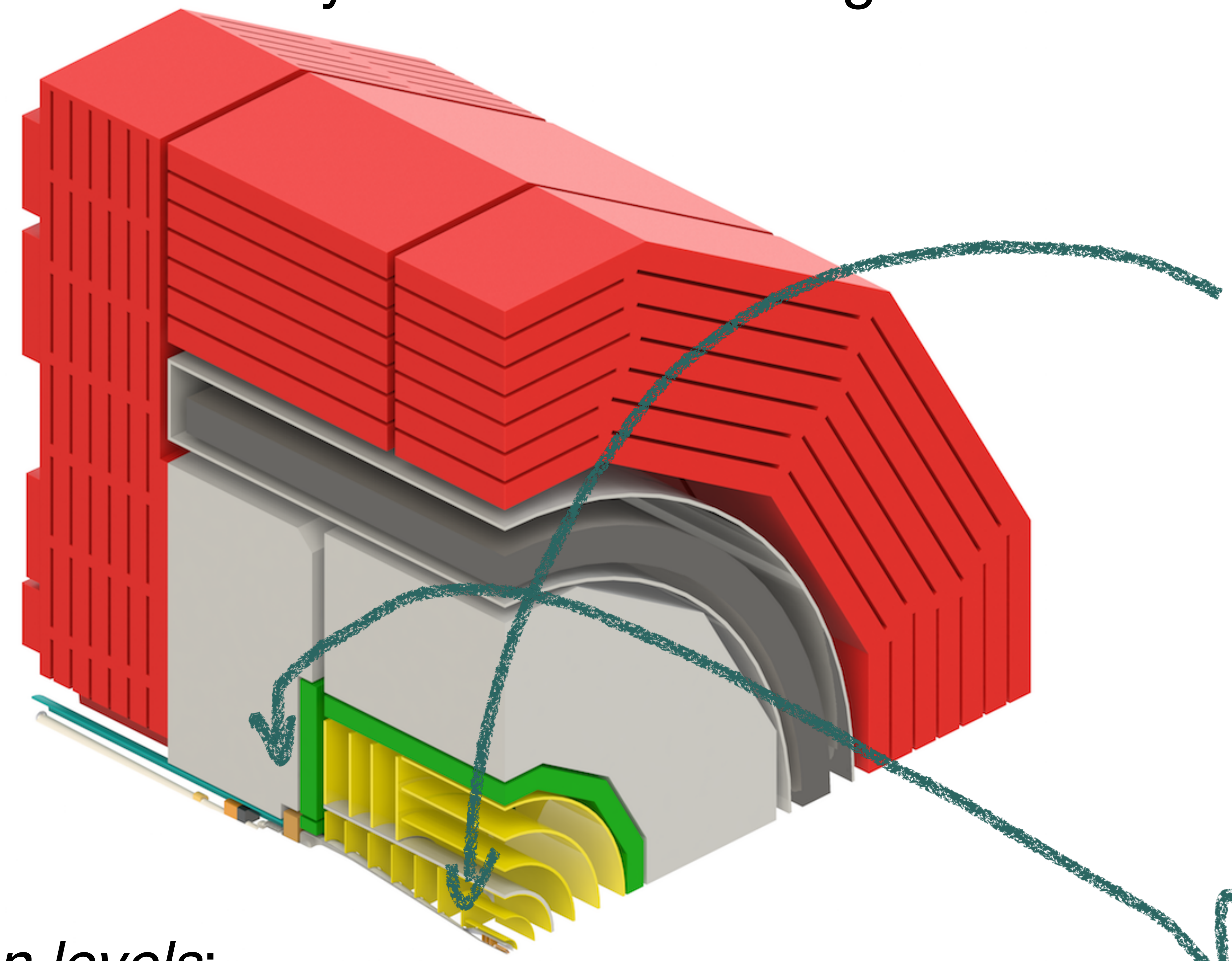
Radiation levels:

- inner vertex: 6 x 10^{10} n_{eq}/cm^2/year; 300 Gy/year
- ECAL endcaps: 2 x 10^{11} n_{eq}/cm^2/year; ~ 10 Gy/year
- BeamCal: 1.4 x 10^{14} n_{eq}/cm^2/year; ~ 7 MGy/year

Occupancies and Radiation

Higher for CLIC - Put in Focus here

- In general the radiation environment and the particle density at Linear Colliders is benign compared to HL-LHC - but not fully free from challenges. The most stringent requirements are imposed by CLIC 3 TeV



Hit rates

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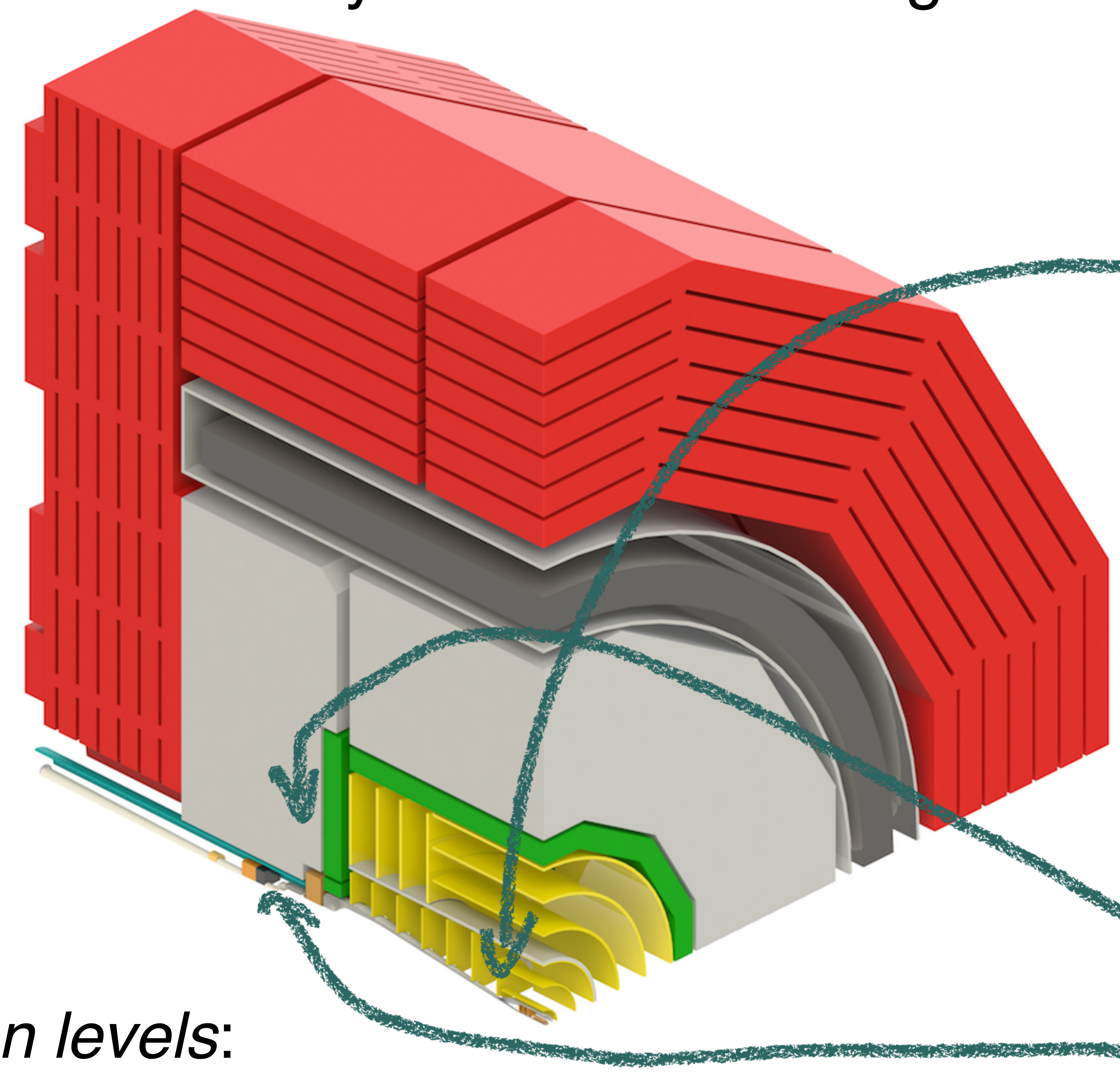

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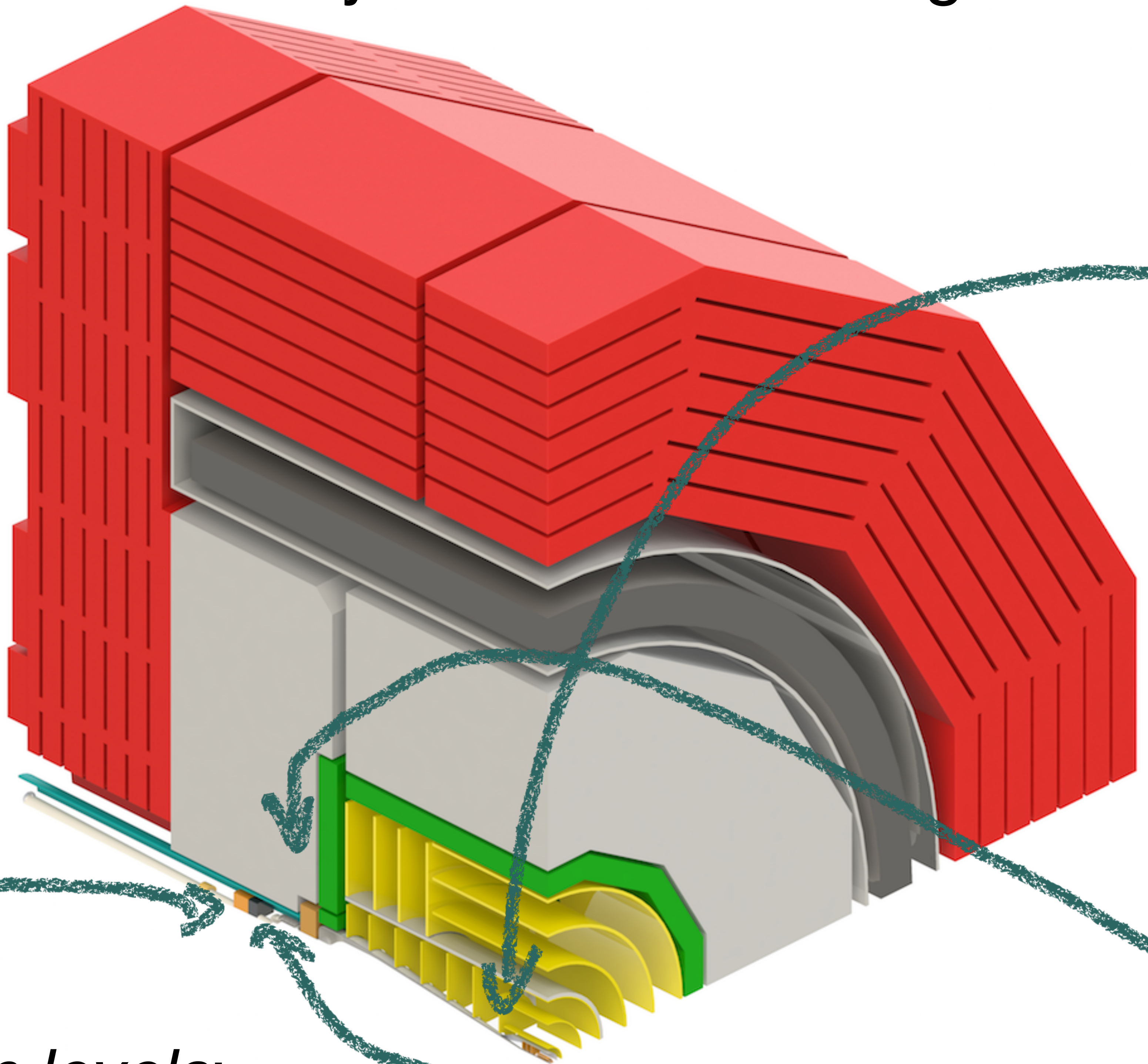

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Technologies for Linear Colliders

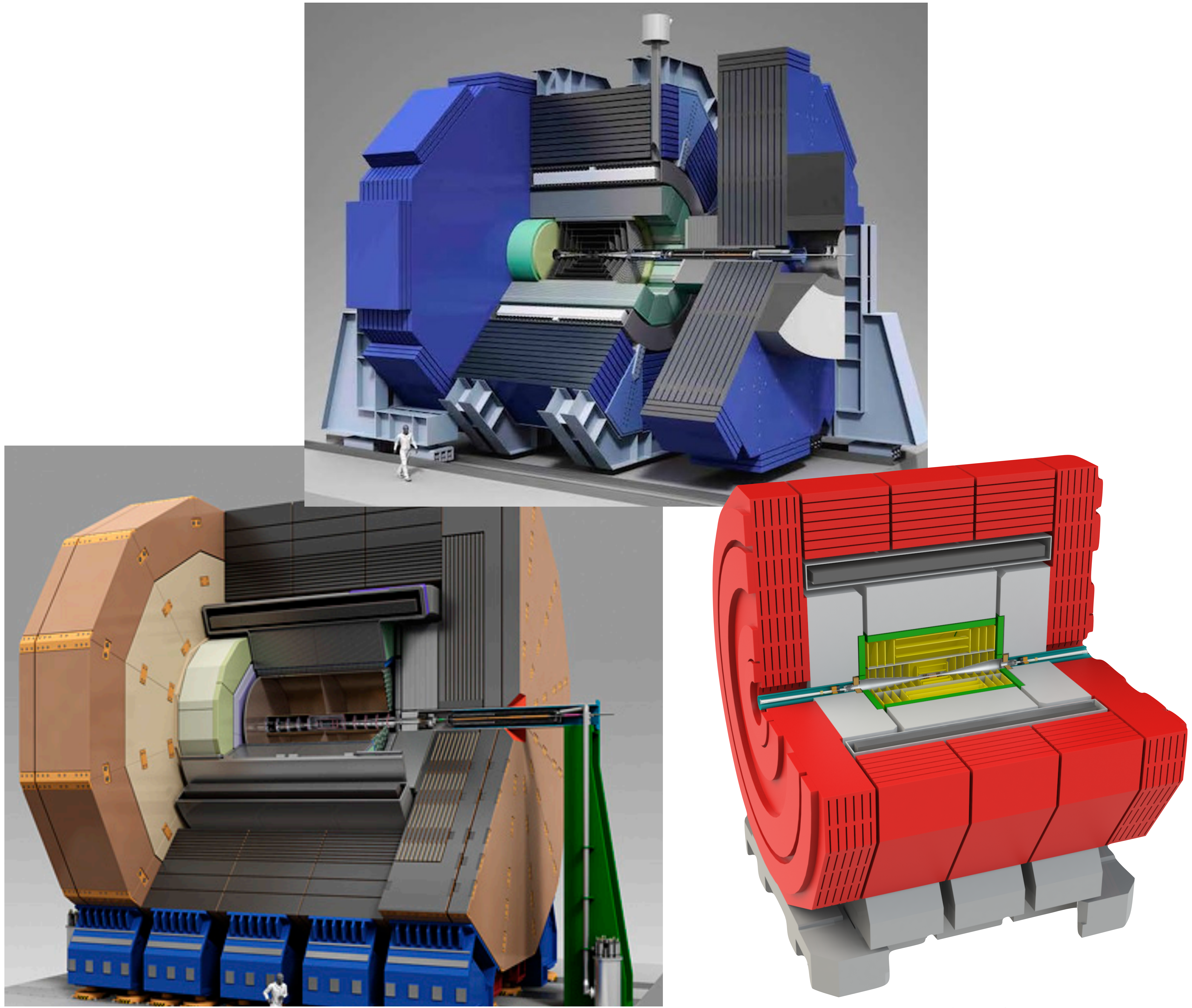
Successful development addressing many key challenges

Key technologies for linear collider detector baselines have been developed and demonstrated in prototypes and test beams - many, but not all central requirements met [but there is always potential for improvement!]

+ activities in different R&D initiatives and consortia, such as EU funded projects EUDET, AIDA, AIDA-2020 and most recently AIDA-Innova

Beyond the Baseline

Possible Ideas going beyond current technology & ideas



particle ID systems - improved flavour tagging with better π/K separation via TOF or other means

added readout dimensions in calorimetry: highly granular dual readout, new optical materials

exploiting ps timing capabilities in calorimeters and trackers

highly pixelated sensors throughout all silicon systems of the detectors

New radiation hard sensor materials for forward instrumentation

Ultra-low mass mechanics, ultra-low mass & ultra-low power interfaces and services

Focus Topics

General areas of particular importance for Linear Colliders

You are here

Significant development of detector technologies in the context of Linear Colliders in the last decades - some, but not all key requirements met

Focus Topics

General areas of particular importance for Linear Colliders

Improved performance:

- Higher granularity & spatial resolution
- Better time resolution
- Faster readout
- Lower noise
- ....

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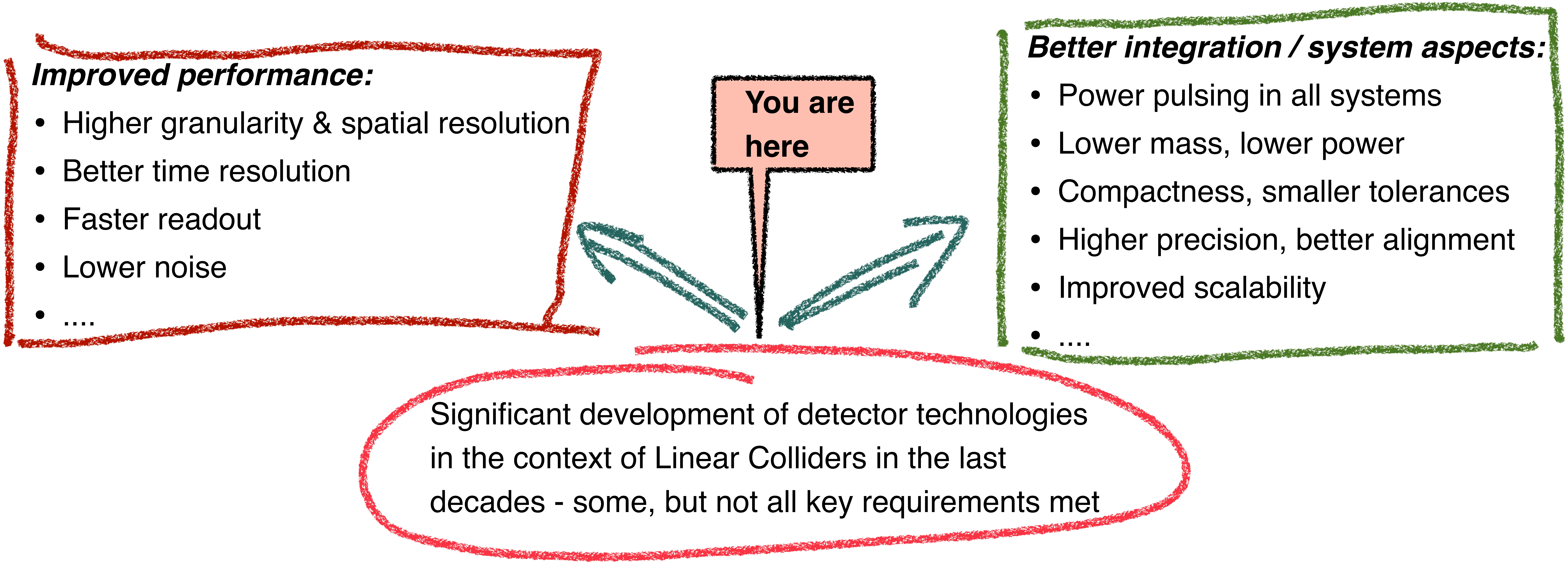

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Better integration / system aspects:

- Power pulsing in all systems
- Lower mass, lower power
- Compactness, smaller tolerances
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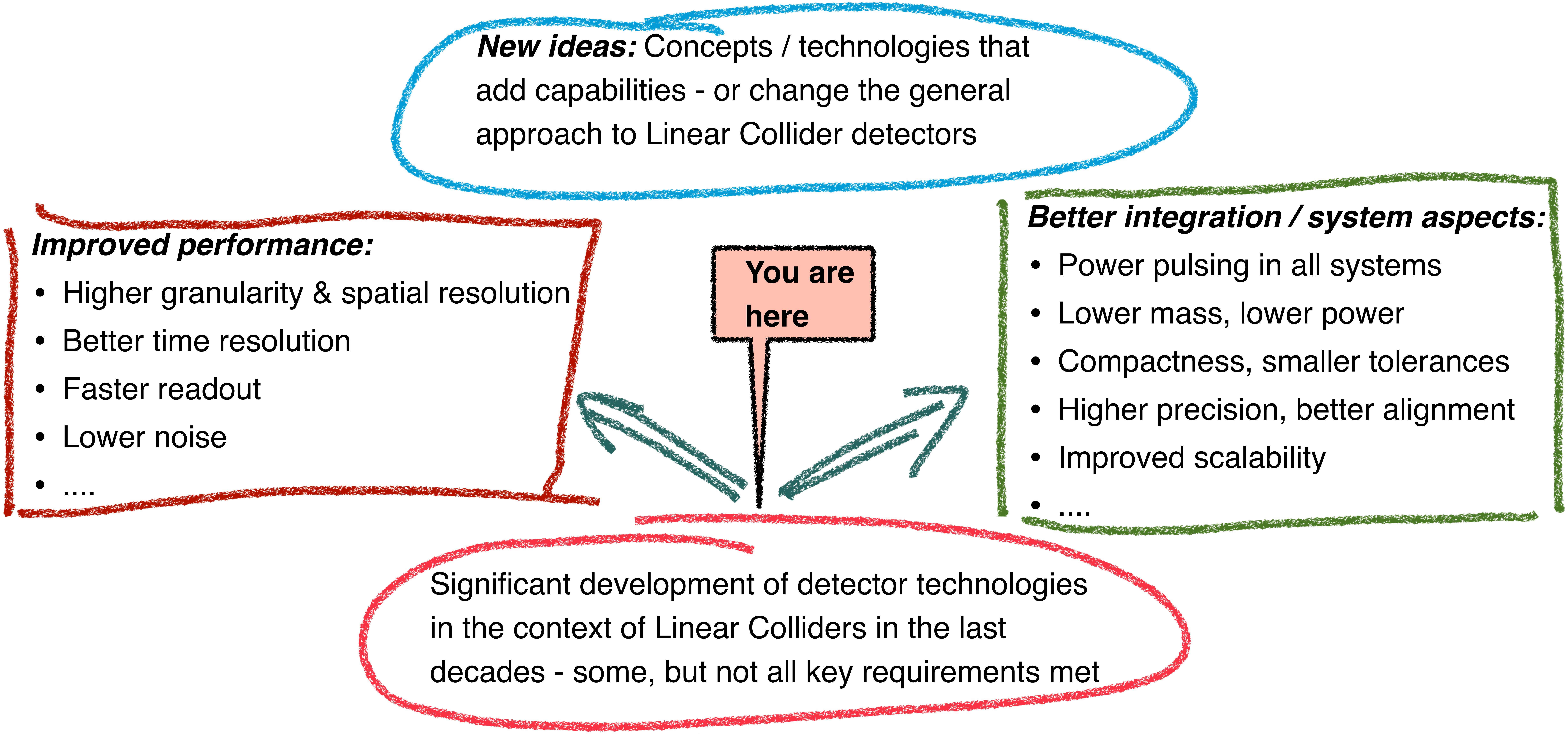

New ideas: Concepts / technologies that add capabilities - or change the general approach to Linear Collider detectors

Improved performance:

- Higher granularity & spatial resolution
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Summary

- The detector concepts for Linear Colliders (ILC and CLIC), CLICdet, ILD, SiD are based on the particle flow paradigm, with highly granular calorimeters and light-weight, high-precision tracking
- Ambitious precision goals and beam-induced backgrounds drive granularity and timing requirements
- Powerpulsing, allowed by the linear collider bunch train structure, is central to achieving low material by eliminating the need for cooling
- adaption to C3 environment should be doable, but needs work

- In an extensive R&D program, technologies for linear collider detectors have been developed and demonstrated in test beams, meeting some but not all performance goals
- R&D is still needed to meet all requirements, and also has the potential to further improve the performance beyond the current baseline

- **also relatively mature detector concepts remain open to new ideas & technologies!**
- need another benchmarking excercise to reduce options?

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Many thanks to
F.Simon,
A. Robson,
R. Pöschl,
V. Boudry
A. White,
W. Lohmann
and many others
who contributed

Documents & Contacts- CLIC

Project Overview & Detector Needs

- The CLIC project, https://arxiv.org/abs/2203.09186
- Compact High-level Summary for ESPPU:
  The Compact Linear e+e- Collider (CLIC): Accelerator and Detector (arXiv:1812.07987)
  https://arxiv.org/abs/1812.07987
- Detector technologies for CLIC (CERN-2019-001, arXiv:1905.02520)
  http://dx.doi.org/10.23731/CYRM-2019-001
- CLIC 2018 Summary Report (CERN-2018-005-M, arXiv:1812.06018)
  http://dx.doi.org/10.23731/CYRM-2018-002
- A detector for CLIC: main parameters and performance (arXiv:1812.07337)
  https://cds.cern.ch/record/2649437
- CLICdet: The post-CDR CLIC detector model; https://cds.cern.ch/record/2254048

Main contacts:

Aidan Robson (aidan.robson@glasgow.ac.uk)

Lucie Linssen (lucie.Linssen@cern.ch)

Documents & Contacts- ILC

Project Overview & Detector Needs

- The International Linear Collider: Report to Snowmass 2021 https://arxiv.org/abs/2203.07622
- The International Linear Collider: A Global Project https://arxiv.org/abs/1903.01629
  - Compact Summary for ESPPU: https://arxiv.org/abs/1901.09829
- The International Linear Collider Machine Staging Report 2017 https://arxiv.org/abs/1711.00568
- The International Linear Collider Technical Design Report - Volume 1: Executive Summary https://arxiv.org/abs/1306.6327
- The International Linear Collider Technical Design Report - Volume 4: Detectors https://arxiv.org/abs/1306.6329
- International Large Detector: Interim Design Report https://arxiv.org/abs/2003.01116
- Linear Collider Collaboration Detector R&D Report https://doi.org/10.5281/zenodo.3749461

Main contacts:

ILD: Ties Behnke (ties.behnke@desy.de)

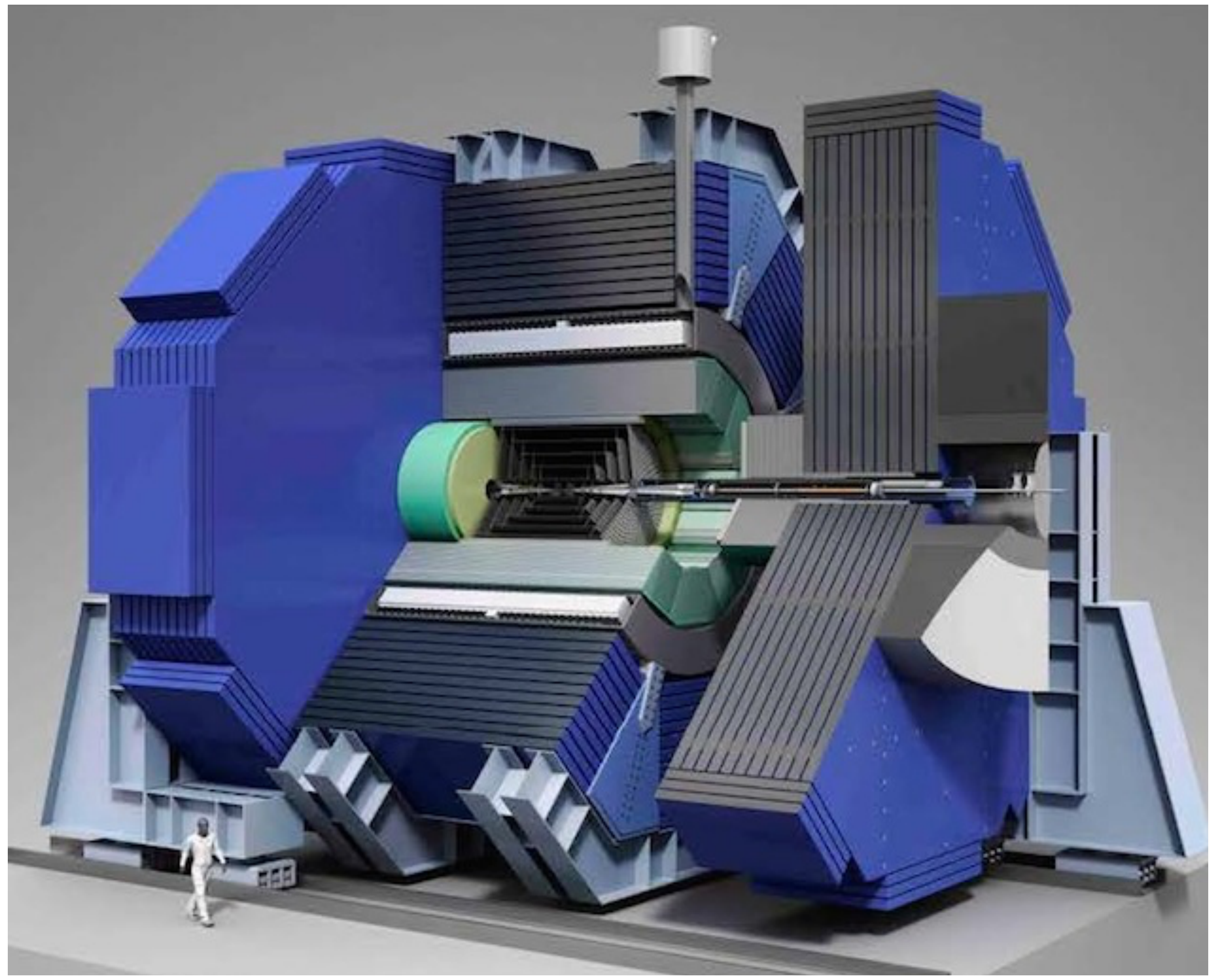
SiD: Andy White (awhite@uta.edu), Marcel Stanitzki (marcel.stanitzki@desy.de)

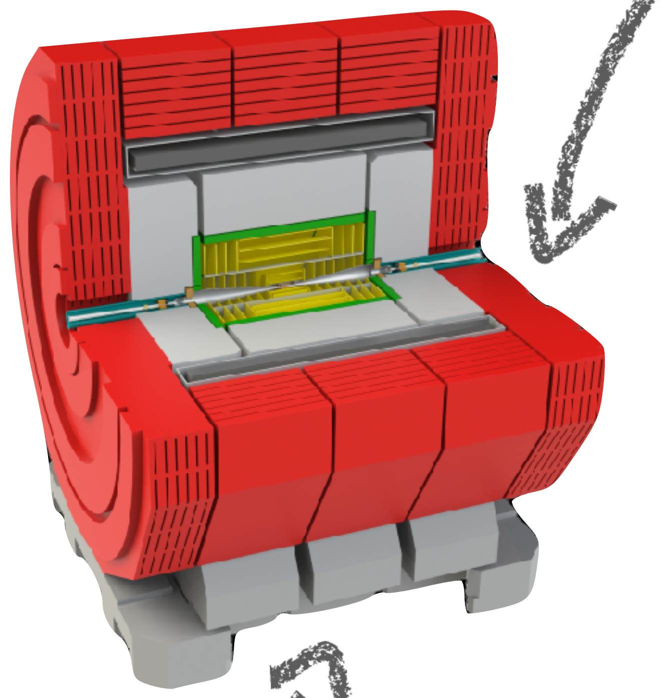
Extras

The Linear Collider Detector Design

Variations of the main design

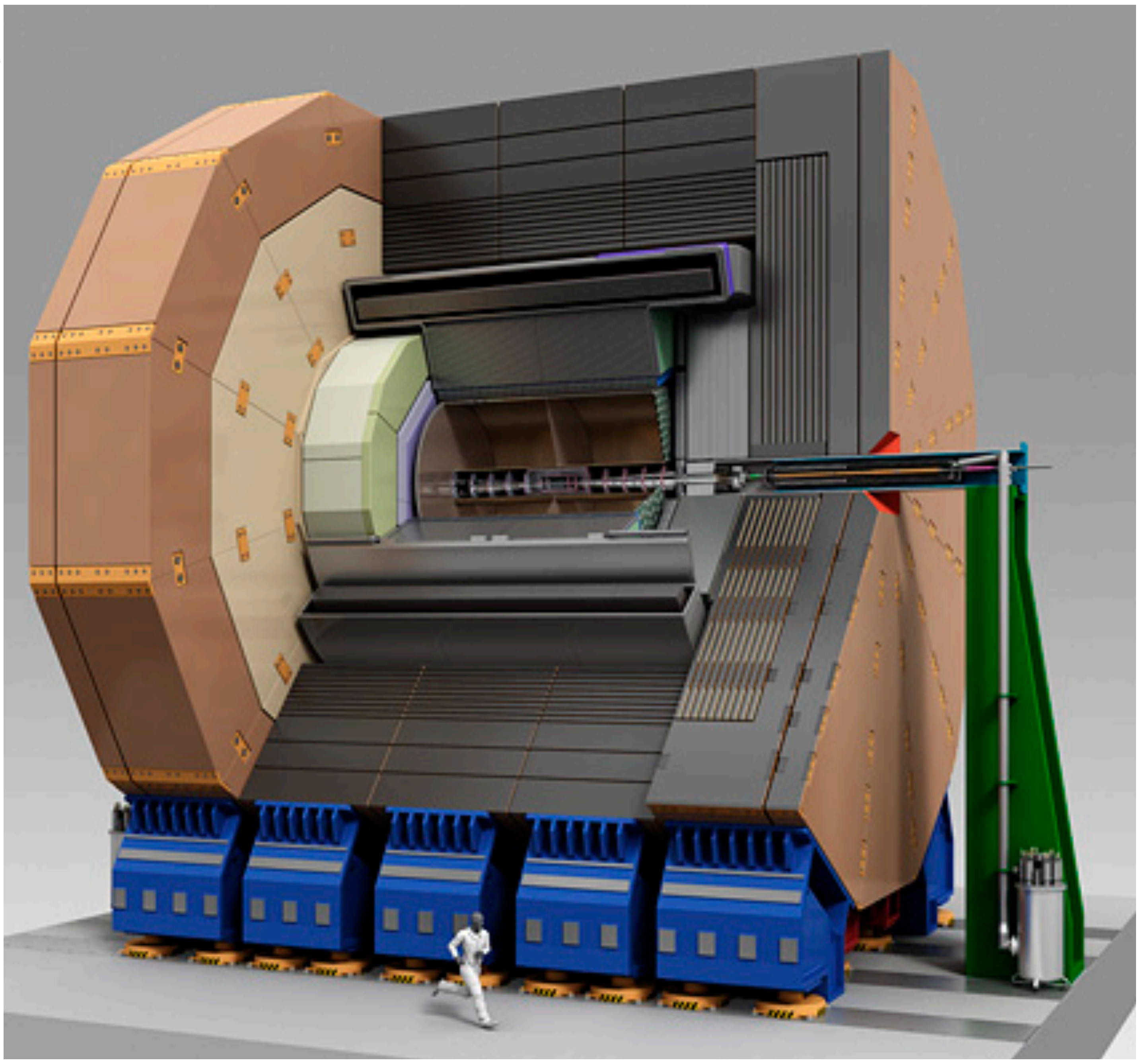
- Two detector concepts for ILC: SiD, ILD - with somewhat different optimisation





larger volume

more compact



For ILD: 2 versions
(large / small)
under study

5T field

all-Si tracker with outer radius of 1.2 m

VTX inner radius 14 mm

4.5 λ_I HCAL

- 3.5T / 4T field
- TPC as main tracker, supplemented by outer Si envelope radius 1.77 m / 1.43 m
- VTX inner radius 16 mm
- 6 λ_I HCAL

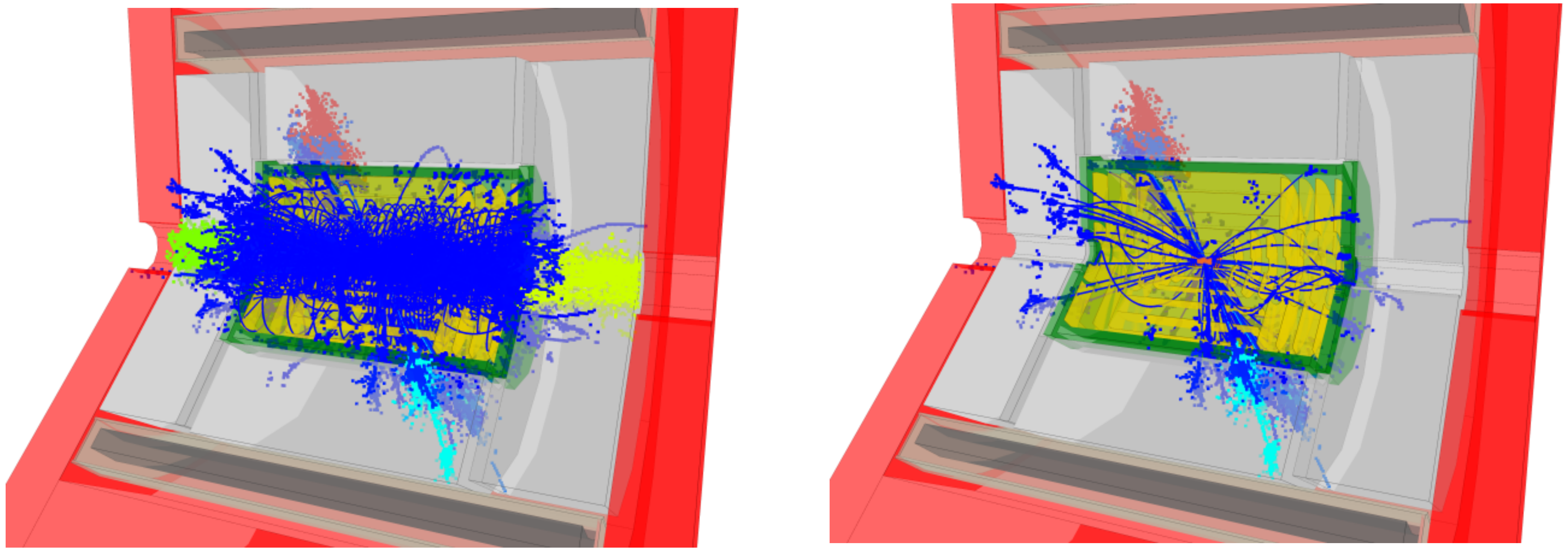
Detector Parameters

	ILD (IDR_L/IDR_S)	**SiD**	**CLICdet**	**CLD**	**IDEA**	**CEPC baseline**
Vertex technology	Silicon	Silicon	Silicon	Silicon	Silicon	Silicon
Vertex inner radius	1.6 cm	1.4 cm	3.1 cm	1.75 cm	1.7 cm	1.6 cm
Tracker technololy	TPC + Silicon	Silicon	Silicon	Silicon	Drift chamber + Si	TPC + Silicon
Tracker outer radius	1.77 m / 1.43 m	1.22 m	1.5 m	2.1 m	2.0 m	1.8 m
Calorimeter	PFA	PFA	PFA	PFA	Dual readout	PFA
(ECAL) inner radius	1.8 m / 1.46 m	1.27 m	1.5 m	2.15 m	2.5 m	1.8 m
ECAL technology	Silicon	Silicon	Silicon	Silicon	-	Silicon
ECAL absorber	W	W	W	W	-	W
ECAL thickness	24 X_0 (30 layers)	26 X_0 (30 layers)	22 X_0 (40 layers)	22 X_0 (40 layers)	-	24 X_0 (30 layers)
HCAL technology	Scintillator	Scintillator	Scintillator	Scintillator	-	RPC
HCAL absorber	Fe	Fe	Fe	Fe	-	Fe
HCAL thickness	5.9 λ_I (48 layers)	4.5 λ_I	7.5 λ_I (60 layers)	5.5 λ_I (44 layers)	8 λ_I (2 m)	4.9 λ_I (40 layers)
(HCAL) outer radius	3.34 m / 3.0 m	2.5 m	3.25 m	3.57 m	≤4.5 m	3.3 m
Solenoid field	3.5 T / 4 T	5 T	4 T	2 T	2 T	3 T
Solenoid length	7.9 m	6.1 m	8.3 m	7.4 m	6.0 m	8.0 m
Sol. inner radius	3.42 m / 3.08 m	2.6 m	3.5 m	3.7 m	2.1 m	3.4 m

Constraints Imposed by Machine Conditions

Backgrounds

- Backgrounds - a key driver at CLIC:
  γγ -> hadrons results in significant backgrounds in the full acceptance of the detector



3 TeV tt event at CLIC, with background overlaid, and removed by reconstruction

➯ Requires timing on the ns level, high segmentation and powerful reconstruction techniques

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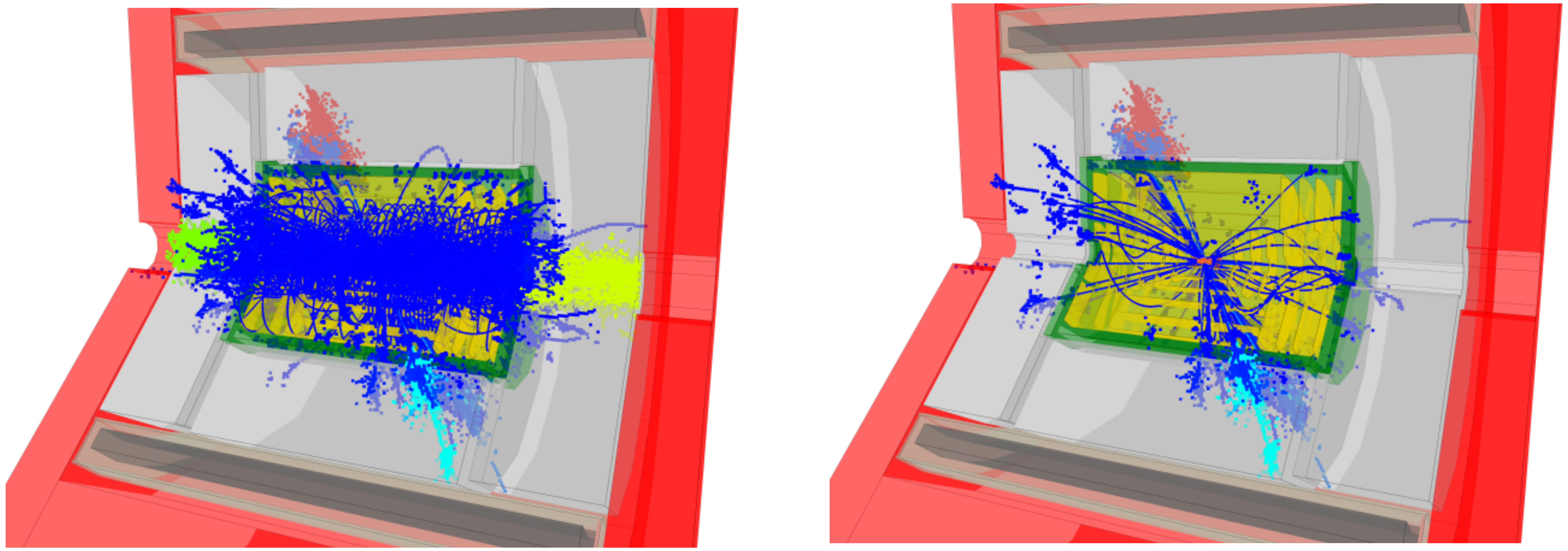

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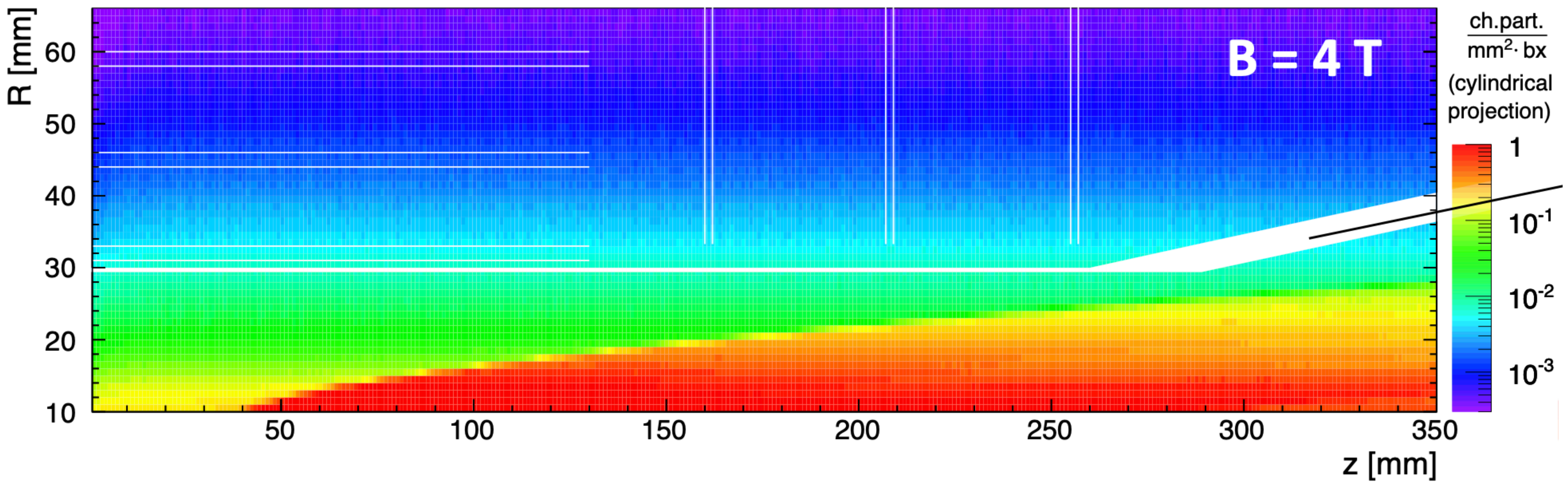
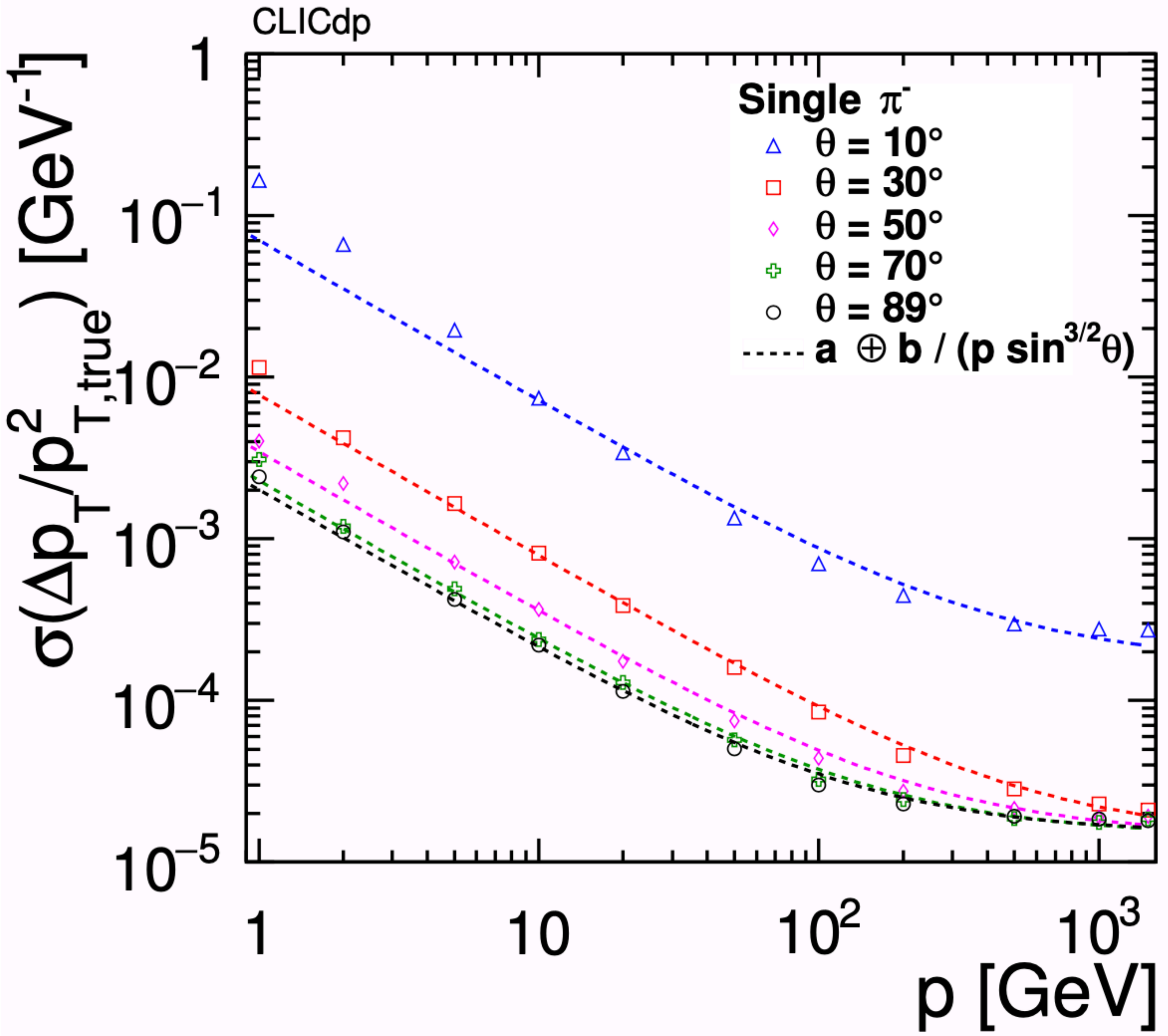


- Significant background from e^+e^- pairs - imposes constraints on beam pipe radius, vertex detector location:

➩ High magnetic field to enable small radius

Exploiting the Detector Capabilities

A few examples: Tracking and flavor tagging



- Momentum resolution well within specs for all concepts - with slight differences depending on size, magnetic field and material
  - Material wins at low p, field and single point resolution at high p

☞ see Emilia Leogrande earlier today

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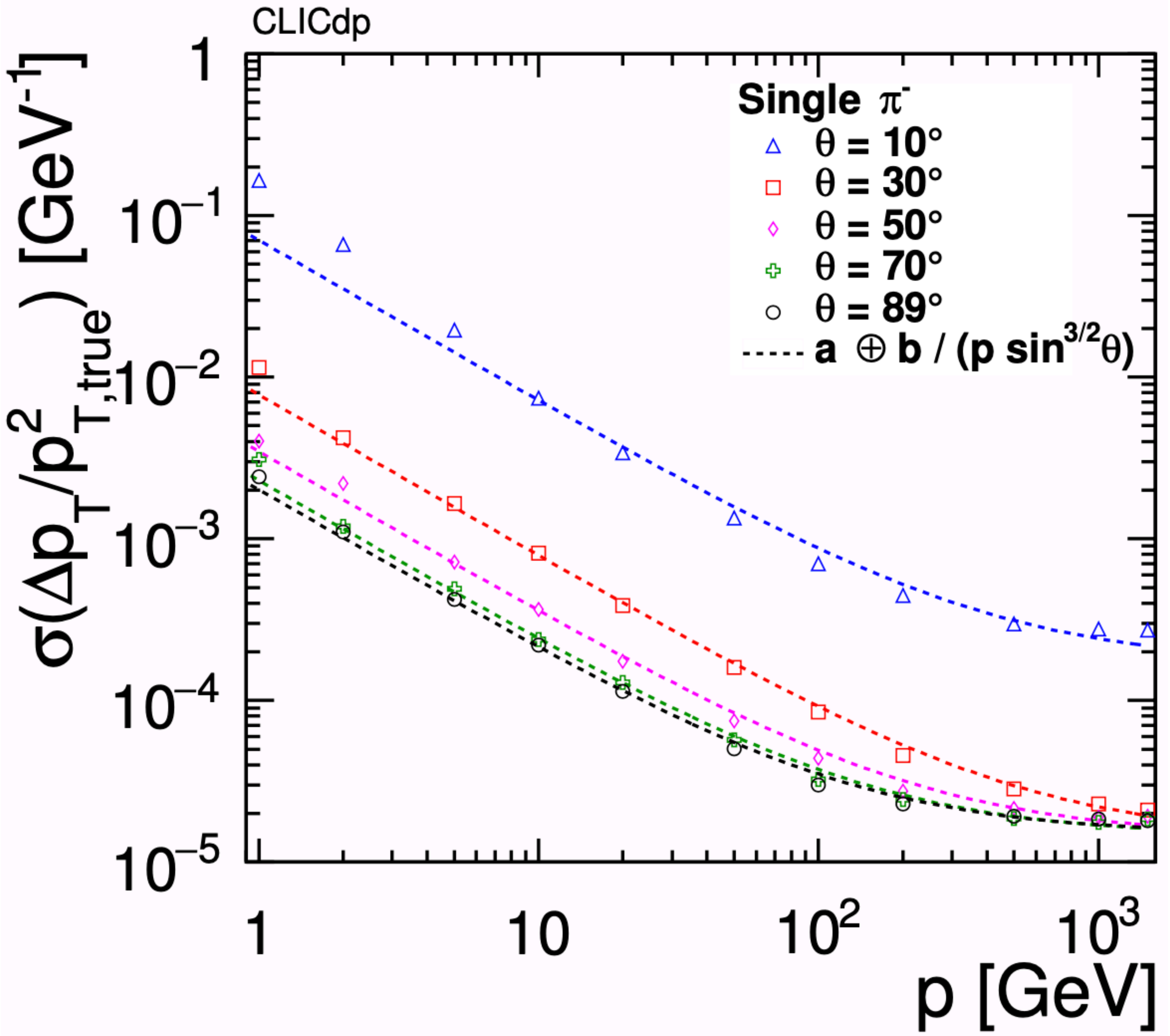

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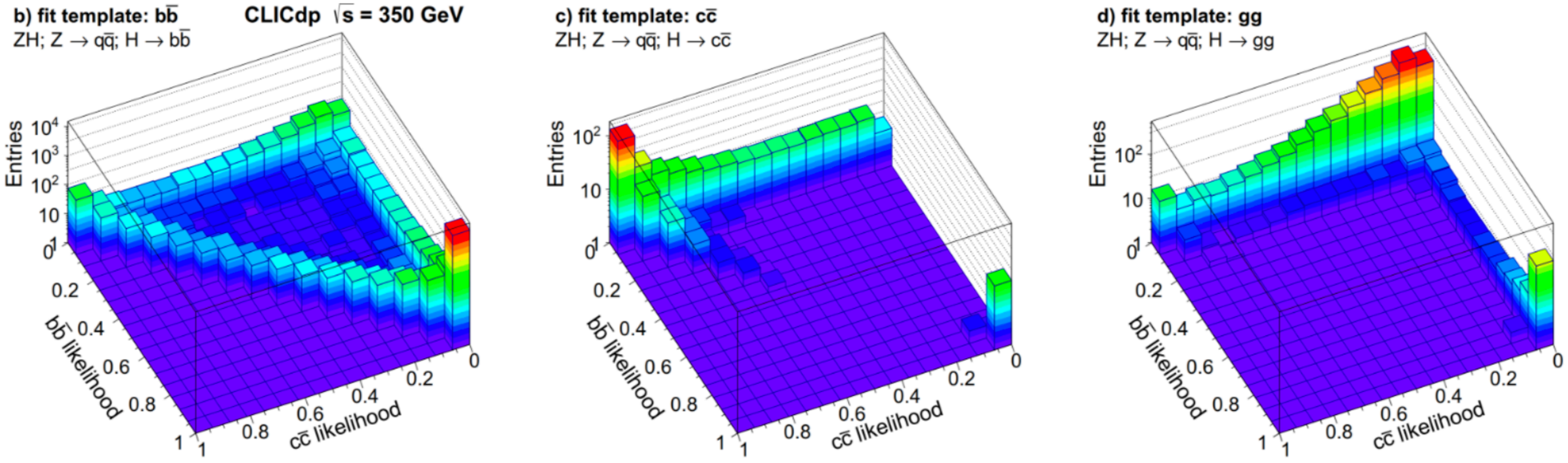
- Excellent flavor tagging: Separation of b, c, g jets from Higgs

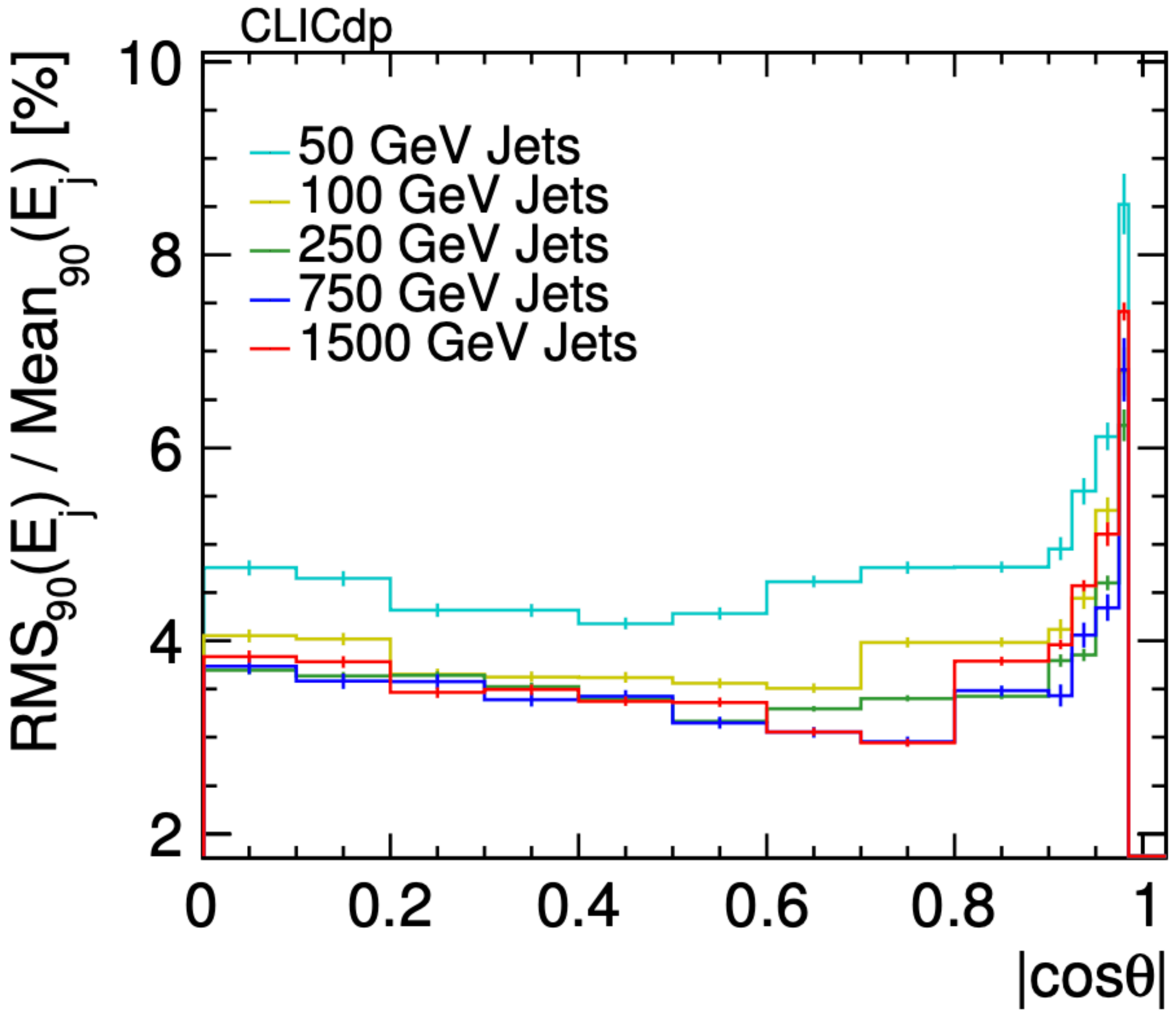


H→$b\bar{b}$ **H→$c\bar{c}$** **H→gg**

- Similar for the three concepts - impact factor resolution at low p profits from smaller radius of ILC vertex detectors

Exploiting the Detector Capabilities

A few examples: Jets & PFA



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Performance drivers:
Calo granularity,
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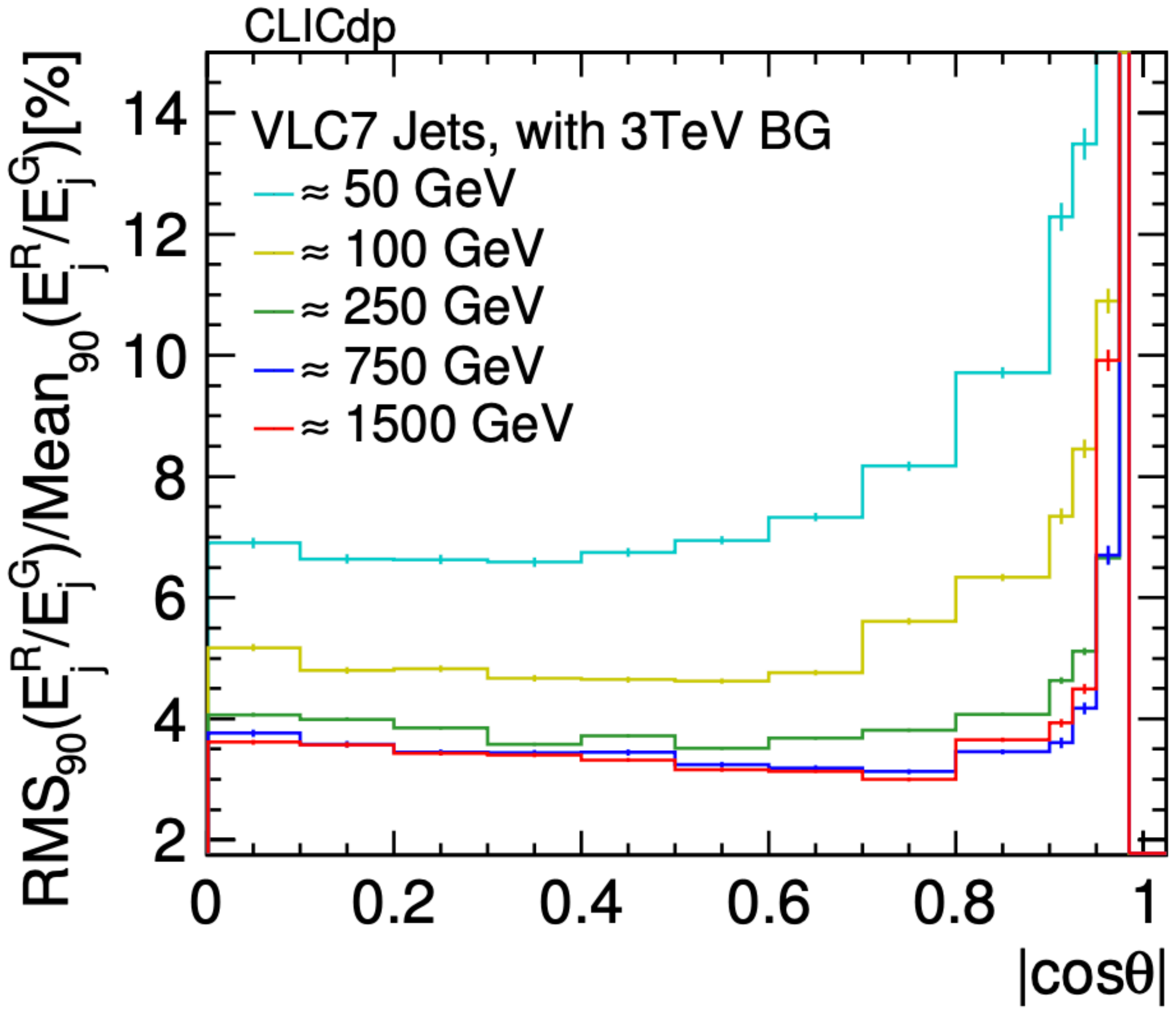

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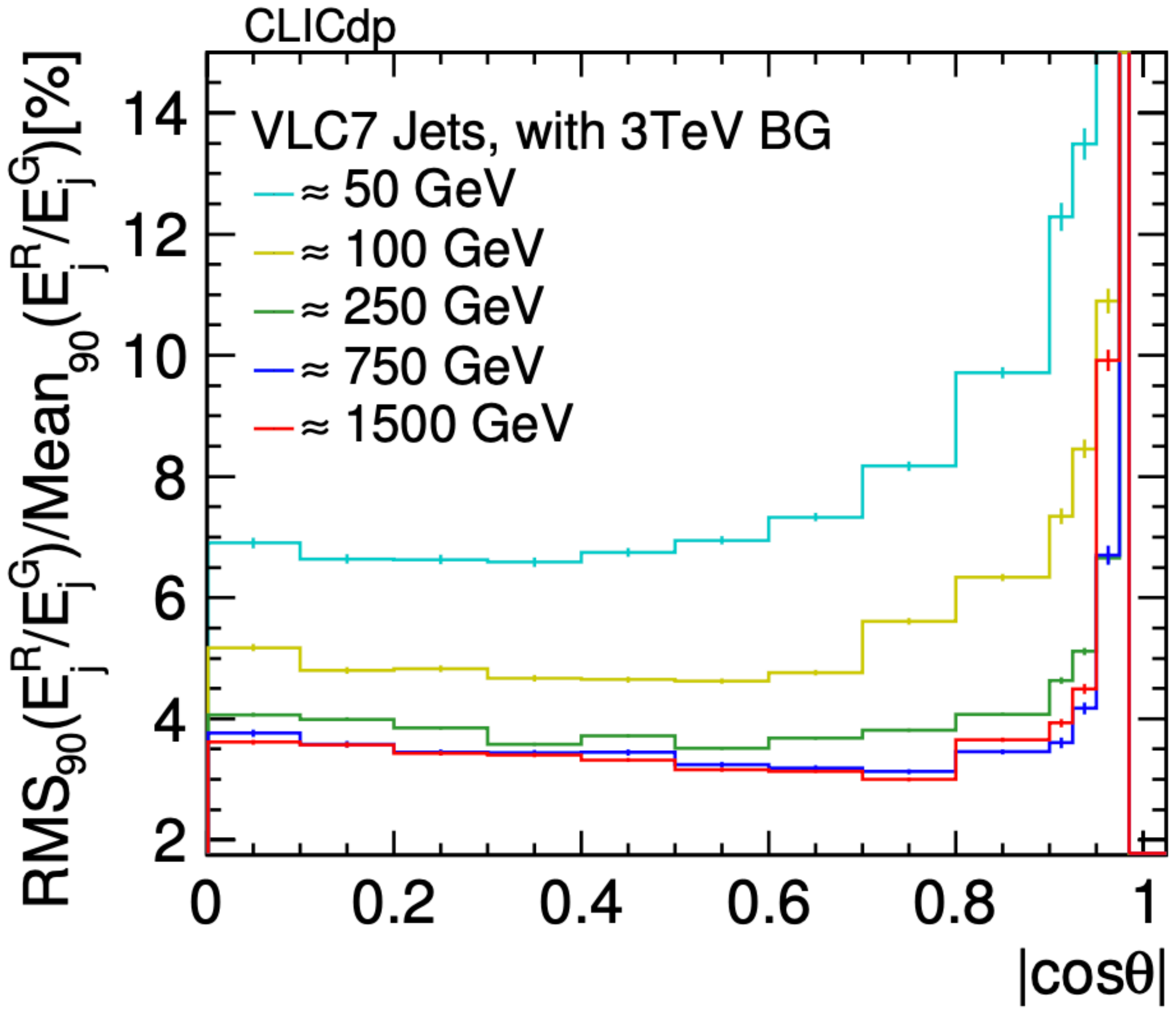

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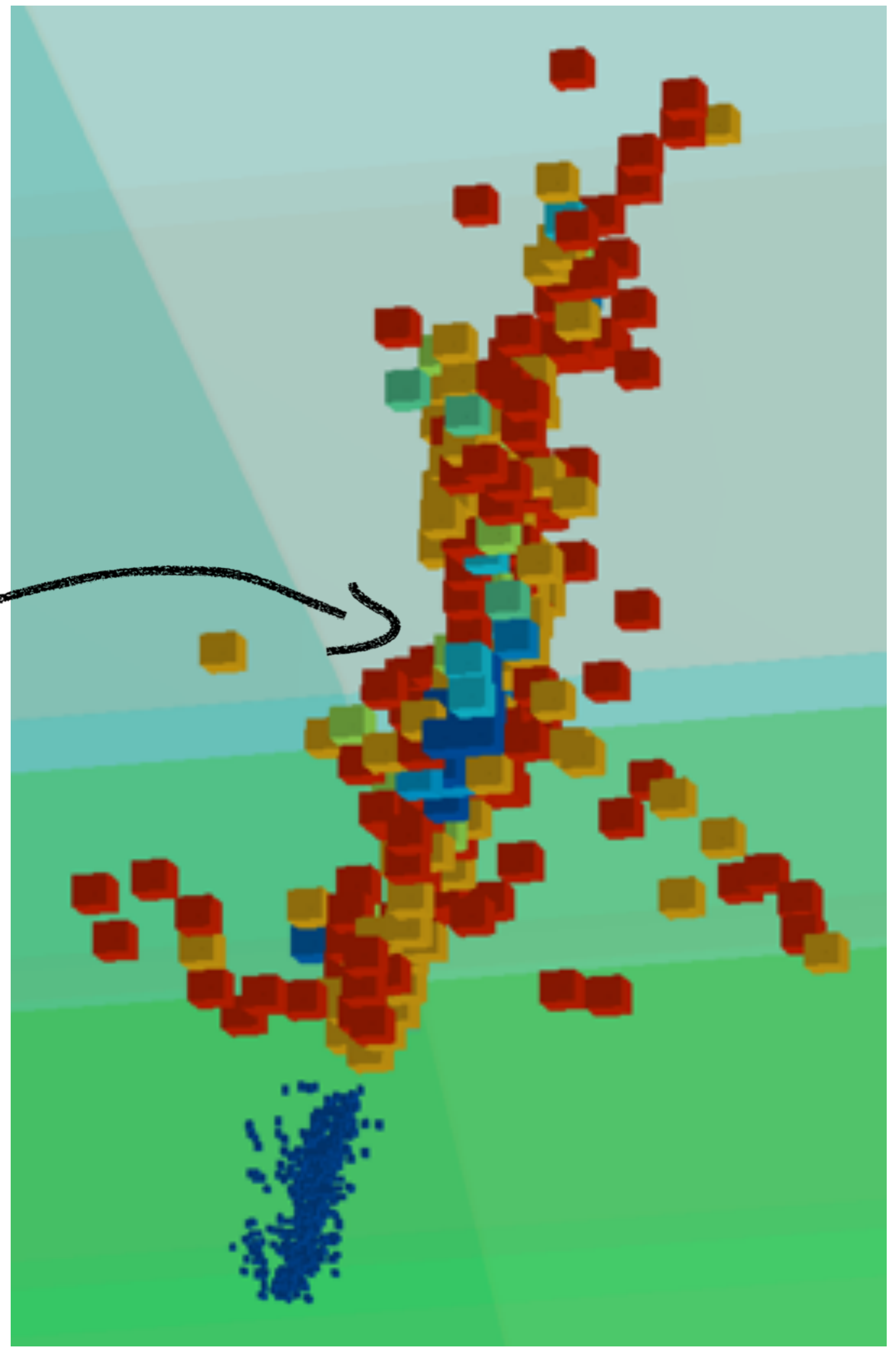
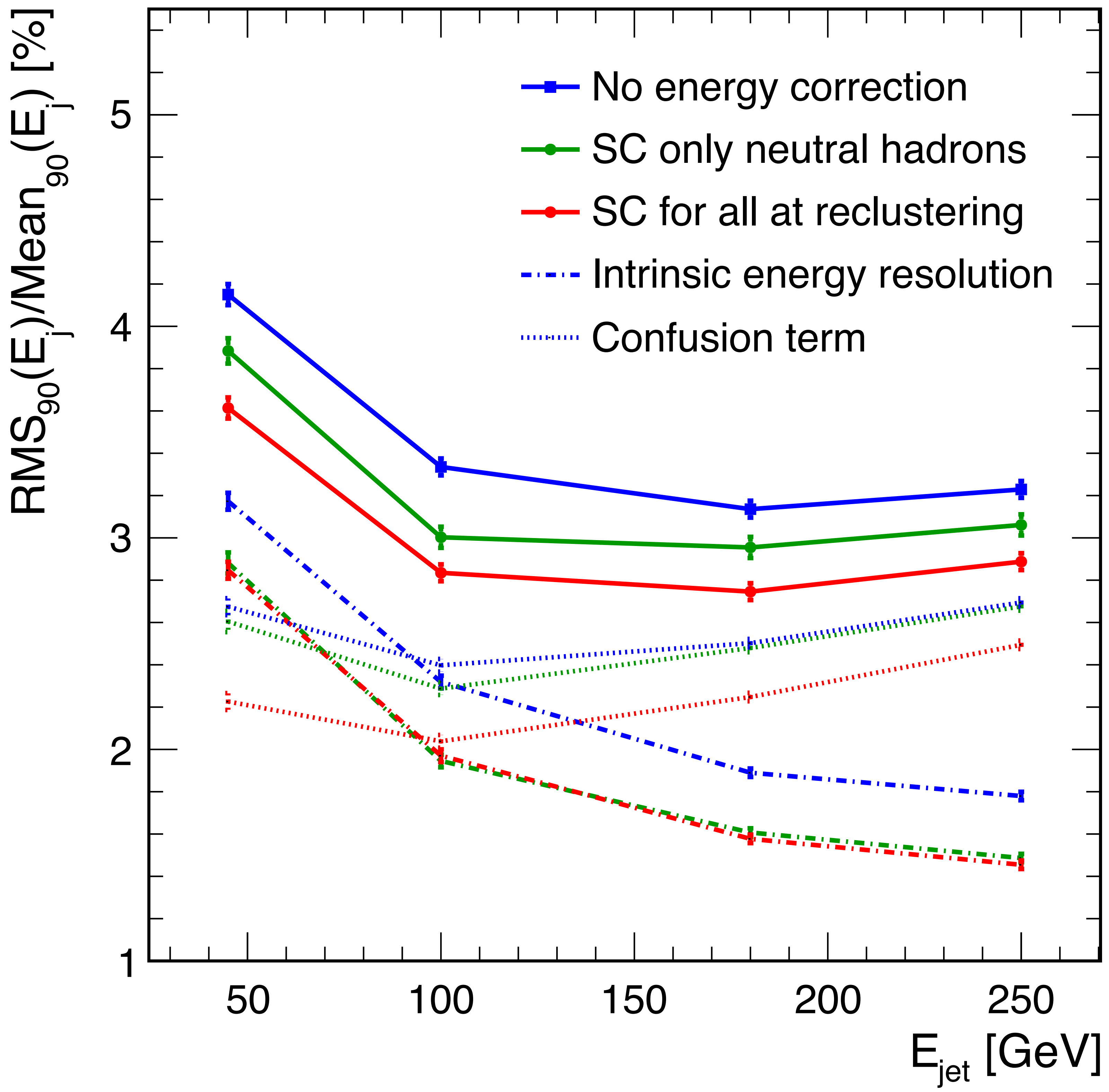
  Local energy density for *software compensation*

em sub showers (in shower core) weighted less than hadronic periphery



ILD concept



EPJ C77, 698 (2017)

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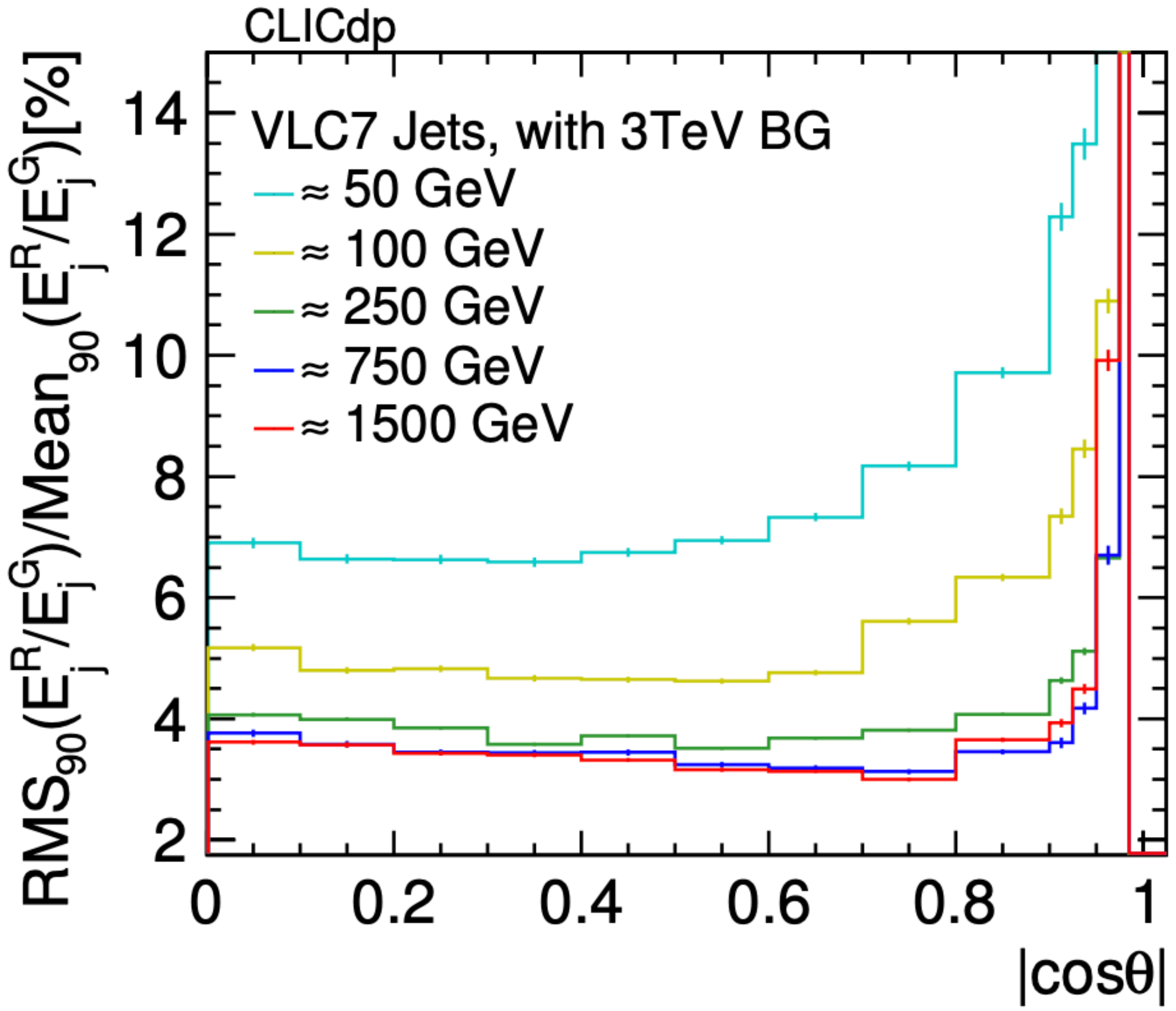

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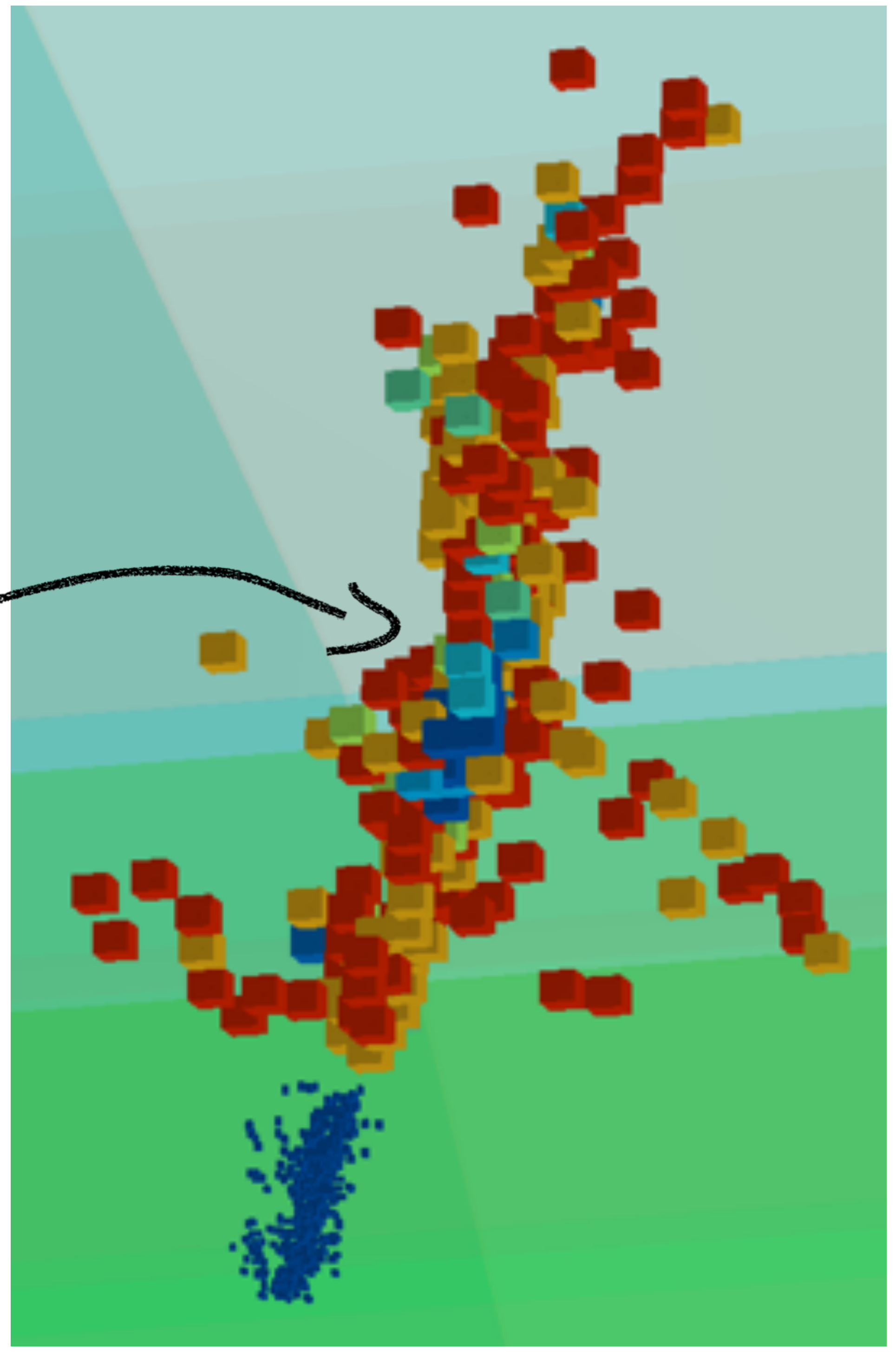

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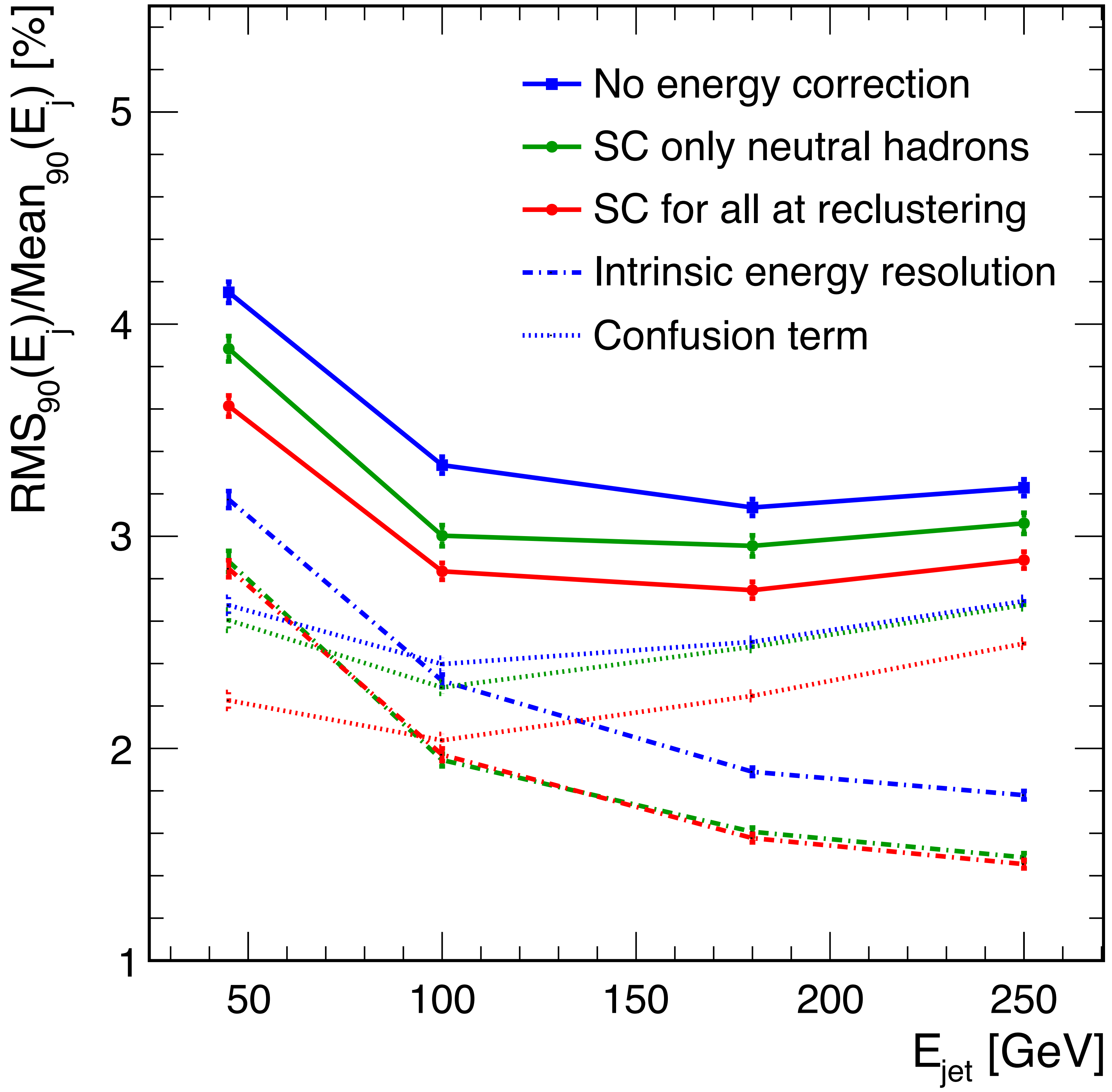


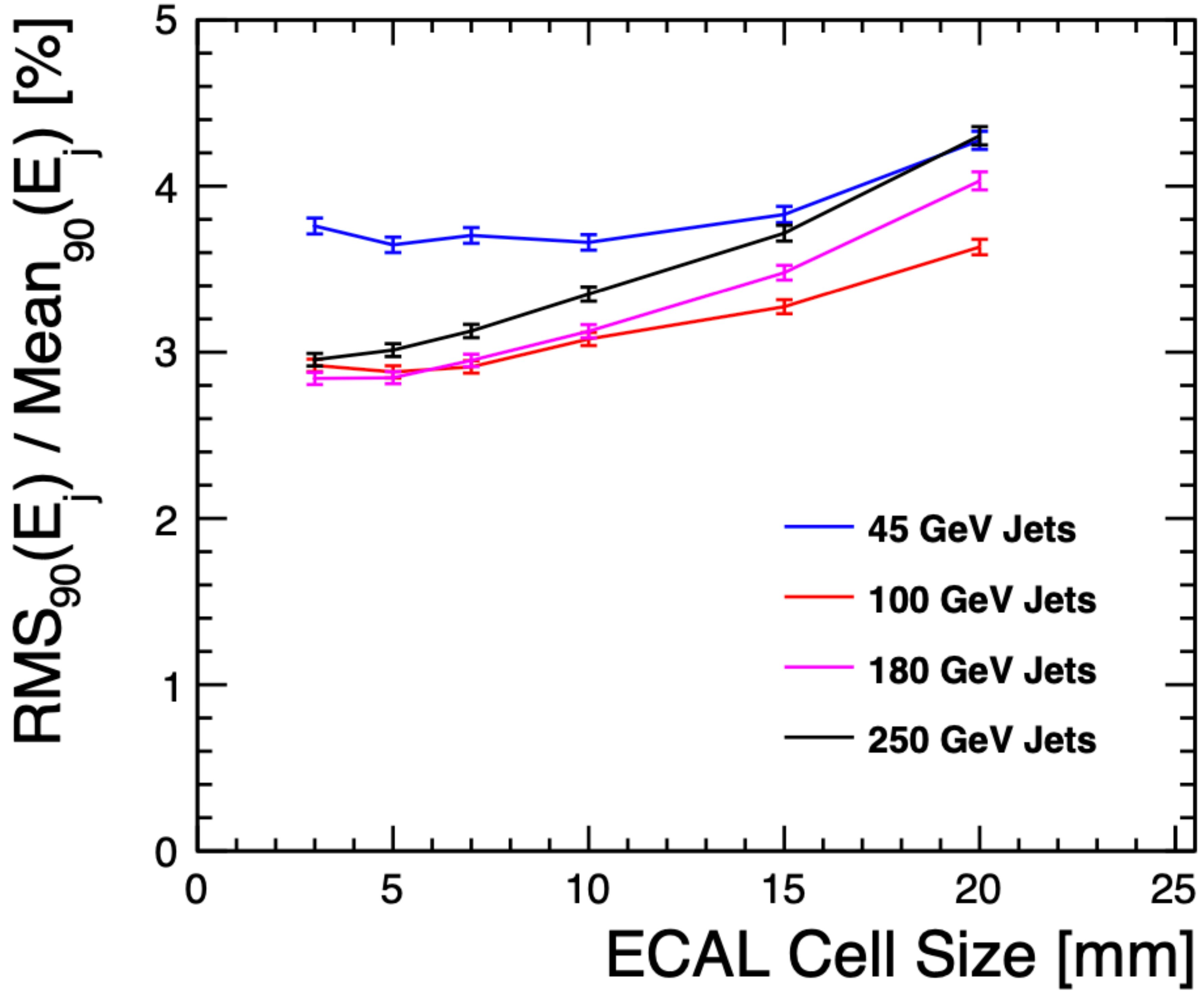
EPJ C77, 698 (2017)

In general: Have not yet tapped the full potential of PFA calorimetry - looking into timing, sophisticated ML techniques, …

Calorimetry

PFA resolution drivers, and a word on photons

- Dependence of PFA JER on ECAL granularity



CLICdp-Note-2017-001

Calorimetry

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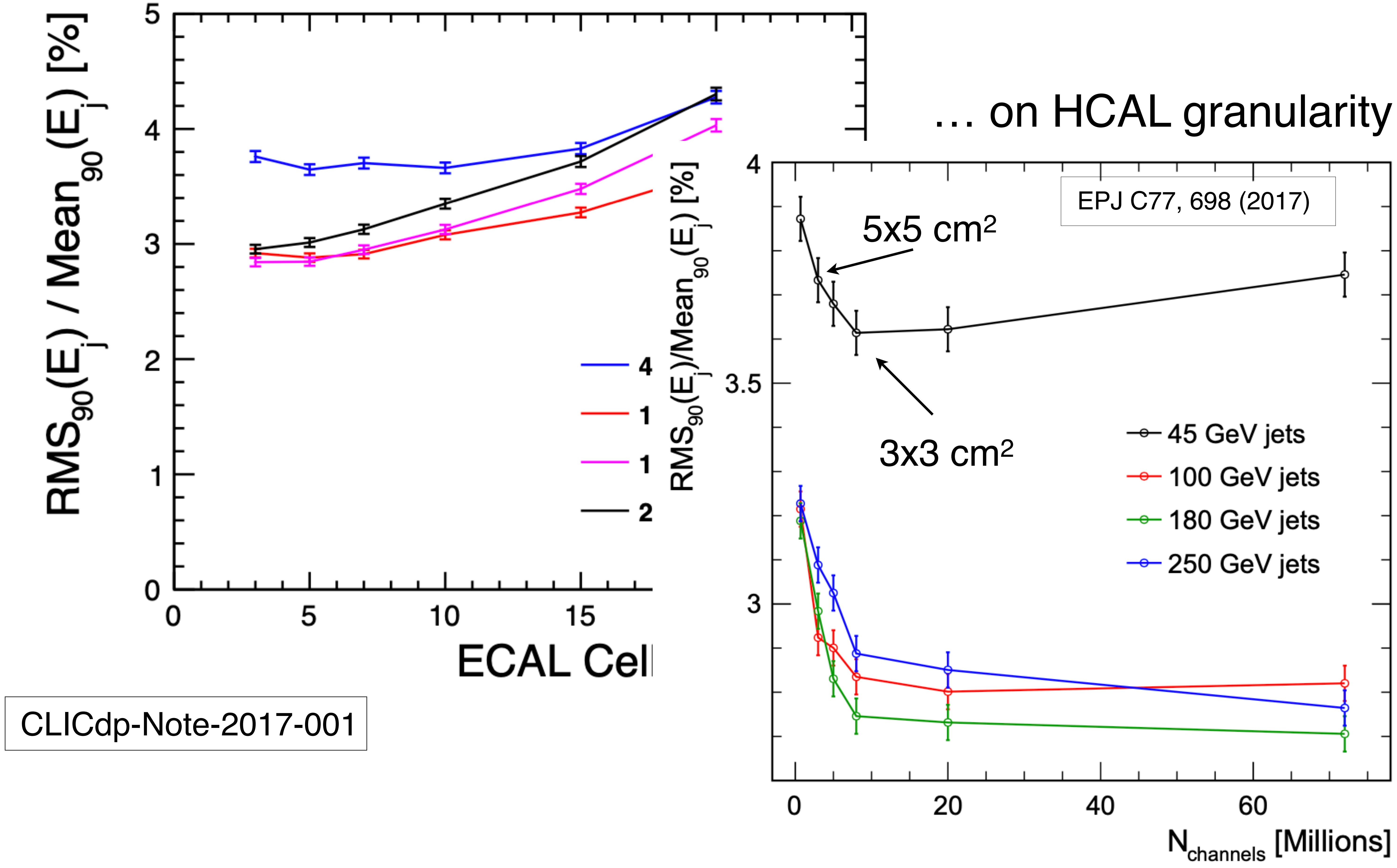
… on HCAL granularity



CLICdp-Note-2017-001

Calorimetry

PFA resolution drivers, and a word on photons

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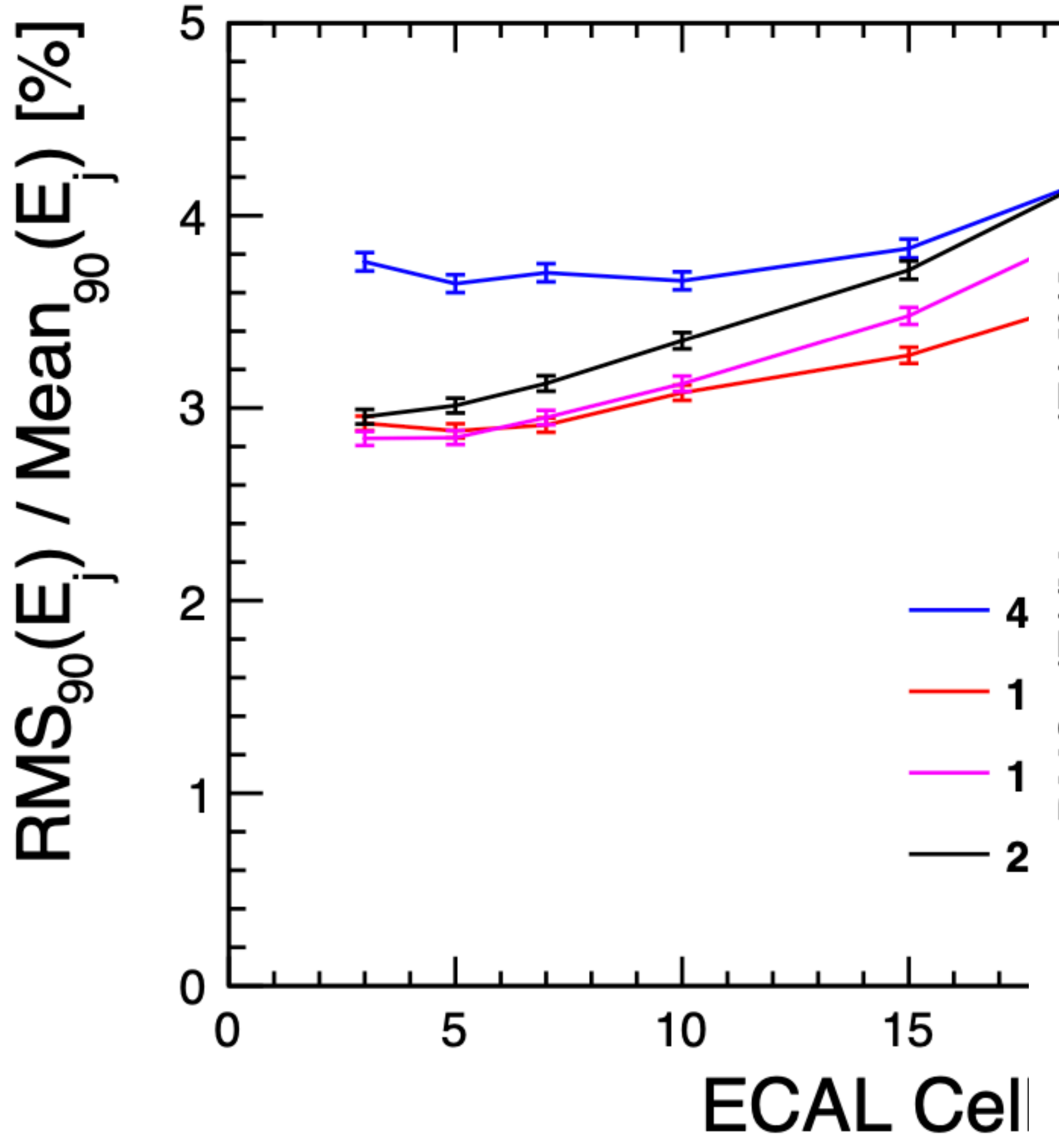
… on ECAL sampling fraction / frequency

… on HCAL granularity



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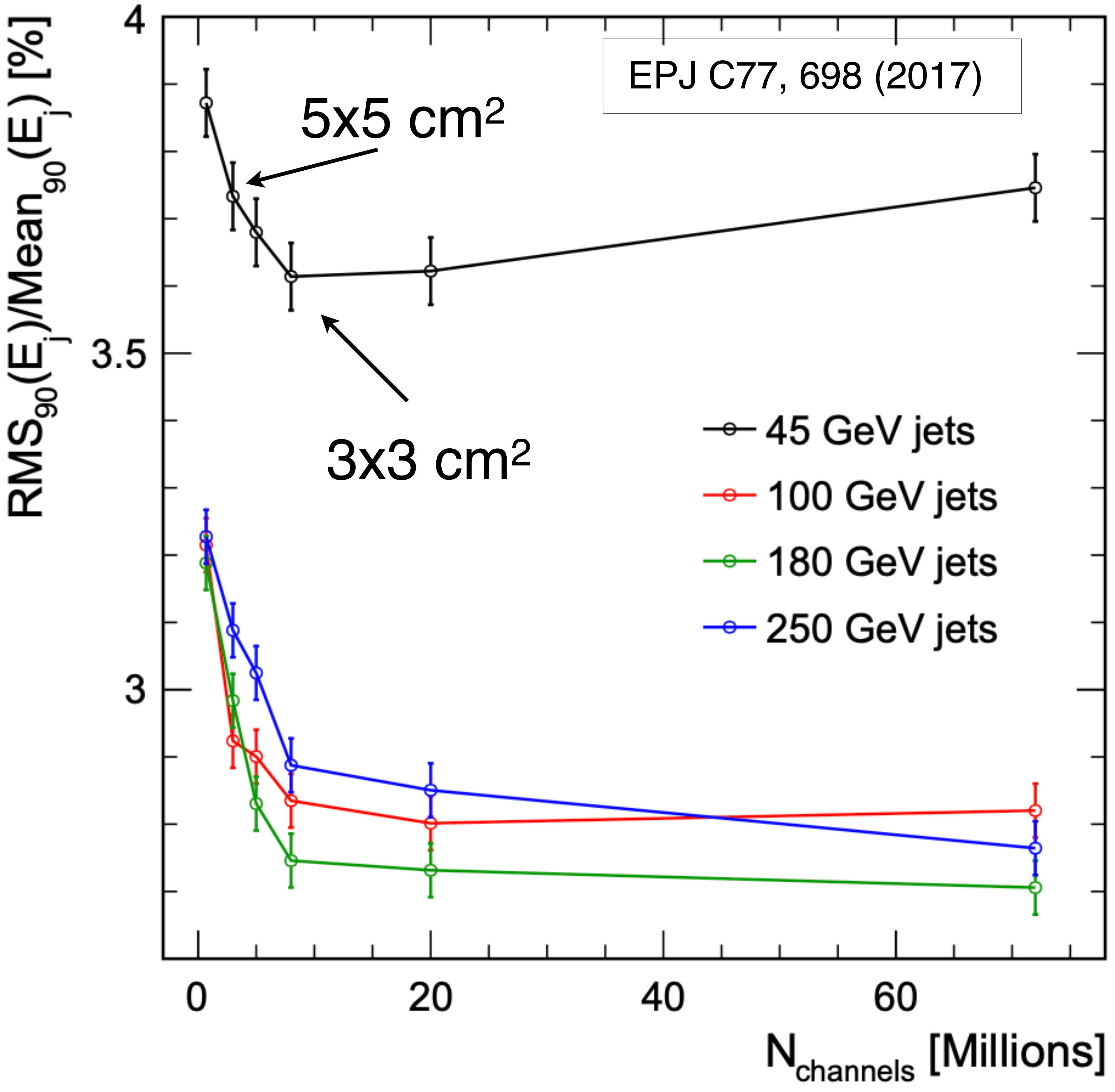
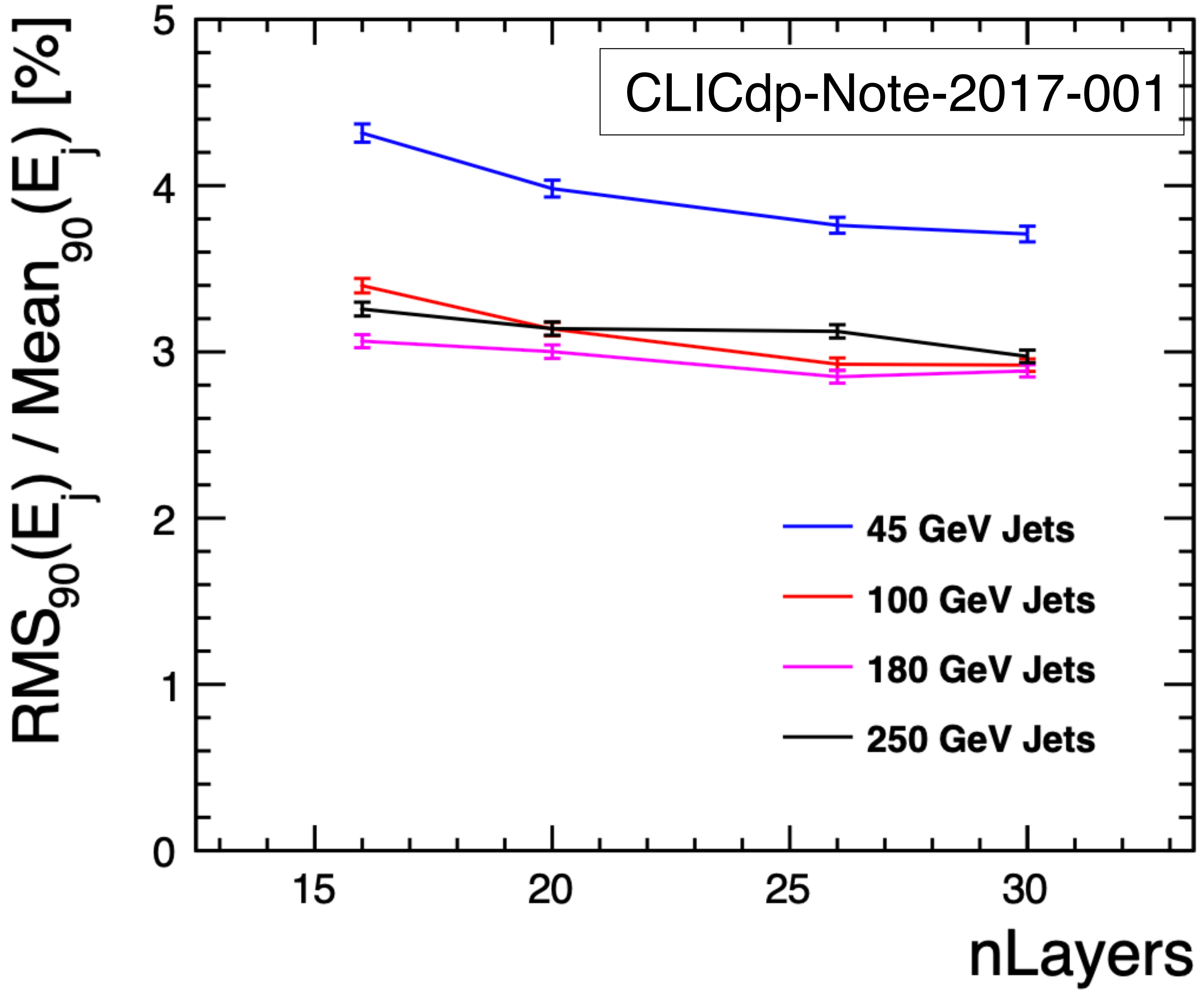


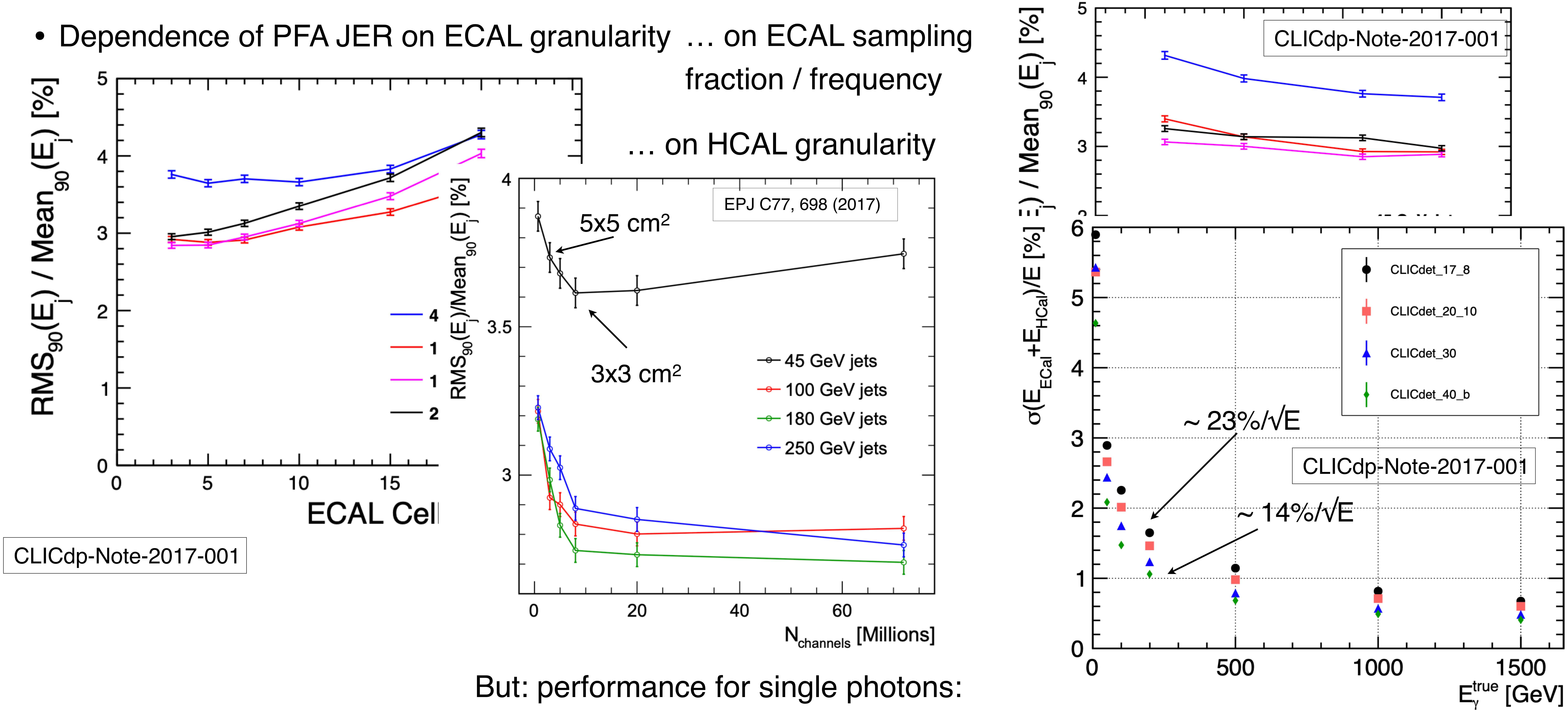
EPJ C77, 698 (2017)



CLICdp-Note-2017-001

Calorimetry

PFA resolution drivers, and a word on photons



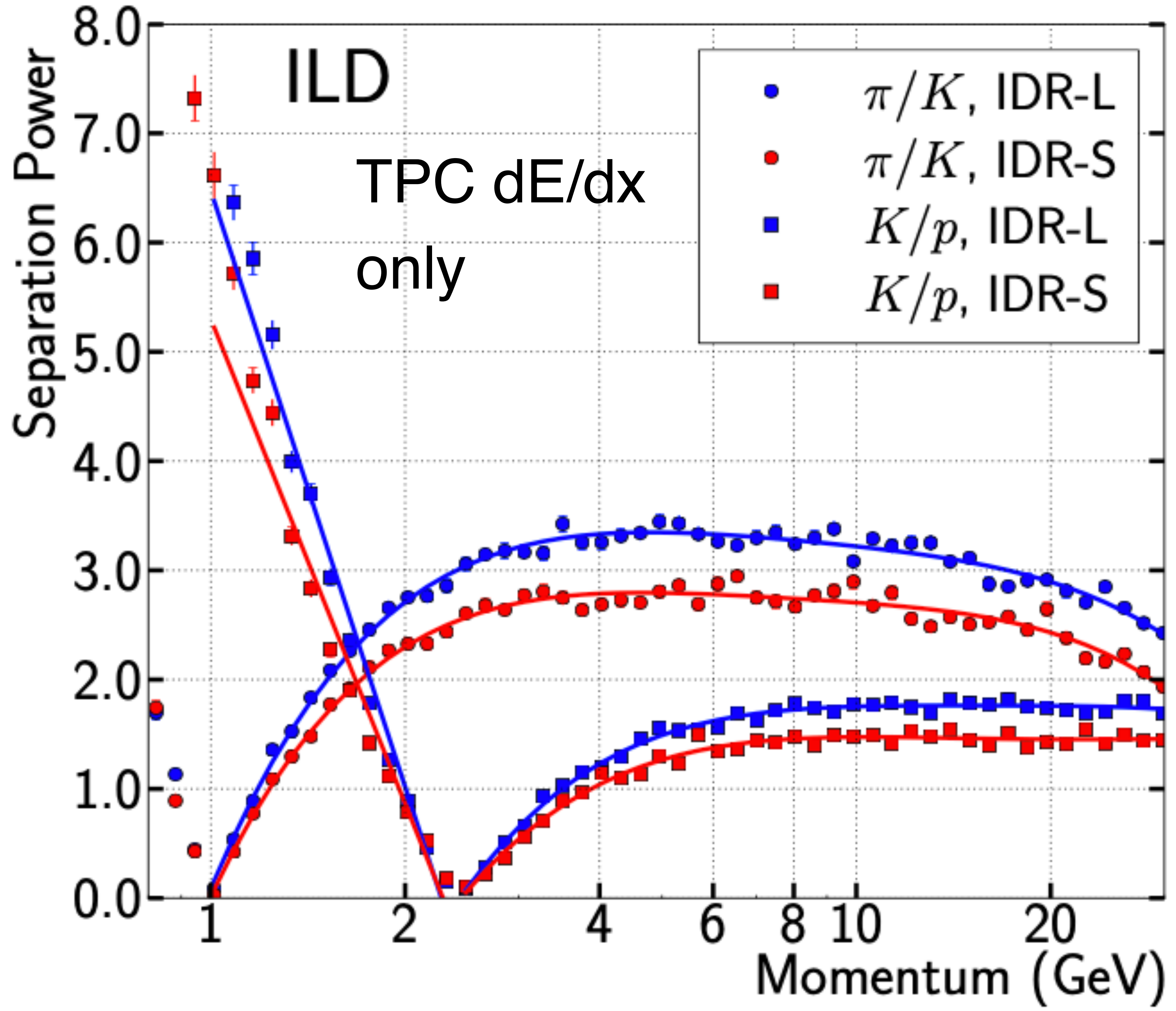
- Dependence of PFA JER on ECAL granularity … on ECAL sampling fraction / frequency

… on HCAL granularity

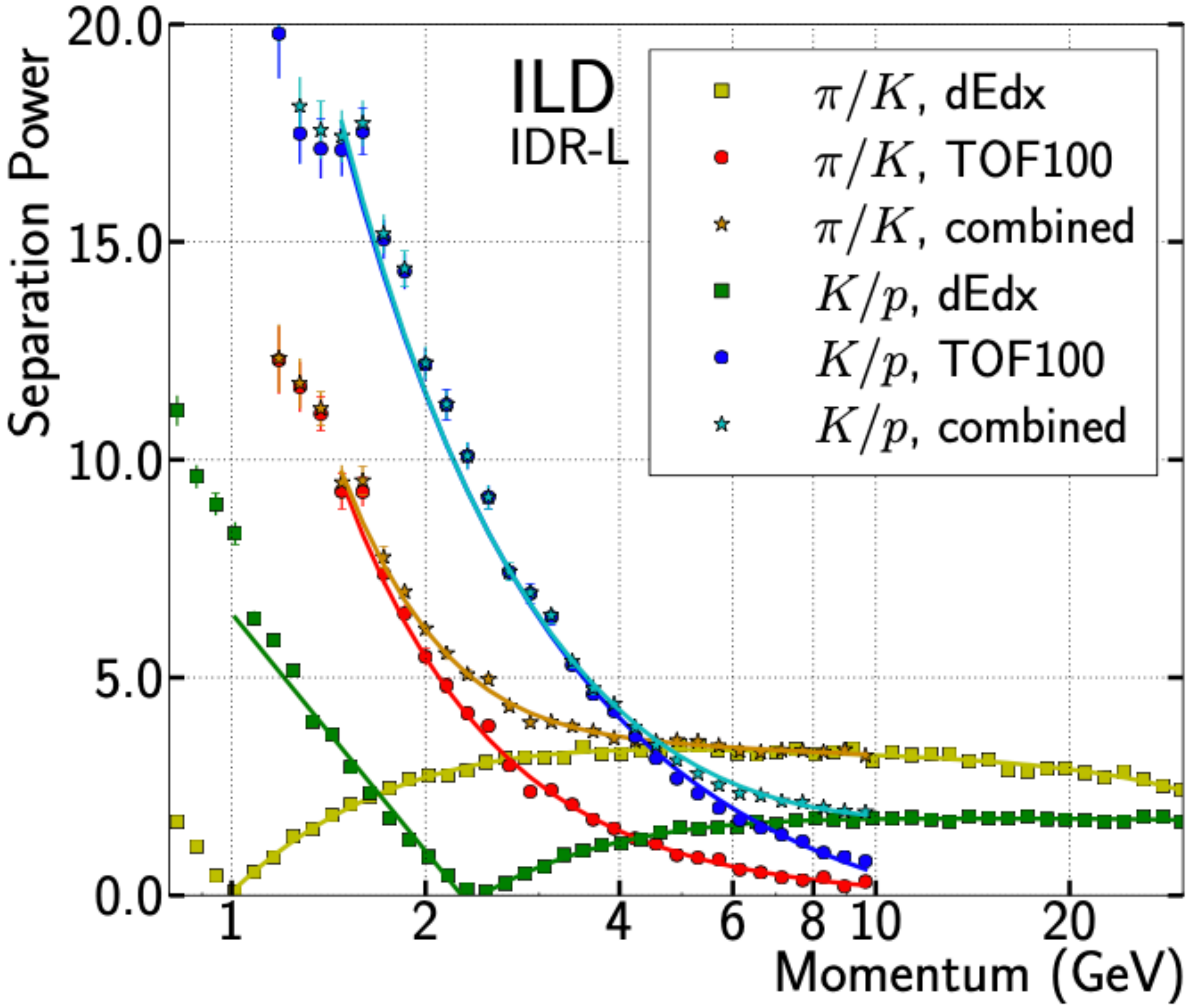
But: performance for single photons:

Particle ID

Studies exploiting dE/dx and TOF with ECAL timing



TPC dE/dx only

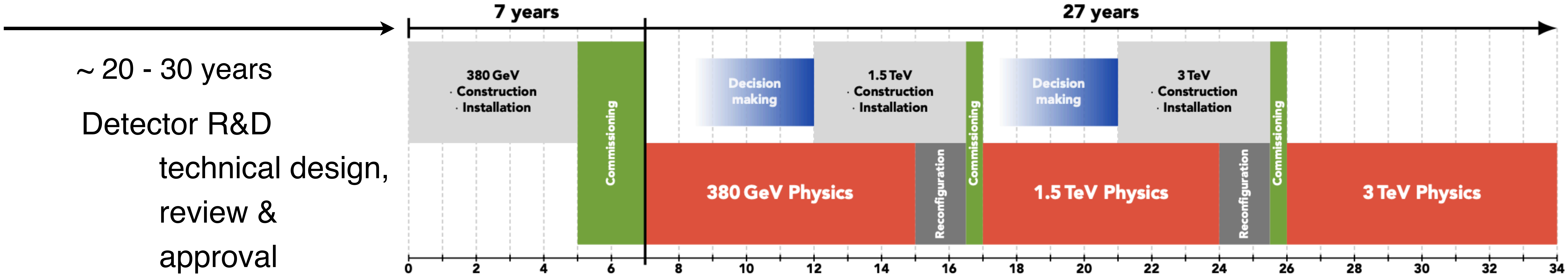


10 ECAL layers with 100 ps

TF9 Training

Not at all Collider - specific

- Experiments on very long time scales - targeted R&D already since 2 decades, first collisions at least 15 years away, operation over decades: Need robust schemes for ***long-term detector maintenance*** and operation, including ***formation of key experts*** and ***preservation of knowledge*** and expertise



~ 20 - 30 years

Detector R&D

technical design,
review &
approval

- Today's students are the (senior) faculty during the main physics exploitation phase:
  Engagement of young generation crucial for planning of priorities, broad community support

From LCs to FCC-ee

Key differences with detector implications

- Energy: Focus on lower energy for FCCee - a maximum of 365 GeV
  - Reduced calorimeter depth
  - Less collimated jets - can potentially compromise on calorimeter compactness, granularity

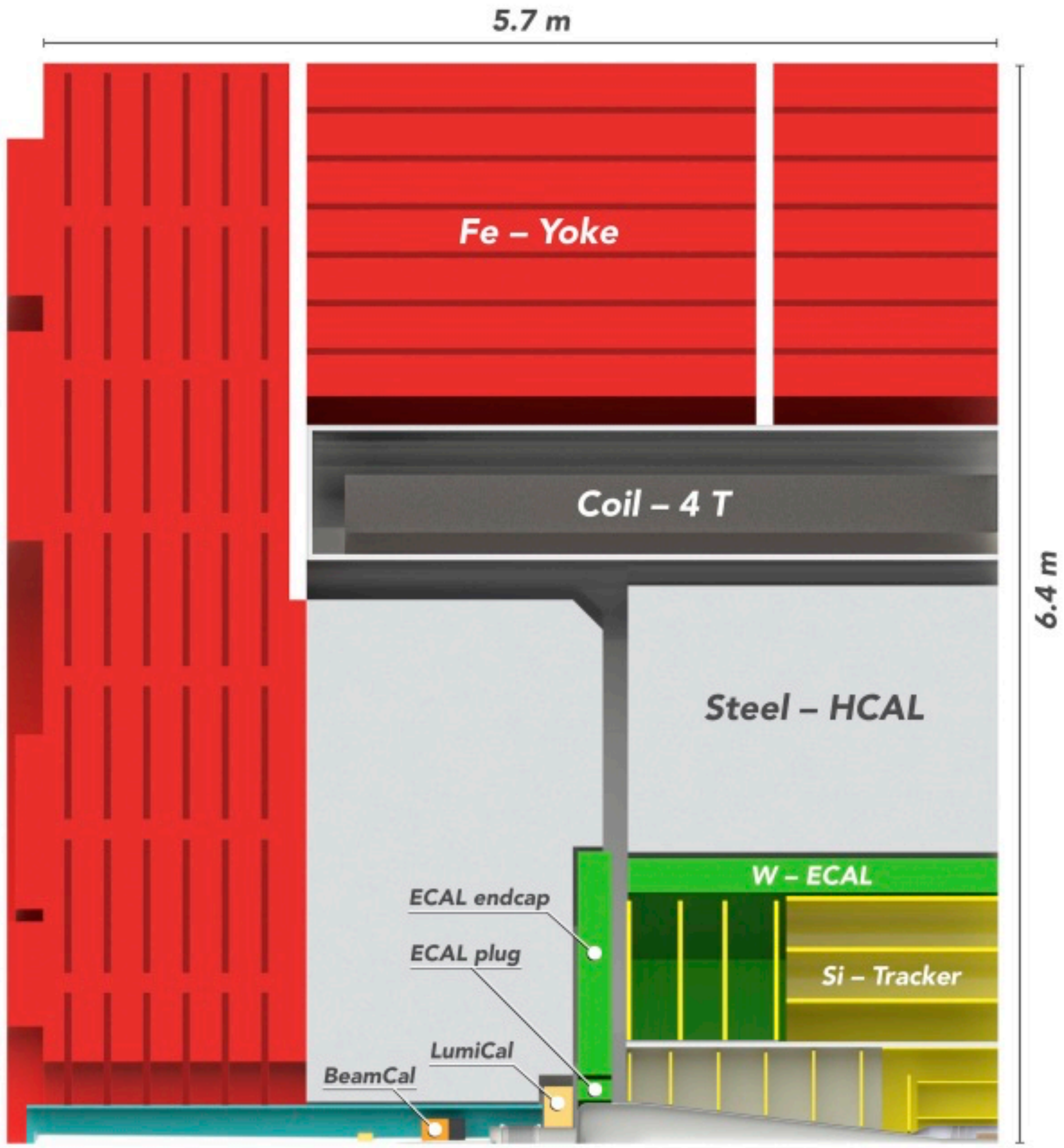
- Need the beams to survive, and reach high luminosity
  - Limits on solenoidal field
    - Reduced momentum resolution at constant tracker size
    - Larger magnetic volume “affordable”: A path to recover momentum resolution

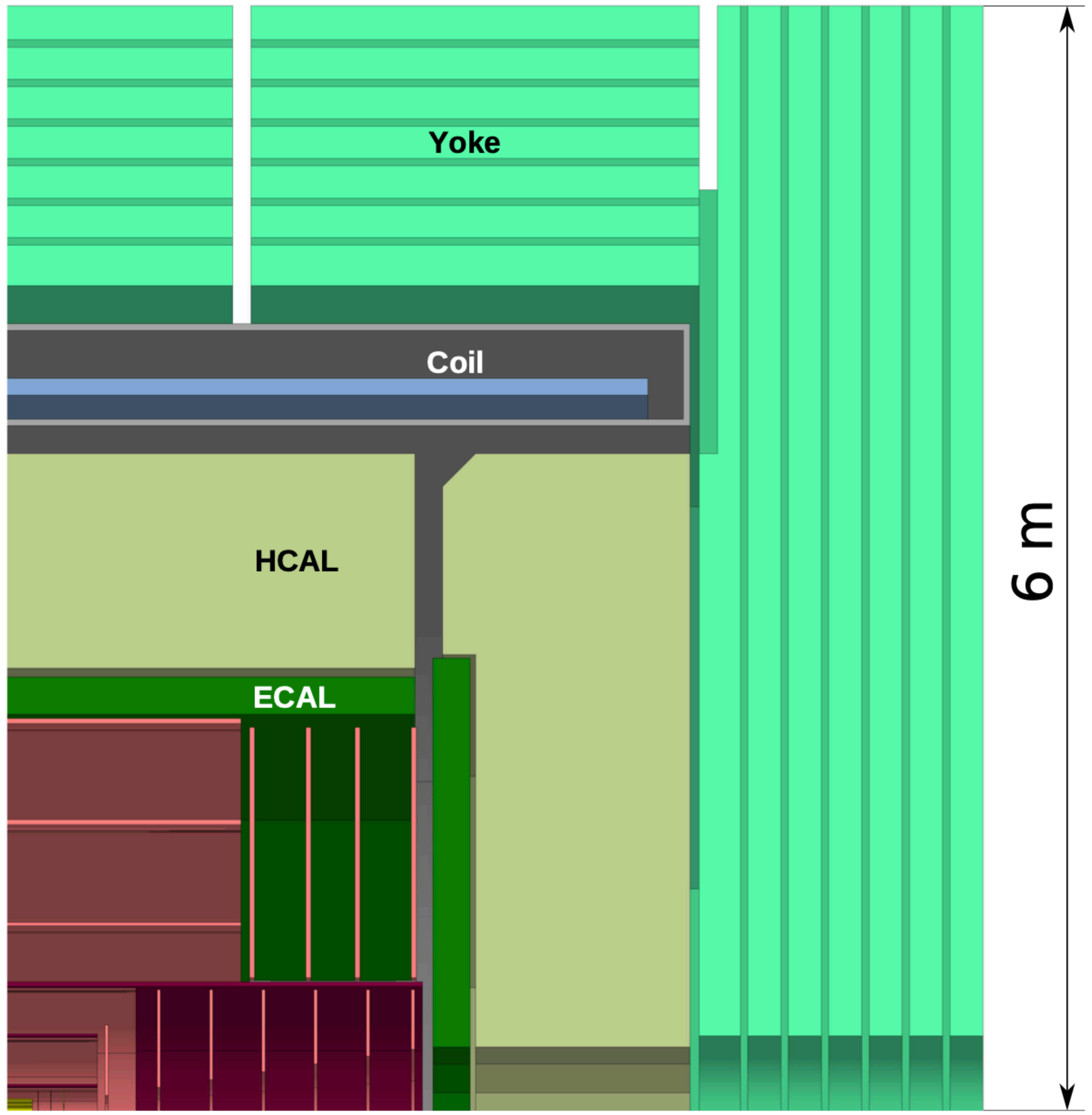
- No bunch train structure: DC operation of the detector readout
  - Active cooling (or compromises on granularity, speed) required in many areas of the detector: Increased material, less compact construction of calorimeters

From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD





From LCs to FCCee

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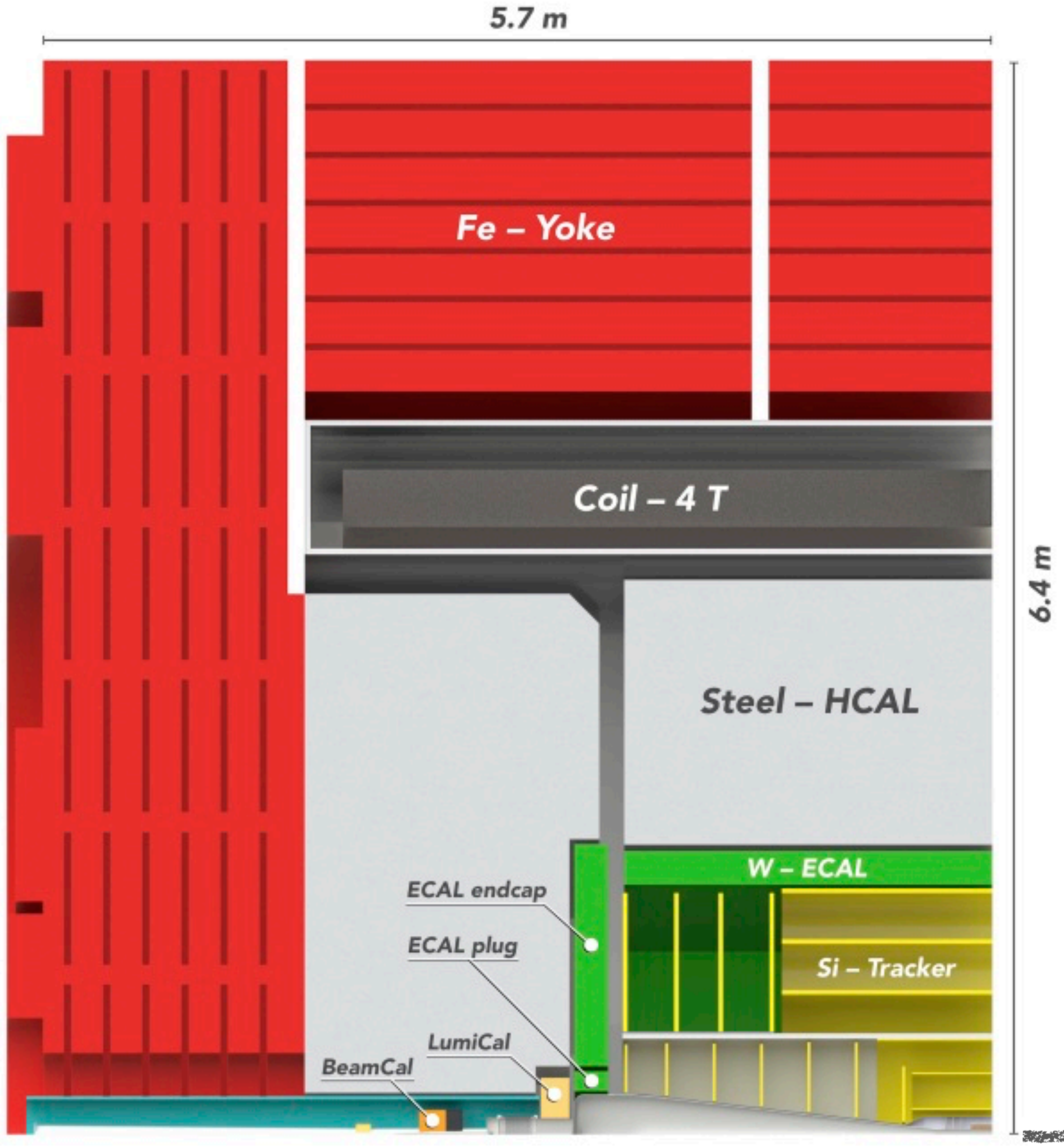
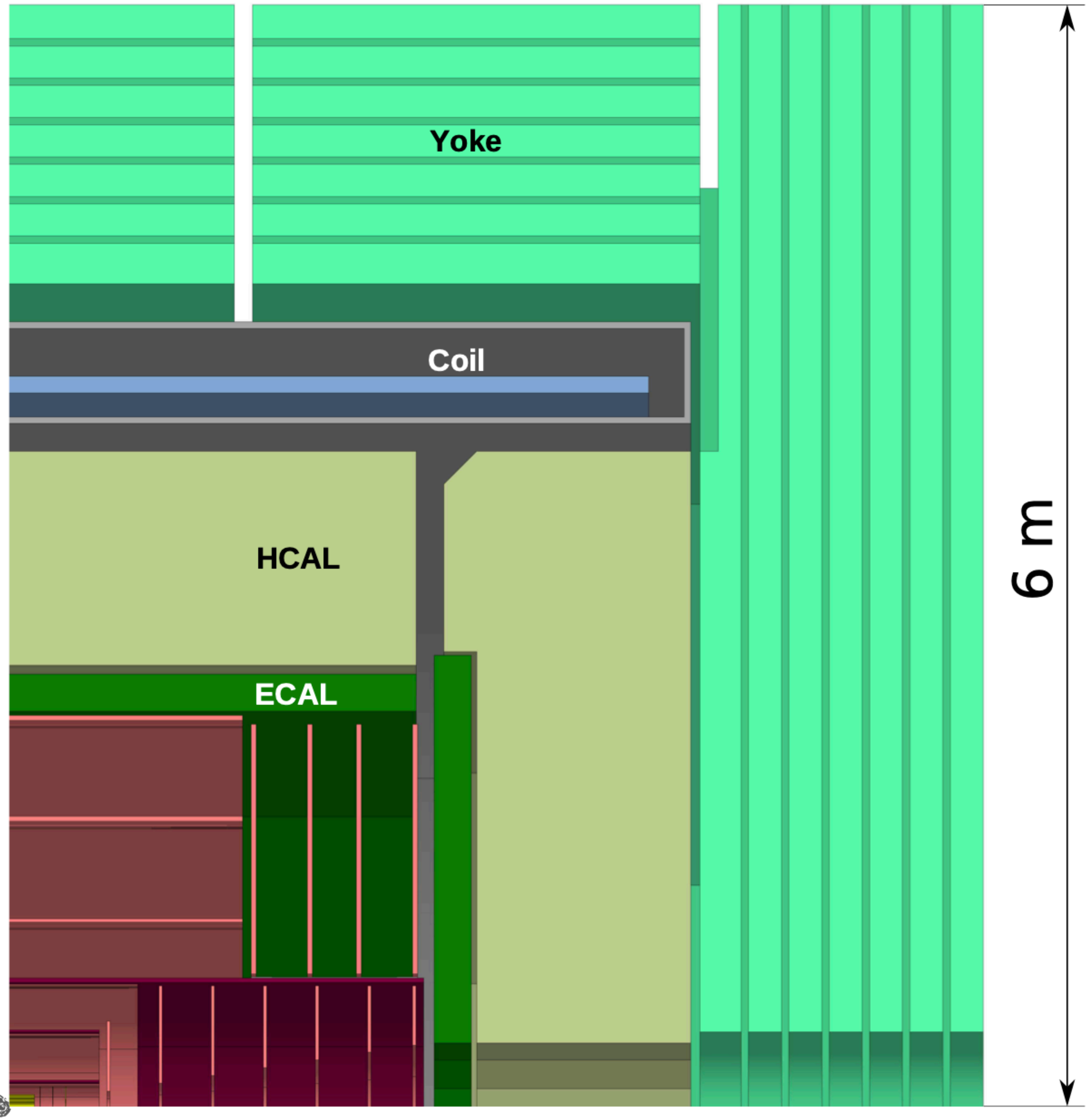


smaller VTX radius: profit from lower backgrounds, compensate material



From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material

From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
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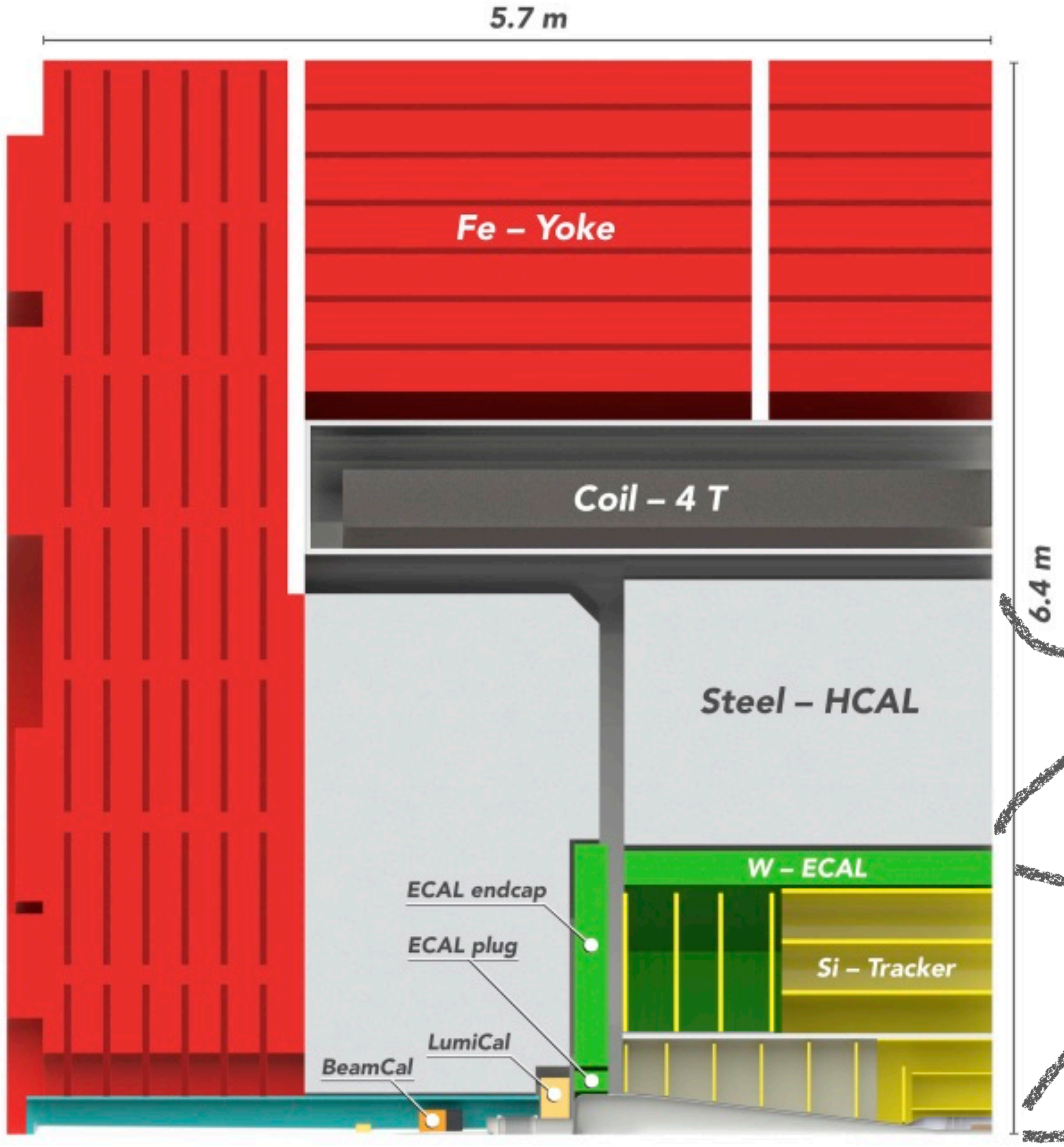
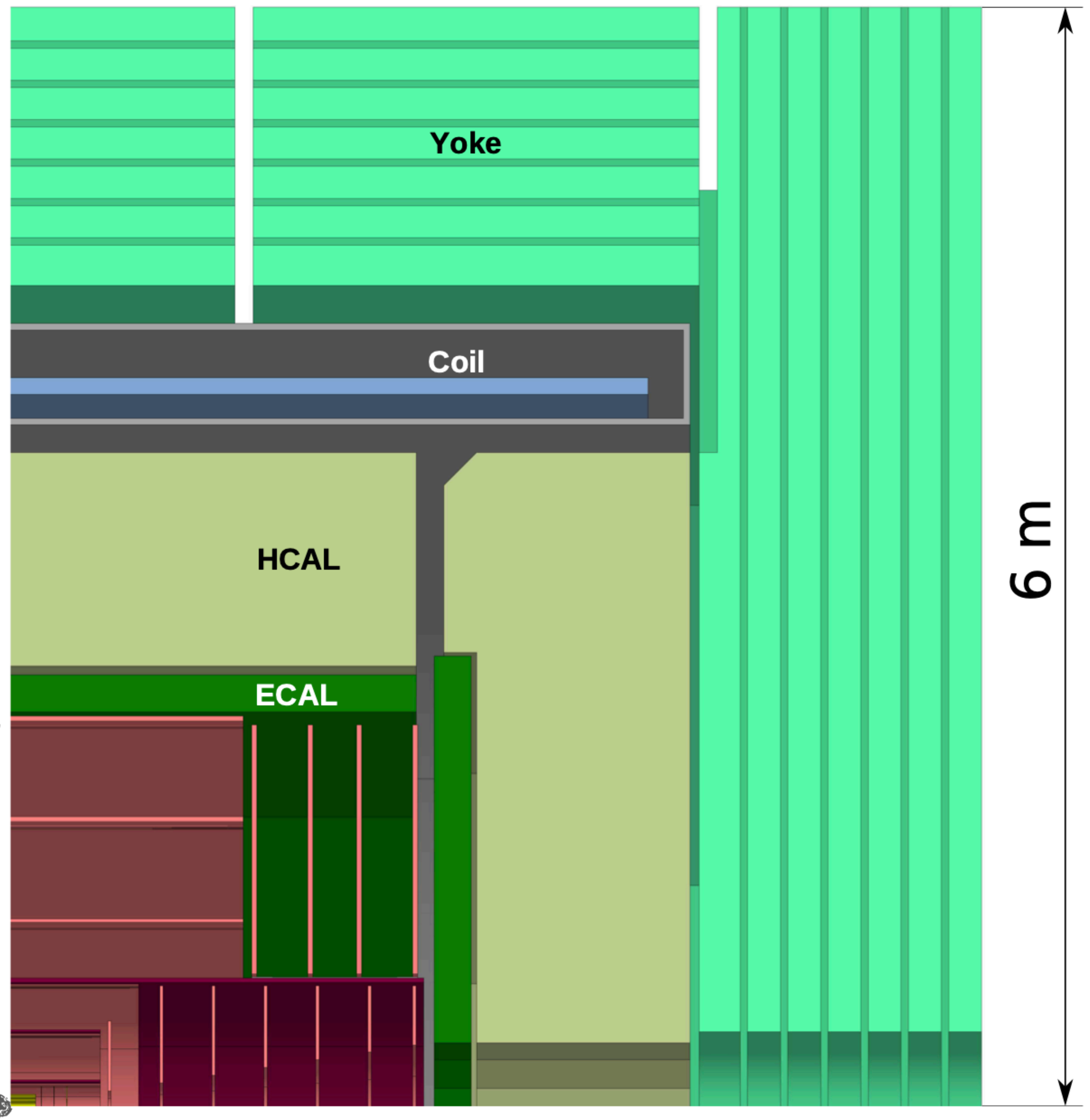


reduced HCAL thickness:
enabled by lower energy

increase in tracker radius:
retain p resolution

smaller VTX radius: profit from lower
backgrounds, compensate material



From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

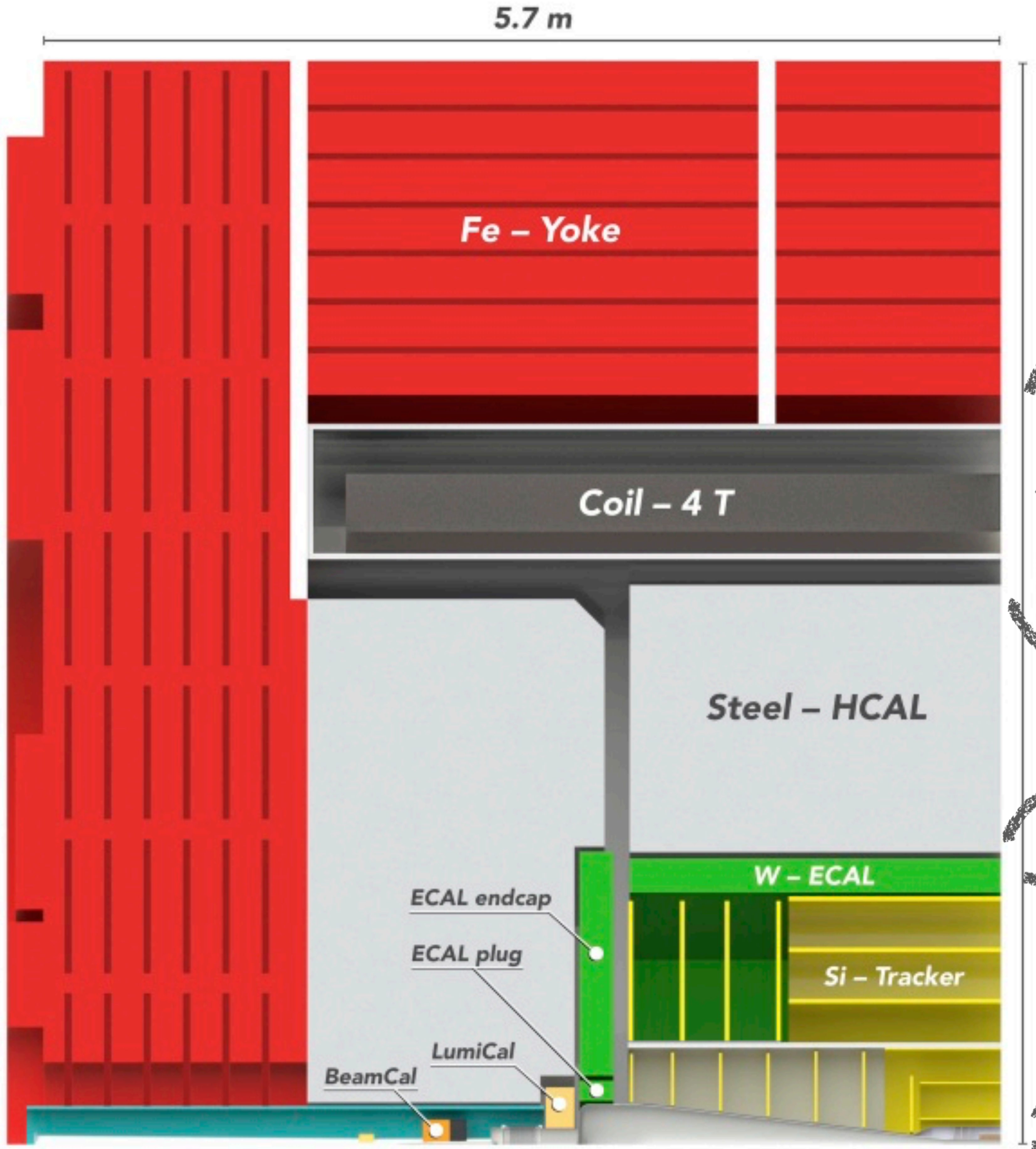
increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material

From LCs to FCCee

From CLICdet to CLD

- A LC-inspired FCCee detector concept - retaining key performance parameters
  Evolving from CLIC to CLD



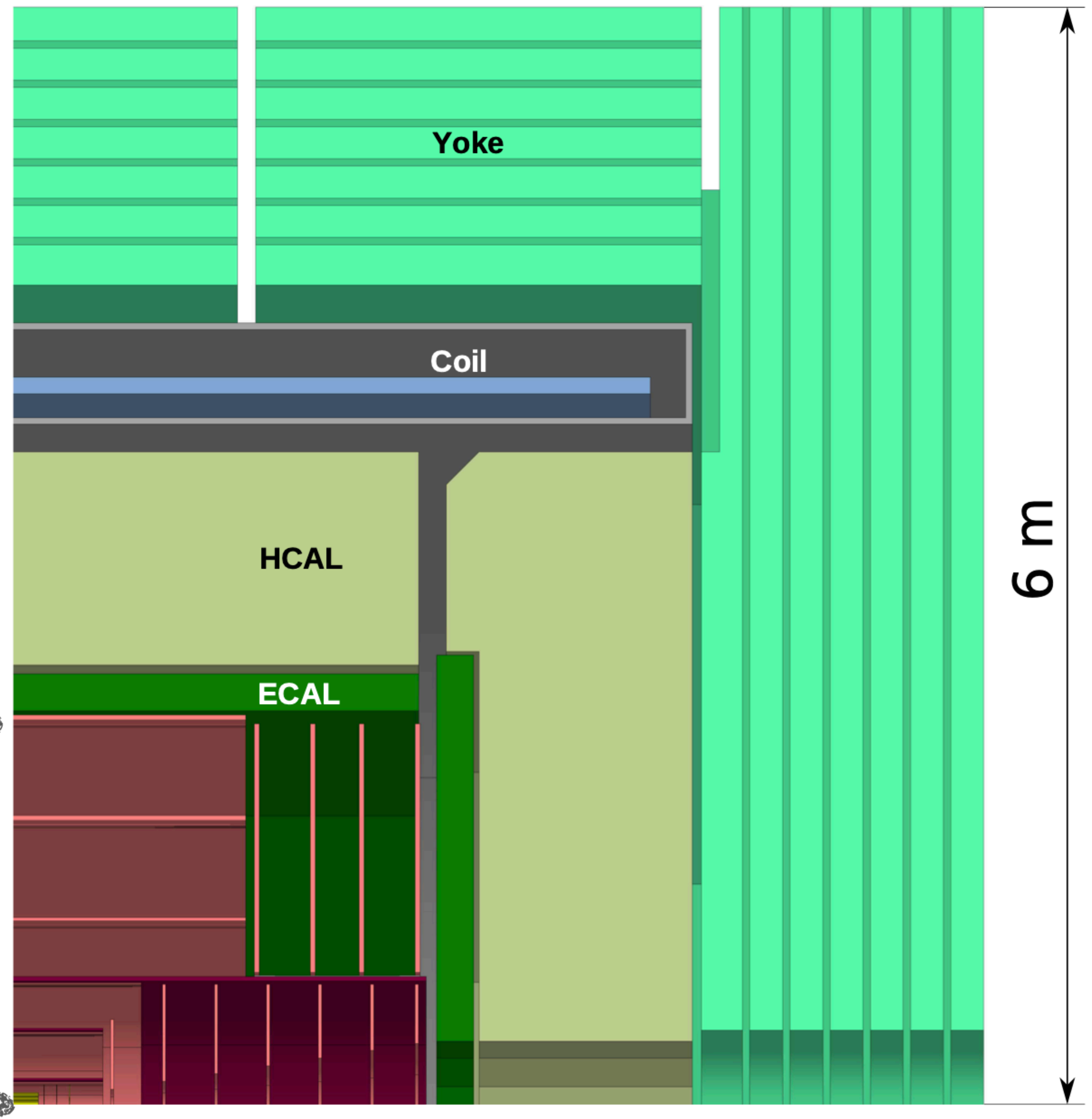
less steel: lower field allows reduced yoke thickness

lower field: enable high luminosity in circular collider

reduced HCAL thickness: enabled by lower energy

increase in tracker radius: retain p resolution

smaller VTX radius: profit from lower backgrounds, compensate material



TF1 Gaseous Detectors

Tracking and Calorimetry

- Two main areas of application: Tracking (TPC), Calorimetry ((semi-)digital HCAL); also muon system
- ***Gaseous tracking:***
  - **TPCs**: Central challenge to reach high resolution in a robust way: controlling ExB effects, field distortions, eliminating ion backflow while keeping transparency. Particular challenge with increasing backgrounds.
  - Low mass endplates: Light materials, low-power readout to reduce required material for cooling
- General need for very low-mass tracking - while meeting resolution requirements for high momentum. For gaseous detectors currently only achievable with external Si tracking.

⇨ Advances in all ***"large-volume" technologies*** (TPCs, Drift Chambers) highly beneficial

- ***(semi-) Digital hadron calorimetry***
  - Primary technology RPCs, also MPGDs:
    - Scalability to very large areas: ~ 10 000 m^2, while keeping uniformity of response and avalanche properties.
      - Requires eco-friendly gas solutions to enable long-term operation of large systems
    - Adding few 10 ps-level time resolution for some layers: Highly compact, scalable MRPC layers
- RPCs also a prime candidate for muon system - similar requirements as for calorimeter, but coarser

TF3 Solid State Detectors

Vertexing, Tracking and Calorimetry

- Silicon is the “work horse” in LC detector concepts - Vertex detector, main tracker, EM calorimetry
  - In general more challenging requirements for CLIC due to backgrounds, timing, but relevant across the board
- ***Vertex detectors:***
  - Lowest possible mass, highest possible resolution: ***~ 3 µm single point resolution***
    < ~0.2% X_0 per layer -> Air flow cooling only
  - Time resolution ***~ 5 ns (or better)*** - interesting additional potential when pushing to the ps range

  ➩ Advances in both ***hybrid*** and ***monolithic*** technologies needed - fine-pitch bump bonding, speed, …
- ***Main trackers:***
  - Low mass, high resolution: ***~ 7 µm resolution, 1 - 2% X_0 / layer, ~5 ns timing***, additional potential with ps level
- ***Calorimeters:***
  - Very large areas***: ~2500 m²*** -> Cost, scalability, production throughput key issues
  - ~ ***1 ns timing*** - additional potential when adding ps capability?
  - Forward calorimeters only: ***Radiation hardness***: up to 7 MGy / year, 1.4 x 10^{14} n_{eq}/cm^2/year

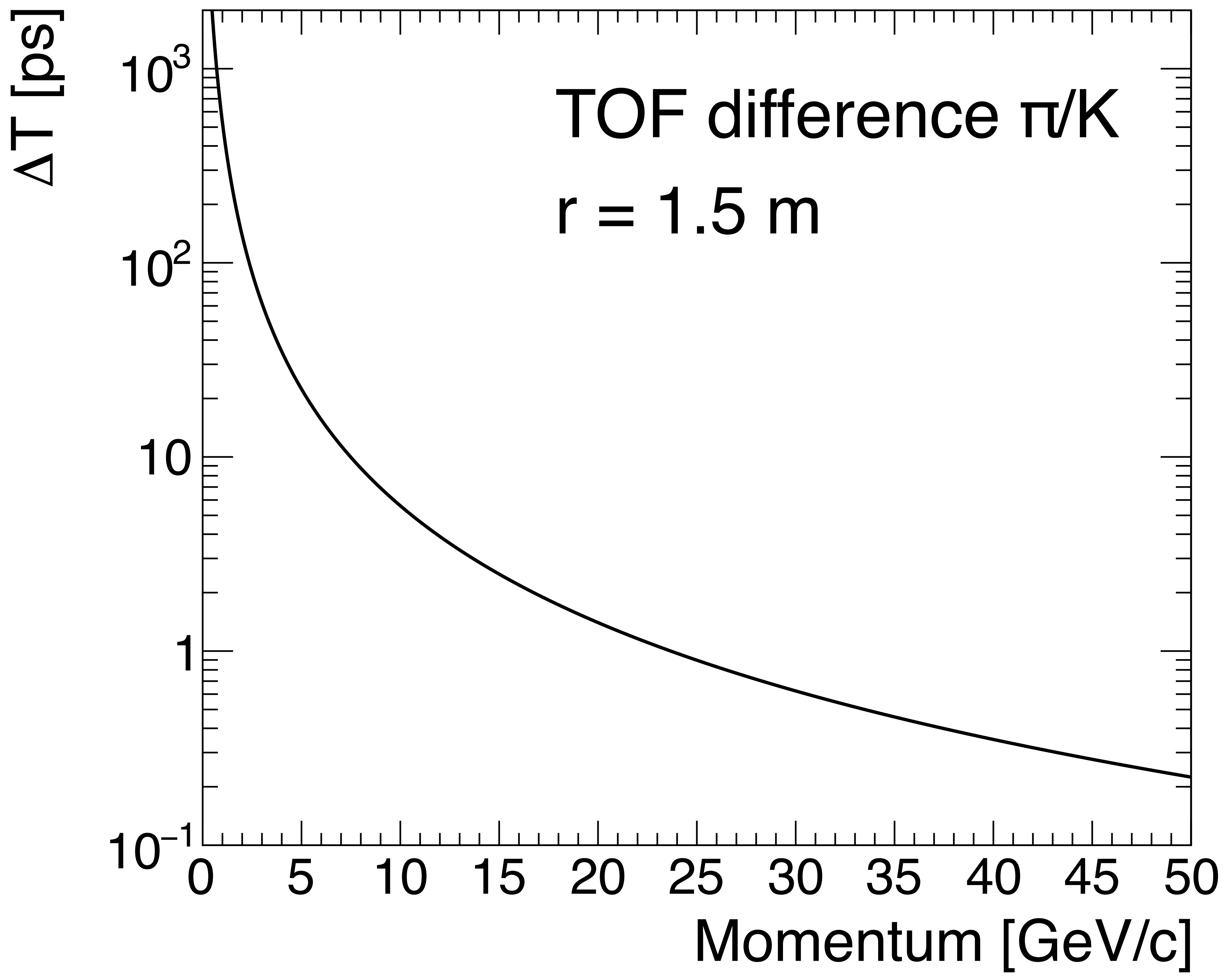
TF4 Photon Detectors and Particle Identification Detectors

Primarily for Calorimetry

- ***SiPMs*** central for calorimetry, scintillator-based muon detectors. Central requirements fulfilled:
  - sensitive to peak wavelength of plastic scintillators, adequate PDE
  - ***moderate dark rate***, ***(very) low cross talk*** (< few %) to allow auto-trigger readout
  - ***Device-to-device uniformity*** to eliminate need of characterisation of each individual sensor

➯ Further improvements in ***scalability*** (= cost), and all other parameters listed above beneficial

- ***Particle ID*** systems not integrated in baseline concepts; potential being studied intensely:
  - A word on ***timing*:** TOF difference for π/K: ***10 ps*** @ 7.5 GeV; ***1 ps*** @ 23.7 GeV
  - Cherenkov-based solutions: ***Extreme compactness*** to be fully compatible with PFA-optimised detector
- ***dE/dx*** in gaseous main tracker - powerful potential in combination with TOF or others
- ***Lepton ID*** crucial - expected to be covered by highly granular calorimetry + muon system



TF5 Quantum and Emerging Technologies

Largely speculation

- Over the last years the focus has been on the feasibility and system demonstration, less on following latest technological developments.
- Still: Significant potential to profit from new technologies
  - New sensor technologies / ideas
  - Novel materials
  - New strategies for data and power transfer - for possible further material reduction and increased compactness
  - Additive manufacturing to improve scalability
  - …

TF6 Calorimetry

A Focus on PFA

- Calorimetry is central to the “philosophy” of Linear Collider detectors optimised for Particle Flow reconstruction - The original motivation for highly granular (“imaging”) calorimeter. Key performance demonstrated in test beams.
- Key topics for further development:
  - ***Scalability*** and ***cost-effective*** mass production
    - Silicon, Scintillator / SiPM, Gas detectors
  - ***Performance improvements*** (in particular in areas of clustering and hadronic resolution) with integration of new technical capabilities, such as ***ps-level timing***, ***novel optical materials, dual readout techniques* in high granularity**; improved ***electromagnetic resolution*** in highly granular calorimeters
  - Development of CMOS-based ***digital ECAL*** solutions
  - Central for all: ***highest possible integration***: compact active layers, smallest mechanical tolerances, minimum volume for interfaces, smallest possible power consumption to avoid active cooling wherever possible, …

⇨ Calorimetry drives developments in sensor and electronics areas - “ripple effects” for other TFs

TF7 Electronics and On-detector Processing

ASICs, Interfaces and Beyond

- Highly integrated electronics crucial for LC detectors, to enable required compactness and hermeticity
- ***ASICs*** central for all subsystems - ***ultra-low power consumption*** a central theme
  - Optimised for ***power-pulsing*** - however, suitability of such ASICs for beam tests, pre-installation calibration and cosmics data taking is a challenge.
  - Maximal integration requires modern technologies, ***small feature size***: costly development, increasing demand on ***verification***
- ***Compact interfaces*** - high-density boards for services and communication between VFE and off-detector electronics
- ***Large-area multi-layer*** electronics boards with high mechanical precision, far beyond industry standards - in particular for highly granular calorimeters
- DAQ requirements relatively benign - ~100 MB of zero-suppressed data per bunch-train, up to ***~5 GB/s***
  - Significantly higher for calibration runs without or with reduced zero suppression

TF8 Integration

- ***Precision*** and ***stability*** on all components and overall detector crucial to achieve ambitious precision goals of e^+e^- colliders
- High ***compactness*** central for Linear Collider concepts:
  - Extreme demands on ***overall integration***: mechanics, electronics, services
  - Minimal tolerances, for example highly ***precise, earthquake-stable*** calorimeter absorber structures
- ***System-level power-pulsing*** concepts with low-mass cables, compatible with magnetic field environment
- ***Reproducible alignment*** after push-pull operations
- Extreme mechanical precision for machine-detector interface, combined with ***fast feedback*** and precise beam steering (nm precision) to maximise luminosity during bunch trains
  - Beam size (σ_x x σ_y) 500 x 8 nm^2 (ILC 250 GeV) - 40 x 1 nm^2 (CLIC 3 TeV), bunch trains at CLIC ~ 160 ns, at ILC ~ 700 μs
- ***Low-mass support structures*** for trackers; tracker supports with integrated cooling - building on significant R&D already performed
  - ***Mechanical stability*** in the presence ***forced air cooling*** - in particular for vertex detectors