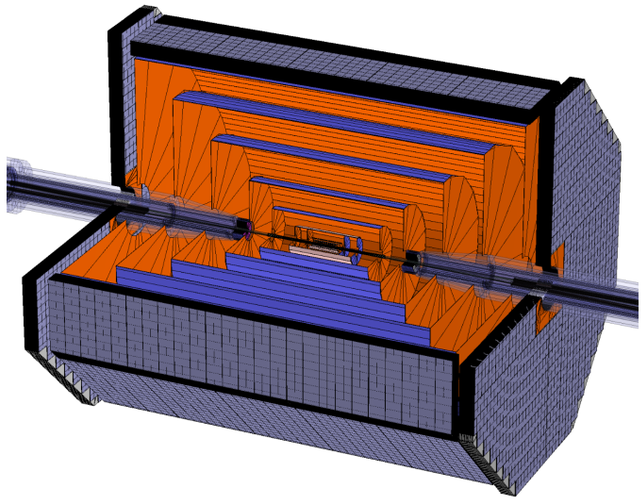
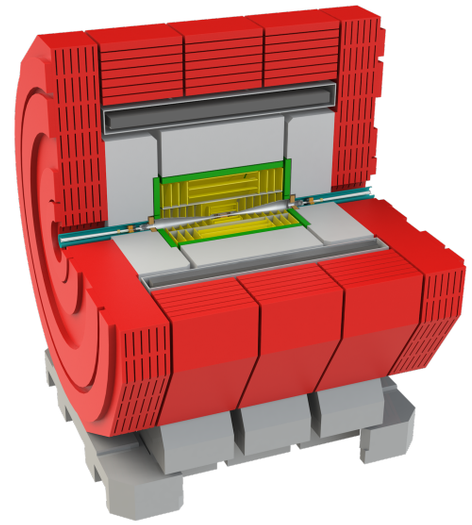
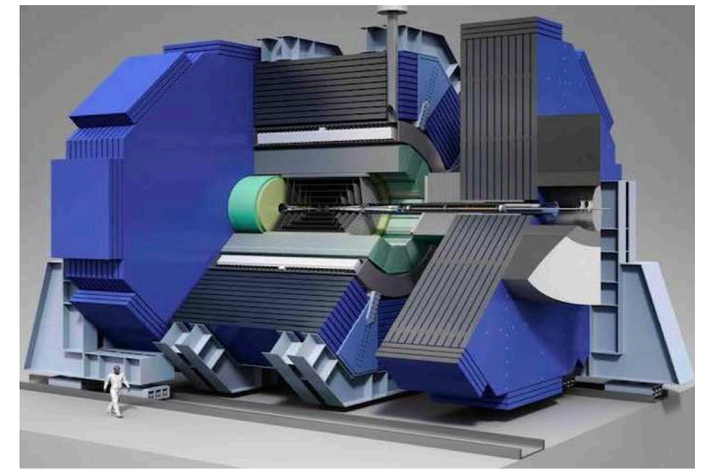
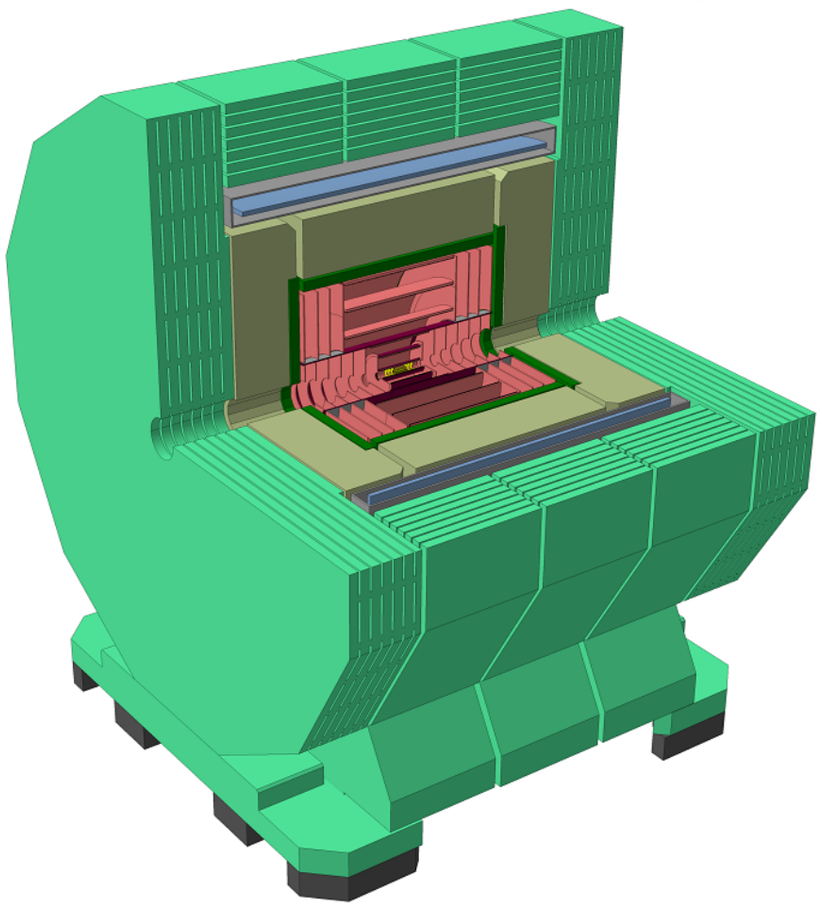








All-silicon tracker concepts for future e^+e^- colliders

- focus on CLD at FCC-ee -

Emilia Leogrande
(CERN, University of Glasgow)

4th FCC Physics and Experiments Workshop
12 Nov 2020

Introduction

- **Detector designs** for future e+e- colliders driven by **physics requirements** and **experimental conditions**

- **Physics requirements** depend on the *energy* and *luminosity* of the accelerator but in all future e+e- colliders they are similar in terms of outstanding precision
  - excellent momentum resolution, impact parameter resolution, jet energy resolution, flavour tagging, lepton identification
  - particle-flow-based designs push the tracking requirements to the limit

- **Experimental conditions** are based on the collider
  - general goal from a detector point of view: background rejection, limit occupancy
  - timing and p_T information fundamental to reject background

All-silicon trackers

The challenges

occupancy

↓

segmentation

↓

power consumption

↓

cooling

single point resolution

↓

thick sensors (charge sharing)

material budget

The guarantees

compactness

validated technology

stability

calibration

redundancy

"I suppose I'll be the one to mention the elephant in the room."

Content of this talk

1. CLD Tracker Concept

- tracker design and optimization
- tracker performance with low-level observables
- cooling considerations
- beam-background and data rate
- tracking (detector and algorithm) performance with complex events

2. FST Tracker Concept

- CEPC experimental conditions
- tracking design and performance

3. Tracker Concepts at Linear Colliders

- LC experimental conditions
- CLICdet concept and performance
- SiD concept and performance

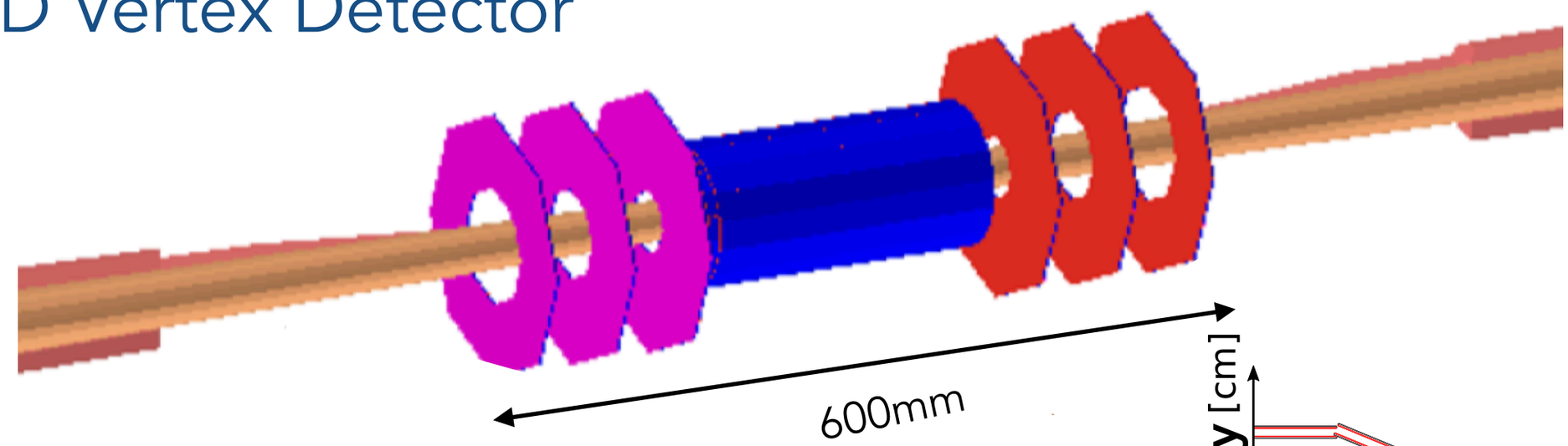
CLD at FCC-ee

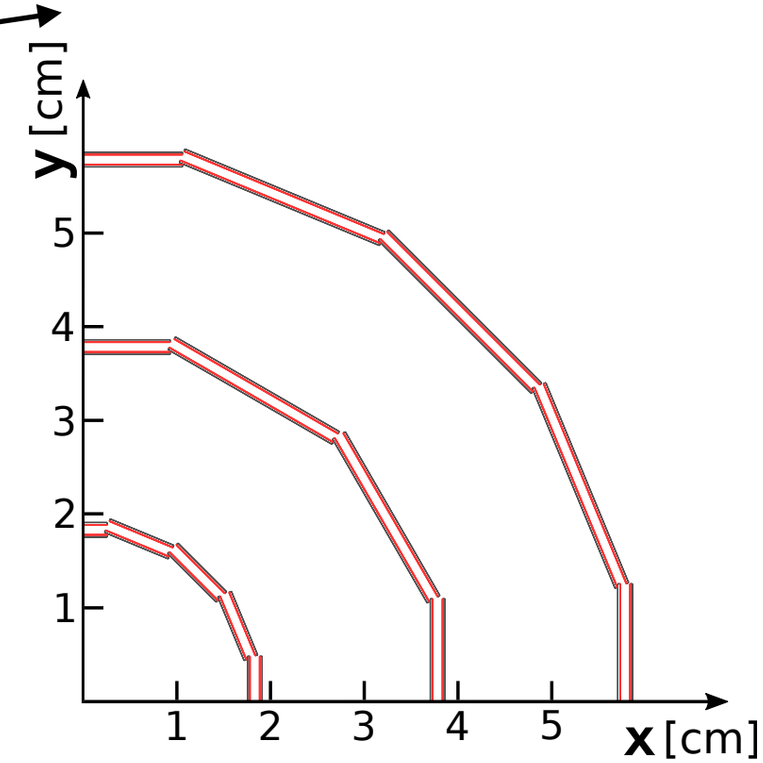
https://arxiv.org/pdf/1911.12230.pdf

CLD is the all-silicon-tracker detector concept developed for FCC-ee

- adapted to B=2T, driven by 30 mrad beam crossing angle and vertical emittance
- respecting 150 mrad forward cone reserved for MDI elements
- built upon a 15 mm radius beam pipe

CLD Vertex Detector



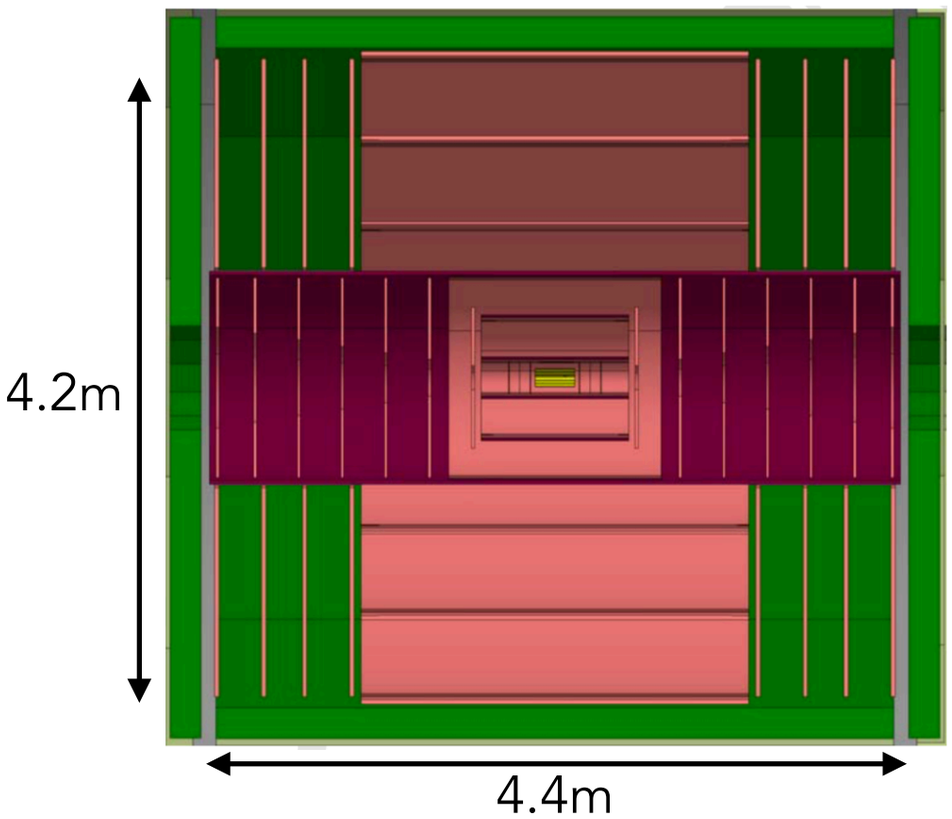


3 double barrel layers + 3 double-layer disks per side
- radius of innermost layer = 17 mm

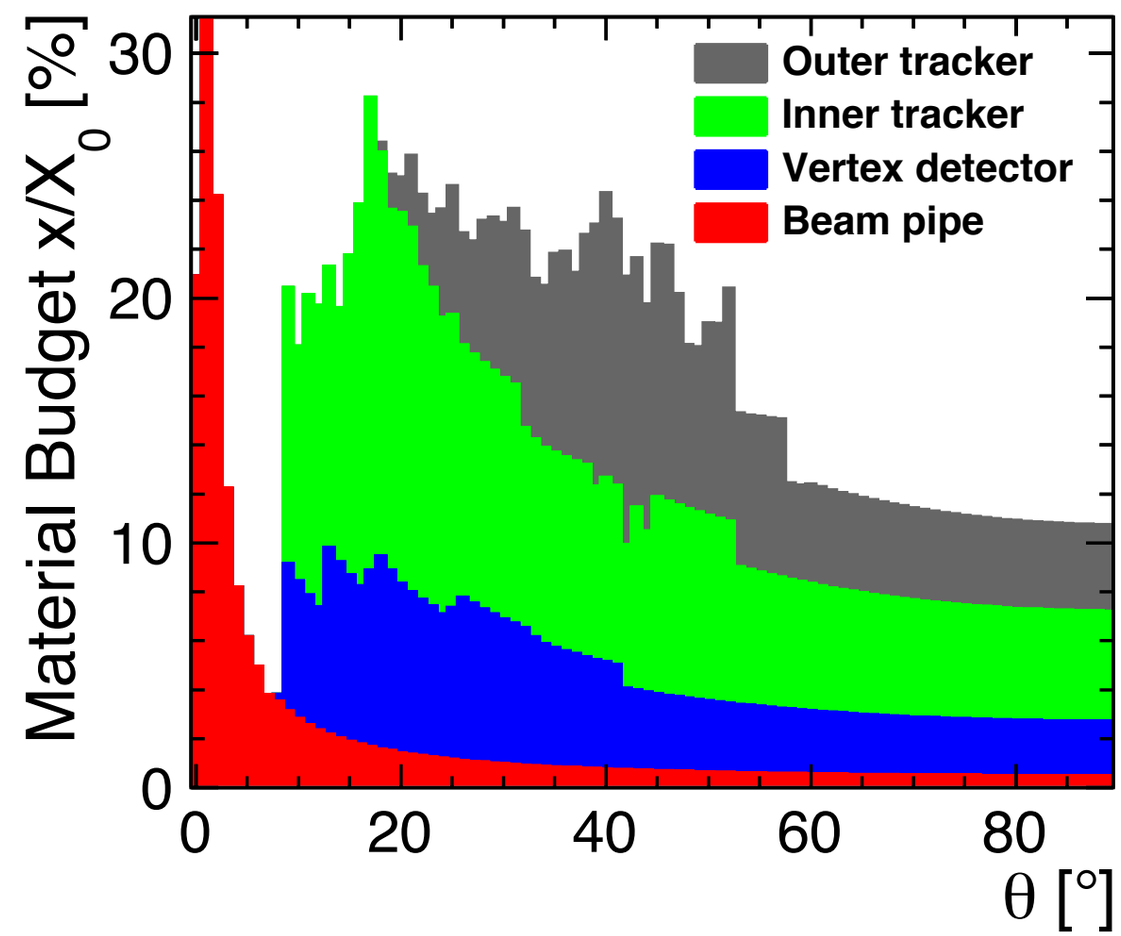
- ➡ as low material budget as possible
  - ➡ sensitive thickness: 50 μm per layer
  - ➡ 0.6% X_0 per double layer
- ➡ pixel size 25 x 25 μm^2
- ➡ total sensitive area = 0.35 m^2

CLD Tracker

https://arxiv.org/pdf/1911.12230.pdf



- Inner Tracker: 3 barrel layers + 7 forward disks per side
- Outer Tracker: 3 barrel layers + 4 forward disks per side
- outer radius = 2.1 m
- microstrips size (50 μm x 1-10 mm)
  - first inner tracker disk pixelated like vertex detector
- total sensitive area = 195.6 m^2



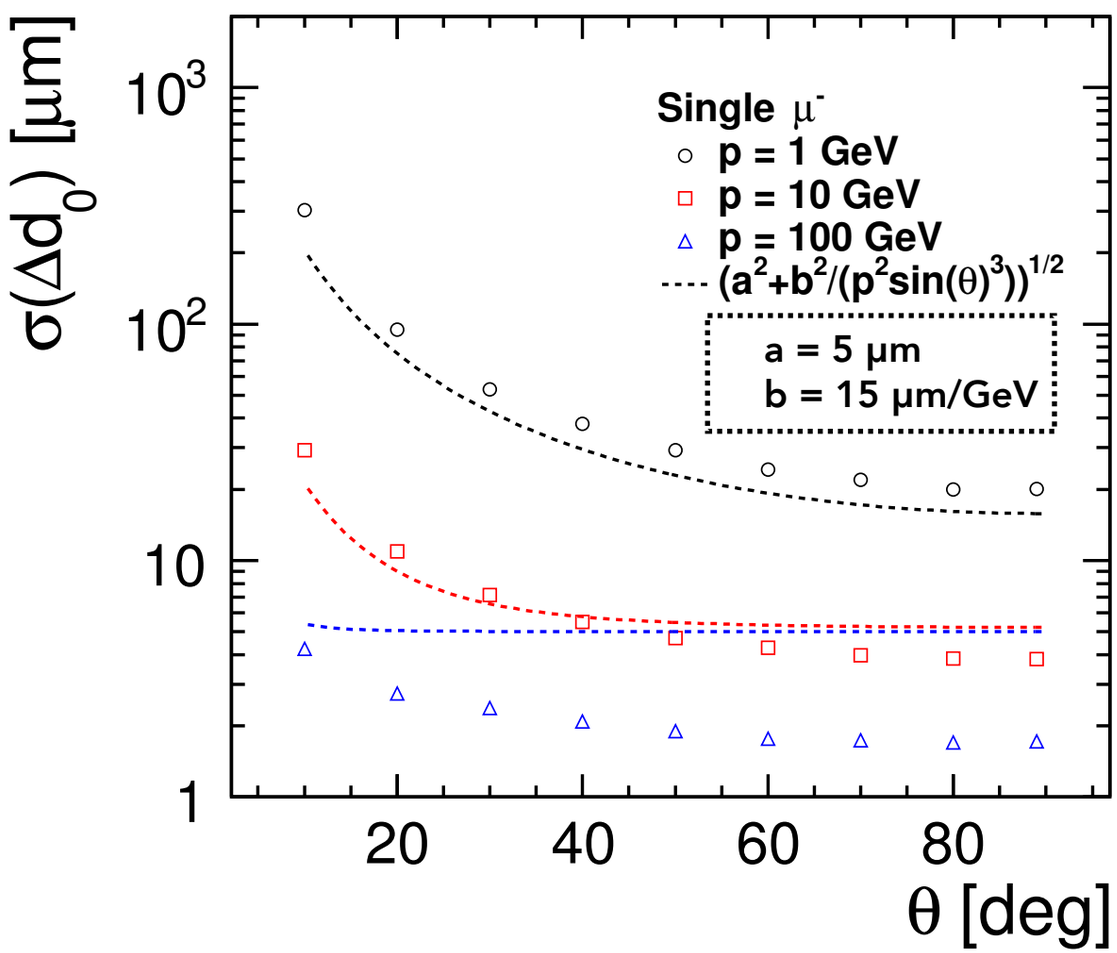
- lightweight tracker:
  - sensitive thickness: 200 μm per layer
  - 1% X_0 per layer (sensitive + liquid cooling + connectivity) + 2.5% X_0 main support, cooling pipes, cabling routes

CLD Tracker Performance

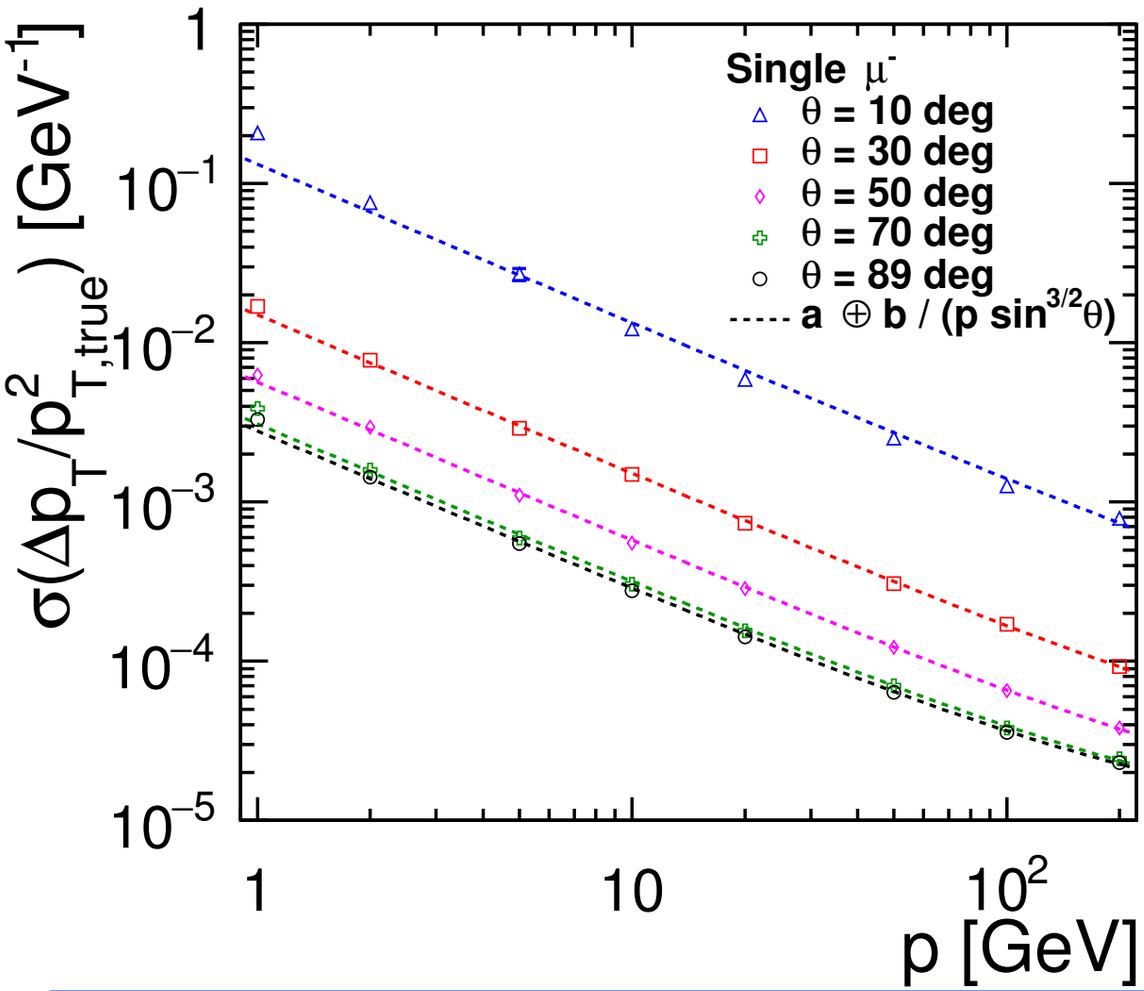
all studies done in full simulation

https://arxiv.org/pdf/1911.12230.pdf

Transverse impact parameter



Transverse momentum



Achieved desired transverse impact parameter resolutions for high-energy muons well below the high-momentum goal of 5 μm

Achieved transverse momentum resolution of ~7×10^{-5} GeV^{-1} for 45 GeV muons at normal incidence (corresponding to required accuracy for Z width measurements)

- curves do not saturate at high momenta => resolution affected by multiple scattering

CLD Tracker Optimization

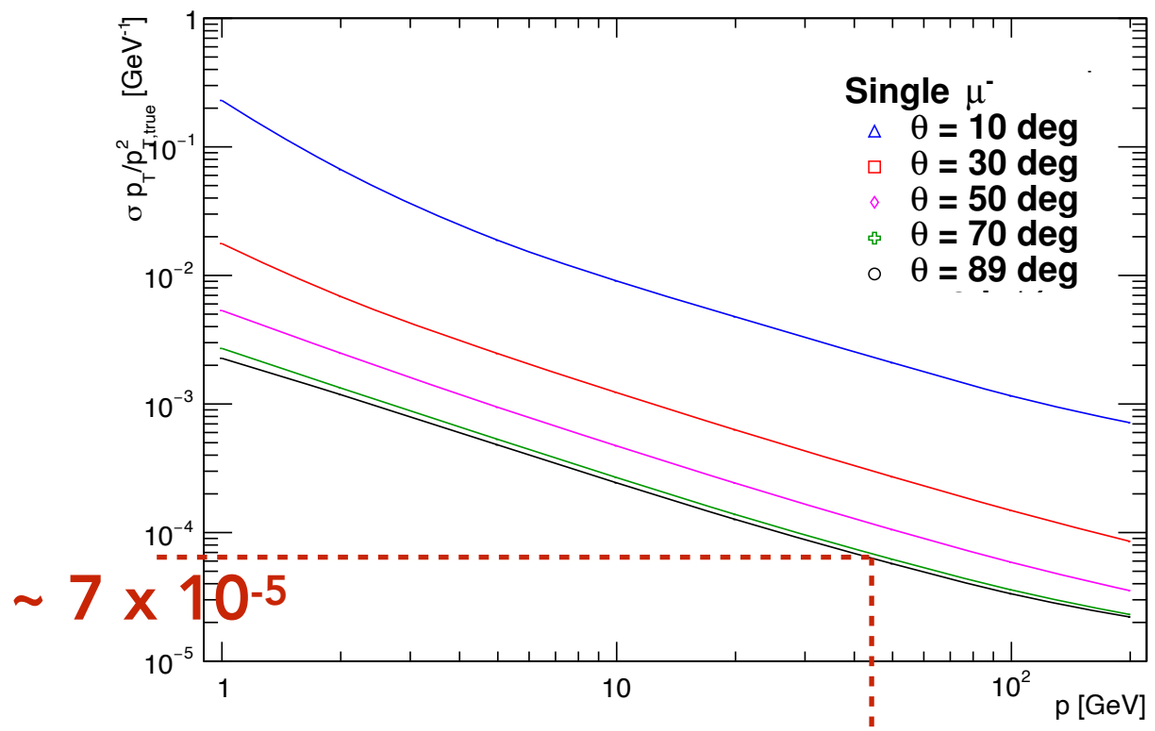
https://arxiv.org/pdf/1911.12230.pdf

Current CLD design straightforwardly adapted by rescaling the CLICdet from B=4T to B=2T.

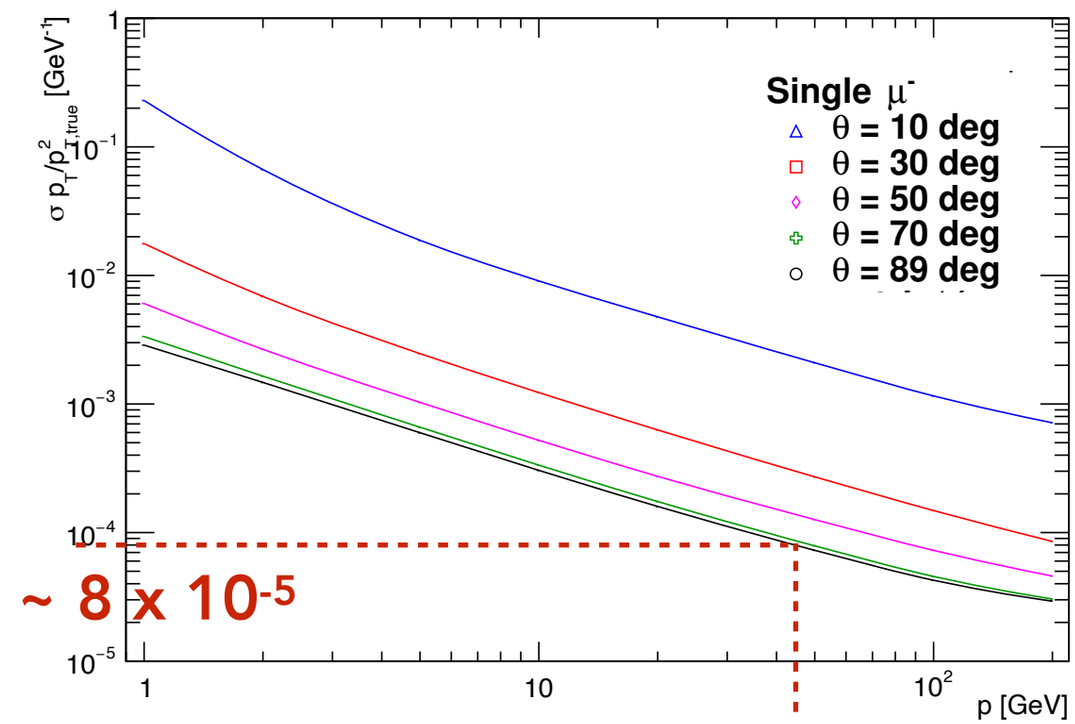
Transverse momentum variation with outer tracker size:

- ➡ fast detector simulation and track reconstruction in `LicToy`
- ➡ reduced outermost layer radius and rescaled other layers

R_{max} = 2.1 m (default)



R_{max} = 1.8 m



With outer tracker radius of 1.8 m, achieved **transverse momentum resolution ~8 x 10^{-5} GeV^{-1}** for 45 GeV muons at normal incidence (still within 100-200 MeV accuracy on muon momentum) required for point-to-point energy error in Z width measurements in Z scan.

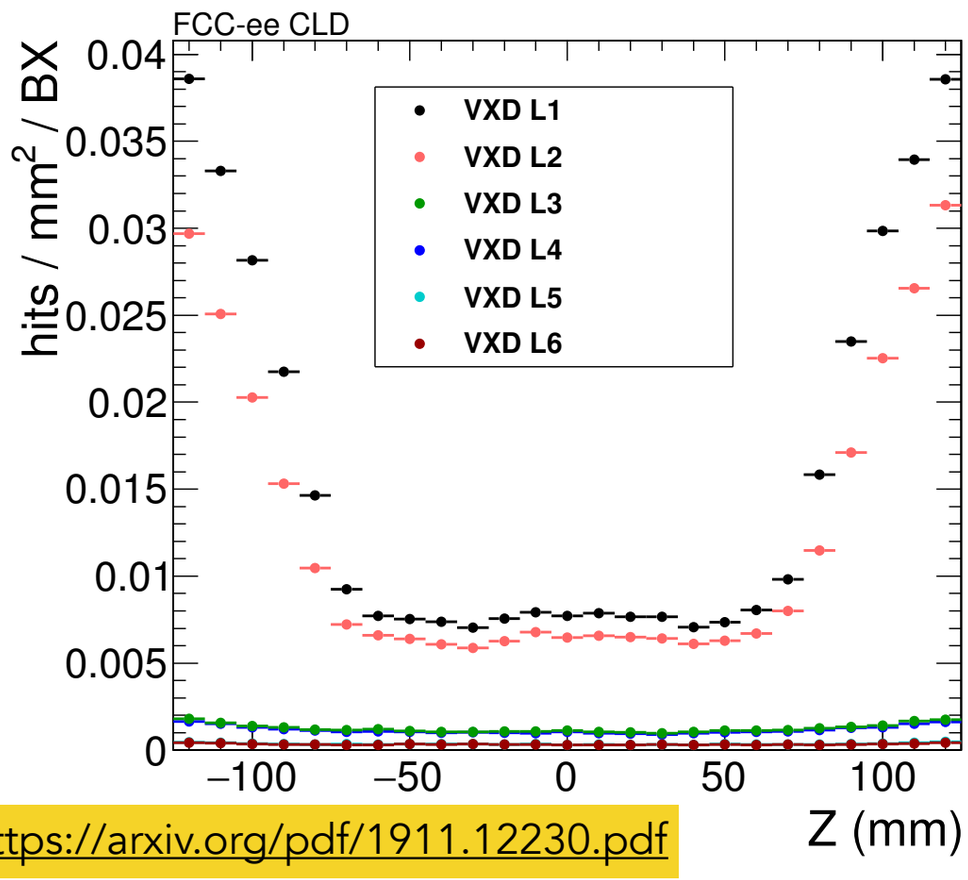
Next step: study material budget reduction in the tracker in terms of best number of layers and location

CLD Tracker Occupancies

Once the beam pipe is shielded, the impact of SR photons on the detector is drastically reduced. The main source of background is the incoherent pairs produced in beamsstrahlung processes.

More on G. Voutsinas' talk > https://indico.cern.ch/event/932973/contributions/4075874/

Impact on the vertex barrel at 365 GeV



https://arxiv.org/pdf/1911.12230.pdf

Assumptions to calculate the occupancy:

- pixel (strip) size 25x25 μm² (0.05x1mm²)
- cluster size = 5
- safety factor = 3

sqrt(s) [GeV]	365 [1 BX]	91.2 [1 BX]
Vertex	~4×10^{-4}	~8×10^{-6}
Tracker	~3×10^{-4}	~2×10^{-5}

Assuming 1 μs integration time

sqrt(s) [GeV]	91.2 [50 BX]
Vertex	~4×10^{-4}
Tracker	~1×10^{-3}

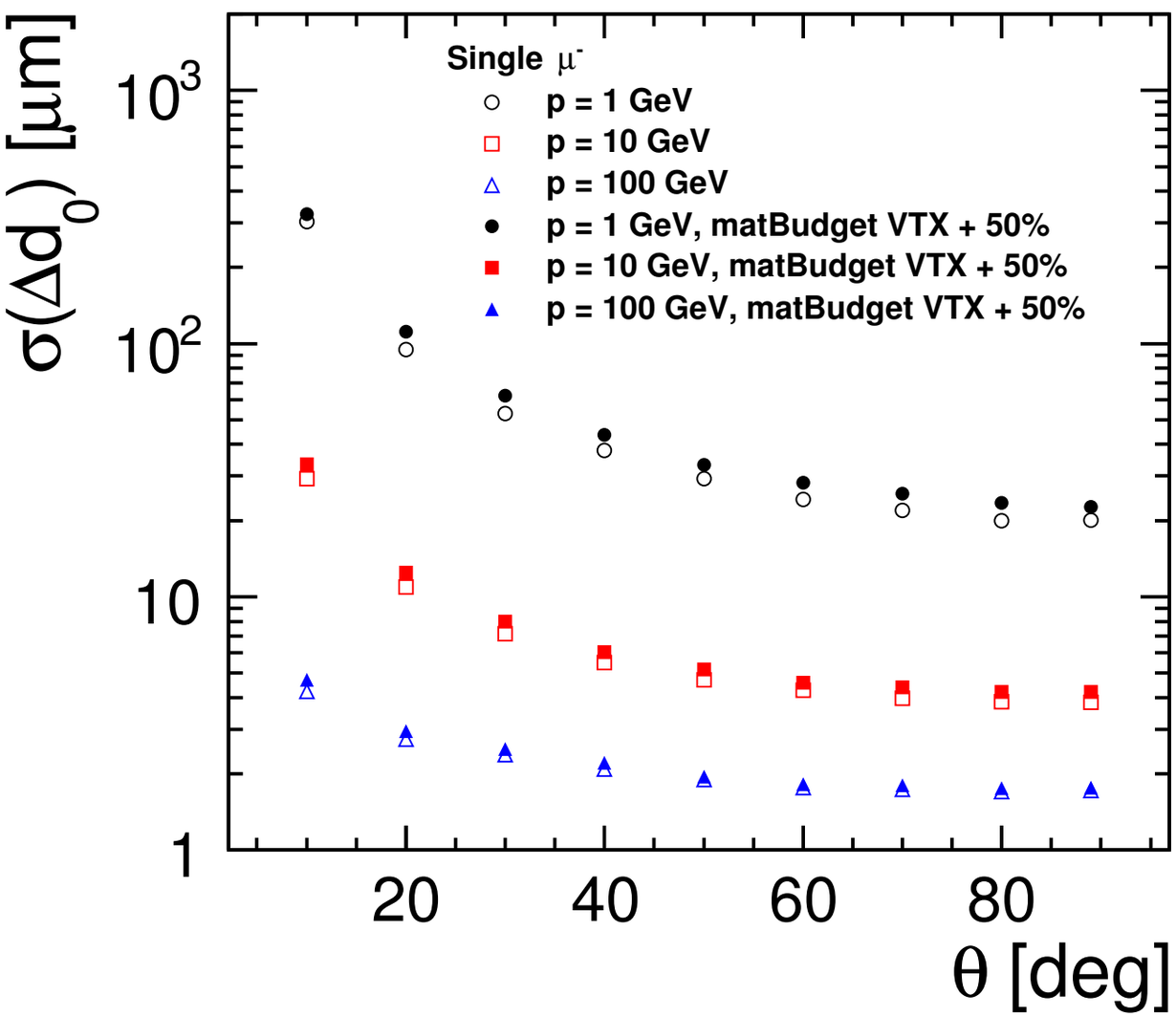
Worst scenario: using10 μs integration time as from ALICE ITS Upgrade Technology

sqrt(s) [GeV]	365 [3 BX]	91.2 [500 BX]
Vertex	~1×10^{-3}	~4×10^{-3}
Tracker	~9×10^{-4}	~1×10^{-2}

CLD Tracker Cooling Considerations

https://arxiv.org/pdf/1911.12230.pdf

- In FCC-ee: continuous operation does not allow for power pulsing
  - impact of cooling and material depends on the technology choices
  - ALICE ITS Upgrade technology
    => current amount of material in the vertex detector 0.3% X_0 per single layer



- In case current amount of material is too optimistic, d_0 resolution probed with an additional 50% to the current thickness

Resolution for low-energy muons worsened only by ~15-20%

CLD Read-out Data Rate

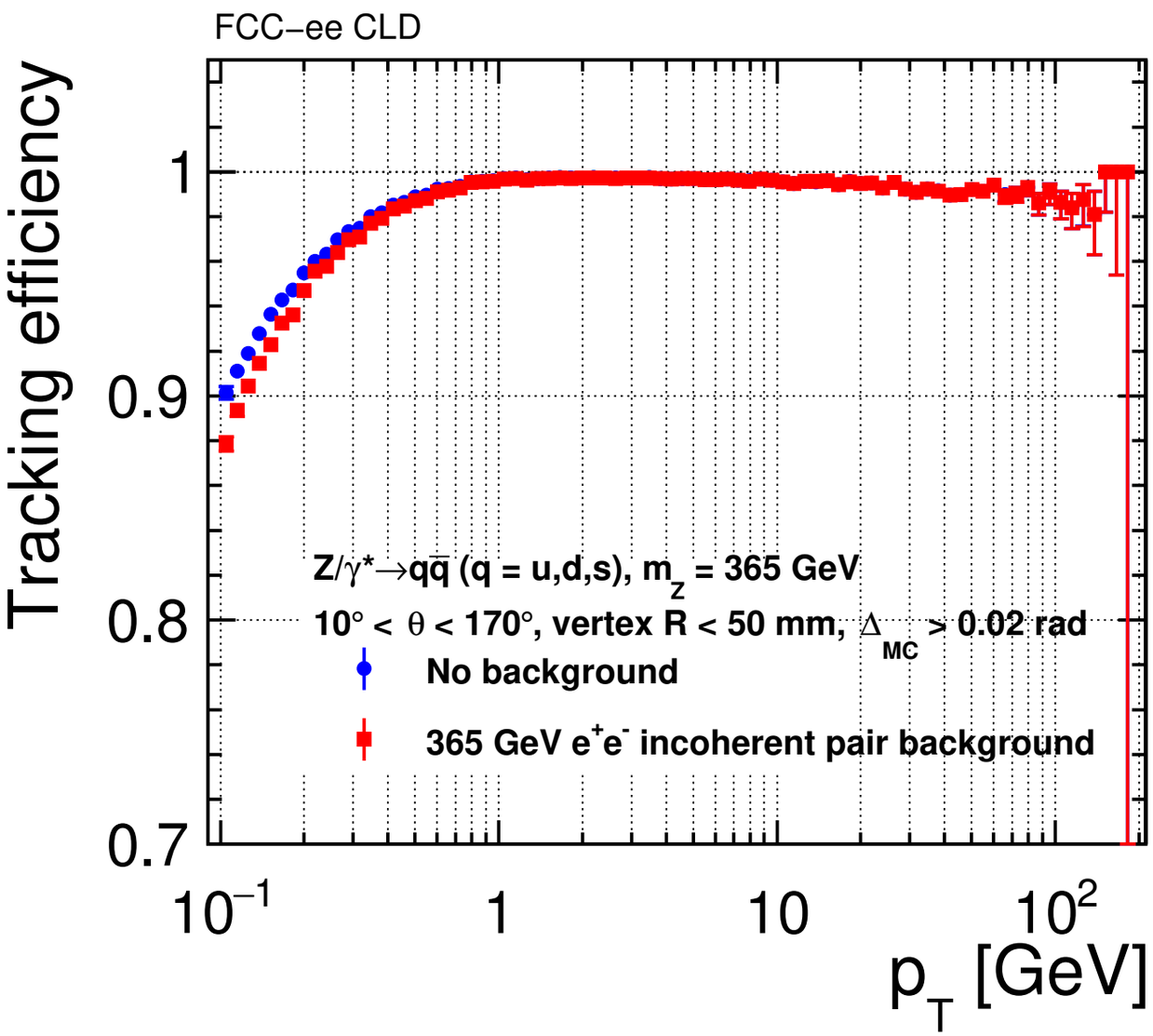
- Current estimate of the data rate is based on several technology assumptions
- **At the Z pole:**
  - event rate to be read-out in the tracking system is dominated by Z production (~100 kHz)
  - for the **vertex detector**:
    - 160 hits on average from hadronic Z decays * 5 (cluster size) = 800 channels / evt
    - 50 hits/BX from incoherent pairs * 3 (safety factor) * 5 (cluster size) = 750 channels / BX
    - assuming 1 μs integration time (~50 BXs) and 13 bits: 1 kB (physics) + 60 kB (bkgd) / evt
    - with 100 kHz trigger rate: **~6 GB/s**
  - for the **tracker**:
    - 200 hits on average for hadronic Z decays * 2.5 (cluster size) = 500 channels / evt
    - 90 hits/BX from incoherent pairs * 3 (safety factor) * 2.5 (cluster size) = 675 channels / BX
    - assuming 1 μs integration time (~50 BXs) and 22 bits: 1.4 kB (physics) + 93 kB (bkgd) / evt
    - with 100 kHz trigger rate: **~10 GB/s**

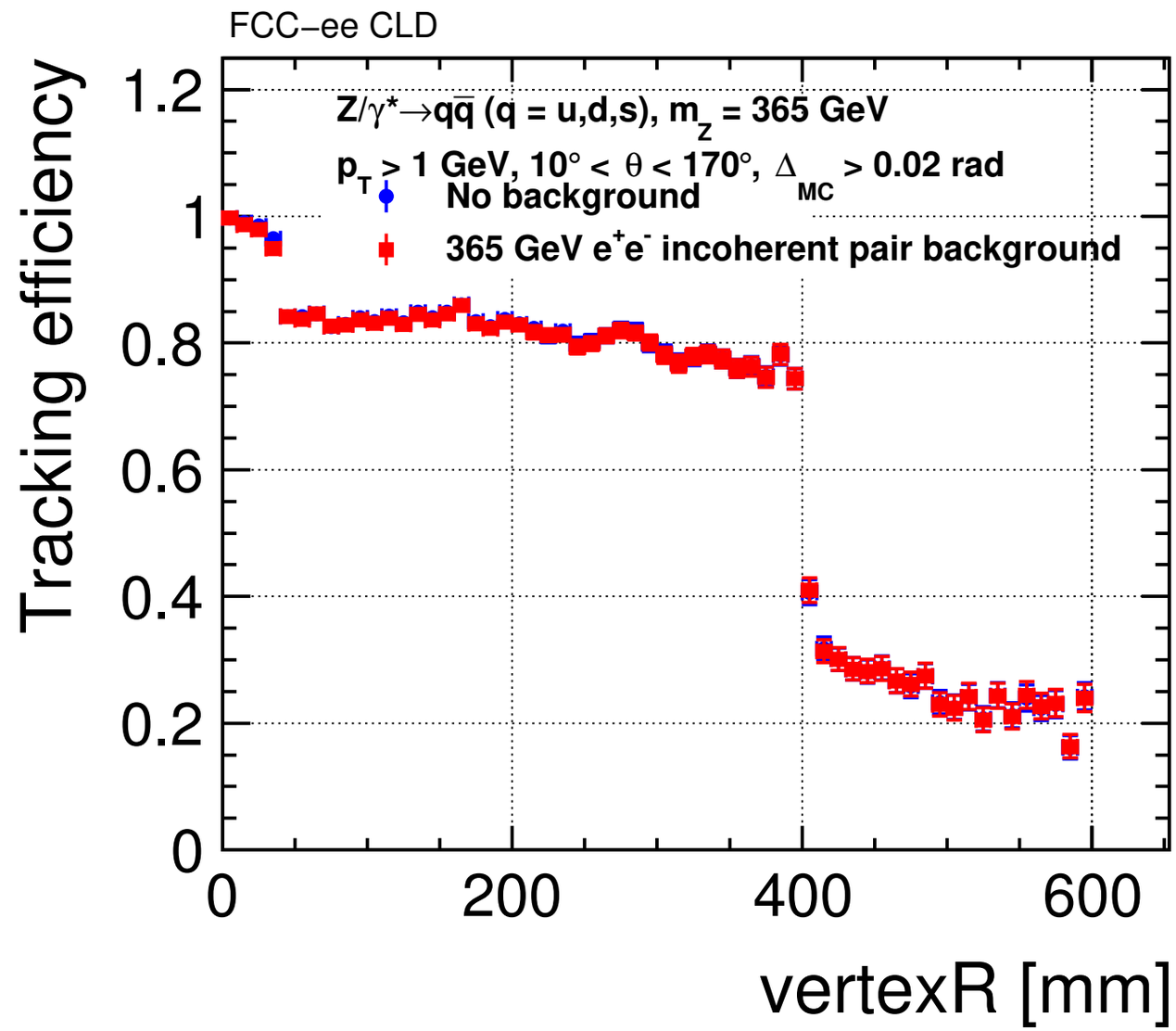
- For comparison:
  CLIC 3 TeV *tracking system*~900 MB/s, ATLAS/CMS pp *full detector* ~100 GB/s (L1)

CLD Tracking Performance

https://arxiv.org/pdf/1911.12230.pdf

Full simulation of incoherent pairs background, integrated in a 10 μs window to probe worse scenario: tracking algorithm performance barely affected by background.





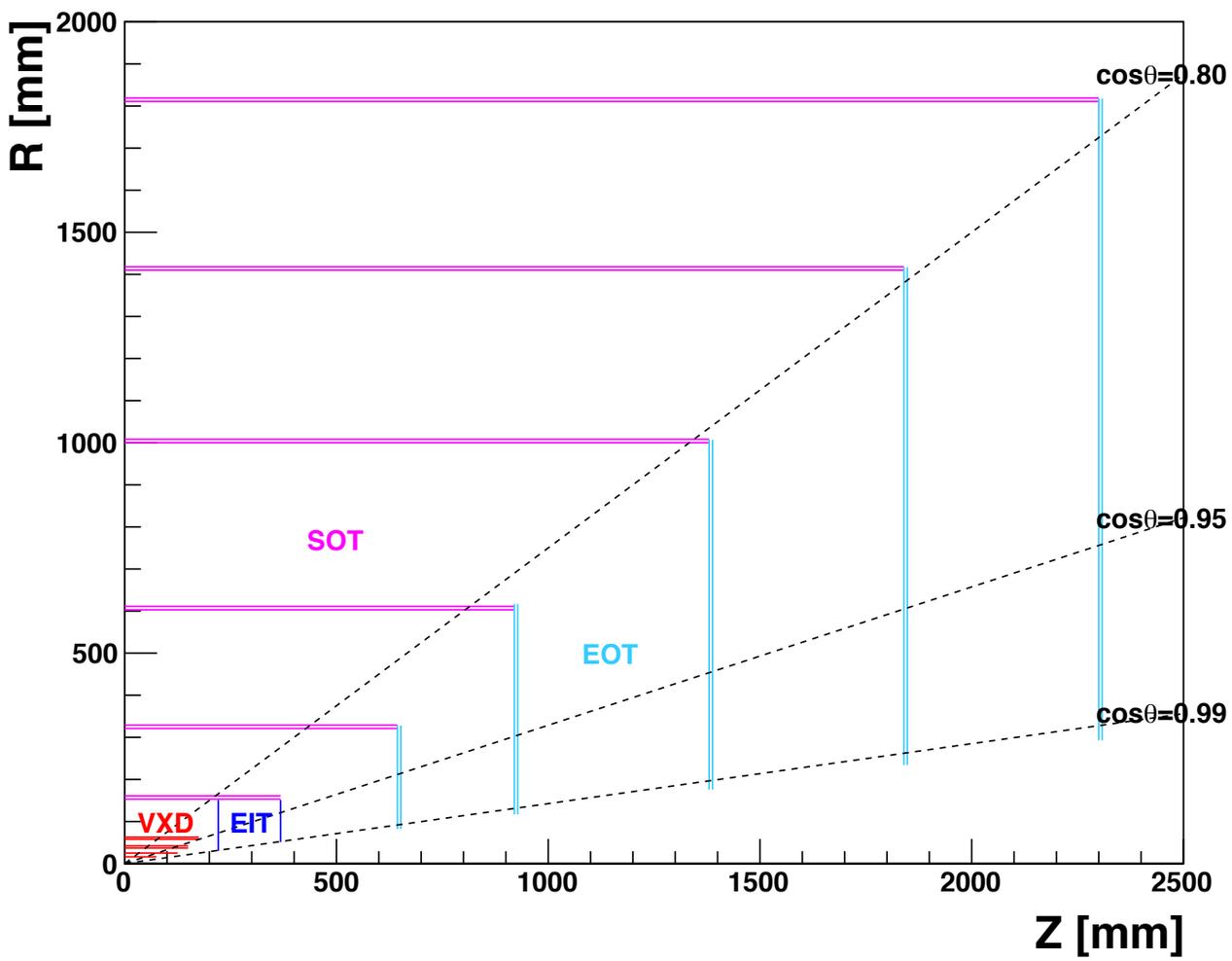
FST at CEPC

https://arxiv.org/pdf/1811.10545.pdf

FST is the version of the baseline detector for CEPC, where the TPC is replaced by an all-silicon tracking system

- adapted to B=3T
- built upon a 14.5 mm radius beam pipe

FST Tracker



VXD

- ➡ 6 pixel layers, radius first layer = 16 mm
- ➡ 3 μm single point res
- ➡ 0.15% X_0 per layer

EIT

- ➡ 2 pixel disks

SOT

- ➡ 6 double-strip layers
- ➡ outer radius = 1.8 m
- ➡ 50 μm pitch

EOT

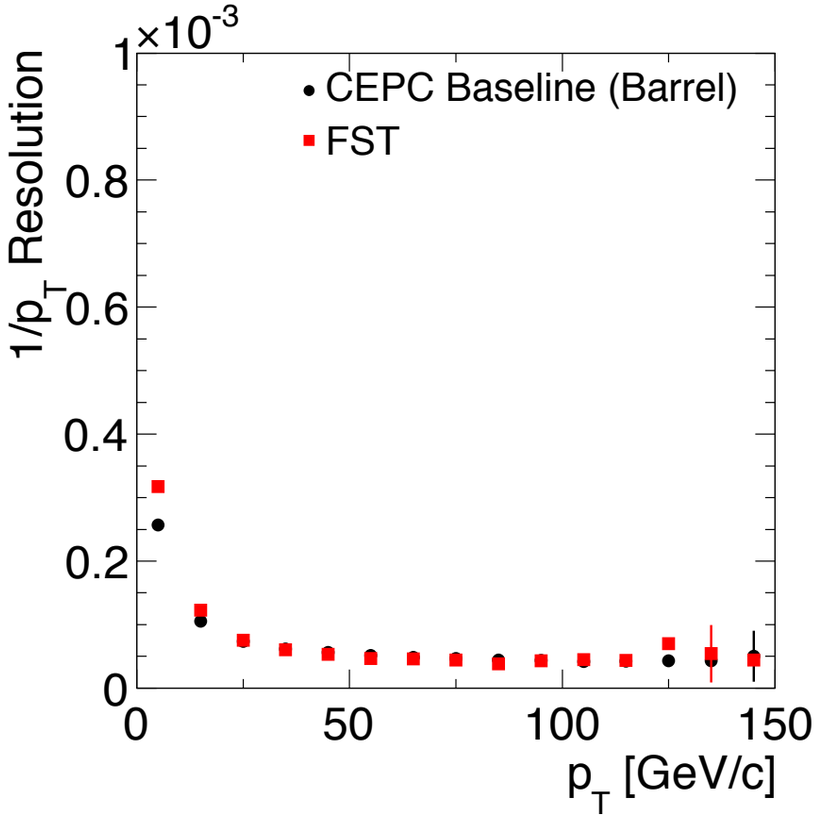
- ➡ 5 double-strip disks
- ➡ 50 μm pitch

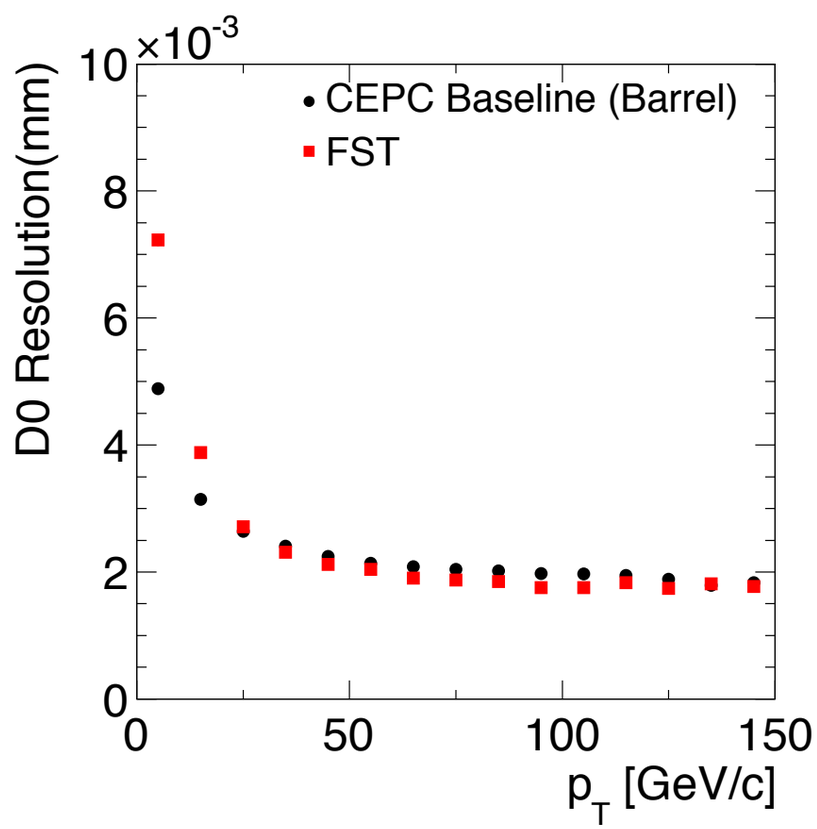
Total sensitive area = 140 m^2

Total radiation length = 5-8% (barrel - endcap)

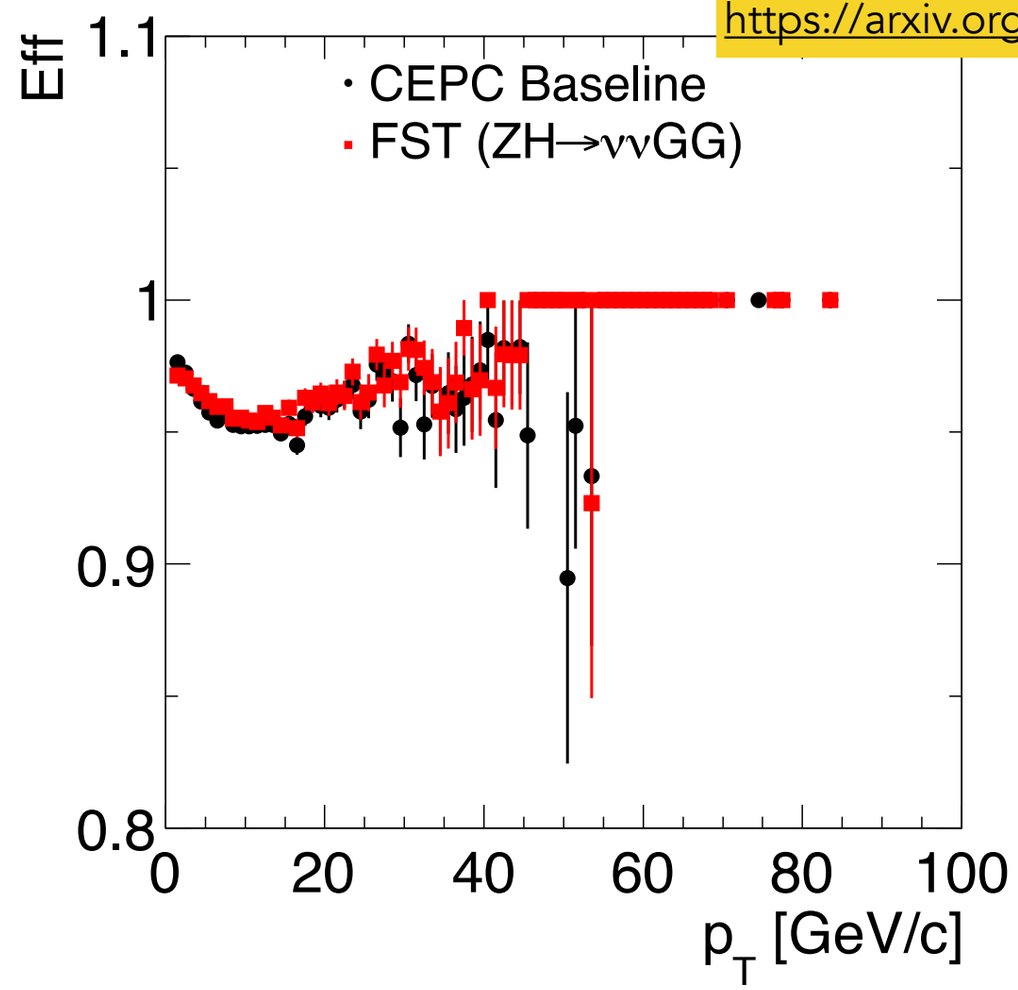
NB: FST2 version exists with single layers replacing the double layers. Not discussed in this talk.

FST at CEPC: Tracking Performance





https://arxiv.org/pdf/1811.10545.pdf



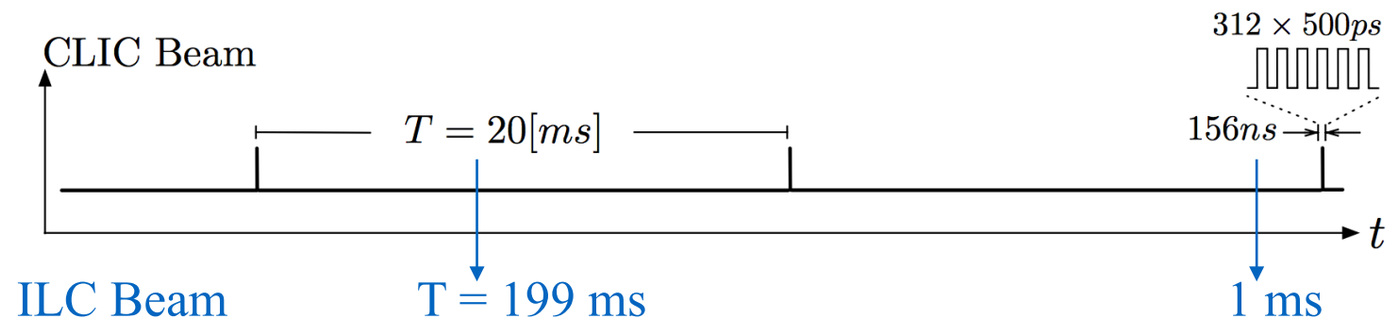
d0 resolution below 5μm
pT resolution 5x10-5 GeV-1
efficiency 100% for pT > 45 GeV, > 95% otherwise

NB: no occupancy and background studies available for this version of the detector.

Linear Colliders experimental conditions

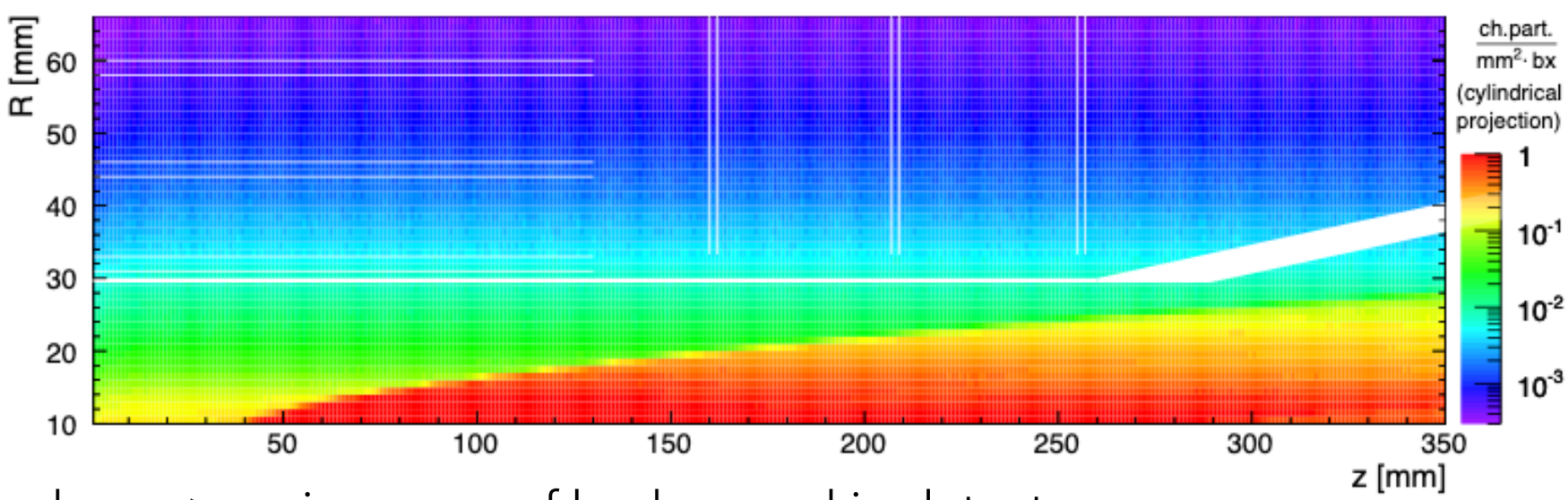
Beam structure:

- allows for power pulsing
  => air cooling possible
  [CLICdet only for vertex detector,
  SiD both for vertex and tracker]



Beam backgrounds:

- incoherent pairs -> for 3 TeV CLIC defines the beam pipe radius, thus the position of the innermost vertex detector layer



- γγ-> hadrons -> main source of background in detectors

https://arxiv.org/pdf/1812.07337.pdf

CLICdet at CLIC

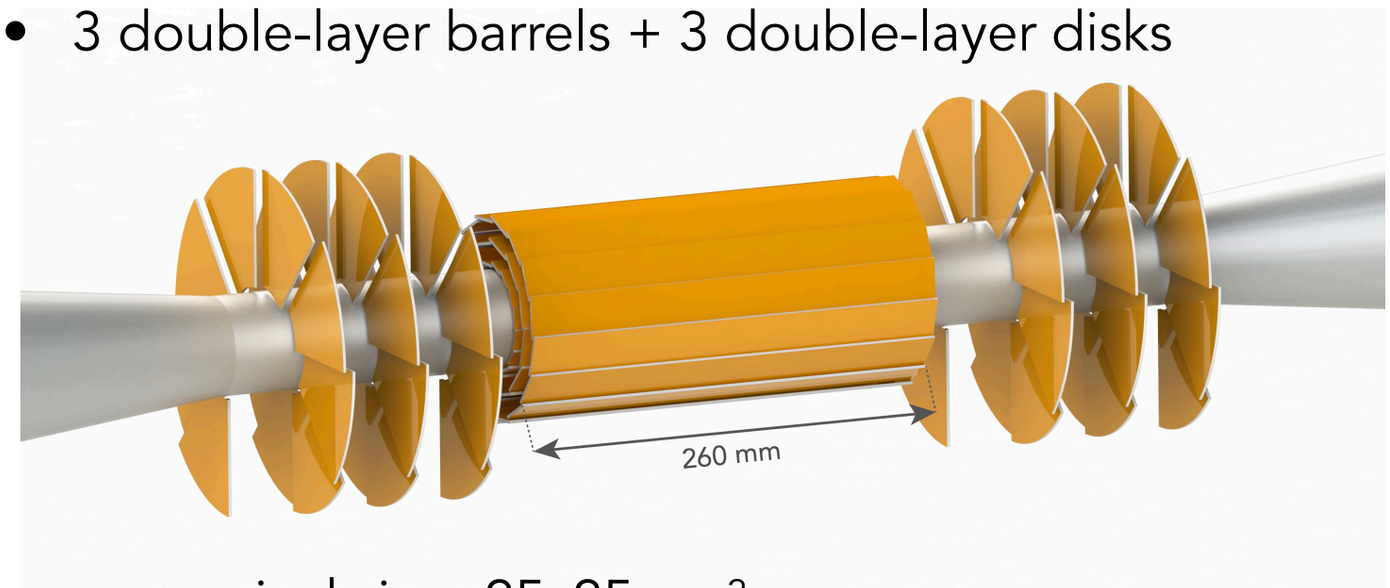
CLICdet is the all-silicon-tracker detector concept developed for CLIC

- designed for B=4T
- built upon a 30 mm radius beam pipe

Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker half length [m]	2.2	
Tracker outer radius [m]	1.5	2.1
ECAL absorber	W	
ECAL X_0	22	
HCAL absorber	Fe	
HCAL λ_I	7.5	5.5
Solenoid field [T]	4	2
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

CLICdet Vertex Detector

- 3 double-layer barrels + 3 double-layer disks

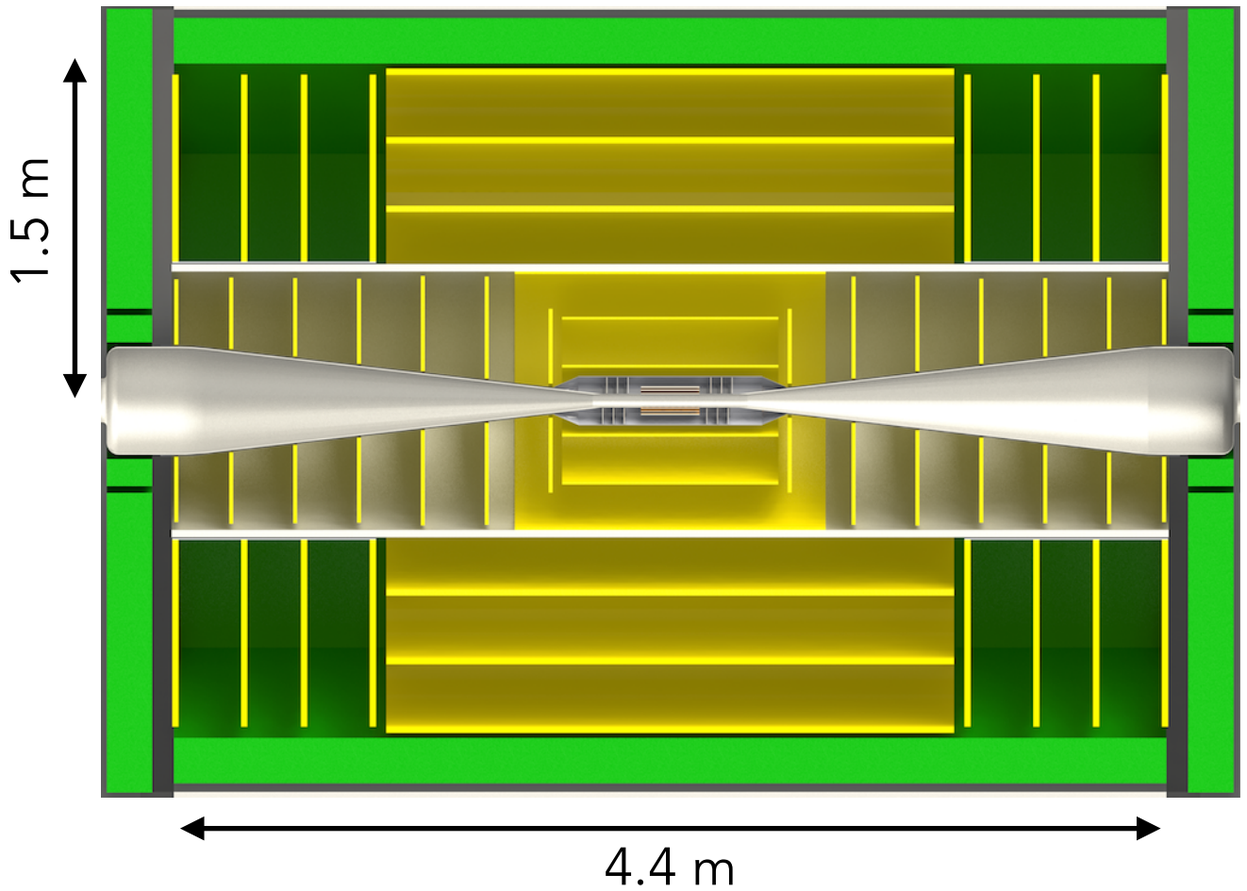


- pixel sizes 25x25 μm^2
  - with analog readout
    => single point resolution 3 μm
  - time resolution ~5 ns
  - max desired occupancy of 3%

- low material budget:
  0.4% X_0 per double layer
  - 50 μm-thick sensors
  - 50 μm-thick ASICs
  - ~100 μm 'equivalent thickness' for cooling, cabling, support
- total sensitive area = 0.84 m^2

CLICdet Tracker

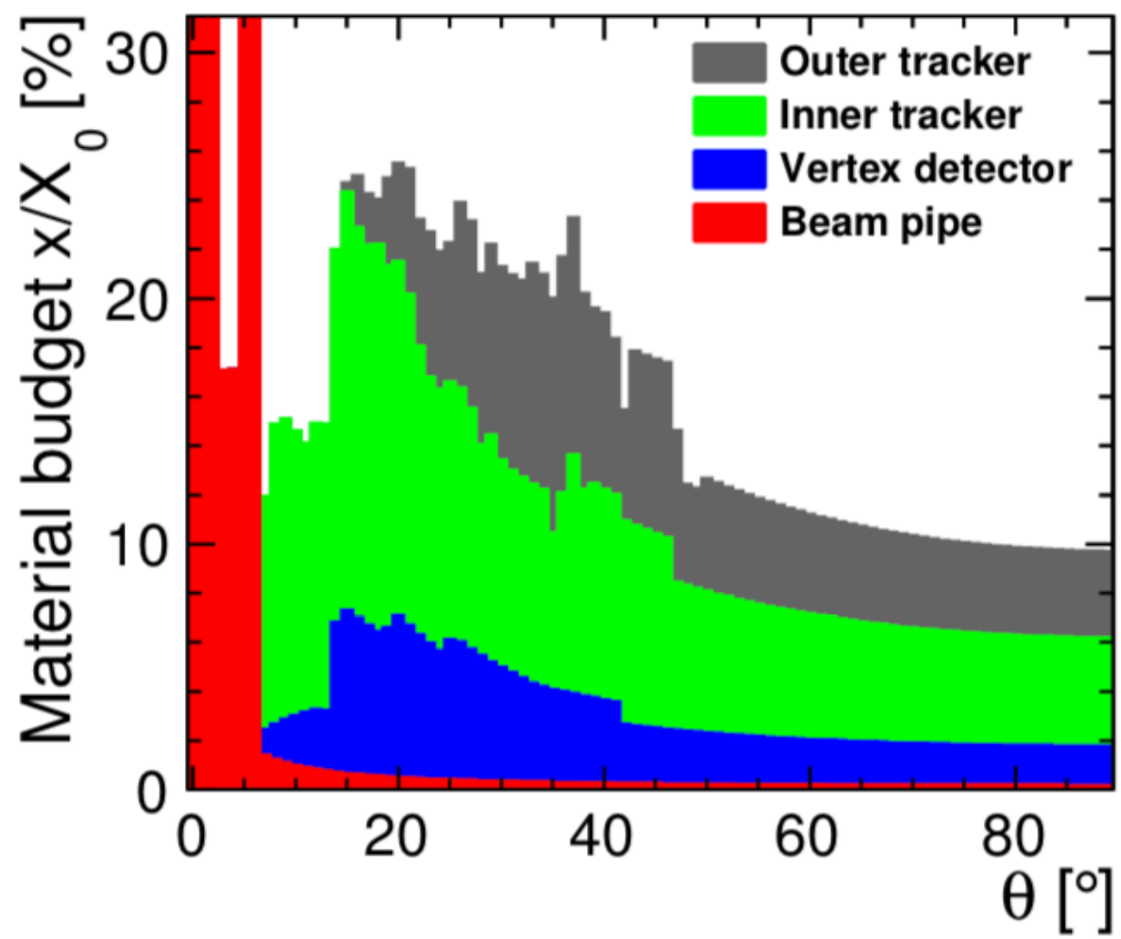
https://arxiv.org/pdf/1812.07337.pdf



- inner tracker: 3 barrel layers + 7 disks
- outer tracker: 3 barrel layers + 4 disks
- carbon fibre support structure
- total sensitive area = 137 m^2

- first inner tracker disk pixelated for pattern recognition needs
- strixels (short strips/ long pixels)
  - with analog readout => single point resolution in (R,φ) 7 μm
  - time resolution of ~5 ns

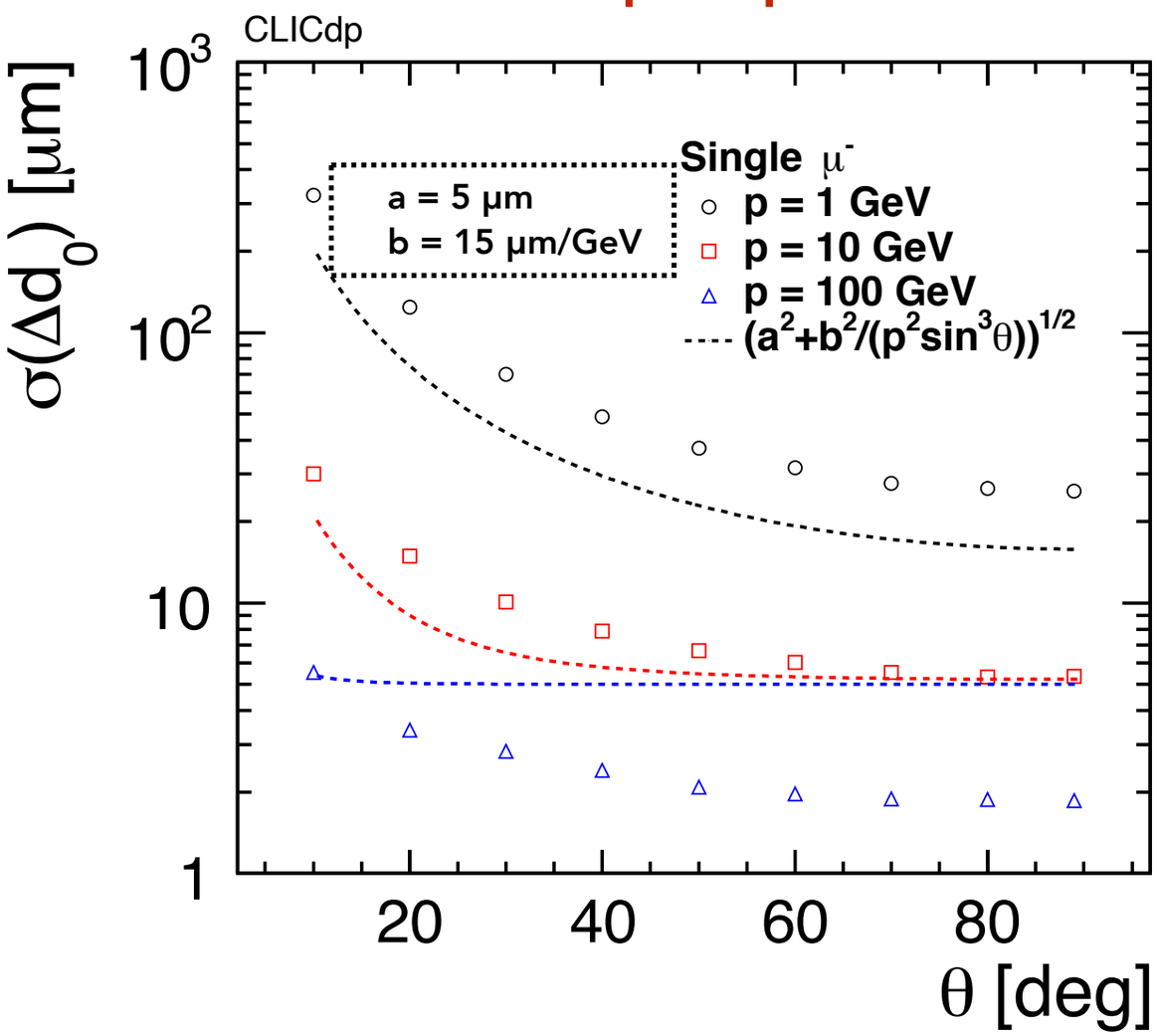
- material budget
  - 200 μm-thick silicon layers (shared between sensor and ASICs)
  - 1% X_0 per tracker layer (sensitive + cooling + cabling)
  - 2.5% X_0 main support tube + supports per layer+ cooling pipes + cable routes



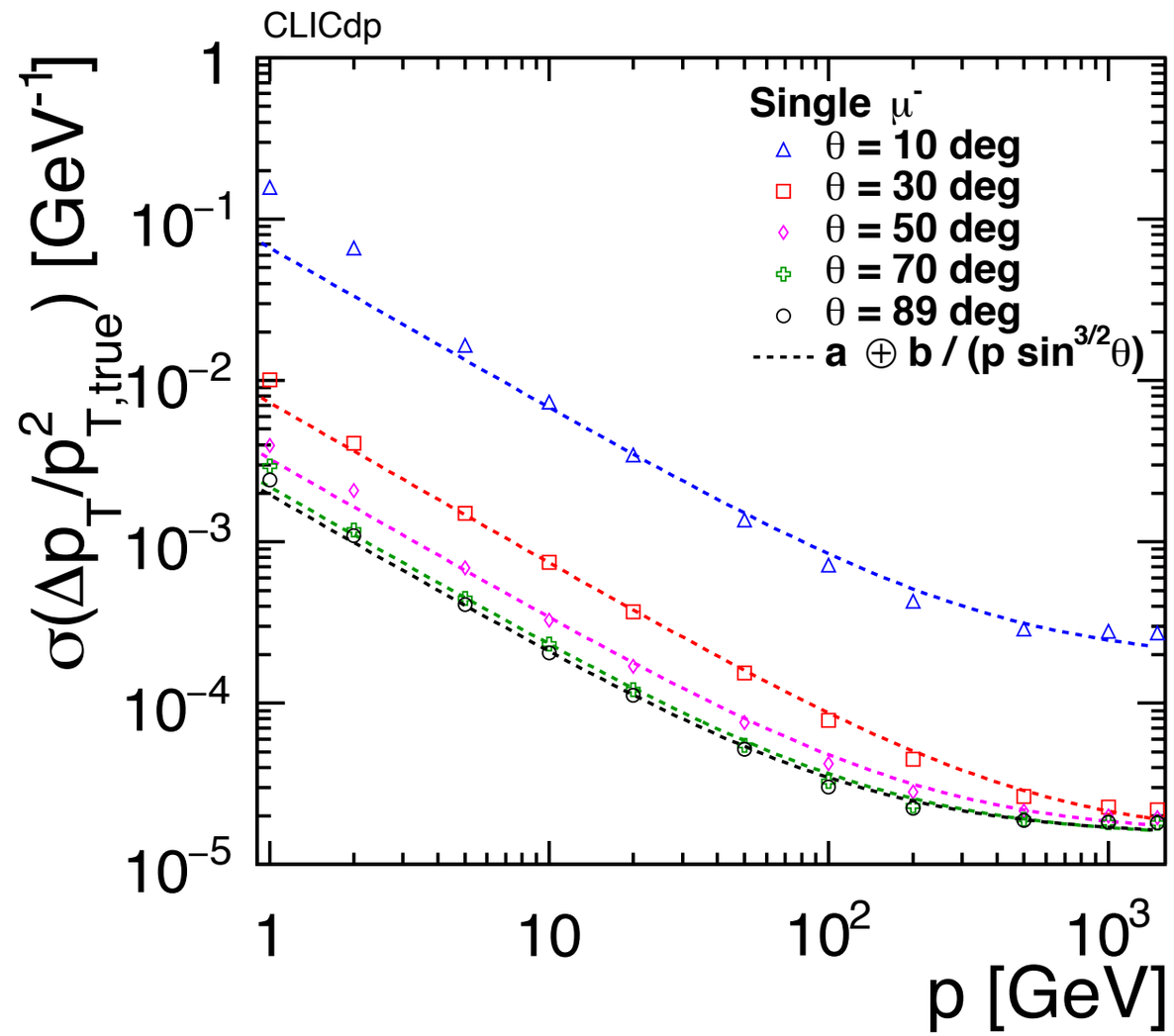
CLICdet Tracking Performance

all studies done in full simulation https://arxiv.org/pdf/1812.07337.pdf

Transverse impact parameter



Transverse momentum



Achieved desired transverse impact parameter resolutions for high-energy muons well below the high-momentum goal of 5 μm

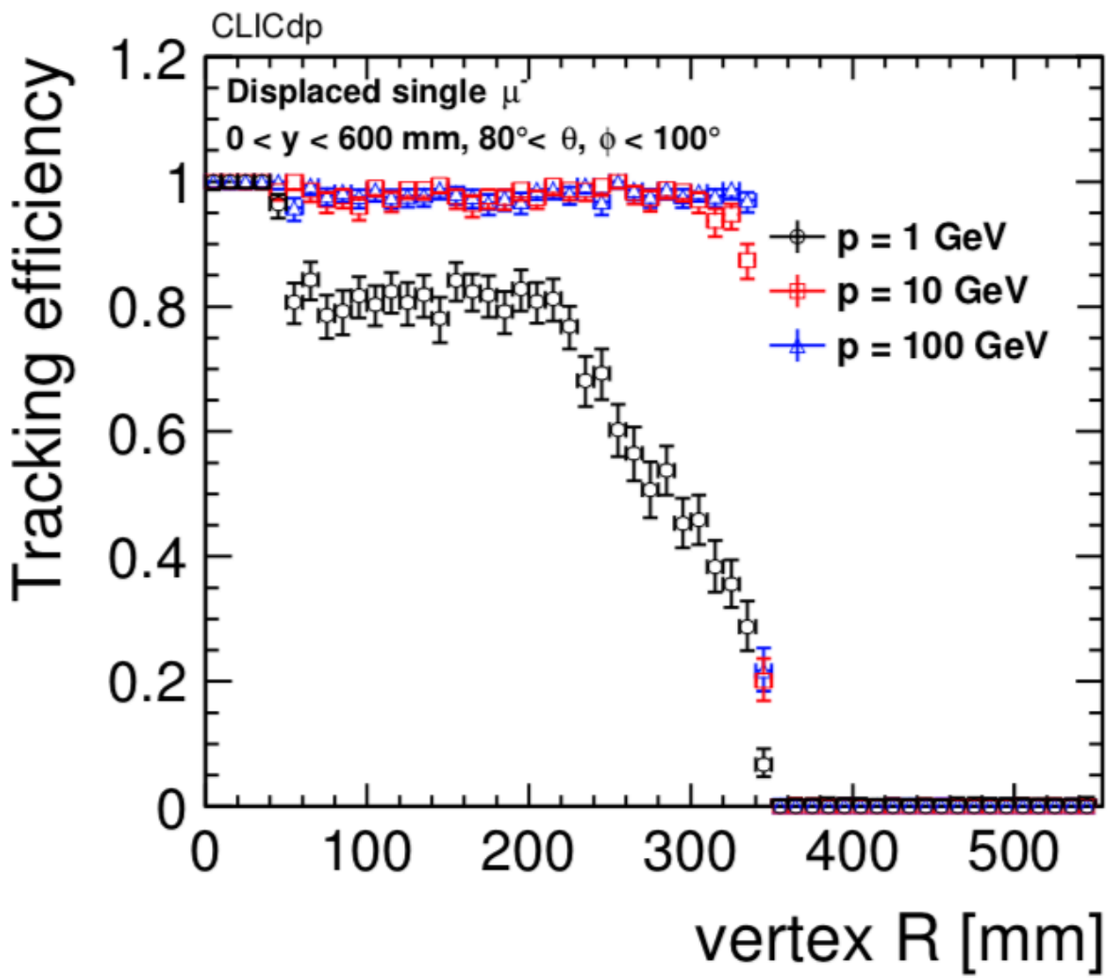
Achieved transverse momentum resolution goal of 2×10^{-5} GeV^{-1} for high-energy muons in the barrel

- curves saturate at high momenta => no multiple scattering, only effect of single point resolution

CLICdet Tracking Performance

all studies done in full simulation https://arxiv.org/pdf/1812.07337.pdf

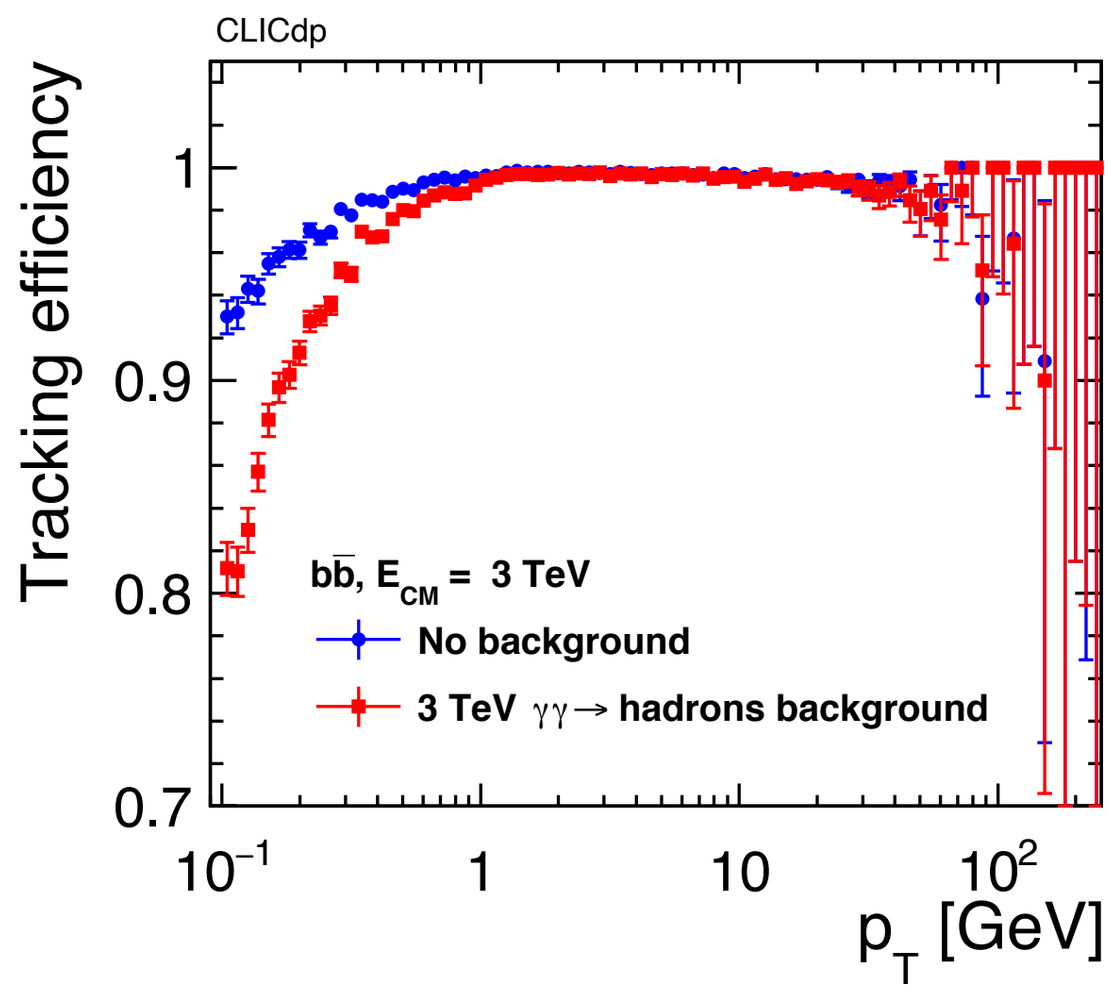
Displaced single muons



Tracking efficiency 100% for p > 1 GeV

- all-silicon tracker no showstopper for V0 decays, secondary vertices, …

Complex events - w/wo background



Tracking efficiency 100% for p_T > 500 MeV

- background does not affect performances for p_T > 1 GeV

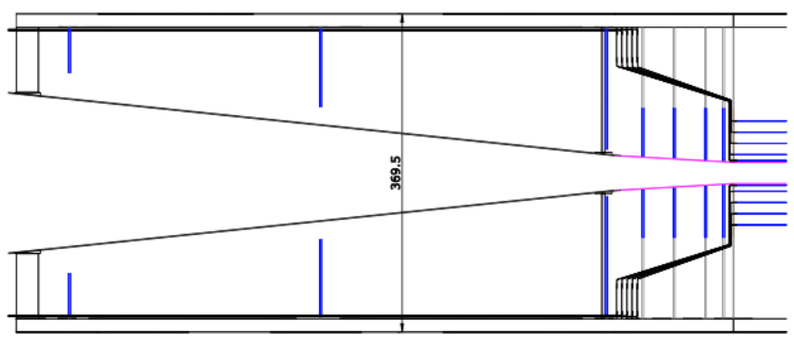
SiD at ILC

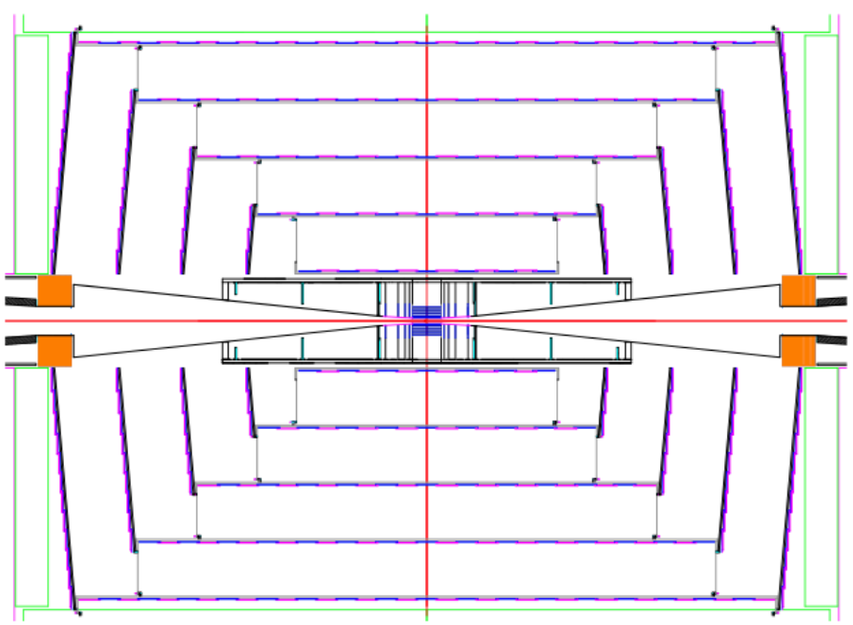
https://arxiv.org/pdf/1306.6329.pdf

SiD is the all-silicon-tracker detector concept developed for ILC

- designed for B=5T
- built upon a 10 mm radius beam pipe

SiD Vertex Detector andTracker





Vertex detector:

- 5 barrel layers, radius first layer = 14 mm
- 4 disks + 3 additional forward disks
- 20 μm pixel pitch up to 50 μm
- 0.1% X_0 per layer
- single BX time stamp: ~300ns
- coverage down to cos(θ) ~ 0.984

Tracker:

- 5 barrel layers, 0.9 % X_0 per layer
- outer radius = 1.25m
- 4 conical disks, 1.3 % X_0 per layer
- 25 μm sensor pitch
- 6 hits down to 8°

Total material budget: < 20% X_0 within 10° of the beam direction

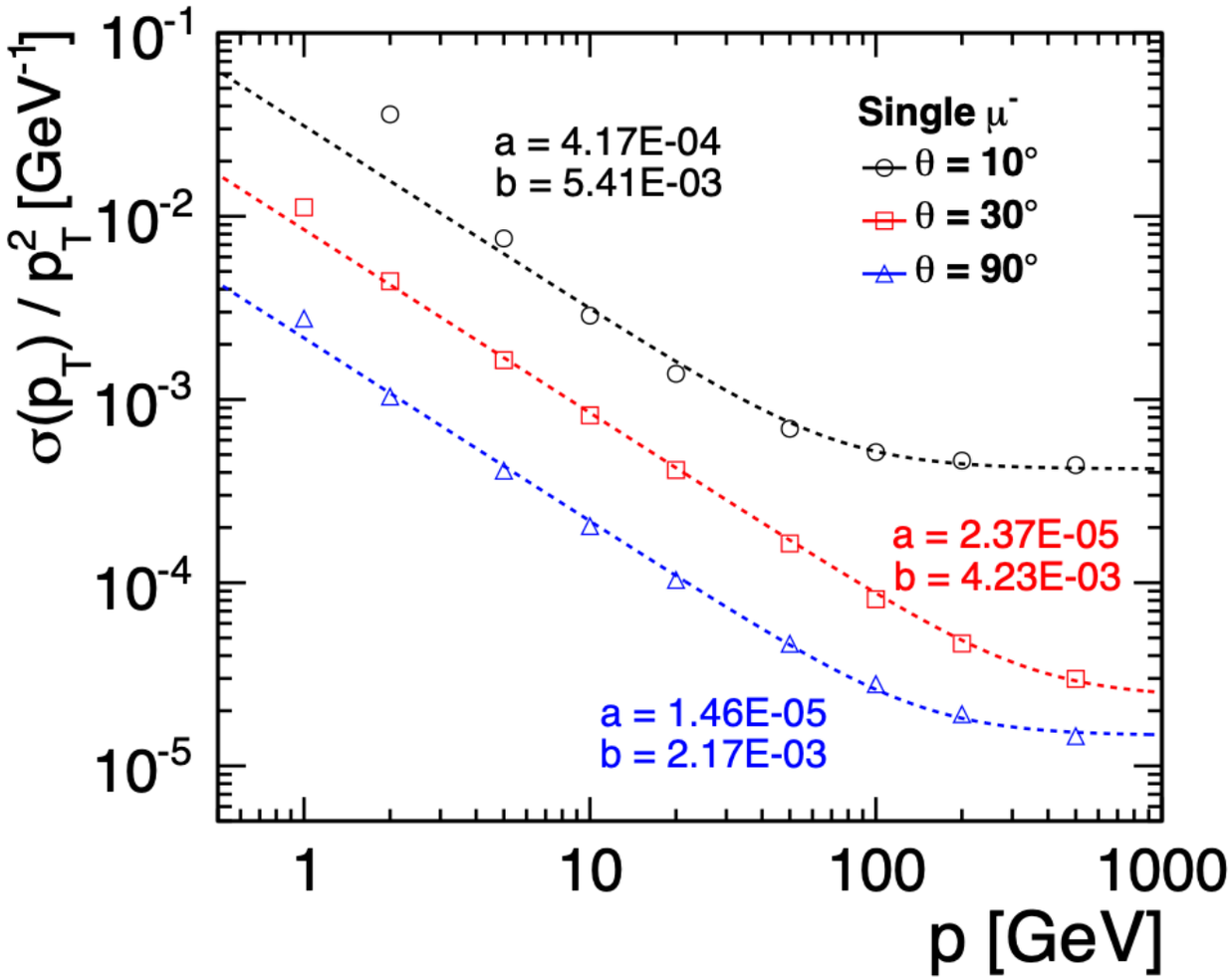
https://indico.cern.ch/event/868940/contributions/3814064/attachments/2081543/3496370/SiD_ICHEP_2020_A_White.pdf

SiD Tracking Performance

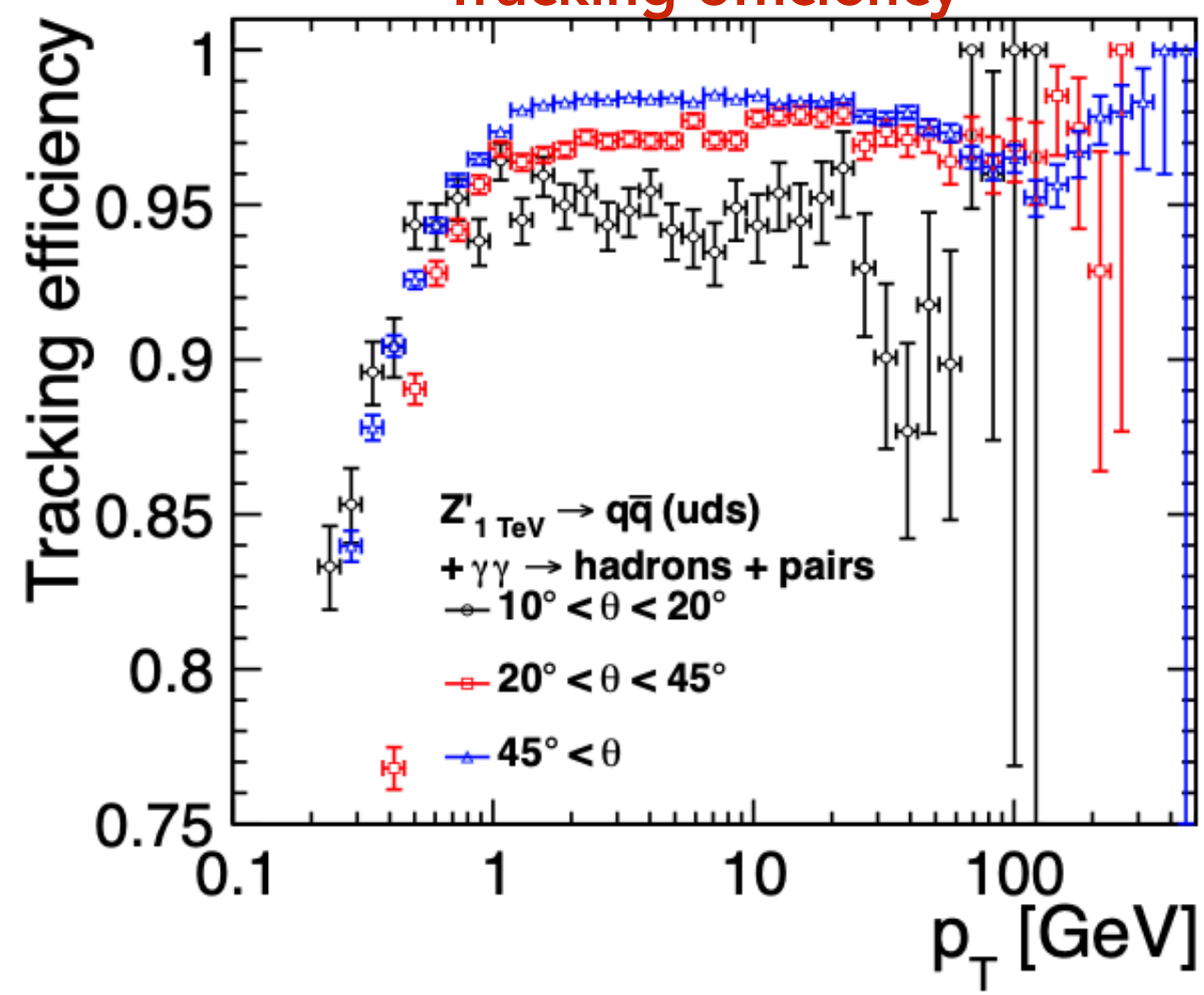
all studies done in full simulation

https://arxiv.org/pdf/1306.6329.pdf

Transverse momentum



Tracking efficiency



Exceeded transverse momentum resolution goal of 2×10^{-5} GeV^{-1} for high-energy muons in the barrel

- 100-200GeV tracks still affected by multiple scattering
- very forward tracks limited by shorter lever arm

Average 98% tracking efficiency with 1BX of beam backgrounds overlaid, except low momenta and very forward tracks.

Summary

- **Detector concepts with all-silicon trackers** for future e+e- colliders comply with experimental constraints and meet physics requirements
- **All-silicon trackers** designs result from a balanced compromise between low occupancy/small single point resolution and material budget

- **R&D in silicon sensors, read-out, cooling and infrastructure ***
  *** Not discussed in this talk**
  - has already achieved promising results in proving feasible to meet the challenging requirements
  - is paving the way to the future of ultra-thin bendable sensors with low power consumptions and minimal cooling

Thank you for your attention

Extra