Long-Lived Particles at FCC-ee with IDEA, CLD Detectors

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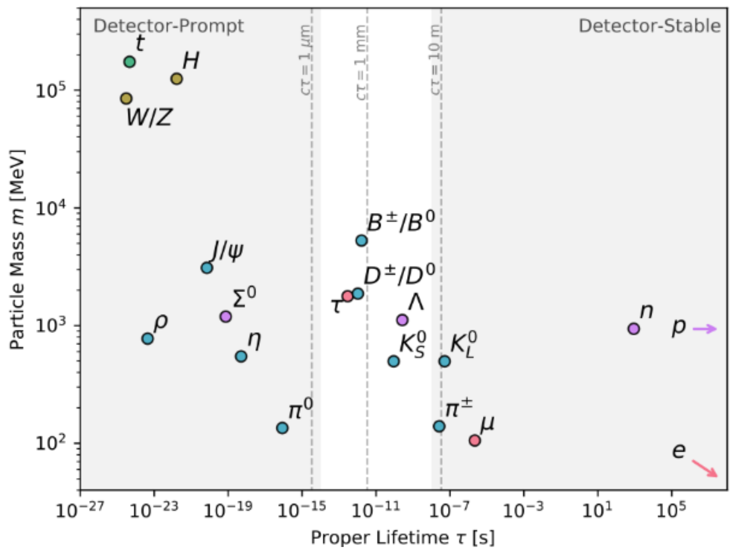
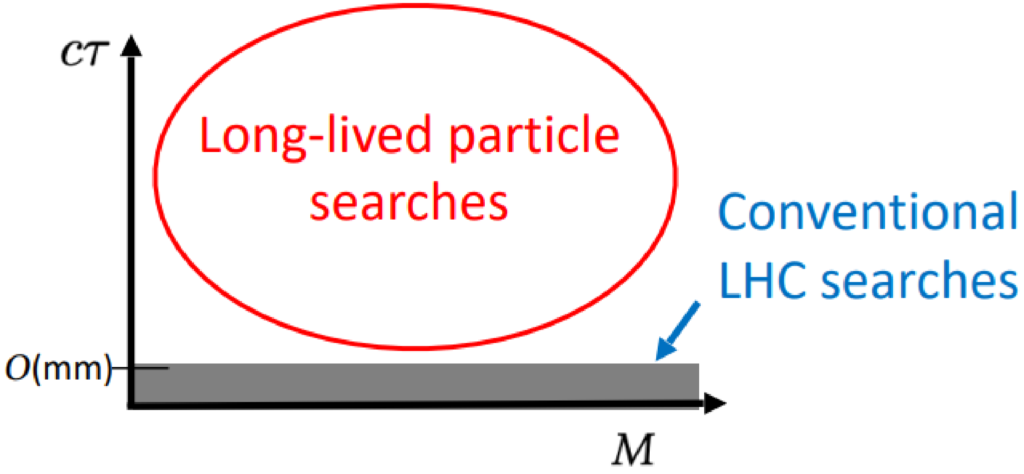
LLPs at the FCC-ee

- **Long-lived particles (LLPs):**
  - Particles w/ decay length resolvable in detector, achieved by small couplings, often leave **displaced signatures**
  - Motivated by numerous open questions, BSM theories
- Experimental challenges of LLP searches:
  - Detectors, triggers, offline reconstruction and subsequent searches are generally designed for **prompt** decays
- Advantages of FCC-ee LLP searches:
  - Clean experimental signatures
  - Few trigger limitations and high luminosity
- Initial studies have motivated further studies:
  - Heavy Neutral Leptons (HNLs)
  - Axion-like Particles (ALPs)
  - **Scalar LLPs from exotic Higgs decays**



arXiv: 1810.1260



J. Alimena

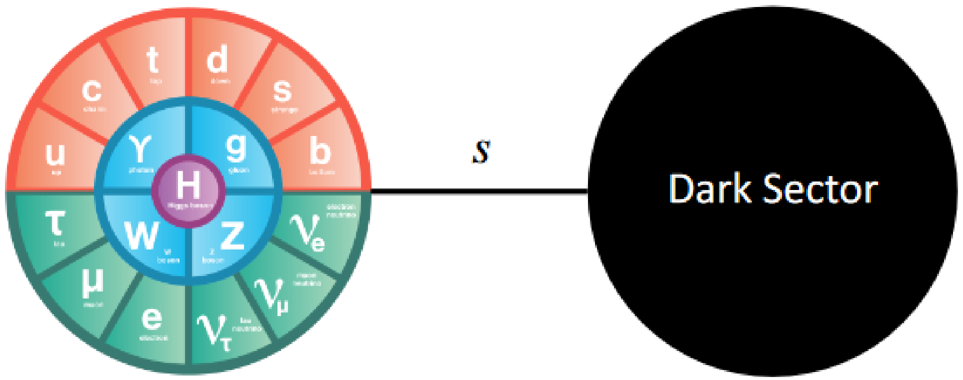
Long-lived scalars from exotic Higgs decays

- Consider a SM + scalar model (arXiv:1312.4992, arXiv:1412.0018)
- Scalar acts as portal between SM and dark sector (e.g., Dark Matter)
- Higgs and scalar coupled by $\boldsymbol{\kappa}$, Higgs and scalar mix with angle $\mathbf{sin}(\boldsymbol{\theta})$

$$\Gamma\left(s \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right) = \sin^2\theta \, \Gamma\left(h(m_s) \to X_{\mathrm{SM}} X_{\mathrm{SM}}\right)$$

- → scalar inherits coupling to SM particles from mixing, so for sufficiently small mixing will be **long-lived**

$$\mathcal{L}_{SM} \ni \underbrace{\frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_s S^4}_{\text{scalar potential}} - \underbrace{\frac{1}{2}\kappa S^2 |H|^2}_{\text{portal term}} + \underbrace{\mu^2 |H|^2 - \lambda |H|^4}_{\text{Higgs potential}}$$



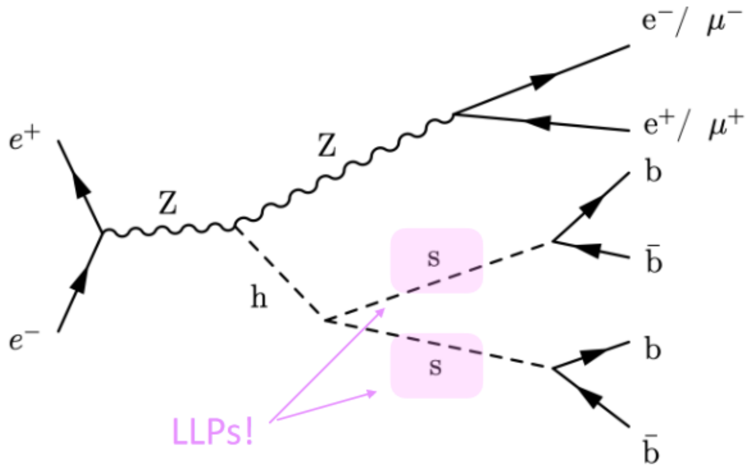
Based on work by Magdalena Vande Voorde, Giulia Ripellino, Axel Gallén, Rebeca Gonzalez Suarez, link to recent talk

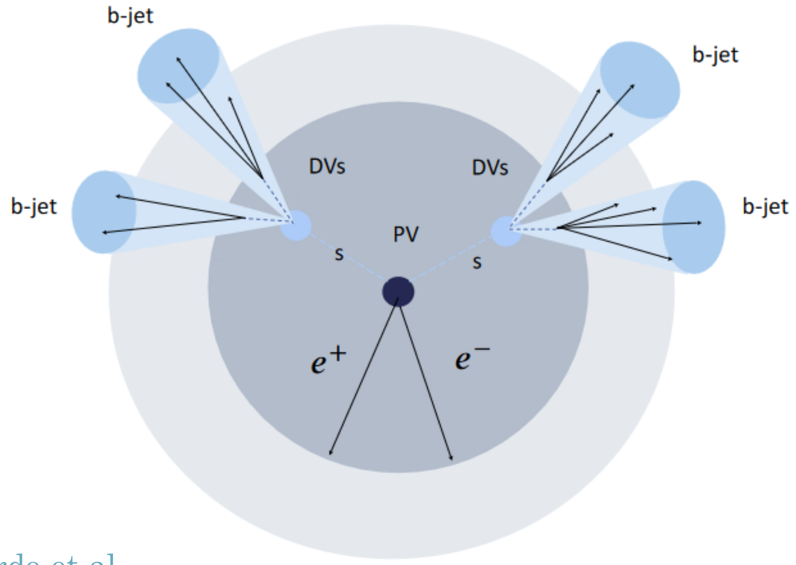
Production at FCC-ee

- Targeting **240 GeV, *Zh* production** stage of FCC-ee w/ signal process:

$$e^+e^- \rightarrow Z\,h \text{ with } Z \rightarrow e^+e^- \text{ or } \mu^+\mu^- \text{ and } h \rightarrow ss \rightarrow b\bar{b}b\bar{b}$$

- This provides following experimental signatures:
  - **Reconstructed Z boson** from e^+e^- or $\mu^+\mu^-$ pairs
  - **Displaced vertices** from b pairs from long-lived scalar decay





M. Vande Voorde et al.

Signal Generation and Selection

- Generated new CLD samples with CLD-like Delphes Card (IDEA card w/ tracker geometry replaced by CLD tracker geometry), IDEA samples (from previous analysis) used Winter2023 IDEA Delphes card
  - Using MadGraph v3.5.3 (3.4.2 for IDEA samples) + Pythia8 + Delphes
  - 6 separate samples generated based on varied scalar mass, mixing angle

Mass of Scalar m_S [GeV]	Mixing angle $\sin\theta$	Mean proper lifetime $c\tau$ [mm]
20	1×10^{-5}	3.4
20	1×10^{-6}	341.7
20	1×10^{-7}	34167.0
60	1×10^{-5}	0.9
60	1×10^{-6}	87.7
60	1×10^{-7}	8769.1

- Event selection (from previous analysis):
  - Note: DV cut rejects all background events from WW, ZZ, ZH processes

	Selection
Pre-selection	≥ 2 oppositely charged electrons or muons
Z boson tag	$70 < m_{ll} < 110$ GeV
Multiplicity of DVs	n_DVs ≥ 2

Preliminary IDEA vs. CLD Results

- Applying cuts yielded following efficiencies for IDEA and CLD samples:

IDEA:

(from previous analysis by Magda Vande Voorde, et al.)

Signal Cut flow efficiencies:

	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7
Before Selection	1.0	1.0	1.0
Pre-selection	0.957	0.950	0.949
$70 < m_{ll} < 110$ GeV	0.888	0.888	0.900
$N_{DVs} \geq 2$	0.091	0.672	0.014
	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Before Selection	1.0	1.0	1.0
Pre-selection	0.957	0.957	0.951
$70 < m_{ll} < 110$ GeV	0.894	0.895	0.896
$N_{DVs} \geq 2$	0.0002	0.672	0.398

Events selected:

m_s, sin θ	n_DVs $\geq$ 2
20 GeV, 1e-5	5.0 $\pm$ 0.166
20 GeV, 1e-6	37.1 $\pm$ 0.453
20 GeV, 1e-7	0.8 $\pm$ 0.067
60 GeV, 1e-5	0.0033 $\pm$ 0.0023
60 GeV, 1e-6	10.96 $\pm$ 0.167
60 GeV, 1e-7	6.49 $\pm$ 0.103

Sensitive (> 3 events)

Sensitive, but significant decline

Not sensitive (< 3 events)

Note: given 1.46×10^6 Zh events

CLD:

Signal Cut flow efficiencies:

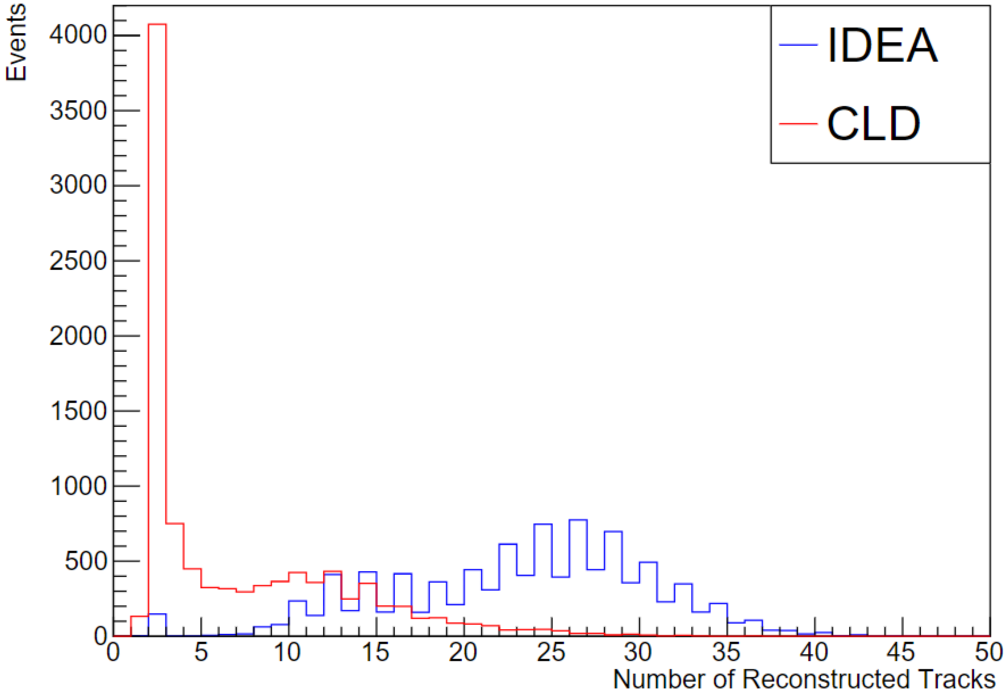
	20 GeV, 1e-5	20 GeV, 1e-6	20 GeV, 1e-7
Before Selection	1.0	1.0	1.0
Pre-selection	0.955	0.952	0.952
$70 < m_{ll} < 110$ GeV	0.891	0.896	0.903
$N_{DVs} \geq 2$	0.092	0.109	0.002
	60 GeV, 1e-5	60 GeV, 1e-6	60 GeV, 1e-7
Before Selection	1.0	1.0	1.0
Pre-selection	0.958	0.958	0.952
$70 < m_{ll} < 110$ GeV	0.895	0.897	0.899
$N_{DVs} \geq 2$	0.0002	0.654	0.0502

Events selected:

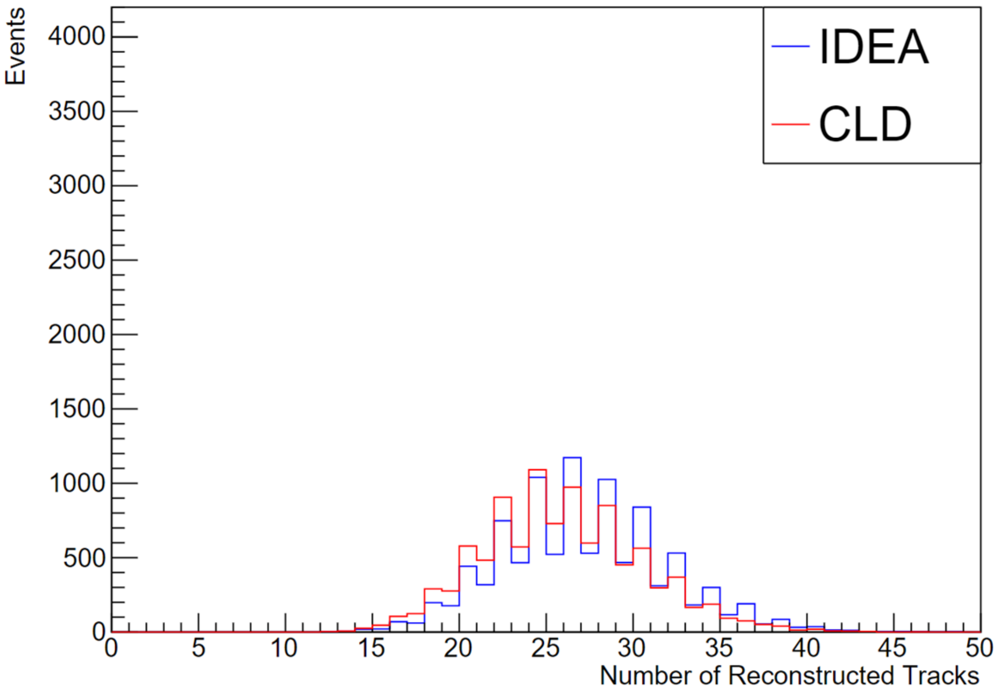
$m_s, sin\theta$	$n_{\rm DVs} \geq 2$	Mean proper lifetime $c\tau$ [mm]
20 GeV, 1e-5	5.10 ± 0.167	3.4
20 GeV, 1e-6	6.02 ± 0.182	341.7
20 GeV, 1e-7	0.11 ± 0.025	34167.0
60 GeV, 1e-5	0.003 ± 0.0023	0.9
60 GeV, 1e-6	10.67 ± 0.132	87.7
60 GeV, 1e-7	0.819 ± 0.036	8769.1

Tracking Performance: IDEA vs. CLD

Longer decay length CLD sample saw reduction in # reco. tracks,
shorter decay length CLD sample saw similar # reco. tracks



$m_s = 20\ GeV, \sin(\theta) = 1e-6, c\tau = 341.7\ mm$ sample saw significant decline in sensitivity



$m_s = 20\ GeV, \sin(\theta) = 1e-5, c\tau = 3.4\ mm$ sample saw similar sensitivity

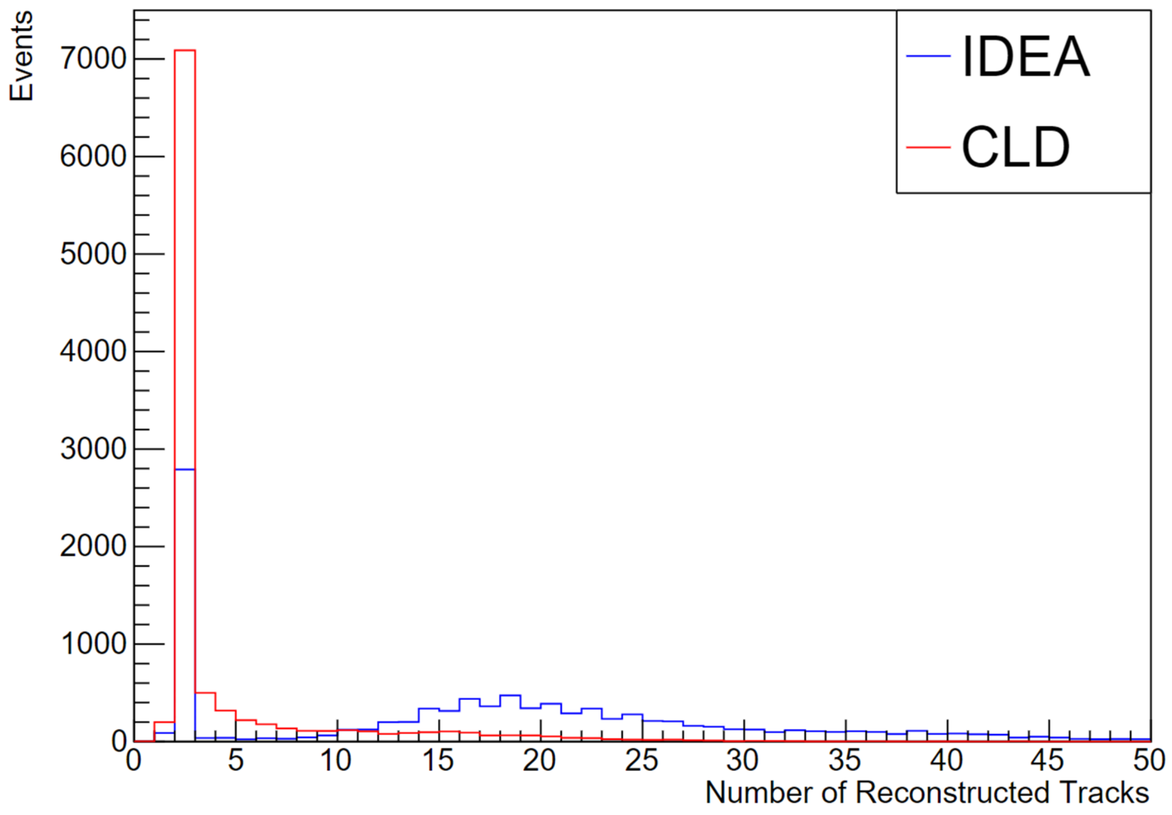
Summary and Future Work

- Have generated preliminary results comparing sensitivity to LLPs using IDEA, CLD tracker geometries
- Initial results indicate similar performance for low displacements, while signal points with larger displacement show significant difference in reconstructed tracks and hence sensitivity
- **Detector Comparison:**
  - Further studies of LLPs tracking and vertexing with IDEA, CLD cards
  - Use full simulation to compare IDEA, CLD cards
- **Extending original analysis:**
  - Incorporate hadronic decay modes of Z boson to increase statistics
  - Apply Machine Learning techniques to improve signal sensitivity and background rejection

Backup

Tracking Performance: IDEA vs. CLD

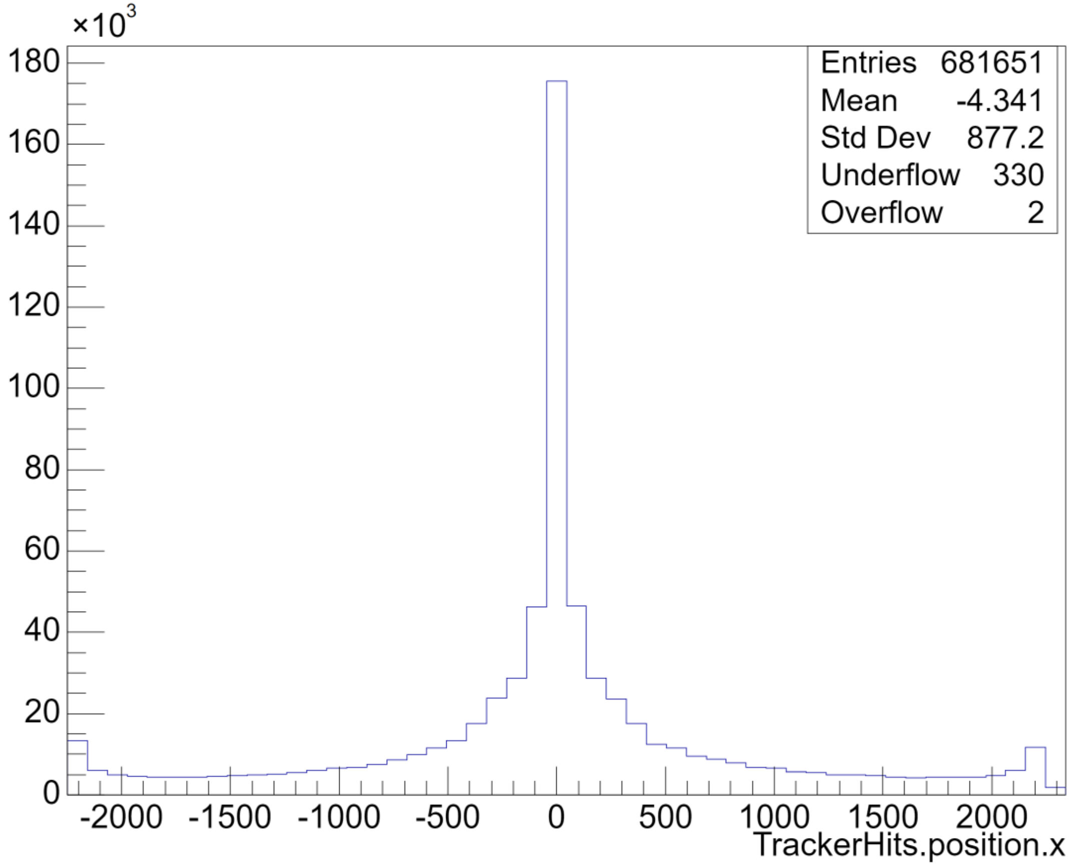
- $m_s = 60\ GeV, \sin(\theta) = 1e-7, c\tau = 8769.1\ mm$ sample saw significant decline in sensitivity
- Supports evidence for poor CLD tracking performance with longer decay lengths



Tracker Hits:

$m_s = 20\ GeV, \sin(\theta) = 1e-6, c\tau = 341.7\ mm$ sample

IDEA:



CLD: