"My own visions of CLIC", artwork by Natasha de Heney, 2010

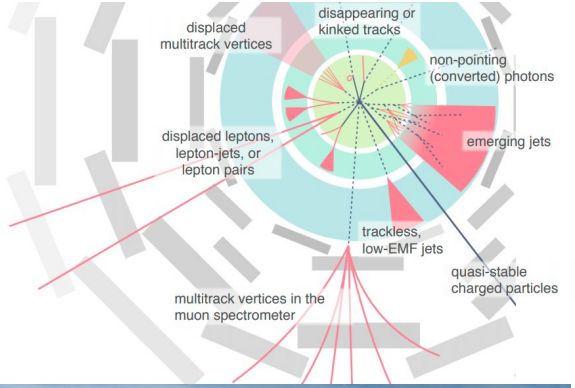
Disappearing tracks at CLIC

Erica Brondolin (CERN), Cecilia Ferrari (CERN), Emilia Leogrande (CERN), Ulrike Schnoor (CERN)
on behalf of the CLICdp Collaboration

Searching for long-lived particles at the LHC: Seventh workshop of the LHC LLP Community - 26th May 2020

Long-lived particles at CLIC

- Various new physics models predict particles with macroscopic lifetimes
- **CLIC** = Compact Linear Collider
- High-luminosity linear e^+e^- collider
- Three centre-of-mass energy stages: 380 GeV, 1.5 TeV, 3 TeV
- **Clean collision environment** compared to hadron colliders
  - Although some beam-induced background present
  - Possibility of triggerless readout

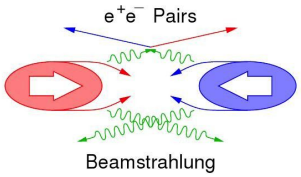


Experimental conditions @ 3TeV

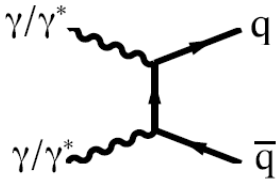
- High luminosities achieved by using extremely small beam sizes
  → CLIC bunch size: **40 nm** (x) **x 1 nm** (y) **x 44 μm** (z)
  → very high EM-fields→ beam-beam interactions

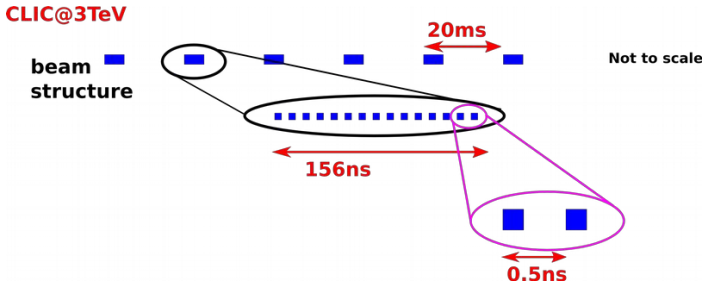
- Main backgrounds:
  - **Incoherent e^+e^- pairs**
  - **γγ → hadrons**

Incoherent e^+e^- pairs



γγ → hadrons

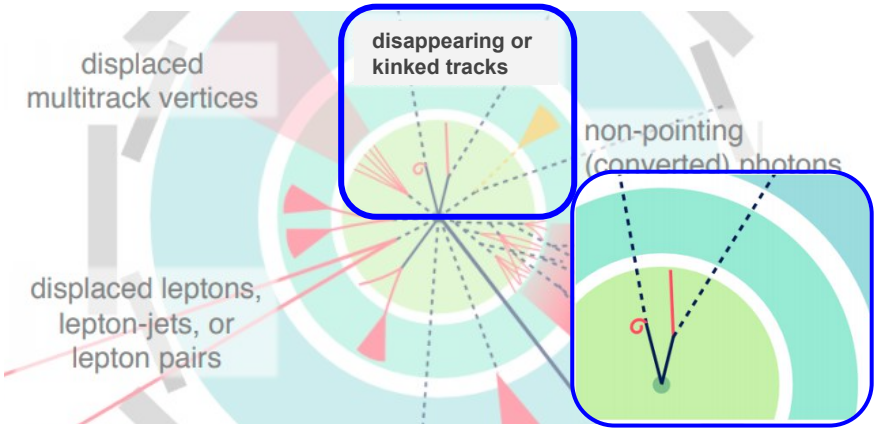




- Linear colliders operate in **bunch trains**:
  - 312 bunches within train separated by 0.5 ns
  - Low duty cycle
  - Possibility of power pulsing of detectors
  - Possiblitiy of triggerless readout
  - Bunch separation → Impact on detector design (timing, granularity)

Degenerate Higgsino Dark Matter

- Example of disappearing tracks signature
- Higgsino as WIMP **dark matter candidate**
- Dark matter relic abundance
  → Thermal higgsino DM mass ~ 1 TeV
- Higgsino multiplet as SU(2)-doublet Dirac fermion ($\chi_1^{\pm}$, χ_1^{0})
- **Decay process:** $\chi_1^{\pm} \rightarrow \pi^{\pm}\chi_1^{0}$
  with **small mass splitting** between charged and neutral components → long-lived chargino
- Model parameters:



chargino mixing	thermal limit mass	mass difference	lifetime	cτ	Γ
pure higgsino	1050 GeV	355 MeV	0.023 ns	6.9 mm	2.86×10^{-14} eV

CLIC @ 3 TeV:

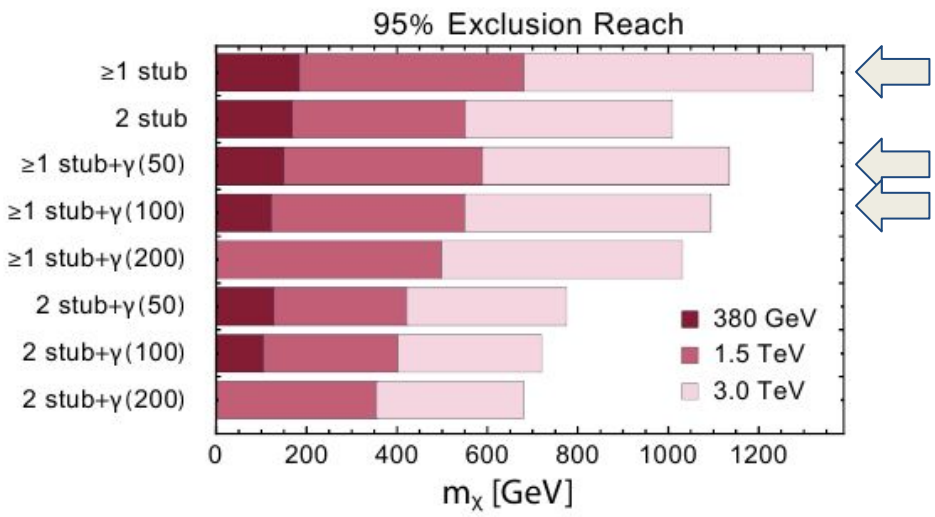
E_e = 1.5 TeV, m_χ ~ 1.05 TeV → p_χ = 1.07 TeV

→ **pion very soft, difficult to detect**

→ **chargino very straight and short track**

Studies at generator level

- Analysis with 1 or 2 identifiable stub tracks and possibly additional photon at 3 TeV
  - Taking into account the geometrical acceptance and requiring a minimum length of the stub tracks to provide 4 hits
  - Background not included



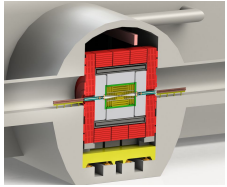
- 95% exclusion reach
  - stub only and stub + ISR photon
  - different cuts on photon energy (50, 100, 200 GeV)

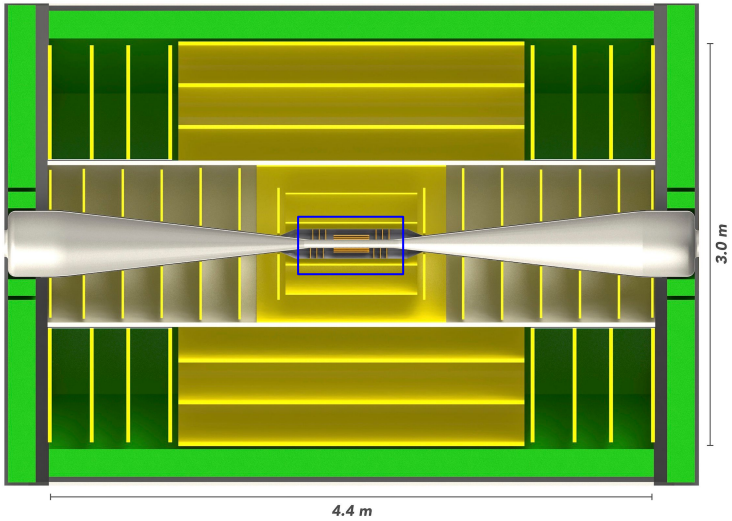
- All analyses cover large range of masses
- Most optimistic strategies up to thermal dark matter target m_χ ~ 1 TeV

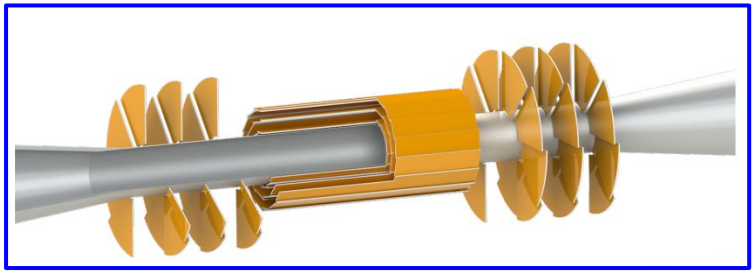
- Results very promising
- Full simulation study on-going

N. Craig and S. Alipour-Fard in [The CLIC Potential for New Physics]

The CLICdet tracker





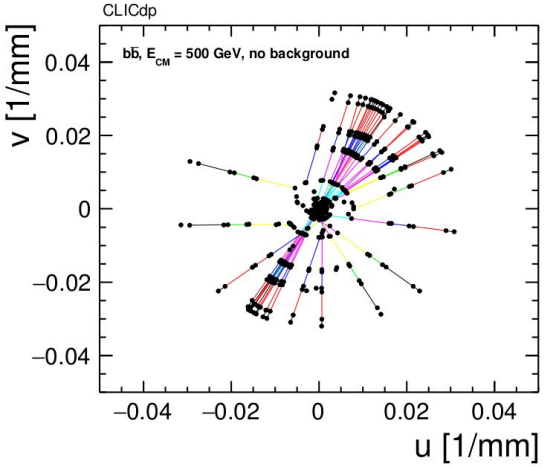


- Superconducting solenoid with 4T magnetic field
- Vertex detector
  - 25 × 25 μm^2 pixels
    - 3 double layers in barrel
    - Spiral arrengement in forward region
  - Single point resolution = 3 μm
  - Material Budget < 0.2 % X_0 per layer
- Silicon Tracker
  - Large pixels/strips
  - Outer R ~ 1.5 m
  - Single point resolution = 7 μm × 90 μm
  - Precise timing for background rejection:
    - < 10 ns hit time-stamping in tracking
- Full simulation with DD4hep geometry

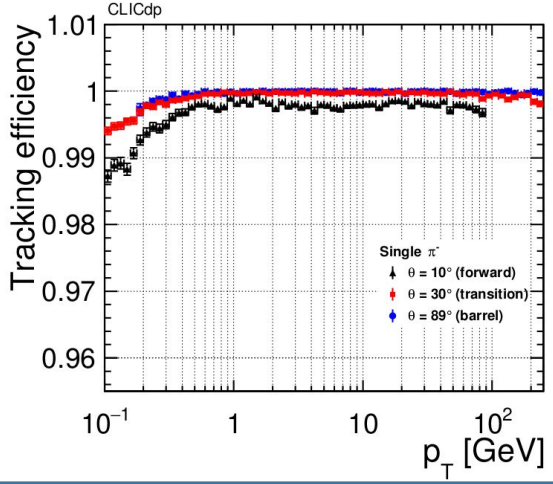
Conformal Tracking

- Cellular Automaton-based track finding in conformal space
- The **conformal mapping** method is based on the fact that circles passing through the origin of a coordinate system can be translated onto straight lines in a new coordinate system (slide in backup)
- Tracking fully efficient in the entire tracker volume and at any transverse momentum more than 0.1 GeV
- Similar performance w/ and w/o background

Example of event in conformal space

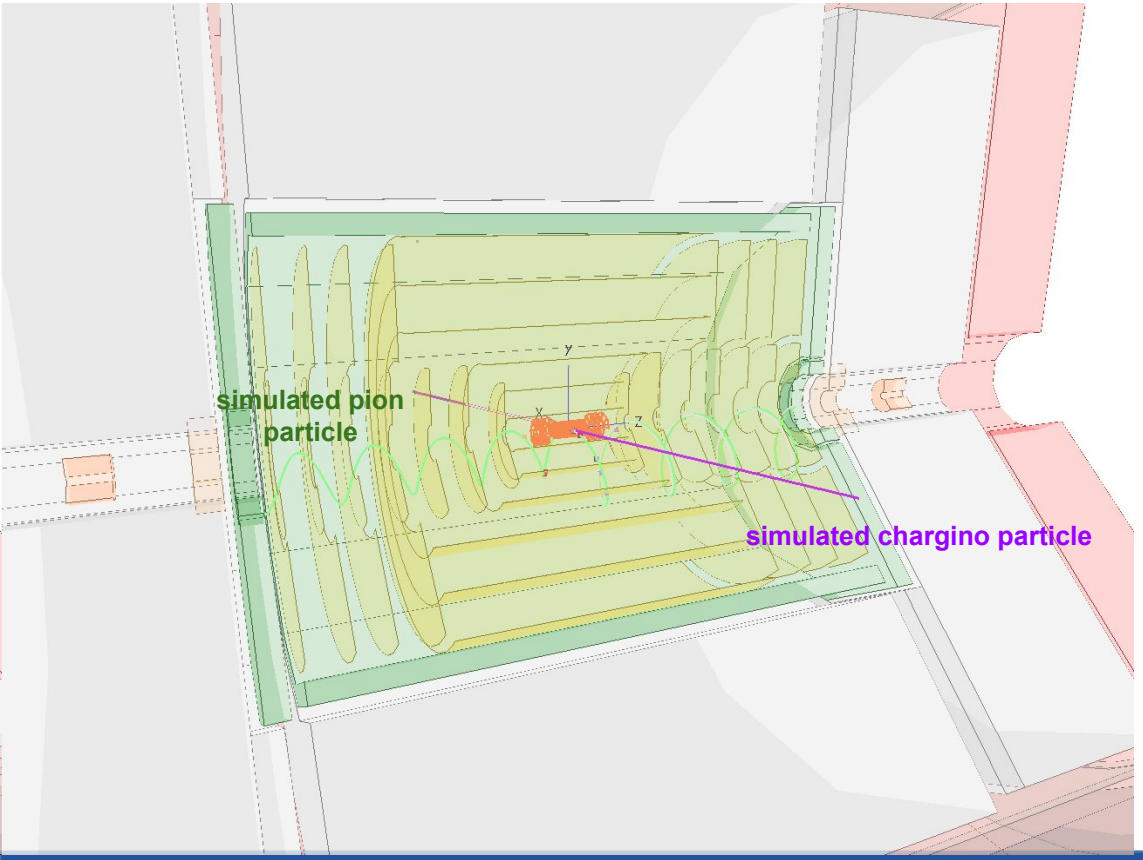


Single isolated prompt pions



Comprehensive article published recently:
doi:10.1016/j.nima.2019.163304

How does an “event” look like?

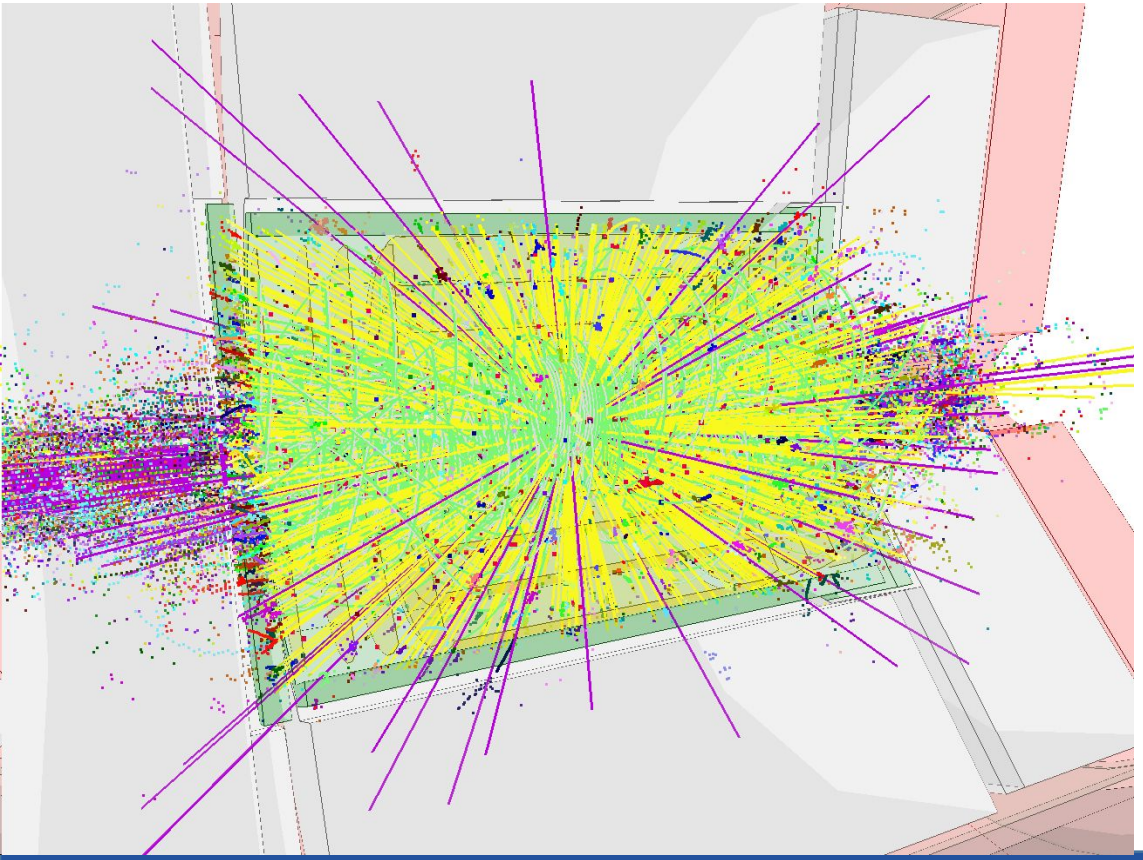


Event display

$e^+e^- \rightarrow \chi^\pm\chi^\pm \rightarrow \pi^\pm\chi^0\,\pi^\pm\chi^0$ @ 3 TeV

without any background overlaid

How does an “event” look like?



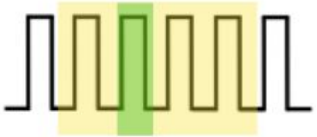
Event display

$e^+e^- \rightarrow \chi^\pm\chi^\pm \rightarrow \pi^\pm\chi^0\,\pi^\pm\chi^0$ @ 3 TeV

with $\gamma\gamma \rightarrow$ had background overlaid

Full simulation used to overlay the simulated hits from $\gamma\gamma \rightarrow$ had background to the signal ones

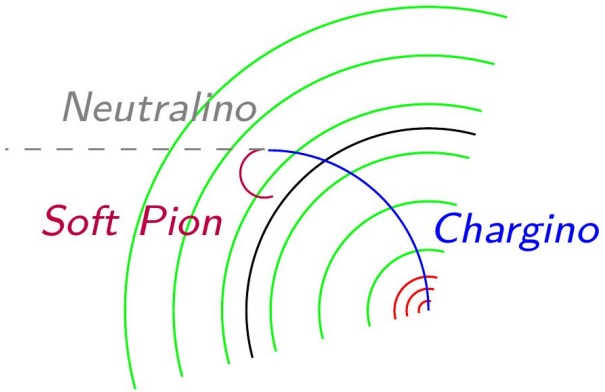
- impose timing cuts ⟶ 30 bunch crossings integrated (10 before, 20 after **hard interaction**)



p_T and timing cuts are <u>usually</u> used to mitigate the background

Analysis strategy

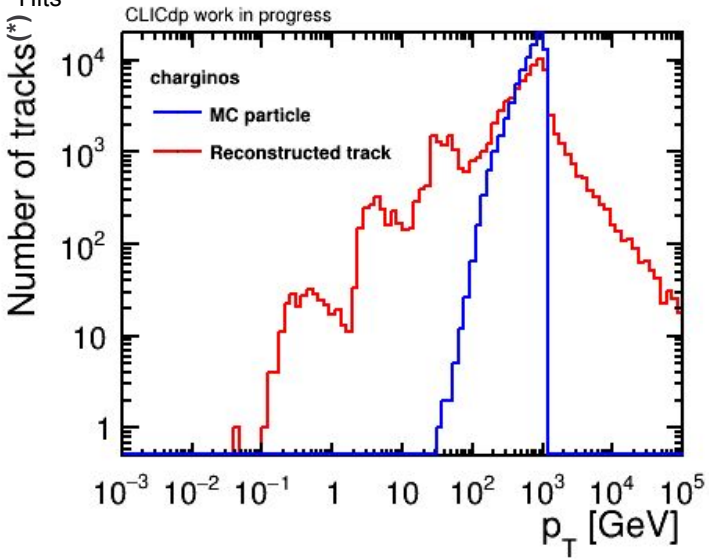
- **Signal**:
  - Stub track candidate definition:
    - At least **four hits** in the tracking system
    - **Prompt, isolated** track
    - Minimum **transverse** momentum
    - **Disappearing** within the tracking system volume
    - No energy deposition in the **calorimeter**
    - Additional: dE/dx requirement
  - At least one stub candidate per event
  - Additional: soft displaced pion(s) and additional photons
  - Samples generated:
    - $c\tau$ = 6.9 mm
    - $c\tau$ = 180 mm
    - $c\tau$ = 600 mm
    - (Default: $c\tau$ = 600 mm to increase statistics)

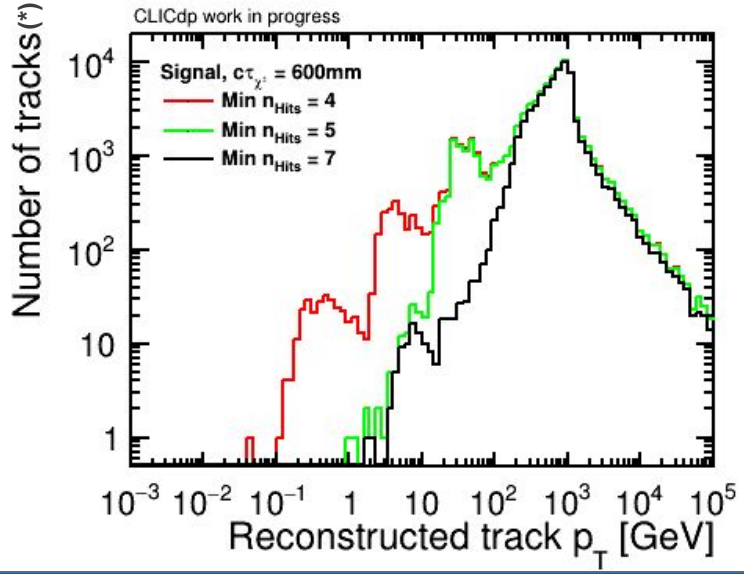


- **Background**:
  - Beam-induced $\gamma\gamma \rightarrow$ hadrons:
    - random combination of hits
    - split tracks
    - conversion

Chargino tracking efficiency

- Challenges for **chargino** tracks reconstruction:
  - Short
  - Straight
- p_T reconstruction of short, straight tracks is limited by the single point resolution and length of the track (~n_{Hits}), but can still be powerful





(*) Arbitrary normalisation

Chargino tracking efficiency

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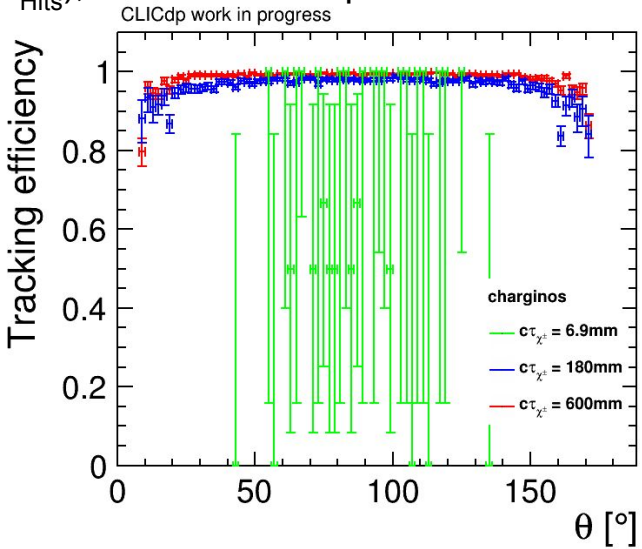
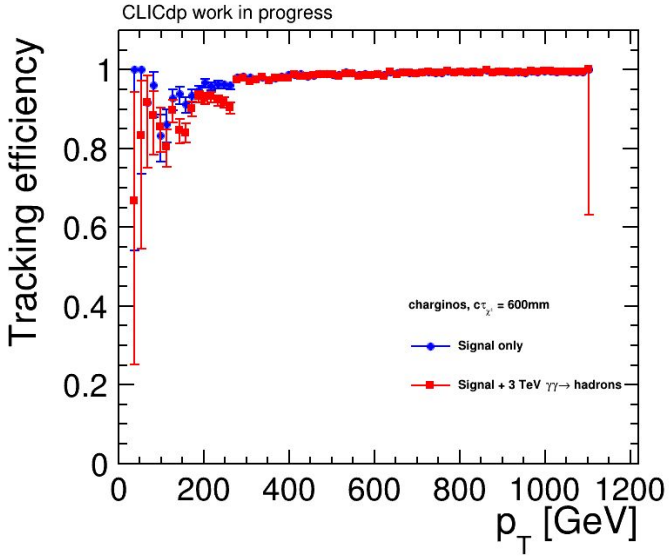
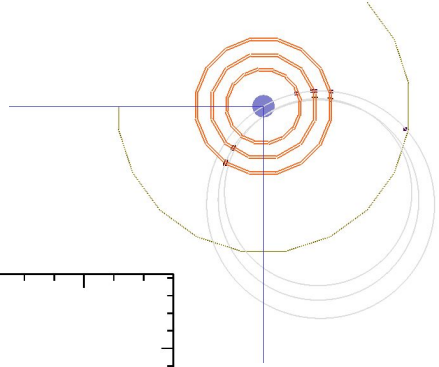


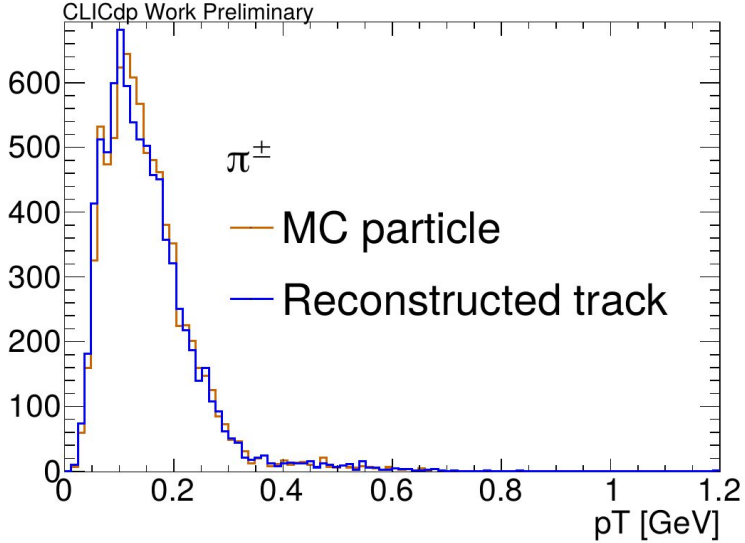
- Reconstruction is more difficult for short charginos
- Performance are similar if background is included

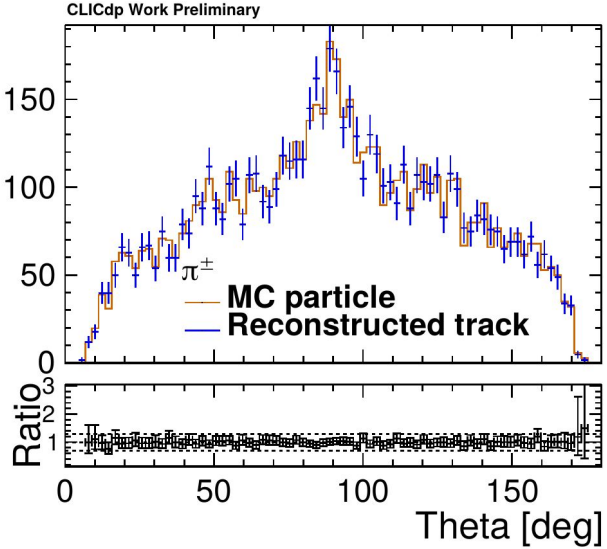


Pion tracking efficiency

- Challenges for **pion** tracks reconstruction:
  - Displaced
  - Very soft
- Soft displaced pions are well reconstructed
- Duplicate tracks in central region due to loopers







Pion tracking efficiency

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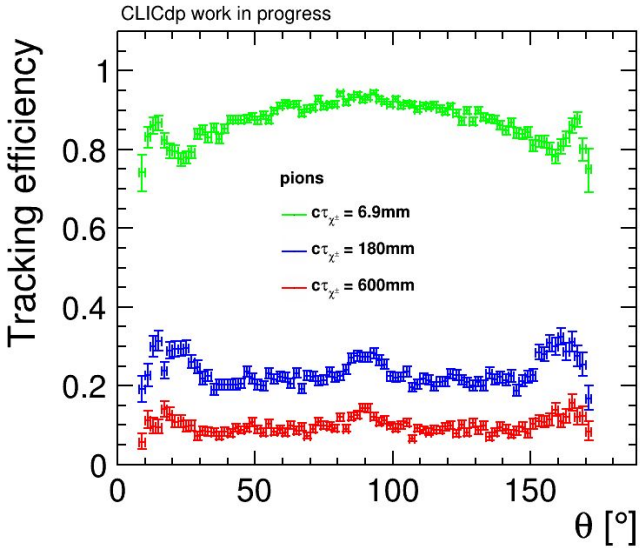
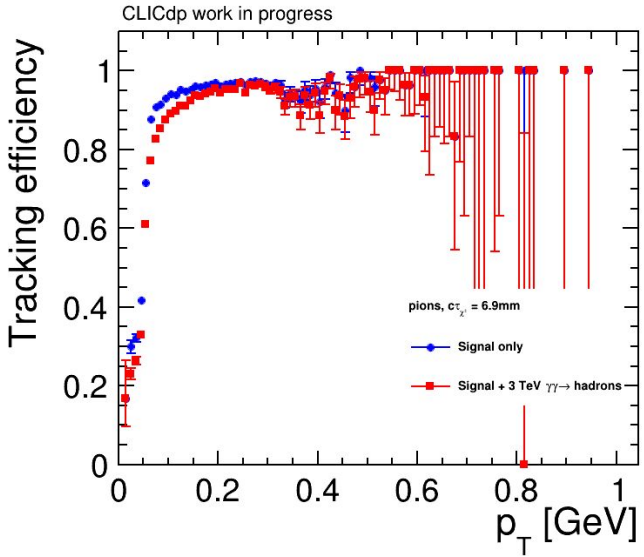
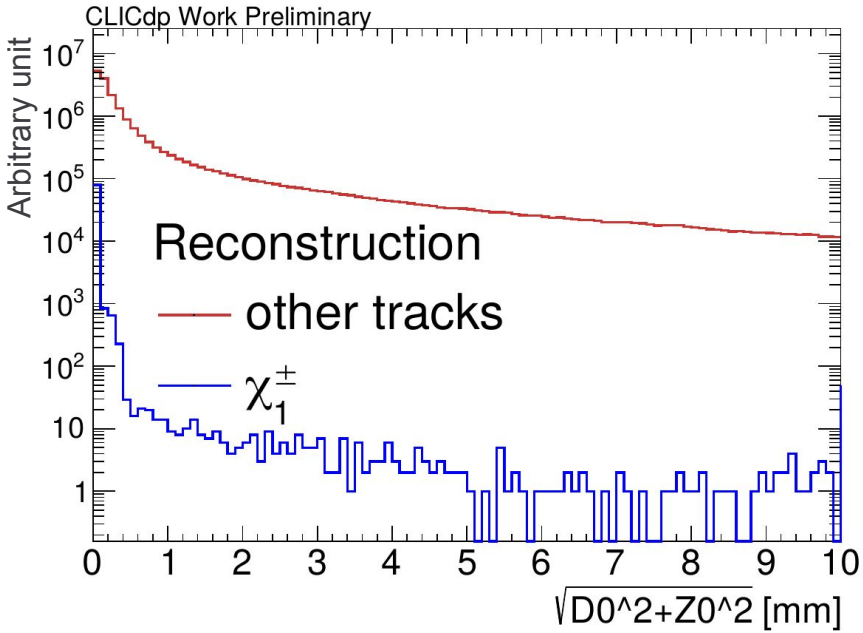




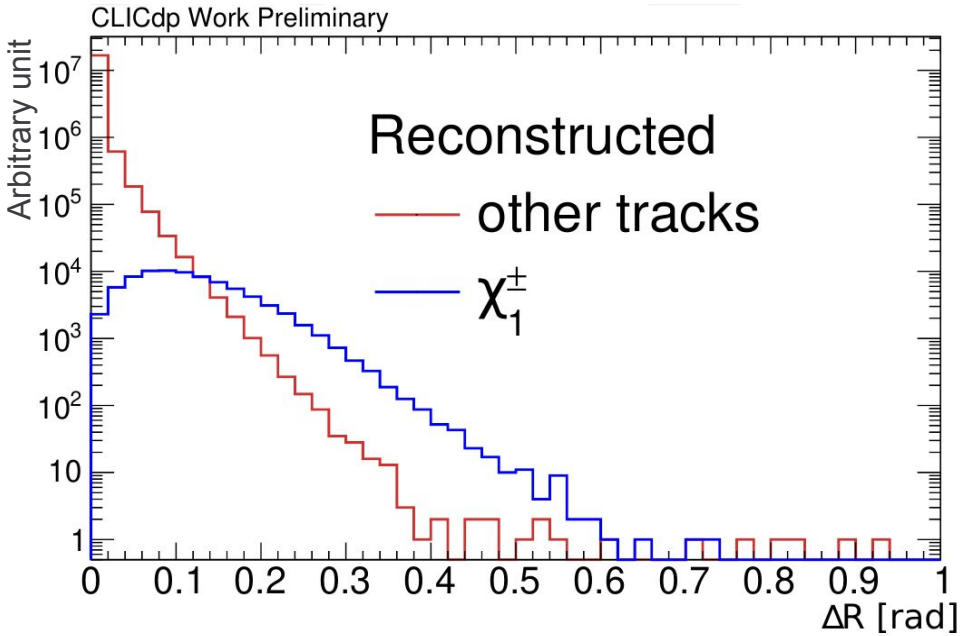
Stub track properties

- Min n_{Hits} = 4
- **Prompt** track
  - Promptness = sqrt($d_0^2 + z_0^2$)
  - Possible cut at 0.5 mm



Stub track properties

- Min $n_{Hits} = 4$
- Prompt track
  - Promptness = $\mathrm{sqrt}(d_0^2 + z_0^2)$
  - Possible cut at 0.5
- **Isolated** track
  - Isolation = $\Delta R_{\text{nearest track}}$
  - Possible cut at 0.1
  - Other isolation criteria are under investigation, e.g. p_T sum in a cone.



Stub track properties

- Min $n_{Hits} = 4$
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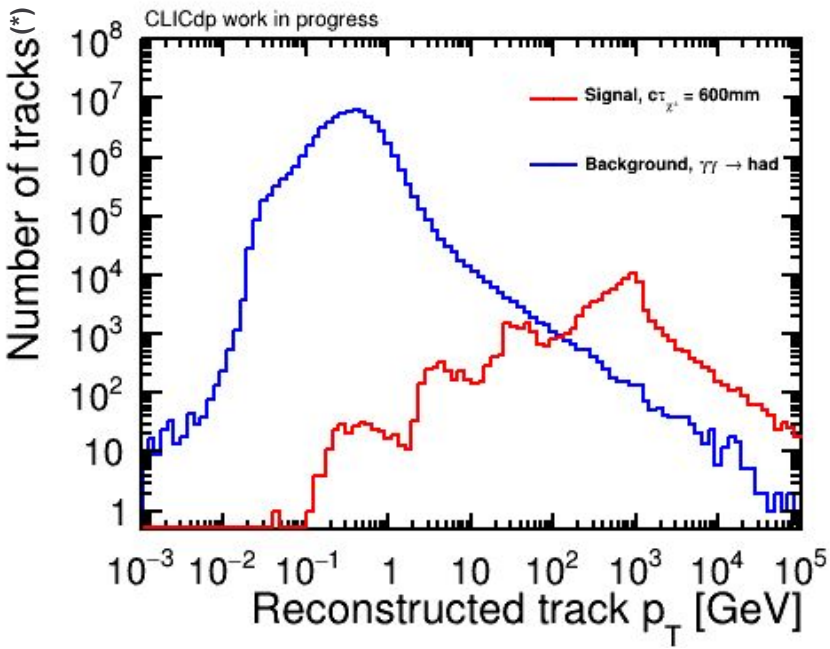
  - Possible cut at 0.5
- Isolated track
  - Isolation = $\Delta R_{\text{nearest track}}$
  - Possible cut at 0.1
- **Transverse momentum** requirement
  - Possible cut at 10 GeV
  - Preliminary with low background statistics
  - Effect on shorter stub under investigation



(*) Arbitrary normalisation

Stub track properties

- Min $n_{Hits} = 4$
- Prompt track
  - Promptness = $\sqrt{d_0^2 + z_0^2}$
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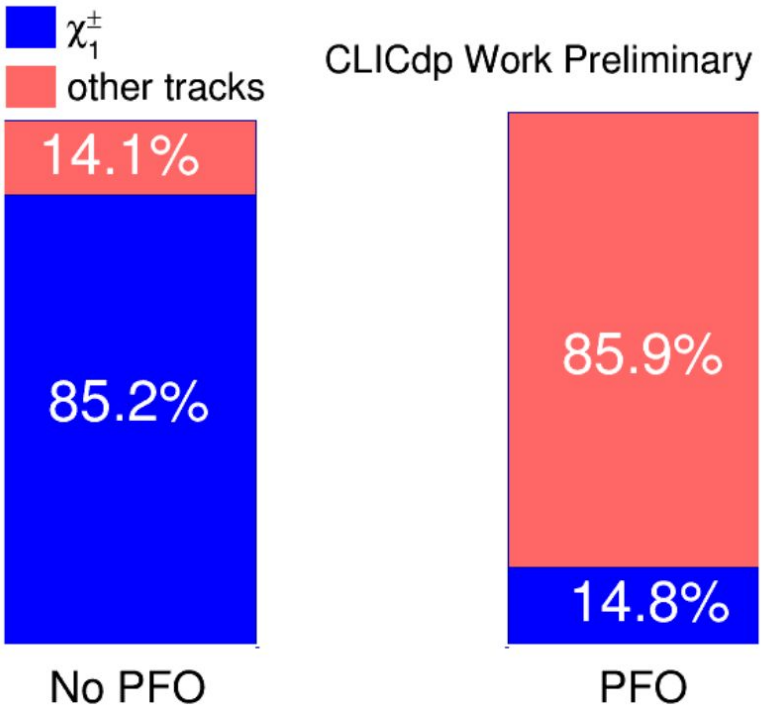
  - Isolation = $\Delta R_{\text{nearest track}}$
  - Possible cut at 0.1
- Transverse momentum requirement
  - Preliminary with low background statistics
  - Possible cut at 10 GeV
  - Effect on shorter stub under investigation
- No **energy deposition** in the calorimeter (PFO)
  - charginos associated to PFO (14.1 %) include:
    - standalone tracks below 1.5 GeV (assigned as PFO)
    - overestimate of the lifetime



Preliminary background study

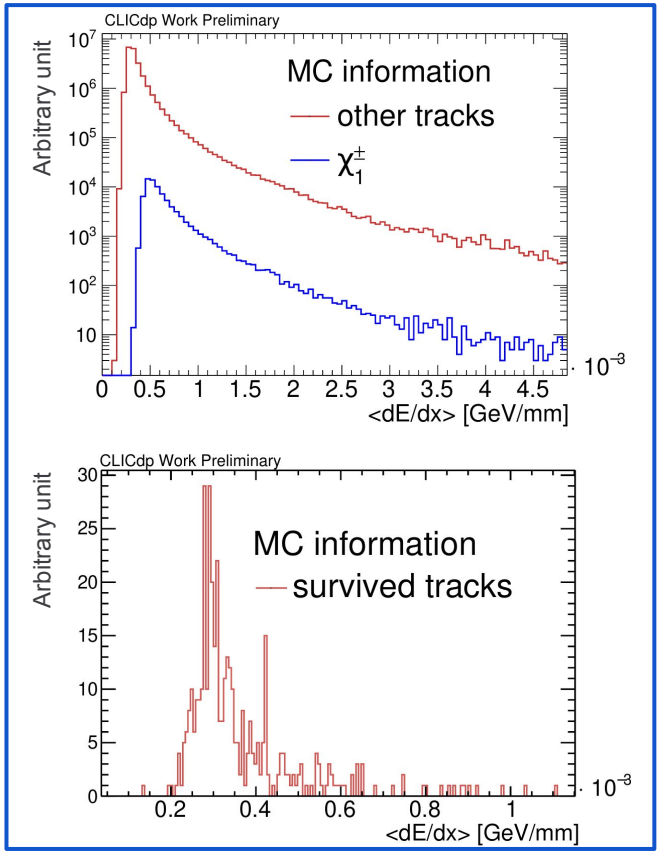
- $\gamma\gamma \rightarrow$ hadrons-only sample is used to study the main background

- By requiring at least on stub candidate with:
  - Promptness < 0.5 mm
  - p_T > 10 GeV
  - No PFO association

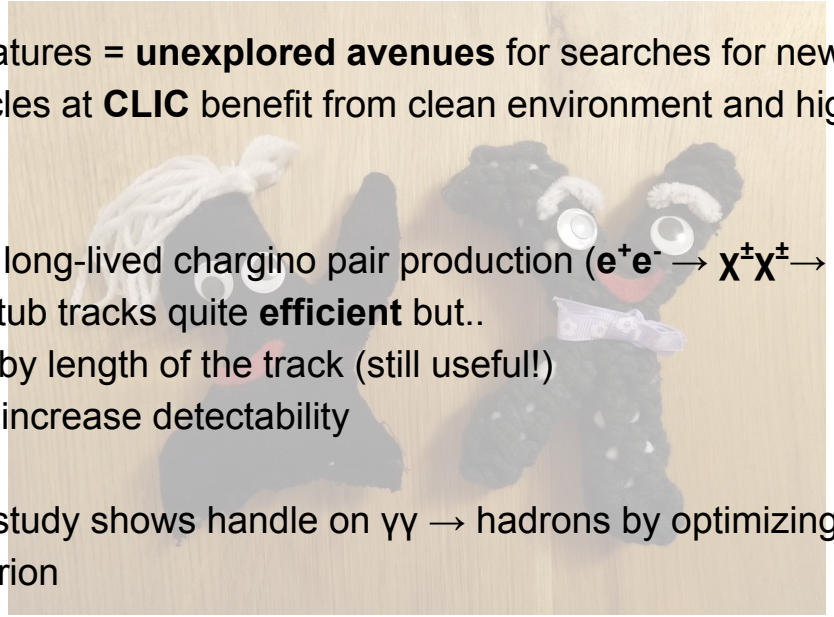
  → Fakerate ~ 0.32%

  → Efficiency ~ 82.7%

- Ongoing study to further understand and suppress the background:
  - Additional cut could be on **<dE/dx>**
    - dE/dx resolution
  - Optimise analysis selection
  - Additional requirement on pions
  - Possibility to add photons



Conclusions and outlook



- Long-lived particles signatures = **unexplored avenues** for searches for new physics
- Charged long-lived particles at **CLIC** benefit from clean environment and high precision of the track reconstruction

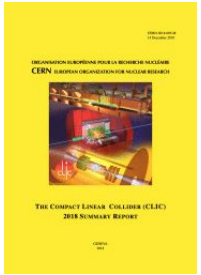
- Investigated a sample of long-lived chargino pair production ($e^+e^- \rightarrow \chi^\pm\chi^\pm \rightarrow \pi^\pm\chi^0\ \pi^\pm\chi^0$)
- Track reconstruction of stub tracks quite **efficient** but..
  p_T reconstruction limited by length of the track (still useful!)
- Additional **soft pion** can increase detectability

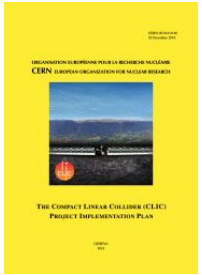
- Preliminary background study shows handle on $\gamma\gamma \rightarrow$ hadrons by optimizing stub track definition and dE/dx criterion

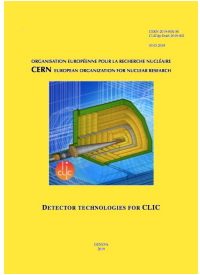
“My own visions of CLIC”, artwork by Natasha de Heney, 2010

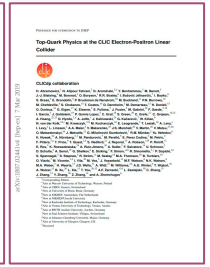
Backup

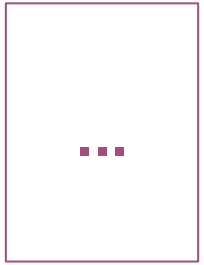
CLIC input to European Strategy Update









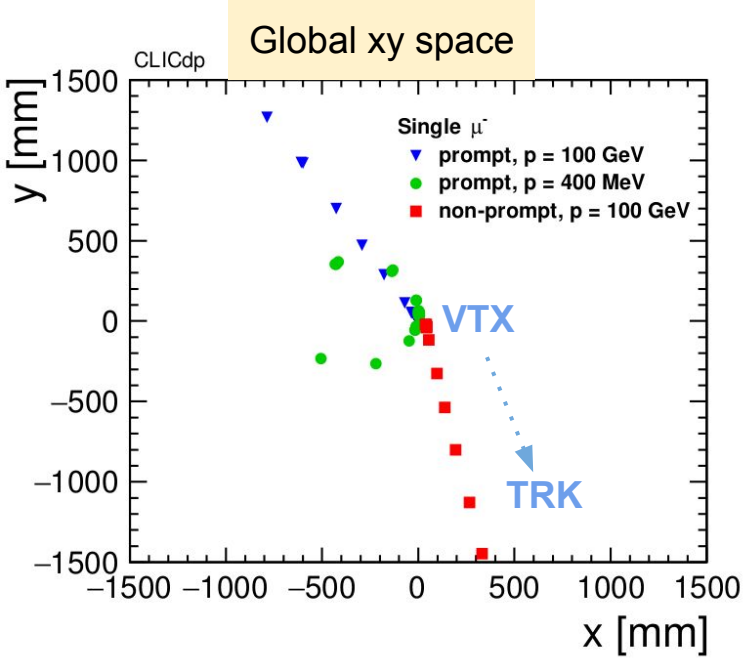


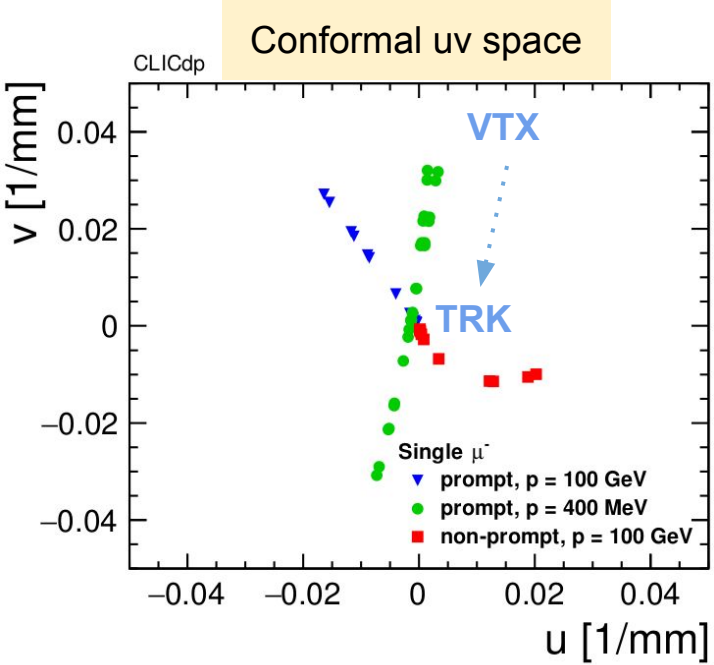
- Yellow Reports:
  - CLIC 2018 Summary Report
  - CLIC Project Implementation Plan
  - The CLIC Potential for New Physics
  - Detector technologies for CLIC
- Two formal ESU submissions:
  - Physics Potential
  - Accelerator and Detector
- Many more Journal publications and CLICdp Notes
- Full list can be found in: http://clic.cern/european-strategy

Conformal Mapping

- The conformal mapping method is based on the fact that circles passing through the origin of a coordinate system xy can be translated onto straight lines in a new coordinate system uv

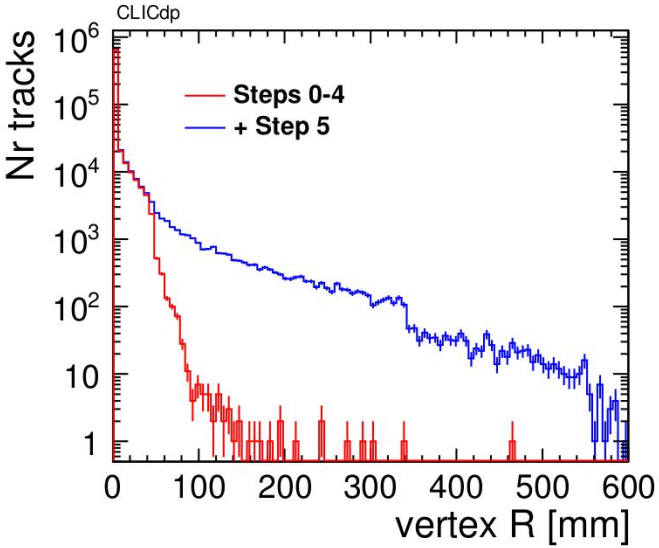
$$u = x / (x^2 + y^2) \qquad v = y / (x^2 + y^2)$$





Conformal tracking in CLICdet

Algorithm	Hit collection	Configuration
Build tracks	Vertex barrel	Standard cuts
Extend tracks	Vertex endcap	Standard cuts
Build tracks	Vertex	Looser cuts (angle x 5)
Build tracks	Vertex	Looser cuts (angle x 10; χ^2 x 20)
Extend tracks	Tracker	Looser cuts (angle x 10; χ^2 x 20)
Build tracks	Vertex + Tracker	Displaced cuts



- 5 steps targeting **prompt-tracks**:
  - From vertex detector to silicon tracker
  - Min number of hits = 4
  - Standard or looser (angle or χ^2) cuts
- 1 step targeting **displaced tracks**:
  - Quadratic terms in conformal space fit added
  - Inverted order search: from silicon tracker to vertex detector
  - Broader search angle than for prompt tracks
  - Min number of hits = 5

Definitions

Associated particle = Simulated MC particle from which the majority of track hits are originated

Reconstructable particle = stable MC particle with following requirements:

- $p_T > 0.1$ GeV
- $|\cos\theta| < 0.99$
- unique hits ≥ 4

Purity = Number of track hits associated to the same MC particle

- ***Pure track*** if purity ≥ 75 %
- ***Fake track*** if purity < 75 %

$$\textit{Efficiency} = \frac{\#\text{pure tracks associated to MC particle}}{\#\text{reconstructable MC particles}}$$

$$\textit{Fake rate} = \frac{\#\text{fake reconstructed tracks}}{\#\text{reconstructed tracks}}$$