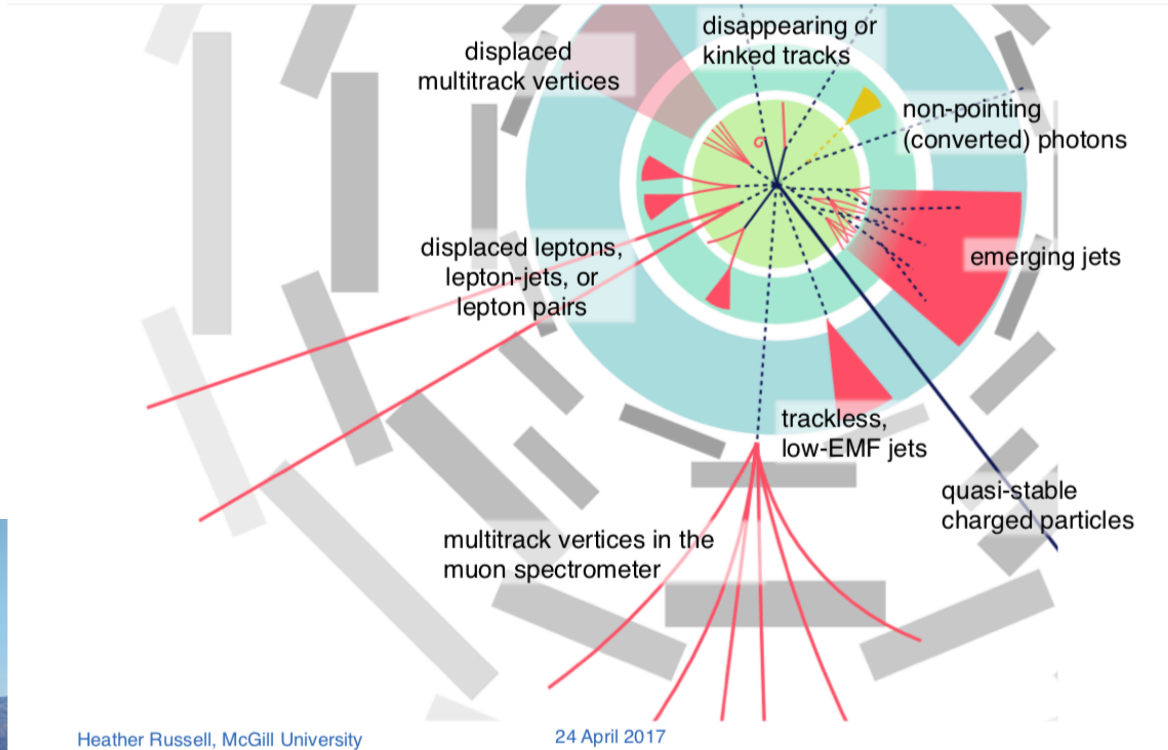
Long-lived particles at CLIC

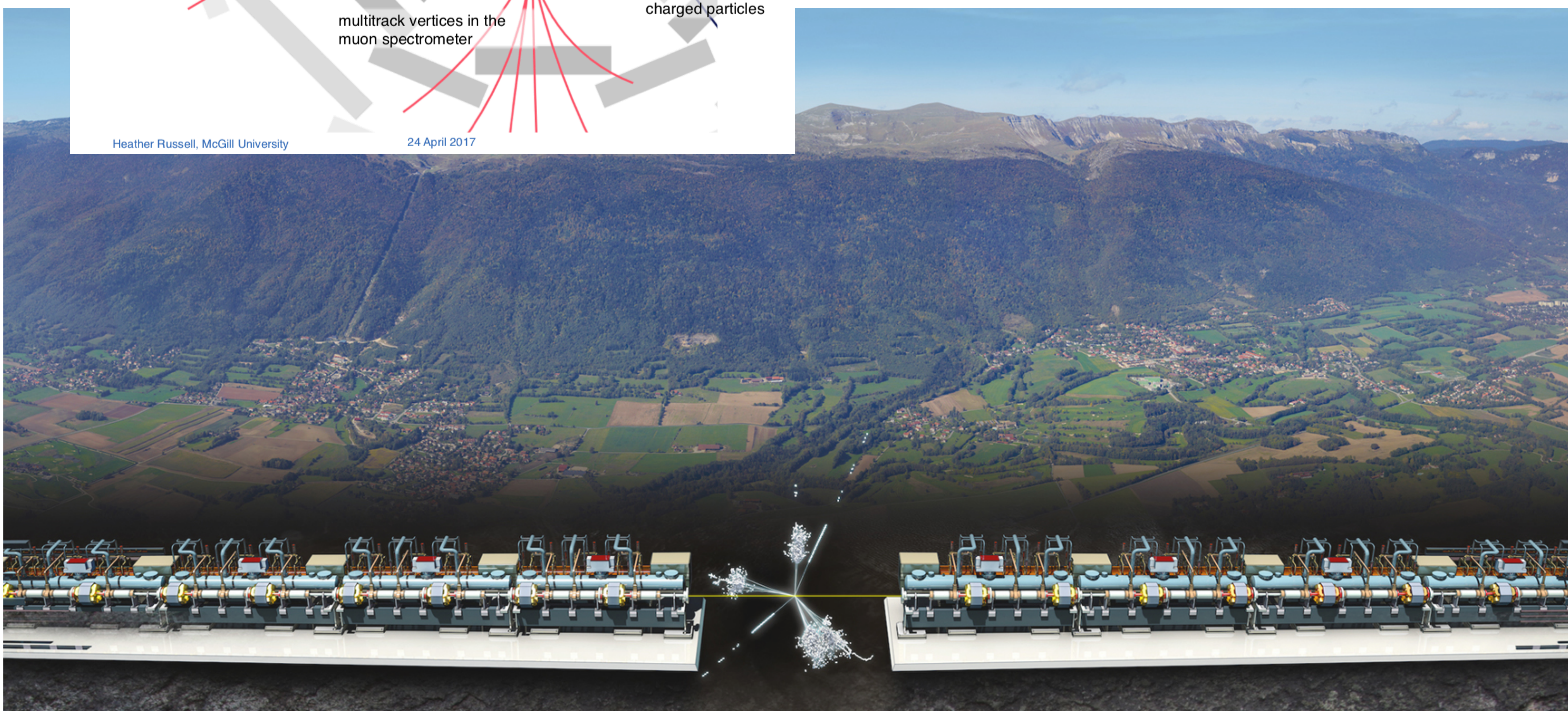
Erica Brondolin (CERN), Emilia Leogrande (CERN), Ulrike Schnoor (CERN)
on behalf of the CLICdp Collaboration

Searching for long-lived particles at the LHC:
5th Workshop of the LHC LLP Community
28 May 2019

Introduction



- signatures of new physics may be very diverse
- detectors at future colliders should be able to assess the broadest possible spectrum



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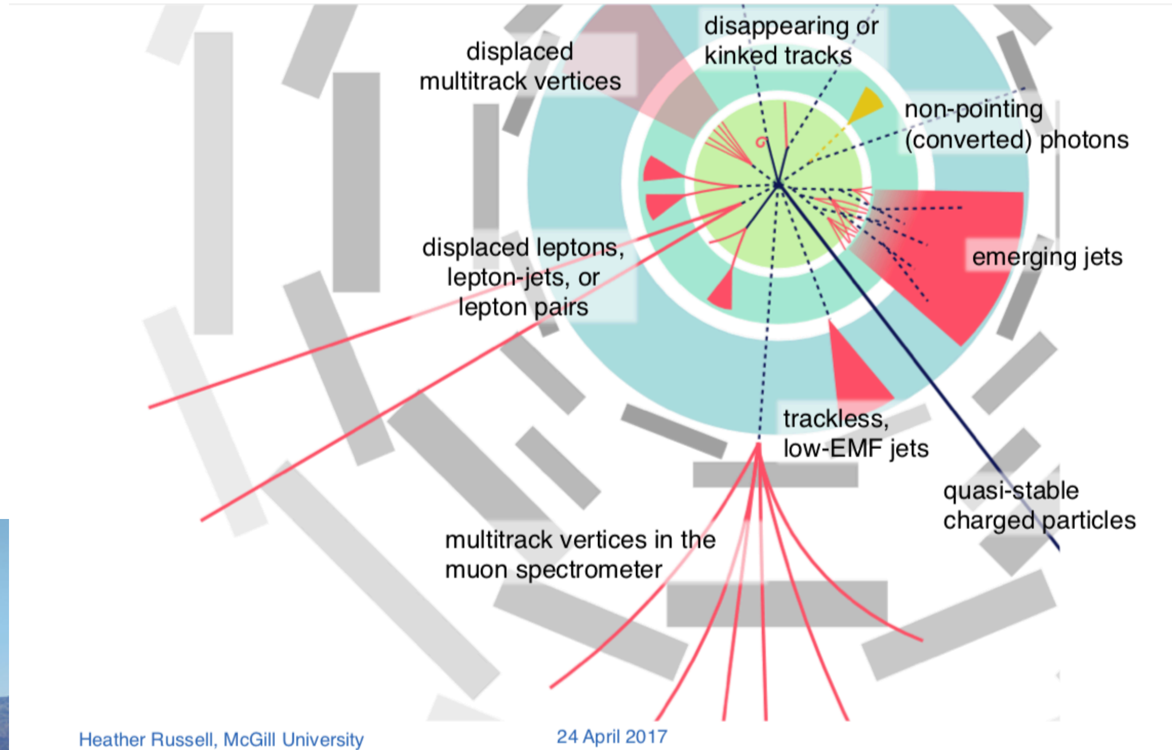
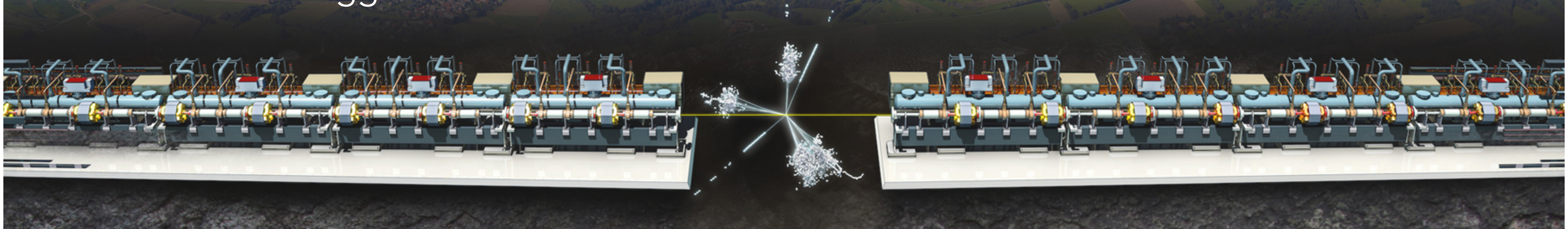


- ✦ signatures of new physics may be very diverse
- ✦ detectors at future colliders should be able to assess the broadest possible spectrum

- **CLIC** (Compact Linear Collider): promising to probe long-lived particles
  - 3 centre-of-mass energy stages: 380 GeV, 1.5 TeV, 3 TeV
  - clean collision environment
    - although some beam-induced background present (e.g. γγ->hadrons)
  - no trigger

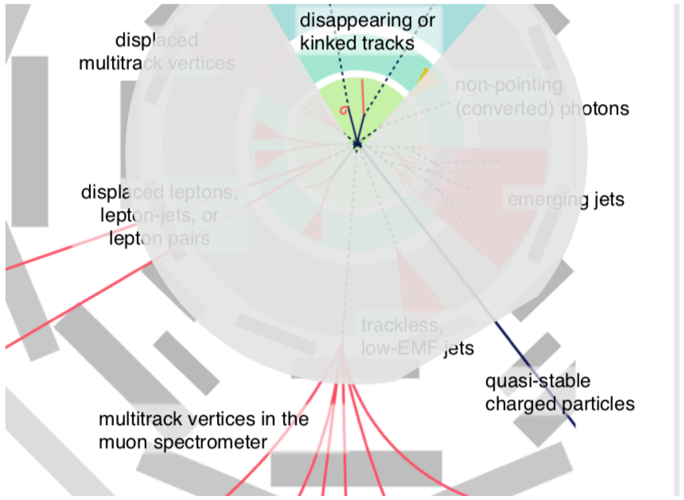


Outline

✦ Two long-lived particle studies performed in the framework of CLIC

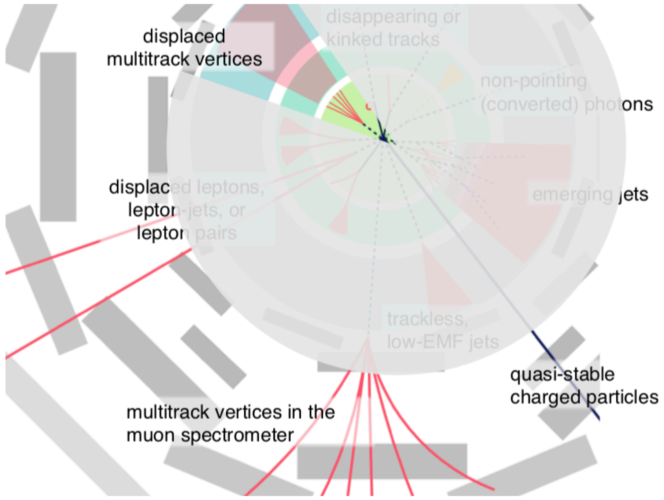
✦ 1. **Degenerate Higgsino Dark Matter** analysis
=> *disappearing tracks*

- ✦ generator level (CLICdet acceptance) [CERN-2018-009-M, Sec 5.2]
- ✦ full simulation study with CLICdet [**new**]



✦ 2. **Hidden valley searches in Higgs boson decays**
=> *displaced multitrack vertices*

- ✦ full simulation study with CLIC_ILD [CERN-2018-009-M, Sec 8.1]

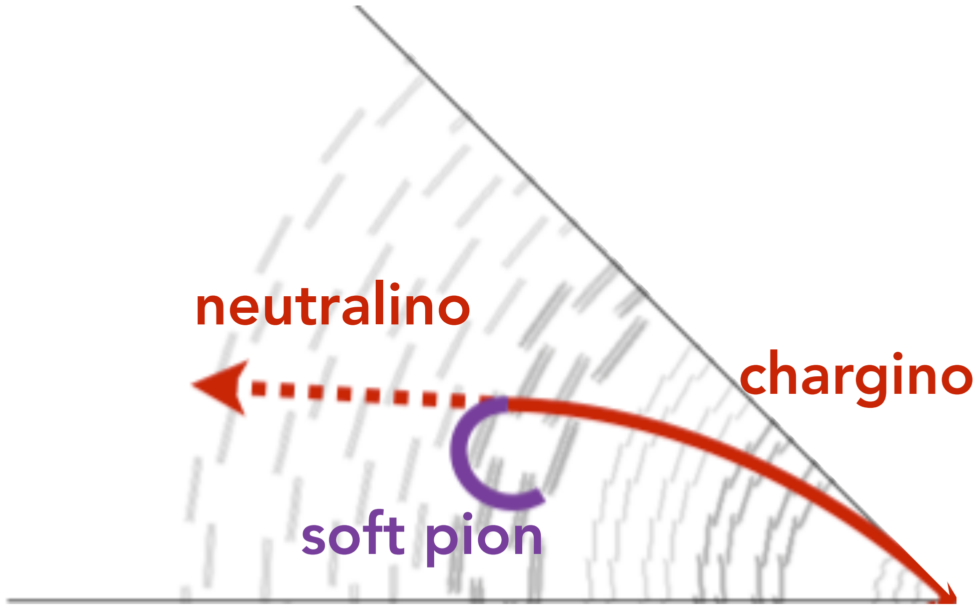


✦ Both searches need full simulation studies to assess the impact of beam-induced background

- ✦ iLCSoft framework to perform simulation, reconstruction and analysis

Degenerate Higgsino DM at CLIC

- Higgsino as WIMP dark mat $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \pi^+ \tilde{\chi}_1^0 \pi^-$
- dark matter relic abundance => thermal higgsino DM mass ~ O(TeV)
  - @ CLIC 3 TeV: E = 1.5 TeV, m ~ 1.05 TeV => **$p^2 = E^2 - m^2$ => p = 1.07 TeV**
- higgsino multiplet as SU(2)-doublet Dirac fermion (small mass splitting between charged and neutral components) => chargino **travels** ~ O(**cm**) before decaying into neutralino and soft pion
  - masses of chargino and neutralino very similar => pion too soft to be detected



=> chargino very straight and short track a.k.a. 'stub' track

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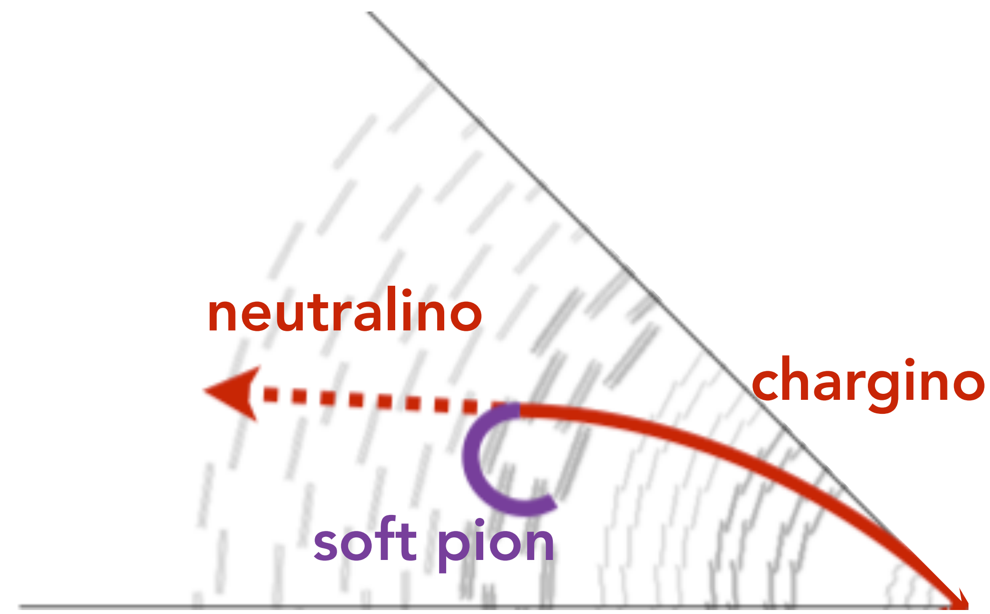
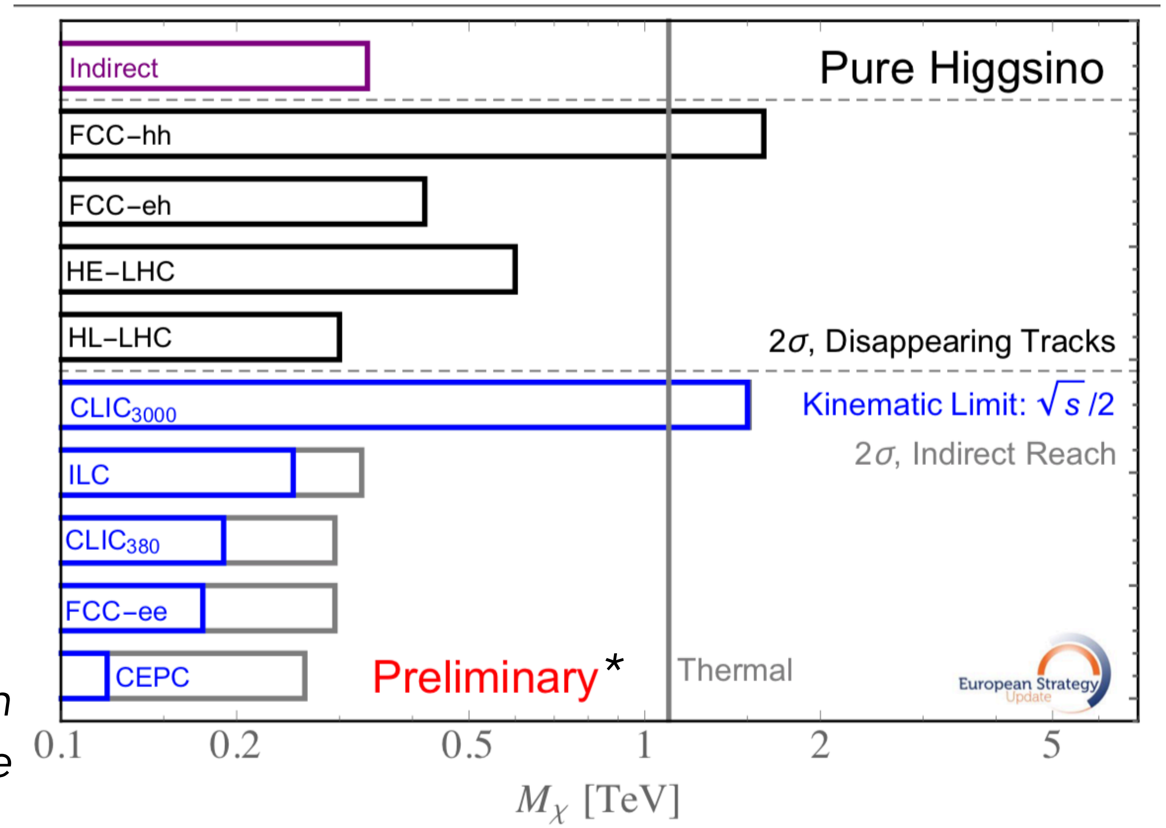


=> **chargino very straight and short track a.k.a. 'stub' track**

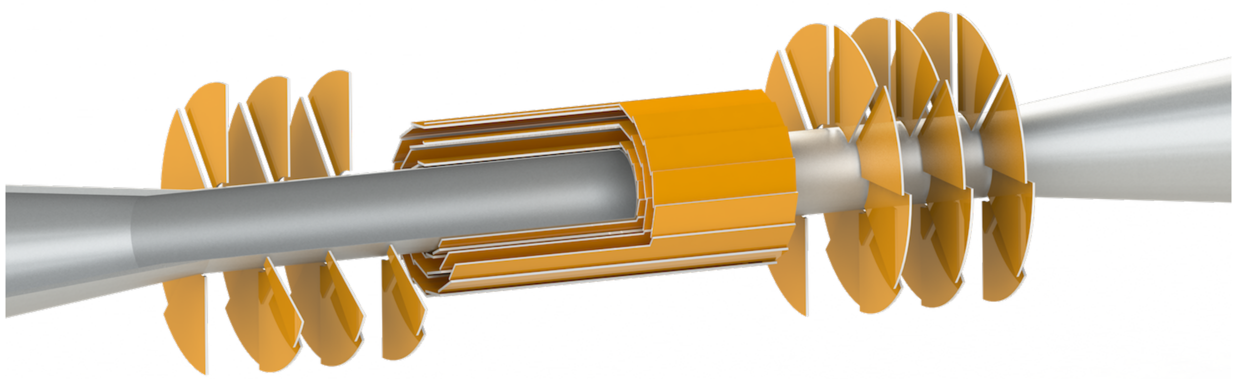
- **CLIC** (Compact Linear Collider) @ 3 TeV: promising to probe signature from thermal higgsino DM

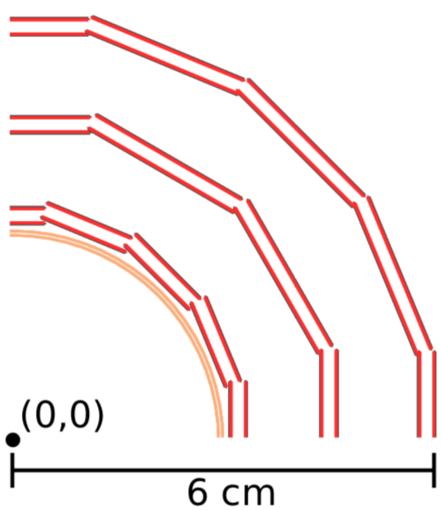


*estimate not based on disappearing track signature

Chargino at CLICdet

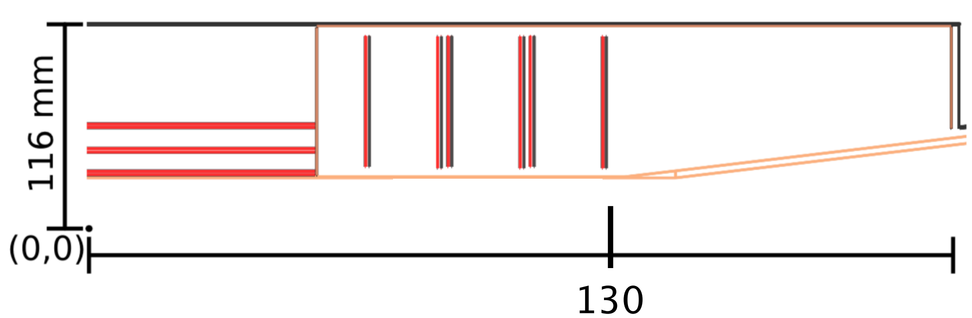
- **CLICdet** acceptance and tracking algorithm determine the capabilities of reconstructing tracks with **O(cm) length**

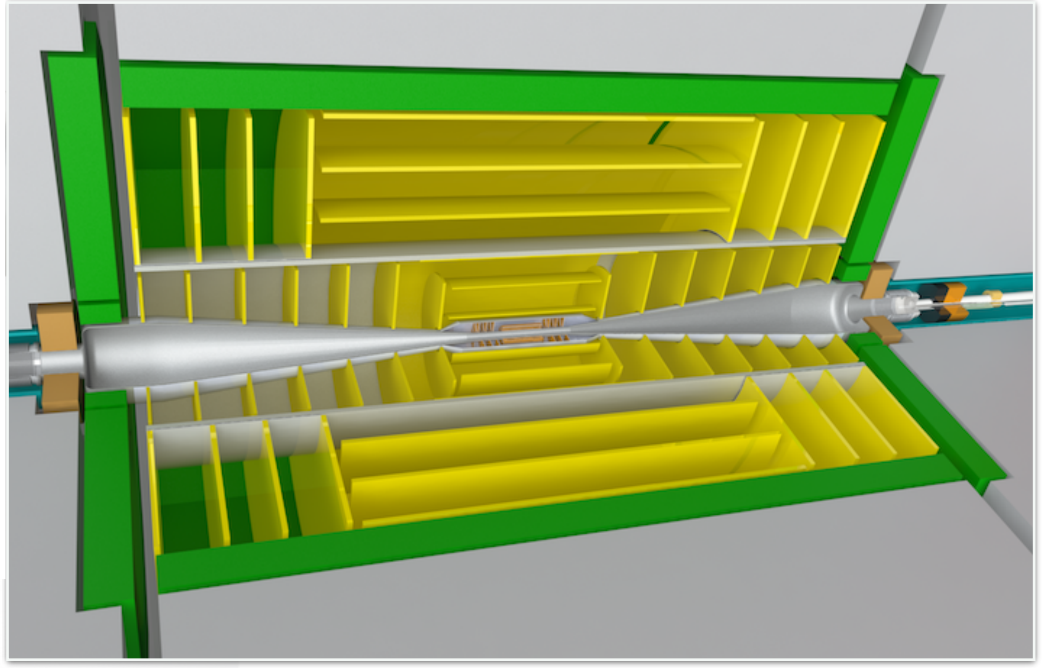




barrel	radii [cm]
1 - 2	3.1 - 3.3
3 - 4	4.4 - 4.6
5 - 6	5.8 - 6.0

endcap	z [cm]
1 - 6	3.5 - 13.0





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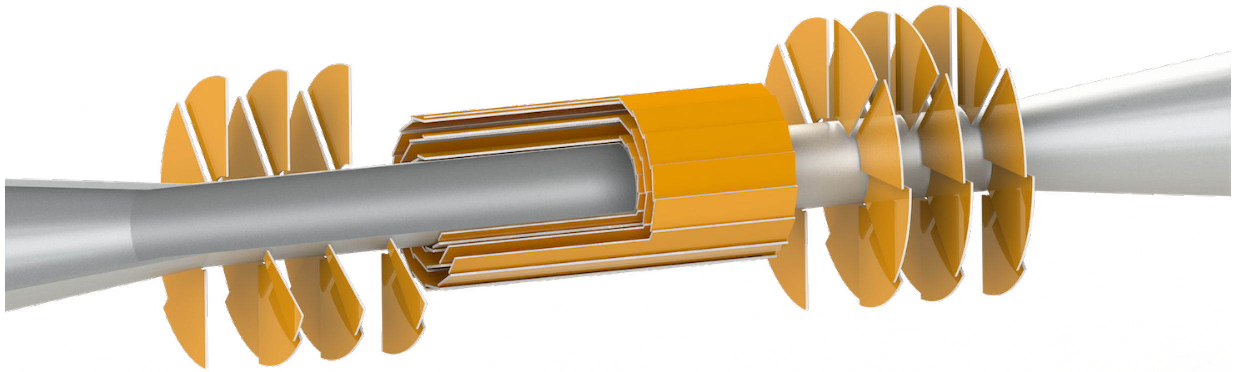

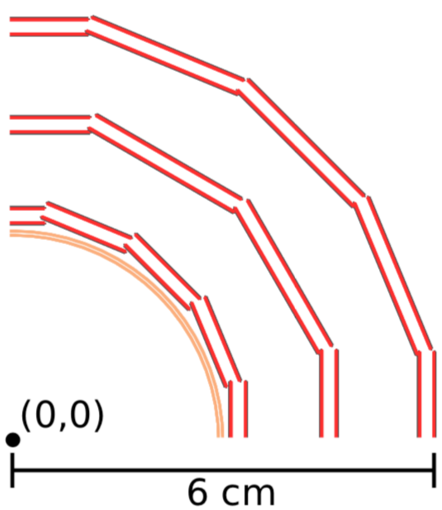

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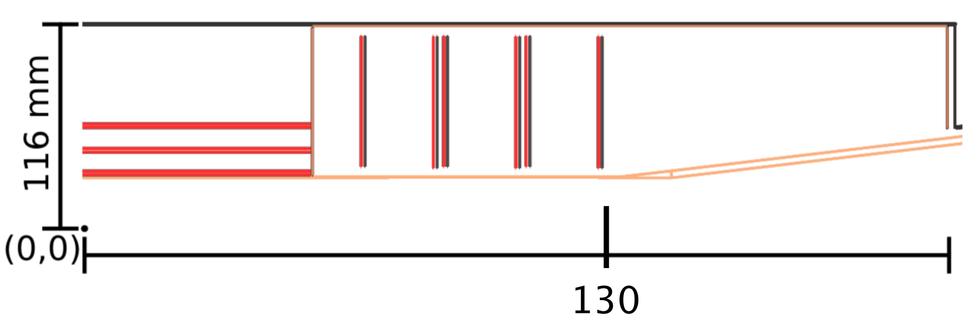

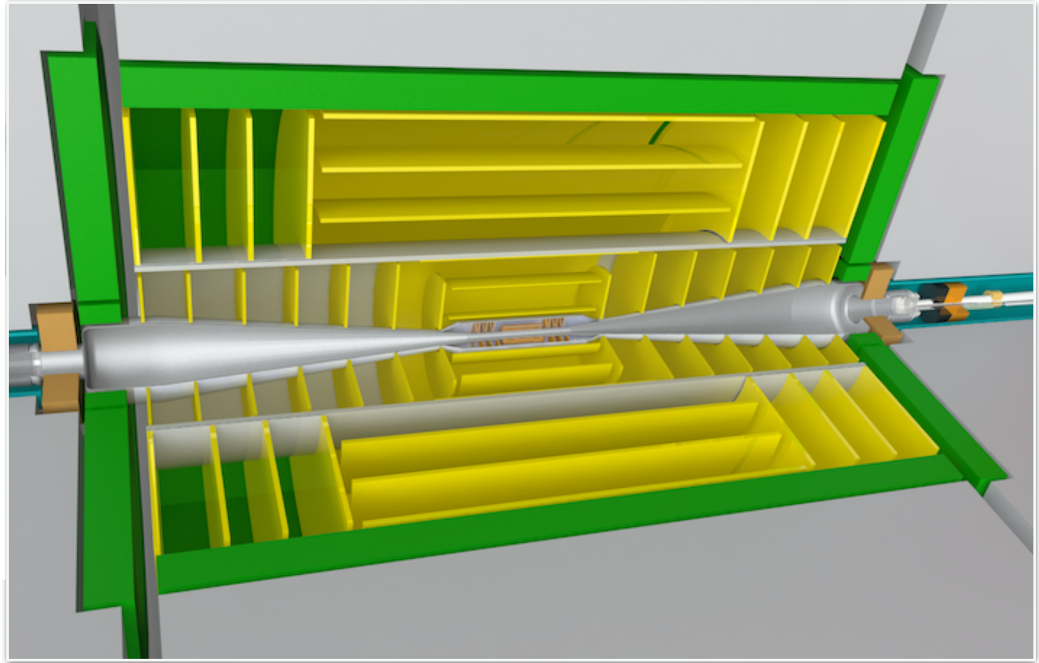

- **Minimum distance d_{min} the chargino must travel to be reconstructable**:
  - given minimum number of hits = 4 for tracking algorithm
  - given the geometric acceptance

$$d_{\min}(\theta) = \begin{cases} \frac{4.4\,\mathrm{cm}}{\sin\theta} & 19^\circ < \theta < 90^\circ \\ \frac{22\,\mathrm{cm}}{\cos\theta} & 13^\circ < \theta < 19^\circ \\ \frac{29\,\mathrm{cm}}{\cos\theta} & 8^\circ < \theta < 13^\circ \end{cases}$$

Charged stub - generator level

- Methods to count expected number of events with at least one (or two) identifiable stub tracks:
  - 100% efficiency assumed
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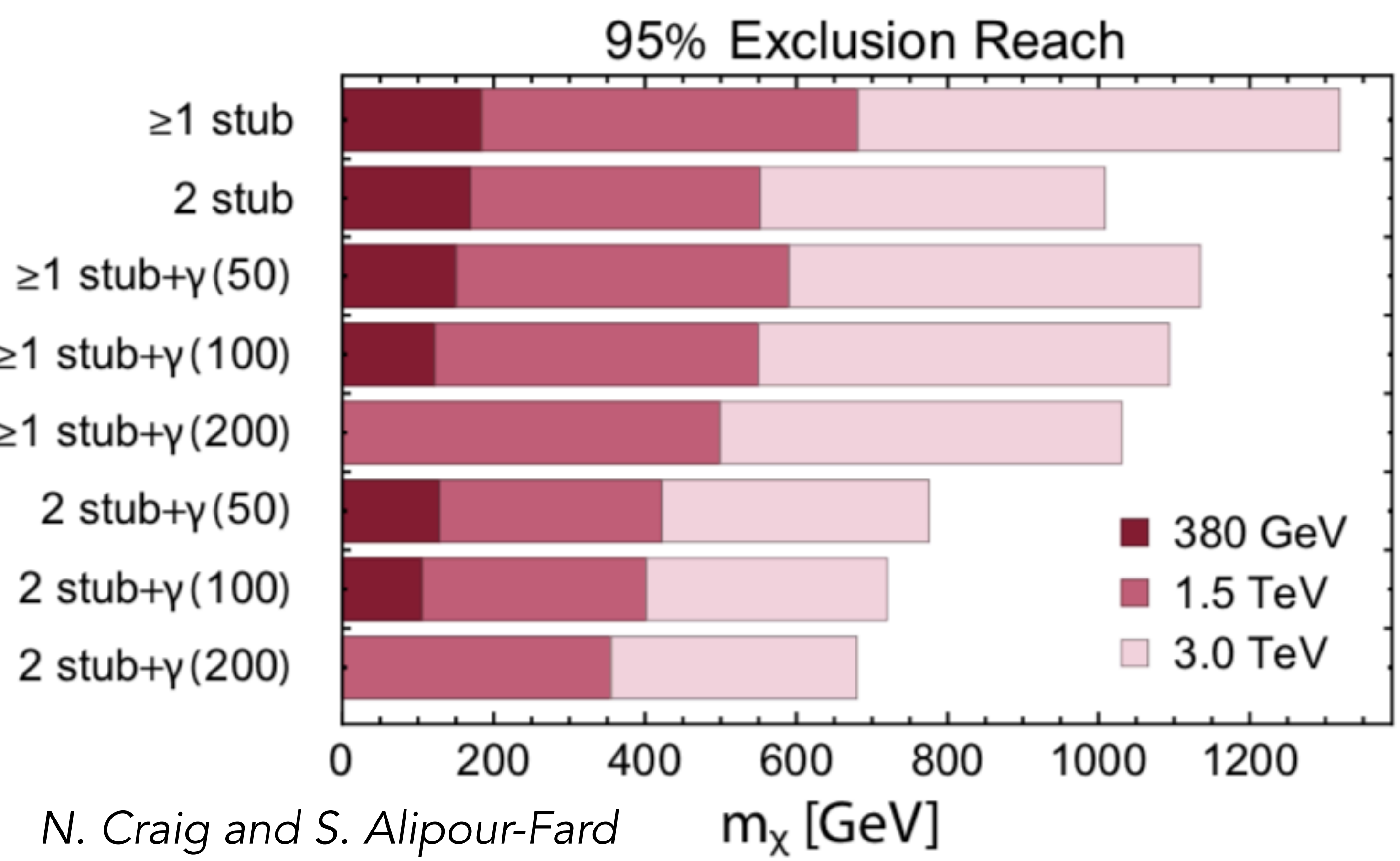
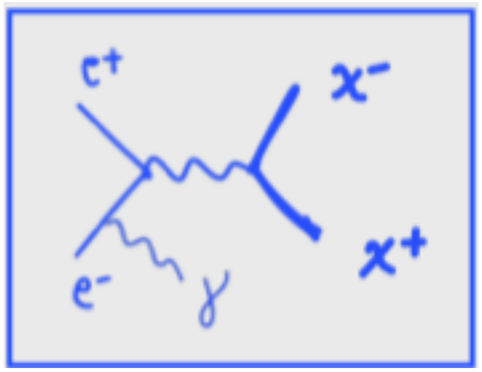


N. Craig and S. Alipour-Fard

- 95% exclusion reach by requiring N_{evts} >= 3 with zero background
  - stub only and stub + ISR photon
  - different cuts on photon energy
    - 50, 100, 200 GeV



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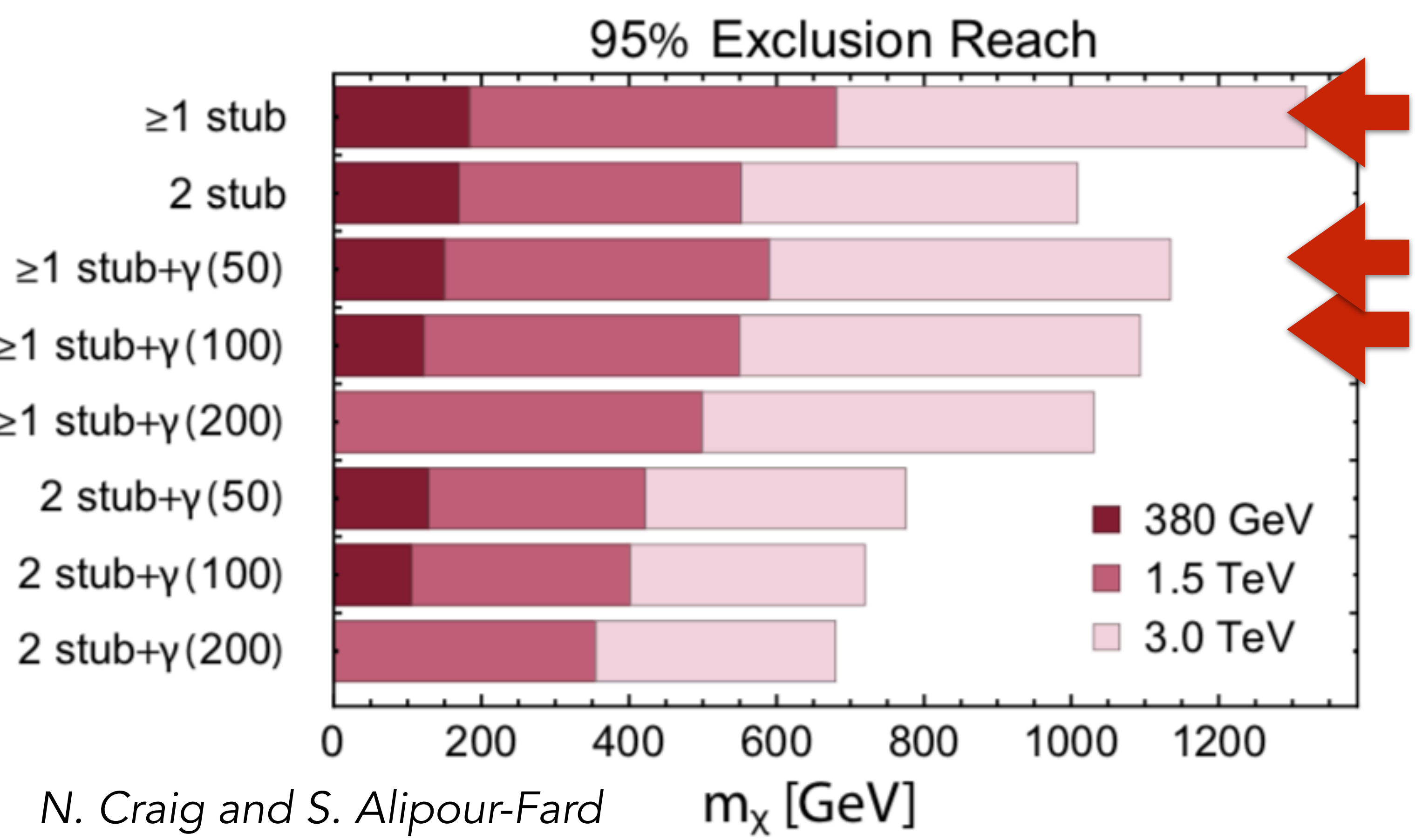

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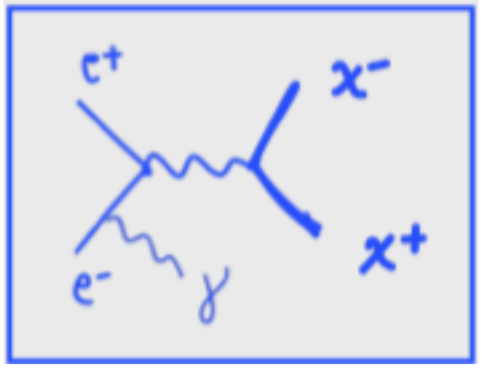

- All analyses cover large range of masses
  - **most optimistic strategies up to thermal dark matter target m_X ~ 1.1 TeV**
- Results very promising, but need to be confirmed by full simulation and reconstruction

Charged stub - full simulation study

1. artificial short track sample

- No chargino sample was available at the time of this preliminary study
  => CLICdet **reduced to the vertex detector only** (workaround to produce **artificially short tracks, i.e. ~ 6 hits on track**)
  - [particle type] muons
  - [momentum] p = 1.0 TeV
  - [angular distribution] cos(theta)

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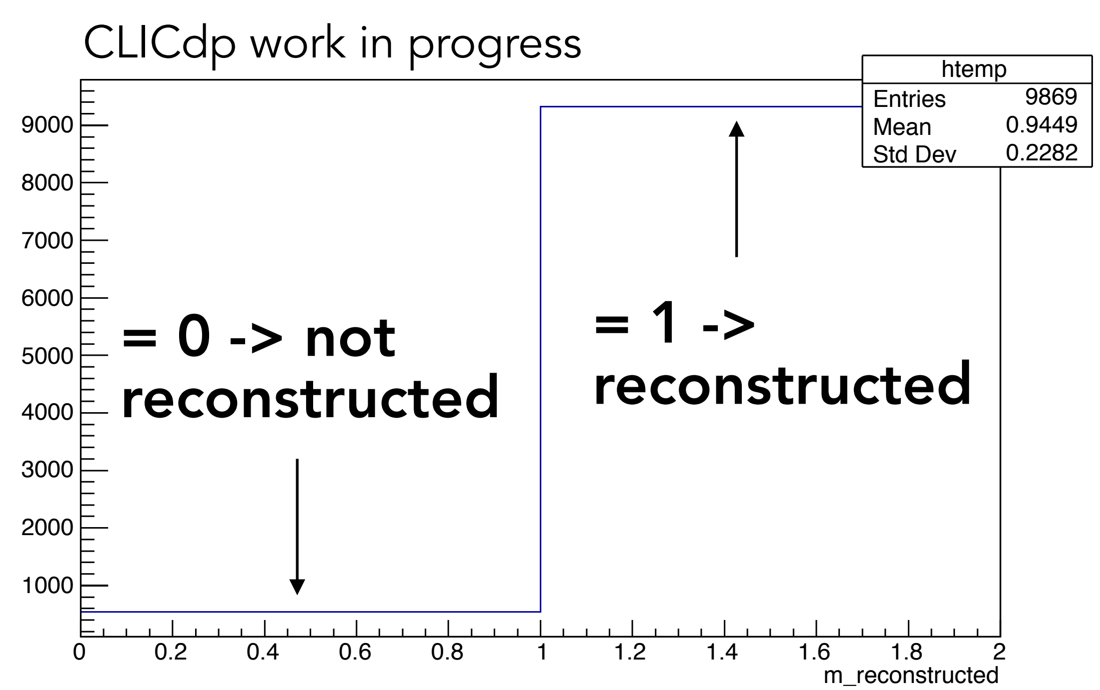
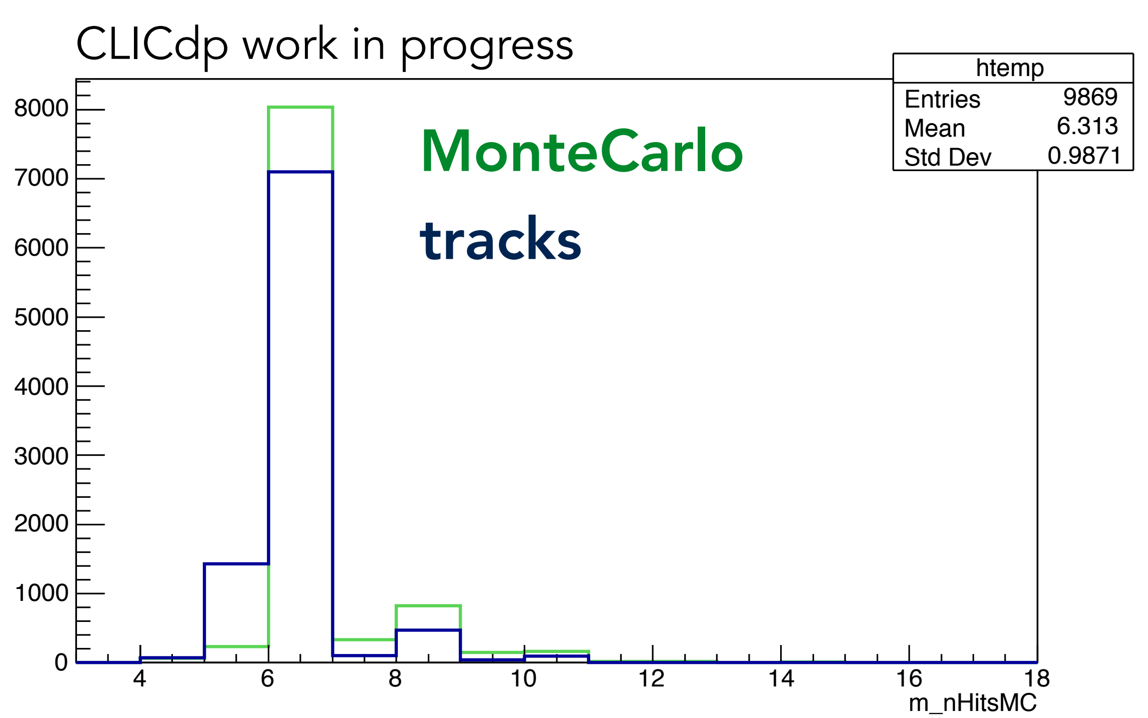


Flag for reconstructed



Number of hits on track

☑ **Efficiency larger than 90%**
☑ **Reconstructed tracks have correct number of hits in most of the cases**

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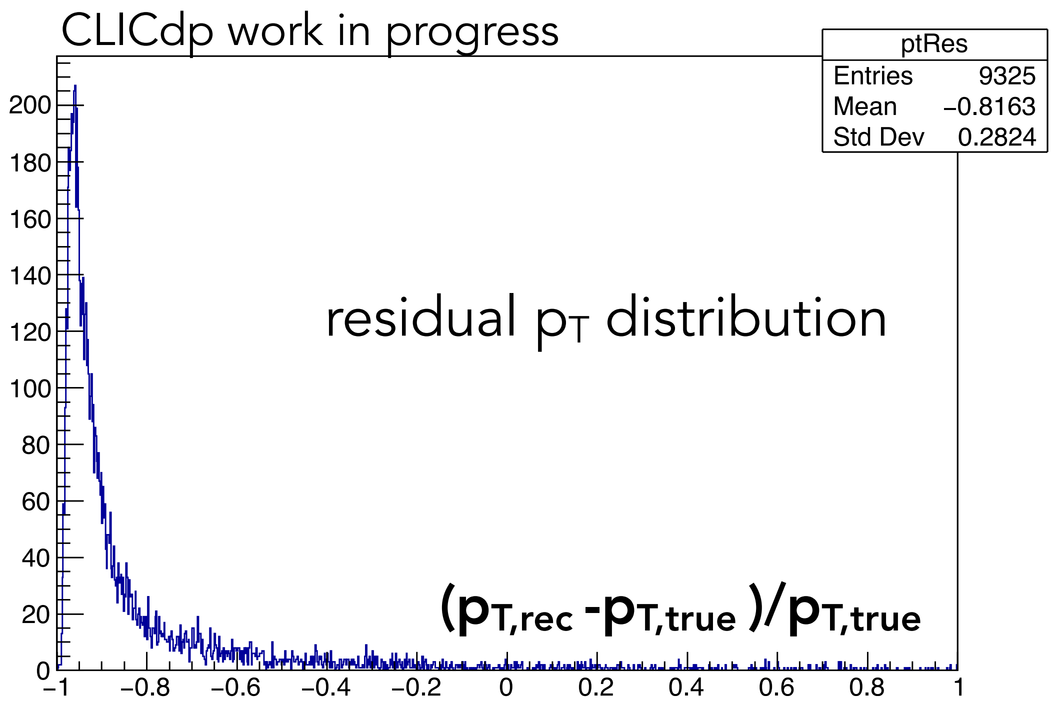

reconstructed p_T does not match the simulated one

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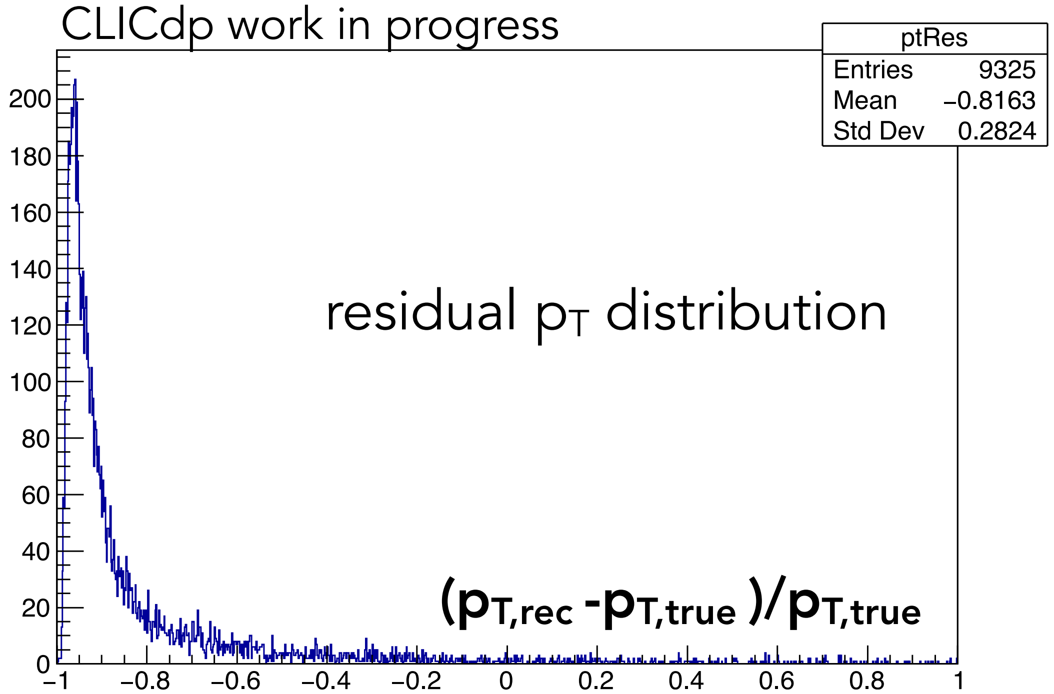
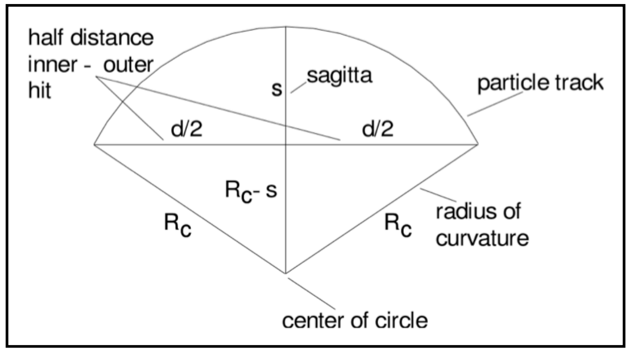


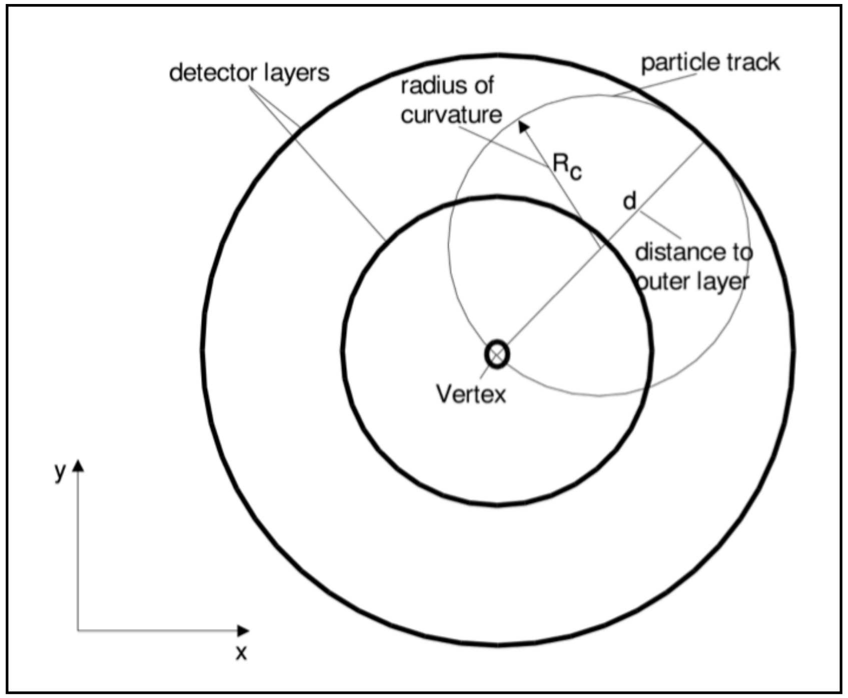
❑ **reconstructed p_T does not match the simulated one**

- The sensitivity to the <u>curvature</u> of a particle in a given magnetic field depends on the **length of the track** (d) and on the **sagitta** (s)

$$p_T = 0.3B\frac{\left(\frac{d}{2}\right)^2 + s^2}{2s}$$



- In the presented study:
  - [**length (d)**] given that the IP is not a measurement* (i.e. a hit on the track), the track length has to be calculated as the **difference between the outermost and innermost hit radii**
    ** CLIC beam spot smaller than LHC (@ 3 TeV: σ_x = 40 nm, σ_y = 1 nm)*
    => this information can be used in a future refined study
  - [**sagitta (s)**] The smallest measurable sagitta is approximately equal to the single point resolution (divided by sqrt(2)).



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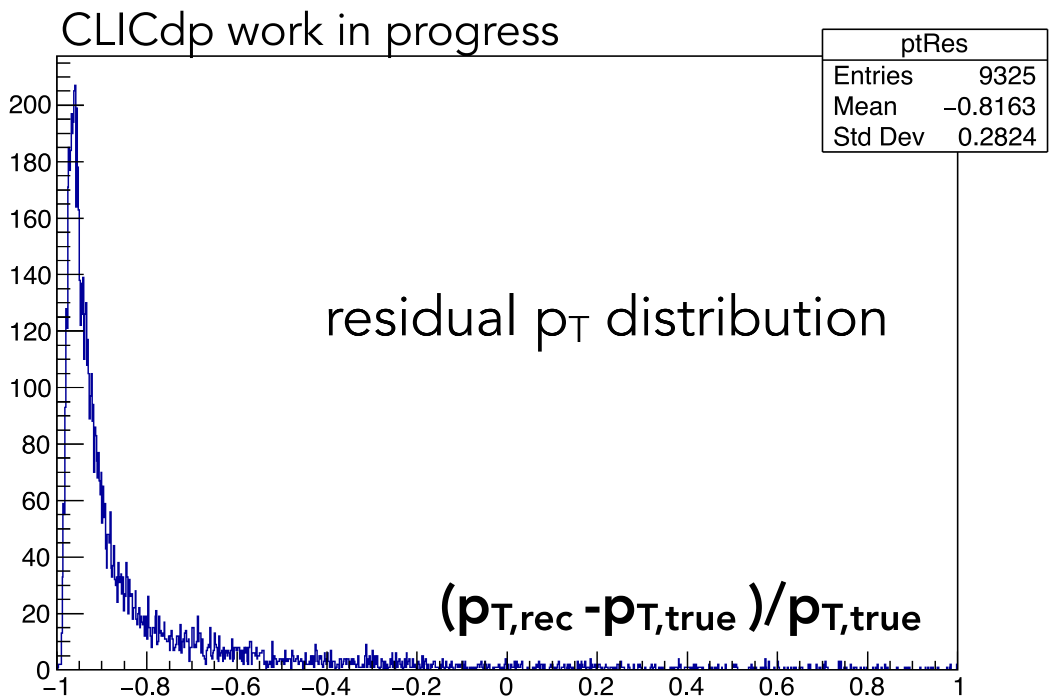

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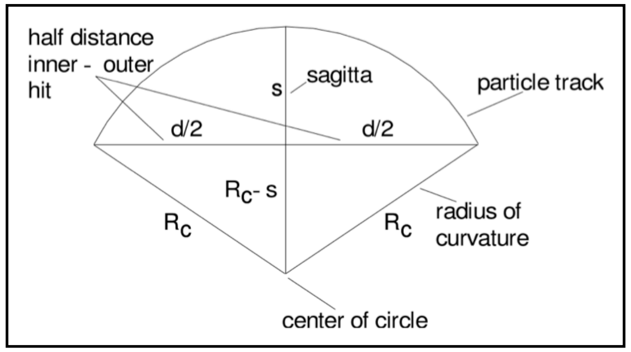

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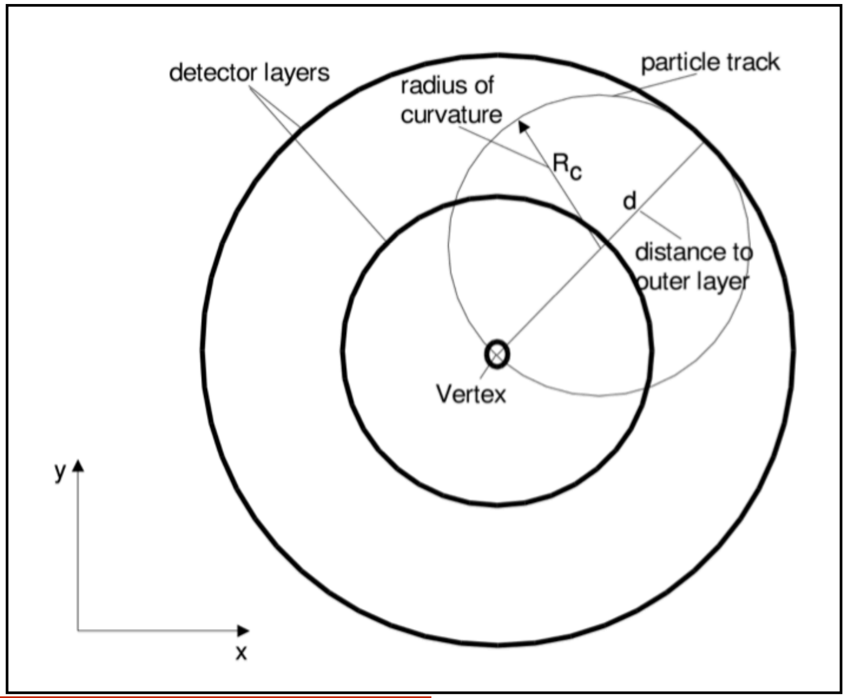


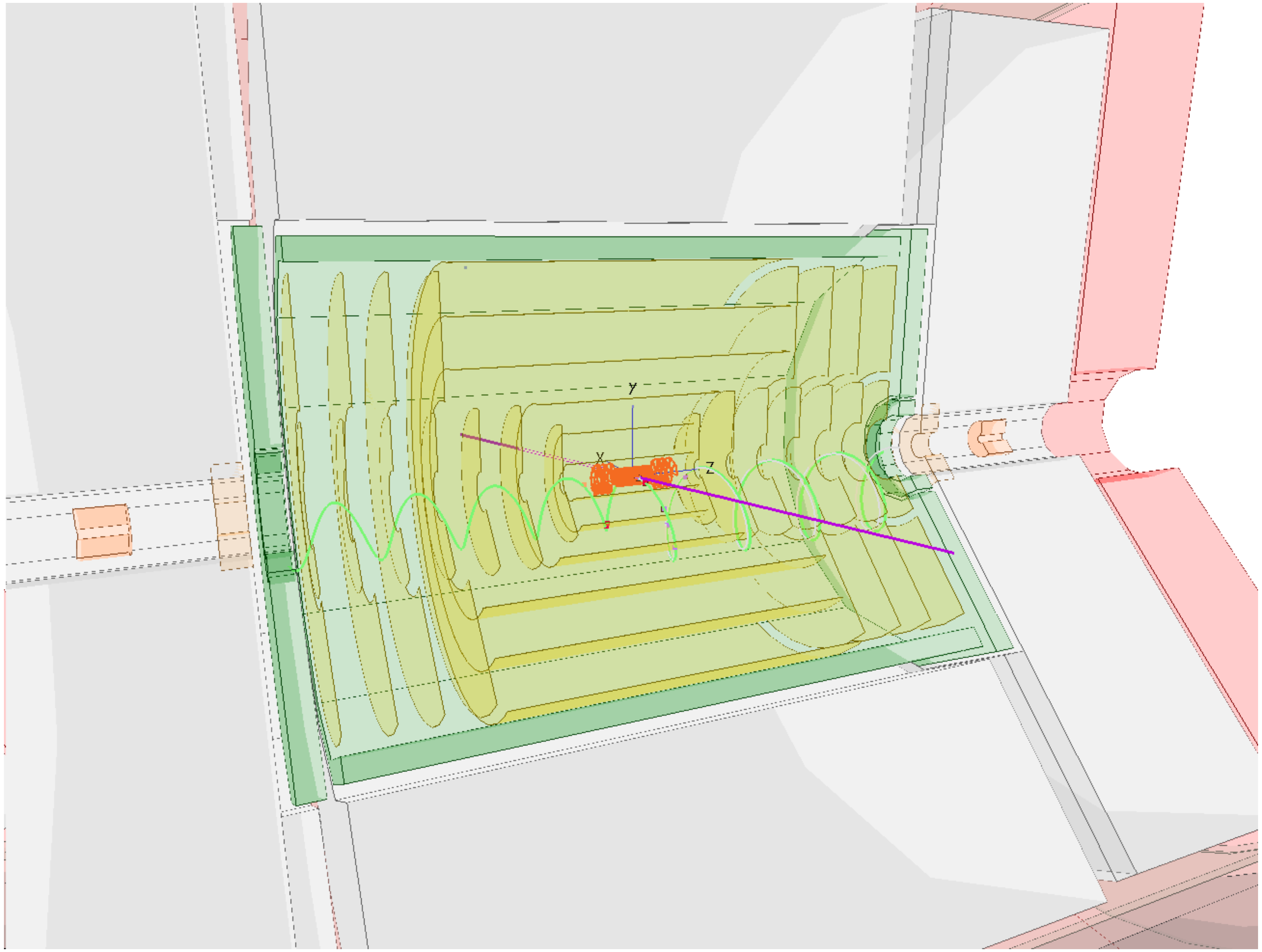
- To be able to reconstruct properly the p_T of a 1 TeV track in the barrel
  - [single point resolution 3μm] stub length should be at least 12 cm

Charged stub - full simulation study

2. chargino samples $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$

(*) more details in back-up

- 10k events produced with WHIZARD(*) => 20k charginos
- chargino decays produced with PYTHIA and GEANT for correct decay vertex assignment (*)
- chargino mass 1050 GeV, neutralino mass 1049.8 GeV
- $c\tau$ = 20 mm



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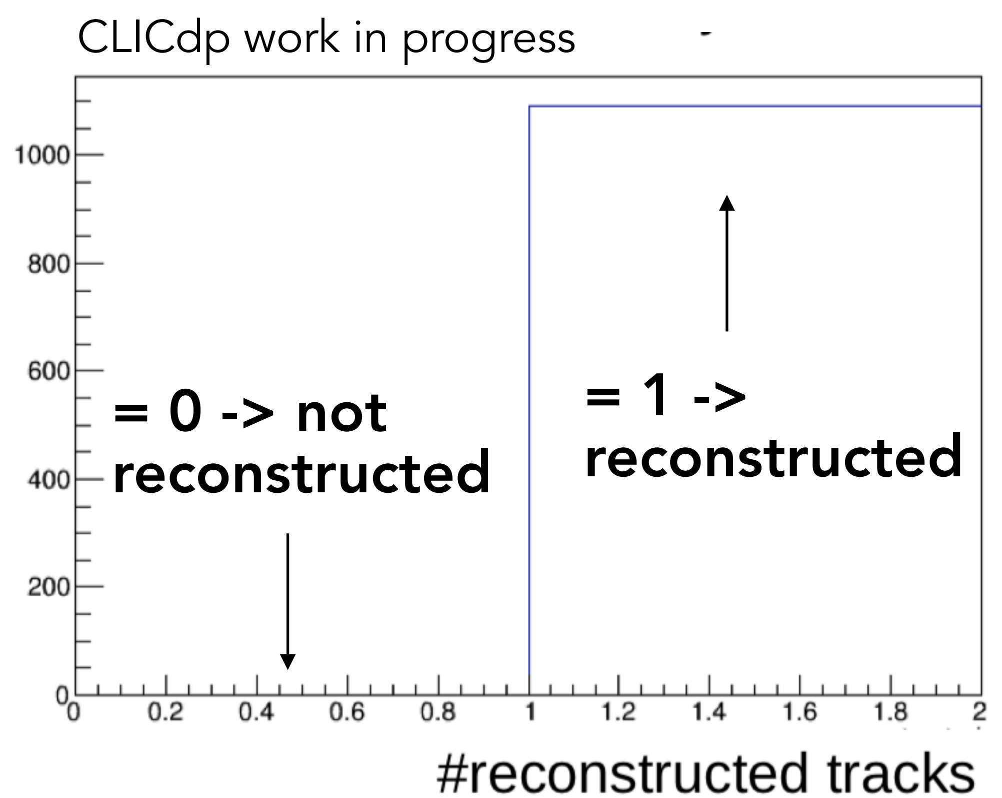
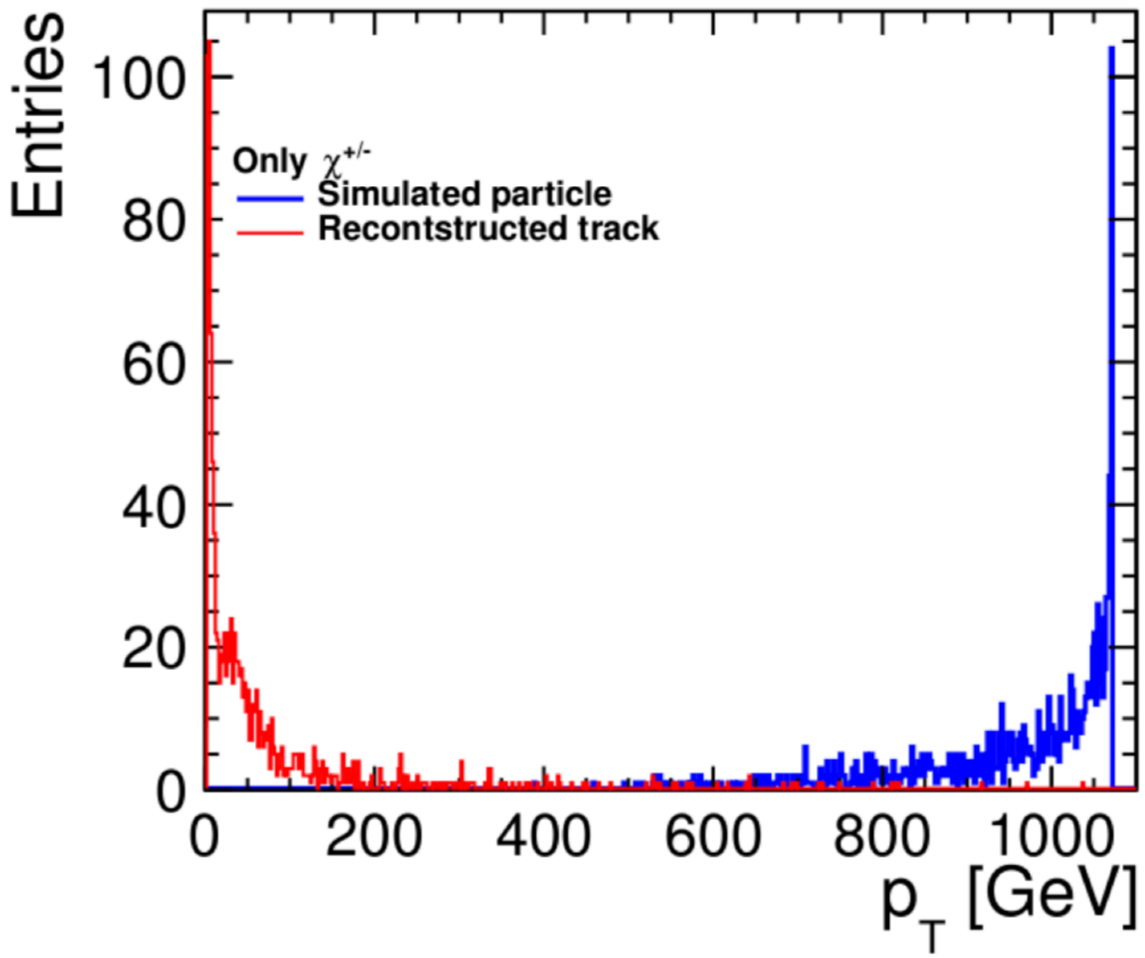




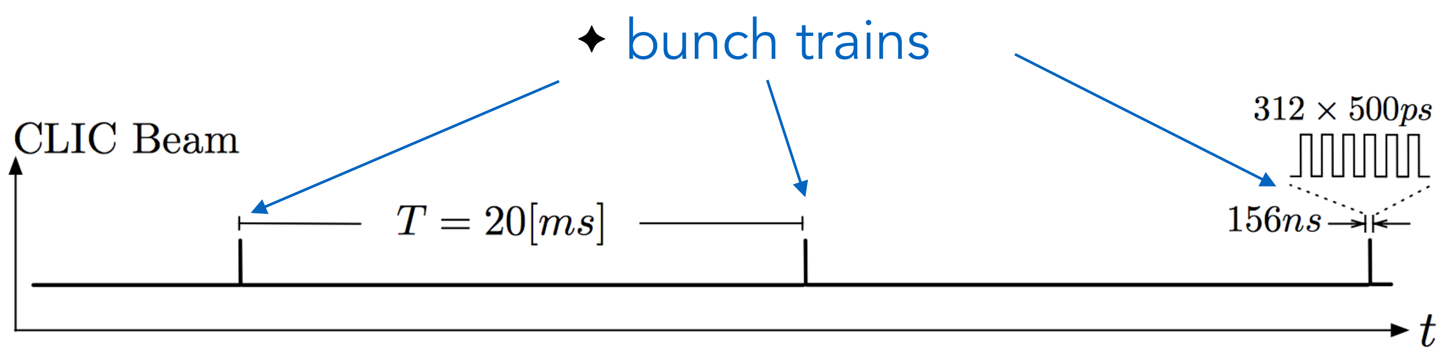
Efficiency 100%

reconstructed p_T distribution compatible with preliminary study with artificially short muons

! Study currently in progress

Charged stub - full simulation study

3. chargino samples with γγ->hadron overlay



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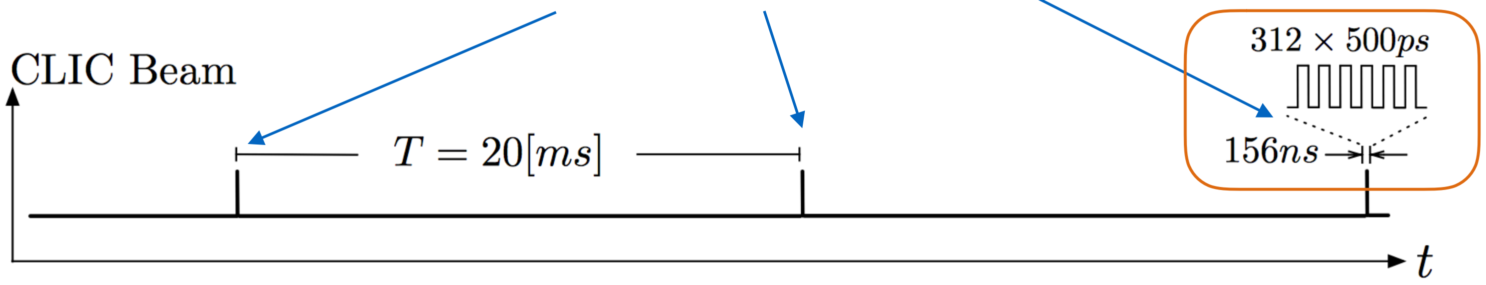
✦ bunch trains



✦ entire bunch train available for offline reconstruction (no trigger)

✦ ~ one hard interaction per bunch train, all other bunch crossings background only

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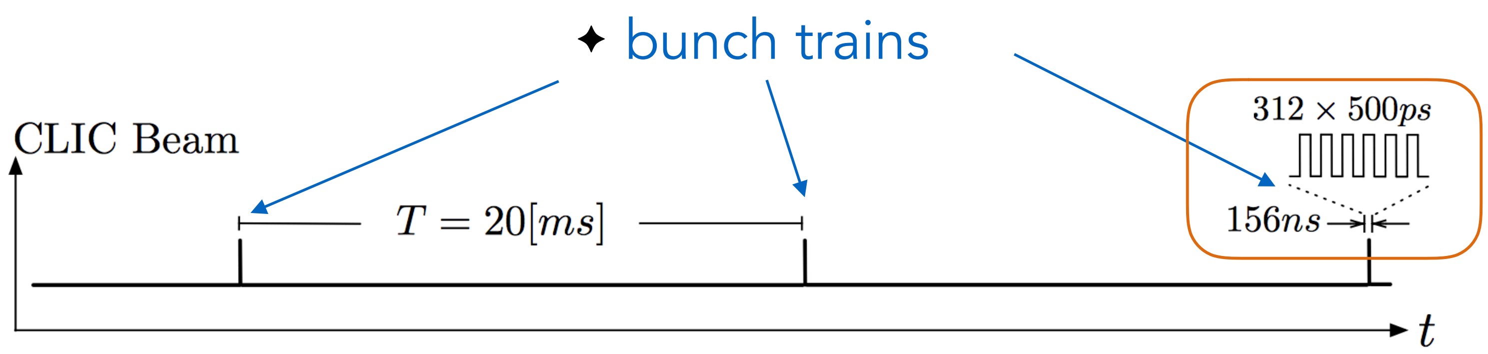

- entire bunch train available for offline reconstruction (no trigger)
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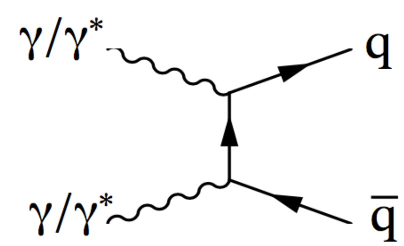
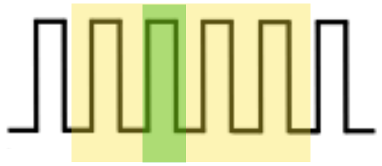
- Main source of background in the barrel: beam-induced γγ->hadrons
- Full simulation used to overlay the simulated hits from background to simulated hits from signal





  - time stamp hits from detectors (central detectors <=> hard interaction)
  - impose timing cuts => 30 bunch crossings integrated (10 before, 20 after hard interaction)
  - reconstruction window in silicon detectors: 10 ns
  - much better timing resolution for particles reaching the calorimeters

Charged stub - full simulation study
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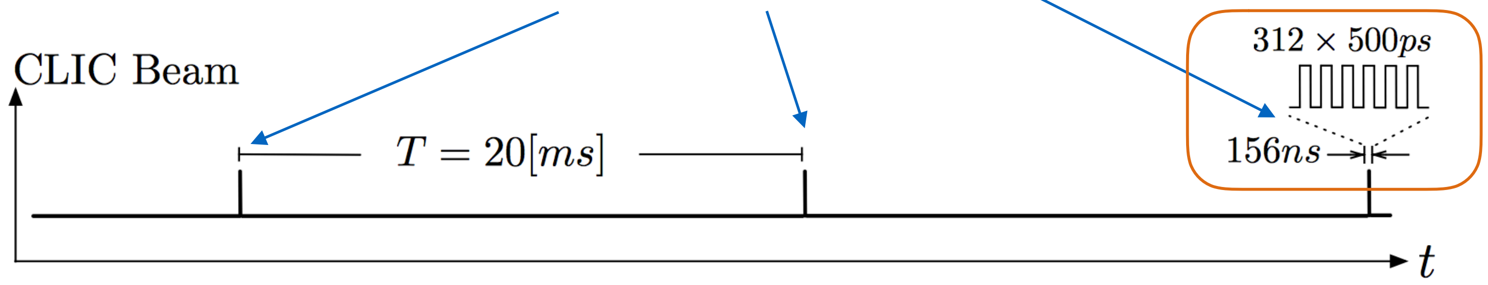
✦ bunch trains



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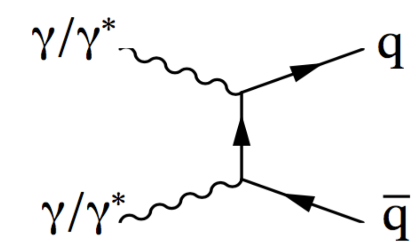

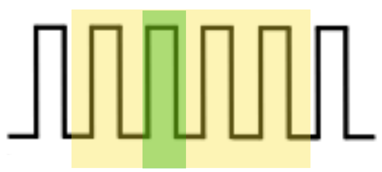

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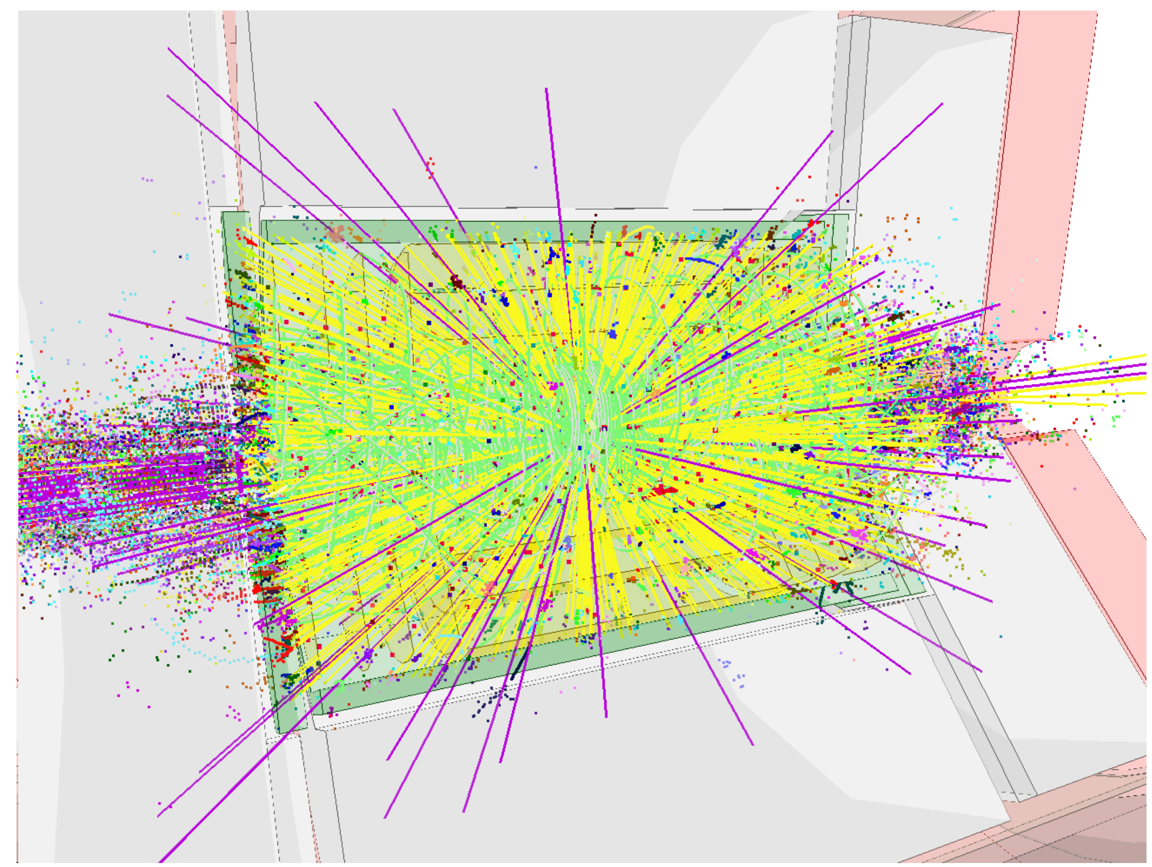

Charged stub - full simulation study

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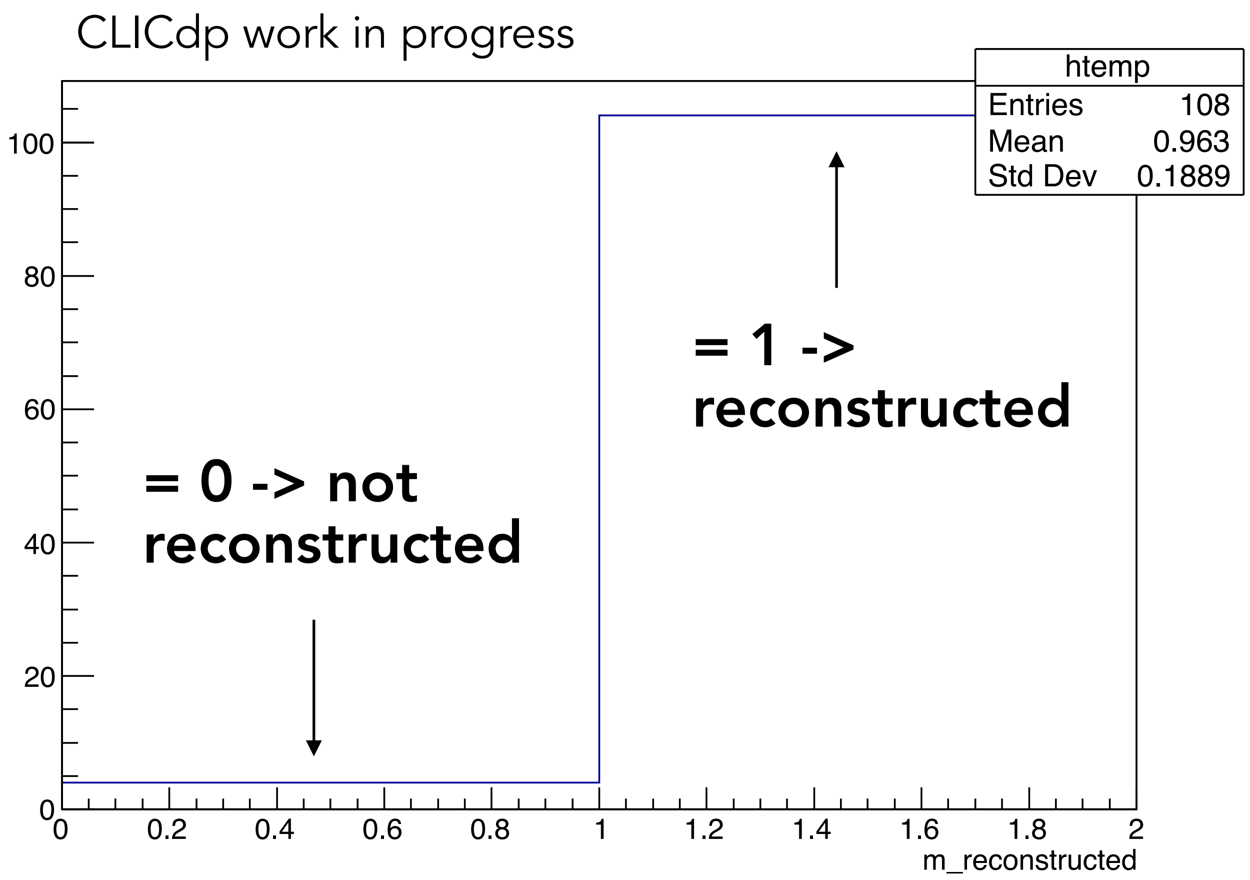
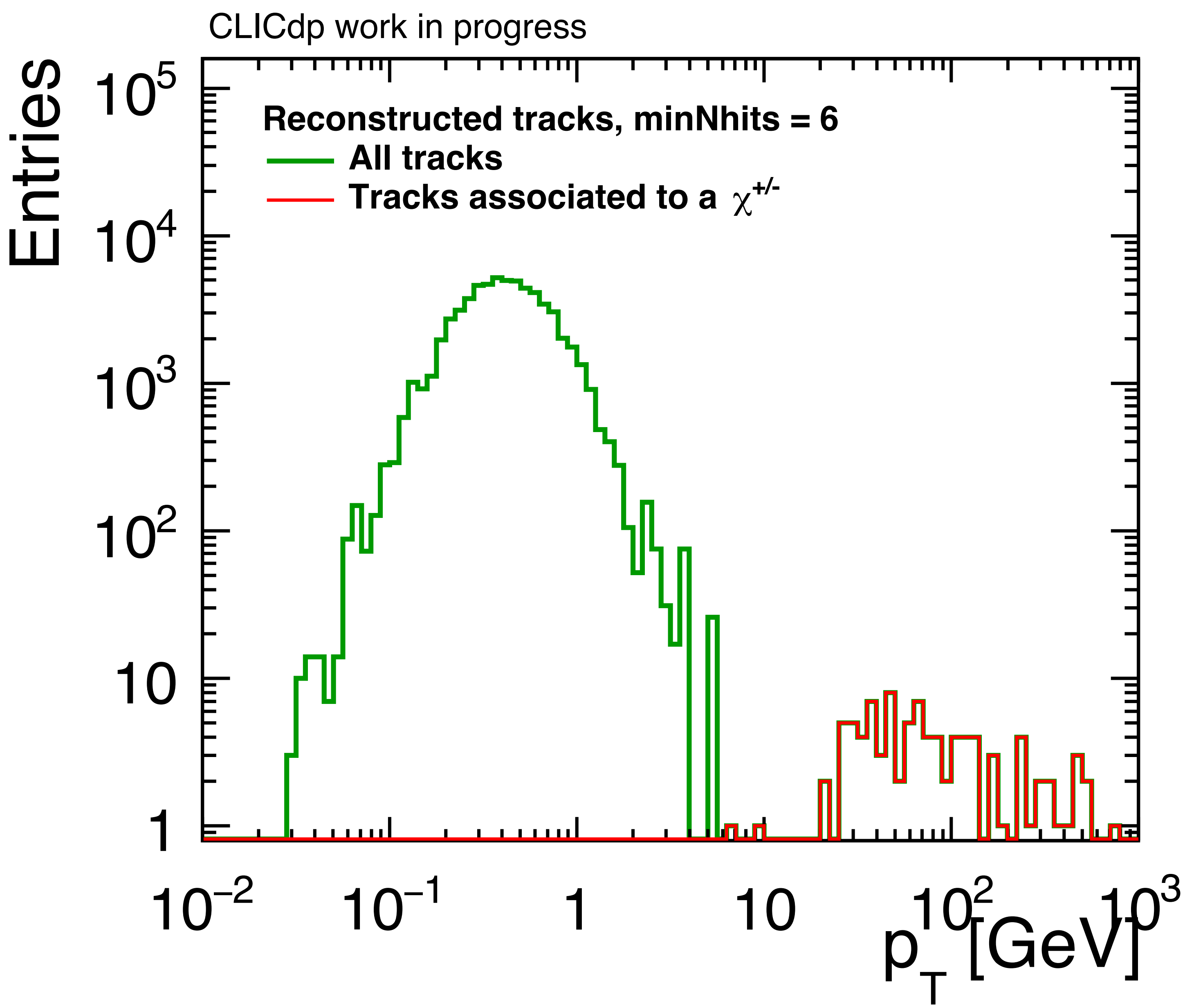




☑ Efficiency ~95%

☑ pT cut to reject beam-induced background

☐ ! Study currently in progress

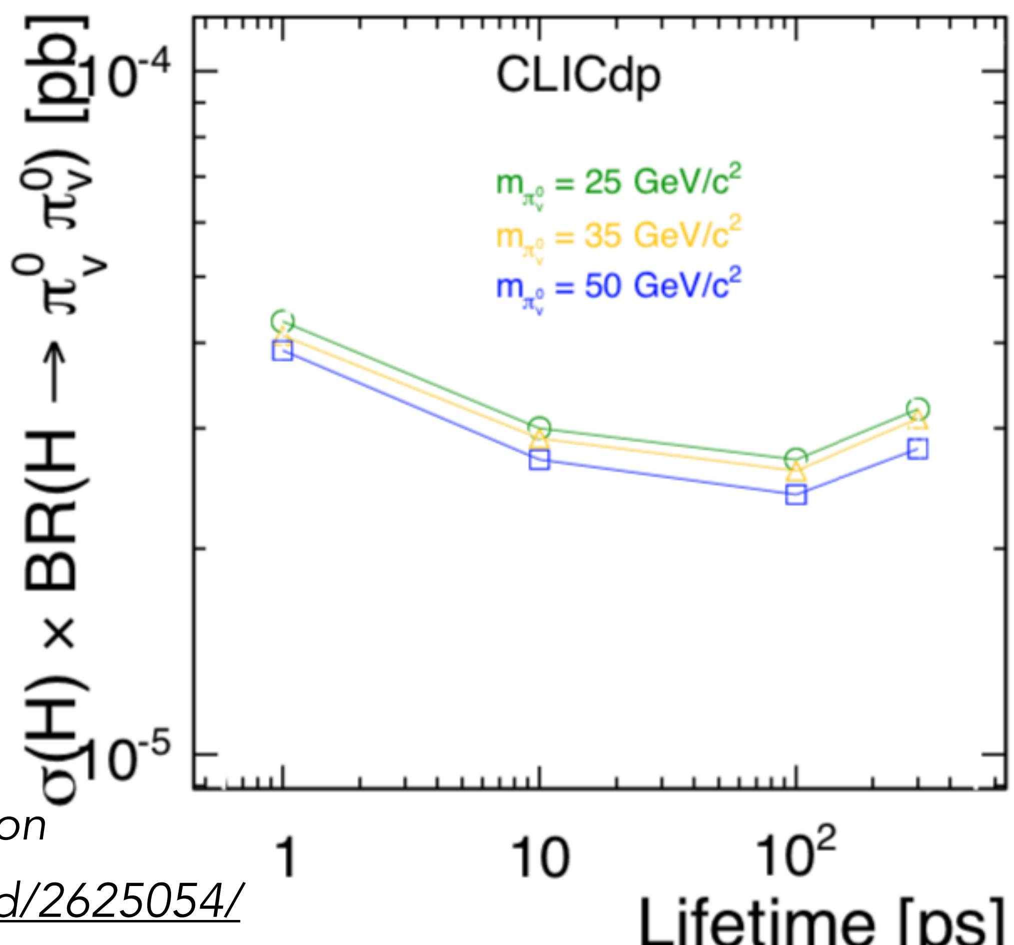
Hidden valley searches in Higgs decays

- hidden gauge sector coupling to SM particles at high energies
- models contain new massive long lived particles
- search for these LLP through displaced vertices reconstruction

- dominant production channel: VBF @ CLIC 3 TeV
- dominant decay mode: $h \to \pi_v^0 \pi_v^0 \to b\bar{b}b\bar{b}$
- search for these LLP through displaced vertices reconstruction

- Observed 95% CL cross-section upper limits on the σ(H) x BR(H->$\pi^0_v\pi^0_v$) for three different π^0_v masses as a function of π^0_v lifetime
  - results from full simulation for CLIC_ILD
  - 100% branching fraction of decay into b quarks

- this analysis has been recast for heavy Higgs boson search (neutral naturalness theories)



M. Kucharczyk and T. Woiton

https://cds.cern.ch/record/2625054/

Conclusions

- **Long-lived particles** occur in many New Physics models
- **CLIC** is **well suited** to investigate signatures from long-lived particles
  - e+e- => clean environment
  - high energy => probe high mass states
  - linear collider => no trigger

Conclusions

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- **CLIC** is **well suited** to investigate signatures from long-lived particles
  - e+e- => clean environment
  - high energy => probe high mass states
  - linear collider => no trigger

- Two analyses performed in CLIC, which underline the importance of full simulation:
  - **Higgsino DM**: chargino leaves short straight track (stub) in the vertex detector
    - study at the reconstruction level (both with artificially short muons and realistic chargino sample) shows very good efficiency but biased p_T reconstruction
      - nevertheless: reconstructed p_T still valuable to reject most of the beam-induced background already from presented preliminary results
      - *background rejection to be further studied and understood*
      - *scan in chargino masses to be performed*
      - *further investigation required with additional photon*
      - *possibility to profit from dE/dx from silicon layers*
  - **Hidden valley in Higgs decays**
    - full simulation study to evaluate the sensitivity to masses and lifetimes
    - recast to heavier Higgs bosons

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Ideas/discussions with LLP community welcome!

Extra slides

Charged stub - generator level

- Two methods to count expected number of events with at least one (or two) identifiable stub tracks:
  - for both: no efficiency factor applied, no background included
- a) purely analytical method based on survival probability $$P_s(d_{\min}) = e^{-m_\chi d_{\min} \Gamma_\chi / |\vec{p}_\chi|}$$
- b) Monte Carlo (MadGraph 5)
  - random decay length from lifetime distribution $$\Gamma(\chi^\pm \to \chi^0 \pi^\pm) = \frac{G_F^2}{\pi} \cos^2\theta_c f_\pi^2 \delta m^3 \sqrt{1 - \frac{m_\pi^2}{\delta m^2}}$$

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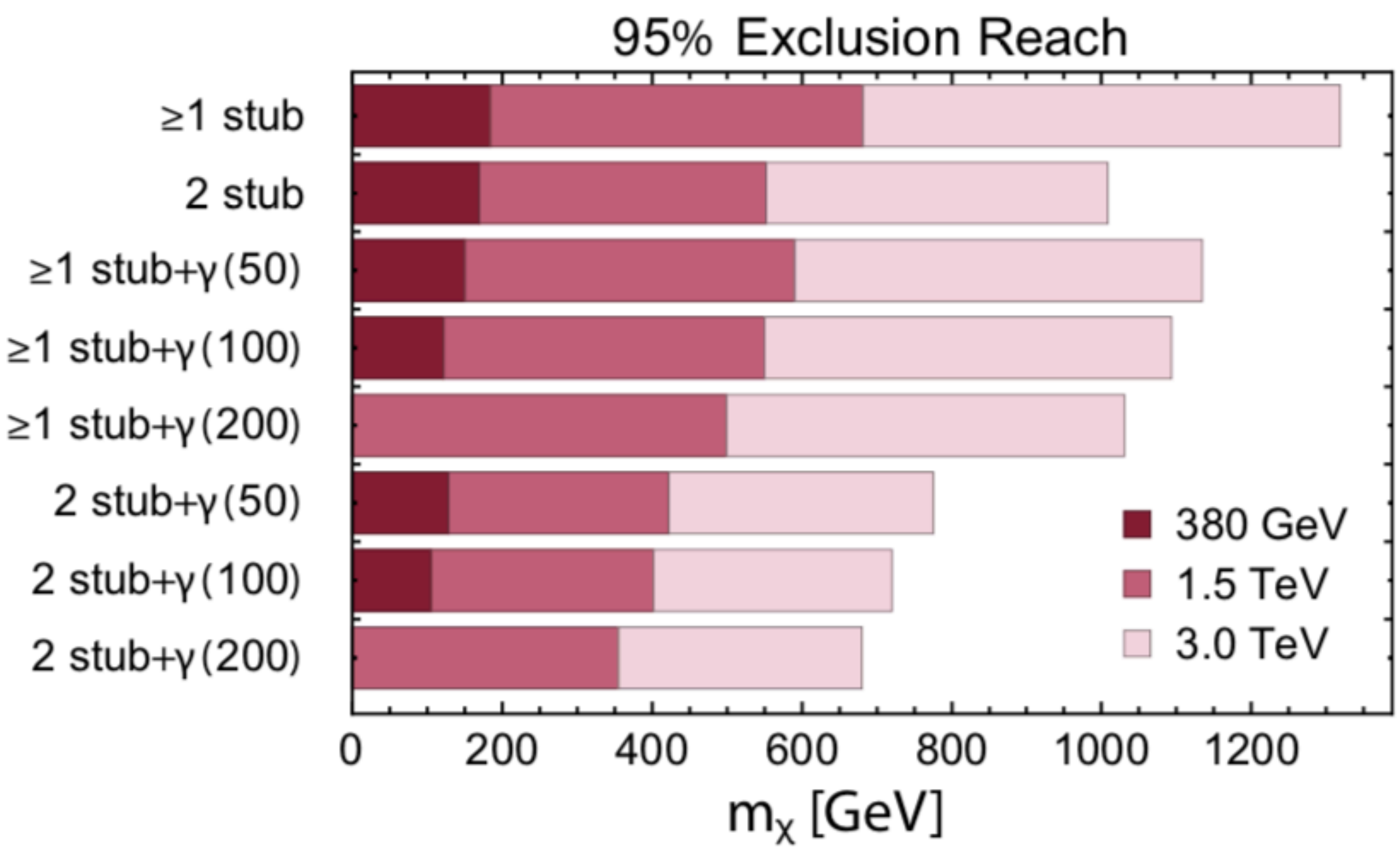

- 95% exclusion reach by requiring at least N_{evts} = 3 with zero background
  - stub only and stub + ISR photon
  - different cuts on photon energy
    - 50, 100, 200 GeV

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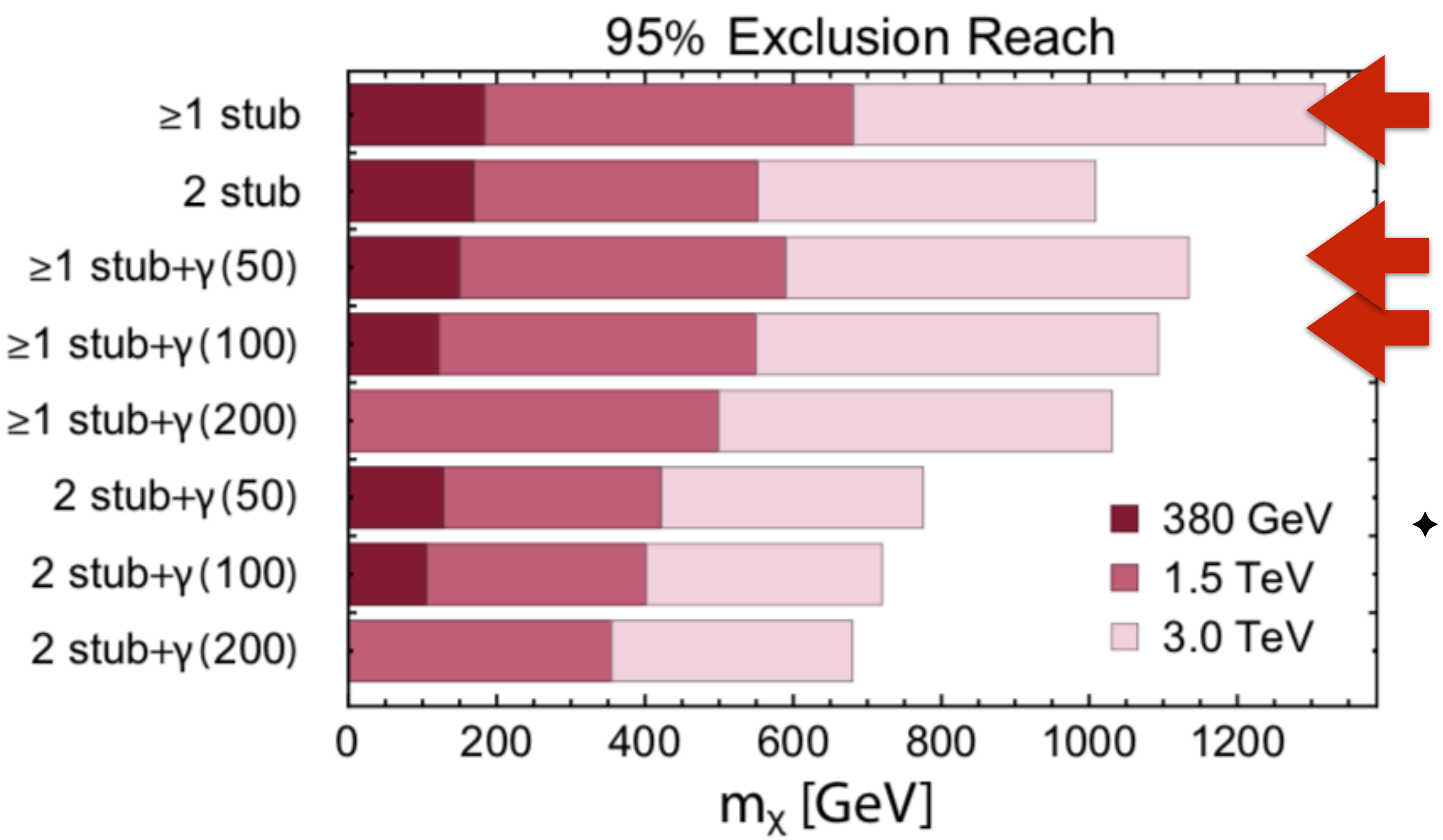
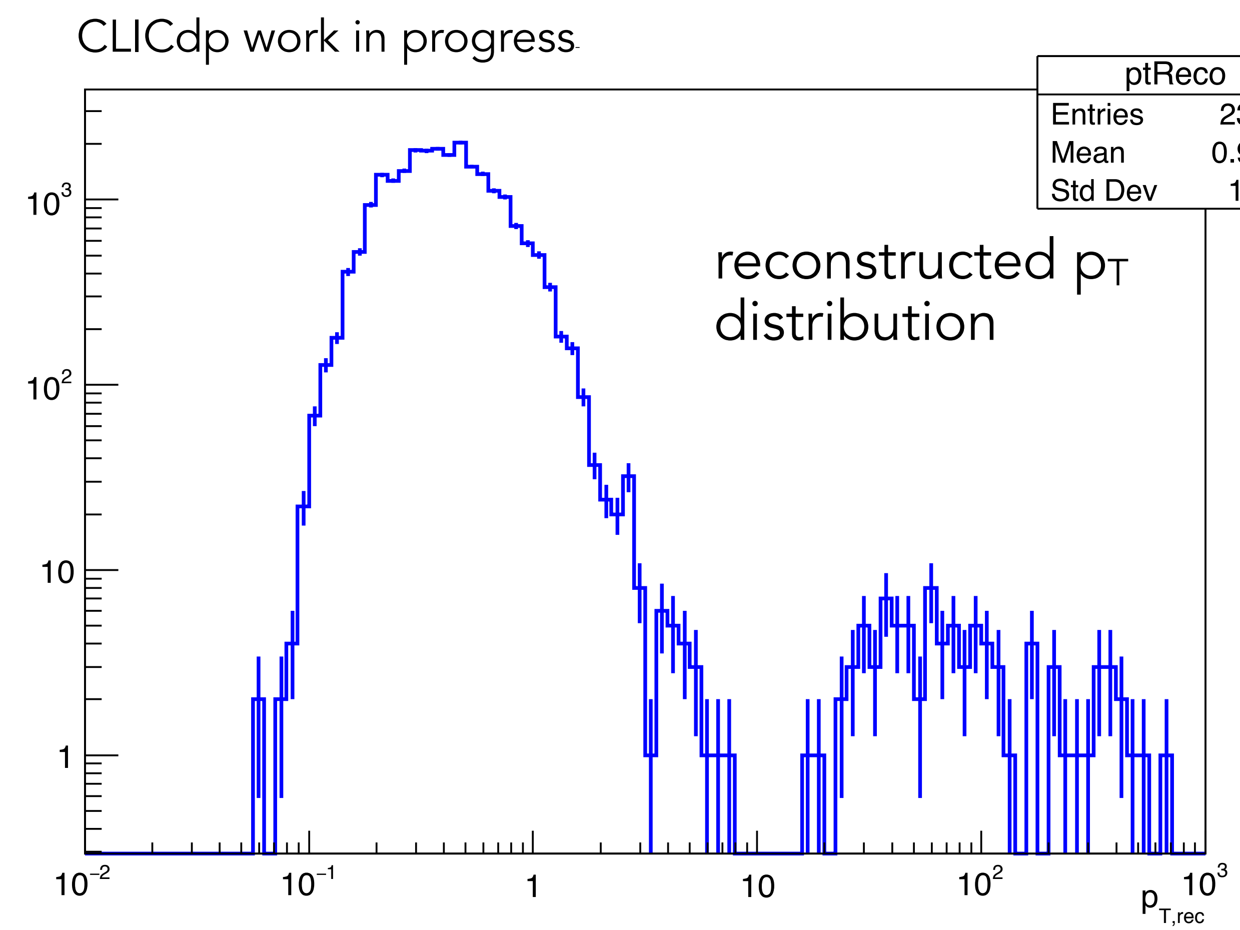


- 95% exclusion reach by requiring at least N_{evts} = 3 with zero background
  - stub only and stub + ISR photon
  - different cuts on photon energy
    - 50, 100, 200 GeV
- All analyses cover large range of masses
  - **most optimistic strategies up to thermal dark matter target m_χ ~ 1.1 TeV**

Charged stub - full simulation study

2. artificial short track sample with γγ->hadron overlay

- 100 physics events: "short" muons with p = 1 TeV, distribution flat in cosθ



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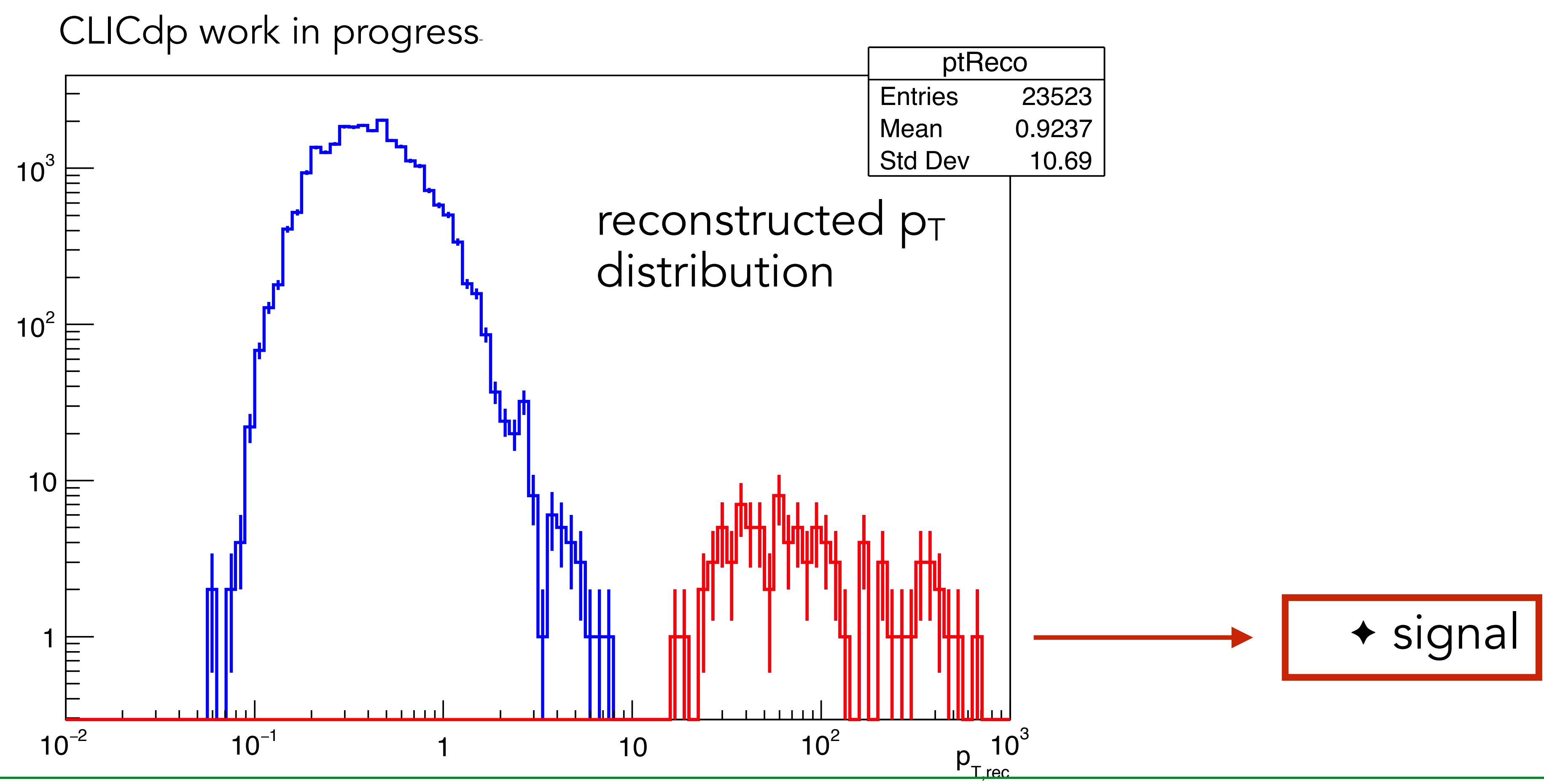


☑ **In spite of the limit on the p_T sensitivity, the signal sample is well separated from the reconstructed tracks from background particles**

- ✓ **p_T cut can be used to reject most of the background**

☐ **NB: with the artificially short muons, most of the tracks have 6 hits**

- **real stub signal may be characterized by fewer hits on tracks => background and signal distributions may be less separated**
- **normalization to be investigated**
- **background from artificially short tracks with n=6 also to be estimated**

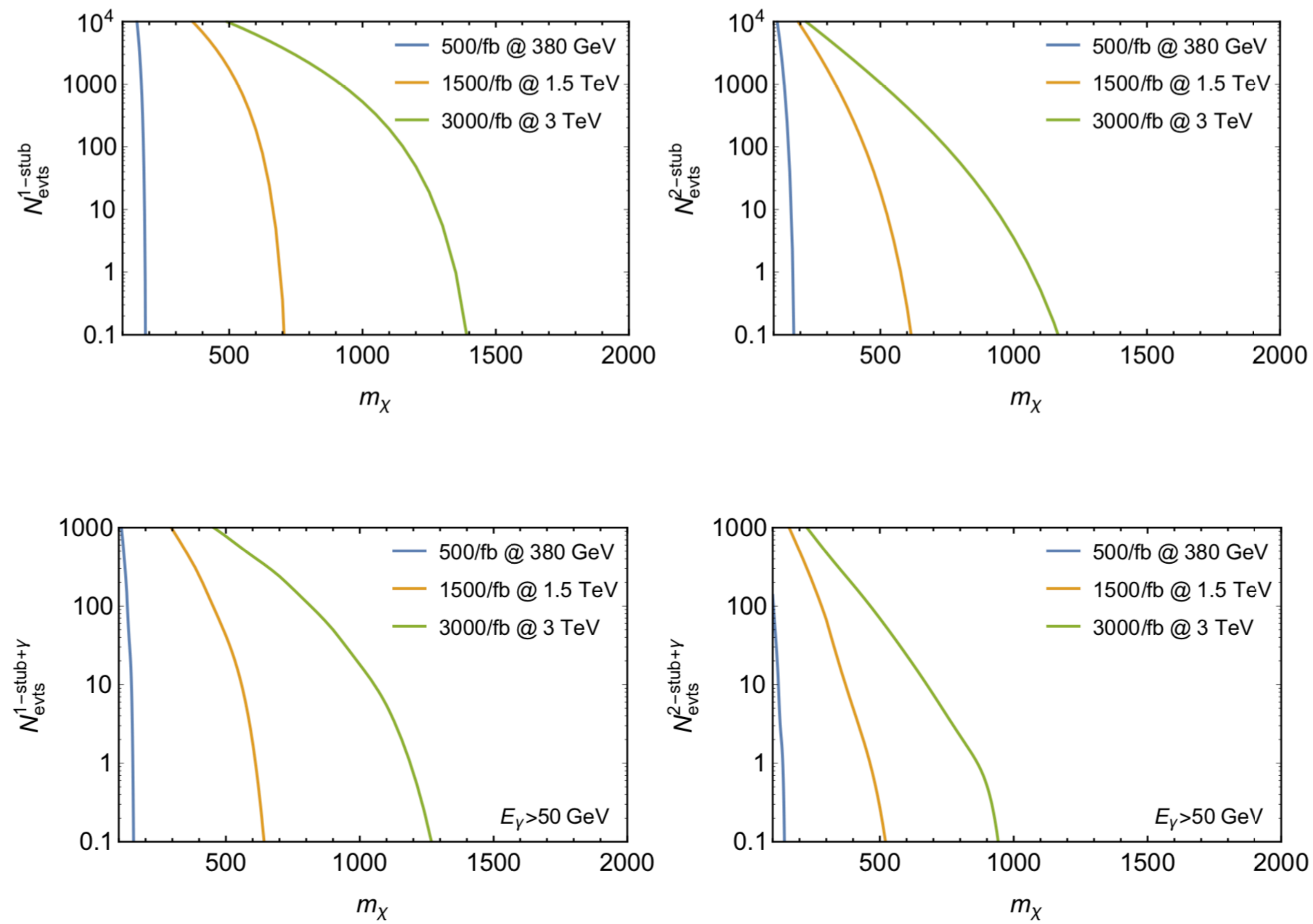
Charged stub - generator level

- Purely analytical method based on survival probability $P_{\rm s}(d_{\rm min}) = e^{-m_\chi d_{\rm min} \Gamma_\chi / |\vec{p}_\chi|}$
    - no efficiency factor applied
    - no background included

$$N_{\rm evts}^{1-{\rm stub}} = \mathcal{L}_{\rm int} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \to \chi^+\chi^-)}{d\cos\theta} [2P_{\rm s}(d_{\rm min}) - P_{\rm s}(d_{\rm min})^2]\, d\cos\theta$$

$$N_{\rm evts}^{2-{\rm stub}} = \mathcal{L}_{\rm int} \times \int_{-1}^{1} \frac{d\sigma(e^+e^- \to \chi^+\chi^-)}{d\cos\theta} P_{\rm s}(d_{\rm min})^2\, d\cos\theta\,.$$

- Monte Carlo validation (MadGraph 5)
    - 5×10^4 events at each m_χ interval
        - 100-180GeV @CLIC 380 GeV
        - 100-800 @CLIC 1.5 TeV
        - 100-1600GeV @CLIC 3 TeV
    - random decay length from lifetime distribution
    - counted if $d > d_{\rm min}$



Charged stub - generator level

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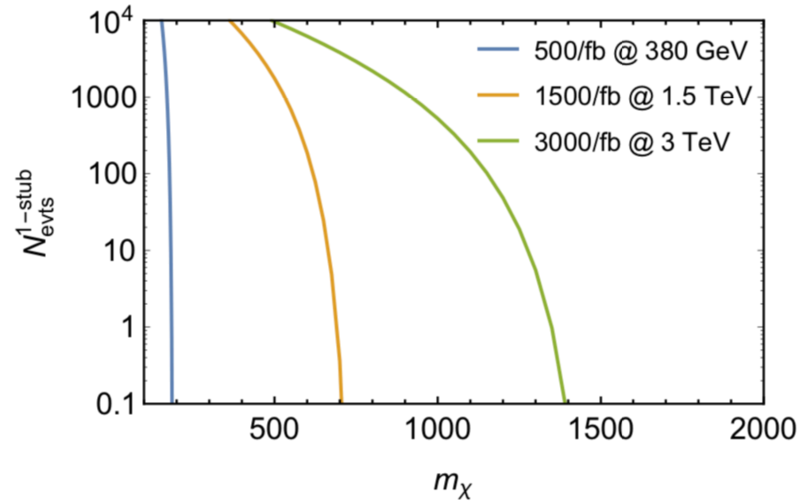
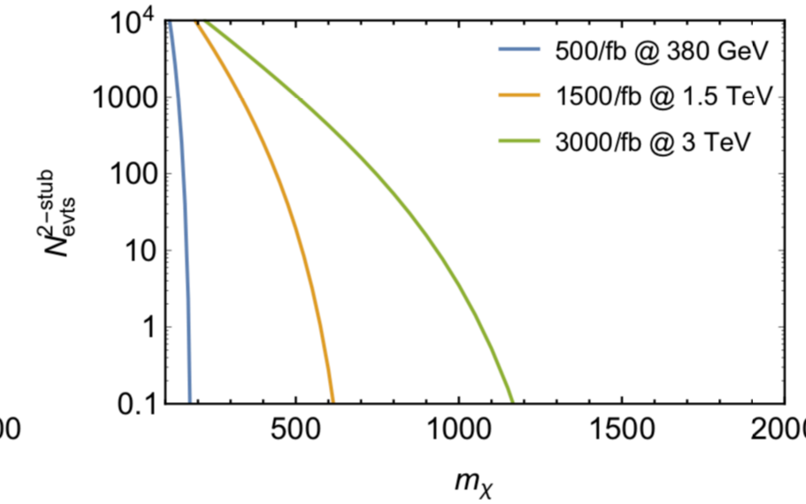
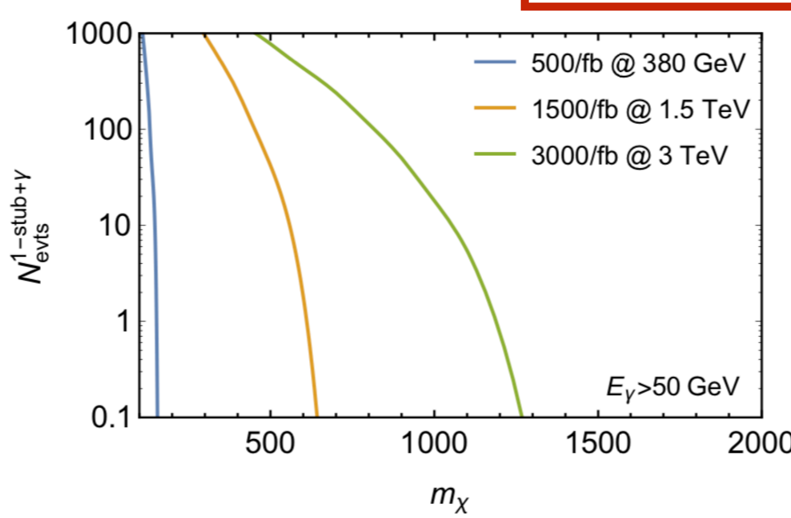
- Monte Carlo validation (MadGraph 5)
  - 5x10[4] events at each m_χ interval
    - 100-180GeV @CLIC 380 GeV
    - 100-800 @CLIC 1.5 TeV
    - 100-1600GeV @CLIC 3 TeV
  - random decay length from lifetime distribution
  - counted if d > d_{min}

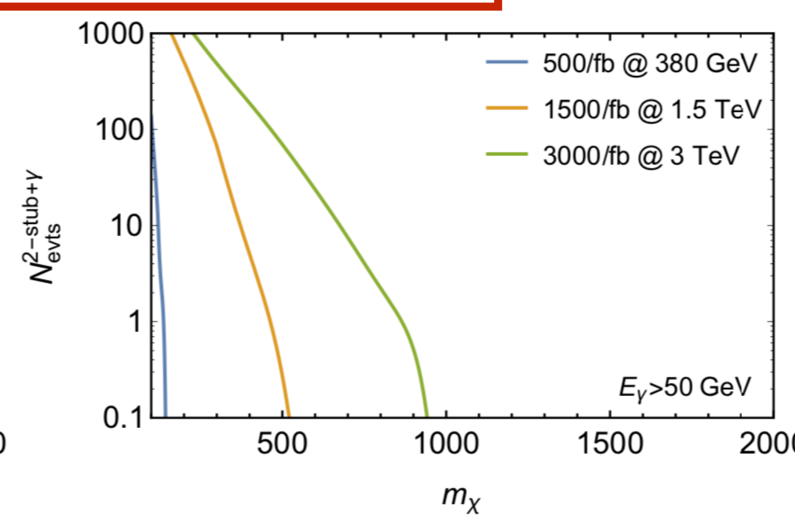
- charged stub only





- charged stub + photon





Charged stub - reconstruction level

1. artificial short track sample

- The hard limit on the maximum reconstructed p_T is given by a combination of magnetic field, stub track length and single point resolution

- For stub tracks of p = 1 TeV in the barrel (θ = 89 deg) and length d
  - From analytical estimate:
    - [max hits = 6] d = r_{max} - r_{min} = 2.9 cm => p_T ~ 60 GeV/c
    - [min hits = 4] d = r_{max} - r_{min} = 1.5 cm => p_T ~ 16 GeV/c
  - From analytical estimate and IP included as innermost hit on track:
    - [max hits = 6] d = 6.0 cm => p_T ~ 254 GeV/c
    - [min hits = 4] d = 4.6 cm => p_T ~ 150 GeV/c
  - From full simulation results [# hits = max hits = 6]:
    - [single point resolution 3μm (default)] mode of the reco p_T distribution ~ 35 GeV/c
    - [single point resolution 1μm] mode ~ 110 GeV/c

$$p_{\mathrm{T}} = 0.3B\frac{\left(\frac{d}{2}\right)^2 + s^2}{2s}$$

- To be able to reconstruct properly the p_T of a 1 TeV track in the barrel
  - [single point resolution 3μm] stub length should be at least 12 cm
  - [single point resolution 1μm] stub length should be at least 7 cm

Charged stub - reconstruction level

3. chargino samples $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$

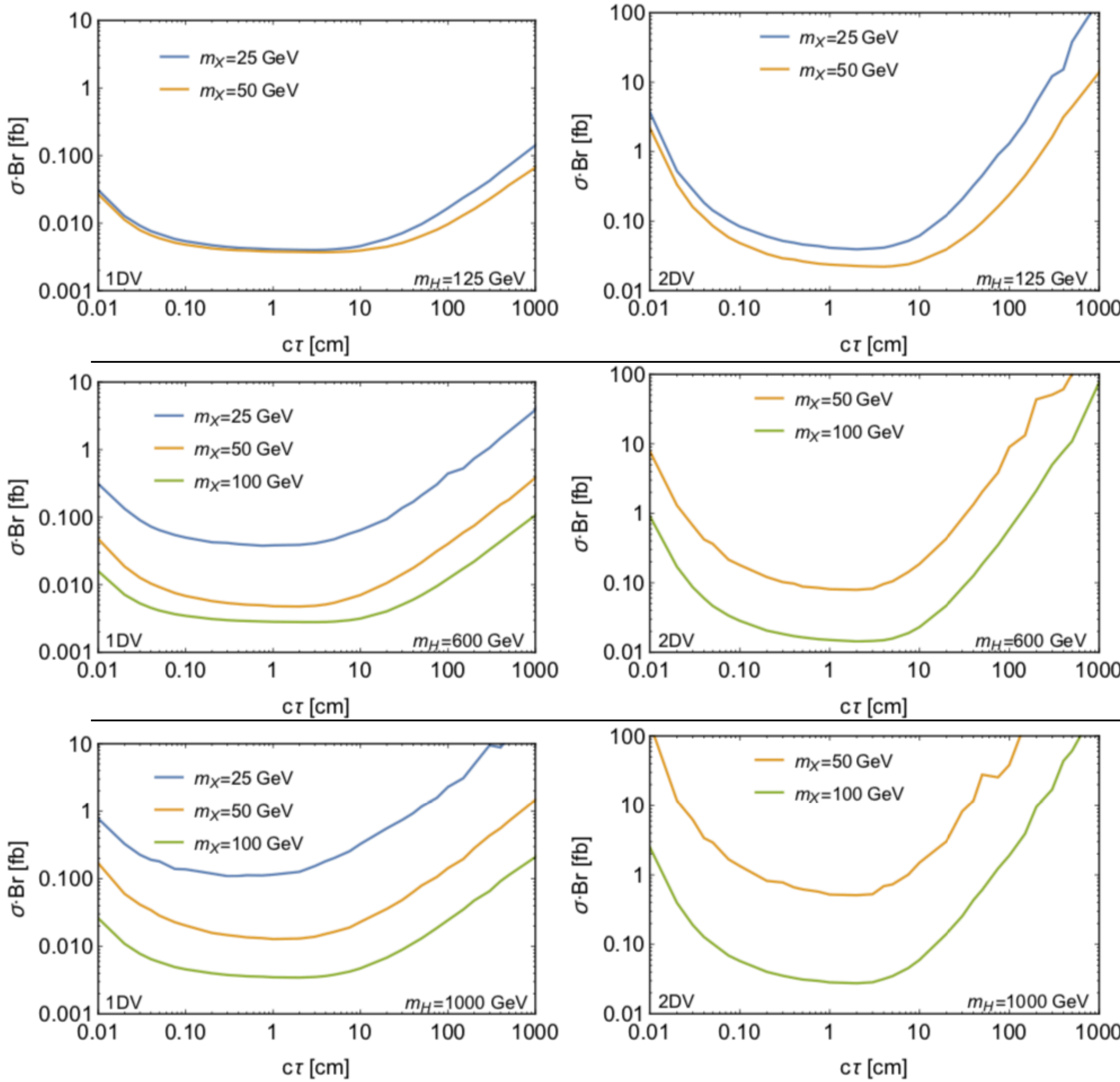
Monte Carlo generation for long-lived chargino pair production

- Process: chargino pair production where the charginos decay to a neutralino and a pion: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\pi^+\tilde{\chi}_1^0\pi^-$
- Chargino mass $m_{\tilde{\chi}_1^\pm} = 1050\,\text{GeV}$ (PDGID = 1000024), neutralino mass $m_{\tilde{\chi}_1^0} = 1049.8\,\text{GeV}$ (PDGID = 1000022)
- Chargino lifetime $c\tau = 60\,\text{mm}$ (to be varied)
- WHIZARD-2.7.0 used for generation of the hard process, PYTHIA6 for the parton shower
  - Full chain in WHIZARD up to neutralino and pion final state, with PYTHIA used for parton shower, OR:
  - PYTHIA can also do the chargino decay, passing the relevant parameters to the WHIZARD-PYTHIA interface:
    ```
    $ps_PYTHIA_PYGIVE = "IMSS(1)=1;PMAS(312,1)=1050.;
    PMAS(312,4)=60.;MDCY(312,2)=2601;MDCY(312,3)=1;PMAS(310,1)=1049.8;MDCY(310,1)=0;
    KFDP(2601,1)=1000022;KFDP(2601,2)=211;KFDP(2601,3)=0;KFDP(2601,4)=0;KFDP(2601,5)=0;BRAT(2601)=1.0"
    ```
- Event record from WHIZARD does not contain the displacement (authors contacted)
- Workaround: Use GEANT4 to obtain the displaced decay by setting the chargino lifetime in the GEANT4 particle table[1]
  - In `ddsim`, this is done via the option `--physics.pdgfile particle.tbl`

[1] https://github.com/AIDASoft/DD4hep/blob/master/DDG4/examples/particle.tbl

Hidden valley searches in Higgs decays

✦ this analysis has been recast for heavy Higgs boson search (neutral naturalness theories)



✦ m_H = 125 GeV

✦ m_H = 600 GeV

✦ m_H = 1000 GeV