LLPs at a muon collider

Experiment

Federico Meloni (DESY),
(presenting work done in the Muon Collider Physics and Detector group)

9th workshop of the LLP Community
28/05/2021

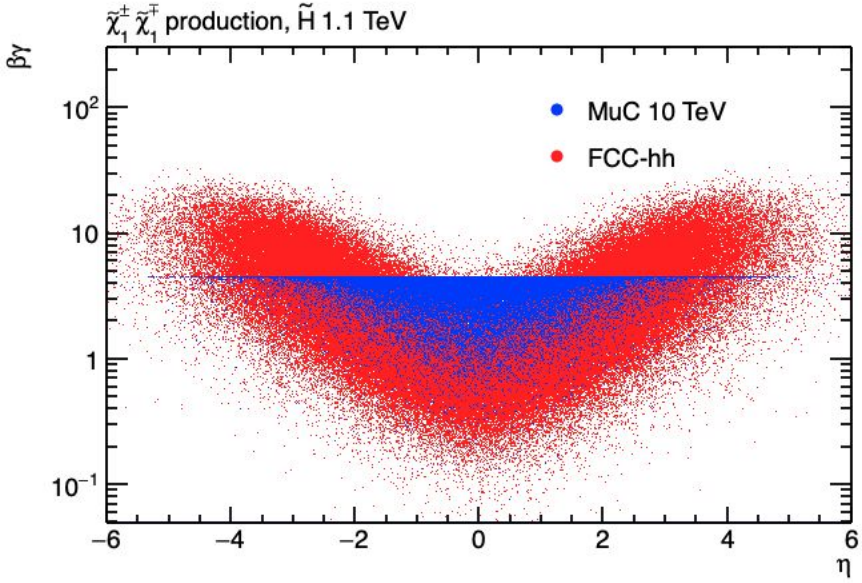
Introduction

Environment different from hadron colliders.

- Dominated by neutrons and photons
- ~Weak radial dependence (except at the first tracker layer)

Kinematics are also generally different.

- No energy “wasted” by parton distribution functions
- If the LLP is produced in the main interaction it can be more boosted than it would be at a hadron collider (probing similar mass scales)



Unique mix of challenges and opportunities to do creative LLP searches.

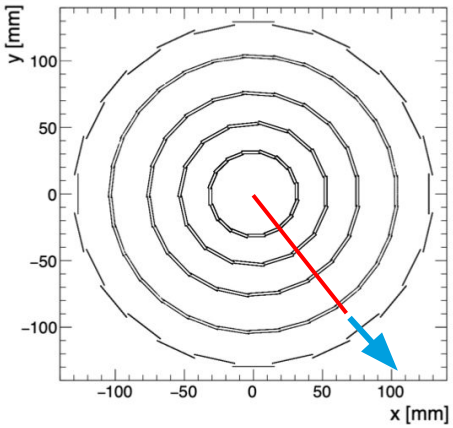
I won’t discuss muon detectors further not because they are not interesting, but because they are relatively similar to the LHC.

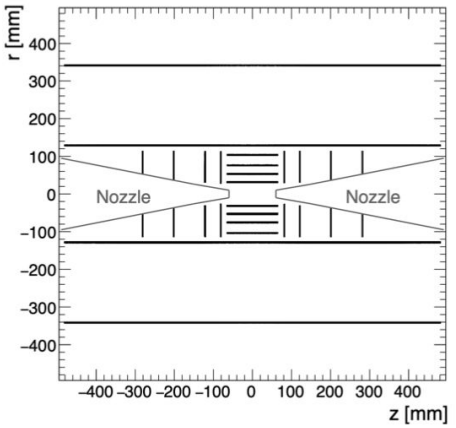
Tracking and trackers

Innermost trackers:
Vertex Detector (VXD)
Inner Tracker (IT)

Tracking detector bombarded by huge amount of randomly distributed hits/BX.

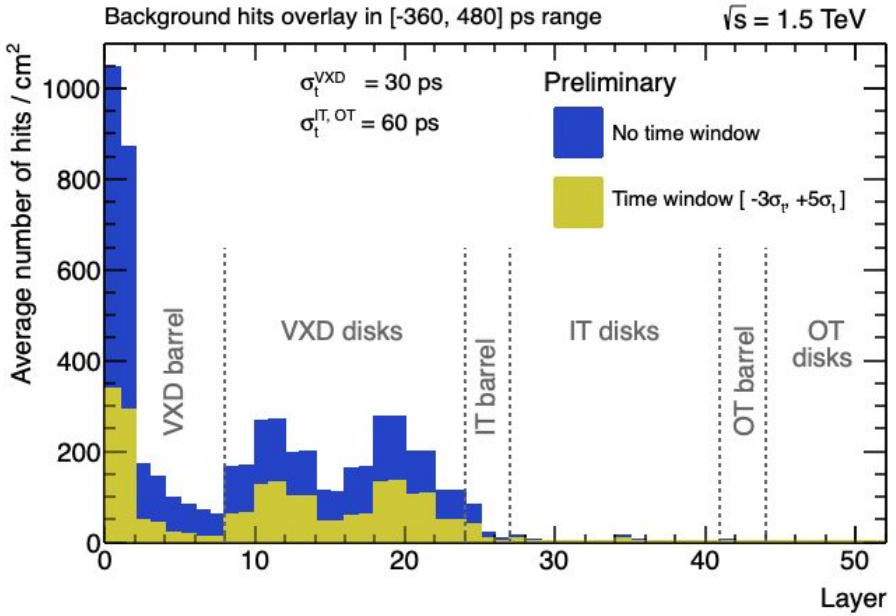
- Extremely challenging track reconstruction





Need to filter hits:

- Timing
- Correlation of hit pairs (either on- or off-detector)
- Cluster shapes
- Energy loss in silicon



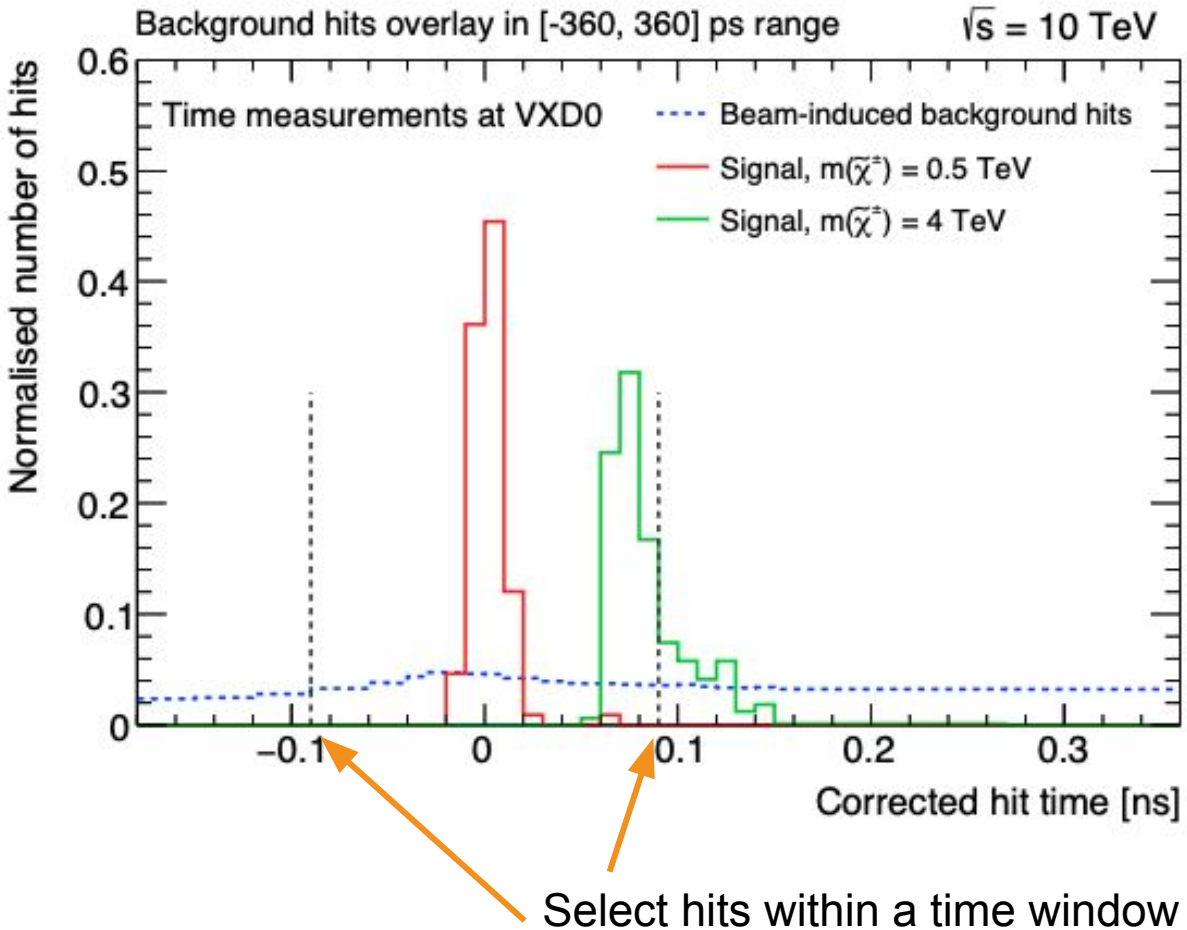
Need to take the potential acceptance losses in account from the beginning!

BIB rejection: timing

Exploit particle arrival times to reduce BIB

- Correct for time of flight (assuming β=1)

$$\text{Corrected time} = t_{measured} - \frac{|r|}{c}$$



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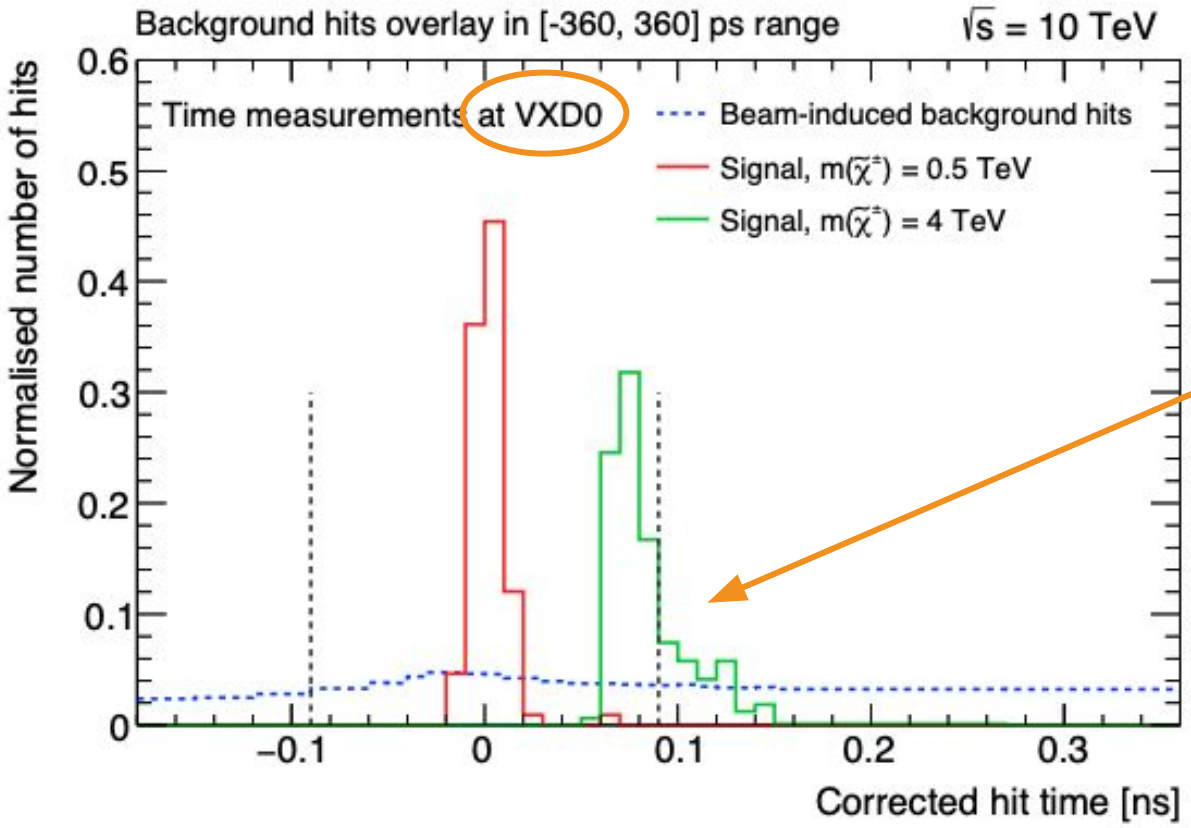
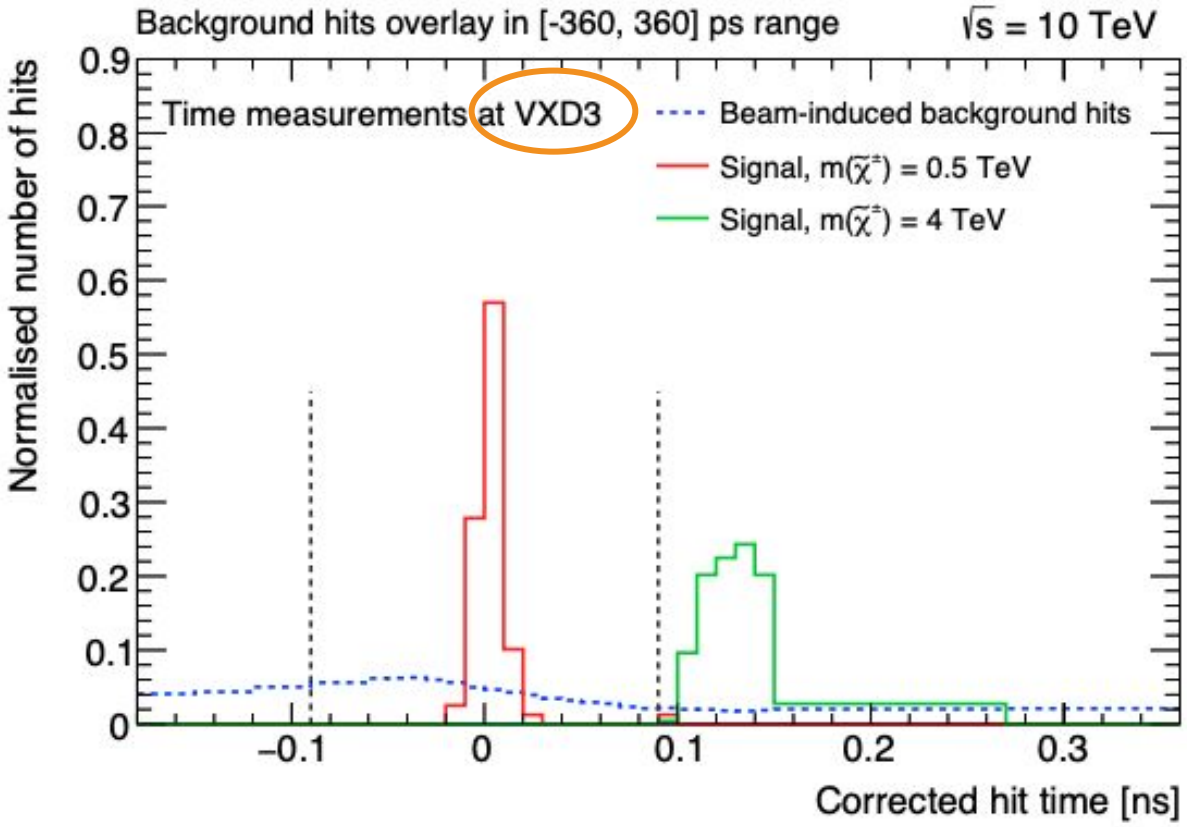


Low(er) β particles can suffer from inefficiencies

BIB rejection: timing

Moving to a different layer at larger radius (VXD3, r ~ 5 cm)

- Slow particles are already completely lost!



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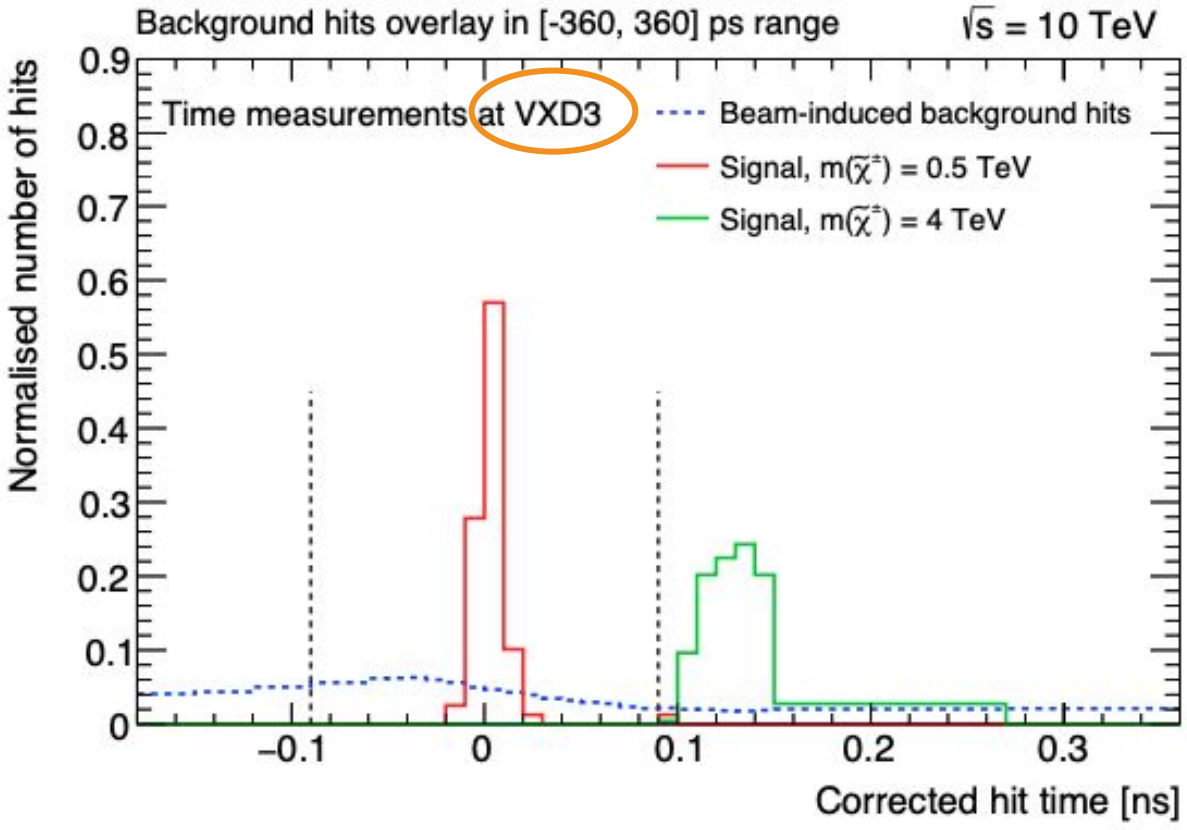
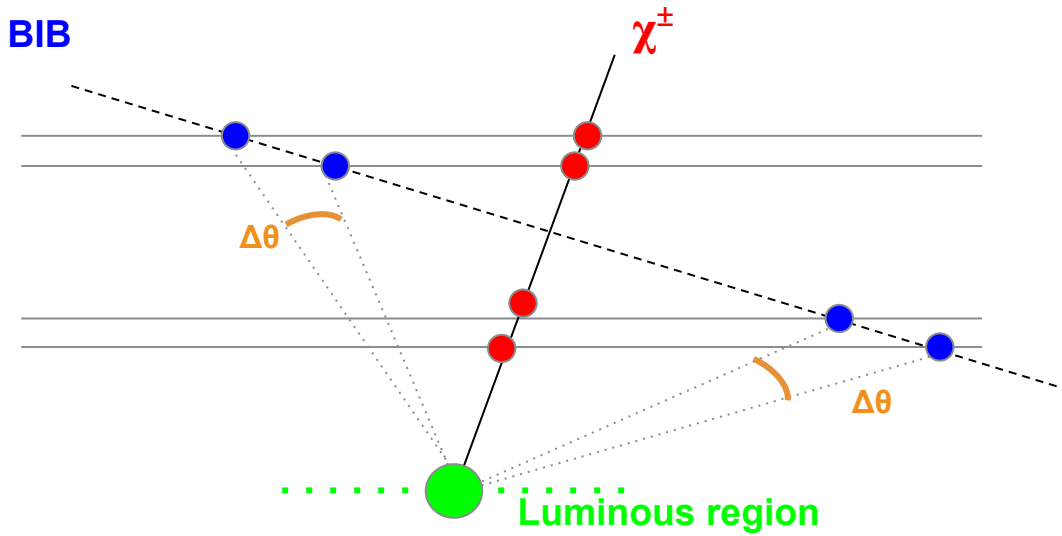


Requires as large as possible acceptance and dedicated reconstruction

BIB rejection: stub tracks

The double-layer layout of the vertex detector can be exploited to reject hits from BIB particles.

- Look for pairs of hits in neighbouring double-layers forming “stub tracks” that point back to the luminous region.



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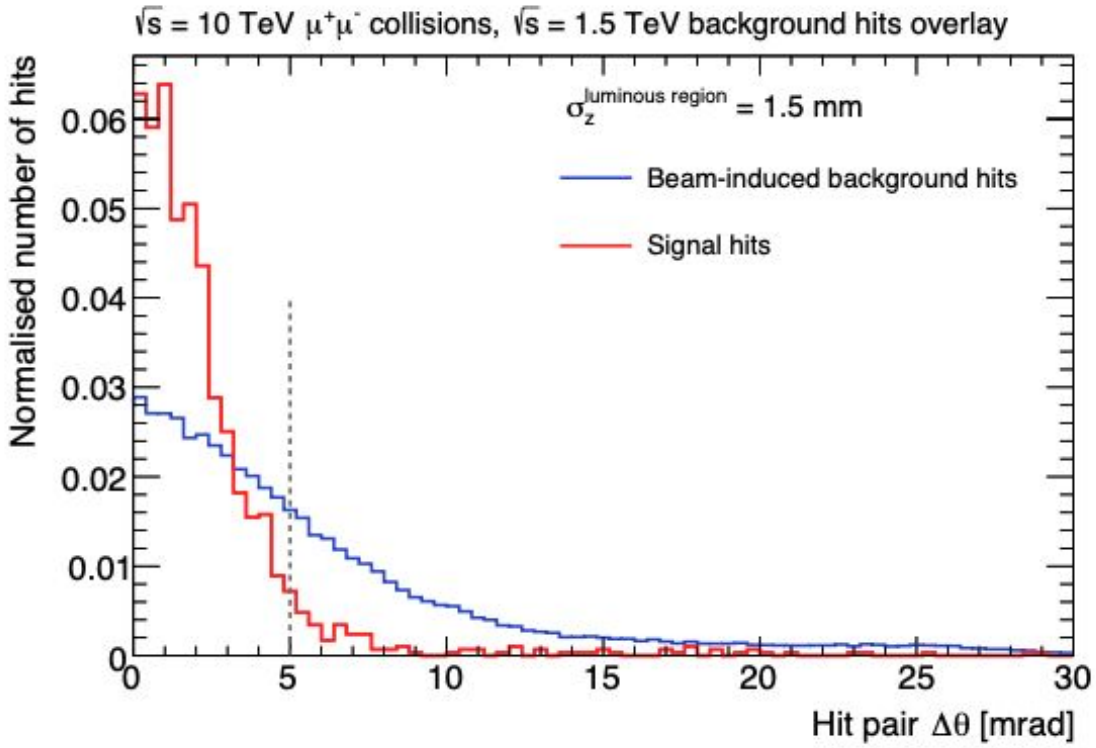

BIB rejection: what about displaced decays?

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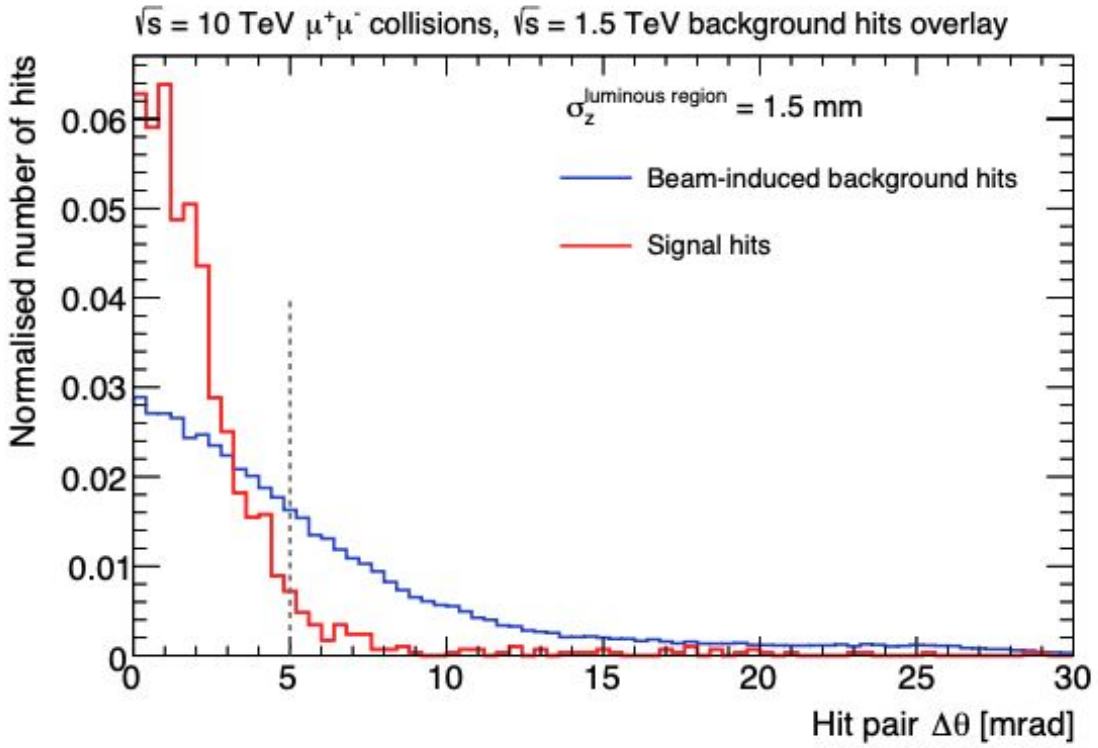
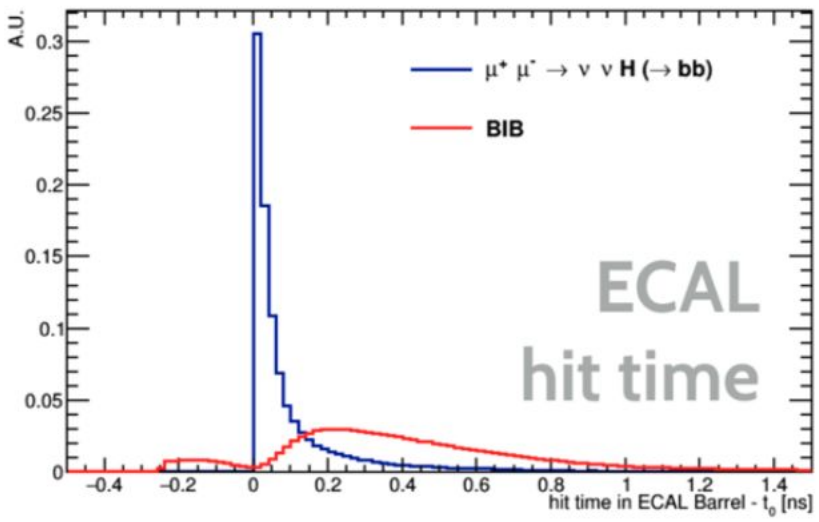


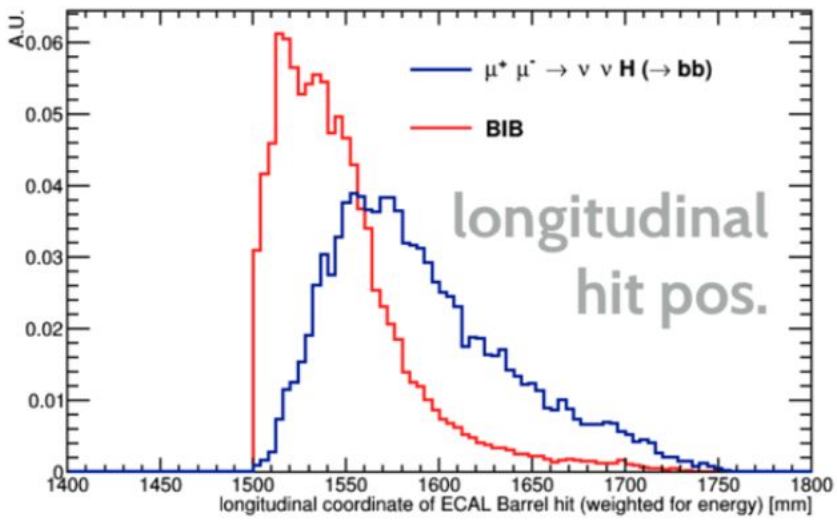
Need to be careful with secondary particles in displaced decays.

They may not point back to the IP!

- Studies underway!

Calorimetry





Various approaches under investigation to mitigate BIB contributions:

- Software BIB subtraction (as discussed in Simone's talk)
- Calorimeter pre-shower to absorb (part of) the BIB

Timing and shower shapes can help with BIB suppression.

No dedicated studies looking at the effect of such selections on LLP searches **yet!**

- Reconstruction generally foreseen to use particle-flow. Need to have "calorimeter only" jet reconstruction for LLP decays!

DAQ considerations

Designing an LLP-friendly data flow

Considering large bunch crossing intervals at the muon collider (~10-20 μs), it is probably best to consider a triggerless (streaming) DAQ system.

- Best scenario for LLPs and unconventional signatures - **data not selected by the trigger is lost forever**
- Higher “quality” decisions (more information)
- Simpler detector front-end electronics (e.g. buffers)
- Software event selection more flexible and maintainable

Can we get all the data out of the detector?

- Preliminary studies indicate that a **trigger-less readout should be possible** from the bandwidth perspective (**assuming a ~2ns window**)
- R&D is needed to advance technology by a factor of x2-3 in various places
- Deploy dedicated “out-of-time” sub-detectors or triggers to probe outside of the nominal readout window?

A case study (arXiv: 2102.11292)

Search for disappearing tracks

DESY 21-019
IFIC/21-03

Hunting wino and higgsino dark matter at the muon collider with disappearing tracks

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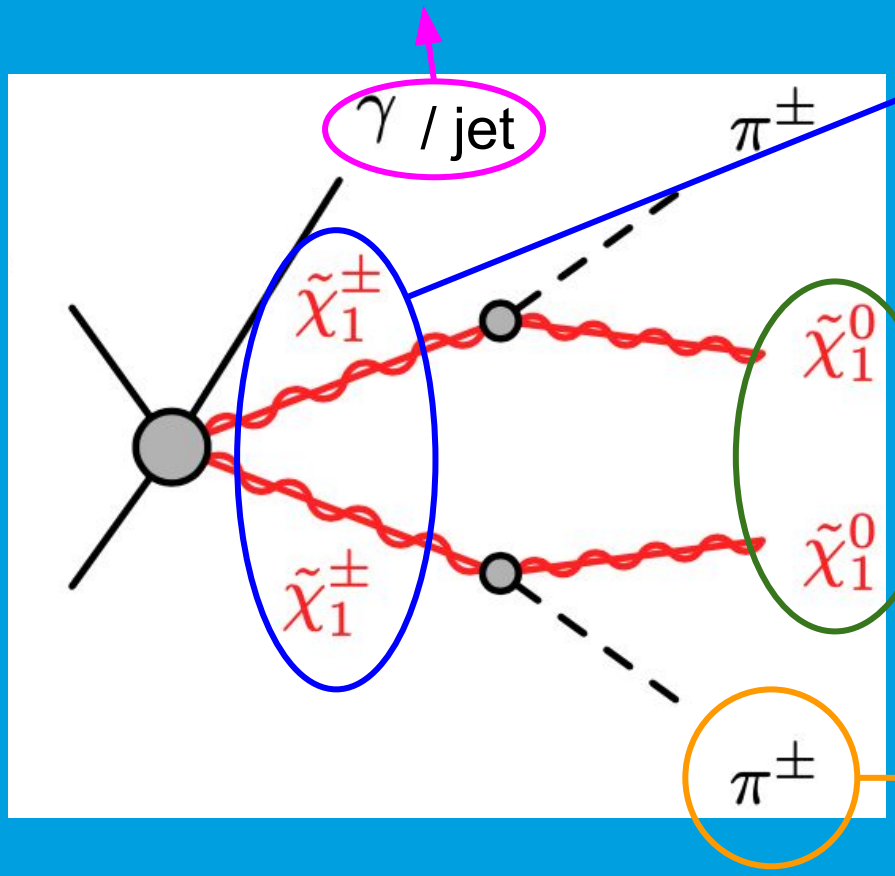
ISR/FSR:

- "Trigger" the event
- Momentum imbalance



Charginos:

- Long lived, charged
- Reconstructable as "tracklets"

Neutralinos:

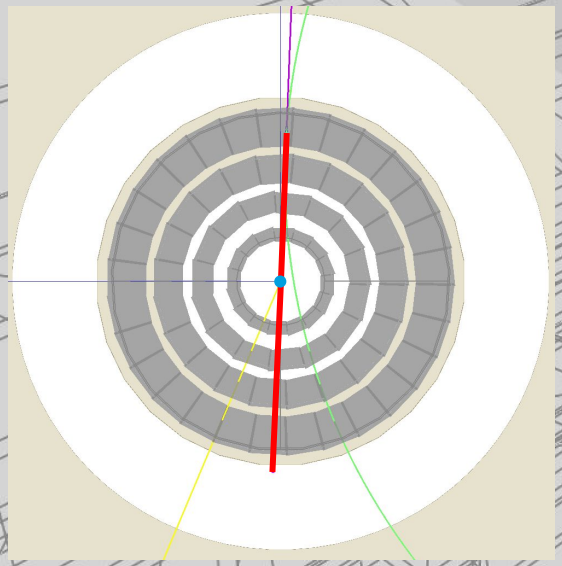
- Stable, neutral
- Invisible
- Momentum imbalance, missing mass

Displaced pions:

- Possibly reconstructable
- Not considered here

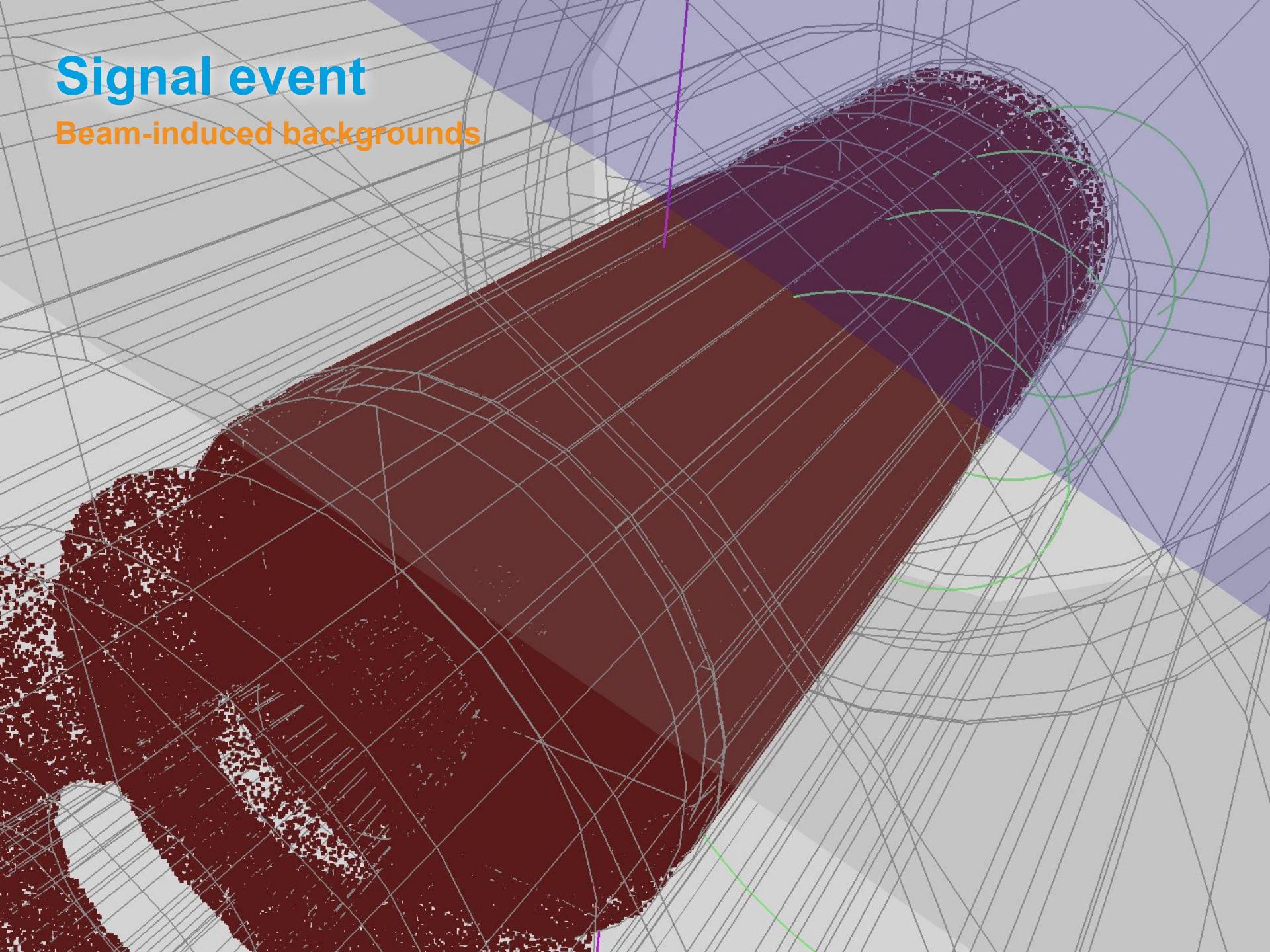
Signal event

No beam-induced backgrounds



Signal event

Beam-induced backgrounds



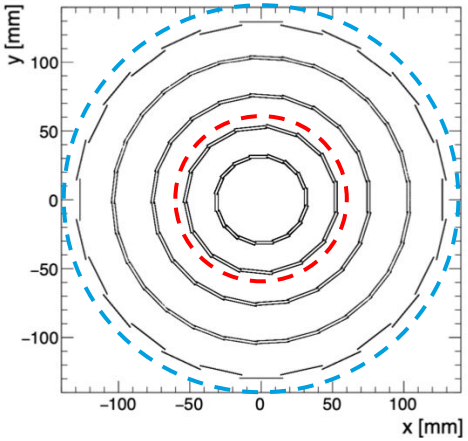
Tracklet reconstruction efficiencies

After BIB rejection cuts

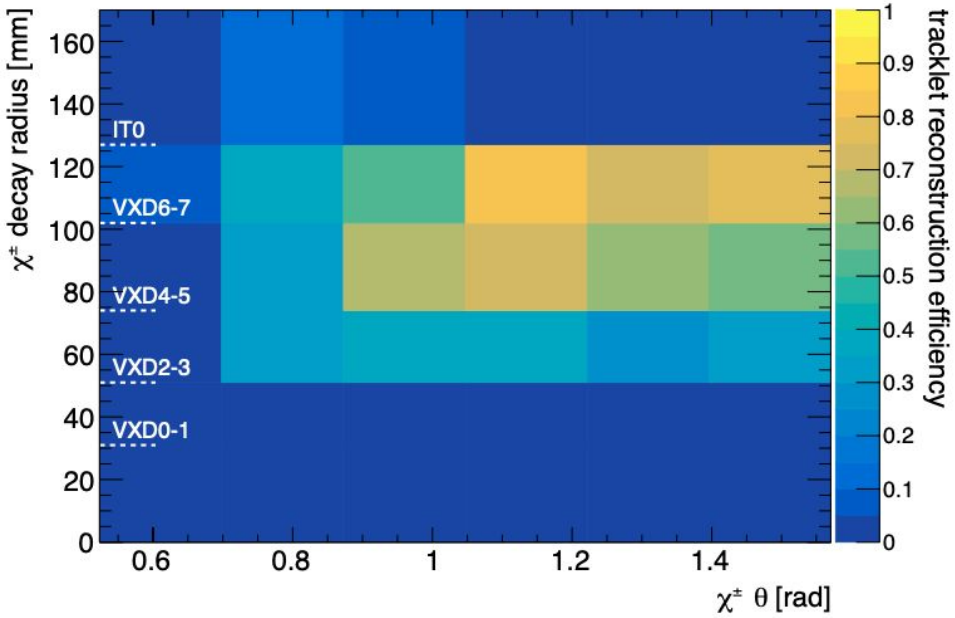
Impose a “disappearing condition” (hit veto)
at the first layer of the IT (12.7 cm)

Efficiencies evaluated with truth matching to $\chi^{\pm}$

- Evaluated vs the $\chi^{\pm}$ decay radius and polar angle θ



Min. requirement
Veto



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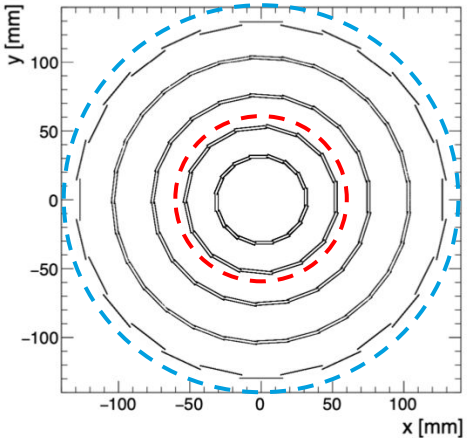
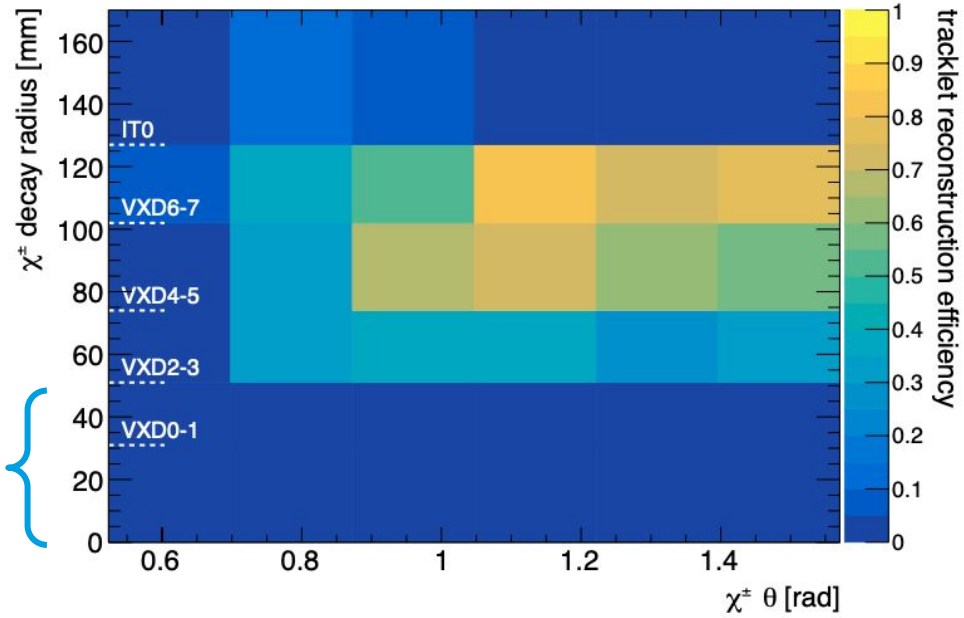


Min. requirement
Veto

Not enough hits



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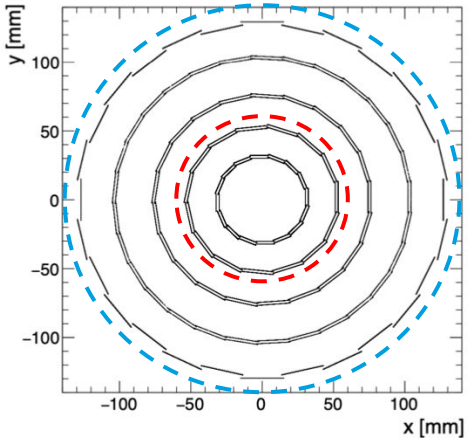
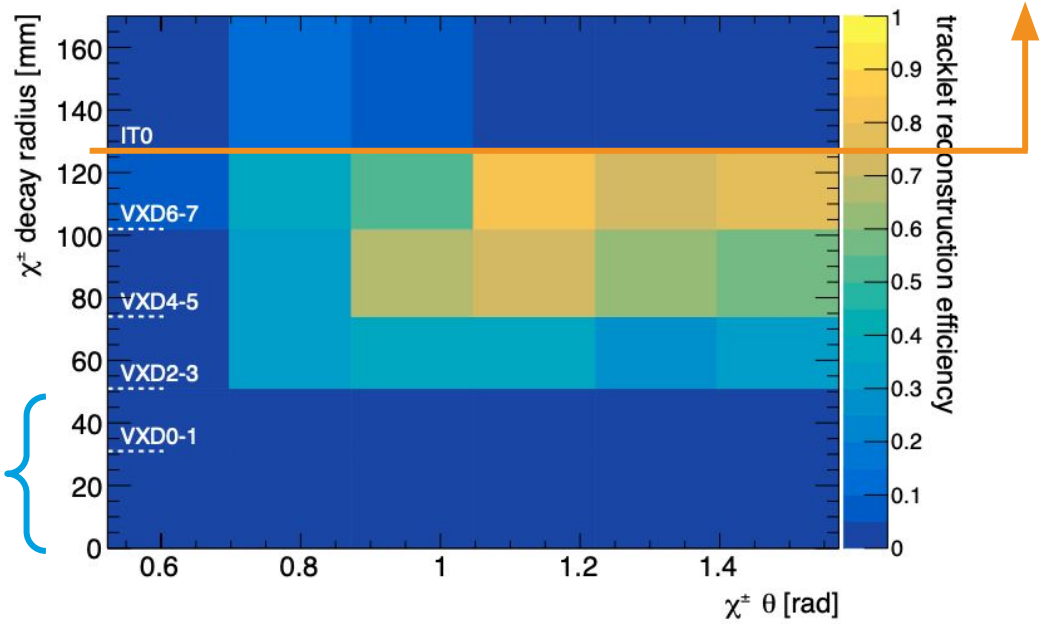


Min. requirement
Veto

Veto from disappearing condition

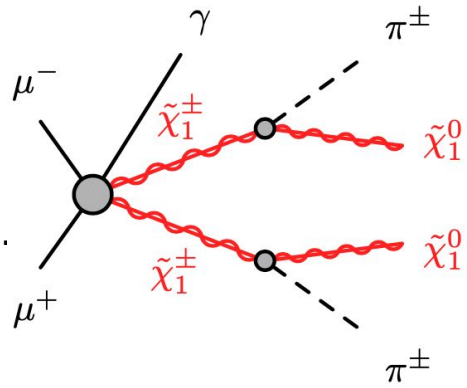


Not enough hits

Event selection

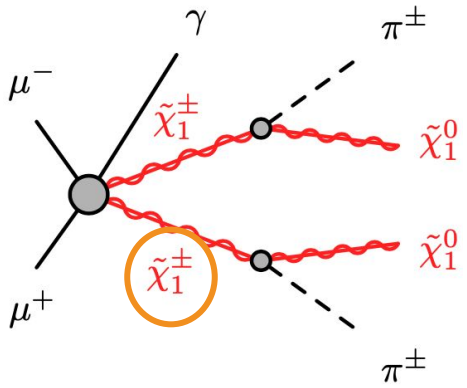
Perform analysis on **smeared truth-level events** using the efficiency parameterisation from full simulation.

- Two regions, based on tracklet multiplicity



Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

Event selection



Relatively simple event selection:

- Tracklet p_T (single most important quantity)

Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
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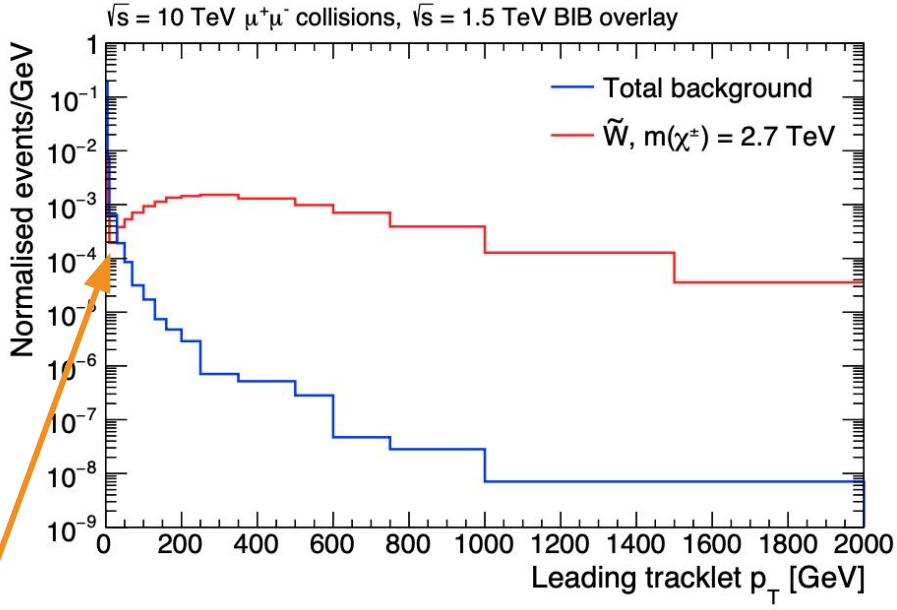
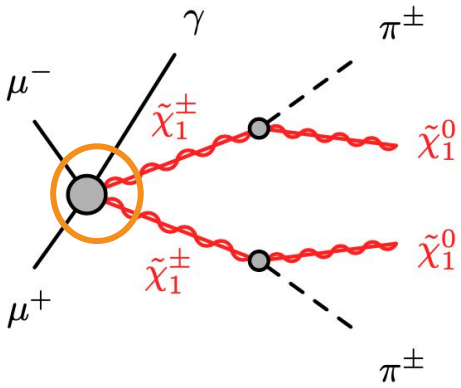


Peak at low p_T in signal events due to BIB overlay

Event selection



Relatively simple event selection:

- The $\chi^{\pm}\chi^{\mp}$ come from the same vertex

Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
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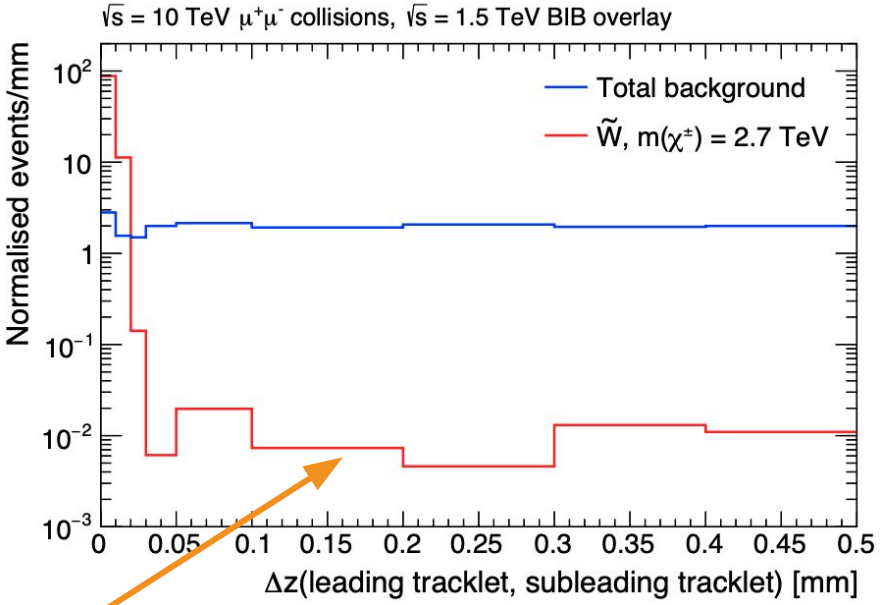
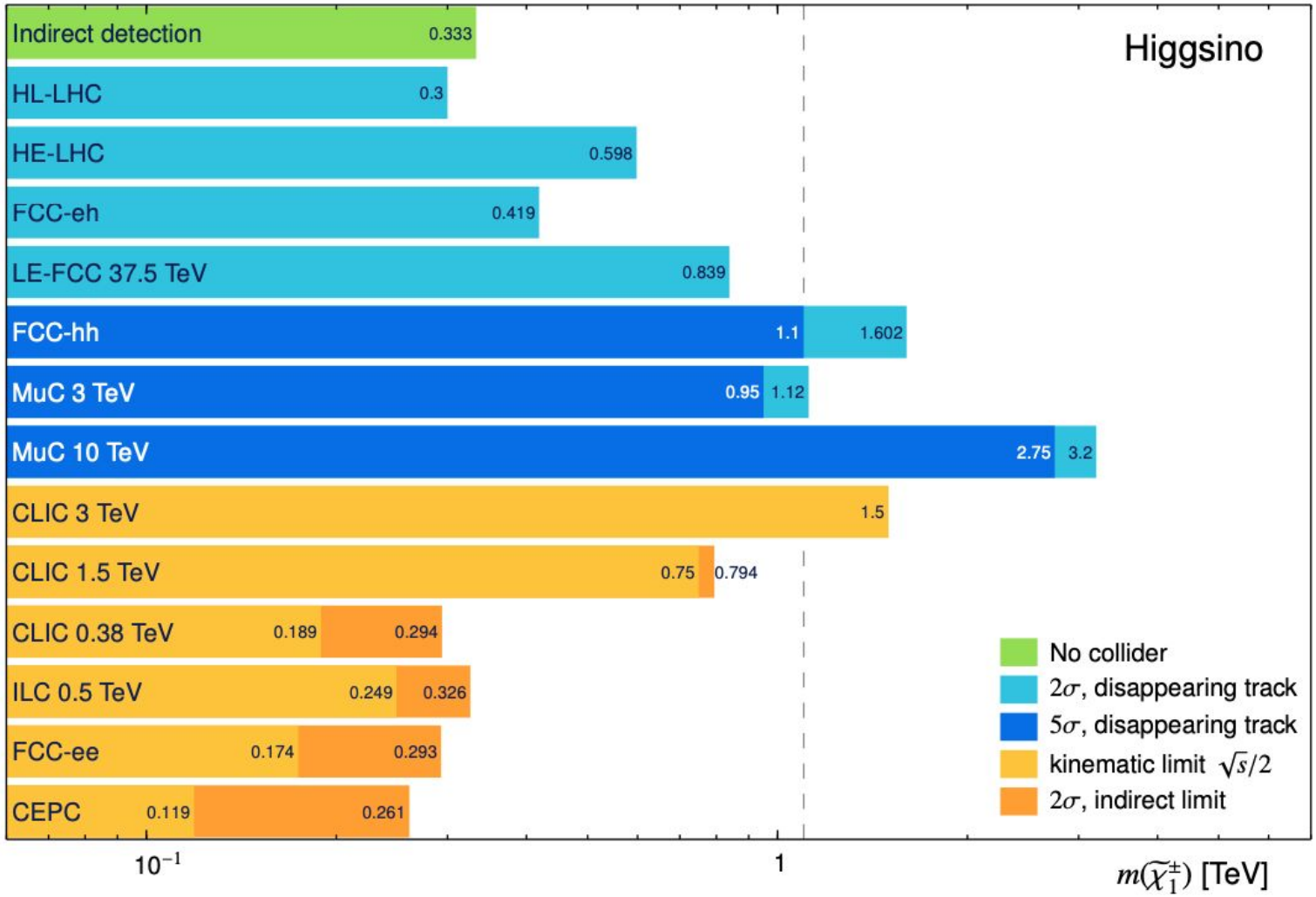


Long tails from events with at least one fake tracklet

Expected sensitivity

Pure-higgsino scenario in MSSM

Other lines taken from arXiv: 1910.11775
arXiv: 1901.02987



Summary

A future high-energy muon collider could rival other future machines such as the FCC-hh in the search for long-lived particles.

The unique environment of the muon collider requires dedicated techniques to mitigate the effect of the BIB.

- I have presented some mitigation strategies and discussed the impact they could have on LLP searches.
- We are aiming for an LLP-conscious detector design.

Many other studies needed or underway to fully characterise the LLP physics potential of a future muon collider facility.

- Your ideas are welcome!
- Join the discussion at next week's Physics and Detector workshop!

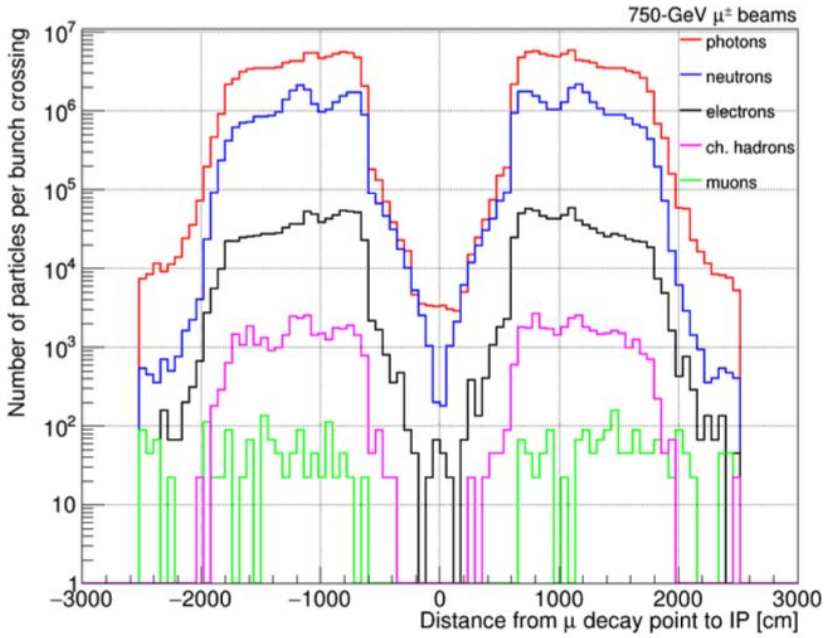
Thank you!

The beam-induced backgrounds (BIB)

arXiv: 1204.6721
arXiv: 1905.03725
arXiv: 2105.09116

The muon decay products interact with machine elements and cause a continuous flux of secondary and tertiary particles that reach the detector.

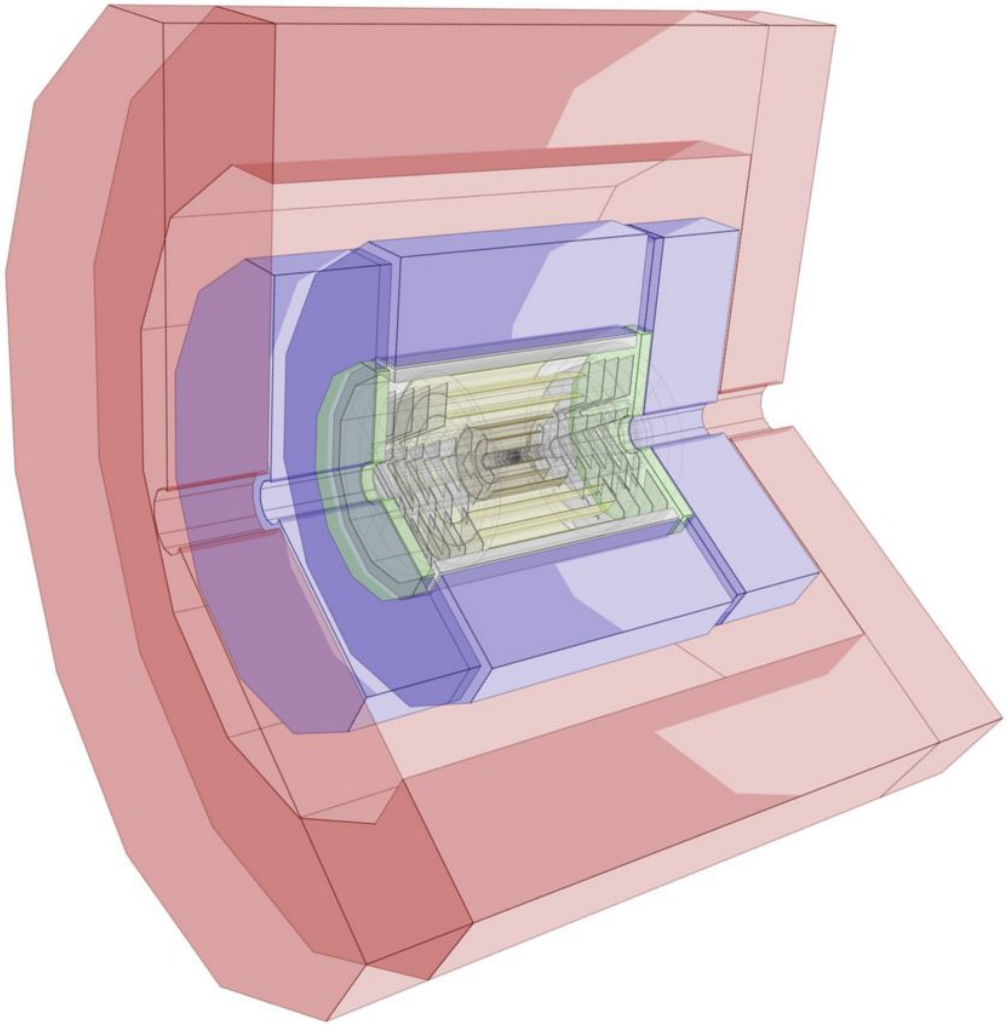
- The BIB depend on √s, the machine optics and lattice elements
- General characteristics: **low energy hits, broad arrival time**



Simulation available only for √s = 1.5 TeV (used as ~pessimistic baseline)

- The large multiplicity of hits makes tracking extremely challenging

Detector layout



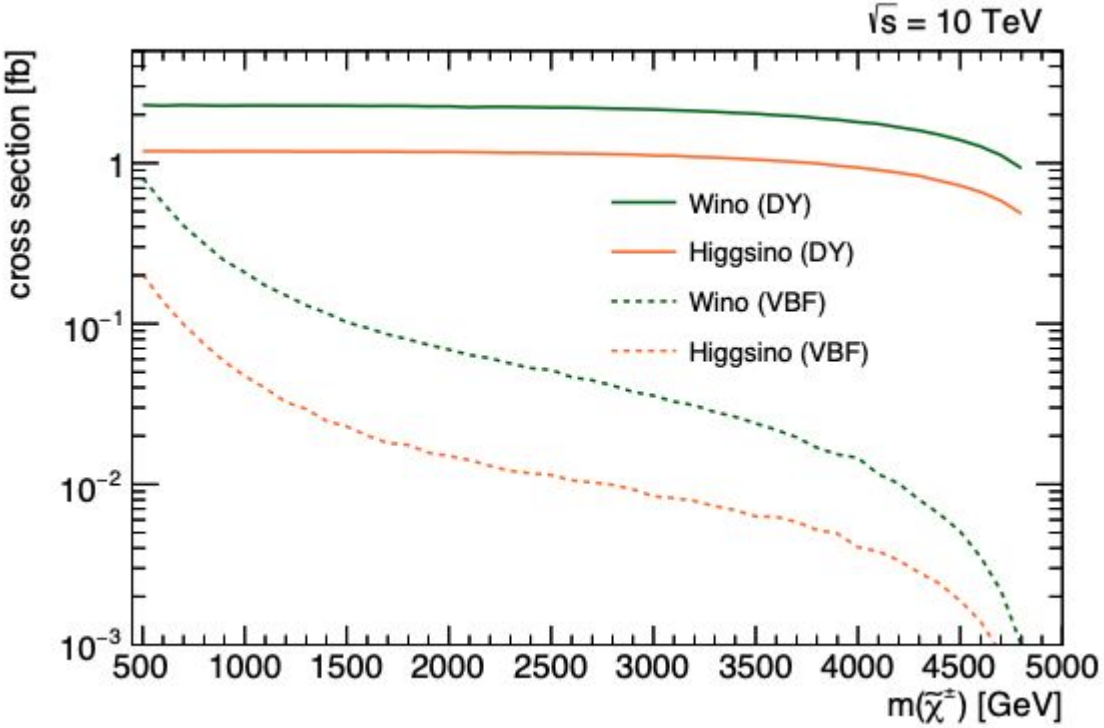
The detector model is based on the SiD ILC concept.

- All-silicon tracker
- Calorimeter systems
- 3.57 T Solenoidal magnet (not shown)
- Magnet yoke instrumented with muon chambers (RPC)

Expected production rates

At the MuC 10

Cross-section predictions from MadGraph5_aMC@NLO 2.8.2



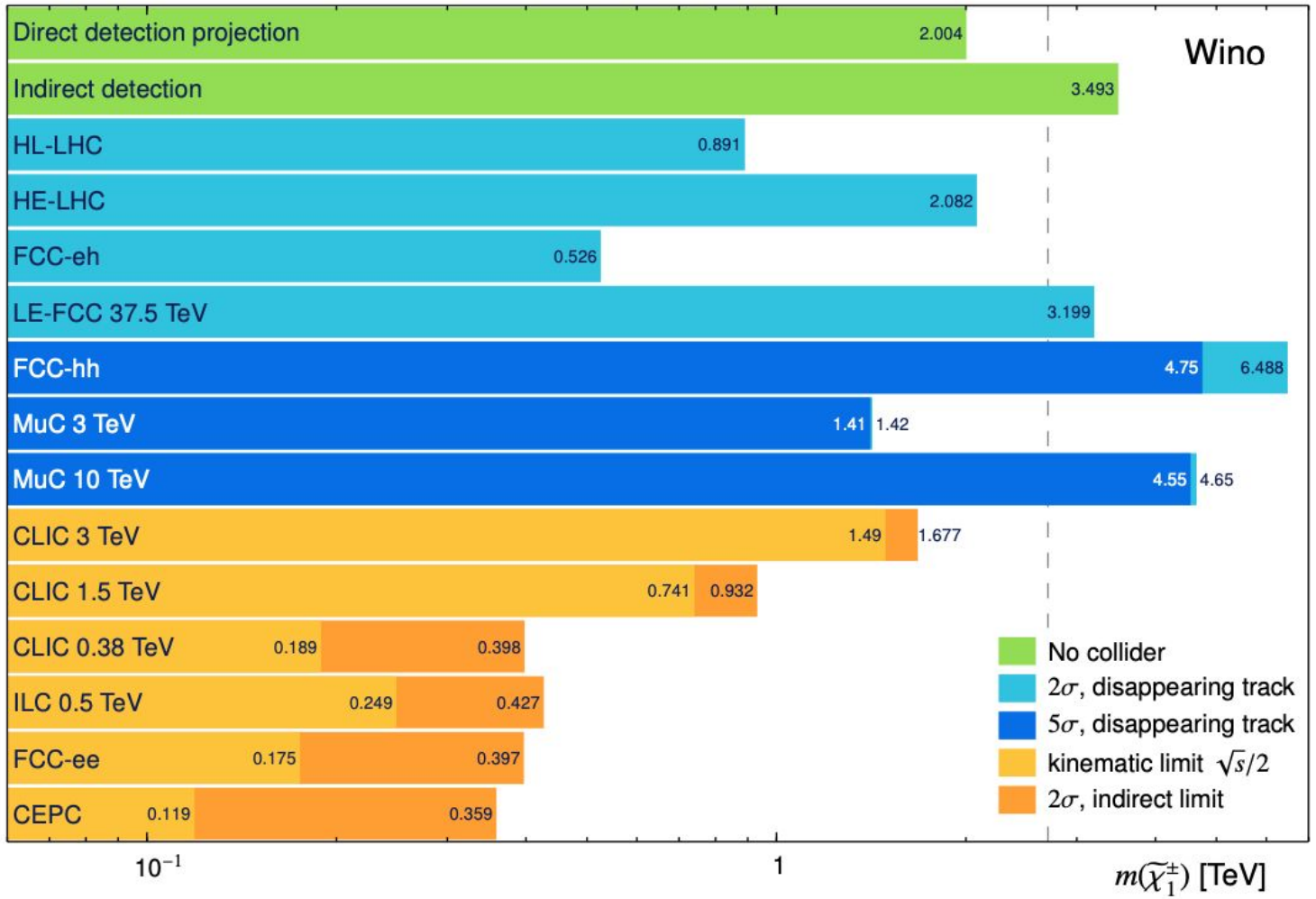
Expect to produce about 10000 $\chi^{\pm}\chi^{\mp}$ in 10 ab^{-1}

- Similar expectation for MuC 3 (1/10 int. luminosity but x10 cross-section)
- s-channel 2→2 “Drell-Yan” dominant in the range of masses considered
- Photon-initiated production possible (arXiv: 2009.11287) but sub-dominant

Comparison with other facilities

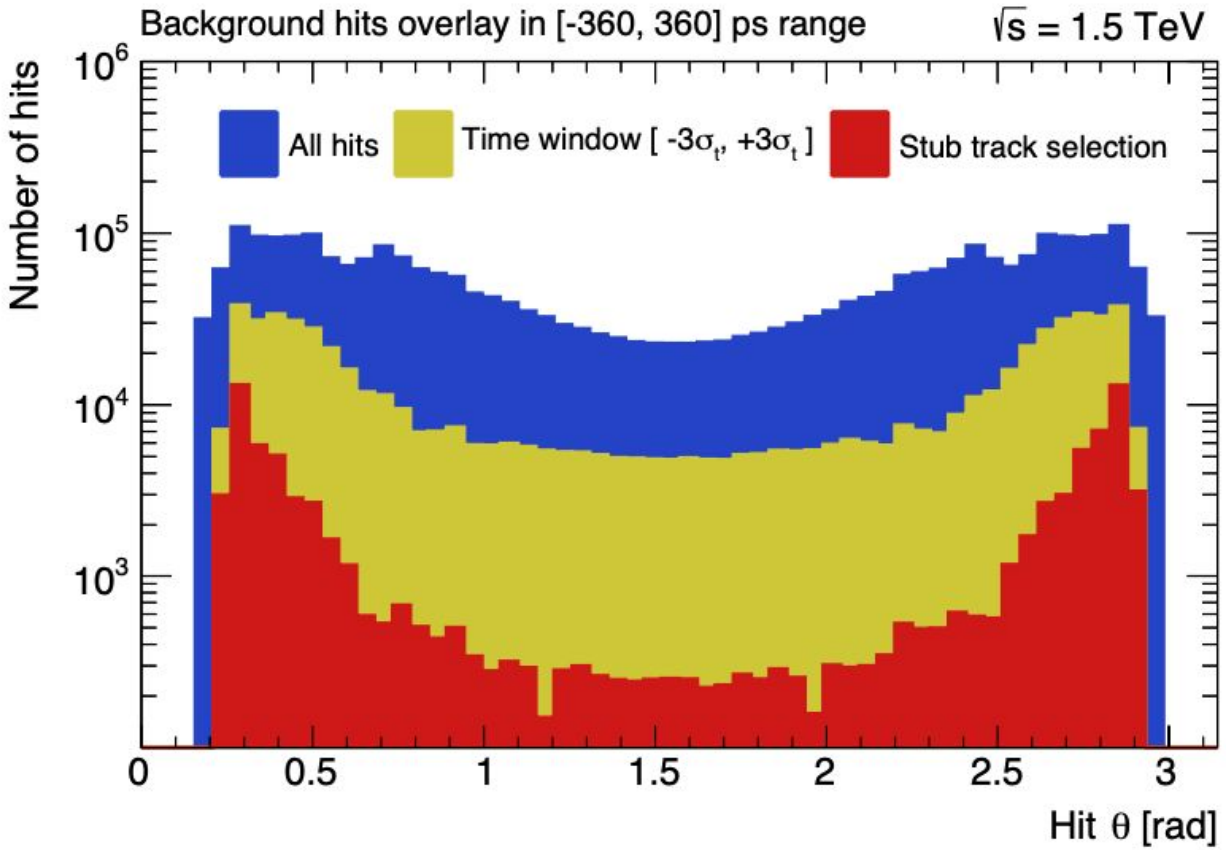
Wino scenario

Other lines taken from arXiv: 1910.11775
arXiv: 1901.02987



BIB rejection

Angular summary



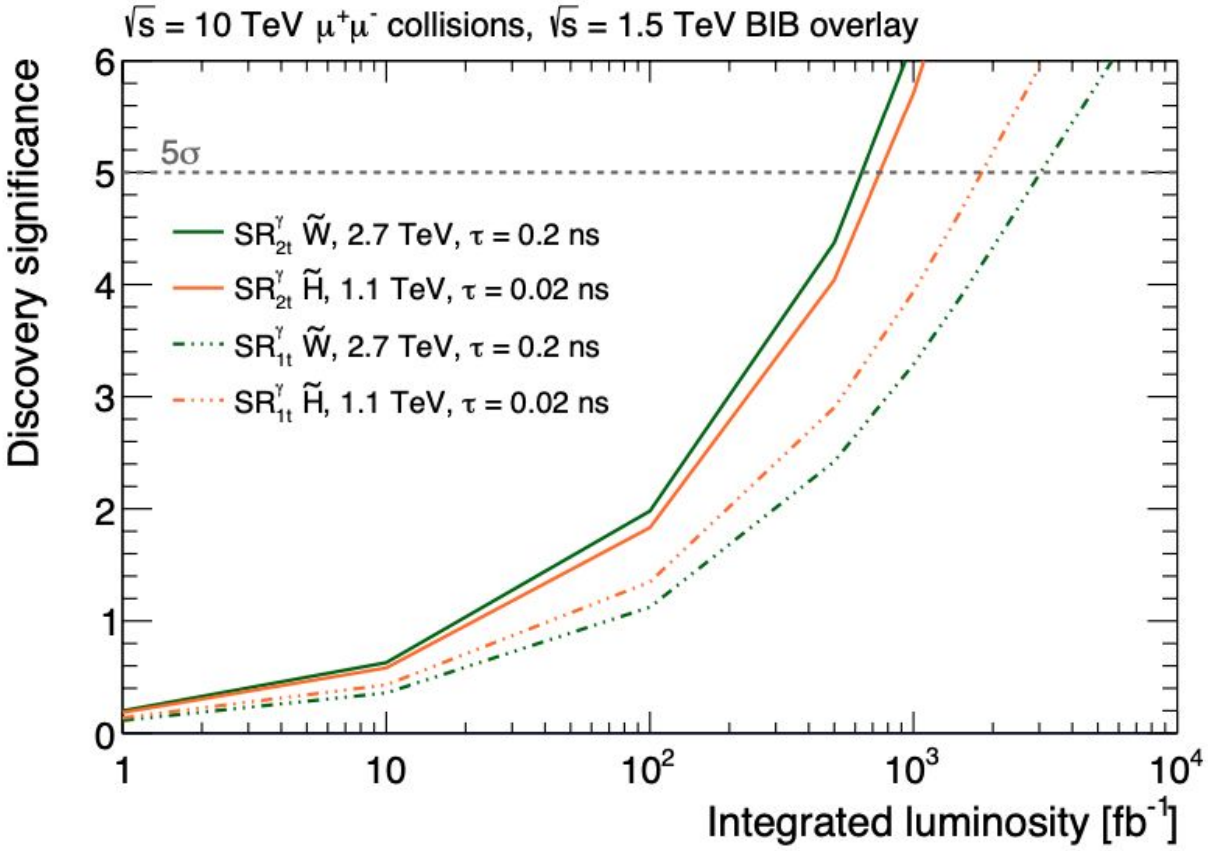
Selections most effective in the central region, which is favoured by signal.

Towards quantifying the sensitivity

- Perform analysis on **smeared truth-level events**
  - Use Delphes card (v0) by M.Selvaggi for high-level reconstructed objects
  - Use tracklet reconstruction our response functions from full simulation
  - Overlay BIB tracklet background from full simulation

- Focus on fake tracklets and assume that hadron and lepton tracks lost to multiple scattering can be made negligible (as in LHC searches)
  - $\sigma(\mu^+\mu^- \rightarrow \nu\nu)$ **~ 60000 fb** (dominated by t-channel W exchange)
  - $\sigma(\mu^+\mu^- \rightarrow \chi^{\pm}\chi^{\mp})$ **~ 1-2 fb**

Integrated luminosity needs

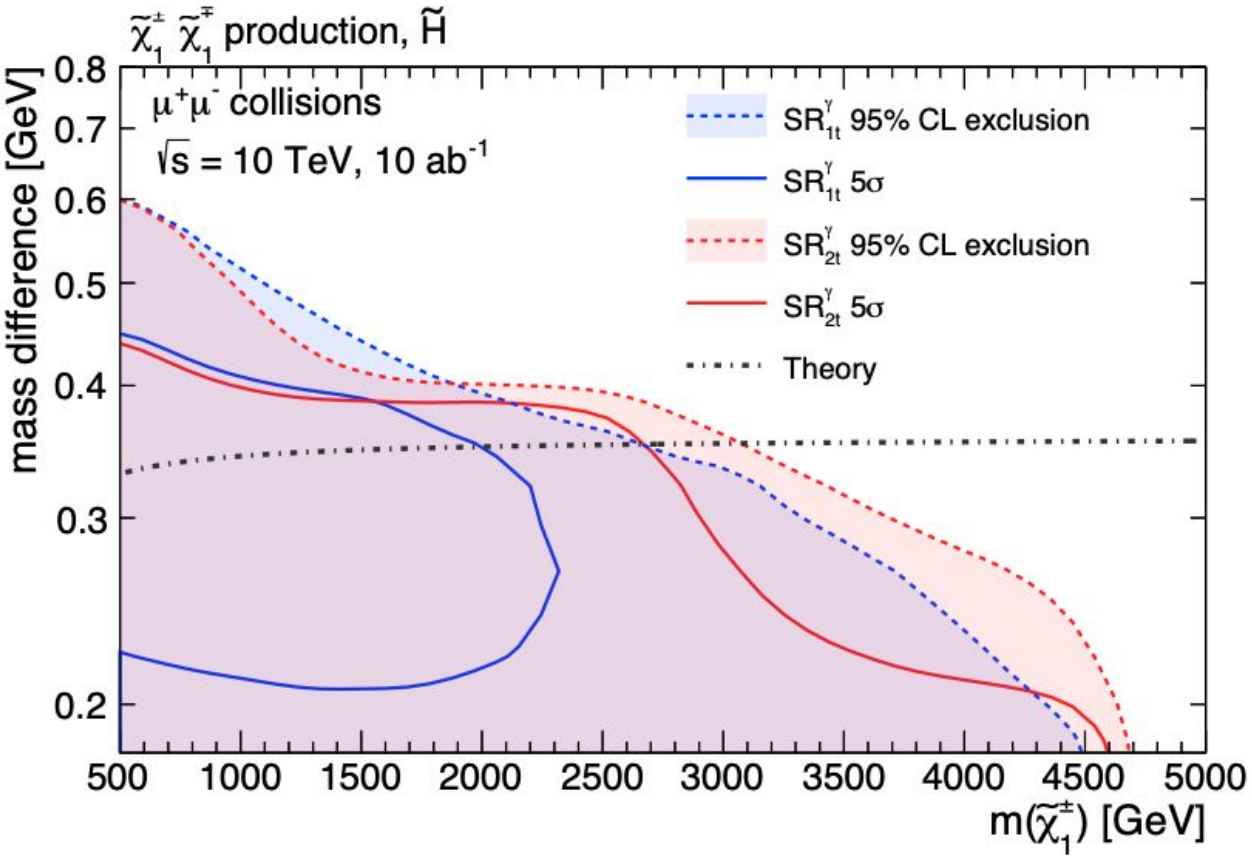


Considering here the targets that would fulfil the dark matter relic density.

- A discovery would be possible with just 0.8 ab^{-1} (~1/10 of target)

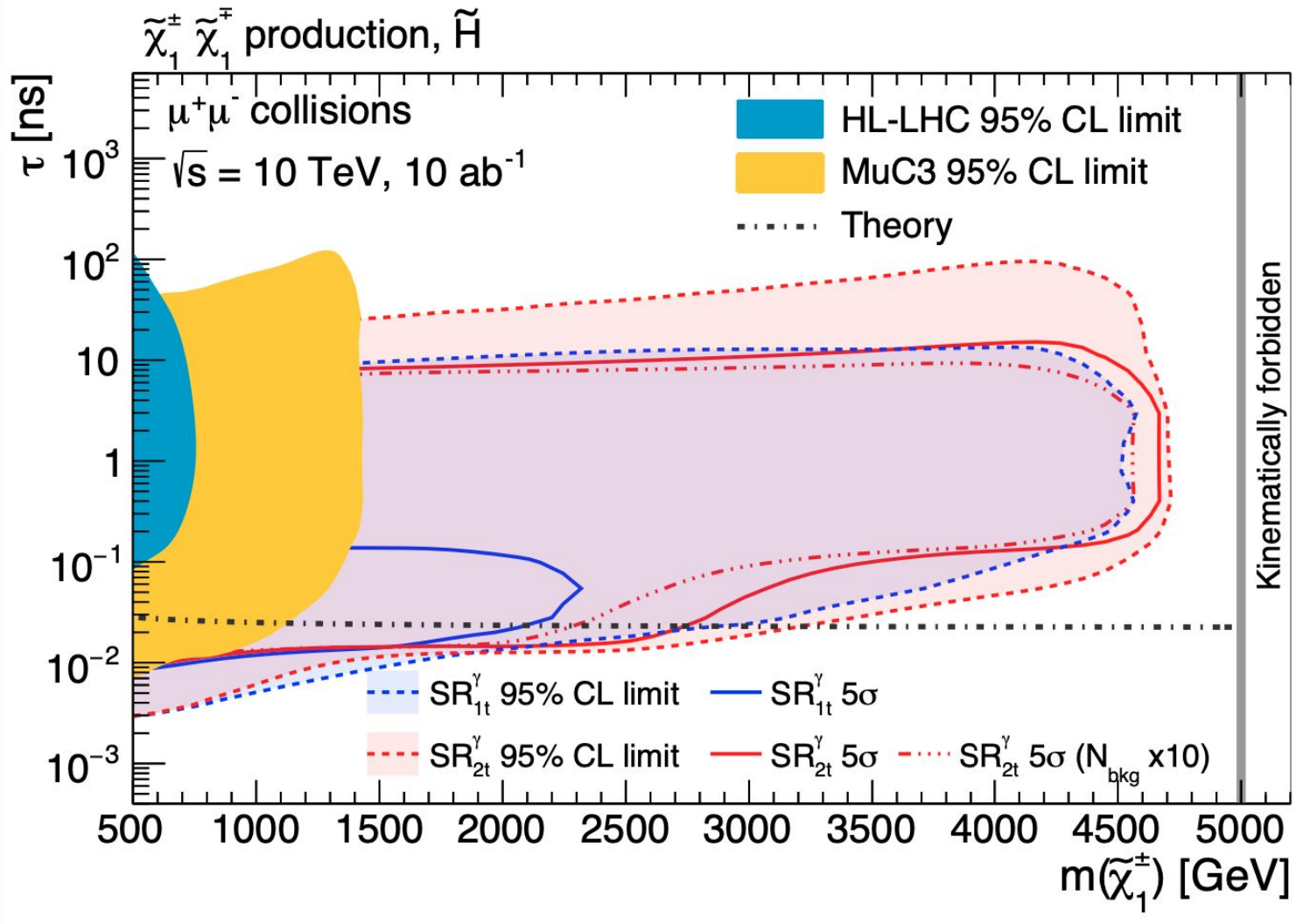
Expected sensitivity

Mass vs mass difference in higgsino scenarios



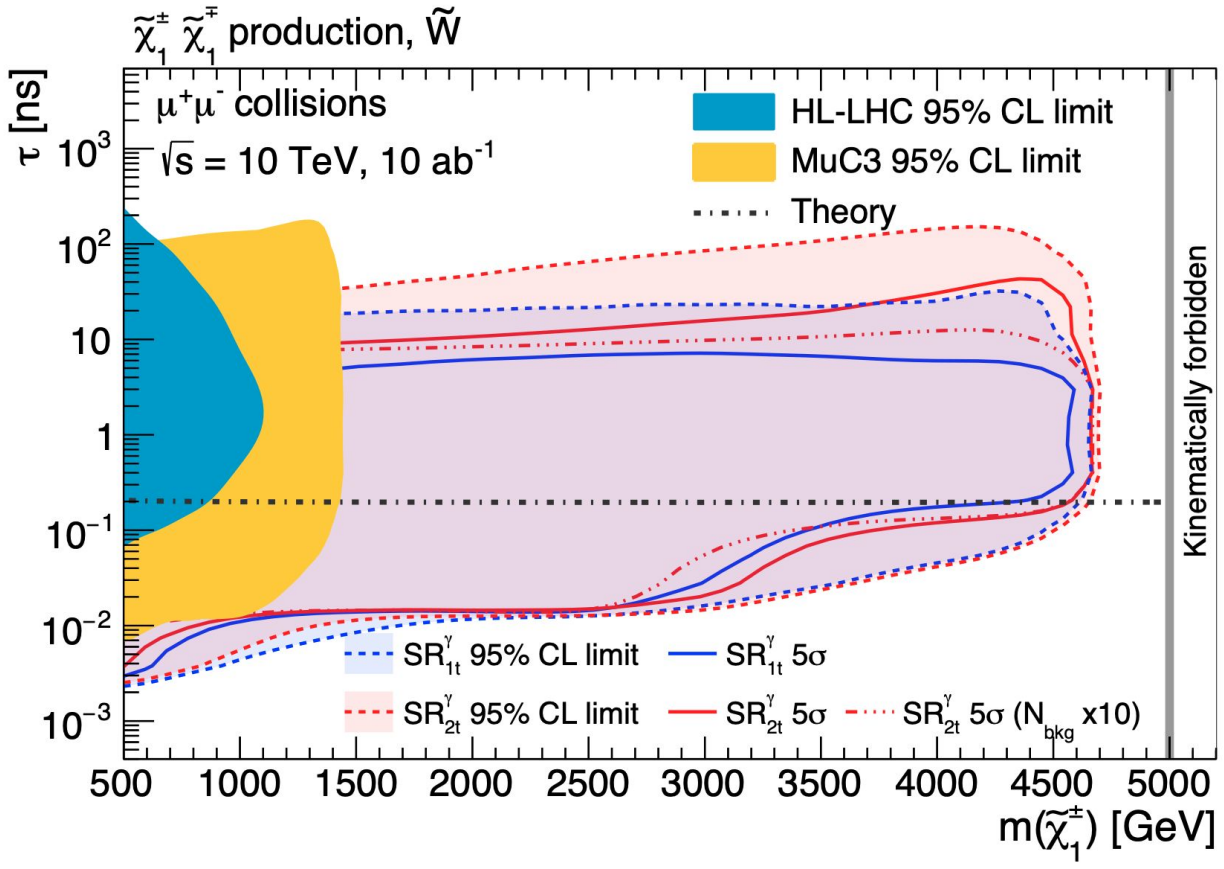
Expected sensitivity

Pure higgsino models at Muc 10



Expected sensitivity

Pure wino models at MuC 10

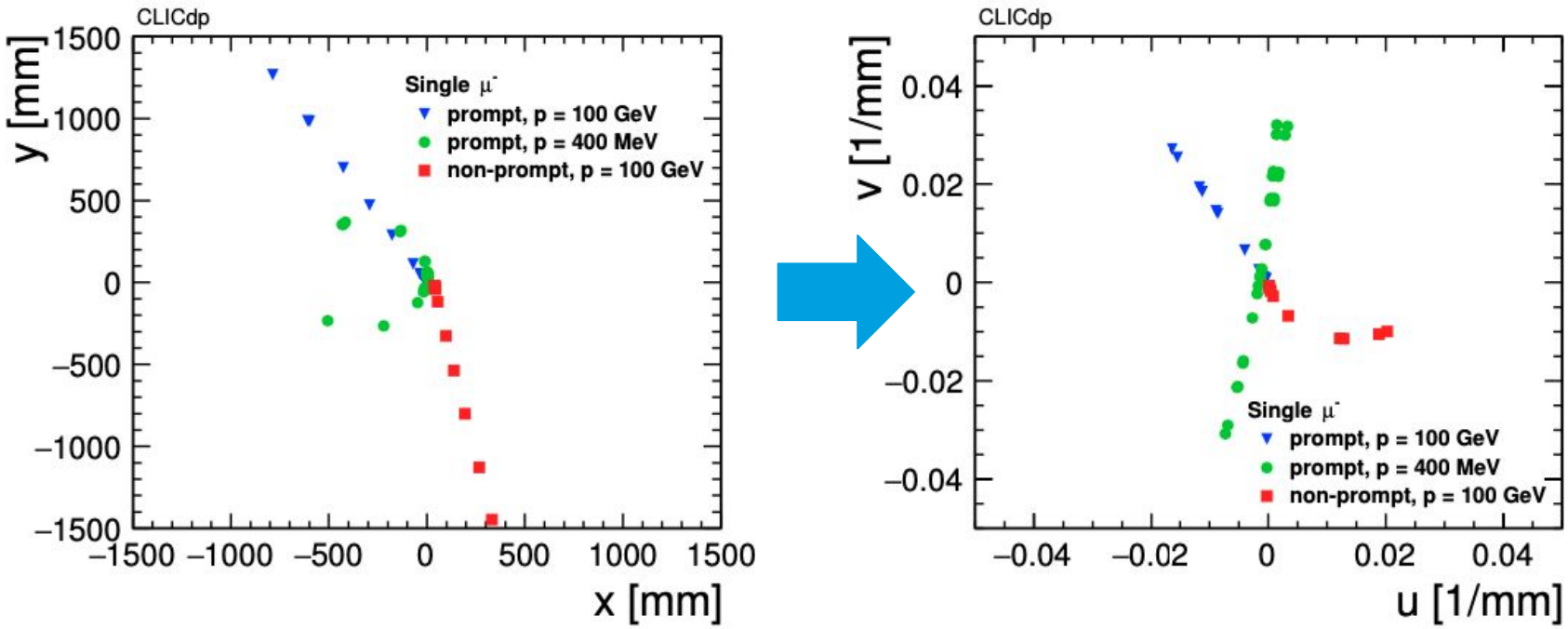


Track reconstruction

Use conformal tracking algorithm (developed for CLIC, arXiv: 1908.00256):

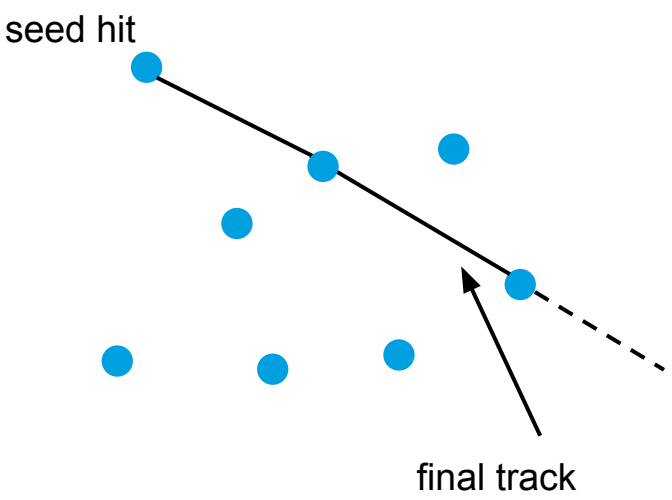
1. Conformal mapping

$$u = \frac{x}{x^2 + y^2} \qquad v = \frac{y}{x^2 + y^2}$$



Track reconstruction

2. Cellular automaton-based track finding



- Consider only a **subset of the hits**
- Each hit is used as seed to **look for neighbours**, with cuts on angles and distances
- **Seed cells** are created and the search for neighbours is repeated
- **Cellular tracks** are groups of cells
- The **best tracks** (lowest χ^2/N.d.f.) are **kept**, the hits marked as used and the search repeated
- Seed tracks can be **extended** (e.g. with hits from another sub-detector)