Feebly interacting particles at the muon collider

Probing the lifetime frontier

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

The 28th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Feeble interactions via portals

Light degrees of freedom can be coupled to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor...).

- New particles feebly coupled to the SM via a portal term

FIPs= Feebly Interacting Particles

$$L = L_{SM} + L_{portal} + L_{NP}$$

Field	**Lagrangian**	**Phenomenology**
Scalar	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Exotic Higgs decays
Vector	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark photon / Z’
Fermion	$\mathcal{L}_N \supset y_{ai}(L_a H) N^i$	Heavy neutral leptons
Pseudoscalar	$\mathcal{L}_a \supset a\left(\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\widetilde{G}^{\mu\nu}}{4f_g}\right) + \frac{\partial^\mu a}{f_f}\bar{f}_i\gamma^\mu\gamma^5 f^i$	ALPs

Feeble interactions via portals

Light degrees of freedom can be coupled to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor...).

- New particles feebly coupled to the SM via a portal term

FIPs= Feebly Interacting Particles

$$L = L_{SM} + L_{portal} + L_{NP}$$

Field	Lagrangian	Phenomenology
Scalar	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Exotic Higgs decays
Vector	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark photon / Z’
Fermion	$\mathcal{L}_N \supset y_{ai} (L_a H) N^i$	Heavy neutral leptons
Pseudoscalar	$\mathcal{L}_a \supset a \left(\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\widetilde{G}^{\mu\nu}}{4f_g} \right) + \frac{\partial^\mu a}{f_f} \bar{f}_i \gamma^\mu \gamma^5 f^i$	ALPs

Small couplings lead to long lifetimes

Other long-lived mechanisms

Several other theoretical models predict additional long-lived particles (LLPs).

$$\Gamma \sim \varepsilon^2 (m/\Lambda)^{2n}\, \Phi$$

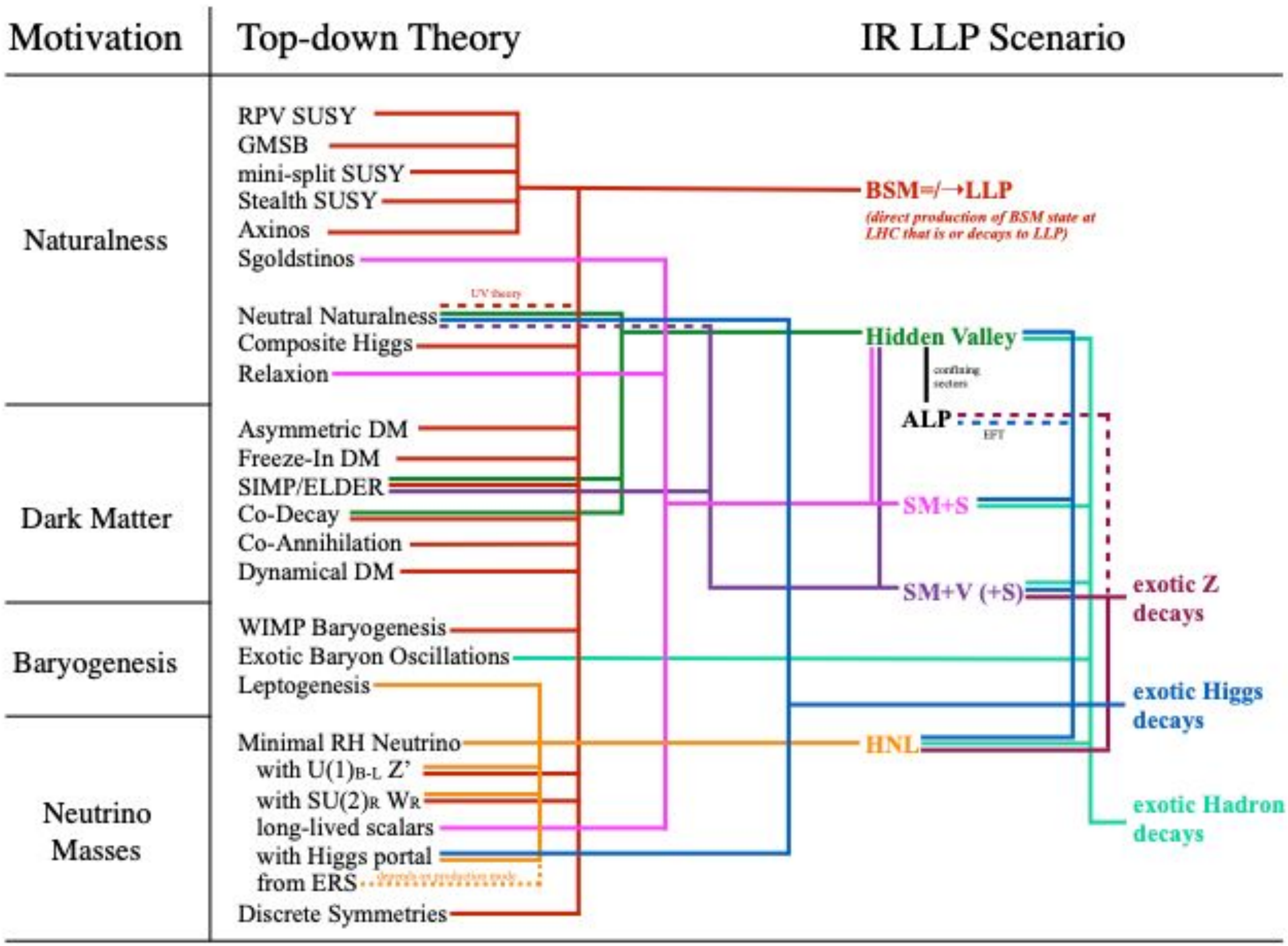
Small couplings

Phase space

Mass hierarchies
(suppressed loops)

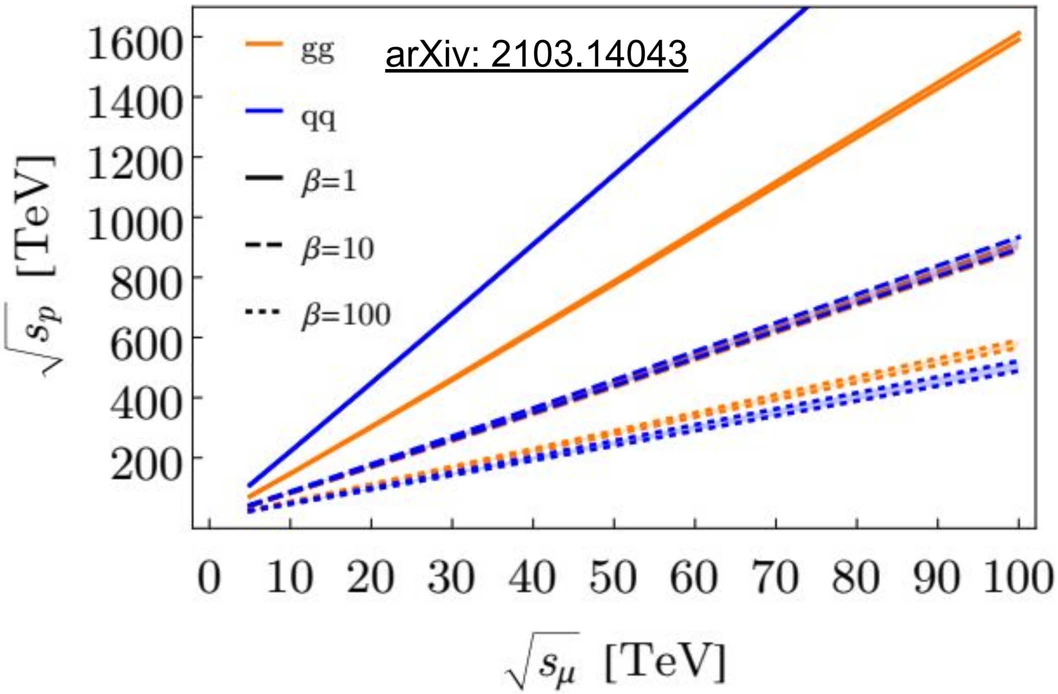
arXiv:1806.07396
arXiv:1812.02093

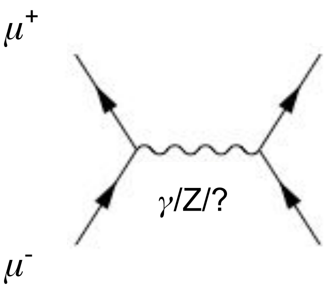
Our maps still hold at a muon collider

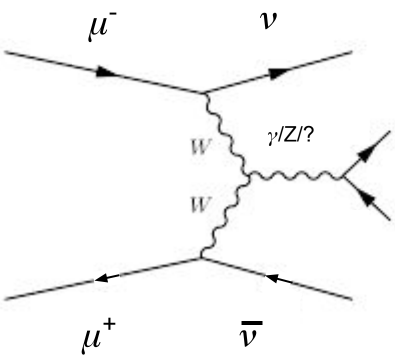


High energy muon collisions

$$\beta \equiv [\hat{\sigma}]_p / [\hat{\sigma}]_\mu$$







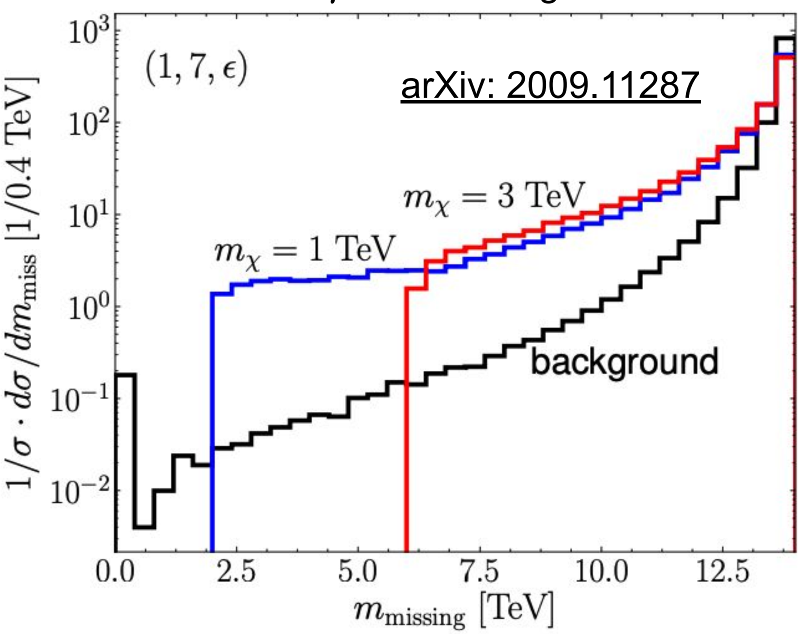
A √s ≥ 10 TeV MuC outperforms 100 TeV collider in almost every aspect.

- Electroweak states are even more competitive

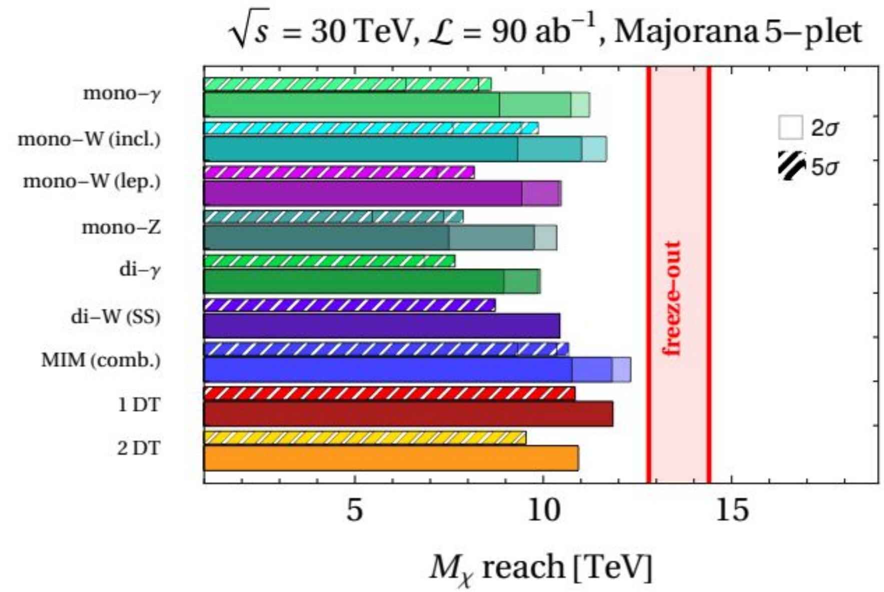
Missing mass searches

When BSM leaves no trace in the detector

Mono-γ with missing mass



arXiv: 2107.09688



Studied for WIMPs, but the general aspects of these searches are more general.

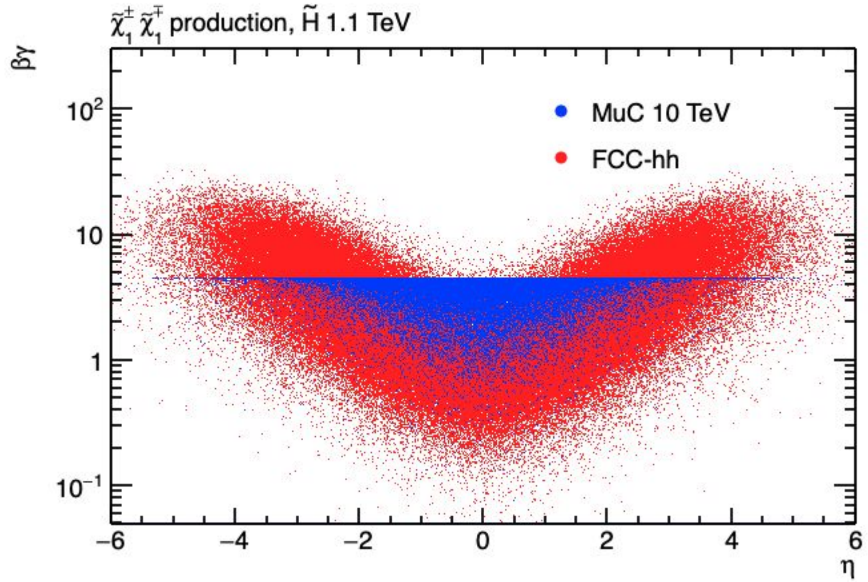
- Signal-to-background ratio is low
- Requires extreme control of systematic uncertainties
- Di-V channels minimise the impact of systematic uncertainties at the cost of statistics

Visible LLPs

When BSM can be observed directly or via its decay

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
- Possibly larger Lorentz boosts than at a hadron collider (probing similar mass scales)

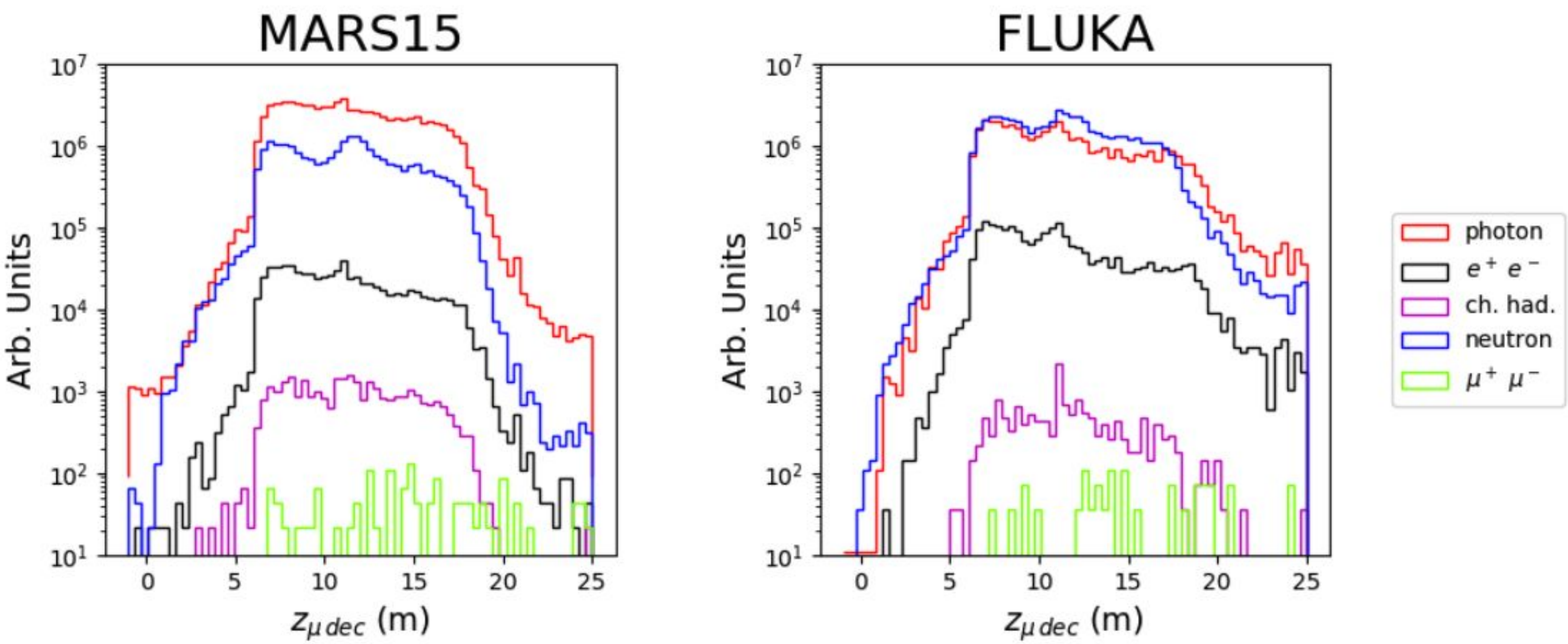
Unique mix of challenges and opportunities to do creative searches.

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 for √s = 1.5 TeV with two independent simulation setups.

- Higher √s will be explored soon

BIB characteristics

- General good agreement (within a factor of three) between MARS15 and FLUKA
- Most discrepancies are attributed to differences in the modelling of passive interaction region elements

Particle (E_{th}, MeV)	MARS15 25 m	FLUKA 25 m	FLUKA 250 m
Photon (0.2)	$8.3\ 10^7$	$4.3\ 10^7$	$5.1\ 10^7$
Neutron (0.1)	$2.4\ 10^7$	$5.4\ 10^7$	$5.9\ 10^7$
Electron/positron (0.2)	$7.2\ 10^5$	$2.2\ 10^6$	$2.3\ 10^6$
Ch. Hadron (1)	$3.1\ 10^4$	$1.5\ 10^4$	$2\ 10^4$
Muon (1)	$1.5\ 10^3$	$1.2\ 10^3$	$3.4\ 10^3$

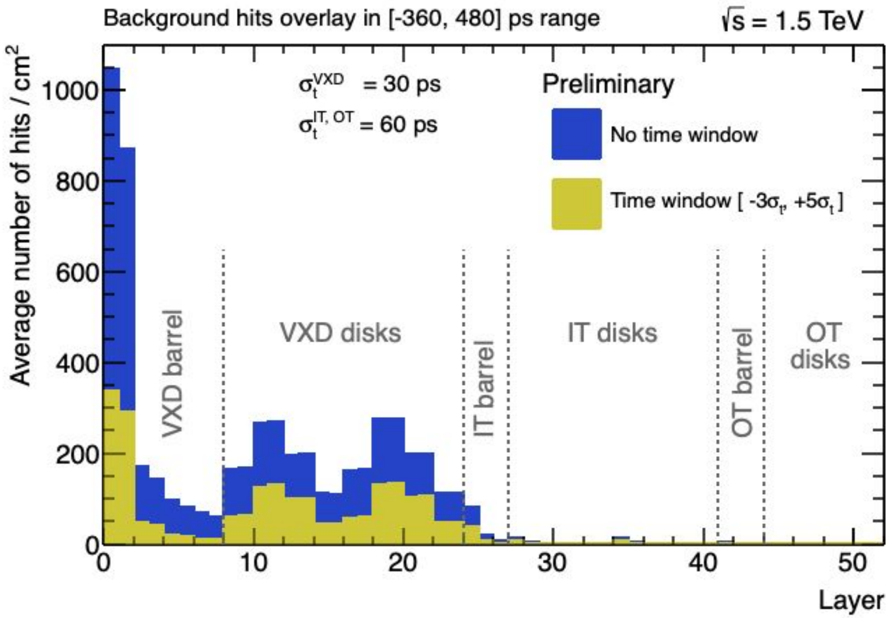
Tracking and trackers

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

- Extremely challenging track reconstruction

Need to filter hits:

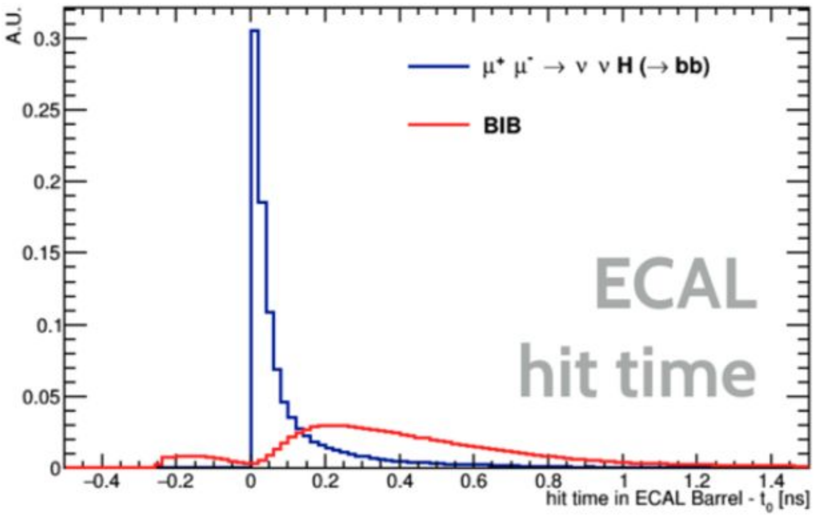
- Timing
- Correlation of hit pairs (either on- or off-detector)
- Cluster shapes
- Energy loss in silicon

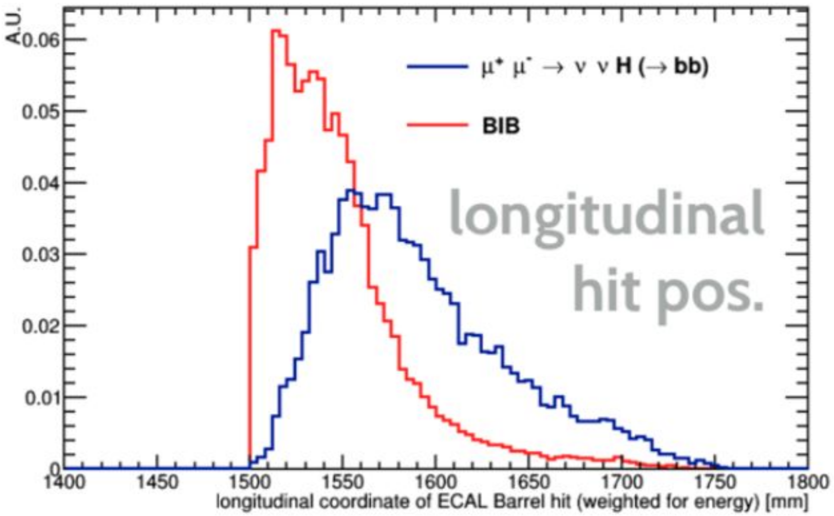


Need to take the potential acceptance losses in account from the beginning!

- Track and vertex-based searches won't come for free

Calorimetry





Various approaches under investigation to mitigate BIB contributions:

- Software BIB subtraction
- 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!

Muon detectors and DAQ

Designing an LLP-friendly data flow

Muon detector operation is the most similar to the LHC.

- Still require BIB-suppression techniques, especially in the forward region
- Good opportunity to detect significantly displaced decays O(m), to be quantified

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

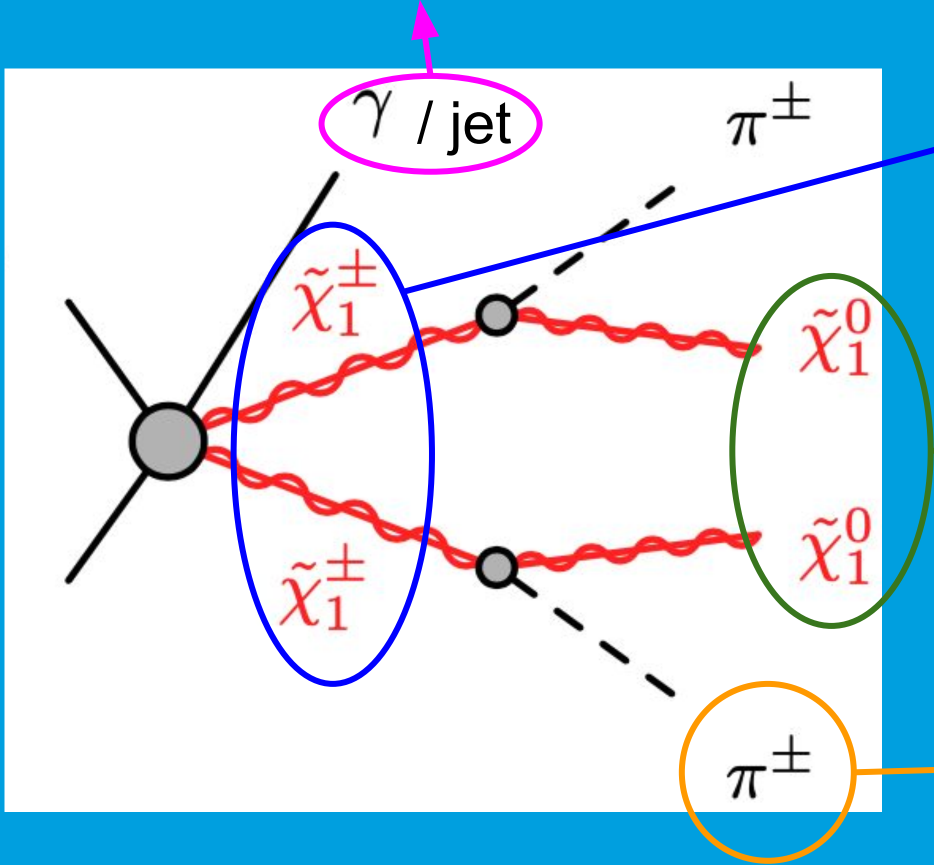
- Best scenario for unconventional signatures - **data not selected by the trigger is lost forever**
- Higher “quality” decisions (more information)
- Simpler detector front-end electronics (e.g. buffers)
- Software event selection more flexible and maintainable

A case study (arXiv: 2102.11292)

Search for disappearing tracks

ISR/FSR:

- “Trigger” the event



Charginos:

- Long lived, charged
- Reconstructable as “tracklets”

Neutralinos:

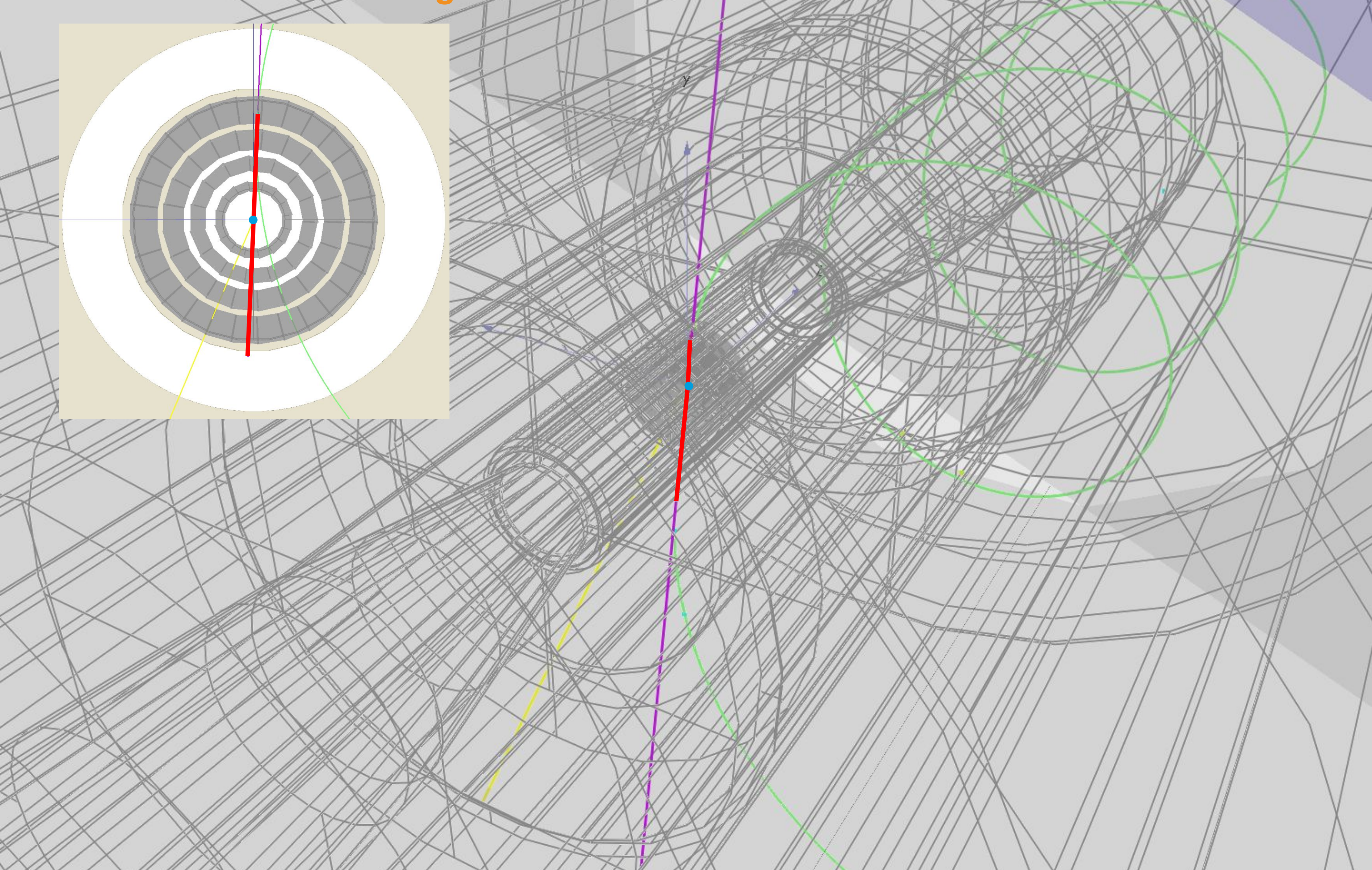
- Stable, neutral
- Invisible

Displaced pions:

- Possibly reconstructable
- Not considered here

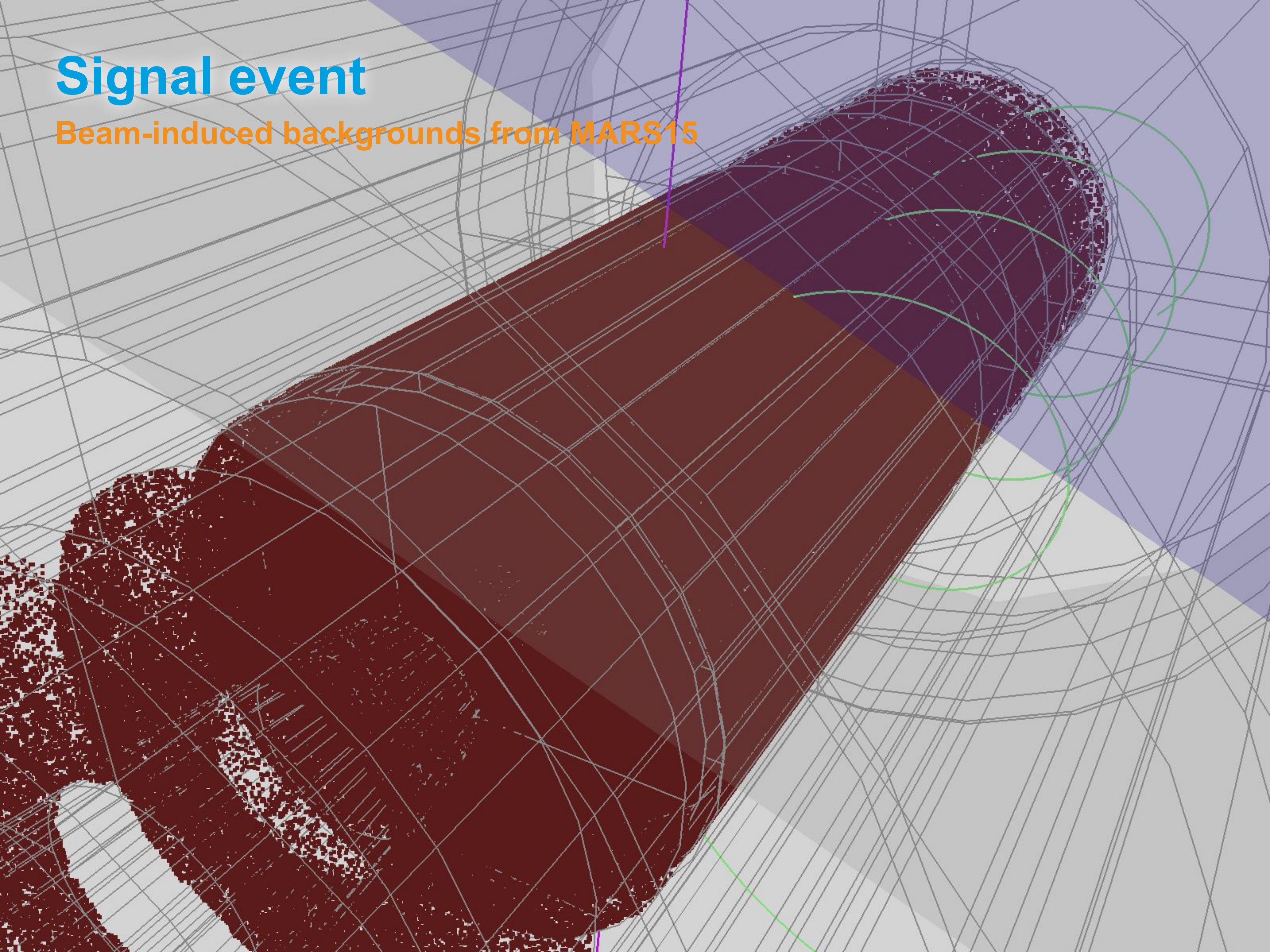
Signal event

No beam-induced backgrounds



Signal event

Beam-induced backgrounds from MARS15



Reconstructing “tracklets”

We want to reconstruct tracks that are as short as possible.

- Minimum 4 hits (2 double layers)
  - Minimal reconstructable length is 5.1cm

If we consider all hits, it takes **more than a week** to reconstruct the tracks from a single event.

Need to simplify the problem!

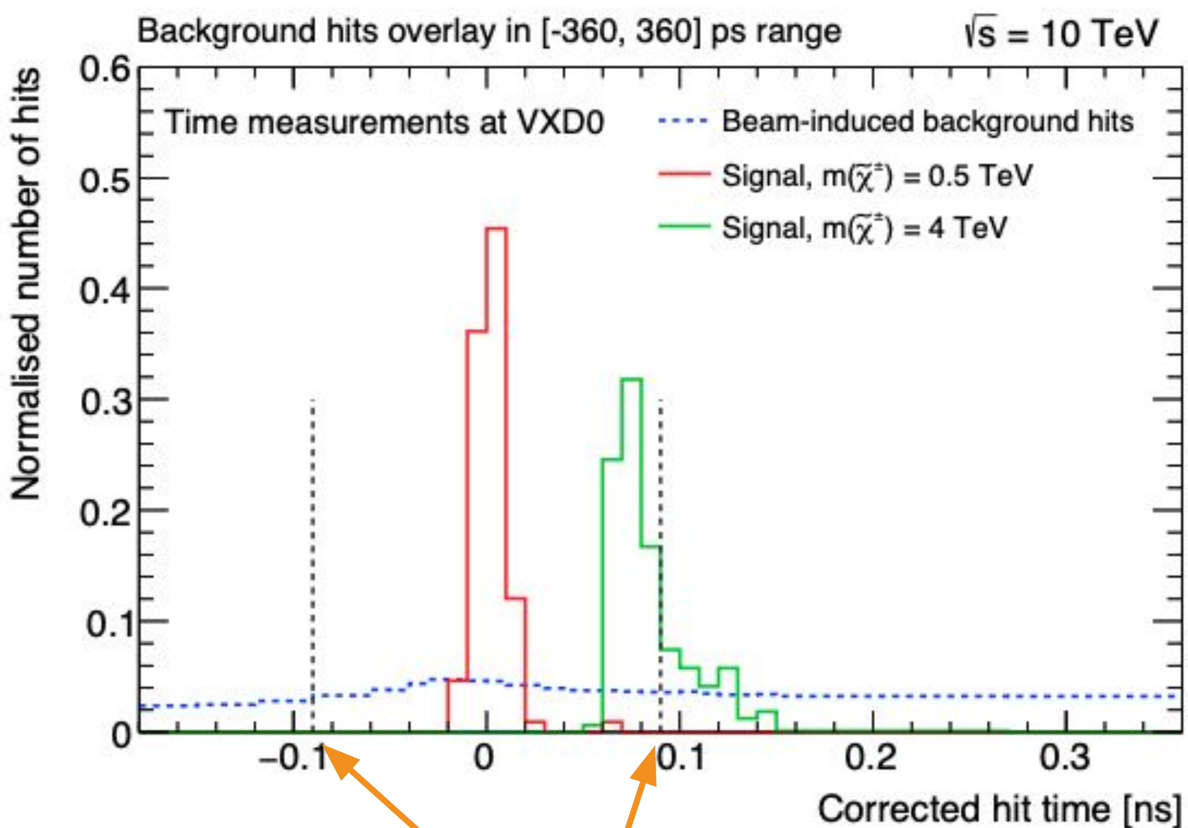
- Regional tracking (in bins of the polar angle θ)
- Tight cuts on track creation (both in *rφ* and *rz*)
- Add hit-level selection requirements

BIB rejection: timing

Exploit particle arrival times to reduce BIB.

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

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



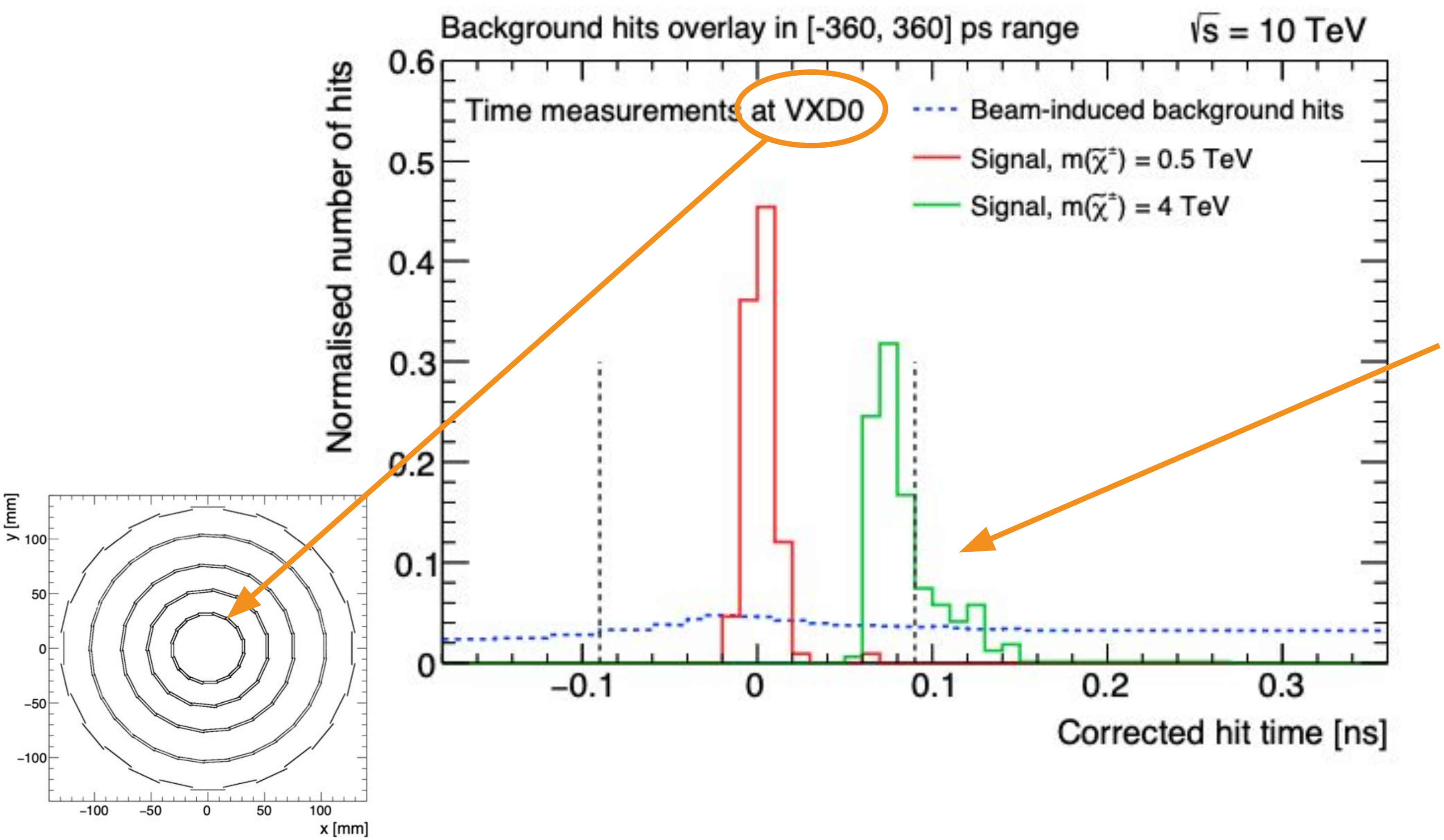
Select hits within a time window

BIB rejection: timing

Exploit particle arrival times to reduce BIB.

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

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

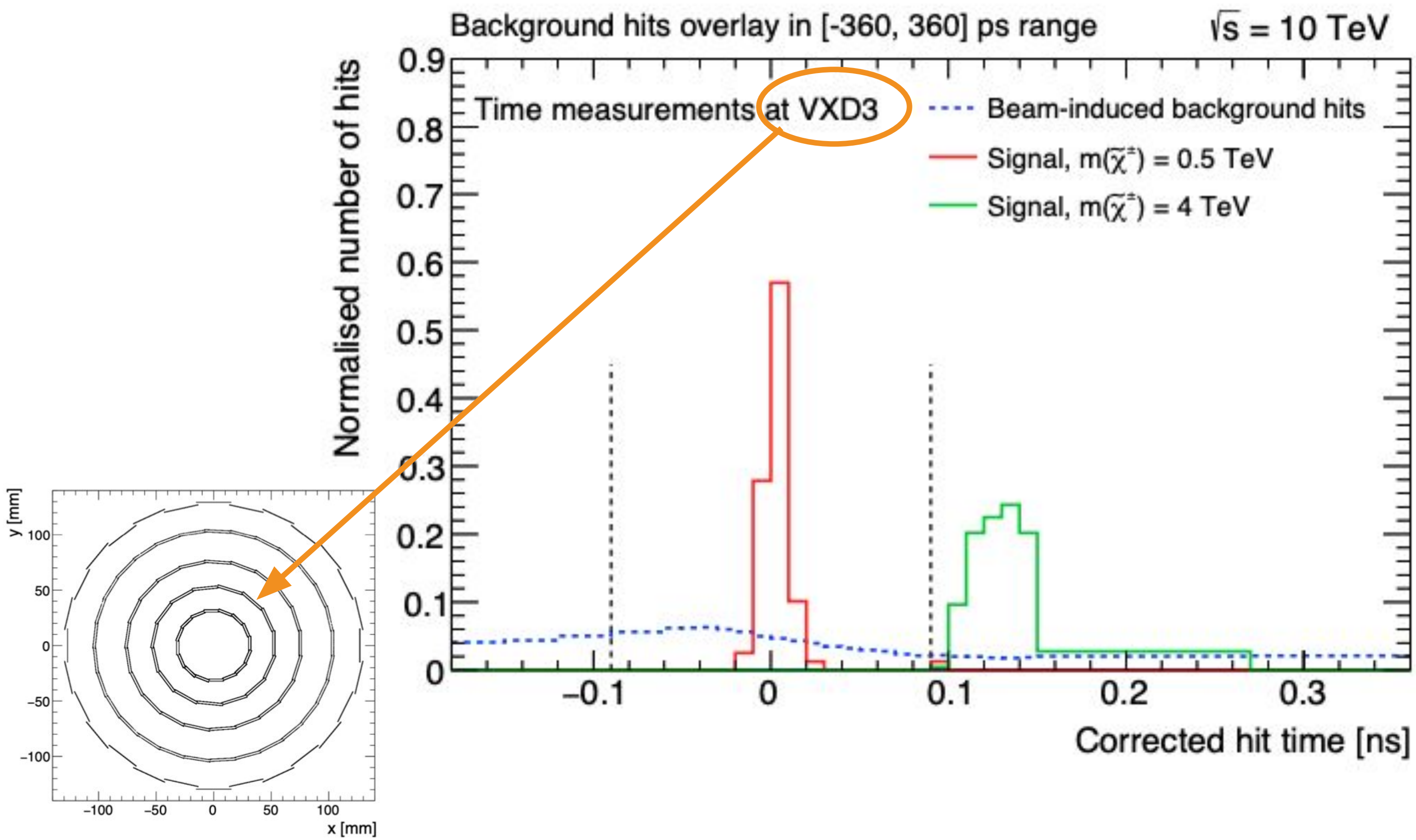


Low(er) β particles can suffer from inefficiencies

BIB rejection: timing

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

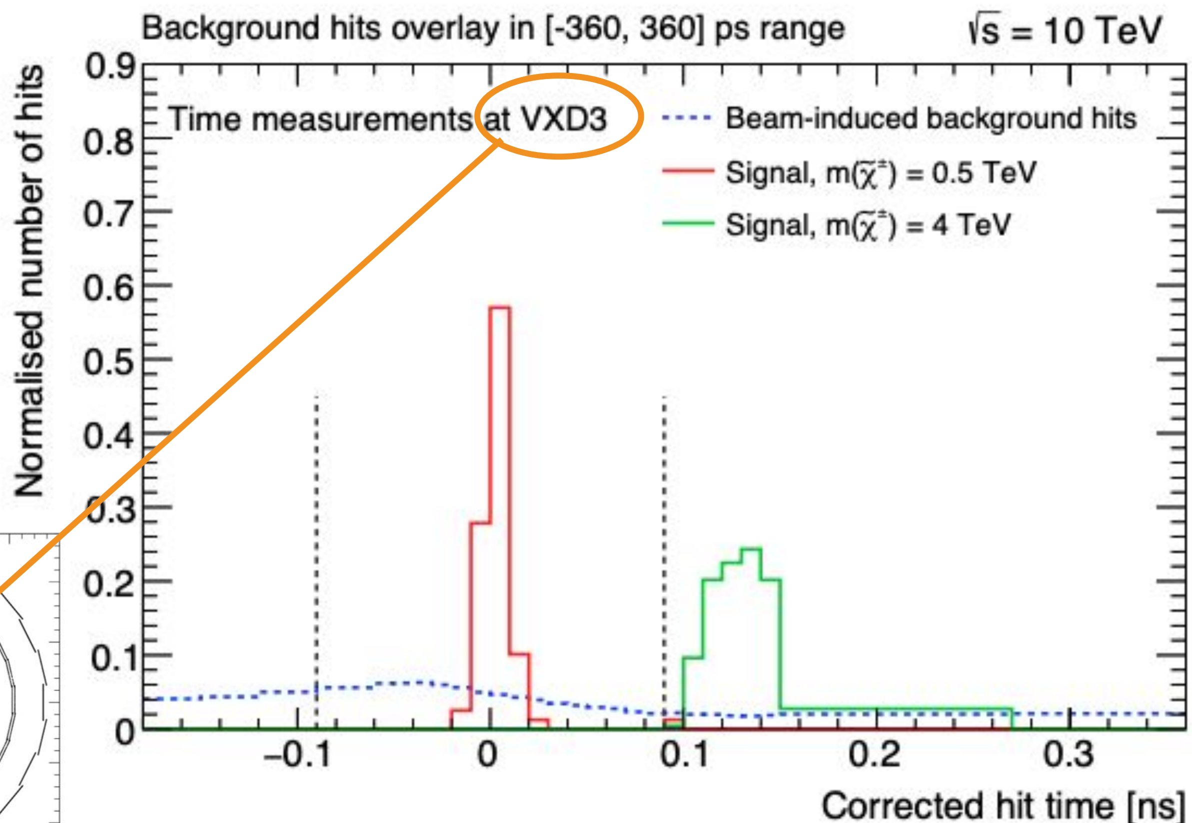
- Slow particles are already completely lost!

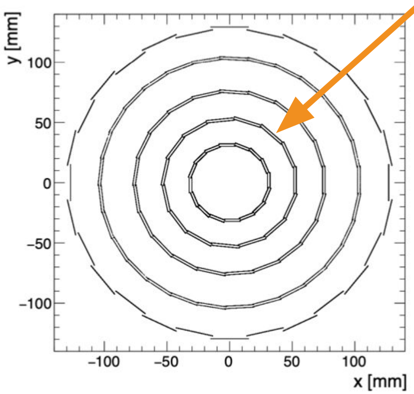


BIB rejection: timing

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

- Slow particles are already completely lost!



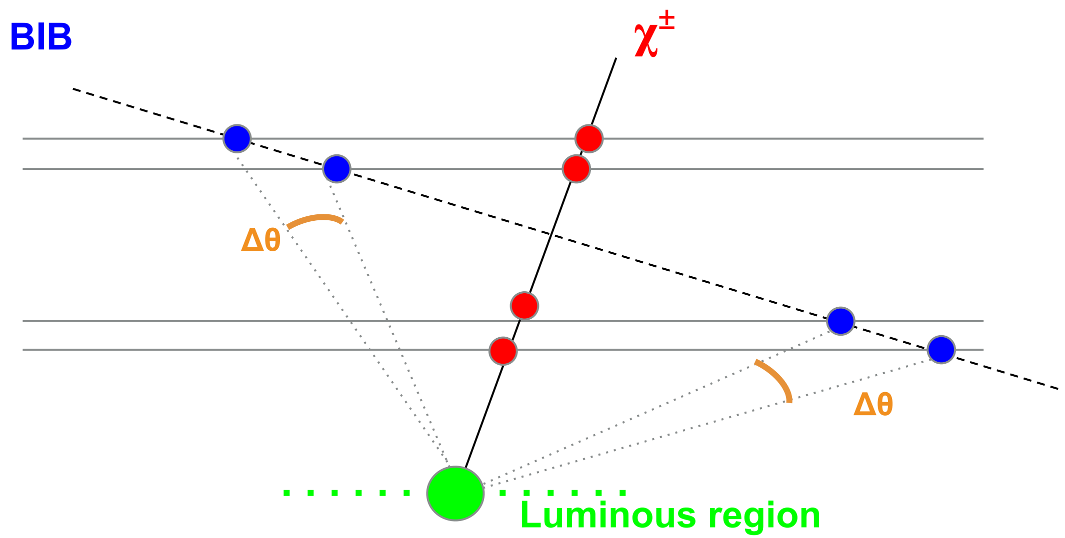


Requires dedicated selections and reconstruction

BIB rejection: stub tracks

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

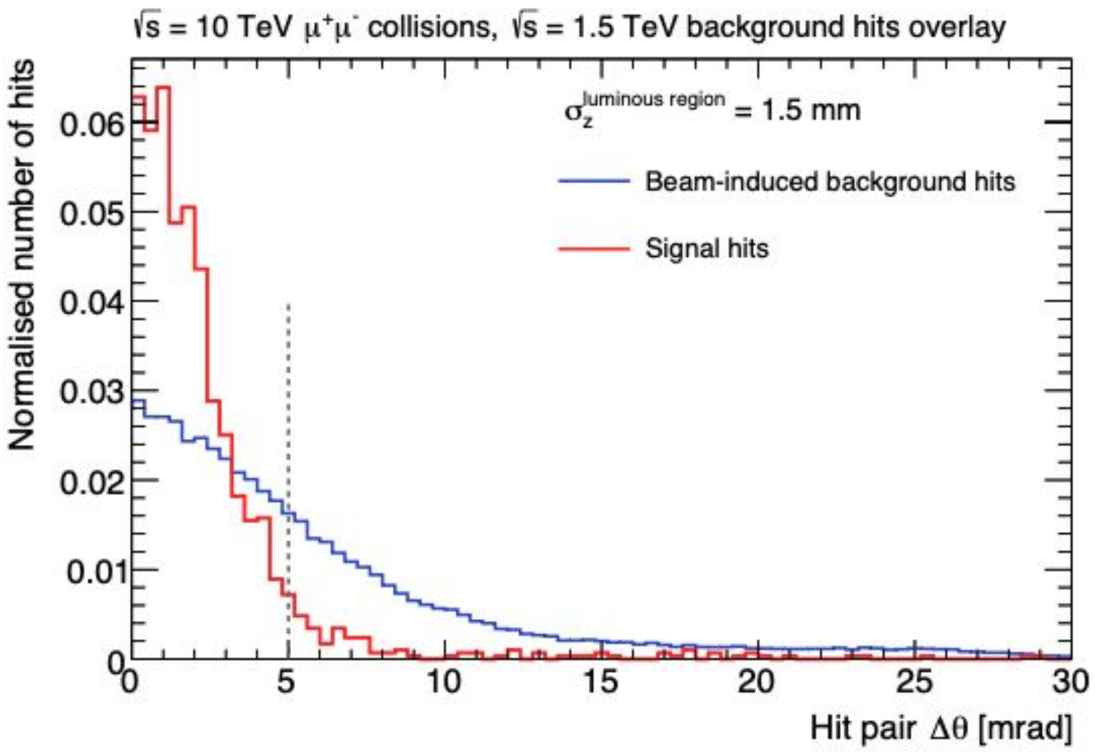
- Look for pairs of hits in neighbouring double-layers forming “stub tracks” that point back to the luminous region.



BIB rejection: stub tracks

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

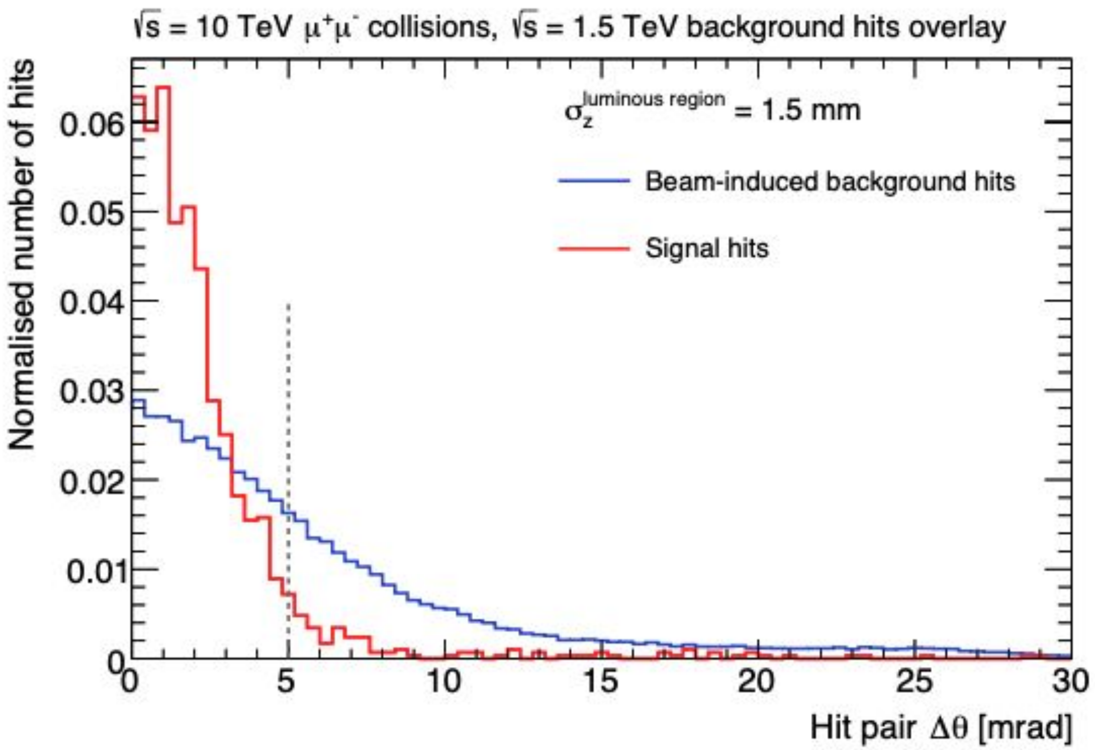
- Look for pairs of hits in neighbouring double-layers forming **“stub tracks” that point back to the luminous region**
- Work ongoing to apply a similar approach at the cluster level



BIB rejection: stub tracks

The 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**
- Work ongoing to apply a similar approach at the cluster level

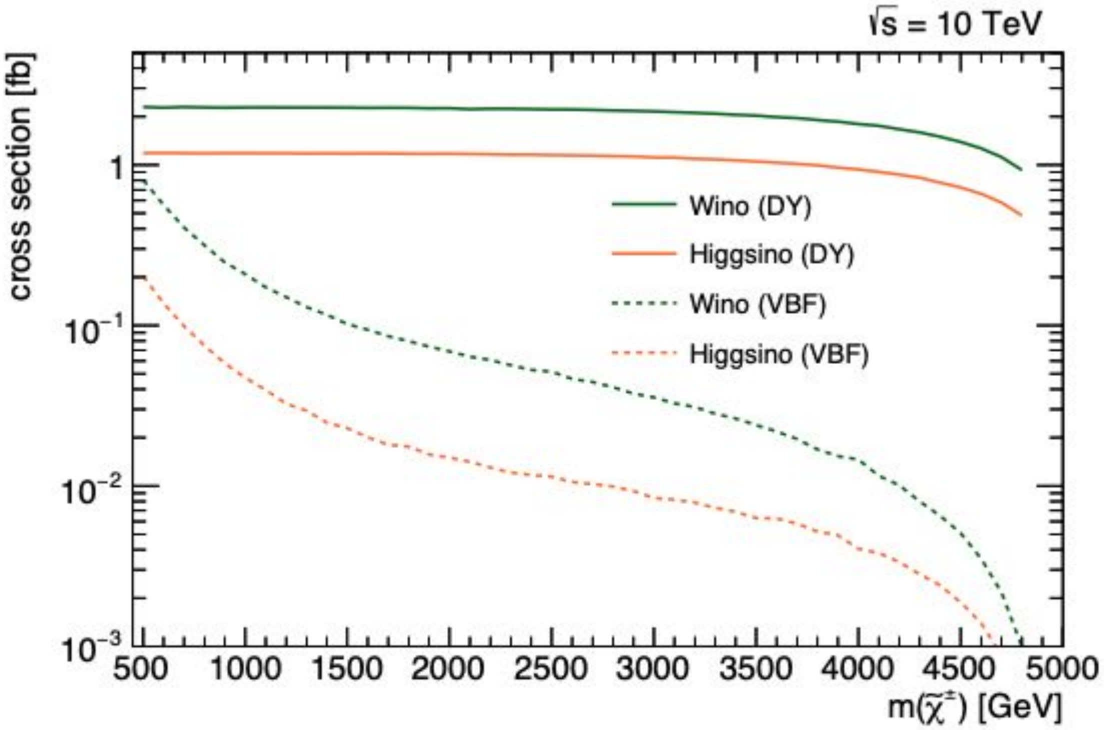


Challenge for long-lived signatures with displaced decays

Expected signal production rates

At the MuC 10

Cross-section predictions from MadGraph5_aMC@NLO 2.8.2



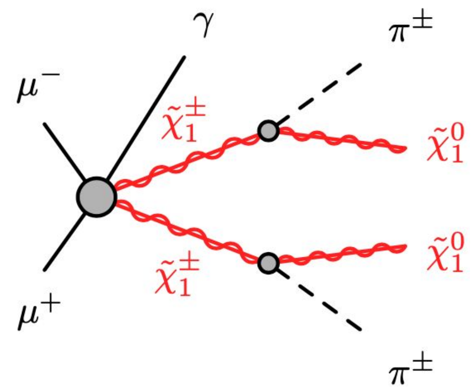
Expect to produce about 10000 $\chi^{\pm}\chi^{\mp}$.

- 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

Event selection

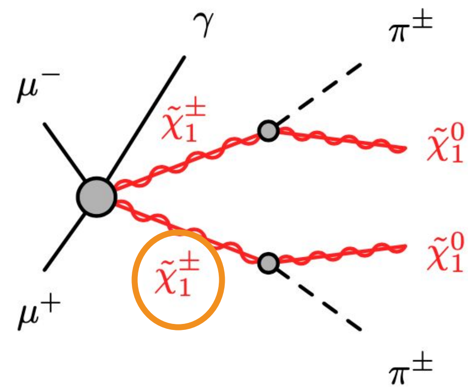
Perform analysis on **smeared truth-level events** using efficiency parameterisation from full simulation.

- Two regions, based on tracklet multiplicity



Requirement / Region	SR_{1t}^{γ}	SR_{2t}^{γ}
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

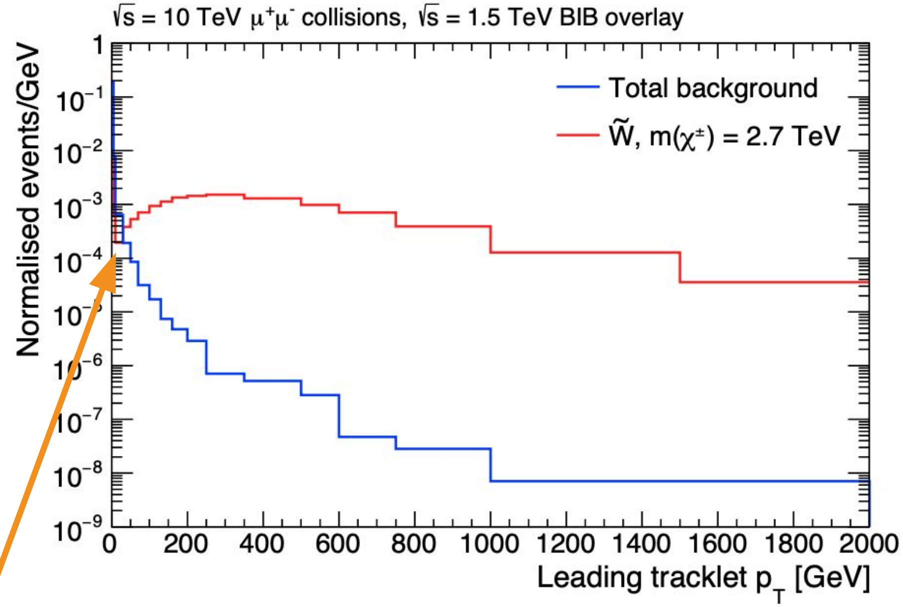
Event selection



Relatively simple event selection:

- Tracklet p_T (single most important quantity)

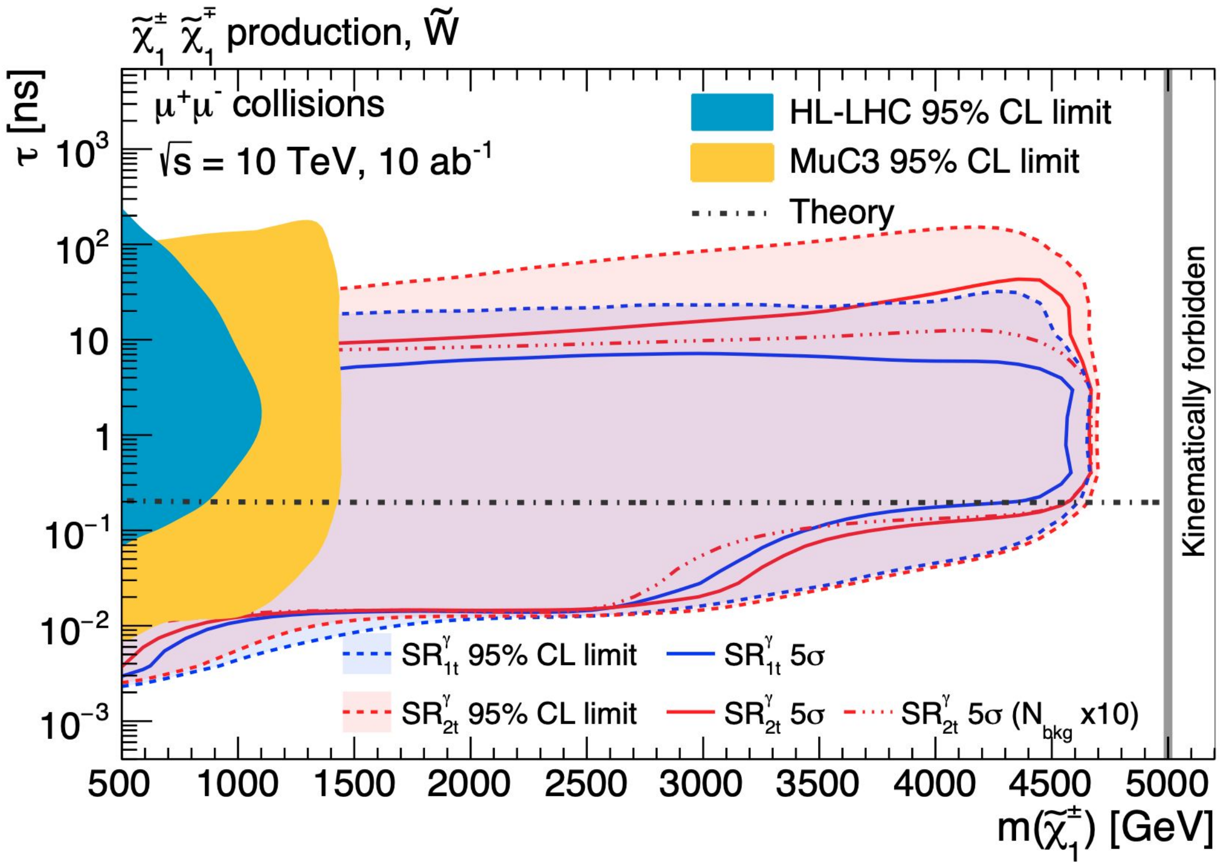
Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25



Peak at low p_T in signal events due to BIB overlay

Expected sensitivity

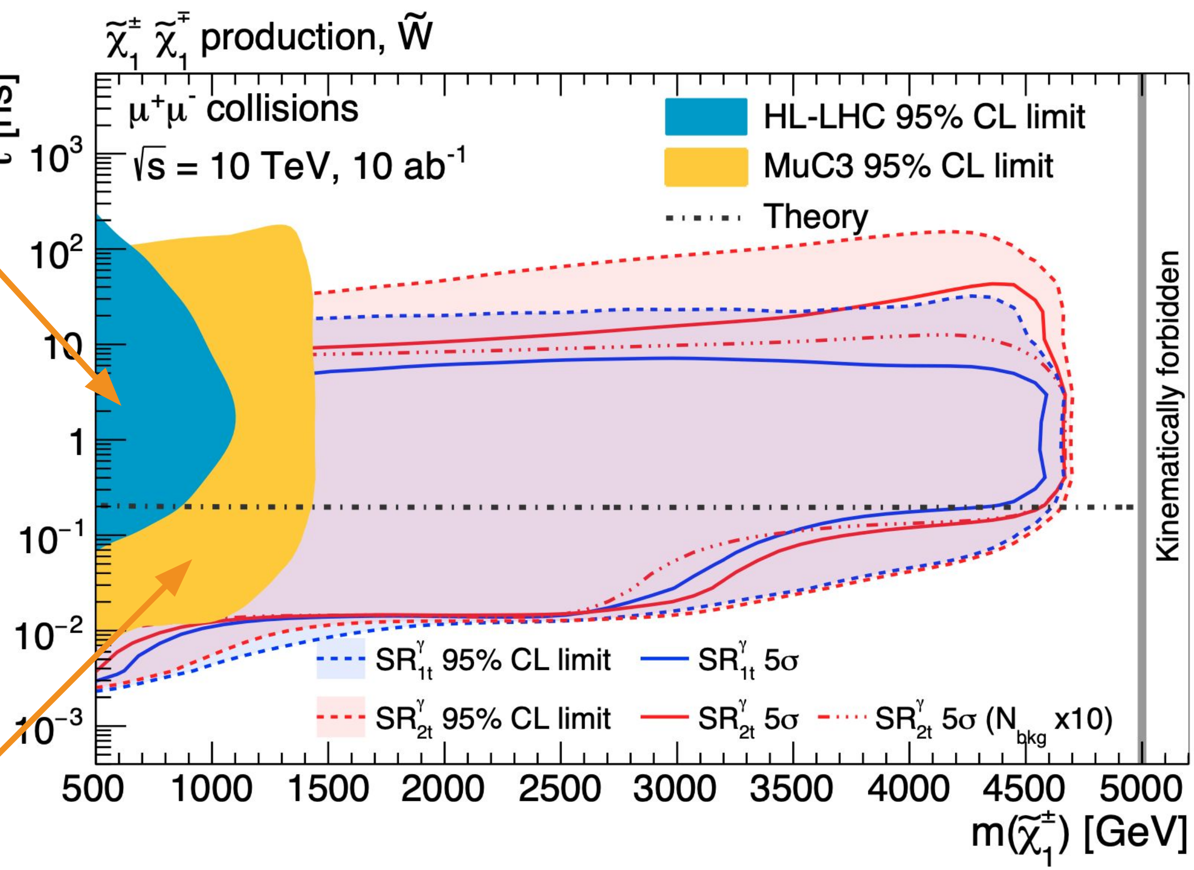
Pure wino models at MuC 10



Expected sensitivity

Pure wino models at MuC 10

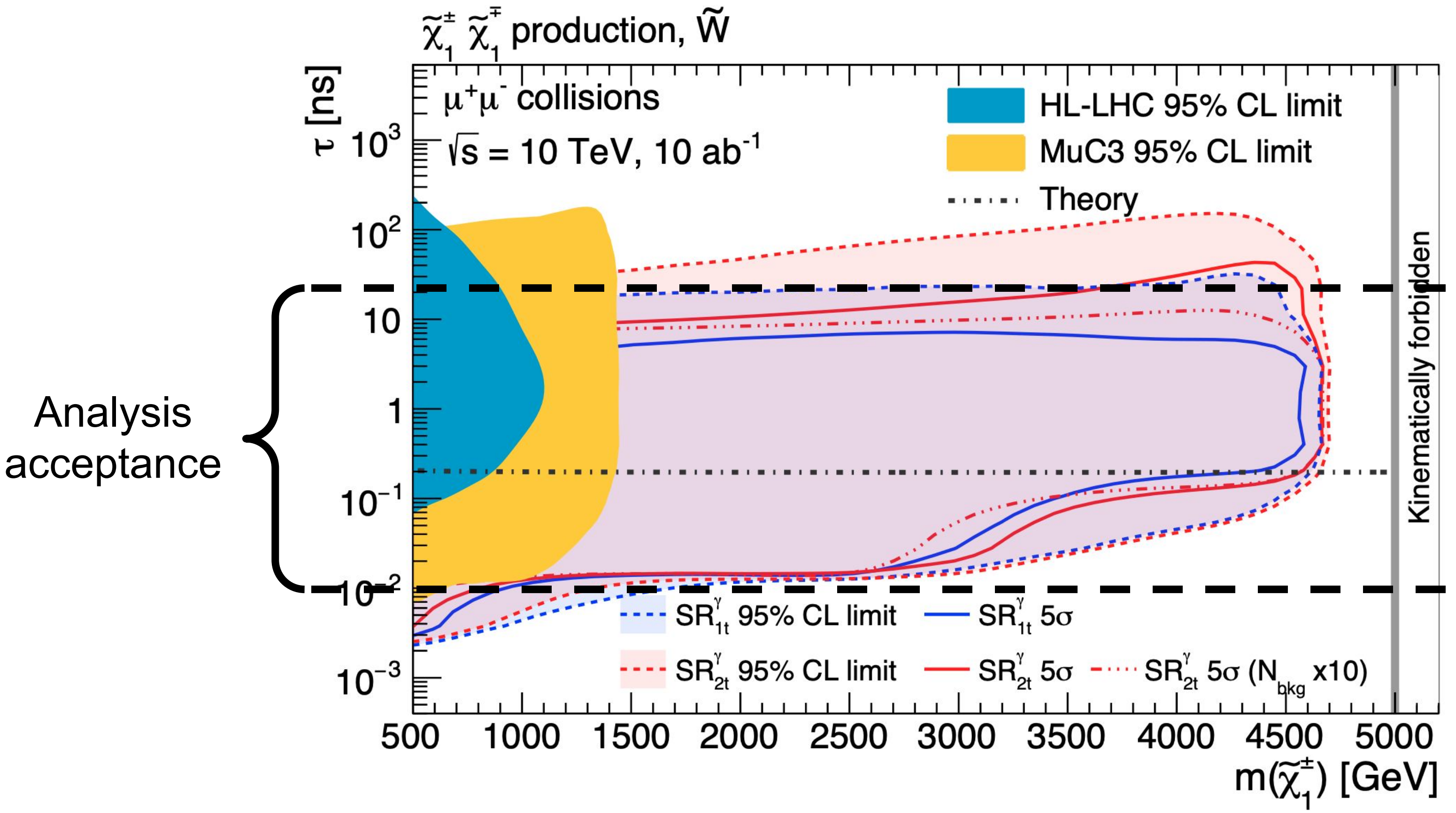
HL-LHC projections
ATL-PHYS-PUB-2018-031



Limits from MuC 3

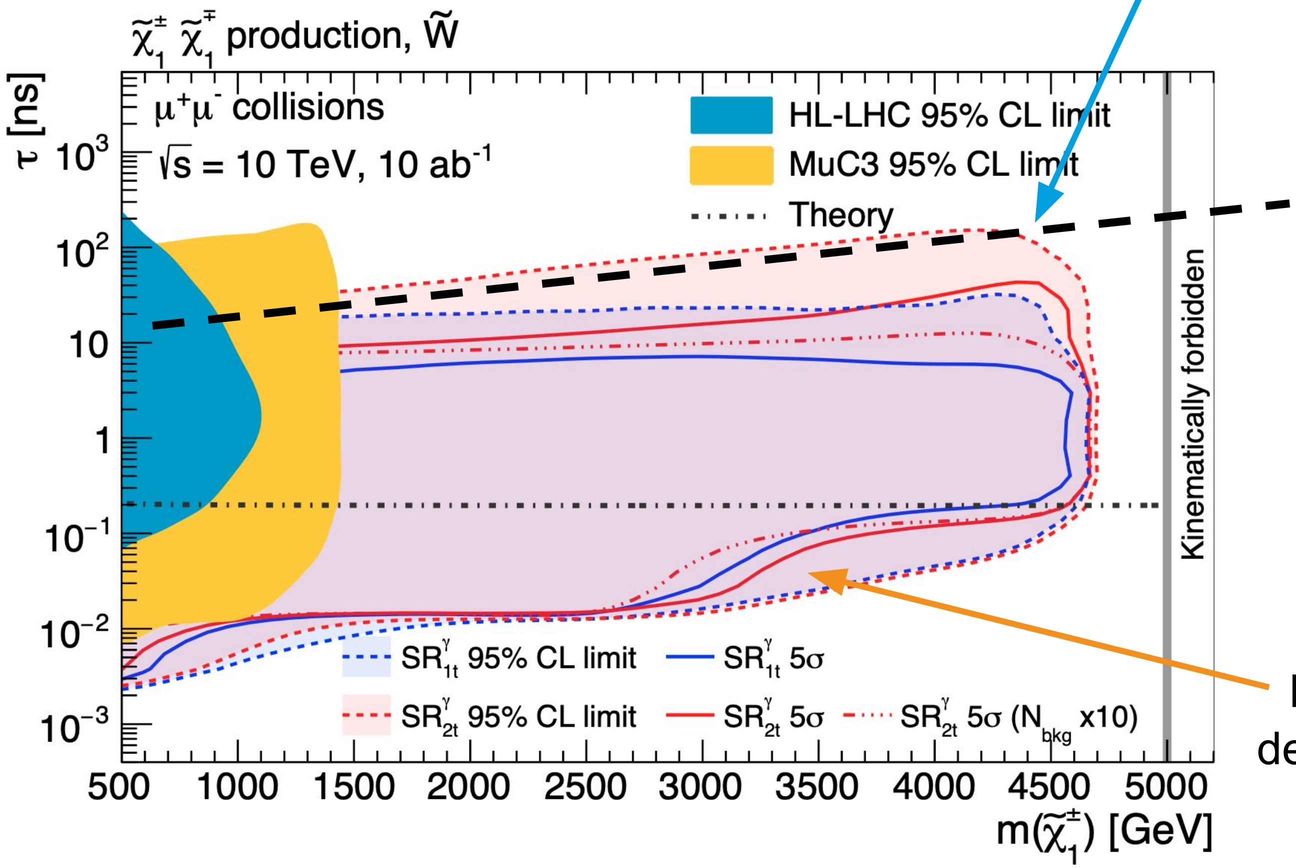
Expected sensitivity

Pure wino models at MuC 10



Expected sensitivity

Pure wino models at MuC 10



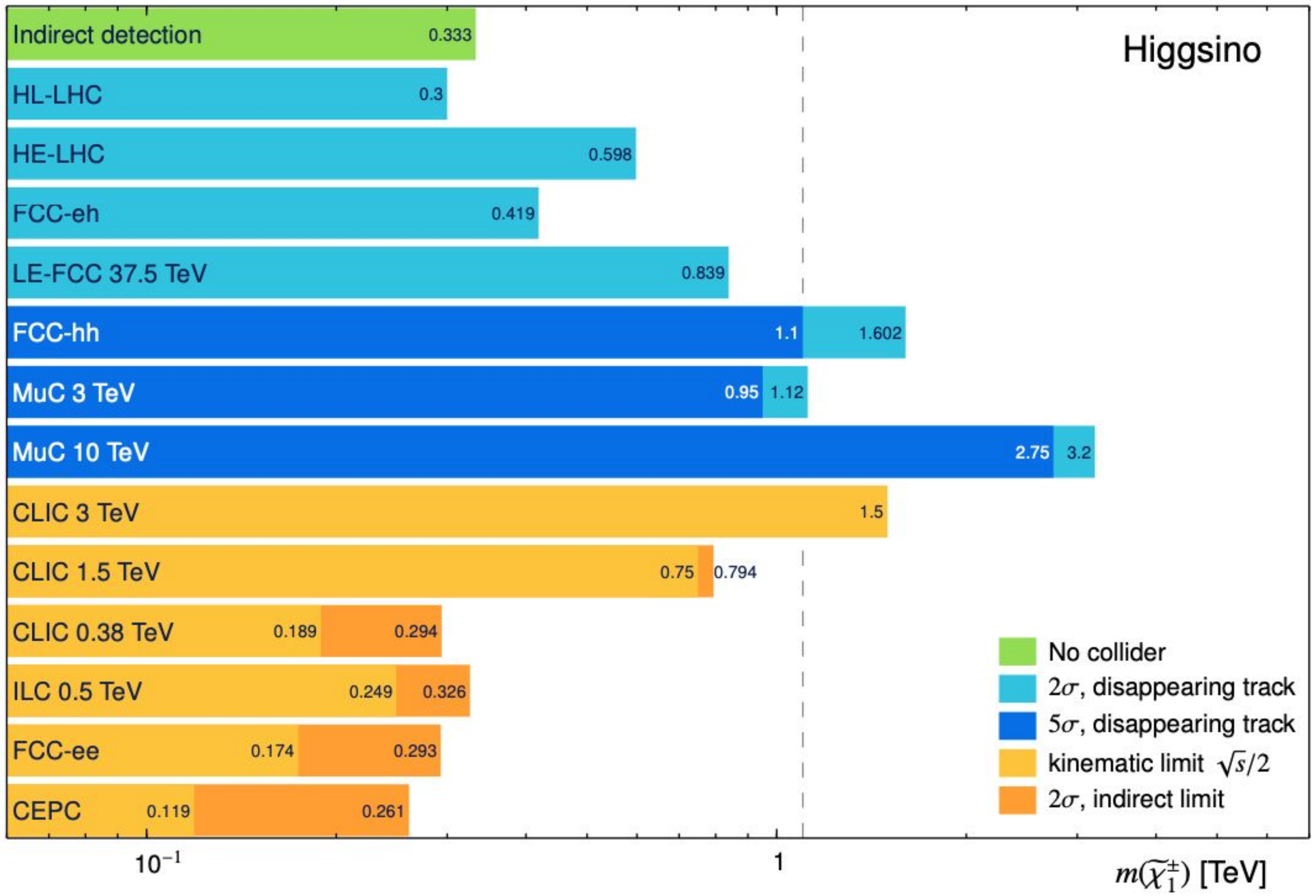
Decreasing βγ: fewer signal tracklets rejected by **veto layer**

Sensitivity loss due to decreasing βγ for larger masses: **missing at least 4 hits**

Expected sensitivity

Non-MuC lines from arXiv: 1910.11775
arXiv: 1901.02987

Pure-higgsino scenario in MSSM



Summary

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

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

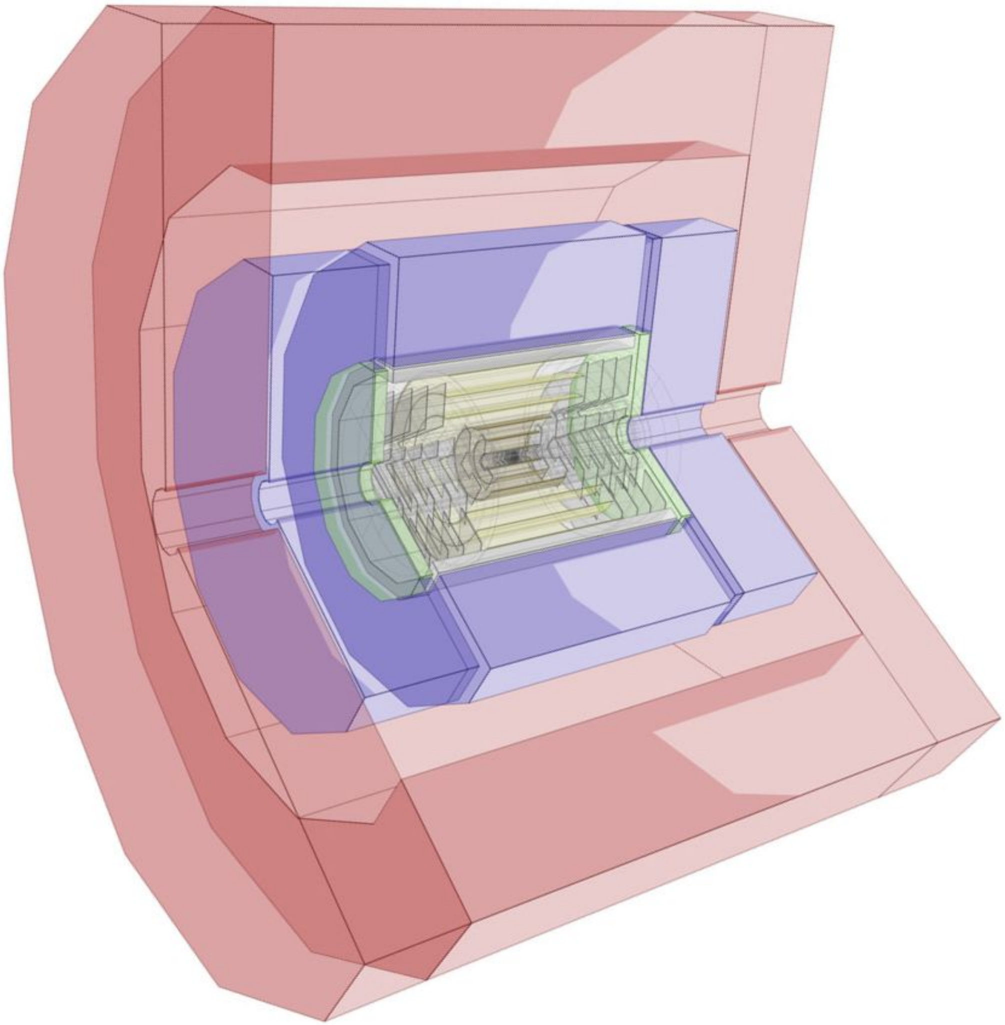
- We are aiming for an LLP-conscious detector design.

I have shown a detailed example studying these effects in detail.

- Many other studies needed or underway to fully characterise the LLP and FIP physics potential of a future muon collider facility.
- Your ideas are welcome!

Thank you!

Detector layout



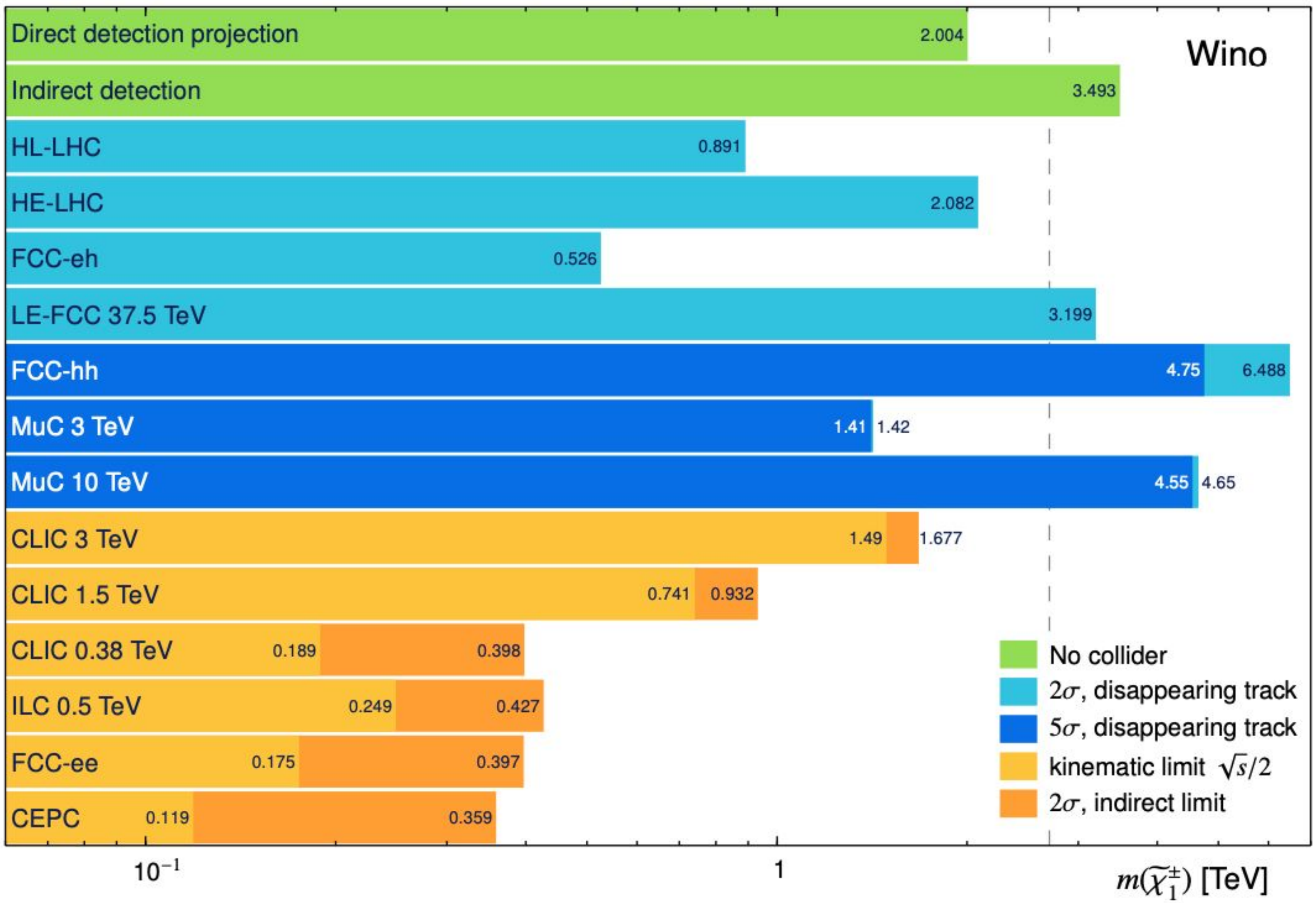
The detector model is based on the SiD ILC concept.

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

Comparison with other facilities

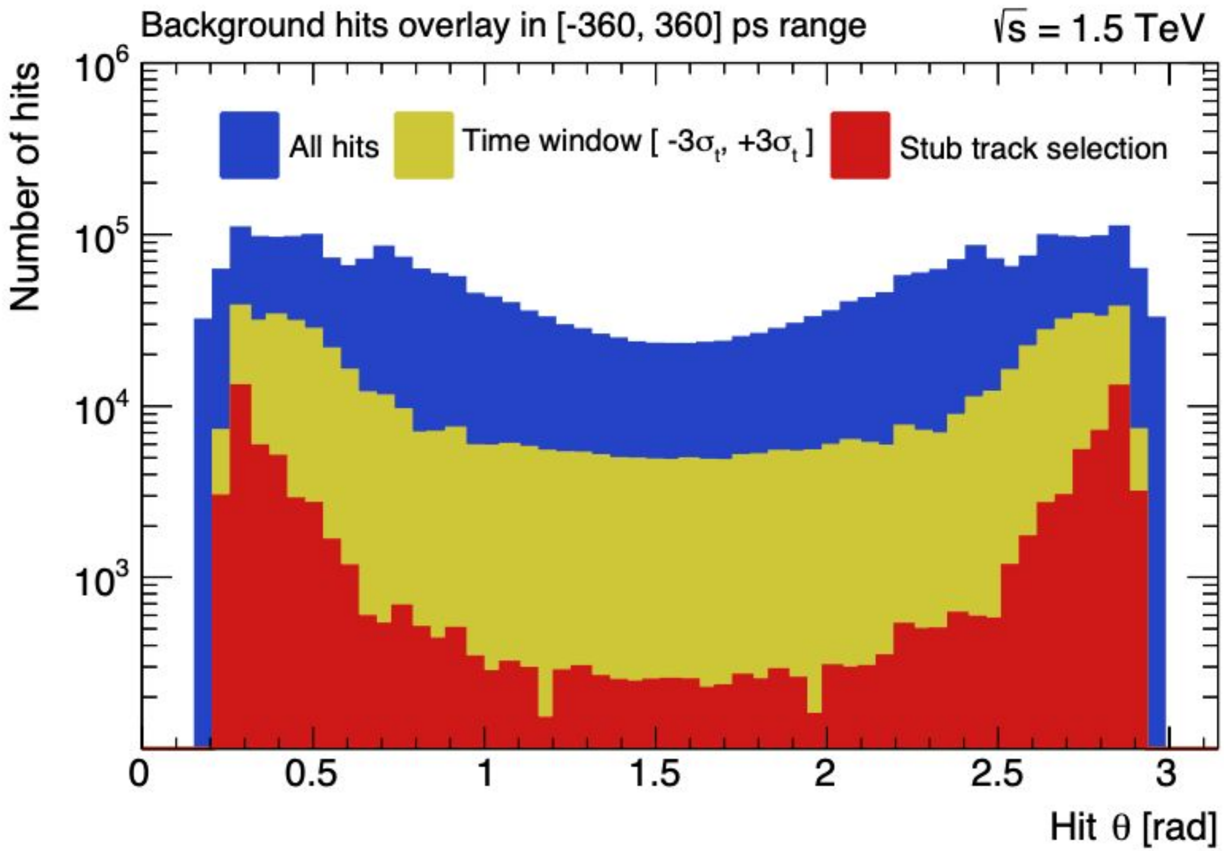
Wino scenario

Other lines taken from arXiv: 1910.11775
arXiv: 1901.02987



BIB rejection

Angular summary



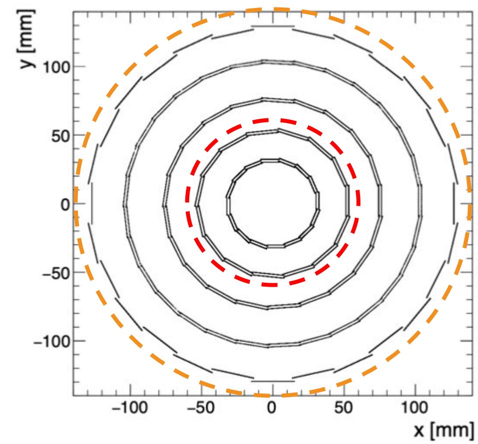
Tracklet reconstruction efficiencies

After BIB rejection cuts

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

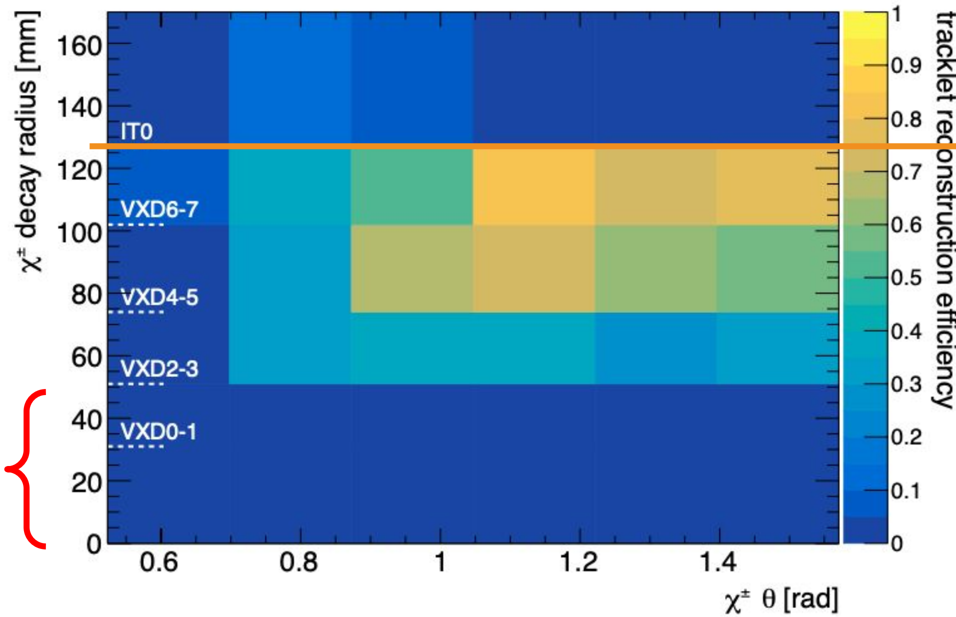
Efficiencies evaluated with truth matching to $\chi^{\pm}$

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



Min. requirement

Veto



Veto from disappearing condition

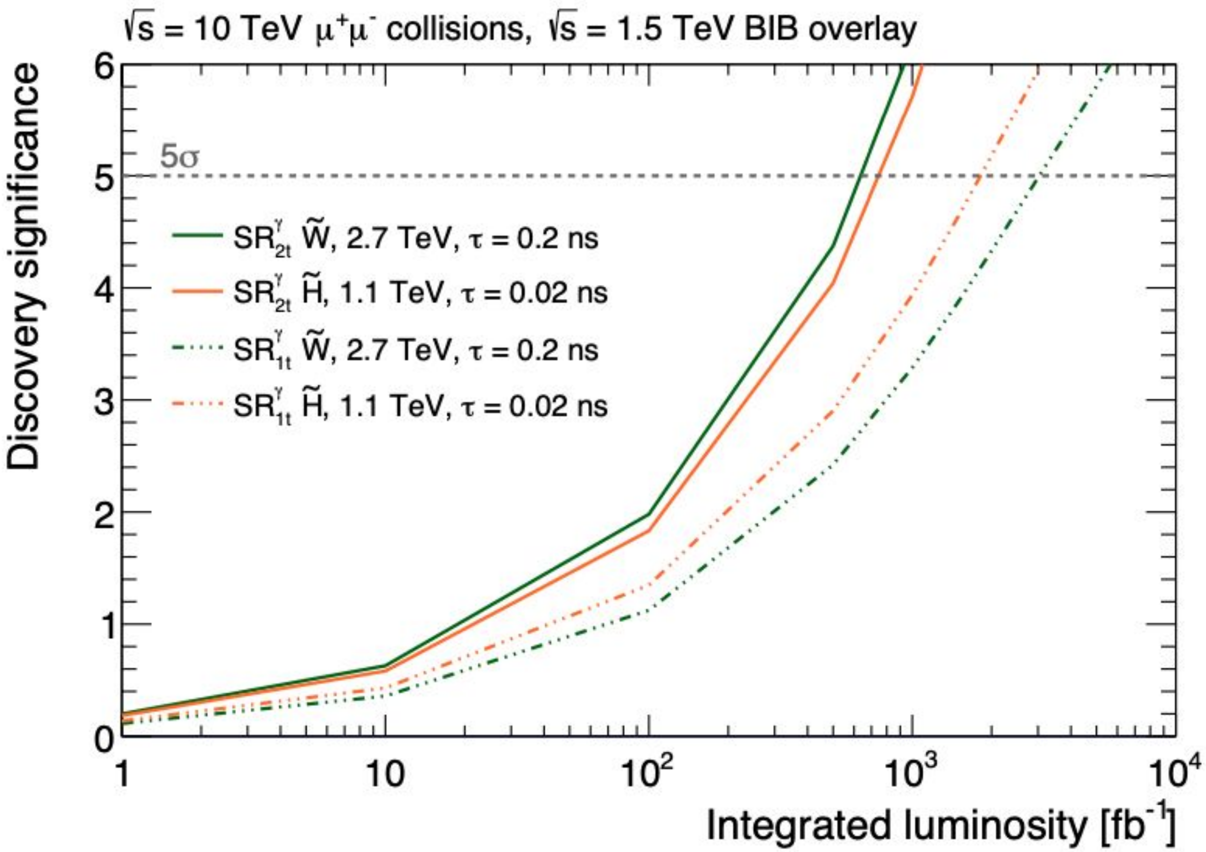
Not enough hits

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)
  - **σ ($\mu^+\mu^- \rightarrow \nu\nu$)** **~ 60000 fb** (dominated by t-channel W exchange)
  - **σ ($\mu^+\mu^- \rightarrow \chi^\pm\chi^\mp$)** **~ 1-2 fb**

Integrated luminosity needs

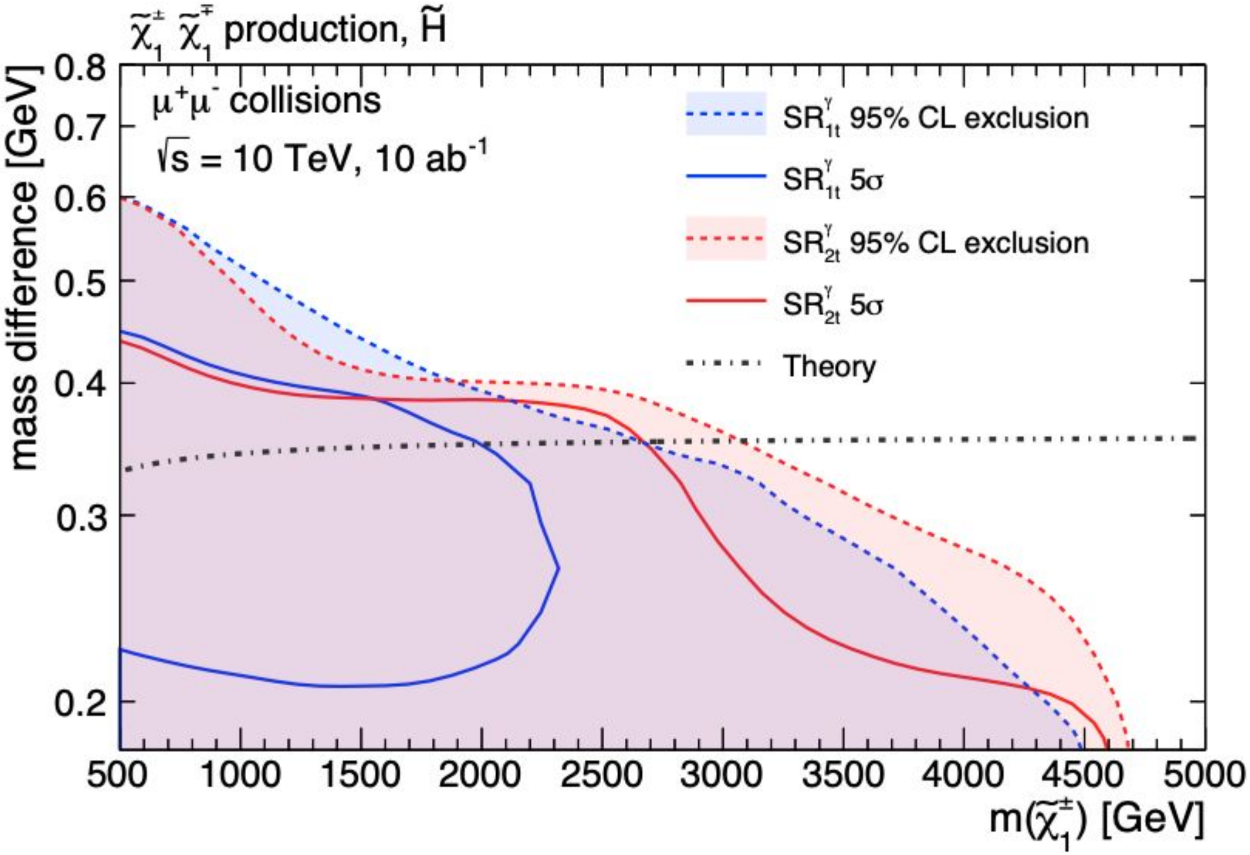


Considering here the targets that would fulfil the dark matter relic density.

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

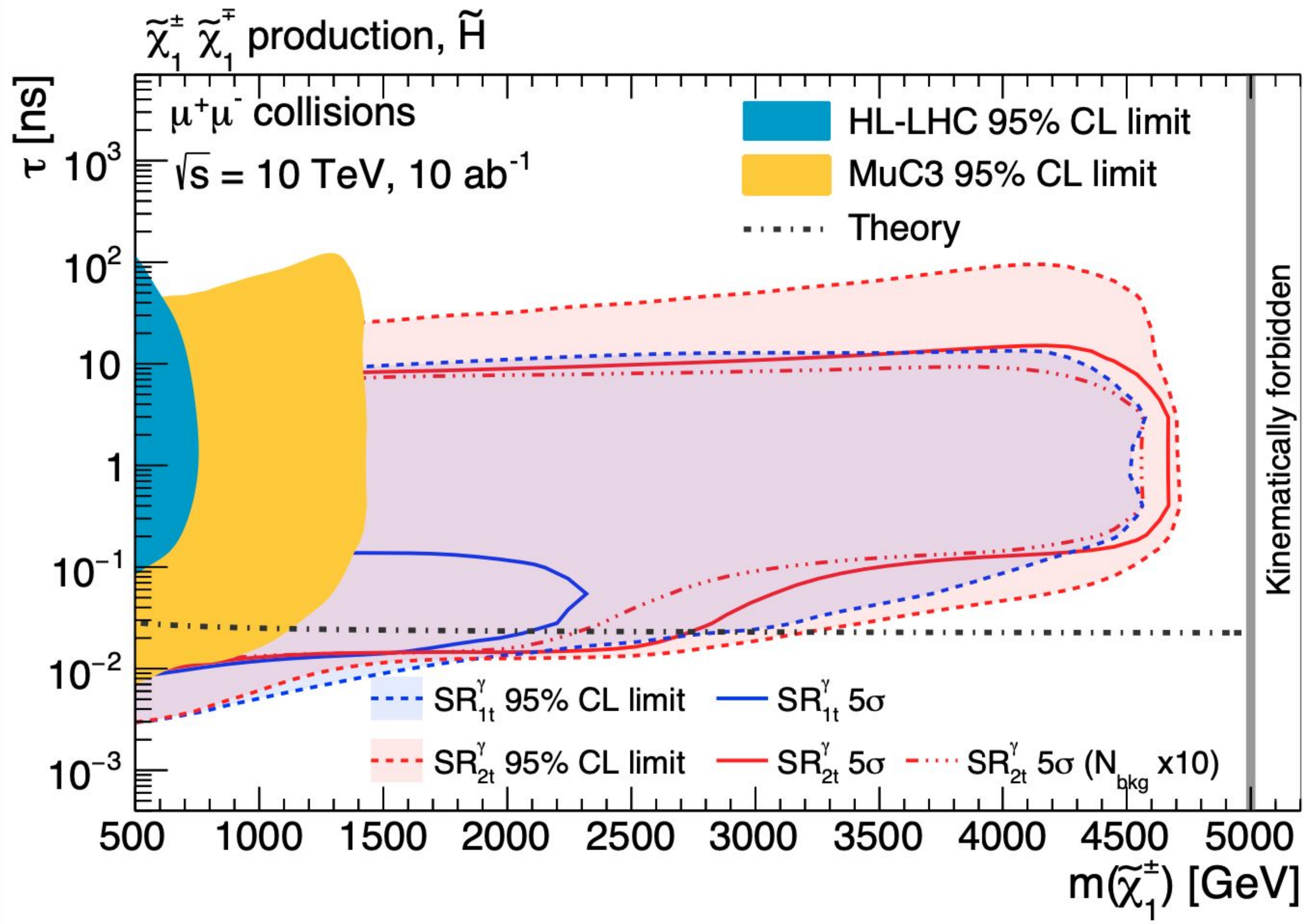
Expected sensitivity

Mass vs mass difference in higgsino scenarios



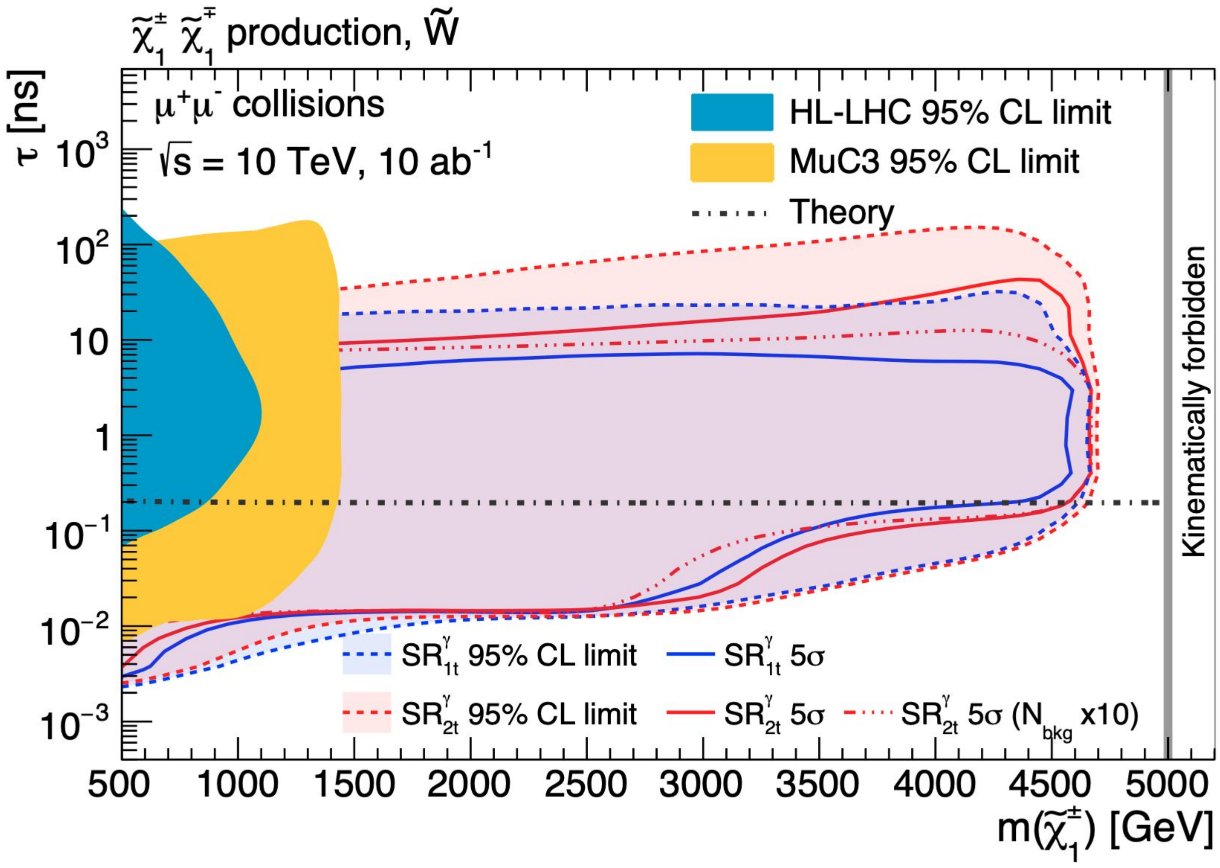
Expected sensitivity

Pure higgsino models at Muc 10



Expected sensitivity

Pure wino models at MuC 10

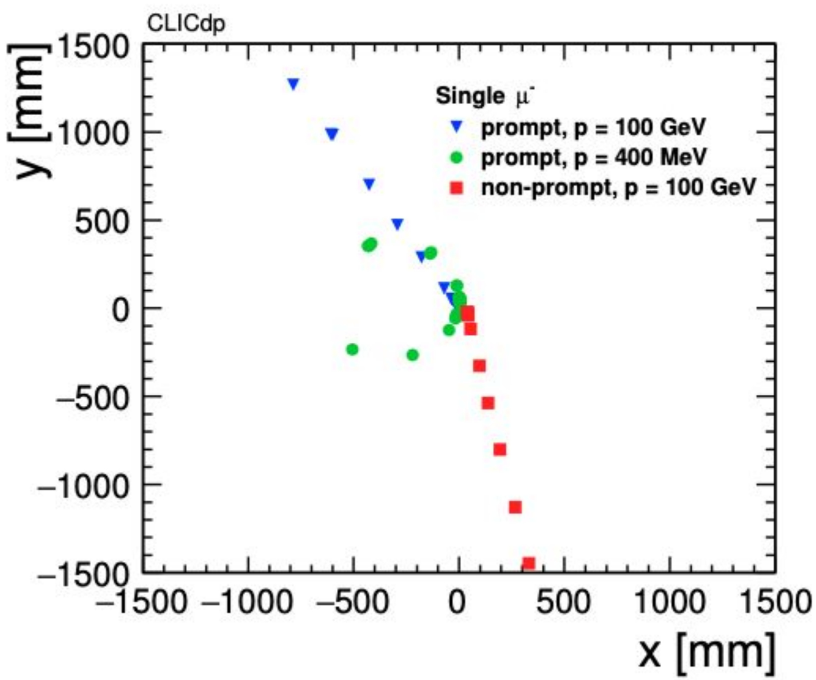


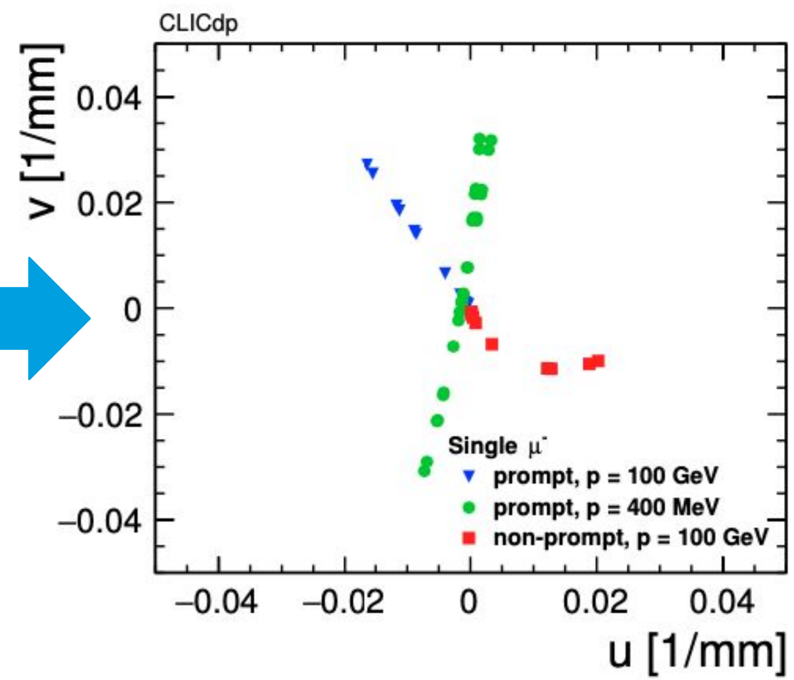
Track reconstruction

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

1. Conformal mapping

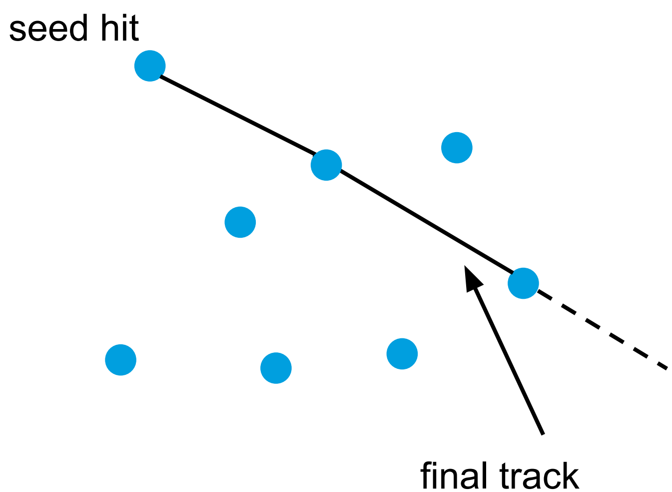
$$u = \frac{x}{x^2 + y^2} \quad v = \frac{y}{x^2 + y^2}$$





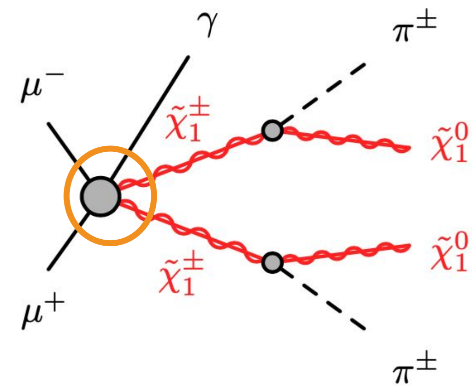
Track reconstruction

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)

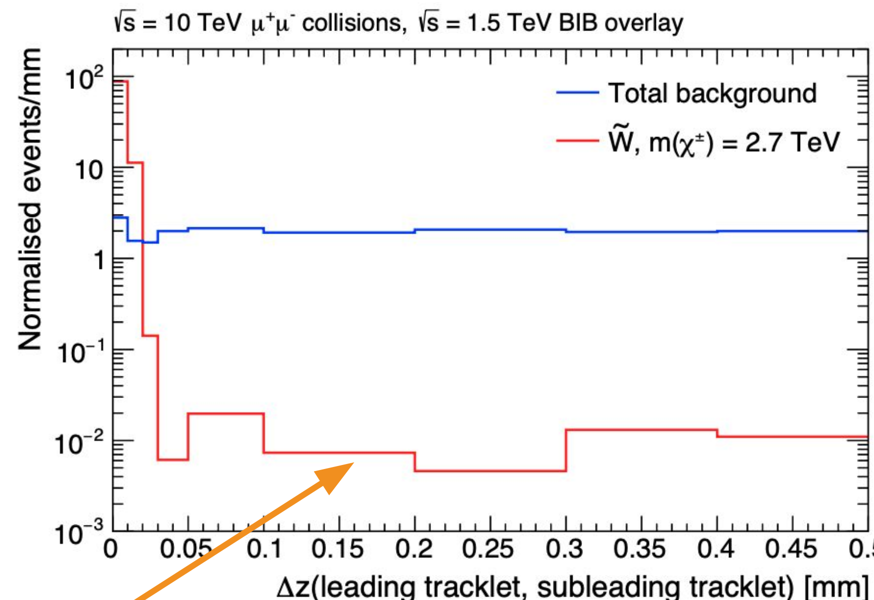
Event selection



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
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



Long tails from events with at least one fake tracklet