Detecting disappearing tracks and other exotica at a Muon Collider

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23/08/2023

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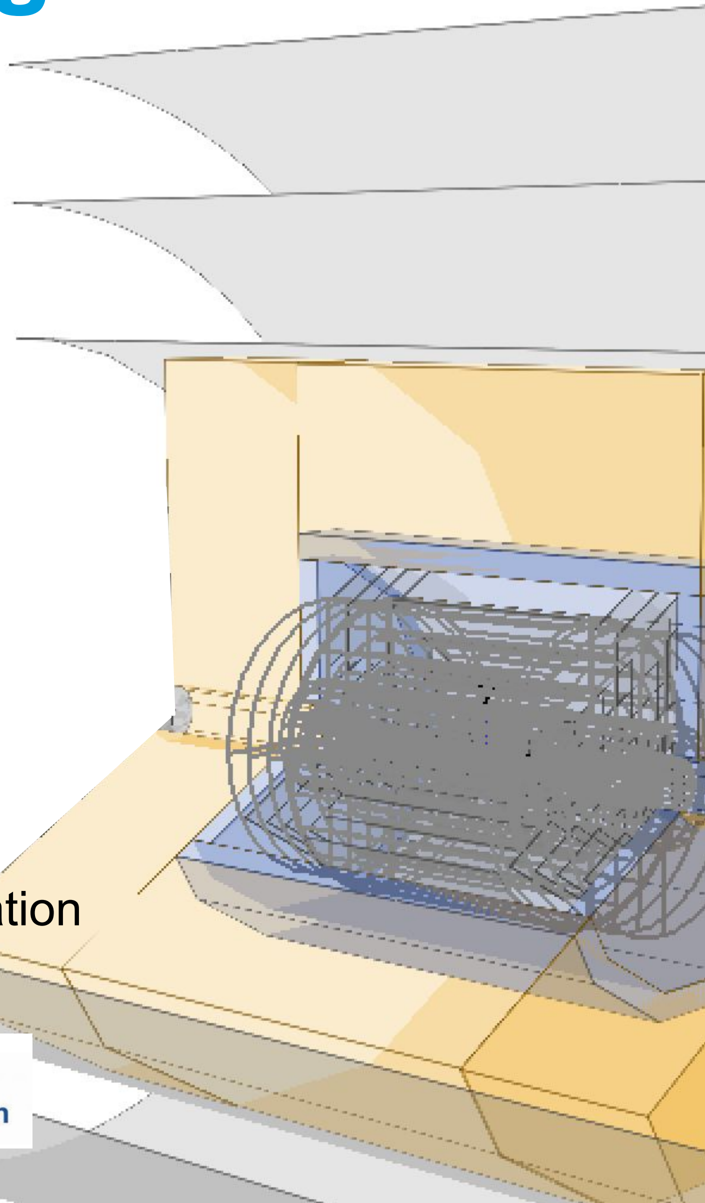
on behalf of the International Muon Collider Collaboration



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DESY.
International MUON Collider Collaboration
MuCol
Co-funded by the European Union

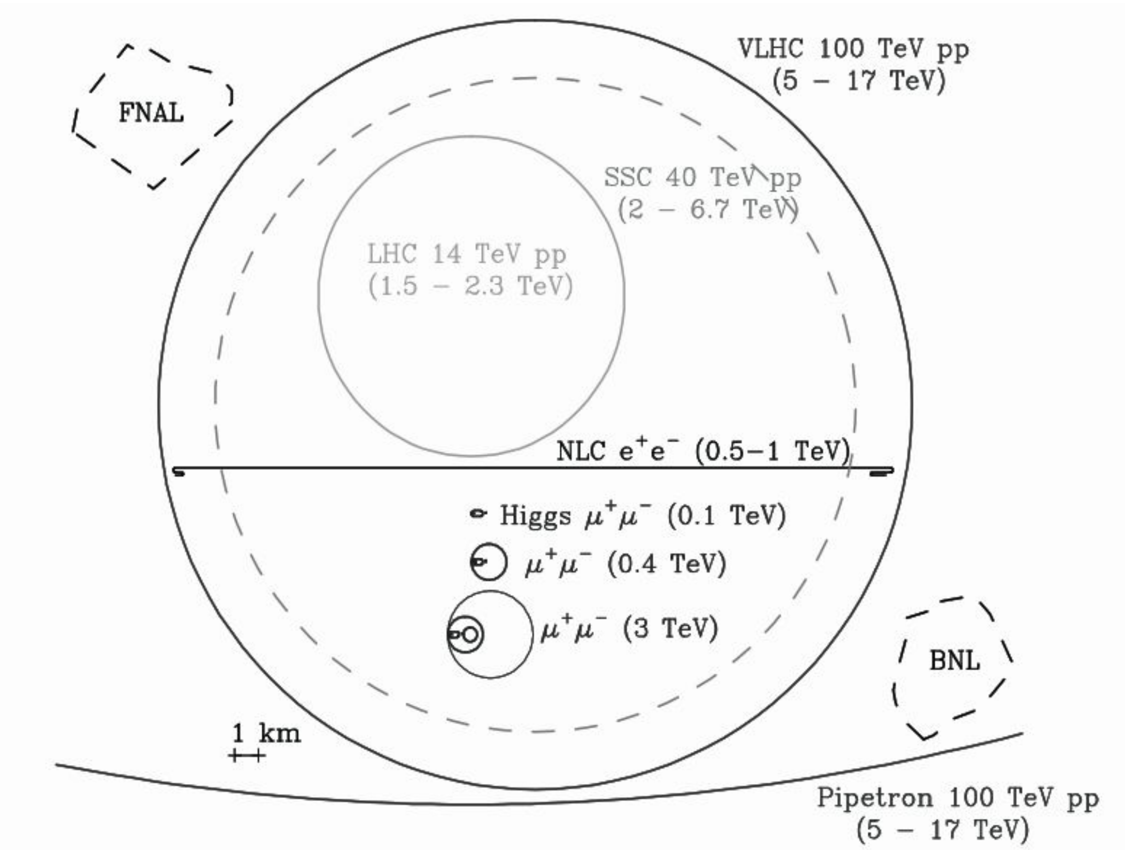
High-energy microscopes

We conventionally pursue HEP research by probing shorter distances with either precision (indirect) or energy (direct)

Muon colliders blur this dichotomy

The muon mass (105.7 MeV/c^2, 207 x $e^{\pm}$ mass) means:

- Negligible synchrotron radiation emission
- Negligible beamstrahlung at collision



Major technical challenges

Key challenges

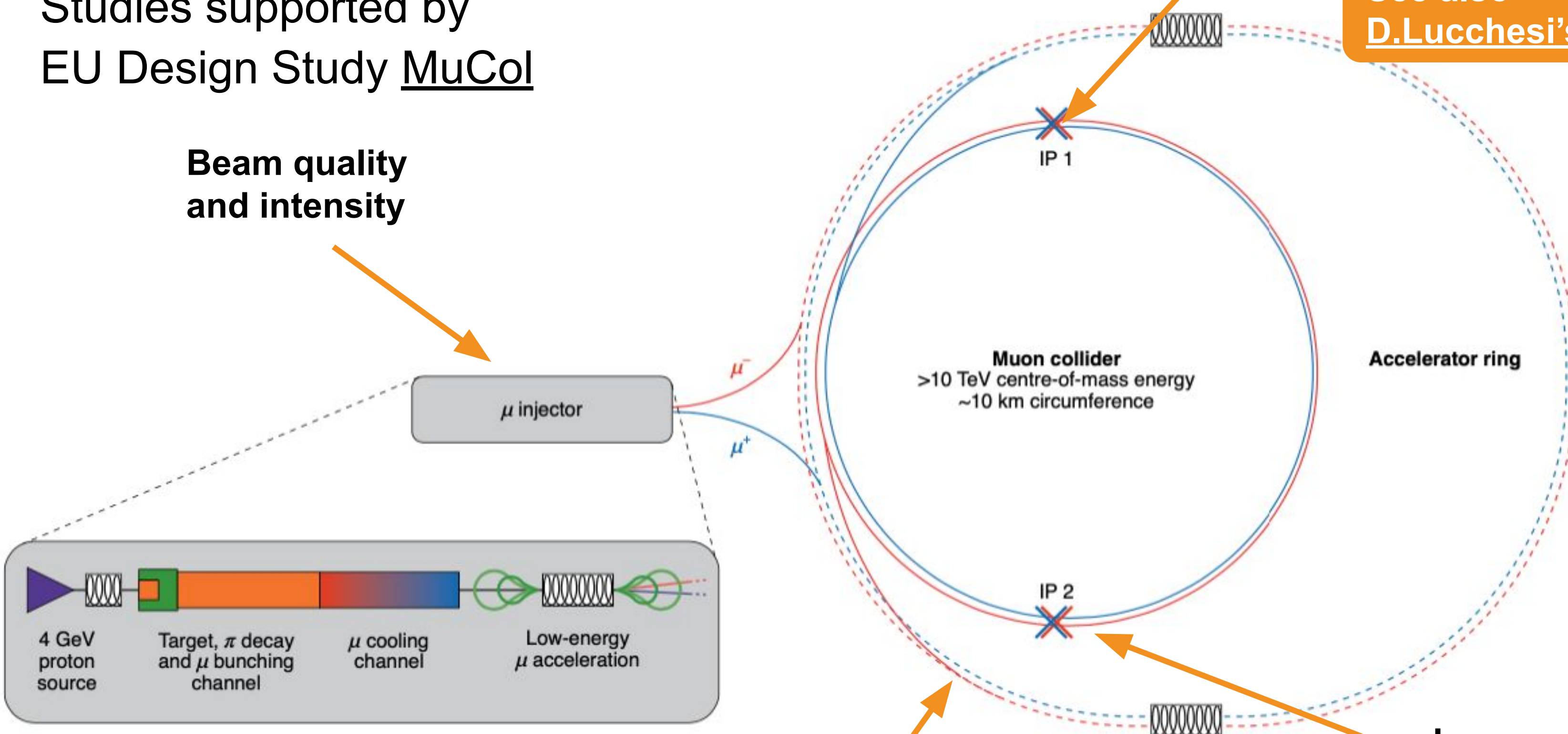
Muons have a **limited lifetime**: 2.2 μs at rest

- Studies supported by EU Design Study MuCol

Beam induced backgrounds

See also D.Lucchesi's talk!

Beam quality and intensity



Large neutrino flux

Cost and power

A new detector for 10 TeV

Detector model based on ongoing work from D. Calzolari, K. DiPetrillo, R. Hillman, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, FM, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

The detectors need to be ready to **measure both TeV-scale particles as well as GeV-scale**

Detector sizes need to grow

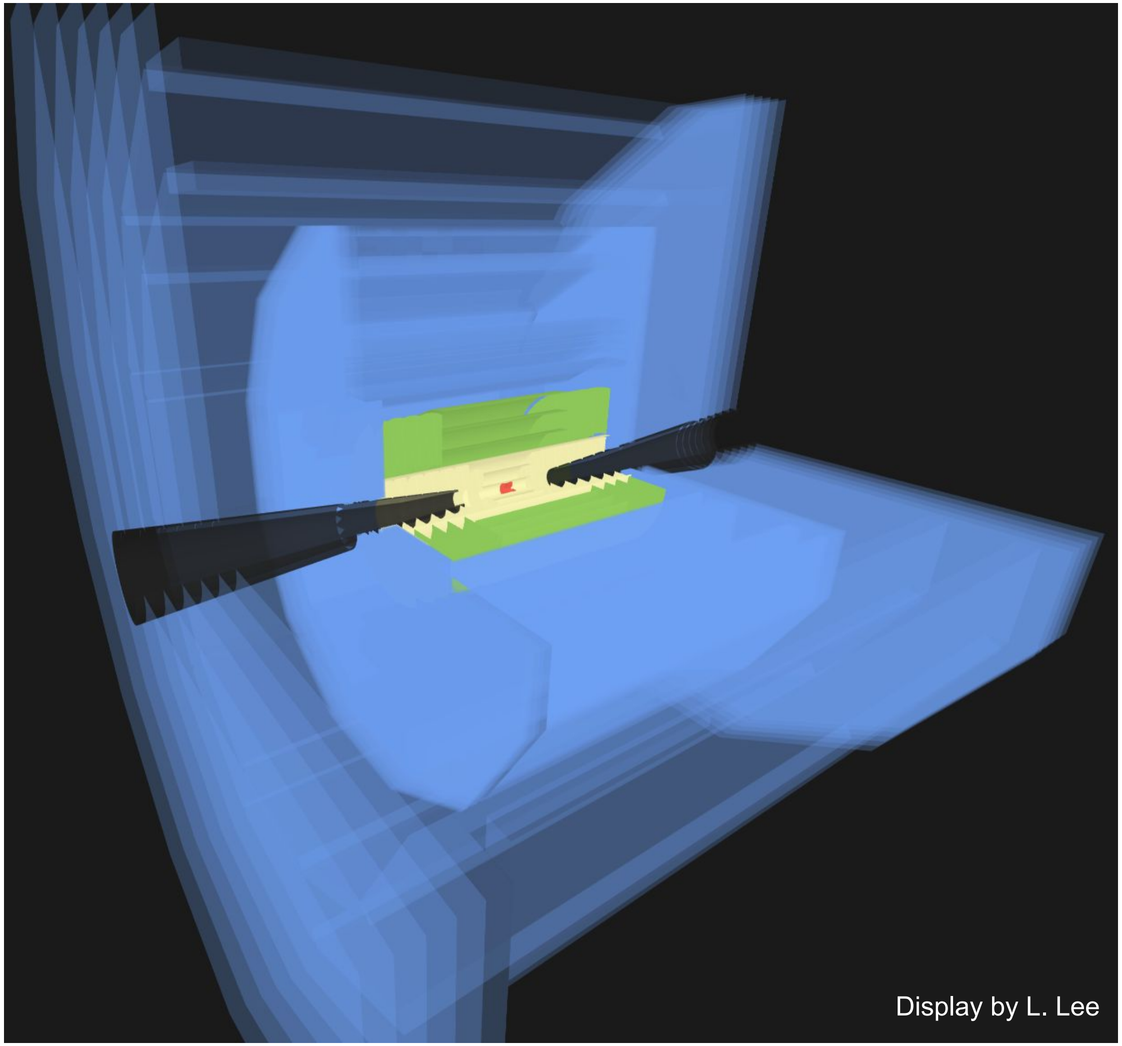
- Thicker calorimeters
- Bigger trackers with high precision in more places

See also L. Sestini's talk!

Physics benchmarks are key to guide the detector a design

In this talk:

- Winos and higgsinos
- Heavy Vector Triplets



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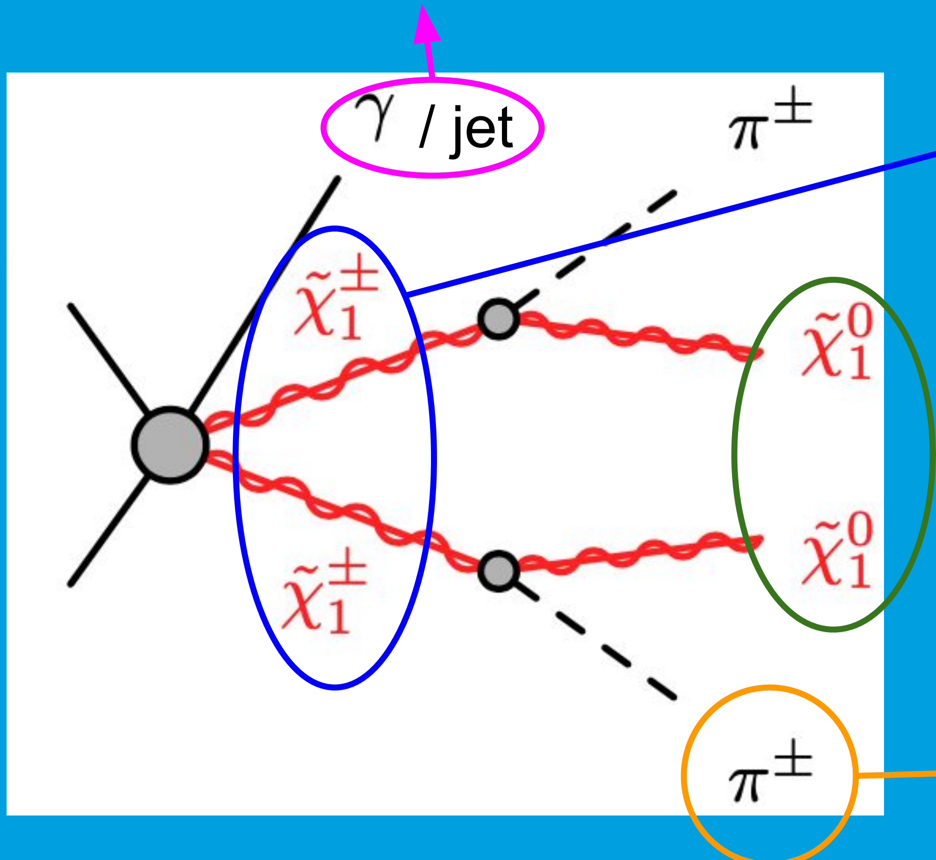
Disappearing tracks

ISR/FSR:
- “Trigger” the event



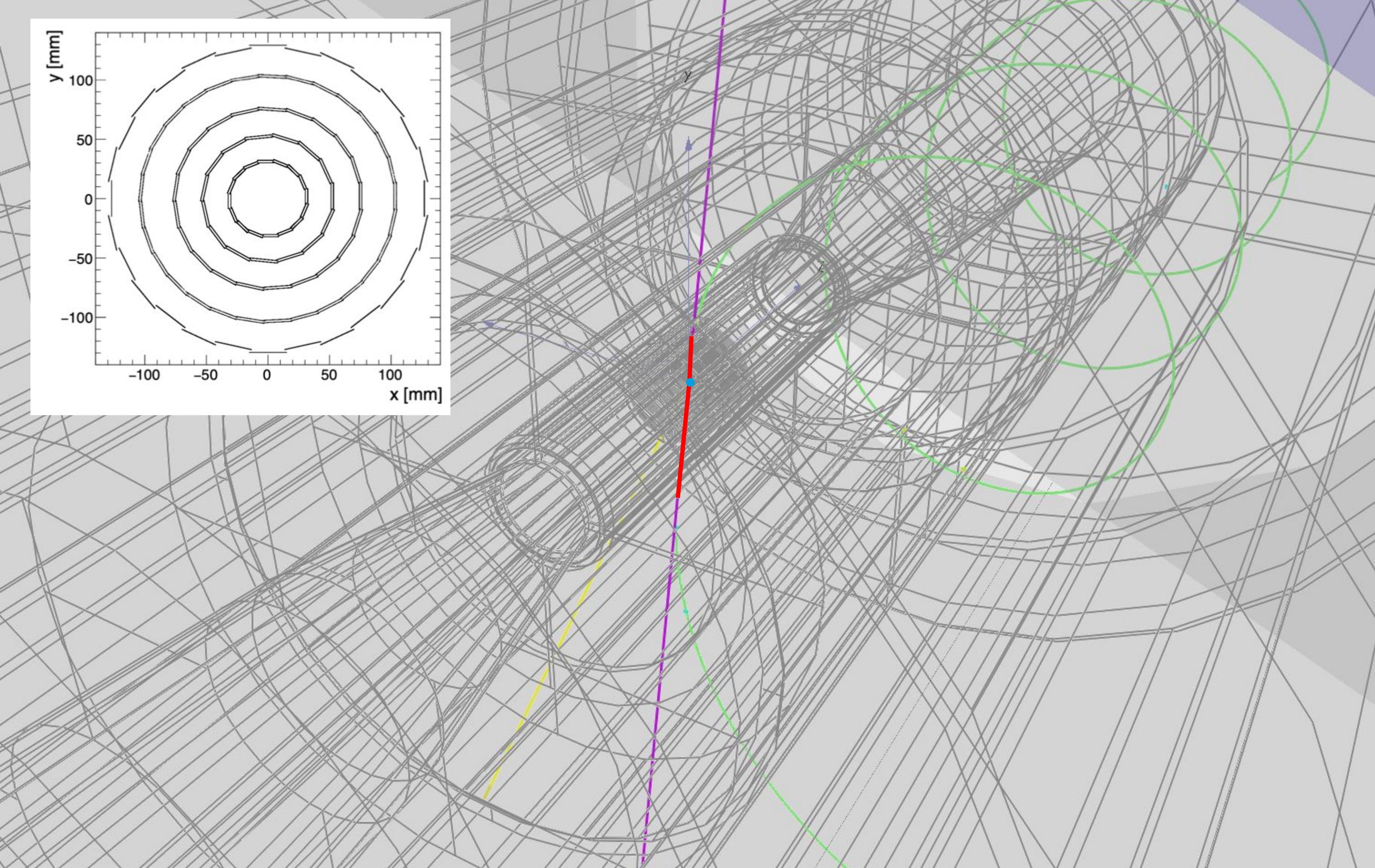
Charginos:
- Long lived, charged
- Reconstructable as “tracklets”

Neutralinos:
- Stable, neutral
- Invisible

Displaced pions:
- Possibly reconstructable
- Not considered here

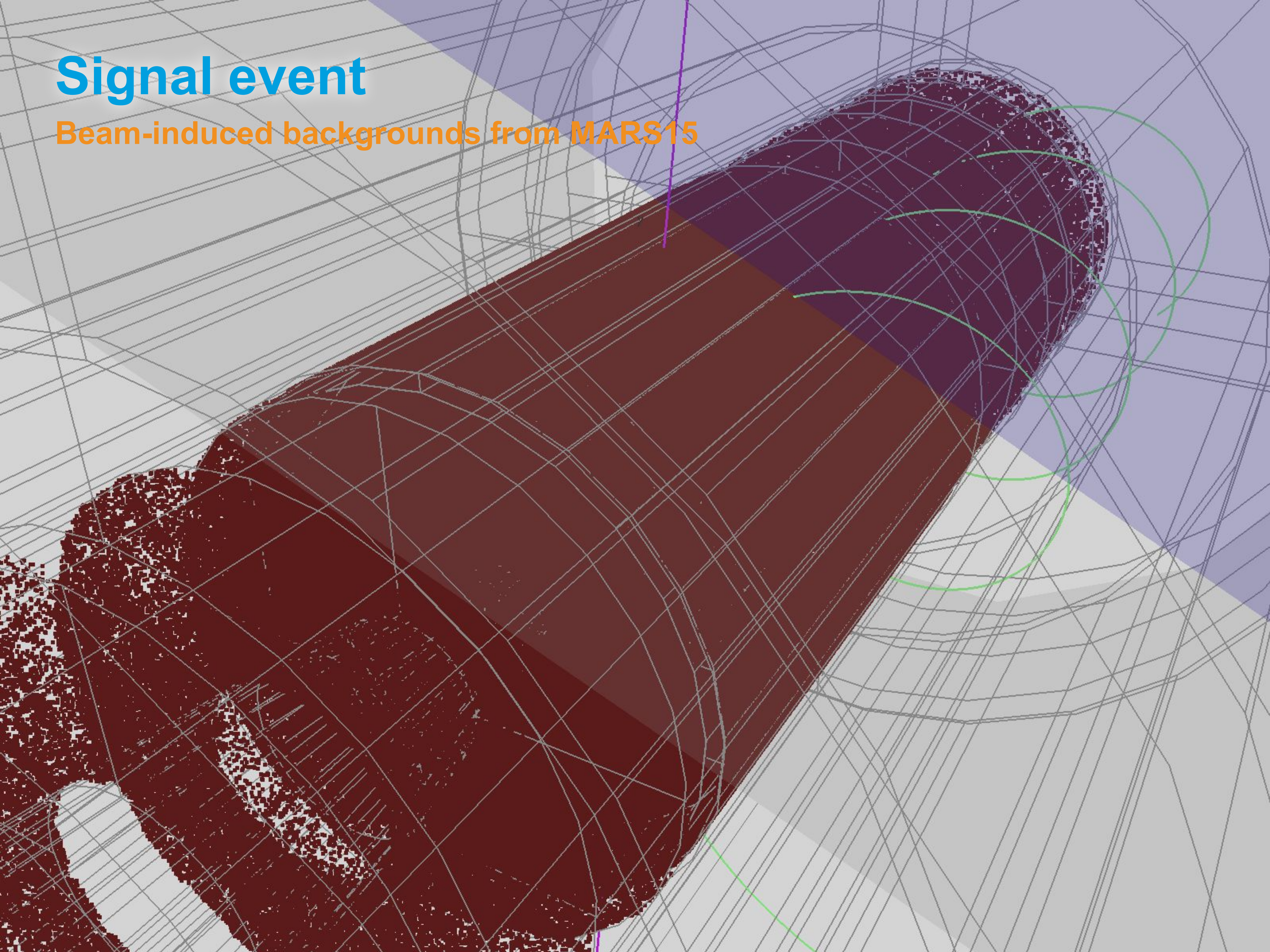
Signal event

No beam-induced backgrounds



Signal event

Beam-induced backgrounds from MARS15

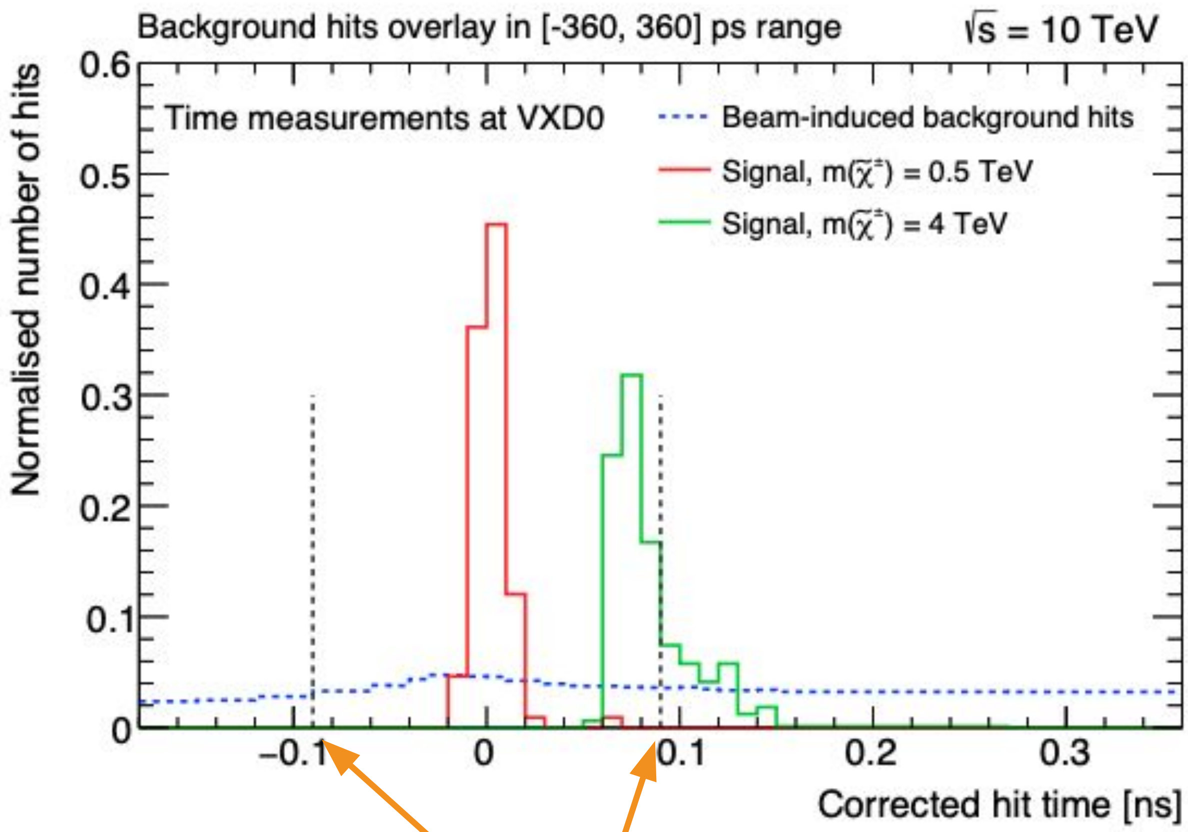


BIB rejection: timing

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV

Exploit particle arrival times to reduce BIB

- Correct for time of flight Corrected time $= t_{measured} - \frac{|r|}{c}$



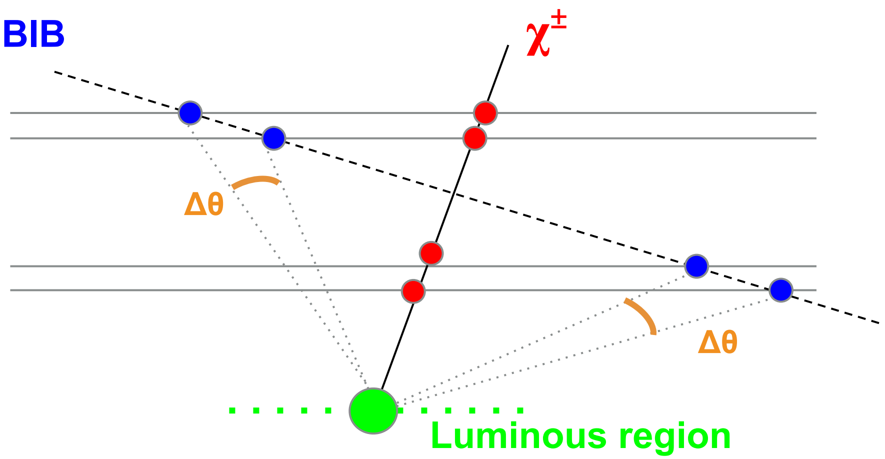
Select hits within a time window

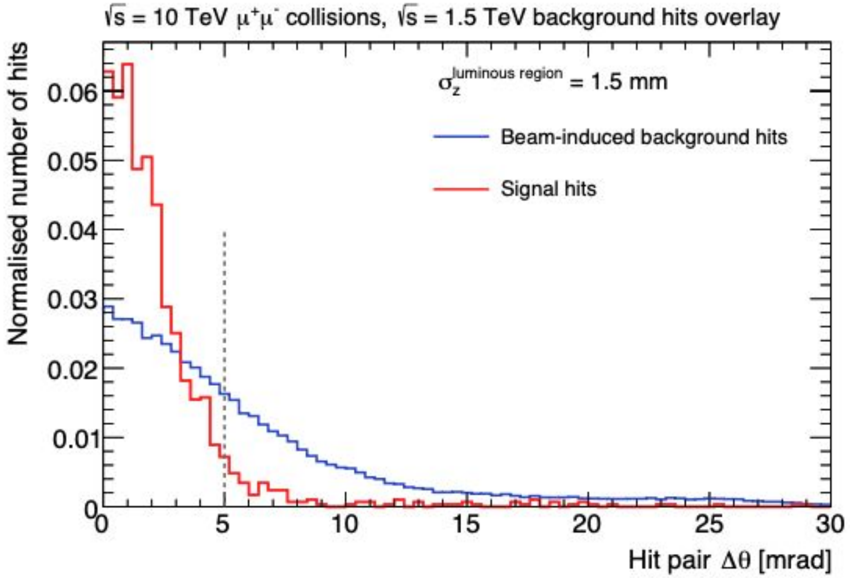
BIB rejection: stubs

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV

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





Tracklet reconstruction

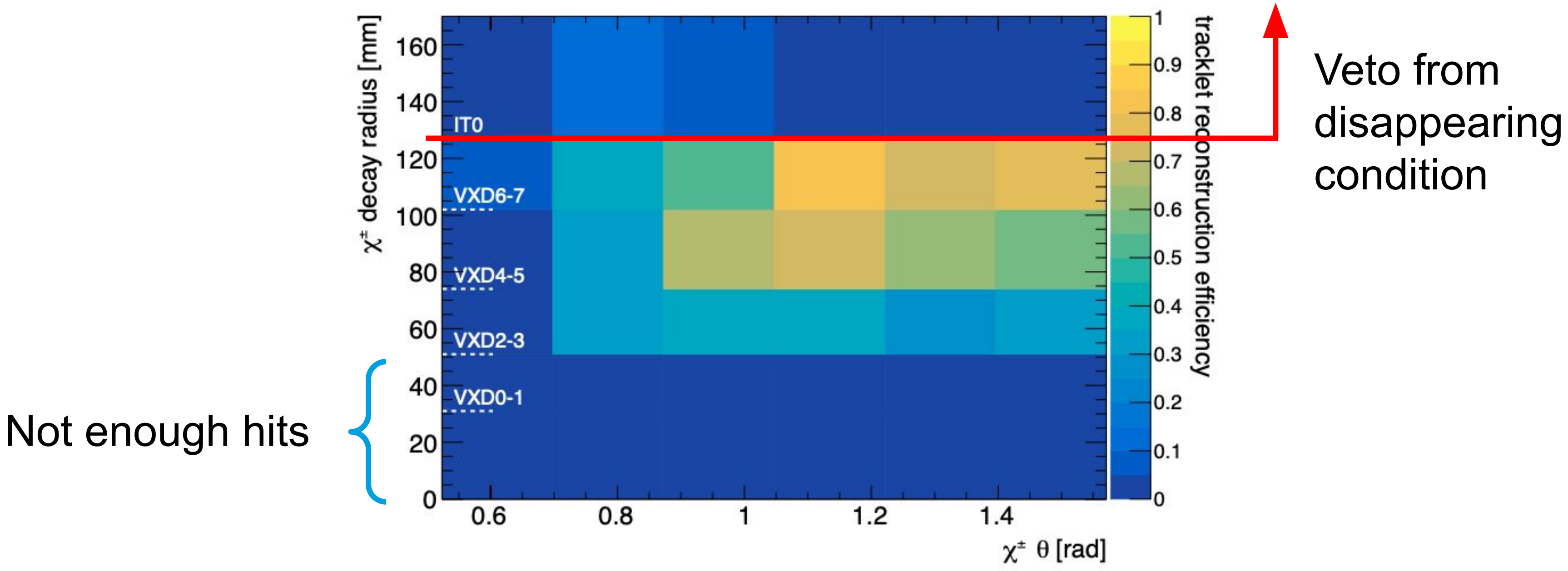
After BIB rejection cuts

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV

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

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

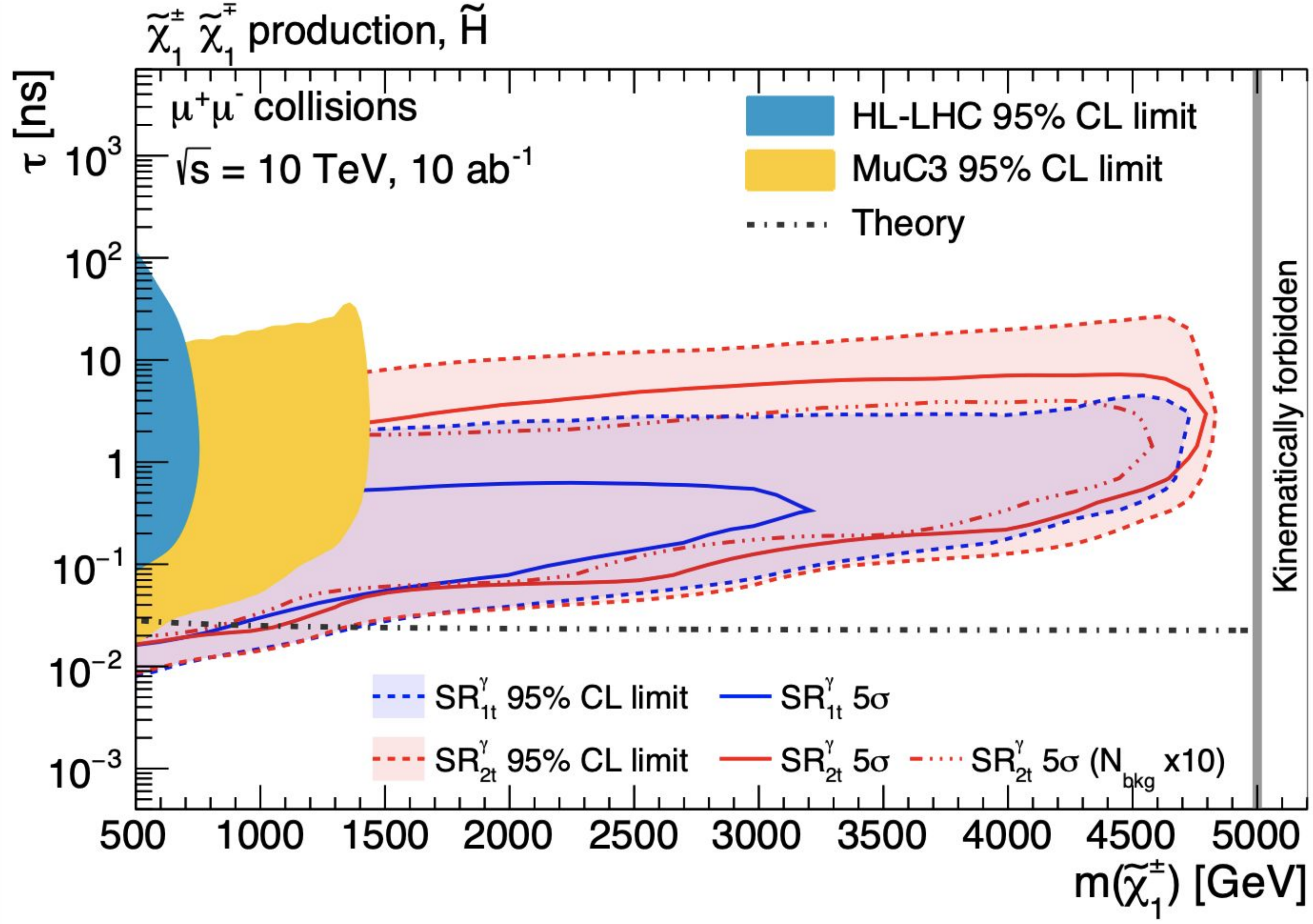
- Evaluated vs the $\chi^{\pm}$ decay radius and polar angle θ



Expected sensitivity

Pure higgsino models at MuC 10

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV



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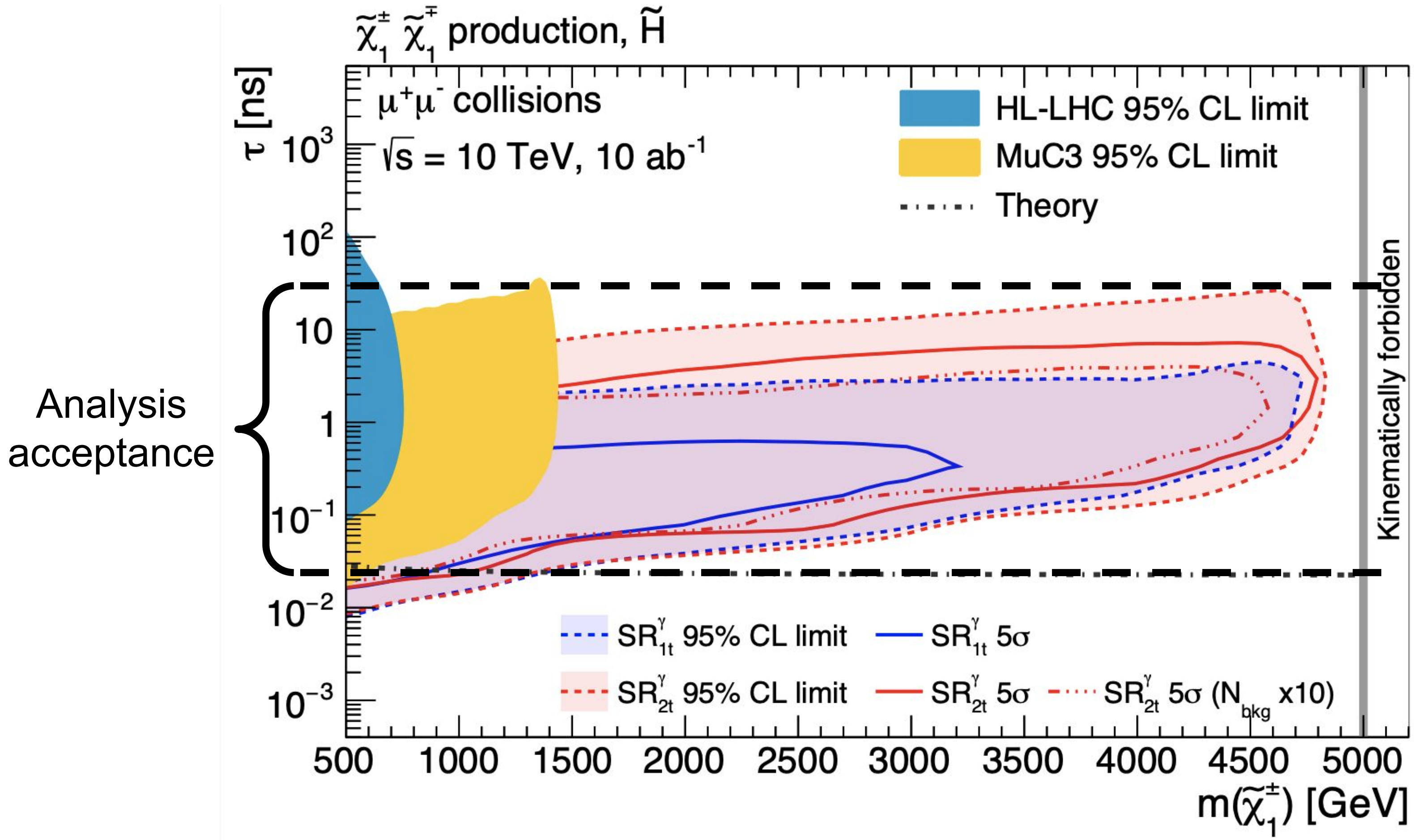
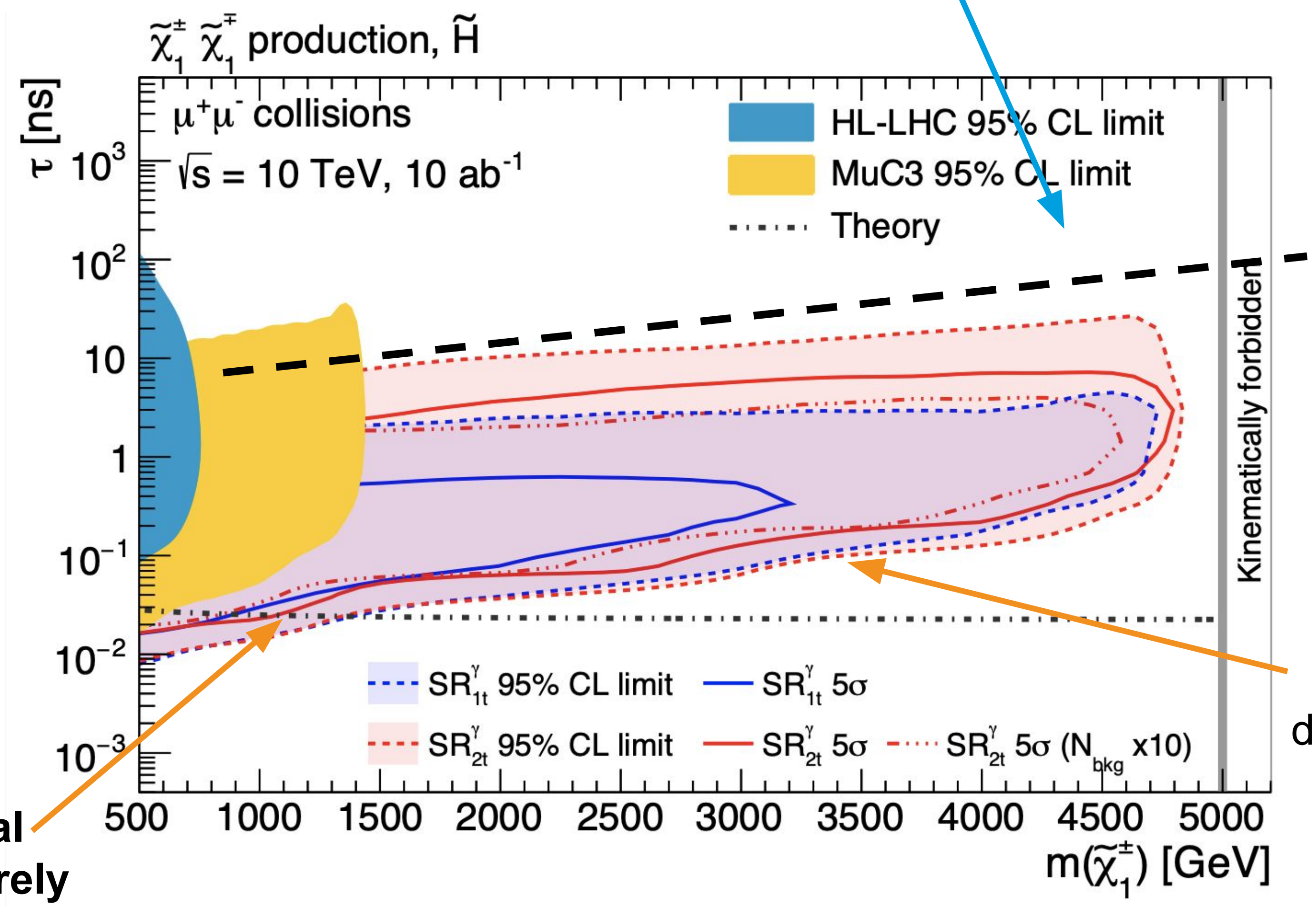


Expected sensitivity

Pure higgsino models at MuC 10

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

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV



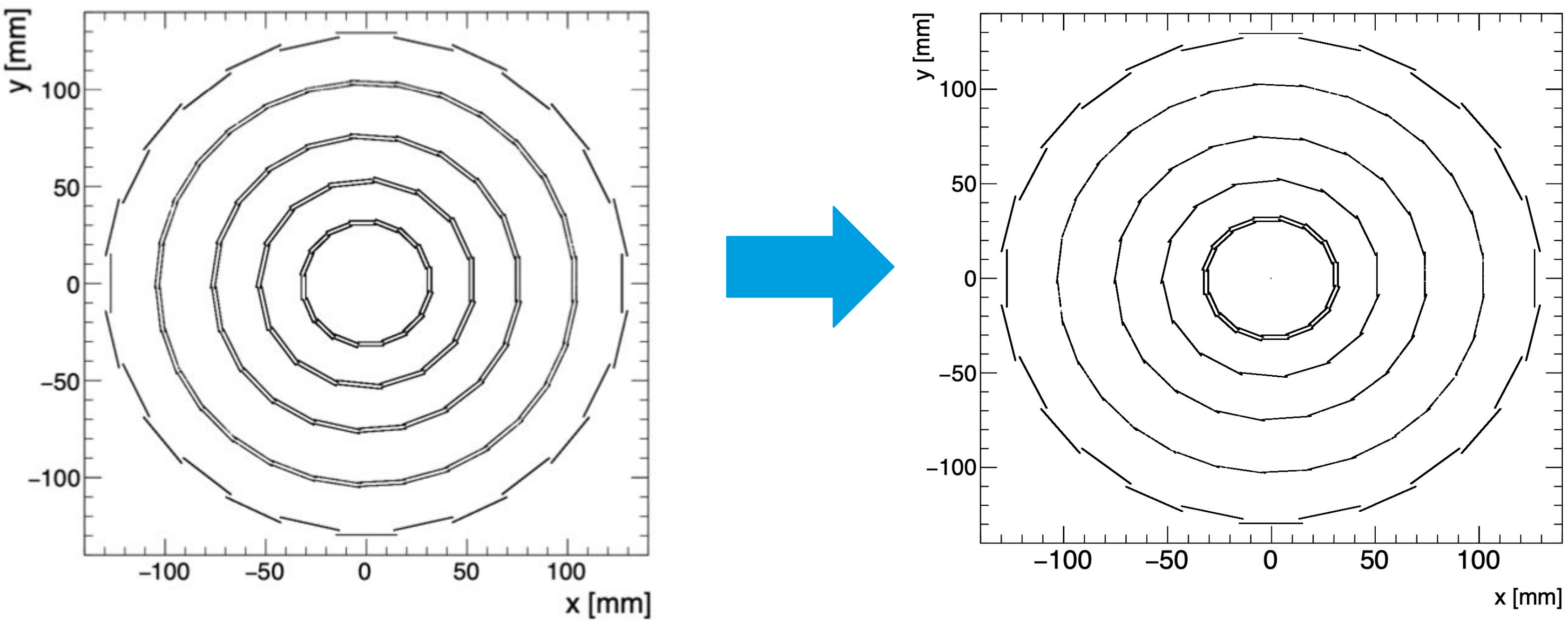
Thermal target barely covered

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

Updating to a new tracker

Power considerations and a greatly improved tracking software (now based on the ACTS library) made the double layers questionable.

- Barrel region of vertex detector revised keeping only one double layer pair



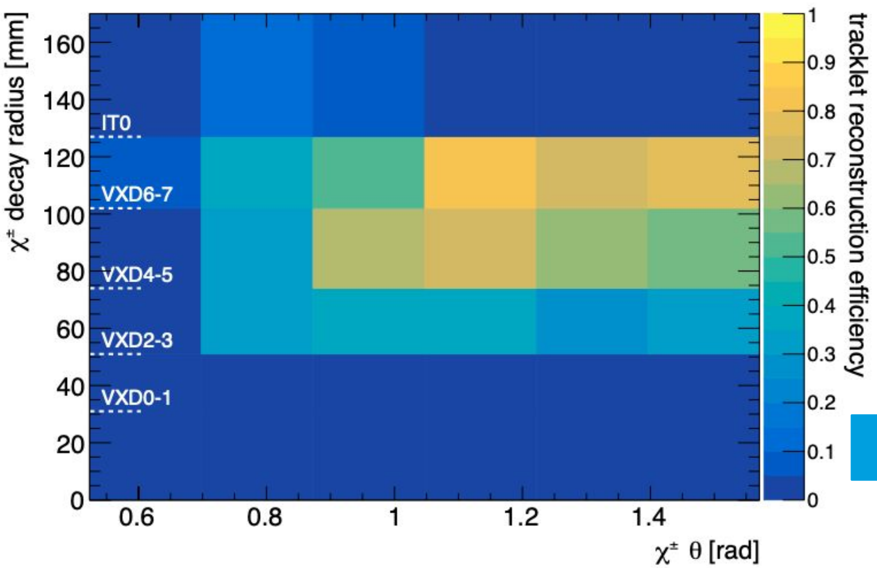
Updating to a new tracker

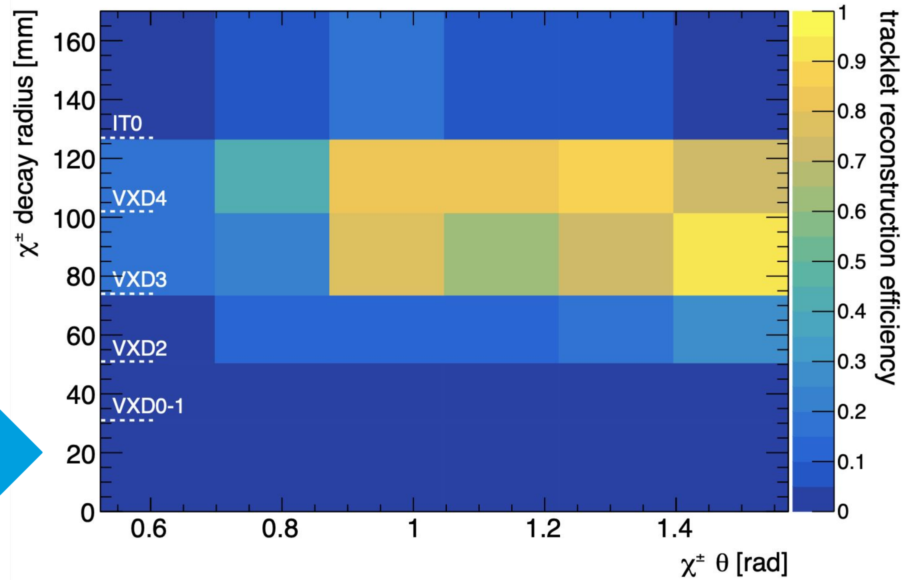
New tracker layout and tracking algorithm

Kept all tracklet quality requirements as before except:

$N_{hit} \geq 3$ hits   No stub track requirement

Found **similar detection efficiency**, and **greatly reduced fake** tracklet rate

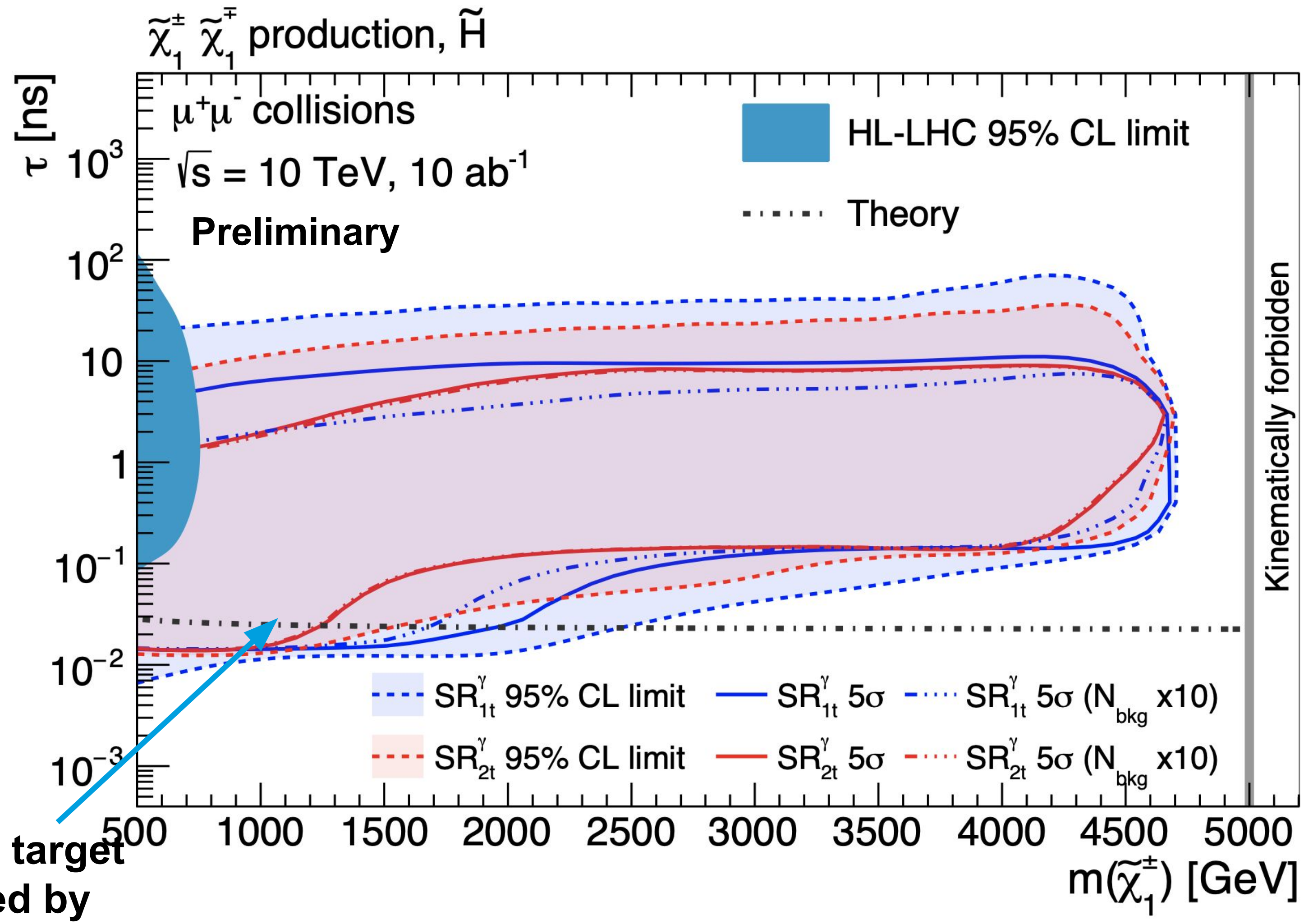




Expected sensitivity

Pure higgsino models at MuC 10

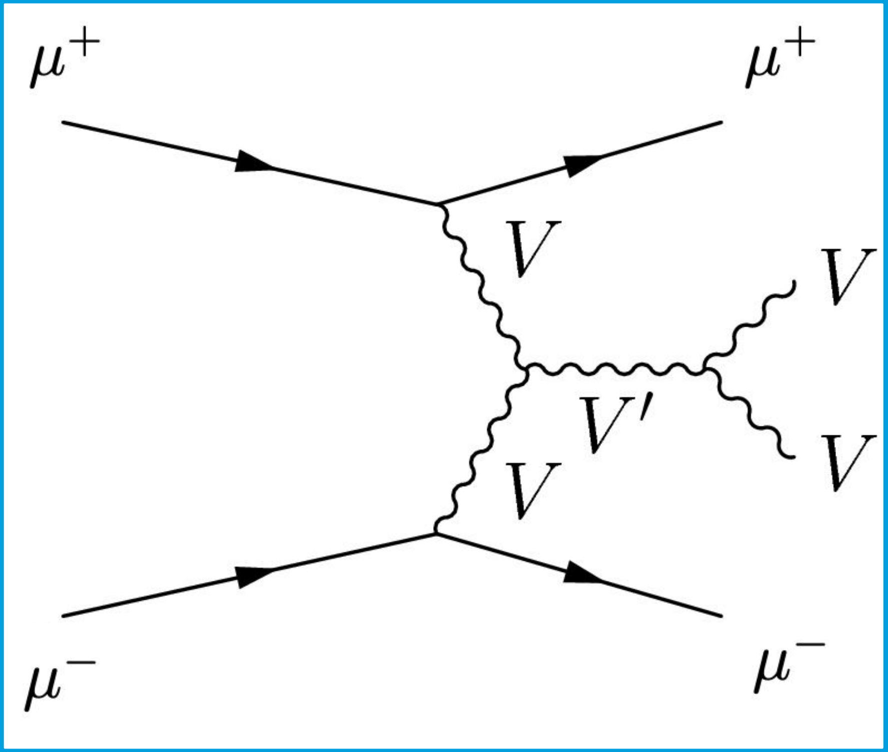
10 TeV detector
Preliminary 10 TeV BIB overlay



Thermal target covered by both selections

Dedicated discussion

Heavy resonances



Very large set of final states

- Leptons, quarks
- Bosons

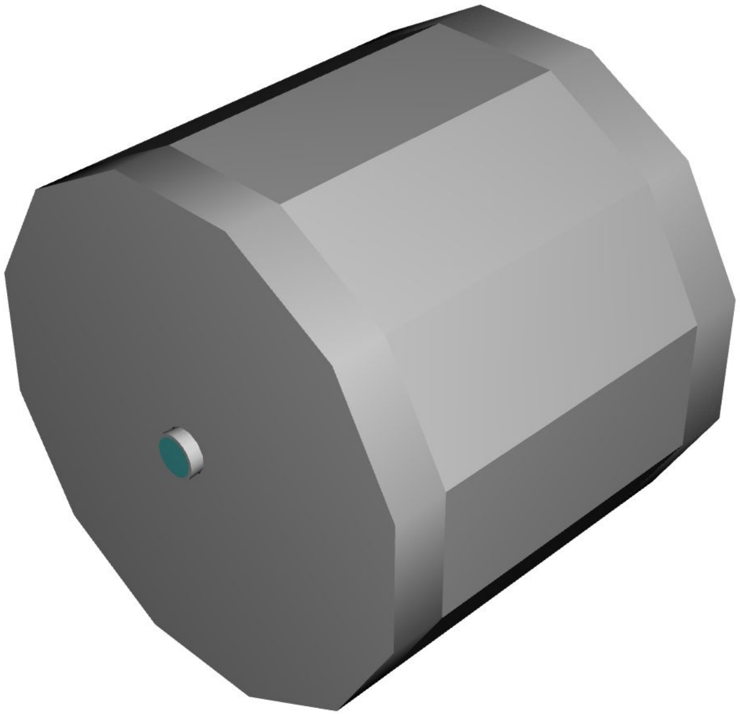
Equally large set of productions modes

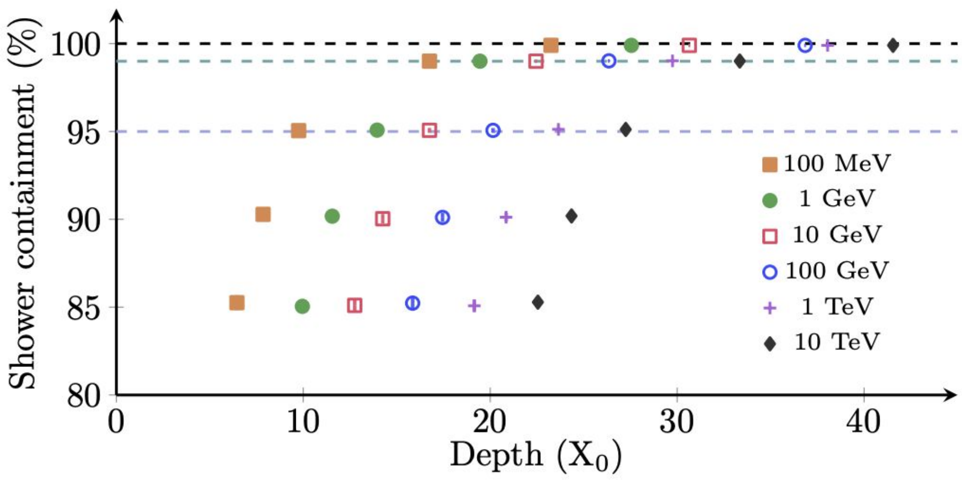
- Powerful probe of high-energy final states

Heavy vector triplets and calorimetry

Design of 10 TeV detector concept
started and progressing vigorously

- **Want to measure, not only discover**
- Many opportunities to experiment with new ideas





Updated calorimetry

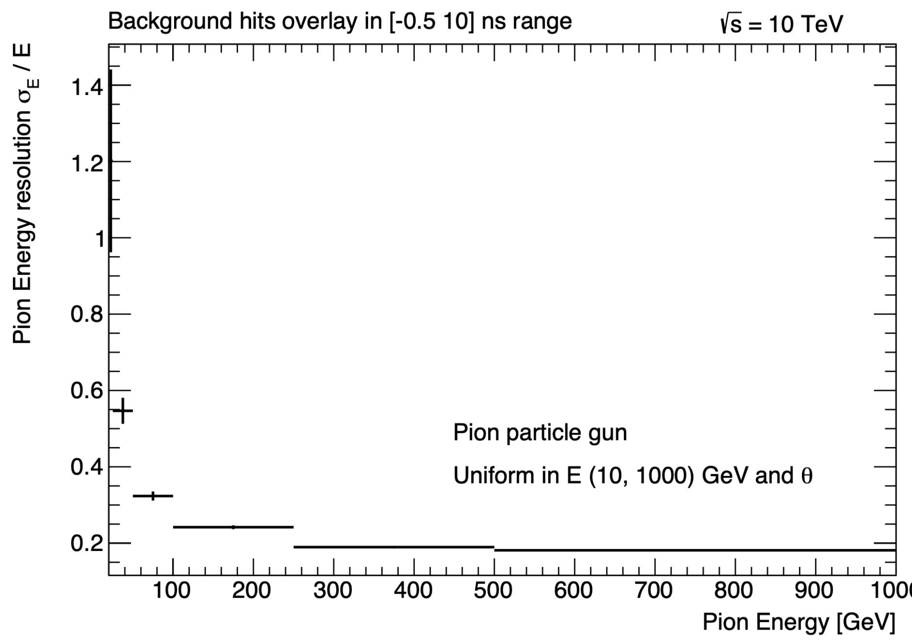
10 TeV detector
Preliminary 10 TeV BIB overlay

Changes to EM calorimeter:

- Kept same Si-W technology
- 40 → 50 layers
- Tungsten absorber 1.9 → 2.20 mm

Changes to Hadron calorimeter:

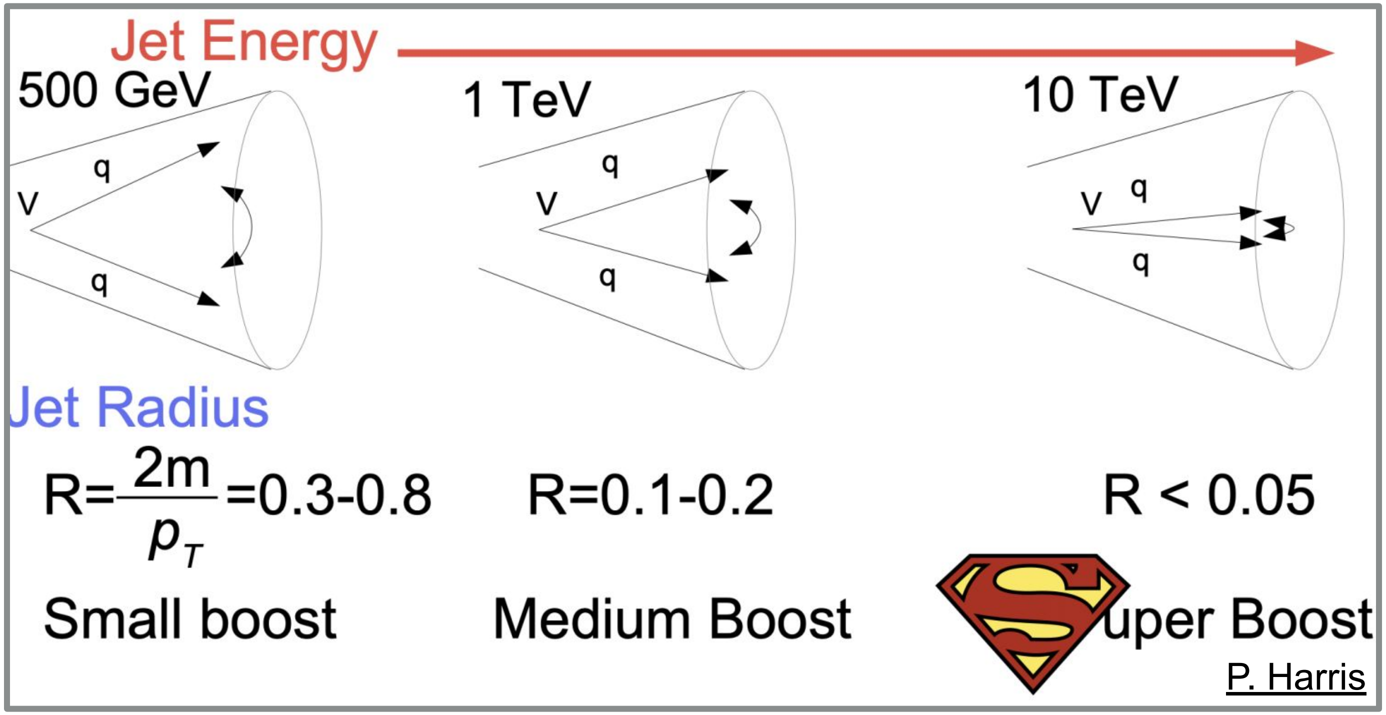
- Kept same Fe-Scintillator technology
- 60 → 75 layers



Towards 10 TeV reconstruction

The reconstruction algorithms that were designed at 3 TeV are not guaranteed to work at 10 TeV

- Significantly different energy regime
- Higher detector granularity might require new approaches

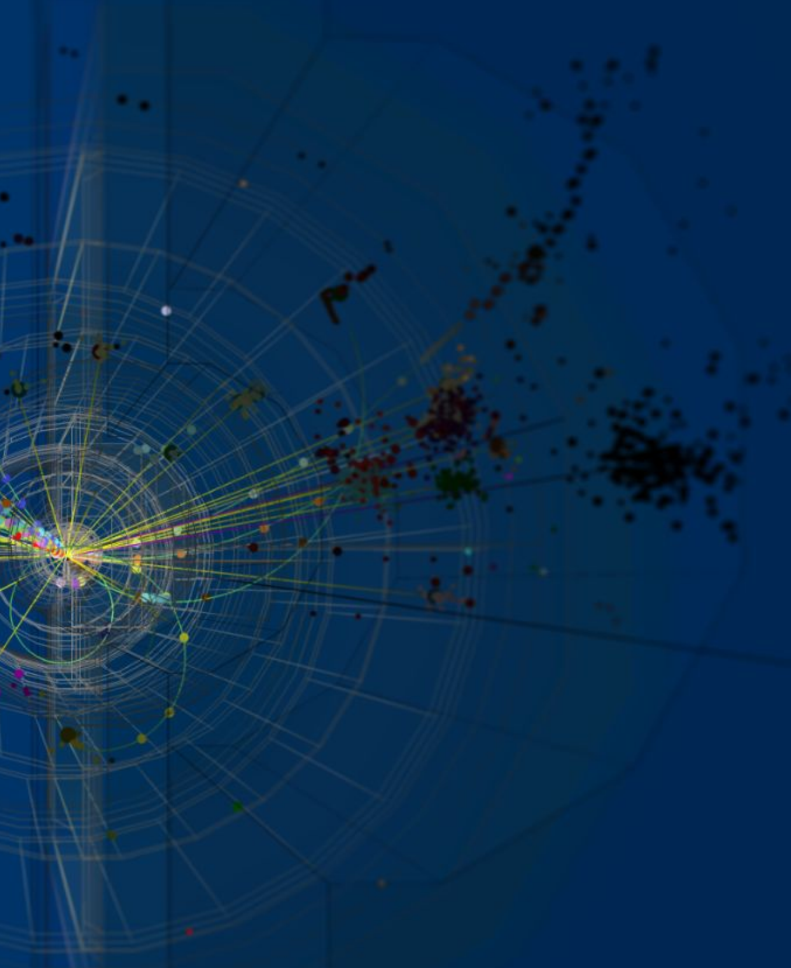


Summary

The muon collider presents **enormous potential for fundamental physics research** at the energy frontier

Physics reach of a multi-TeV μC relies on (among other things) **successful detector design programme today**

The road ahead is filled with challenging and **interesting R&D**!



Background image credit: L. Lee

Thank you!

Interested?

Join the IMCC physics studies (https://indico.cern.ch/category/12792/)
and Detector and MDI (https://indico.cern.ch/category/13145/) communities!

Contact

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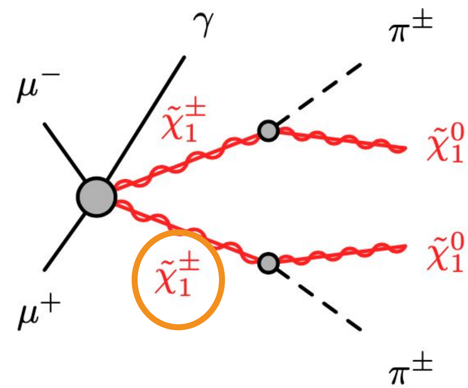
Background image credit: L. Lee

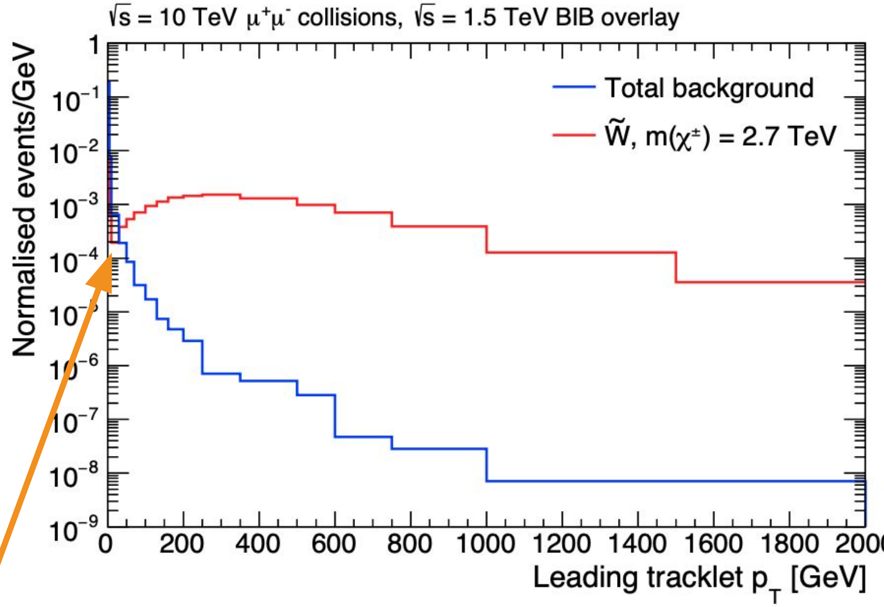
Event selection



Relatively simple event selection:

- Tracklet p_T (single most important quantity)

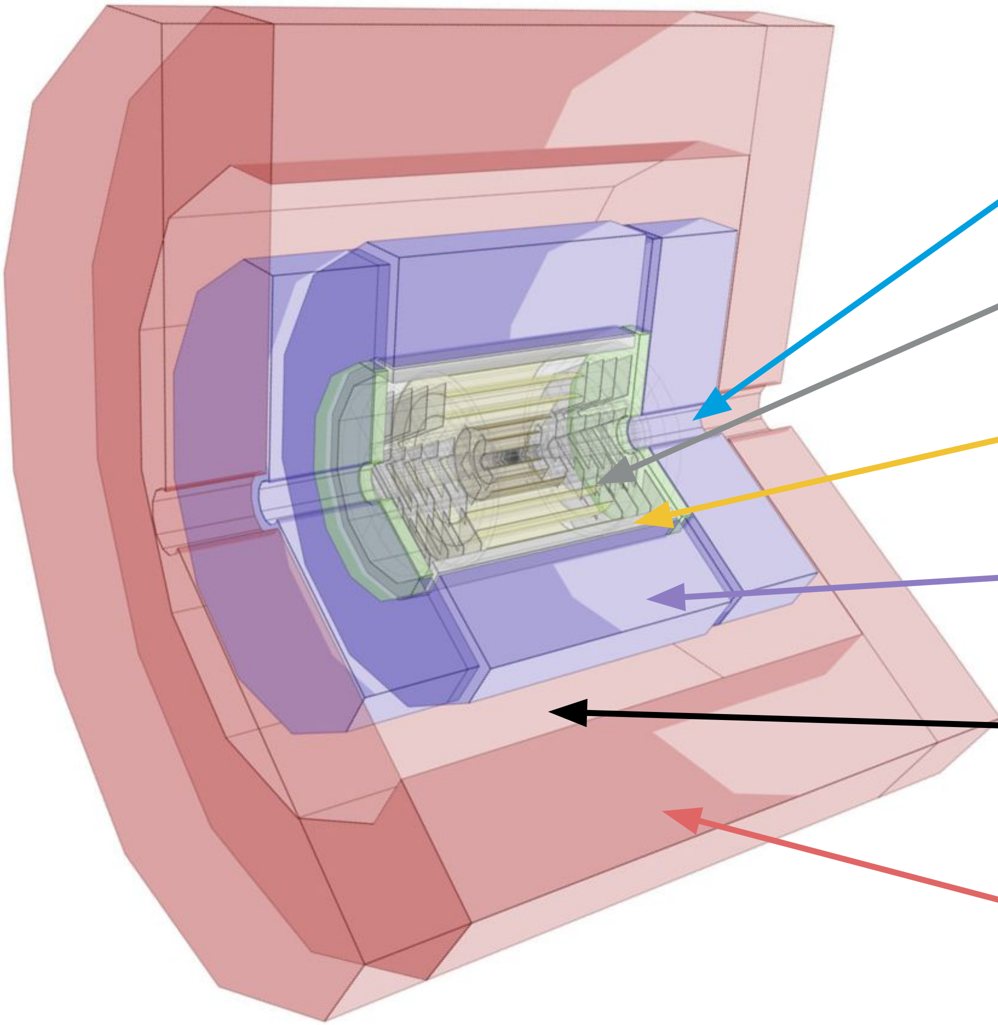
Requirement / Region	SR^{γ}_{1t}	SR^{γ}_{2t}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25



Peak at low p_T in signal events due to BIB overlay

Current detector design

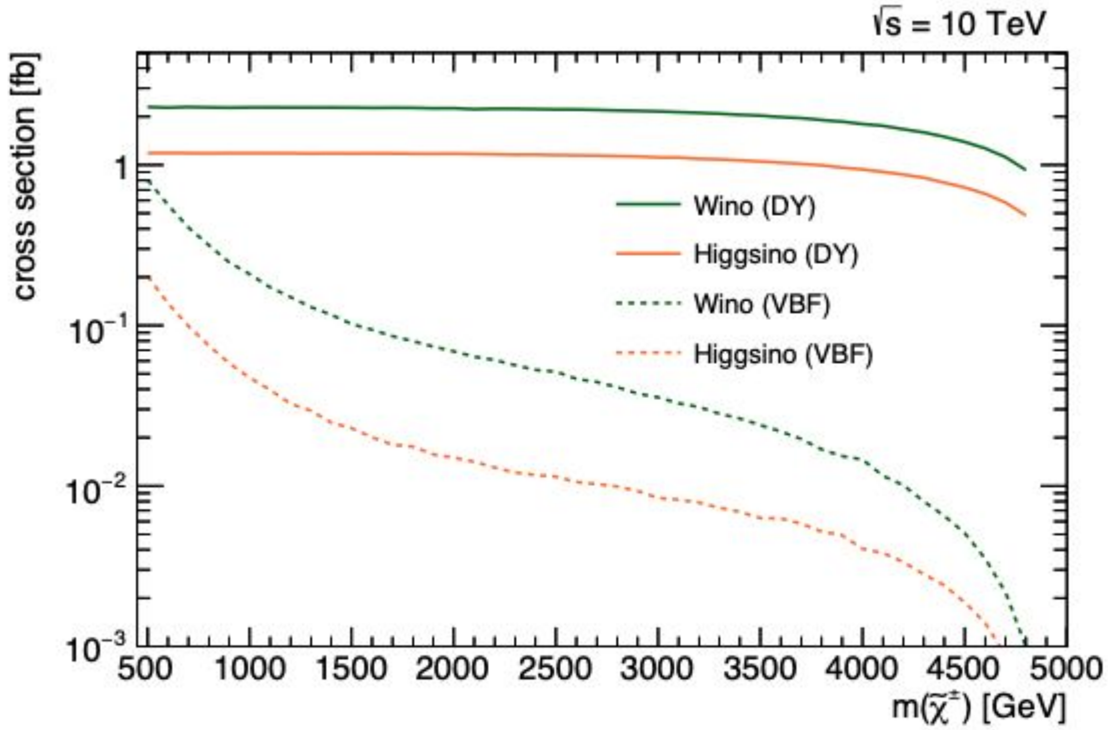
The detector model is based on the CLIC concept



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

The 12 challenges of a MuC

Many thanks to S. Jindariani, D. Schulte, and M. Wing for inputs and useful discussions

	Target	Status	Notes	Future work
Pulse compression	1-3 ns	SPS does O(1) ns	Need higher intensity. O(30) ns loses only factor 2 in the produced muons.	Refine design, including proton acceleration. Accumulation and compression of bunches.
High-power targets	2 MW	2 MW	Available for neutrino and spallation neutrons. Aim for 4 MW to have margin.	Develop target design for 2 MW, O(1) ns bunches create larger thermal shocks. Prototype in 2030s.
Capture solenoids	15 T	13 T	ITER central solenoid.	Study superconducting cables and validate cooling. Investigate HTS cables.
Cooling solenoids	50 T	30-40 T	30 T leads to a factor 2 worse transverse emittance with respect to design.	Extend designs to the specs of the 6D cooling channel. Demonstrator.
RF in magnetic field	>50 MV/m	65 MV/m	MUCOOL published results. Requires test in non-uniform B.	Design to the specs of 6D cooling. Demonstrator.
6D cooling	10^{-6}	0.9 (1 cell)	MICE result (no re-acceleration). Emittance exchange demonstrated at g-2.	Optimise with higher fields and gradients. Demonstrator.
RCS dynamics	-	-	Simulation. 3 TeV lattice design in place.	Develop lattice design for a 10 TeV accelerator ring.
Rapid cycling magnets	2 T/ms 2 T peak	2.5 T/ms 1.81 T peak	Normal conducting magnets. HTS demonstrated 12 T/ms, 0.24 T peak.	Design and demonstration work. Optimise power management and re-use.
Ring magnets aperture	20 T quads	12-15 T (Nb3Sn)	Need HTS or revise design to lower fields.	Design and develop larger aperture magnets, 12-16 T dipoles and 20 T HTS quads.
Collider dynamics	-	-	3 TeV lattice in place with existing technology.	Develop lattice design for a 10 TeV collider.
Neutrino radiation	10 μSv/year	-	3 TeV ok with 200 m deep tunnel. 10 TeV requires a mover system.	Study mechanical feasibility of the mover system impact on the accelerator and the beams.
Detector shielding	Negligible	LHC-level	Simulation based on next-gen detectors.	Optimise detector concepts. Technology R&D.

Muon collider target parameters

Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	E_{cm}	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}cm^{-2}s^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}cm^{-2}s^{-1}$	1.8	20	40	2
Collider circumference	C_{coll}	km	4.5	10	14	—
Muons/bunch	N	10^{12}	2.2	1.8	1.8	0.0037
Repetition rate	f_r	Hz	5	5	5	50
Beam power	P_{coll}	MW	5.3	14.4	20	28
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5	0.2
Transverse emittance	ϵ	μm	25	25	25	660/20
Number of bunches	n_b		1	1	1	312
Number of IPs	n_{IP}		2	2	2	1
IP relative energy spread	δ_E	%	0.1	0.1	0.1	0.35
IP bunch length	σ_z	mm	5	1.5	1.07	0.044
IP beta-function	β	mm	5	1.5	1.07	
IP beam size	σ	μm	3	0.9	0.63	0.04/0.001

Beamstrahlung

Based on extrapolation of the MAP parameters

- Plan to operate 5 years at each centre-of-mass energy (FCC-hh to operate for 25 years)

A brief history of muon colliders

1970/90 Initial proposal

G.I. Budker, Accelerators and colliding beams, 1969
A.N. Skirnsky, Intersecting storage rings at Novosibirsk, 1971
D. Neuffer, Multi-TeV muon colliders, 1986

2013 - LEMMA

- Propose positron-driven scheme

2019 - MICE

- Demonstrates ionisation cooling

Today
IMCC

2011 - 2014 US Muon Accelerator Program MAP

- Short- and long-baseline neutrino facilities
- Higgs factory with good energy resolution
- TeV-scale muon collider

Muon Accelerators for Particle Physics

European Strategy for Particle Physics Update 2020

- Set up an international collaboration