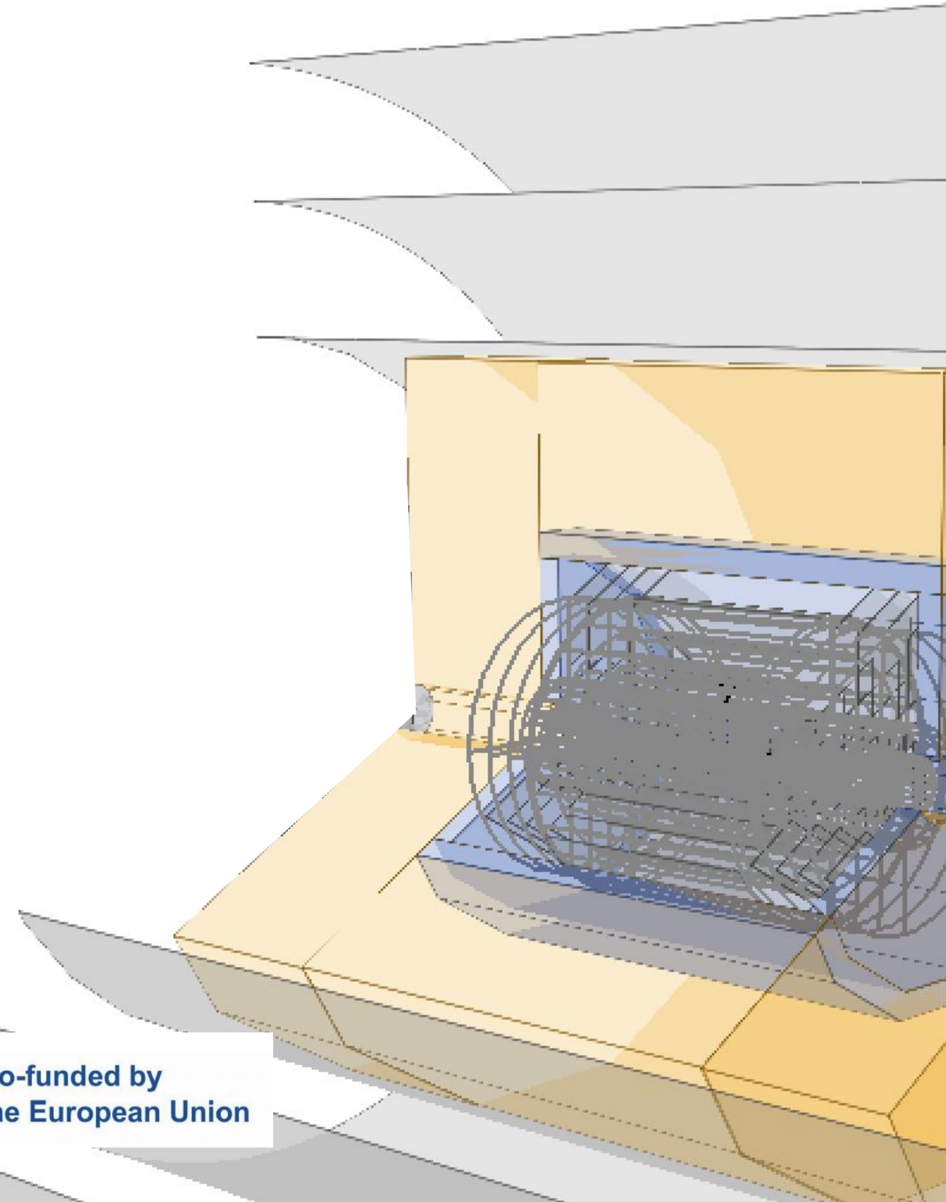
Disappearing tracks at a 10 TeV Muon Collider

IMCC physics studies meeting
07/09/2023

Federico Meloni (DESY)

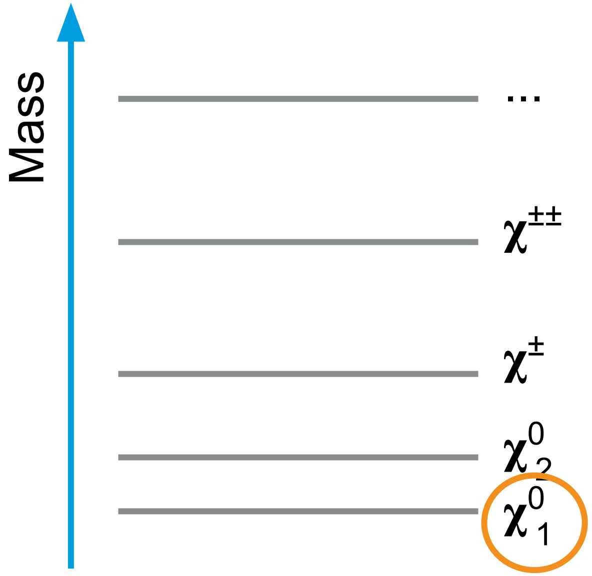


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DESY.
International MUON Collider Collaboration
MuCol
Co-funded by the European Union

Electroweak multiplets and dark matter

Start from the simplest interpretation of dark matter:
it is the **thermal relic of at least a new stable neutral particle**.

- The SM is extended with *n*-tuplets that predict such neutral state χ^0



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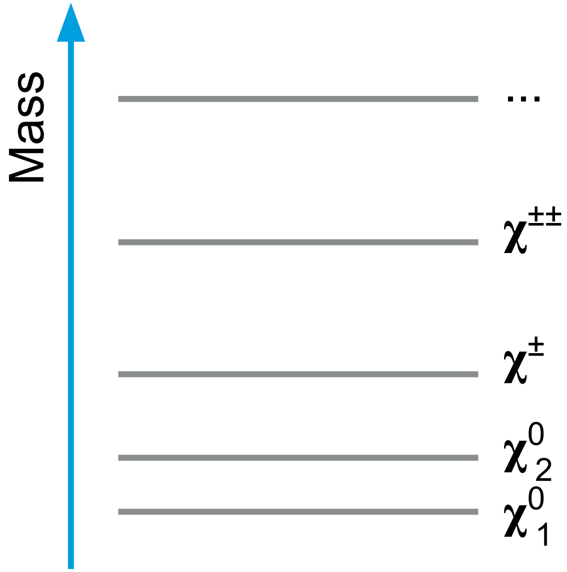

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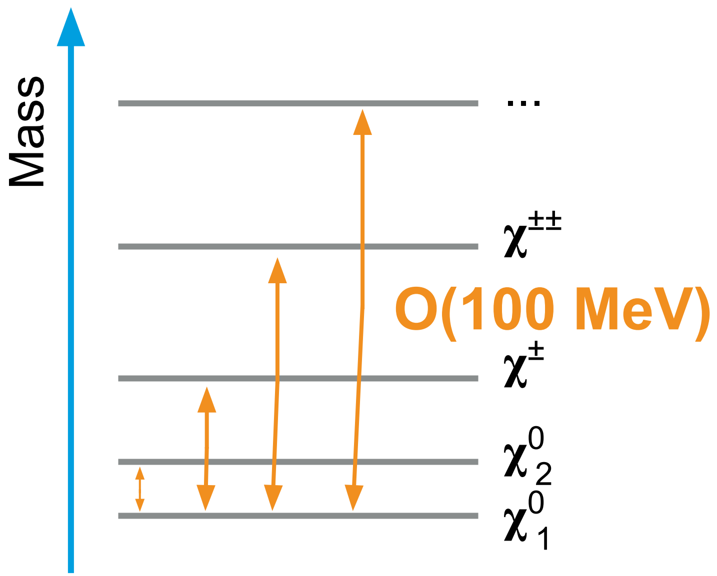

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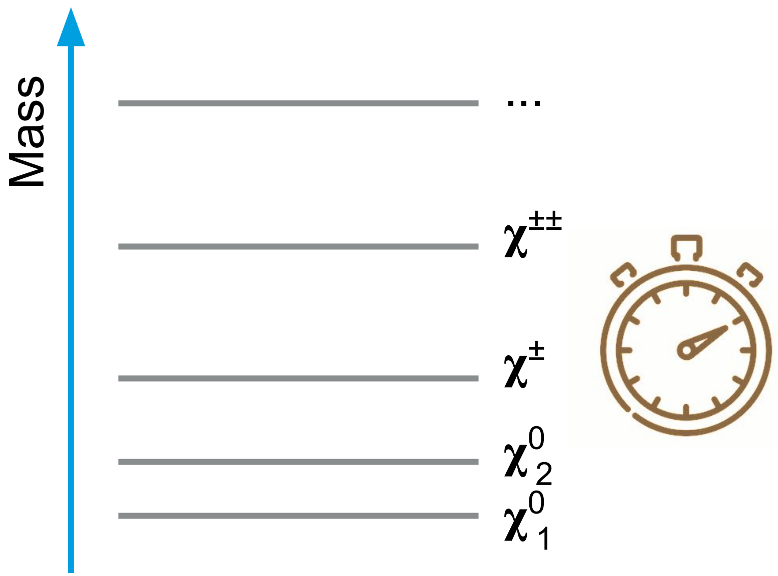

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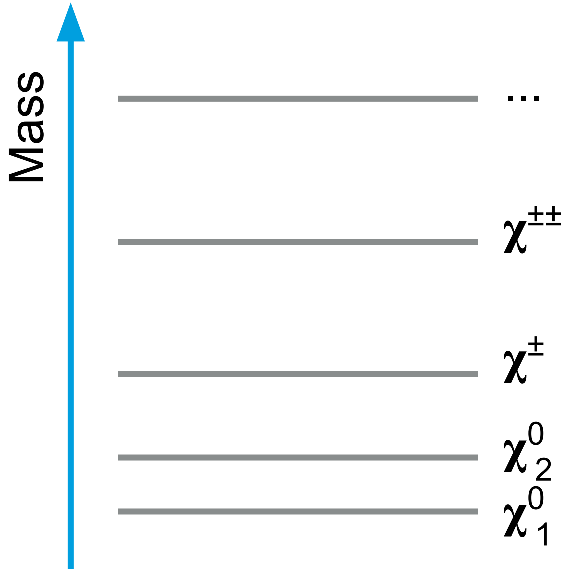

Experimental signatures:

- Displaced vertices
- Kinked tracks
- Displaced tracks
- Disappearing tracks

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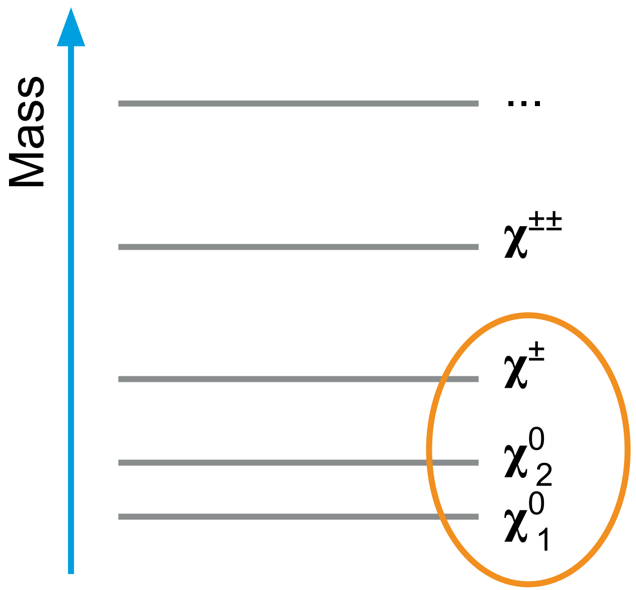


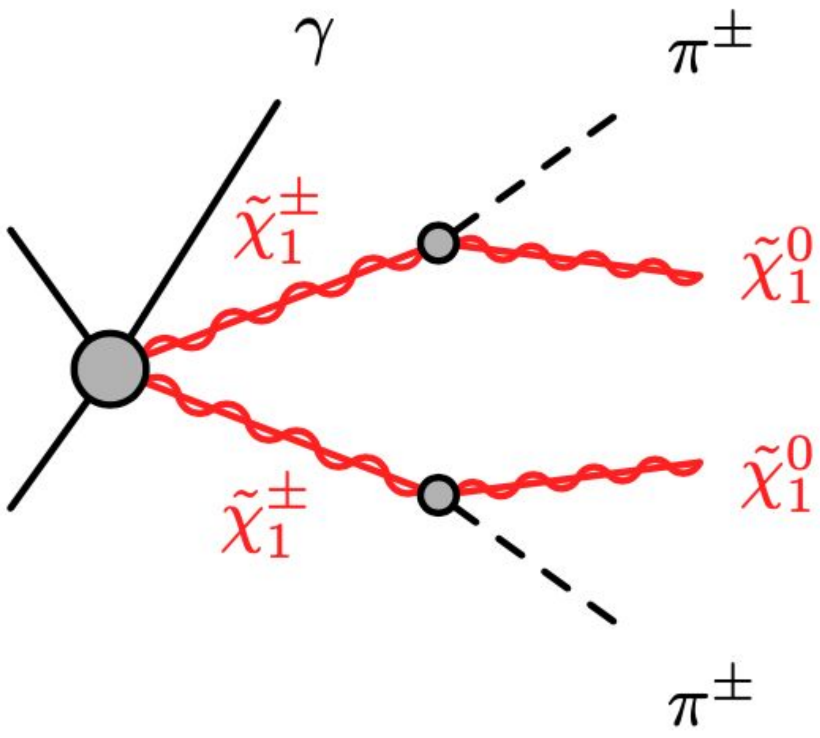
Experimental signatures:

- Displaced vertices
- Kinked tracks
- Displaced tracks
- **Disappearing tracks**

Consider the MSSM case: doublets (winos) and triplets (higgsinos)

The search for disappearing tracks

An example from supersymmetry



The search for disappearing tracks

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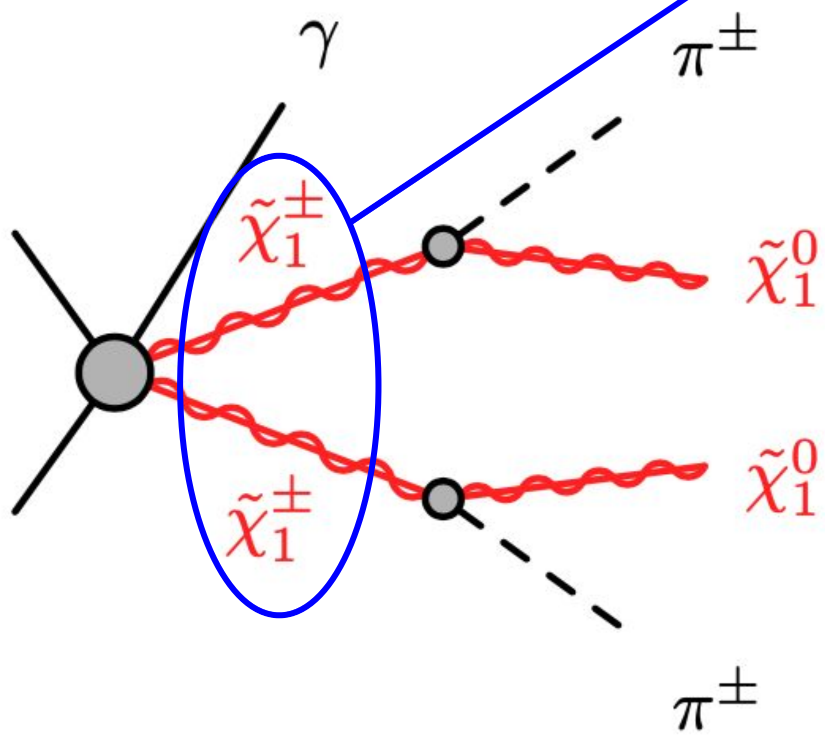
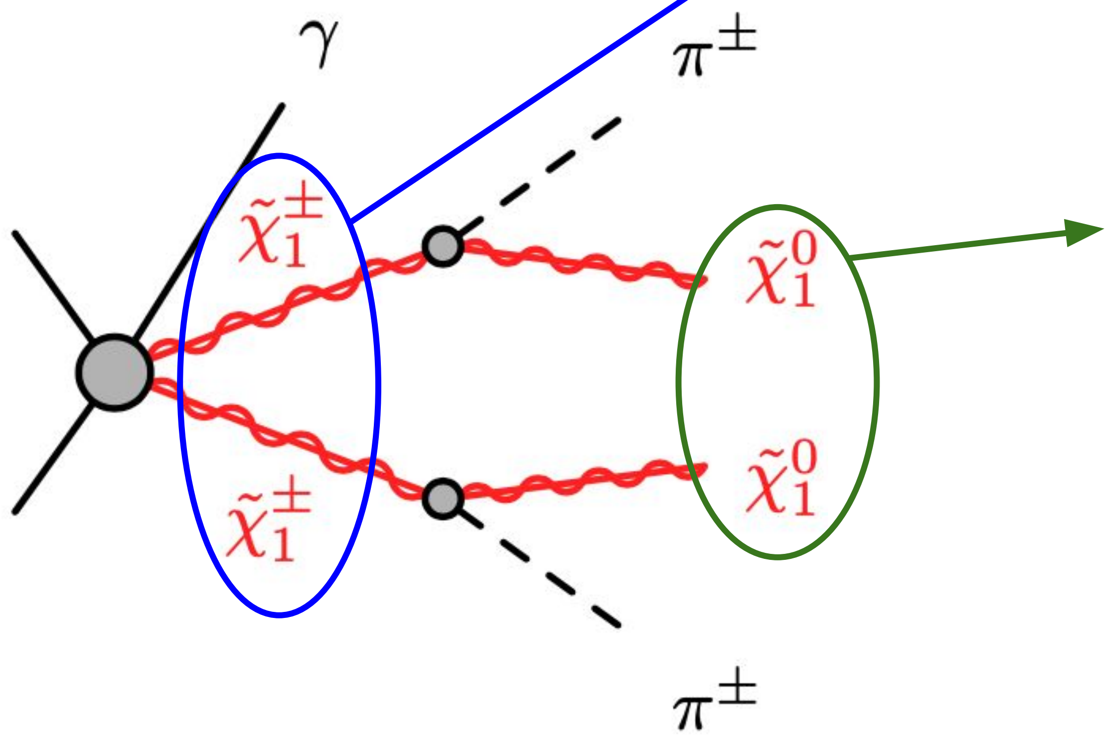


Charginos:

- Long lived, charged
- Reconstructable as "tracklets"

The search for disappearing tracks

An example from supersymmetry



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

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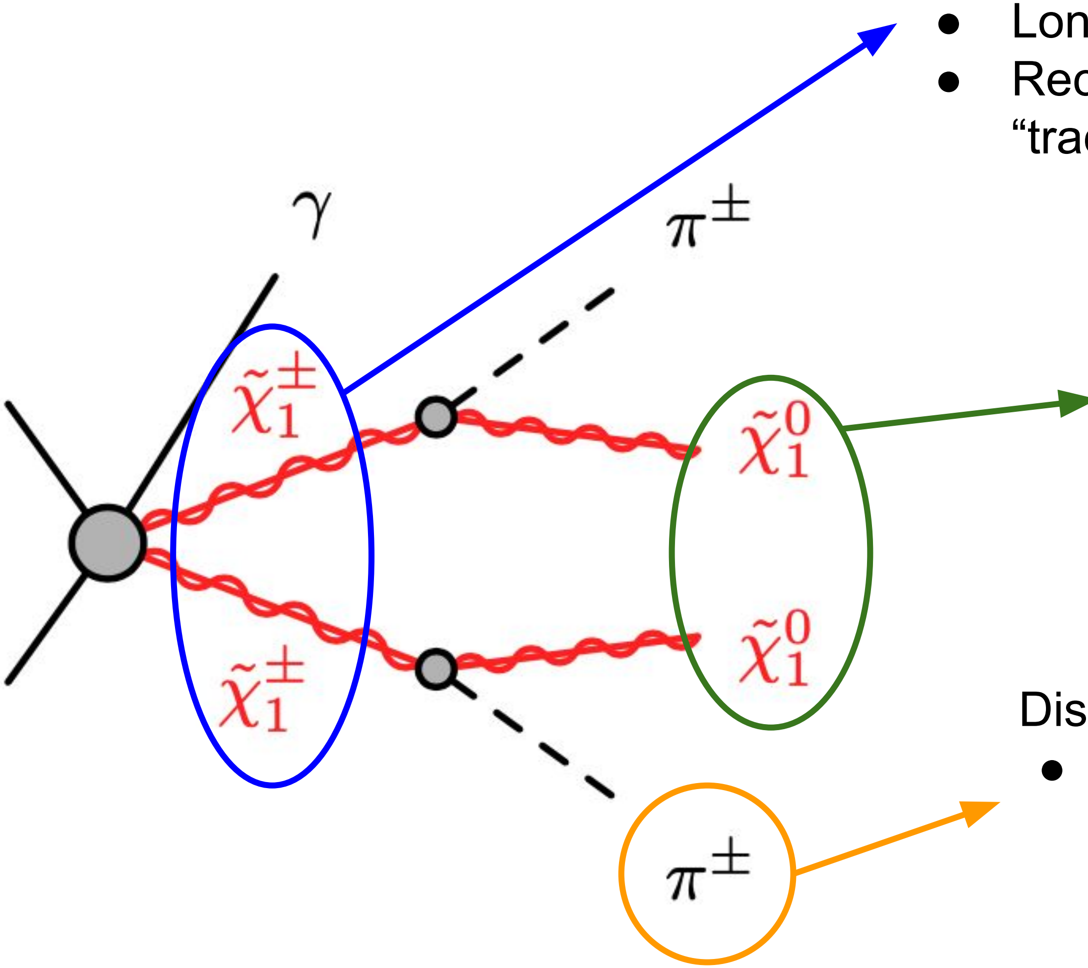

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Displaced pions:

- Not considered here

The search for disappearing tracks

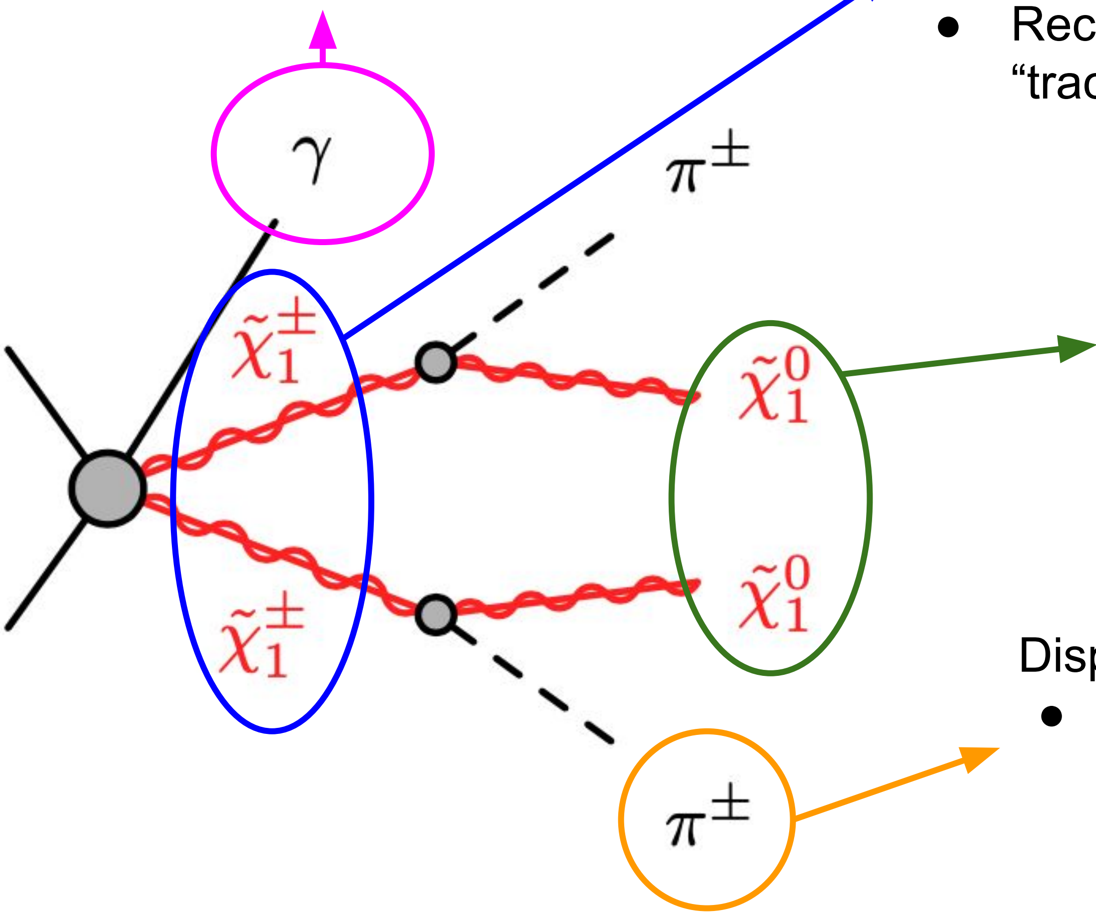
An example from supersymmetry

ISR/FSR:

- "Trigger" the event
- Momentum imbalance

Charginos:

- Long lived, charged
- Reconstructable as "tracklets"



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Displaced pions:

- Not considered here

Where to look for these?

If dark matter is explained by a single particle, we expect this particle to be heavy

Higgsino ~ 1.1 TeV

Wino ~ 2.7 TeV

A muon collider is an excellent machine to look for these

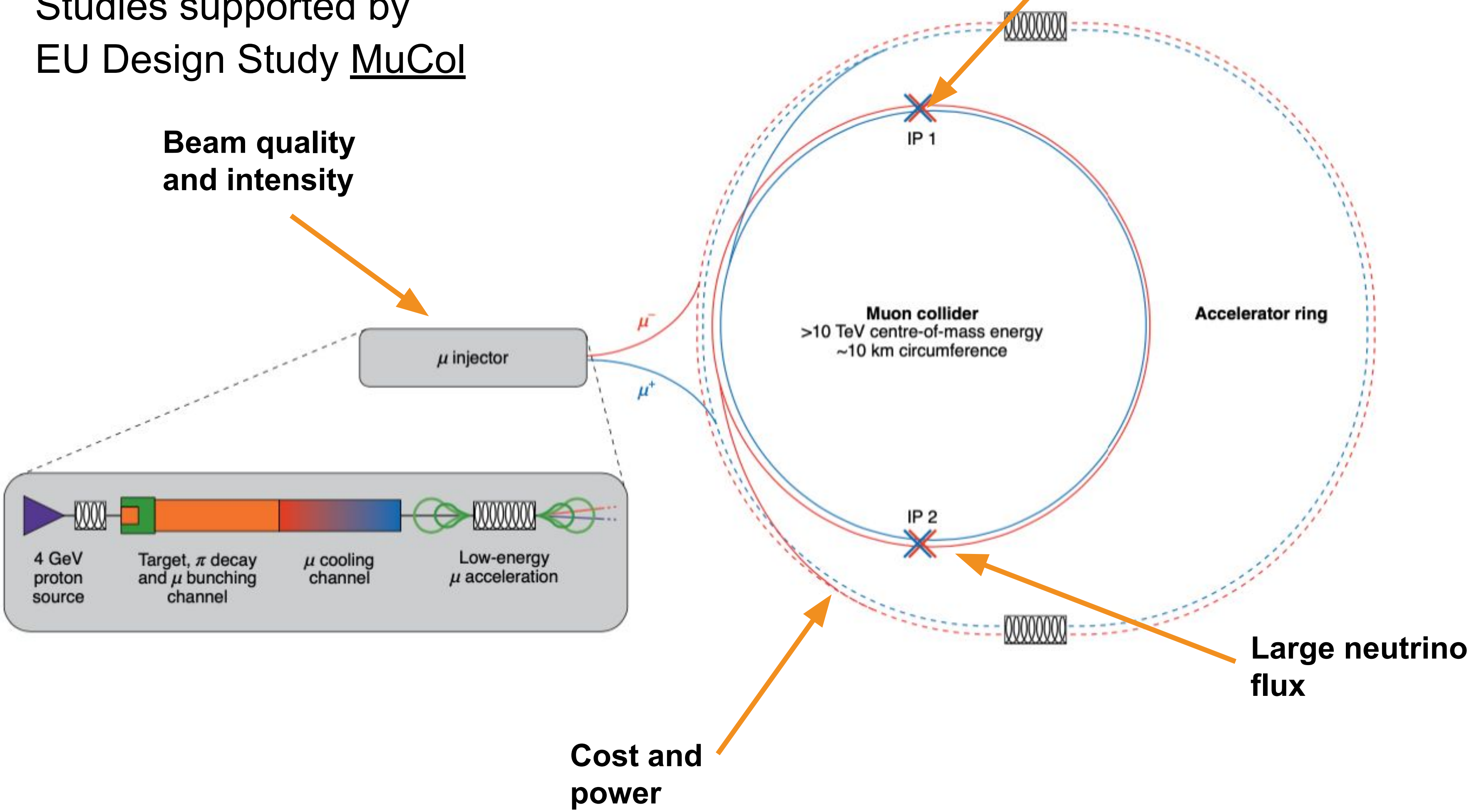
Had a first look with full simulation in
R. Capdevilla, FM, R. Simoniello, J, Zurita [2102.11292]

2303.08533

Key challenges

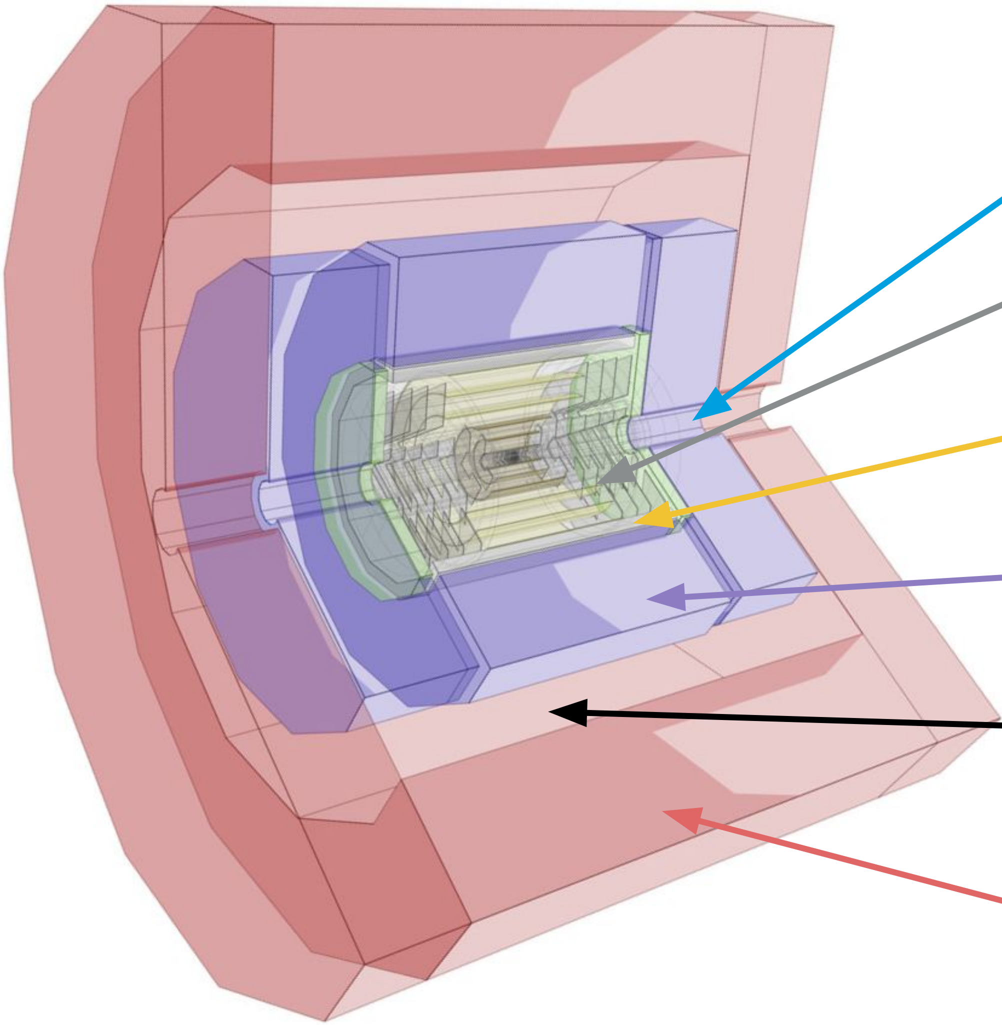
Muons have a **limited lifetime**: 2.2 μs at rest

- Studies supported by EU Design Study MuCol



3 TeV detector design

The detector model is based on the CLIC concept



Nozzles

All-silicon tracker

ECAL (Tungsten+Silicon)

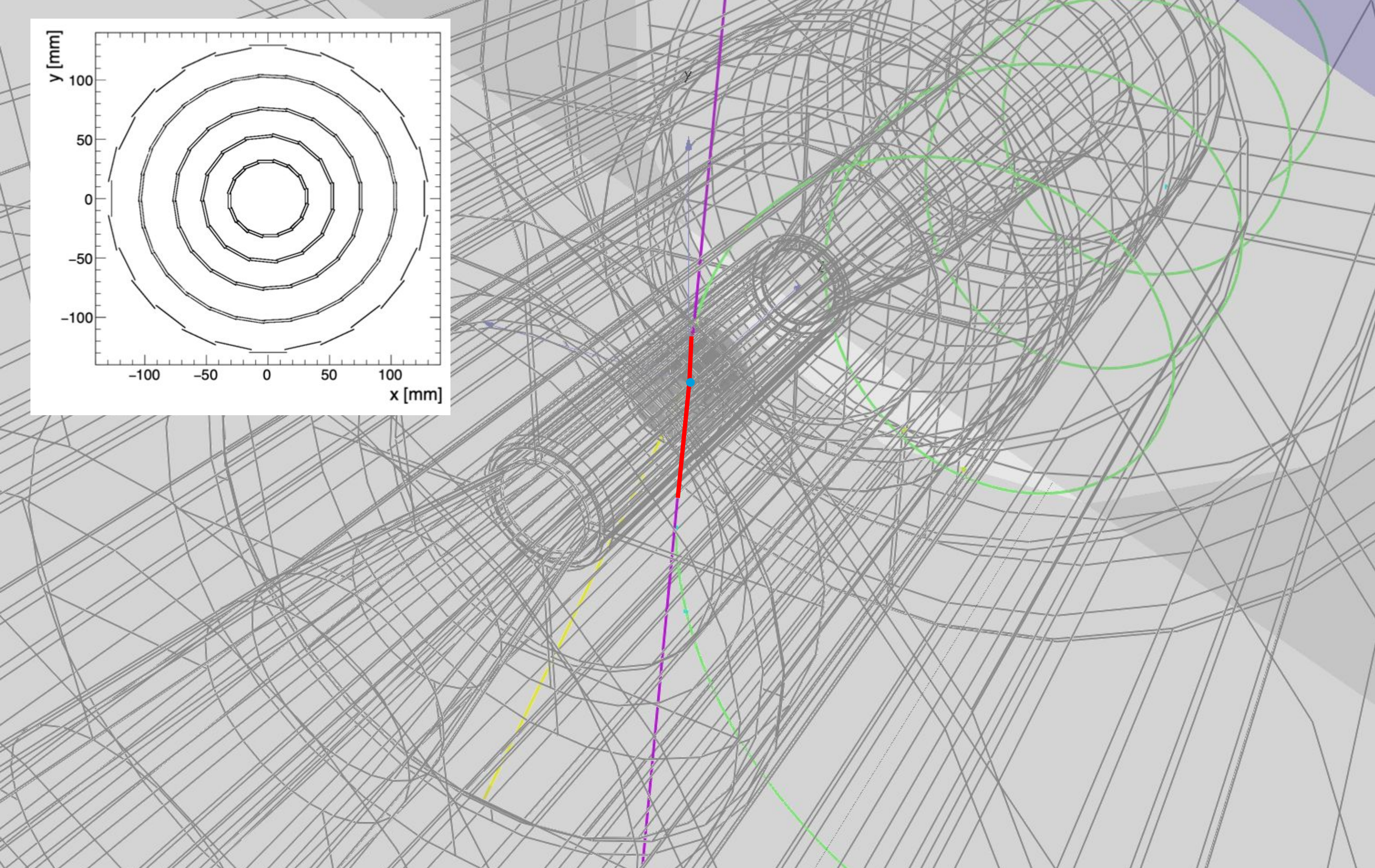
HCAL (Steel+Scintillators)

3.57 T Solenoid

Muon chambers (RPC) in magnet yoke

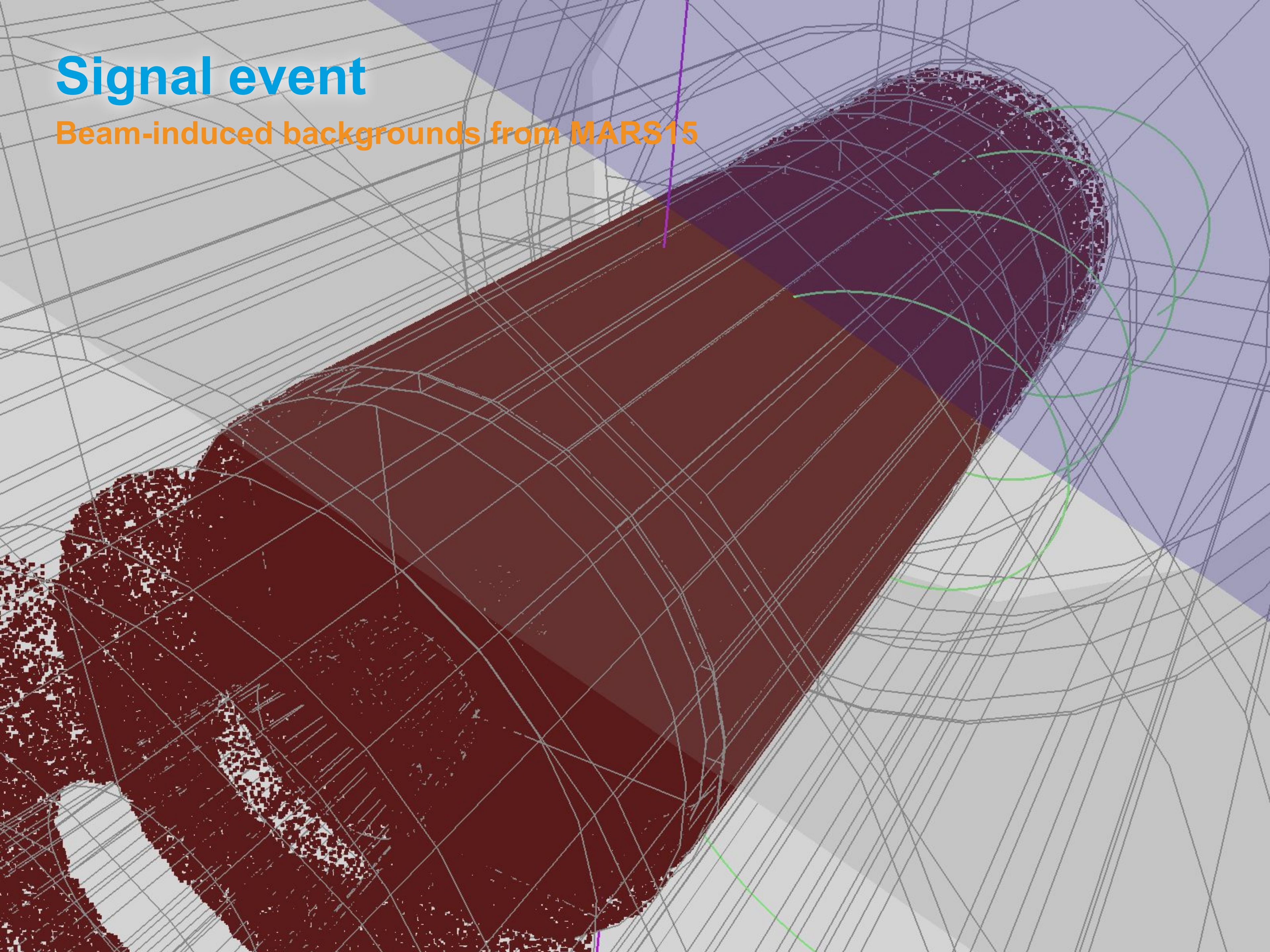
Signal event

No beam-induced backgrounds



Signal event

Beam-induced backgrounds from MARS15

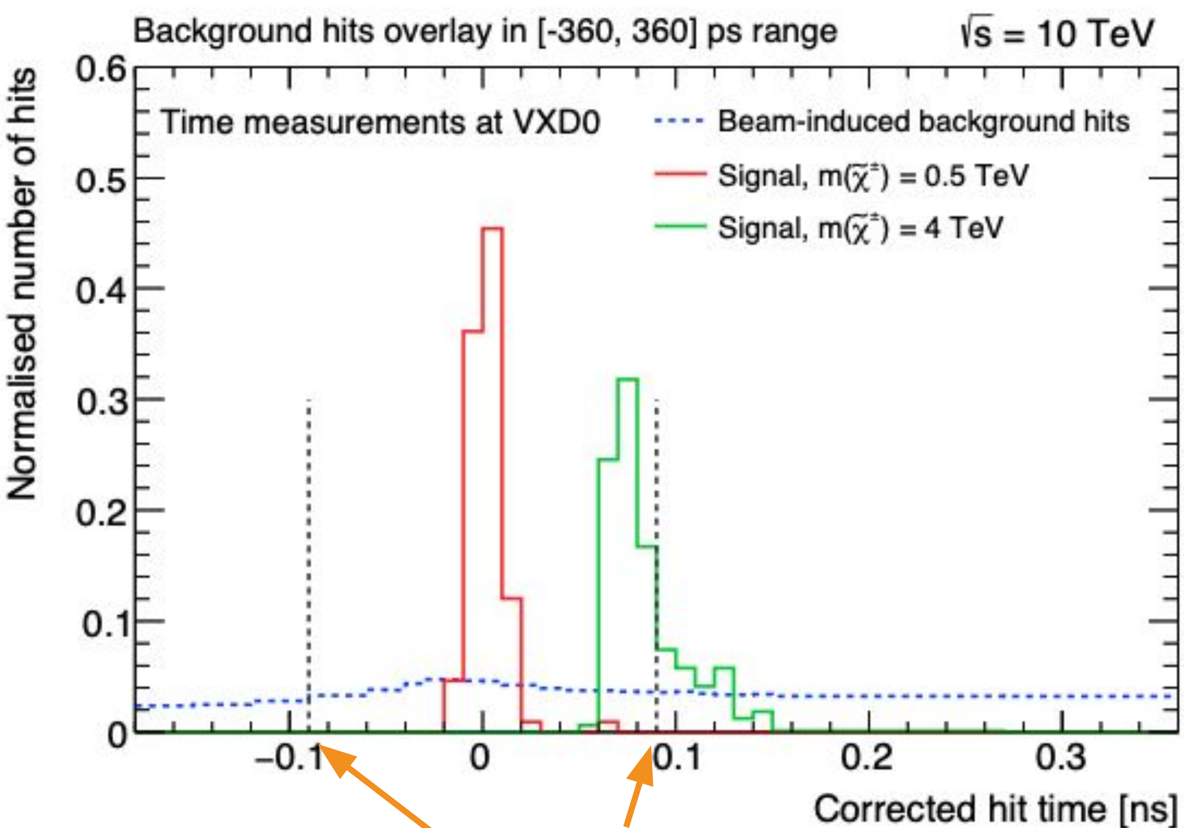


BIB rejection: timing

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



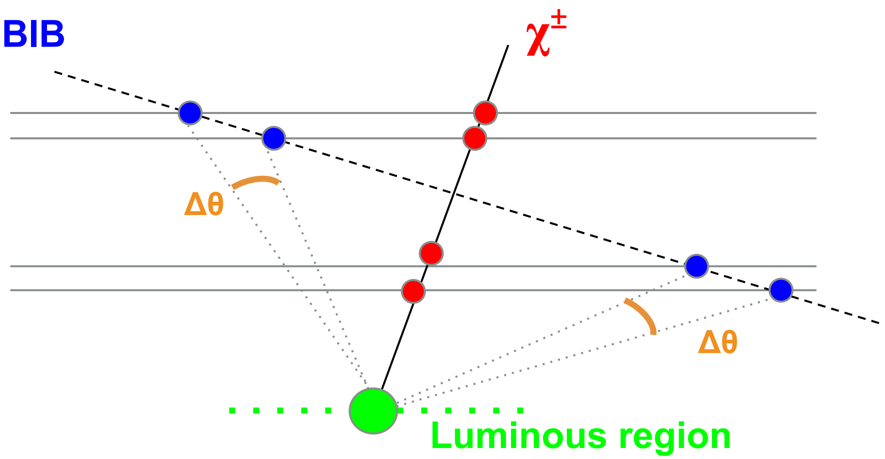
Select hits within a time window, but **still would like to read them out**

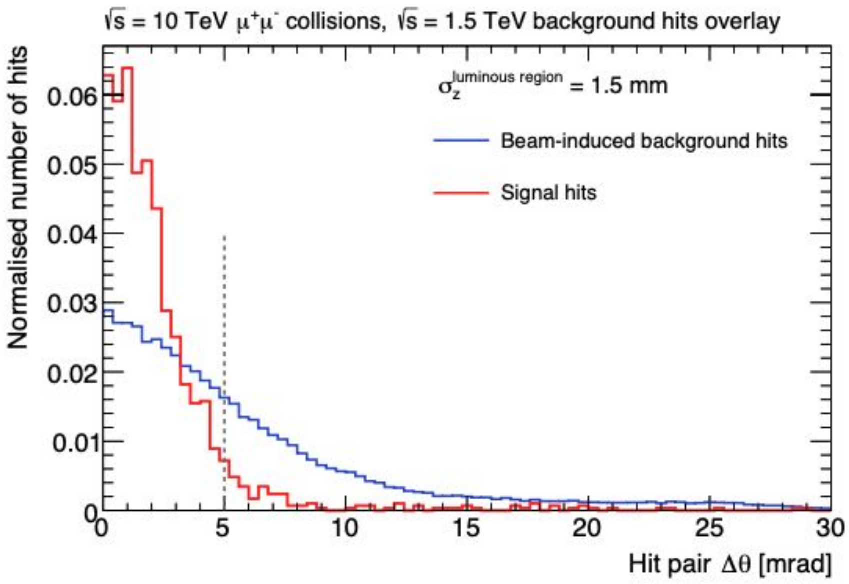
BIB rejection: stubs

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 **"stubs" that point back to the luminous region**
- Work ongoing to apply a similar approach at the cluster level





Tracklet reconstruction

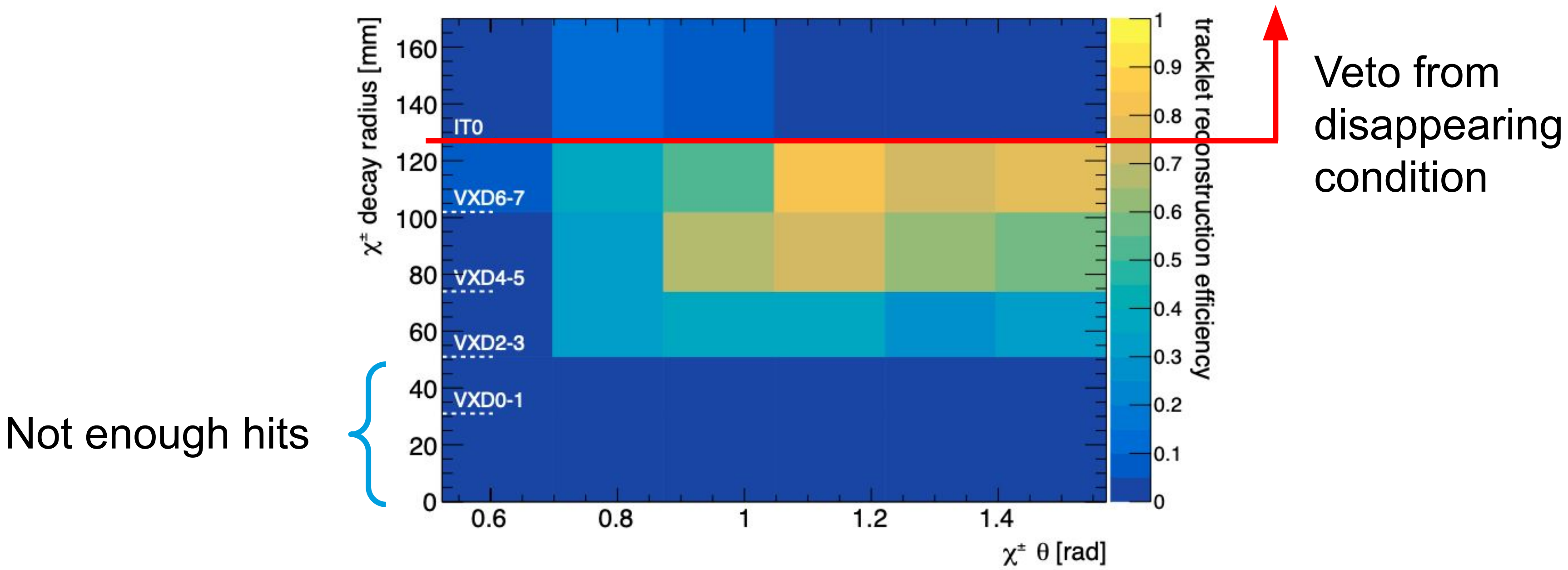
After BIB rejection cuts

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV

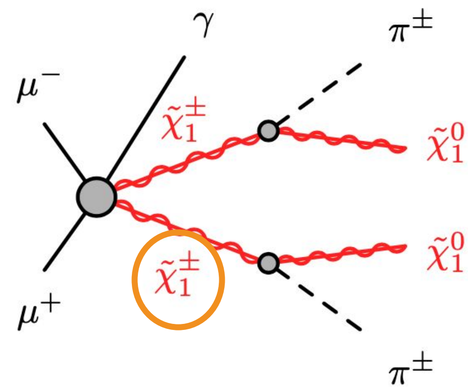
Impose a “disappearing condition” (hit veto) at the first layer of the IT (12.7 cm)

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

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



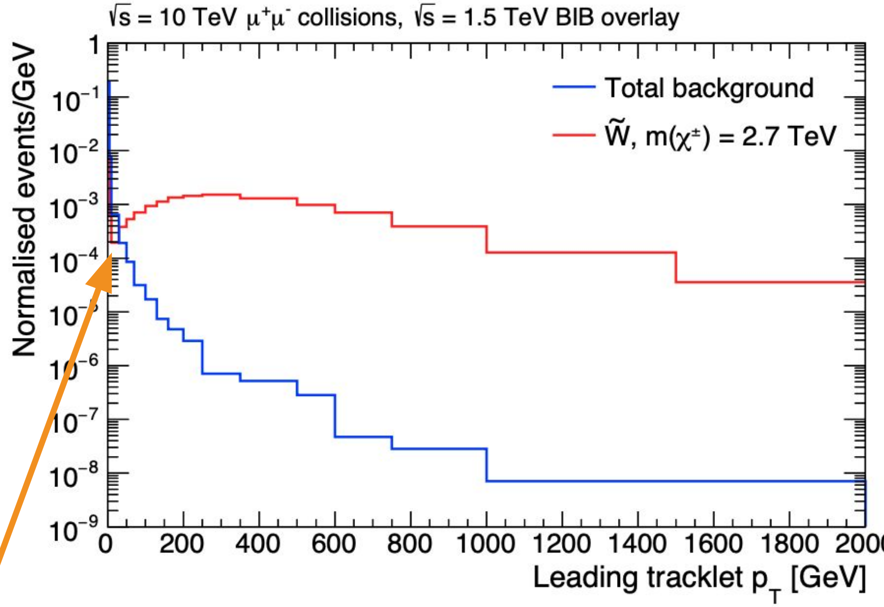
Event selection



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

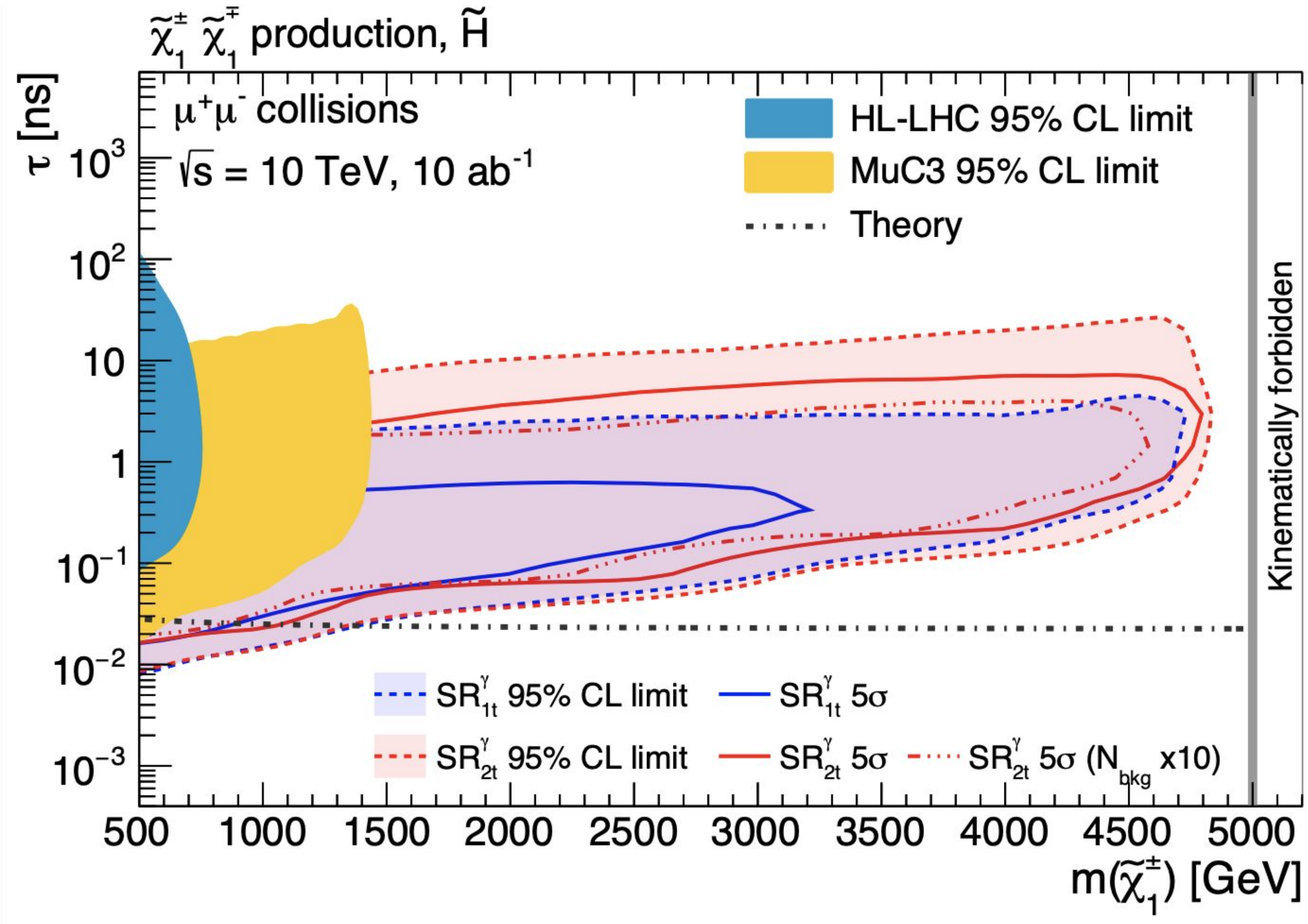


Peak at low p_T in signal events due to BIB overlay

Expected sensitivity

Pure higgsino models at MuC 10

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV



See also detailed comparison with fast sim results from Han, Liu, Wang, Wang [2009.11287, 2203.07351] in MuC Forum report [2209.01318]

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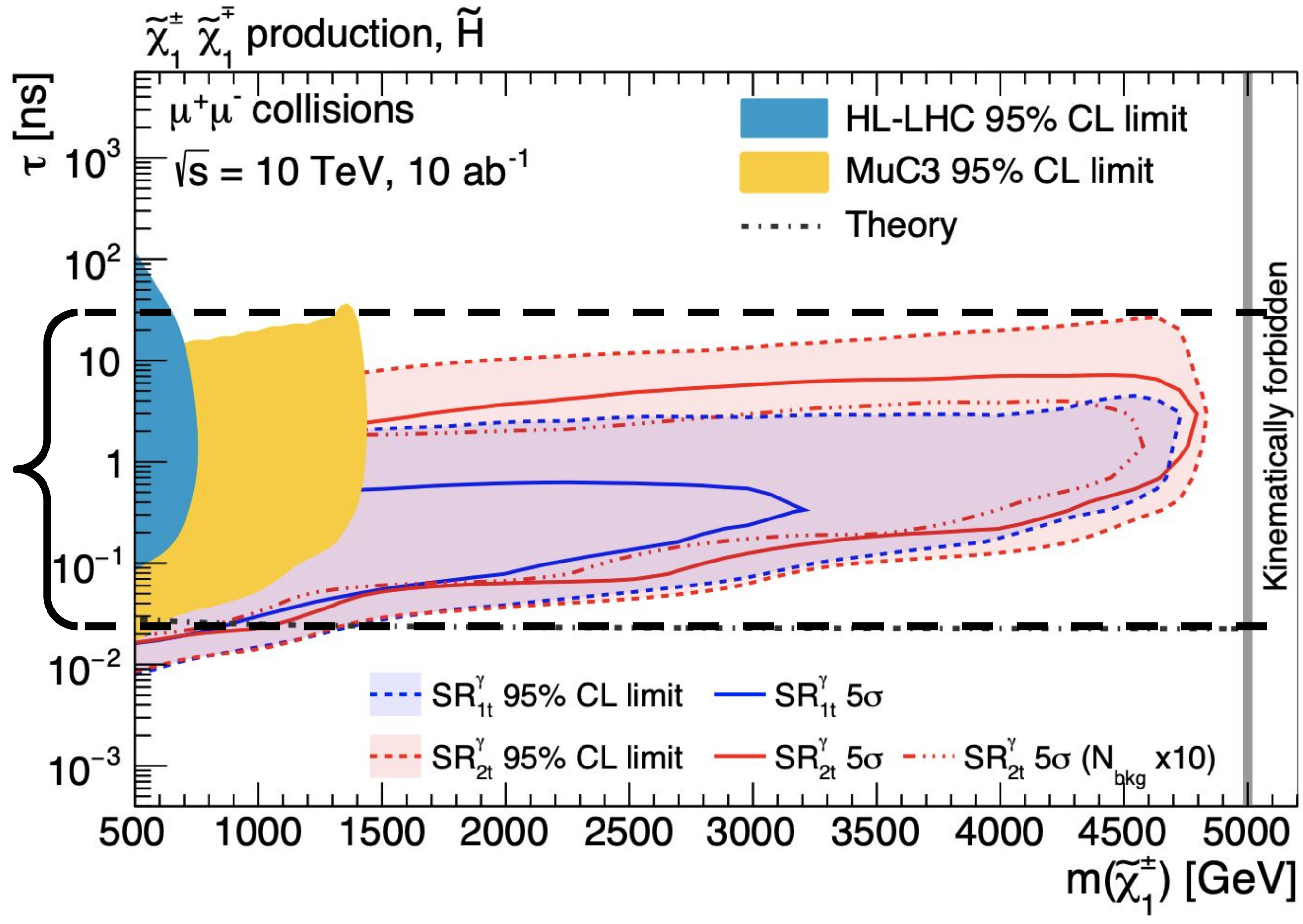
Analysis acceptance



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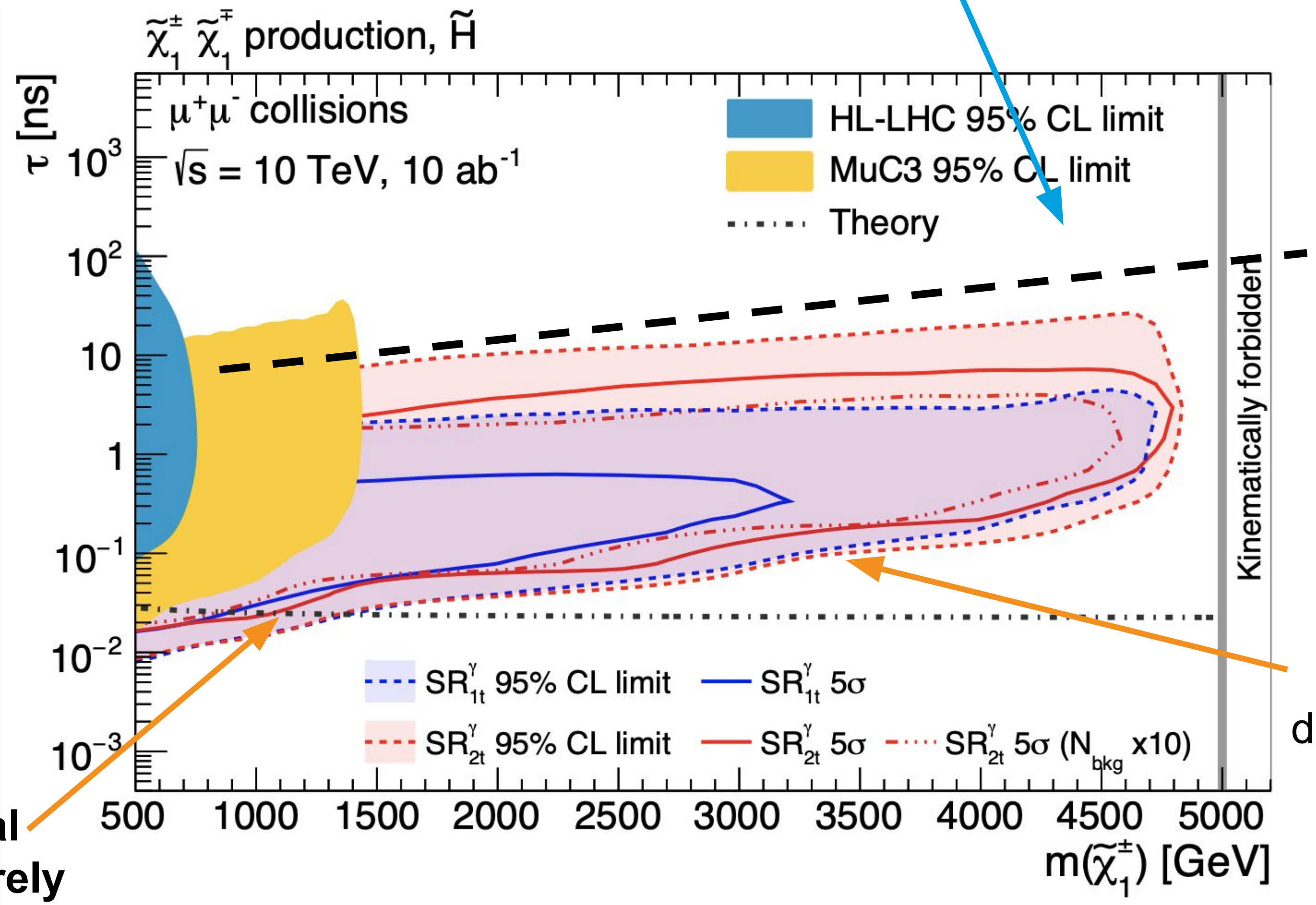
Decreasing βγ: fewer signal tracklets rejected by **veto layer**



Thermal target barely covered

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

A new detector for 10 TeV

Detector model based on ongoing work
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

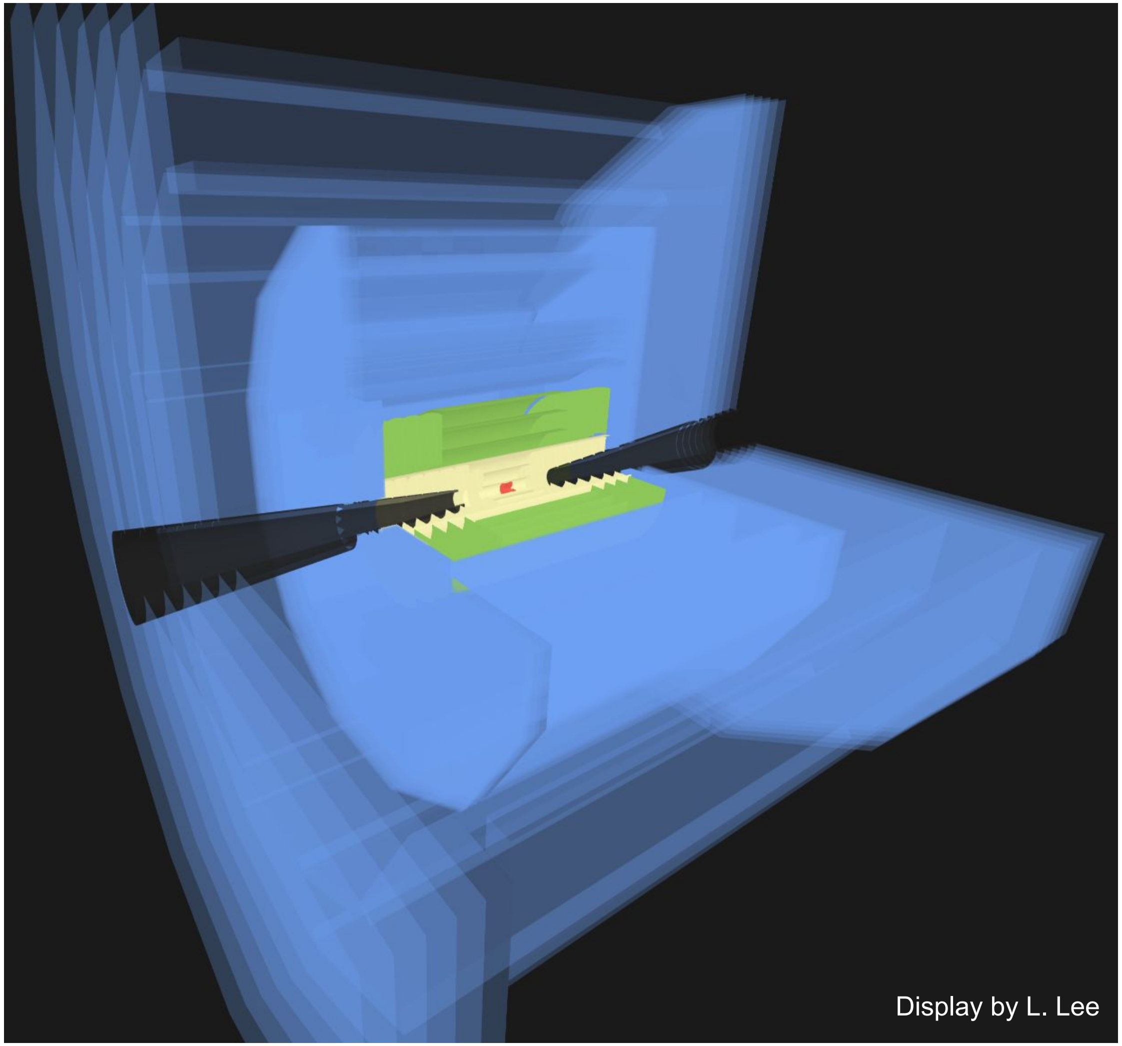
The detectors need to be ready to **measure both TeV-scale particles as well as GeV-scale**

Detector sizes need to grow

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

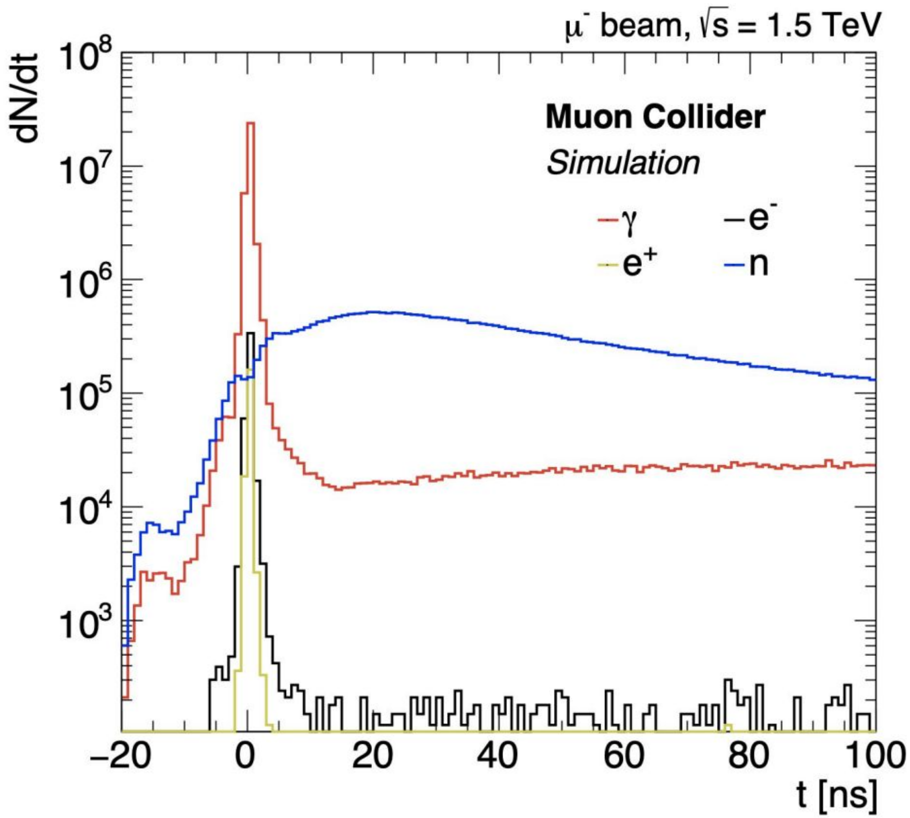
Physics benchmarks are key to guide the detector a design

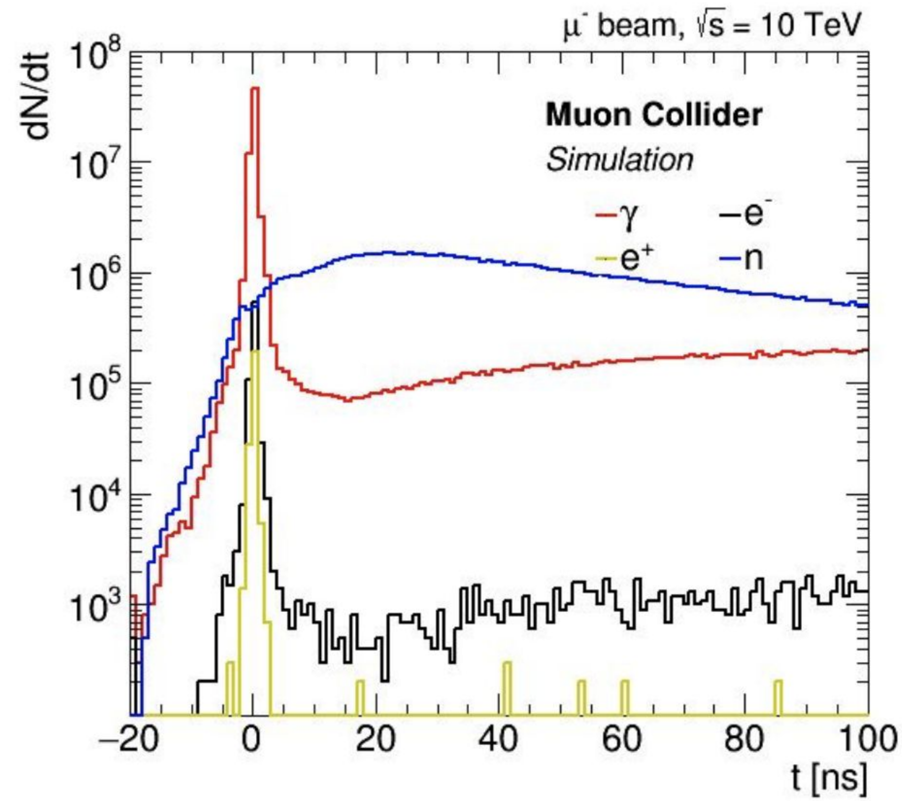
Can a revised detector preserve, or even improve, the sensitivity to winos and higgsinos?



Display by L. Lee

Moving to 10 TeV BIB simulation: time

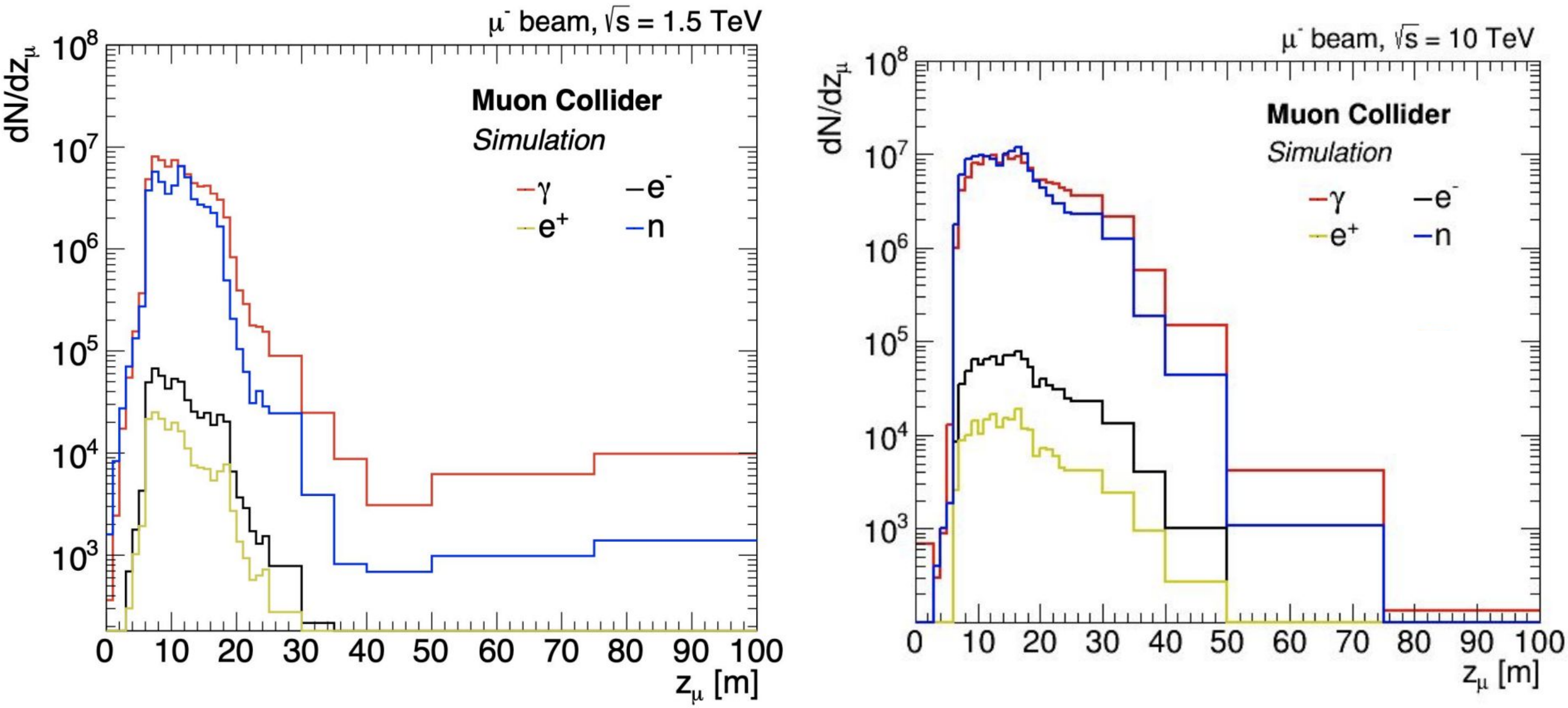




Simulation based on FLUKA (thanks to Daniele Calzolari and the MDI group!)

- 5 TeV muon and anti-muon beams
- Sampled 110 metres of decays in the collider lattice

Moving to 10 TeV BIB simulation: μ decay z

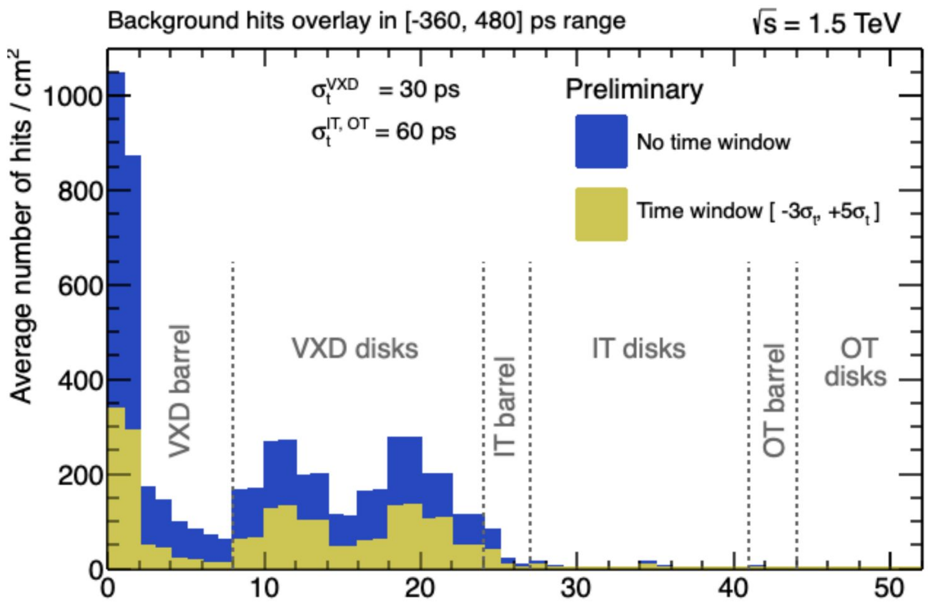


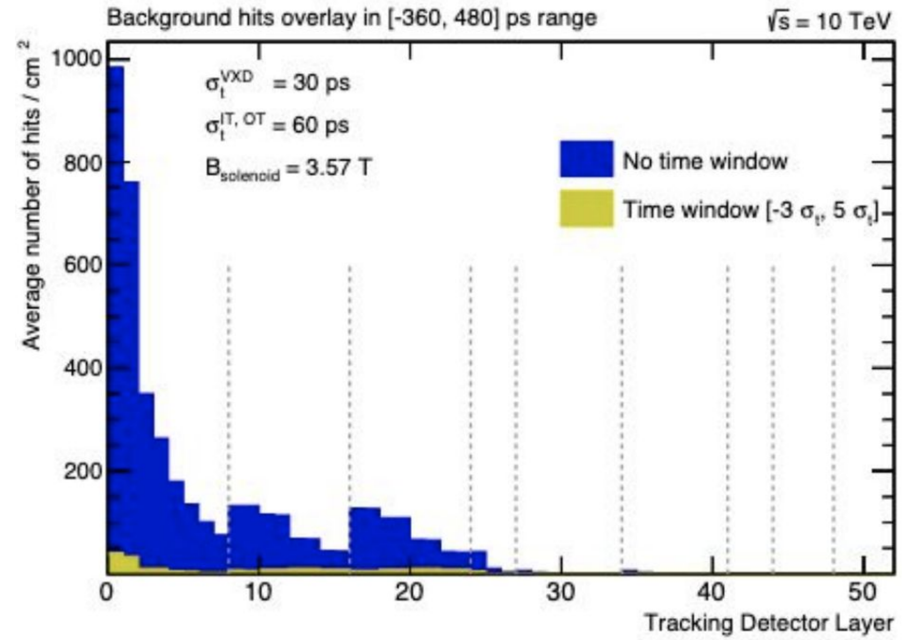
Lack of very-long tail comes from better modelling in FLUKA (now including synchrotron radiation)

- See more in Daniele's talk

Occupancies: tracker

See also
Nazar Bartosik's
10 TeV BIB study





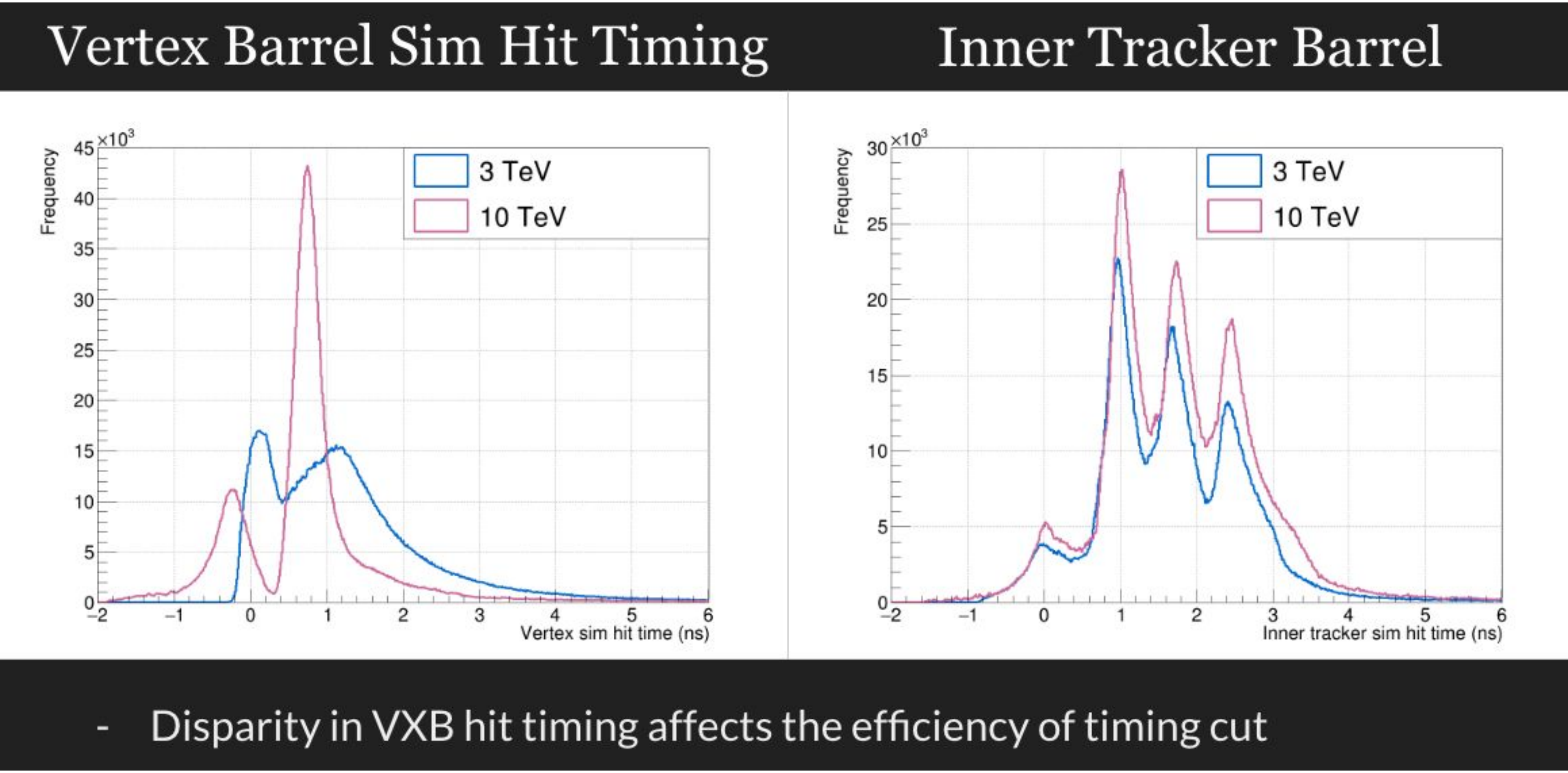
Increasing solenoid field to 5T has an effect of the order of 10% pre-timing

Work in progress on:

- Different BIB structure in endcaps
- Timing selections seem much more effective than at 3 TeV

Effectiveness of timing selections

From [Chris Sellegren's talk]



Different timing structure being investigated

- No obvious bugs found so far, looking at dependency on machine lattice

Table: courtesy of Sergo Jindariani

Data rates and power

	Upper timing cut (ns)	Module size (cm^2)	Maximum hits/cm^2	Reduction using cluster shapes	Data payload per module (Gbps)	Transmission power per module (W)	Total Transmission Power (W)
VXD barrel L1/L2	15	10	3000	x2	50	0.5	25
VXD barrel L1/L2	1	10	2400	x2	35	0.3	20
VXD barrel L3-8	15	10	1400	-	50	0.5	100
VXD disks	15	10	700	-	21	0.2	60
IT barrel	15	50	170	-	24	0.2	360
IT disks	15	50	60	-	9	0.09	100
OT barrel	15	100	10	-	3	0.03	170
OT disks	15	100	5	-	1.5	0.15	30

L1/L2 rates still require tighter time window (~1ns)

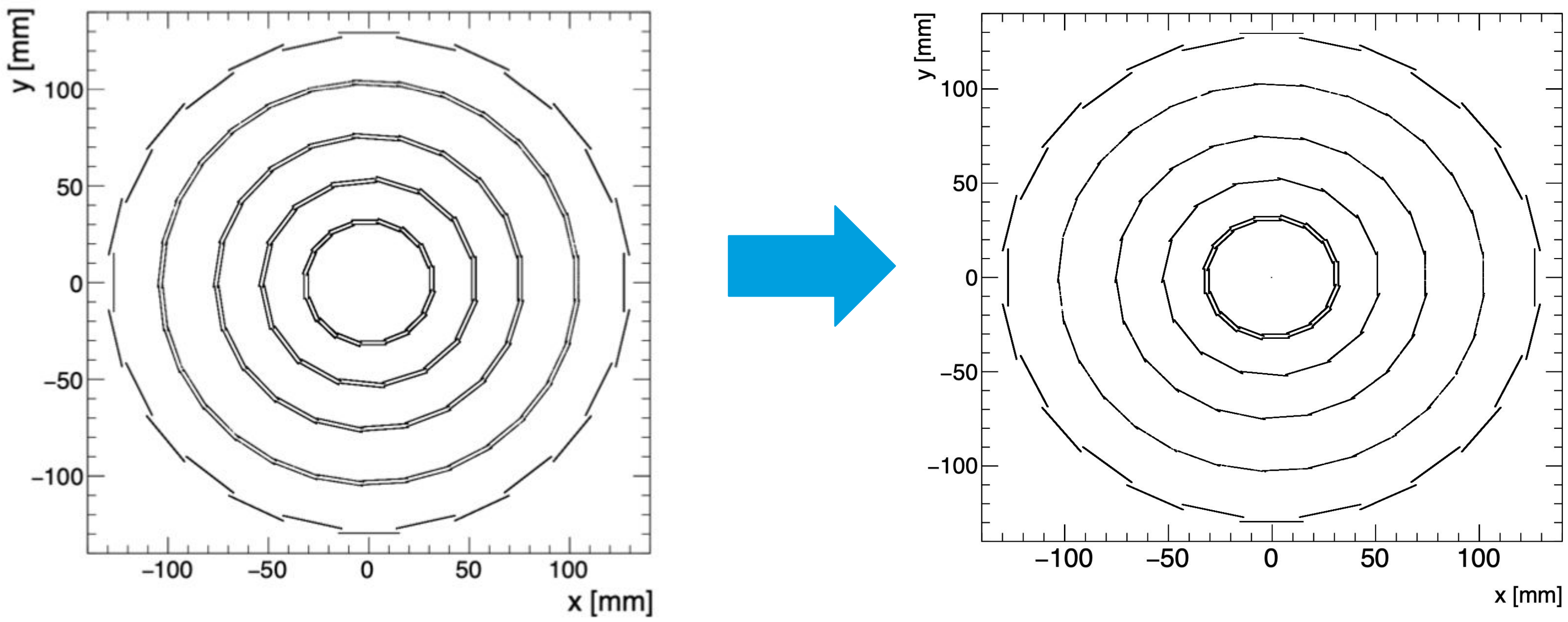
L3/L8 now less comfortable

- Total L3/L8 power could be halved by removing the double layers

Updating to a new tracker

These considerations, together with a greatly improved tracking software (now based on the ACTS library) made the double layers possibly redundant

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



Updated detection efficiency

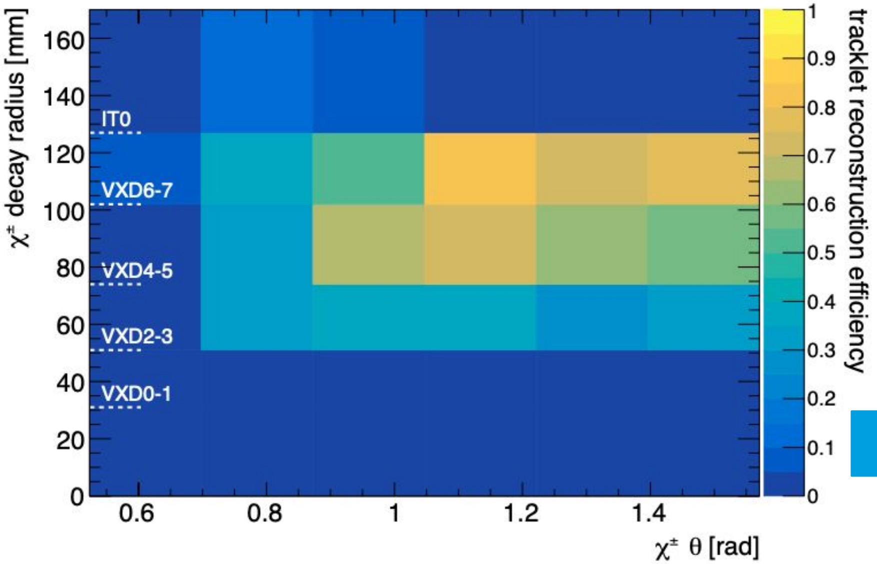
10 TeV detector
Preliminary 10 TeV BIB overlay

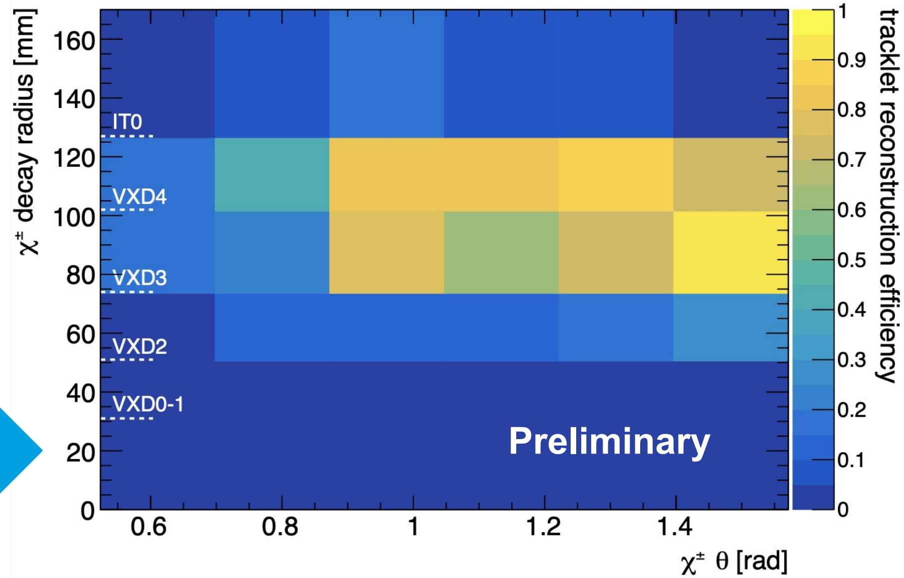
New tracker layout and tracking algorithm

Kept all tracklet quality requirements as before except:

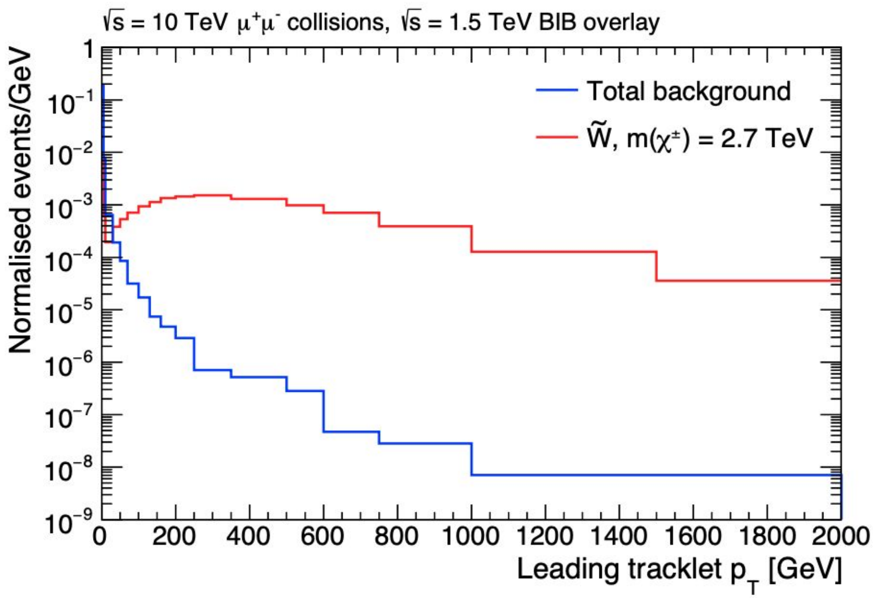
$N_{hit} \geq 3$ hits　　　　No requirement on stubs

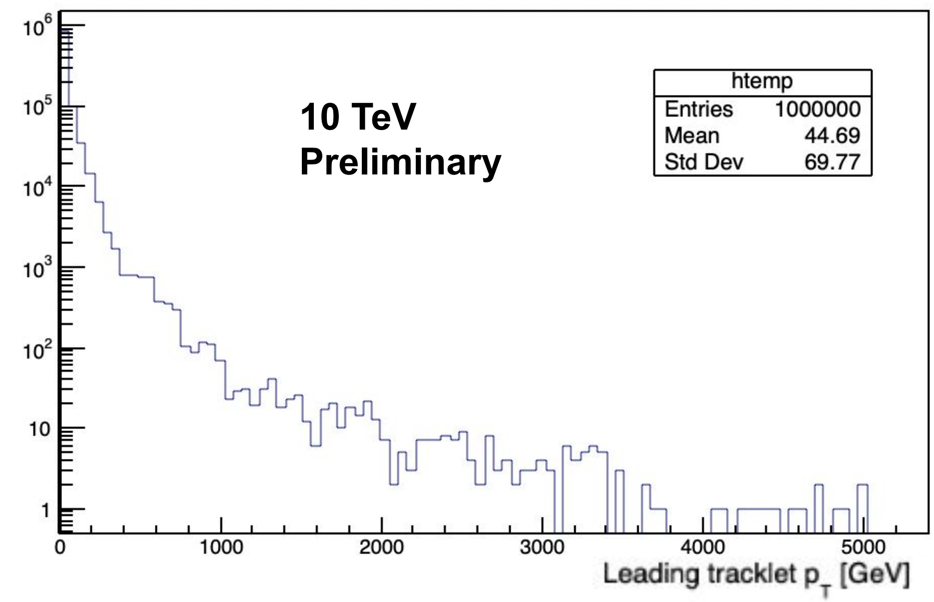
Found **similar detection efficiency**, and **greatly reduced fake** tracklet rate





Updated fake rates





Reconstructed fake tracklet p_T spectrum similar

Probability of finding a fake tracklet per event lowered by ~1/10

- Estimates being refined with higher MC statistics

Expected sensitivity

Pure higgsino models at MuC 10

10 TeV detector
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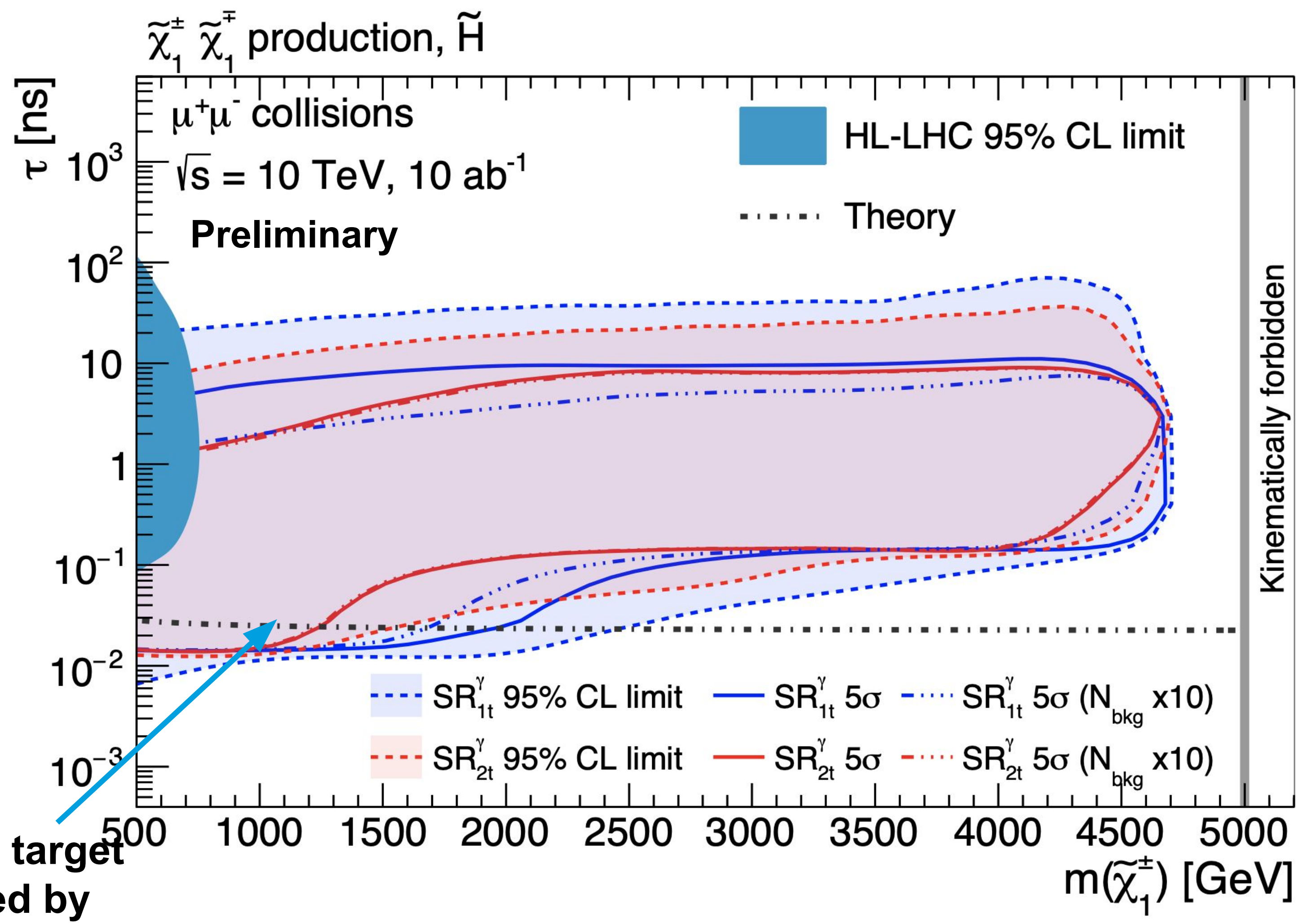

Thermal target covered by both selections

Summary

Physics benchmarks are key in evaluating new detector design options

Dark matter is one of the most important topics of research in particle physics, and **disappearing tracks are the ultimate handle** to target minimal dark matter models

The preliminary update to a 10 TeV detector model and simulation seems to indicate the **initial estimates were conservative**

- Thermal targets possibly well within reach

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

Thank you!

Contact

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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.

2201.07895

Muon collider target parameters

Parameter	Symbol	Unit	Target value			CLIC
Centre-of-mass energy	E_{cm}	TeV	3	10	14	3
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.8	20	40	5.9
Luminosity above $0.99 \times \sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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)