(Exotic) Signal Benchmarks for a Muon Collider

Muon Collider Workshop

KITP

Mar 01, 2023

Rodolfo Capdevilla
Fermilab

Great inputs from:

Federico Meloni, Sergo Jindariani, Nathaniel Craig, Jose Zurita, David Curtin, Bogdan Dobrescu, Paddy Fox

In case you like it

***RC**, Federico Meloni, Rosa Simoniello, Jose Zurita, JHEP **06** (2021) 133*

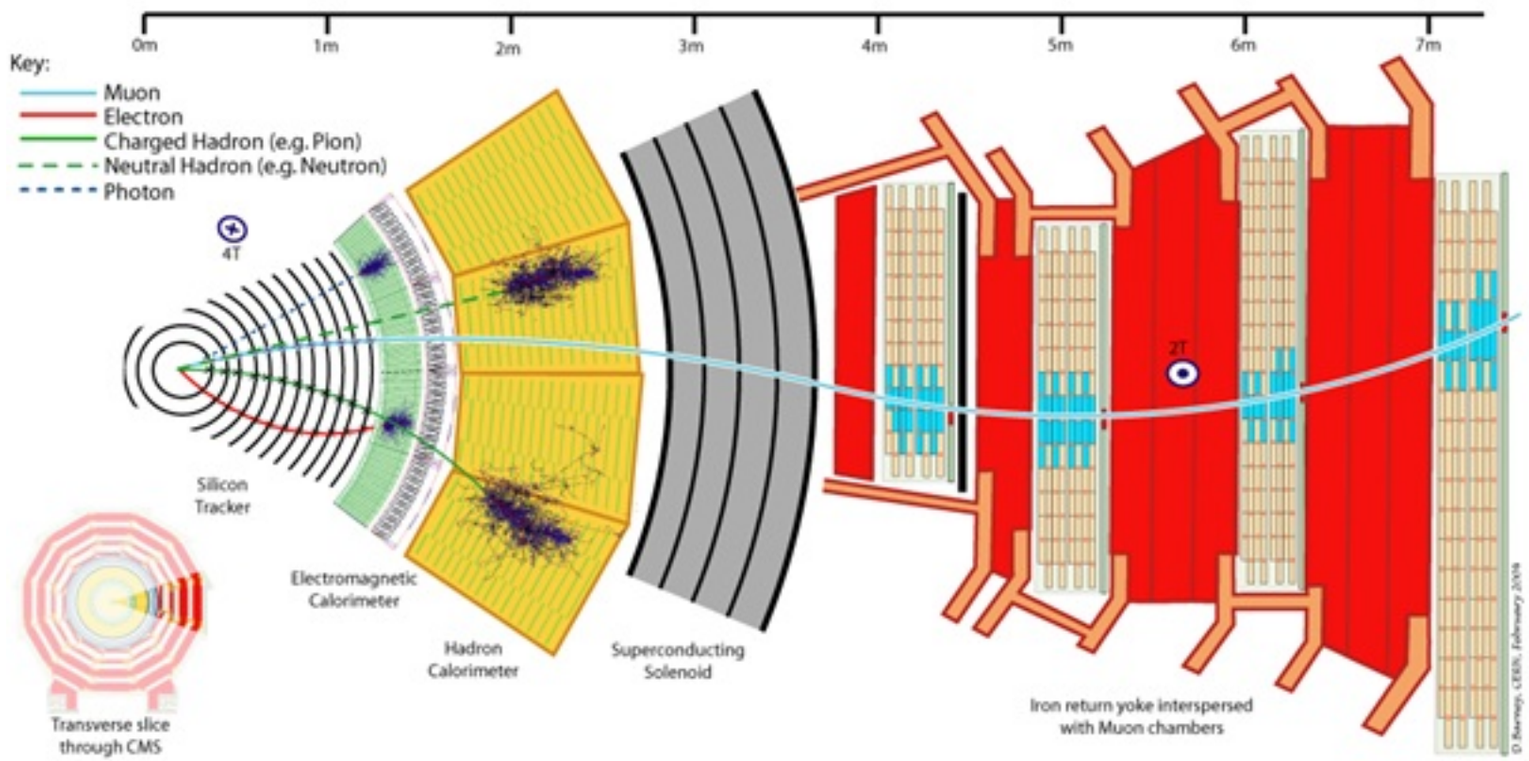
Question:

Can we identify BSM ***motivated*** *scenarios with exotic signals that can have implications in detector and accelerator/facility design?*

Prior to LHC:

Multi-purpose detector:

Particle ID

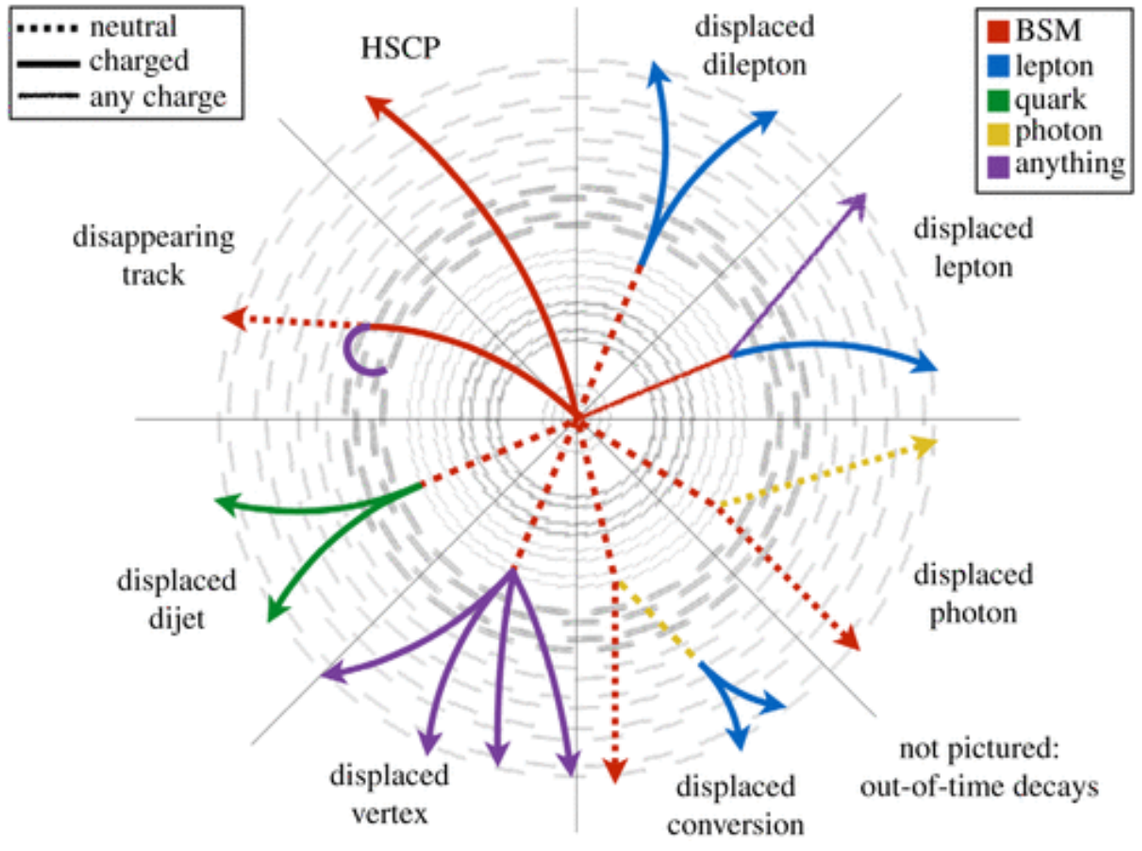


During LHC:

Multi-purpose detector:

~~Particle~~ ID Signal

Particle ID
Software: Triggering, Timing
Hardware: Geometry



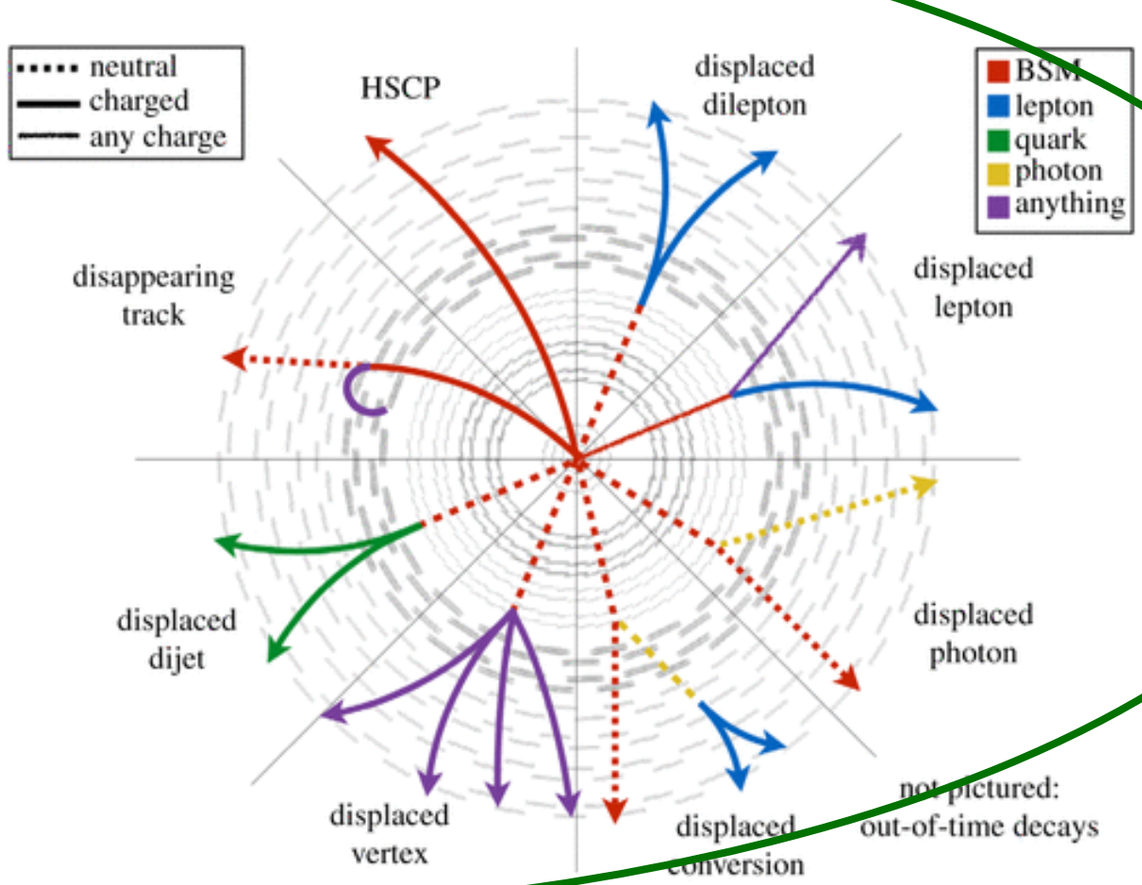
For FUTURE colliders we can start from here!

During LHC:

Multi-purpose detector:

~~Particle~~ ID
Signal

Particle ID
Software: Triggering, Timing
Hardware: Geometry



Question:

Can we identify BSM ***motivated*** *scenarios with exotic signals that can have implications in detector and accelerator/facility design?*

Outline

1. Electroweakinos-like Dark Matter

   - Higgsinos and Winos
   - Disappearing Tracks


Federico Meloni, DESY


Rosa Simoniello, CERN

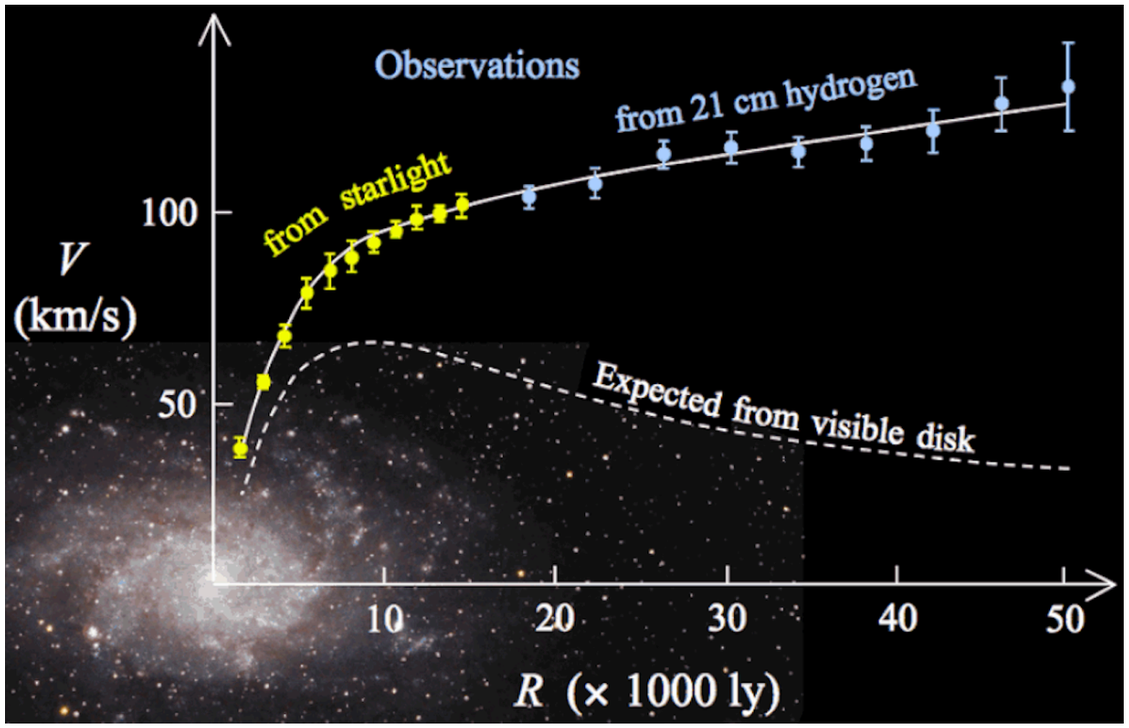

Jose Zurita, U. Valencia

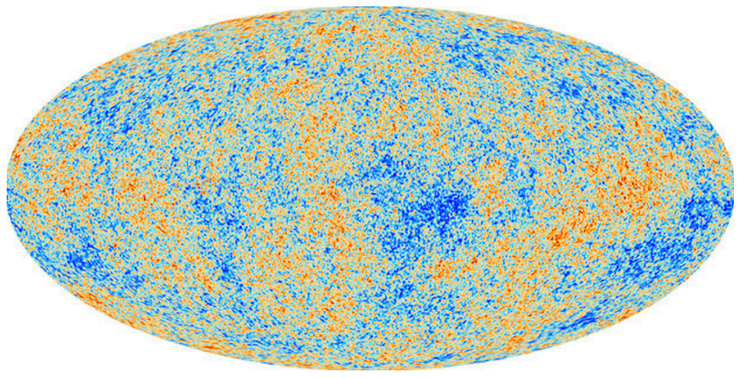
2. BSM and Exotic Signals

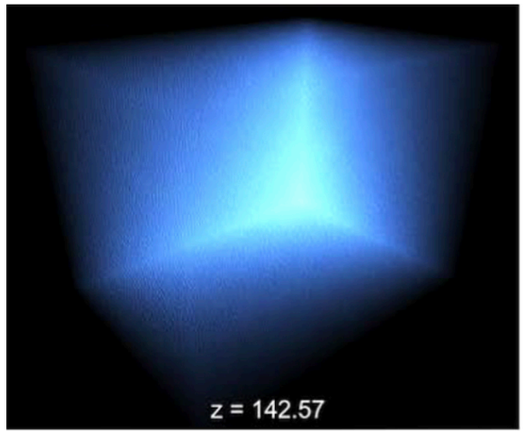
   - Landscape (partially)
   - Some Examples

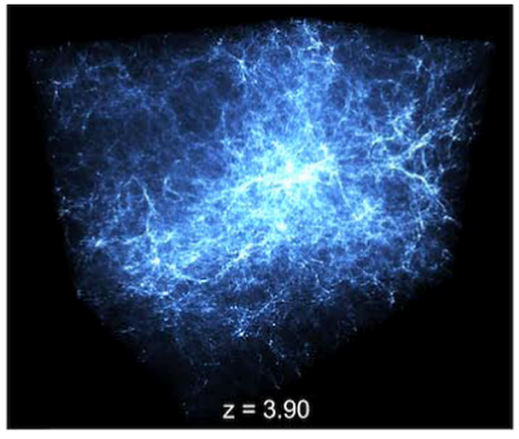
1. Electroweakinos-Like Dark Matter

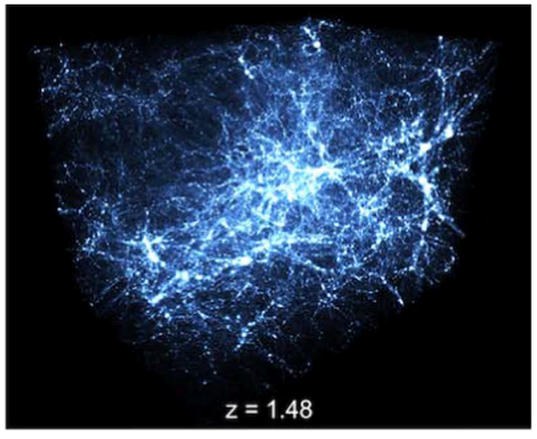
- Ubiquitous evidence of DM

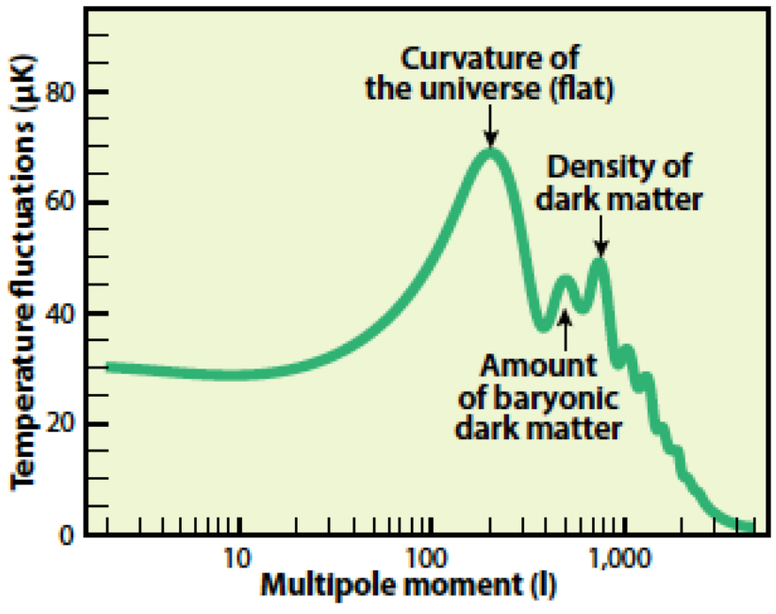






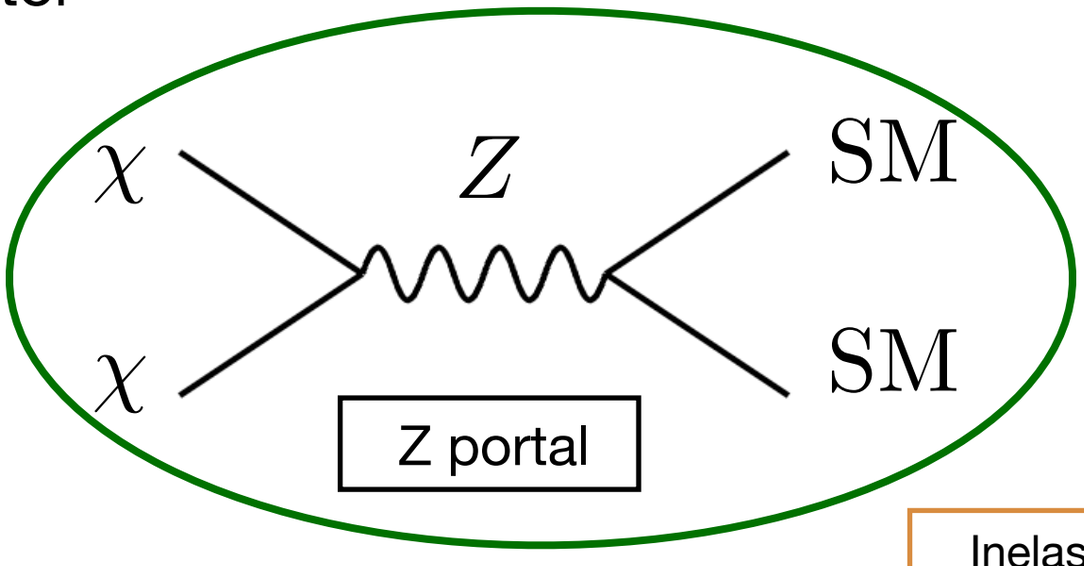






1. Electroweakinos-Like Dark Matter

- Minimal -> SM Mediator



Inelastic!

- Electroweakinos-like DM

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^+_{\tilde{H}} \\ \chi^0_{\tilde{H}} \end{pmatrix} \qquad (\mathbf{1}, \mathbf{2}, 1/2)$$

Higgsino-like

$$\chi_{\tilde{W}} = \begin{pmatrix} \chi^0_{\tilde{W}} & \chi^+_{\tilde{W}} \\ \chi^-_{\tilde{W}} & -\chi^0_{\tilde{W}} \end{pmatrix} \qquad (\mathbf{1}, \mathbf{3}, 0)$$

Wino-like

Neutral component

1. Electroweakinos-Like Dark Matter

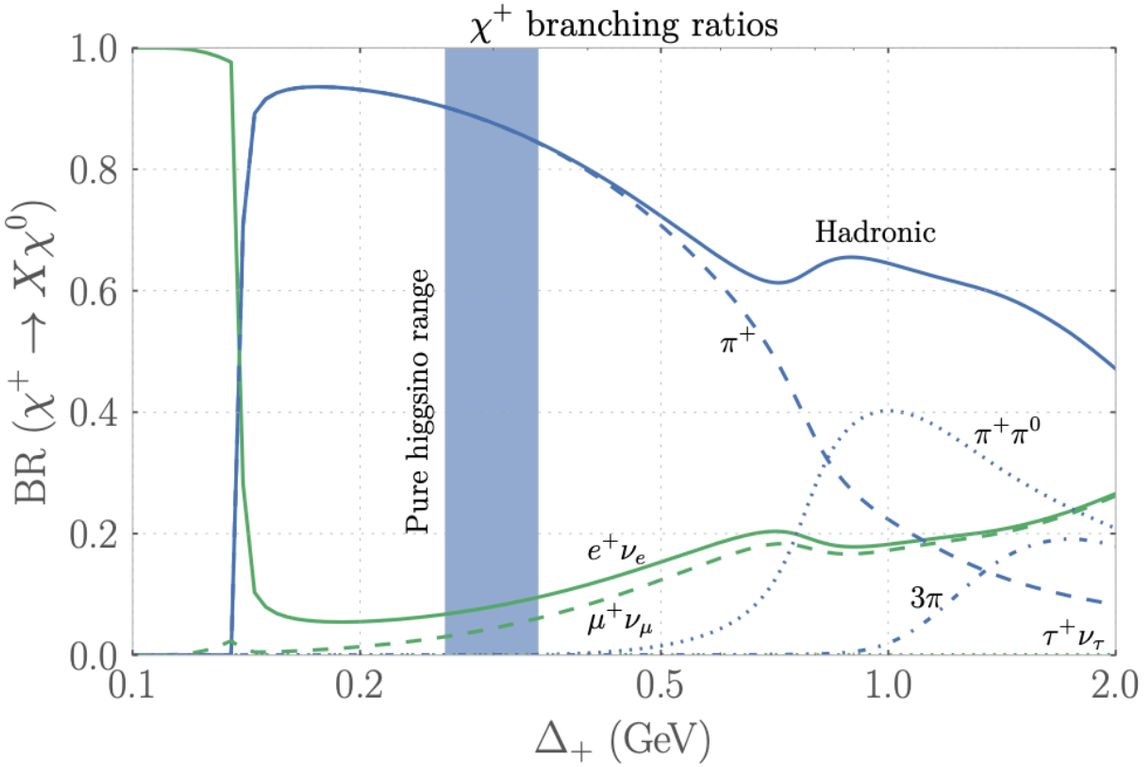
- Small mass splitting from radiative corrections

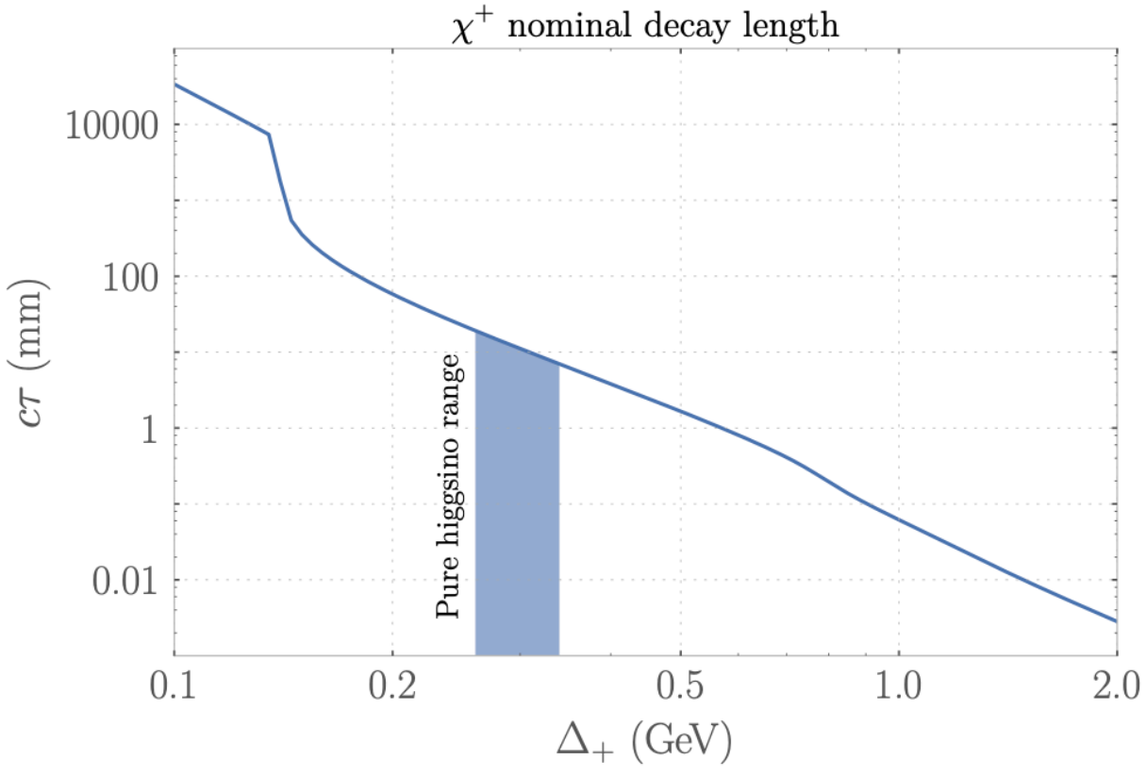
$$\chi_{\tilde{H}} = \begin{pmatrix} \chi^{+}_{\tilde{H}} \\ \chi^{0}_{\tilde{H}} \end{pmatrix}$$

$$\Delta m = m_{\chi^+} - m_{\chi^0} > 0$$

Feature of the model!

- DM candidate stable
- Charged states are long-lived



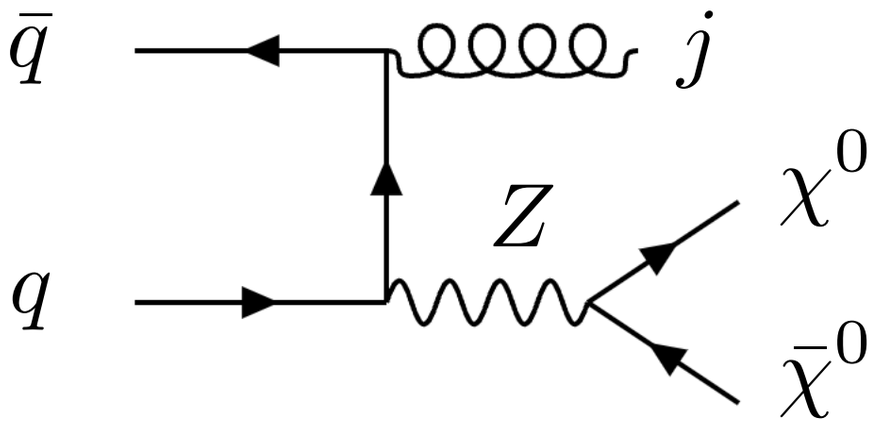


R. Mahbubani, P. Schwaller, J. Zurita,
JHEP 06 (2017) 119

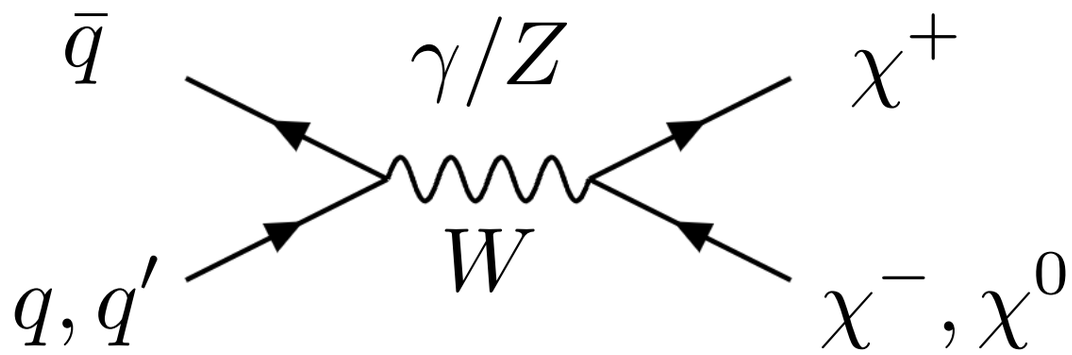
1. Electroweakinos-Like Dark Matter

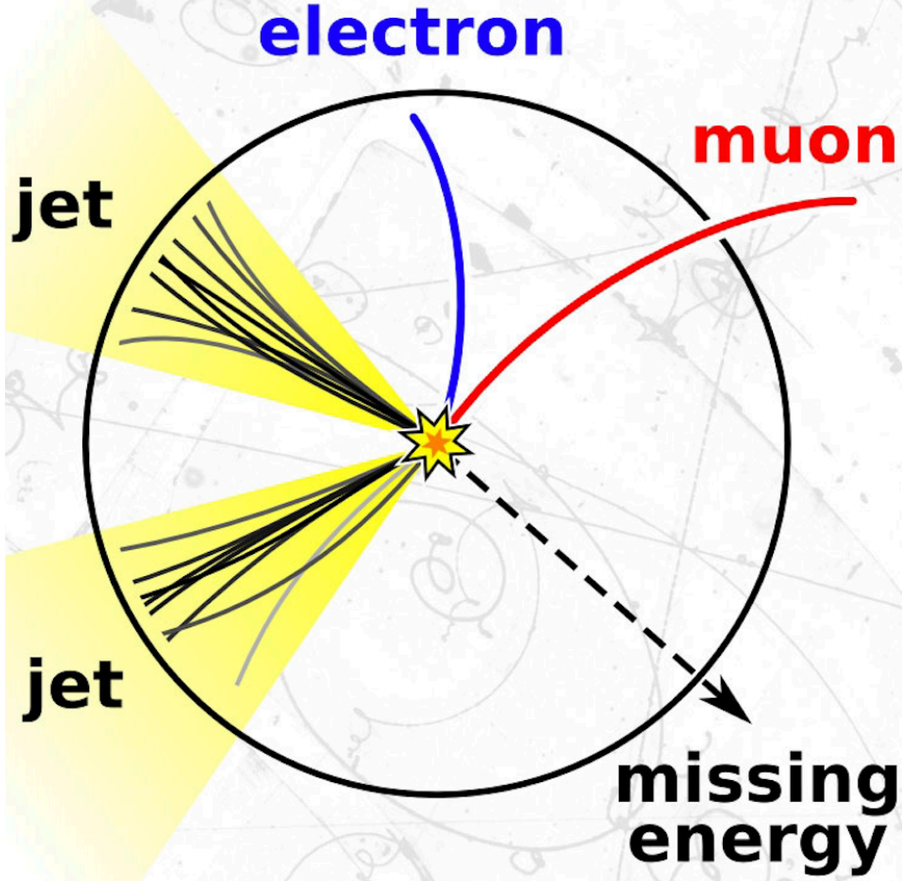
- Collider Searches

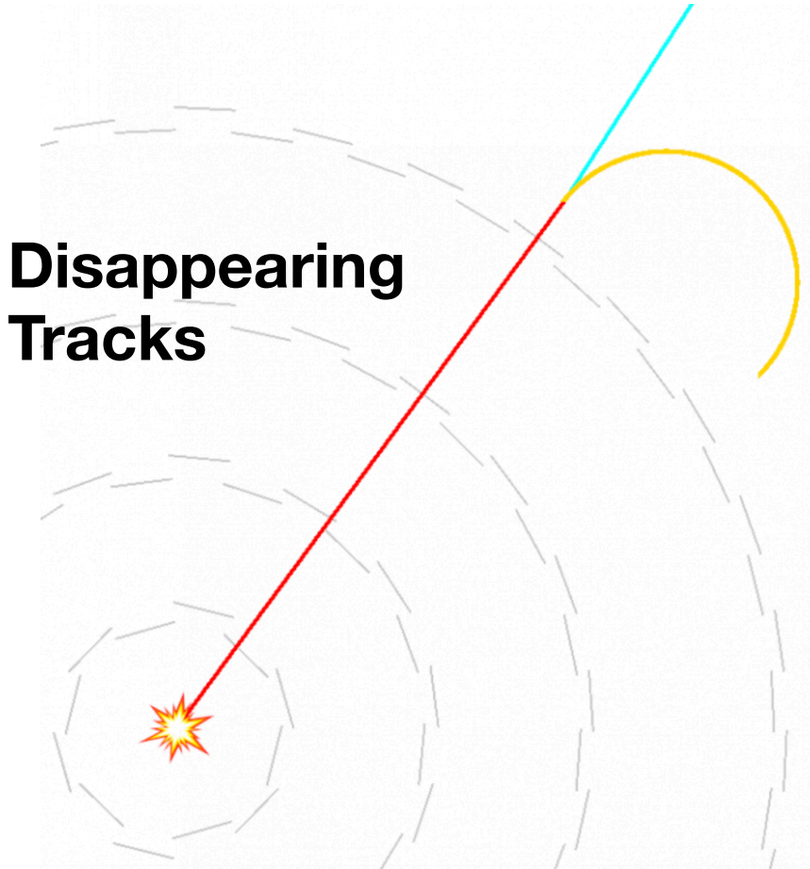
Directly produce DM



Produce the long-lived charged state



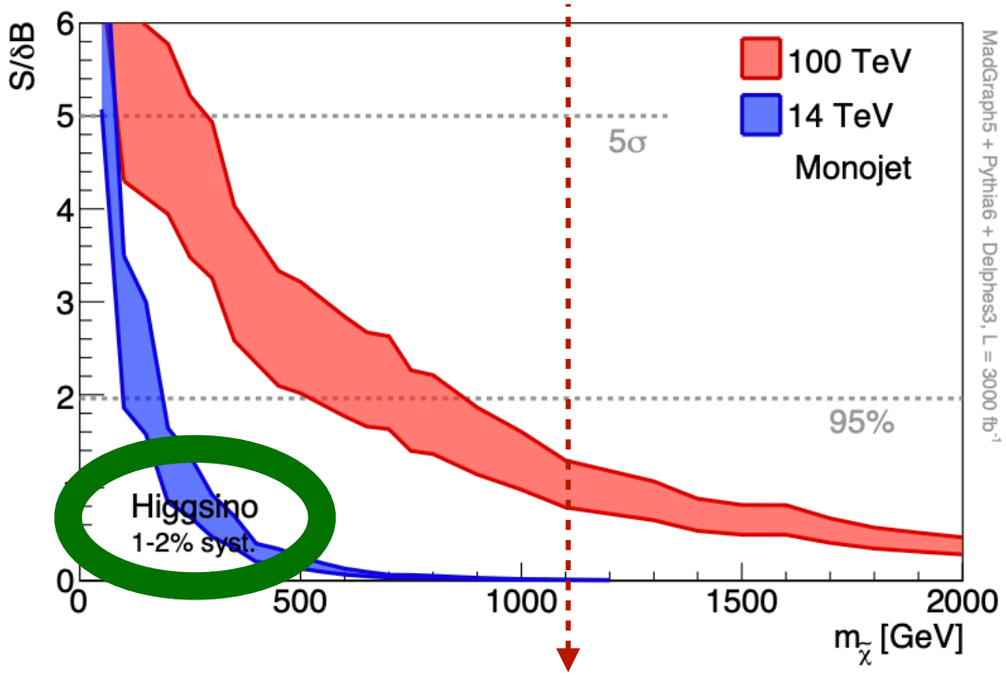




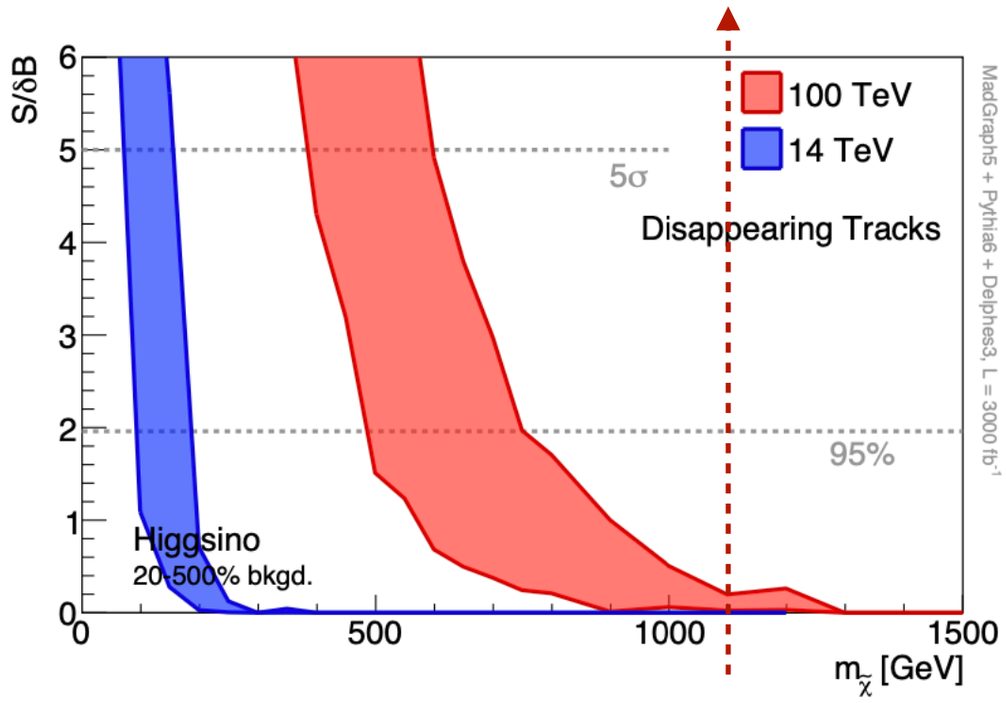
1. Electroweakinos-Like Dark Matter

- Hadron colliders

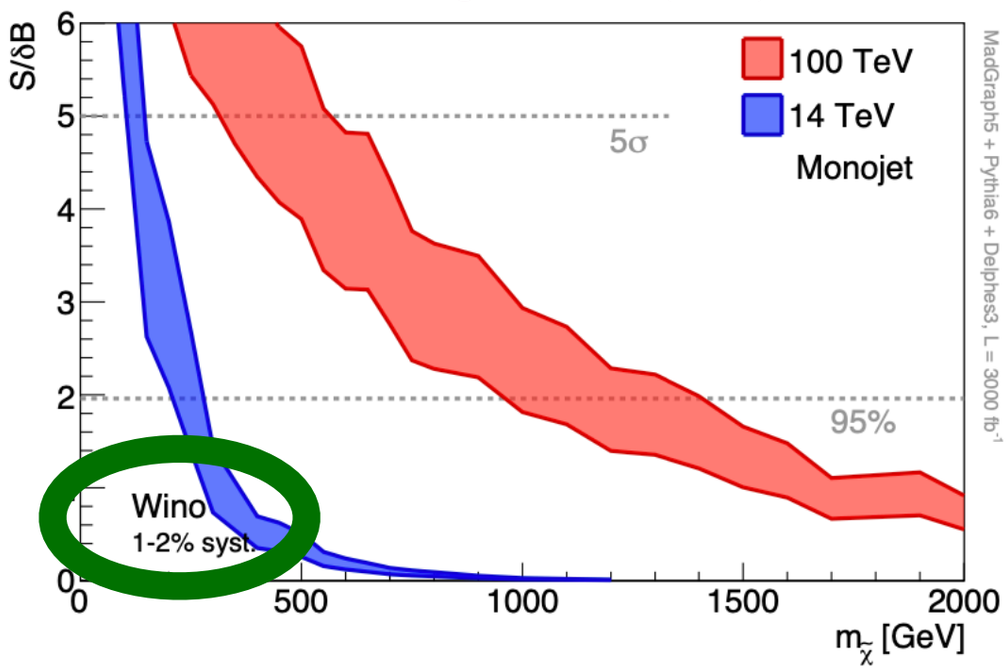
M. Low, L. Wang, JHEP 08 (2014) 161



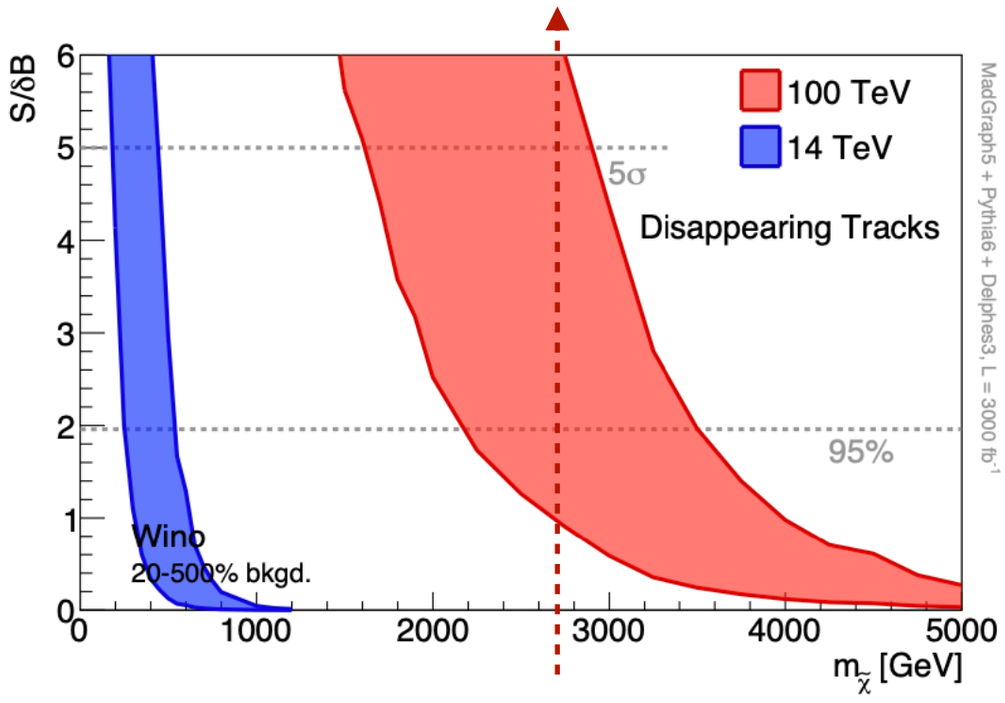
Thermal Target! $\sim 1.1\,\mathrm{TeV}$



In more recent studies FCChh can reach the thermal target!



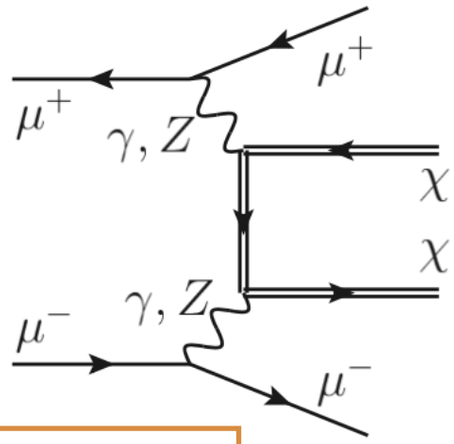
$\sim 2.7\,\mathrm{TeV}$



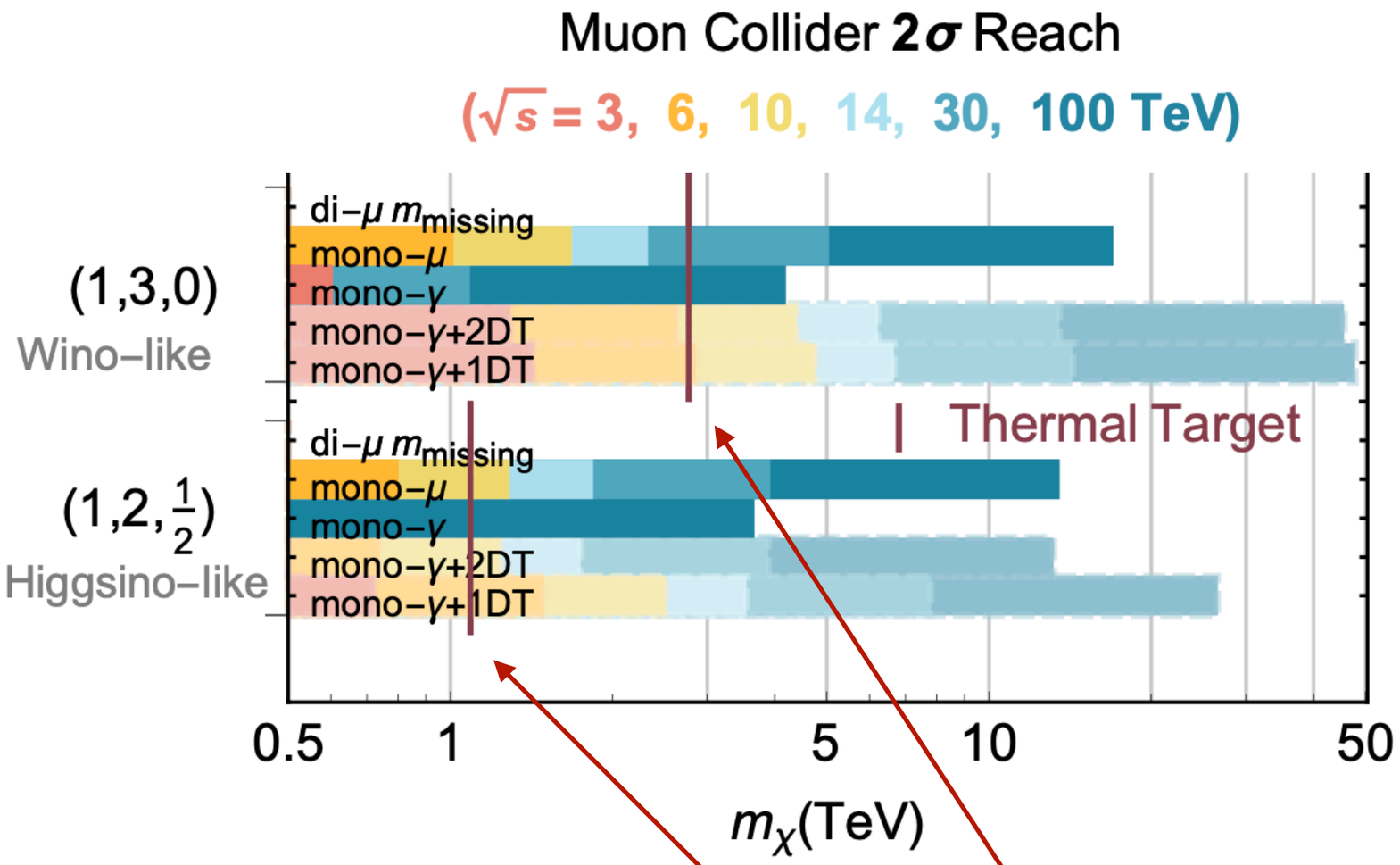
1. Electroweakinos-Like Dark Matter

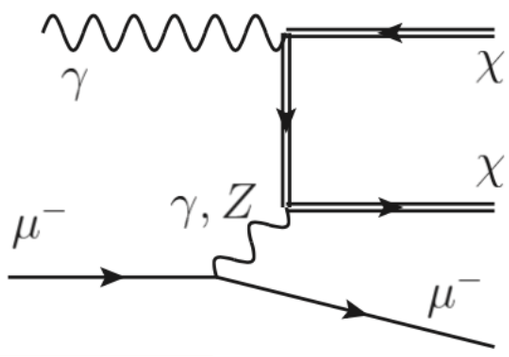
- Muon colliders

T. Han, Z. Liu, L. Wang, X. Wang,
Phys. Rev. D 103 (2021) 7, 075004

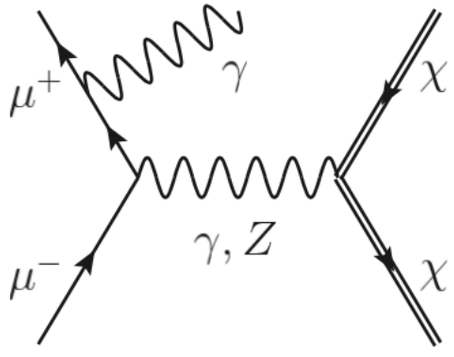


di-muon + MET





mono-muon



Mono-photon

The 10 TeV MuC can reach the thermal target (?)

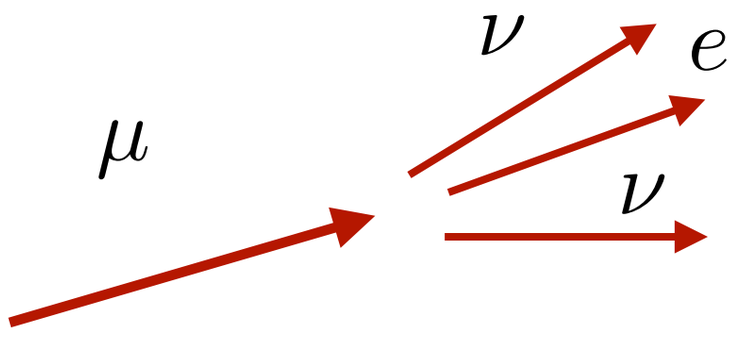
Need DT

BIB impact?

1. Electroweakinos-Like Dark Matter

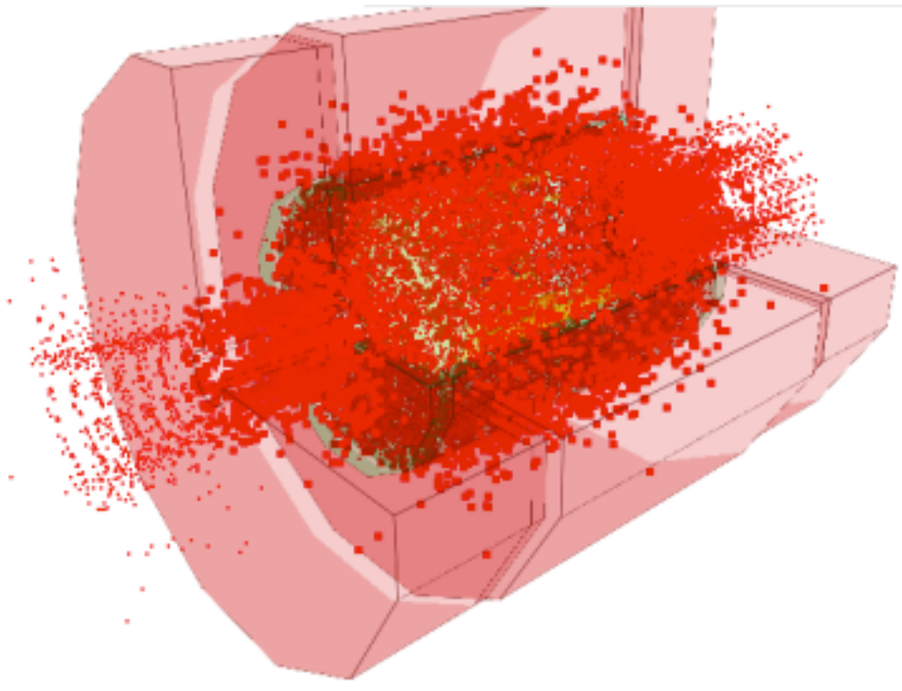
- Beam Induced Background:

Muons decay in flight!



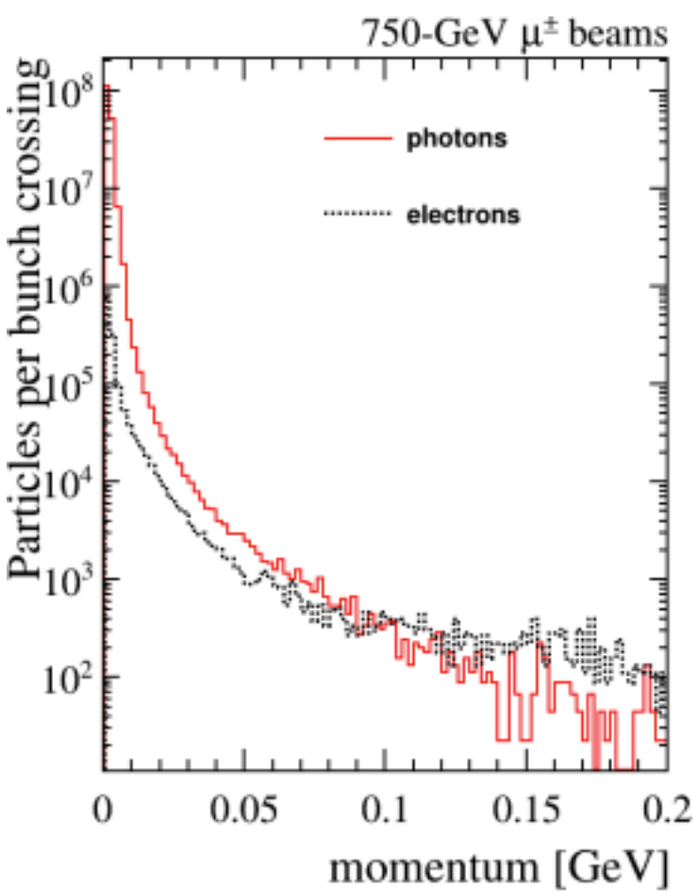
Donatella's talk

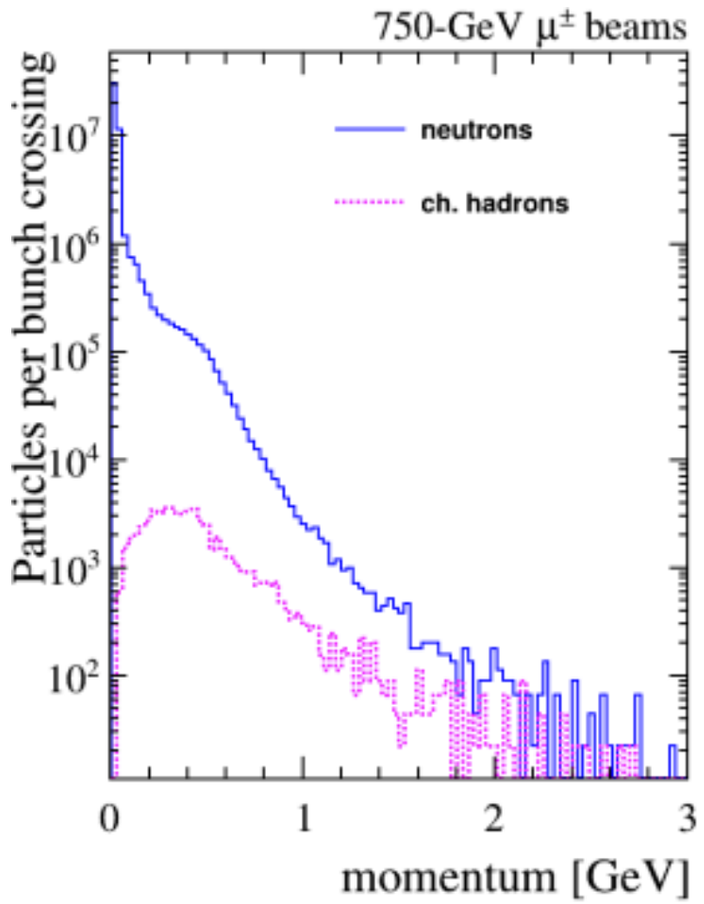
Sestini and Casarsa

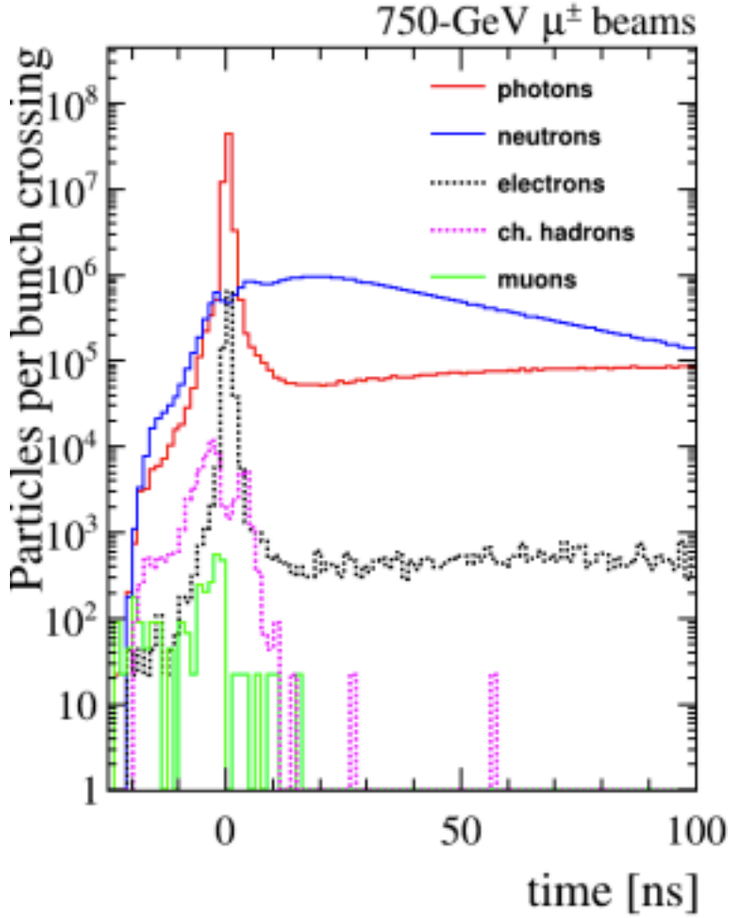


1. Soft
2. Arrives late
3. Mostly forward

N. Bartosik et al.,
2020 JINST 15 P05001

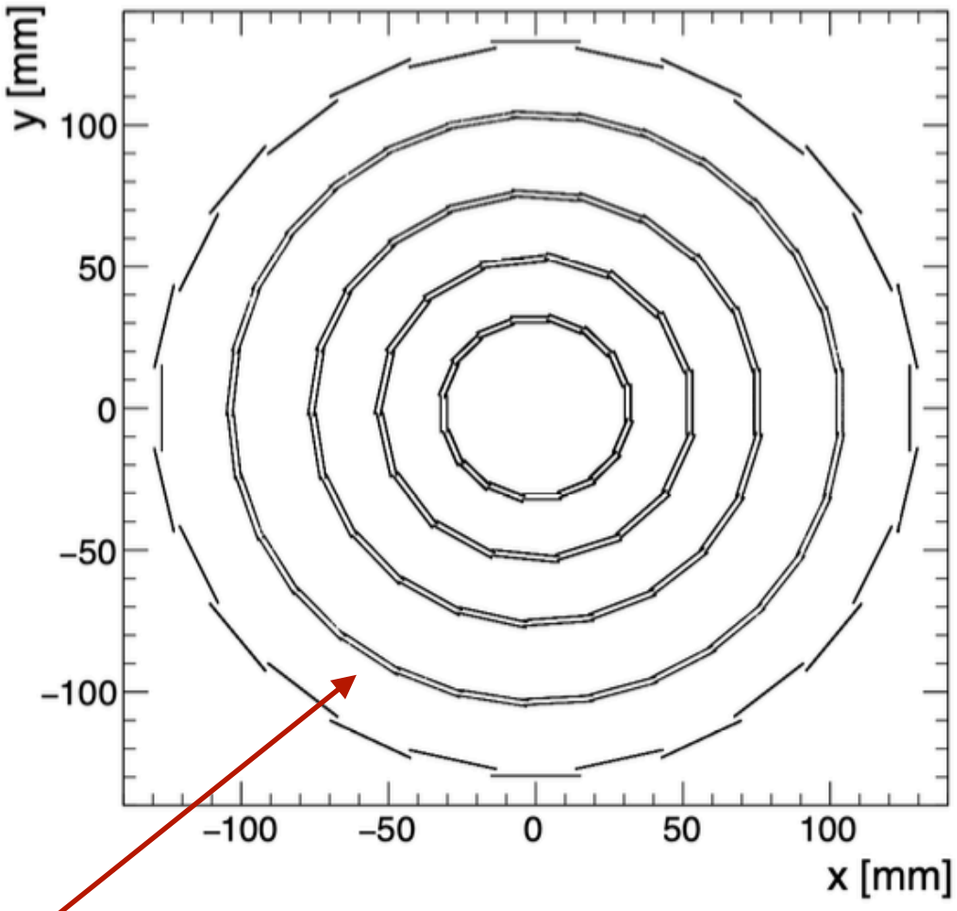






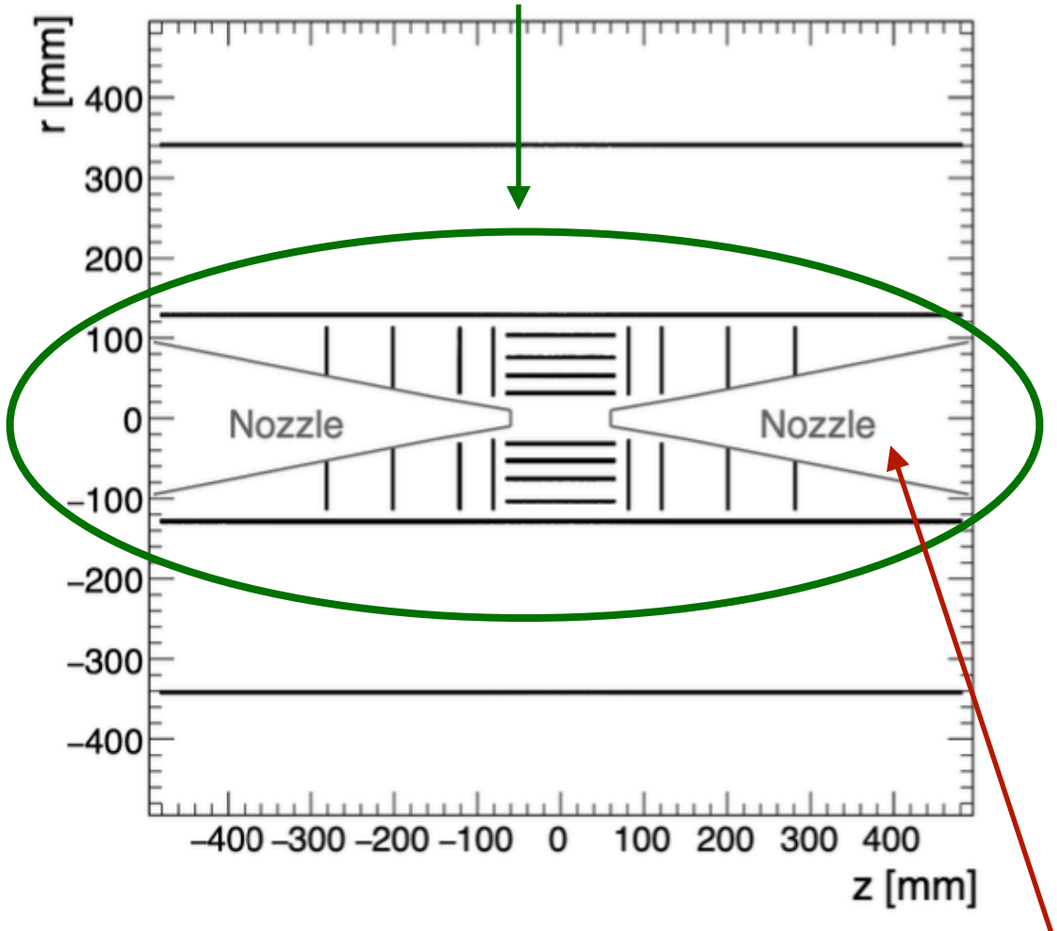
1. Electroweakinos-Like Dark Matter

- Muon colliders: Detector Geometry



Double layer structure!

Vertex Detector

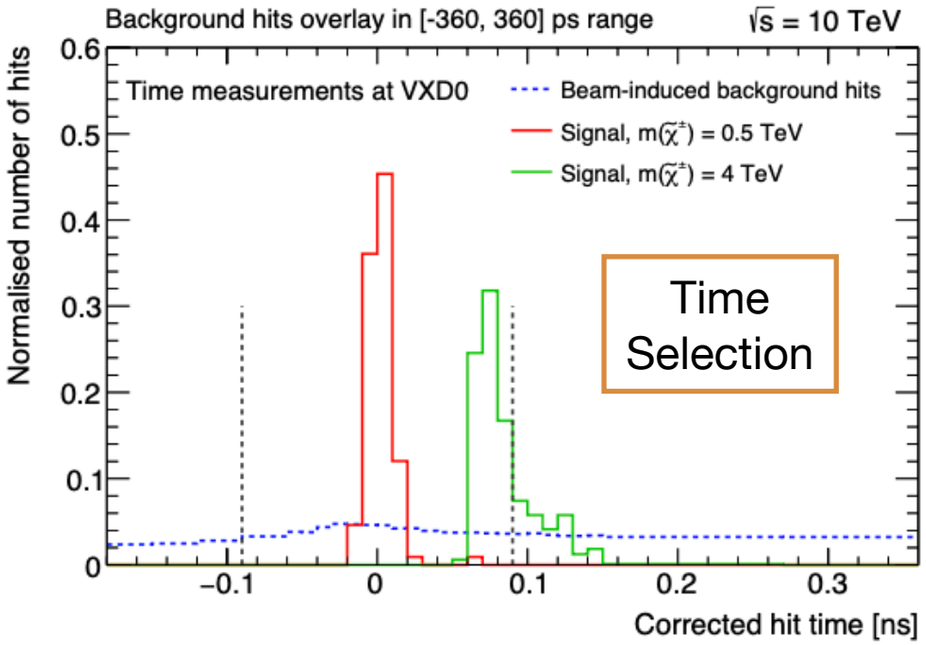


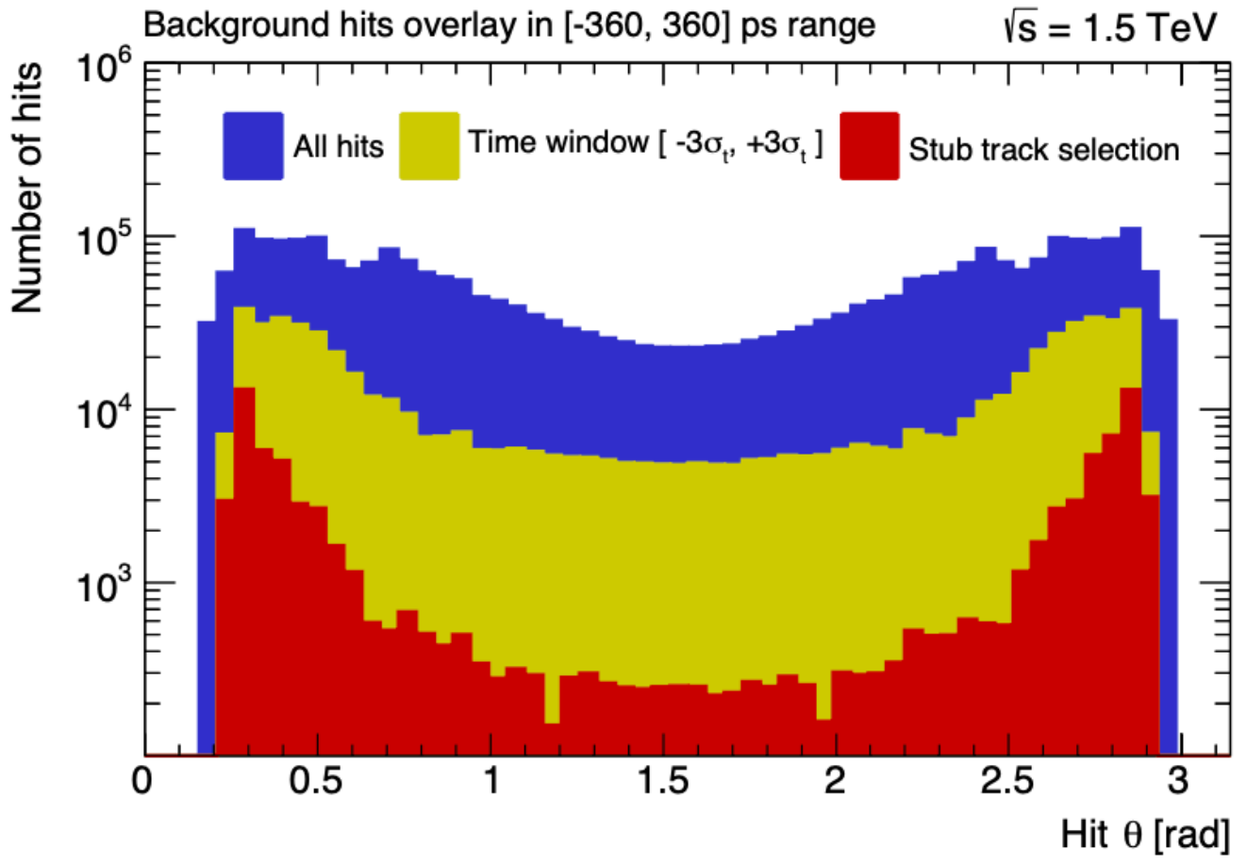
Shielding Tungsten Nozzles!

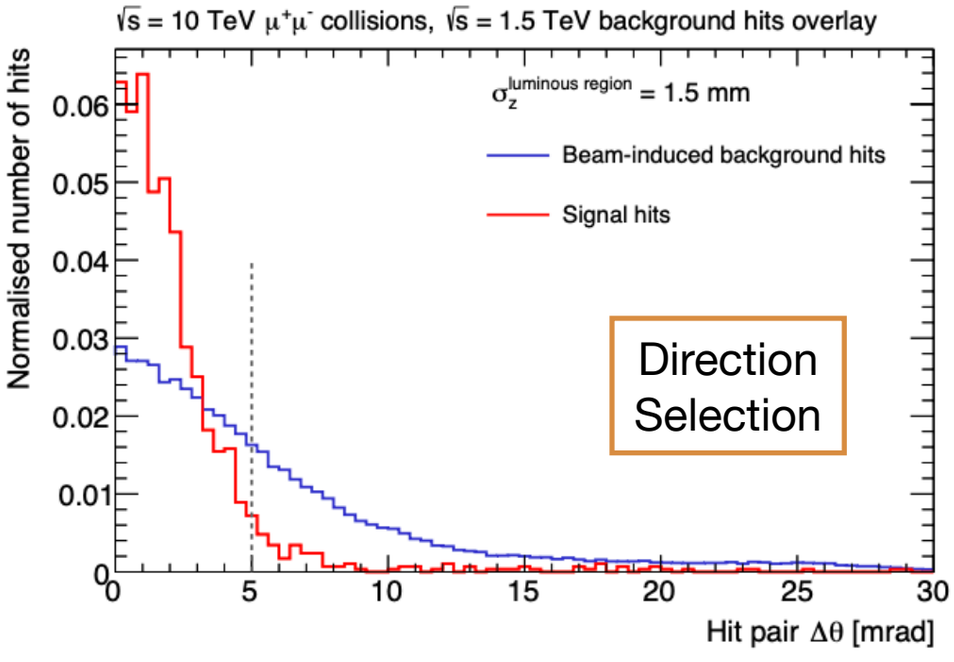
1. Electroweakinos-Like Dark Matter

- Muon colliders: Remember the BIB!

1. Soft
2. Arrives late
3. Mostly forward







	SR^{γ}_{1t}	SR^{γ}_{2t}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	253 ± 4	170.5 ± 2.1

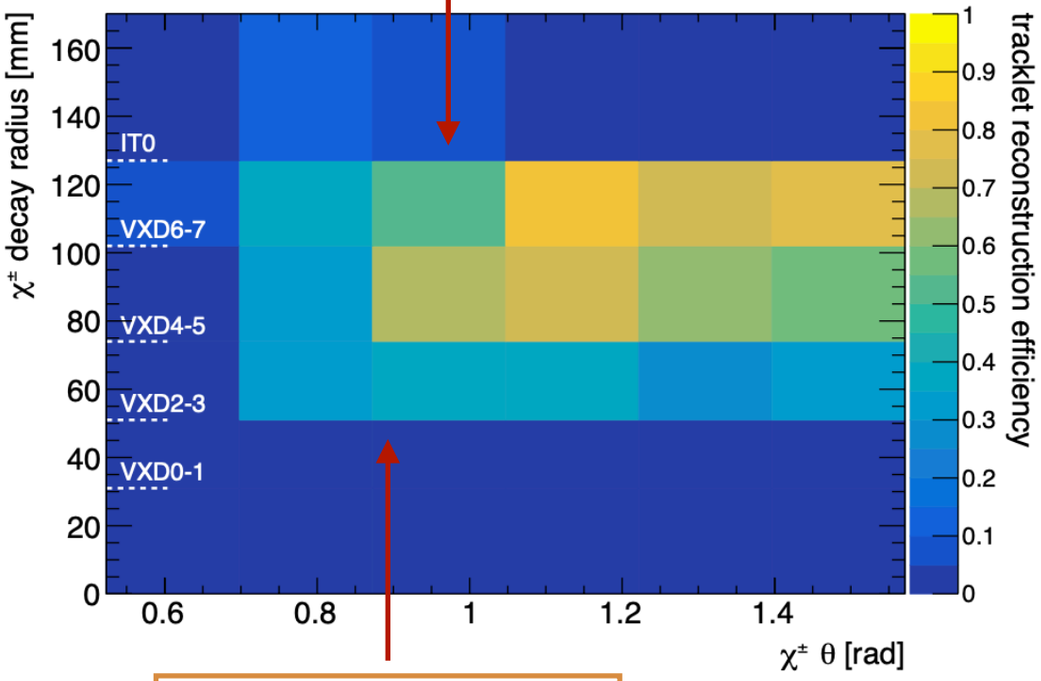
O(3) background rejection

1. Electroweakinos-Like Dark Matter

- Muon colliders

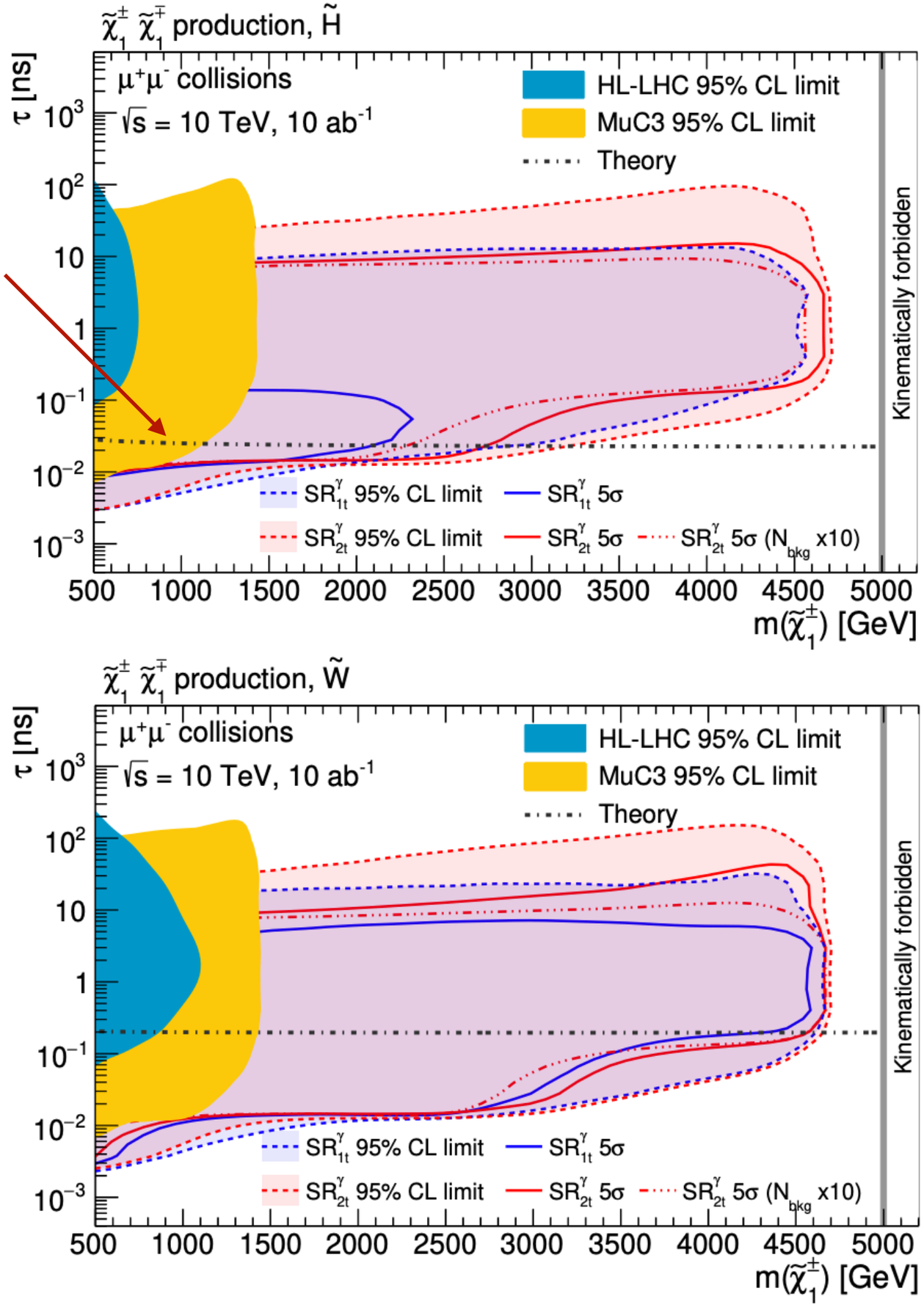
Lifetime from "pure" cases

Veto layer!
(Inner tracker 1st layer)



Second double layer!

	SR^{γ}_{1t}	SR^{γ}_{2t}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	253 ± 4	170.5 ± 2.1



Outline

1. Electroweakinos-like Dark Matter

- Higgsinos and Winos
- Disappearing Tracks

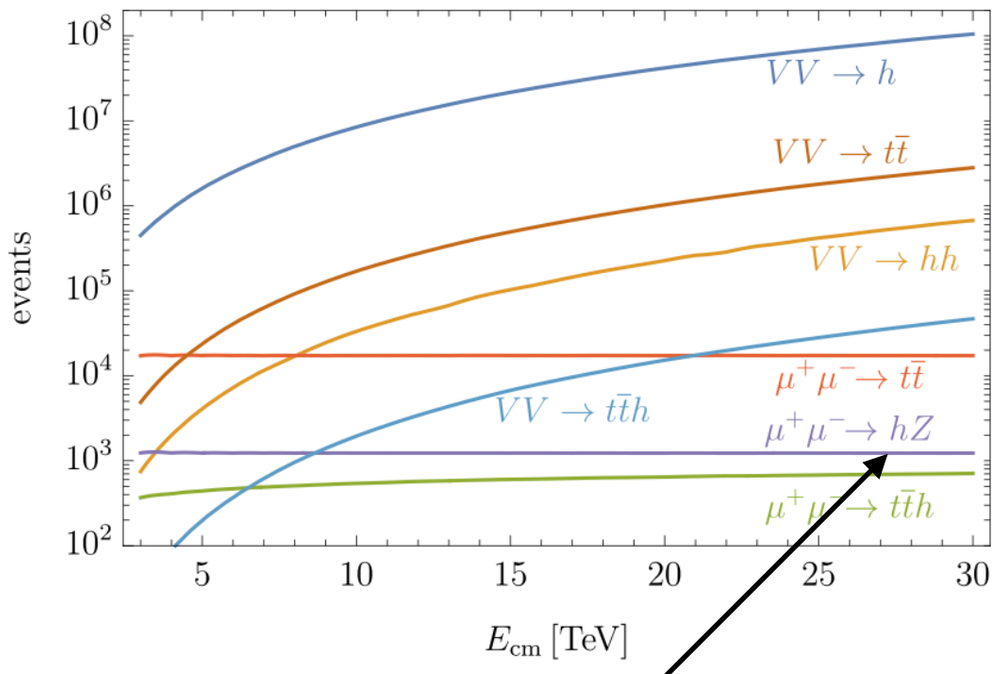
2. **BSM** and Exotic Signals

- Landscape (partially)
- Some Examples

(before BSM…) SM

1. Highly boosted SM objects:

Can we (angular) separate decay products of a ~TeV Z/W/H? (Leptonic? Hadronic?)

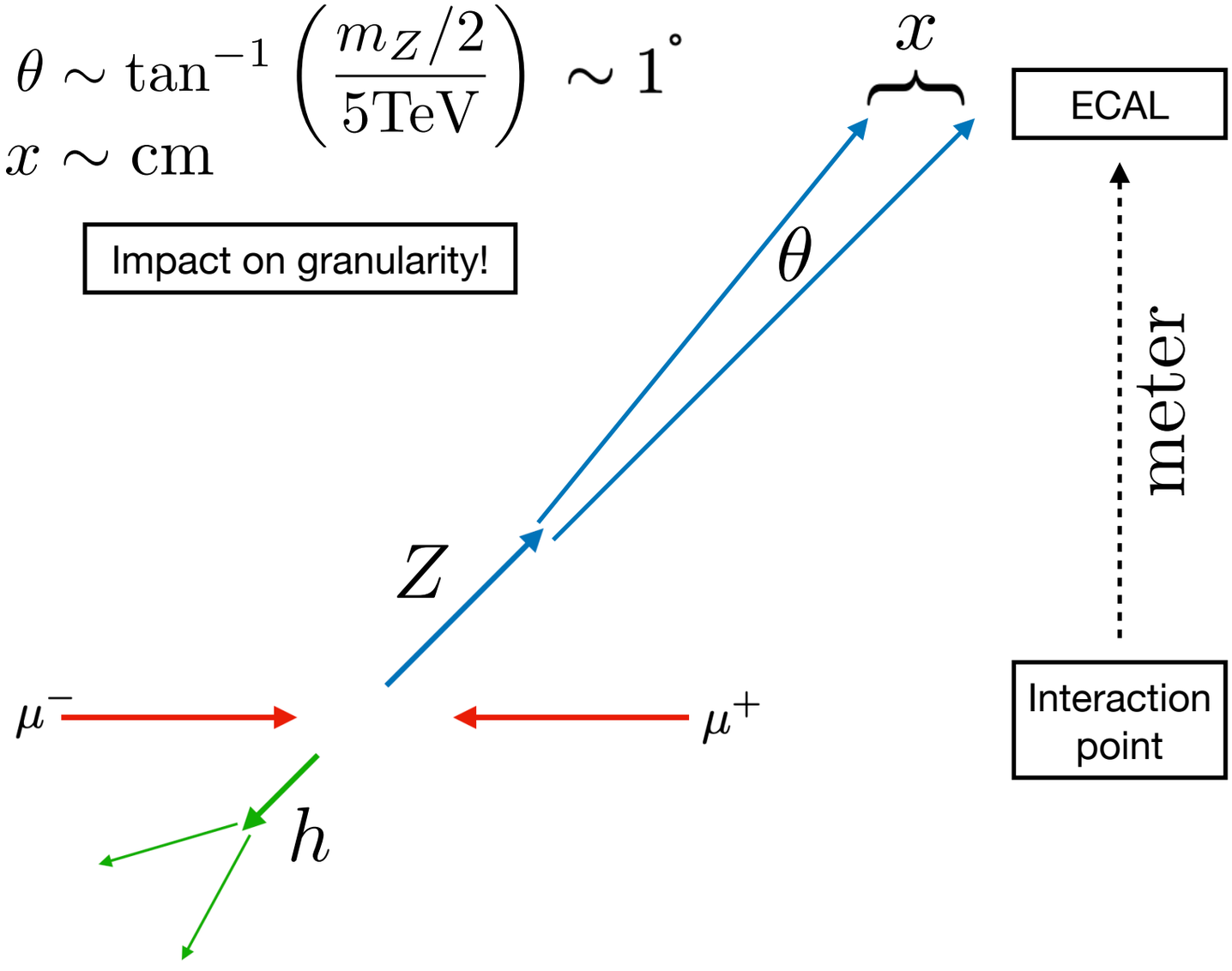


Decay product of 2->2 processes will be highly collimated!

$$\theta \sim \tan^{-1}\left(\frac{m_Z/2}{5\text{TeV}}\right) \sim 1^\circ$$

$$x \sim \text{cm}$$

Impact on granularity!



(before BSM…) SM

1. Highly boosted SM objects:

Can we separate decay products of a ~TeV Z/W/H? (Leptonic? Hadronic?)

2. Precision ZZH couplings:

Is it possible to measure the forward muon? What angles?

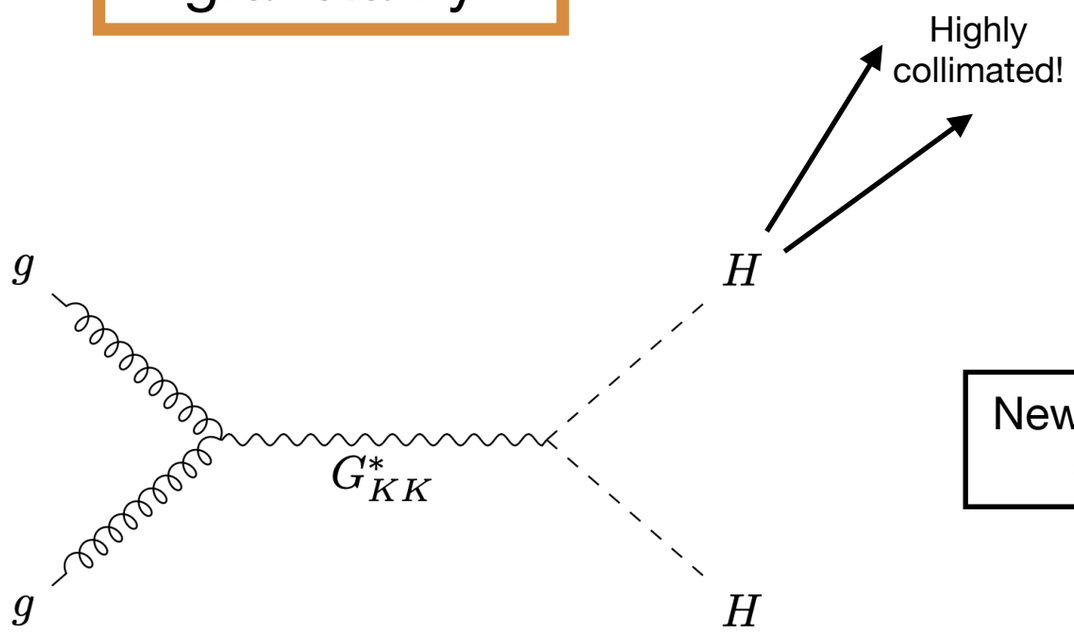
3. Precision VBF:

Can we measure the polarization of outgoing VB?

Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals (Potential Implications for Detector/Facility Design)**								
			Boosted objects	Small splittings	Stopping particles	Disappearing tracks	Displaced vertices	Exotic tracks	Emerging jets	Exotics in the mu system	Forward detector
Exotics	SM+singlet	S	x				x			x	
	2HDM	$H^{\pm}$, H^{0}, A	x	x			x				
	New gauge groups	Z', W'	x	x		x					
	VLF	Q', L'	x	x				x			
	HNL	N_i	x							x	x
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	x	x							
	Quirks	$q'\bar{q}'$ (bound state)			x			x		x	x
	Hidden valleys						x	x	x	x	
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x	x	x						
		$\chi^{\pm}, \chi^{0}, \tilde{\tau}$ (not colored)	x	x		x		x		x	
	Composite	$X_{5/3}, T_{2/3}$	x	x							
	Extra dimensions	G_{KK}	x								
	Neutral naturalness	Glueballs, sQuirks					x	x	x	x	
DM	Z portal	EWikinos-like (inelastic)				x		x			
	H portal	S (Z2 symmetric)									
	Nu portal	ν_s									x
	U(1) portal	$U(1)_{B-L_i-L_j}$					x			x	

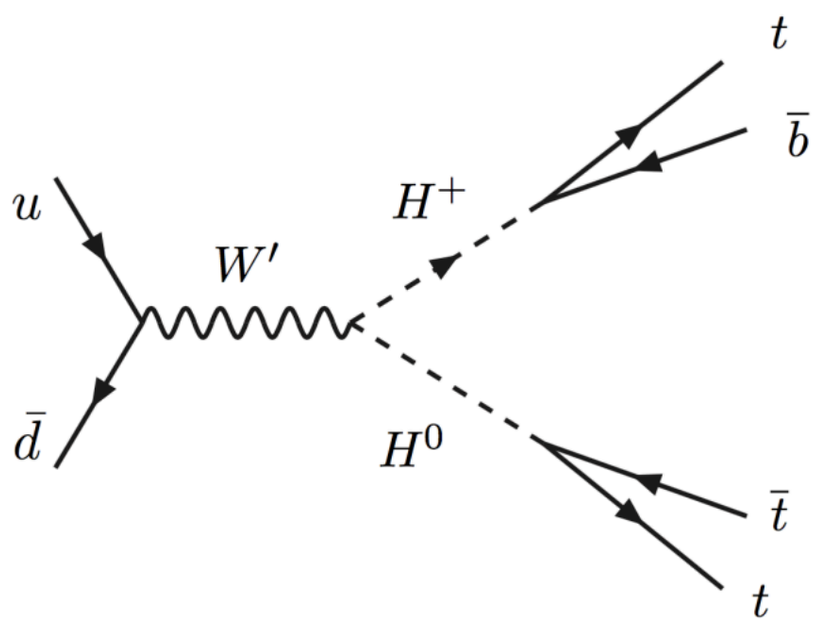
Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals…** Boosted objects
Exotics	SM+singlet	S	x
	2HDM	$H^{\pm}$, H^0, A	x
	New gauge groups	Z', W'	x
	VLF	Q', L'	x
	HNL	N_i	x
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	x
	Quirks	$q'\bar{q}'$ (bound state)	
	Hidden valleys		
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x
		$\chi^{\pm}, \chi^0, \tilde{\tau}$ (not colored)	x
	Composite	$X_{5/3}, T_{2/3}$	x
	Extra dimensions	G_{KK}	x
	Neutral naturalness	Glueballs, sQuirks	
DM	Z portal	EWikinos-like (inelastic)	
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

High granularity



New physics directly decay to SM

A. Fitzpatrick, J. Kaplan, L. Randall, L. Wang, JHEP 09 (2007) 013



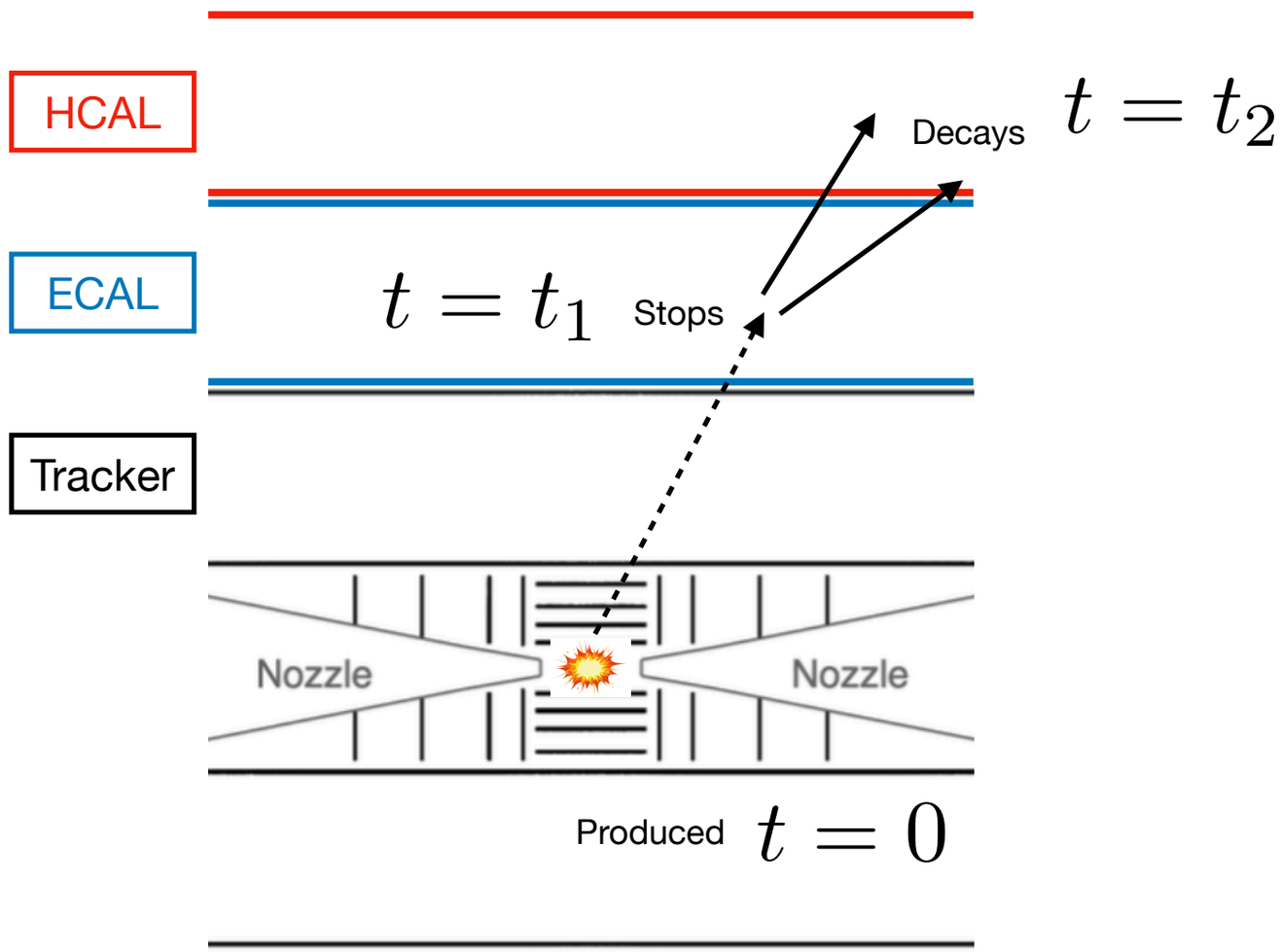
There is a relatively light mediator

Bogdan Dobrescu, Zhen Liu, JHEP 10 (2015) 118

Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals…** Stopping particles
Exotics	SM+singlet	S	
	2HDM	$H^{\pm}$, H^0, A	
	New gauge groups	Z', W'	
	VLF	Q', L'	
	HNL	N_i	
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	
	Quirks	$q'\bar{q}'$ (bound state)	x
	Hidden valleys		
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x
		$\chi^{\pm}, \chi^0, \tilde{\tau}$ (not colored)	
	Composite	$X_{5/3}, T_{2/3}$	
	Extra dimensions	G_{KK}	
	Neutral naturalness	Glueballs, sQuirks	
DM	Z portal	EWikinos-like (inelastic)	
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

Timing

Data Acquisition

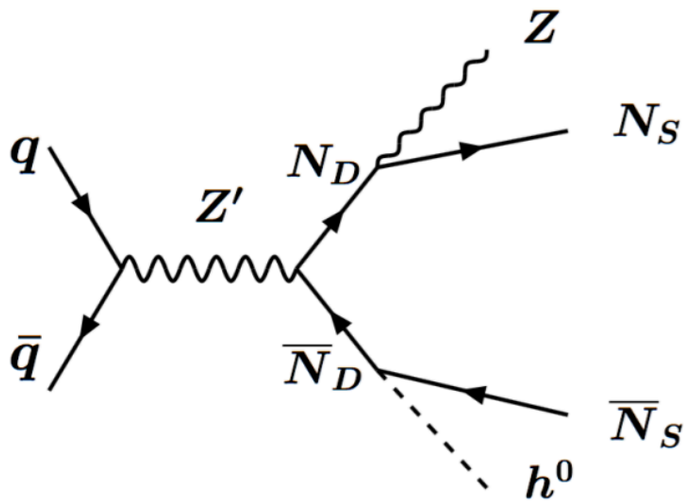


A. Arvanitaki, S. Dimopoulos, A. Pierce, S. Rajendran, J. Wacker, Phys. Rev. D 76 (2007) 055007

Junhai Kang, Markus Luty, JHEP 11 (2009) 065

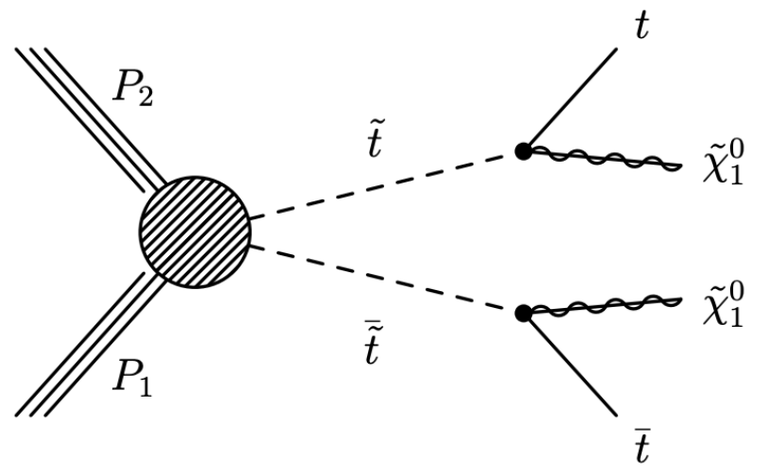
Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals…** Small splittings
Exotics	SM+singlet	S	
	2HDM	$H^{\pm}$, H^{0}, A	x
	New gauge groups	Z', W'	x
	VLF	Q', L'	x
	HNL	N_i	
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	
	Quirks	$q'\bar{q}'$ (bound state)	
	Hidden valleys		
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x
		$\chi^{\pm}, \chi^{0}, \tilde{\tau}$ (not colored)	x
	Composite	$X_{5/3}, T_{2/3}$	x
	Extra dimensions	G_{KK}	
	Neutral naturalness	Glueballs, sQuirks	
DM	Z portal	EWikinos-like (inelastic)	
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

Soft objects (prompt)



B. Dobrescu, arXiv:1506.04435

Soft secondary vertices (LLP)



V. Khachatryan et al.,
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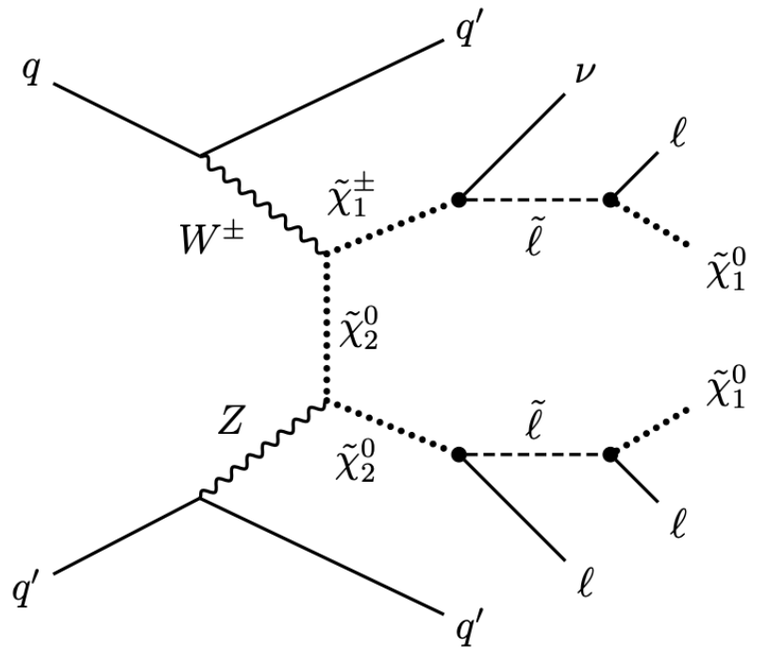

G. Giudice, T. Han, K. Wang, L. Wang,
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Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals (Potential Implications for Detector/Facility Design)**								
			Boosted objects	Small splittings	Stopping particles	Disappearing tracks	Displaced vertices	Exotic tracks	Emerging jets	Exotics in the mu system	Forward detector
Exotics	SM+singlet	S	**7**, **10**, **13**, **15**, **16**,				**7**, **10**, **13**, **15**, **16**,			**7**, **10**, **13**, **15**, **16**,	
	2HDM	$H^{\pm}$, H^{0}, A	**1**, **2**, **4**, **11**,	**1**, **2**, **4**, **11**,			**1**, **2**, **4**, **11**,				
	New gauge groups	Z', W'	**3**, **20**, **21**, **30**,	**3**, **20**, **21**, **30**,		**3**, **20**, **21**, **30**,					
	VLF	Q', L'	x	x				x			
	HNL	N_i	**17**, **19**, **24**, **25**, **26**,							**17**, **19**, **24**, **25**, **26**,	**17**, **19**, **24**, **25**, **26**,
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	**8**, **12**,	**8**, **12**,							
	Quirks	$q'\bar{q}'$ (bound state)			x			x		x	x
	Hidden valleys						x	x	x	x	

High connection to exotic signals

No connection to exotic signals

1) Eichten, Martin, Phys. Lett. B 728 (2014) 125-130
2) Chakrabarty, Han, Liu, Mukhopadhyaya, Phys. Rev. D 91 (2015) 1, 015008
3) Huang, Queiroz, Rodejohann, Phys. Rev. D 103 (2021) 9, 095005
4) Han, Li, Su, Su, Wu, Phys. Rev. D 104 (2021) 5, 055029
5) Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
6) Bottaro, Strumia, Vignaroli, JHEP 06 (2021) 143
7) Al Ali et al., Rept. Prog. Phys. 85 (2022) 8, 084201
8) Asadi, Capdevilla, Cesarotti, Homiller JHEP 10 (2021) 182
9) Franceschini, Greco, Symmetry 13 (2021) 5, 851
10) Haghighat, Najafabadi, Nucl. Phys. B 980 (2022) 115827
11) Sen, Bandyopadhyay, Dutta, KT, Eur. Phys. J. C 82 (2022) 3, 230
12) Qian et al., JHEP 12 (2021) 047
13) Costantini, PoS EPS-HEP2021 (2022) 717
14) Casarsa, Fabbrichesi, Gabrielli, Phys. Rev. D 105 (2022) 7, 7
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17) Chakraborty, Roy, Srivastava, e-Print: 2206.07037
18) Inan, Kisselev, eprint: 2207.03325
19) Liu, Han, Jin, Li, eprint: 2207.07382
20) Allanach, Loisa, eprint: 2212.07440
21) Das, Nomura, Shimomura, eprint: 2212.11674
22) Franceschini, Zhao, eprint: 2212.11900
23) Lv, Cui, Li, Liu, Nucl. Phys. B 985 (2022) 116016
24) Mekala, Reuter, Zarnecki, eprint: 2301.02602
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27) Li, Yao, Yuan, eprint: 2301.07274
28) Inan, Kisselev, eprint: 2301.08585
29) Jueid, Nasri, eprint: 2301.12524
30) Li et al., eprint: 2302.02203
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Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals (Potential Implications for Detector/Facility Design)**								
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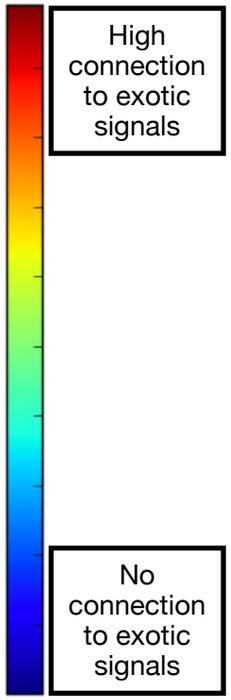

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Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	**7**,	**7**,	**7**,						
		$\chi^{\pm}, \chi^{0}, \tilde{\tau}$ (not colored)	**7**,	**7**,		**7**,		**7**,		**7**,	
	Composite	$X_{5/3}, T_{2/3}$	**23**,	**23**,							
	Extra dimensions	G_{KK}	**28**,								
	Neutral naturalness	Glueballs, sQuirks					x	x	x	x	

Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals (Potential Implications for Detector/Facility Design)**								
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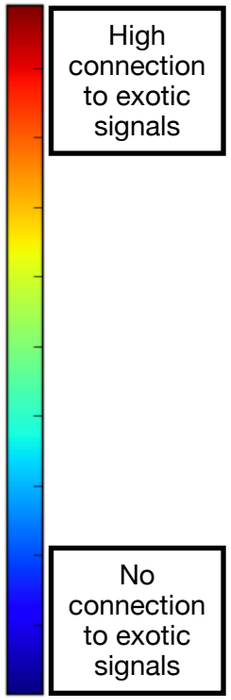

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…

DM	Z portal	EWikinos-like (inelastic)				**5**, **6**, **22**,		**5**, **6**, **22**,			
	H portal	S (Z2 symmetric)									
	Nu portal	ν_s									**19**, **29**,
	U(1) portal	$U(1)_{B-L_i-L_j}$					x			x	

Summary

1. We explored a highly motivated BSM scenario that can lead to exotic signals at future colliders: Electroweakino-Like WIMPs that produce disappearing tracks in the vertex detector. The double-layer design of the vertex detector is important to mitigate BIB!

2. It is important for future colliders detector and accelerator/facility design to identify BSM scenarios that can lead to exotic signals.

3. This important task requires the close collaboration of HEP-th, HEP-ex, and Accelerator Physicists.

Thank You!