

# *(Exotic) Signal Benchmarks for a Muon Collider: Part II*

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IJCLab

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***Rodolfo Capdevilla***  
Fermilab

Part 2 of the talk at KITP!

Great inputs from: F. Meloni, S. Jindariani,  
N. Craig, J. Zurita, D. Curtin, B. Dobrescu,  
P. Fox, M. Ruhdorfer

*Question:*

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

# Outline

1. Disappearing Tracks
2. Forward Detectors
3. Displaced Vertices
4. Stopping Particles

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	$S, a$	x									x
	2HDM	$H^\pm, H^0, A$	x	x		x	x			x	x	
	New gauge groups	$Z', W', \gamma'$	x									x
	VLF	$Q', L'$	x	x		x						
	HNL	$N_i$				x	x				x	x
	Leptoquarks	$\tilde{R}_2, U_1$ (UV motivated)	x	x								
	Quirks	$q' \bar{q}'$				x				x	x	
	Hidden valleys	(bound states) $g' g'$						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	x
DM	Z portal	EWinos-like (inelastic)				x		x		x		
	H portal	$S$ (Z2 symmetric)										
	Nu portal	$\nu_s$										x
	U(1) portal	$U(1)_{B-L_i-L_j}$						x				x

# *Outline*

## **1. Disappearing Tracks**

2. Forward Detectors

3. Displaced Vertices

4. Stopping Particles

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

Timing

Tracking

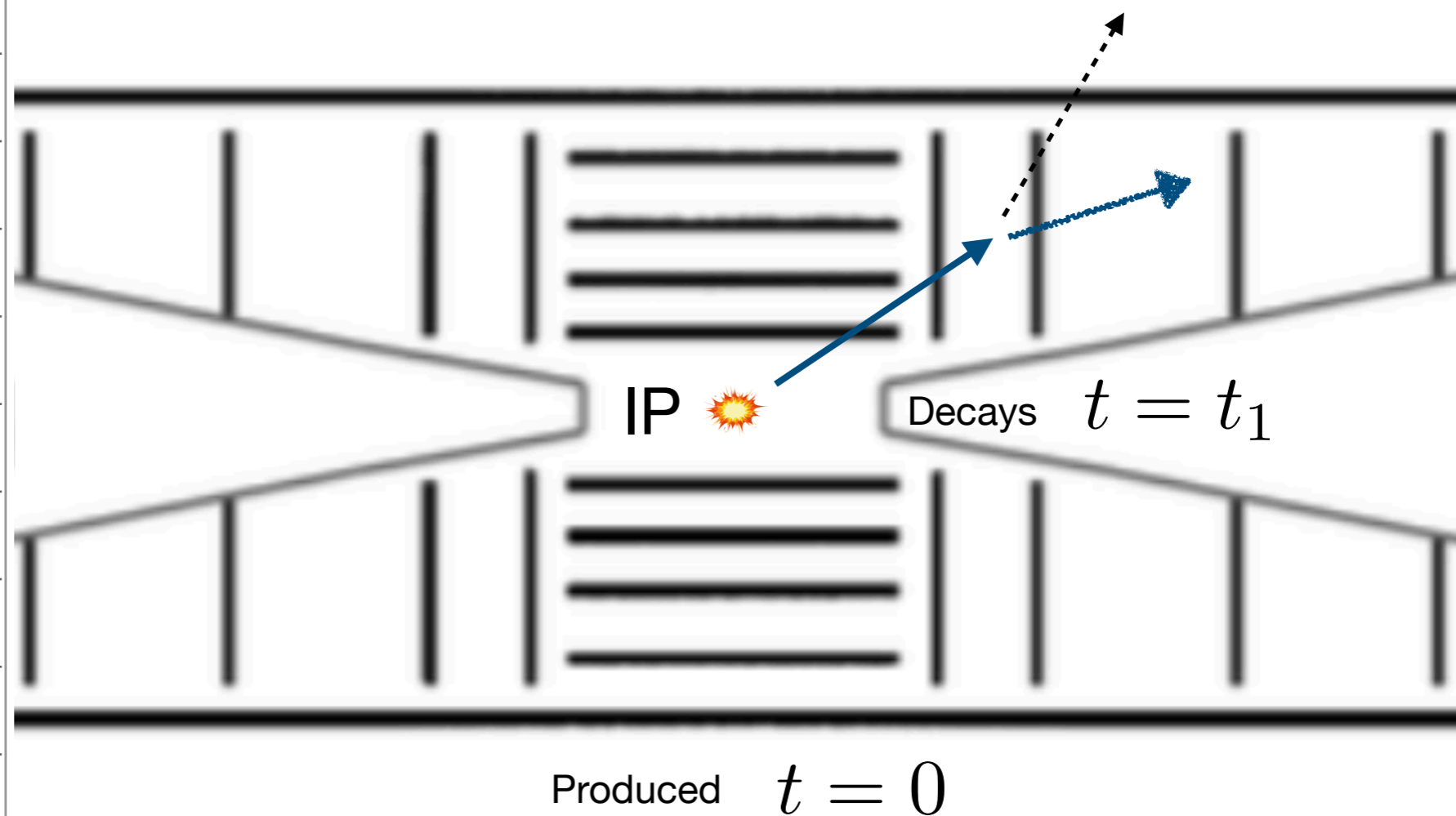
*Particle(s) produced at the interaction point*

*Initial time is set by the bunch crossing*

*Particle(s) passes through at least two double layers*

*Particle(s) travels as far as the first layer of the inner tracker*

*Particle(s) decays to missing energy and a soft particle*

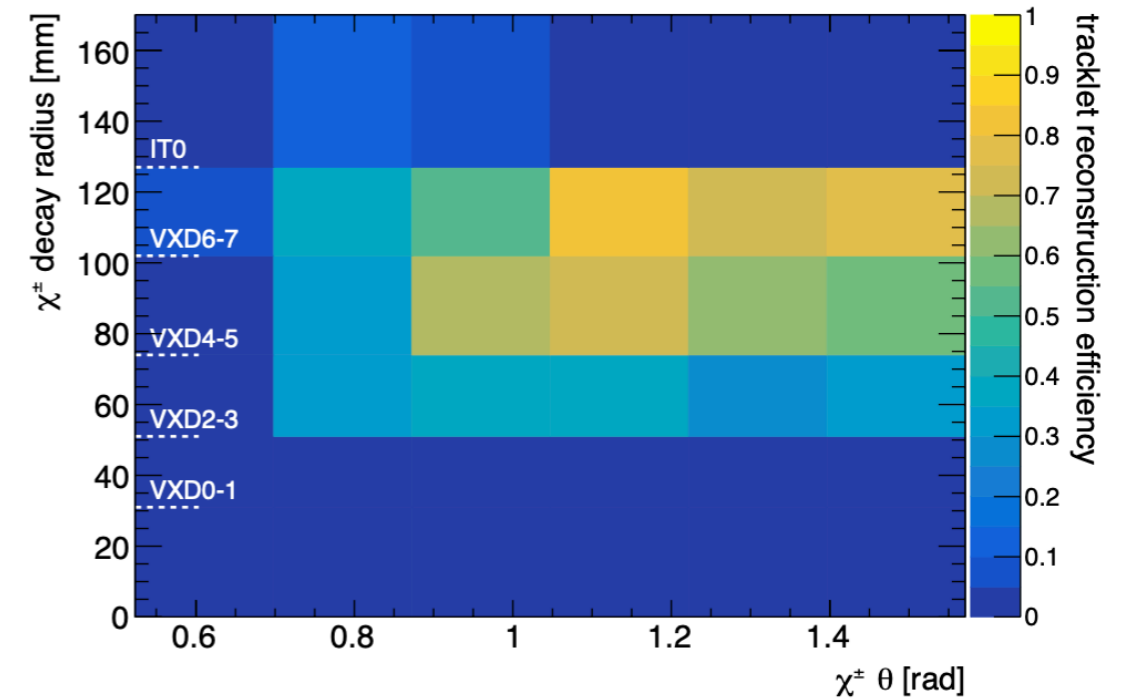
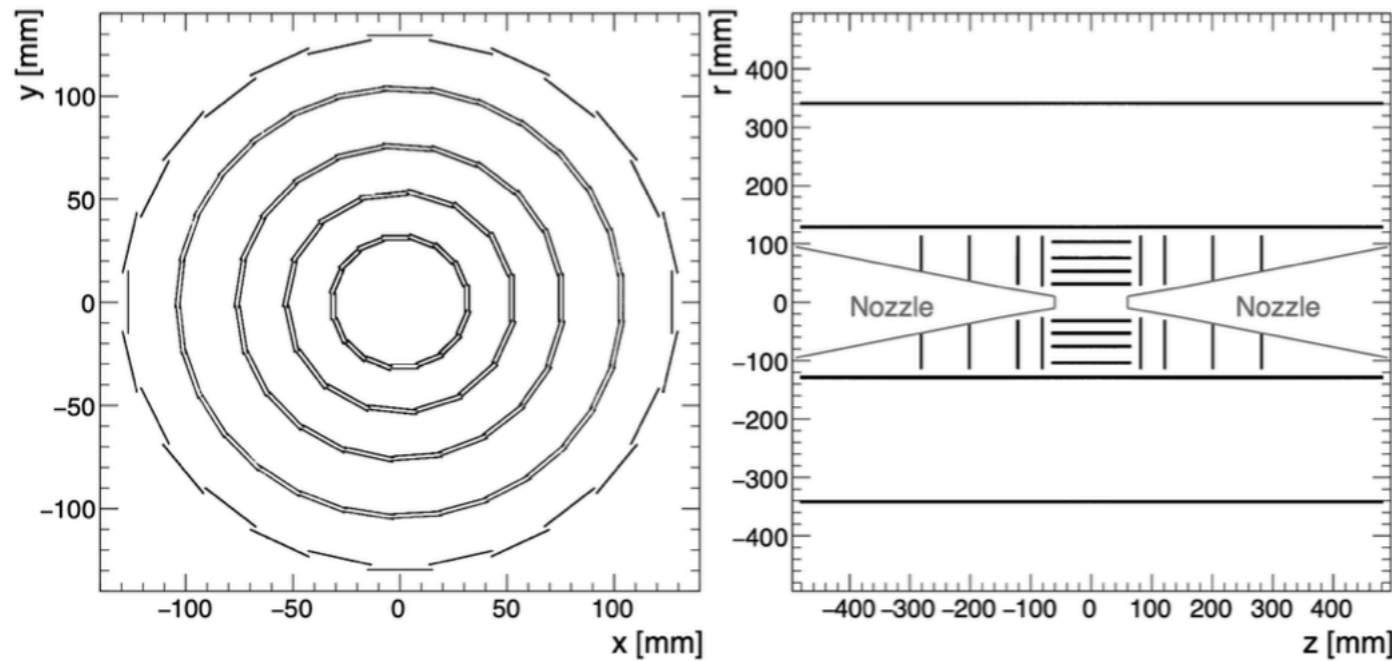


# 1. Disappearing Tracks

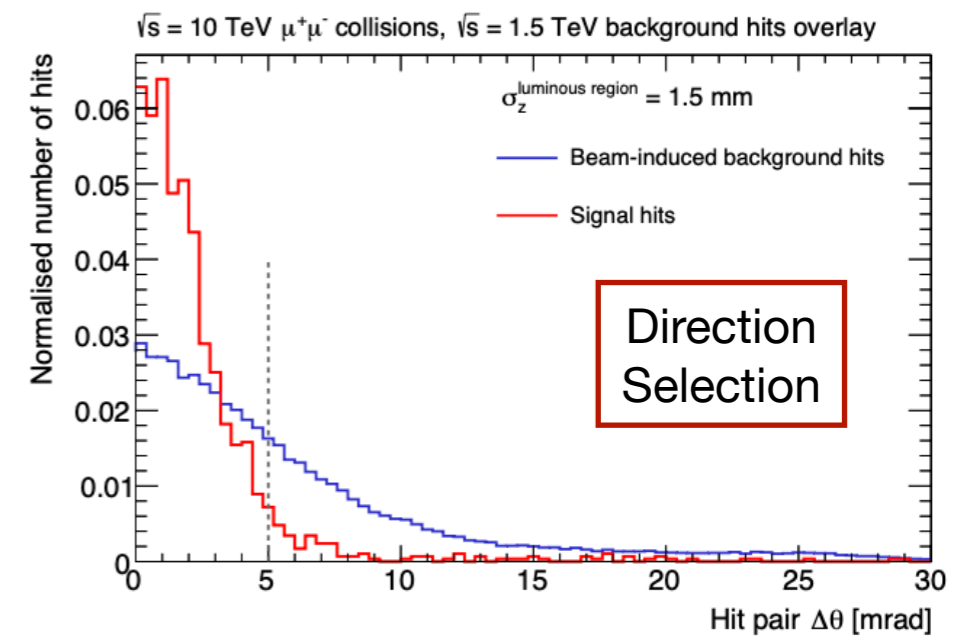
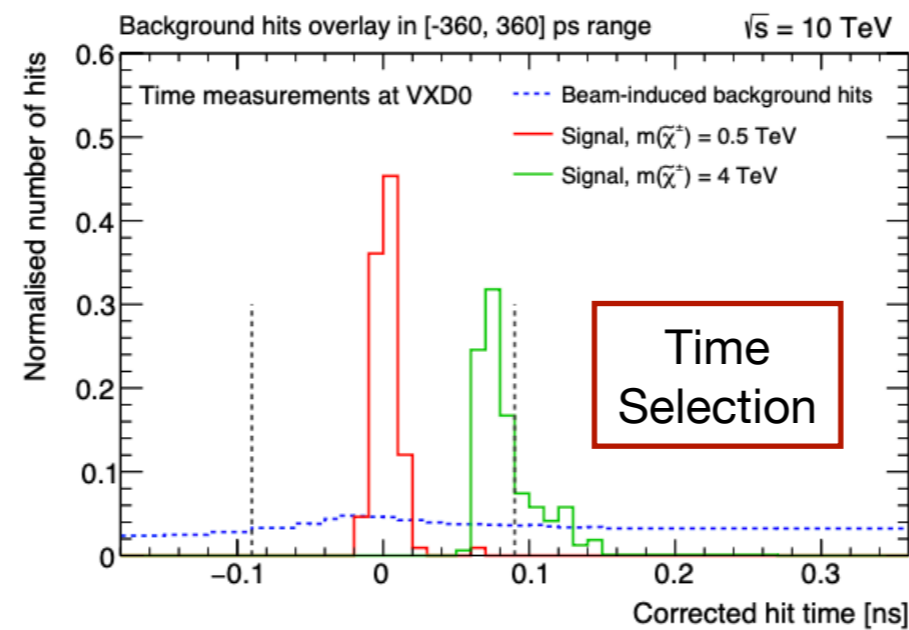
- Efficiency:

RC, F. Meloni, R. Simoniello,  
J. Zurita, JHEP **06** (2021) 133

Vertex detector Double layer geometry



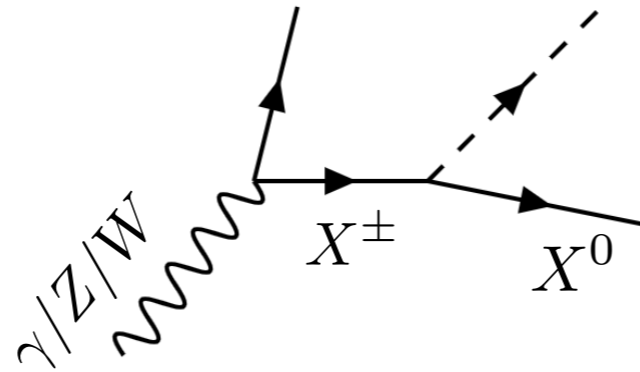
Requirement / Region	$SR_{1t}^\gamma$	$SR_{2t}^\gamma$
Veto	leptons and jets	
Leading tracklet $p_T$ [GeV]	$> 300$	$> 20$
Leading tracklet $\theta$ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet $p_T$ [GeV]	—	$> 10$
Tracklet pair $\Delta z$ [mm]	—	$< 0.1$
Photon energy [GeV]	$> 25$	$> 25$



Uses 1.5 TeV  
BIB from MAP

Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals Disappearing tracks
Exotics	SM+singlet	$S, a$	
	2HDM	$H^\pm, H^0, A$	1, 2, 3, 4, 8, 17,
	New gauge groups	$Z', W', \gamma'$	
	VLF	$Q', L'$	7, 13, 17,
	HNL	$N_i$	
	Leptoquarks	$\tilde{R}_2, U_1$ (UV motivated)	
	Quirks	$q' \bar{q}'$ (bound states)	
	Hidden valleys	$g' g'$	
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored) $\chi^\pm, \chi^0, \tilde{\tau}$ (not colored)	11, 18,
	Composite	$X_{5/3}, T_{2/3}$	
	Extra dimensions	$G_{KK}$	
	Neutral naturalness	Glueballs, sQuirks	
DM	Z portal	EWinos-like (inelastic)	5, 6, 9, 10, 11, 12, 14, 16,
	H portal	$S$ (Z2 symmetric)	
	Nu portal	$\nu_s$	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

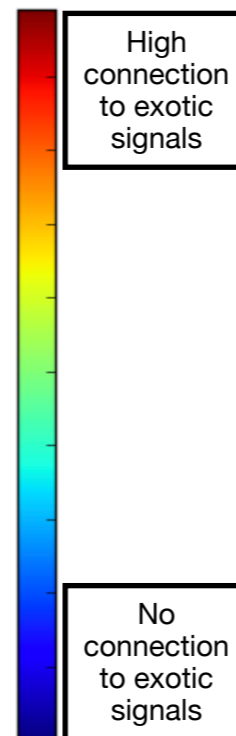
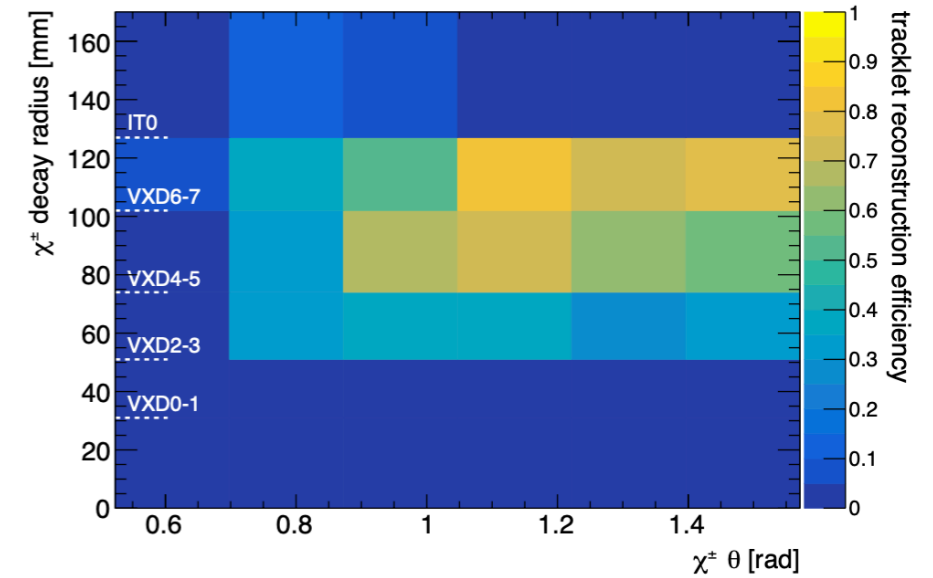
## Timing



Long lifetime:  
Small splitting  
Small coupling

## Tracking

RC, F. Meloni, R. Simoniello,  
J. Zurita, JHEP 06 (2021) 133



- 1) Eichten, Martin, Phys. Lett. B 728 (2014) 125-130
- 2) Barger, Everett, Logan, Shaughnessy, Phys. Rev. D 88 (2013) 11, 115003
- 3) Chakrabarty, Han, Liu, Mukhopadhyaya, Phys. Rev. D 91 (2015) 1, 015008
- 4) Chakrabarty, Mukhopadhyaya, Phys. Rev. D 96 (2017) 3, 035028
- 5) Han, Liu, Wang, Wang, Phys. Rev. D 103 (2021) 7, 075004
- 6) Bandyopadhyay, Costantini, Phys. Rev. D 103 (2021) 1, 015025
- 7) Bandyopadhyay, Karan, Sen, ArXiv:2011.04191
- 8) Han, Li, Su, Su, Wu, Phys. Rev. D 104 (2021) 5, 055029
- 9) Capdevilla, Meloni, Simoniello, Zurita, JHEP 06 (2021) 133
- 10) Bottaro, Strumia, Vignaroli, JHEP 06 (2021) 143
- 11) Al Ali et al., Rept. Prog. Phys. 85 (2022) 8, 084201
- 12) Bottaro, Buttazzo, Costa, Franceschini, Panci, Eur. Phys. J. C 82 (2022) 1, 31
- 13) Sen, Bandyopadhyay, Dutta, KT, Eur. Phys. J. C 82 (2022) 3, 230
- 14) Bottaro et al., Eur. Phys. J. C 82 (2022) 11, 992
- 15) Liu, Han, Jin, Li, JHEP 12 (2022) 057
- 16) Franceschini, Zhao, ArXiv:2212.11900
- 17) Li, Yao, Yuan, JHEP 03 (2023) 137
- 18) Jueid, Nasri, ArXiv:2301.12524



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**2. Forward Detectors**

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

Timing

FD

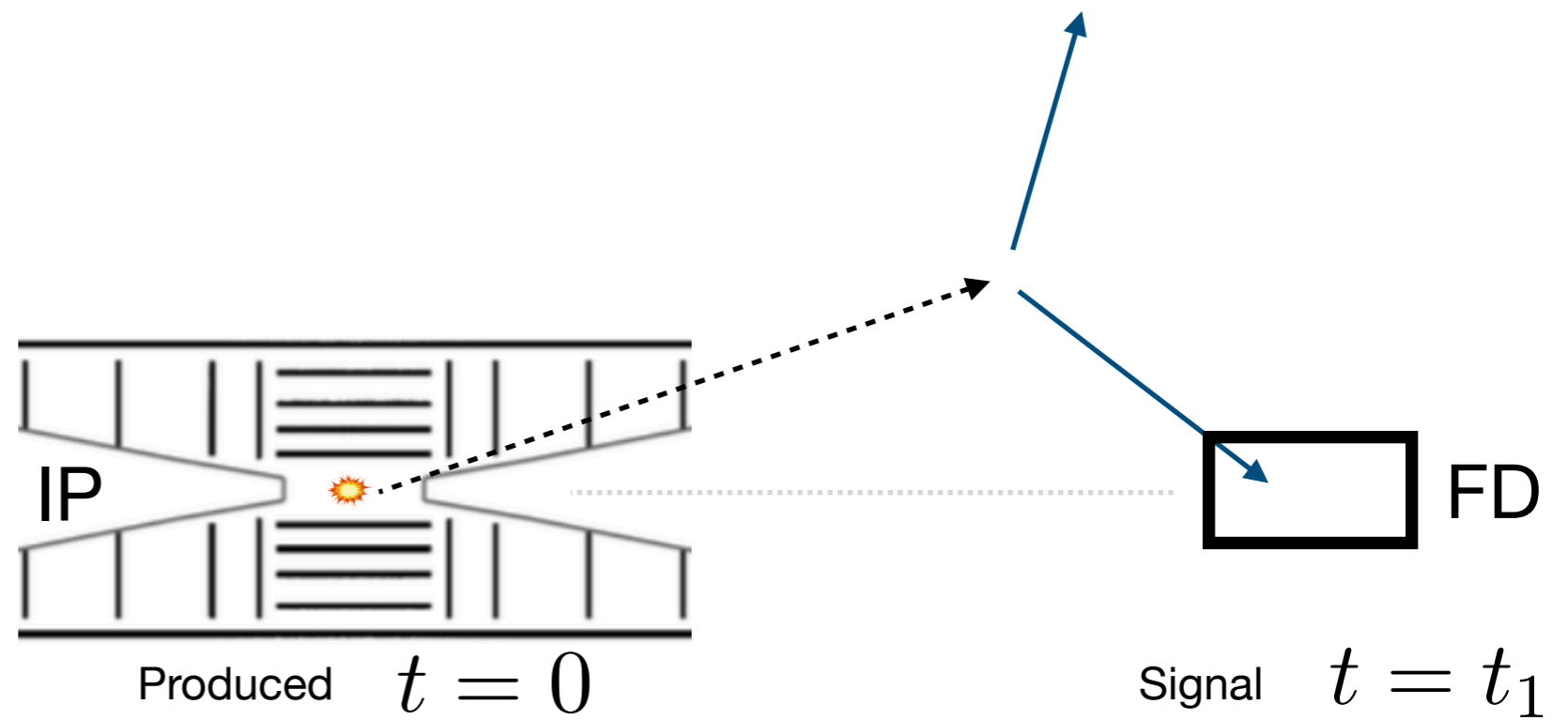
*Particle(s) produced at the interaction point*

*Initial time is set by the bunch crossing*

*Particle(s) decay beyond the main detector*

*Decay products will get caught by the forward detector(s)*

*There must be muons in the decay products(?)*

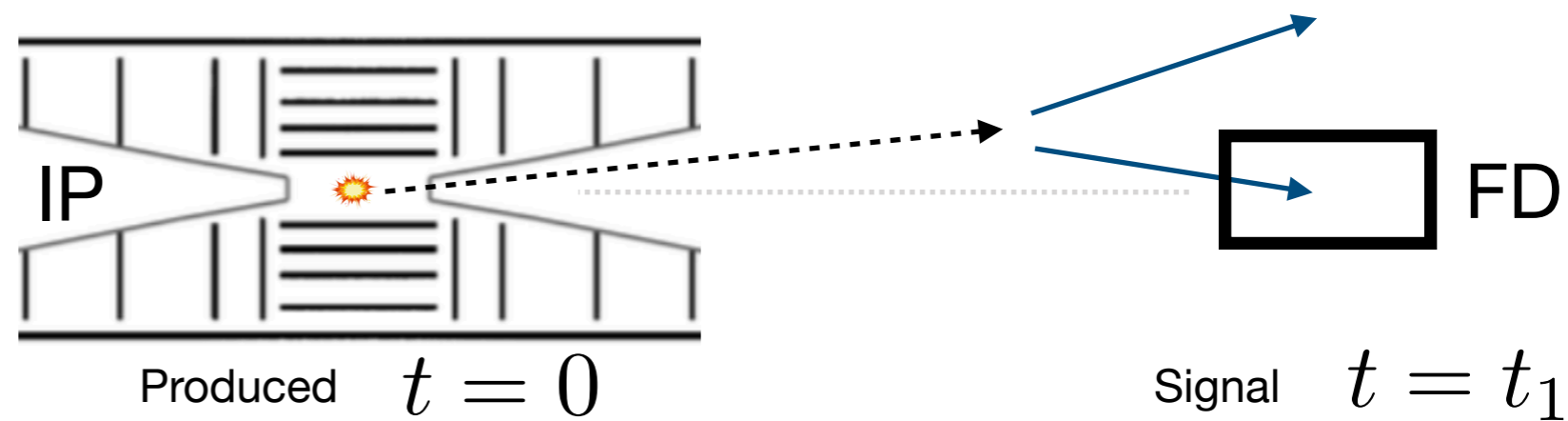
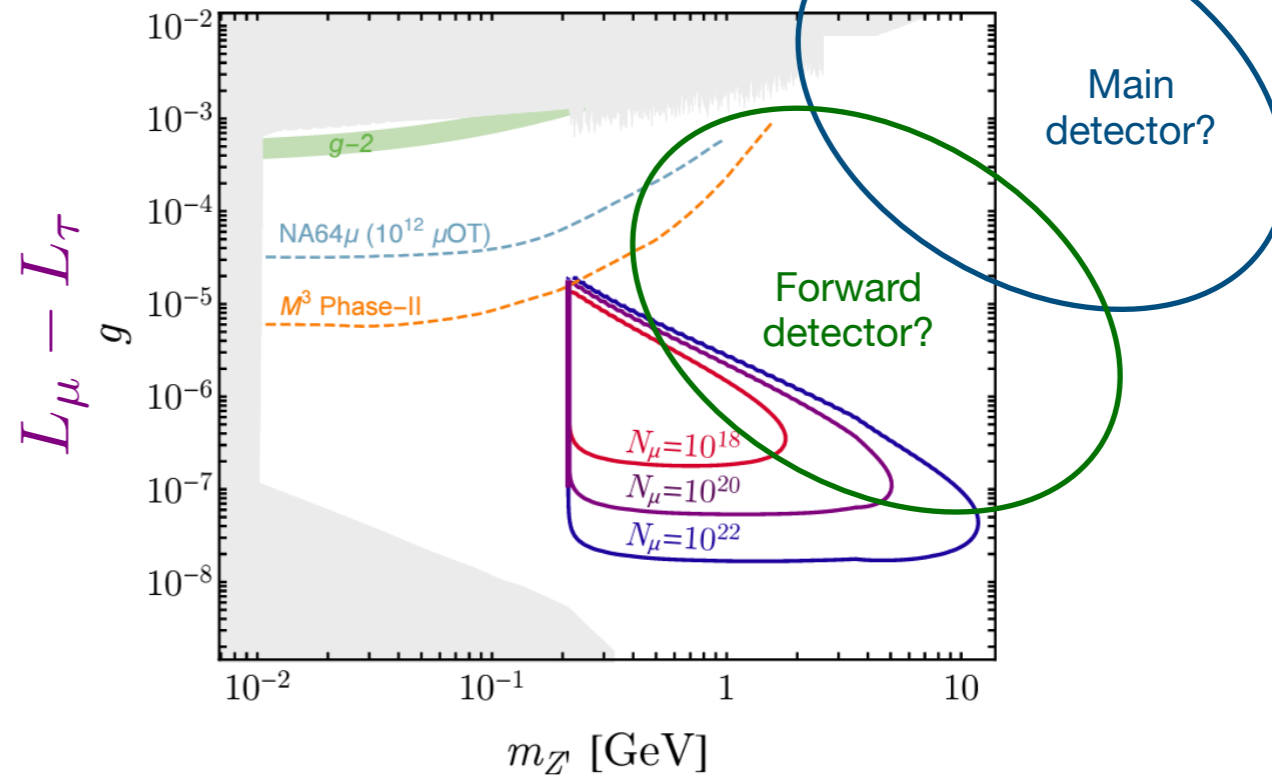


Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals
			Forward detector
Exotics	SM+singlet	$S, a$	x
	2HDM	$H^\pm, H^0, A$	
	New gauge groups	$Z', W', \gamma'$	x
	VLF	$Q', L'$	
	HNL	$N_i$	x
	Leptoquarks	$\tilde{R}_2, U_1$ (UV motivated)	
	Quirks	$q' \bar{q}'$ (bound states)	x
Hierarchy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

Timing

FD

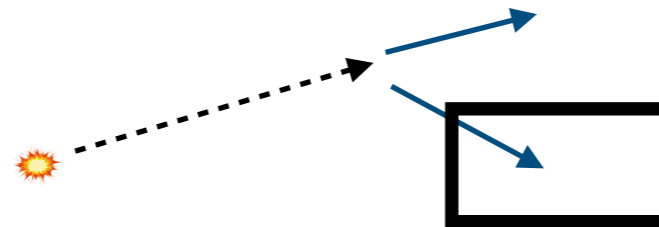
Cesarotti, Homiller, Mishra, Reece,  
Phys. Rev. Lett. 130 (2023) 7, 071803



Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals	
Exotics	SM+singlet	$S, a$	3, 4, 6, 8, 10,	
	2HDM	$H^\pm, H^0, A$		
	New gauge groups	$Z', W', \gamma'$	2, 5, 7, 13, 14,	
	VLF	$Q', L'$		
	HNL	$N_i$	1, 5, 9, 11, 12, 15,	
	Leptoquarks	$\tilde{R}_2, U_1$ (UV motivated)		
	Quirks	$q' \bar{q}'$ (bound states)	x	
	Hidden valleys	$g' g'$		
	Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored) $\chi^\pm, \chi^0, \tilde{\tau}$ (not colored)	
		Composite	$X_{5/3}, T_{2/3}$	
Extra dimensions		$G_{KK}$		
Neutral naturalness		Glueballs, sQuirks	x	
DM	Z portal	EWinos-like (inelastic)		
	H portal	$S$ (Z2 symmetric)		
	Nu portal	$\nu_s$	1, 5, 9, 11, 12, 15,	
	U(1) portal	$U(1)_{B-L_i-L_j}$	2, 5, 7, 13, 14,	

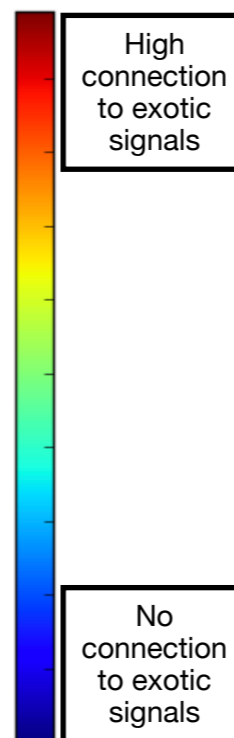
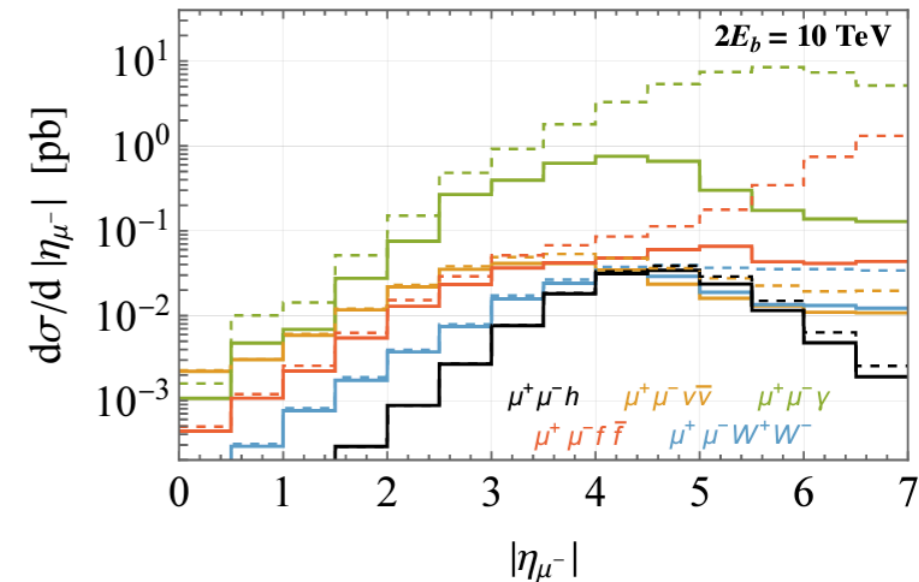
Timing

FD



Long lifetime  
Final state muons?

Ruhdorfer, Salvioni, Wulzer,  
Phys. Rev. D 107 (2023) 9, 095038



- 1) Bandyopadhyay, Karan, Sen, ArXiv:2011.04191
- 2) Huang, Queiroz, Rodejohann, Phys. Rev. D 103 (2021) 9, 095005
- 3) Al Ali et al., Rept. Prog. Phys. 85 (2022) 8, 084201
- 4) Haghighat, Najafabadi, Nucl. Phys. B 980 (2022) 115827
- 5) Liu, Xie, Yi, Phys. Rev. D 105 (2022) 9, 095034
- 6) Capdevilla, Curtin, Kahn, Krnjaic, JHEP 04 (2022) 129
- 7) Cesarotti, Homiller, Mishra, Reece, Phys. Rev. Lett. 130 (2023) 7, 071803
- 8) Bao, Fan, Li, JHEP 08 (2022) 276
- 9) Chakraborty, Roy, Srivastava, ArXiv:2206.07037
- 10) Inan, Kisselev, ArXiv:2207.03325
- 11) Sen, Bandyopadhyay, Dutta, KT, Eur. Phys. J. C 82 (2022) 3, 230
- 12) Liu, Han, Jin, Li, JHEP 12 (2022) 057
- 13) Allanach, Loisa, JHEP 03 (2023) 253
- 14) Das, Nomura, Shimomura, ArXiv:2212.11674
- 15) Li, Yao, Yuan, JHEP 03 (2023) 137

# Outline

1. Disappearing Tracks

2. Forward Detectors

**3. Displaced Vertices**

4. Stopping Particles

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

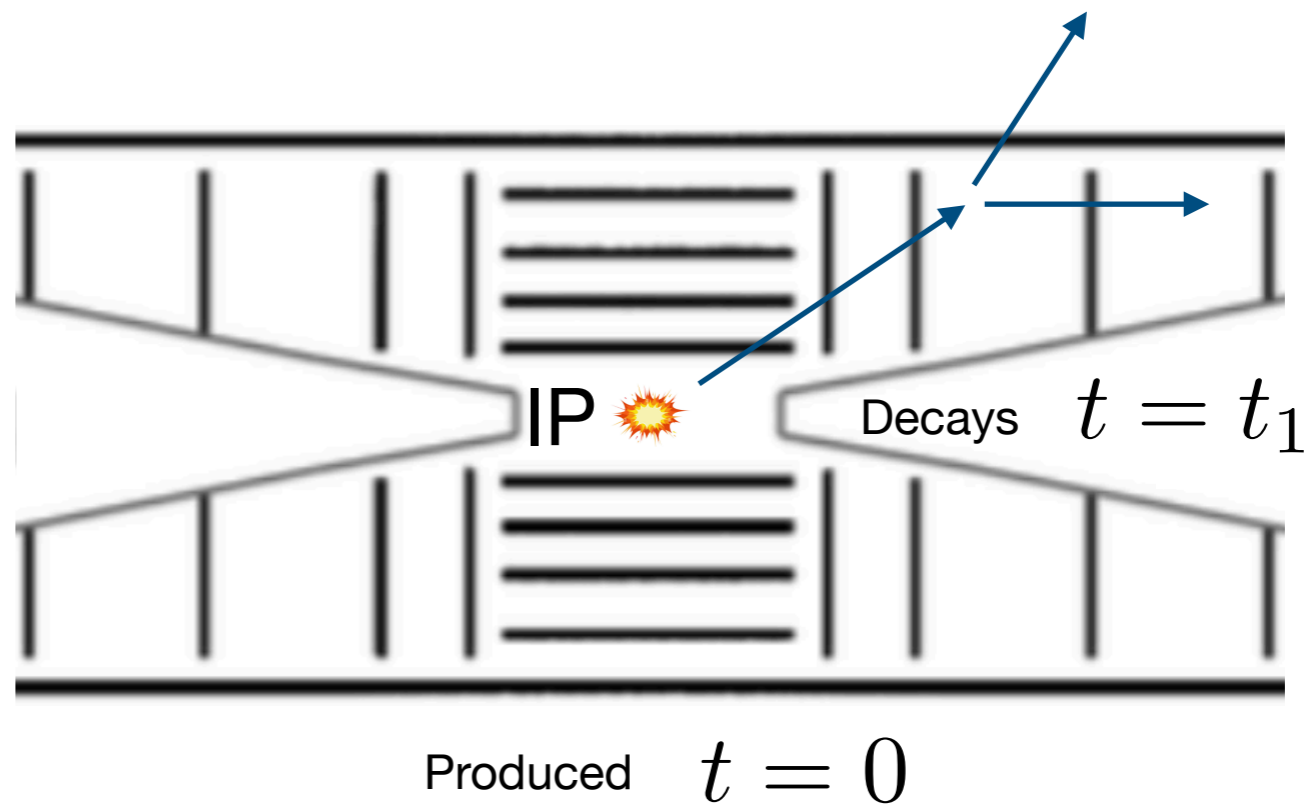
Timing

Tracking

*Particle(s) produced at the interaction point*

*Initial time is set by the bunch crossing*

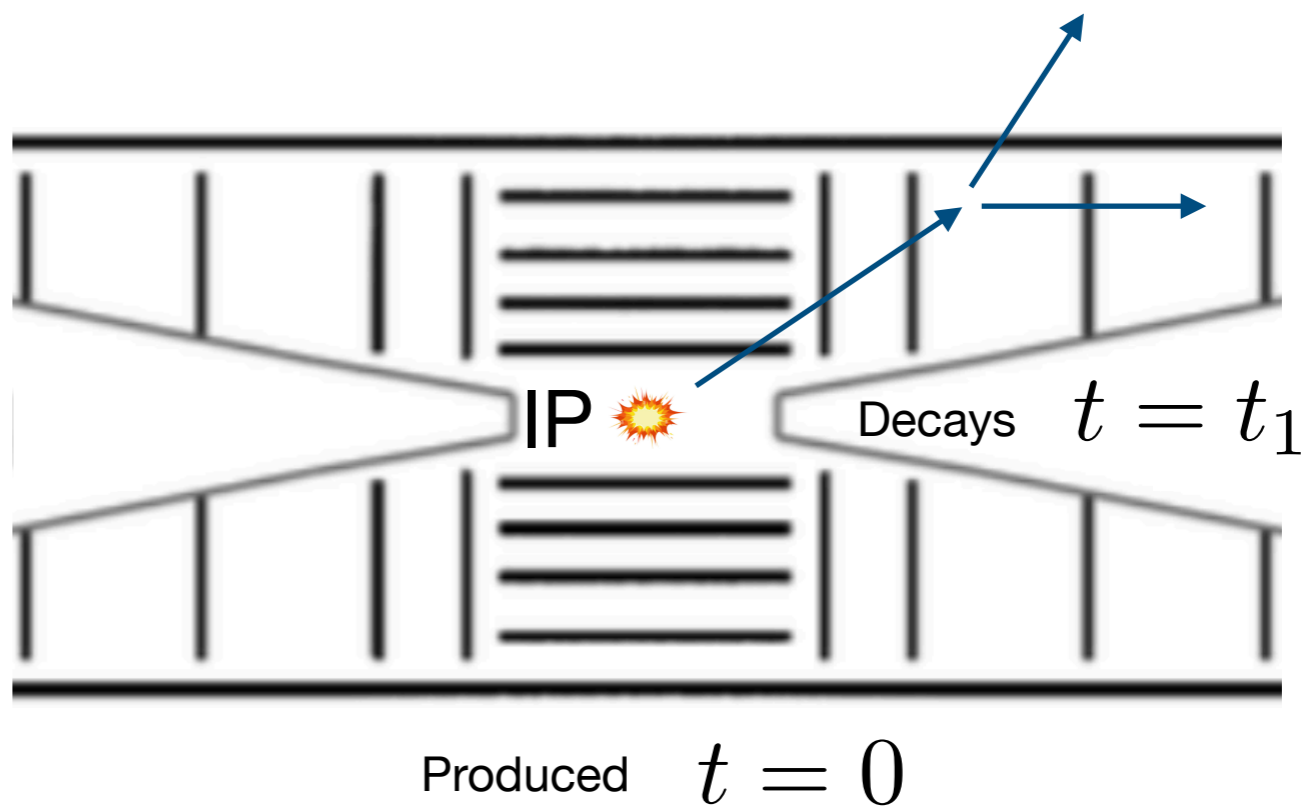
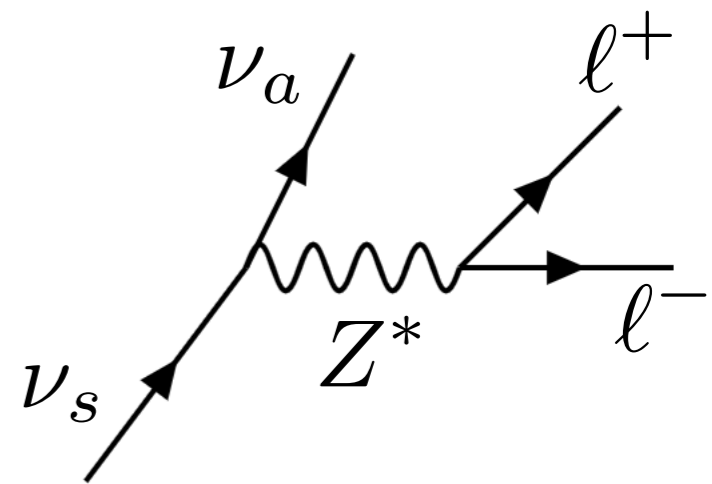
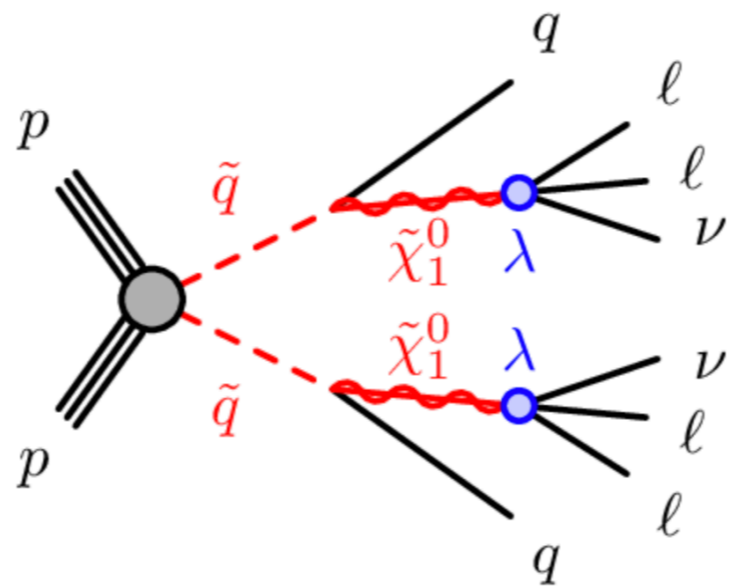
*Particle(s) decays to a pair of leptons inside the tracker*



Motivation	Theoretical scenario	Candidate particle(s)	Exotic Signals
			Disappearing tracks
Exotics	SM+singlet	$S, a$	x
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	New gauge groups	$Z', W', \gamma'$	x
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Timing

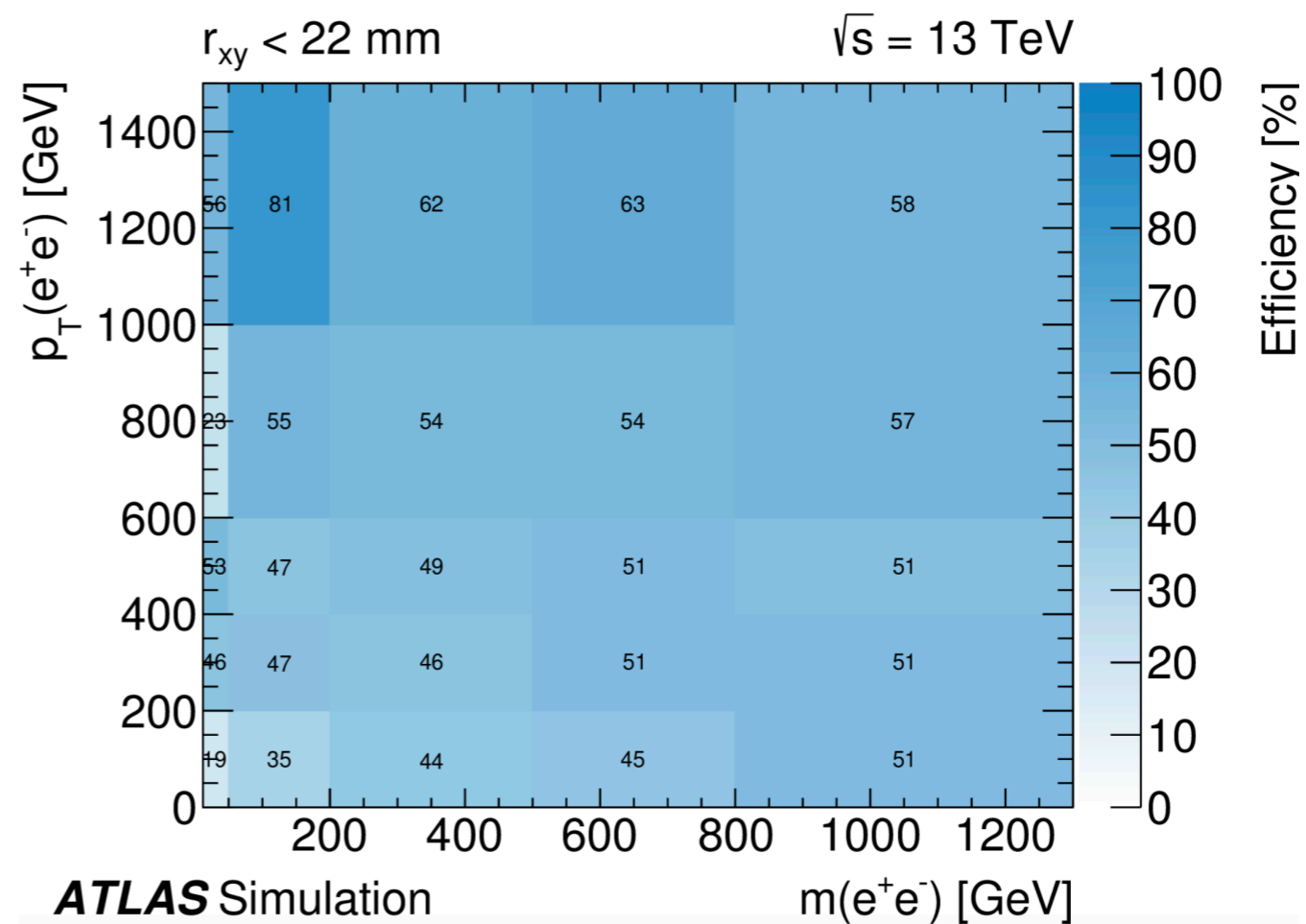
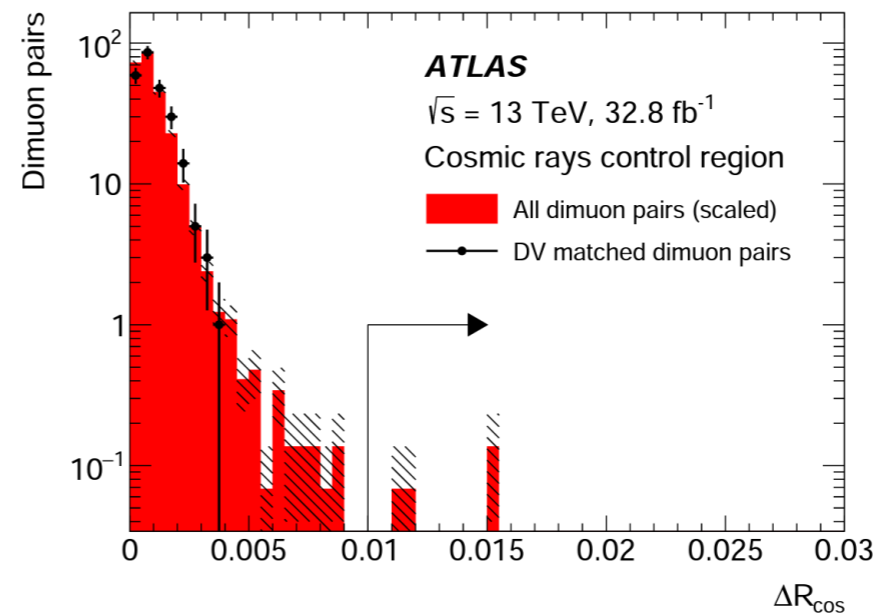
Tracking



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Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x
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	HNL	$N_i$	
	Leptoquarks	$\tilde{R}_2, U_1$ (UV motivated)	
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	Hidden valleys	$g' g'$	
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	x
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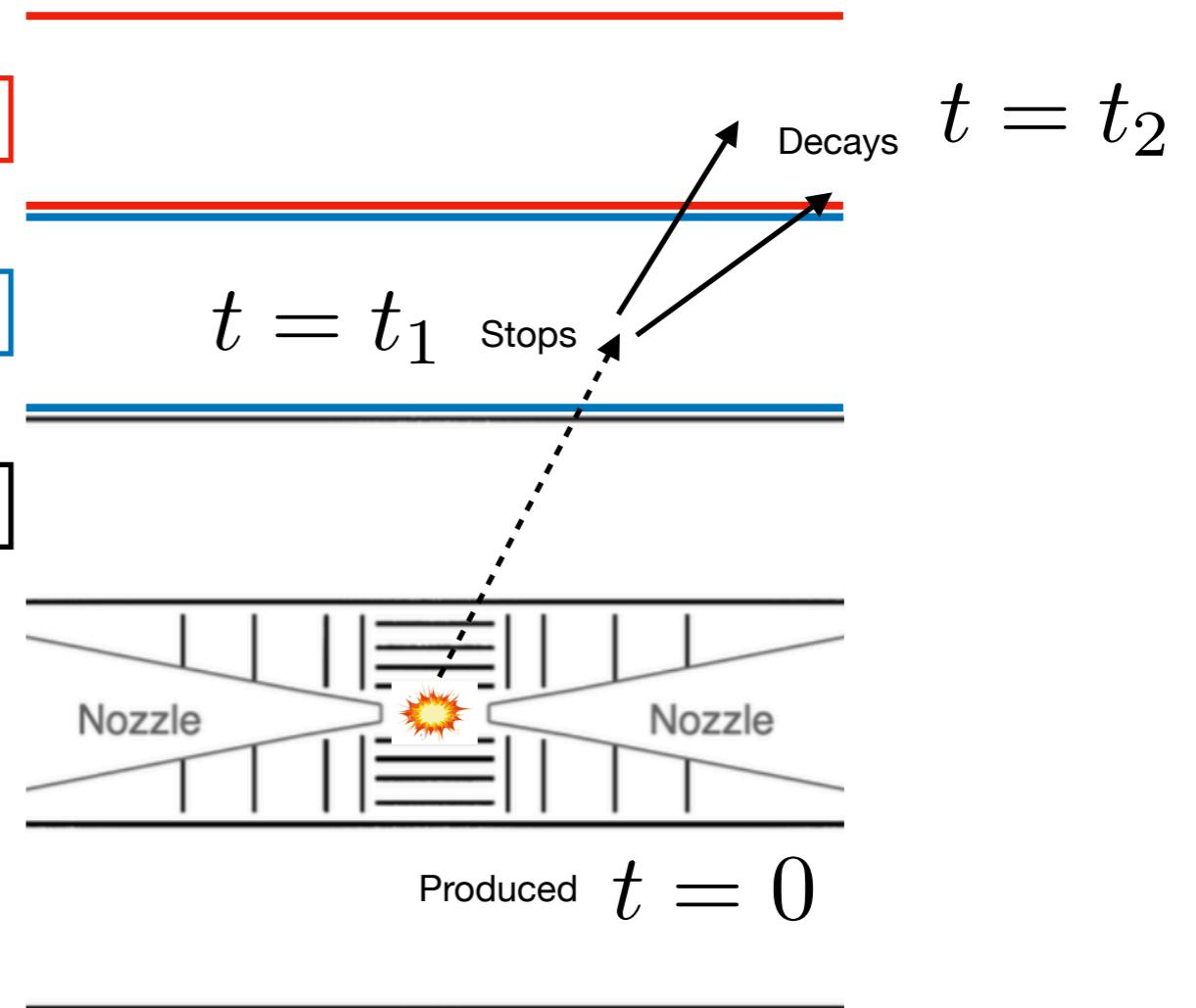
Timing

Data acquisition

HCAL

ECAL

Tracker



Glennys Farrar, Pierre Fayet, Phys. Lett. B 76 (1978) 575-579

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

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Timing

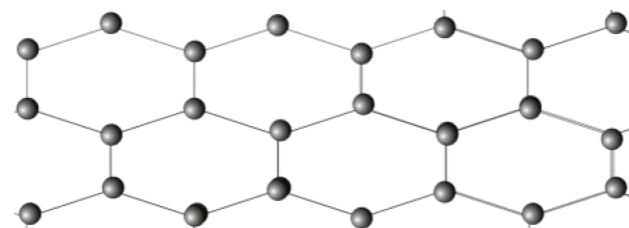
Data acquisition

Fermi velocity of nucleons

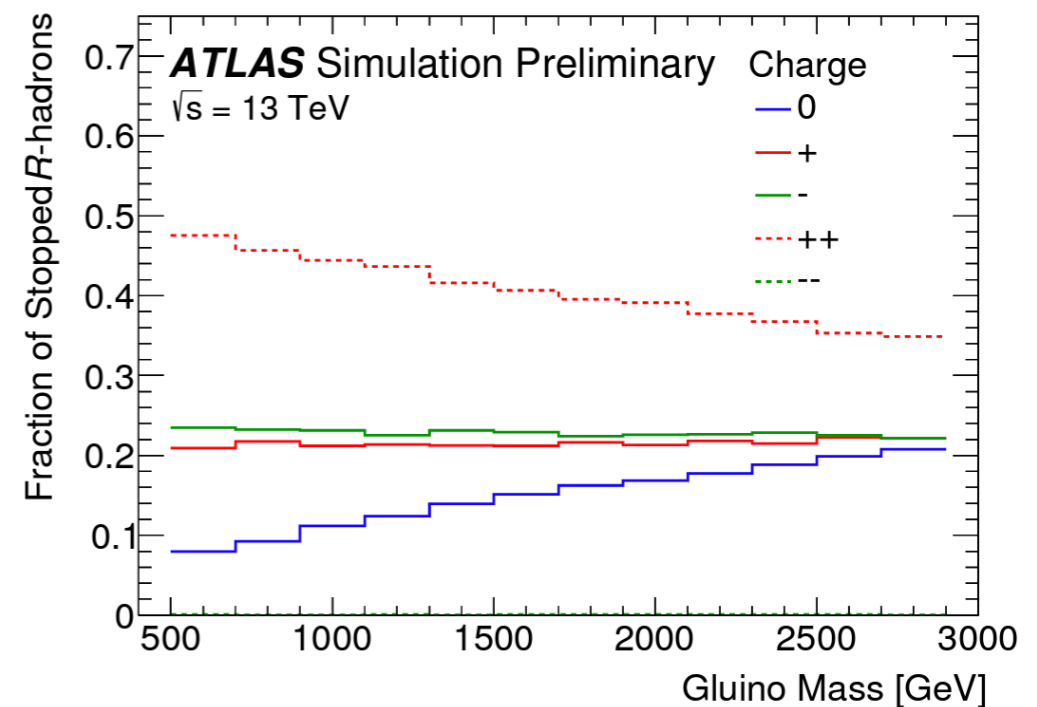
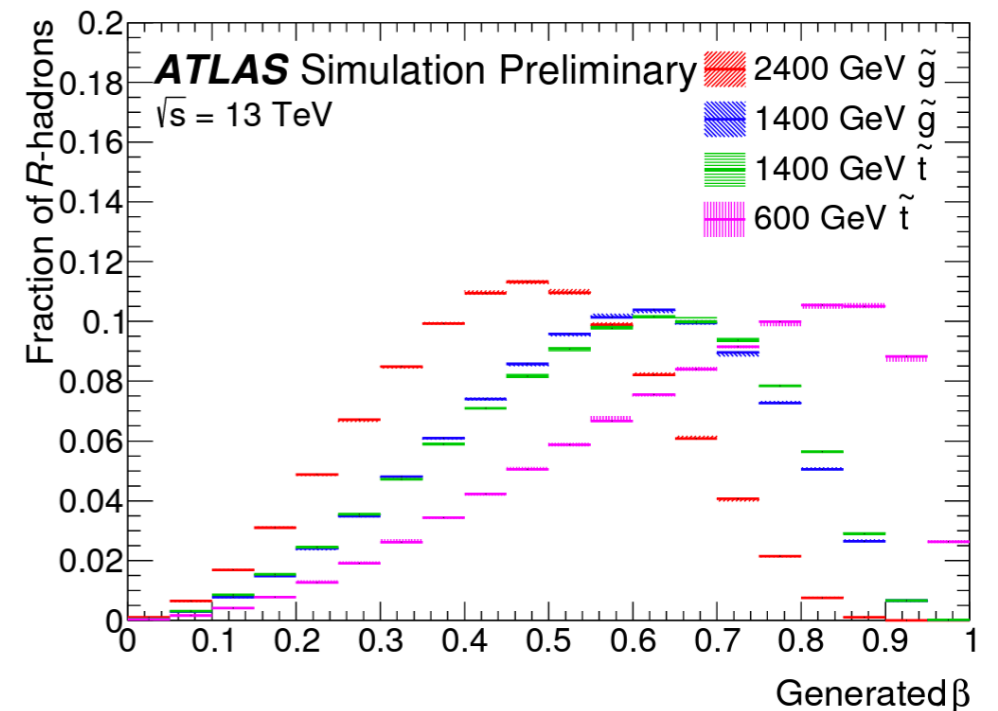
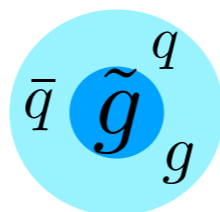
$$v \leq \frac{v_F}{A^{2/3}}$$

Atomic mass number

ATLAS Collaboration, ATL-PHYS-PUB-2019-019



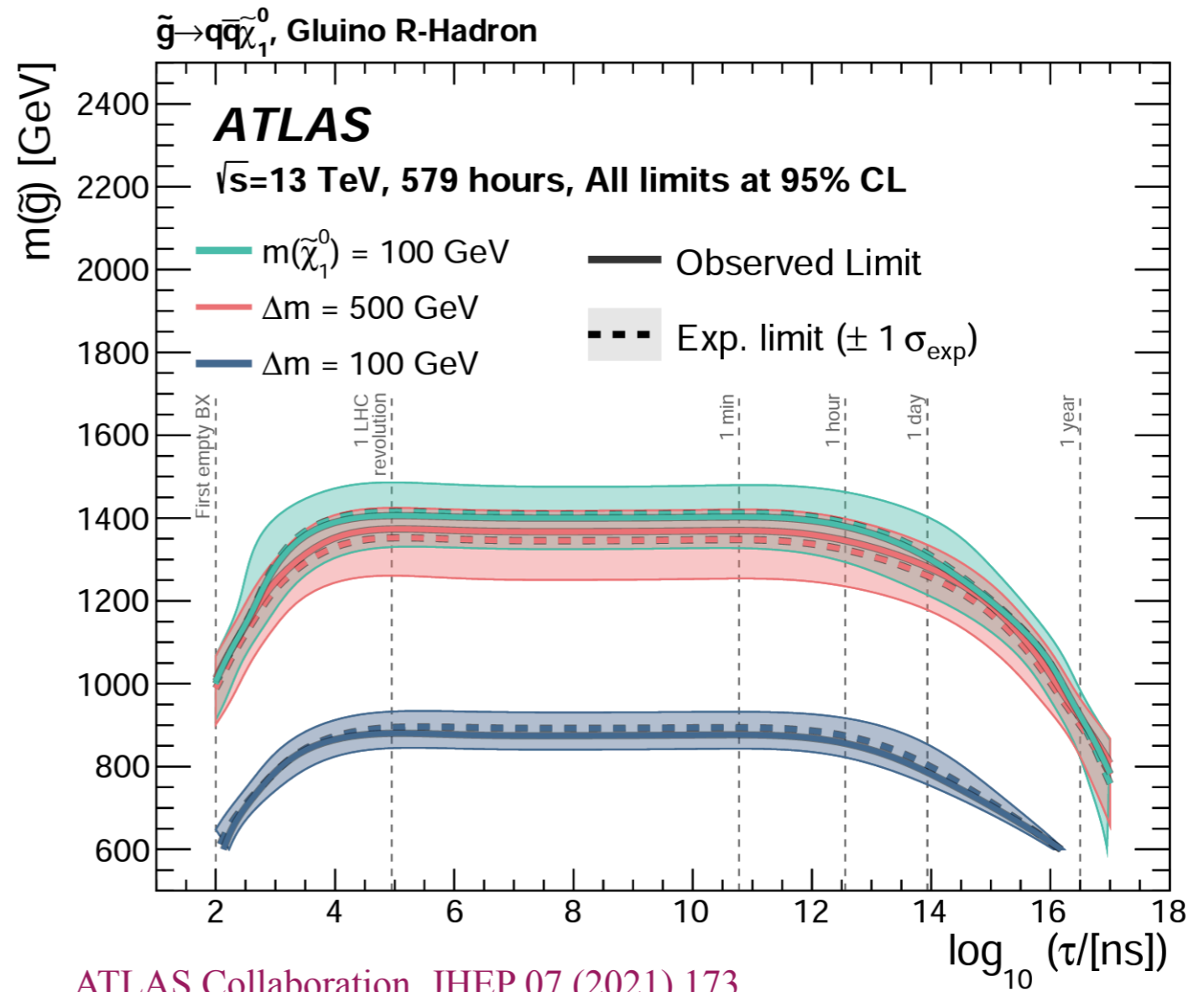
$X^0, X^+, \dots$  Exchange of mesons



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			Stopping particles
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	Quirks	$q' \bar{q}'$ (bound state)	x
	Hidden valleys	$g' g'$	
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	x
DM	Z portal	EWinos-like (inelastic)	
	H portal	$S$ (Z2 symmetric)	
	Nu portal	$\nu_s$	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

Timing

Data acquisition



# Summary

1. Disappearing track efficiency map: Great opportunities for long-lived sleptons, co-annihilation, scalar or fermion multiplets with small splittings...
2. Forward detector: Opportunities for long-lived light new physics, dark photons, axions, sterile neutrinos?
3. Stopping particles and Displaced vertices can be performed assuming similar efficiencies to LHC. Compelling models can motivate our experimental colleagues to produce efficiency maps including BIB.

***Thank You!***

# *Discussion*

1. Disappearing Tracks

2. Forward Detectors

3. Displaced Vertices

4. Stopping Particles