FERMILAB-SLIDES-23-272-T

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

IMCC Anual Meeting

IJCLab

Jun 20, 2023

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

***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?*

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', γ'	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	$q'\bar{q}'$ (bound states)			x			x	x		
	Hidden valleys	$g'g'$					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	x
DM	Z portal	EWikinos-like (inelastic)				x	x	x			
	H portal	S (Z2 symmetric)									
	Nu portal	ν_s									x
	U(1) portal	$U(1)_{B-L_i-L_j}$					x			x	x

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	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

Timing

Tracking

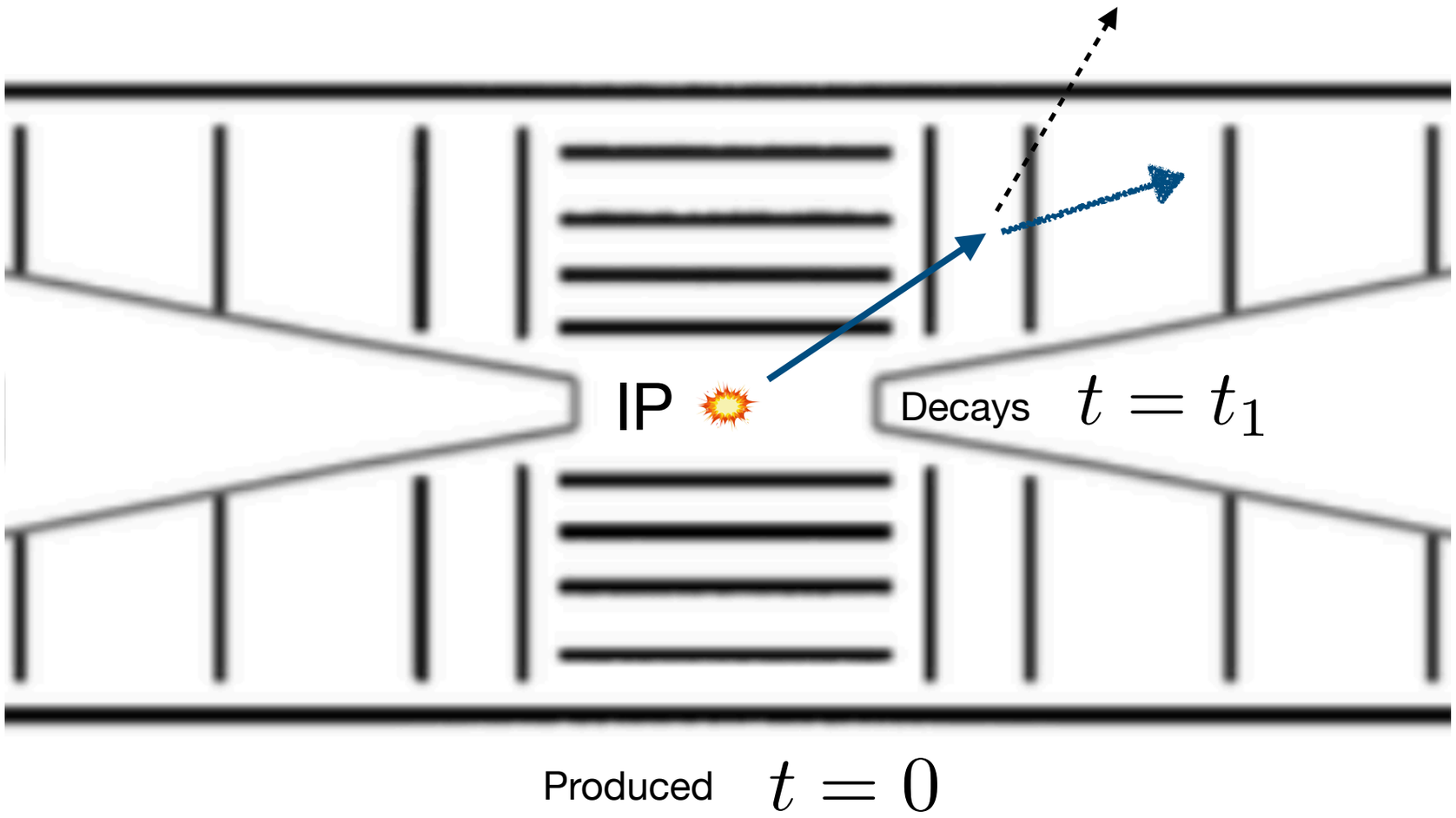
Particle(s) produced at the interaction point

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

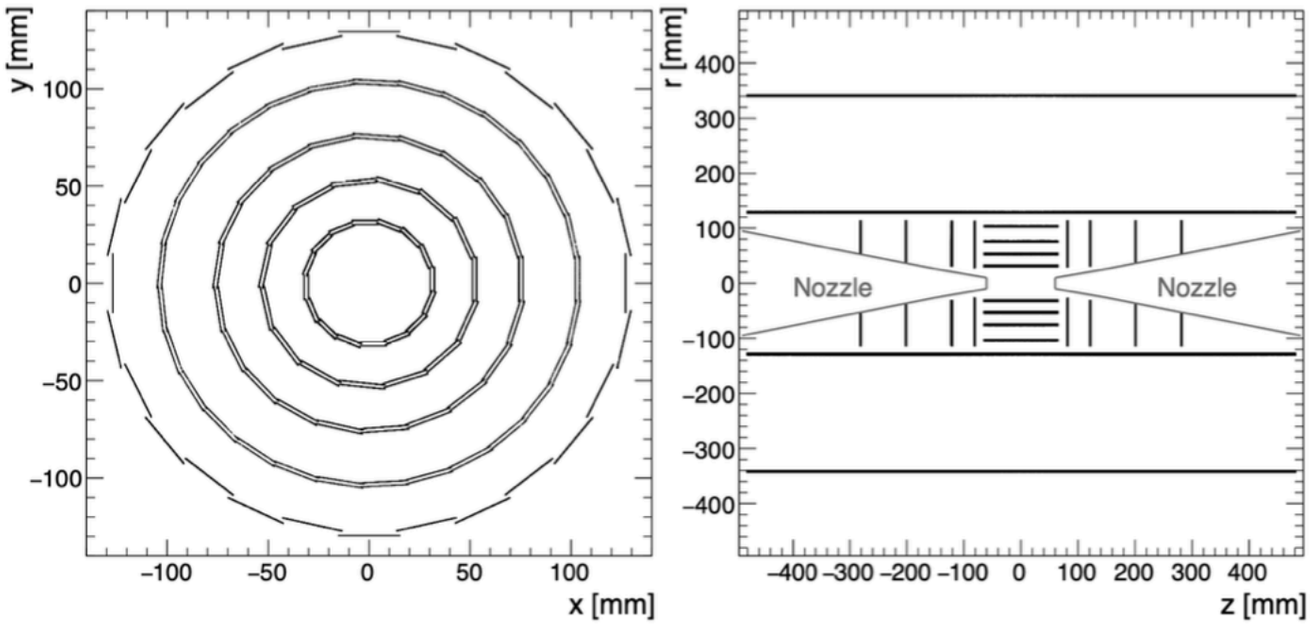


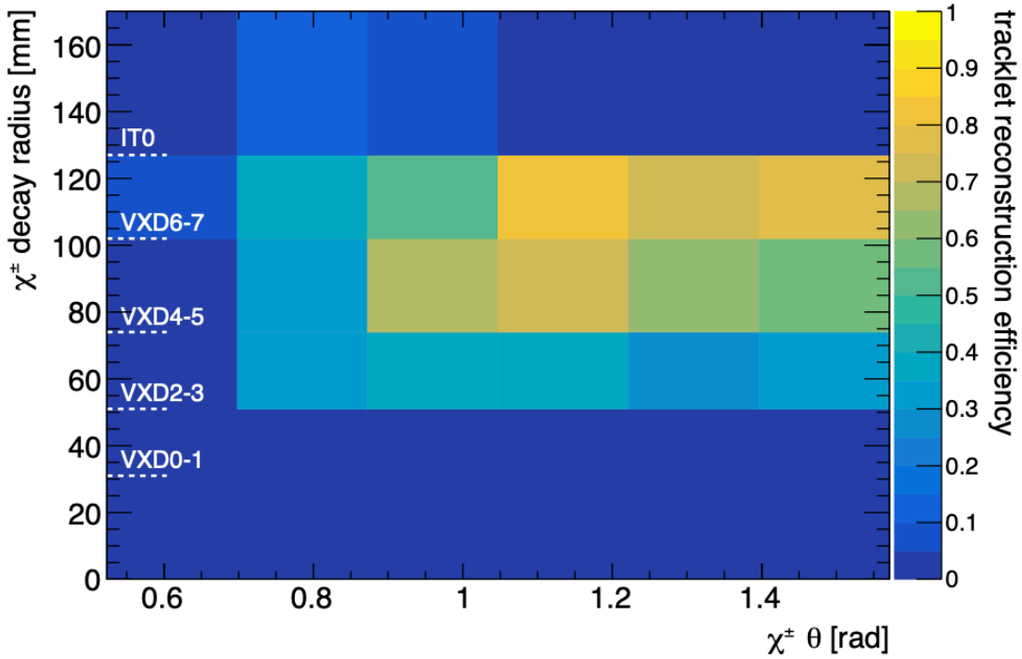
1. Disappearing Tracks

- Efficiency:

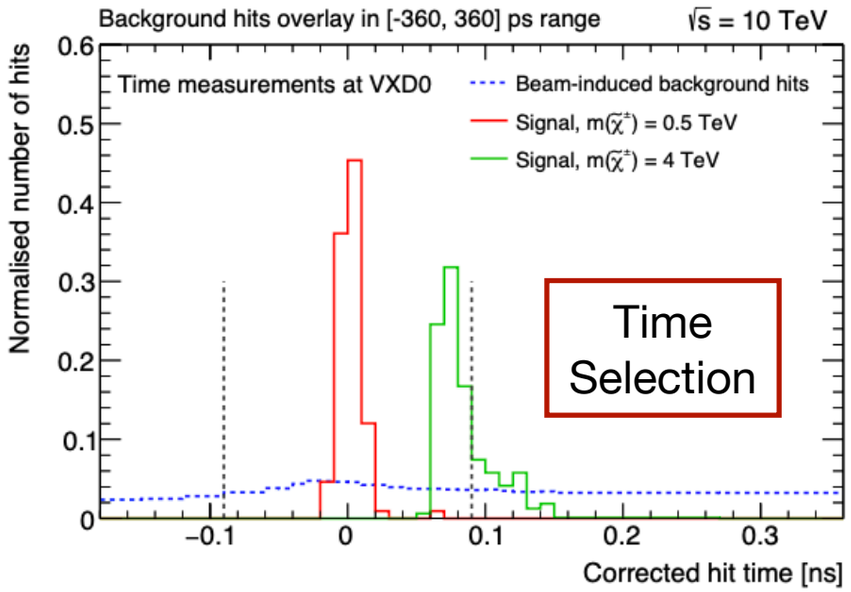
RC, F. Meloni, R. Simoniello, J. Zurita, JHEP **06** (2021) 133

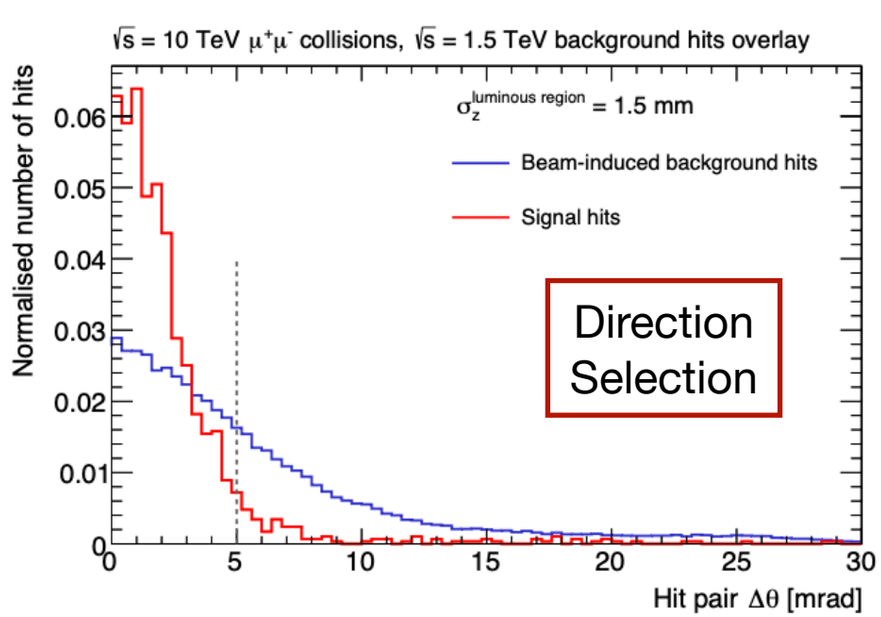
Vertex detector *Double layer geometry*





Requirement / Region	SR^{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



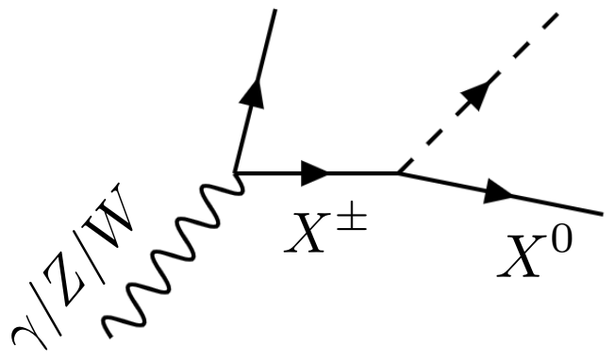


Uses 1.5 TeV BIB from MAP

N. Mokhov, S. Striganov, Phys. Procedia 37 (2012) 2015-2022
N. Mokhov, S. Striganov, I. Tropin, IPAC 2014, 1081-1083

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', γ'	
	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	EWikinos-like (inelastic)	**5**, **6**, **9**, **10**, **11**, **12**, **14**, **16**,
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

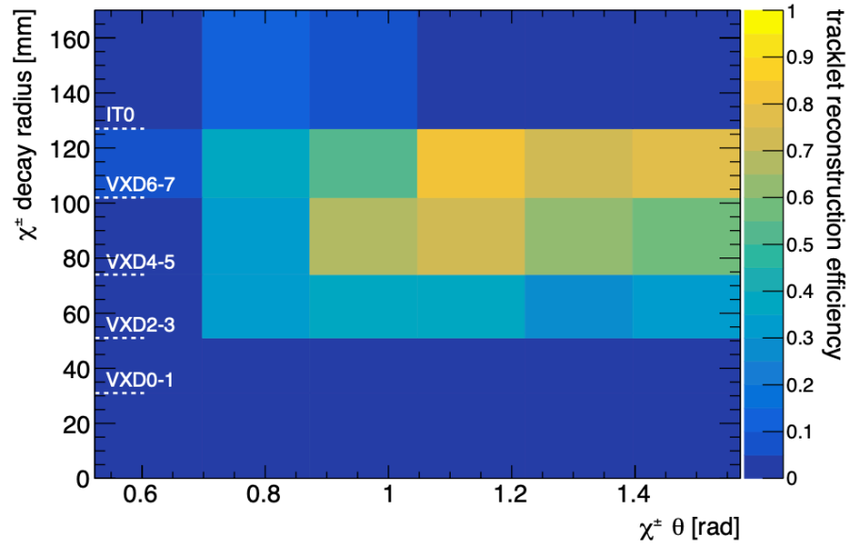
Timing

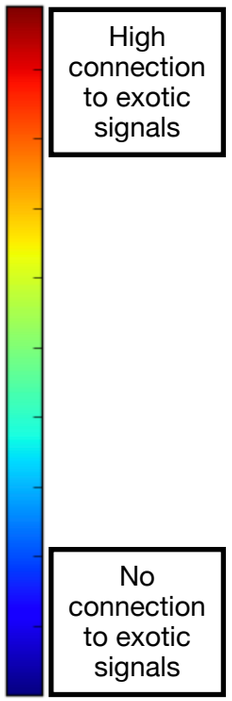


Long lifetime:
Small splitting
Small coupling

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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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', γ'	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}	
	Neutral naturalness	Glueballs, sQuirks	x
DM	Z portal	EWikinos-like (inelastic)	
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	x
	U(1) portal	$U(1)_{B-L_i-L_j}$	x

Timing

FD

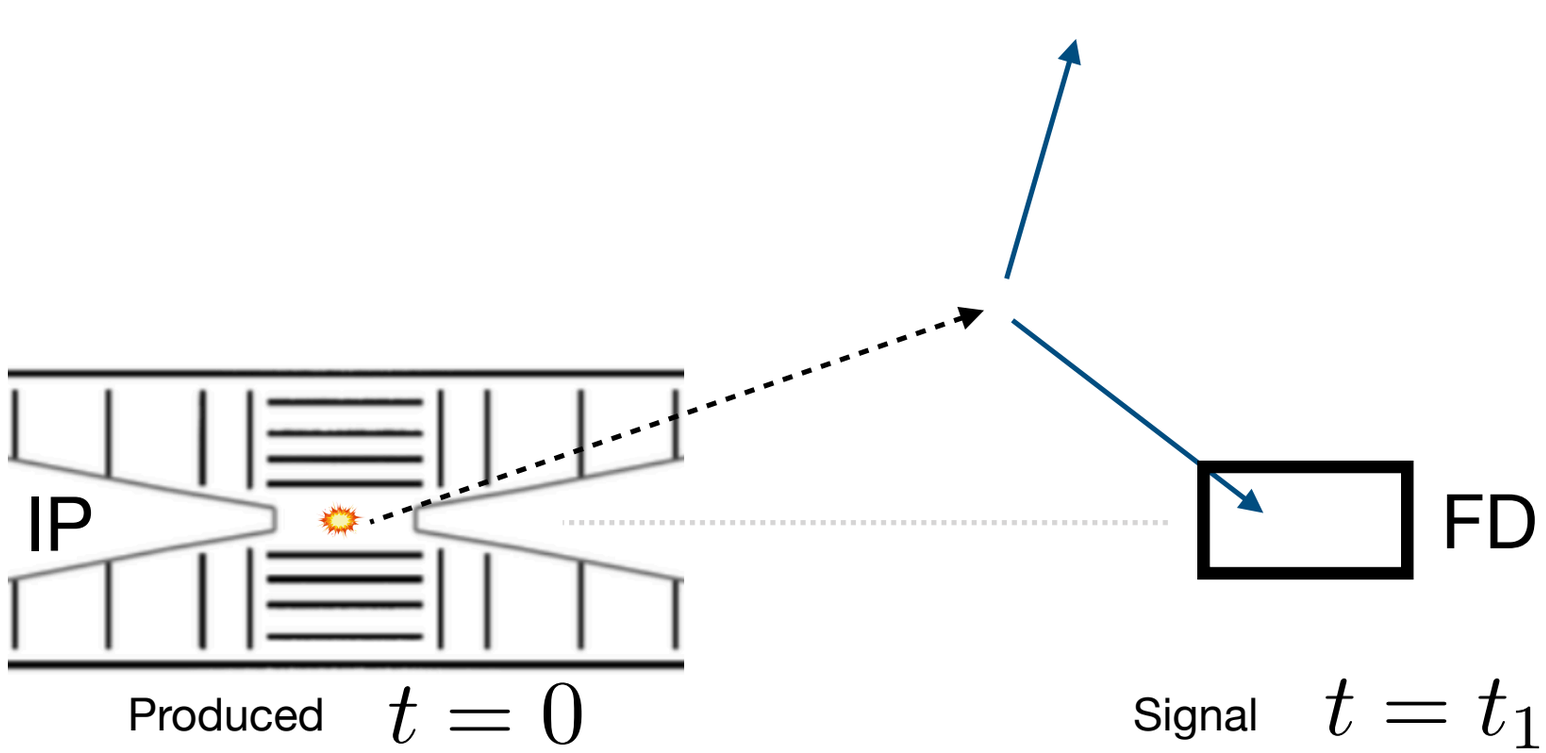
Particle(s) produced at the interaction point

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(?)



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			Forward detector
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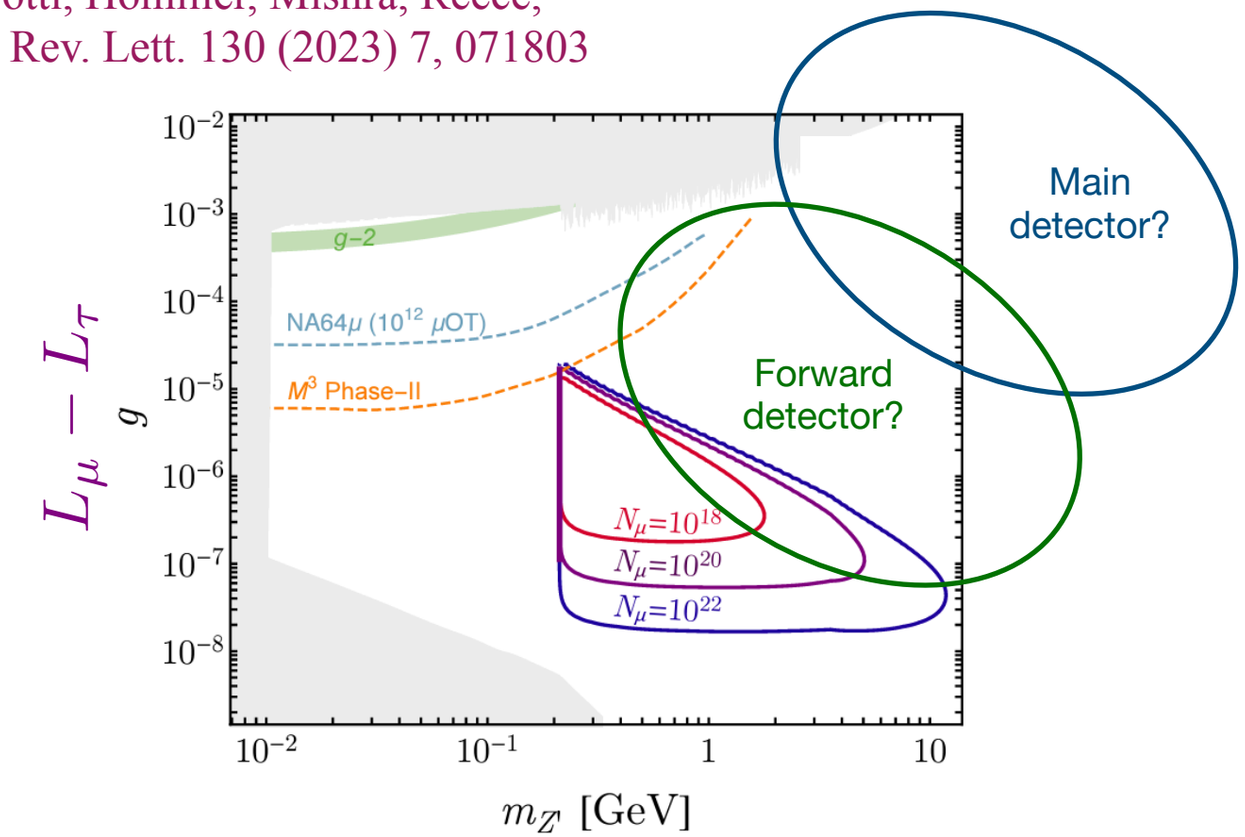
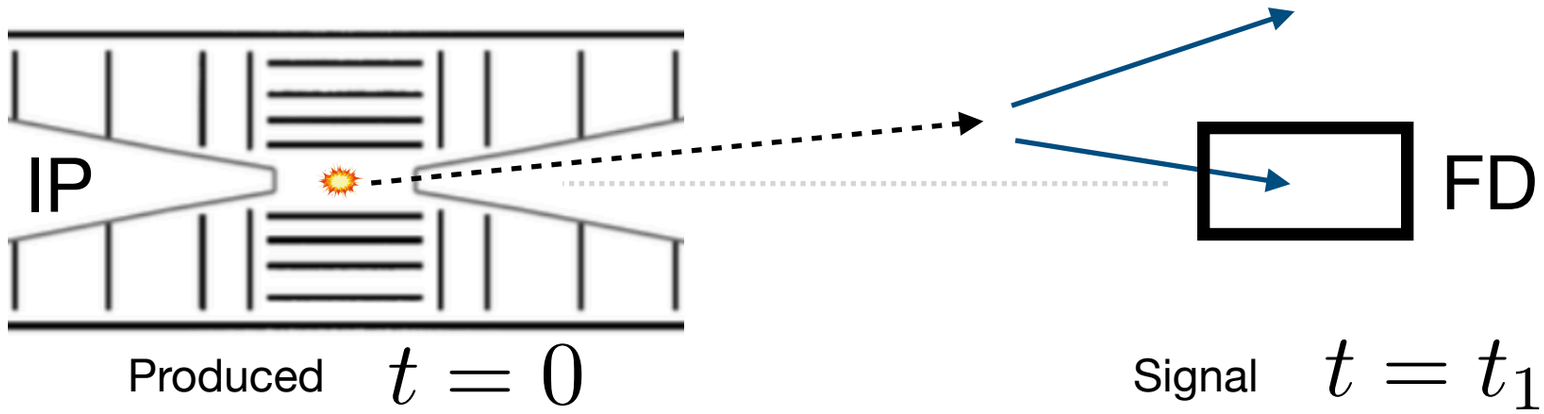
Timing

FD

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





Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals** Forward detector
Exotics	SM+singlet	S, a	**3**, **4**, **6**, **8**, **10**,
	2HDM	$H^{\pm}$, H^{0}, A	
	New gauge groups	Z', W', γ'	**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)	
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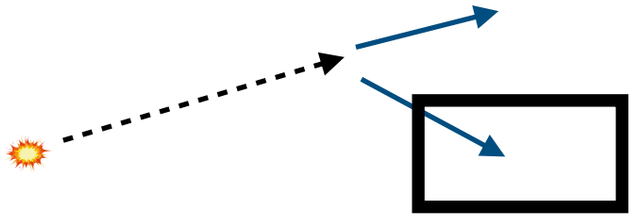
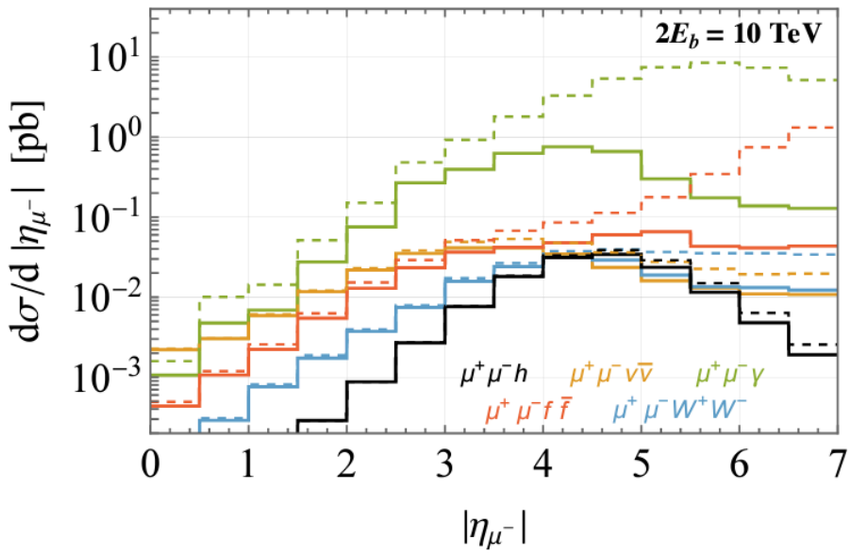
Timing

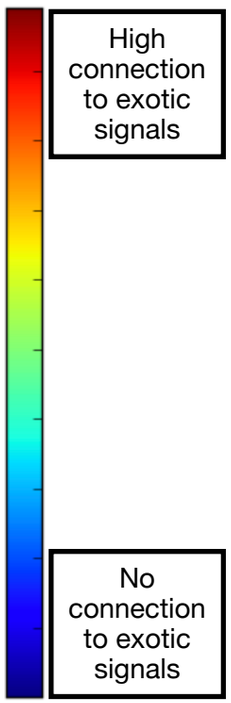
FD



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

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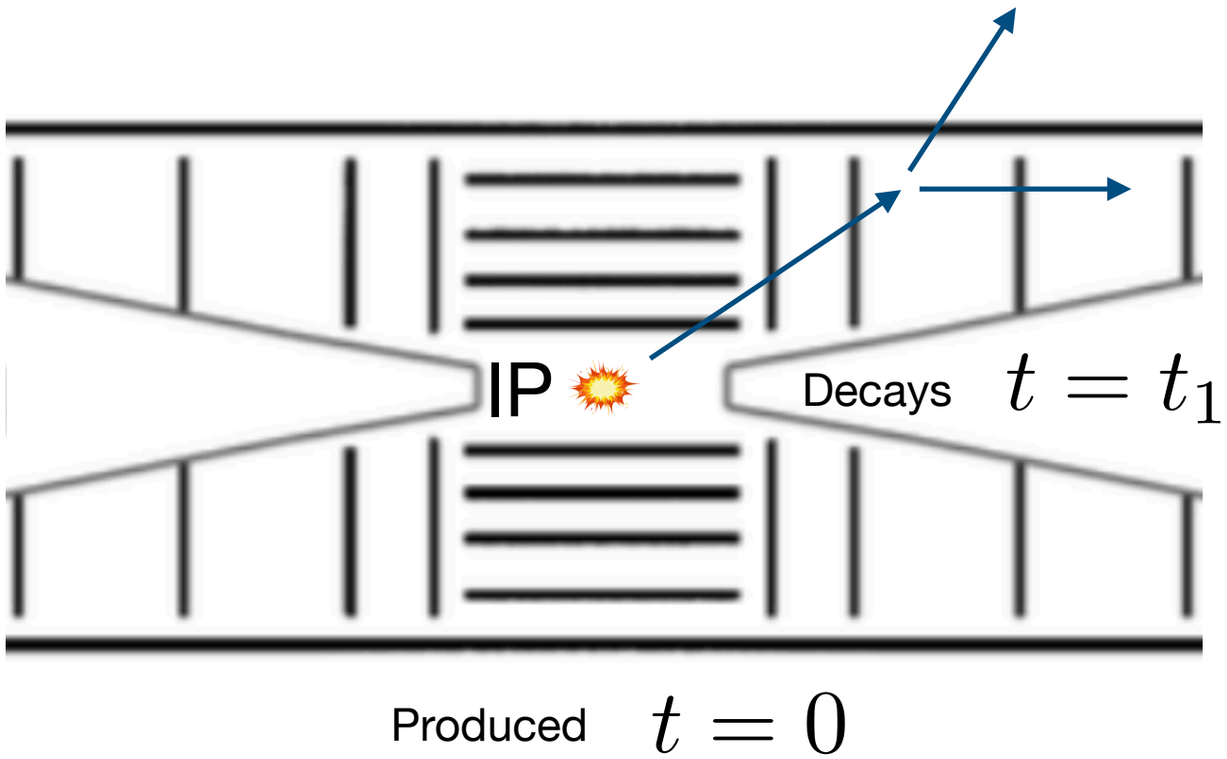
Timing

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



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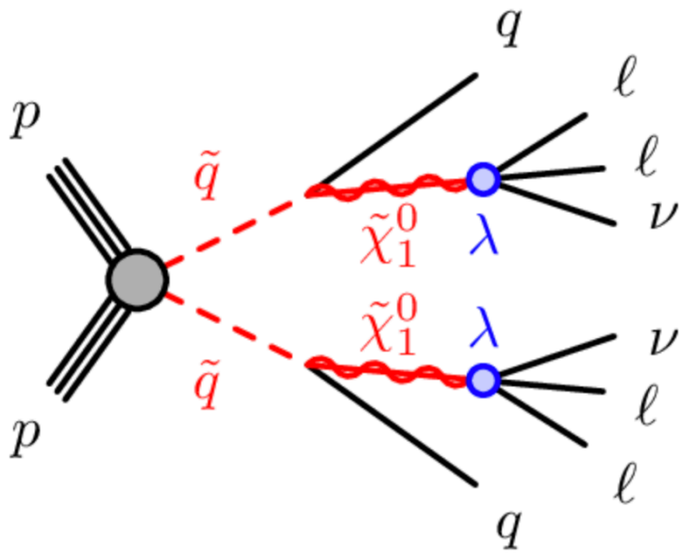
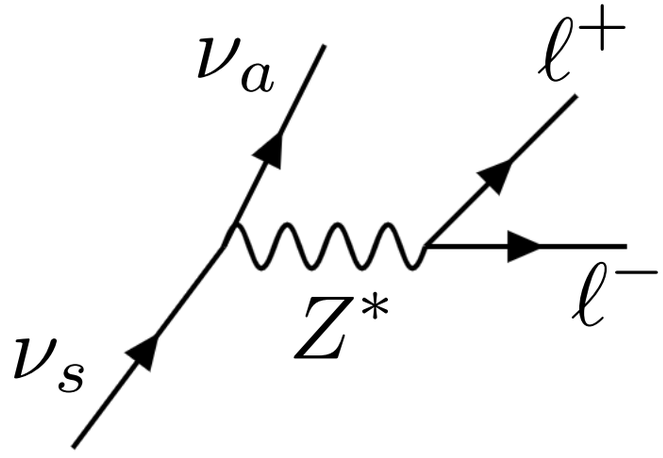
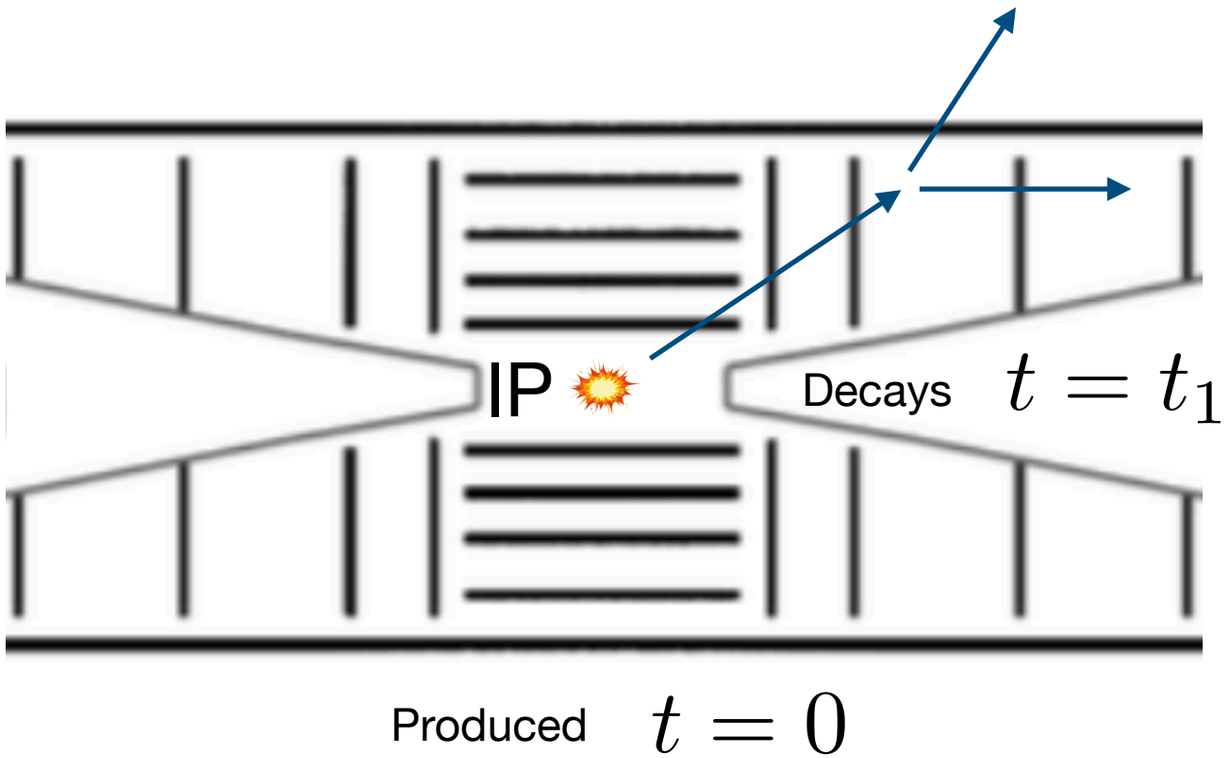


Tracking





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Timing

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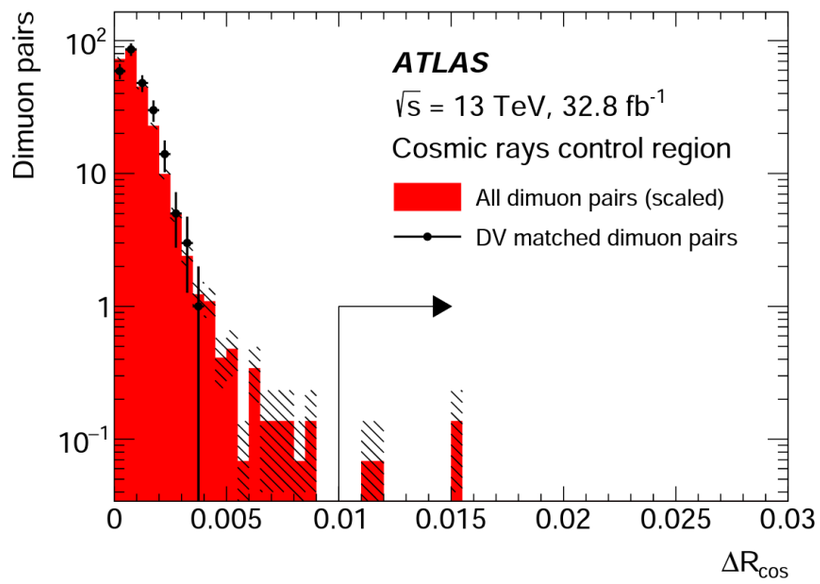

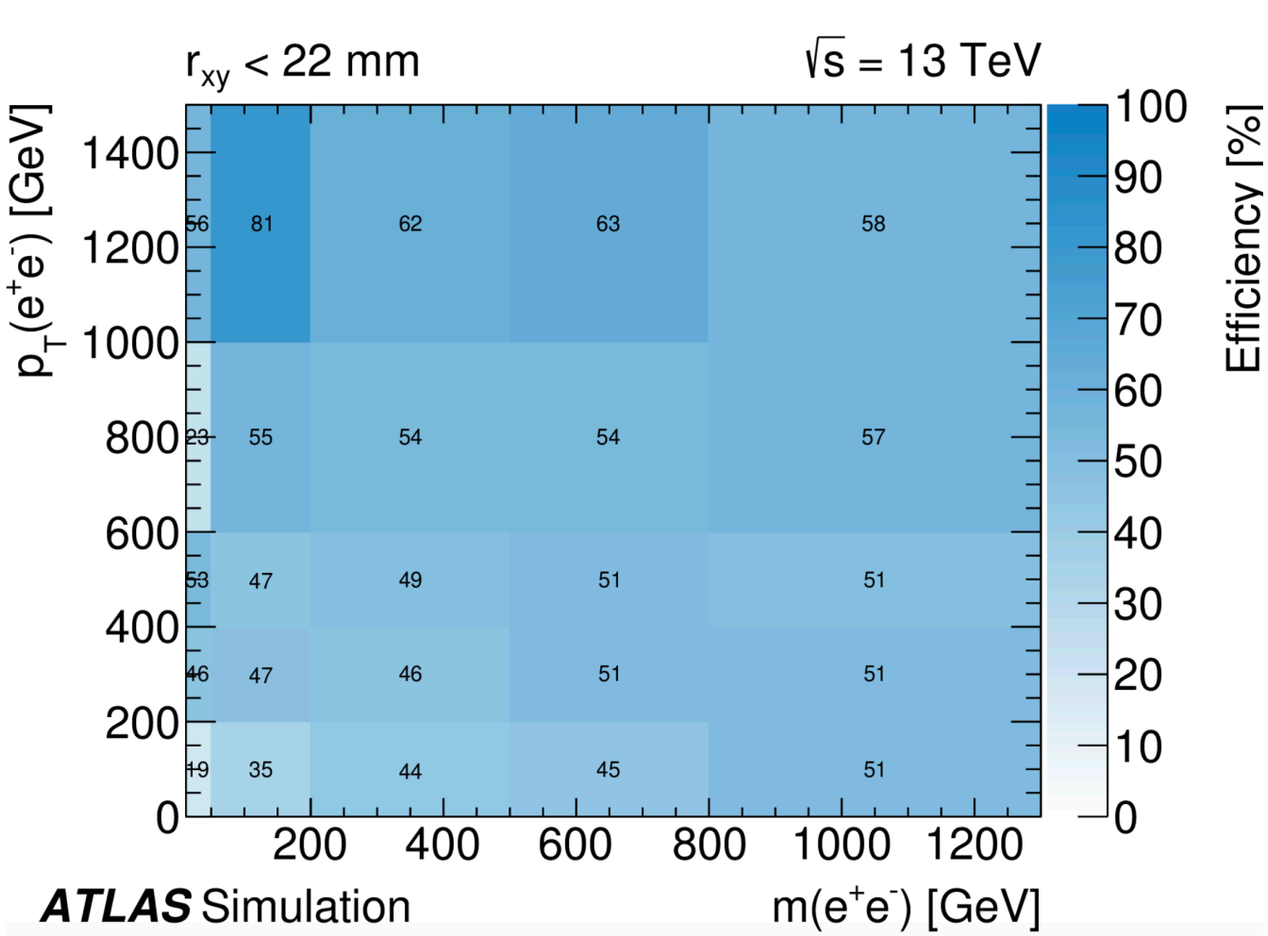

ATLAS Collaboration, Phys. Lett. B 801 (2020) 135114

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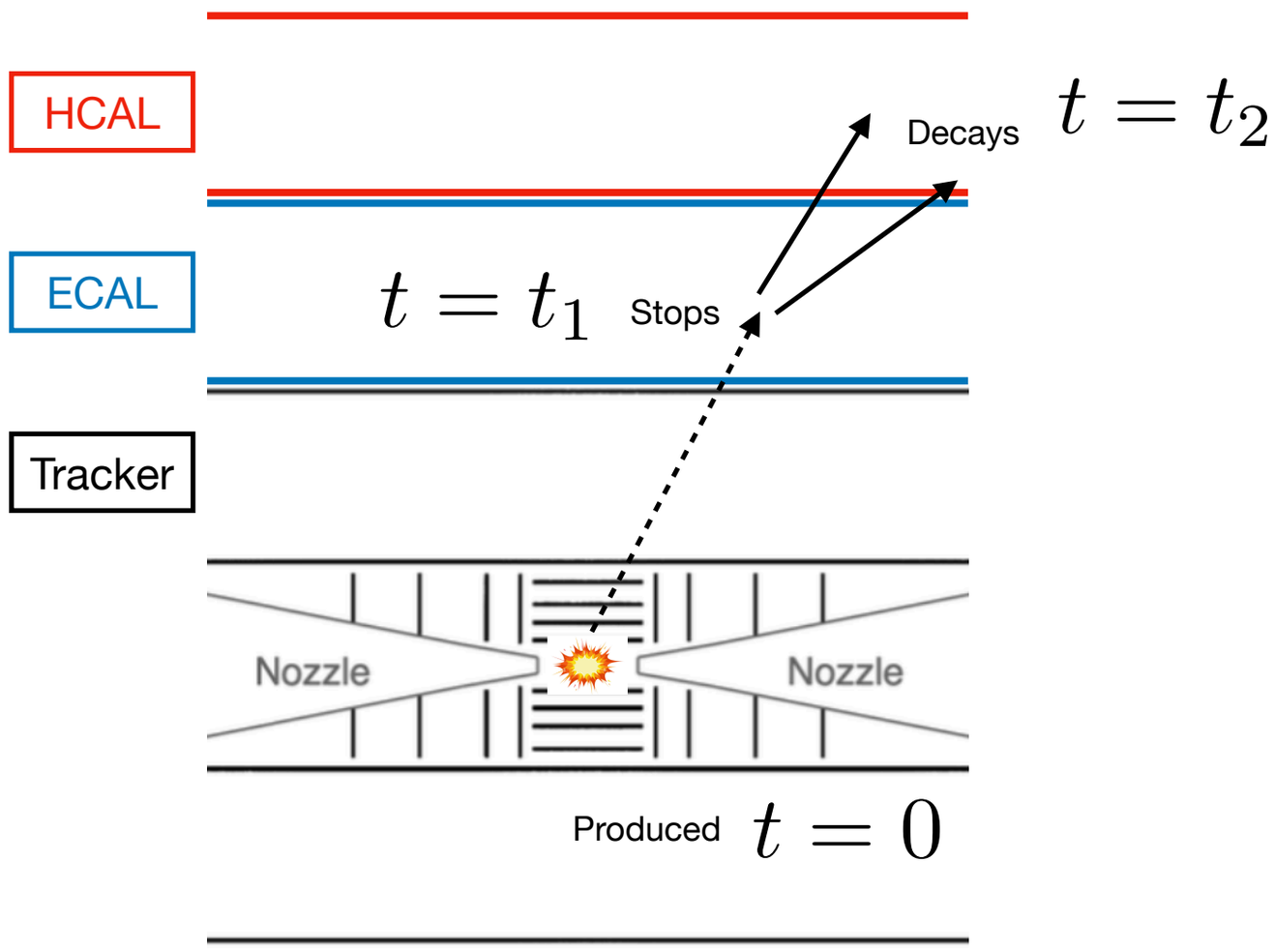
Timing

Data acquisition



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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	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	EWikinos-like (inelastic)	
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

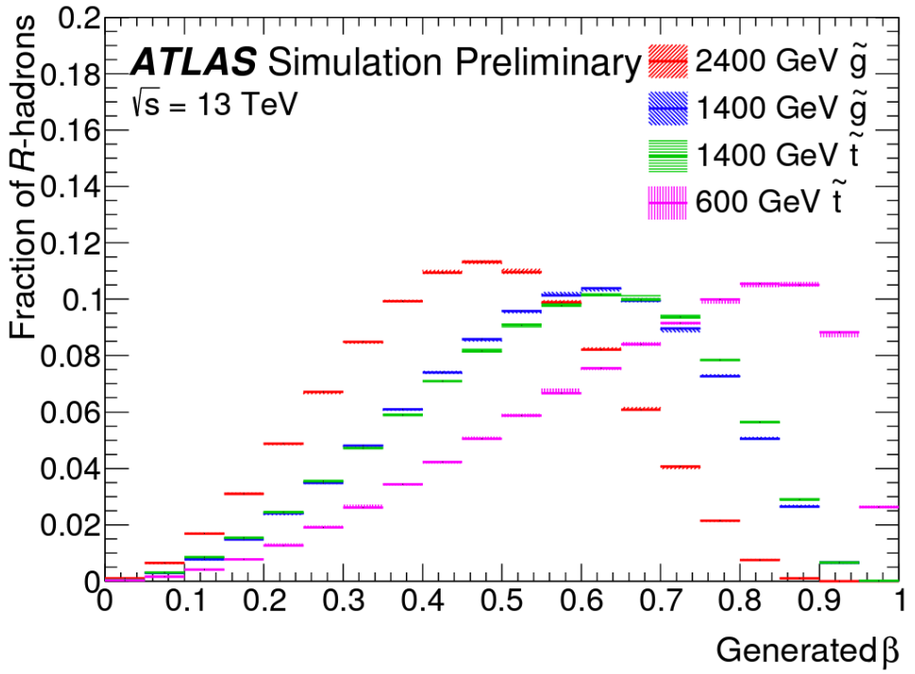
Timing

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

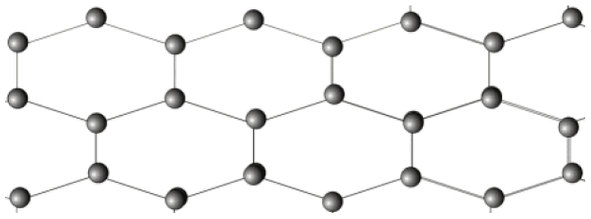
Fermi velocity of nucleons

Atomic mass number

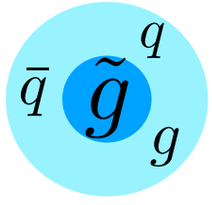
Data acquisition

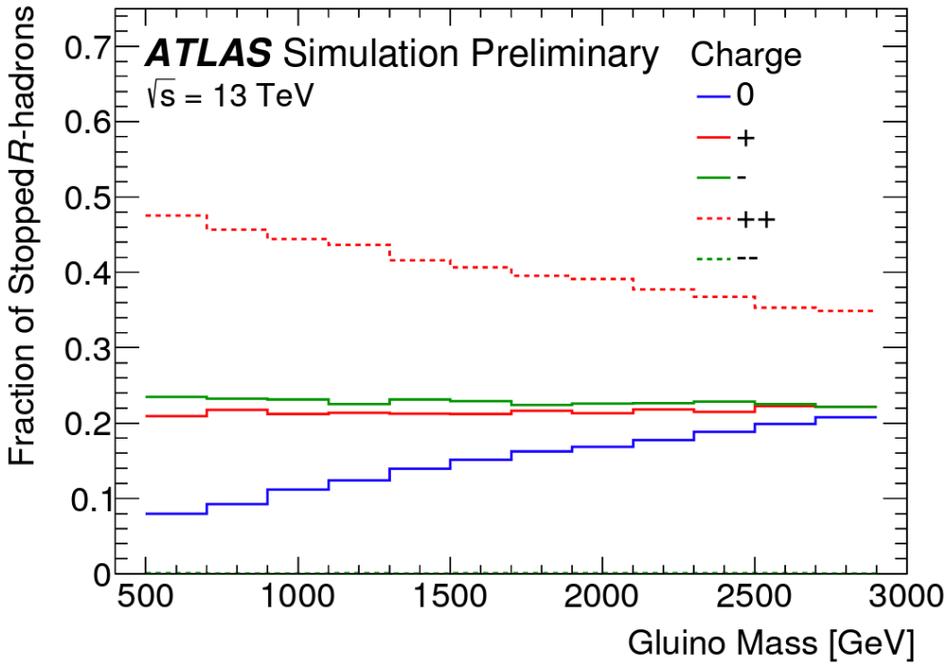


ATLAS Collaboration, ATL-PHYS-PUB-2019-019



$X^0, X^+, \ldots$ *Exchange of mesons*





Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals**
			Stopping particles
Exotics	SM+singlet	S, a	
	2HDM	$H^{\pm}$, H^{0}, A	
	New gauge groups	Z', W', γ'	
	VLF	Q', L'	
	HNL	N_i	
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	
	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	EWikinos-like (inelastic)	
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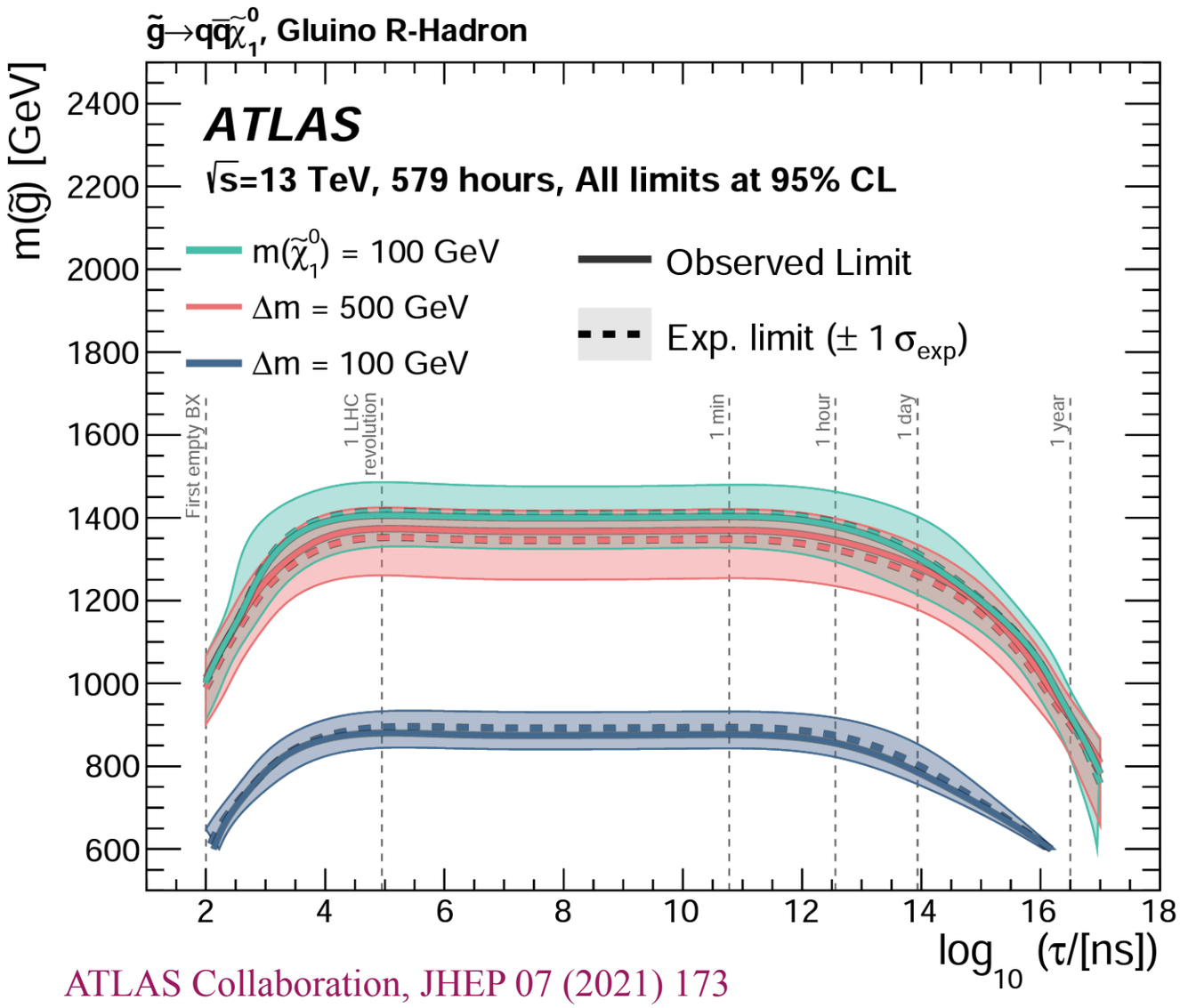
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	

Timing

Data acquisition



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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