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

Muon Collider

Physics Studies

Jul 06, 2023

Rodolfo Capdevilla
Fermilab

Part 3 of the KITP talk!

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?*

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

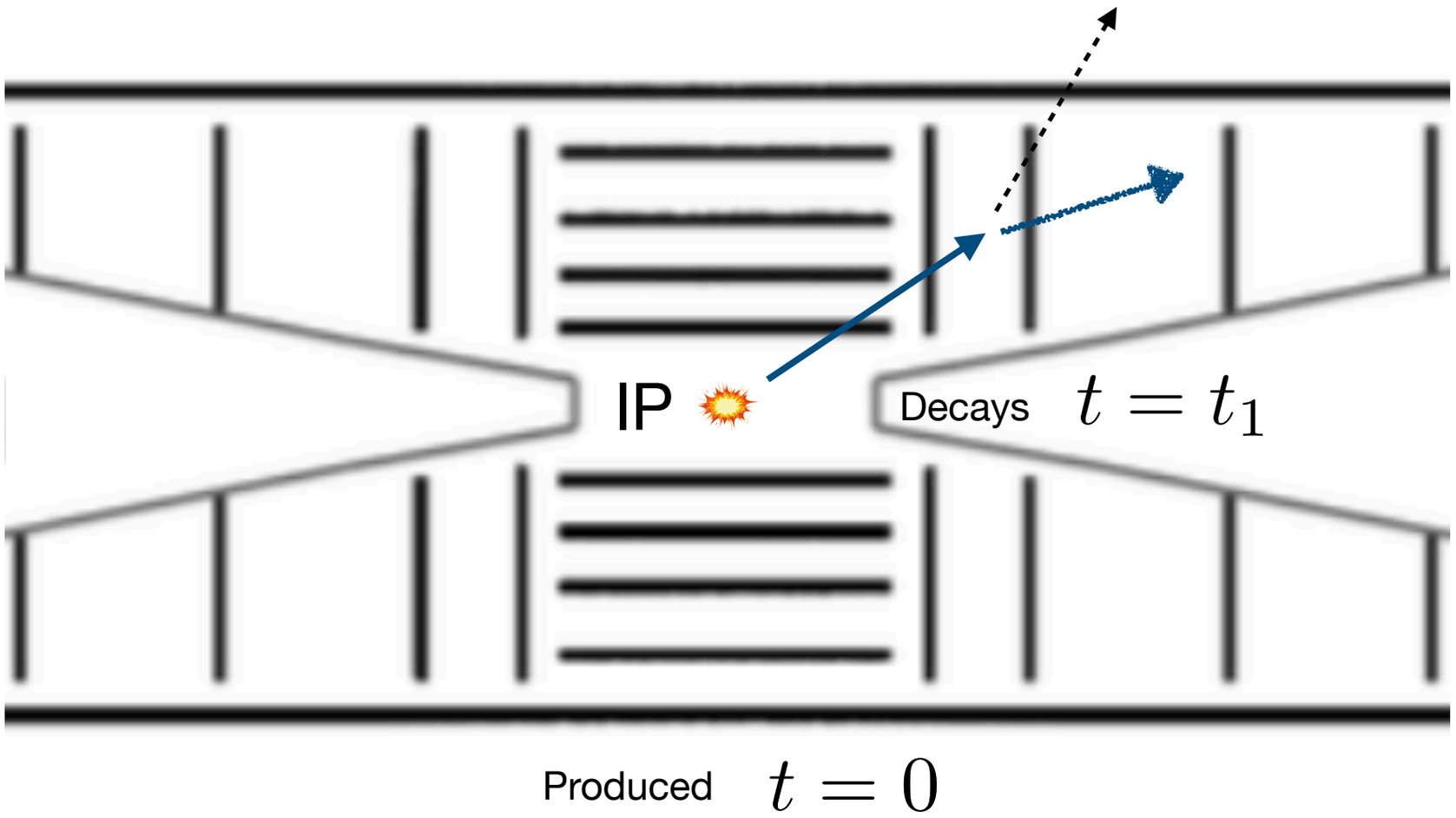
Particle(s) produced at the interaction point

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



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	2HDM	$H^{\pm}$, H^{0}, A	**1**, **2**, **3**, **4**, **8**, **17**,
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DM	Z portal	EWikinos-like (inelastic)	**5**, **6**, **9**, **10**, **11**, **12**, **14**, **16**,
	H portal	S (Z2 symmetric)	
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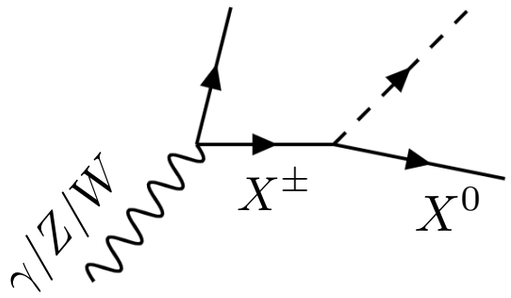
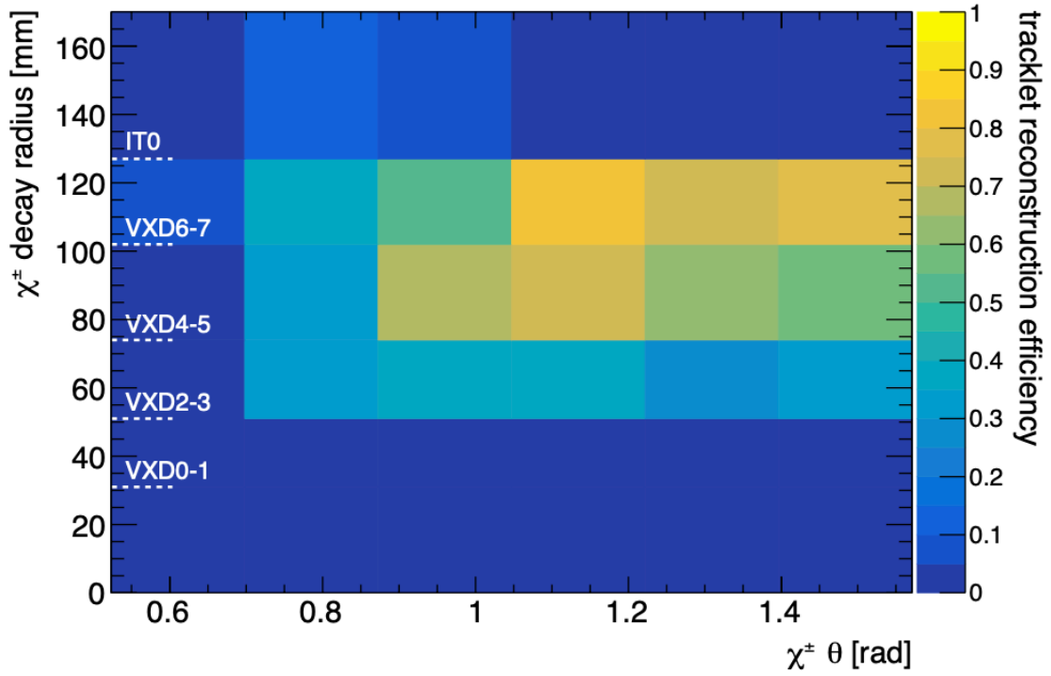
Timing

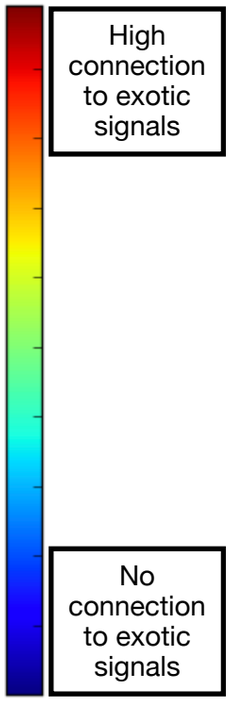
Tracking



Long lifetime:
Small splitting
Small coupling

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





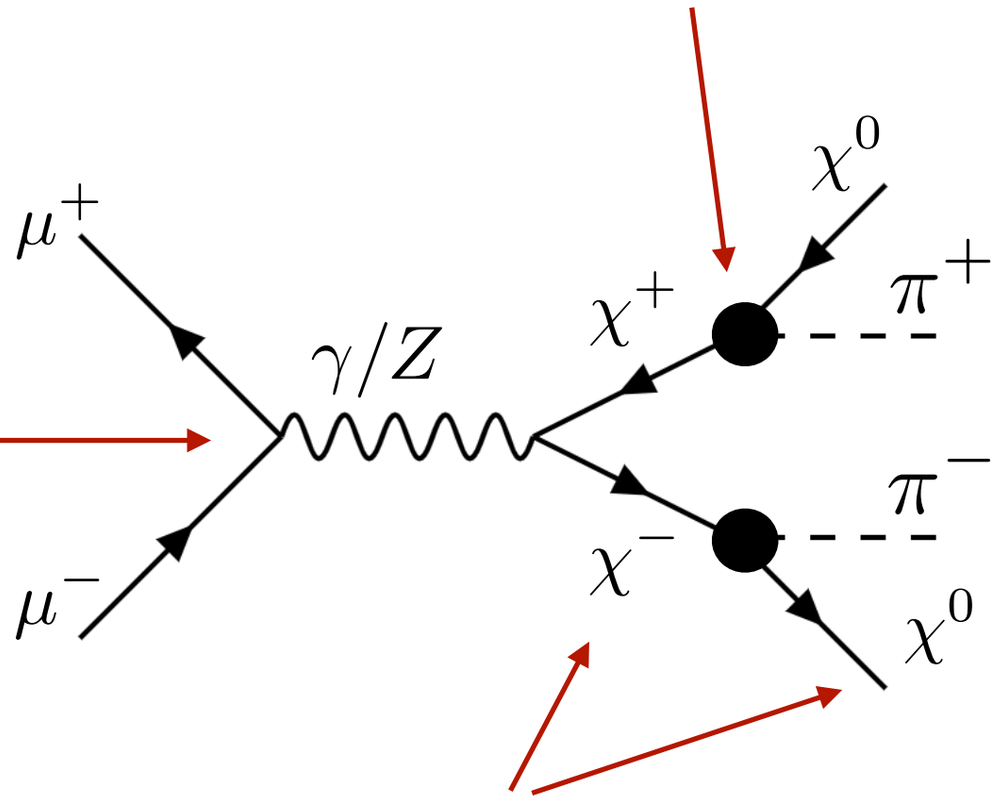
1) Eichten, Martin, Phys. Lett. B 728 (2014) 125-130
2) Barger, Everett, Logan, Shaughnessy, Phys. Rev. D 88 (2013) 11, 115003
3) Chakrabarty, Han, Liu, Mukhopadhyaya, Phys. Rev. D 91 (2015) 1, 015008
4) Chakrabarty, Mukhopadhyaya, Phys. Rev. D 96 (2017) 3, 035028
5) Han, Liu, Wang, Wang, Phys. Rev. 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

Minimal Dark Matter: Features

Long lifetime comes from very suppressed phase space

Charginos are electroweakly produced

Undetectable decay products!



Very compressed spectrum emerges naturally

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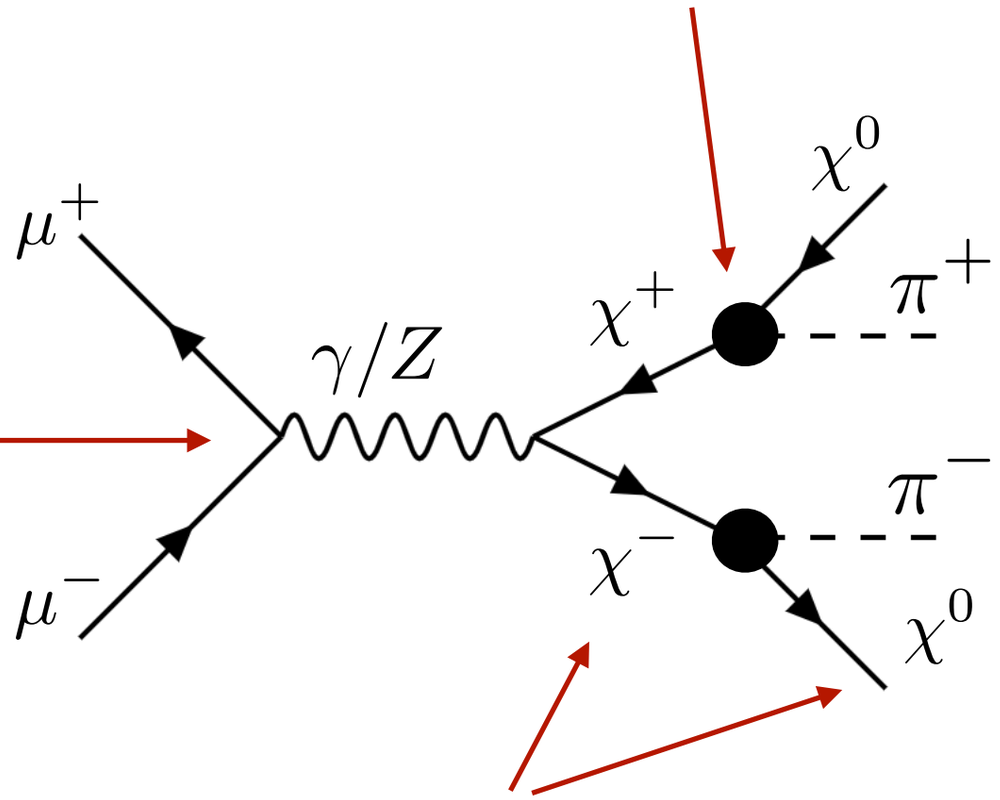
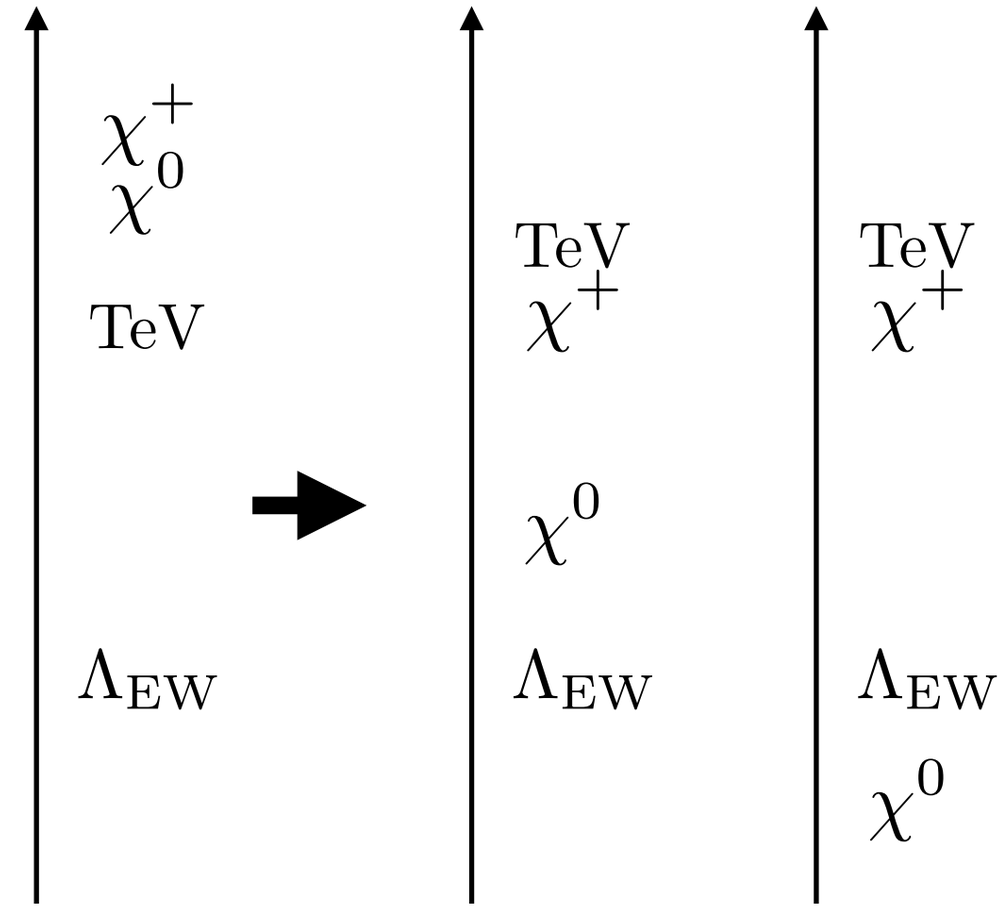


Very compressed spectrum emerges naturally

All of the above come from the same minimal assumption: $\begin{pmatrix} \chi^+ \\ \chi^0 \end{pmatrix}$ *Both particles belong to the same EW multiplet!*

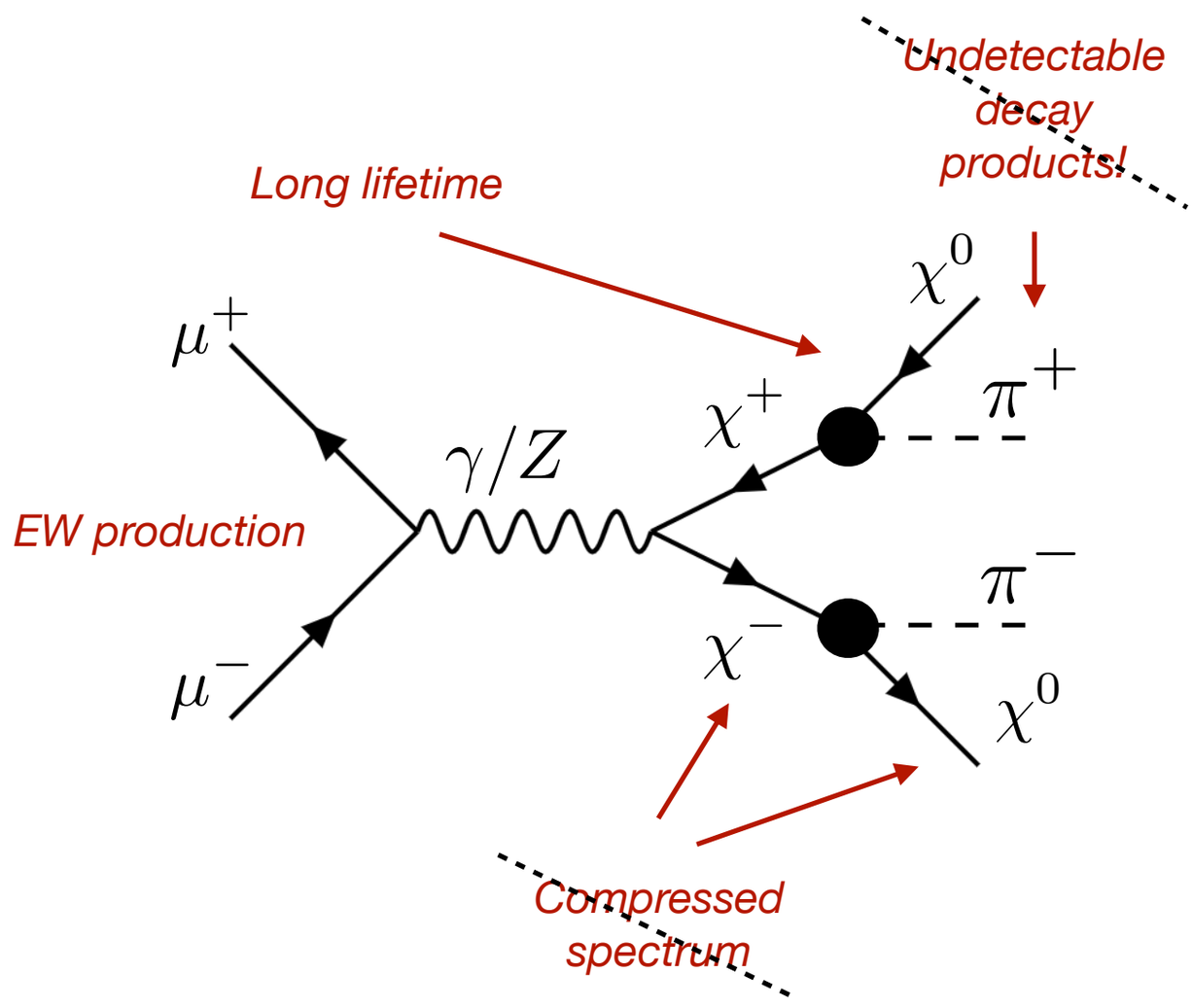
Beyond Minimal Dark Matter!



Minimal DM

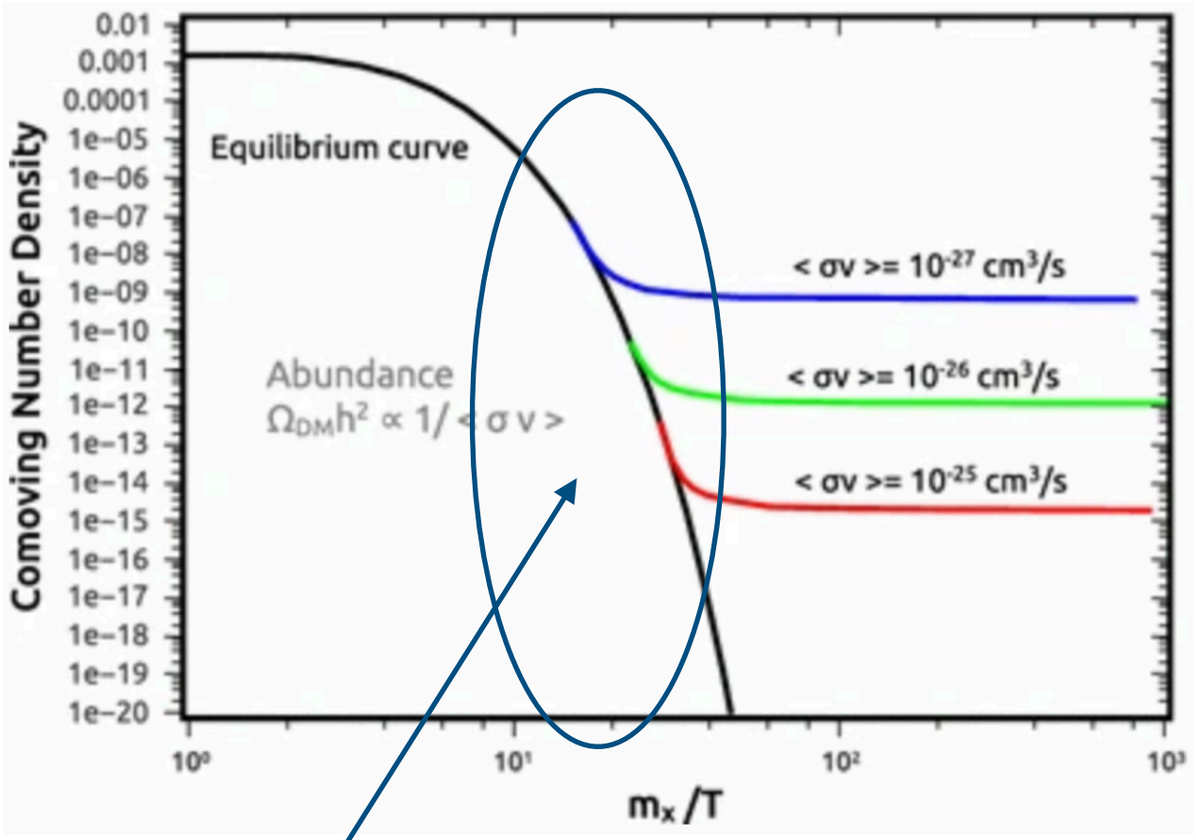
$$\begin{pmatrix} \chi^+ \\ \chi^0 \end{pmatrix}$$

Both particles belong to the same EW multiplet!

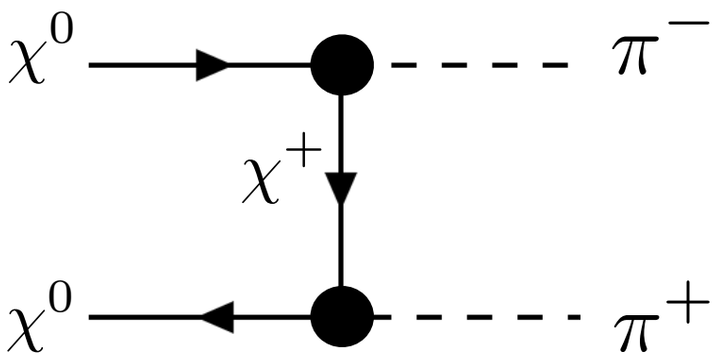


Beyond Minimal Dark Matter!

Arcadi et al., Eur. Phys. J. C 78 (2018) 3, 203



Long lifetime = Small coupling
= inefficient DM annihilation

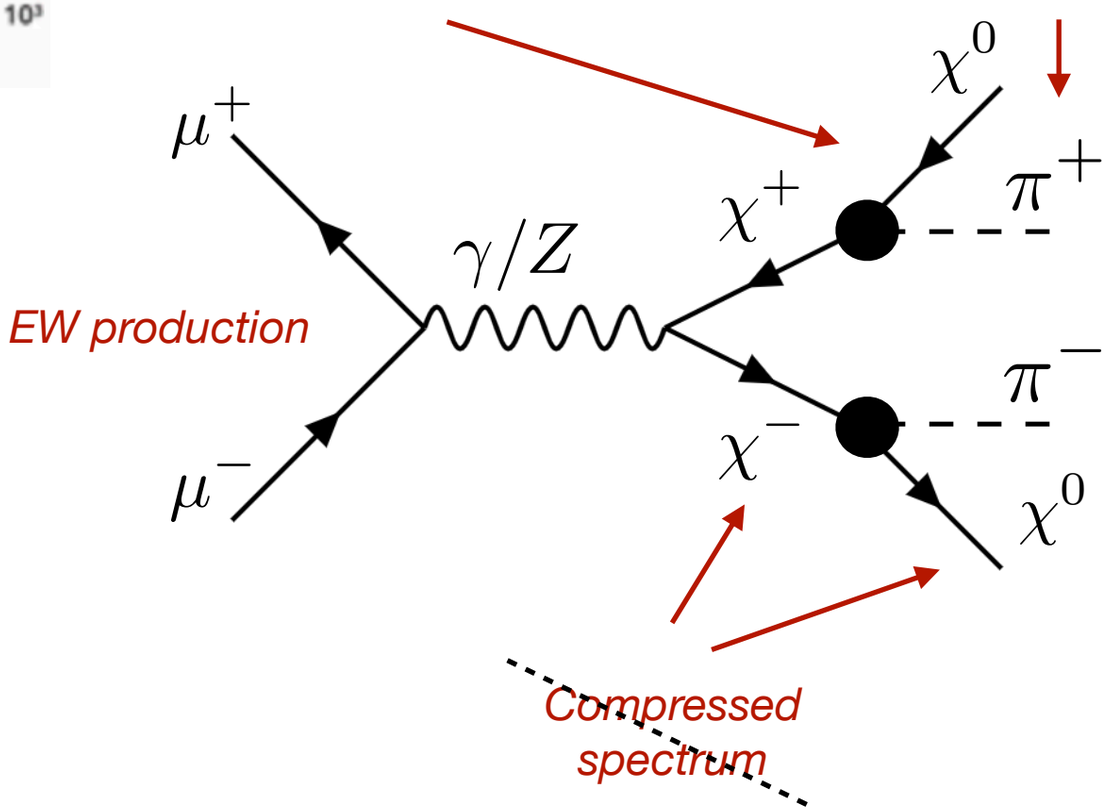


$$\begin{pmatrix} \chi^+ \\ \chi^0 \end{pmatrix}$$

~~*Both particles belong to the same EW multiplet!*~~

Undetectable decay products!

Long lifetime

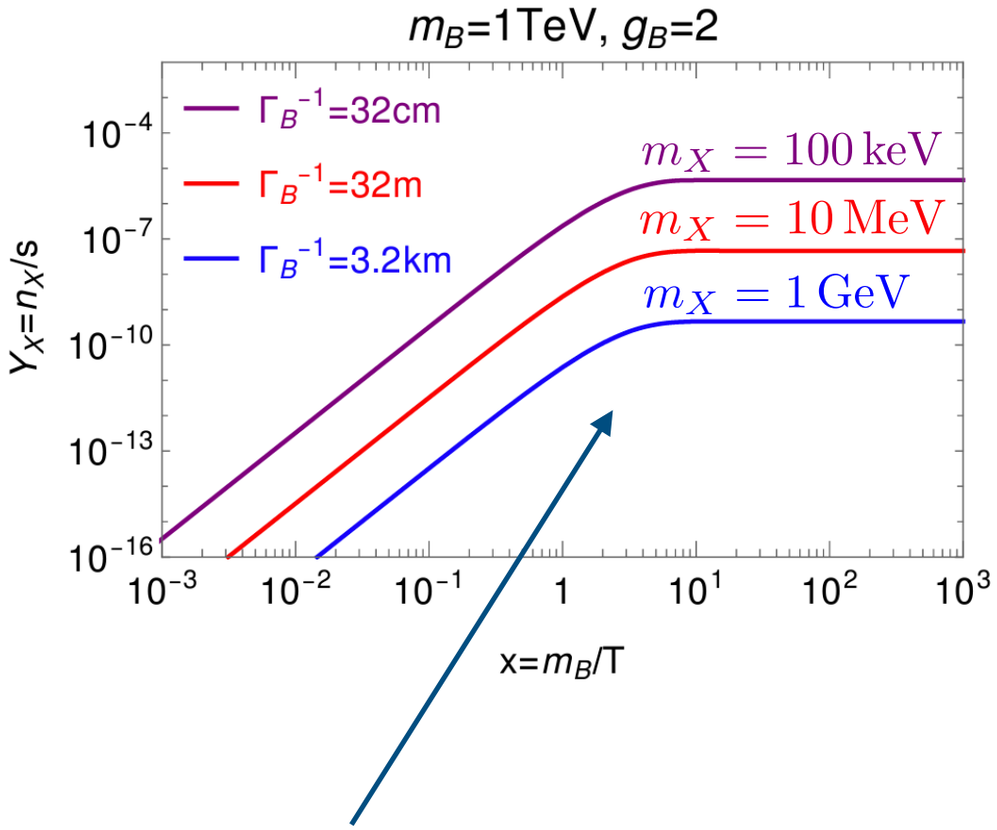


EW production

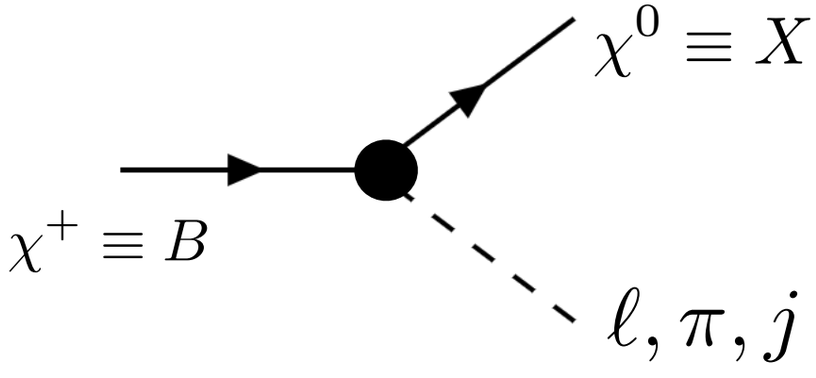
Compressed spectrum

Beyond Minimal Dark Matter!

Calibbi, D'Eramo, Junius, Lopez-Honorez,
Mariotti, JHEP 05 (2021) 234



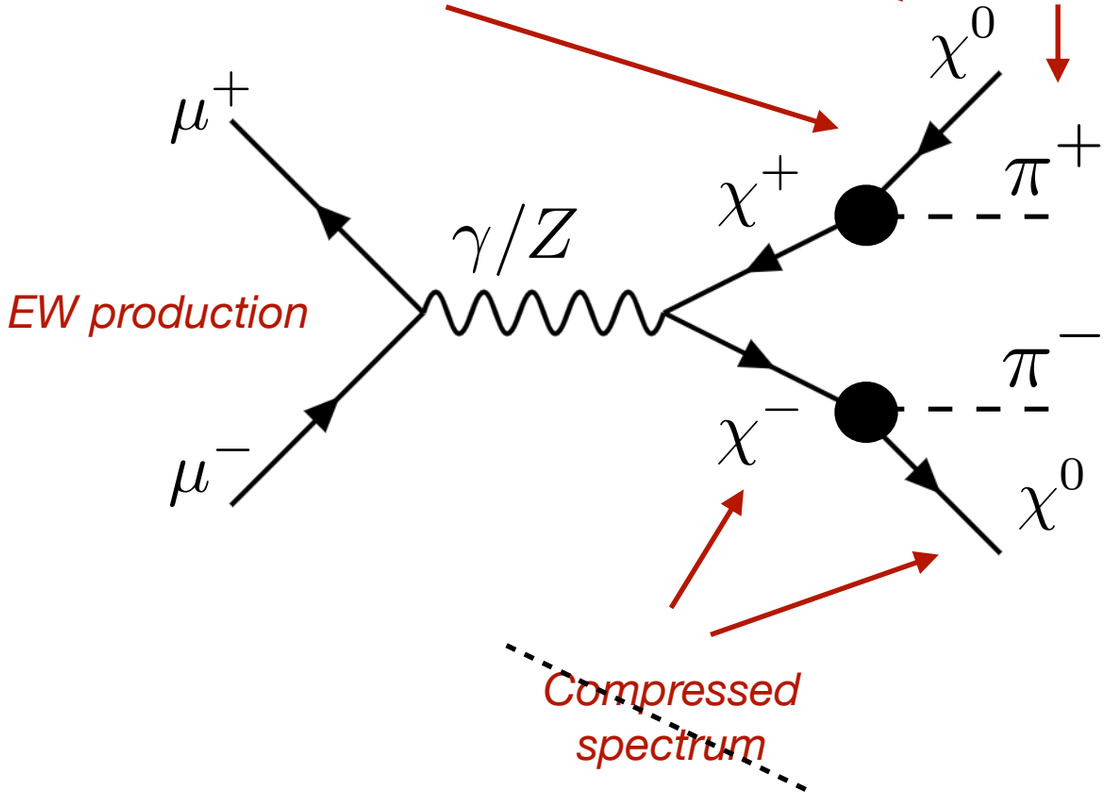
Long lifetime = Small coupling
= Slow DM population



Negligible abundance in the early Universe

Undetectable decay products!

Long lifetime



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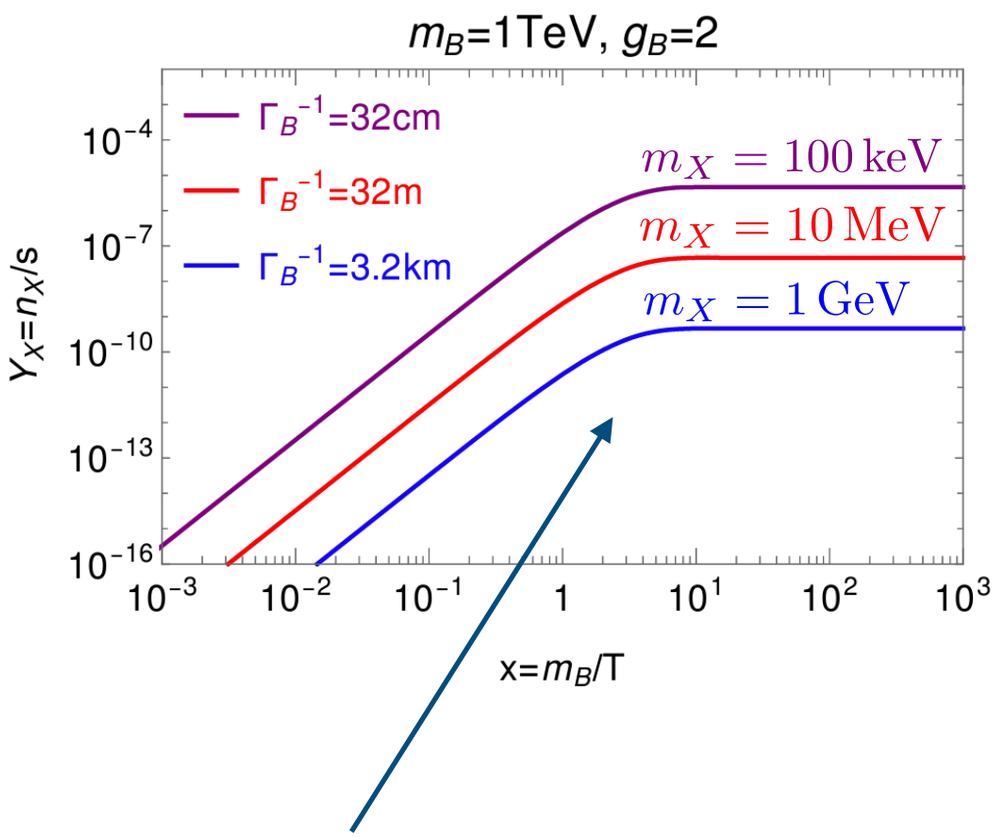

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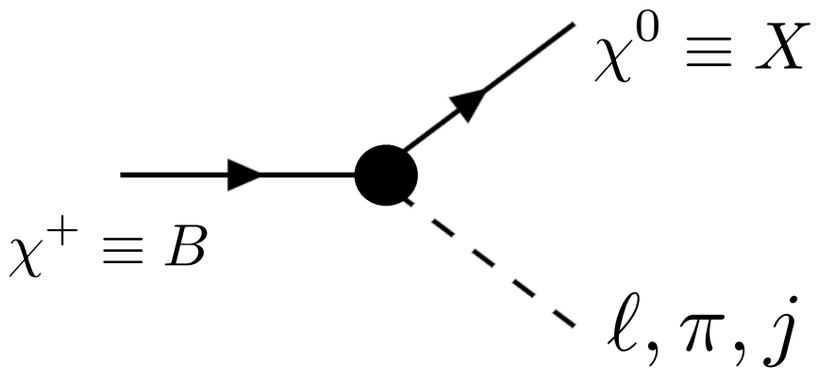
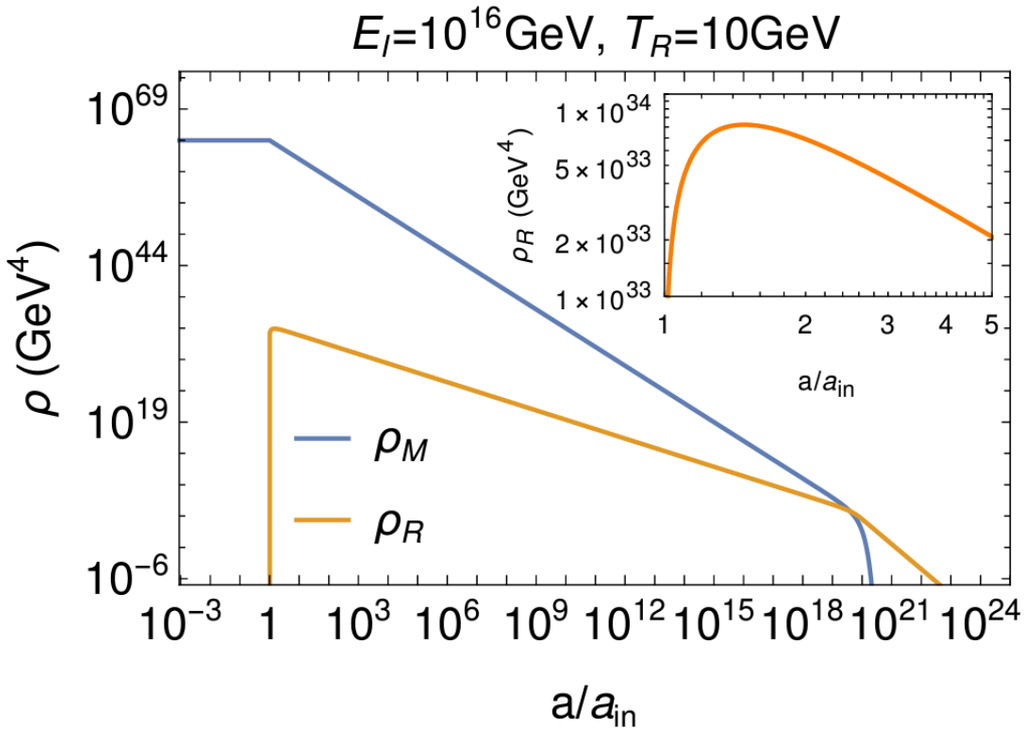
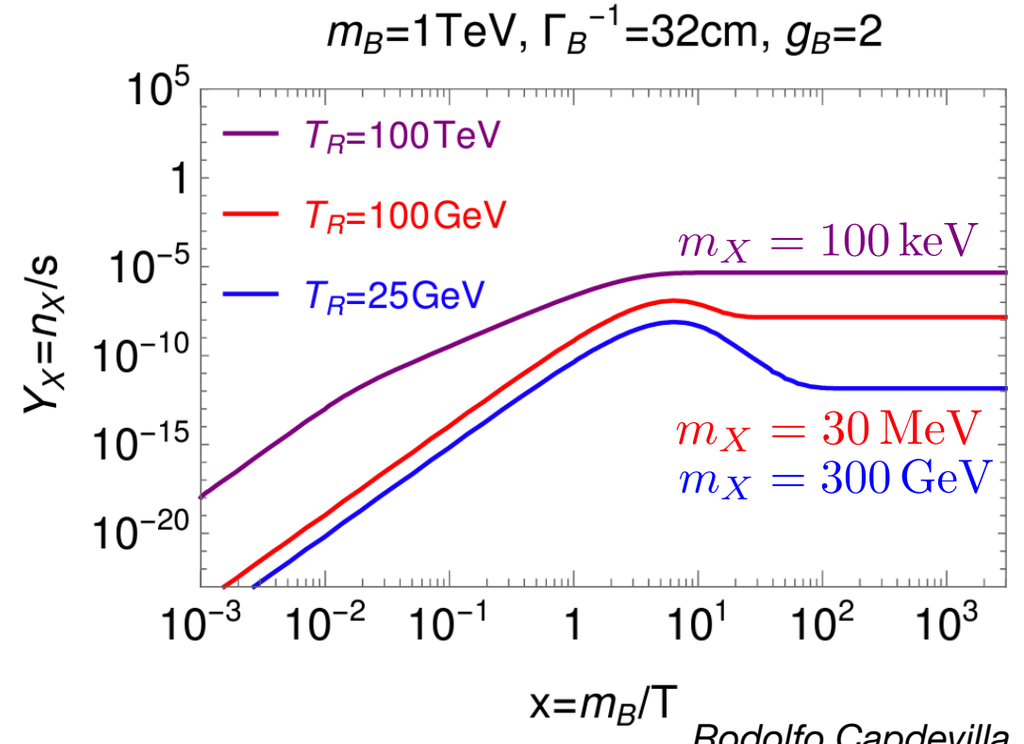
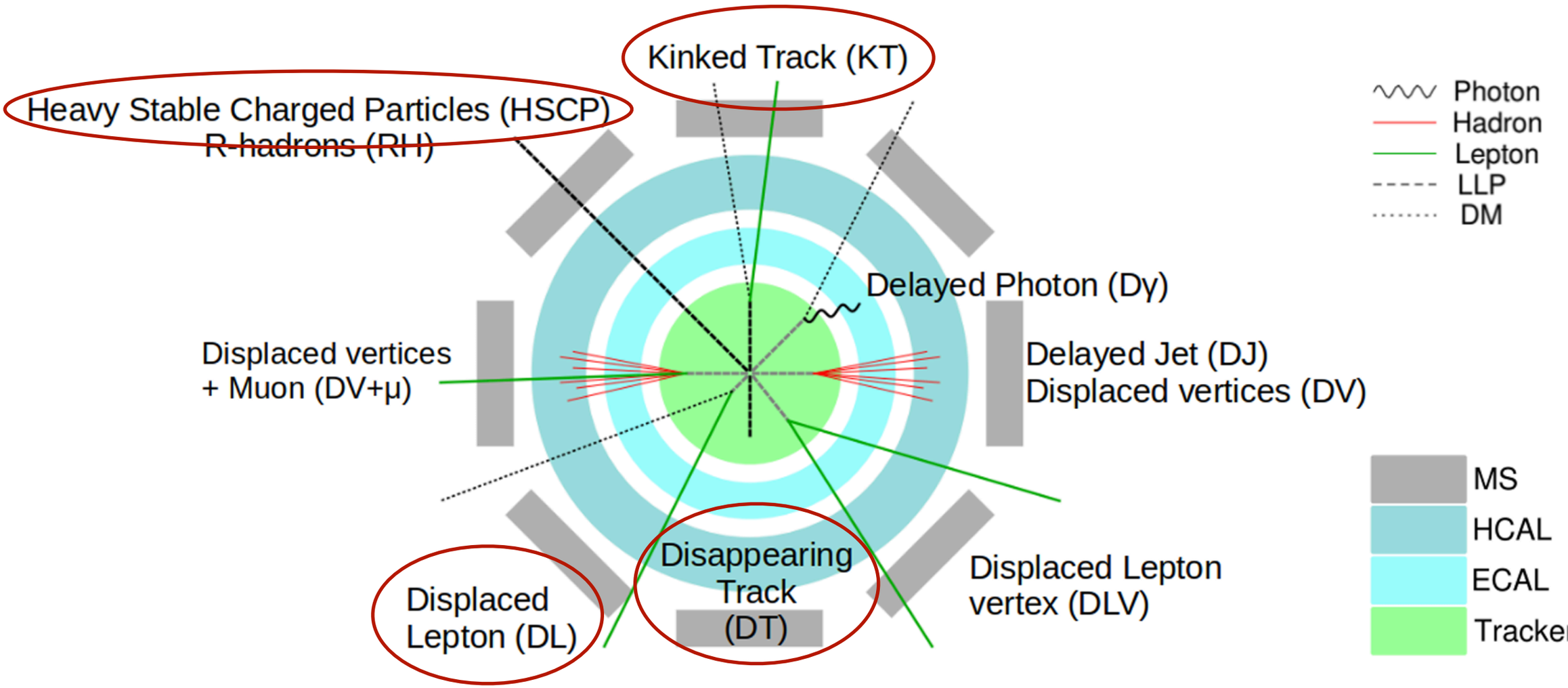


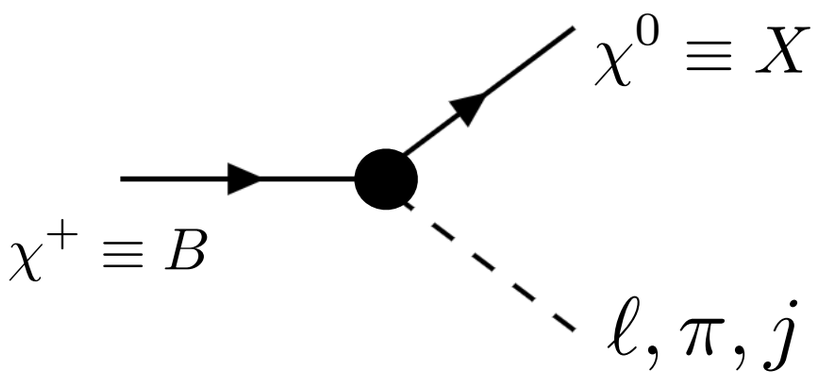




Exotic Signals



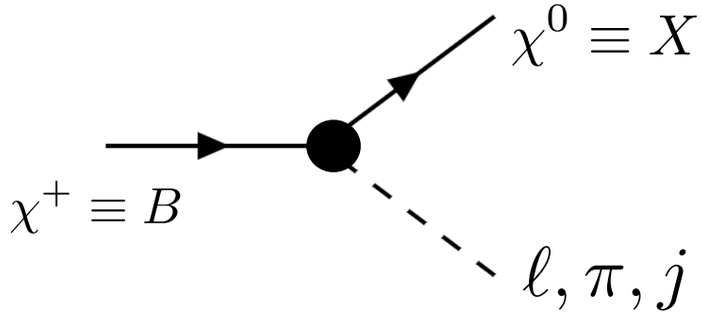
Calibbi, D'Eramo, Junius, Lopez-Honorez, Mariotti, JHEP 05 (2021) 234

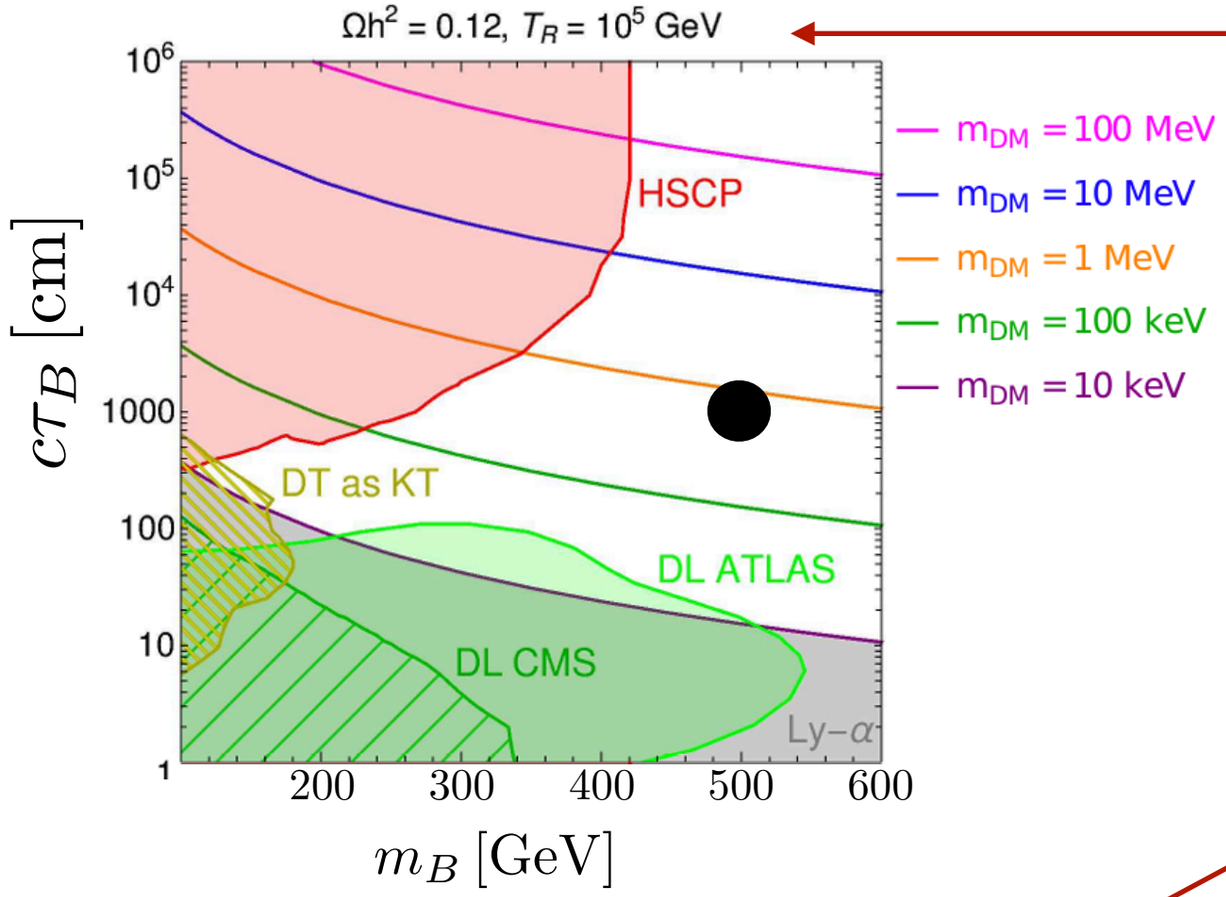


Signature	Exp. & Ref.	$\mathcal{L}$	Maximal sensitivity	Label
R-hadrons	CMS [63]	12.9 fb^{-1}	$c\tau \gtrsim 10$ m	RH
Heavy stable charged particle	ATLAS [64]	36.1 fb^{-1}		HSCP
Disappearing tracks	ATLAS [65]	36.1 fb^{-1}	$c\tau \approx 30$ cm	DT
	CMS [66, 67]	140 fb^{-1}	$c\tau \approx 60$ cm	
Displaced leptons	CMS [68]†	19.7 fb^{-1}	$c\tau \approx 2$ cm	DL
	CMS [69]	2.6 fb^{-1}		
	ATLAS [70]	139 fb^{-1}	$c\tau \approx 5$ cm	

Exotic Signals

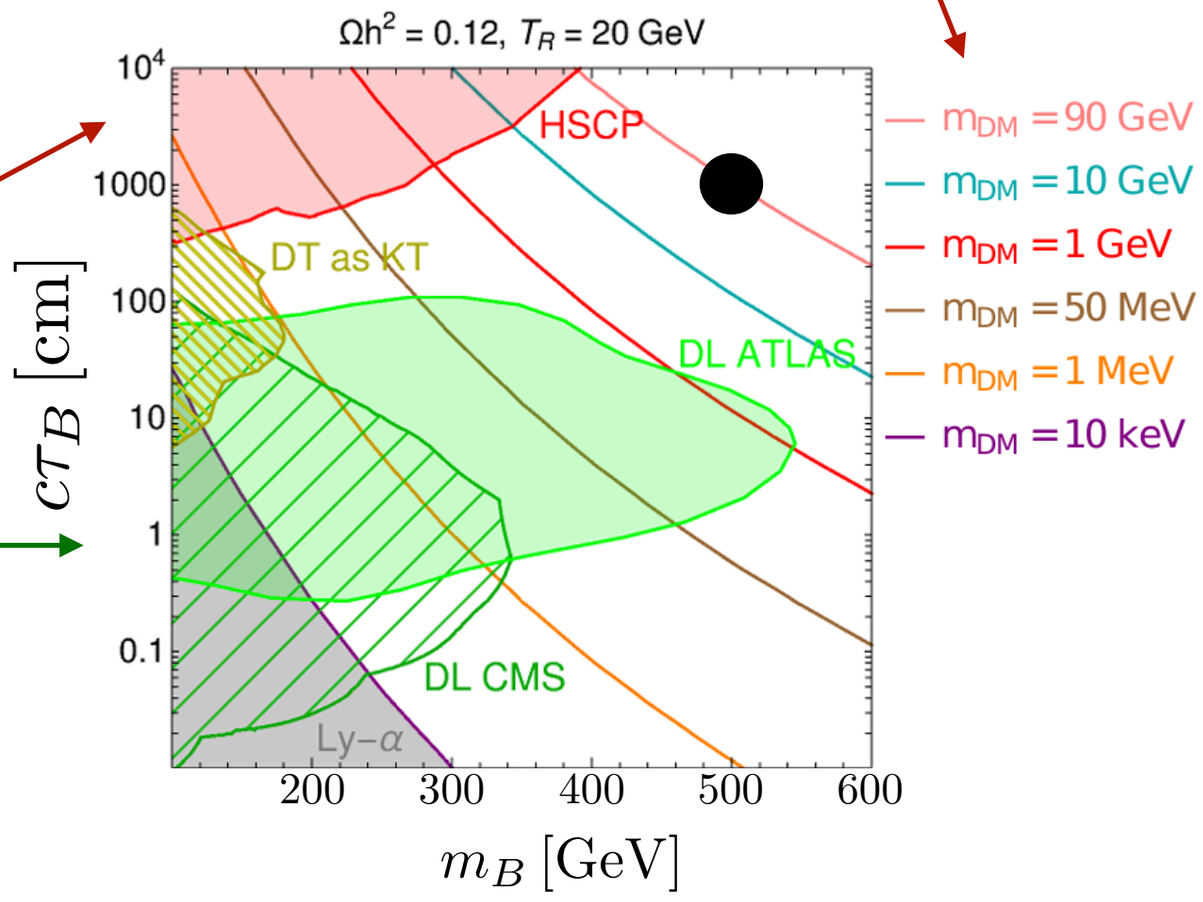
High RHT
Light DM





Small RHT
Heavier DM

Longer lifetimes: HSCP
Intermediate lifetimes: DT
Shorter lifetimes: DL



Calibbi, D'Eramo, Junius, Lopez-Honorez, Mariotti, JHEP 05 (2021) 234

Summary

1. Disappearing tracks: Great opportunities for Minimal DM (small splittings), but also for long-lived sleptons (small couplings).

2. LLP signatures can probe Cosmological scenarios of out of equilibrium DM production. For a given parent particle mass and lifetime one can find a connexion between the reheat temperature and the DM mass.

3. Some of these models can produce displaced jets. **Can we measure the impact parameter of a jet?**

Thank You!

Backup!

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)	
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	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

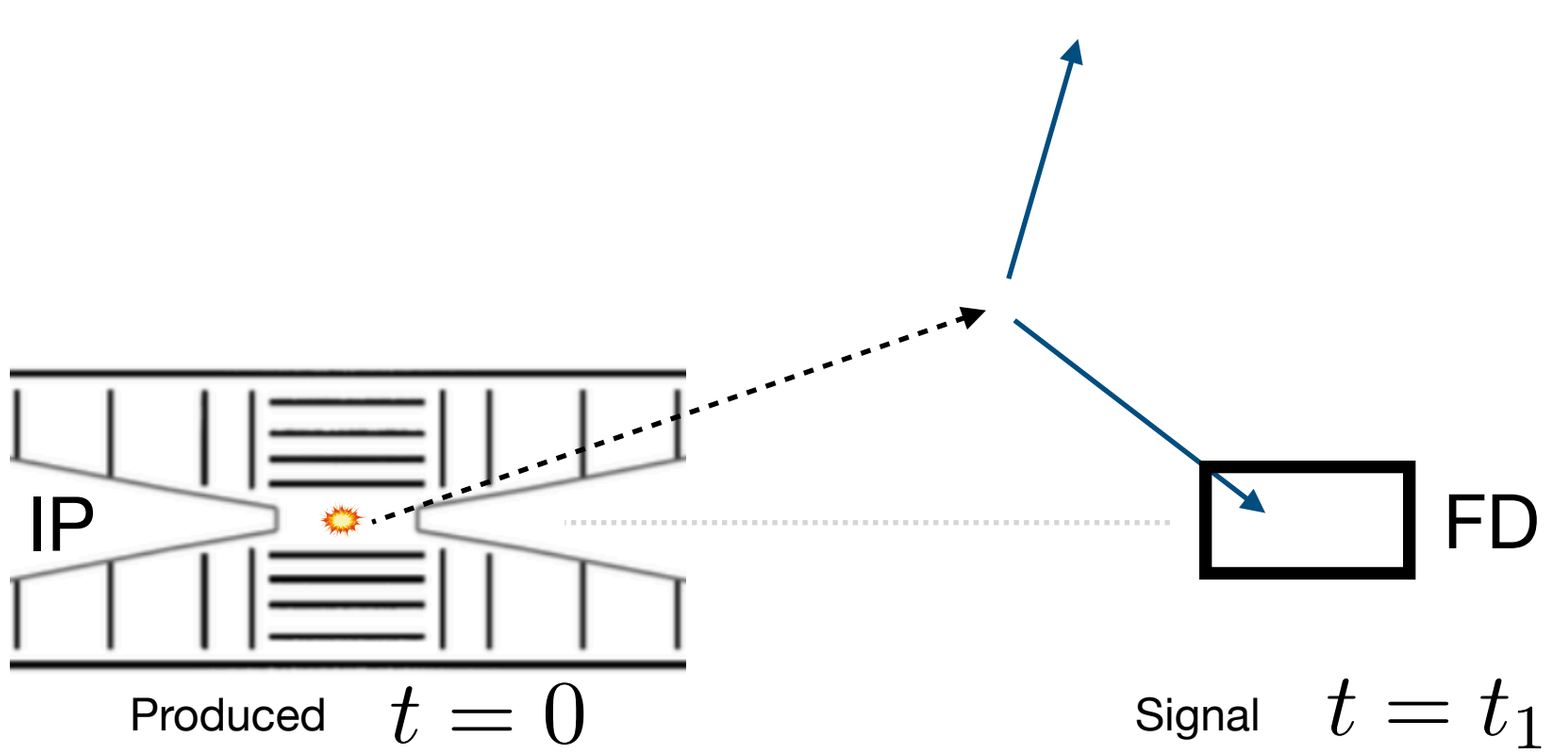
Particle(s) produced at the interaction point

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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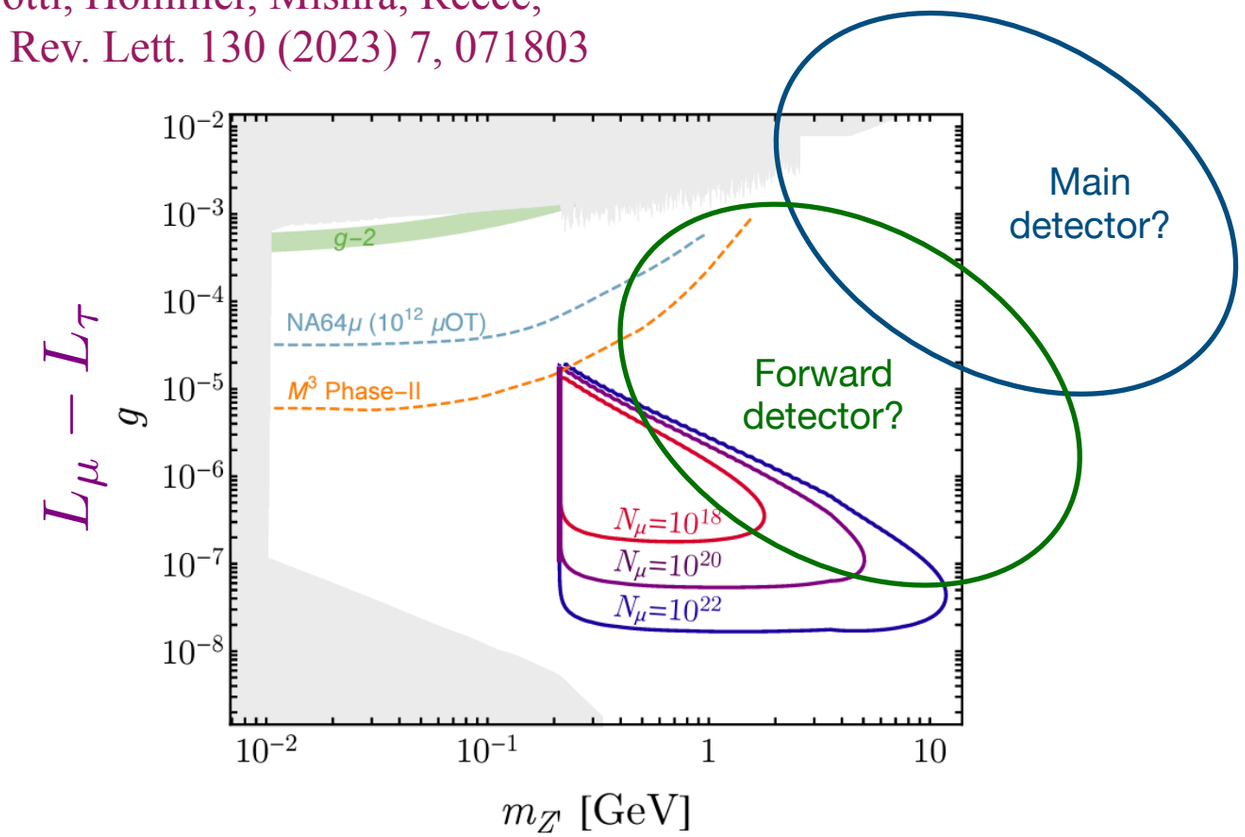
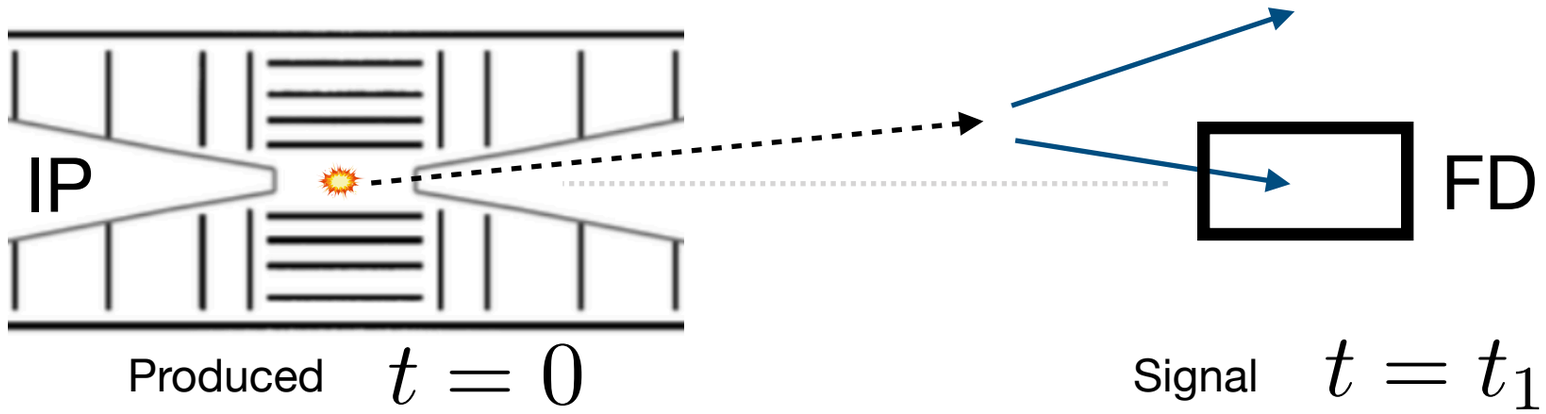
Timing

FD

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





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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**,
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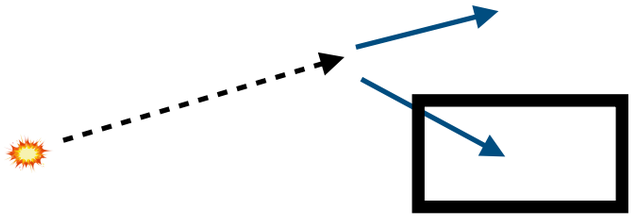
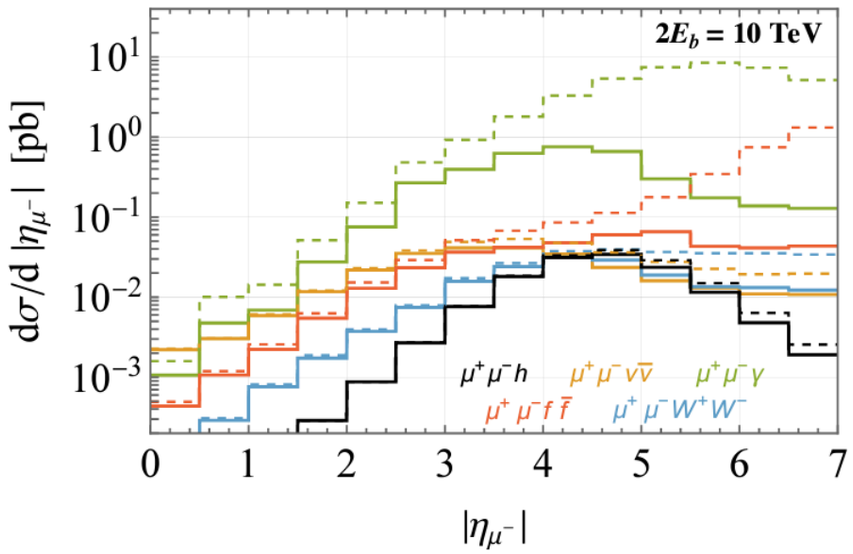
Timing

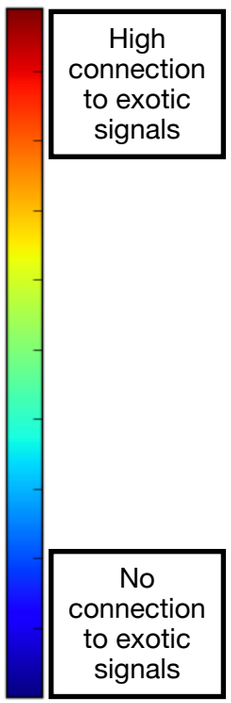
FD



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

Motivation	Theoretical scenario	Candidate particle(s)	**Exotic Signals** Displaced vertices
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Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	
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	Composite	$X_{5/3}, T_{2/3}$	
	Extra dimensions	G_{KK}	
	Neutral naturalness	Glueballs, sQuirks	x
DM	Z portal	EWikinos-like (inelastic)	x
	H portal	S (Z2 symmetric)	
	Nu portal	ν_s	
	U(1) portal	$U(1)_{B-L_i-L_j}$	x

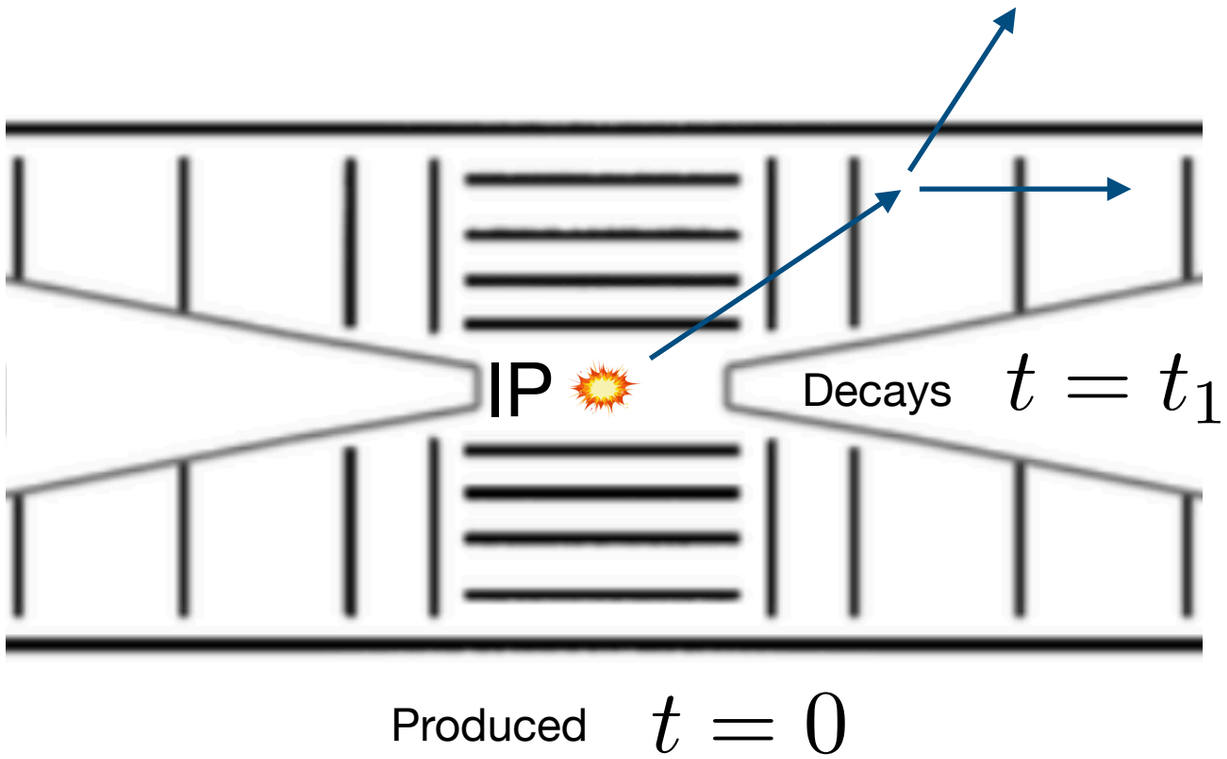
Timing

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**
			Displaced vertices
Exotics	SM+singlet	S, a	
	2HDM	$H^{\pm}$, H^0, A	x
	New gauge groups	Z', W', γ'	
	VLF	Q', L'	
	HNL	N_i	x
	Leptoquarks	$\tilde{R}_2$, U_1 (UV motivated)	
	Quirks	$q'\bar{q}'$ (bound states)	
	Hidden valleys	$g'g'$	x
Hierarchy problem	SUSY	$\tilde{t}, \tilde{q}, \tilde{g}$ (colored)	
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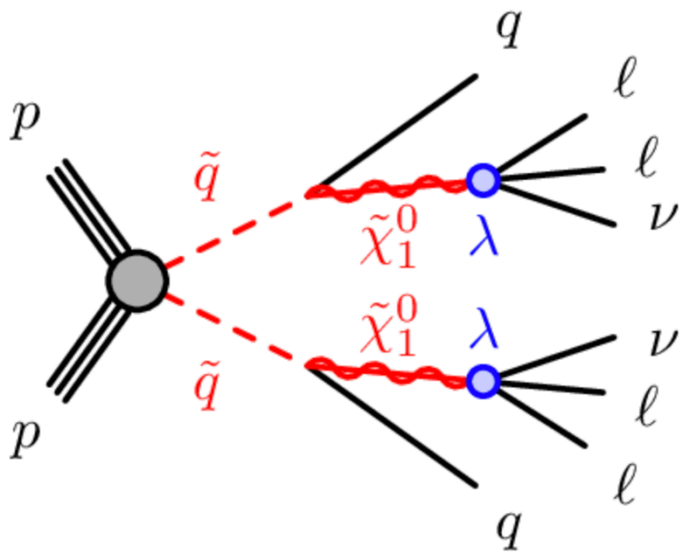
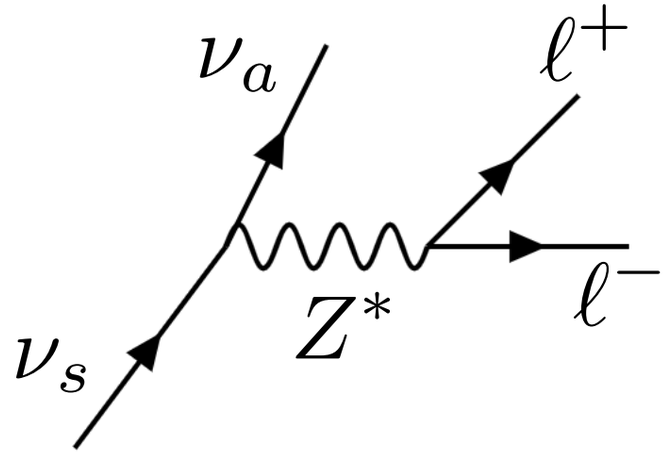
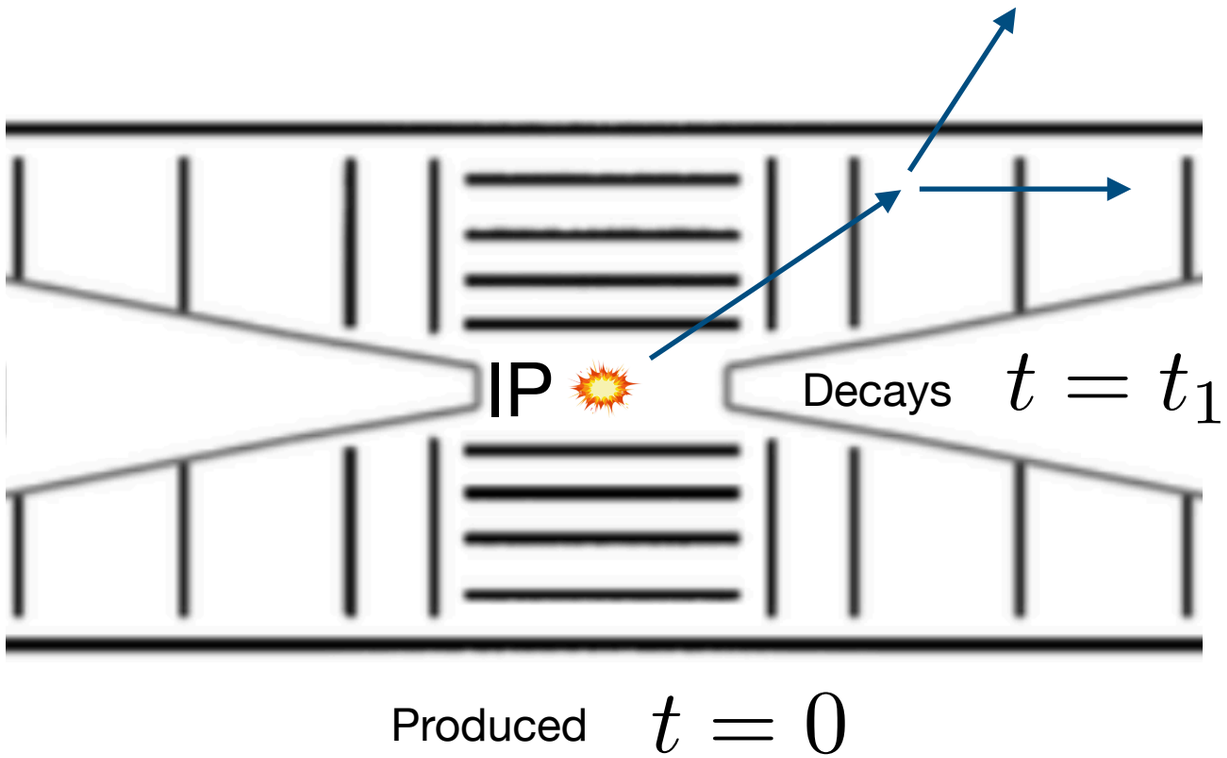
Timing



Tracking





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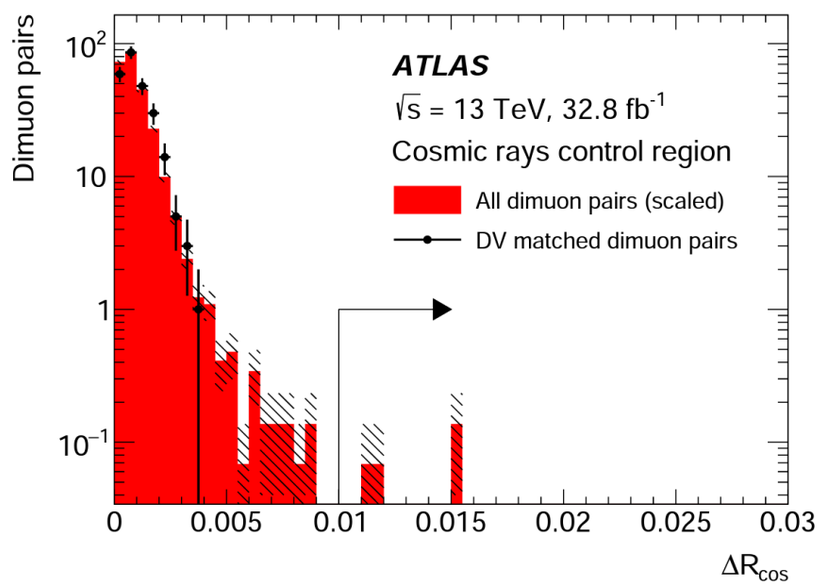
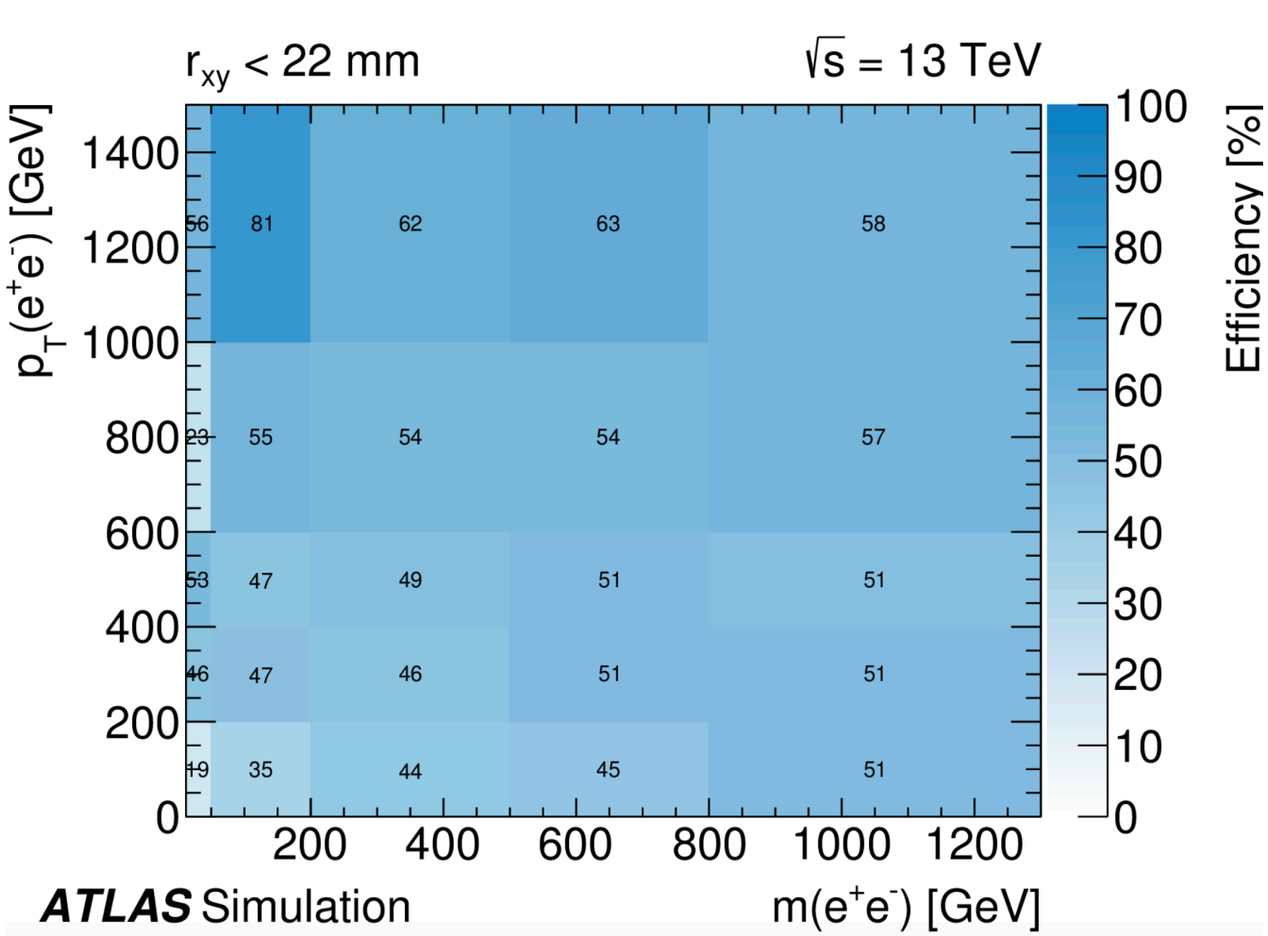
Timing

Tracking





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

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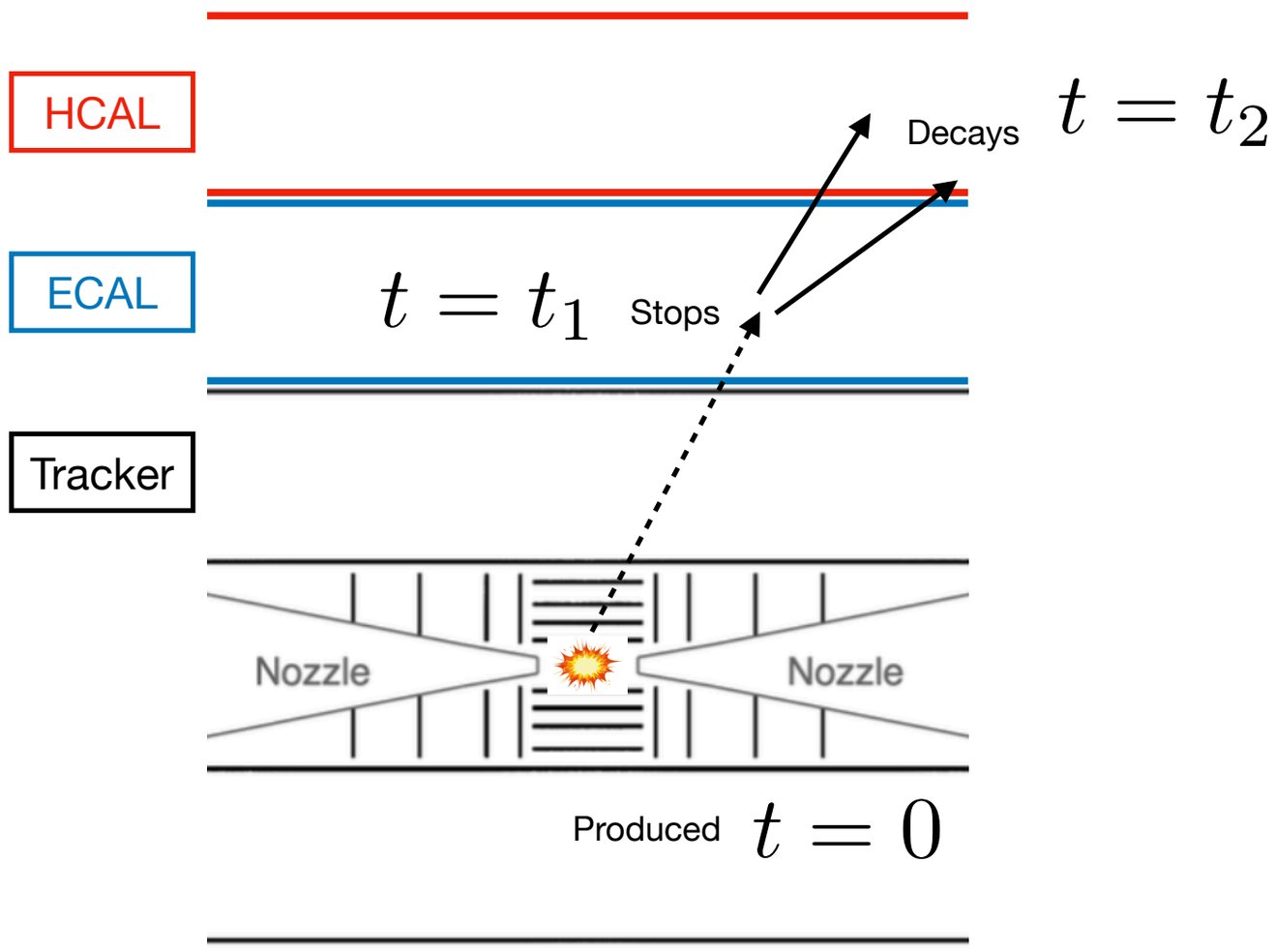
	U(1) portal	$U(1)_{B-L_i-L_j}$	

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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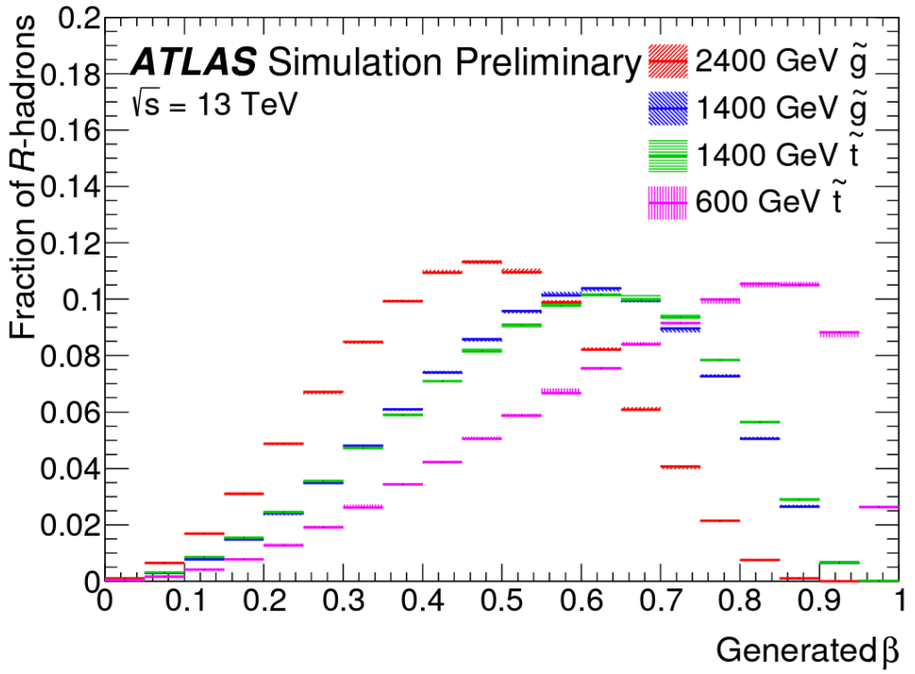
Timing

Data acquisition

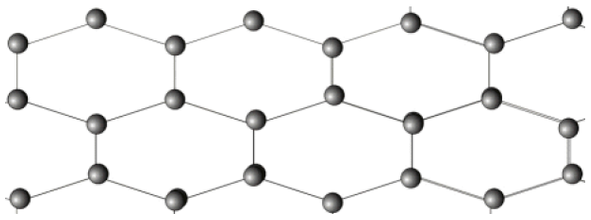
$$v \leq \frac{v_F}{A^{2/3}}$$

Fermi velocity of nucleons

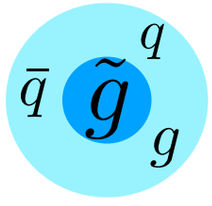
Atomic mass number

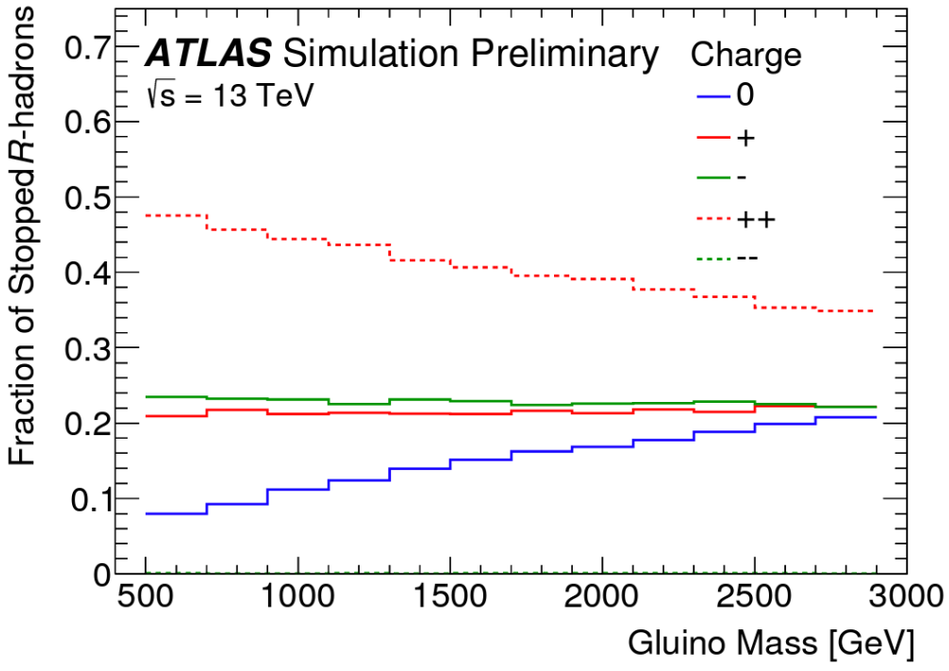


ATLAS Collaboration, ATL-PHYS-PUB-2019-019



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





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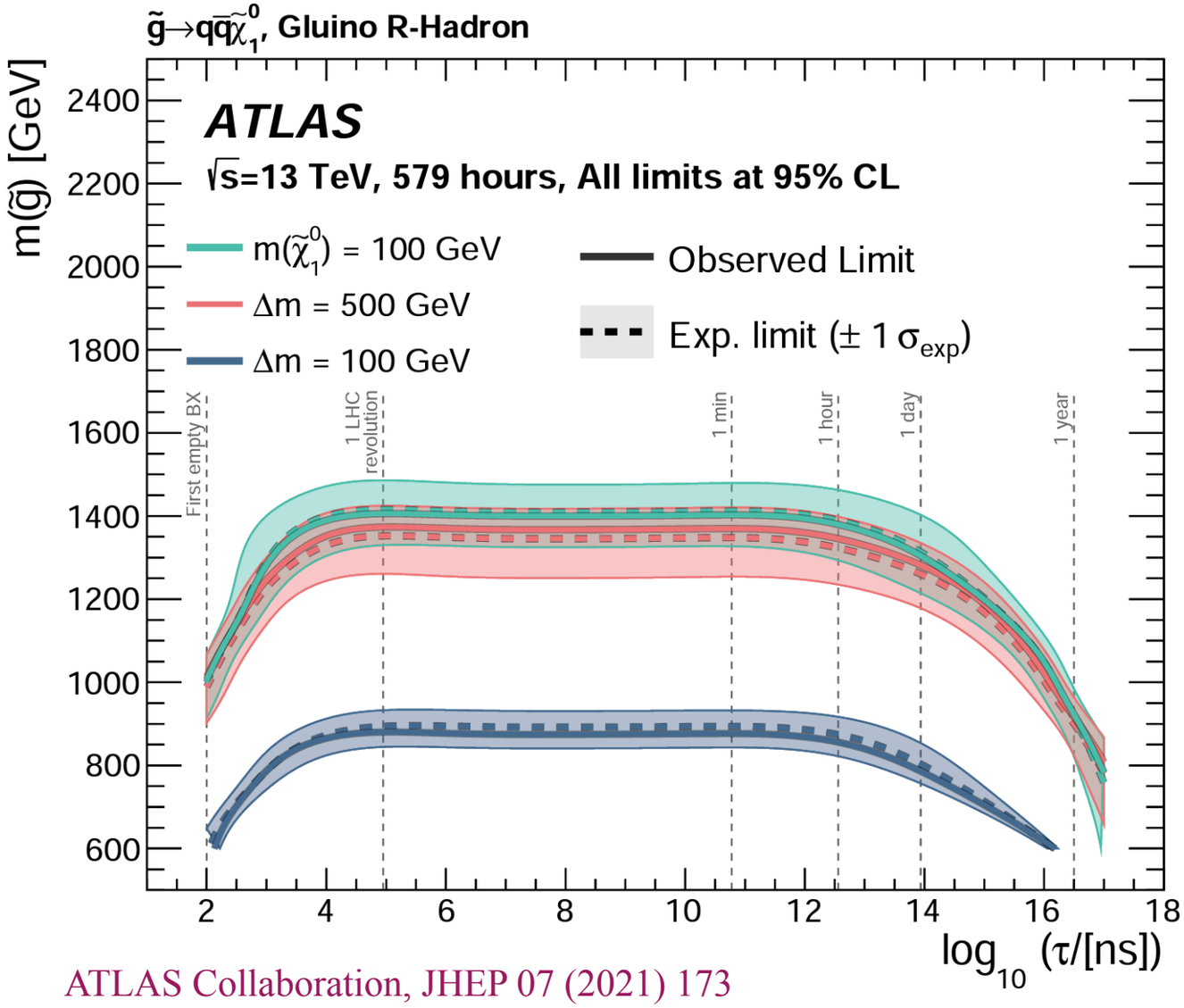
Timing

Data acquisition



ATLAS Collaboration, JHEP 07 (2021) 173