

# Dark Sectors at a Muon Collider

Navin McGinnis

Dark Interactions workshop, Oct. 16 -18 2024



BCG vaccination for  
cattle pp. 1410 & 1433

Steps toward regulating  
indoor air quality p. 1418

Landfills emit methane  
persistently p. 1499

# Science

\$15  
29 MARCH 2024  
science.org

AAAS

A radical new  
particle accelerator  
concept emerges. Call it physicists'

## MUON SHOT

p. 1405

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Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

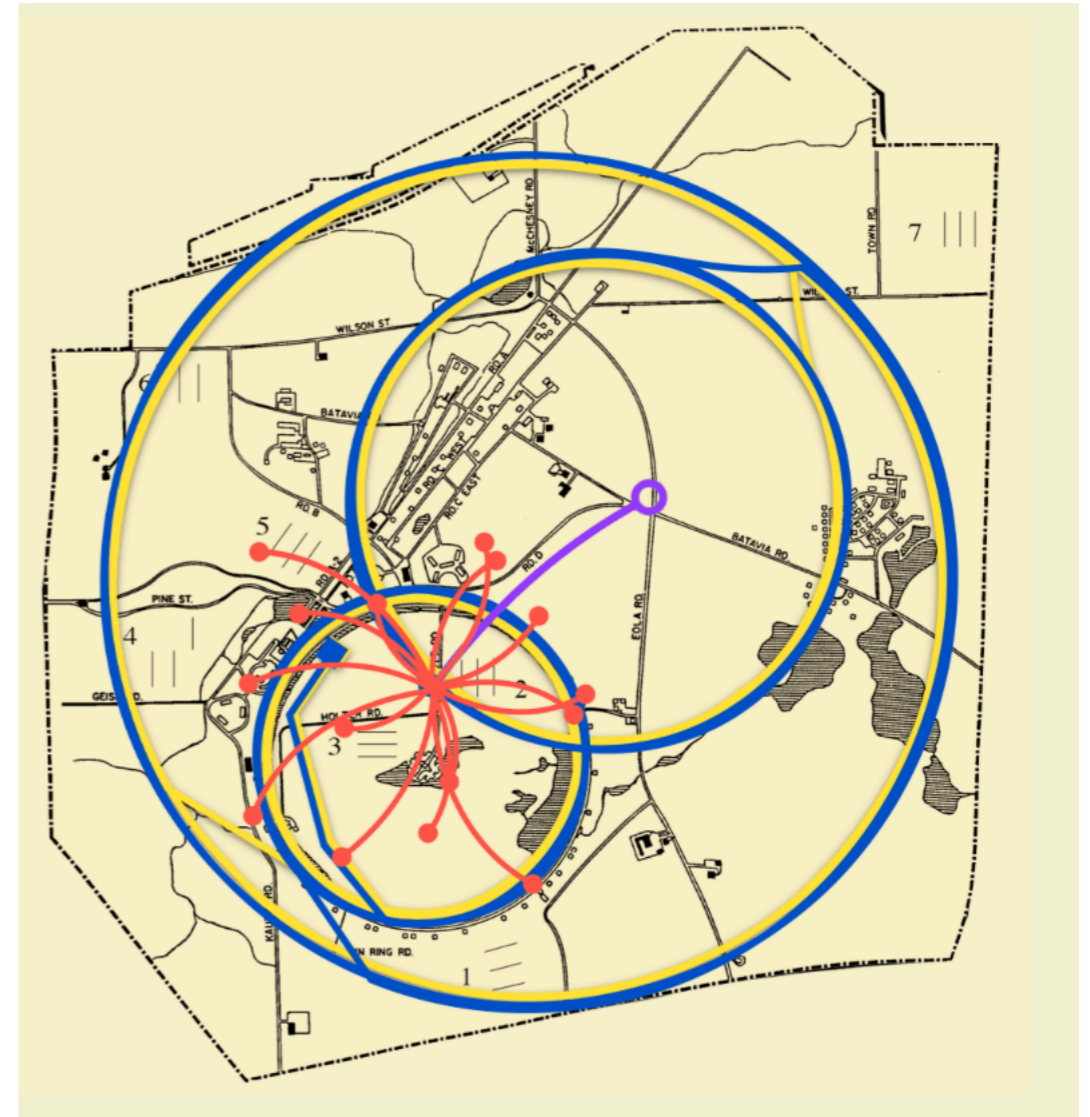
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# MUON SHOT

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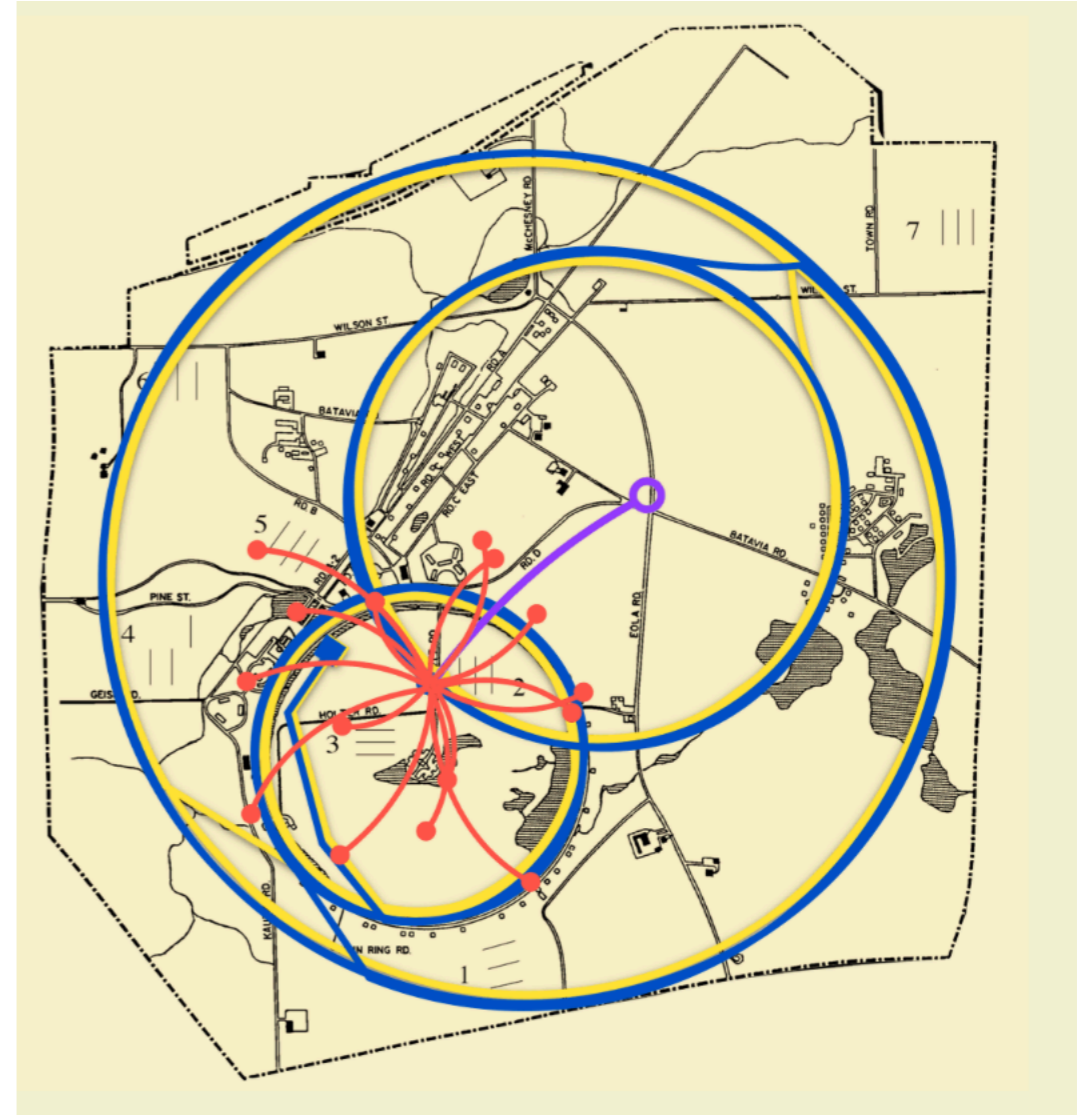
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- Not a new idea (~1970's, ~1990's, now)



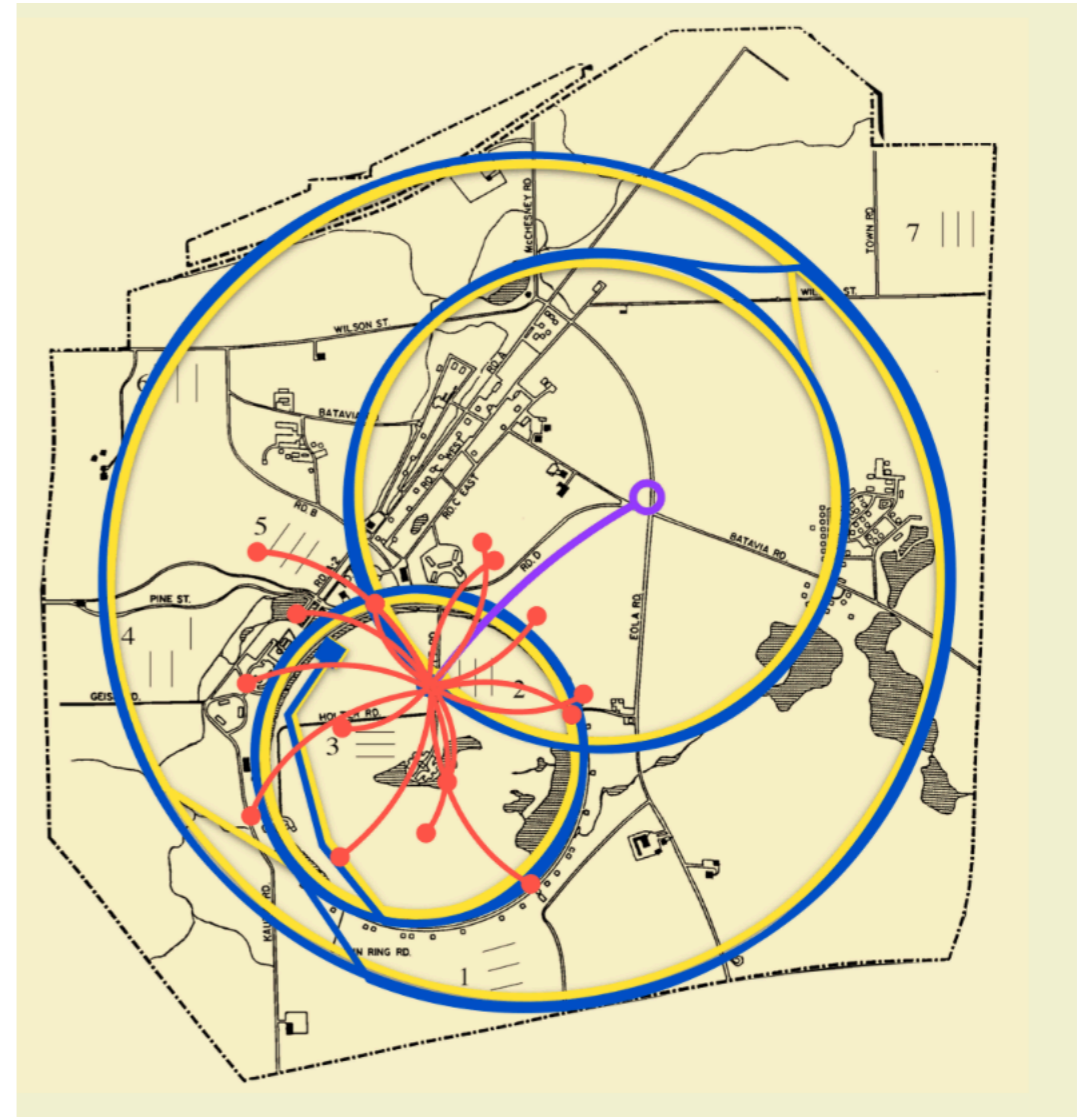
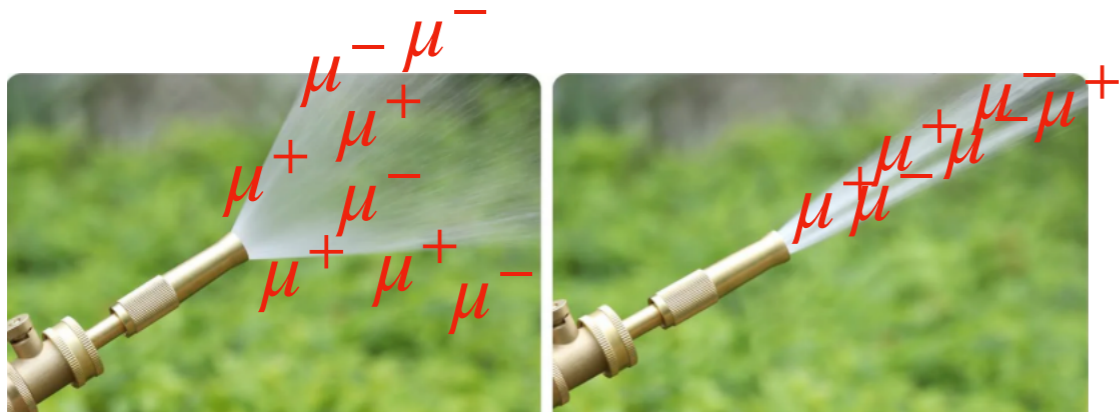
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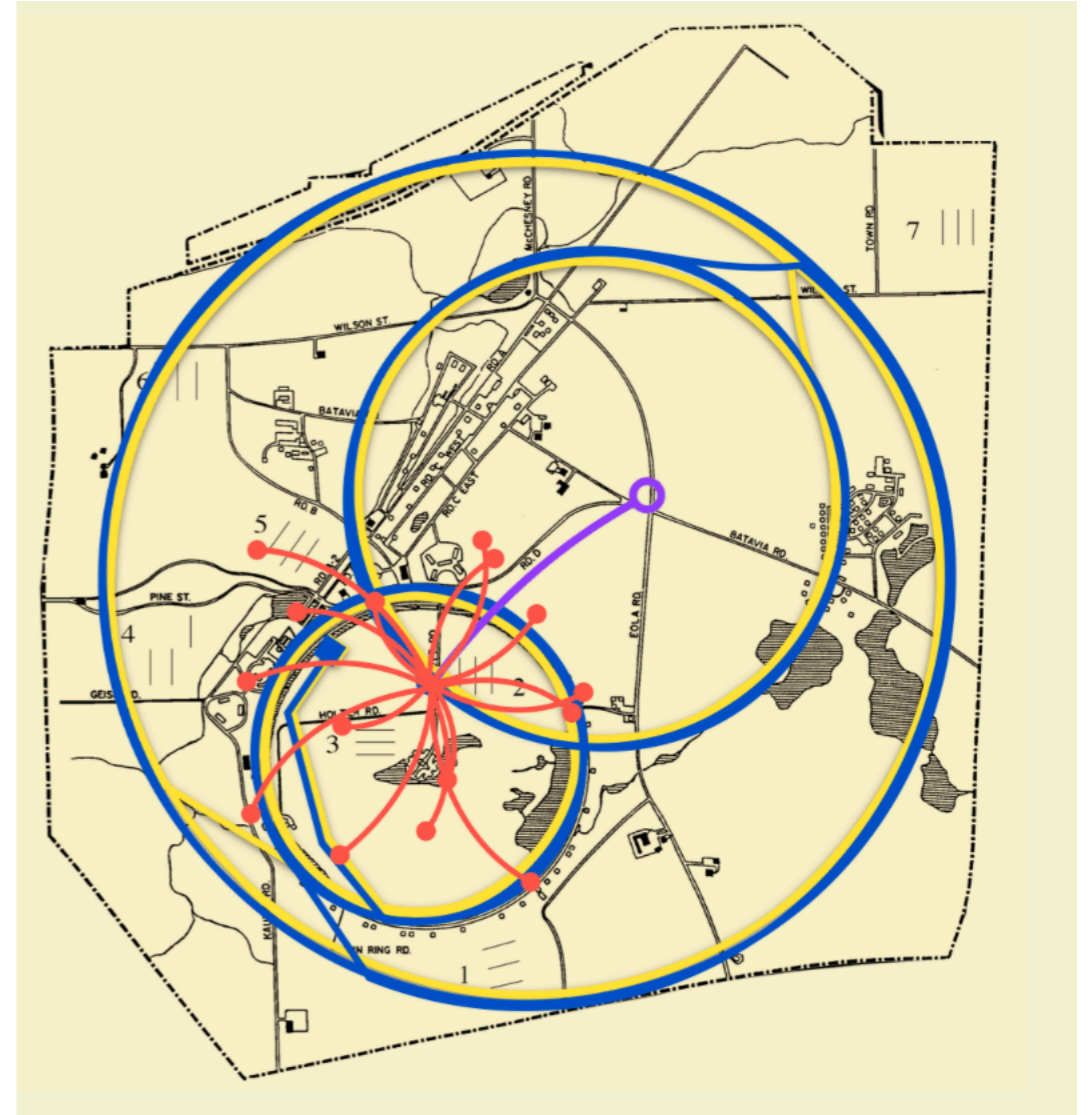
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A Muon collider can do both!

- $m_\mu \simeq 200 m_e \implies$  Red synchrotron rad.  $\implies$  allows for higher running energies
- Fundamental particle, full access to beam energy, no crazy QCD junk flying around



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- ***Muon Collider Forum Report*: [2209.01318](#)**
- ***Towards a Muon Collider*: [2303.08533](#)**
- ***Interim Report for the International Muon Collider Collaboration (IMCC)*: [2407.12450](#)**



Inaugural US Muon Collider Community Meeting  
Fermilab, August 7-9 2024



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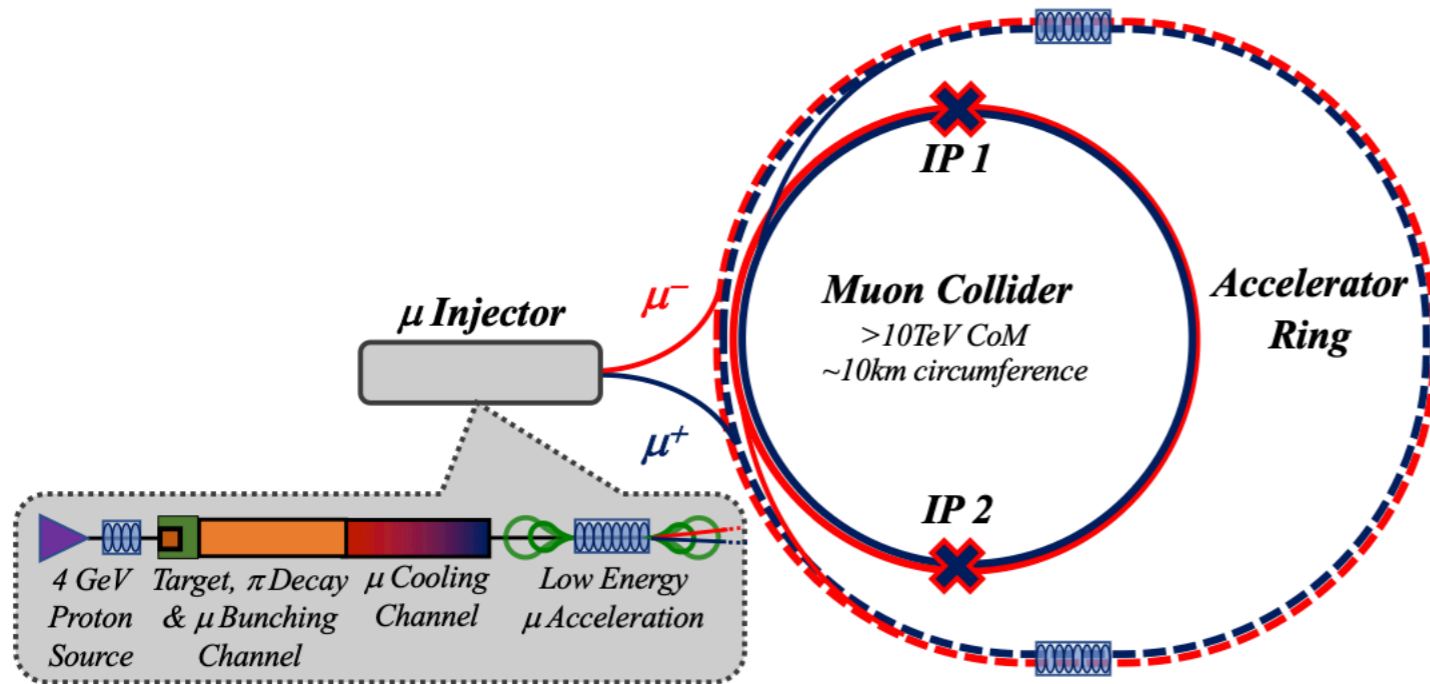
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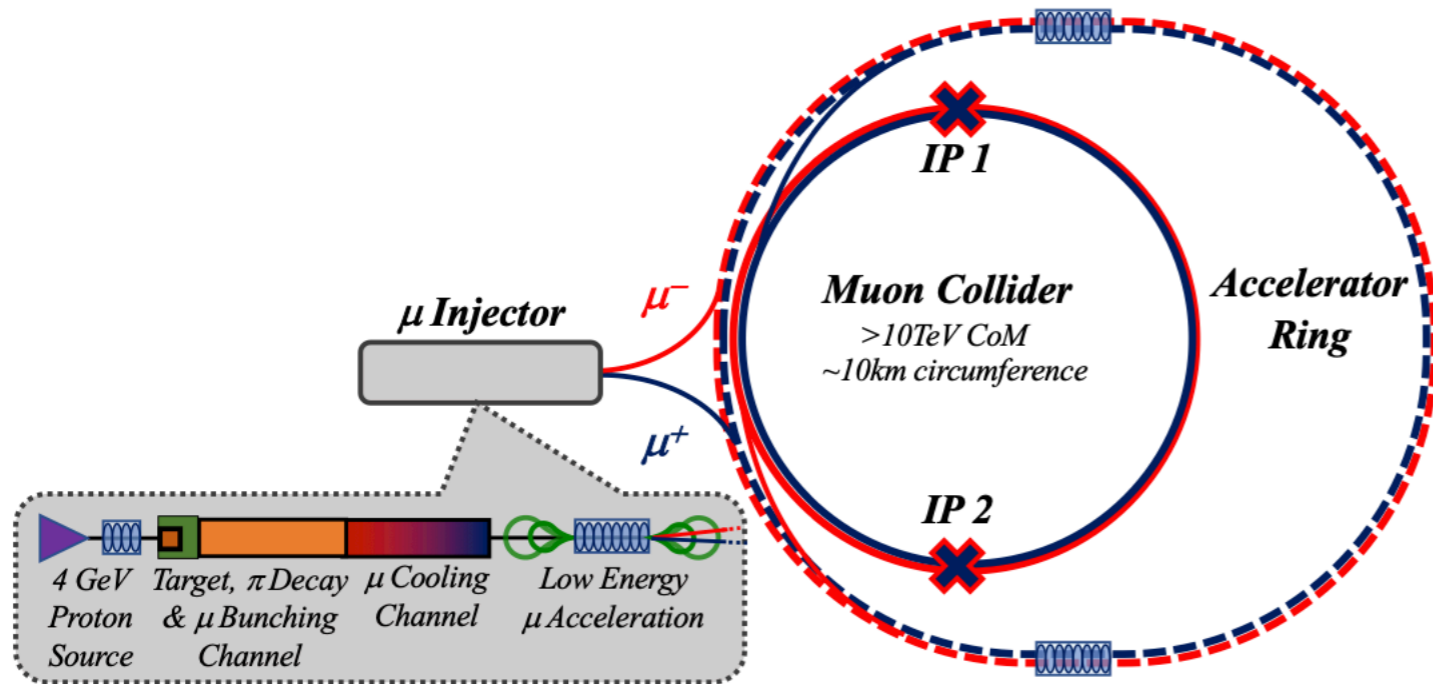
Still some R&D challenges to go before things are "collider-ready", but I'm told are no "showstoppers"

# Not another collider proposal...



**Fig. 1** A conceptual scheme of the muon collider.

# Not another collider proposal...

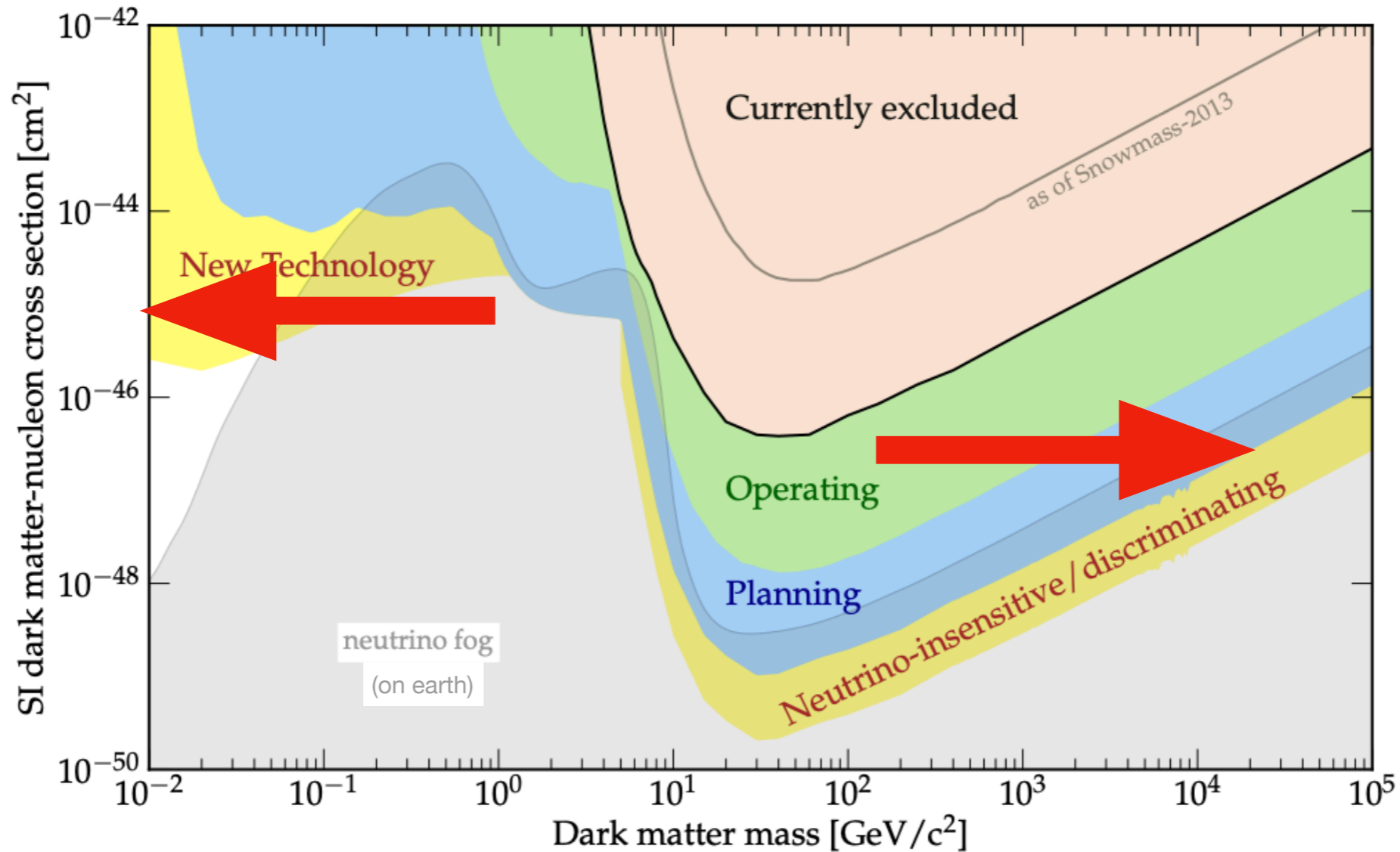


**Fig. 1** A conceptual scheme of the muon collider.

Overall goal is to achieve 10+ TeV energies

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	$E_{cm}$	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	2	20	40
Collider circumference	$C_{coll}$	km	4.5	10	14

# Not another collider proposal...



Snowmass '21 [arXiv:2209.07426](https://arxiv.org/abs/2209.07426) [hep-ph]

A Muon Collider offers almost perfect conditions for fundamental electroweak physics:

- ⇒ WIMP's
- ⇒ Portals
- ⇒ Dark Sectors

# Hunting for thermal targets

Model (color, $n$ , $Y$ )		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3, $\epsilon$ )	Dirac	2.0 TeV
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$SU(3)_C \times SU(2)_L \times U(1)_Y$

$\Omega_{DM}$

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Higgsino

Wino

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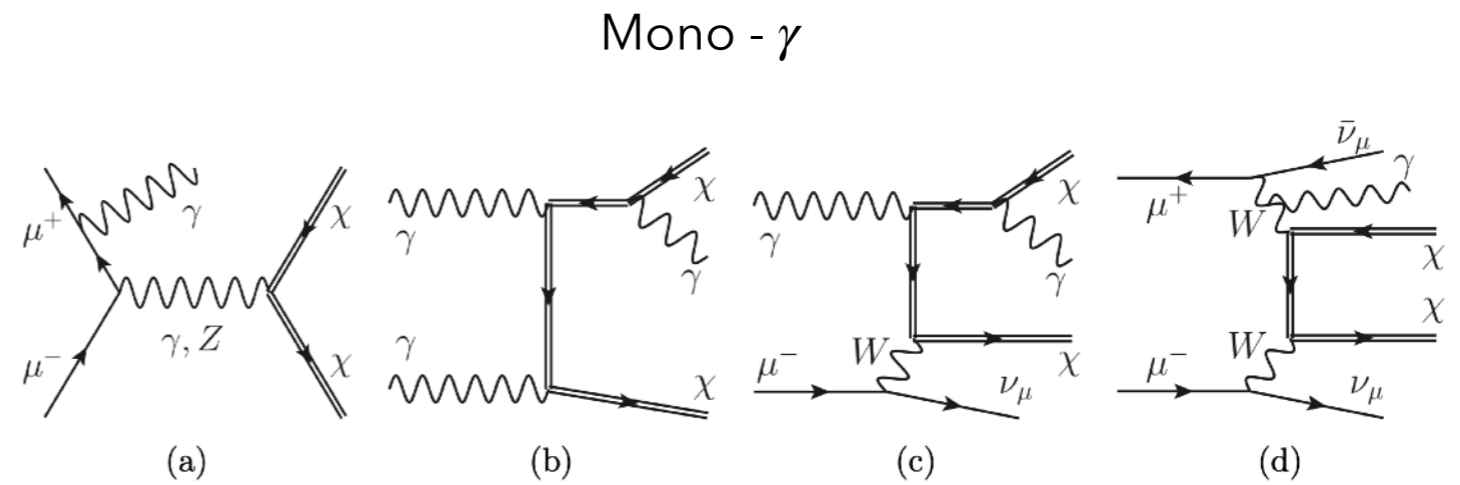
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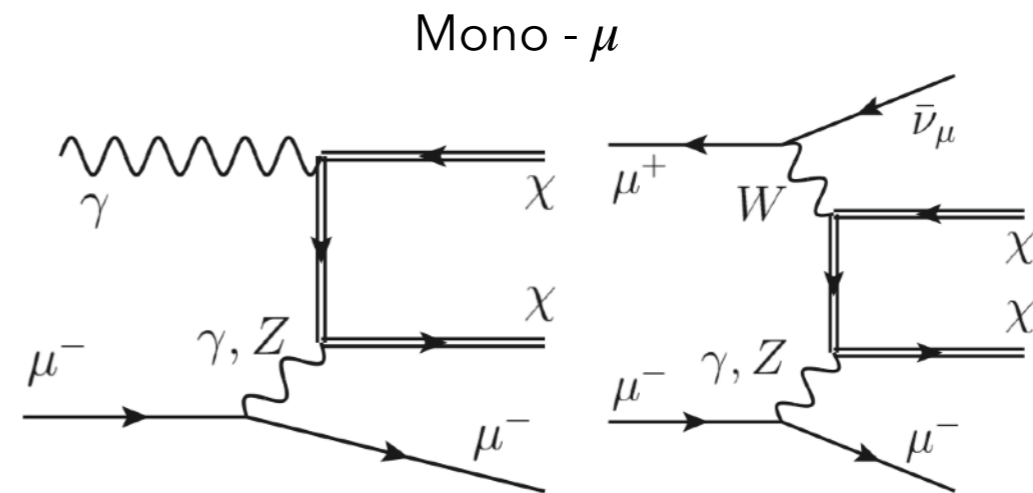
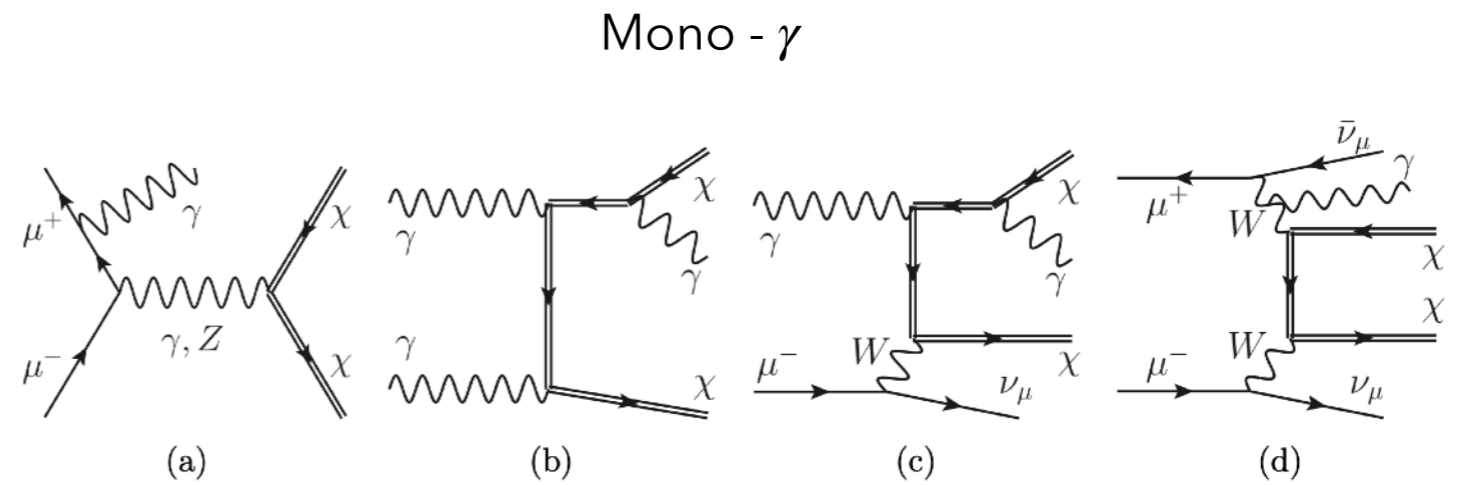


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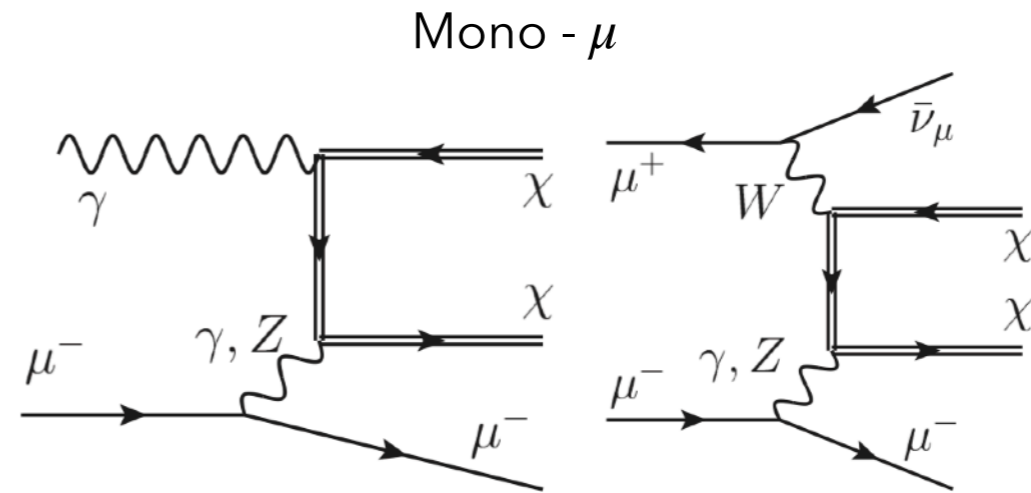
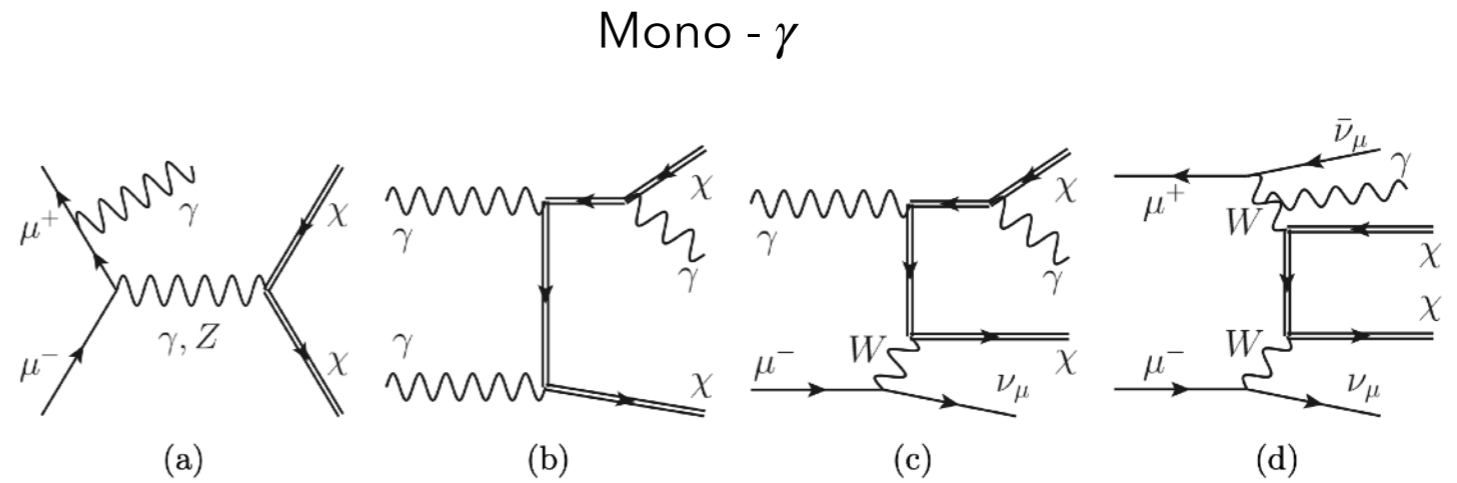


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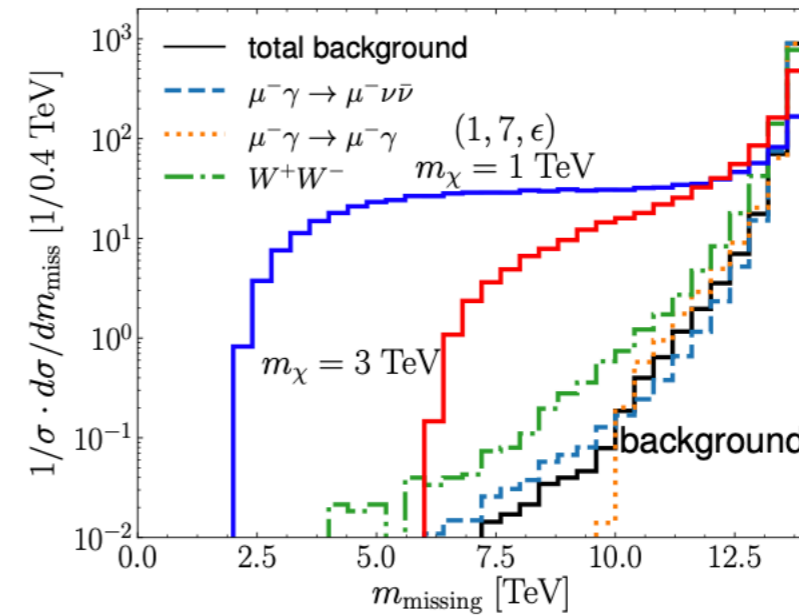
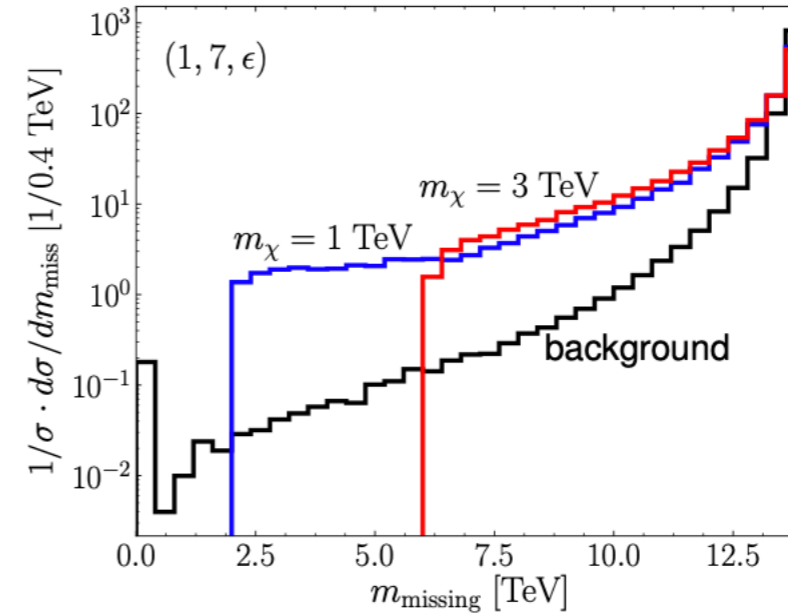
$$m_{\text{missing}}^2 \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$

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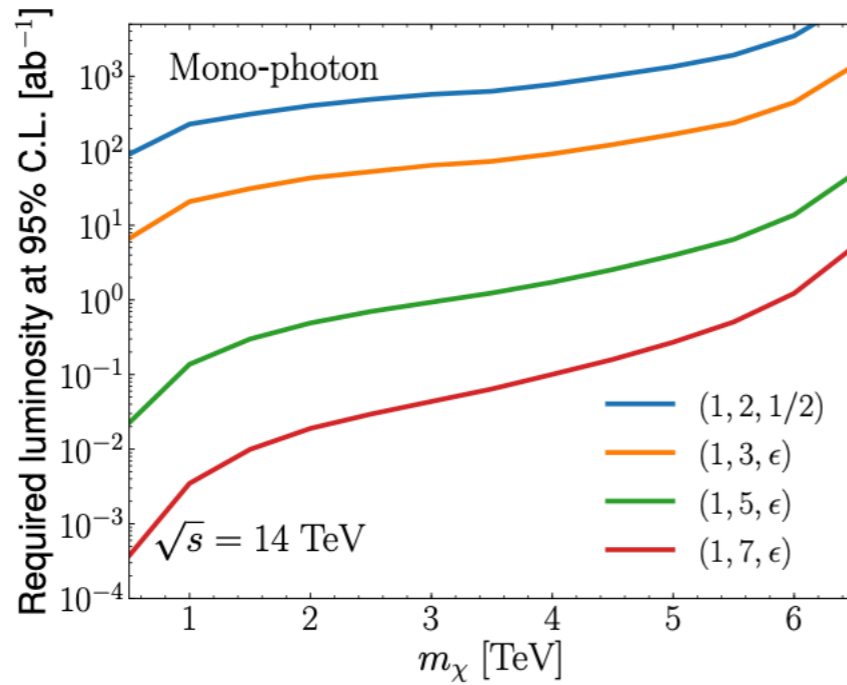


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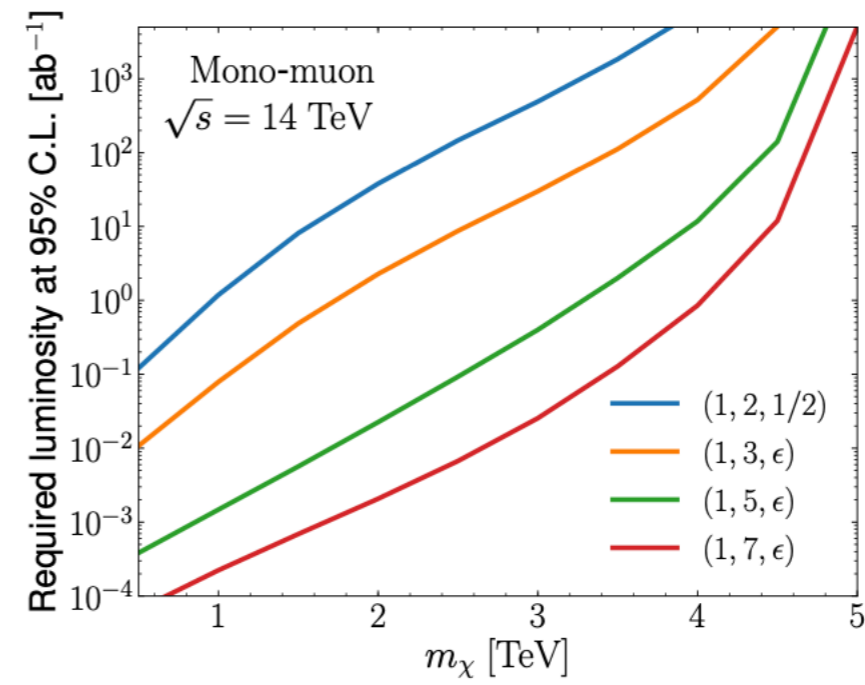
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$(1, 3, 0)$	
$(1, 3, \epsilon)$	
$(1, 5, 0)$	
$(1, 5, \epsilon)$	
$(1, 7, 0)$	
$(1, 7, \epsilon)$	

$SU(3)_C \times SU(2)_L \times$



(a)



(b)

**Figure 5:** Integrated luminosities needed for (a) mono-photon and (b) mono-muon channels, to reach  $2\sigma$  statistical significance at  $\sqrt{s} = 14$  TeV.

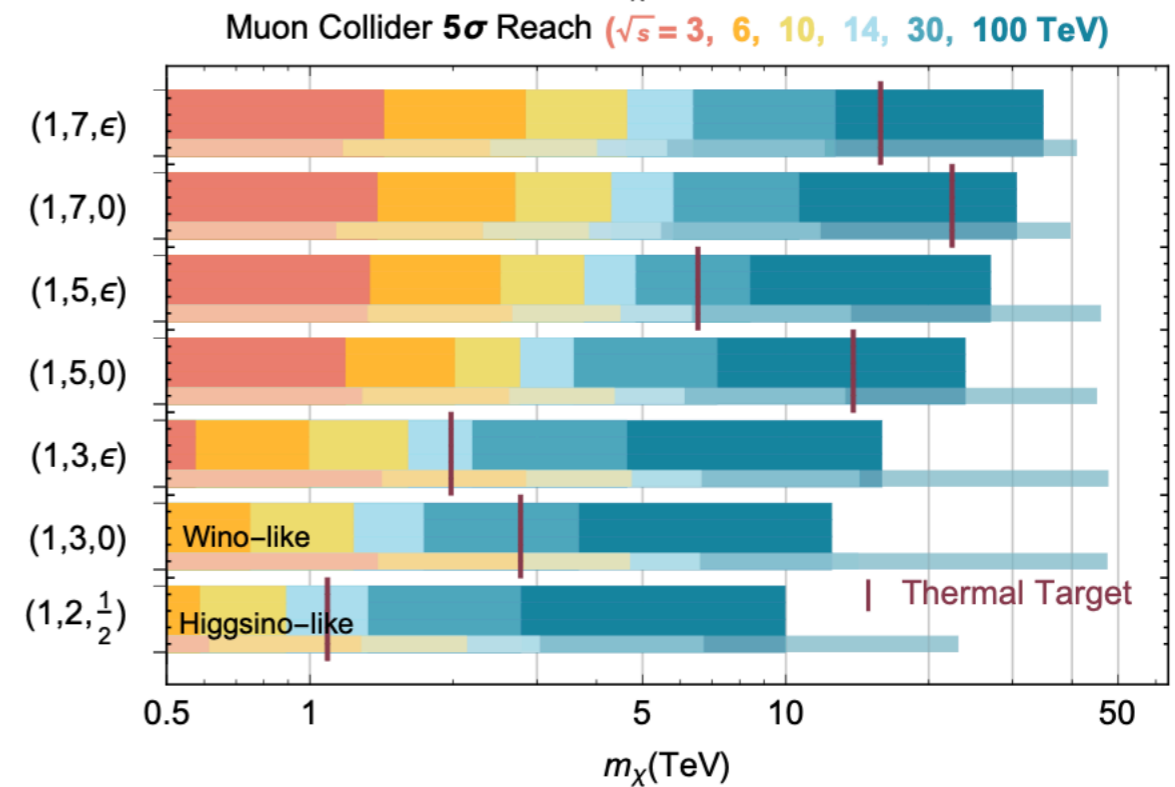
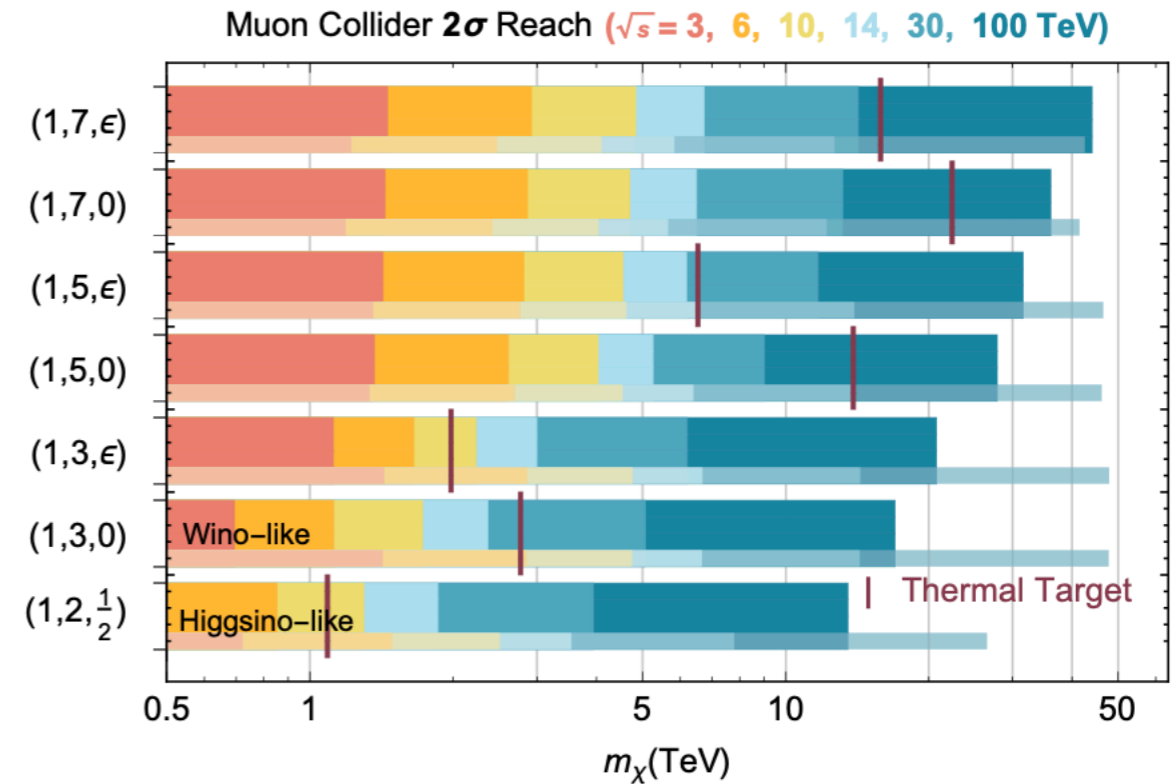
$$N_{\text{SD}} = \frac{S}{\sqrt{S + B + (\epsilon_S S)^2 + (\epsilon_B B)^2}},$$

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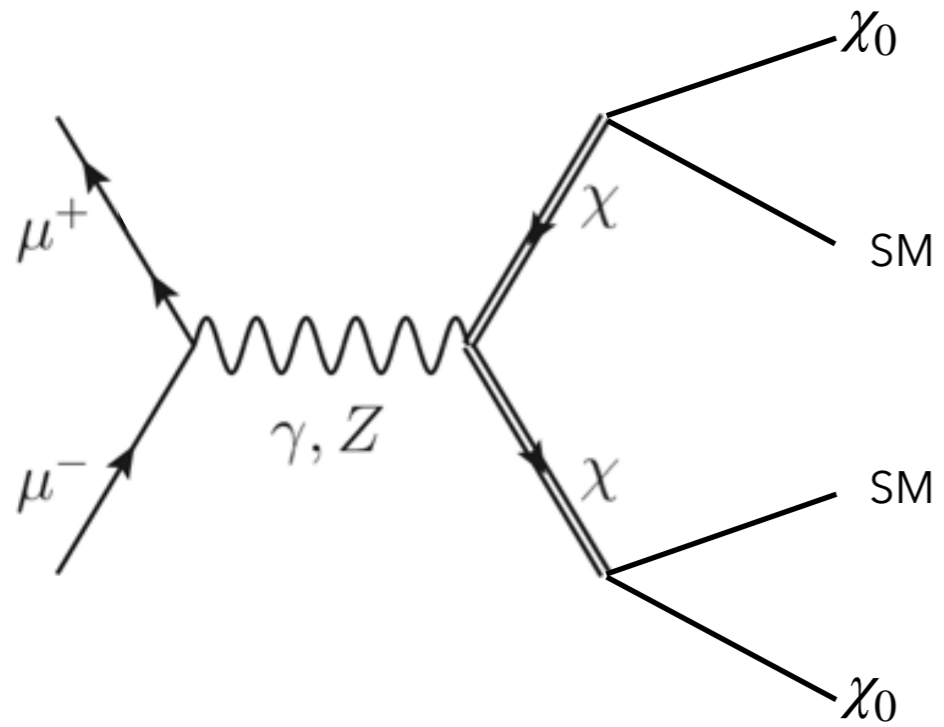
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$\Omega_0$



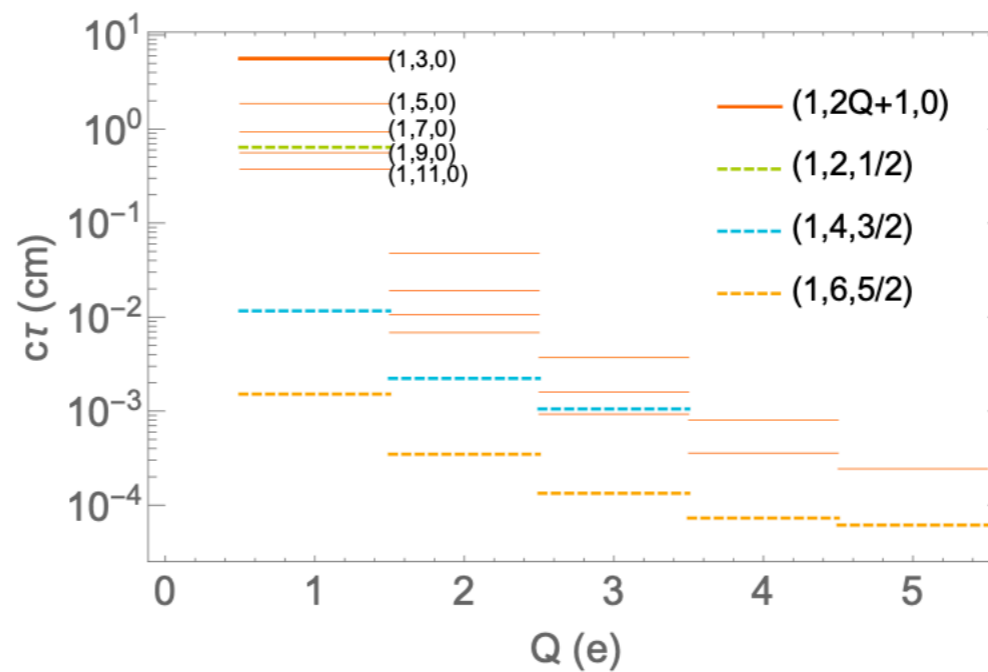
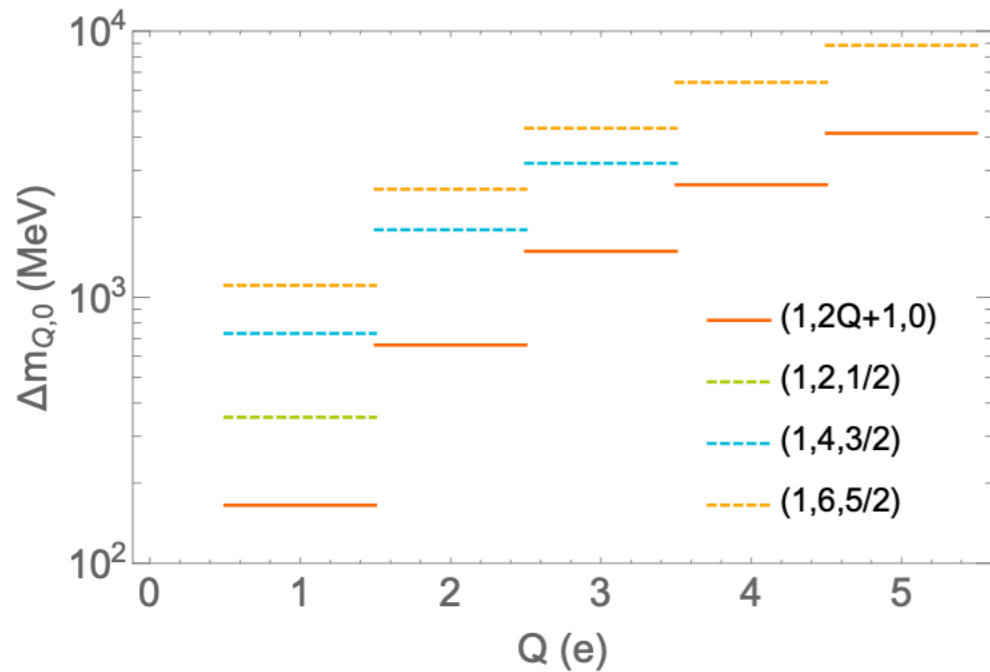
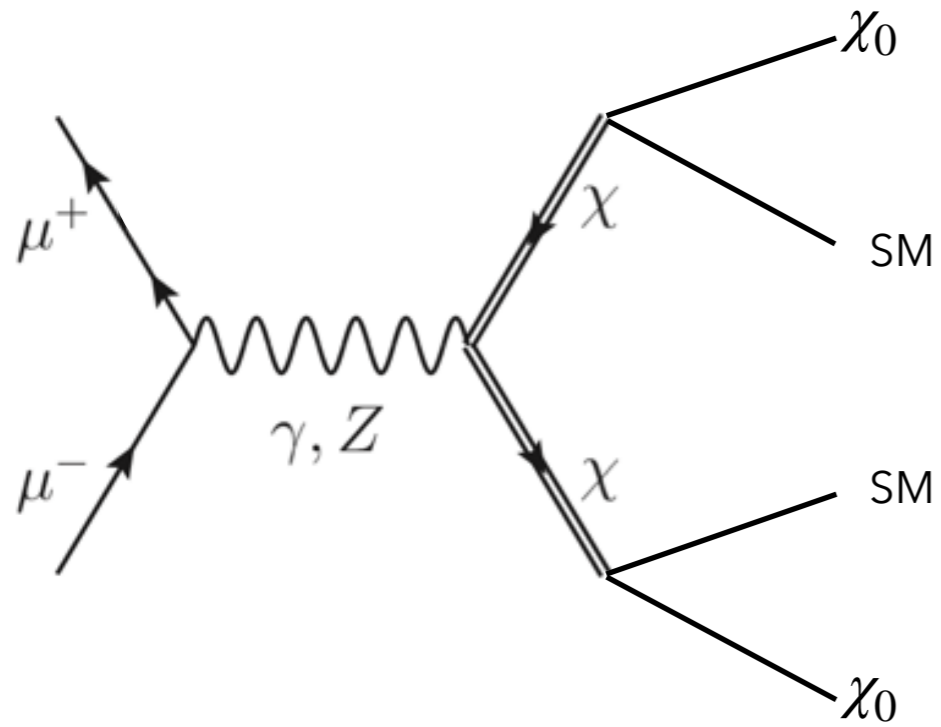
# Hunting for thermal targets



R. Capdevilla, F. Meloni, R. Simoniella, J. Zurita: *JHEP* 06 (2021) 133

T. Han, Z. Liu, LT. Wang, X. wang: *Phys. Rev. D* 103, 075004 (2021)

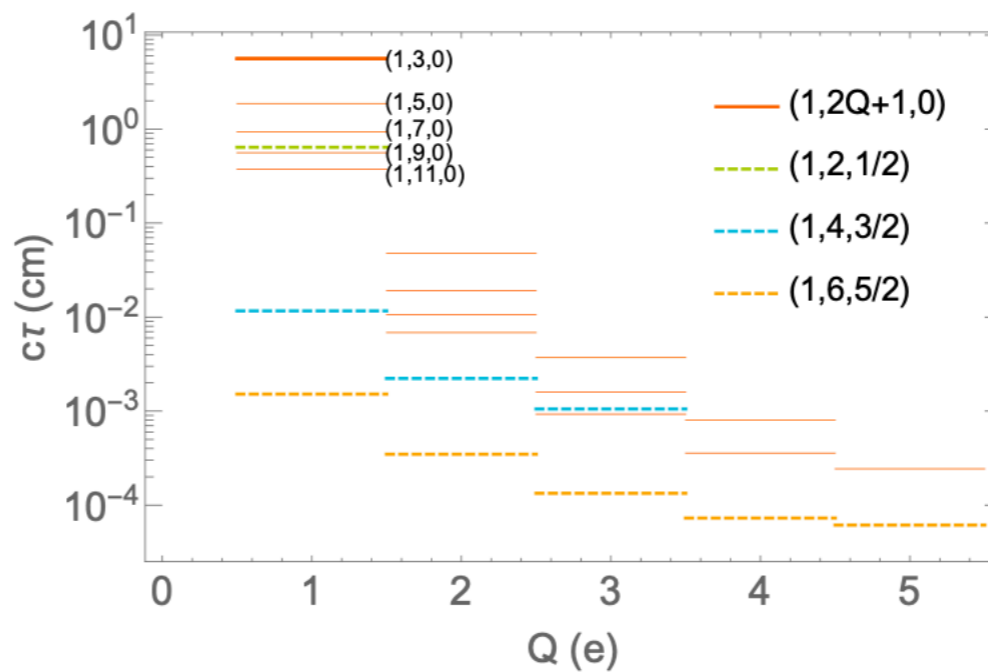
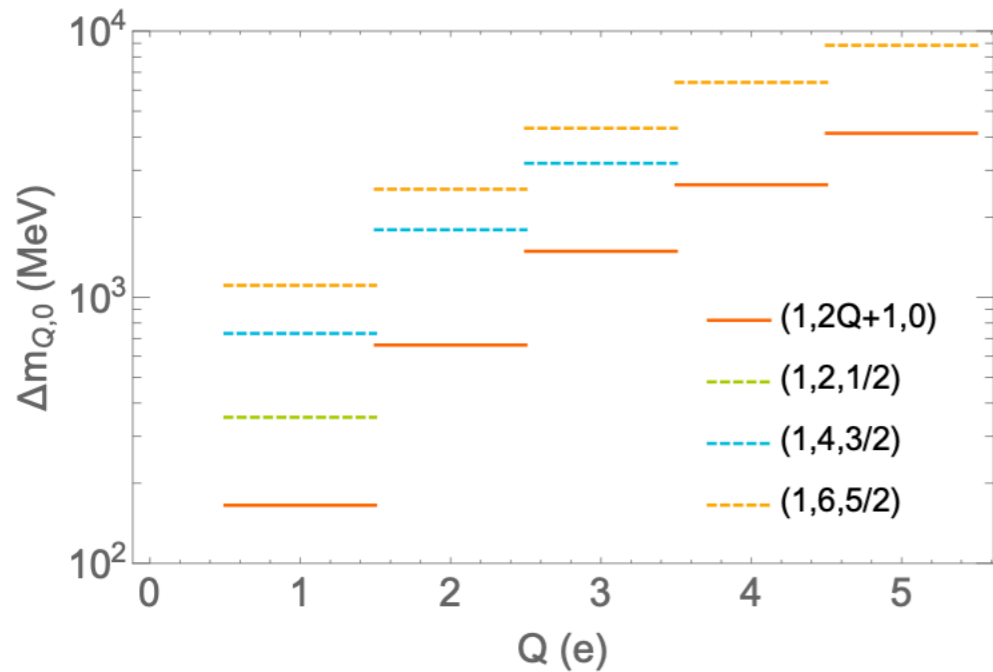
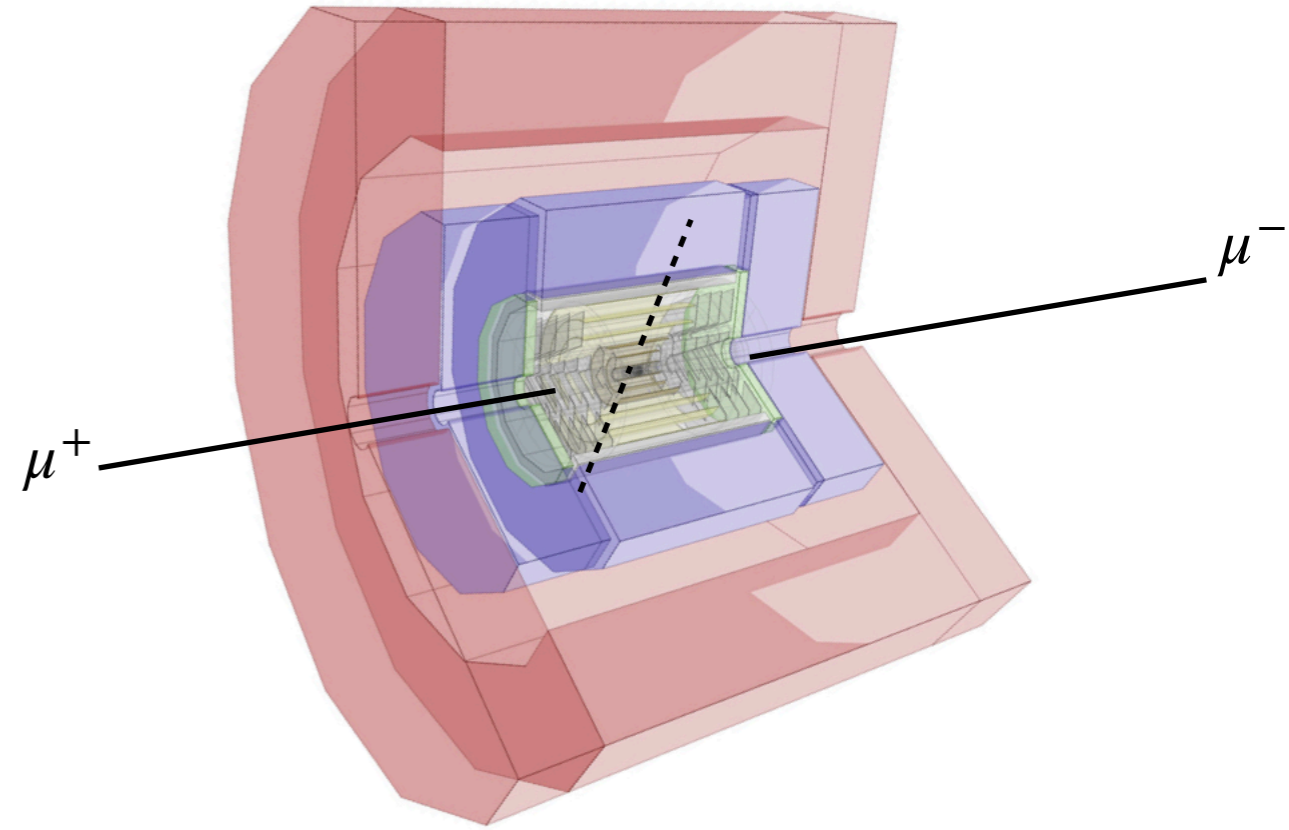
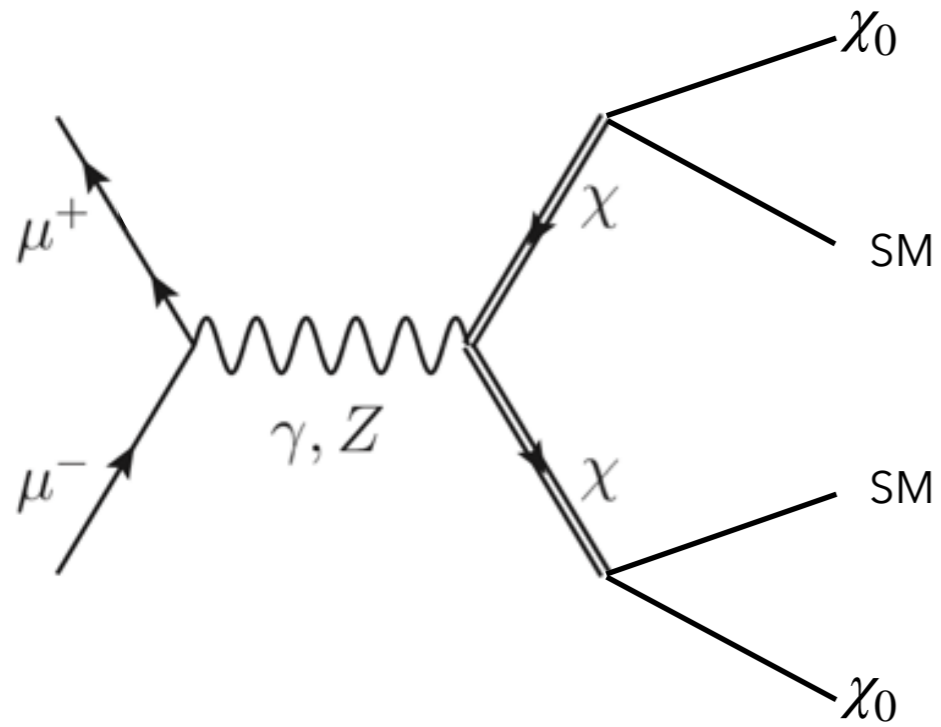
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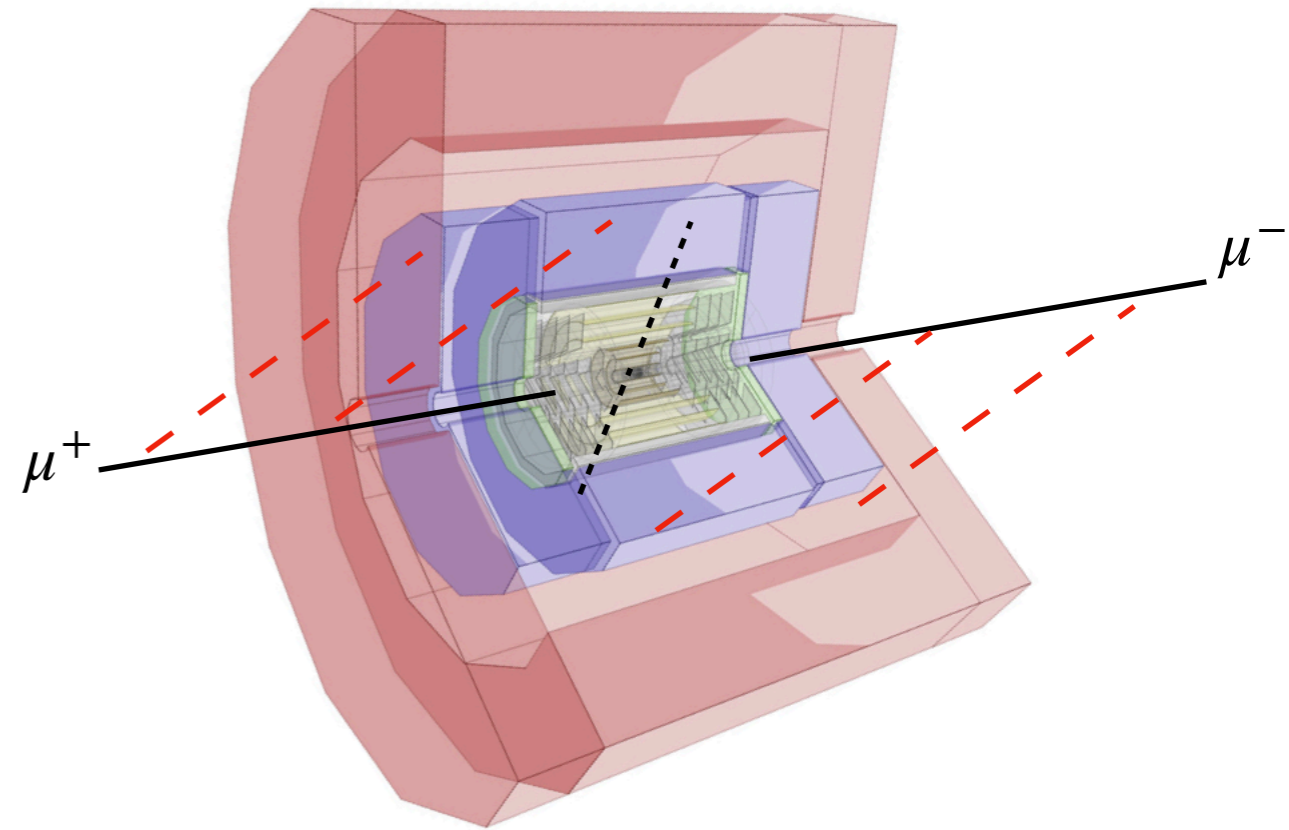


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- For DM studies, BIB could be significant source of background
- Need careful simulation when considering soft-particles/LLPs
- Timing and spatial information between detector layers helps distinguish particles that originated from central collision region

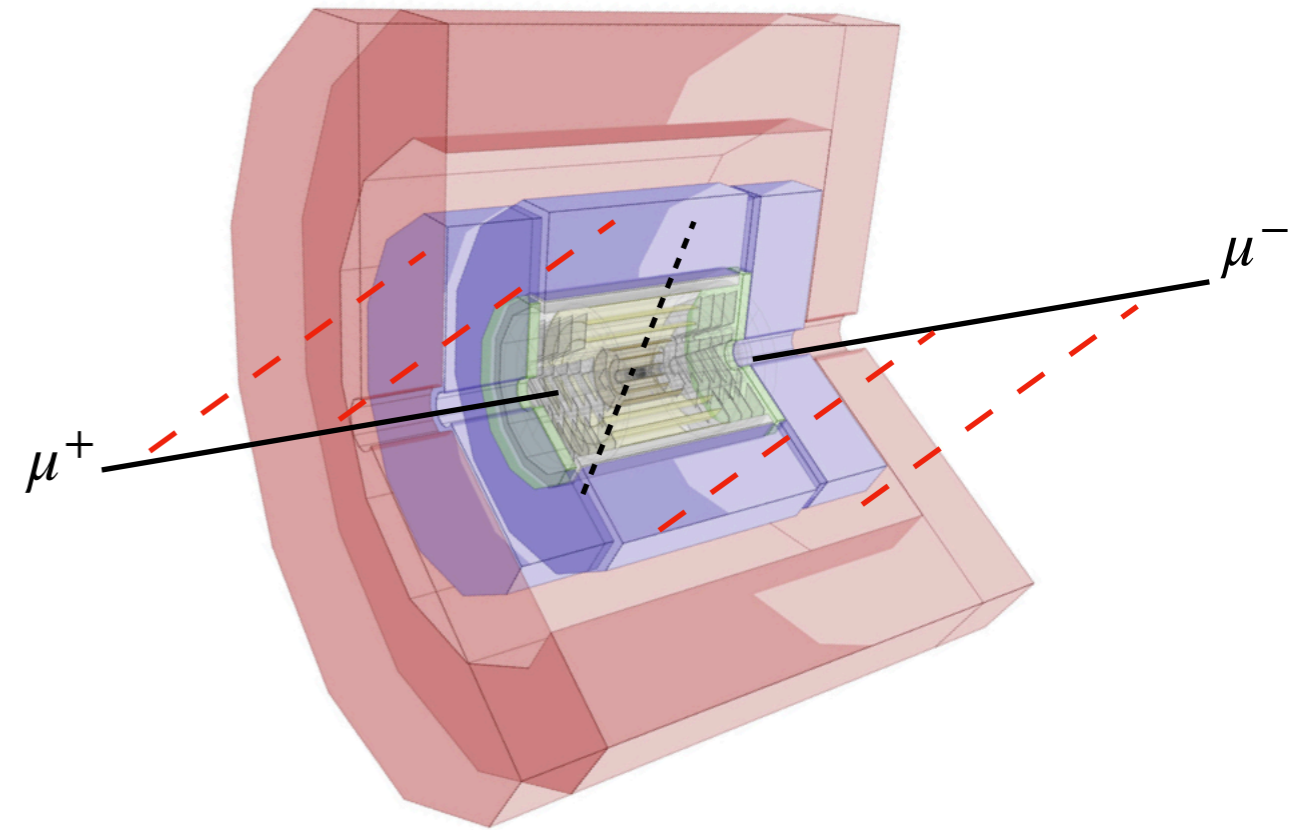


Det sim based on SiD ILC concept

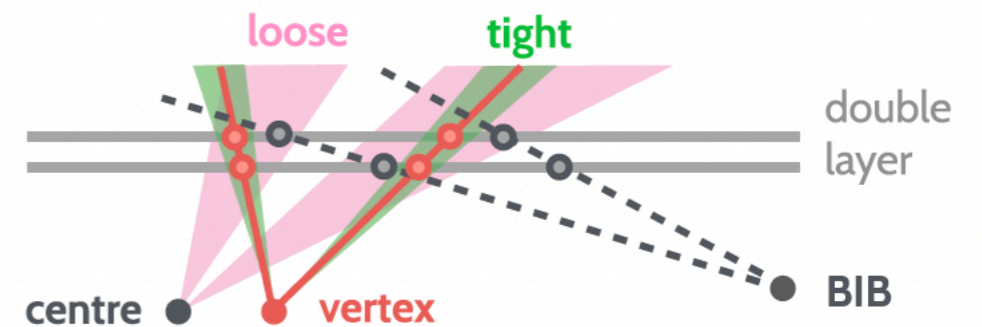


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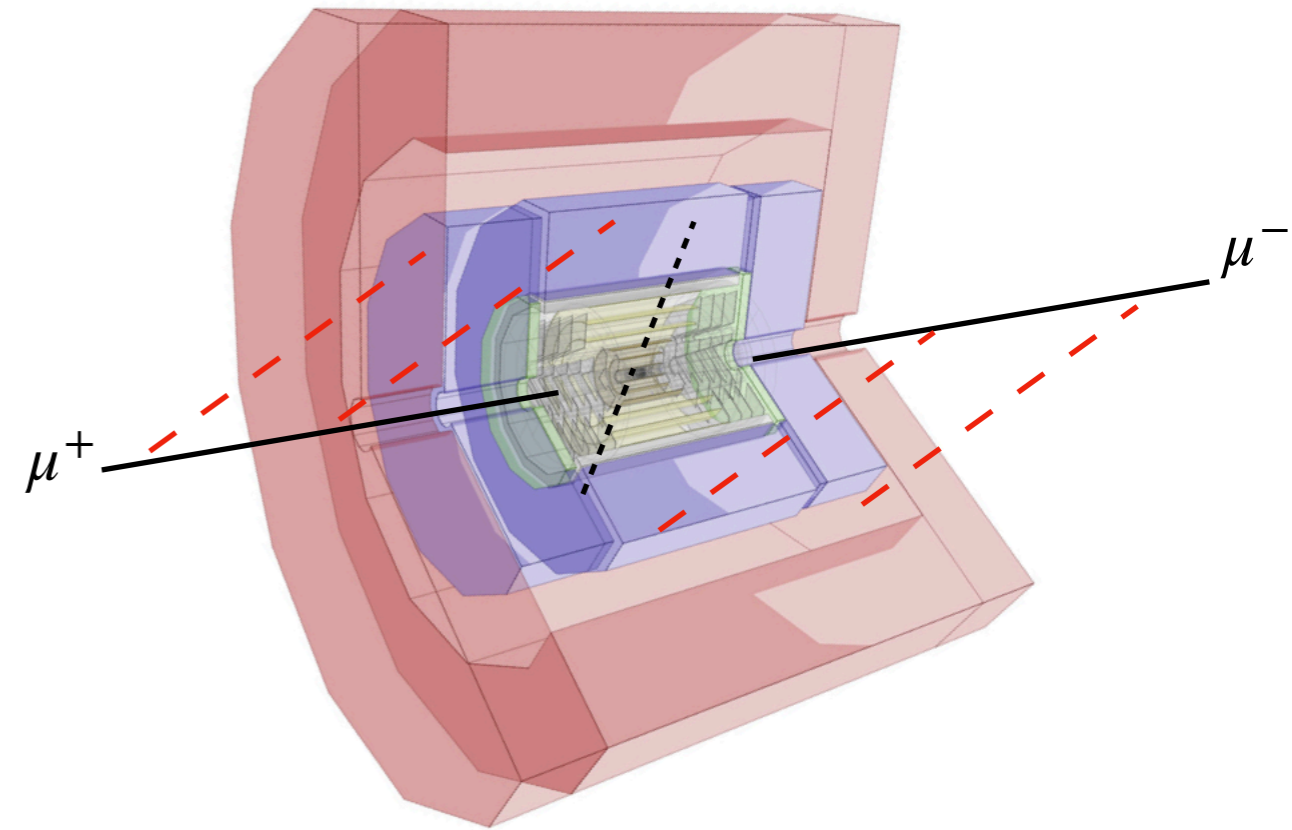
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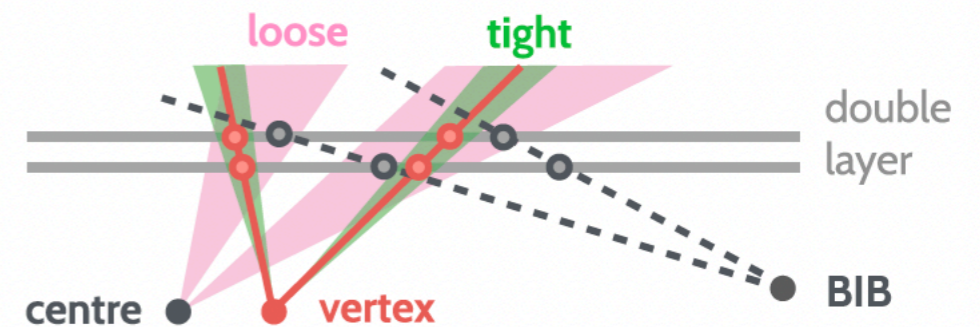
*Comput.Softw.Big Sci.* 5 (2021) 1, 21

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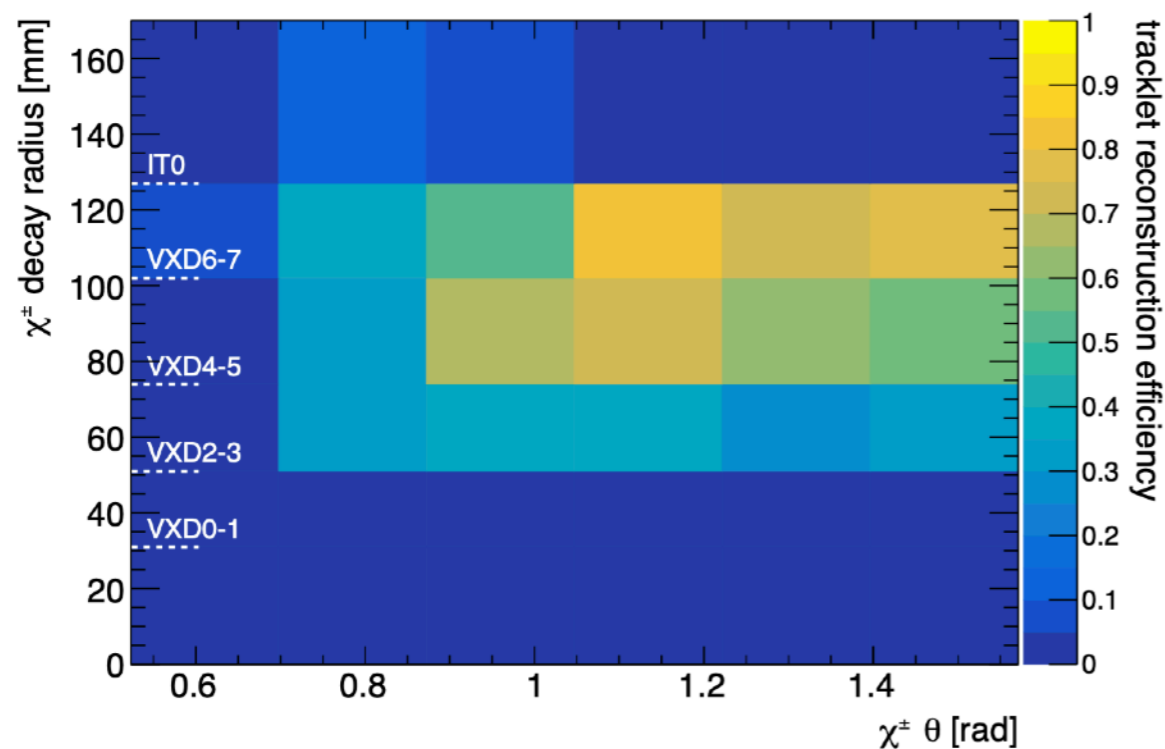
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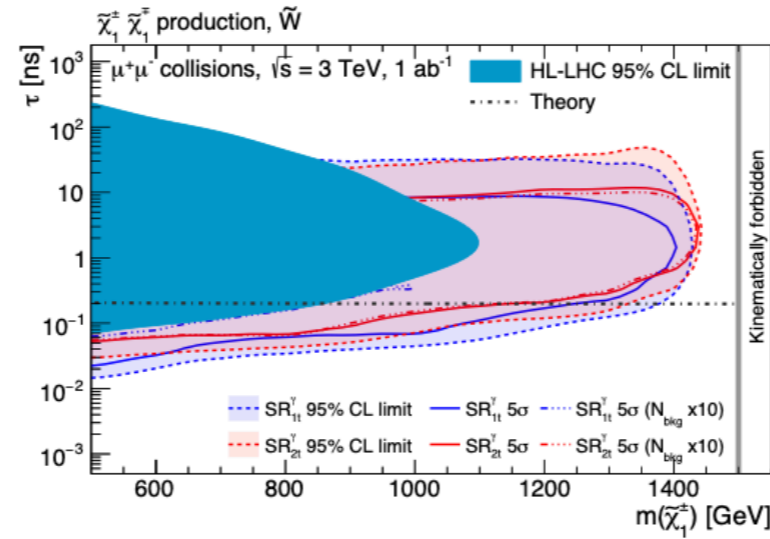
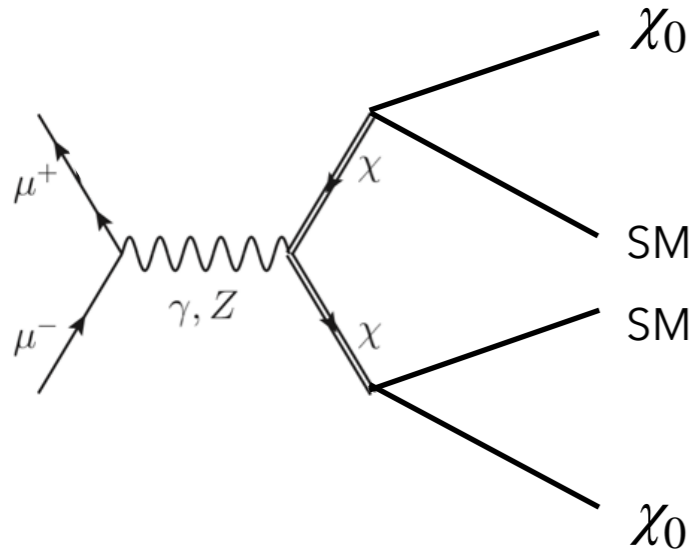
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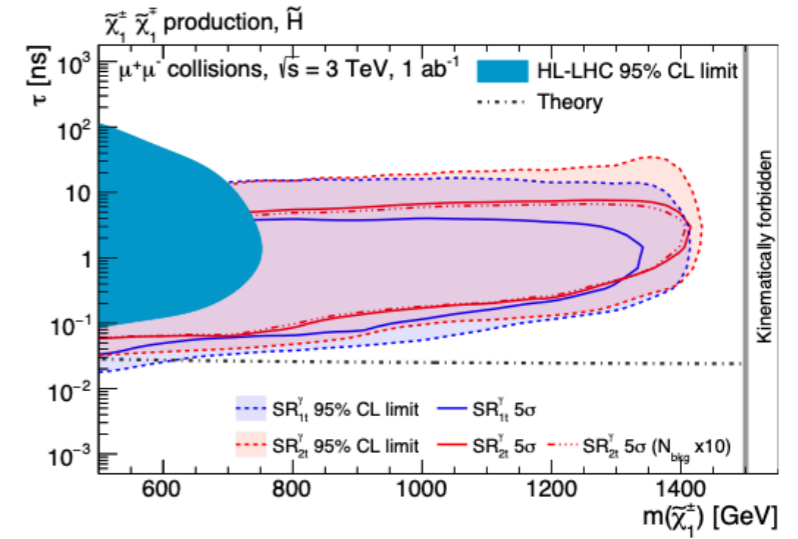
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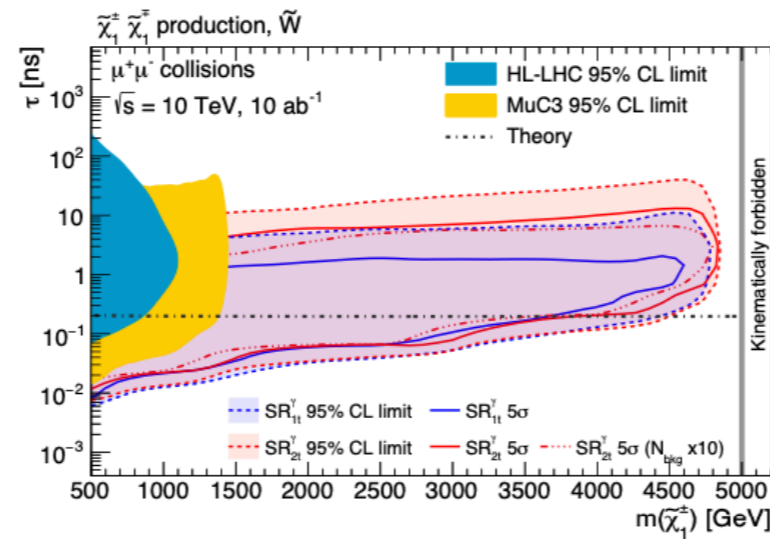
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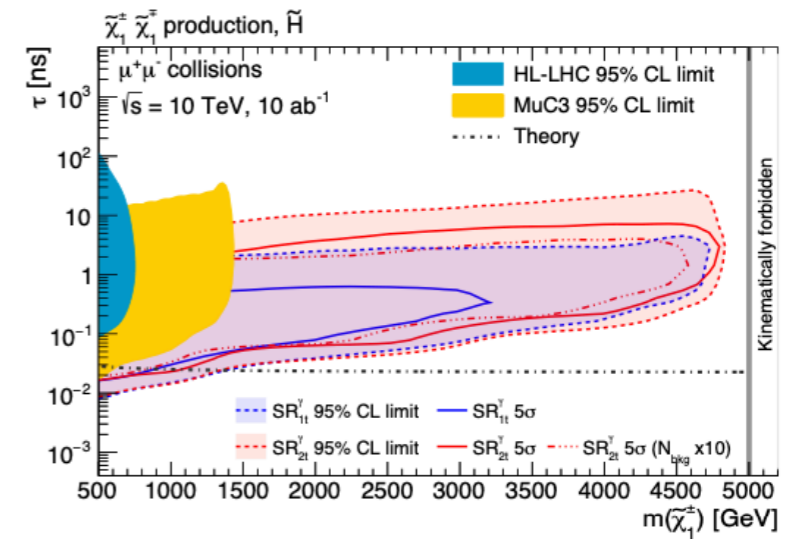
(a)



(b)



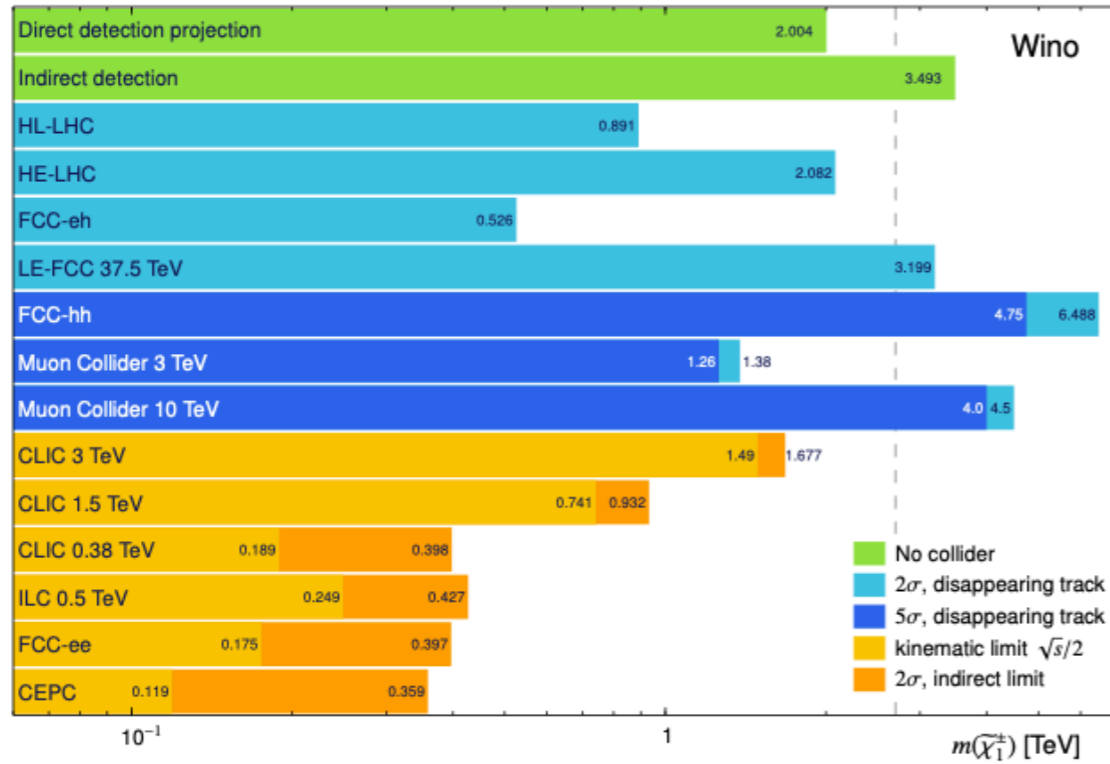
(c)



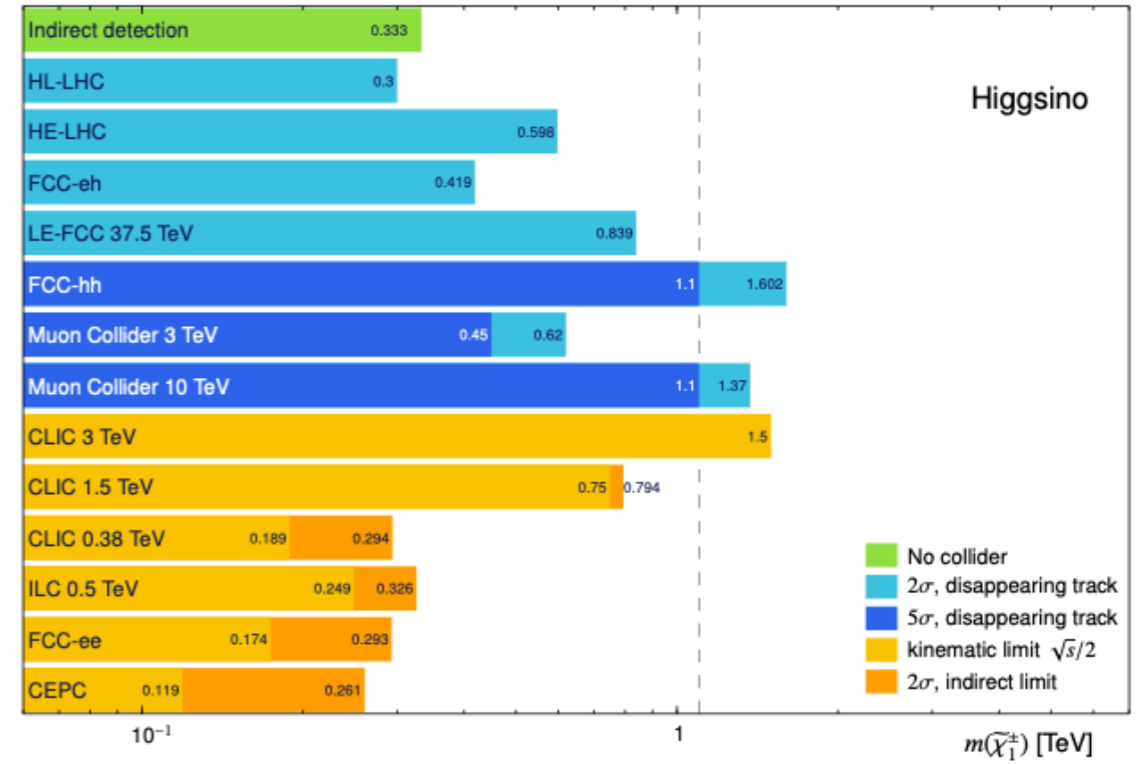
(d)

**Figure 14:** Expected sensitivity using  $1 \text{ ab}^{-1}$  of 3 TeV or  $10 \text{ ab}^{-1}$  of 10 TeV  $\mu^+\mu^-$  collision data as a function of the  $\tilde{\chi}^\pm$  mass and lifetime.

# WIMP Summary

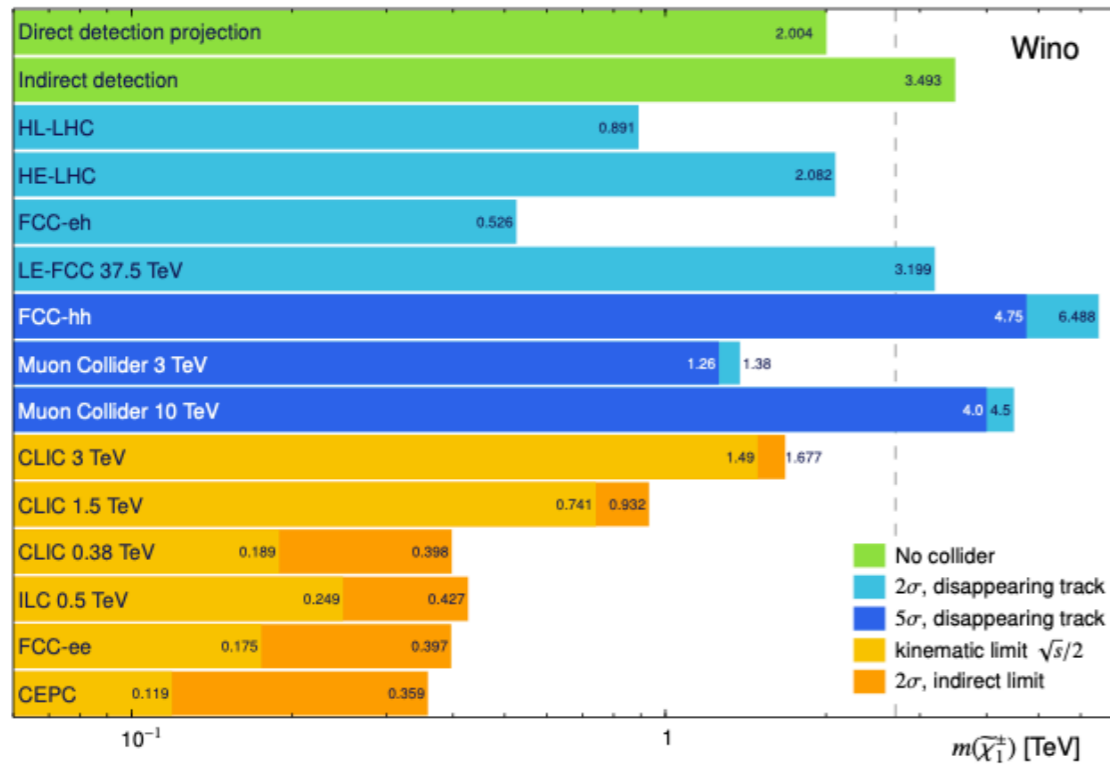


**Figure 17:** Summary of the sensitivity to pure wino models at future experimental facilities. The results for other facilities are taken from Refs. [18, 62].

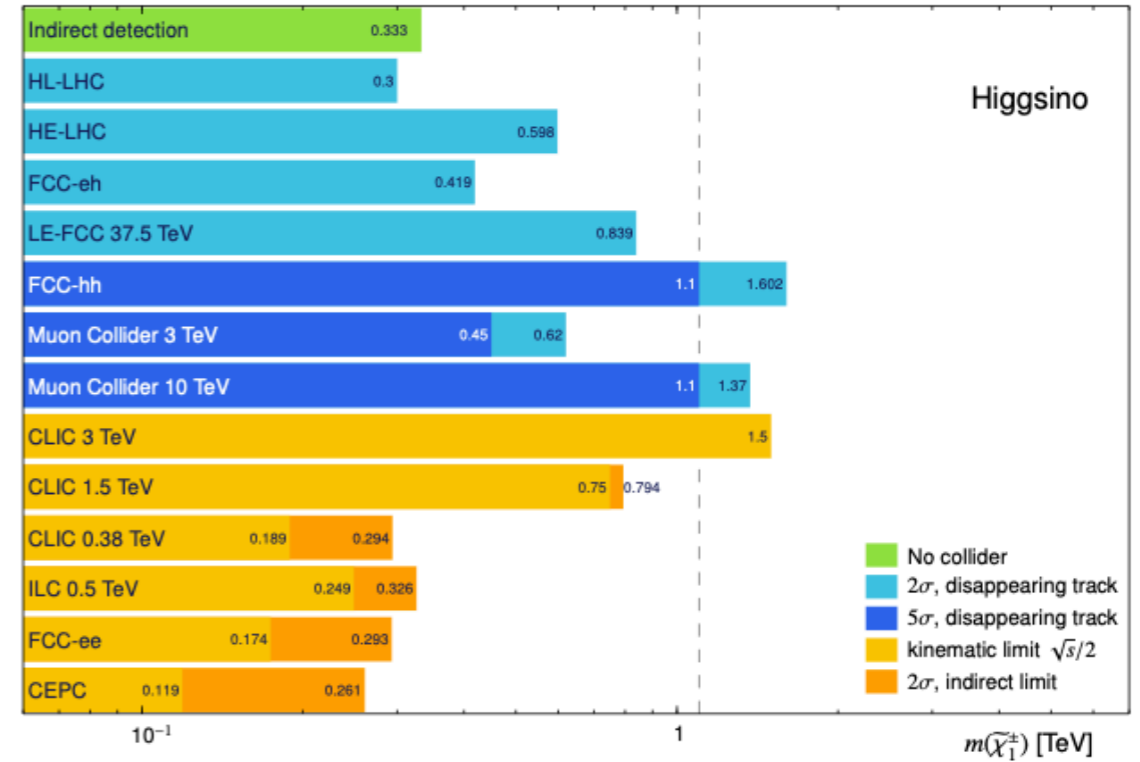


**Figure 18:** Summary of the sensitivity to pure higgsino models at future experimental facilities. The results for other facilities are taken from Refs. [18, 62].

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10 TeV MC already performs ~comparably to FCC-hh

# Dark Sectors

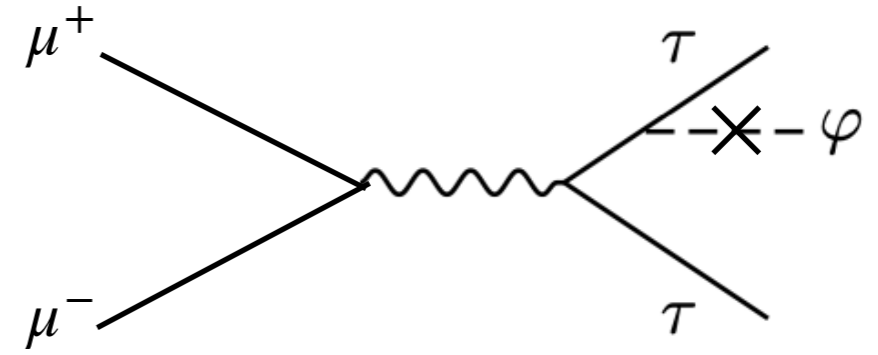


# Dark Sectors

$$\mathcal{L} \supset \begin{cases} (\mu\phi + \lambda\phi^2)H^\dagger H, \\ A'_{\mu\nu}F^{\mu\nu}, \\ \lambda_N \bar{L}HN, \\ a\tilde{F}_{\mu\nu}F^{\mu\nu} \end{cases}$$

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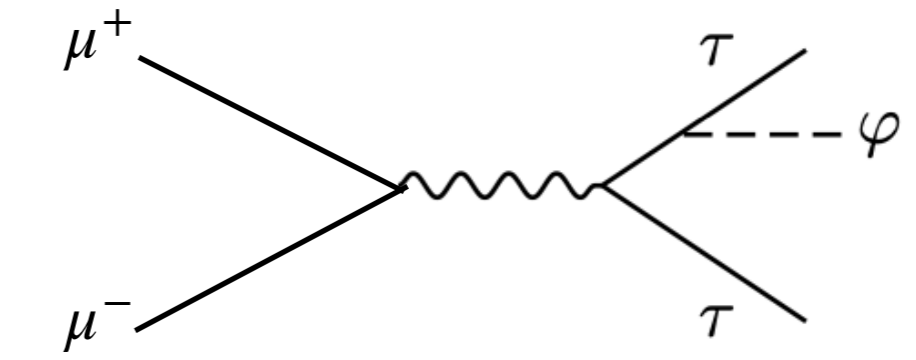


$$\mu^+\mu^- \rightarrow X\varphi \rightarrow X\cancel{E}$$



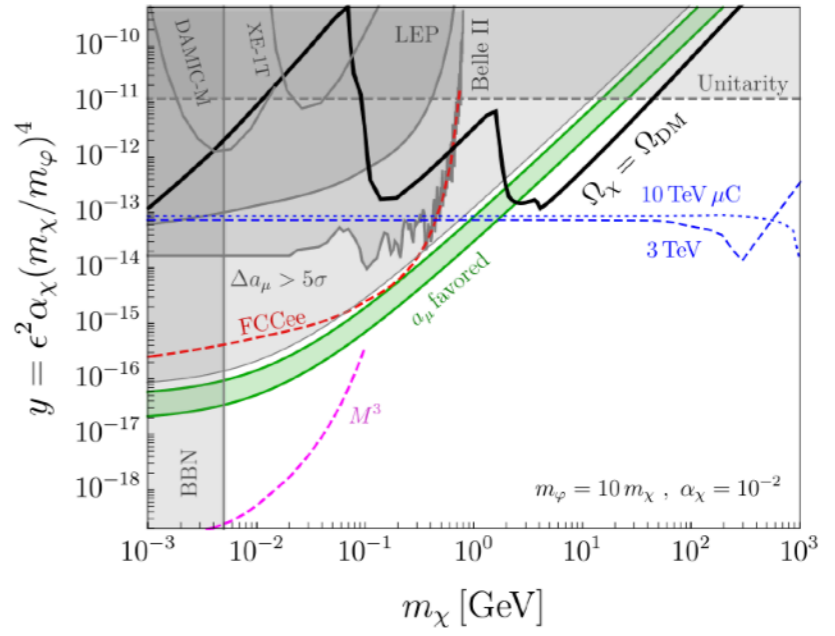
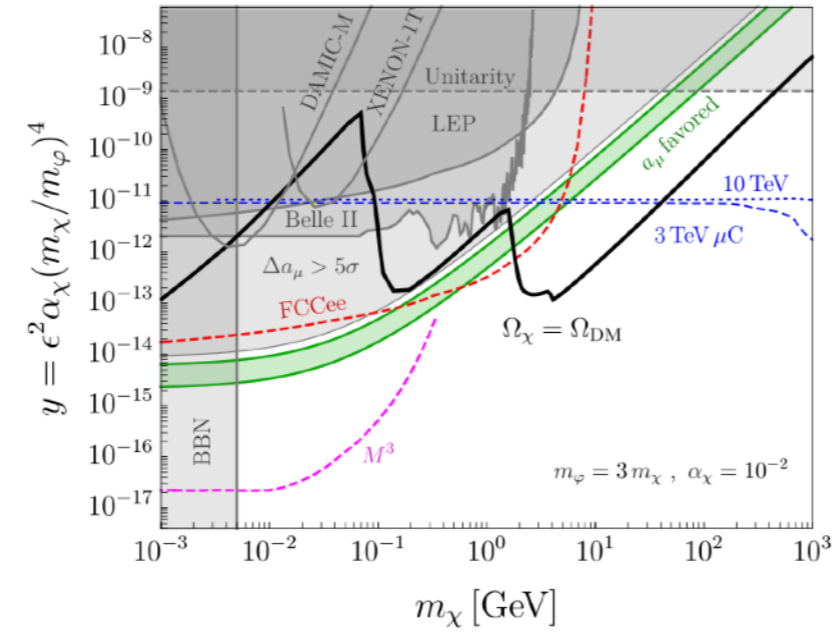
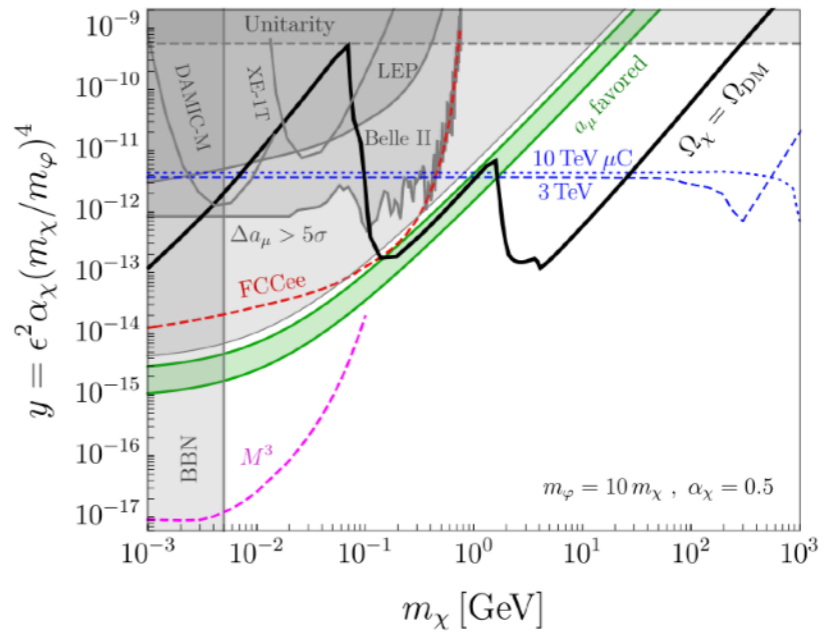
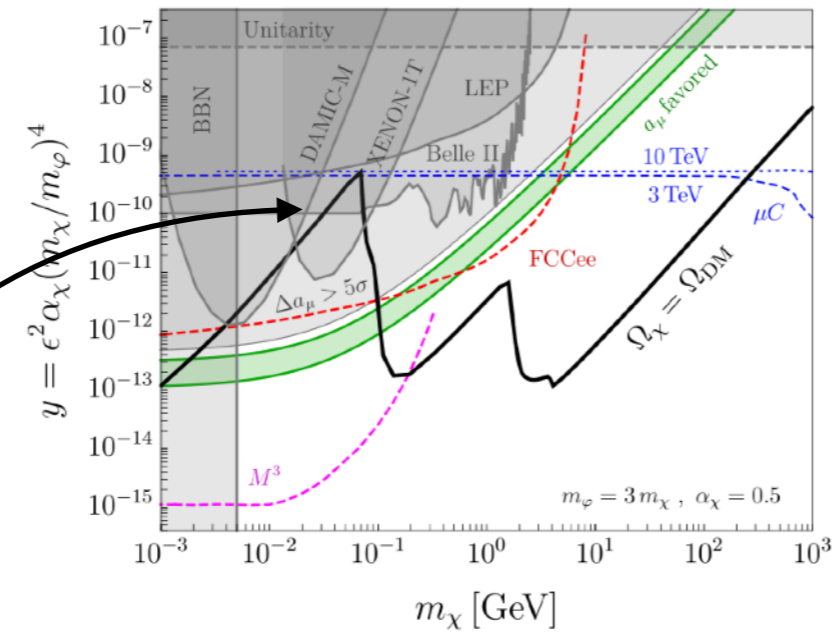
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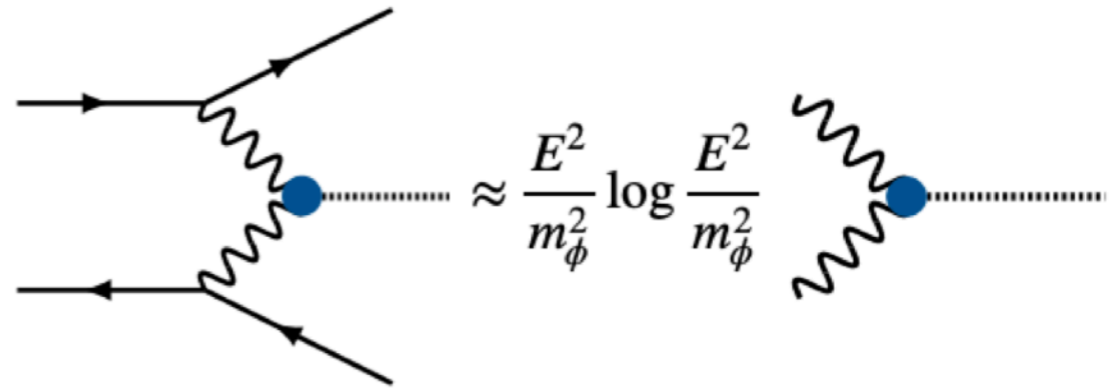
Assuming freezeout

$$\chi\chi \rightarrow \phi \rightarrow l^+l^-$$



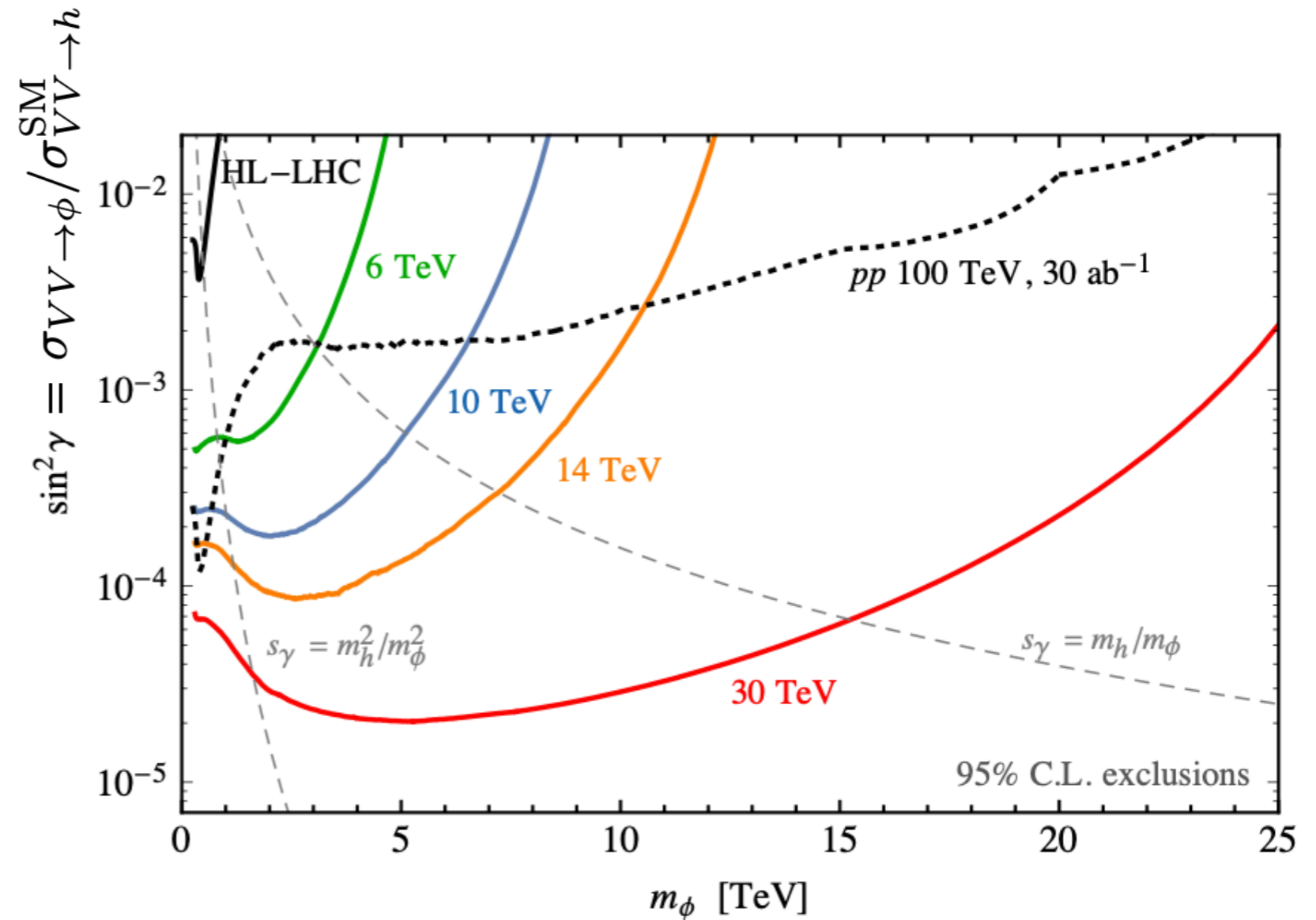
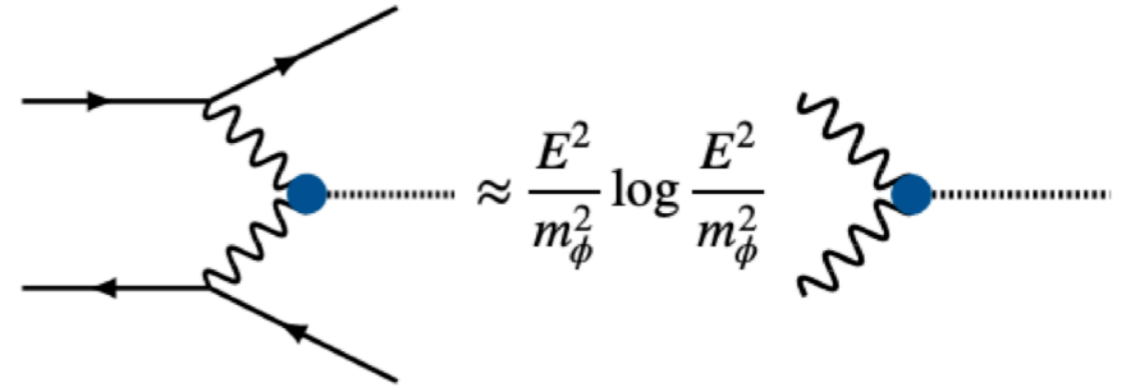
# Dark Sectors

$$\mathcal{L} \supset \begin{cases} (\mu\phi + \lambda\phi^2)H^\dagger H, \\ A'_{\mu\nu}F^{\mu\nu}, \\ \lambda_N \bar{L}HN, \\ a\tilde{F}_{\mu\nu}F^{\mu\nu} \end{cases}$$



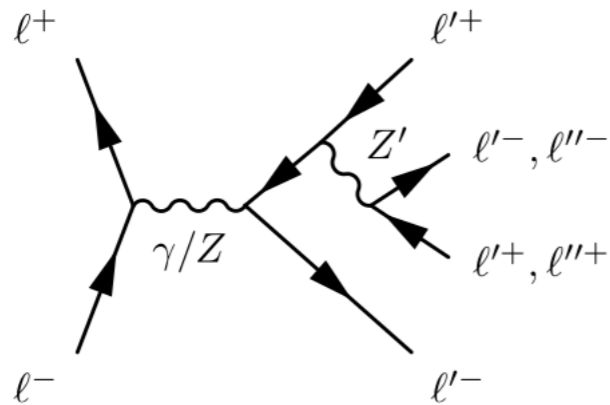
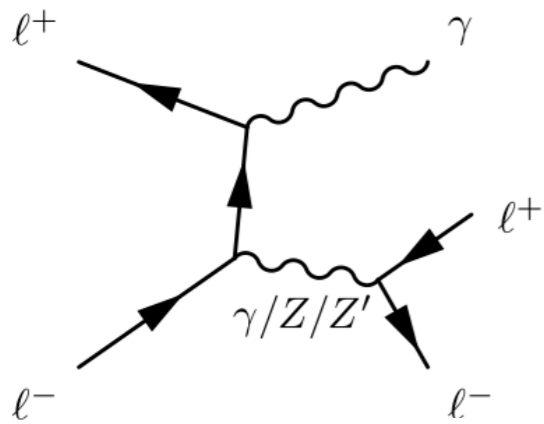
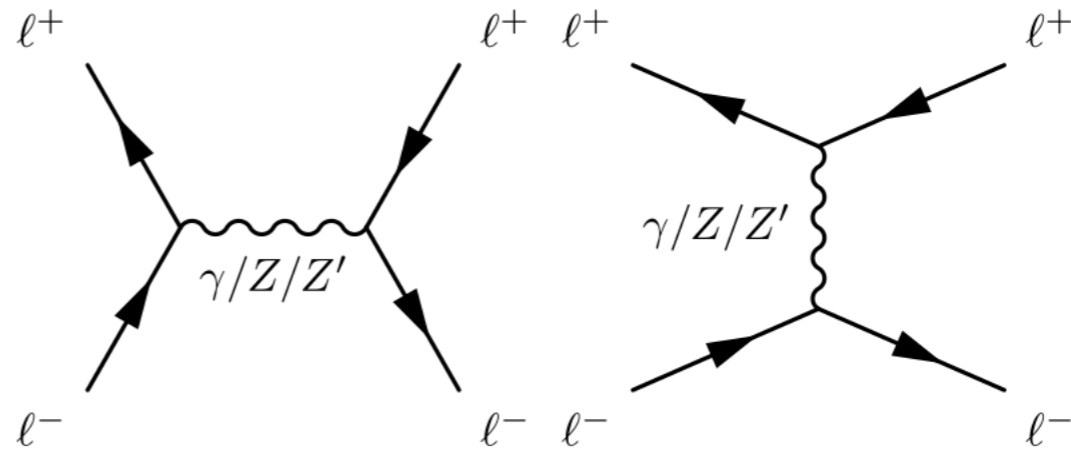
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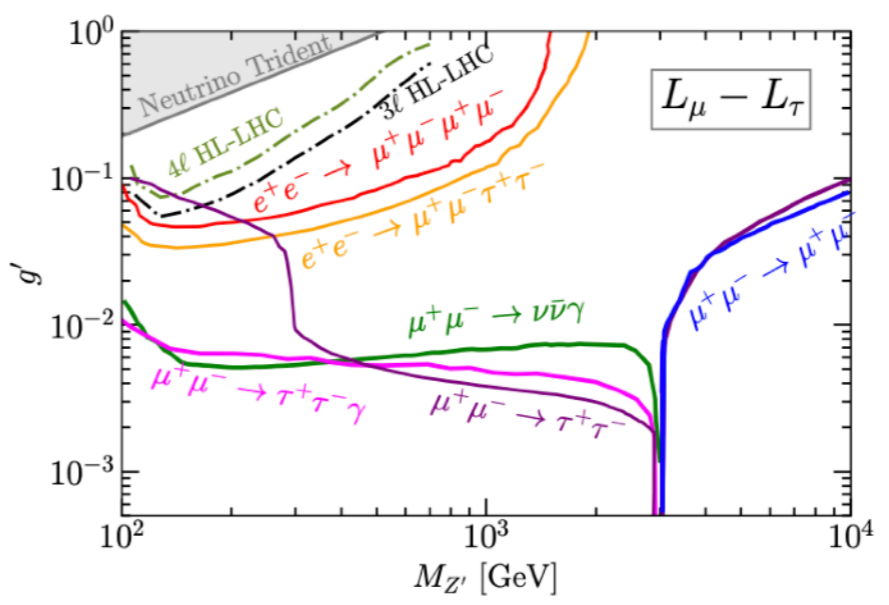
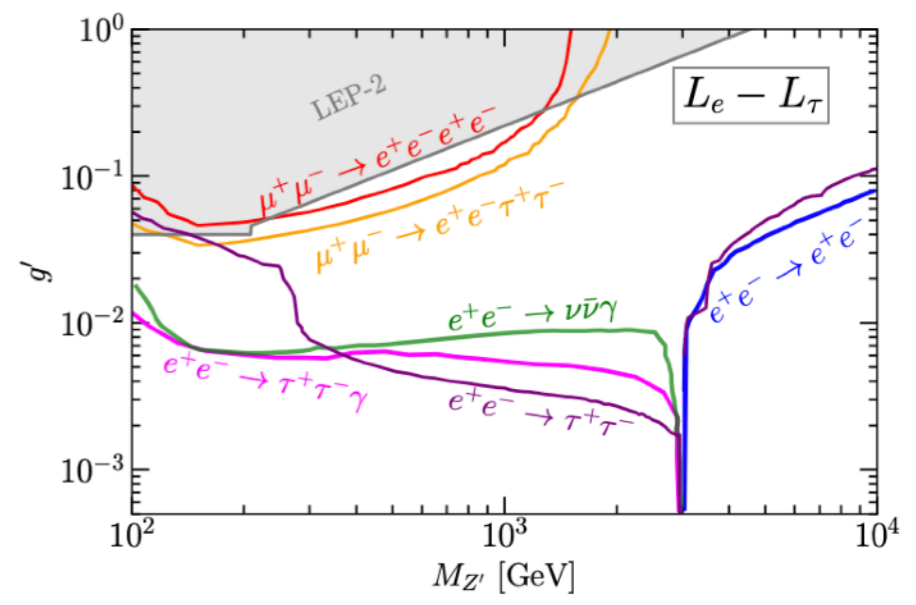
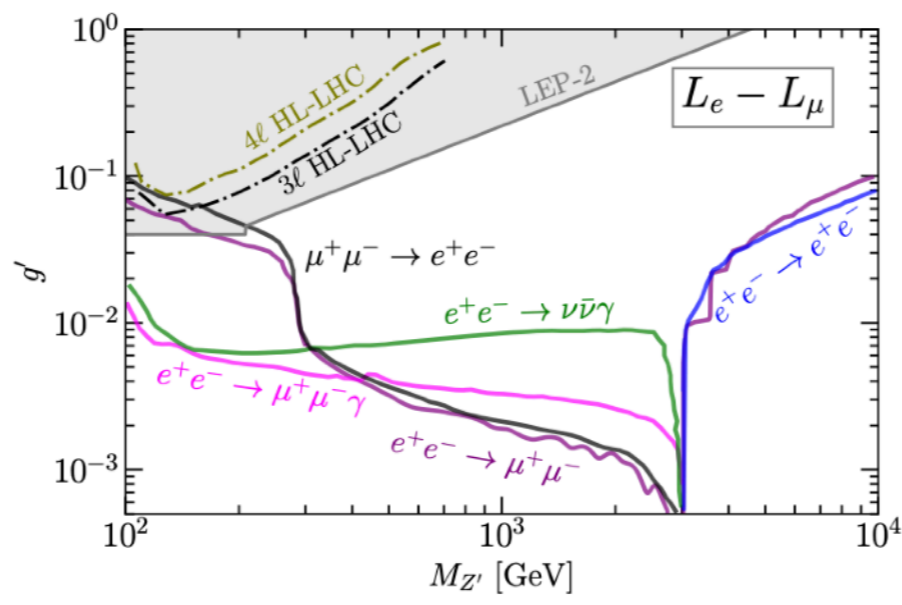
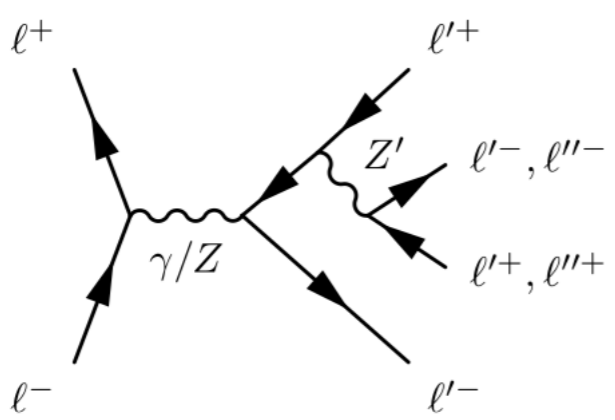
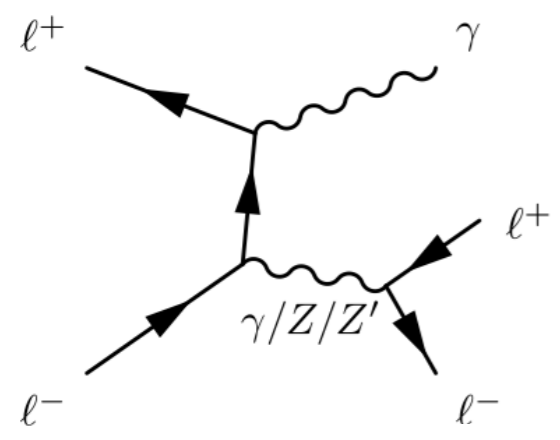
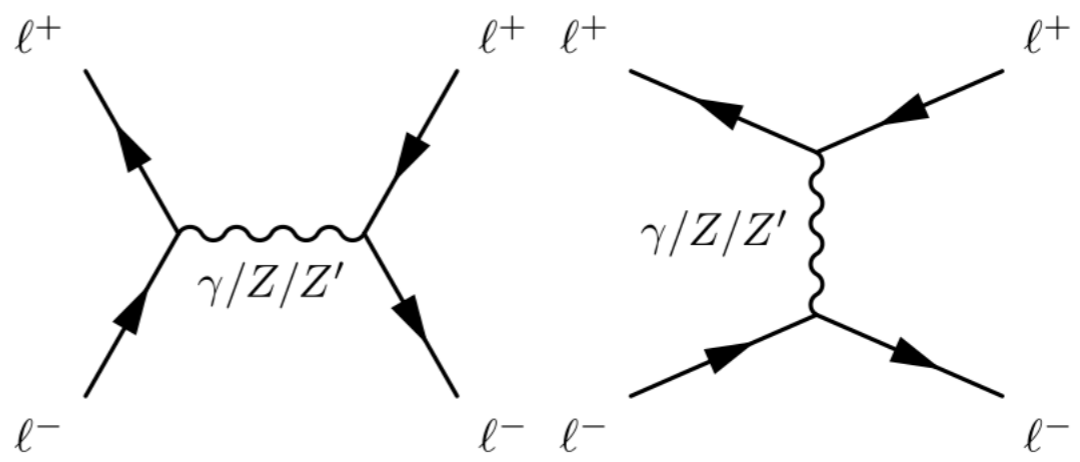
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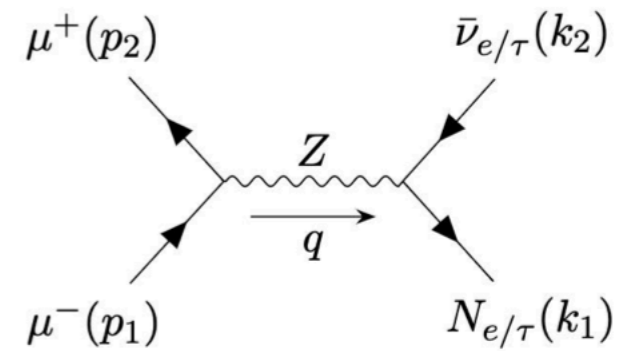
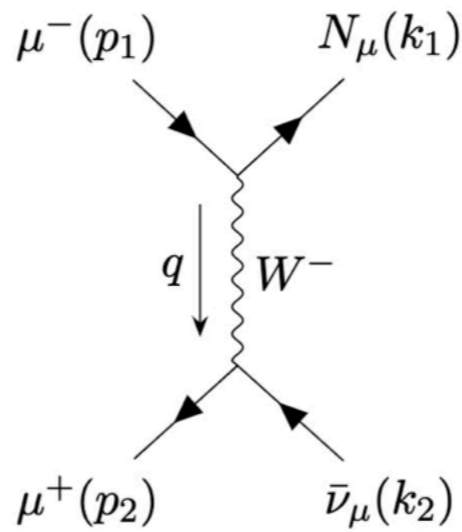
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$\sqrt{s} = 3 \text{ TeV}$

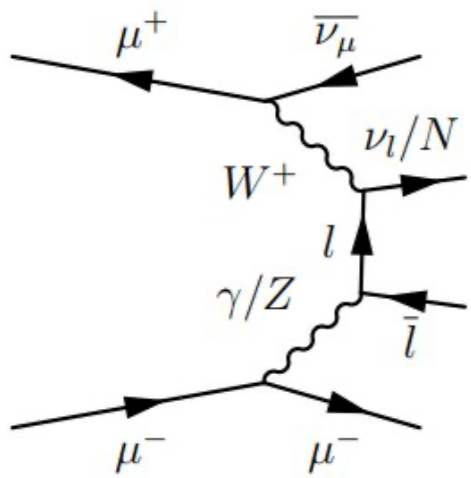
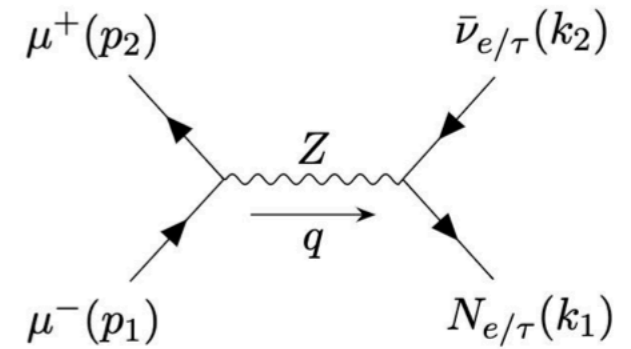
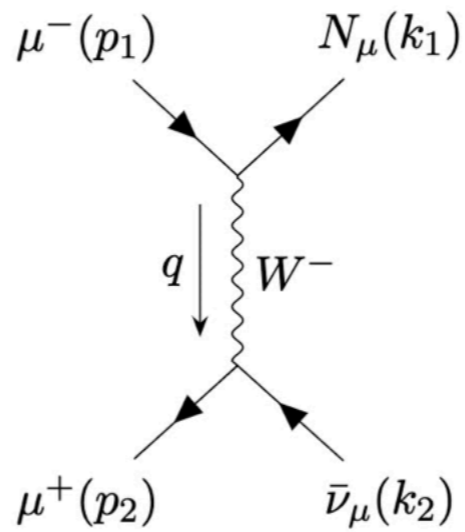
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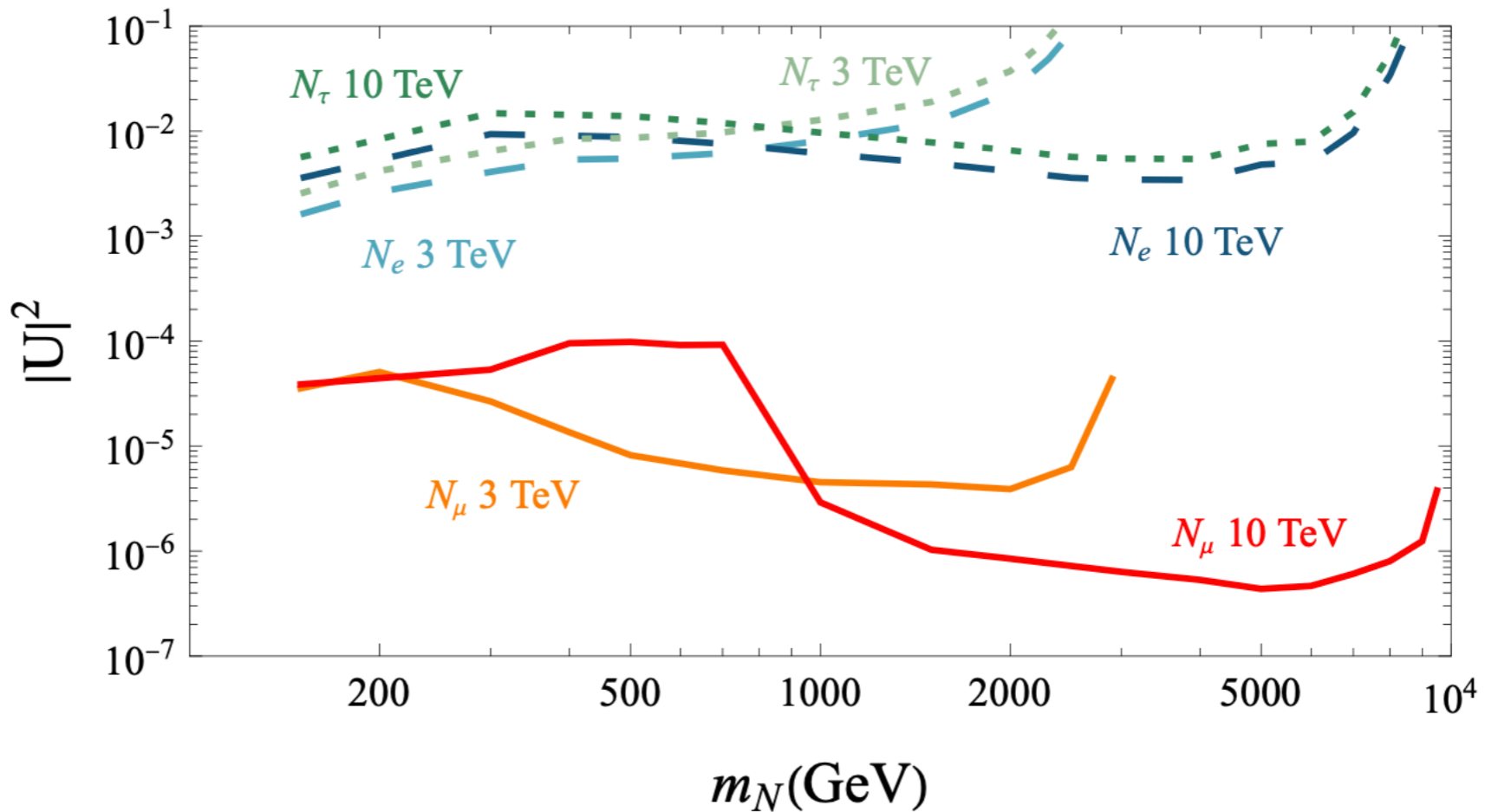
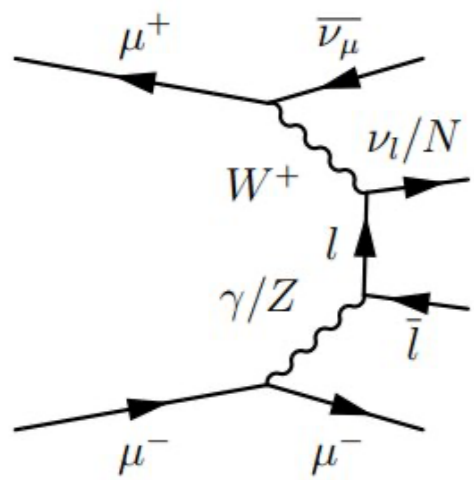
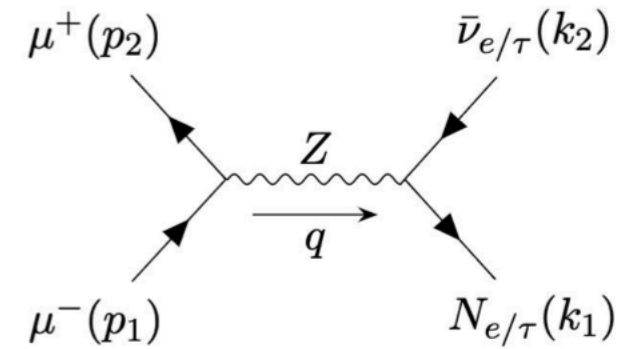
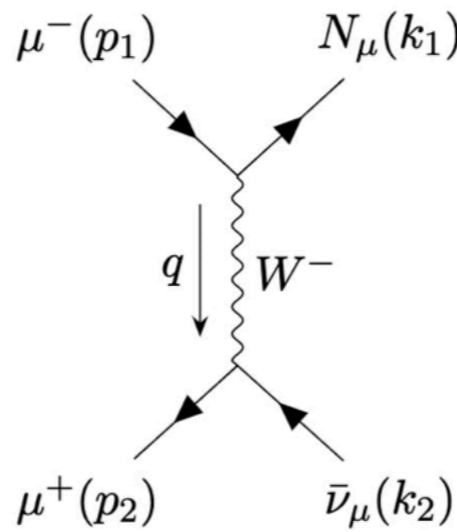
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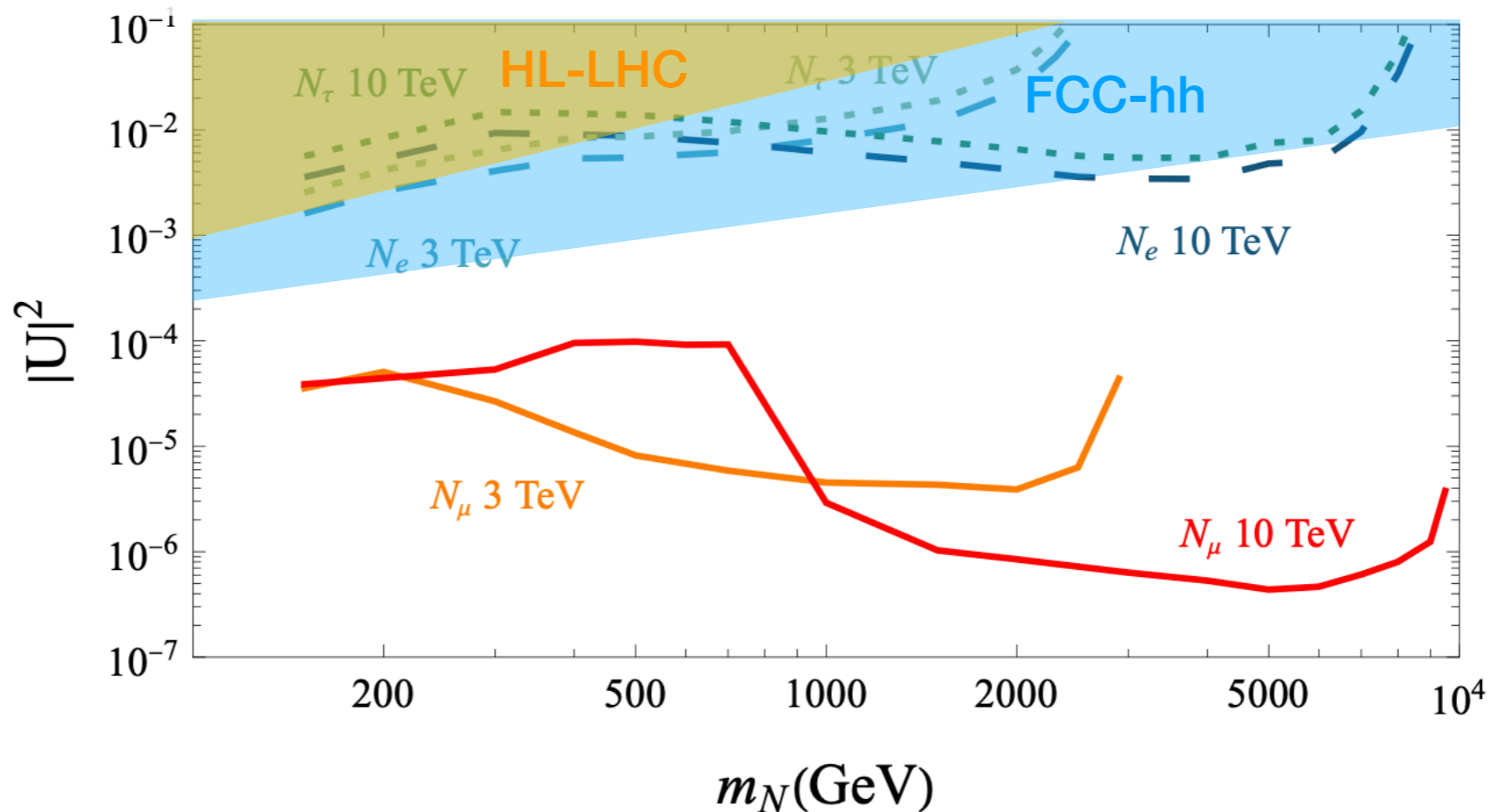
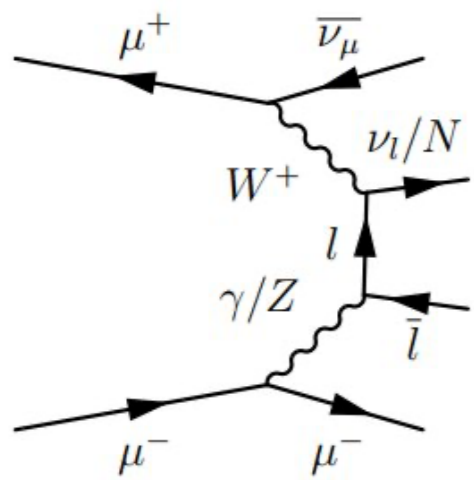
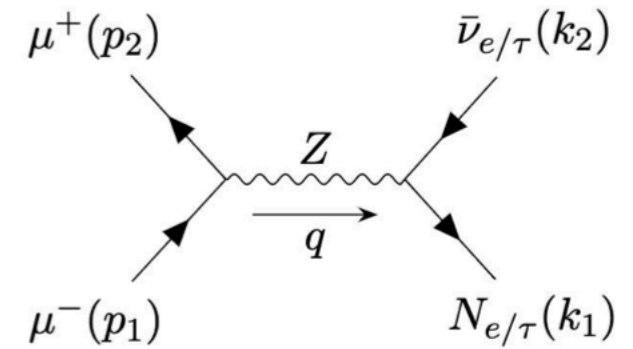
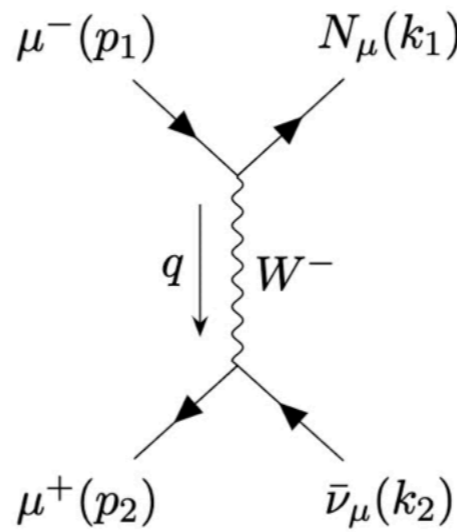
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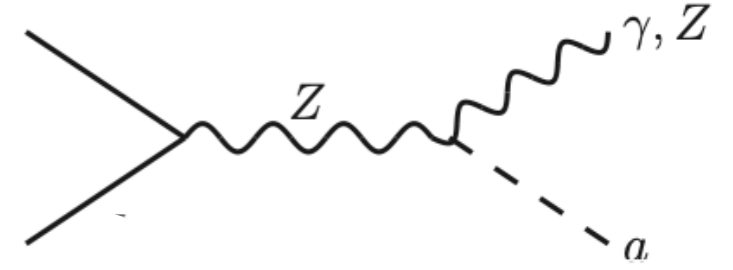
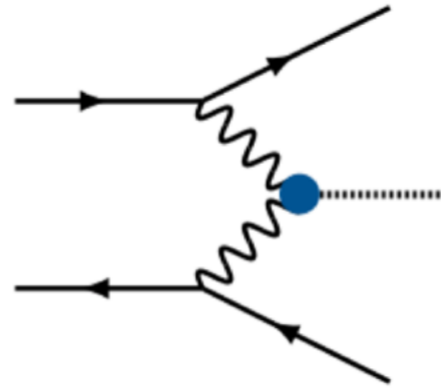
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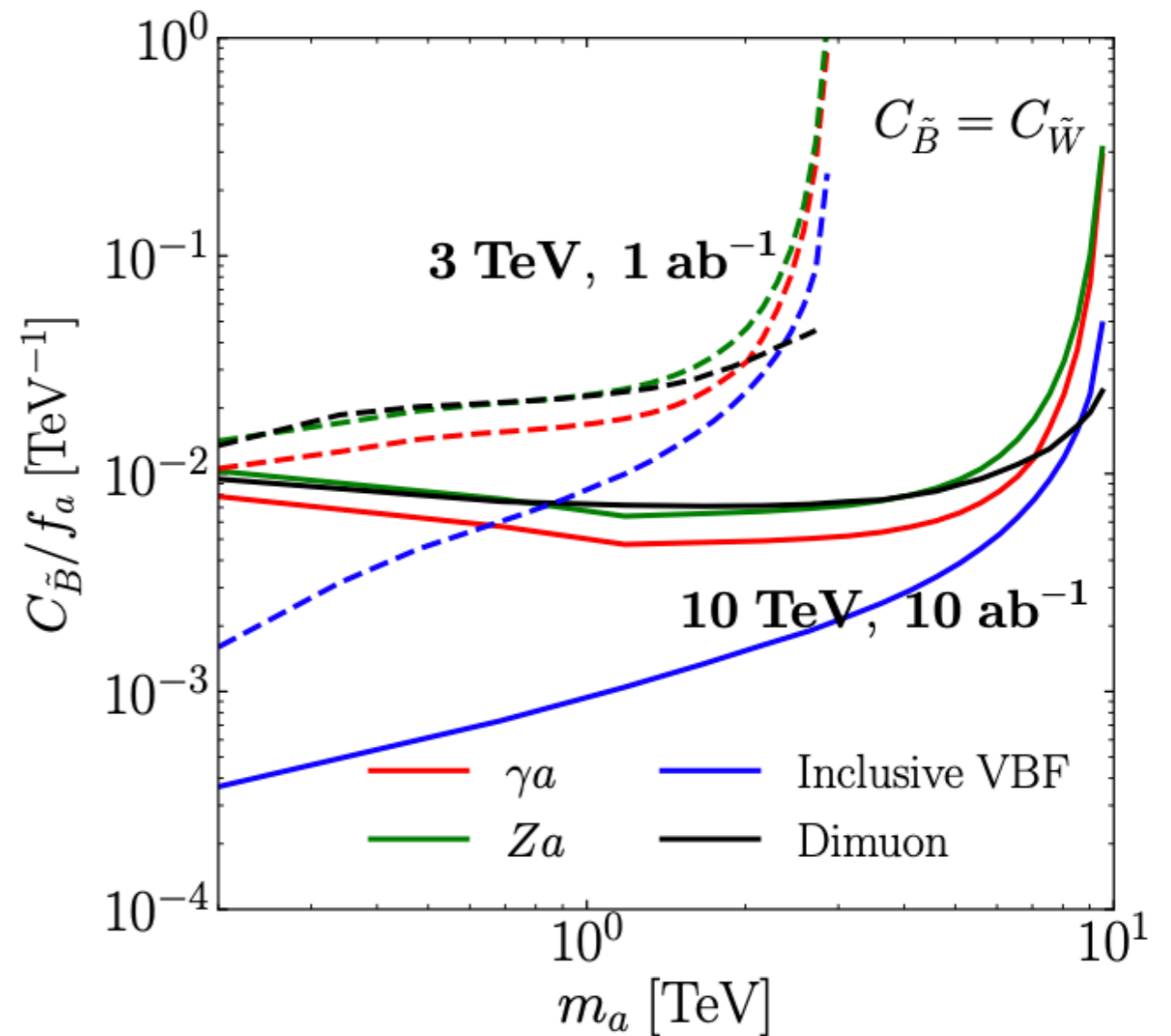
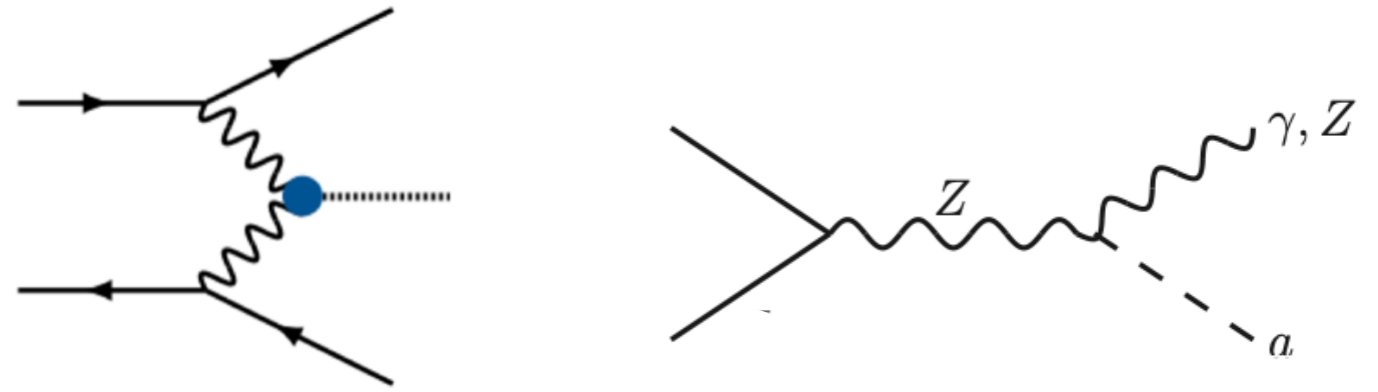
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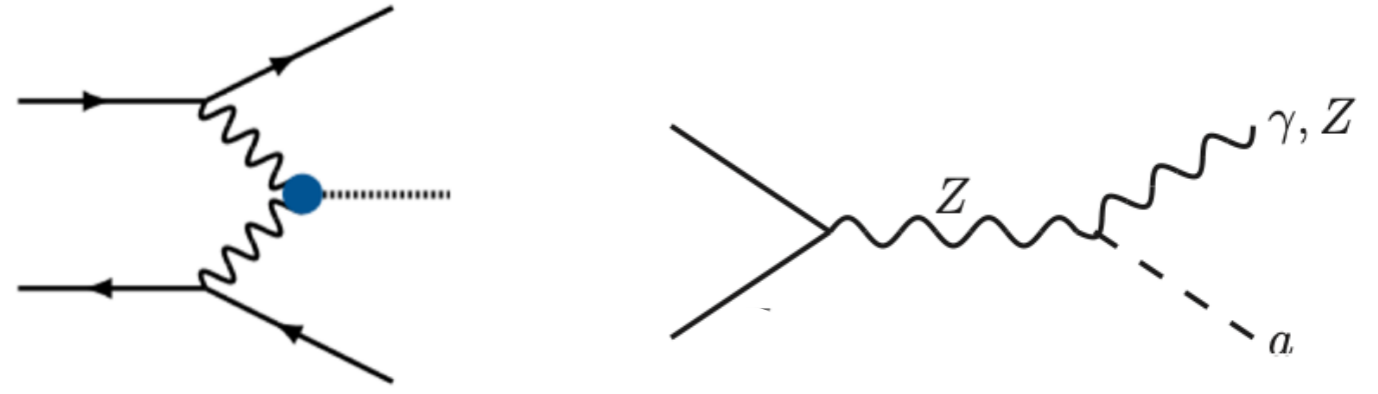
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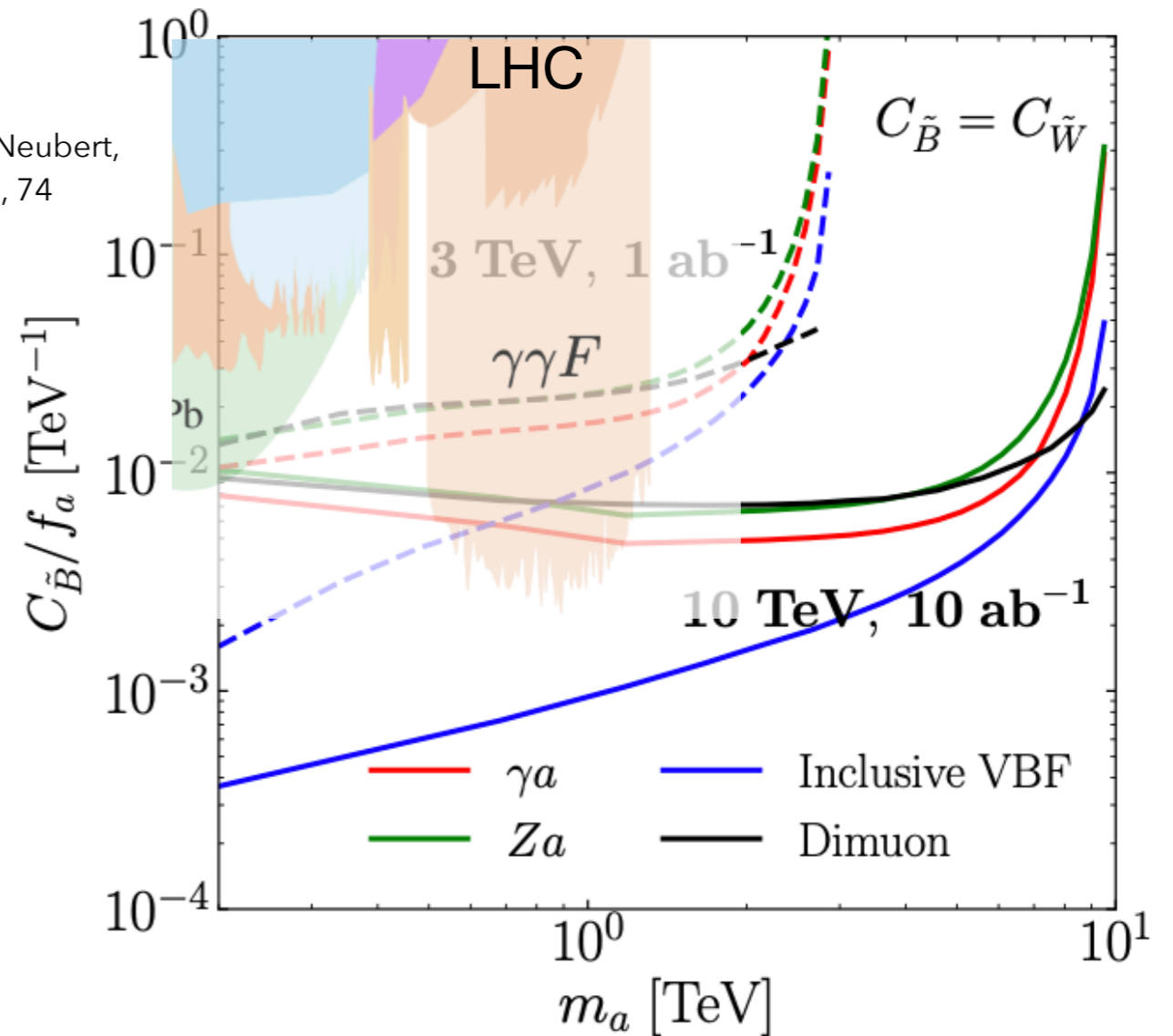


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Roughly adapted from Bauer, Heiles, Neubert, and Thamm: *Eur.Phys.J.C* 79 (2019) 1, 74



# Staging opportunities

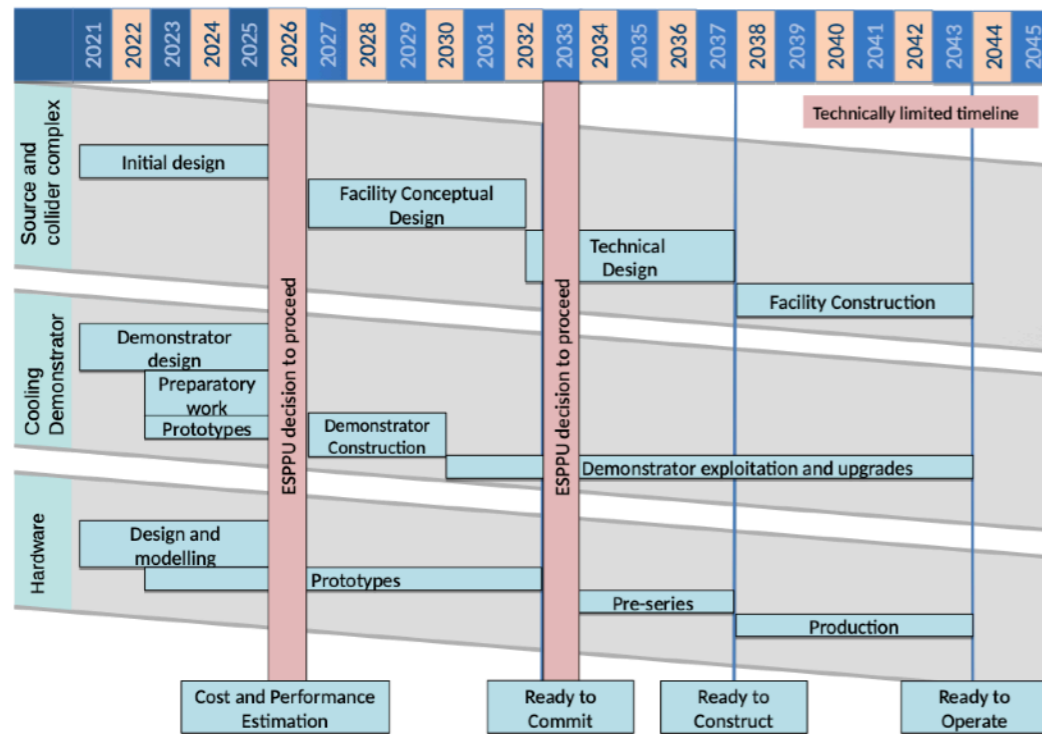
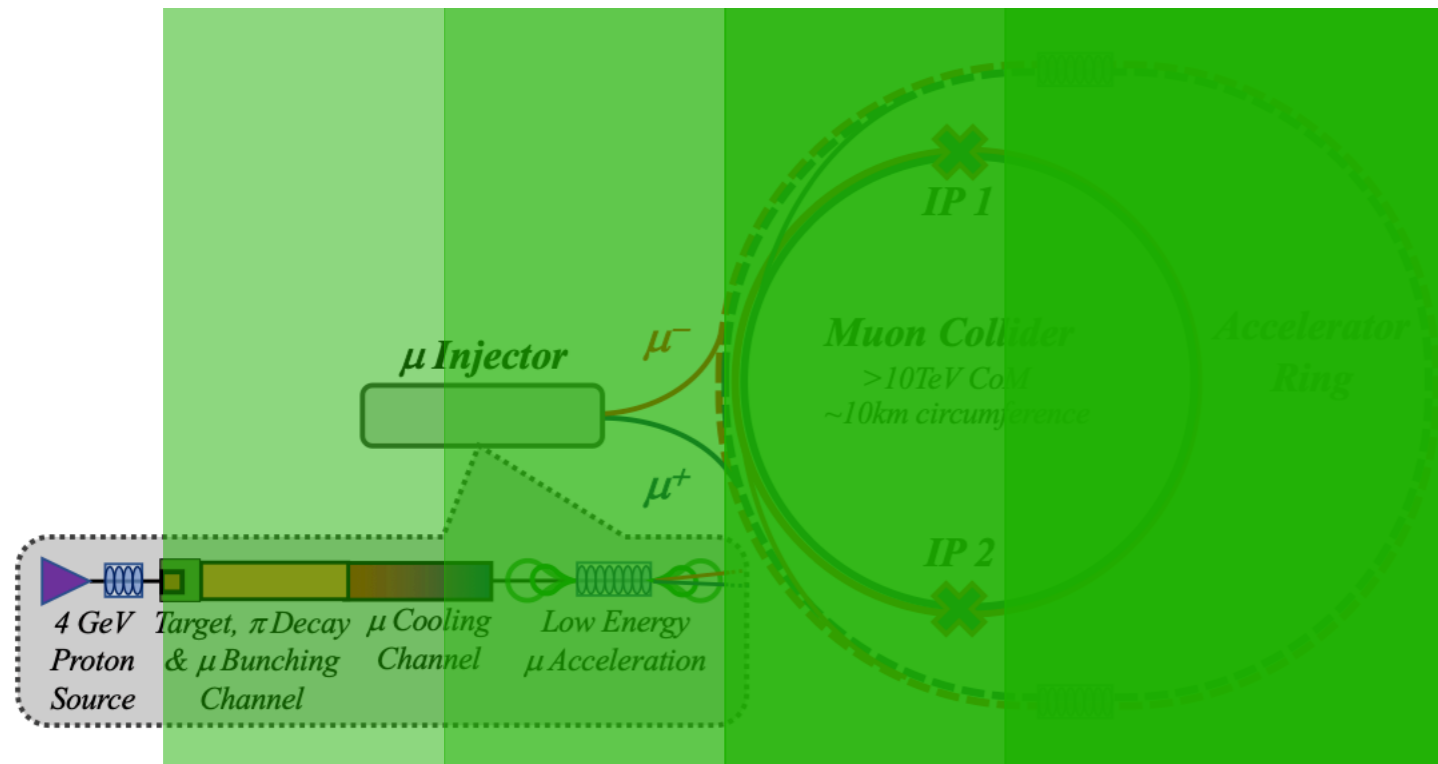


Fig. 2: A technically limited timeline for the Muon Collider R&D programme

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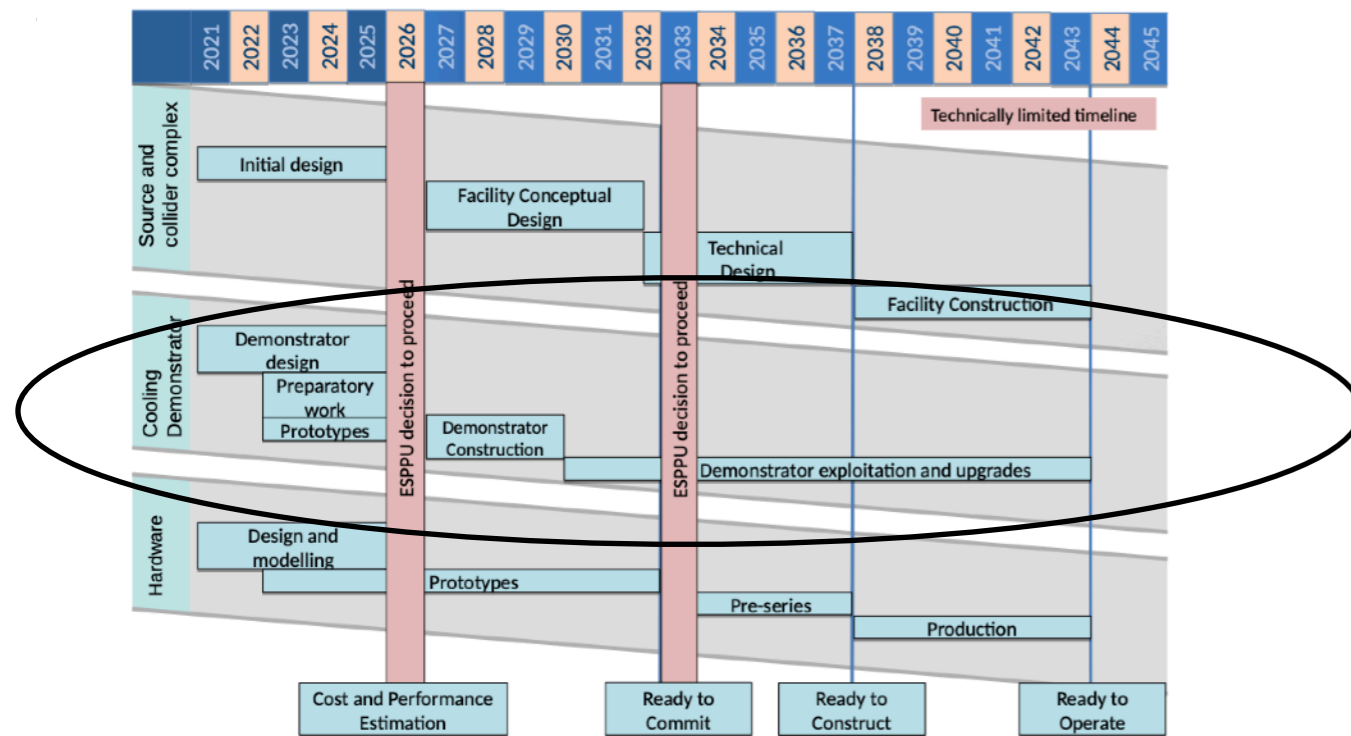
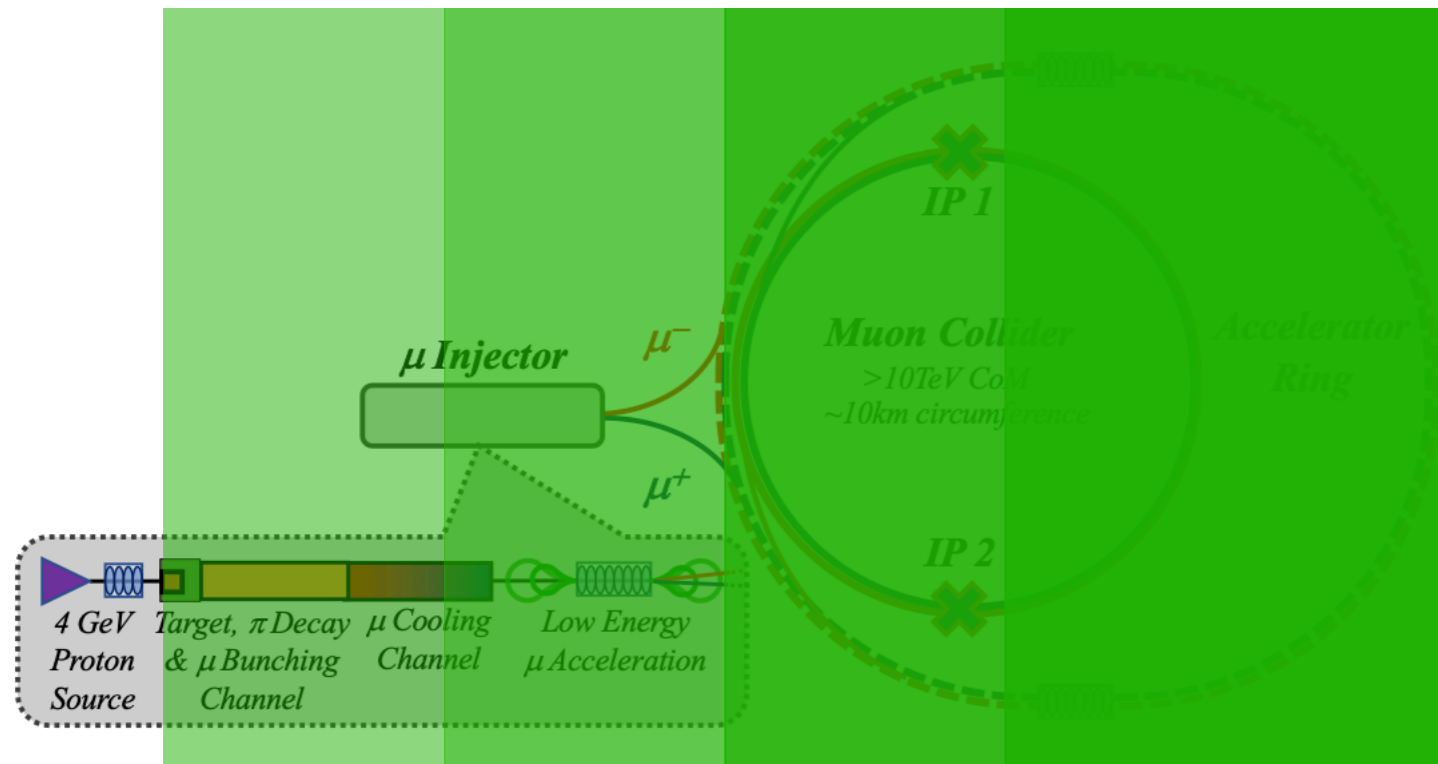


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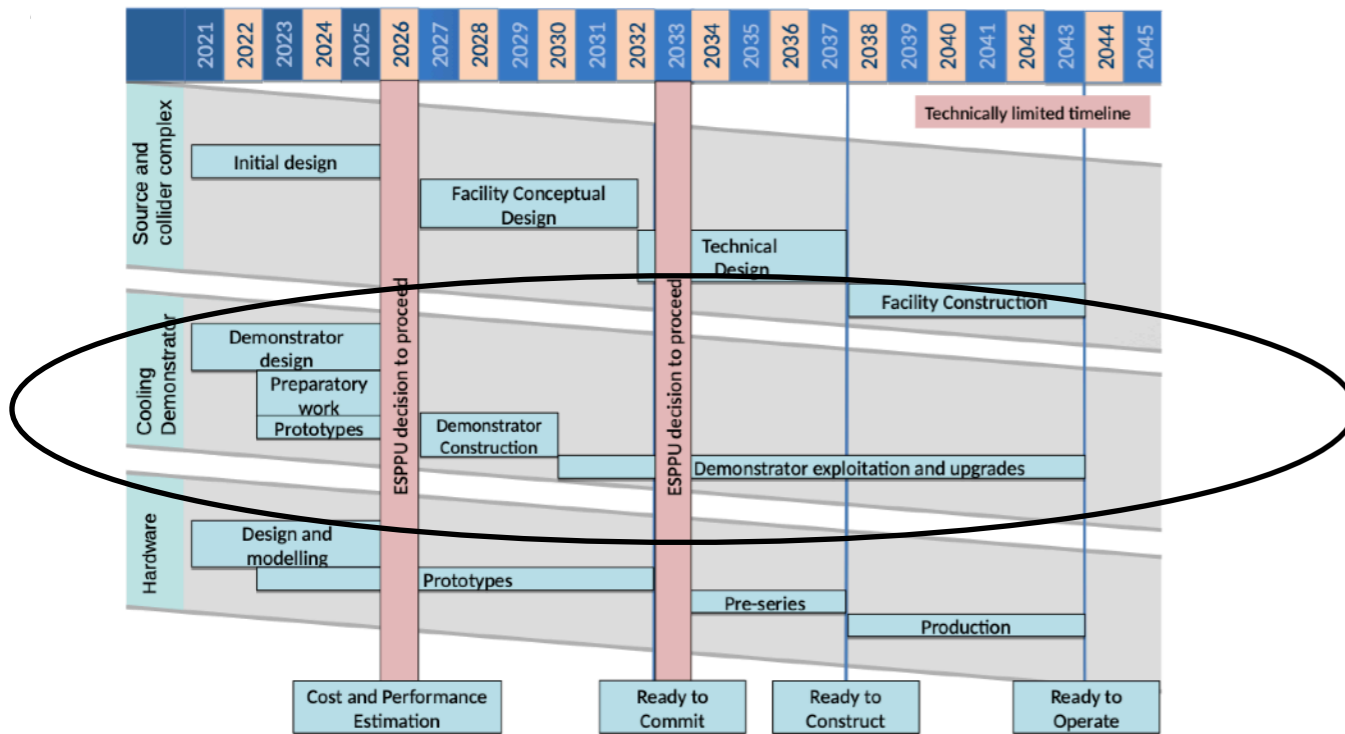
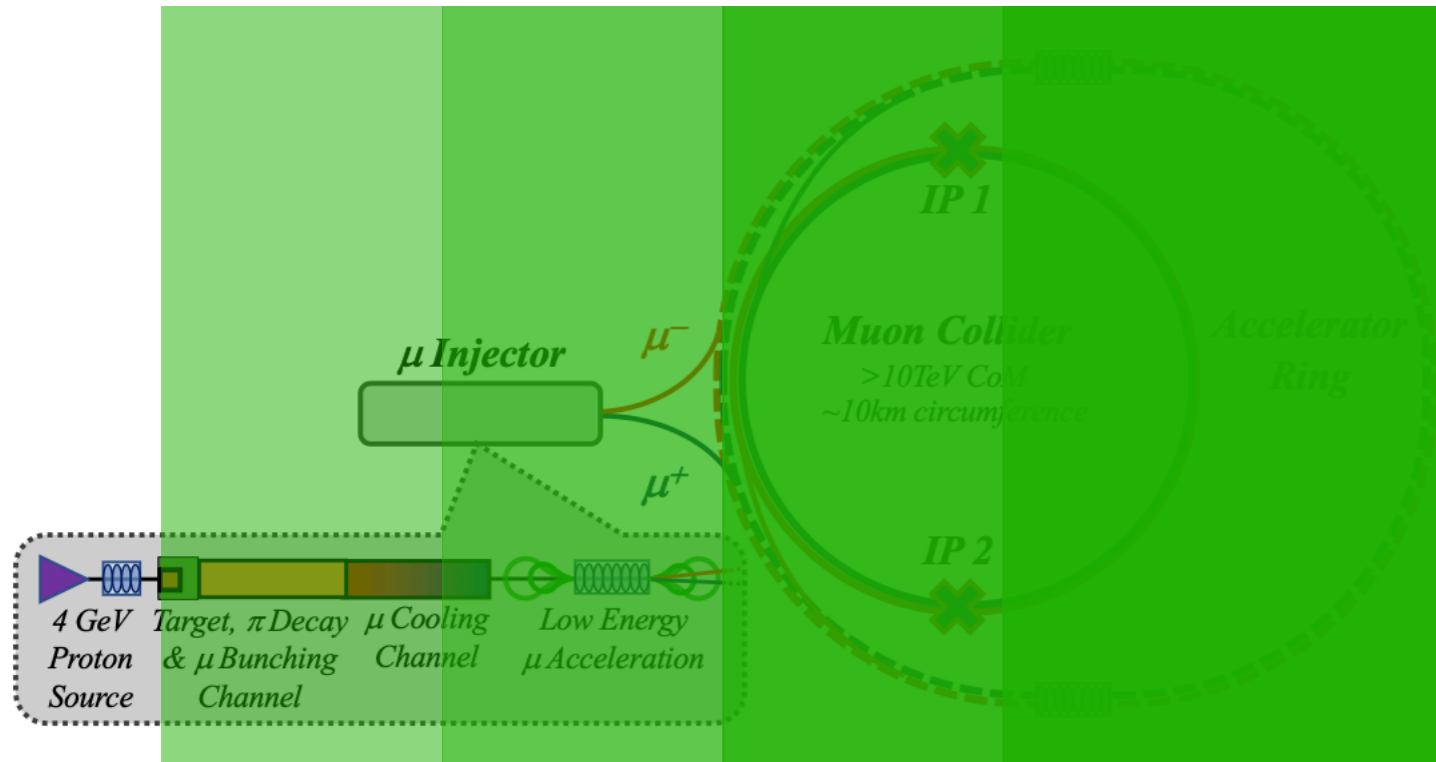
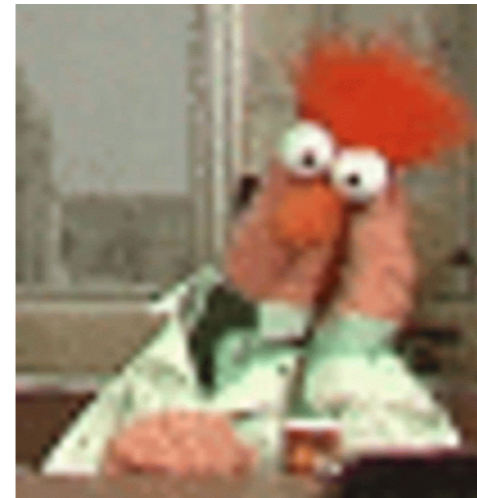


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What physics can we do along the way?



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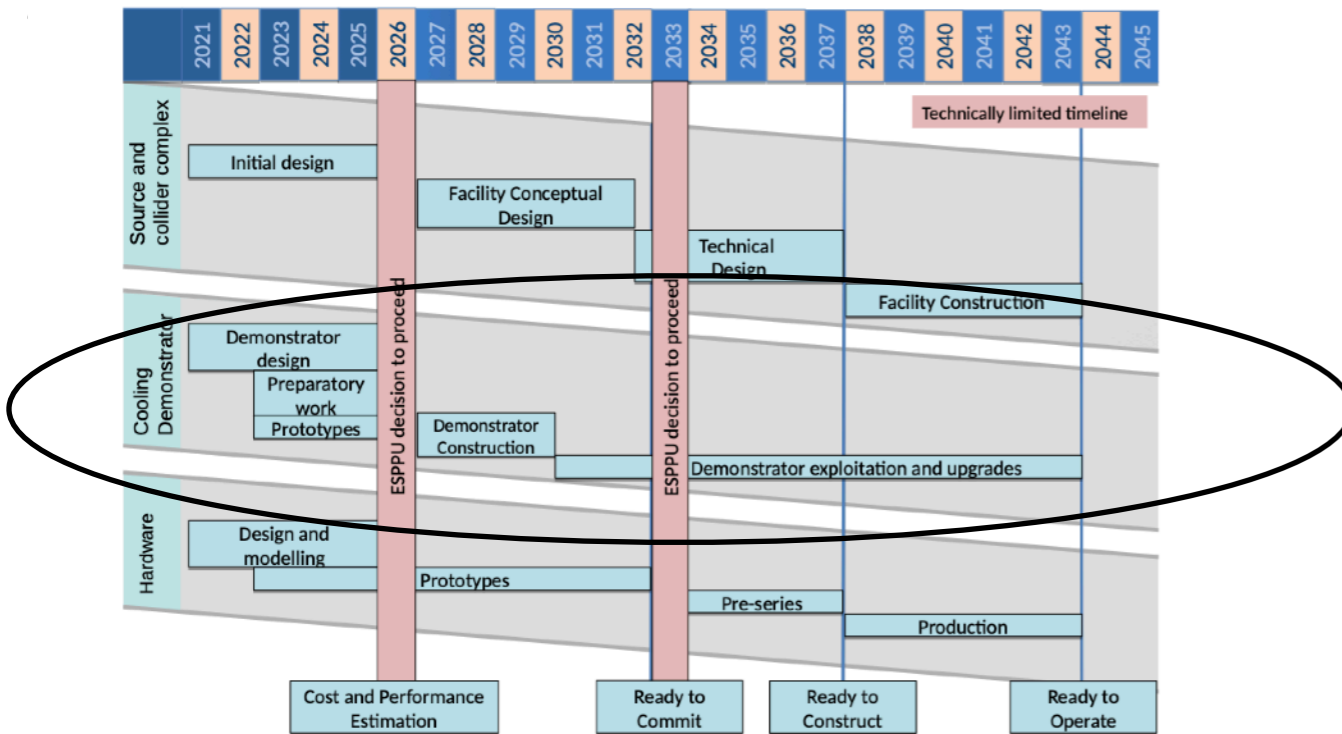
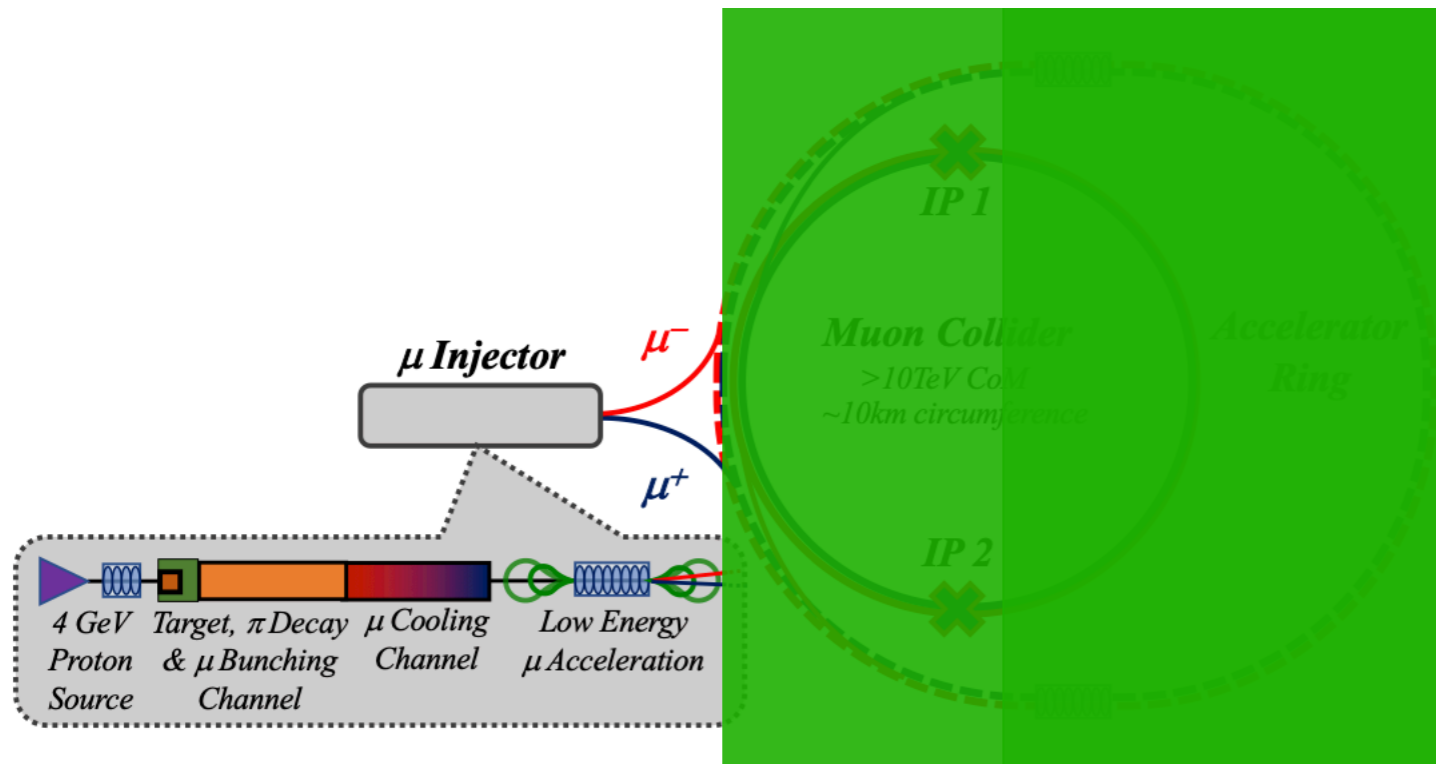
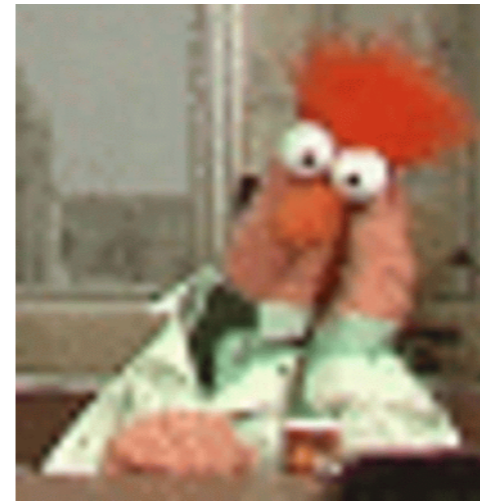


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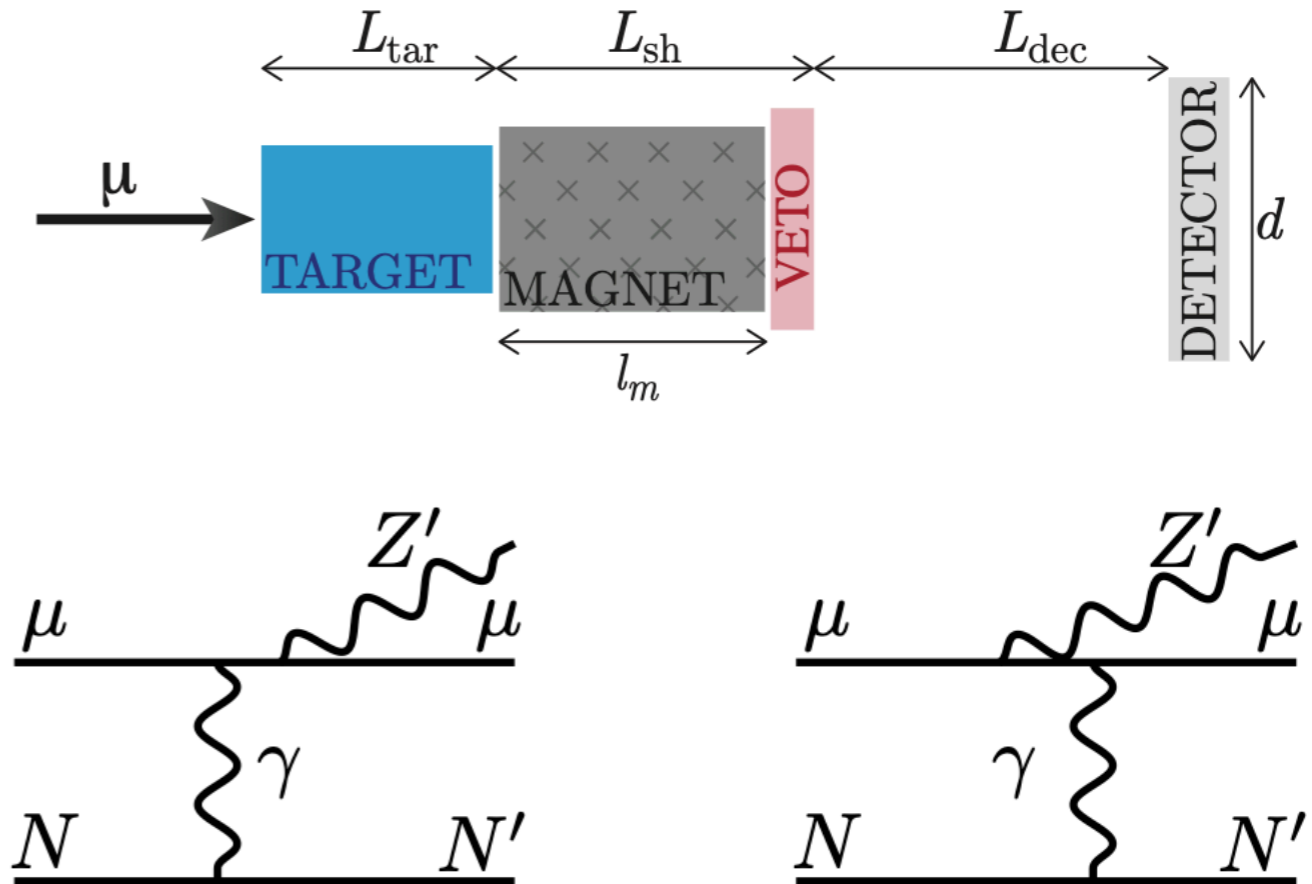
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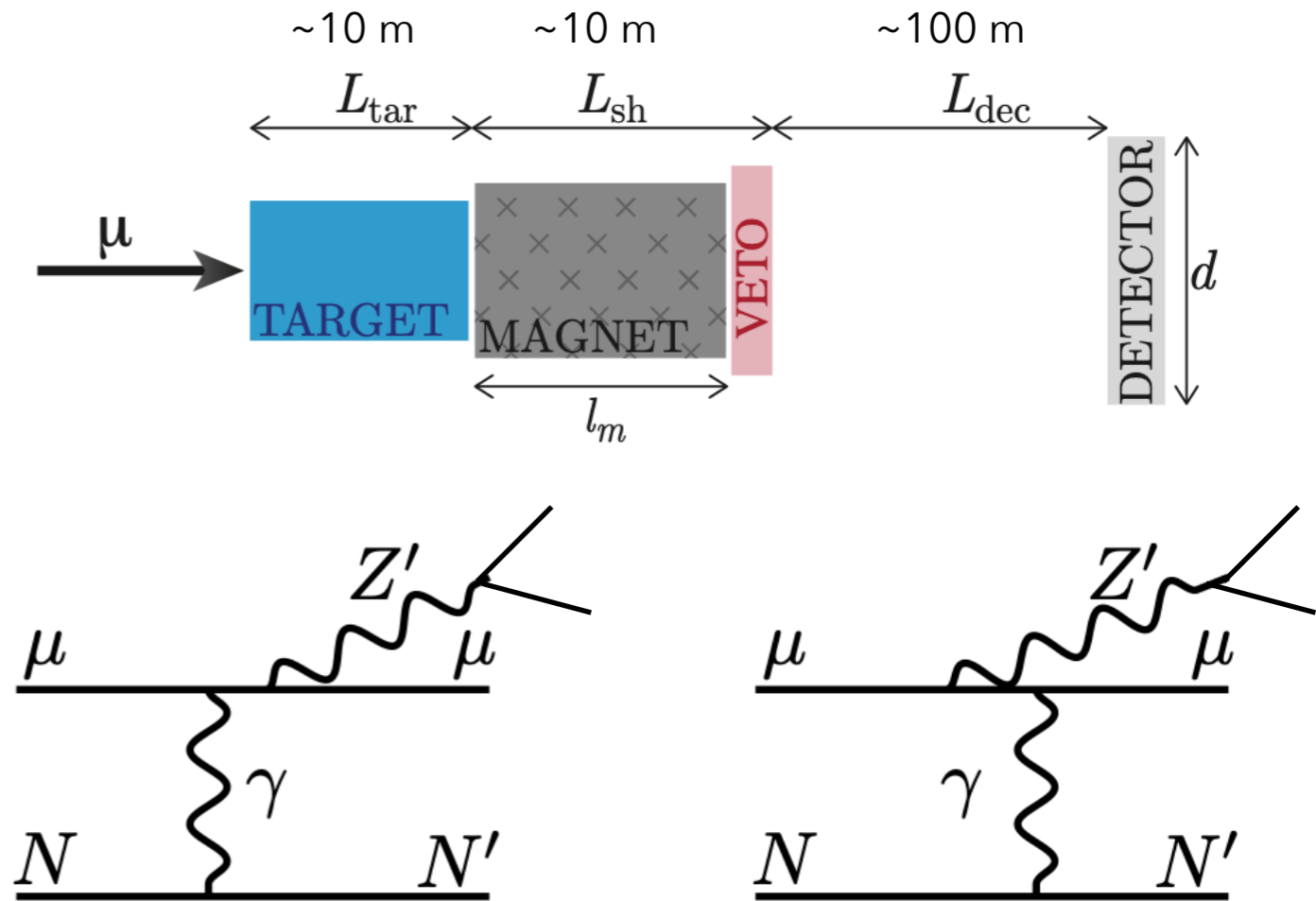
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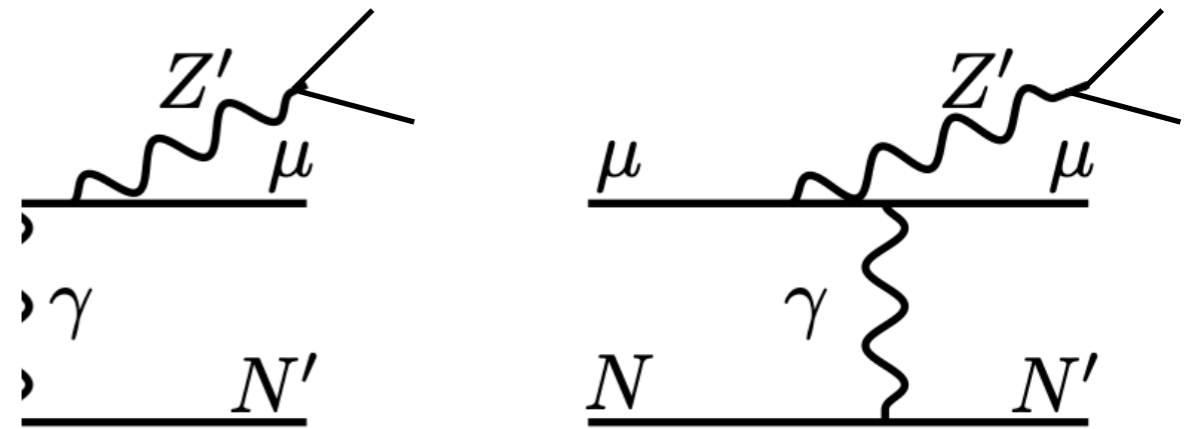
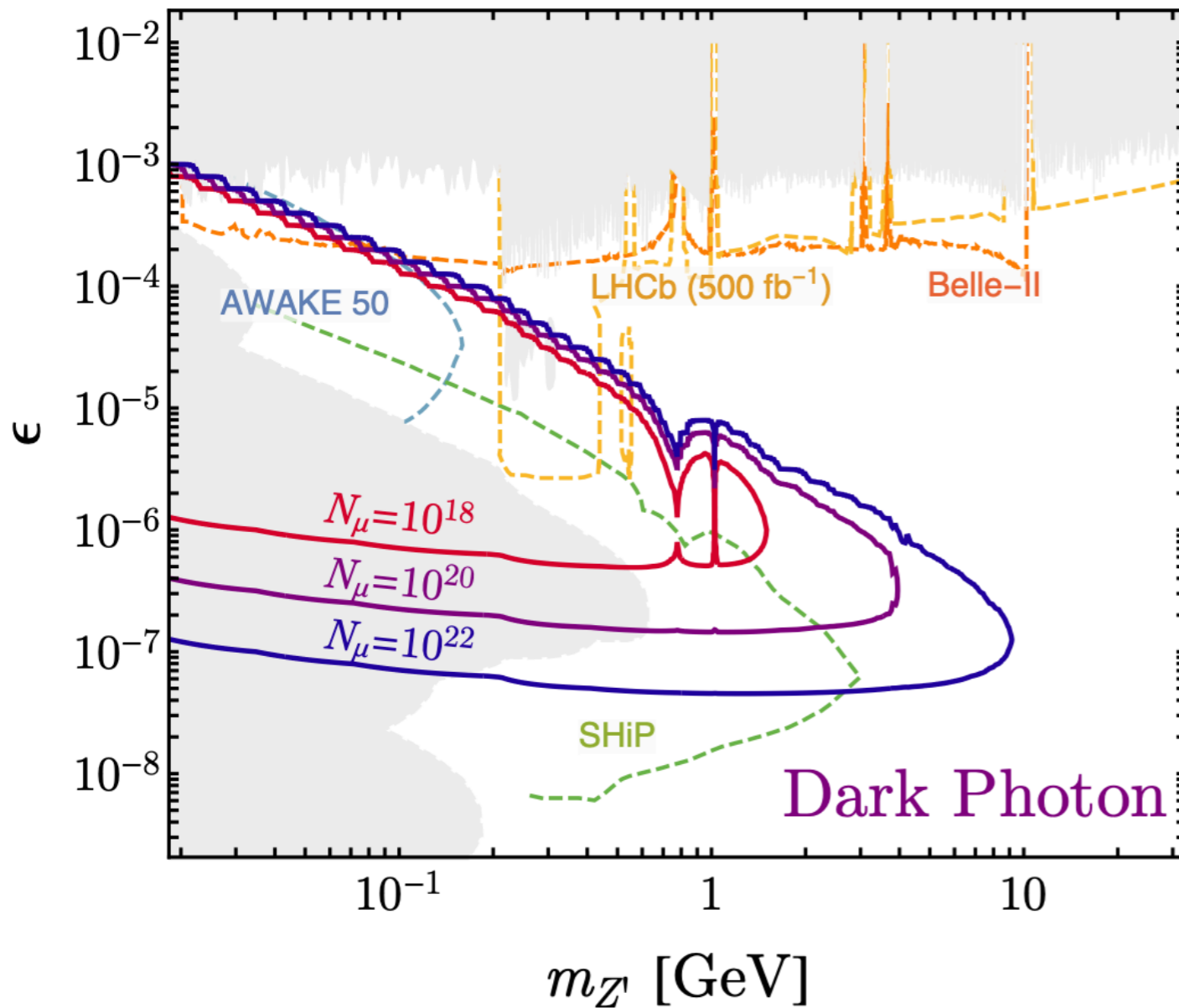
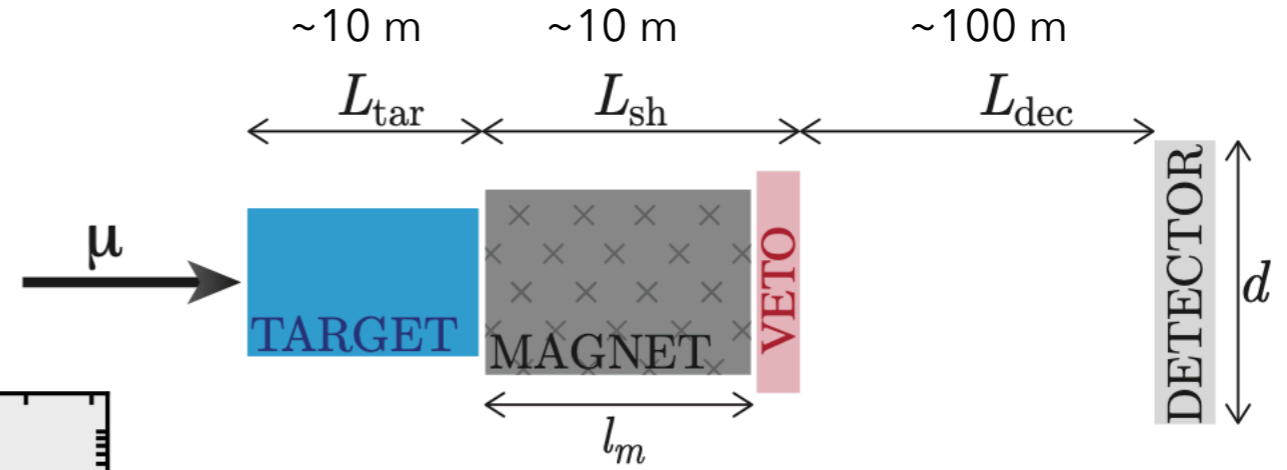
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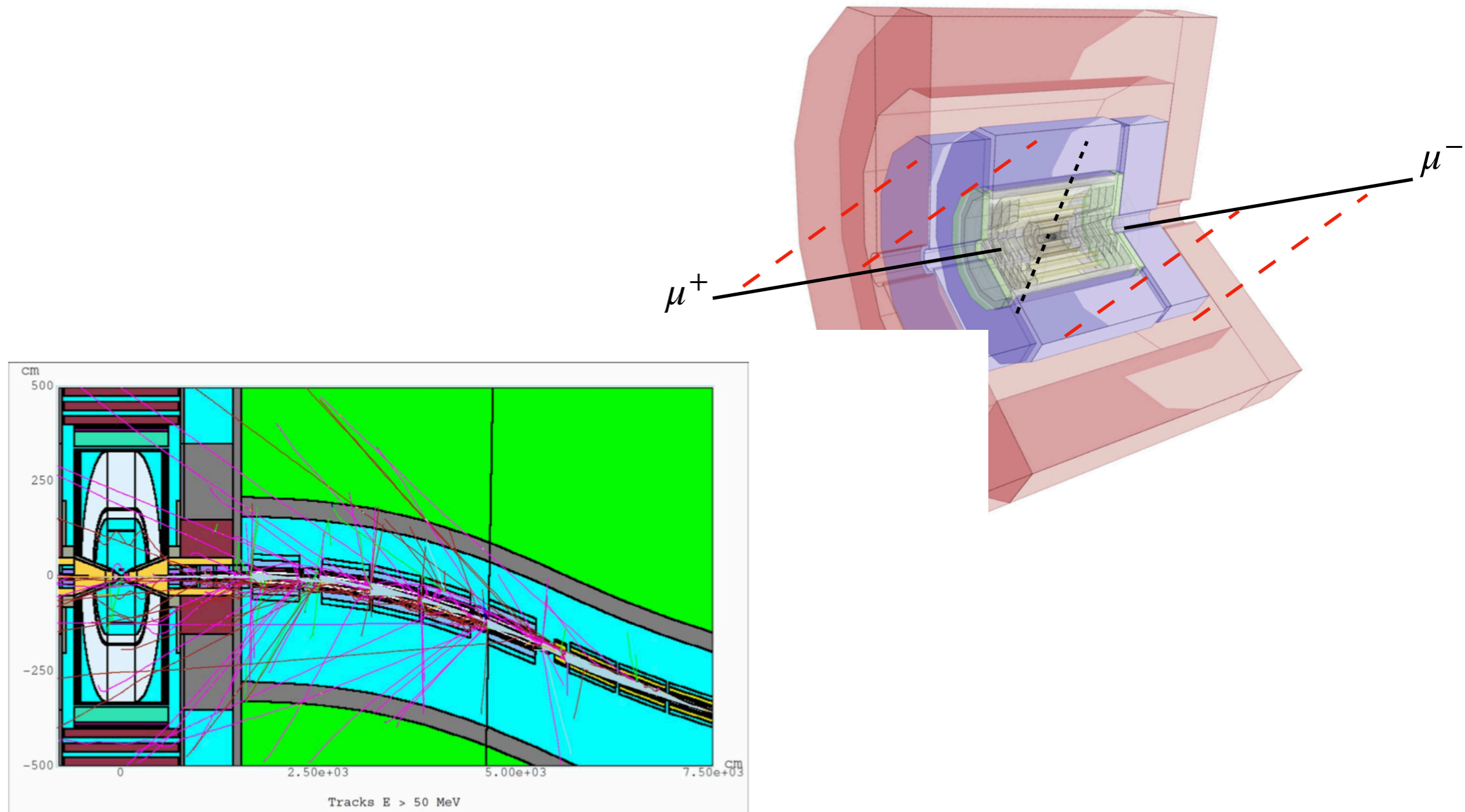
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Assuming beam energy of  $E_0 = 1.5$  TeV

# Beam induced background



**Figure 1.** A MARS15 model of the Interaction Region (IR) and detector with particle tracks  $> 1$  GeV (mainly muons) for several forced decays of both beams.

# Summary

While still at speculative stages, a Muon Collider has the promising potential for a vibrant physics program. Early studies show impressive projections for Higgs physics, EW precision, flavor, and dark matter.

Has the potential to make clear definitive statements about some DM scenarios.

If we start thinking now, opportunities to do interesting physics during the full R&D lifetime, way before first collisions.

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