UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Long live the Higgs Portal!

Anastasia Filimonova

Based on 1812.04628 with Susanne Westhoff

Planck 2019, Granada, 4 June

Image credit:
ATLAS collaboration

Higgs portal for fermionic dark matter

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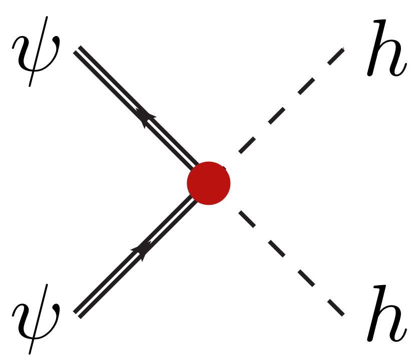
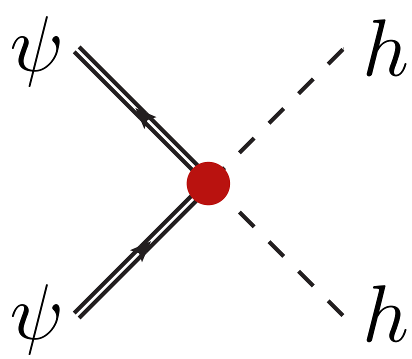


Pure electroweak singlet, doublet, triplet.

Dark matter candidate **only at Higgs threshold** or **too heavy for colliders.**

[Beniwal et al.,1512.06458] [Cirelli *et al.*, 1507.05519]

Higgs portal for fermionic dark matter



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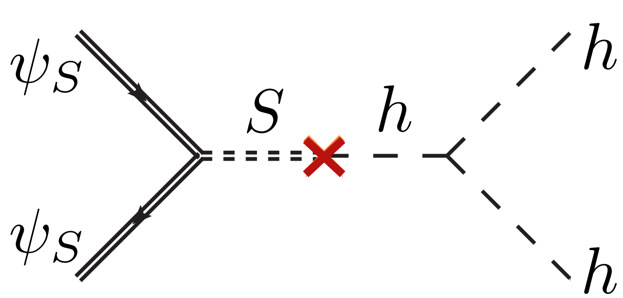

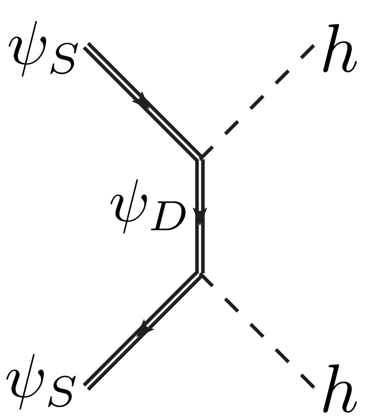

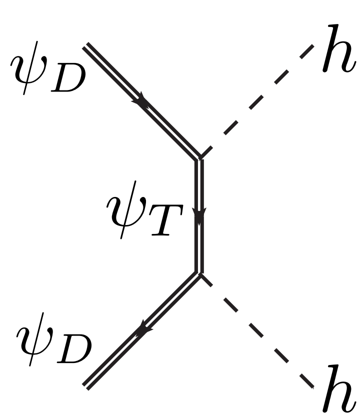

Minimal renormalizable extensions: singlet-singlet, singlet-doublet, doublet-triplet.

Tiny portal coupling: **naturalness**?

[Freitas, Westhoff, Zupan, 1506.04149]

[Lee et al., 0803.2932] [Mahbubani, Senatore, hep-ph/0510064]

[Dedes, Karamitros, 1403.7744]

Singlet-triplet model for dark matter

2 majorana fields: $SU(2)$ singlet χ_S and triplet χ_T

$$\mathcal{L}_{\text{eff}} \supset -\frac{m_S}{2}\overline{\chi}_S\chi_S - \frac{m_T}{2}\text{Tr}[\overline{\chi}_T\chi_T] + \frac{\kappa_{ST}}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + h.c.\right]$$

with $\chi_S = \chi_S^0, \quad \chi_T = \begin{pmatrix} \chi_T^0/\sqrt{2} & \chi^+ \\ \chi^- & -\chi_T^0/\sqrt{2} \end{pmatrix}$

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- Three new parameters: $m_S, \ m_T, \ \mu = \frac{\kappa_{ST} v^2}{\sqrt{2}\Lambda}$
- Freedom in the field definitions: can choose $m_T, \ \kappa_{ST} > 0$

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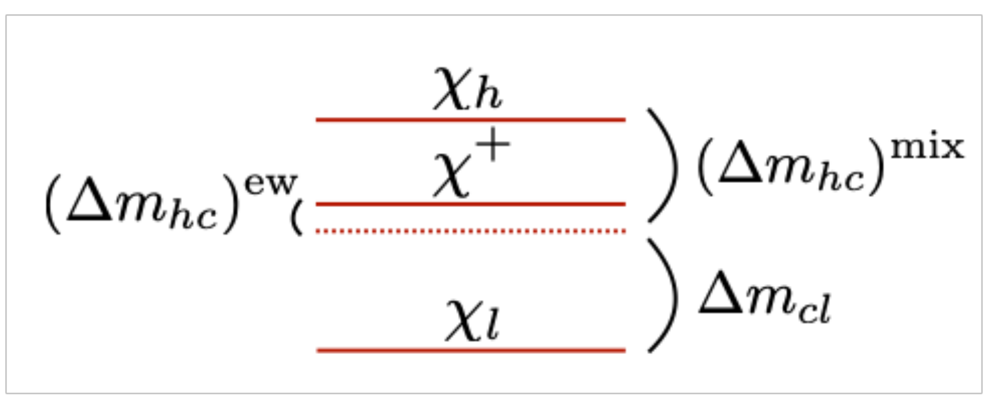
Tree-level structure + electroweak corrections:



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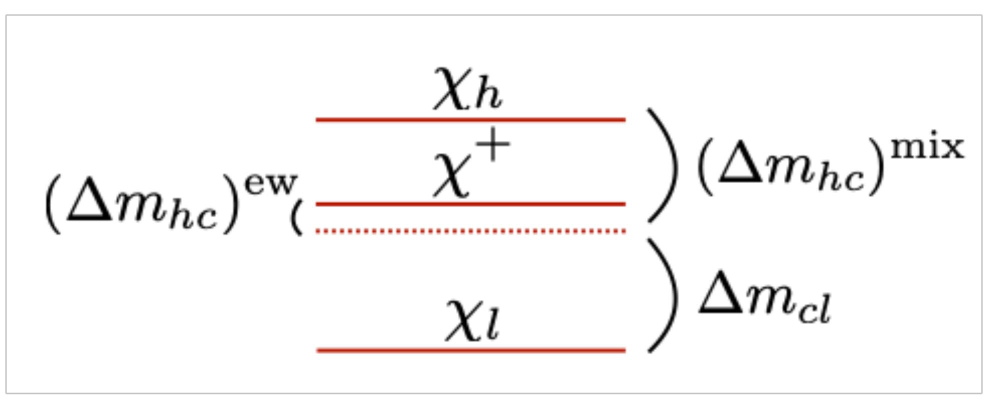
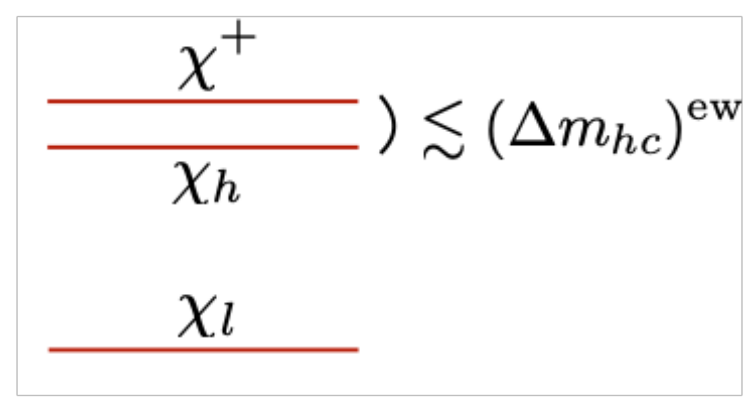


Small μ:



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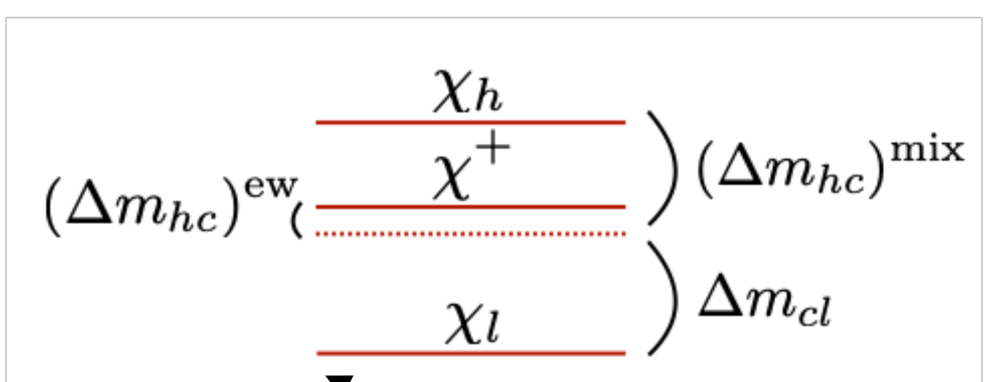

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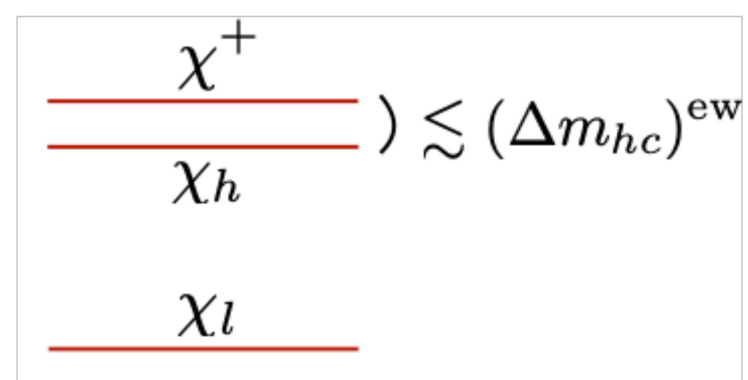
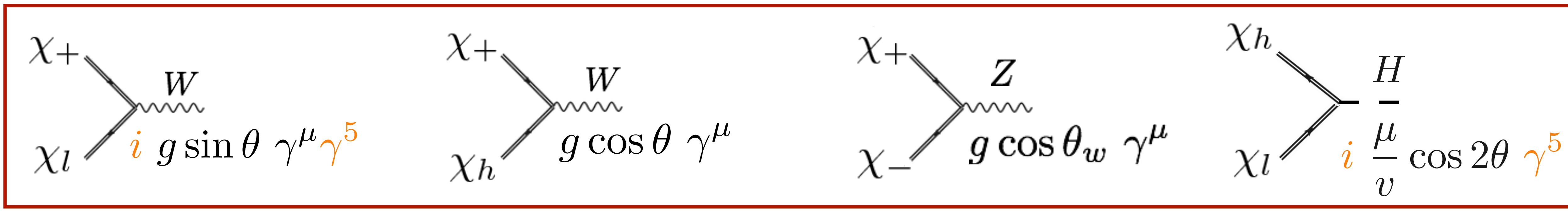


Dark matter candidate

Couplings of dark fermions

Gauge and Higgs couplings



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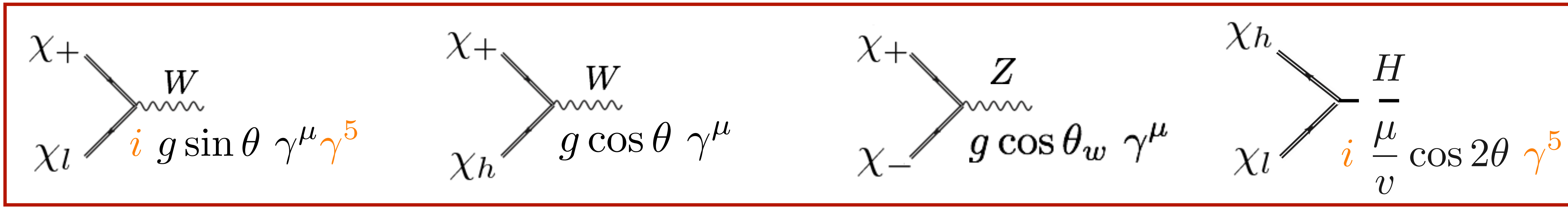

Two physical scenarios, depending on parameters of the theory:

Scalar case:

Couplings $\propto 1, \gamma_\mu$

Pseudo-scalar case:

Couplings $\propto \gamma_5, \gamma_\mu \gamma_5$

See also [hep-ph/0702148]

Direct detection

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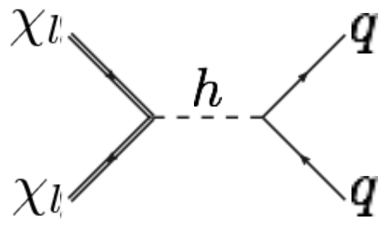

$\propto \mu/v \sin(2\theta)$

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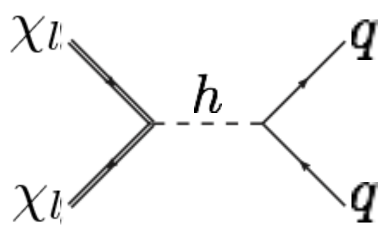

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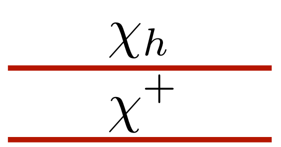

$$(\Delta m_{hc})^{\text{mix}} \simeq \mu \sin(2\theta)/2$$

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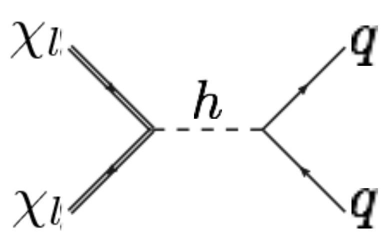

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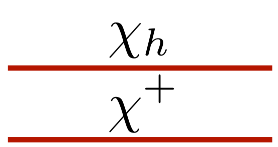

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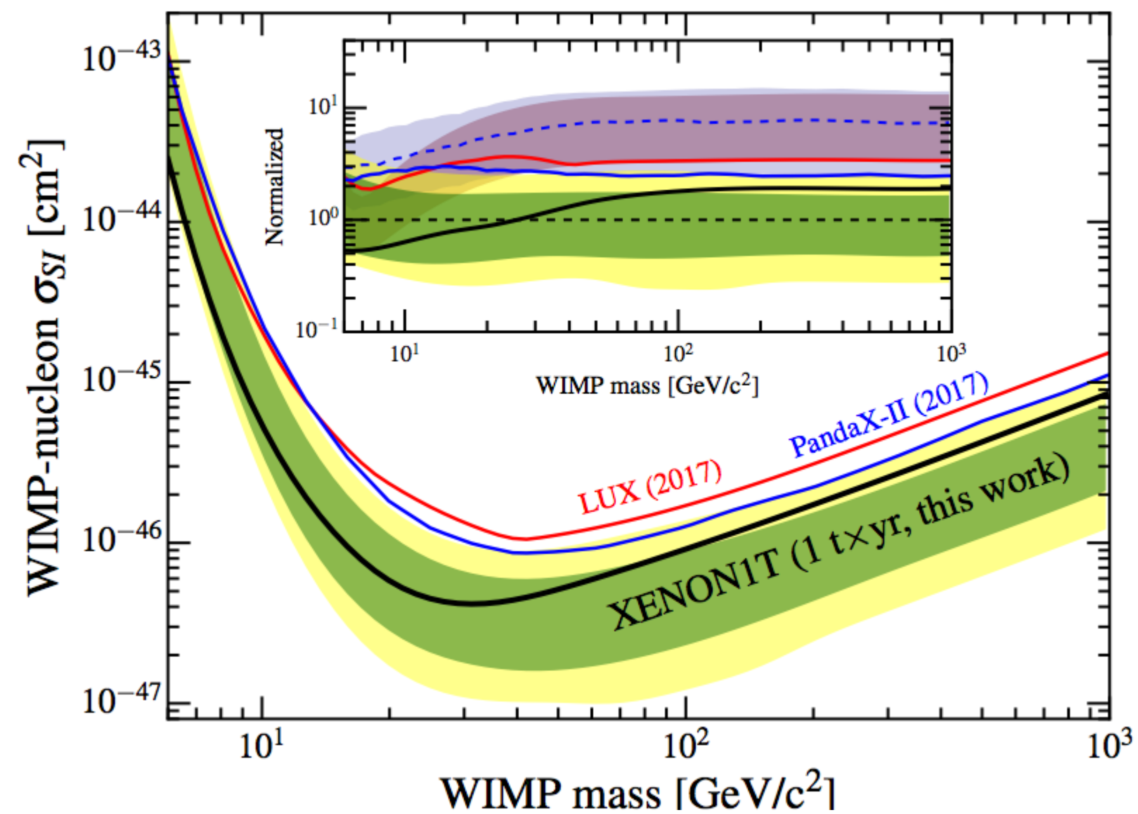
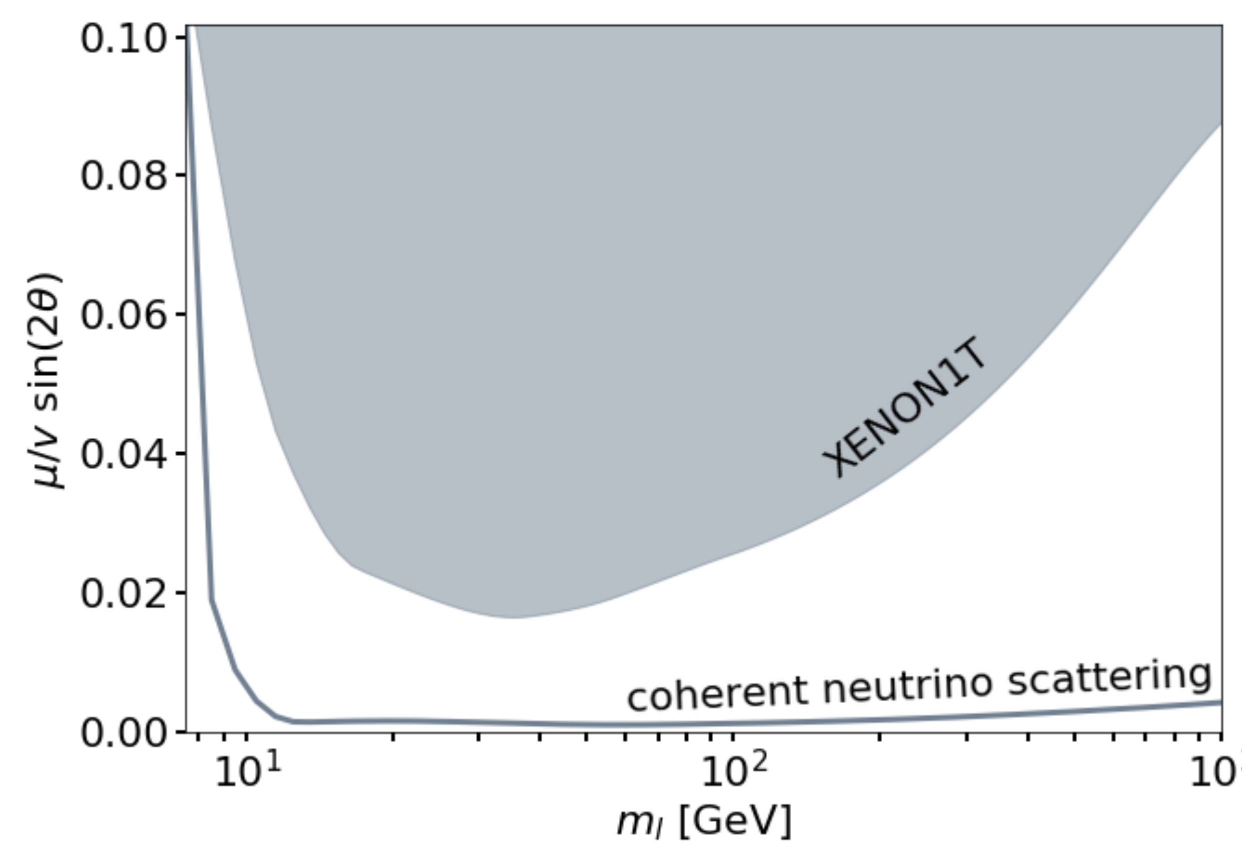
[1805.12562]





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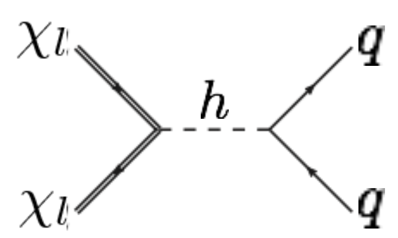

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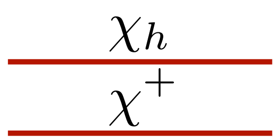

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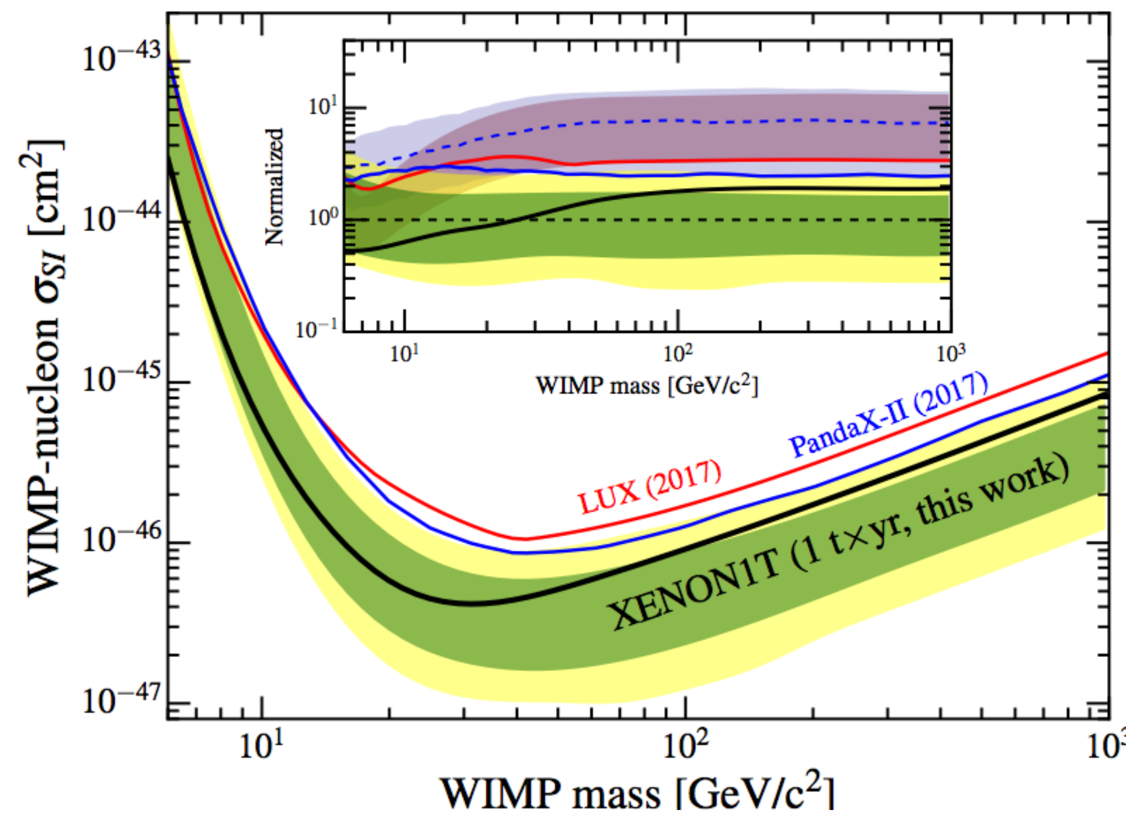

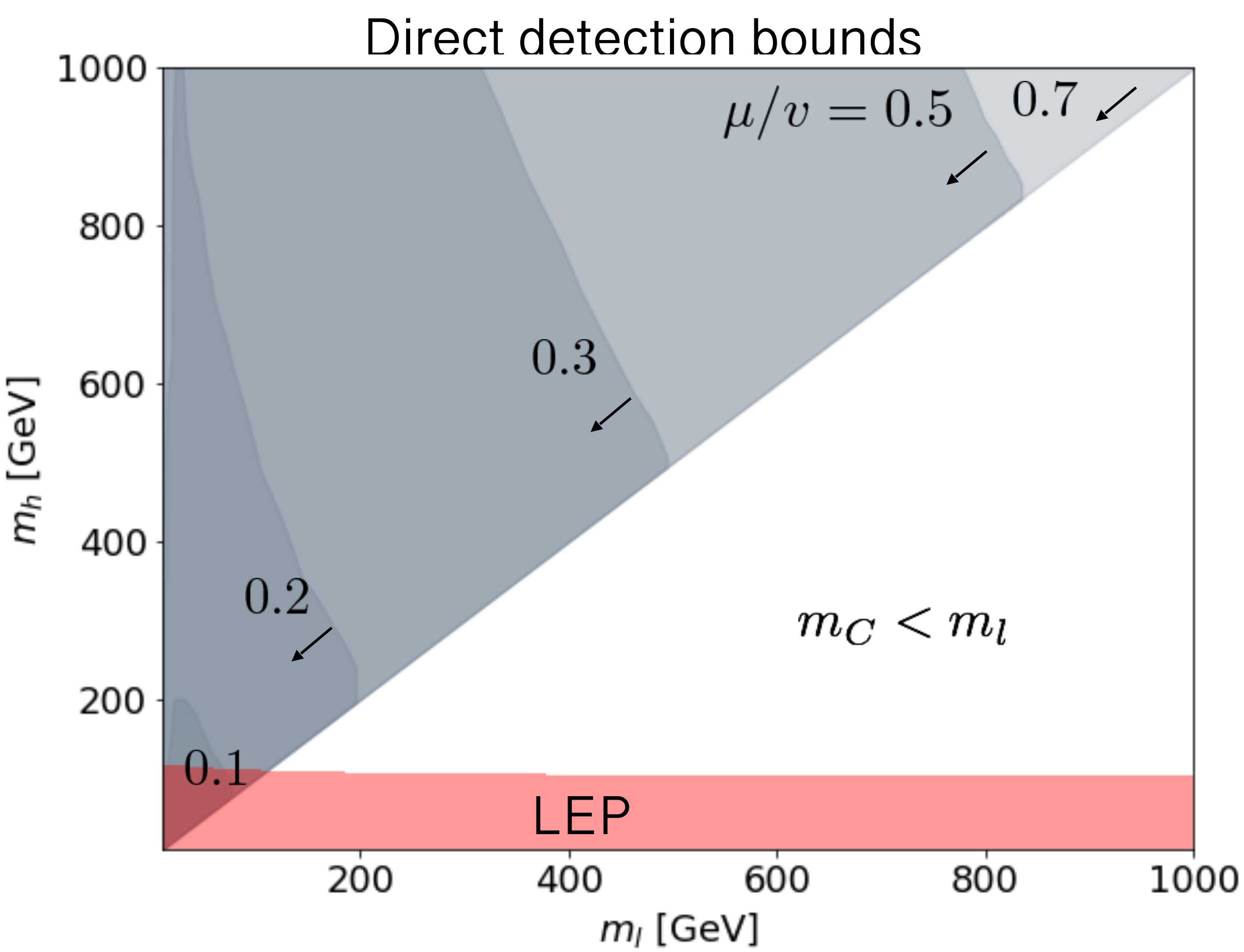

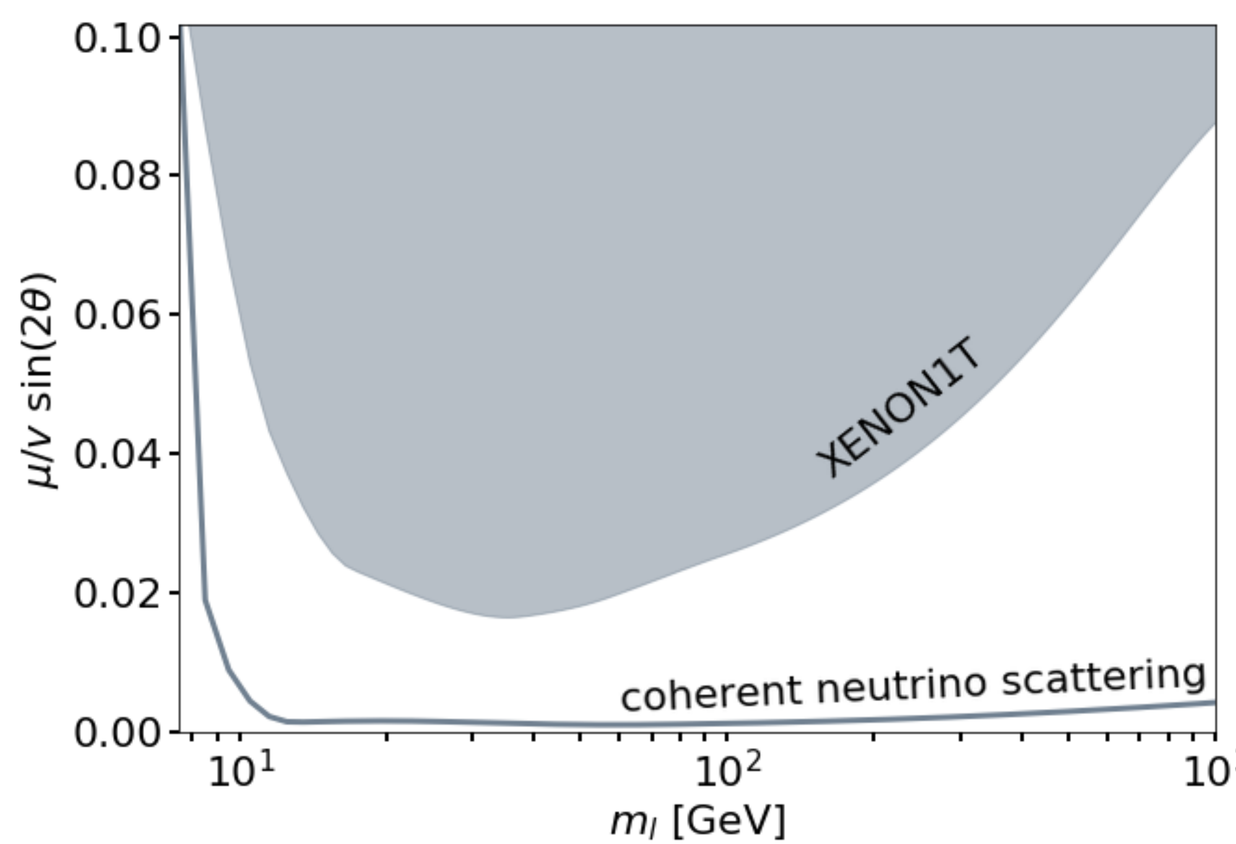

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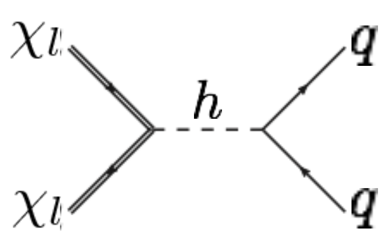

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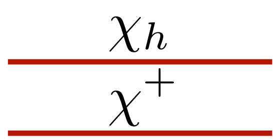

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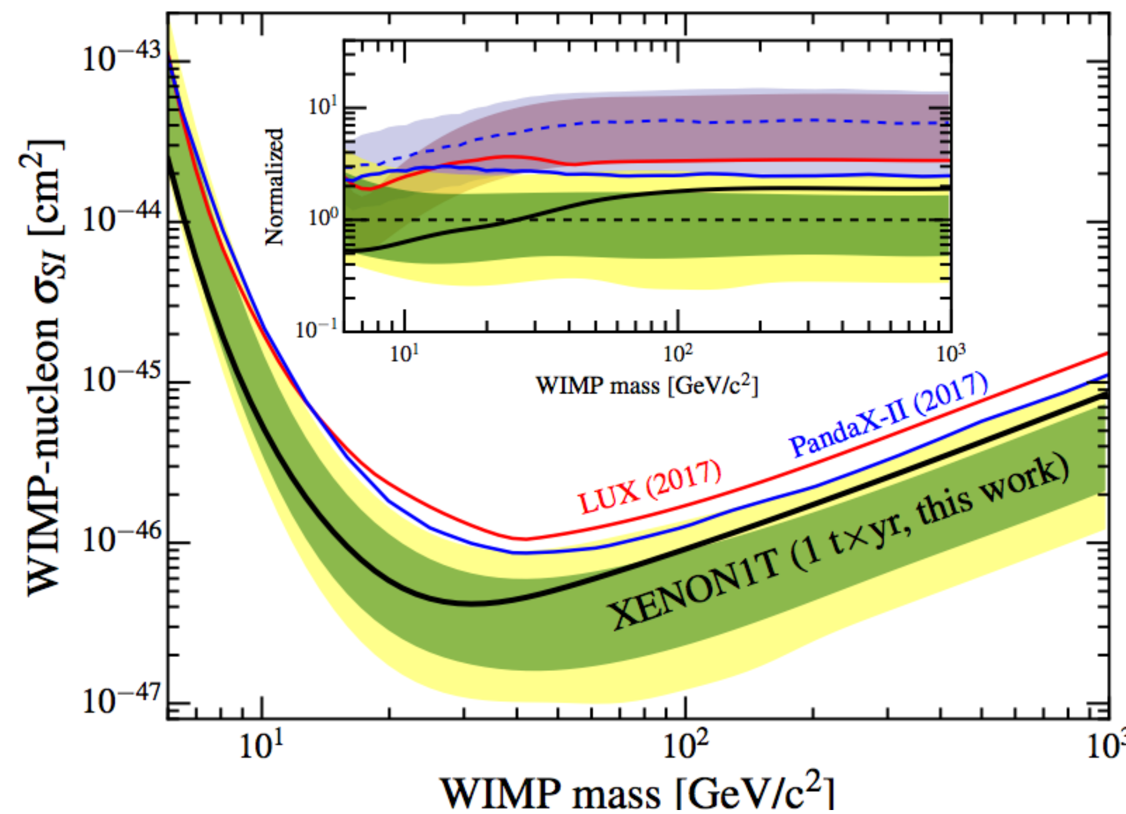
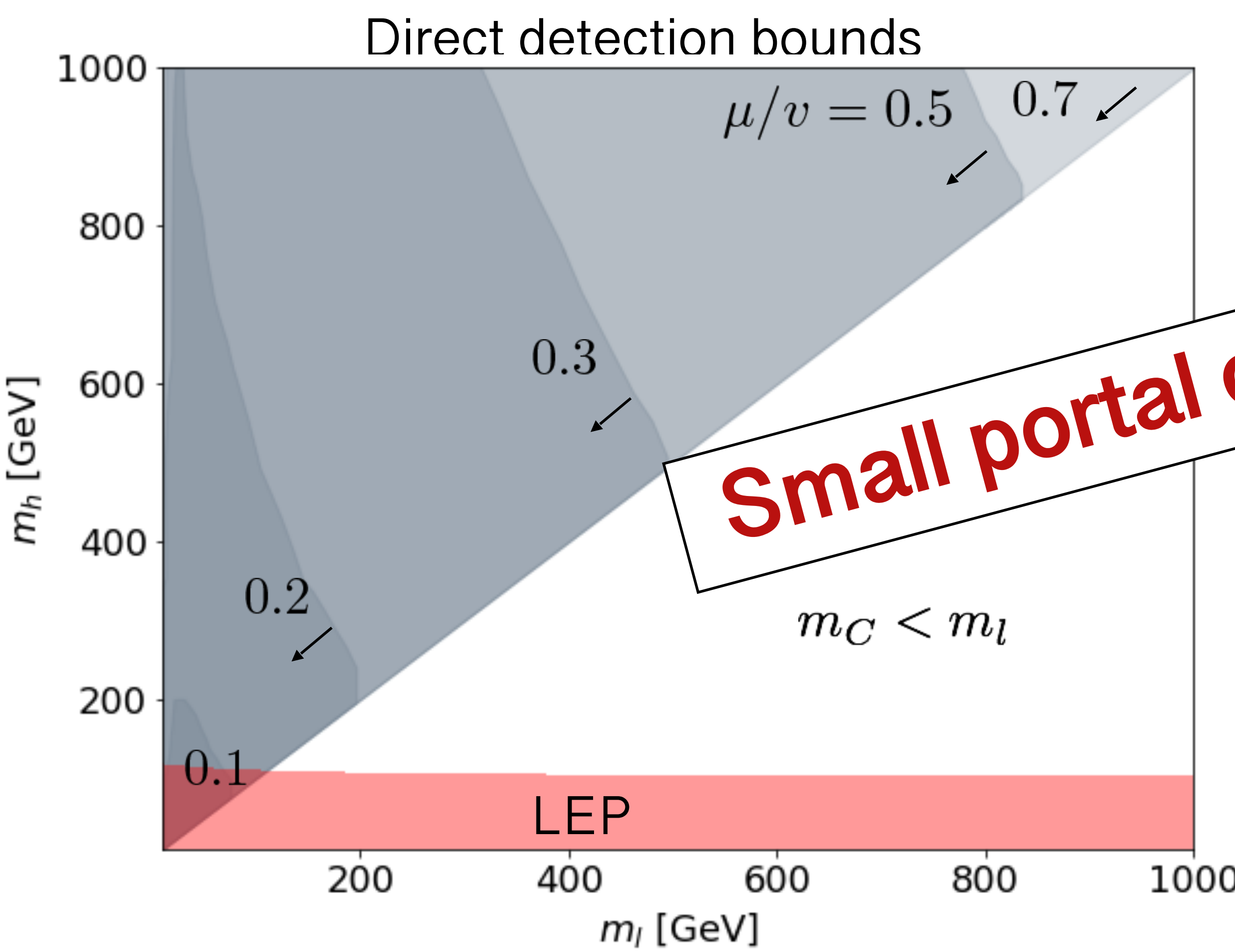
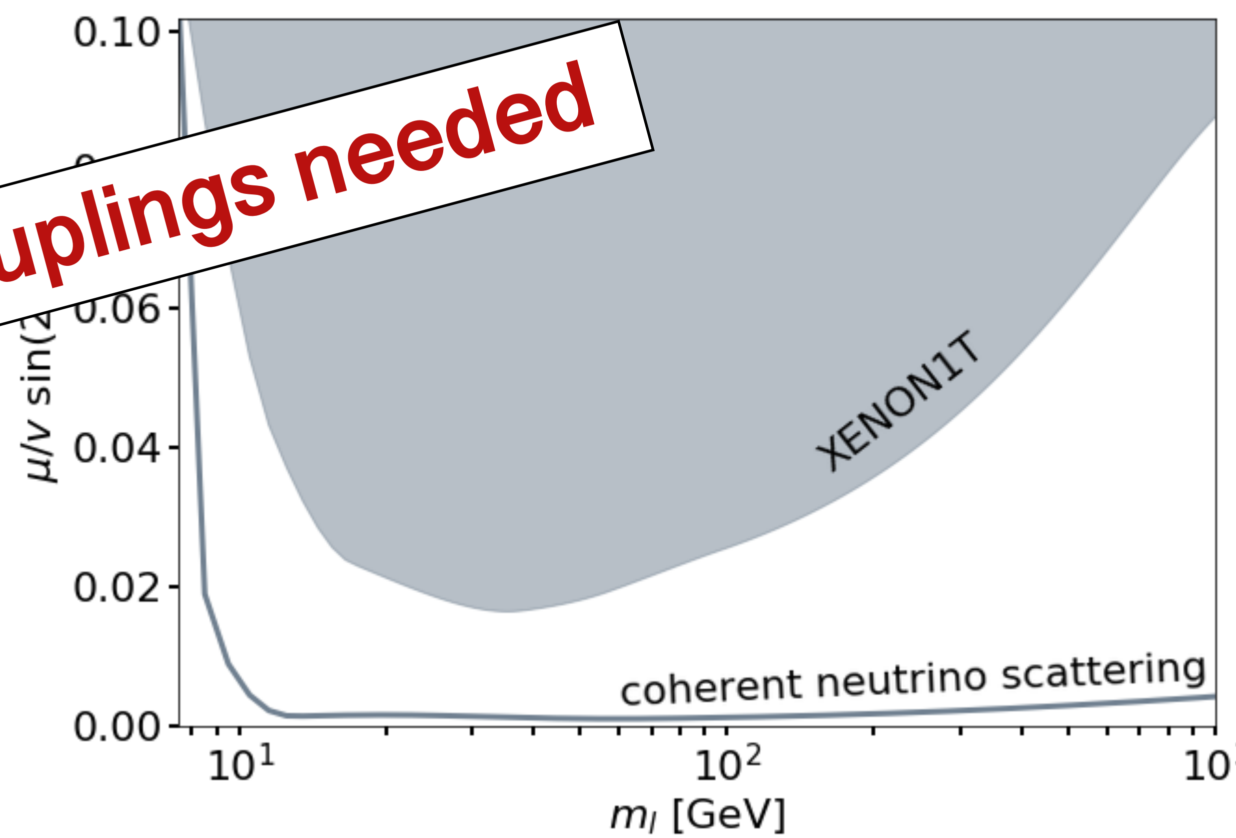
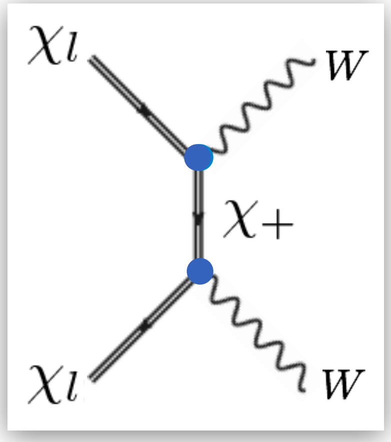






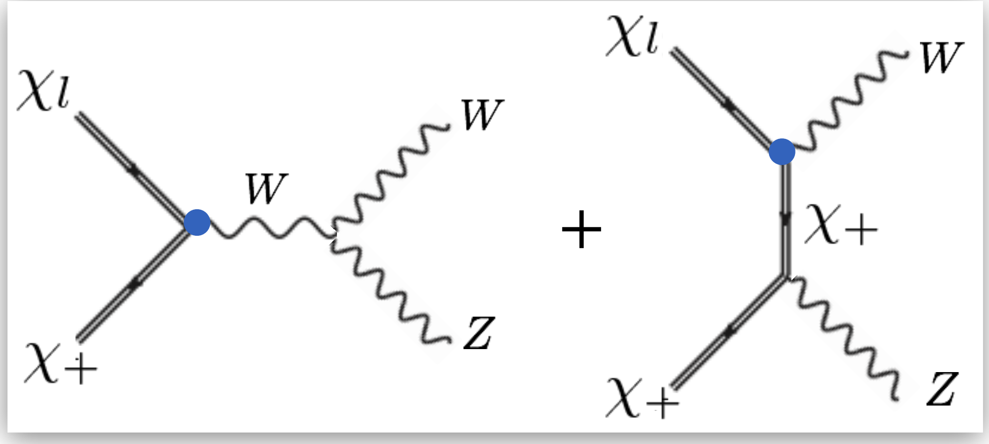
Small portal couplings needed

Surviving regions: scalar case



$(g \sin\theta)^4$

Annihilation



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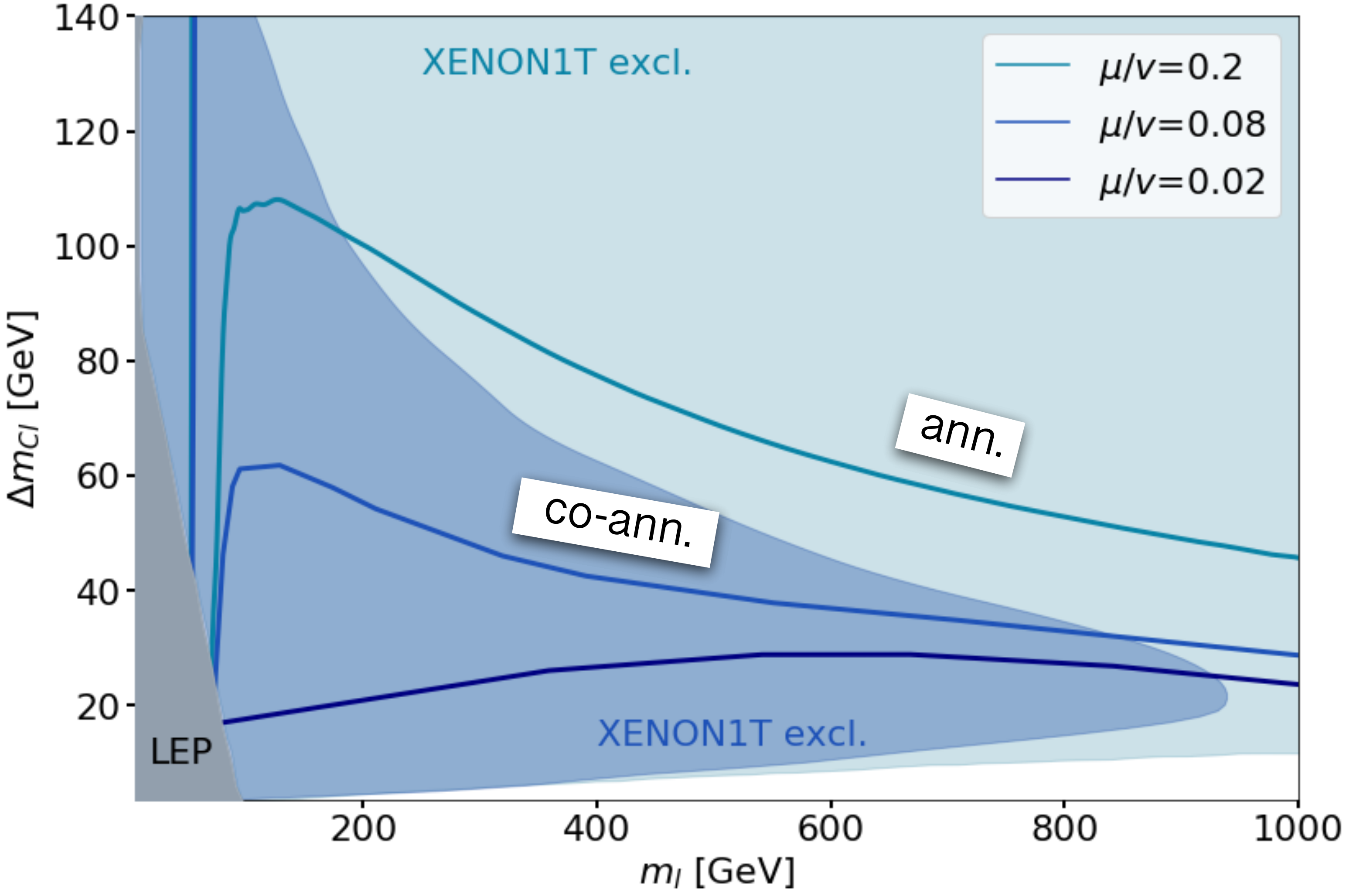
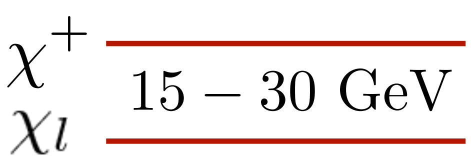
Co-annihilation

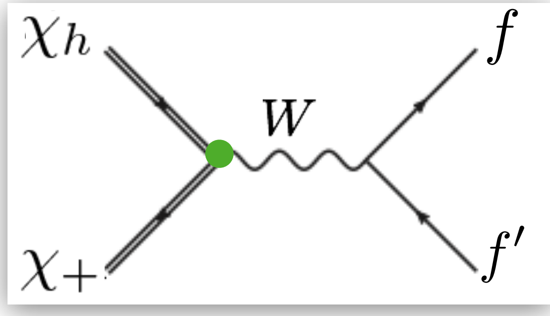




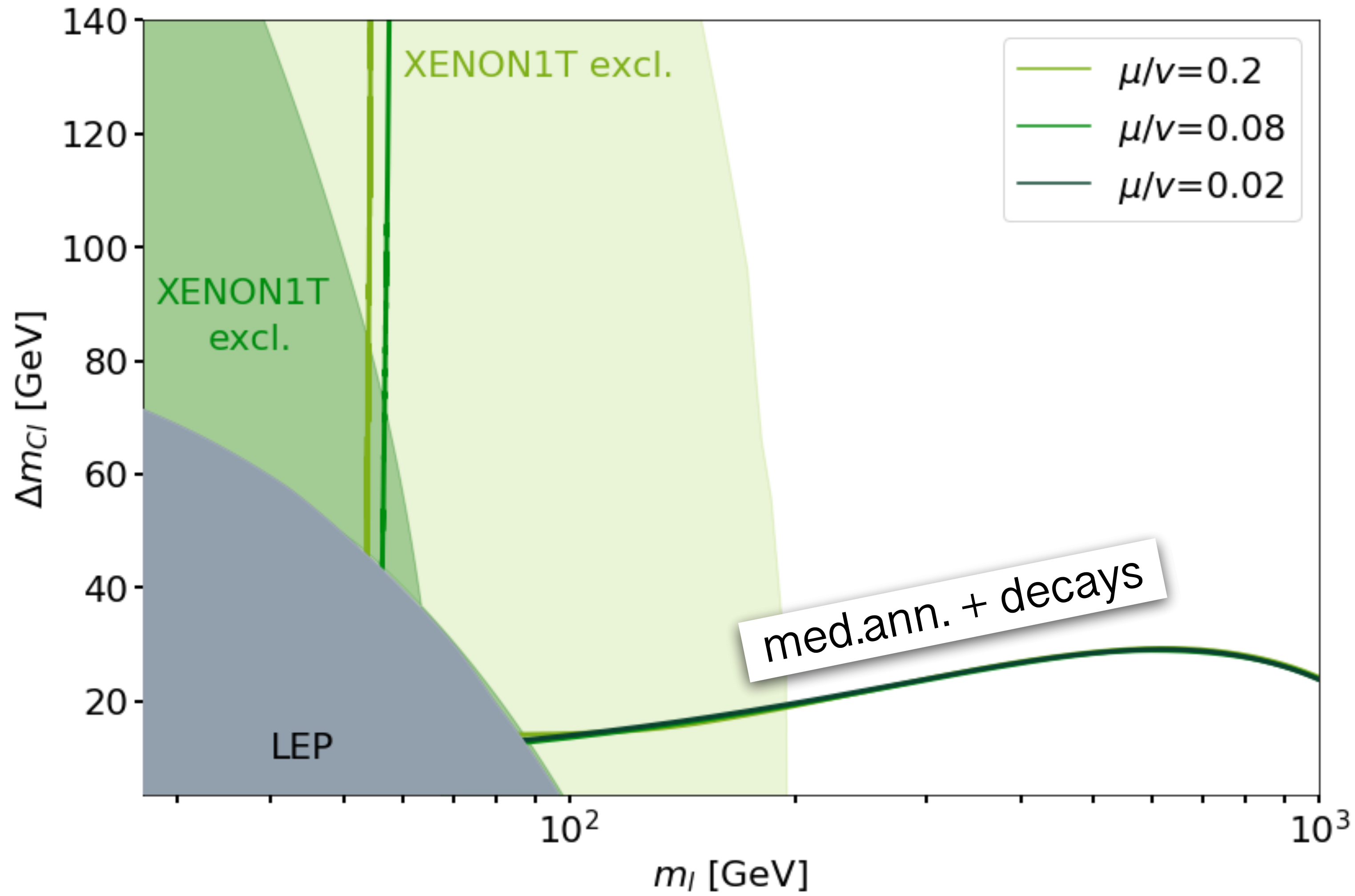
Lines: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$ [Planck coll., 1502.01589]

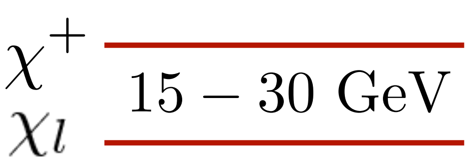
Surviving regions: pseudoscalar case

Mediator annihilation + further decays to χ_l



$(g \cos\theta)^2$





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Warning: co-scattering regime

Small portal

	process	scaling		process	scaling
pair annihilation	$\chi_\ell\chi_\ell \to W^+W^-$ $\chi_\ell\chi_\ell \to h^* \to f\bar{f}, VV$ $\chi_\ell\chi_\ell \to hh$	$(g\sin\theta)^4$ $(\mu\sin(2\theta)/v)^2$ $(\mu\cos(2\theta)/v)^4$	mediator annihilation	$\chi_h\chi_h \to W^+W^-$ $\chi_h\chi^+ \to f\bar{f}', VV$ $\chi^+\chi^- \to f\bar{f}, VV$	$(g\cos\theta)^2$ $(g\cos\theta)^2$ g^2
co-annihilation	$\chi_\ell\chi^+ \to f\bar{f}', VV$ $\chi_\ell\chi_h \to W^+W^-$ $\chi_\ell\chi_h \to h^* \to f\bar{f}, VV$	$(g\sin\theta)^2$ $(g\sin\theta)^2$ $(\mu/v)^2$	mediator decays	$\chi^+ \to \chi_\ell f\bar{f}'$ $\chi_h \to \chi_\ell f\bar{f}$	$(g\sin\theta)^2$ $(\mu/v)^2$
co-scattering	$\chi_\ell f \to \chi^+ f'$ $\chi_\ell f \to \chi_h f$	$(g\sin\theta)^2$ $(\mu/v)^2$	scattering	$\chi_\ell f \to \chi_\ell f$	$(\mu\sin\theta/v)^2$

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- Decays become very slow
- Mediators are still in chemical equilibrium
- Equilibrium is lost for dark matter
- Relic abundance is set by co-scattering + mediator annihilation

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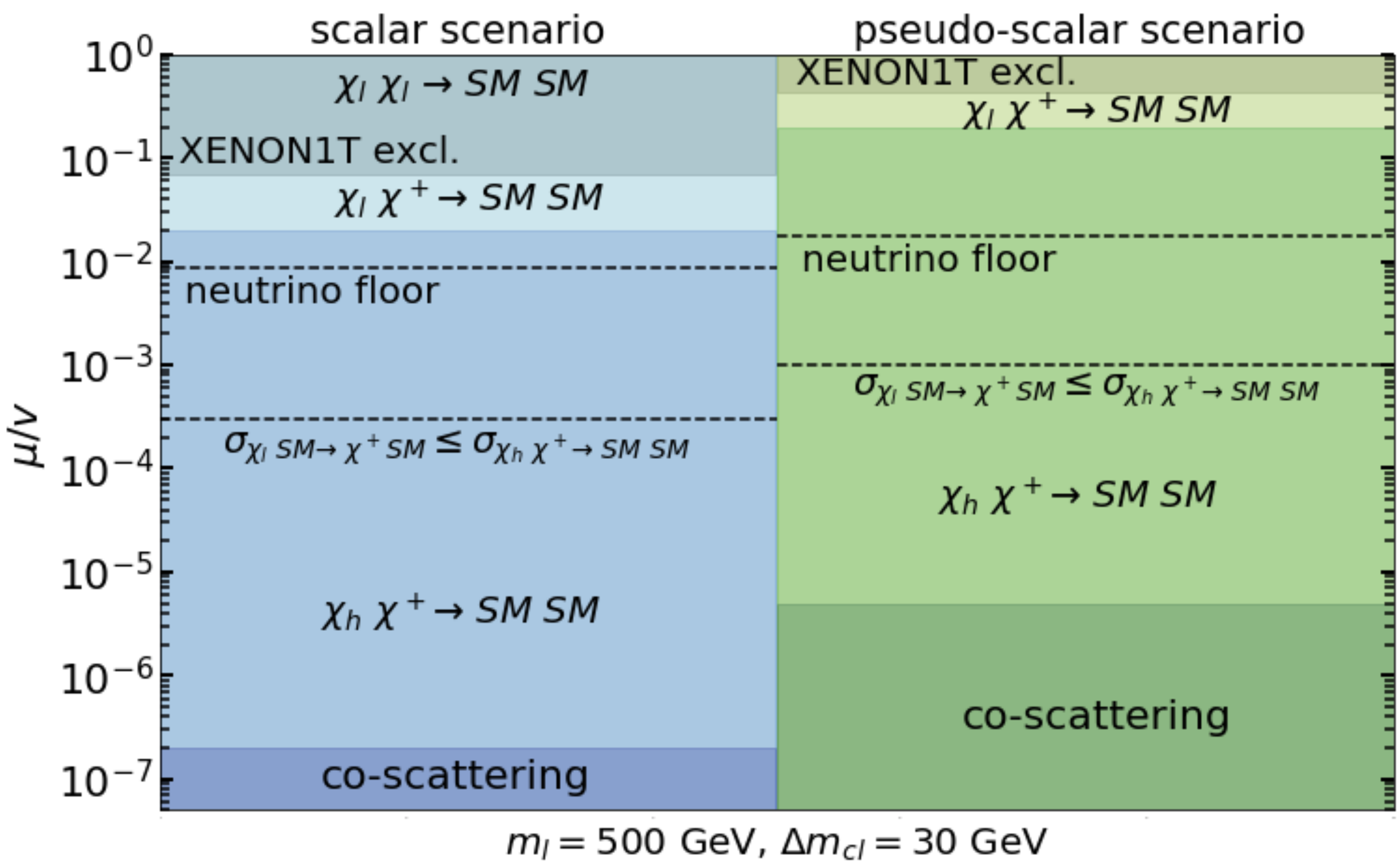
These processes are not included in public codes e.g. MicrOMEGAs!

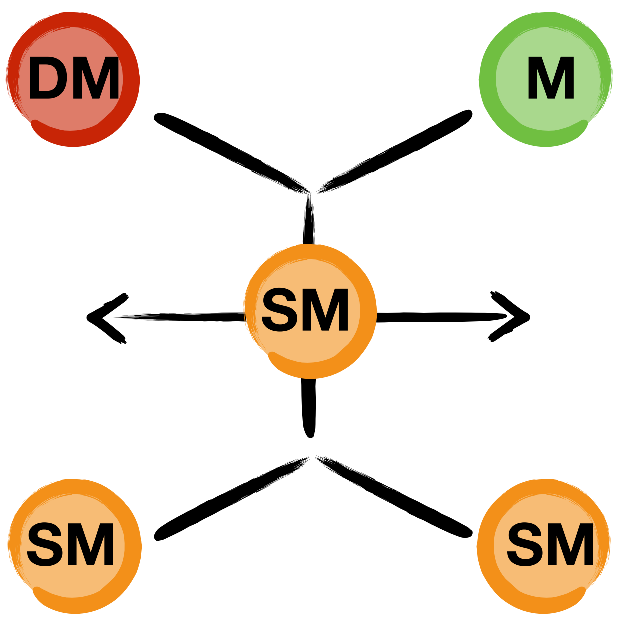
Is a common feature of theories with nontrivial dark sector in a small-coupling regime

see [1904.07513], [1705.08450] and [1705.09292] as an example

Small-coupling regime: phases



Co-scattering @ decoupling & colliders



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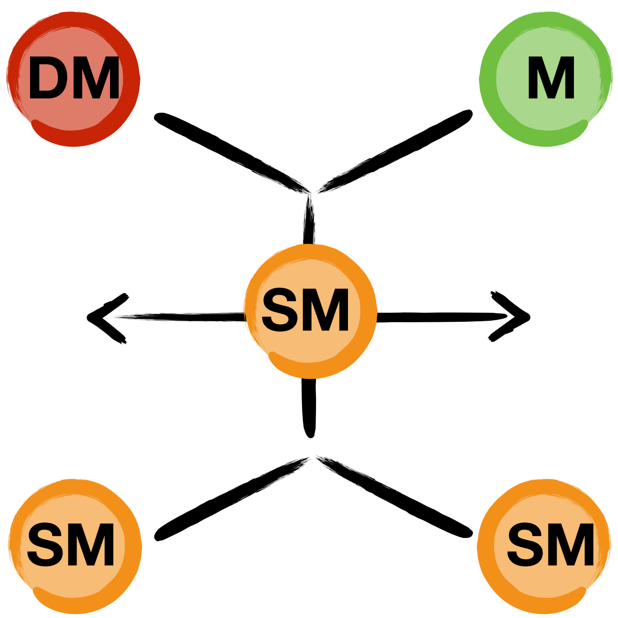

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- **But they are also long-lived at colliders!**

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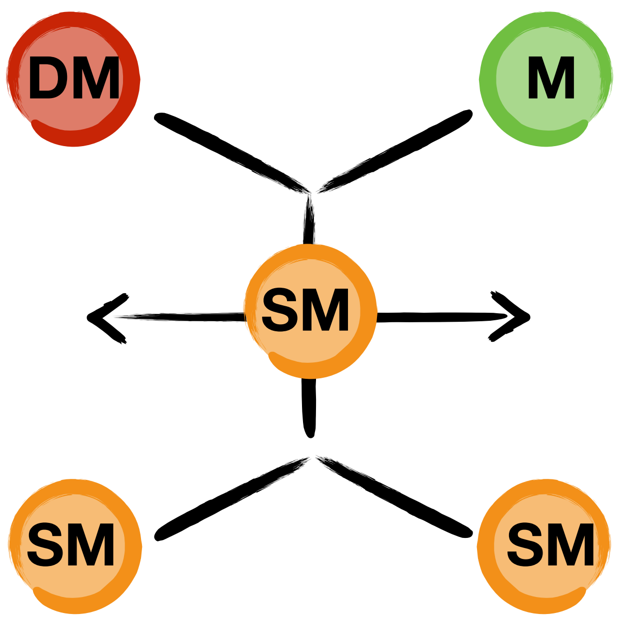

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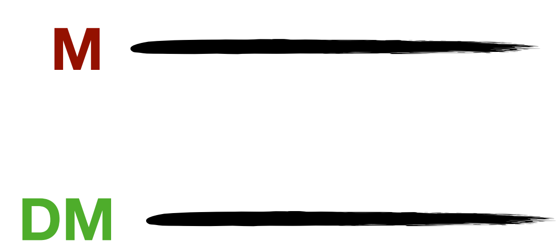
- Both dark states present at decoupling— **compressed spectrum.**

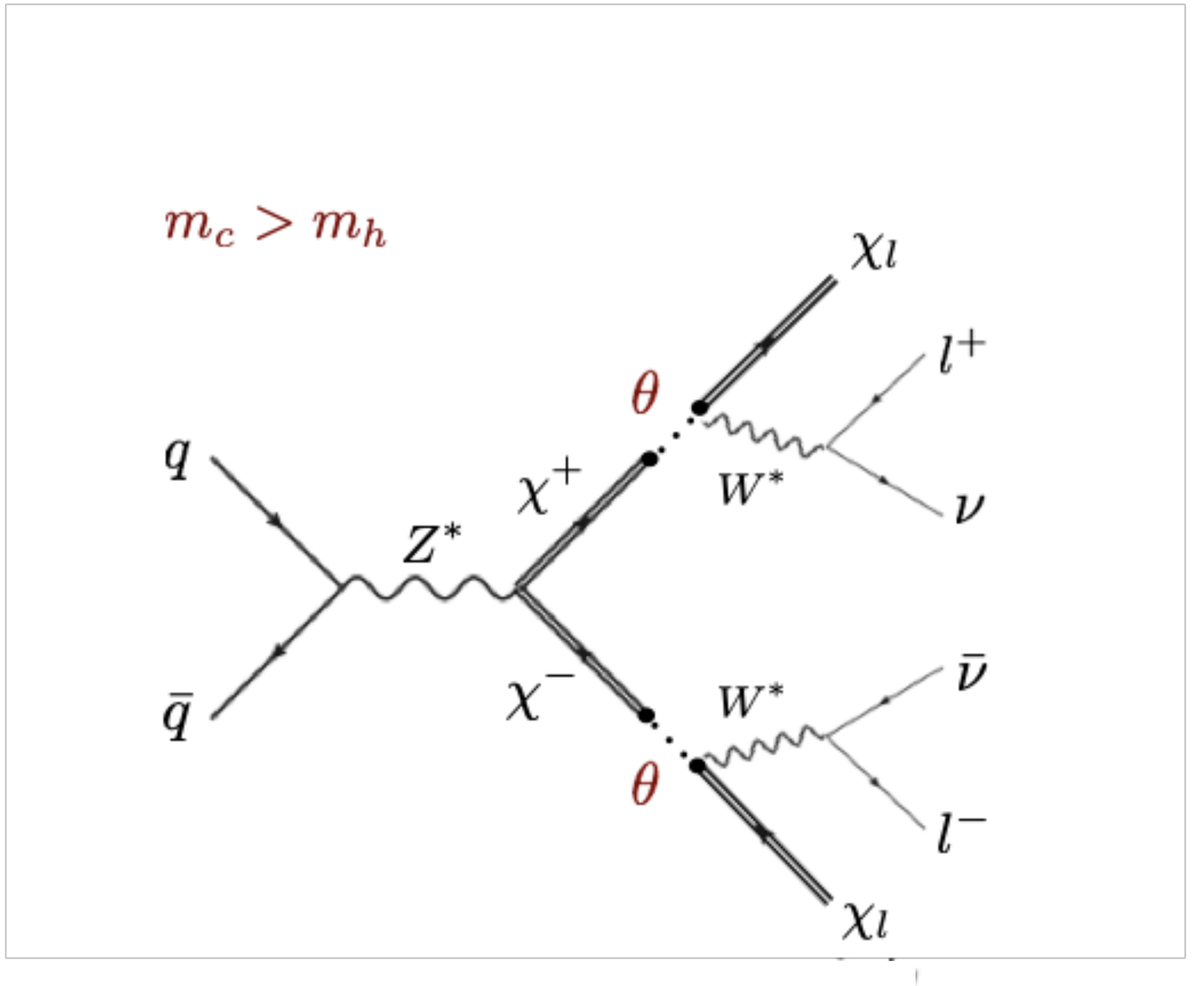


$$\frac{\Delta m}{m} \simeq 10\%$$

Soft displaced signatures @ LHC

Soft displaced signatures @ LHC

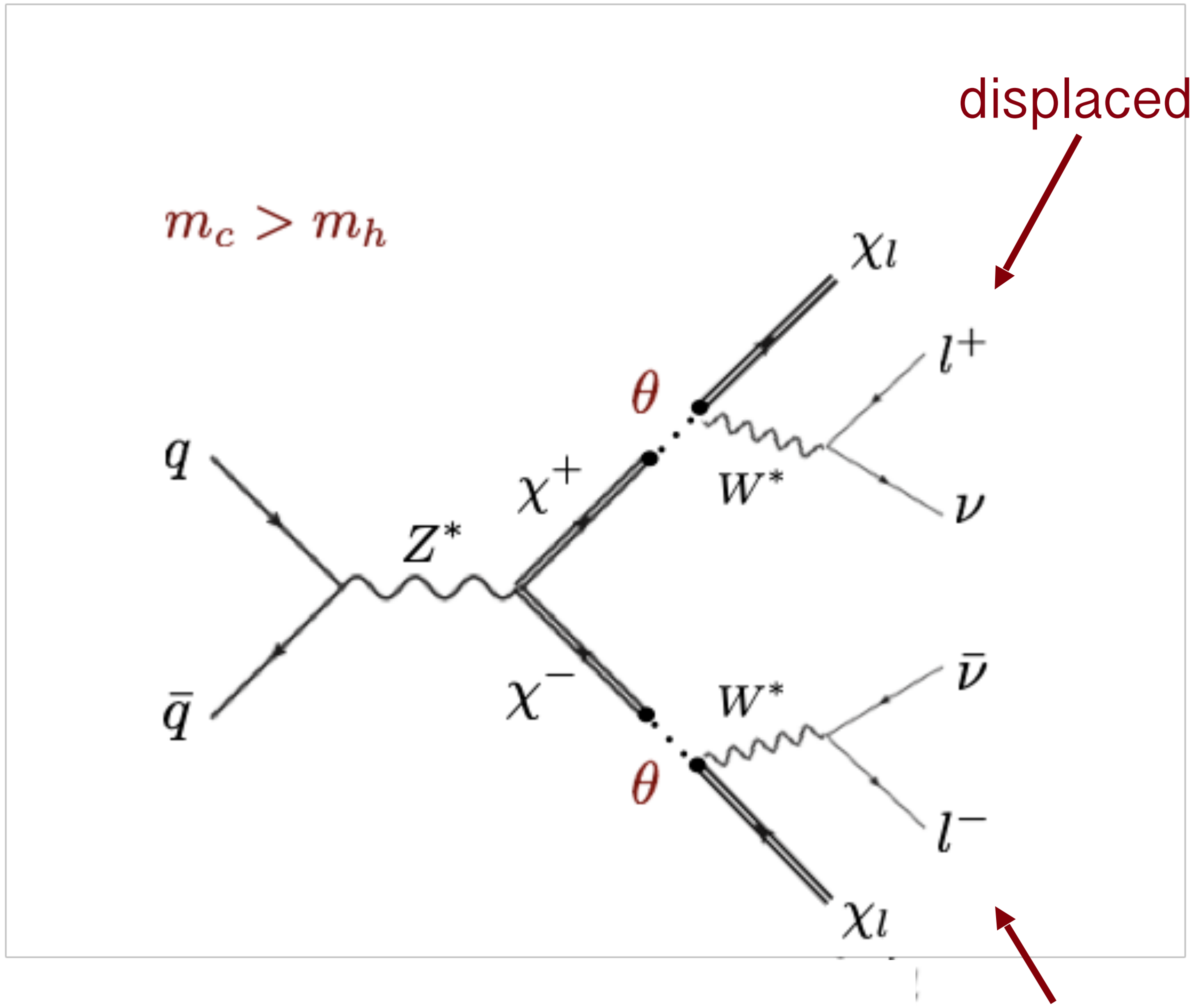
Soft displaced lepton pair



$\Delta M_{+,l} = 15 - 30$ GeV

Soft displaced signatures @ LHC

Soft displaced lepton pair



$\Delta M_{+,l} = 15 - 30$ GeV

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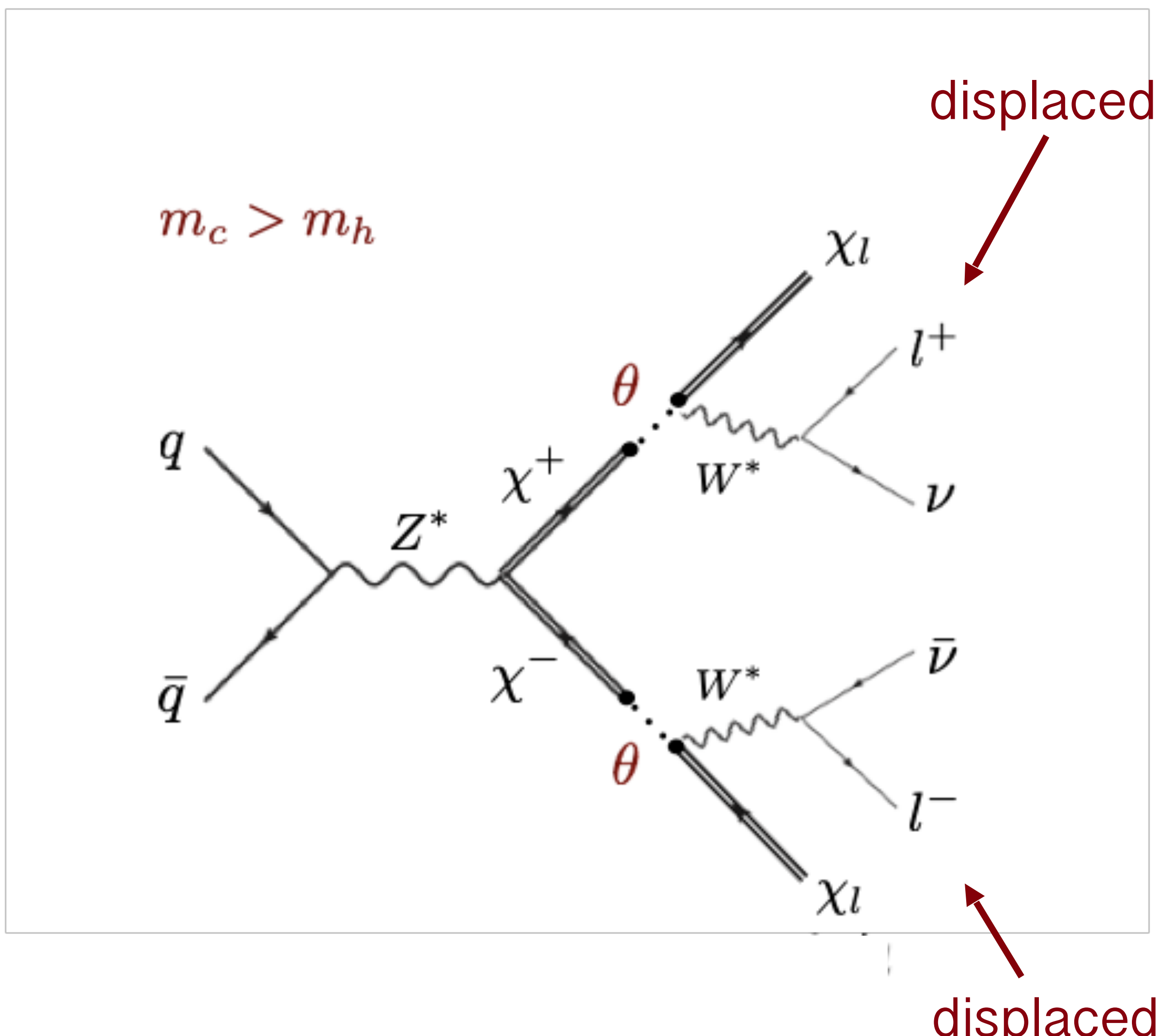
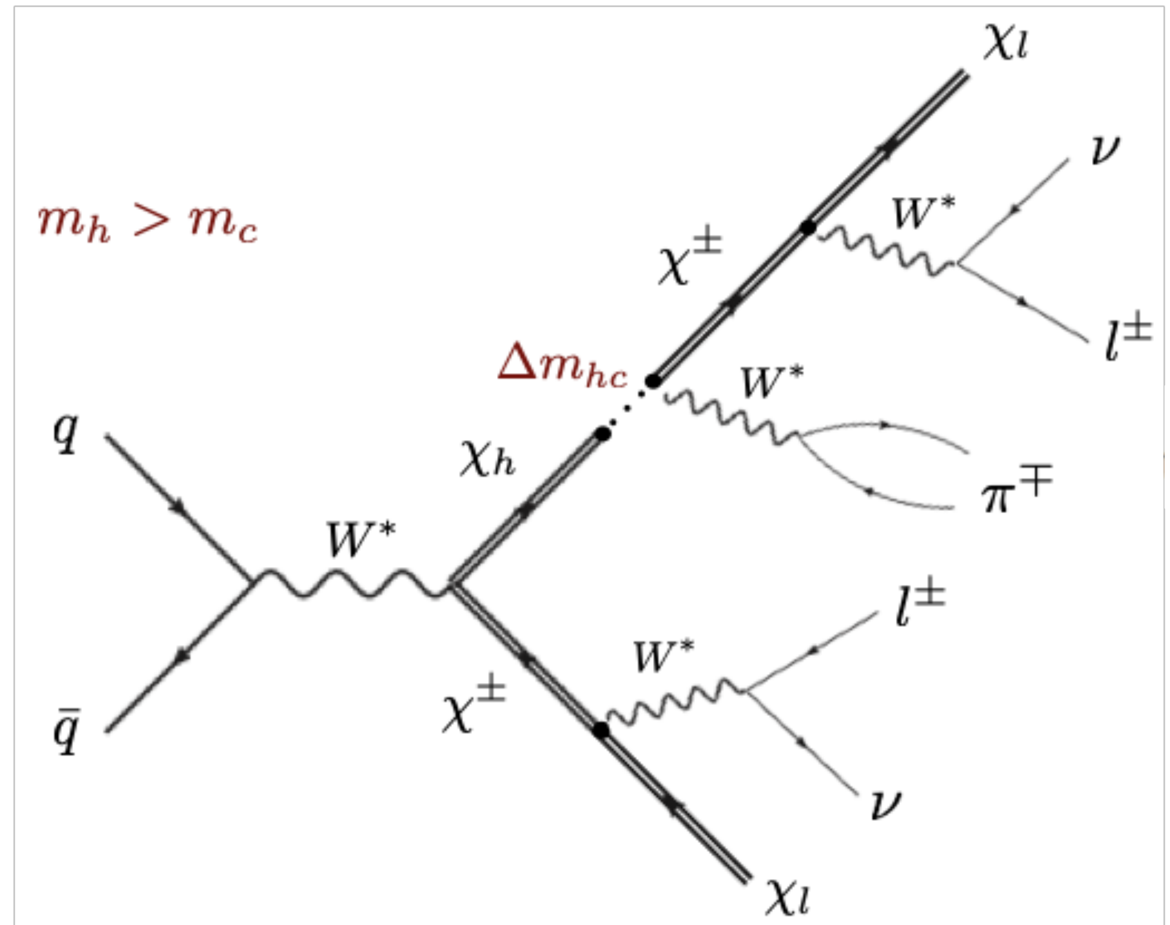


$\Delta M_{+,l} = 15 - 30$ GeV

Displaced soft leptons + prompt jets



$\Delta M_{+,l} = 15 - 30$ GeV

$\Delta M_{+,h}$ arbitrarily small

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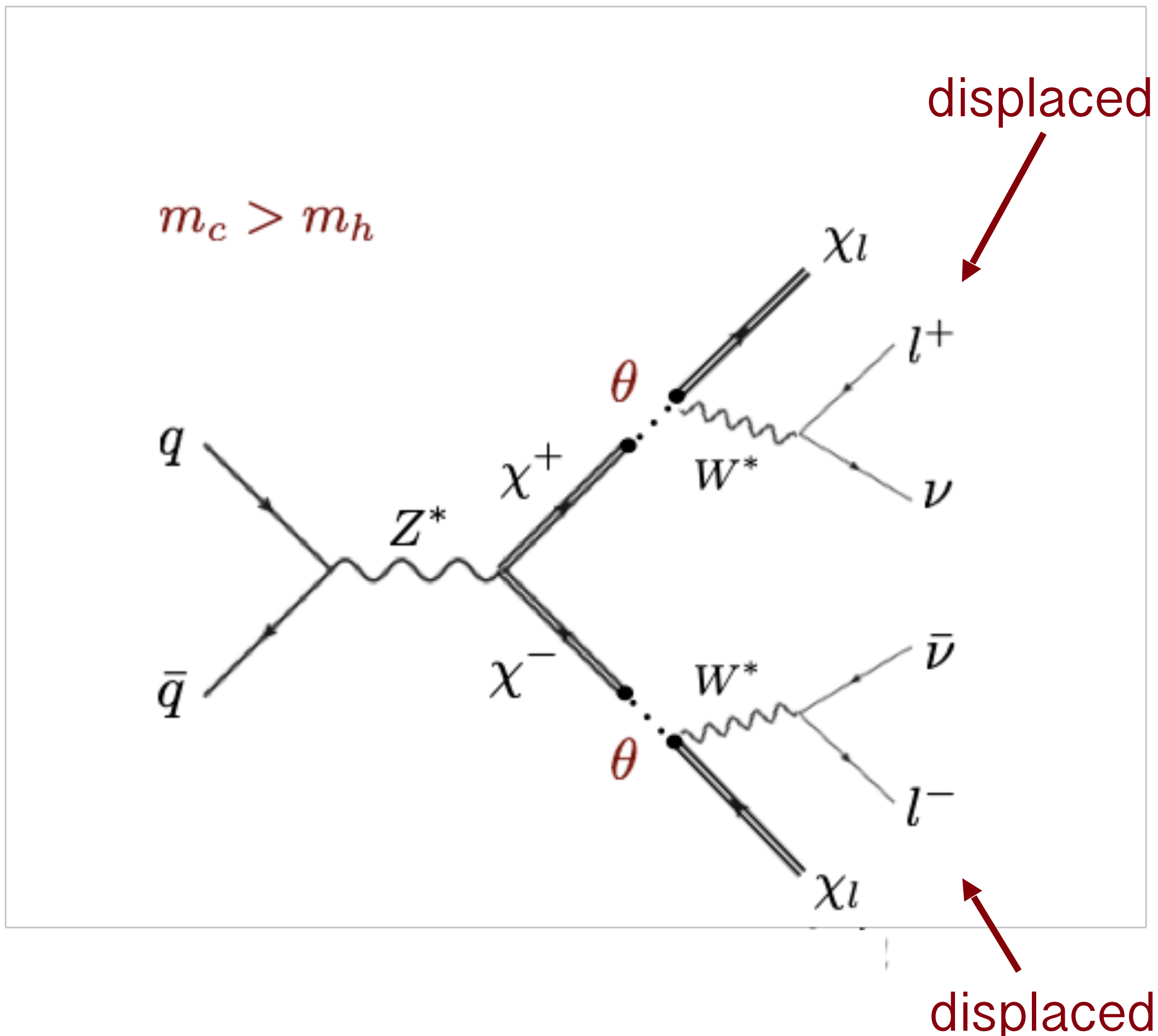

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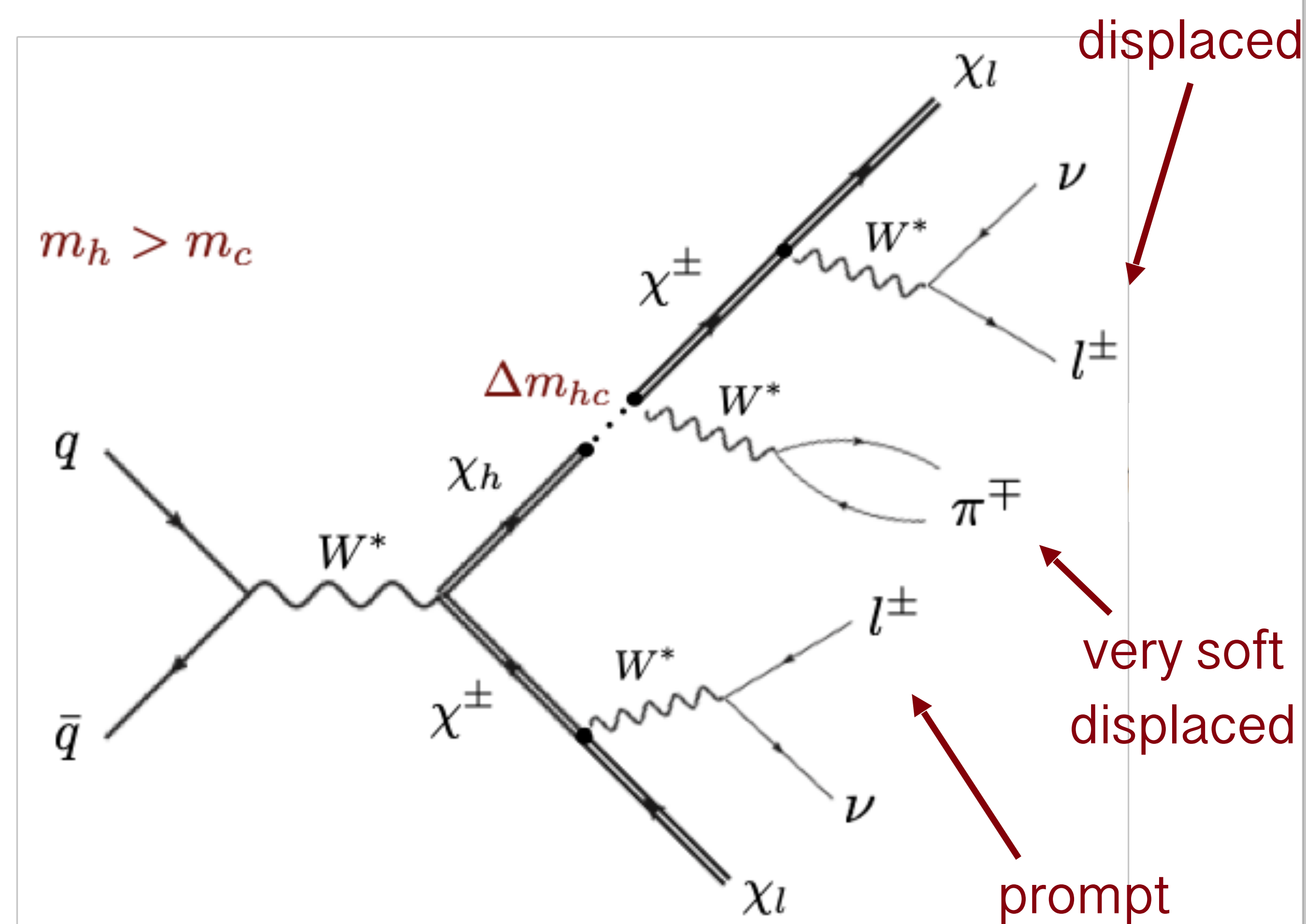

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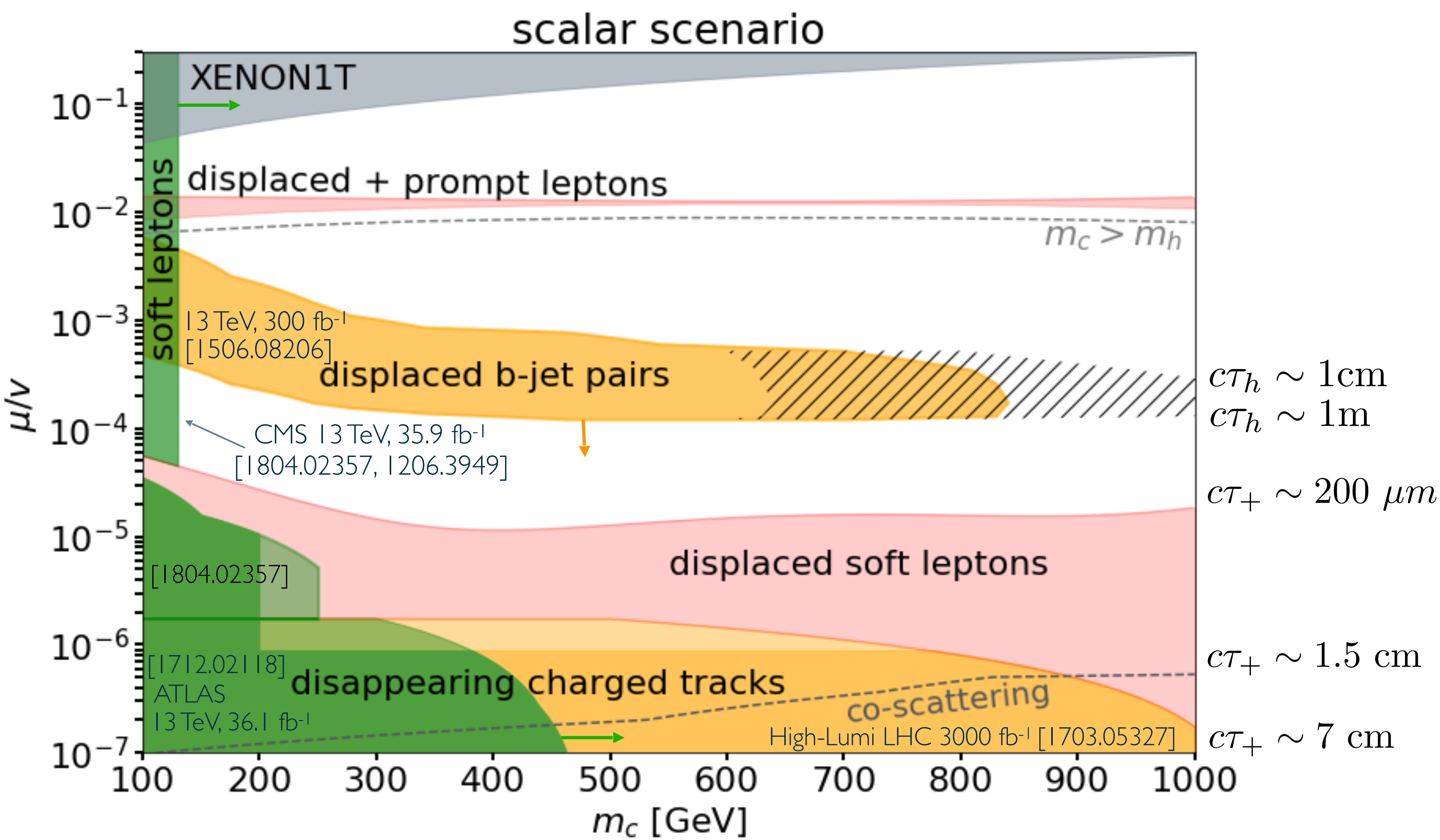
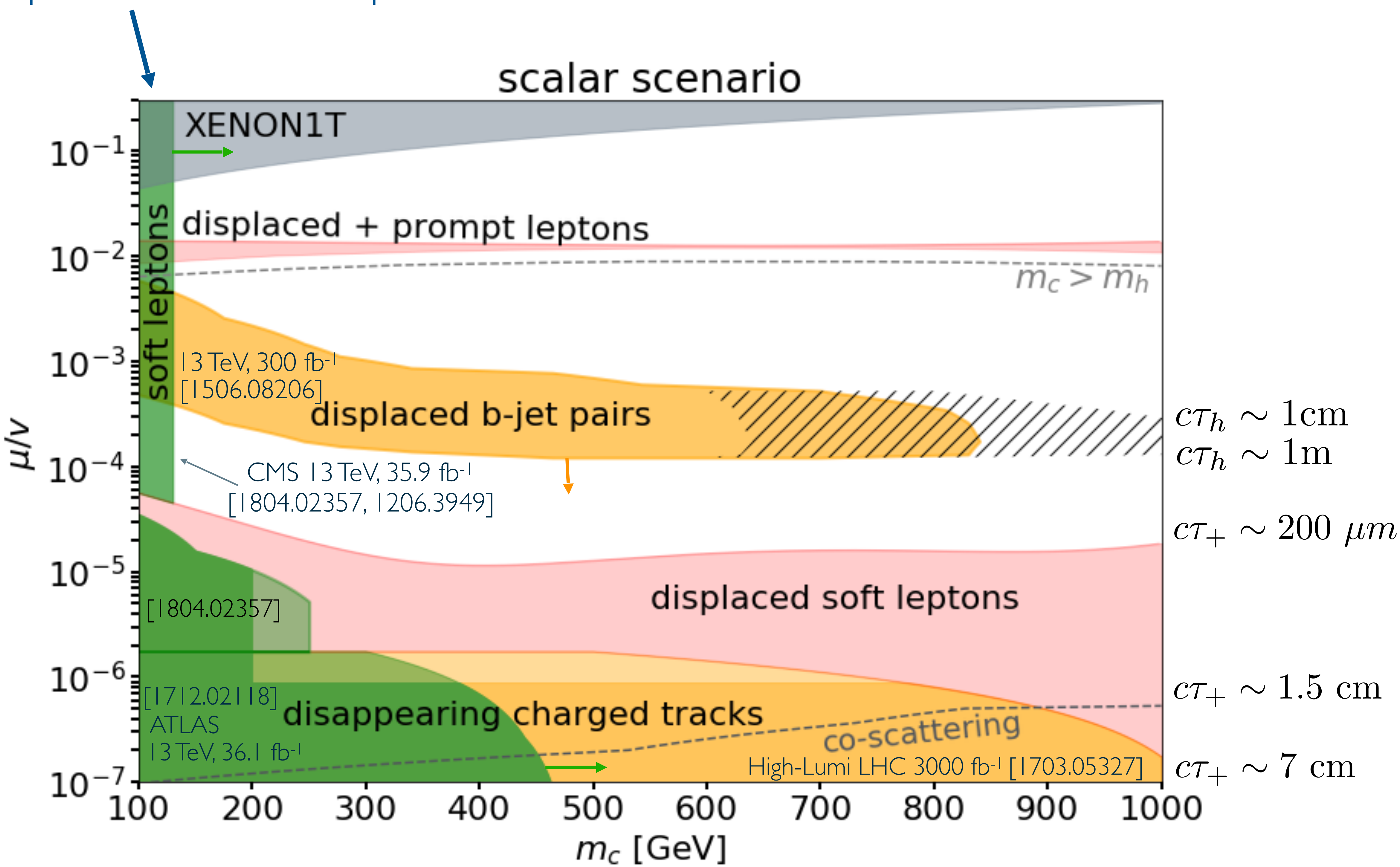
Collider searches

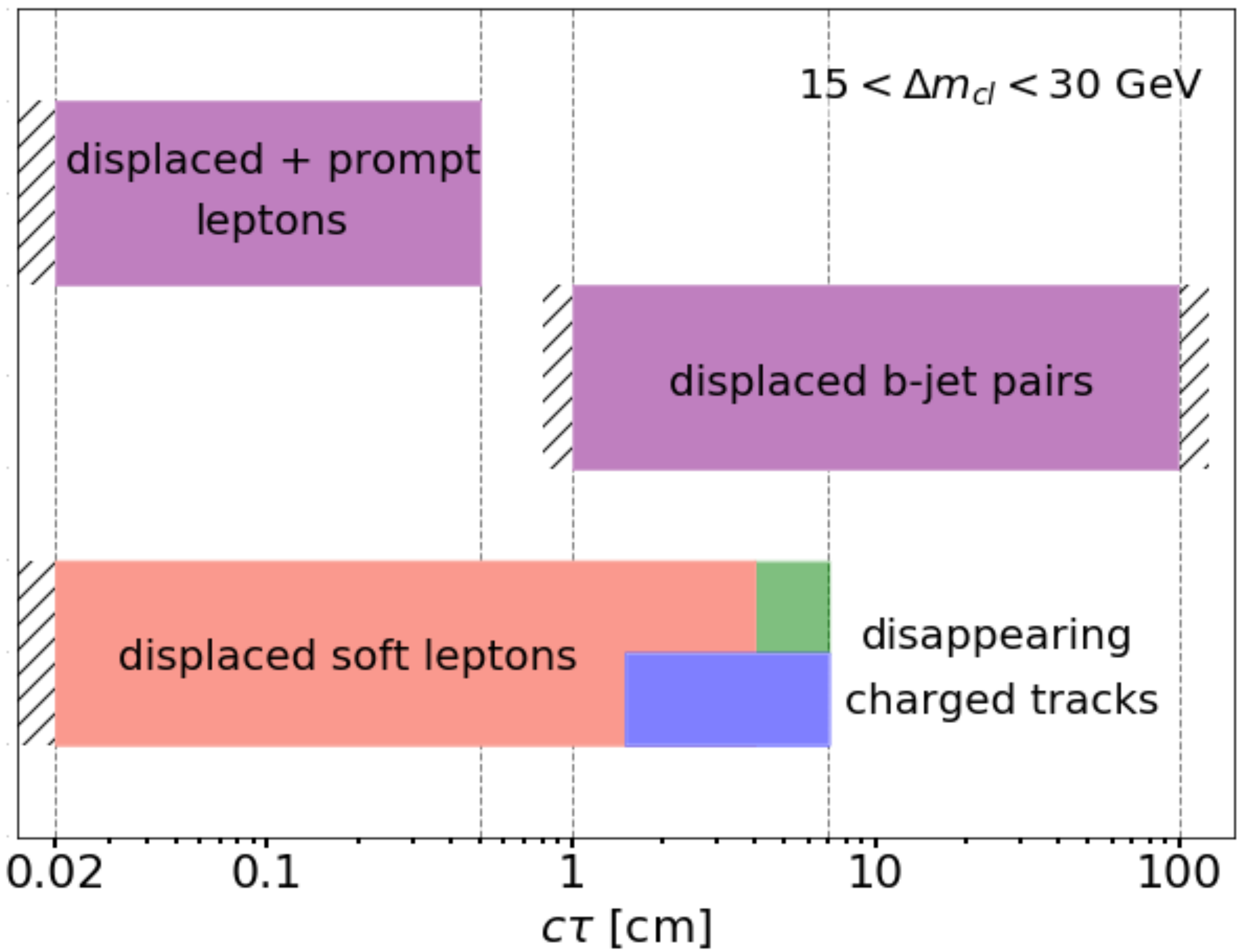


Collider searches

Prompt searches can not help



Lifetimes accessible @ LHC



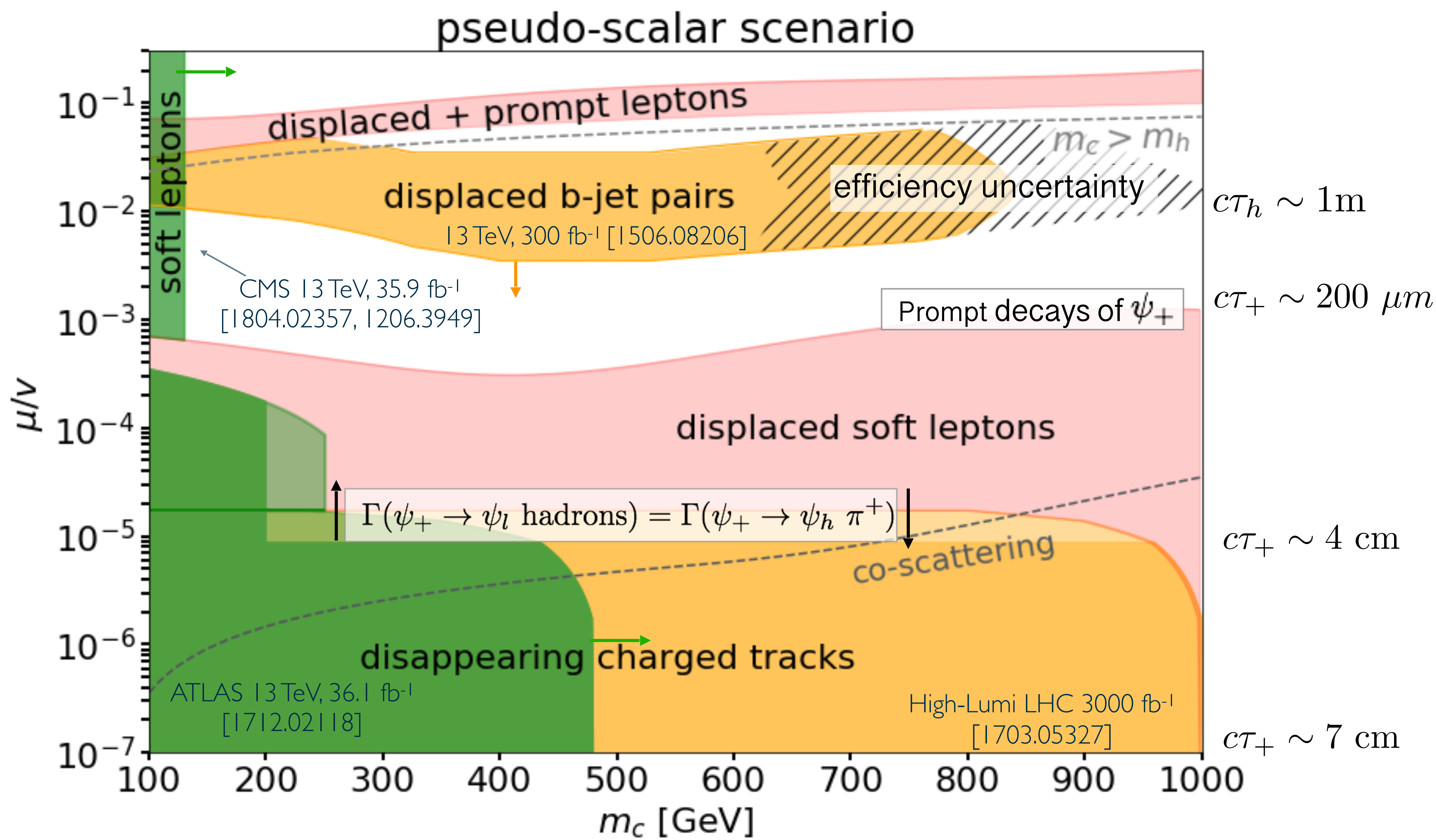
Summary

- The singlet-triplet Higgs portal is a minimal fermionic extension to the SM weak sector with a naturally small coupling.
- There are two physical scenarios in this model: with scalar (vector) and pseudo-scalar (axial-vector) couplings to Higgs (W bosons) which are phenomenologically different.
- Due to strong direct detection constraints, the thermal relic abundance of dark matter is set by mediator annihilation and co-scattering processes.
- This also leads to a natural appearance of the long-lived states. The most promising collider signatures involve displaced particles.
- New searches are needed to conclusively test this scenario: displaced soft leptons, appearing tracks, etc.

Thank you!

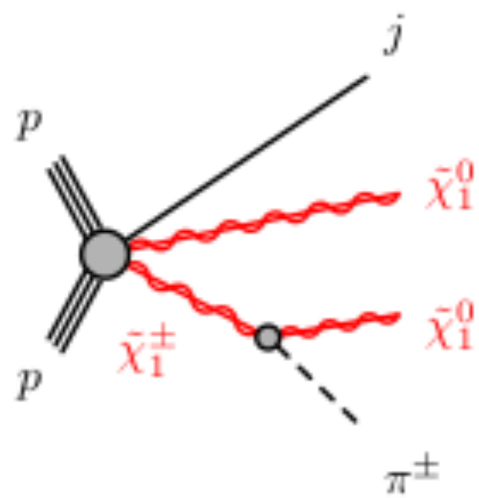
Backup slides

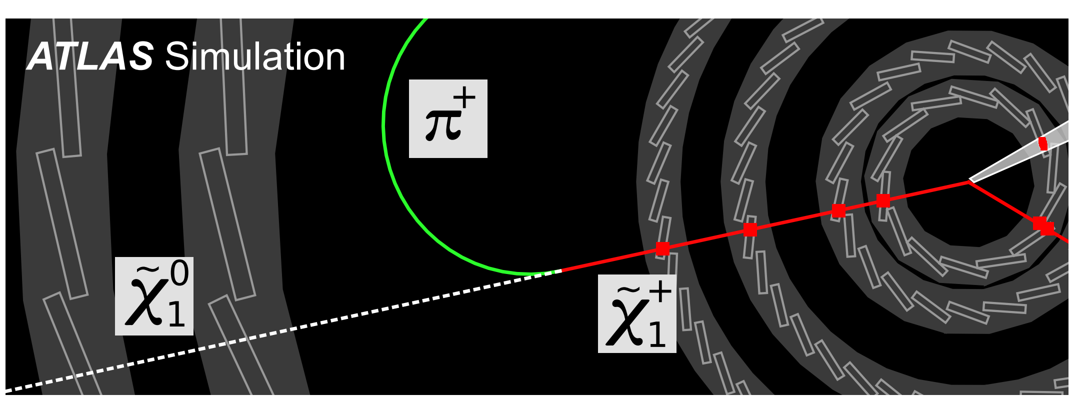
Collider searches

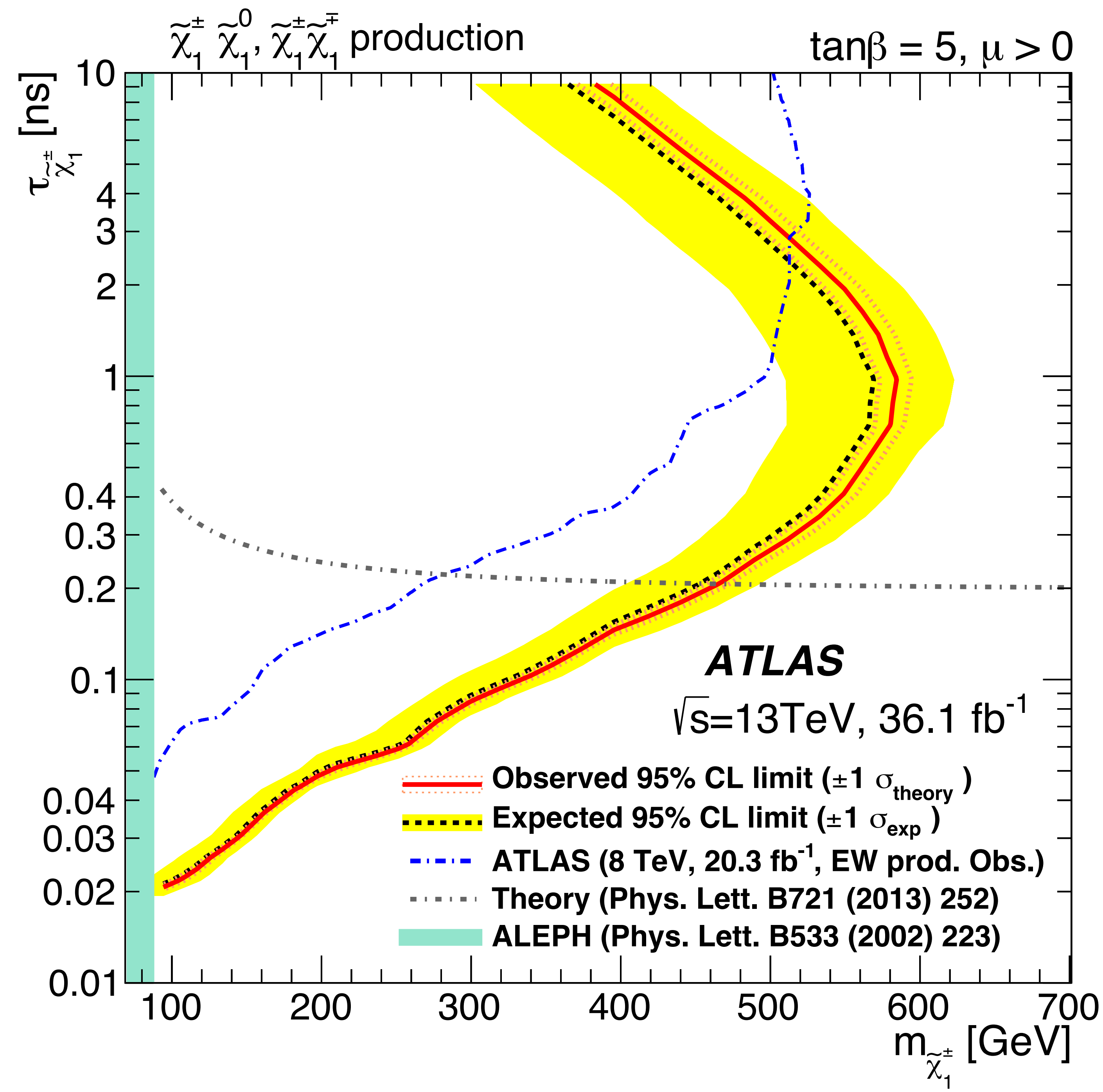


Disappearing charged tracks

Charged mediator leaves track in the inner detector

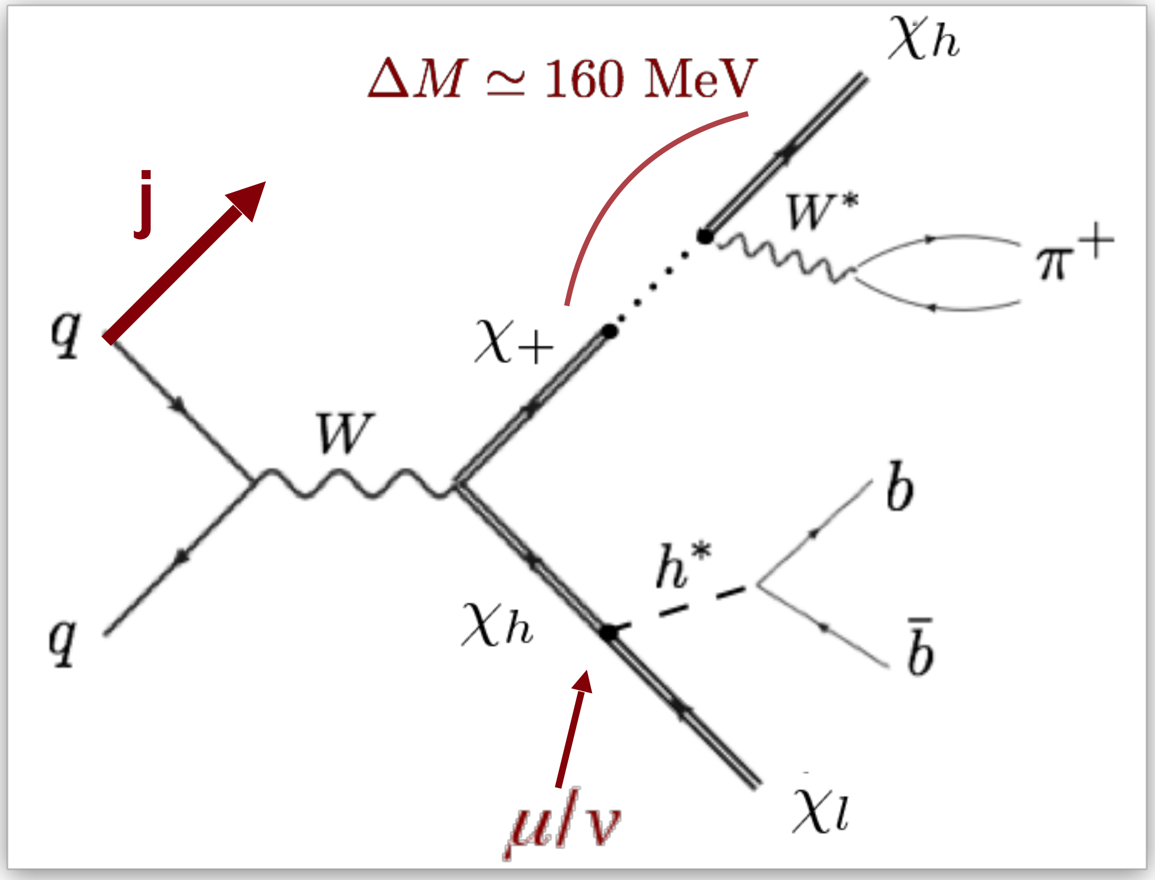






ATLAS [1712.02118]

LHC: prompt and displaced soft particles

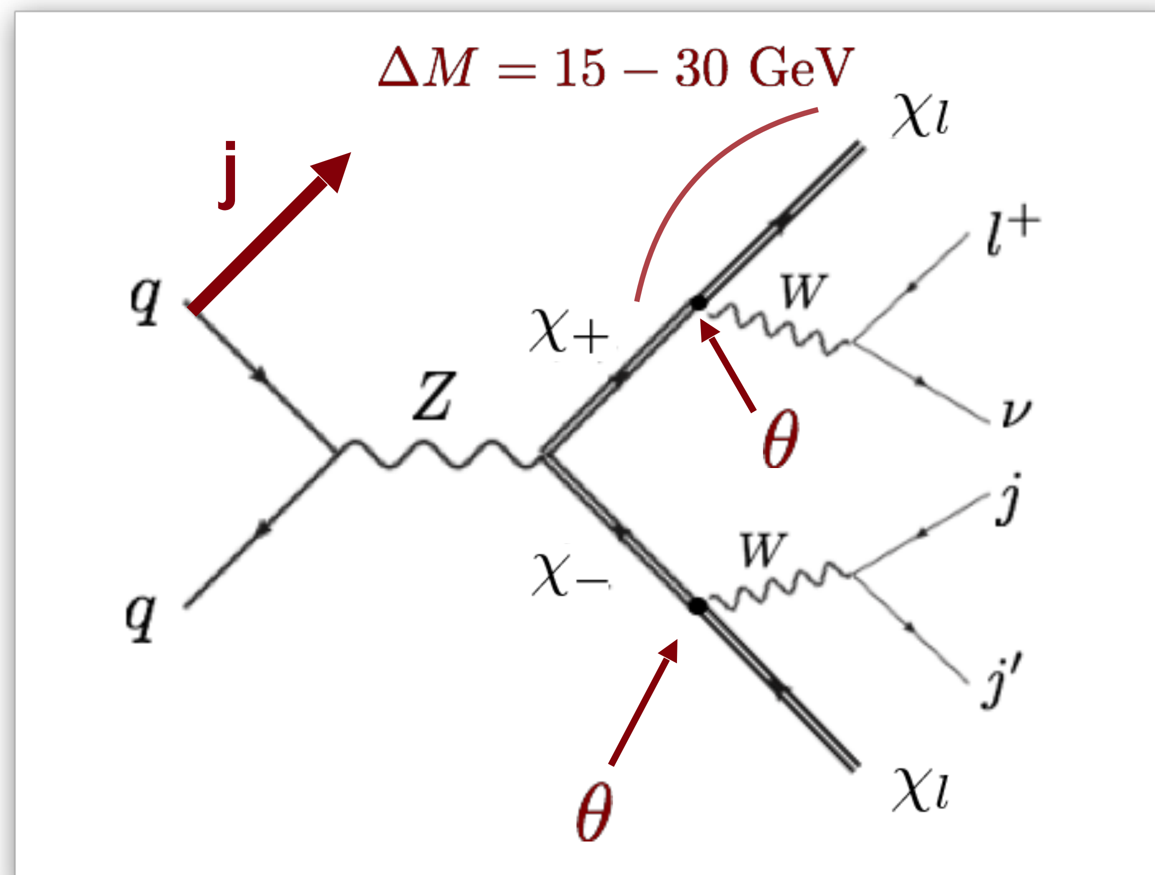


Disappearing charged tracks

ATLAS [1712.02118]
Mahbubani, Schwaller, Zurita [1703.05327]

Soft leptons

Bharuchaa, Brümmer, Desai [1804.02357]
CMS [1206.3949]



Displaced jets

Nagata, Otono, Shirai [1506.08206]

Going to the mass basis: two cases

Scalar scenario

$$m_S > \mu^2/m_T$$

$$\begin{pmatrix} \chi_\ell \\ \chi_h \end{pmatrix} = \begin{pmatrix} \cos\theta\, \chi_S^0 - \sin\theta\, \chi_T^0 \\ \sin\theta\, \chi_S^0 + \cos\theta\, \chi_T^0 \end{pmatrix}$$

$$m_{h,\ell} = \frac{1}{2}\Big(m_T + m_S \pm \Delta m_{h\ell}\Big)$$

$$m_c = m_T$$

Pseudo-scalar scenario

$$m_S < \mu^2/m_T$$

$$\begin{pmatrix} \chi_\ell \\ \chi_h \end{pmatrix} = \begin{pmatrix} \cos\theta\, \chi_S^0 + \sin\theta\, i\gamma_5 \chi_T^0 \\ \sin\theta\, i\gamma_5 \chi_S^0 + \cos\theta\, \chi_T^0 \end{pmatrix}$$

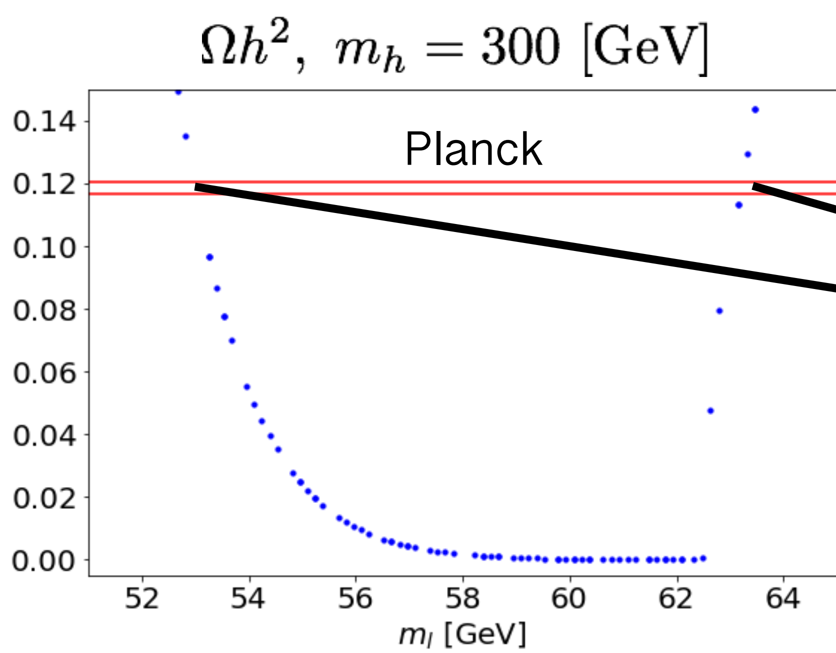
$$m'_{h,\ell} = \frac{1}{2}\Big(\Delta m_{h\ell} \pm (m_T + m_S)\Big) = \pm m_{h,\ell}$$

$$m_c = m_T$$

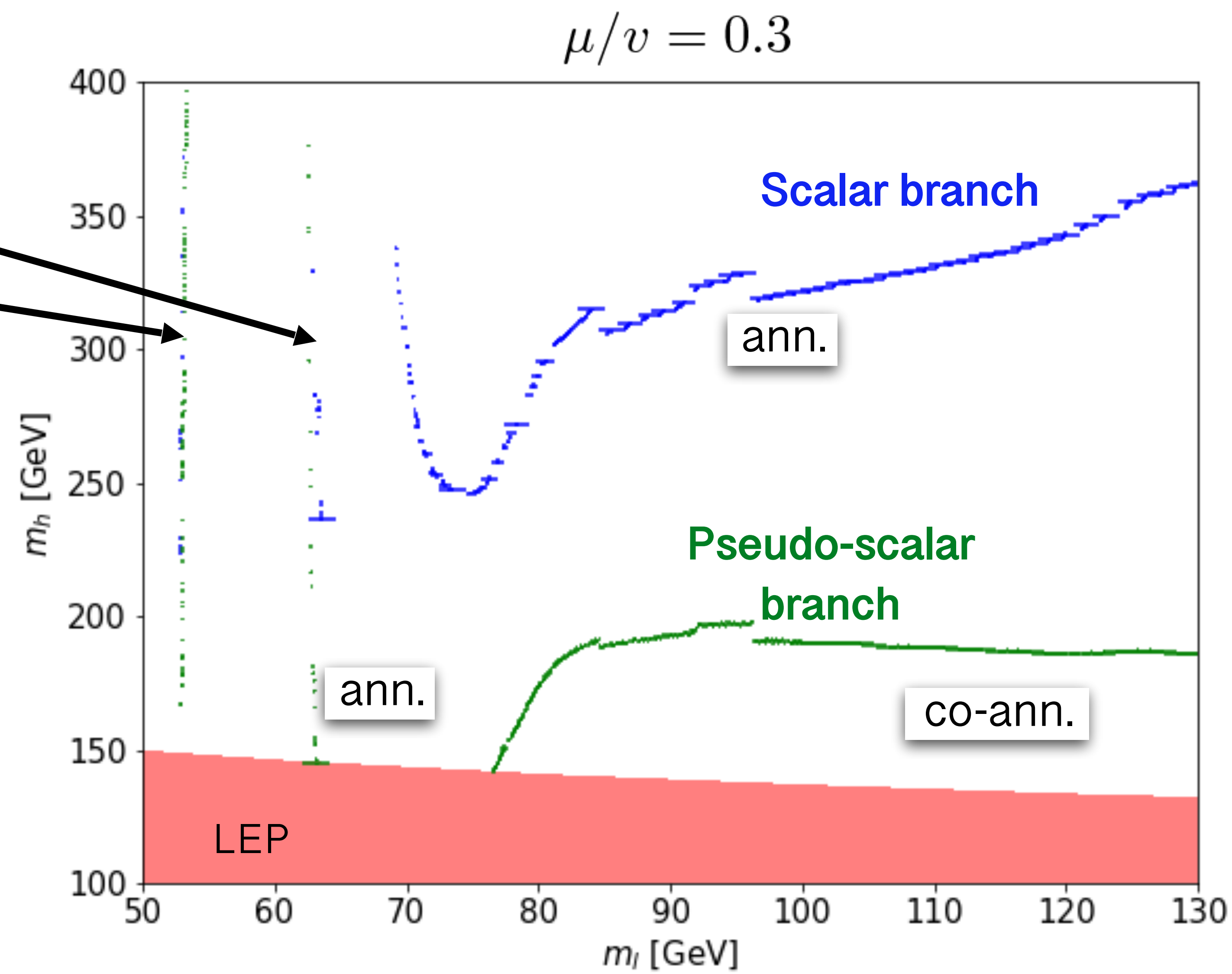
with $\Delta m_{h\ell} = \sqrt{(m_T - m_S)^2 + 4\mu^2}$ $\qquad \theta \simeq \dfrac{\mu}{m_T - m_S}$

In both scenarios $m_\ell / m'_\ell > 0$

Relic density



Higgs resonance region



$$\theta \simeq \frac{\mu}{m_T - m_S}$$

Blue/green: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$

[Planck coll., 1502.01589]

Scalar vs. Pseudo-scalar decay rates

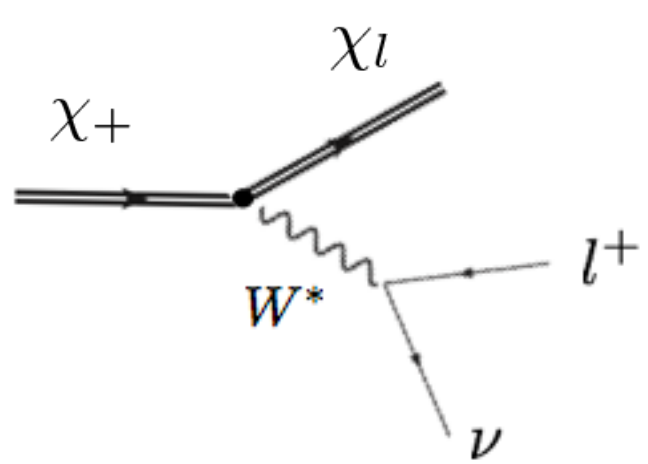
$$\Gamma_\psi = \theta^2 G_F^2 \Delta M^x \times \text{PS}$$

x: ΔM^5 (3-body) or $f_\pi^2 \Delta M^3$ (2-body)

Example:

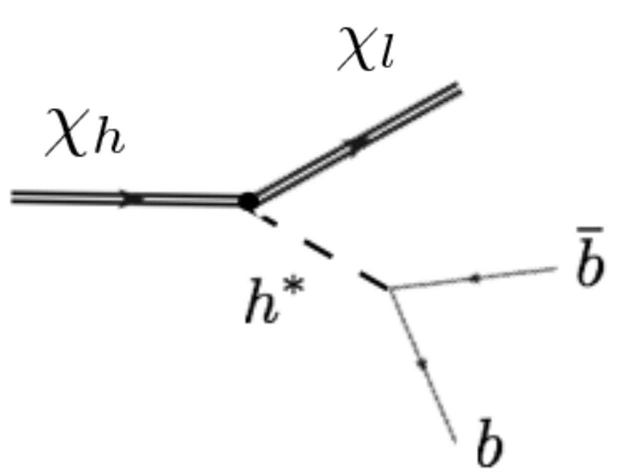
$$\chi_+ \to \chi_h \pi^+: \ \text{PS} = \left[1 - \left(\frac{m_\pi}{\Delta M}\right)^2\right]^{1/2}$$

For small mass splittings:



$$\Gamma_+^{\text{sc}} \propto \frac{\Delta M_{Cl}^5}{120}$$

$$\Gamma_+^{\text{ps-sc}} \propto \frac{\Delta M_{Cl}^5}{40}$$



$$\Gamma_h^{\text{sc}} \propto \frac{\Delta M_{hl}^5}{60}$$

$$\Gamma_h^{\text{ps-sc}} \propto \frac{\Delta M_{hl}^7}{560}$$