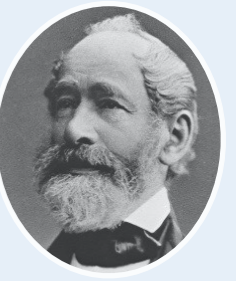




Heidelberg University

Carl Zeiss Foundation



DARK MATTER SEARCHES WITH SOFT DISPLACED PARTICLES

Susanne Westhoff



5th LHC LLP workshop | May 27-29, 2019 at CERN

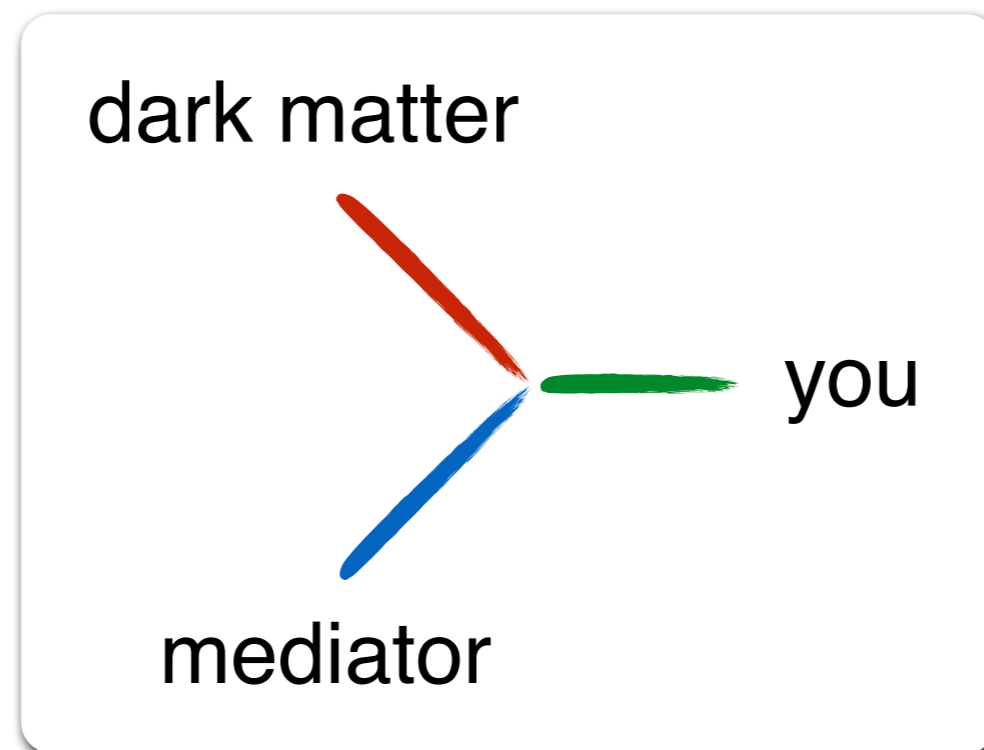
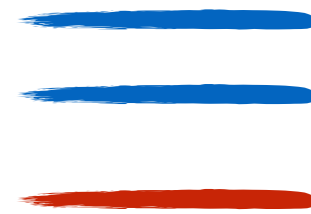
DARK MATTER INTERACTIONS

visible sector



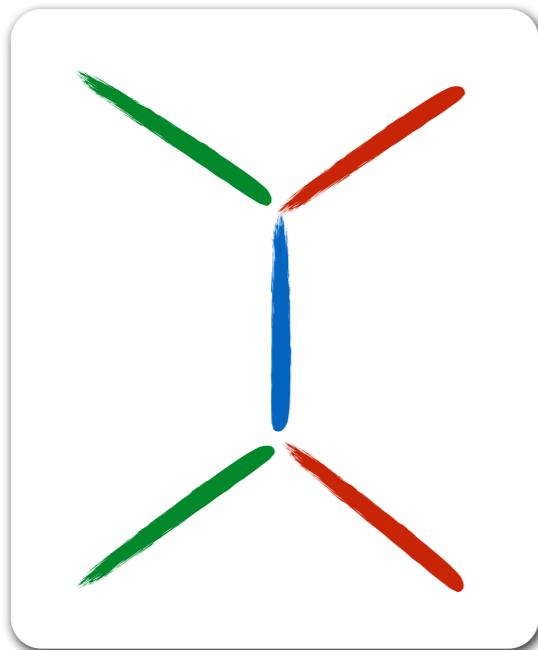
dark force
↔

dark sector



AT THE LHC

strong dark force

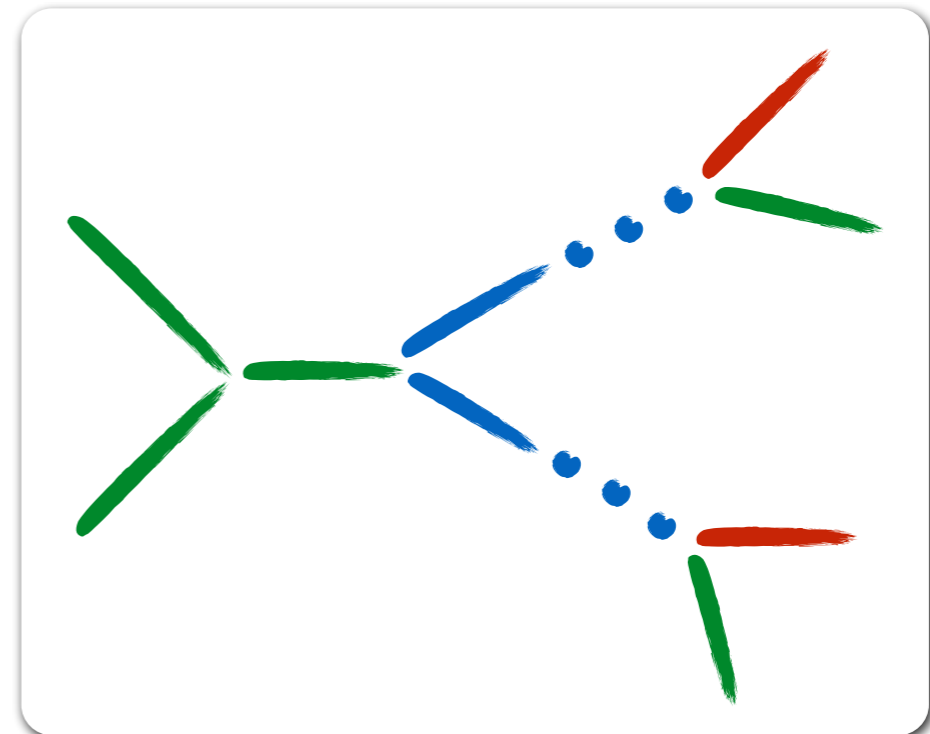


DM pair production



missing energy

weak dark force



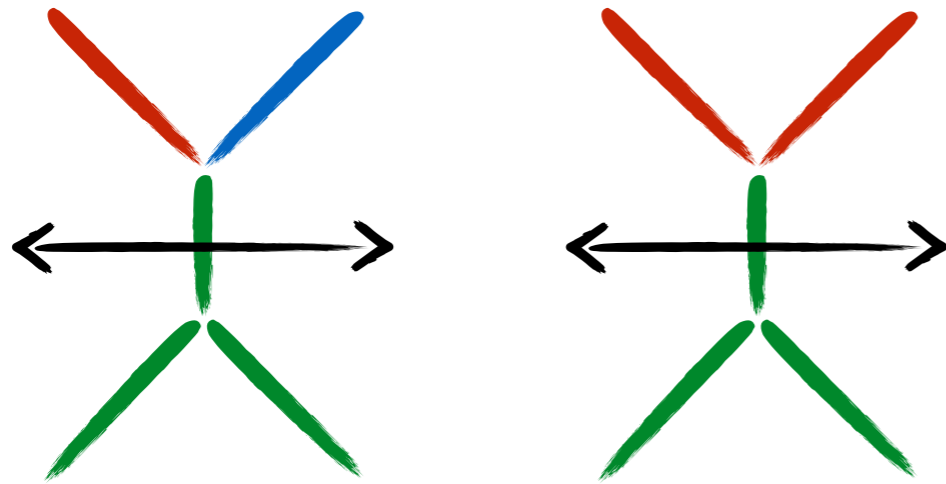
long-lived mediators



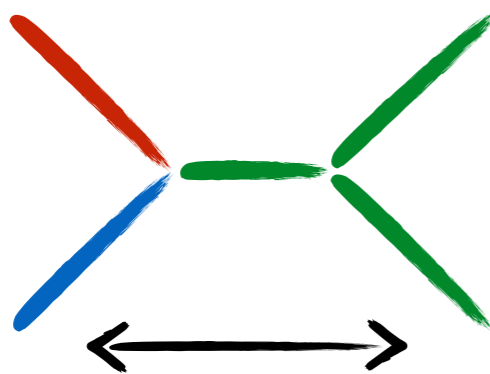
displaced particles

DARK MATTER ABUNDANCE

dark matter in equilibrium:

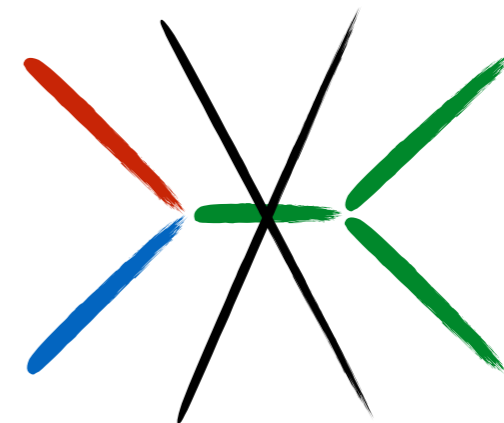


co-annihilation



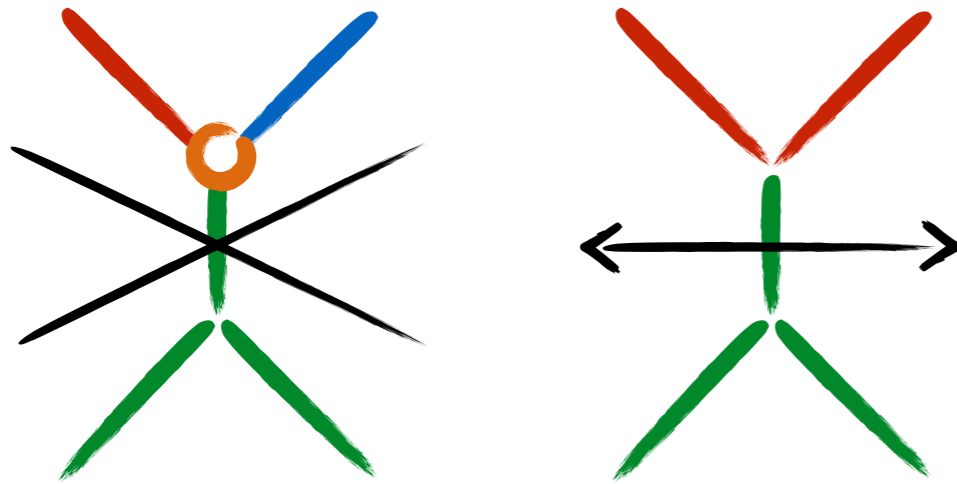
universe
expands

„freeze-out“

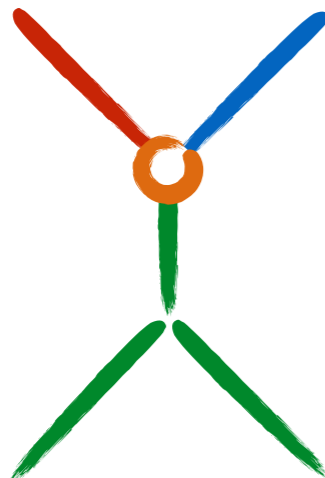


CO-SCATTERING

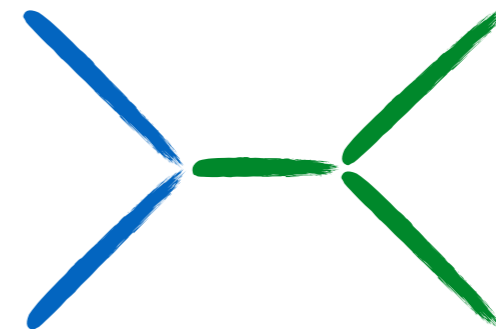
DM leaves chemical equilibrium:



co-scattering

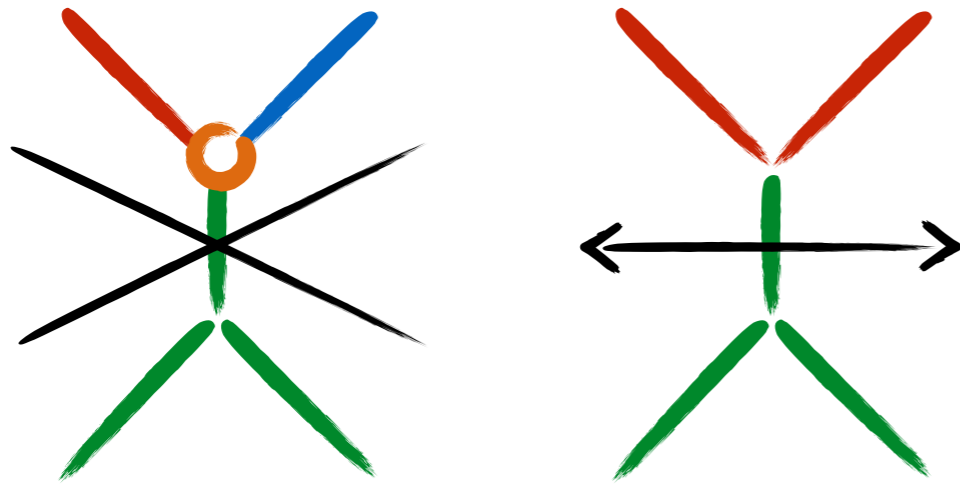


mediator annihilation

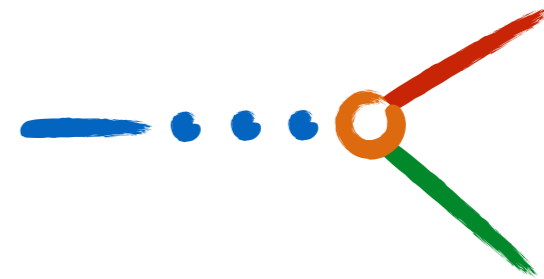


CO-SCATTERING

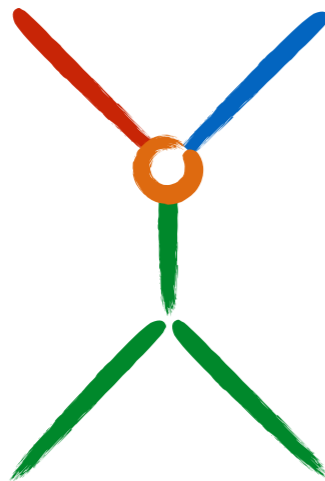
DM leaves chemical equilibrium:



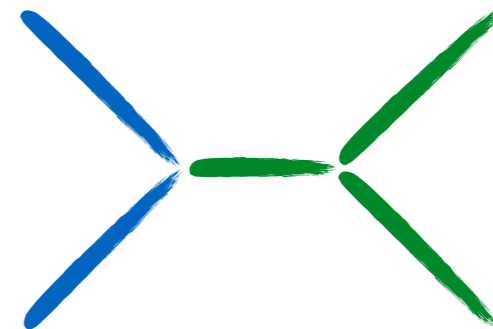
long-lived mediators



co-scattering

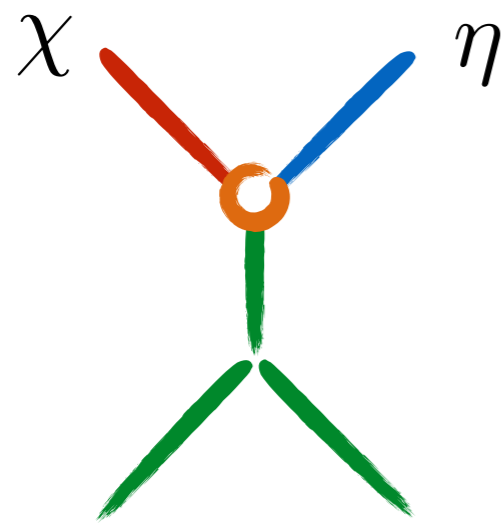


mediator annihilation



LONG-LIVED AND COMPRESSED

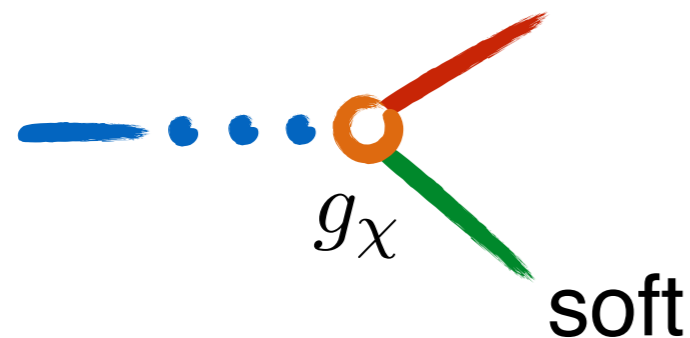
co-scattering



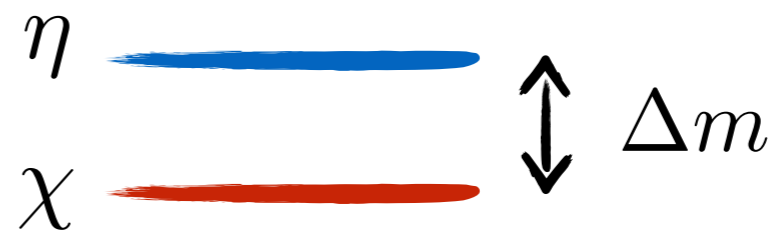
number densities related:

$$\frac{n_\eta}{n_\chi} \sim \left(\frac{m_\eta}{m_\chi} \right)^{\frac{3}{2}} e^{-\frac{\Delta m}{T}}$$

long-lived: $g_\chi \ll 1$



compressed: $\frac{\Delta m}{m} \approx 10\%$

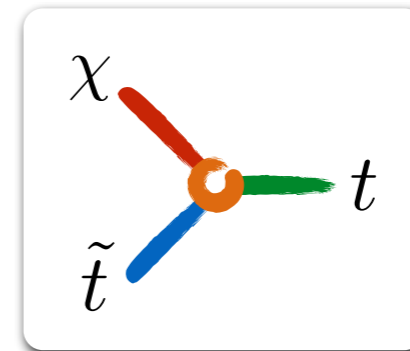
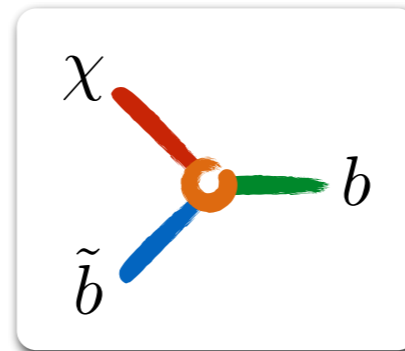


MODELS FEATURING CO-SCATTERING

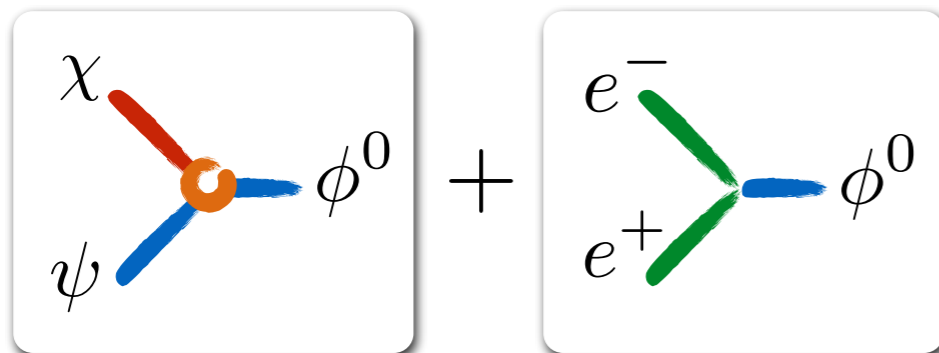
Fermion portal

cf. SUSY sbottom, stop

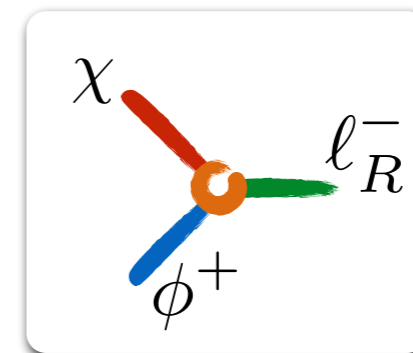
[Garny et al., 1705.09292 & 1802.00814]



Leptophilic dark matter



[D'Agnolo et al., 1705.08450]



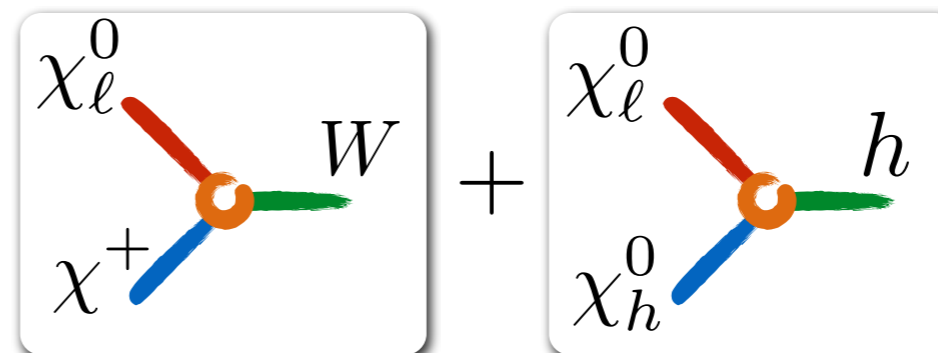
[Junius et al., 1904.07513]

Higgs portal

cf. SUSY wino-bino

[Bharucha et al., 1804.02357]

[Filimonova, SW, 1812.04628]



A HIGGS PORTAL EXAMPLE

Naturally small portal coupling

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\bar{\chi}_S\chi_S - \frac{m_T}{2}\bar{\chi}_T\chi_T + \frac{\kappa}{\Lambda} \left[(H^\dagger\bar{\chi}_T H)\chi_S + \bar{\chi}_S(H^\dagger\chi_T H) \right]$$

Mixing via ew. symmetry breaking

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

with $\mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$

Mass eigenstates

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

A HIGGS PORTAL EXAMPLE

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$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2} \bar{\chi}_S \chi_S - \frac{m_T}{2} \bar{\chi}_T \chi_T + \frac{\kappa}{\Lambda} \left[(H^\dagger \bar{\chi}_T H) \chi_S + \bar{\chi}_S (H^\dagger \chi_T H) \right]$$

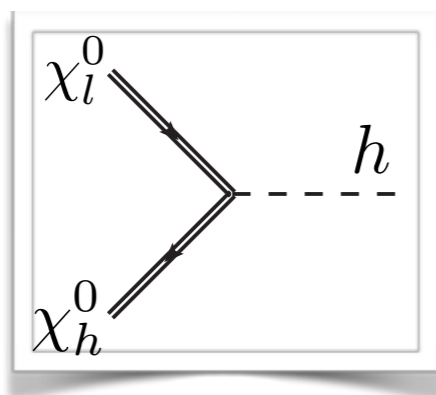
Mixing via ew. symmetry breaking

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

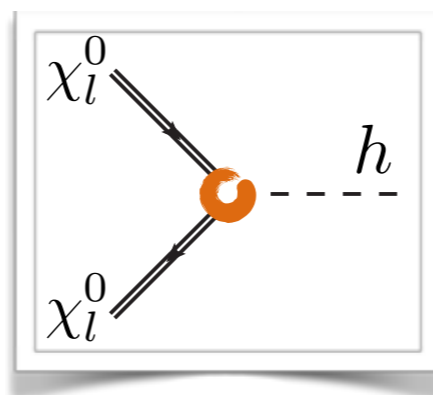
with $\mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$

Mass eigenstates

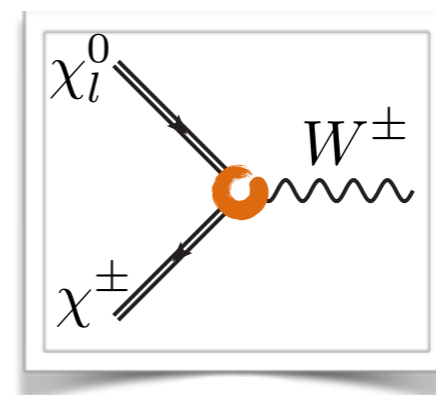
-  $\chi_\ell^0 = \cos \theta \chi_S^0 - \sin \theta \chi_T^0$
-  $\chi_h^0 = \sin \theta \chi_S^0 + \cos \theta \chi_T^0$
-  χ^+, χ^-



$$\frac{\mu}{v} \cos(2\theta)$$



$$\frac{\mu}{v} \sin(2\theta)$$



$$g \sin \theta \gamma_\mu$$

A HIGGS PORTAL EXAMPLE




Naturally small portal coupling

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2} \bar{\chi}_S \chi_S - \frac{m_T}{2} \bar{\chi}_T \chi_T + \frac{\kappa}{\Lambda} [(H^\dagger \bar{\chi}_T H) \chi_S + \bar{\chi}_S (H^\dagger \chi_T H)]$$

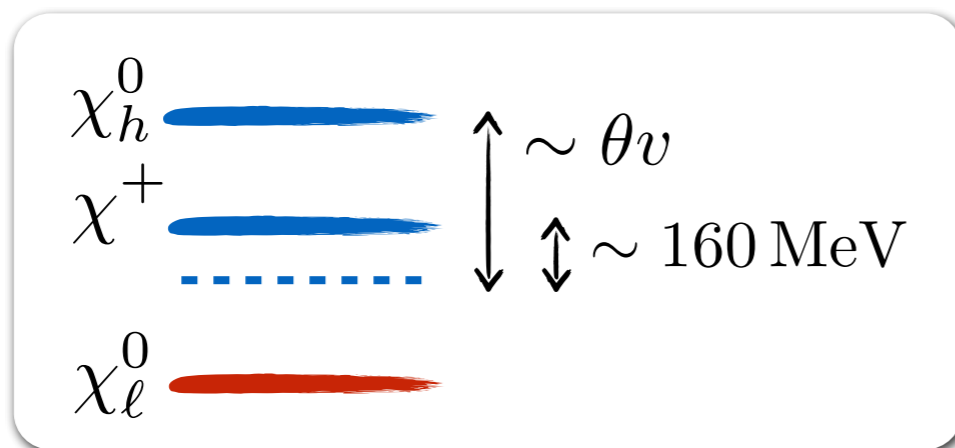
Mixing via ew. symmetry breaking

$$\theta \sim \frac{\mu}{m_T - m_S} \quad \text{with} \quad \mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

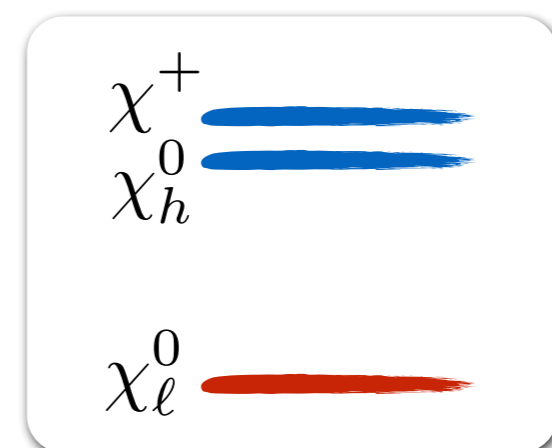
Mass eigenstates

-  $\chi_\ell^0 = \cos \theta \chi_S^0 - \sin \theta \chi_T^0$
-  $\chi_h^0 = \sin \theta \chi_S^0 + \cos \theta \chi_T^0$
-  χ^+, χ^-

$\theta v > 160 \text{ MeV}$

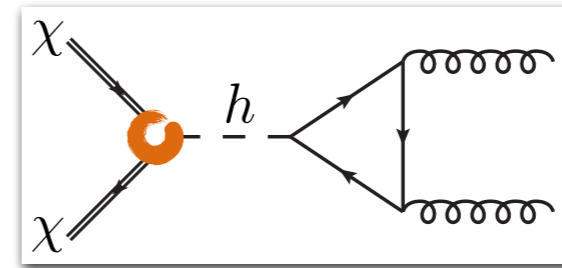


$\theta v \lesssim 160 \text{ MeV}$

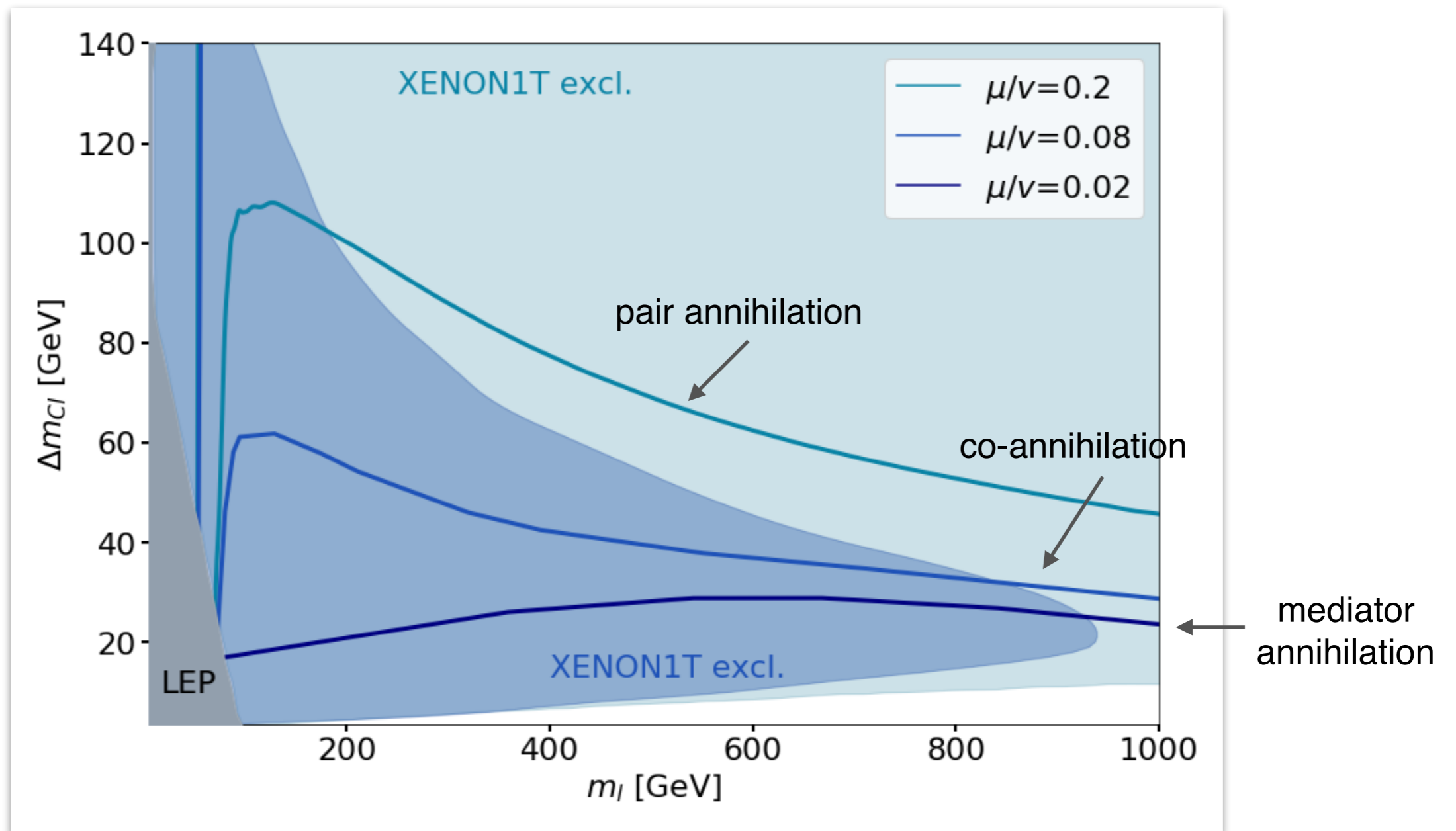


DIRECT DETECTION BOUNDS

Dark matter - nucleon scattering:

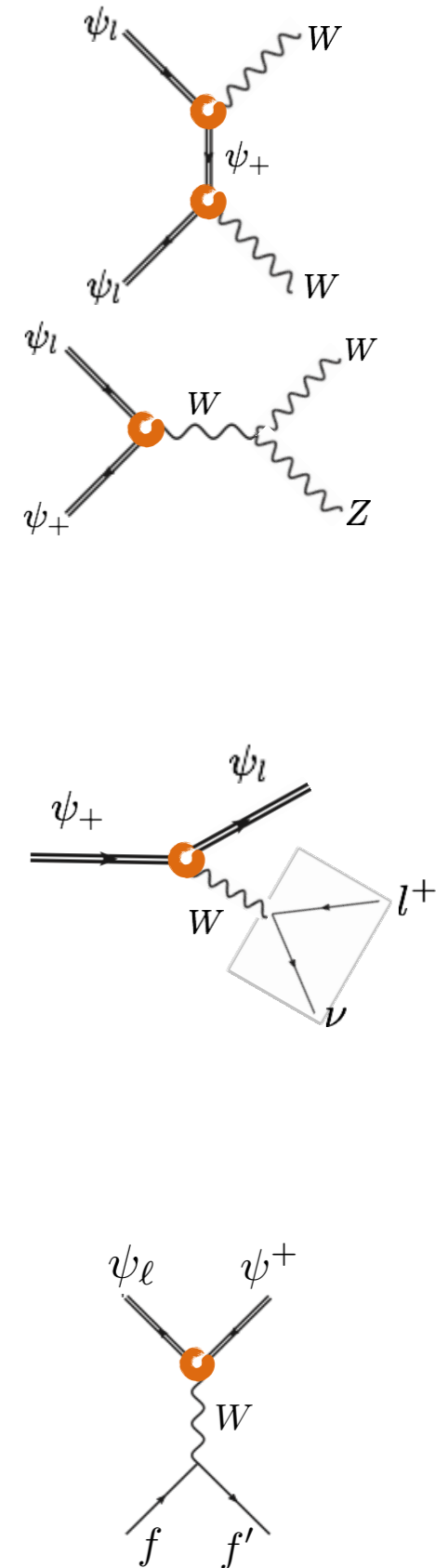
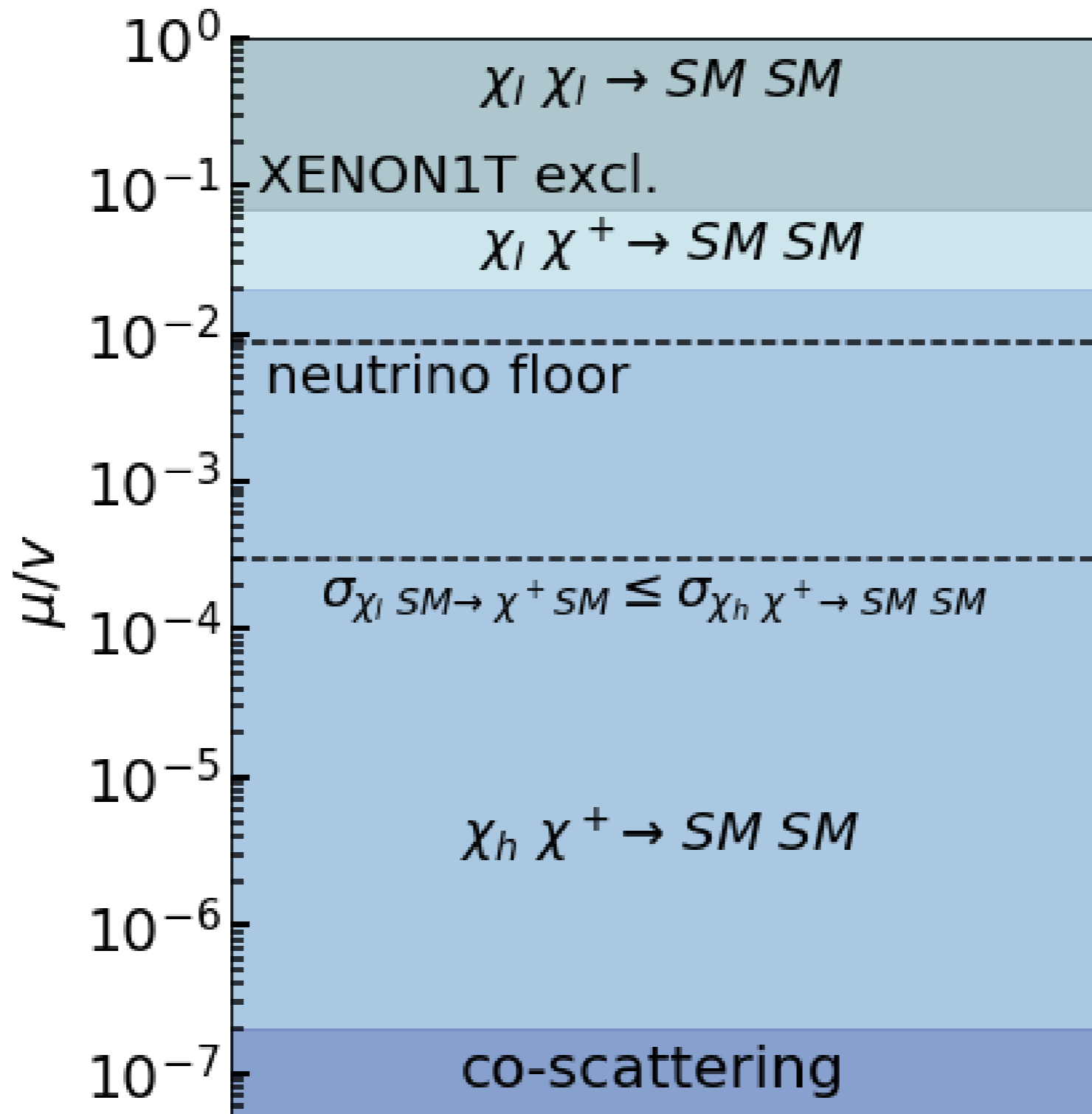


$$\frac{\mu}{v} \sin(2\theta)$$



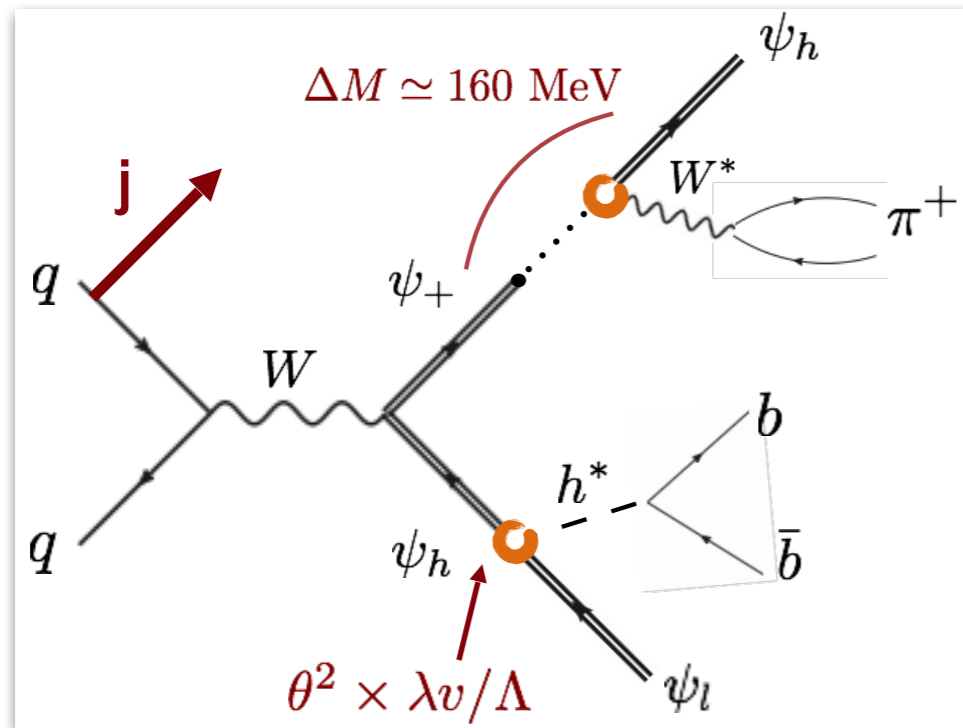
PHASES OF FREEZE-OUT

dark sector decouples



LONG-LIVED MEDIATORS AT LHC

Mediator decays suppressed: $\Gamma_\chi \sim g_\chi^2 (\Delta m)^x$.



disappearing tracks

[Mahbubani et al., 1703.05327]

[Filimonova, SW, 1812.04628]

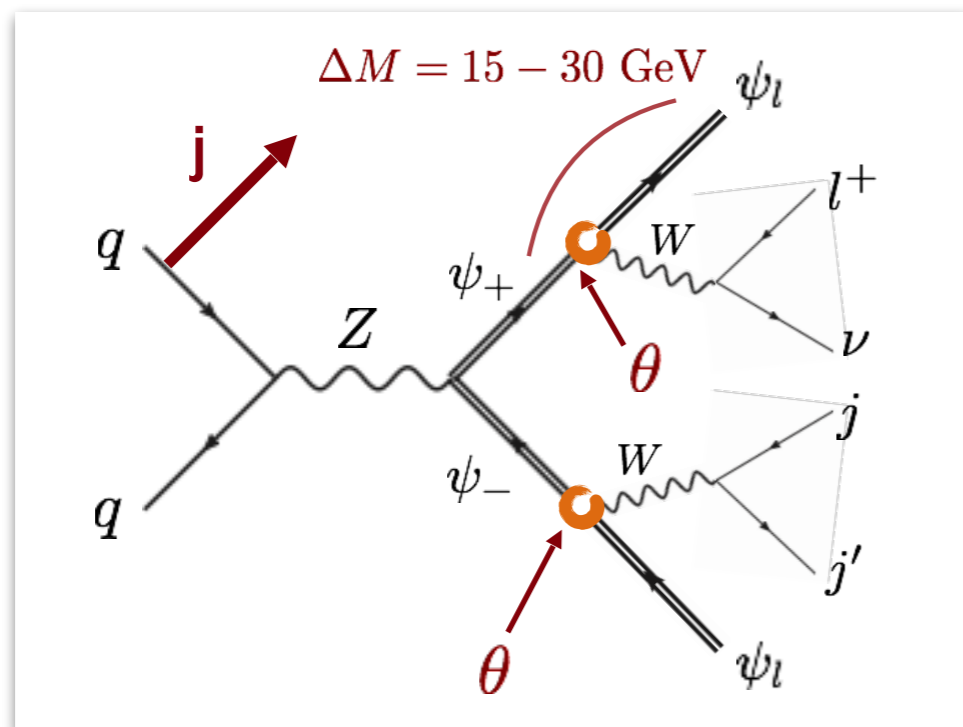
[Junius et al., 1904.07513]

displaced b-jets

[Nagata, Otono, Shirai, 1506.08206]

[Garny et al., 1705.09292 & 1802.00814]

[Filimonova, SW, 1812.04628]



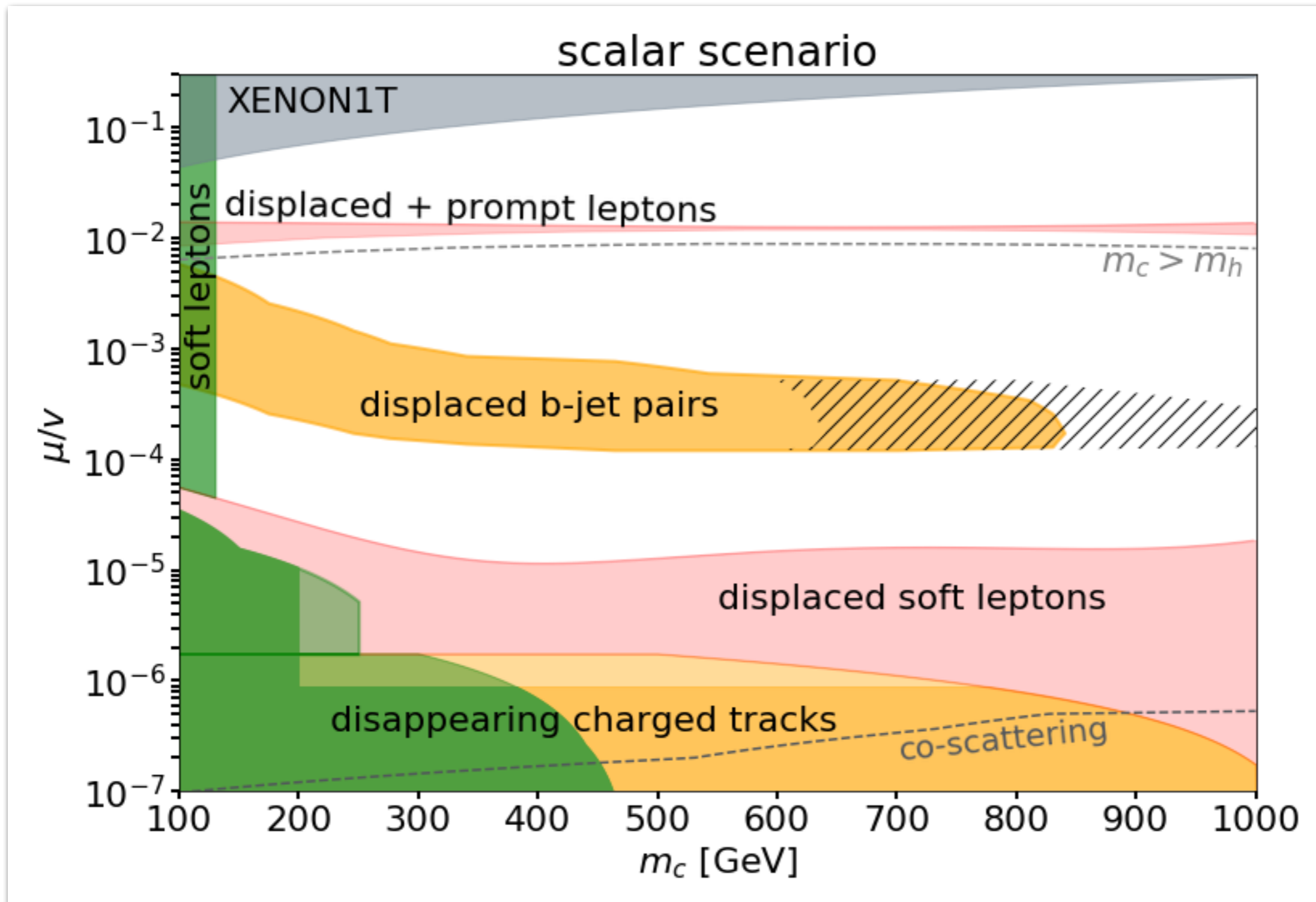
displaced soft leptons

[Bharucha et al., 1804.02357]

[Filimonova, SW, 1812.04628]

[Junius et al., 1904.07513]

LHC SEARCH POTENTIAL

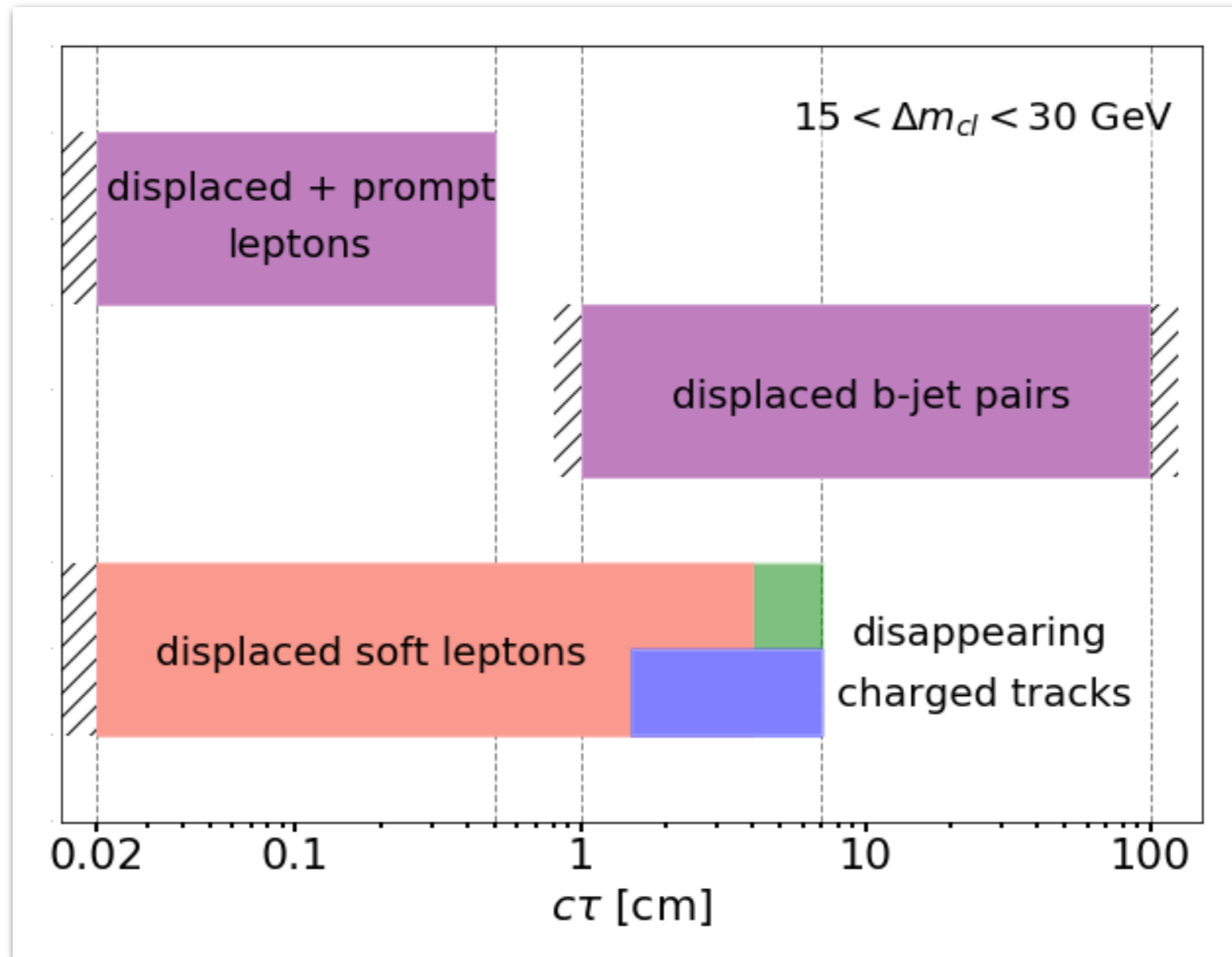


$$\chi_h^0 \rightarrow \chi_\ell^0 b \bar{b}$$

$$\chi^+ \rightarrow \chi_\ell^0 \ell^+ \nu_\ell$$

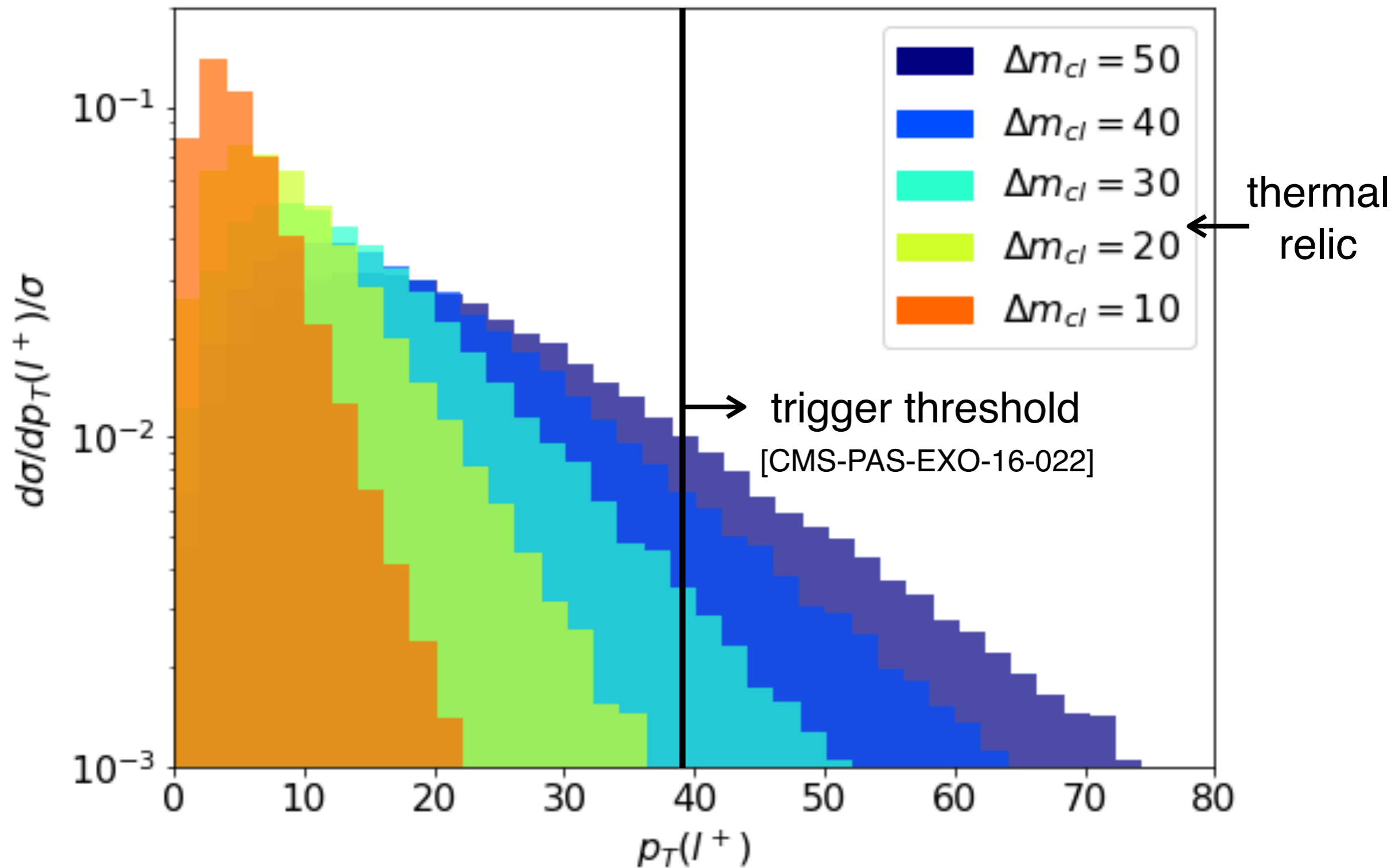
$$\chi^+ \rightarrow \chi_h^0 \pi^+$$

HOW DISPLACED?

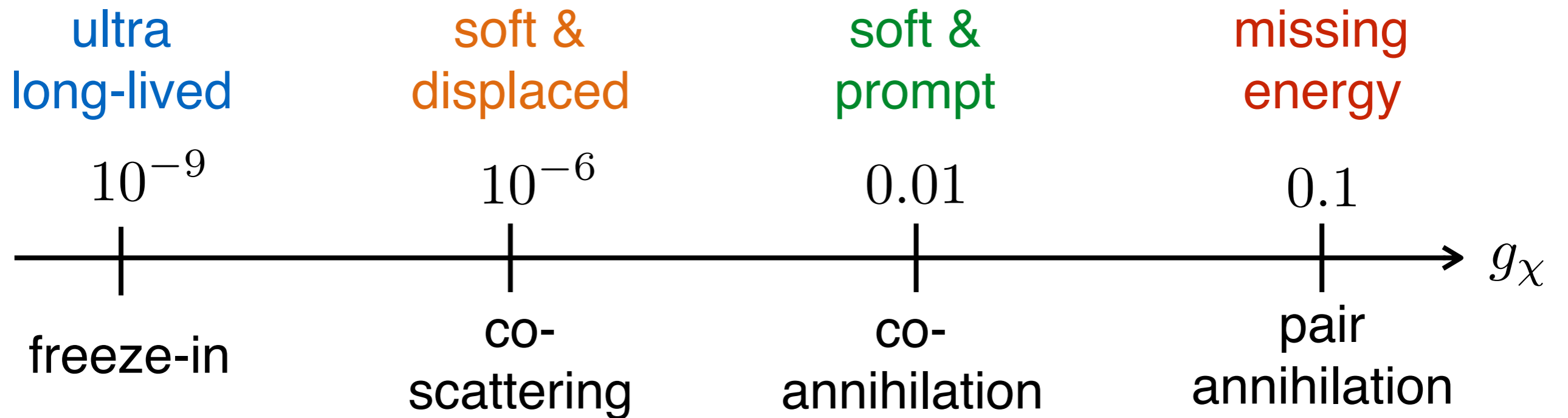


Mediators decay within the ATLAS and CMS detectors.

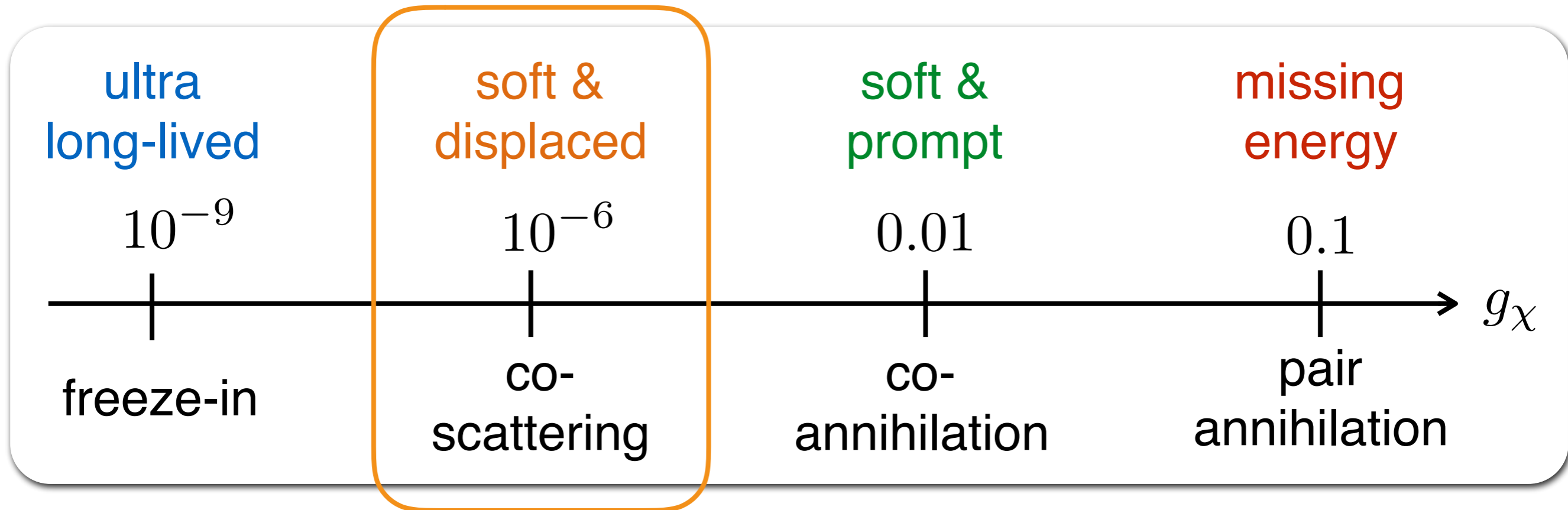
HOW SOFT?



CONCLUSION



CONCLUSION



LHC observables:

- displaced b-jet pairs
- displaced soft leptons
- prompt + displaced leptons

Ideas:

- displaced b-tagging
- lower pT threshold
- trigger on prompt objects