Long-lived particles
Connecting early universe dynamics to collider signatures

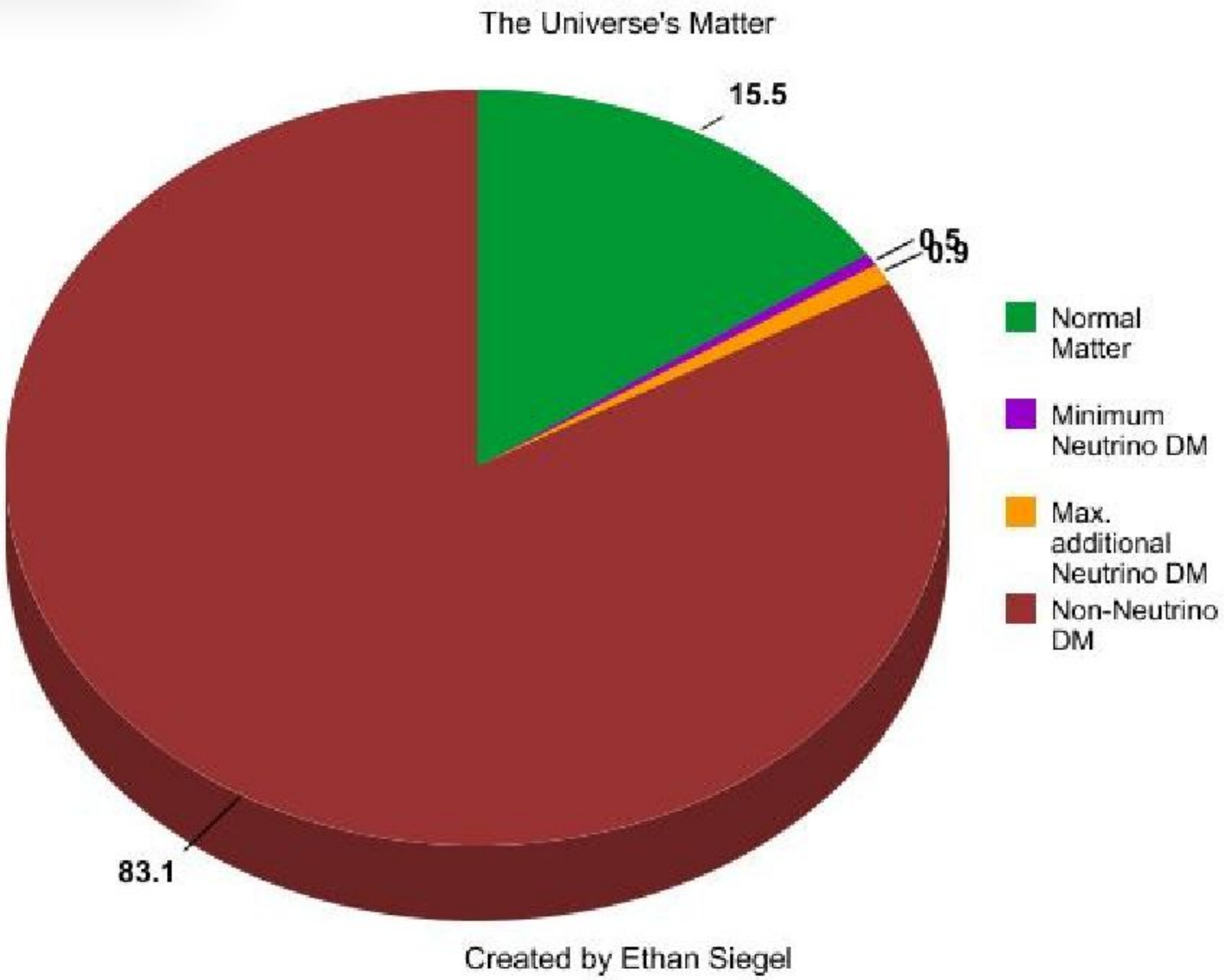
Anastasia Filimonova

Helsinki, 2.12.2020

DM particles: general properties

What we do know:

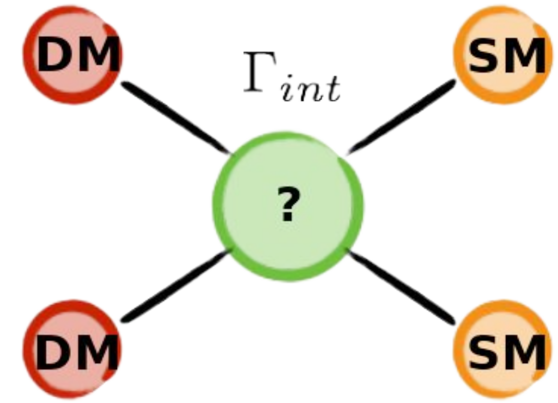
- Interact through gravity
- Massive (to cluster)
- If DM particles ever were relativistic – they should have slowed down early in the history of the Universe
- Electrically neutral (do not interact with photons)
- Stable on cosmological scales



What we don't know:

- Other interactions?
- Mass, spin….?
- Several species?

Why the electroweak scale?



Assumption:

thermal production

$\Gamma_{int} > H$ In equilibrium with plasma

$\Gamma_{int} < H$ Not in equilibrium with plasma

Relic abundance

Very simplified WIMPS

One new "heavy" particle

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{DM}^2} \quad + \quad n_{DM} \langle \sigma v \rangle \sim H$$

at decoupling

$$\Omega_{DM} h^2 \sim 0.12 \frac{10^{-26} \mathrm{cm}^3 s^{-1} (\mathrm{or}\ 10^{-9} [GeV]^{-2})}{\langle \sigma v \rangle}$$

Planck

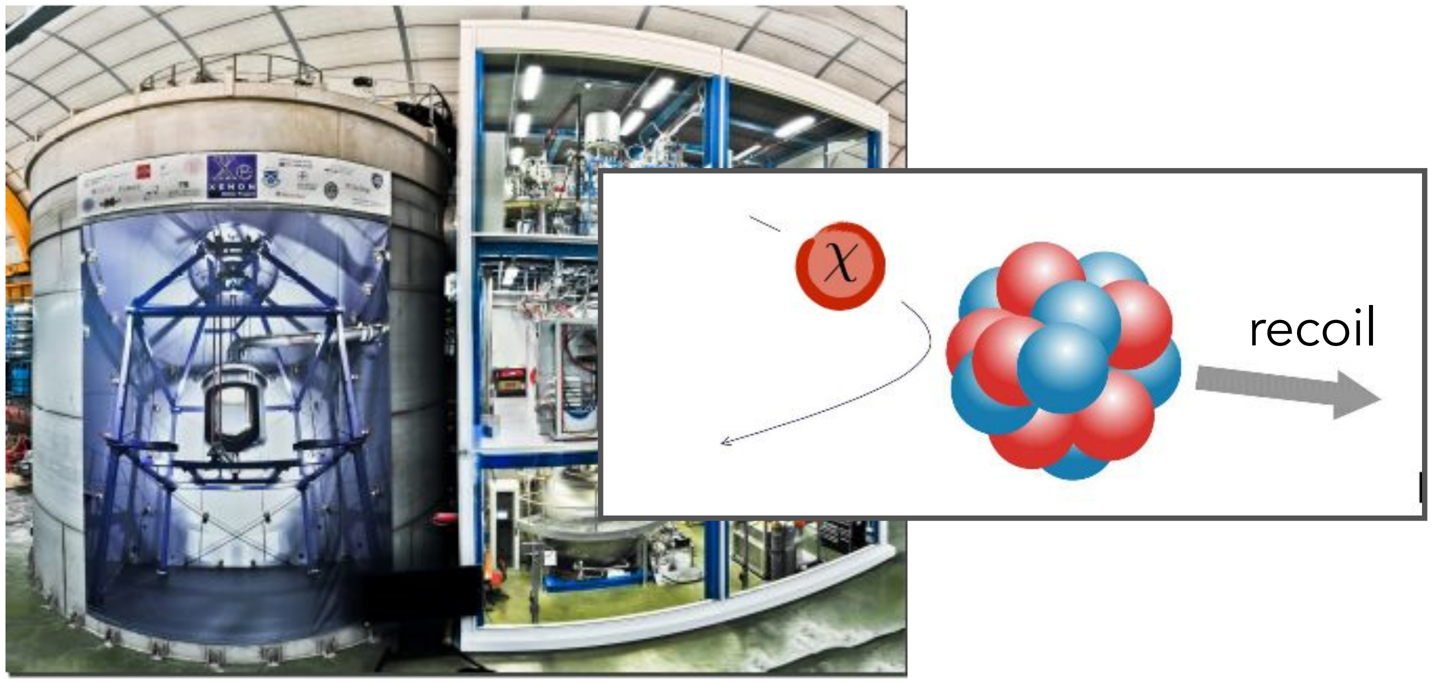
"Natural" choice:

$\alpha \sim \alpha_{EW}$

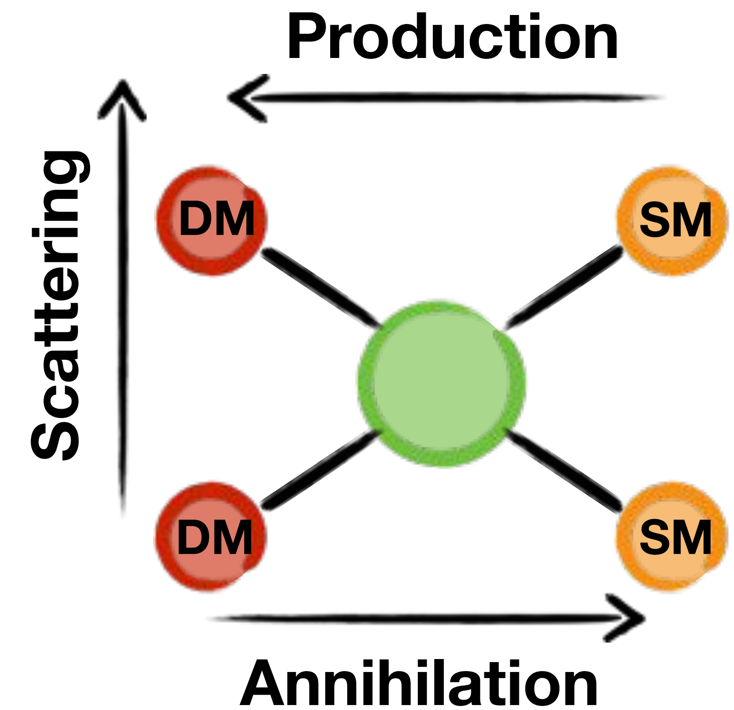
$m_{DM} \sim O(100 \mathrm{GeV})$

Constraints

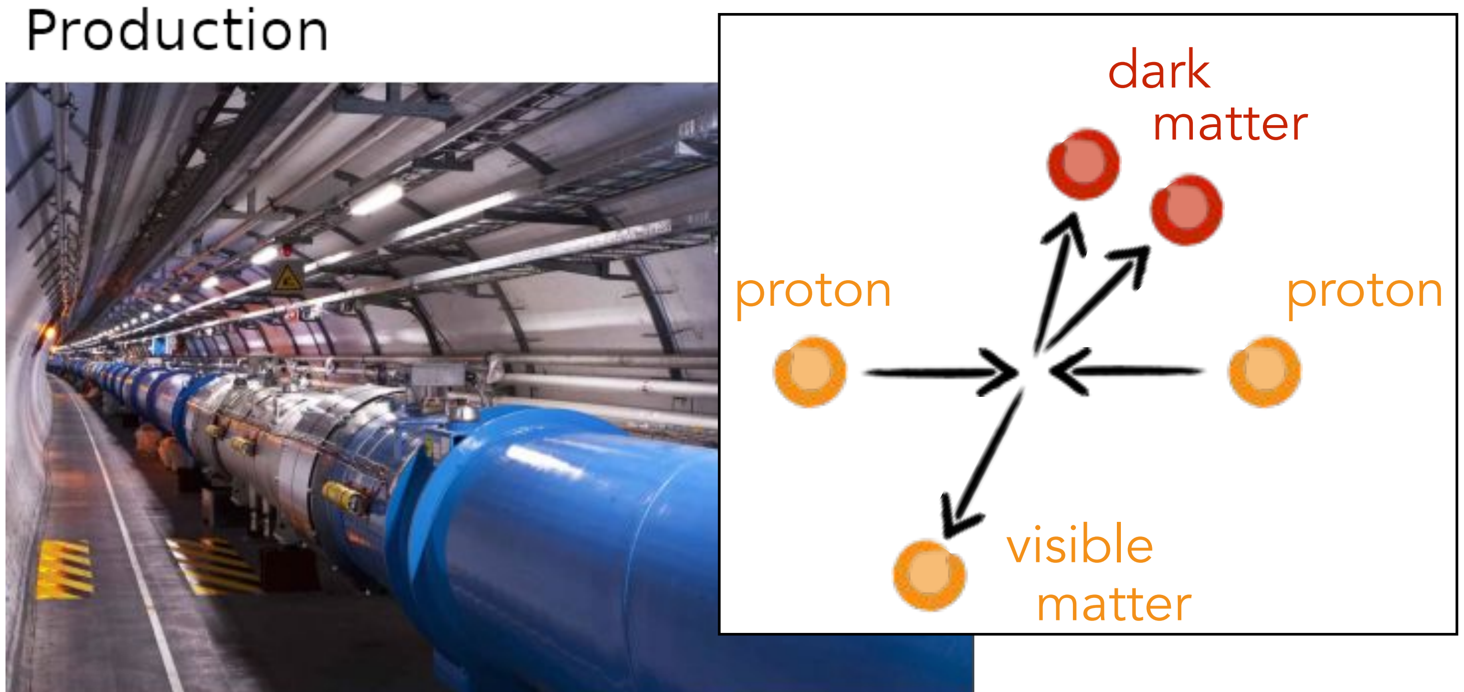
Scattering (direct detection)



Xenon experiment



Production



Large Hadron Collider

Annihilation (indirect detection)

Fermi satellite

Main problem: direct detection

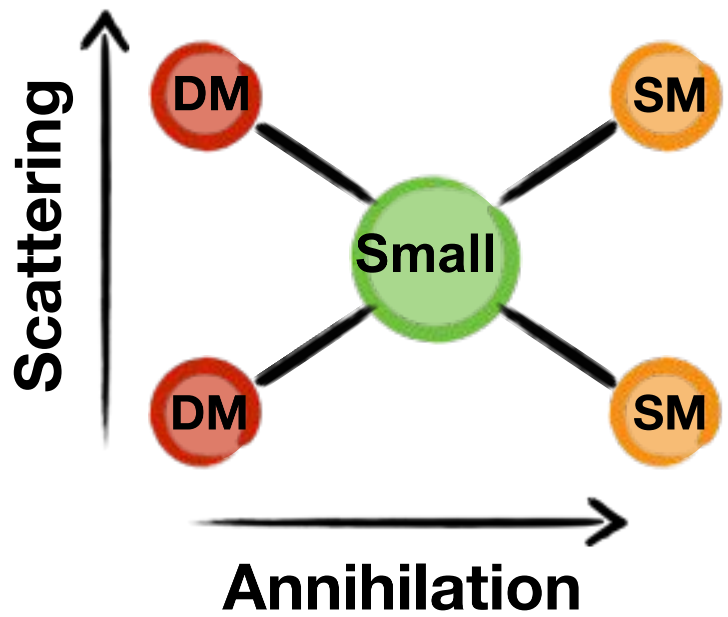
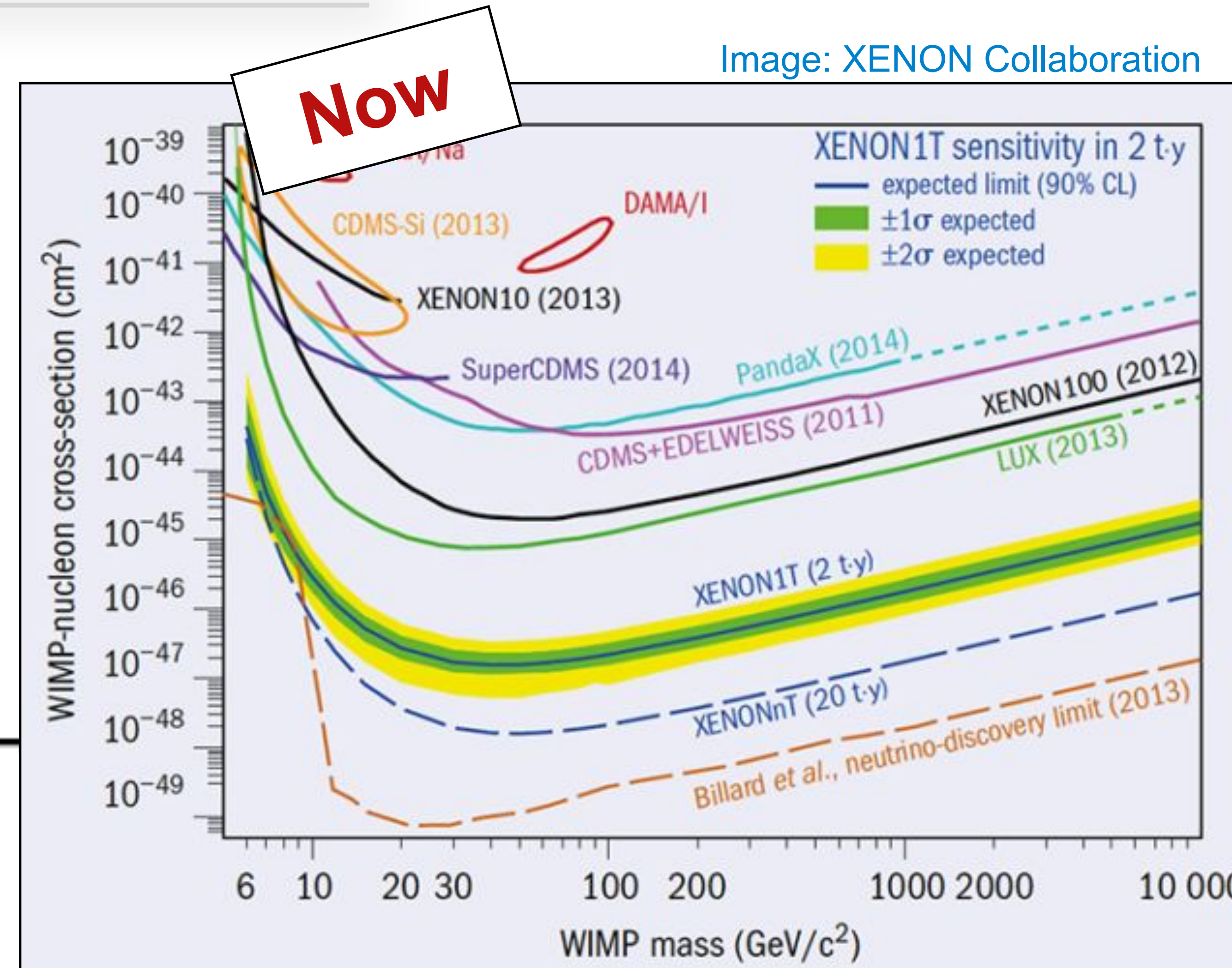
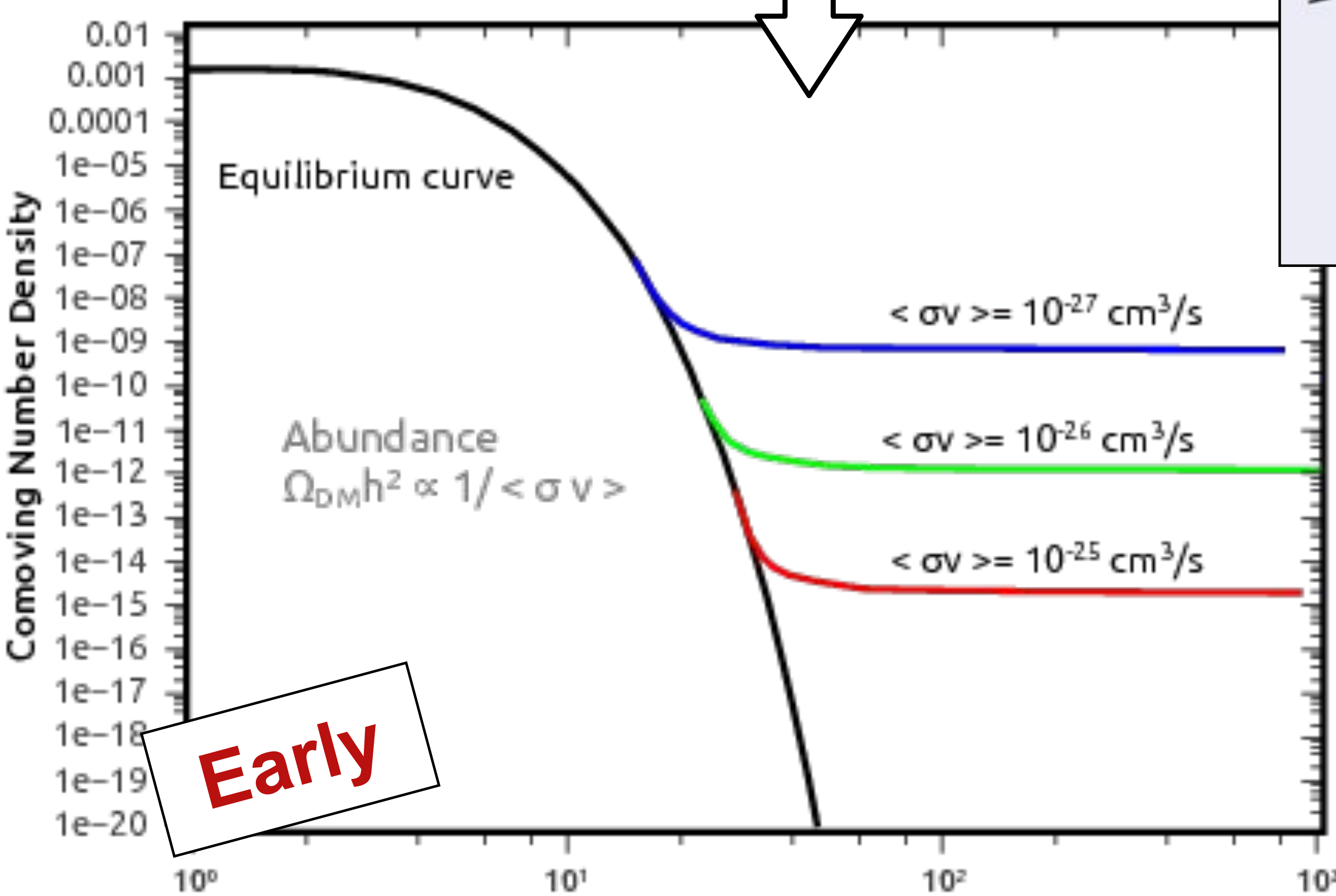


Image: XENON Collaboration





Arcadi et al. 1703.07364 m_χ/T

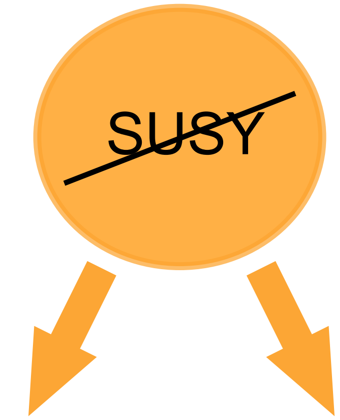
Overabundance

"Exceptions"

"WIMPless miracle"

Feng & Kumar [0905.3039]

$$\langle\sigma v\rangle \sim \frac{\alpha^2}{m_{DM}^2}$$



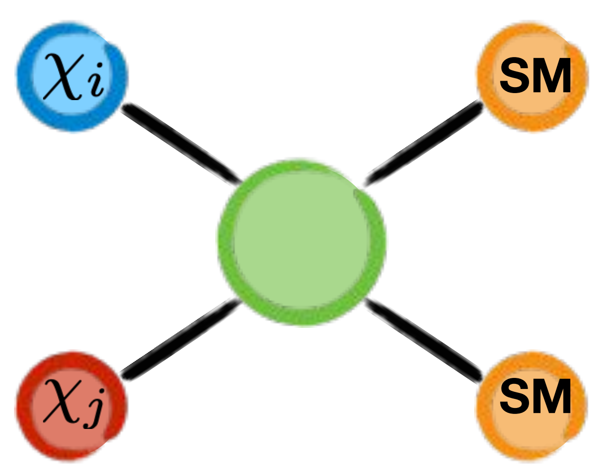
Hidden SM

$$\boxed{\frac{\alpha_D^2}{m_D^2}} \sim \boxed{\frac{\alpha_{EW}^2}{m_W^2}}$$

Co-annihilation

Griest & Seckel 1991

$$\sum_{ij}$$



$\langle\sigma v\rangle_{eff} \uparrow$

at decoupling

But eventually $\chi_i \Rightarrow$ DM No Direct detection signal

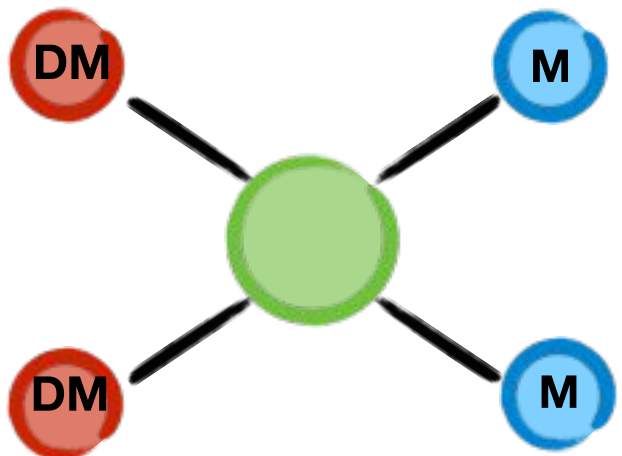
"Exceptions"

"Forbidden" DM

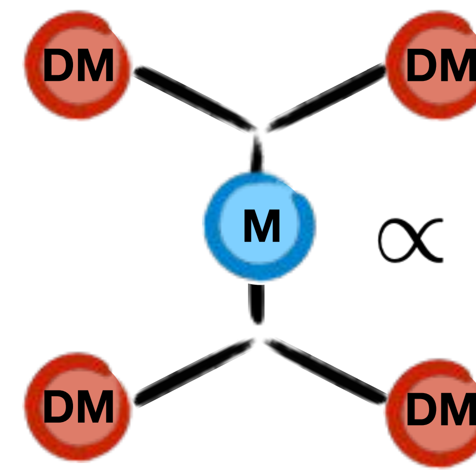
D'Agnolo & Ruderman [1505.07107]

Exponentially suppressed by $\frac{m_M - m_{DM}}{T}$ ⇨ Allows for large α and light DM

From thermal tail



$m_{DM} < m_\chi$

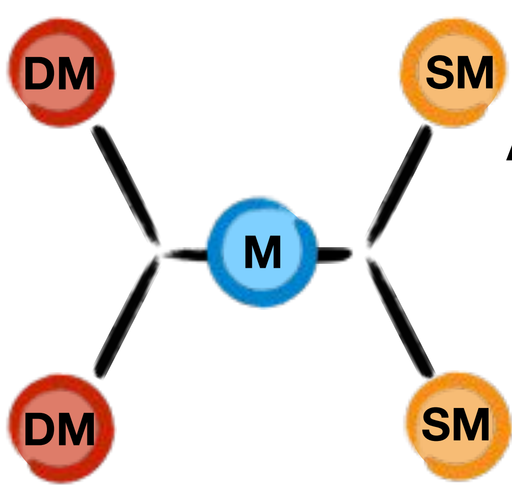


$\propto \alpha^2$

Induces self-interactions

Resonant production

Feng & Smolinsky [1707.03835]

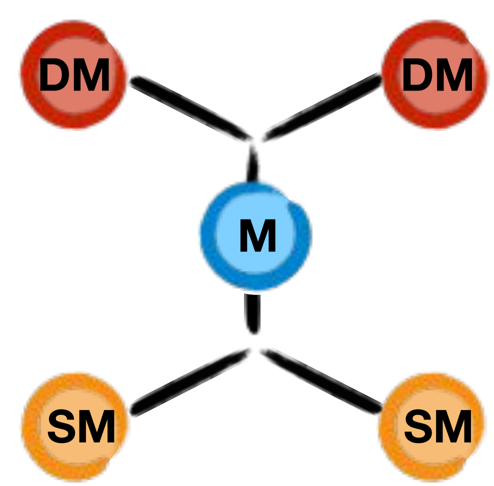


Allows for couplings

10-100 times smaller

$m_M = 2m_{DM}$

Can happen when

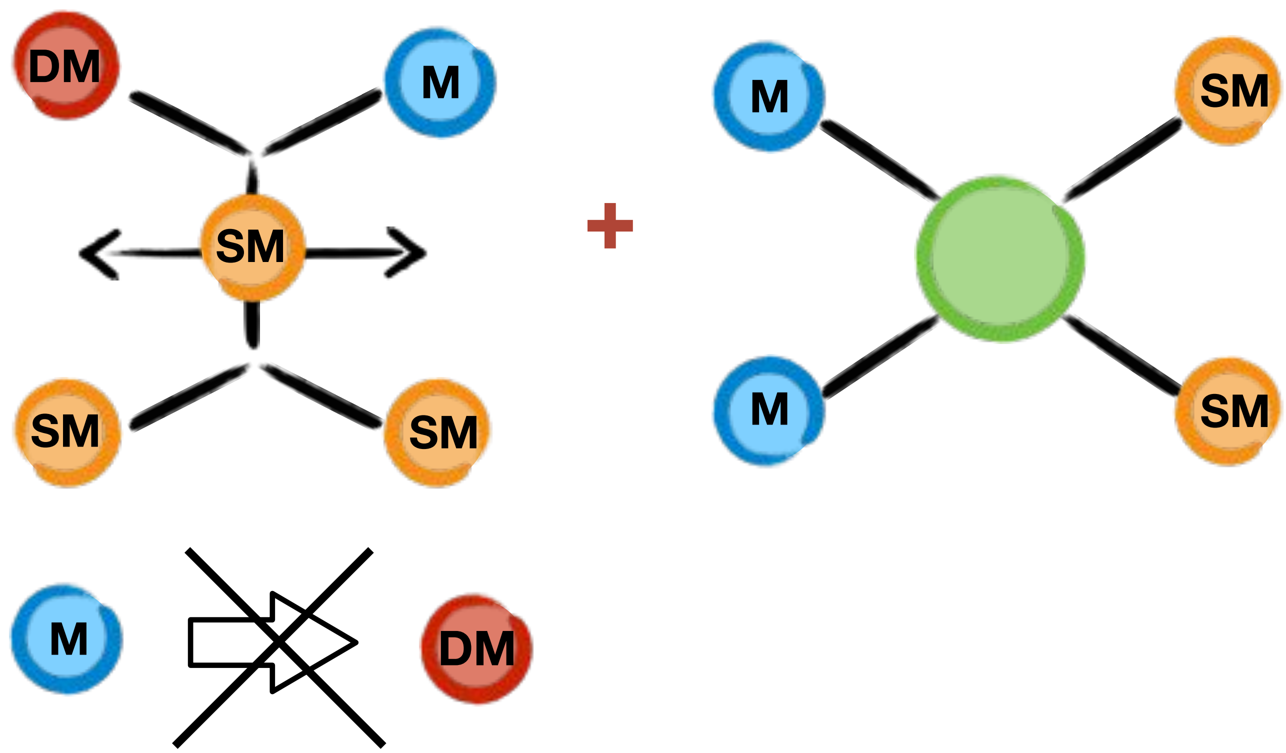


$O(10)$ effect on Ω

is out of equilibrium

Binder, Bringmann, Gustafsson, Hrzczuk [1805.00526]

"4th" exception: co-scattering



$$n_{SM}\langle\sigma v\rangle_{DM\to M} \sim H$$

Very high

$\Downarrow$

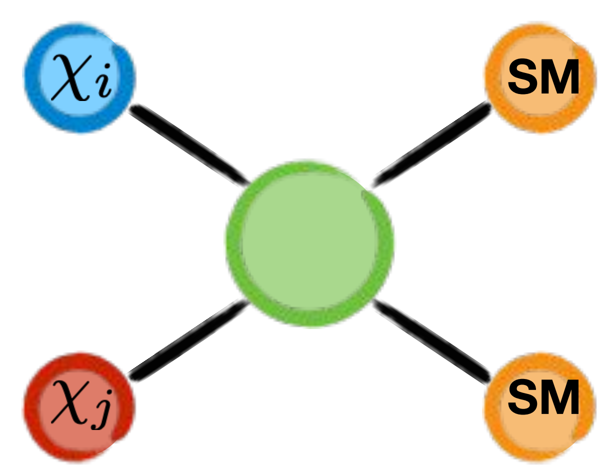
Correct relic abundance

for much smaller couplings

Compare to (co-)annihilation:

$$n_{dark}\langle\sigma v\rangle_{eff} \sim H$$

Boltzmann suppressed



Example: singlet-triplet model

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

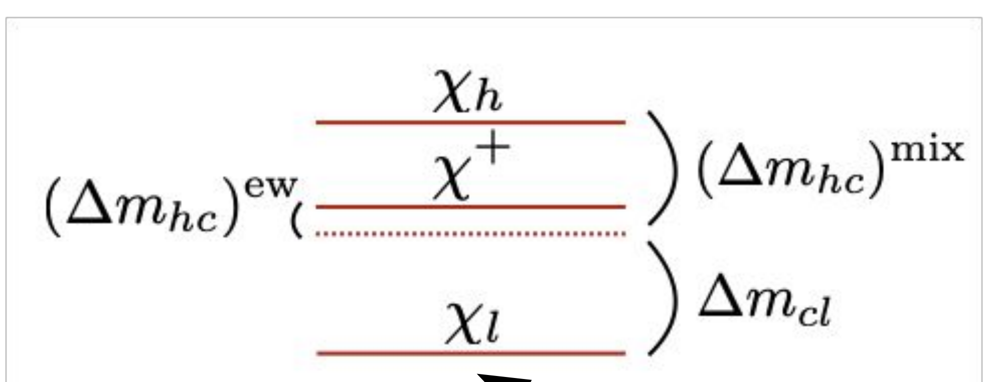
Naturally small

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

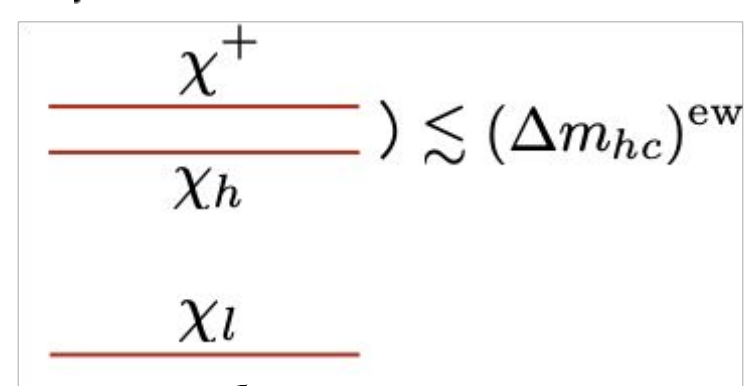
with $\chi_S = \chi_S^0, \quad \chi_T = \begin{pmatrix} \chi_T^0/\sqrt{2} & \chi^+ \\ \chi^- & -\chi_T^0/\sqrt{2} \end{pmatrix}$

Three new parameters: $m_S, \; m_T, \; \mu = \frac{\kappa_{ST} v^2}{\sqrt{2}\Lambda}$

Tree-level structure + electroweak corrections:



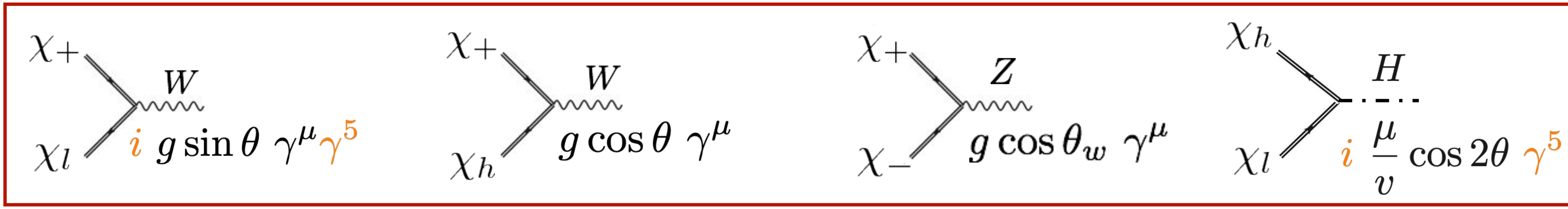
Small μ:



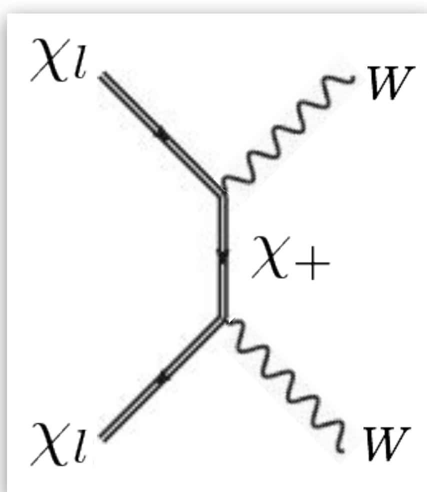
DM Candidate

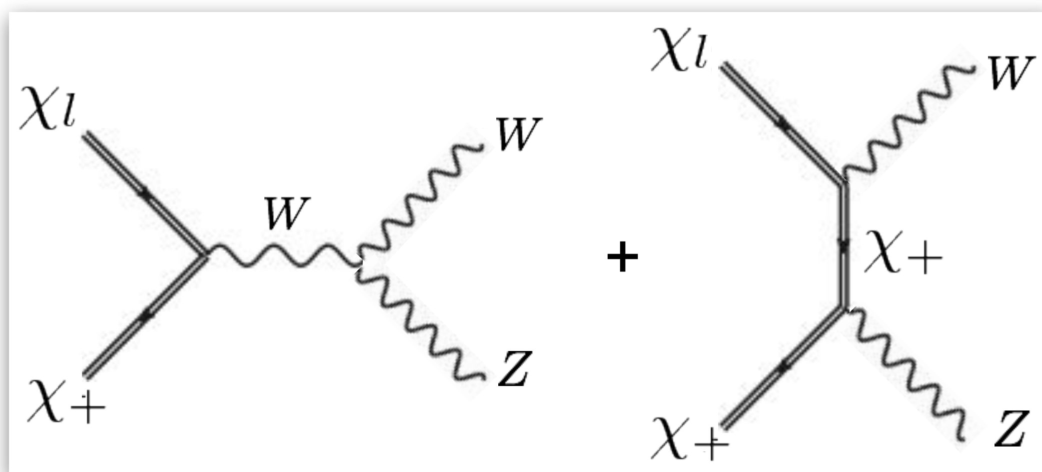
Conventional processes

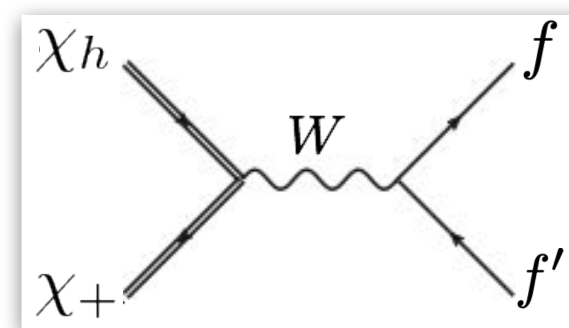
Gauge and Higgs couplings



Main contributions from:





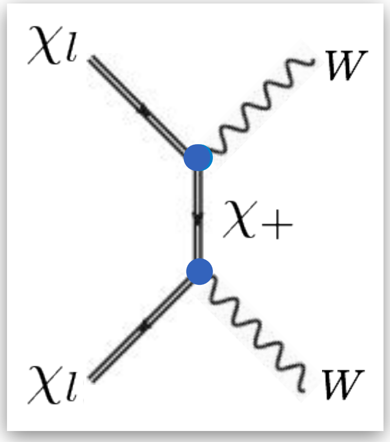


Annihilation

Co-annihilation

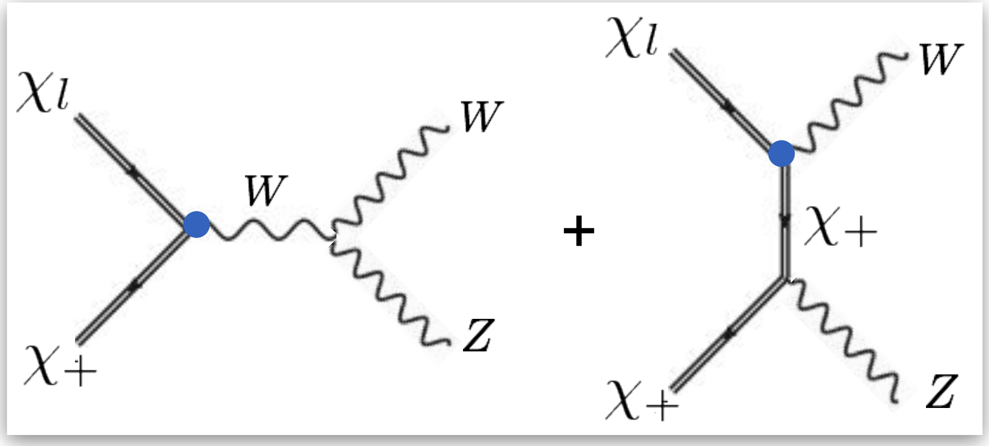
Mediator annihilation + further decay to χ_l

Naive picture



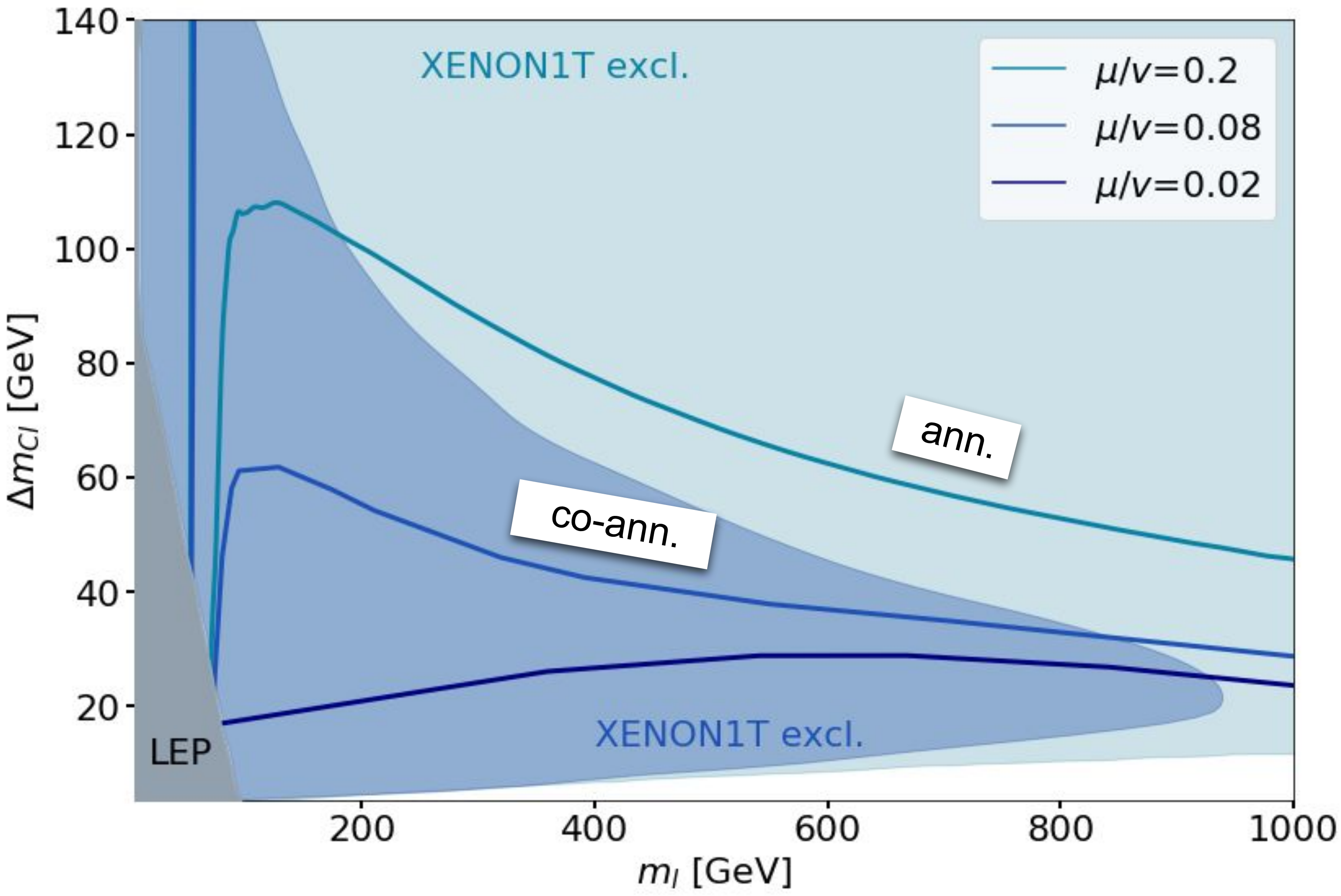
$(g\sin\theta)^4$

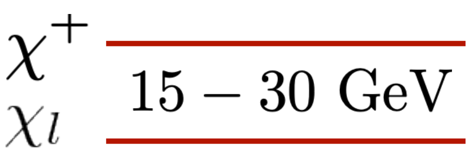
Annihilation



$(g\sin\theta)^2$

Co-annihilation





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

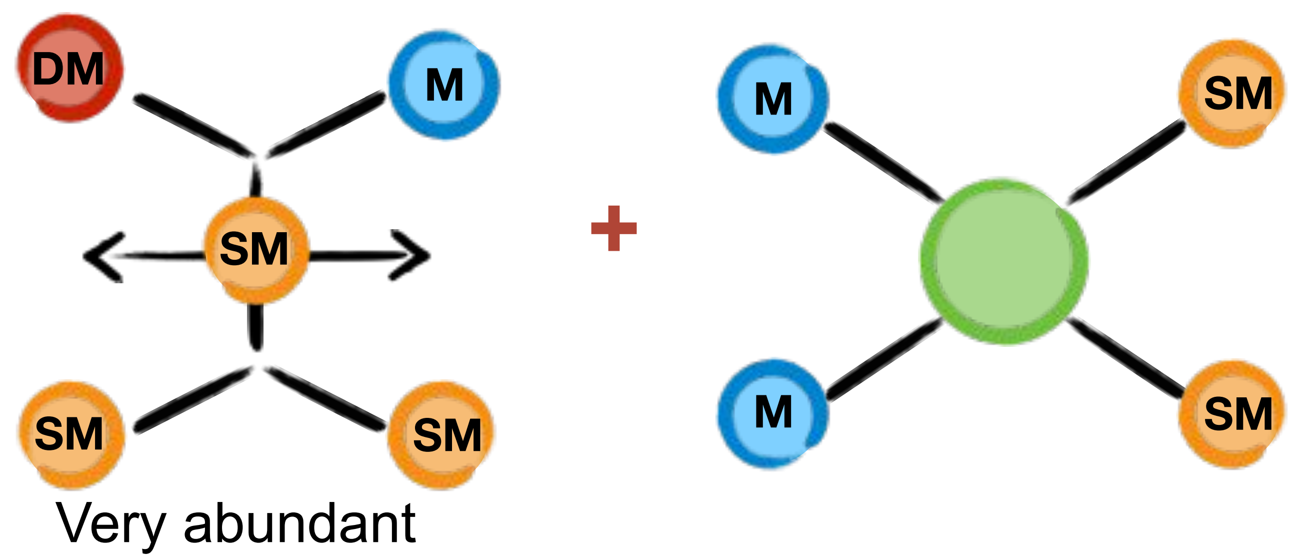
Co-scattering

Small portal coupling

	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	$\chi_\ell f \to \chi_\ell f$	$(\mu\sin\theta/v)^2$

- Mediator annihilations are still in chemical equilibrium
- Decays become very slow
- Equilibrium may be lost for dark matter

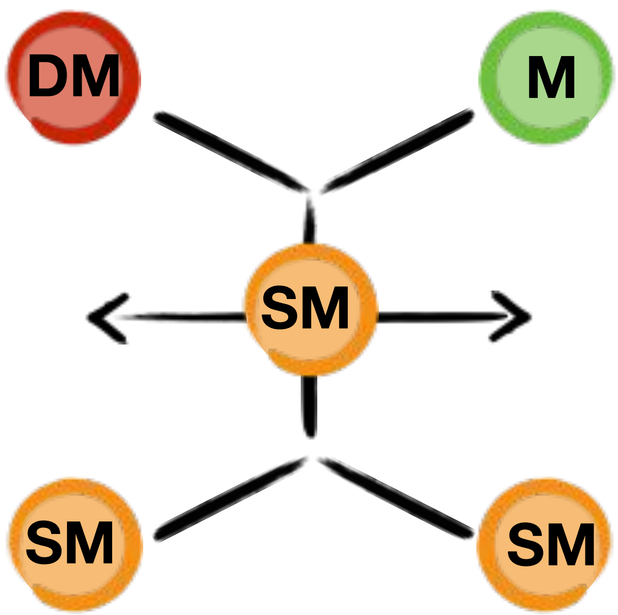
Relic abundance:
co-scattering + mediator annihilation



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

See also Garny et. al[1705.09292], D'Agnolo et al. [1705.08450], [1803.02901], [1906.09269] and Junius et al. [1904.07513]

So just continue searching?



- Mediator decays are slow during decoupling.
- **But they are also long-lived at colliders!**

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

M

DM

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

We search for:

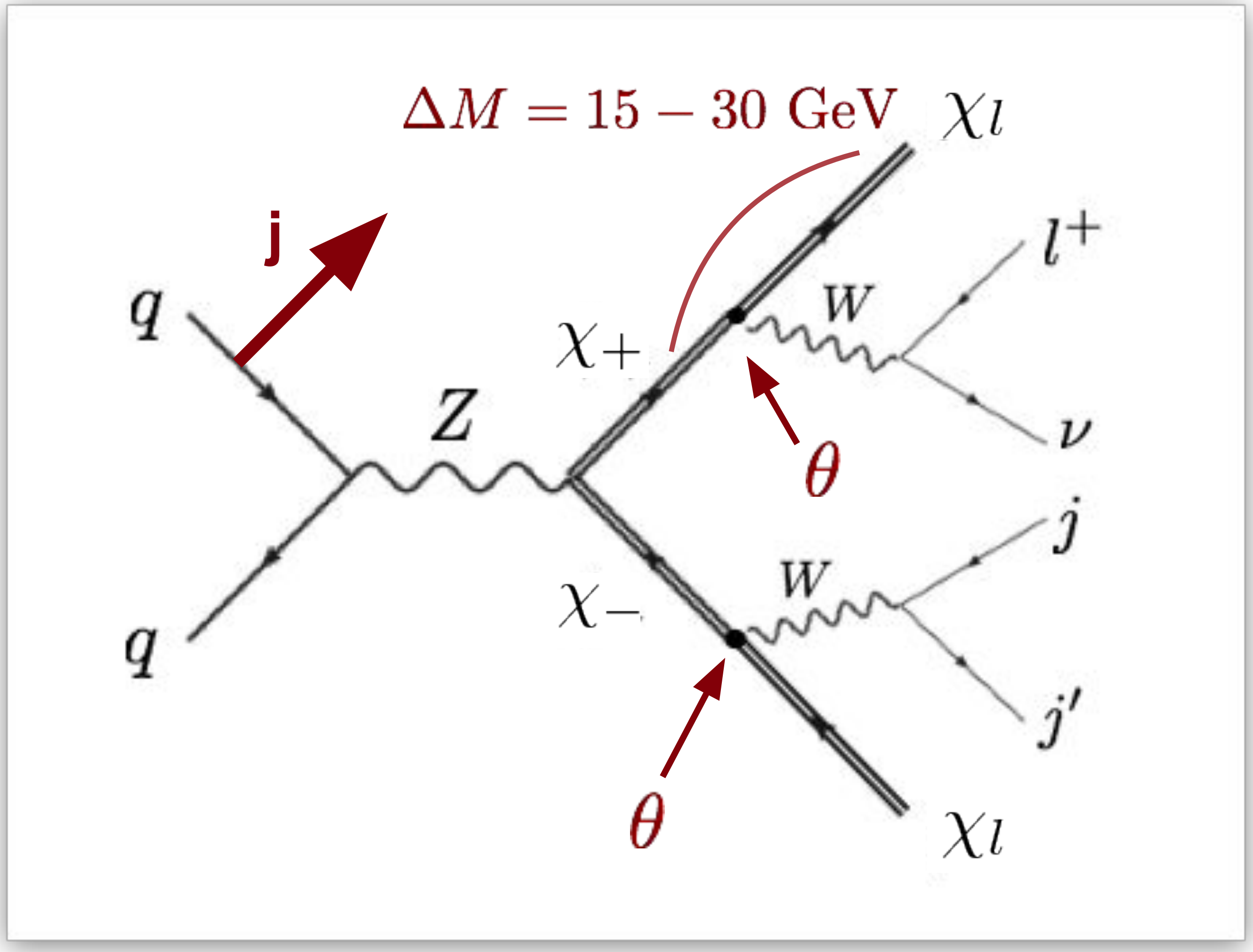
M

DM + SM

Defines p_T of SM

Particles are soft

Prompt searches are having a hard time



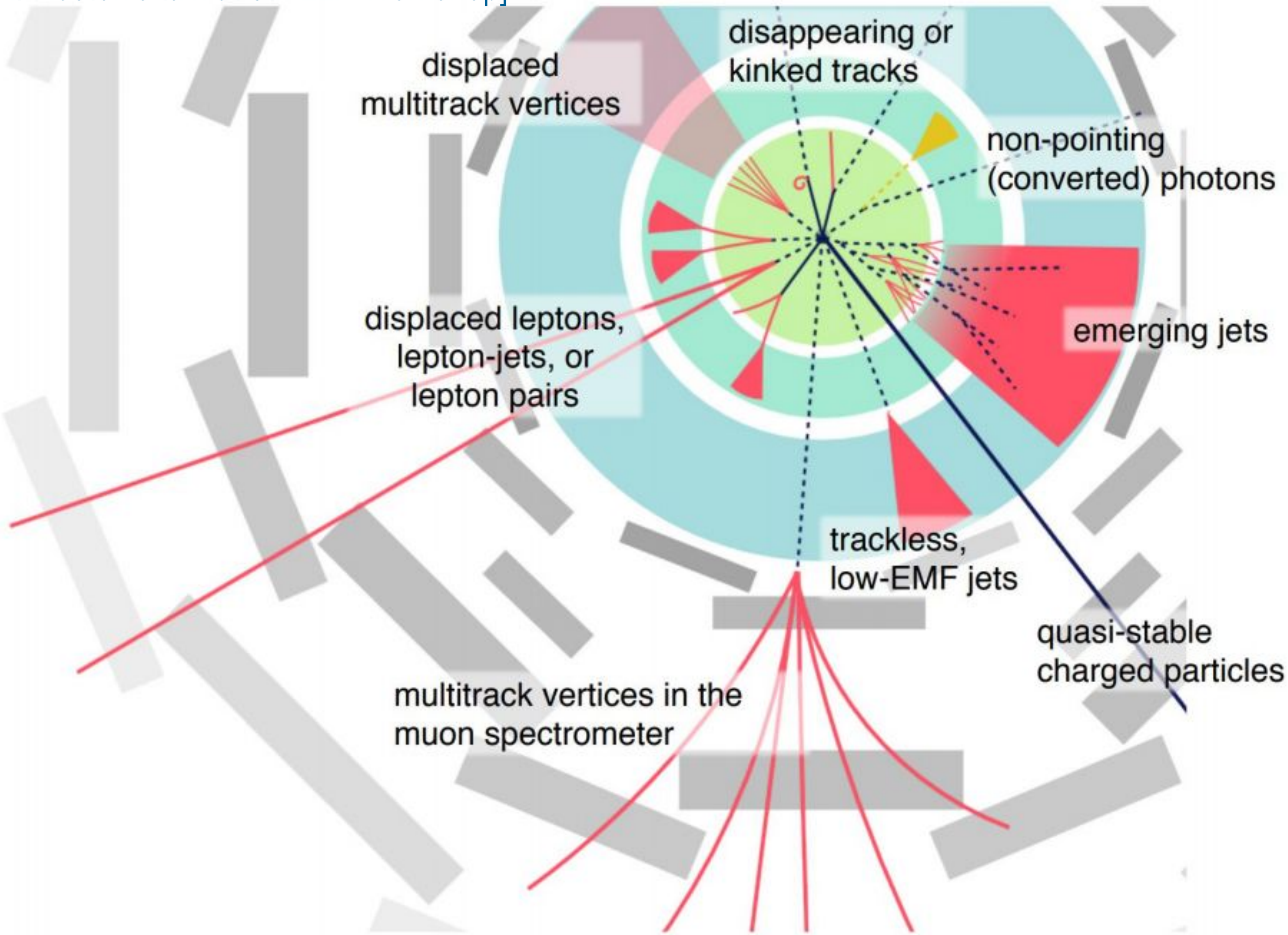
Bharuchaa, Brümmer, Desai [1804.02357]
CMS [1206.3949]

σ_{prod} ↓

Only light masses are probed

LLP analyses at ATLAS & CMS

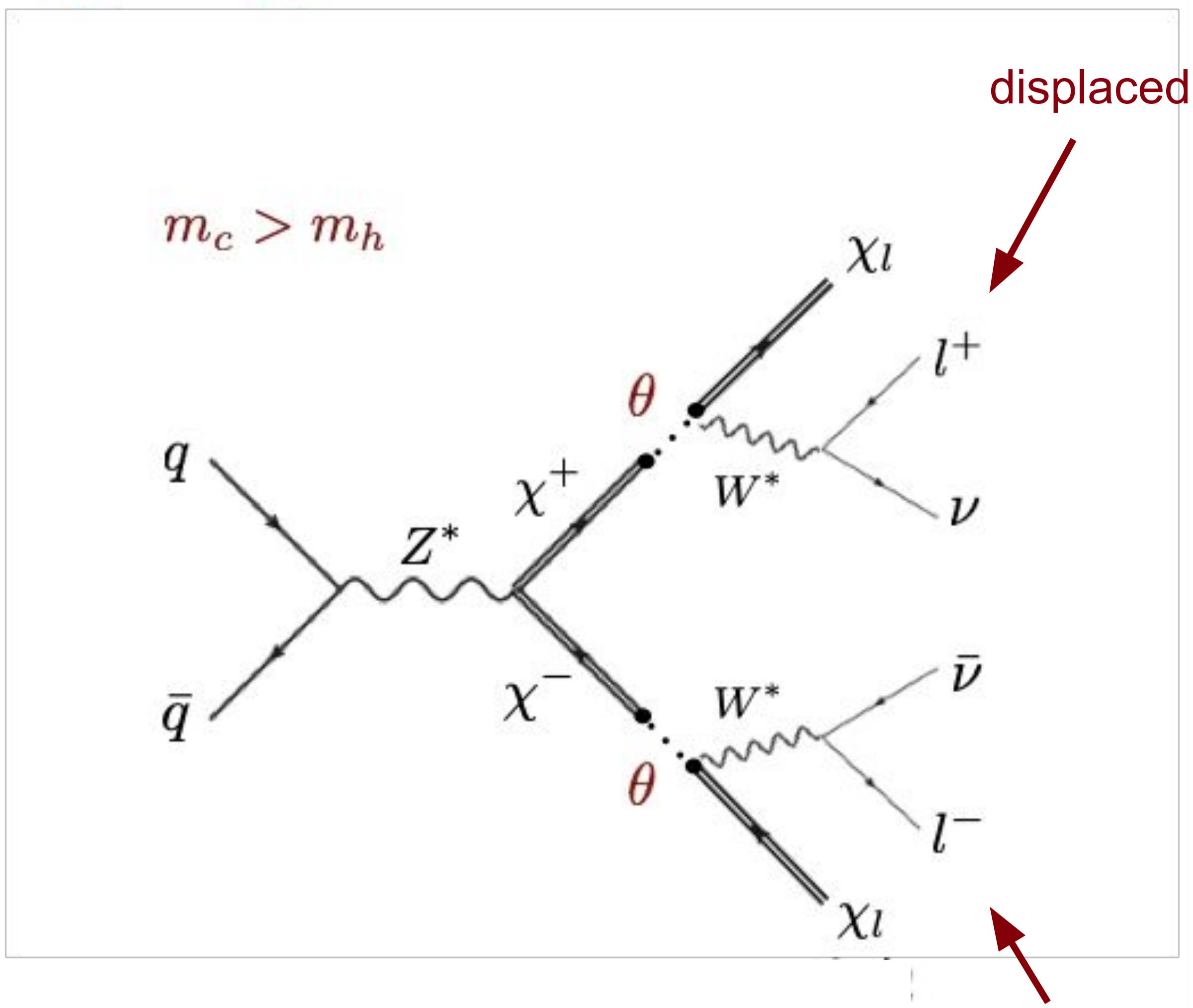
[R. Rosten's talk at 5th LLP Workshop]



Latest reports from the LHC LLP Community available at https://indico.cern.ch/event/922632/

Promising soft displaced signatures

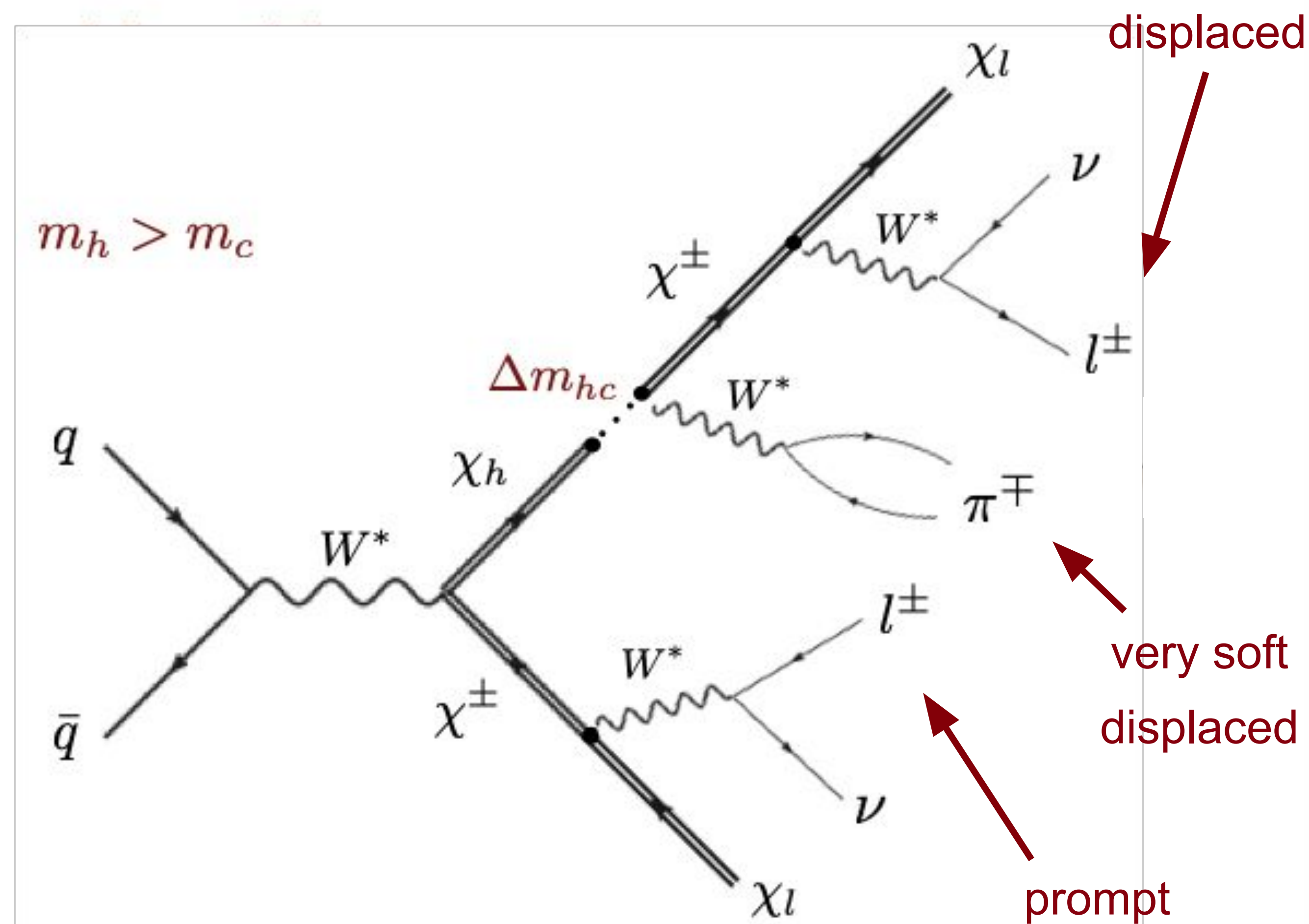
Soft displaced lepton pair



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

displaced

Displaced soft leptons + prompt jets



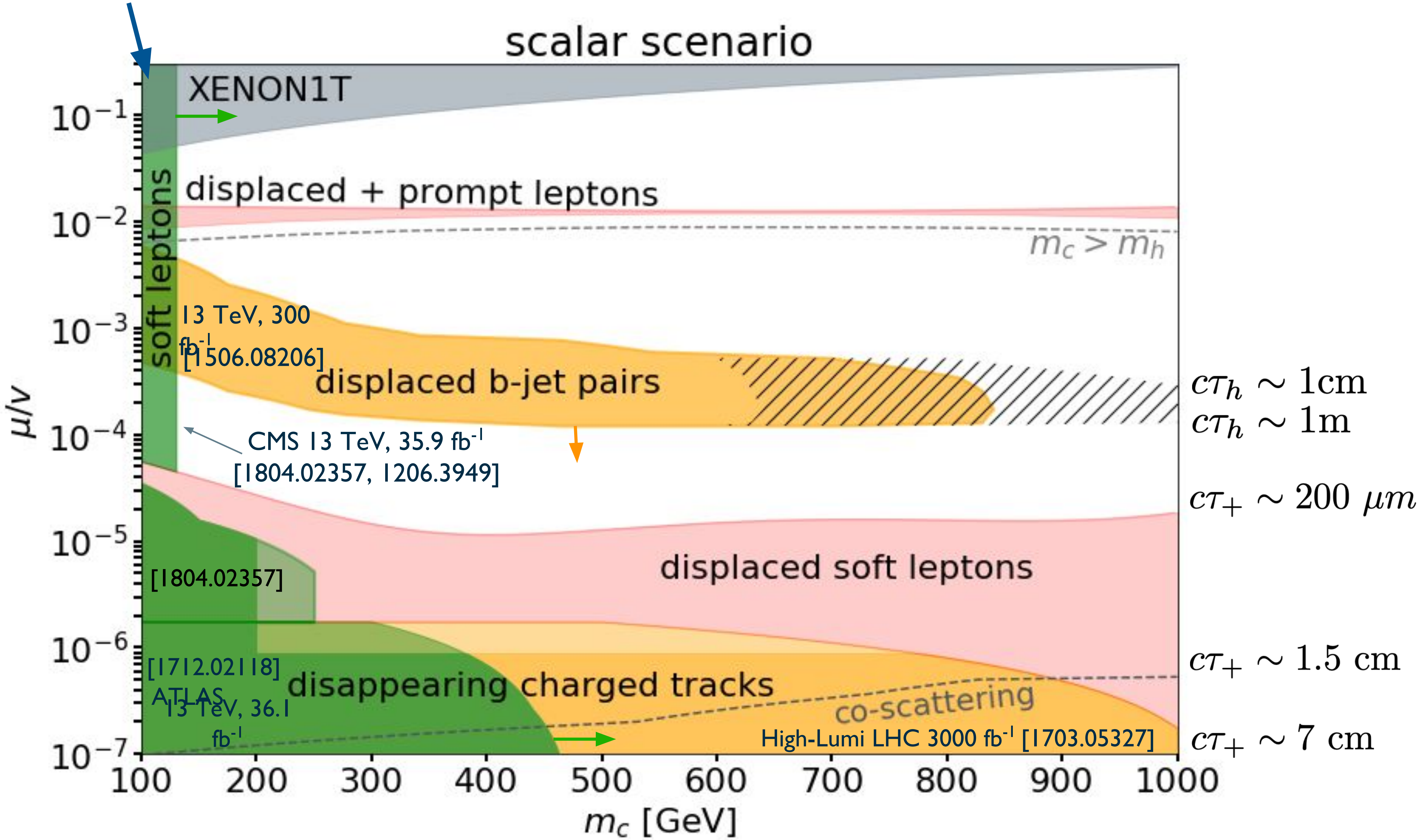
$\Delta M_{+,l} = 15 - 30$ GeV

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

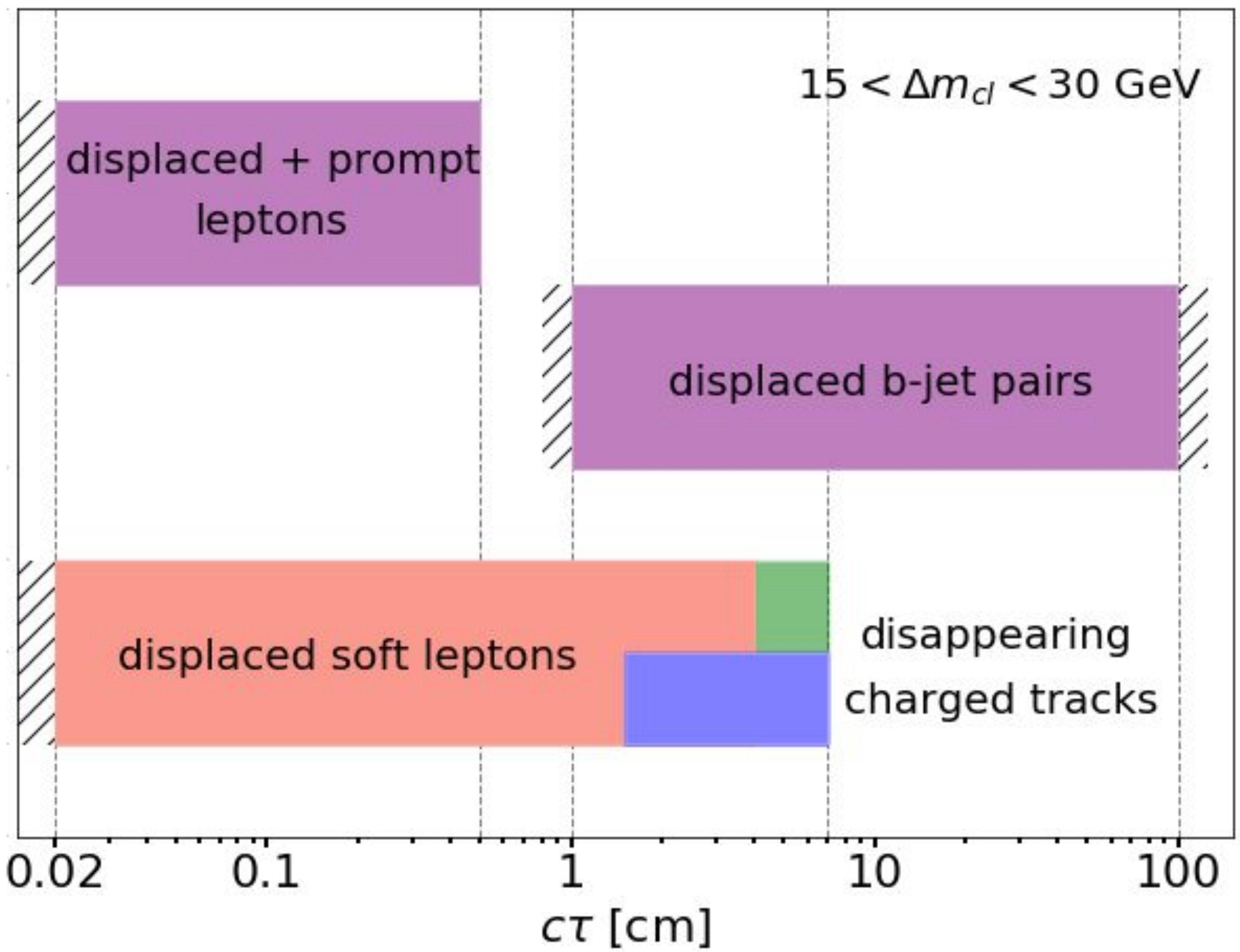
AF & S. Westhoff [1812.04628]

Collider searches

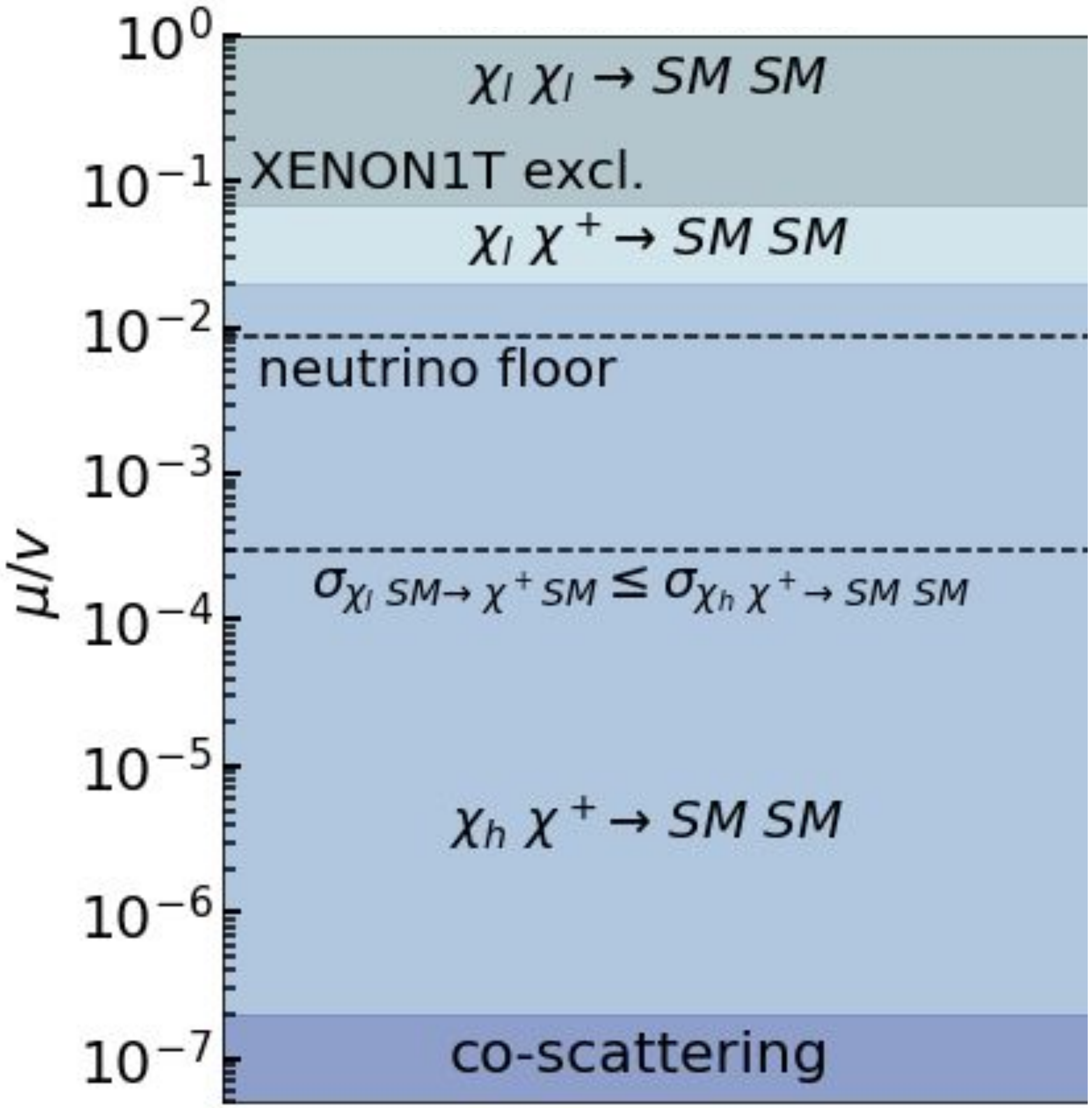
Prompt searches can not help

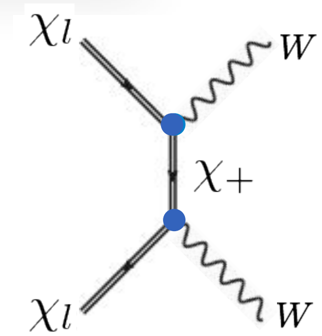


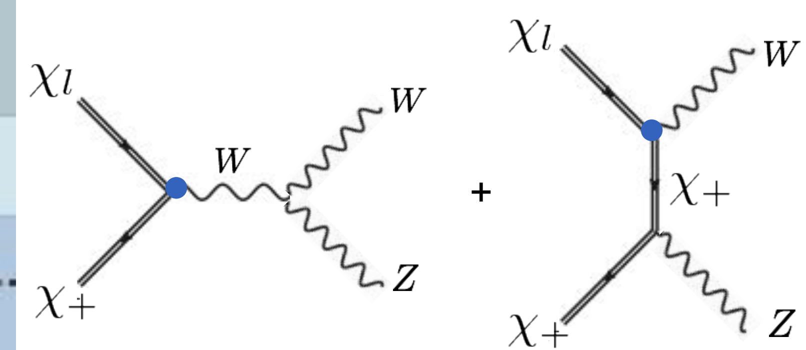
Lifetimes accessible @ LHC

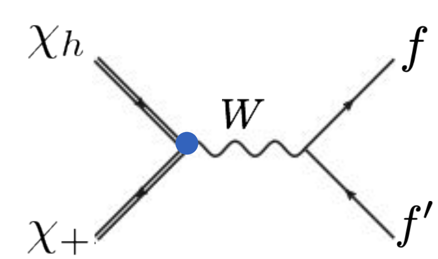


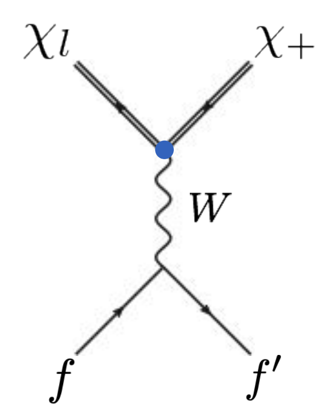
Higgs portal again: freeze-out phases







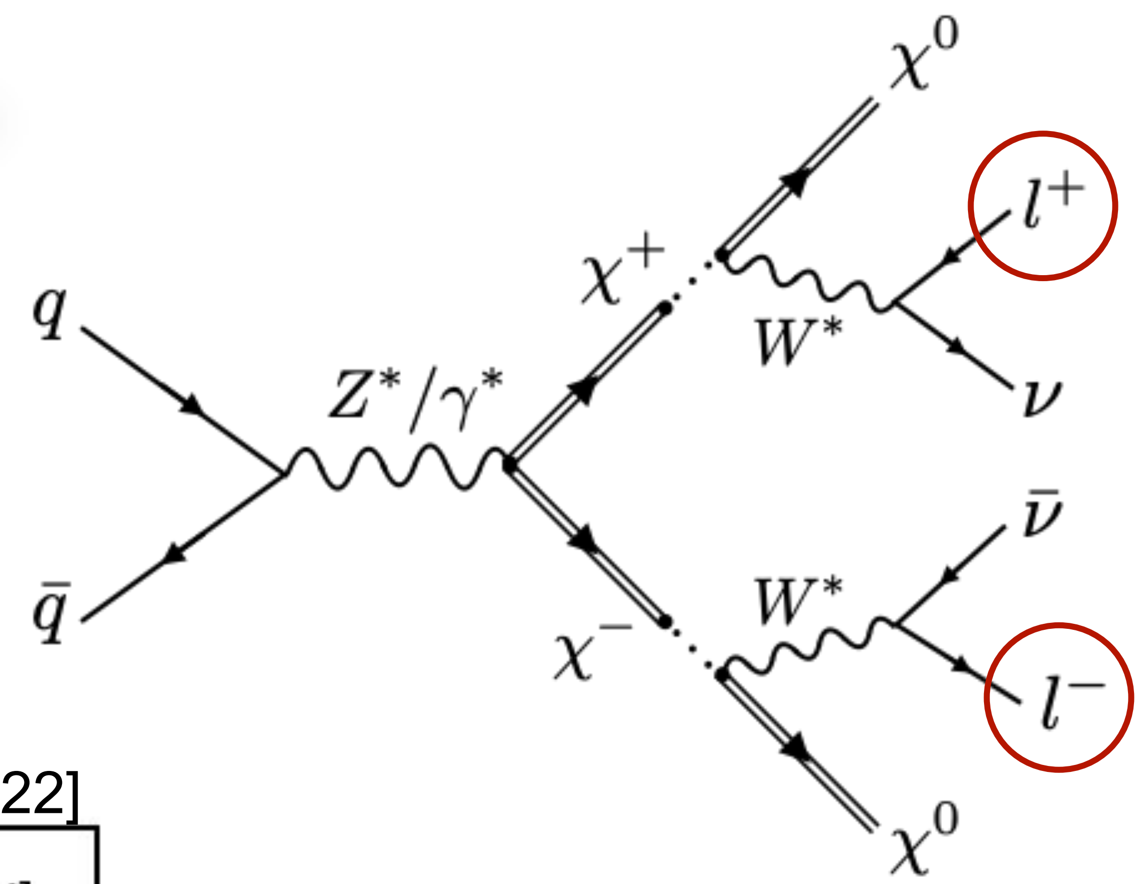


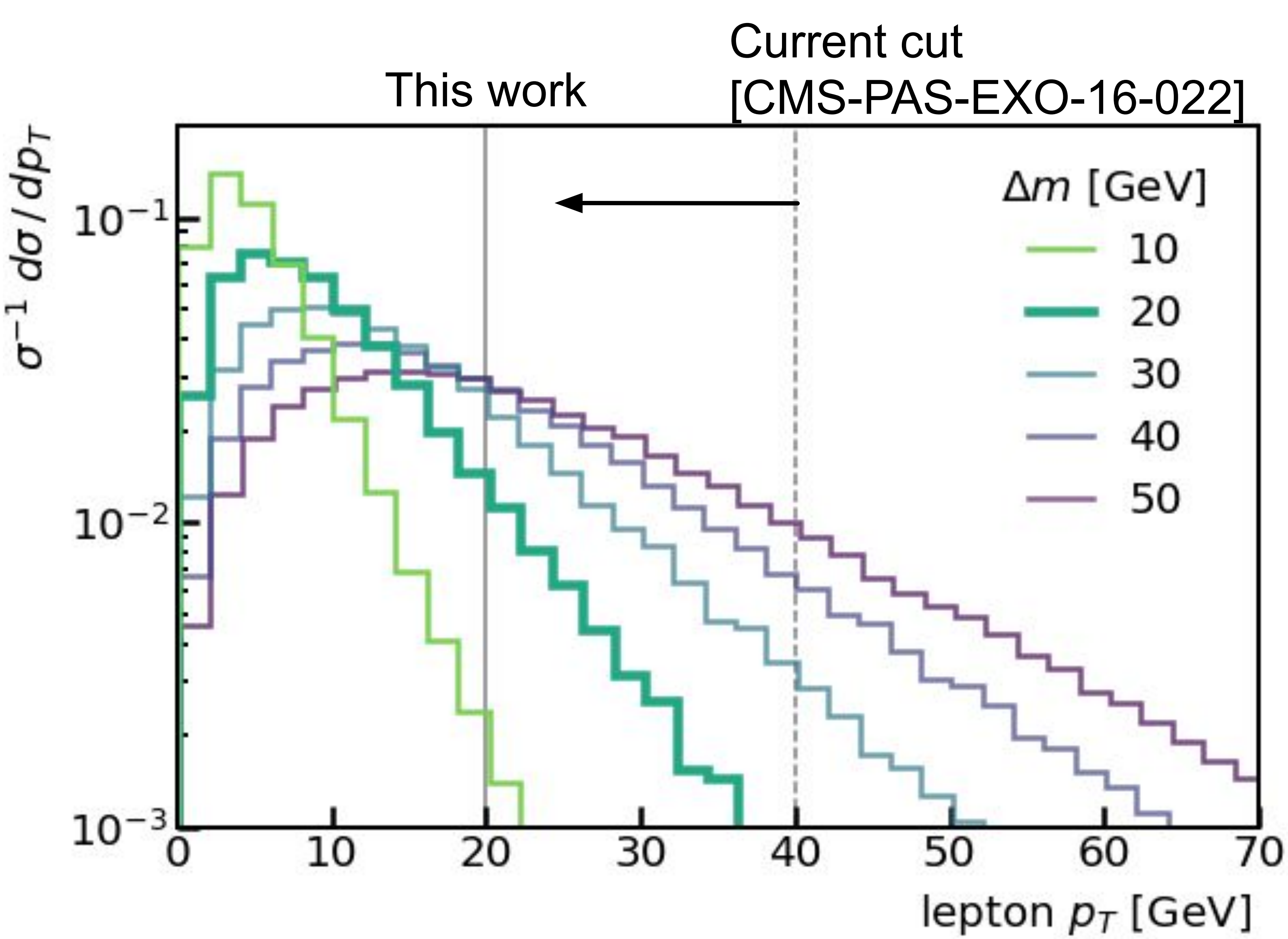


LLPs @ the LHC

F. Blekman, N. Desai, AF, A. R. Sahasransua & S. Westhoff [2007.03708]

Soft displaced leptons @ CMS





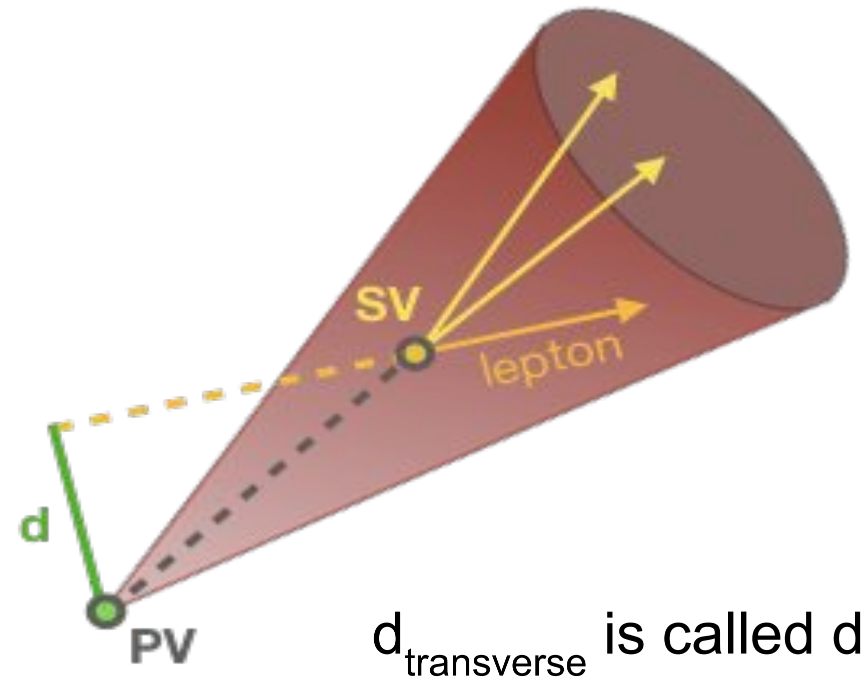
Displacements considered

Sensitive to

200 μm < d_0 < 10 cm

⇩

1 mm < cτ < 20 cm



$d_{transverse}$ is called d_0

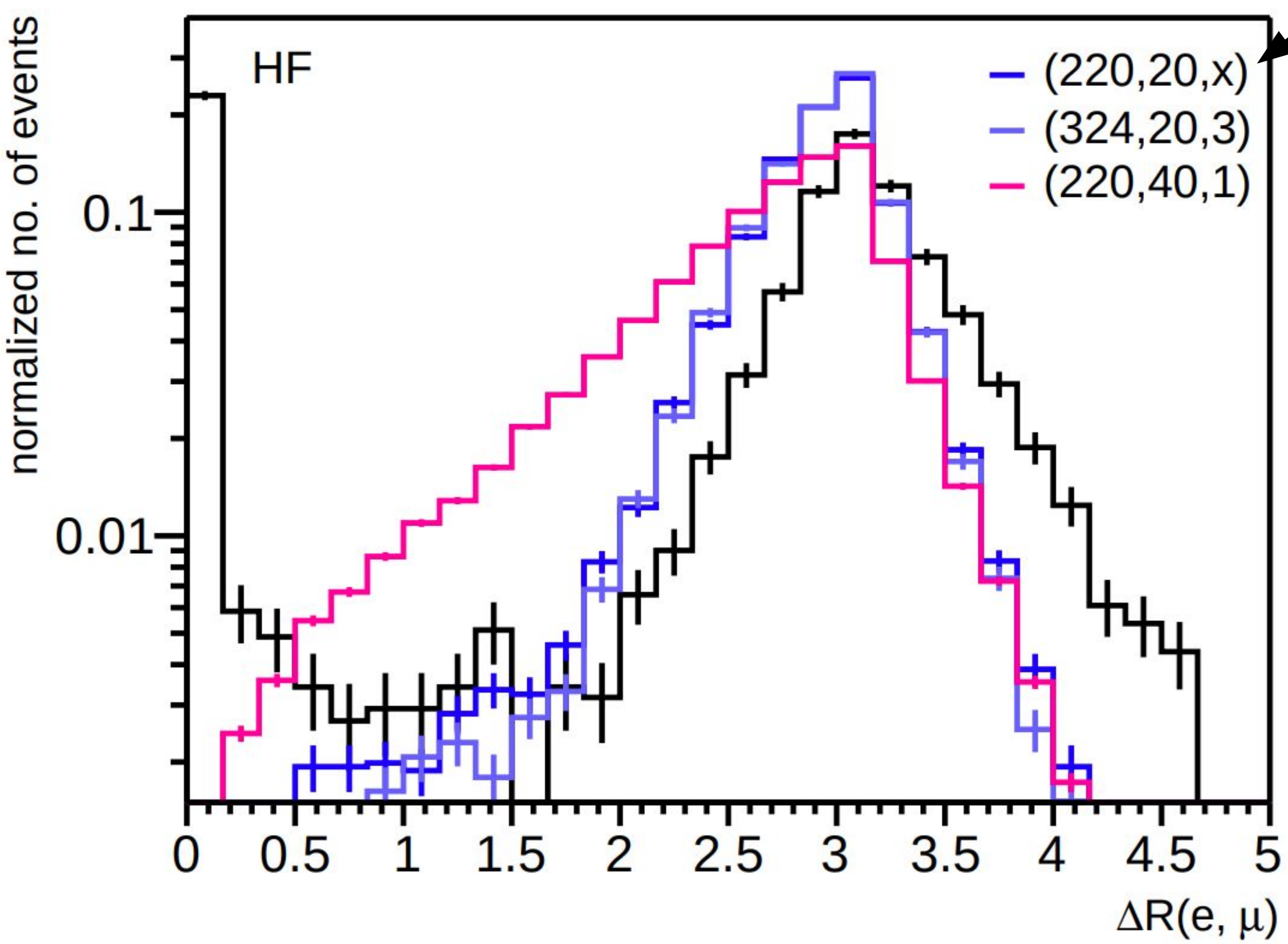
Benchmarks

	#	m_c [GeV]	Δm [GeV]	$c\tau_c$ [cm]	$\mathcal{B}(\ell^+\ell^-)$
DM candidate	1	324	20	2	0.025
	2	220	20	3	0.014
Various lifetimes	3	220	20	0.1	1
	4	220	20	1	1
	5	220	20	10	1
	6	220	20	100	1
Cross-check (excluded)	7	220	40	1	1

Signal/background discrimination

Main background $b\,\bar{b} \to e^{\pm}\,\mu^{\mp} + X$ hurts! ⇨ Making use of differences in kinematics

Indepent from lifetime



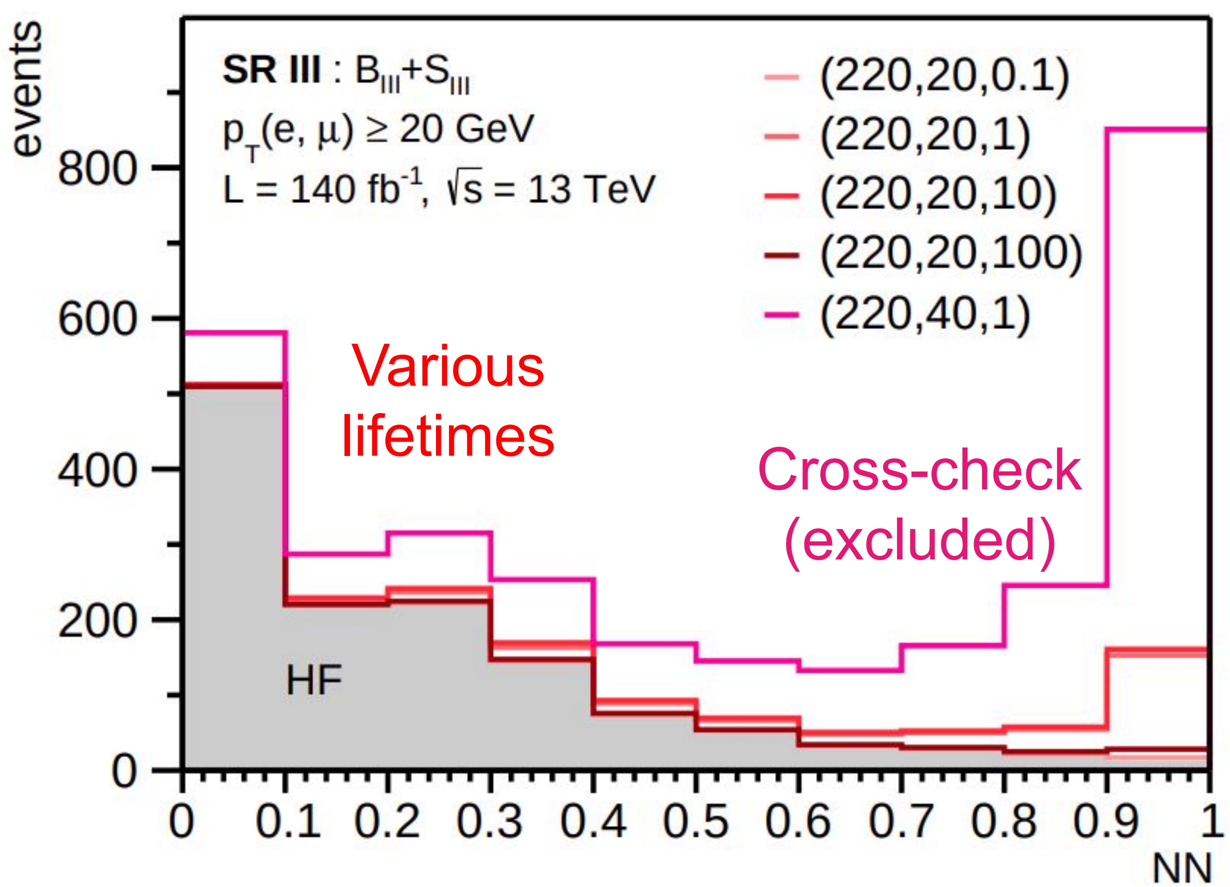
$$\Delta R(e,\mu) = \sqrt{\Delta\eta^2(e,\mu) + \Delta\phi^2(e,\mu)}$$

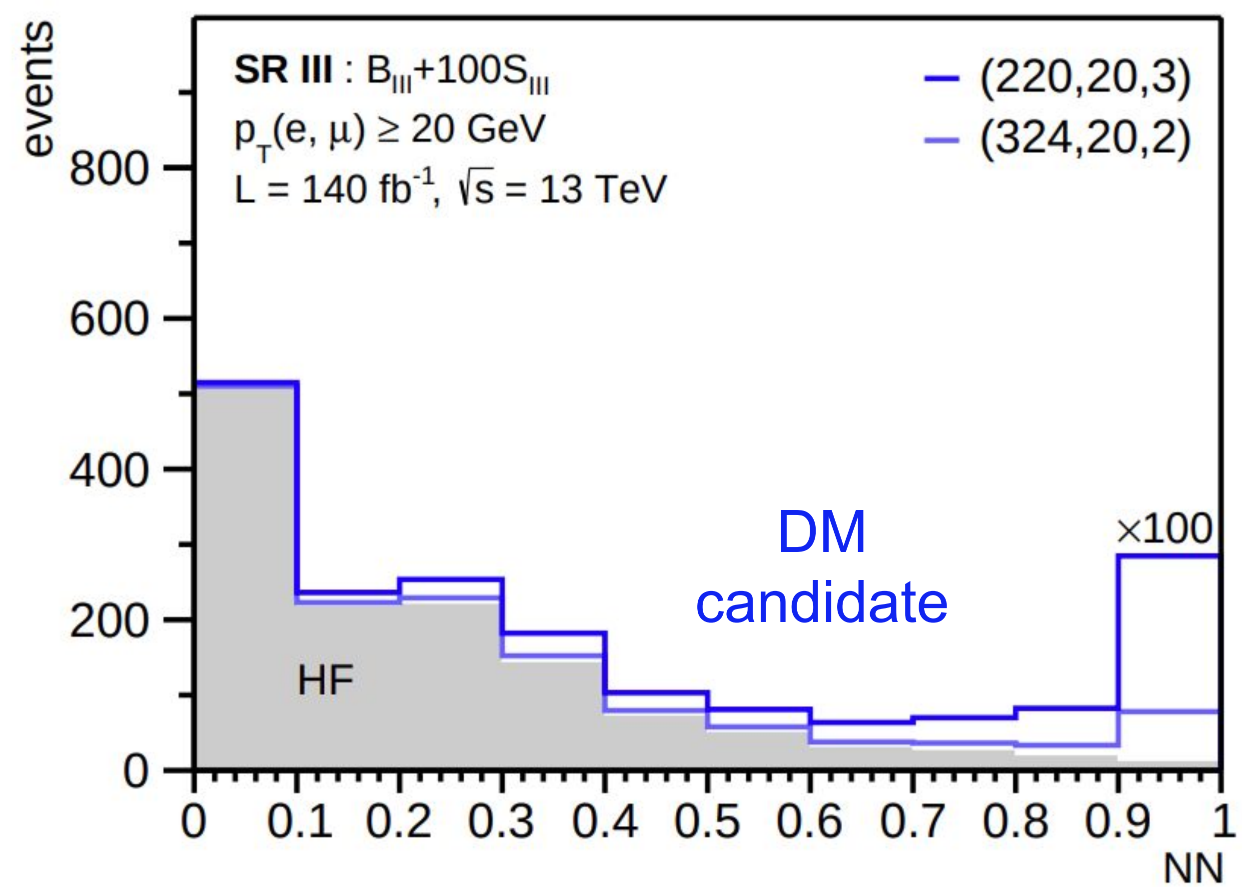
Background still too high

Cut-based analysis is inefficient!

Resorting to neural networks

- Using 9 MET and geometry-related variables (d_0- related ones are excluded to prevent unrealistic modelling)
- Trained (80%) and tested (20%) on (324, 20, 2)
- Modest kinematic differences between BP ⇨ one classifier for all benchmarks.





Hard cut at NN > 0.9: successful for red/magenta, blue is unseen due to small cross section

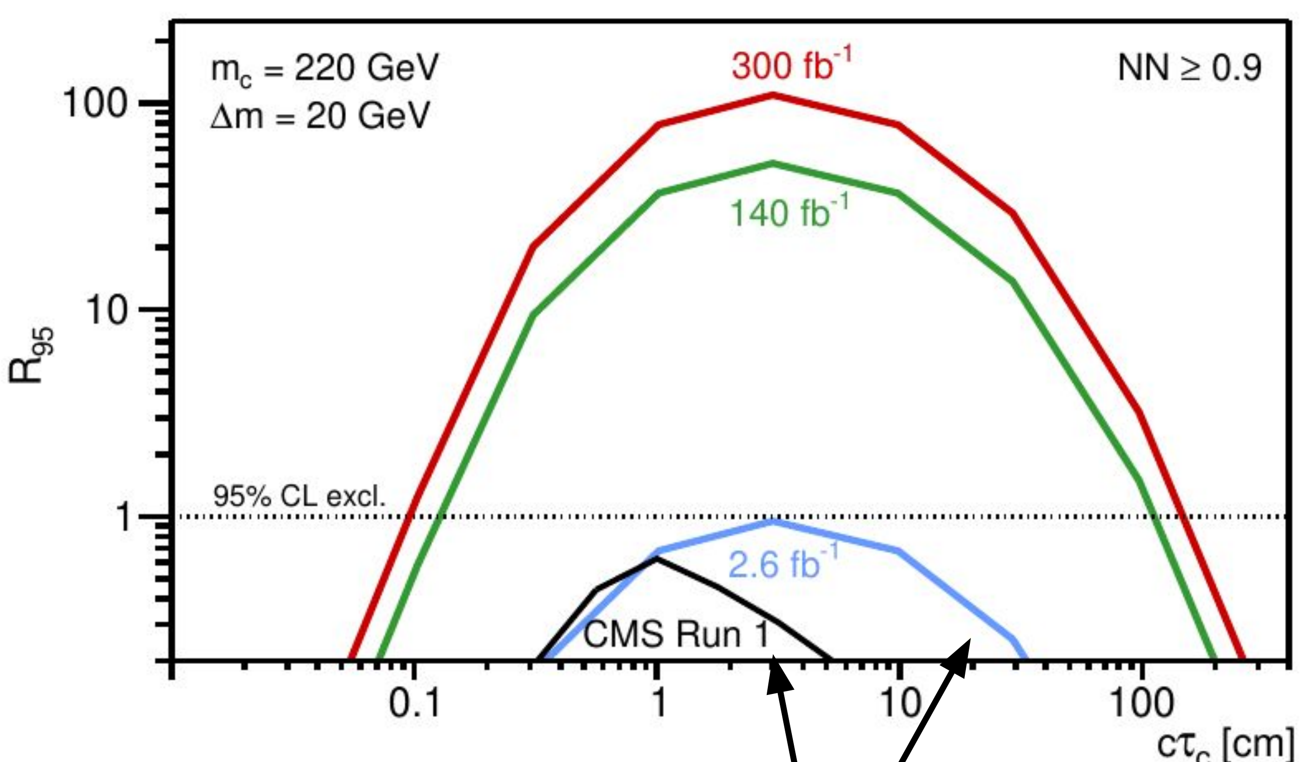
F. Blekman, N. Desai, AF, A. R. Sahasransua & S. Westhoff [2007.03708]

Expected sensitivity

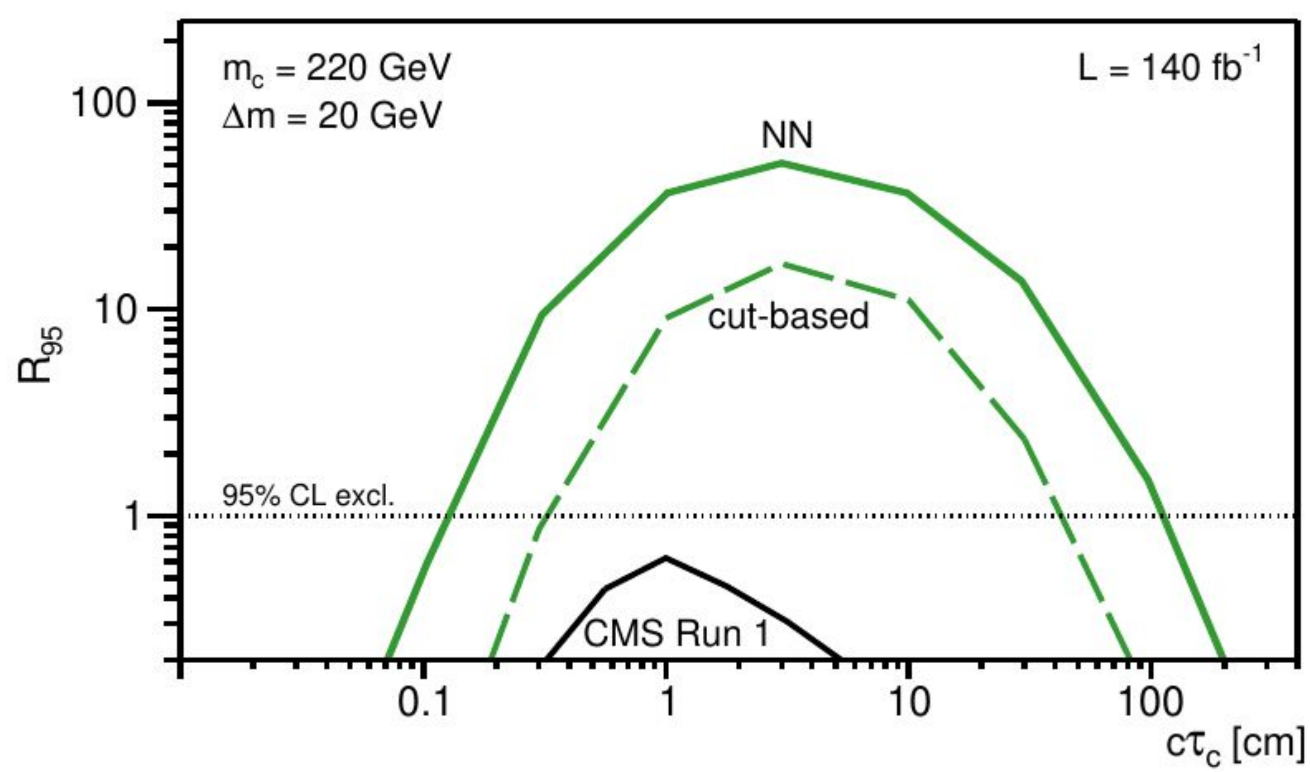
Poisson log likelihood ratio

$$\mathcal{Q} = \sum_{i=\mathrm{I,II,III}} -2\log\left(\frac{\mathcal{L}_{S_i+B_i}}{\mathcal{L}_{B_i}}\right), \qquad \mathcal{L}_{S_i+B_i} = e^{-(S_i+B_i)}\frac{(S_i+B_i)^{N_i}}{N_i!}, \qquad R_{95} = \mathcal{Q}/5.99$$

Predictions for the LHC



Cut-based vs NN analyses



Performance for the 8 TeV search
[1409.4789]

LLPs beyond the LHC

AF, R. Shäfer, S. Westhoff [1911.03490]

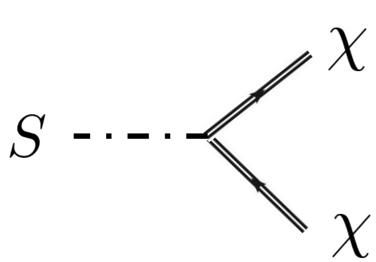
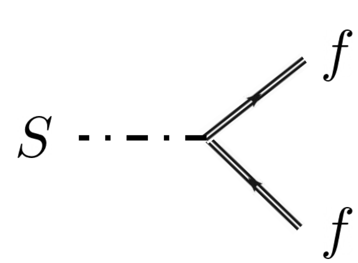
LLPs @ Belle II: example of light scalars

$$\mathcal{L} = -\tfrac{1}{2}m_\phi^2\phi^2 - \mu\,|H|^2\phi - y_\chi\bar{\chi}\chi\phi - \tfrac{1}{2}m_\chi\bar{\chi}\chi$$

DM Candidate

Search regions

$$\Gamma_S = c_\theta^2\,\Gamma_{\chi\bar{\chi}} + s_\theta^2\,\Gamma_{\rm SM}$$

$m_S > 2m_\chi$	$m_S < 2m_\chi$
Invisible decays dominate	Visible decays only
	
Missing energy	Displaced searches

Mass basis:

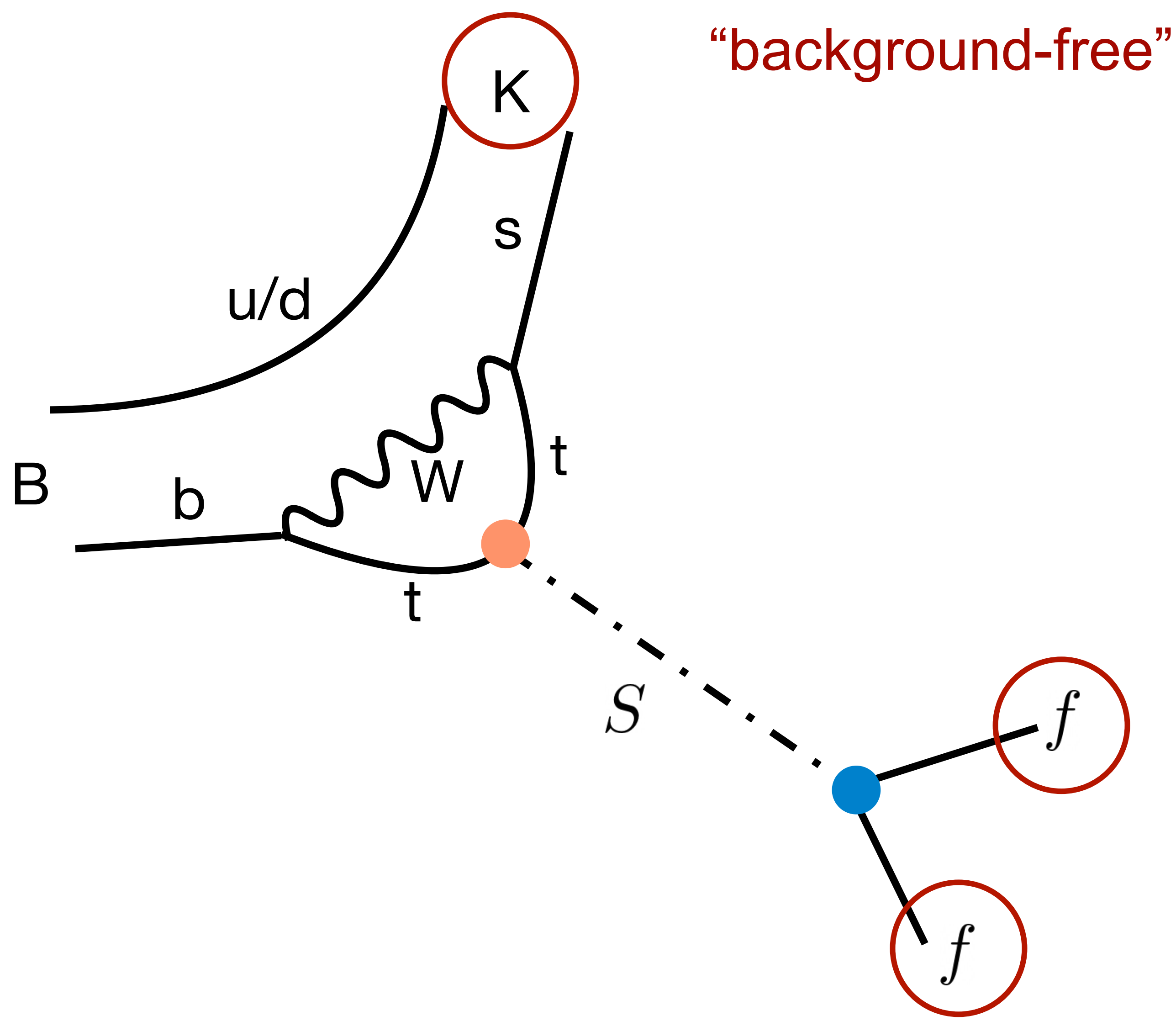
$h,\ S$

Higgs

New scalar

AF, R. Shäfer, S. Westhoff [1911.03490]

Displaced semi-leptonic decays

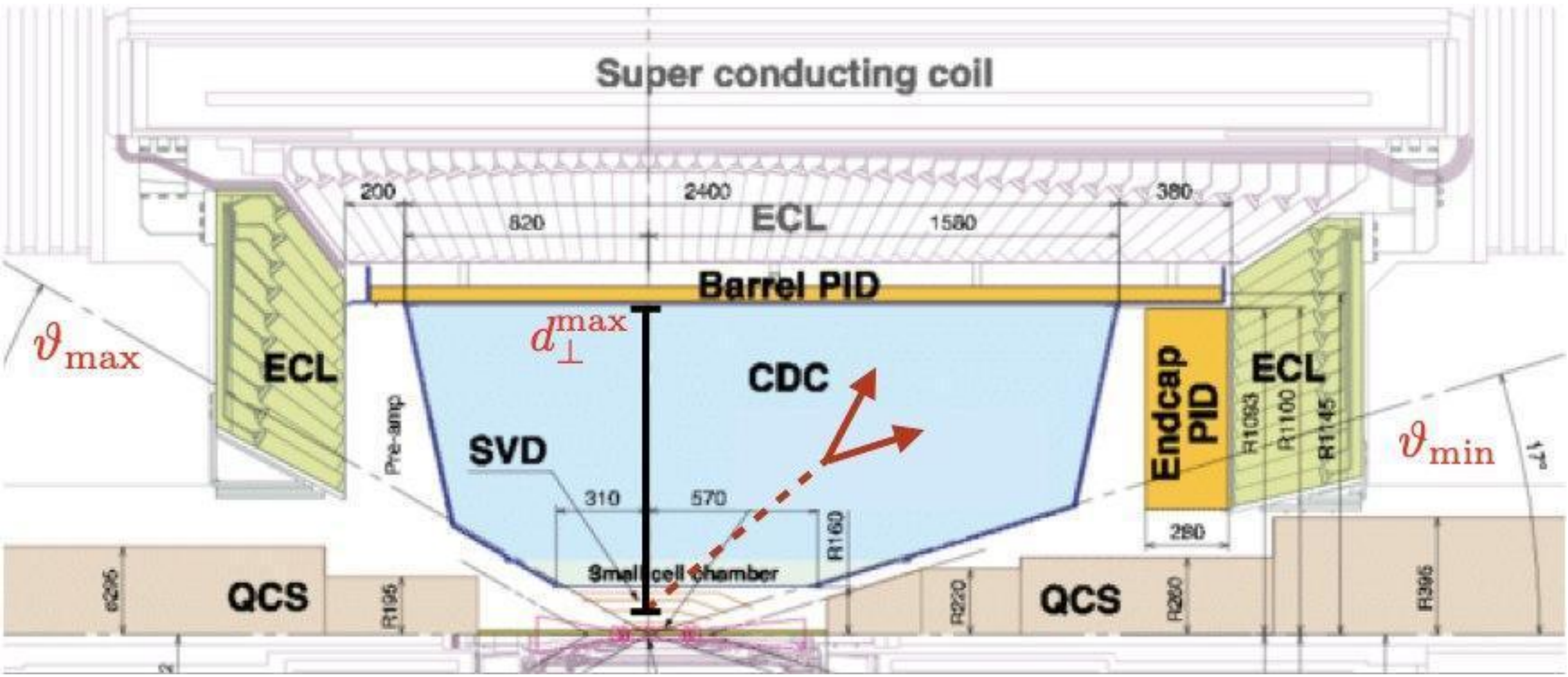


$$\frac{m_t}{v} s_\theta$$

$$\frac{m_f}{v} s_\theta$$

Displaced decays for decent rate

Displaced signatures @ Belle II



$$N_{f\bar{f}} = N_{B\bar{B}} \times 1.93\,\mathcal{B}(B \to KS)\mathcal{B}(S \to \mu\bar{\mu})$$

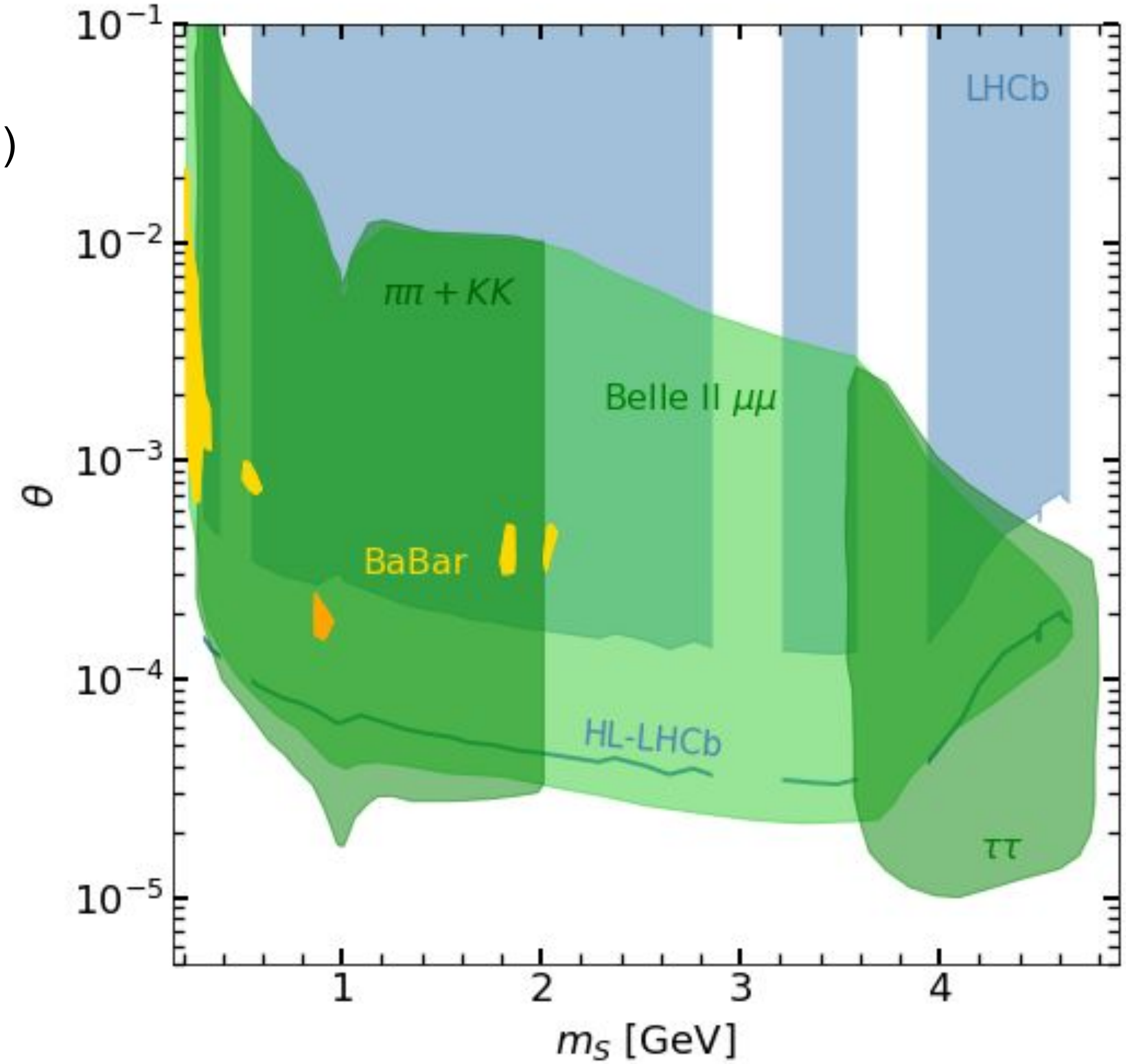
$$\times \int_{r_{\min}}^{r_{\max}} \frac{r^2 dr}{2d_S^3} \int_{\vartheta_{\min}}^{\vartheta_{\max}} \frac{d\vartheta}{2\sin^2\vartheta} e^{-\frac{r/\sin\vartheta}{d_S}}$$

B-factories: comparison

LHCb

Large boost

(particles decay outside)

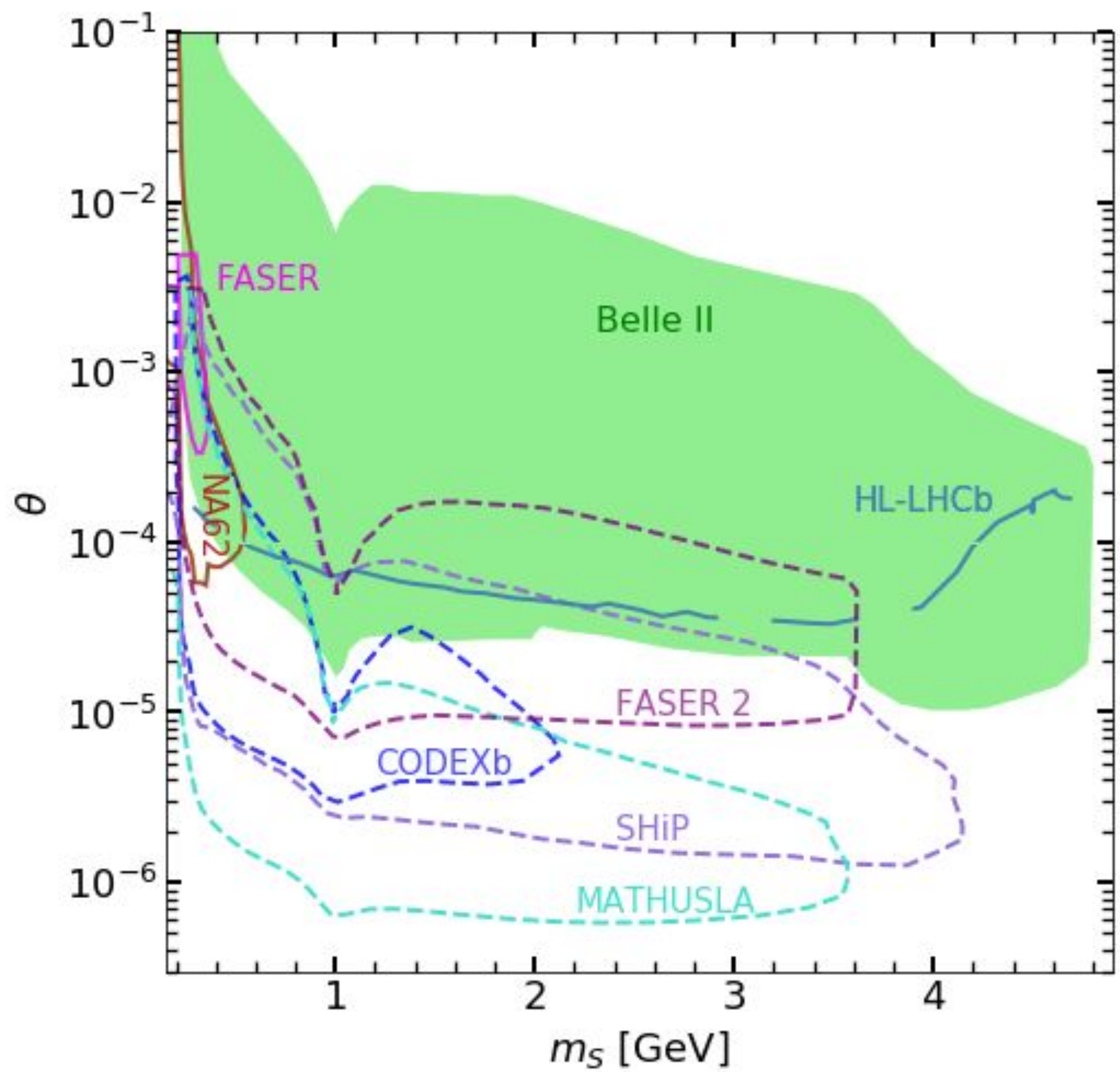


Belle II

B-s almost at rest

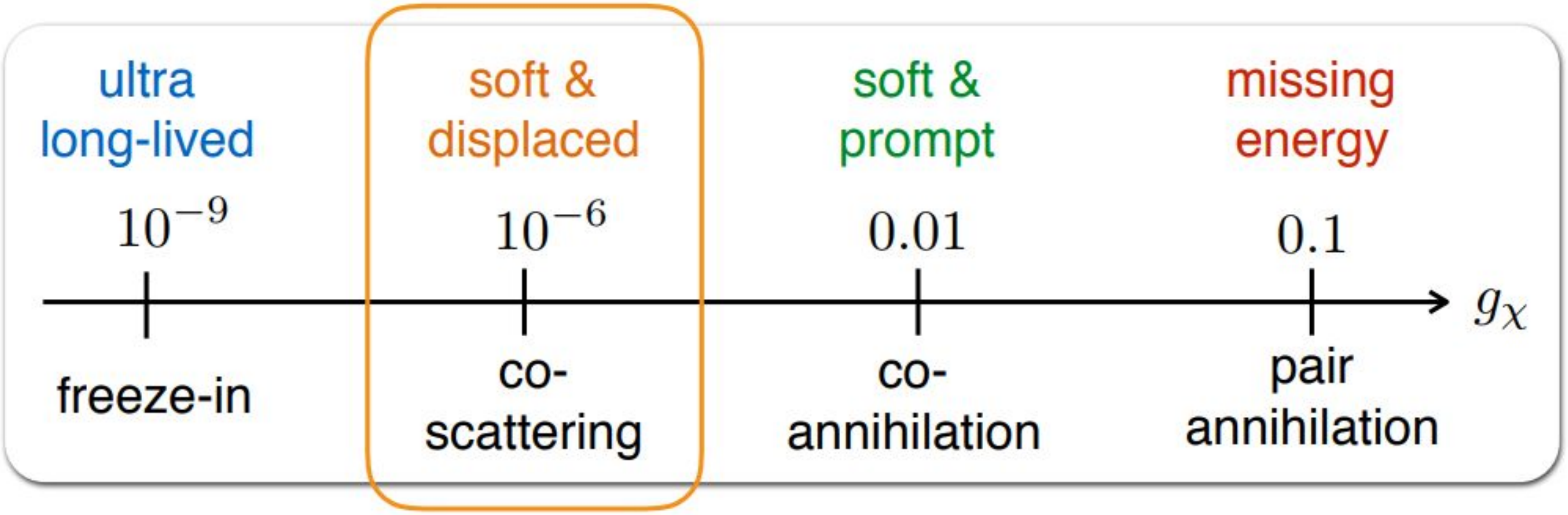
(larger lifetimes probed)

Belle II and fixed-target experiments



Take-home message(s)

- Strong direct detection constraints point us to a very weakly coupled dark sectors.
- Consequently, the “non-conventional" processes set the DM relic abundance.
- This also leads to a natural appearance of the long-lived states at collider scales. The most promising collider signatures involve displaced particles.
- New searches are needed to conclusively test this scenario: displaced soft leptons, appearing tracks, etc.
- Soft objects require new experimental developments (e.g. cross-triggers) .



[S.Westhoff's talk at 5th LLP Workshop]

Open questions

- How powerful are displaced searches?
- Which experiments can probe the co-scattering regime (are the lifetimes at the scale of ATLAS/CMS or beyond i.e. FAZER/MATHUSLA/ShiP…)?
- What happens for even weaker couplings? At which point we switch to the freeze-in scenarios?
- Are there any hints from cosmological observations about the properties of the non-thermal dark matter momentum distribution?

Thank you!

Singlet-triplet model: mass basis

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 $m_\ell/m'_\ell > 0$

AF & S. Westhoff [1812.04628]

Couplings of dark fermions

Two physical scenarios, depending on parameters of the theory:

Scalar case:

Couplings $\propto 1, \gamma_\mu$

Pseudo-scalar case:

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

Connected through chiral rotation:

$$\chi_l \to i\gamma_5 \chi_l$$

- Changes the sign of the mass term:

$$-m_l \bar{\chi}_l \chi_l \to m_l \bar{\chi}_l \chi_l$$

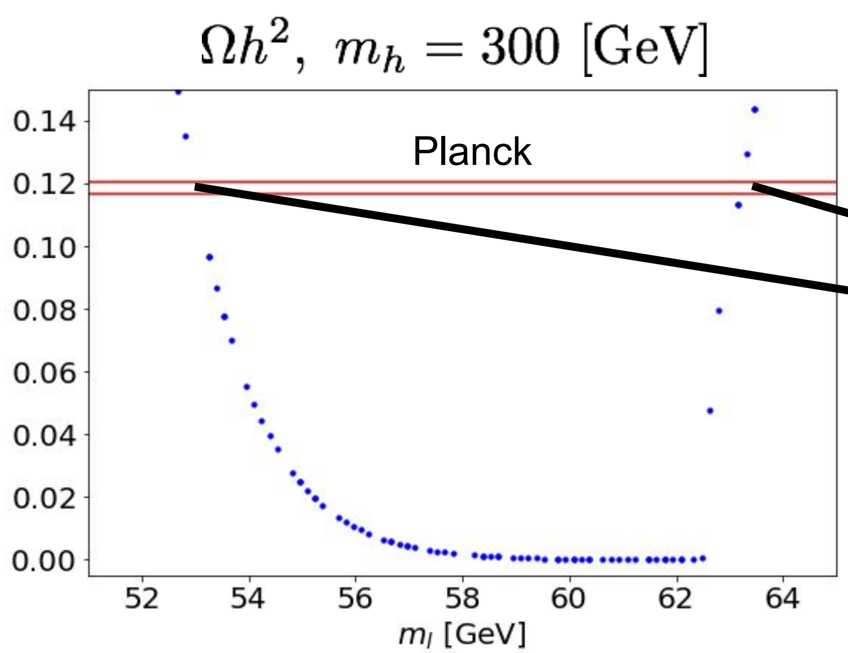
- Leads to pseudo-scalar (axial-vector) interactions:

$$\bar{\chi}_h \chi_l \to i\bar{\chi}_h \gamma_5 \chi_l$$

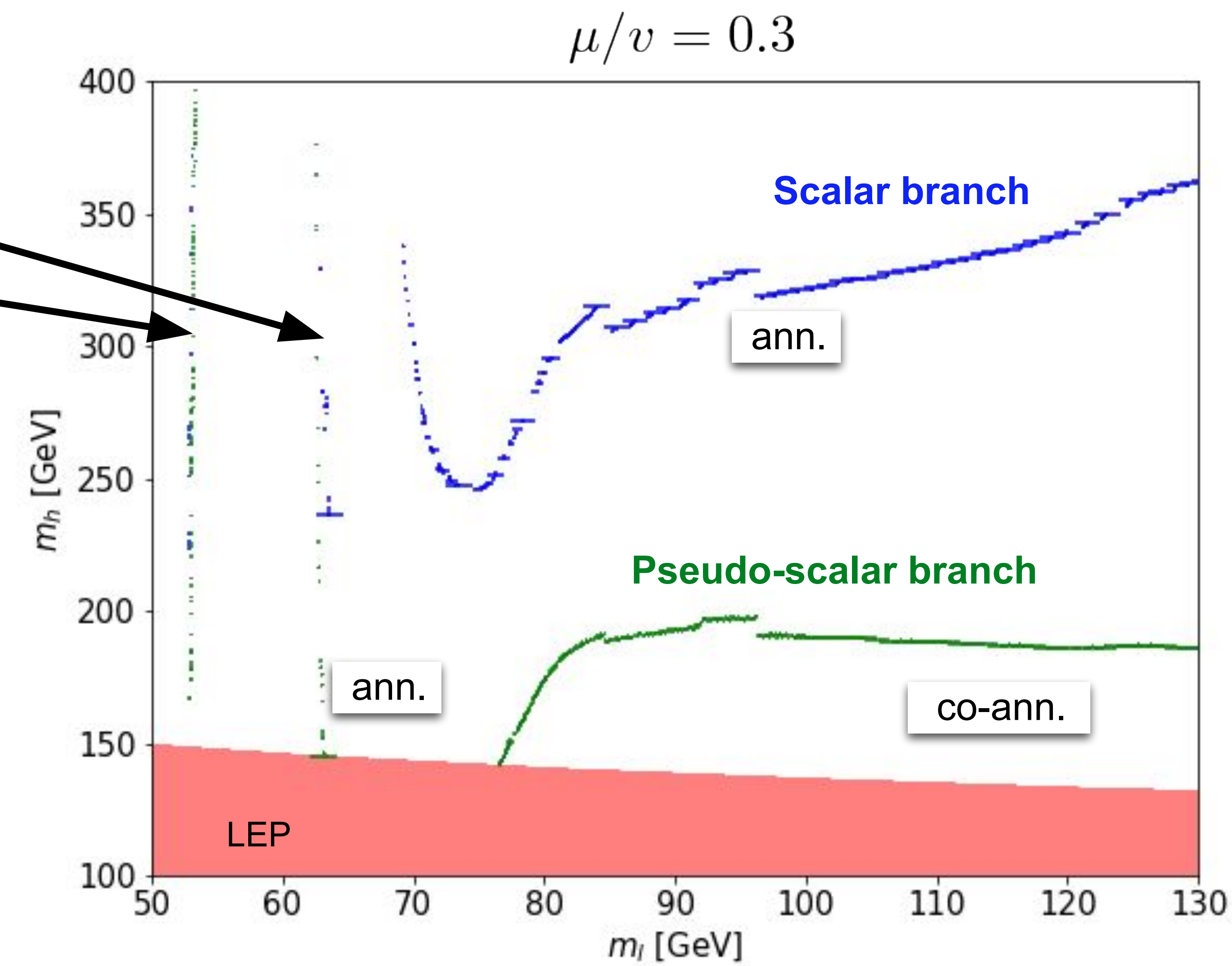
$$\bar{\chi}_+ \gamma^\mu \chi_l \to i\bar{\chi}_+ \gamma^\mu \gamma_5 \chi_l$$

See also [hep-ph/0702148]

Relic density: threshold effects



Higgs resonance region



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

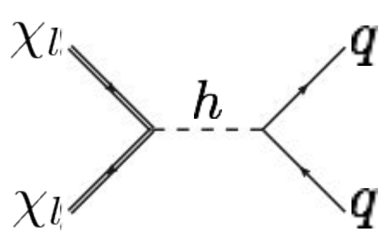
Blue/green: $\Omega_\psi h^2 = 0.1199 \pm 0.0022$

[Planck coll., 1502.01589]

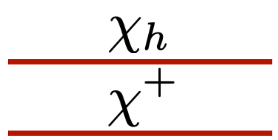
AF & S. Westhoff [1812.04628]

[1805.12562]

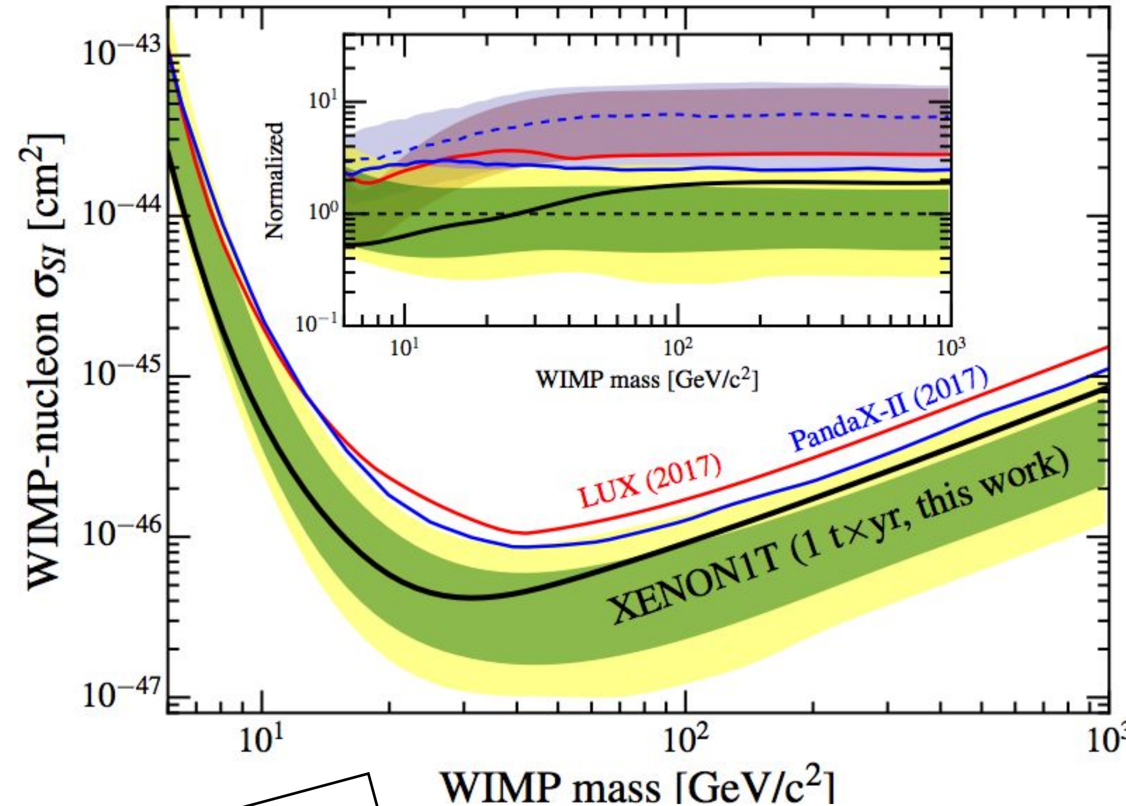
Direct detection

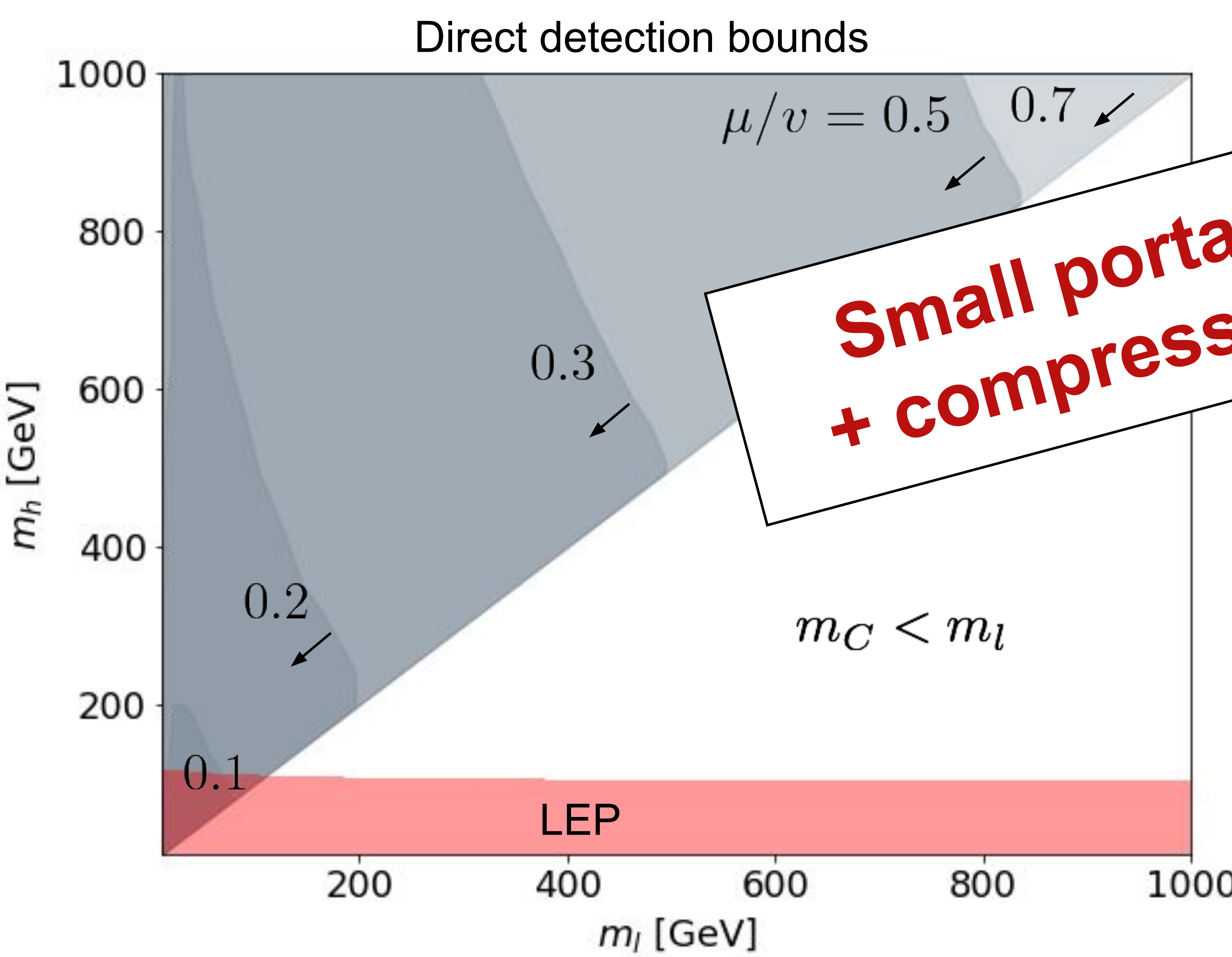


$$\propto \mu/v \sin(2\theta)$$

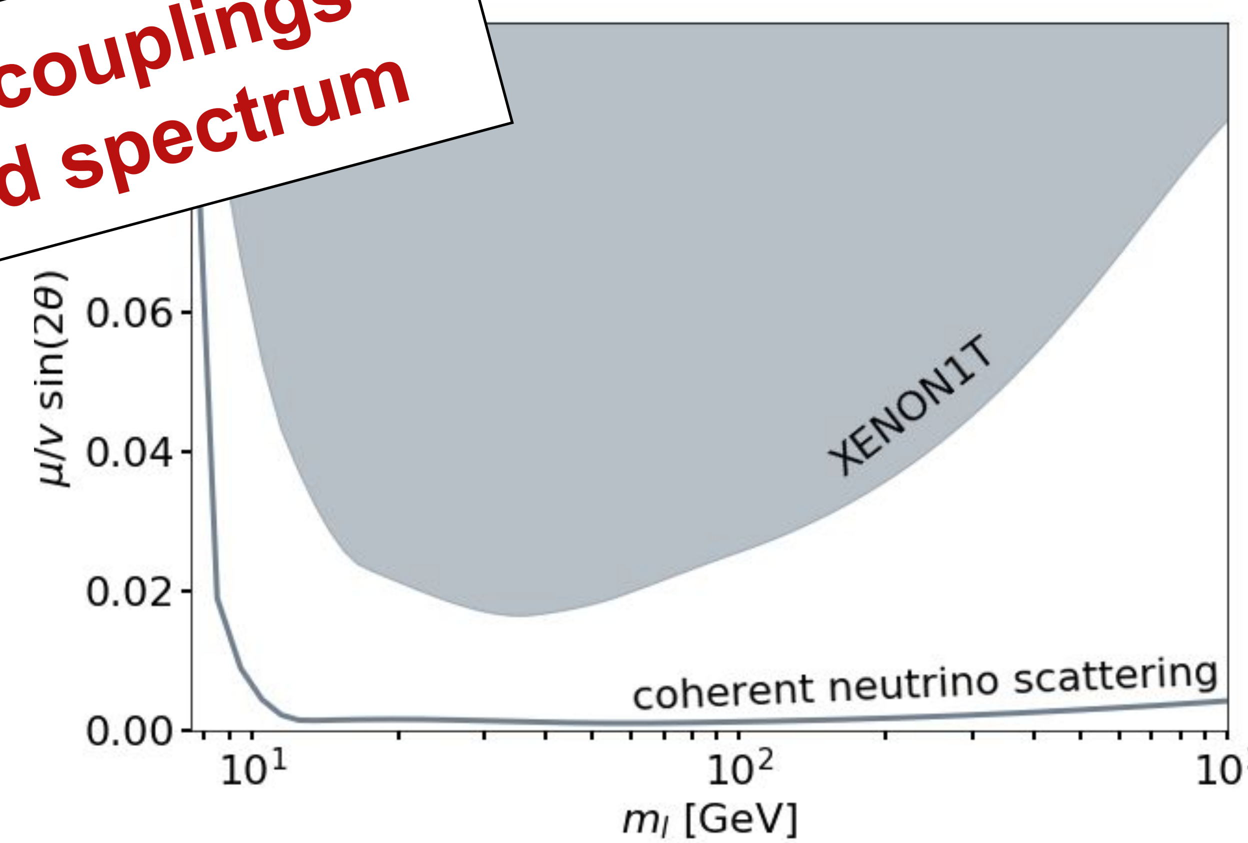


$$(\Delta m_{hc})^{\text{mix}} \simeq \mu \sin(2\theta)/2$$





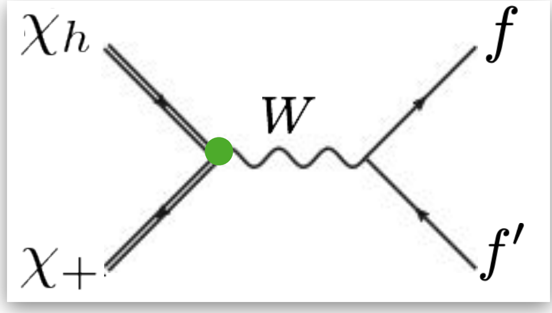
Small portal couplings + compressed spectrum



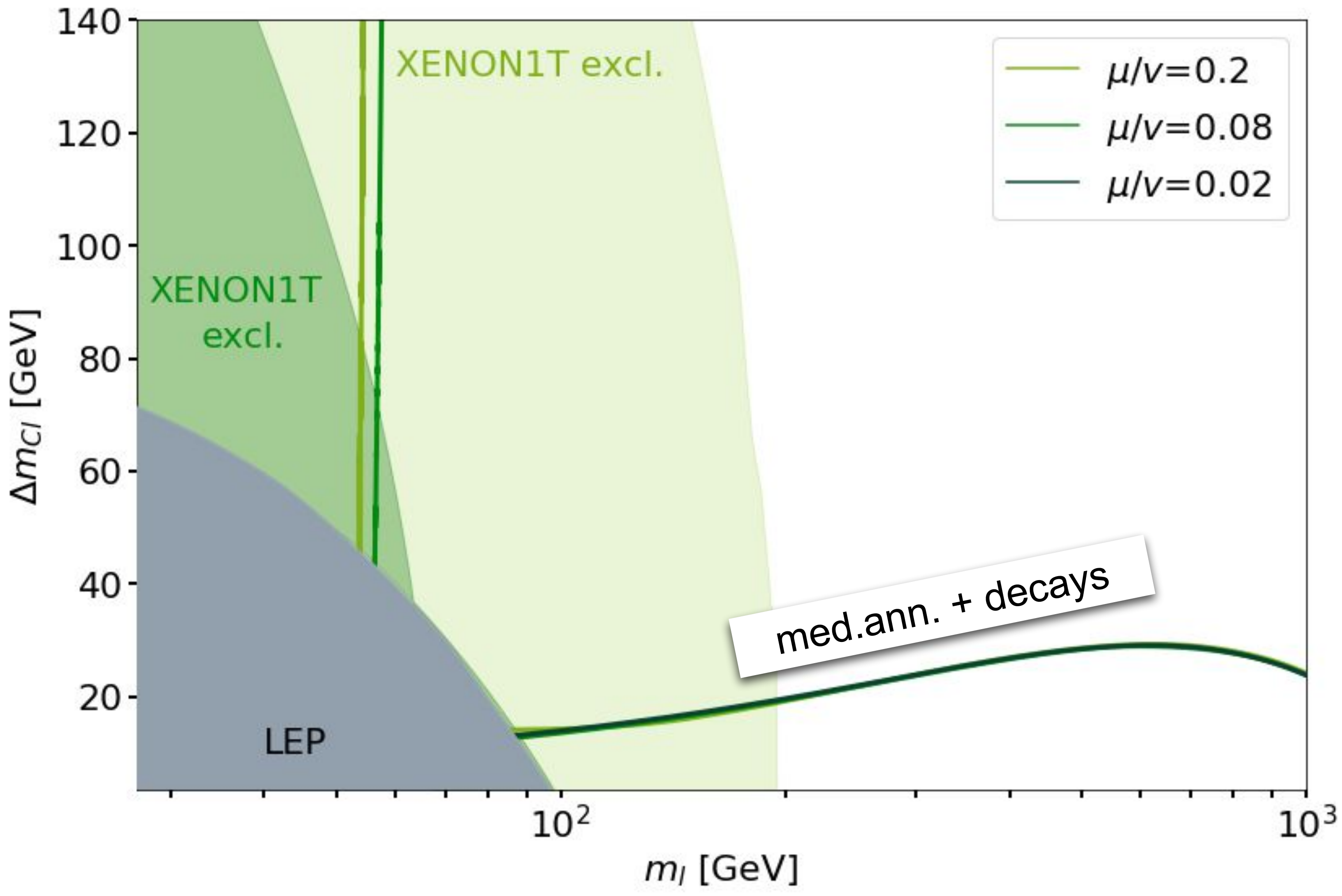
AF & S. Westhoff [1812.04628]

Surviving regions: pseudoscalar case

Mediator annihilation + further decays to χ_l



$(g\cos\theta)^2$



χ^+

χ_l

$15 - 30$ GeV

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

Relic density: implementation

Co-scattering processes are important for accurate prediction of dark matter relic density.

Not included in public codes e.g. MicrOMEGAs, MadDM, DarkSUSY

Complication:

the DM particles are frequently not in thermal equilibrium

In principle

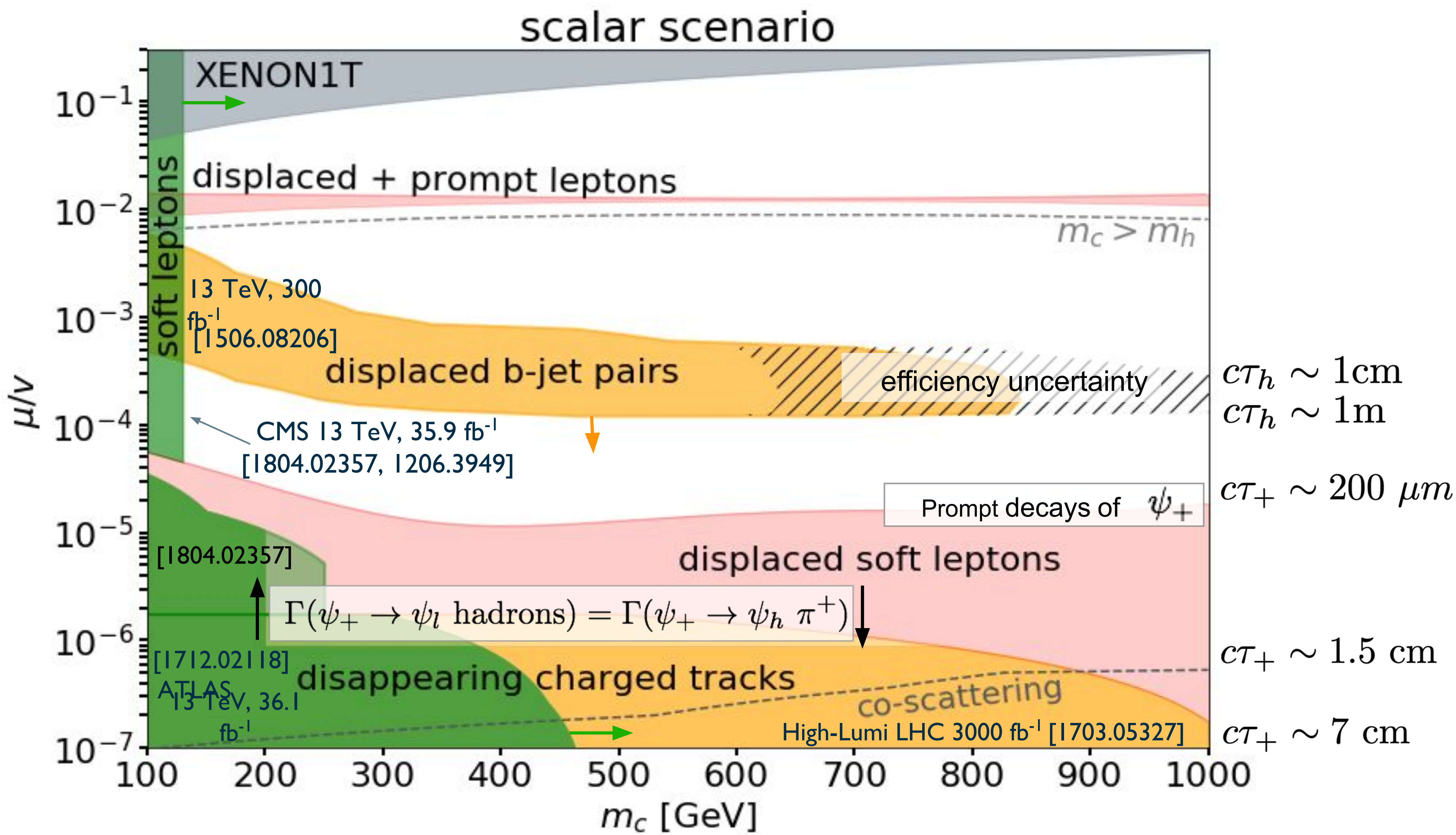
the coupled system non-integrated Boltzmann equations for all dark states must be solved

However, in many cases simplified approaches are possible

(see Binder at al. 1805.00526, D'Agnolo et al. 1906.09269)

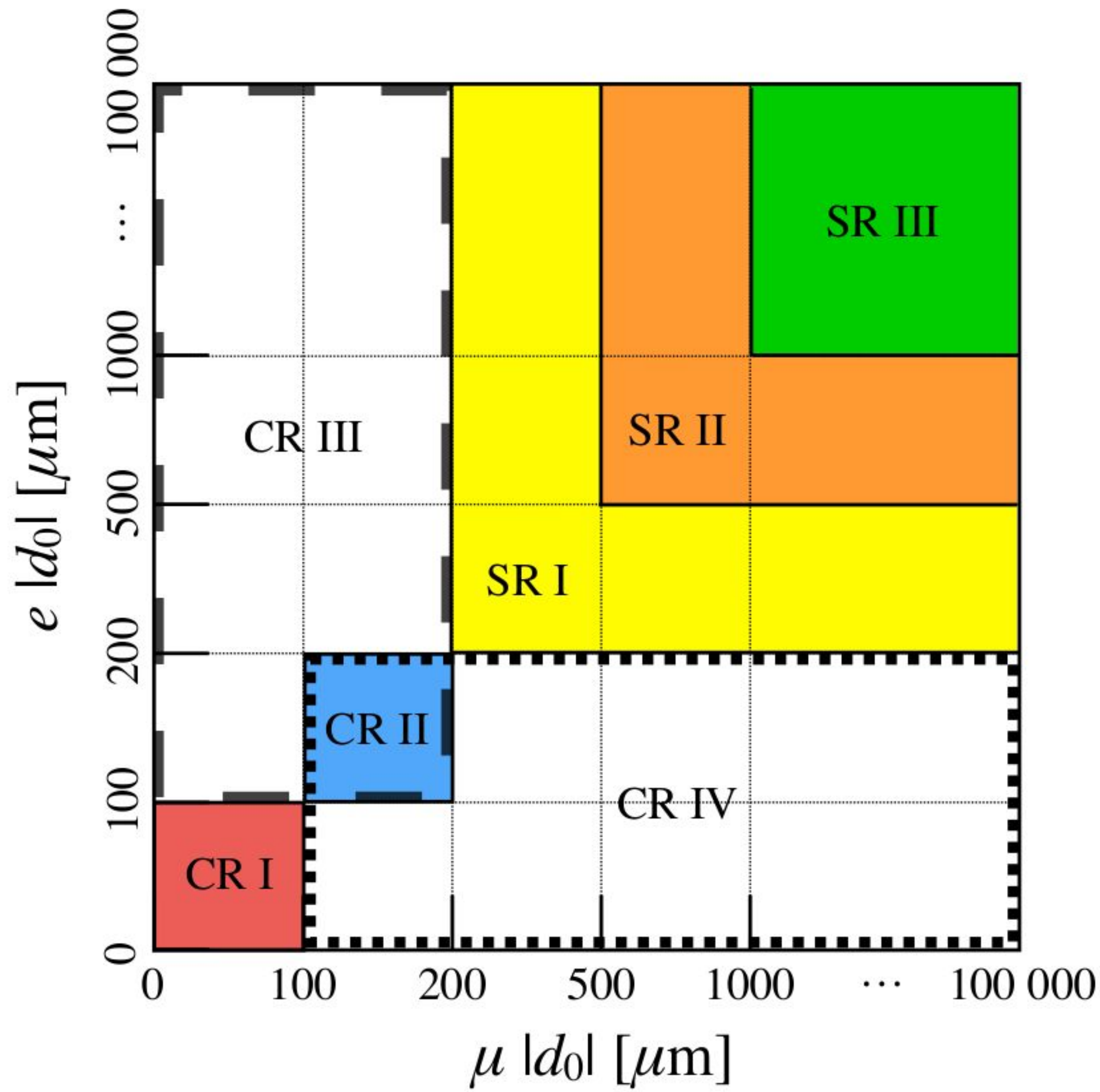
AF & S. Westhoff [1812.04628]

Collider searches: details



CMS-PAS-EXO-16-022 analysis

- Oppositely charged e and μ with ΔR>0.5
- One μ: $p_T > 40$ GeV, $\eta < 2.4$, Isolation < 0.15
- One e: $p_T > 42$ GeV, $\eta < 2.4$, Isolation < 0.12



F. Blekman,a N. Desai,b AF, A. R. Sahasransua & S. Westhoff
[2007.03708]

NN performance