FIMPs @ LHC

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My definition of FIMPs for this talk

WIMPs are weak scale; $\alpha \sim 0.01$

FIMPs have coupling to SM $\alpha < 10^{-4}$
(often 10^{-8} - 10^{-20} to get LLPs)

How to get LLPs at the LHC

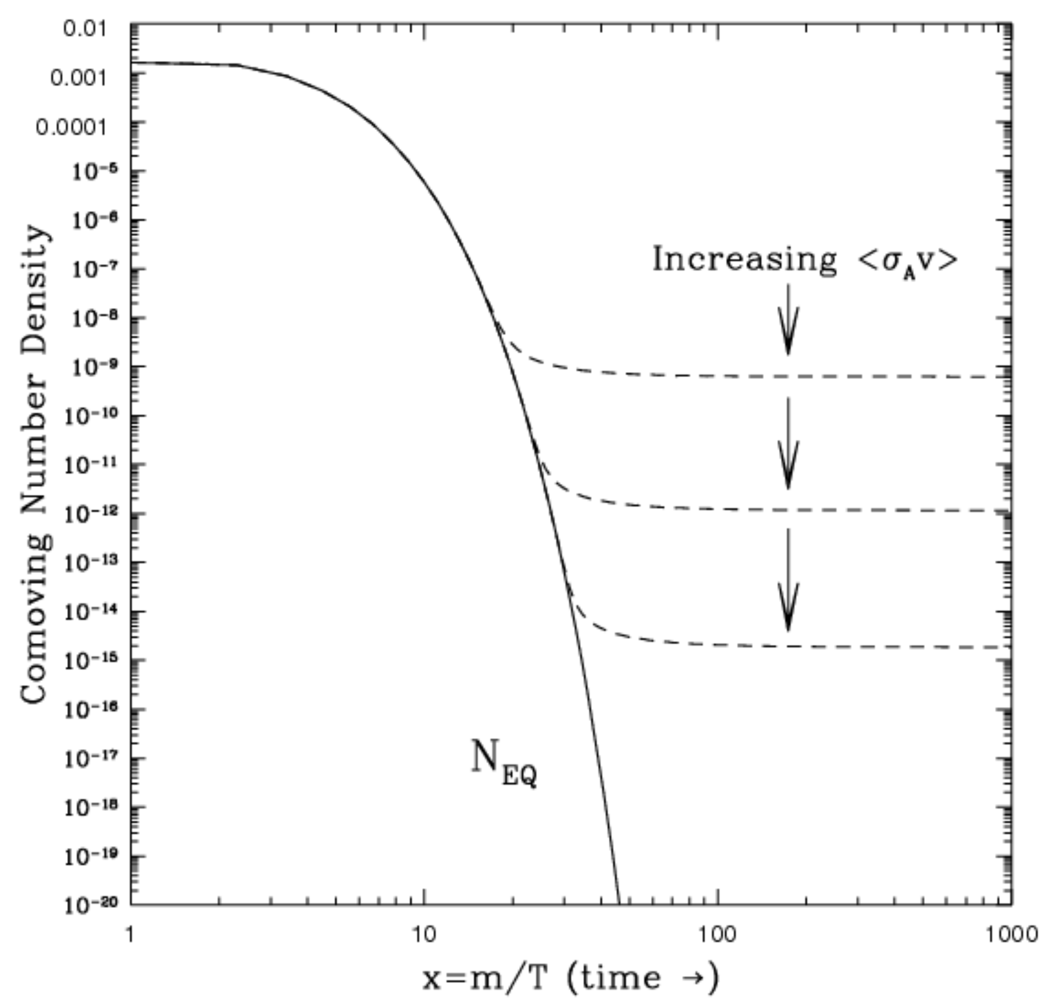
LLPs require Γ < 10^$^{-13}$ GeV to have a visible displacement

How to get LLPs?
(a) small coupling
(b) compressed parameter space
(c) Muti-body decay

Case (a) can be described in an EFT via large suppression scale and (c) by higher-dim operator (i.e. higher powers of suppression scale) respectively.

Motivation for FIMPs (like WIMPs) comes mainly from Dark Matter

Older picture: Thermal freeze-out



Coupling (here I mean α/Λ^n) to SM determines the "thermal relic density". If coupling is too small, the leftover density is too high to explain DM. This gives a <u>lower bound</u> on possible couplings for any given model.

Motivation for FIMPs (like WIMPs) comes mainly from Dark Matter

Modern picture: For the same model, size of coupling determines the mechanism of achieving the right relic density.

Thermal Freeze-out

- Direct annihilation to SM → No LLPs
- Co-annihilation (e.g. with “staus”) → LLPs due to spectrum compression
- Conversion-driven freezout (aka co-scattering) → LLPs due to compression and/or small coupling

Freeze-in

- Freeze-in → LLPs due to small coupling

All LLPs but different strategies to search

Case (a) Small coupling:

Have to worry about why this FIMP was motivated.

- If DM, there are two mechanisms of freeze-in: (a) decay of mediator or (b) 2->2 scattering.
- In case of decay, there is a mediator with higher coupling to SM; have to rely on producing the mediator.
- If scattering (e.g. Higgs portal, Z') then answer is more difficult because precise measurements needed

All LLPs but different strategies to search

Case (b) Compression: If charged, use (possibly disappearing) tracks. If neutral, main problem is softness of decay products: use ISR.

Case (c) Multi-body decay: If charged, use (possibly disappearing) tracks. If neutral, multi body decay usually makes possible to use displaced vertex or emerging jets or displaced leptons

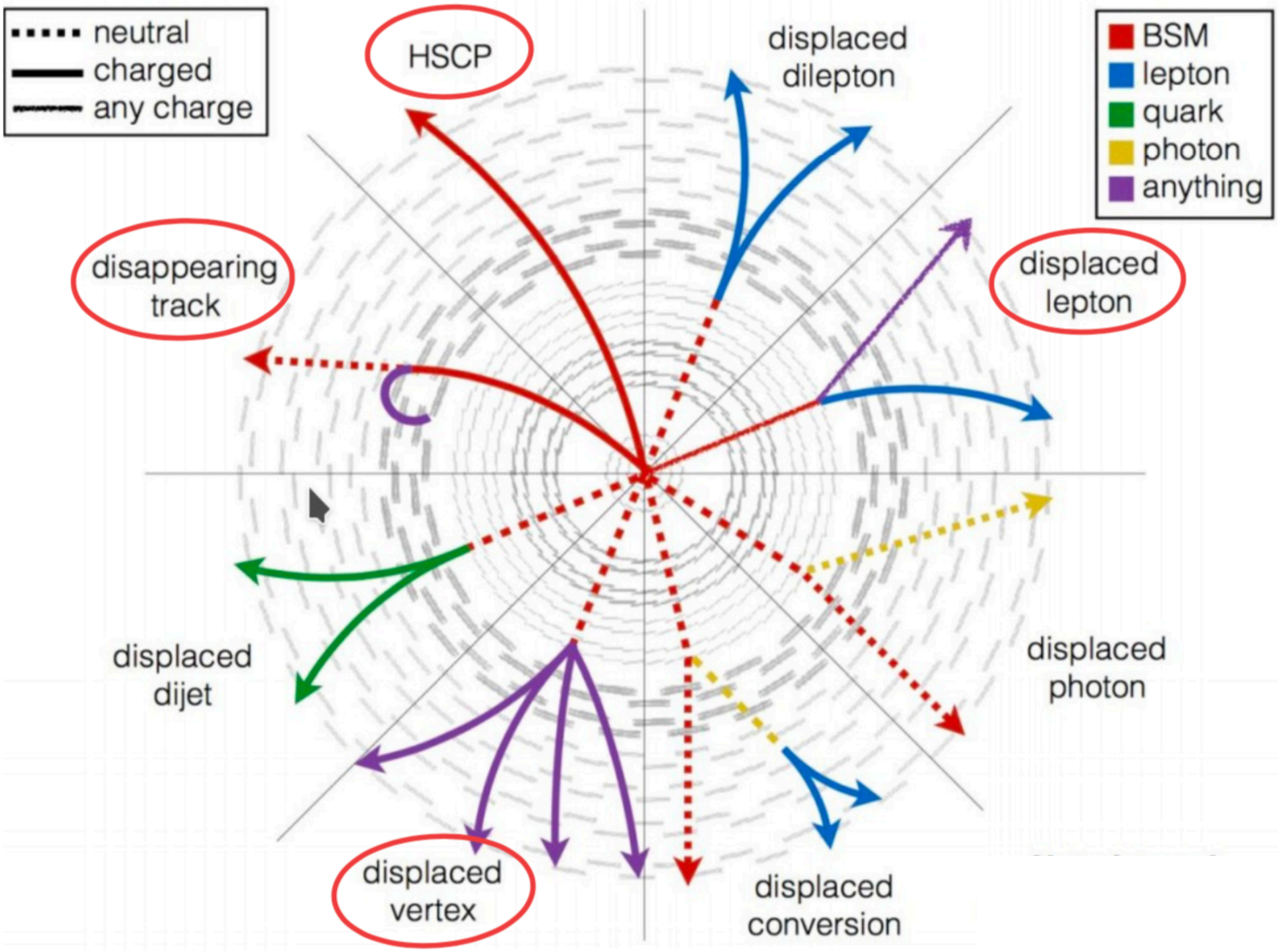


Figure credit: J. Antonelli

Known Gaps

1. Compression is particularly problematic because soft + displaced is double trouble

2. Intermediate lifetimes (1-10mm) are complicated for models with third generation

3. Models with decays to b/τ harder to distinguish because DV searches require higher number of tracks from one vertex (to remove SM b/c/τ background)

4. Models with decays to taus have not been explored at all (other than vanilla stau co-annihilation by freeze-out)

Goal of this talk

1. Introduce a collider friendly freeze-in model (straightforward generalisation to 3rd gen)

2. Give an overview of models with similar (identical?) signatures but different motivations

3. Some thoughts about how to pick benchmark models when trying to do 3rd generation and LLPs together

Idea of Freeze-in

1. Start with zero DM density

2. DM is produced later by either
   (a) Scattering SM SM to DM DM or
   (b) Decay of a very scarce new particle that freezes out in the normal way

The minimal Freeze-in model

$$\lambda X_{\rm SM} X_{\rm SM} Z Z$$

One new field
one* coupling

SM field

FIMP

$$y X_{\rm SM} Y Z$$

Two new fields
one coupling

SM field

Connector

FIMP

The minimal Freeze-in model

X=higgs

One new field
one* coupling

$$\lambda X_{\rm SM} X_{\rm SM} Z Z$$

SM field

FIMP

Operator still 4D, no UV completion necessary

1. If Z is lighter than X, need precise Higgs width measurement (impossible precision)
2. If Z is heavier than X, cross section is too small. Not visible

The minimal Freeze-in model

X=fermion

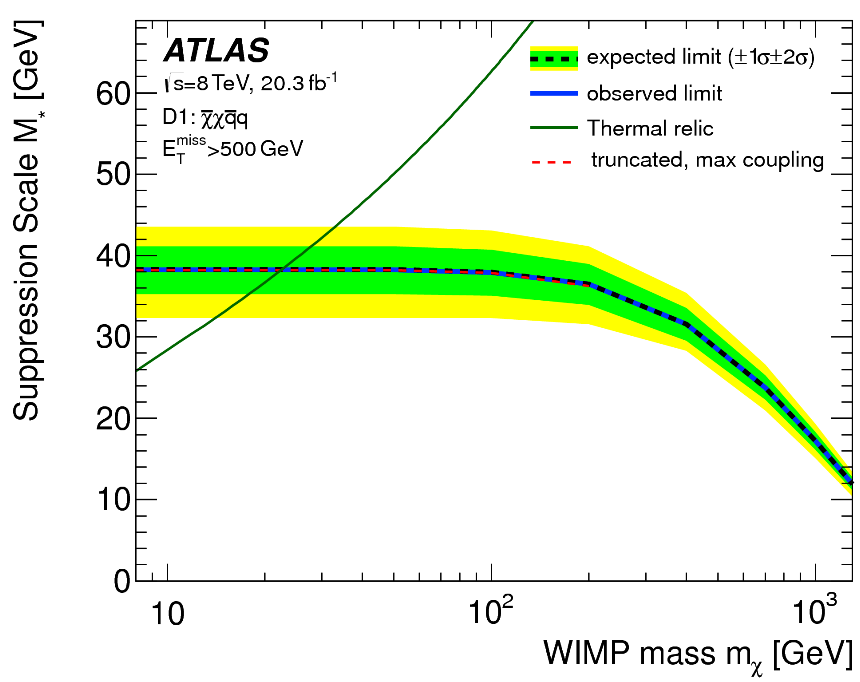
$$\lambda X_{\rm SM} X_{\rm SM} Z Z$$

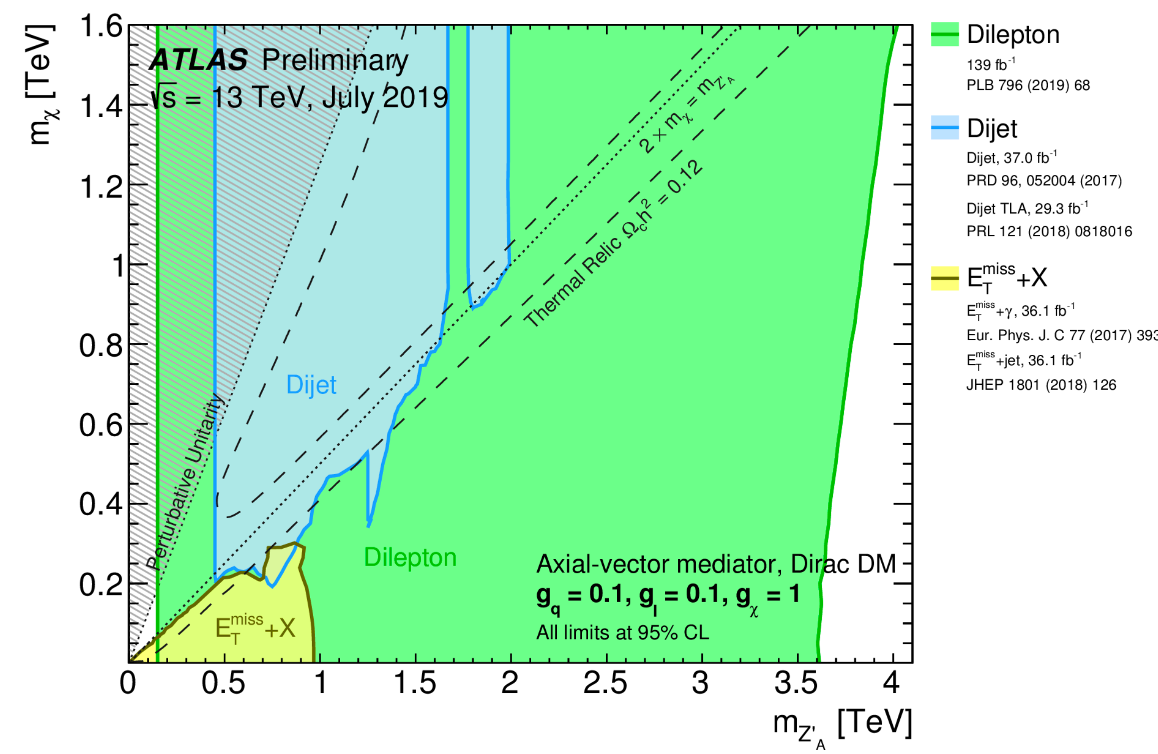
One new field
one* coupling

SM field

FIMP

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \xrightarrow{M\gg p} \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$





The minimal Freeze-in model

X=fermion

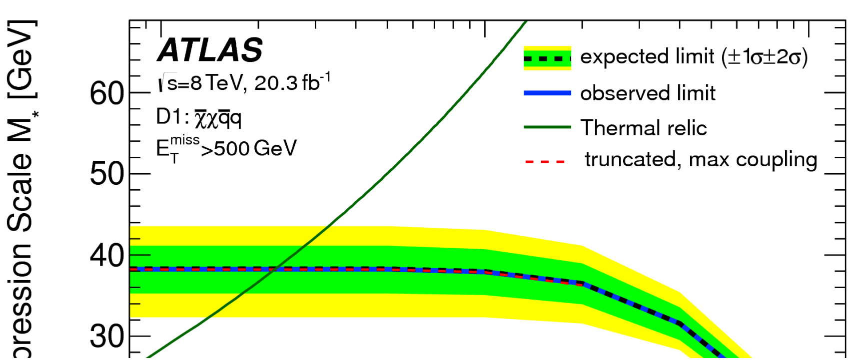
One new field
one* coupling

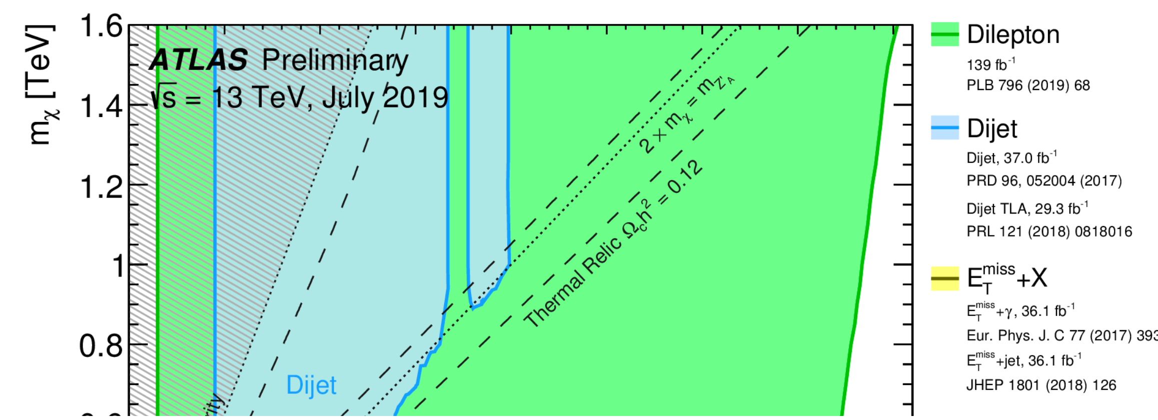
$$\lambda X_{\mathrm{SM}} X_{\mathrm{SM}} Z Z$$

SM field

FIMP

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \xrightarrow{M\gg p} \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$





Only produced in sufficient numbers when coupling is large or mediator is light

The minimal Freeze-in model

X=Gauge boson

$$\lambda X_{\rm SM} X_{\rm SM} Z Z$$

One new field
one* coupling

SM field

FIMP

1. EDMs?
2. Completion by axions? (Work in progress ⋯)
3. Can you get the right DM density? (Work in progress ⋯)

Next-to-

The minimal Freeze-in model

$$y X_{\rm SM} Y Z$$

Two new fields
one coupling

SM field

FIMP

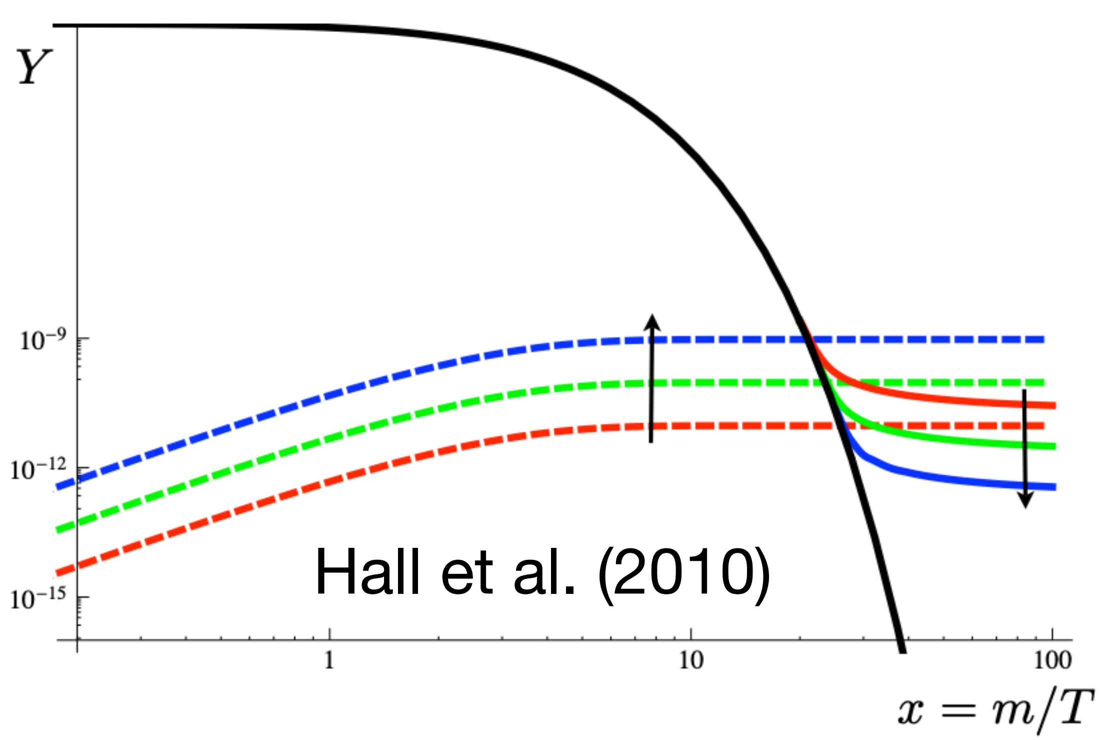
Connector
(has to carry SM charge)

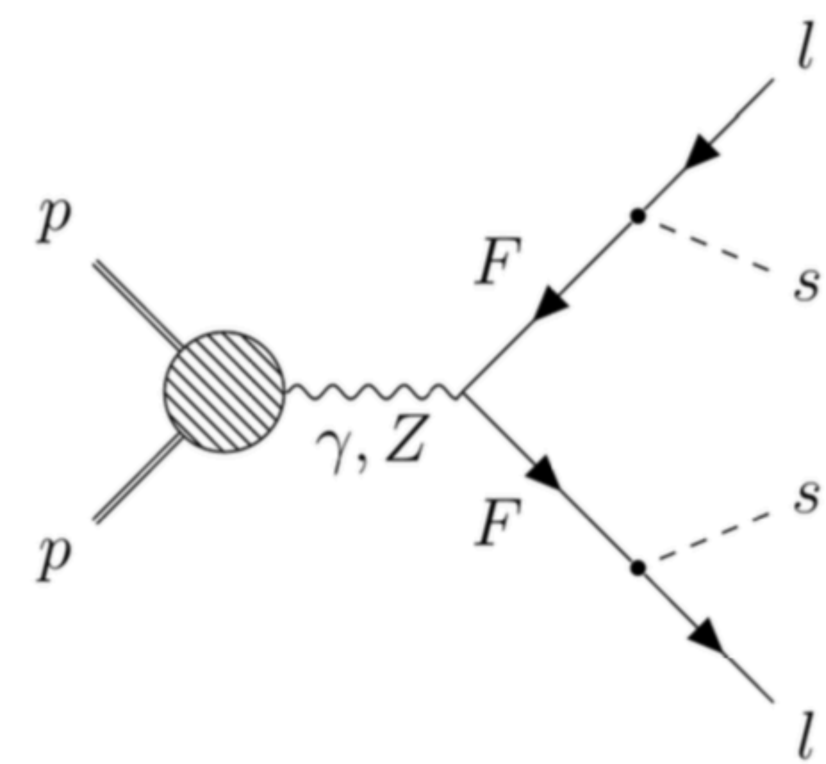
X	Y	Z	
Fermion	Fermion	Scalar	Belanger et al (2019)
Fermion	Scalar	Fermion	ala co-annihilation/co-scattering
Scalar (Higgs)	Fermion	Fermion	co-annihilation/co-scattering with Brümmer et al (2018)

The minimal Freeze-in model

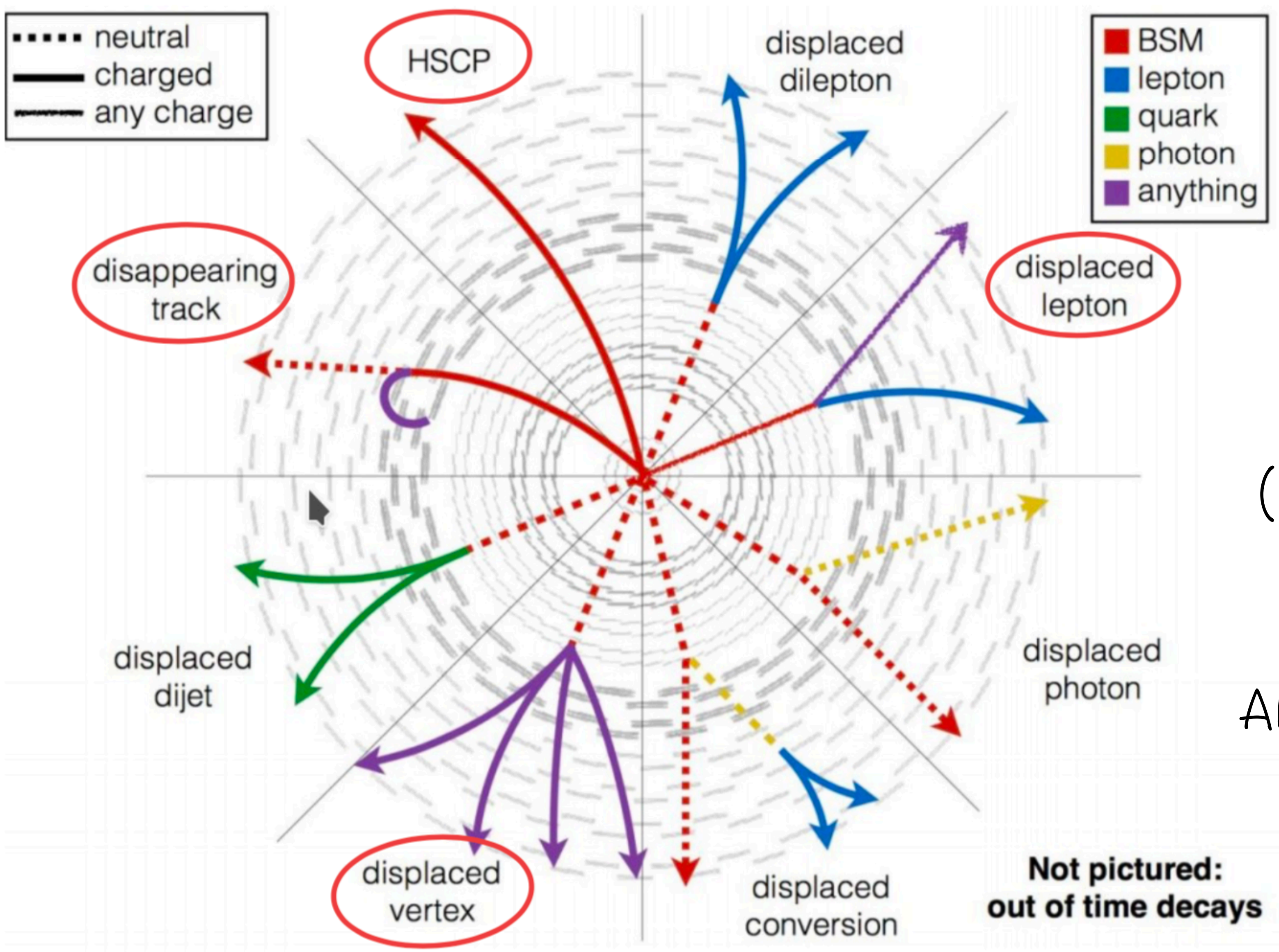
Belanger et al. JHEP 1902 (2019) 186

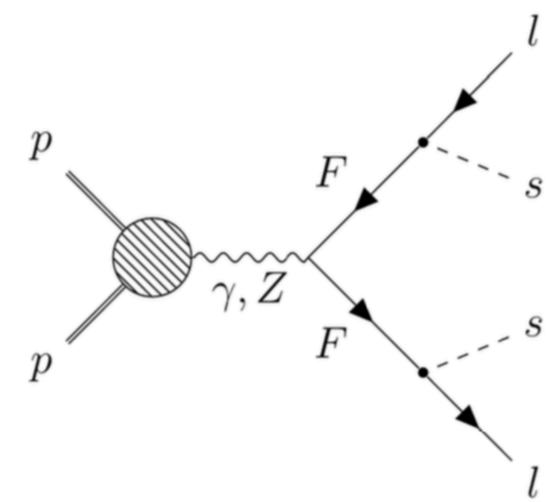
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\,\partial^\mu s - \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4 + \lambda_{sh}s^2\left(H^\dagger H\right)$$
$$+ \bar{F}\left(iD\right)F - m_F\bar{F}F - \sum_f y_s^f\left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right)f + \text{h.c.}\right)$$





LLP signatures for this model



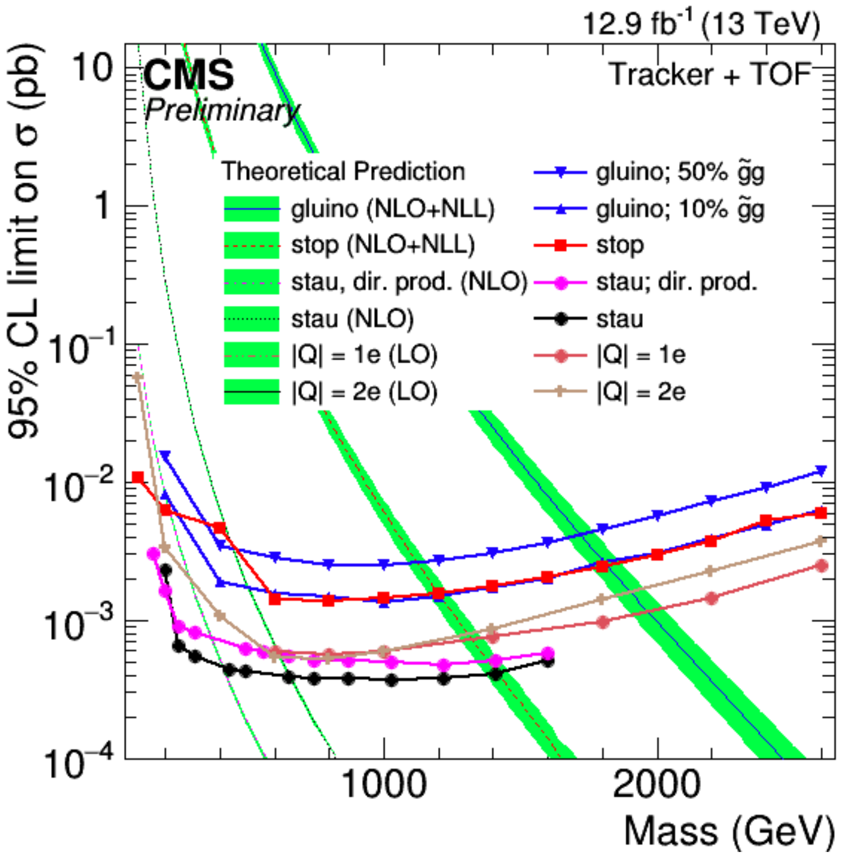


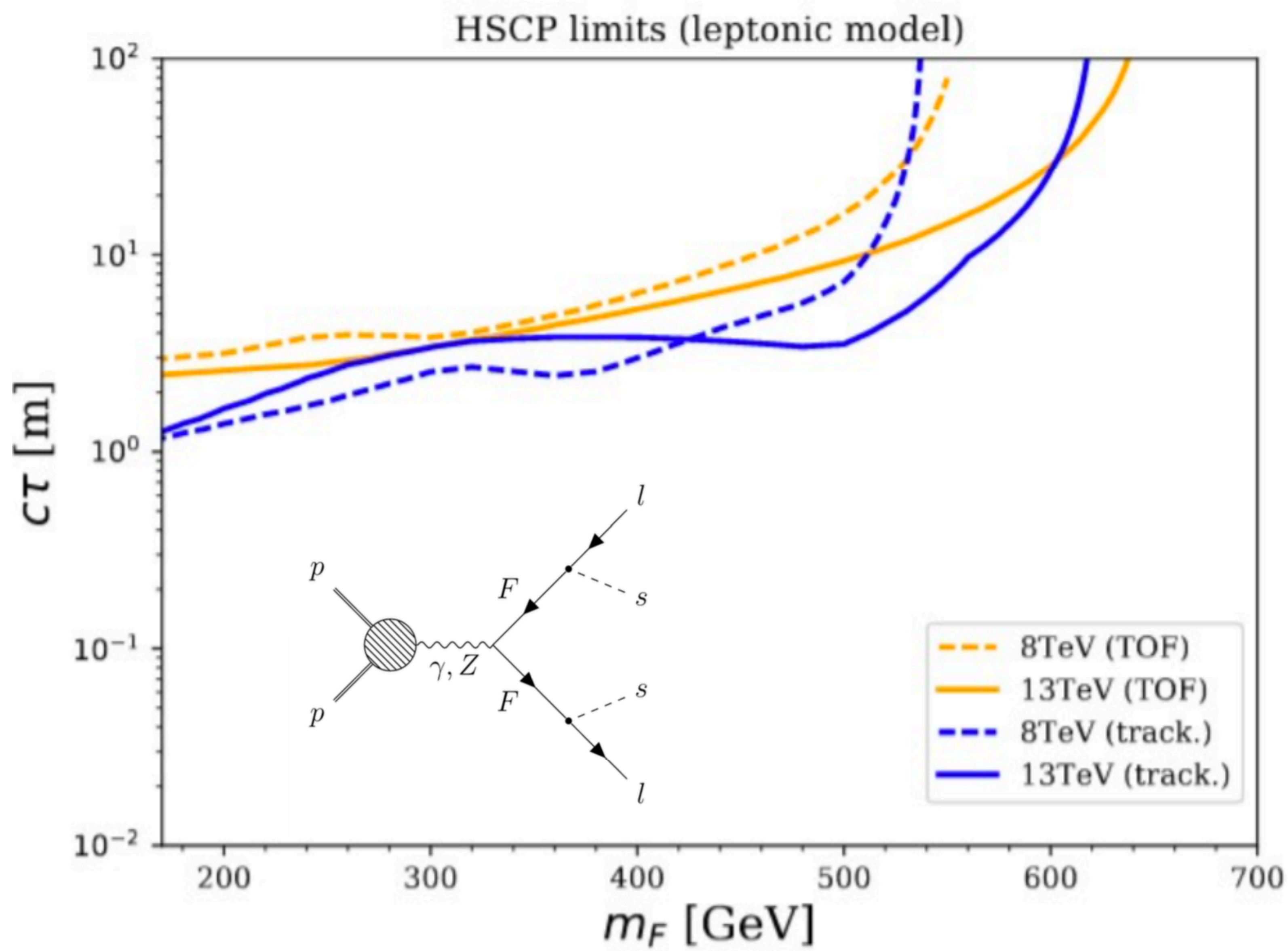
We studied cases
(1) F carries charged lepton Q nos.
(2) F carries quark (u/d) Q nos.

Also possible: RH neutrino-like Q.nos
but this is same as invisible

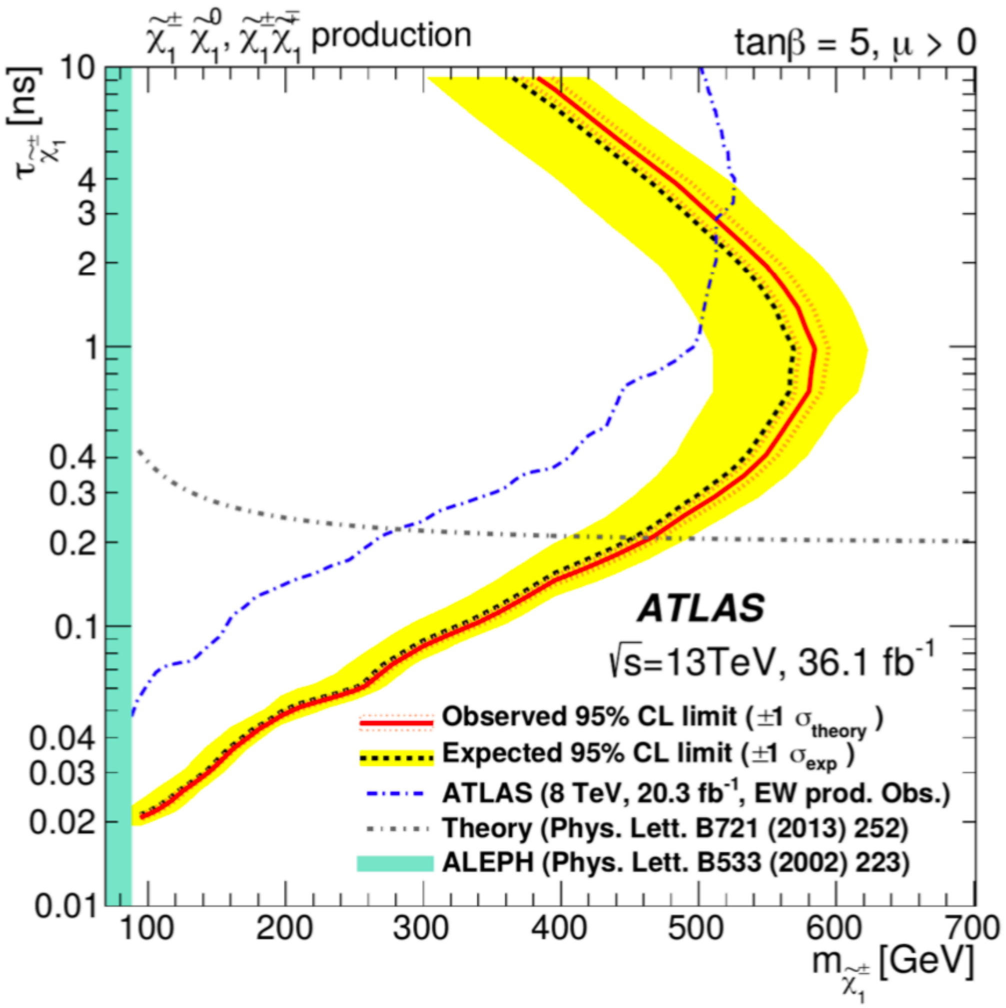
HSCP limit

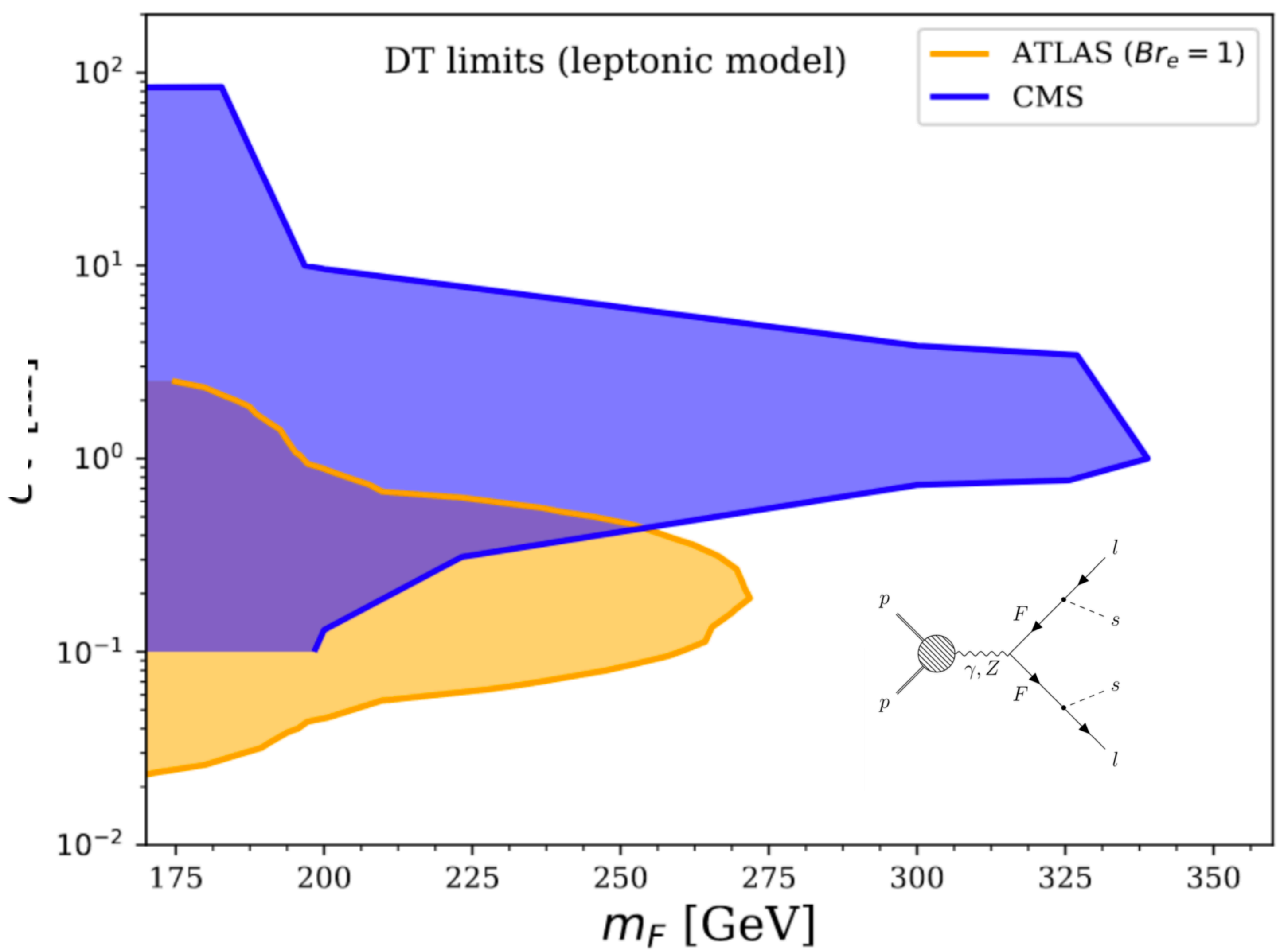
CMS PAS EXO-16-036



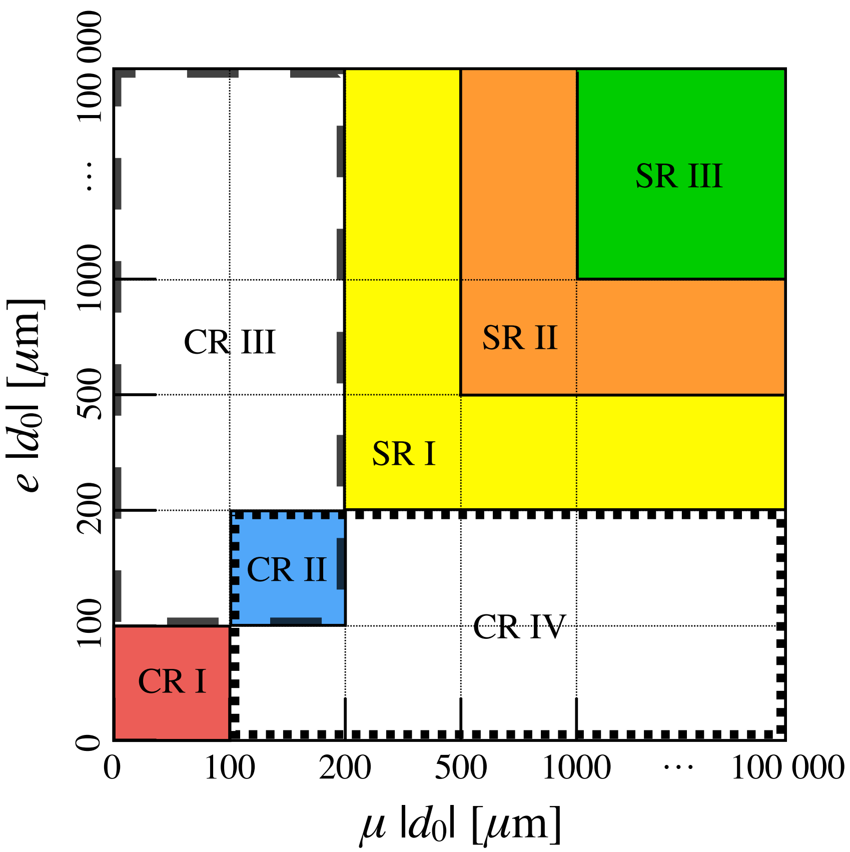


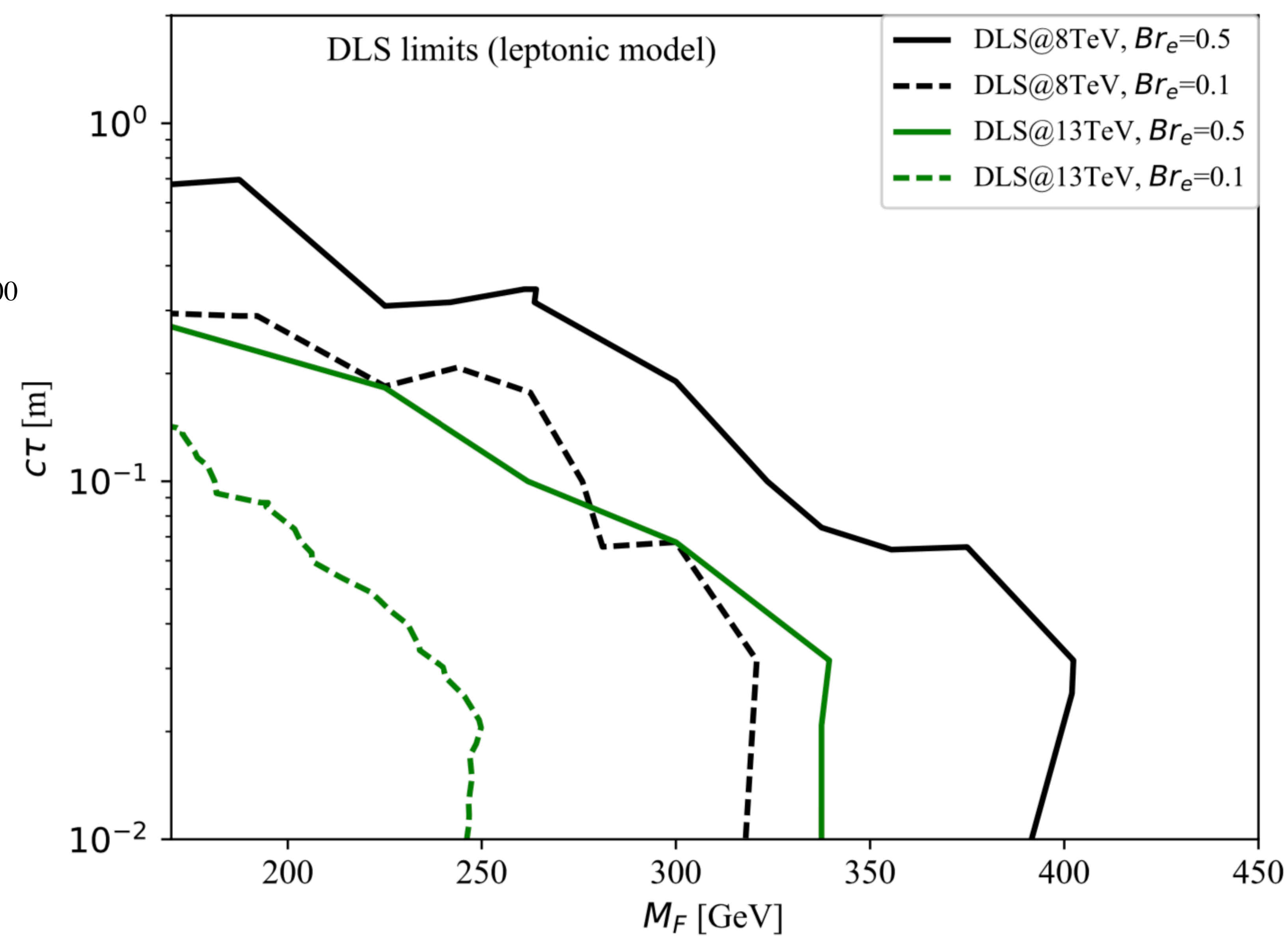
Disappearing track limit



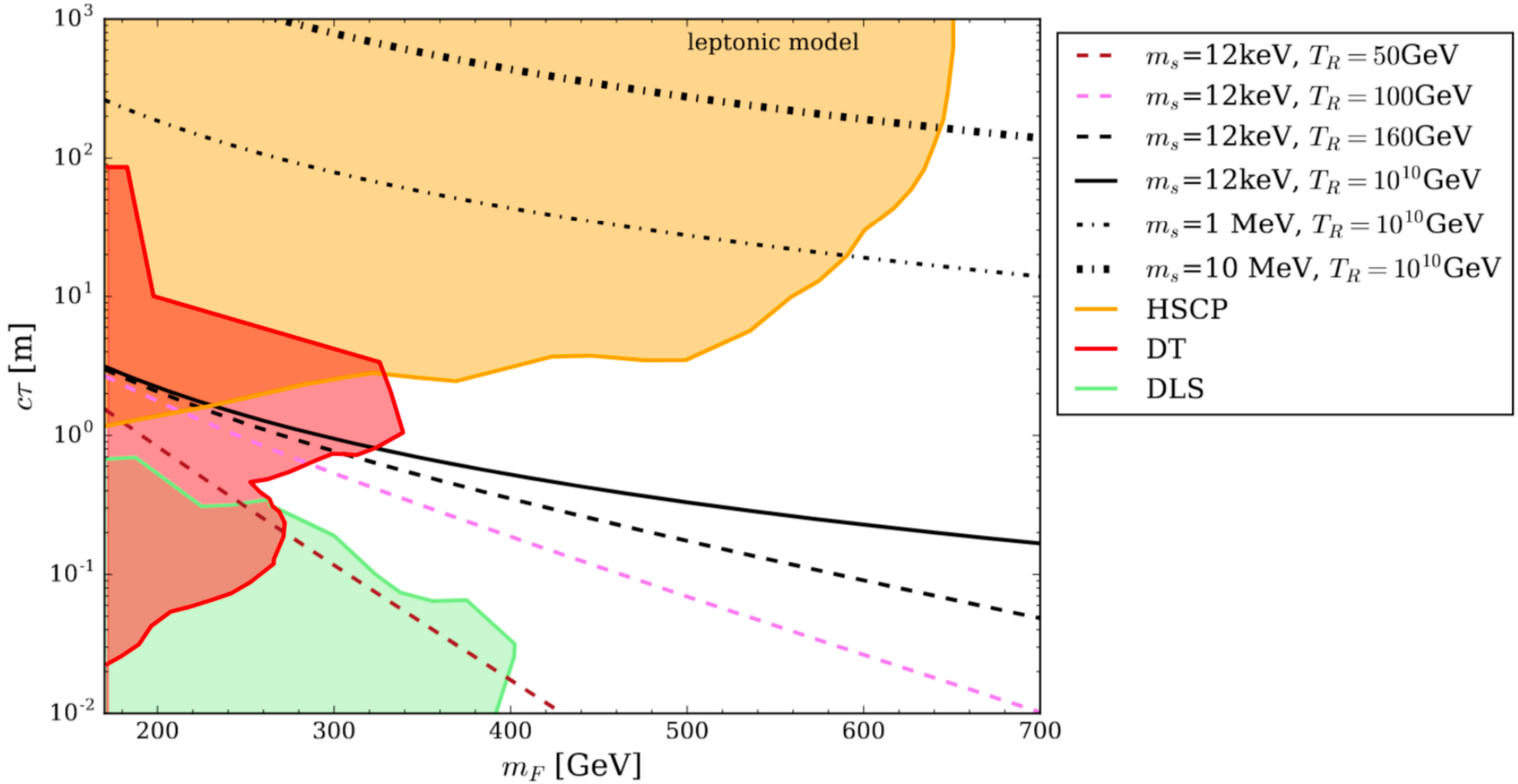


Displaced Lepton (DL) limit

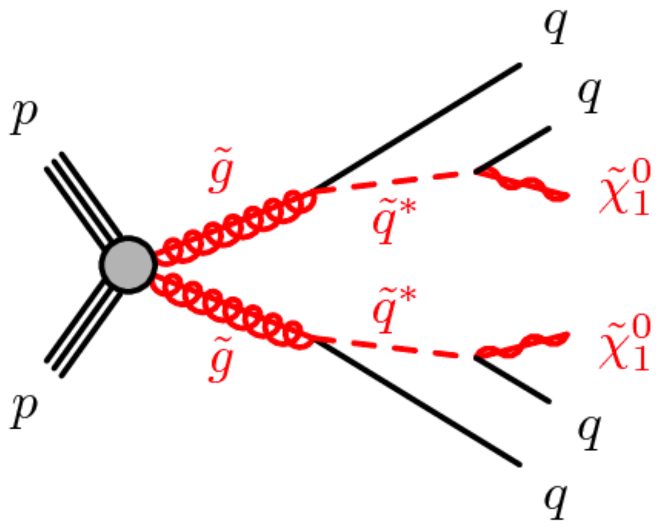


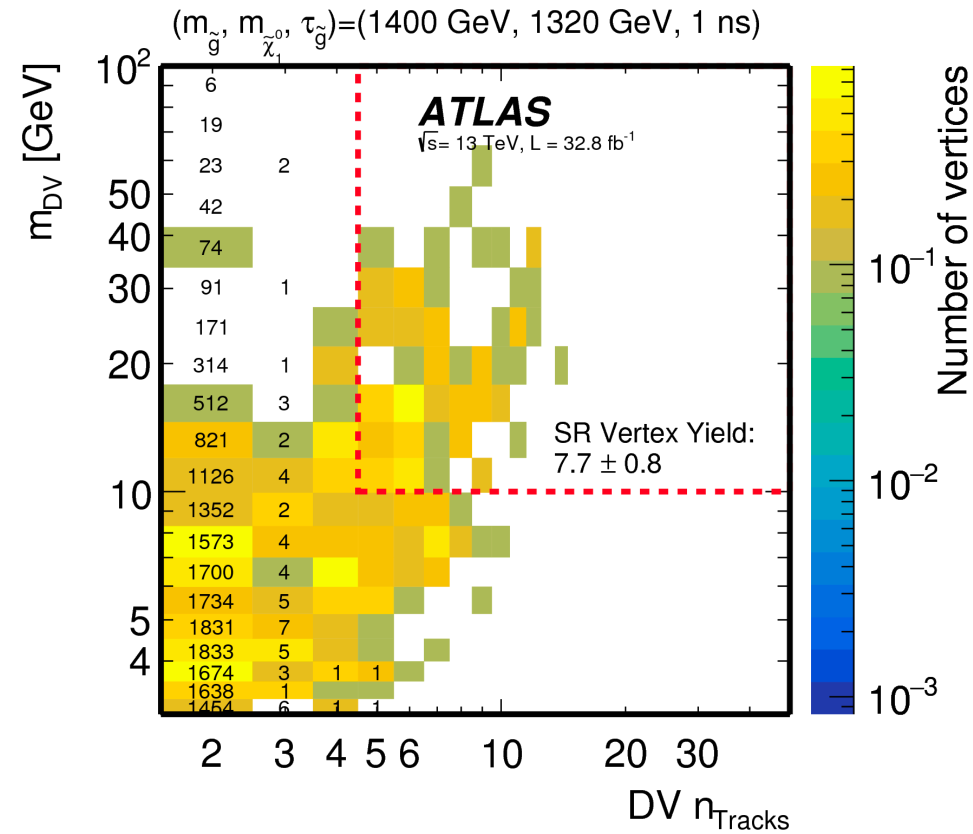


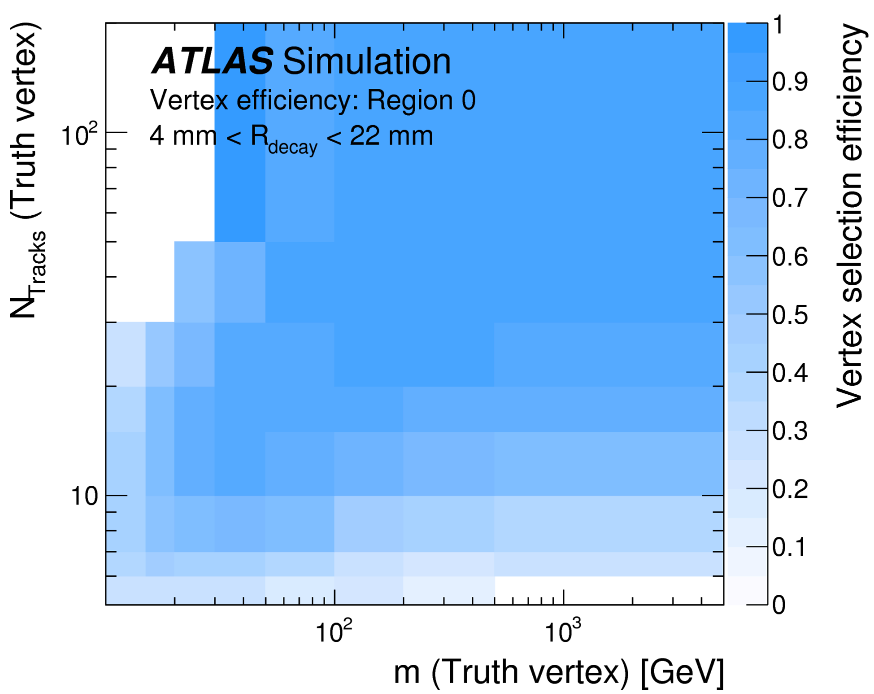
Full results for leptonic model

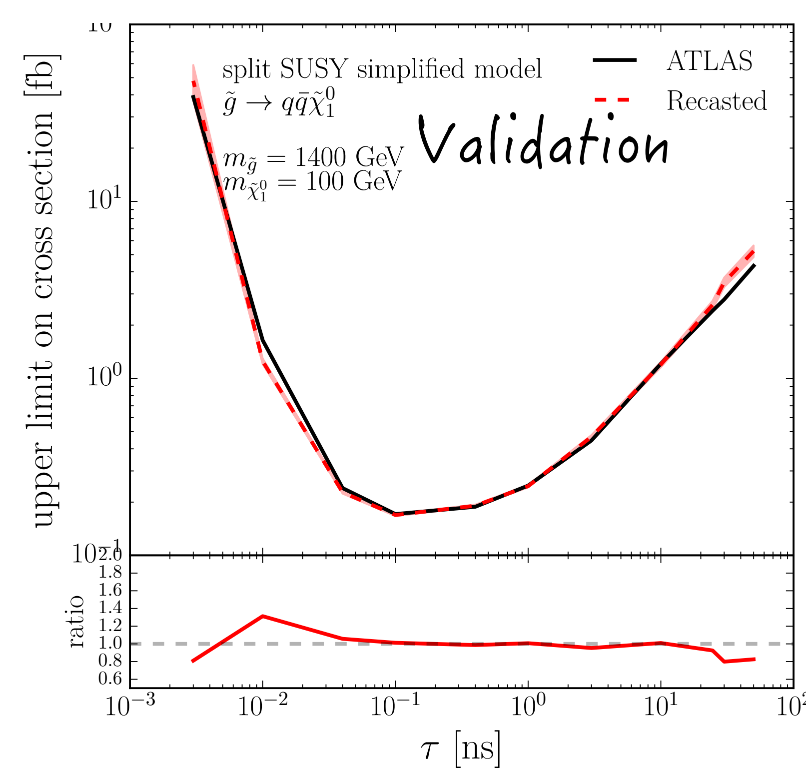


Displaced Vertex (DV) search





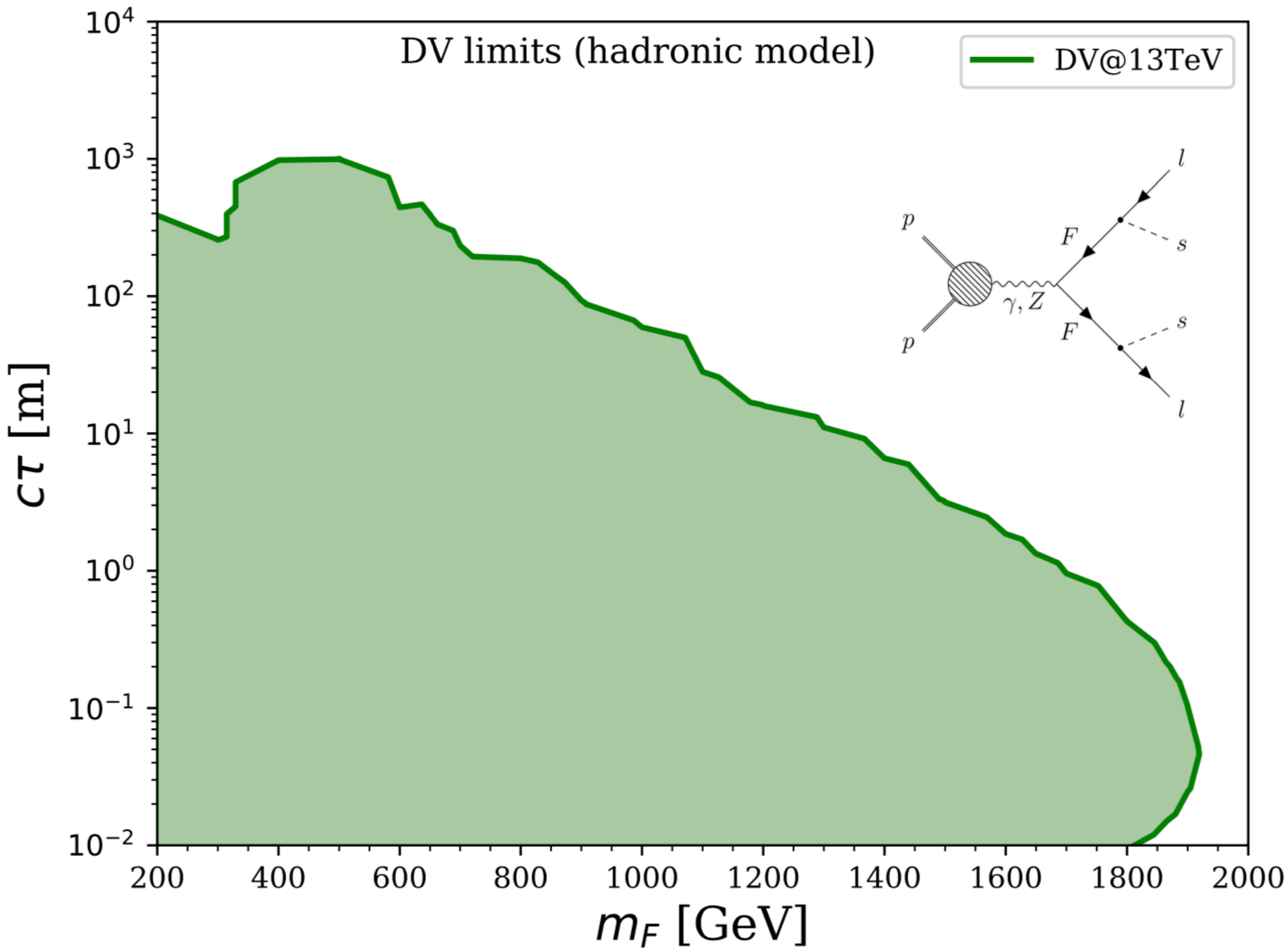




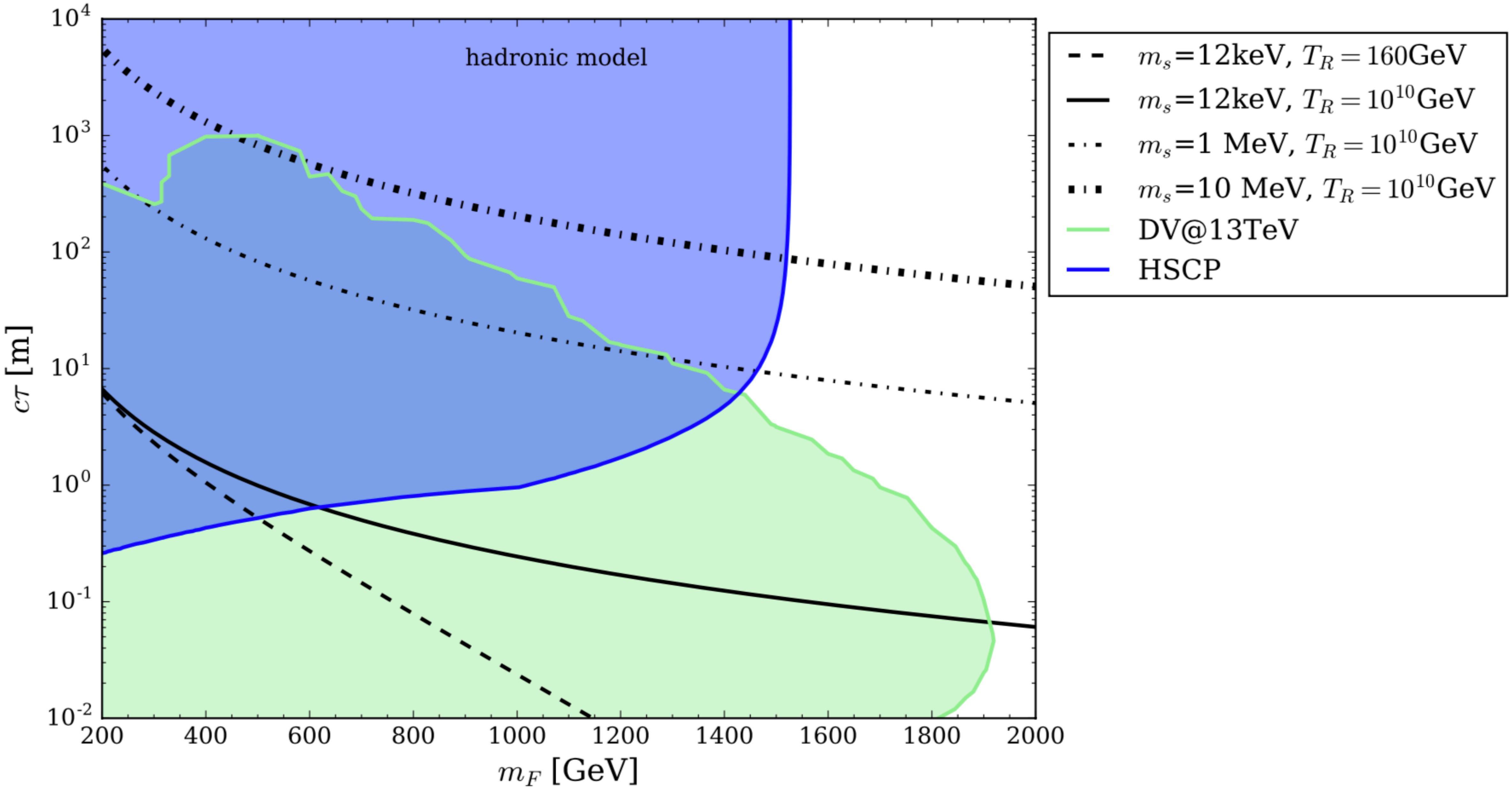
Phys. Rev. D 97 (2018) 052012

Reinterpretation by G. Cottin. & A. Lessa

Displaced Vertex search



Full results for hadronic model



Comments on things to be studied further

1. On theory side, straight-forward to extend to tau/b/top.

2. Known problems with displaced tau/b — extra secondary (tertiary?) vertices

3. Displaced tops possibly easier because jets/leptons from W will give DV and DL signatures. But harder to do re-interpretation because efficiencies only on truth-level particles.

4. Need to have symmetric ee/$\mu\mu$(/$\tau\tau$) regions for full coverage of model.

Summary of minimal Freeze-in model

1. It is possible to have freeze-in with visible collider signature
2. Freeze-in mechanism requires small couplings + a connector particle with SM Quantum numbers
3. Connector can be produced via standard production mechanisms, decay is suppressed due to small coupling hence particle is long-lived
4. Combination of searches needed to cover parameter space. (possible lifetimes from 1mm - several km)

Goal of this talk

1. Introduce a collider friendly freeze-in model (straightforward generalisation to 3rd gen)

2. Give an overview of models with similar (identical?) signatures but different motivations

3. Some thoughts about how to pick benchmark models when trying to do 3rd generation and LLPs together

Next-to-

The minimal Freeze-in model

$$yX_{\mathrm{SM}}YZ$$

Two new fields
one coupling

SM field

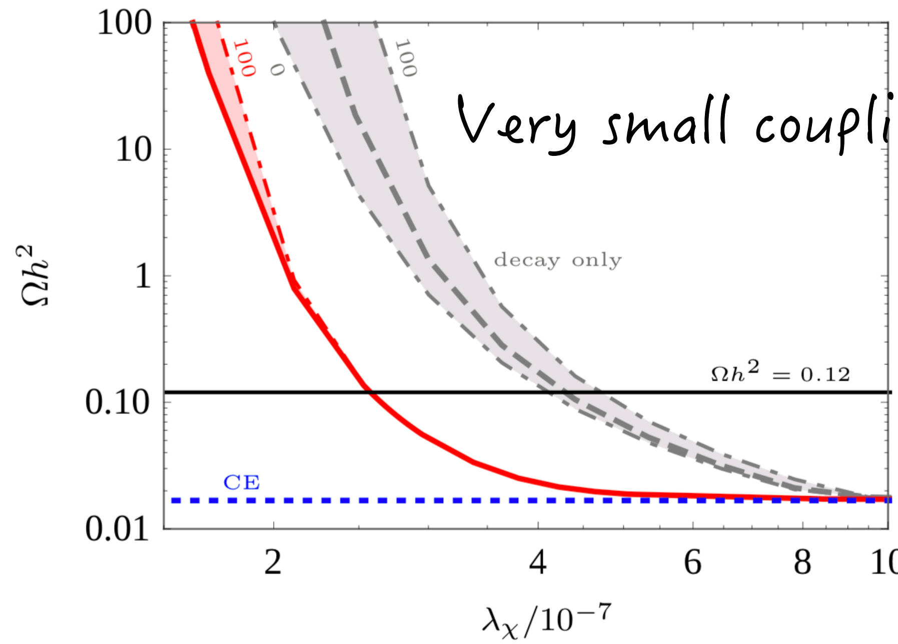
FIMP

Connector
(has to carry SM charge)

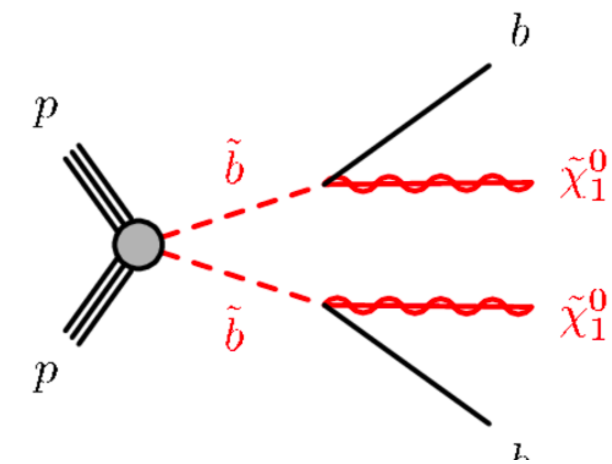
X	Y	Z	
Fermion	Fermion	Scalar	Belanger et al (2019)
Fermion	Scalar	Fermion	co-annihilation/co-scattering
Scalar (Higgs)	Fermion	Fermion	co-annihilation/co-scattering with Brümmer et al (2018)

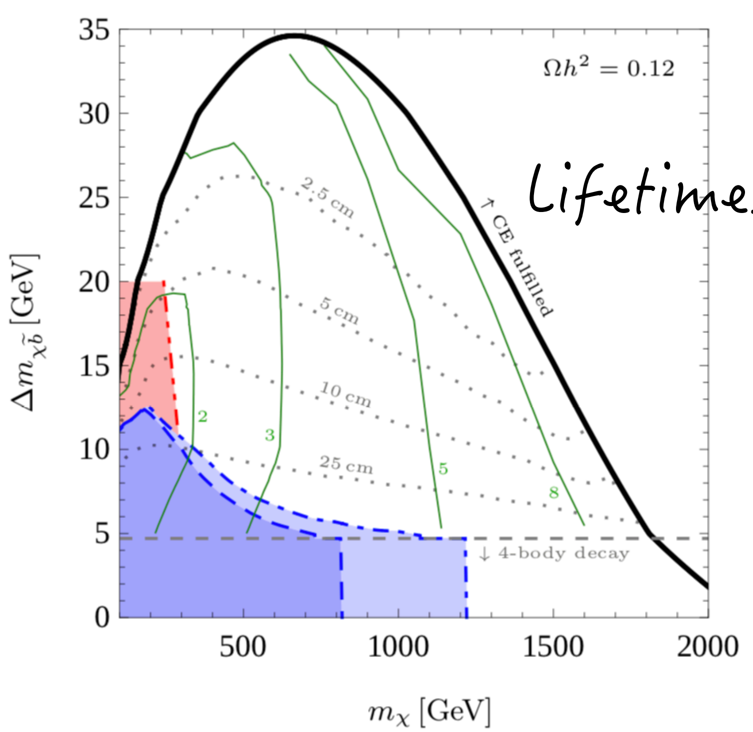
Conversion driven freeze-out

Garny et al. Phys. Rev. D 96, 103521 (2017)

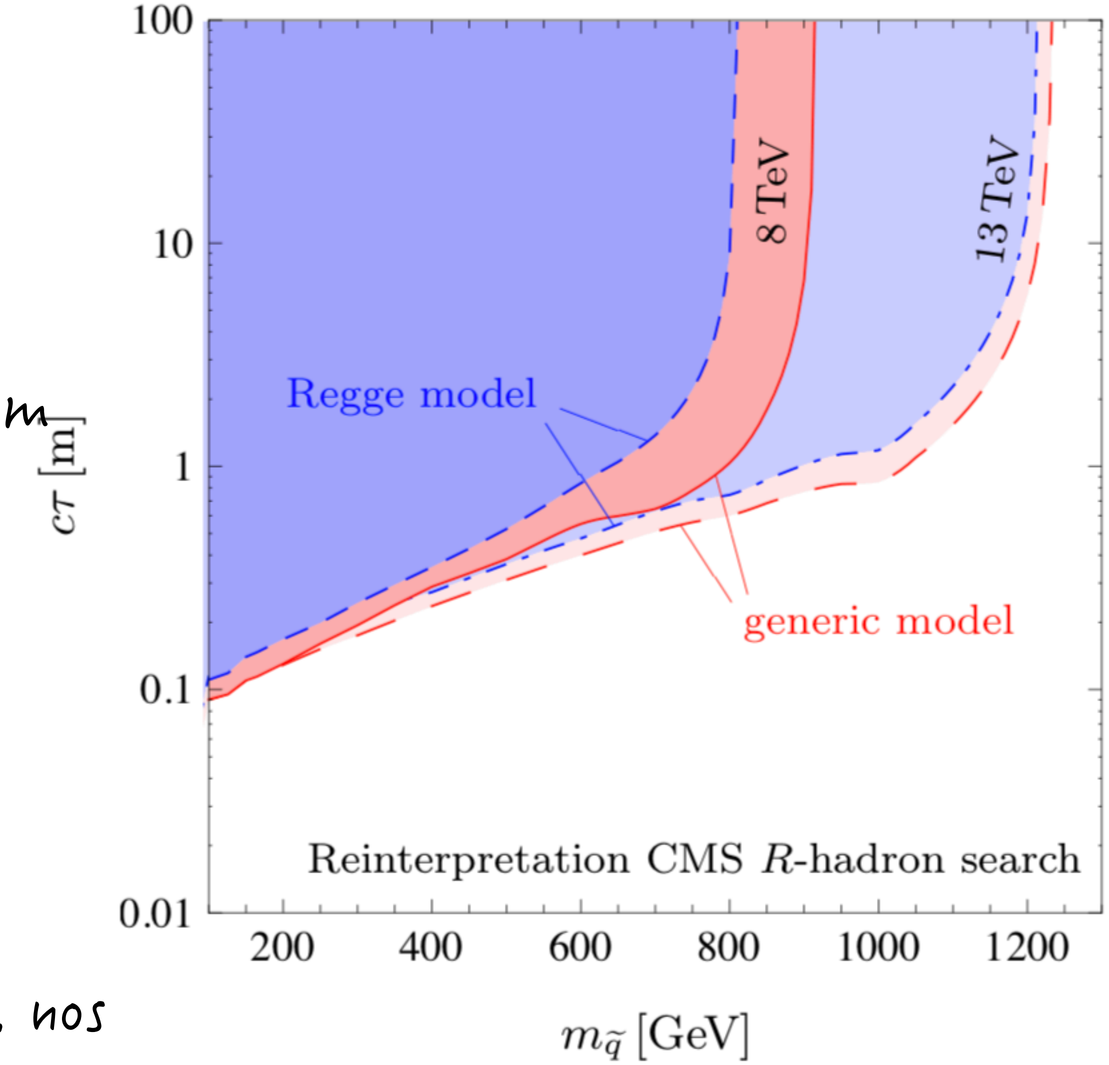


Very small couplings = FIMPs





Lifetimes ~ O(10) cm



Scalar with b Q. nos could have been tau-like Q. nos

The minimal Freeze-in model

Two new fields
one coupling

$$y X_{\mathrm{SM}} Y Z$$

SM field

Connector

FIMP

X	Y	Z	
Fermion	Fermion	Scalar	Belanger et al (2019)
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Scalar (Higgs)	Fermion	Fermion	co-annihilation/co-scattering with Brümmer et al (2018)

The minimal Freeze-in model

Next-to- not really

Brümmer, Bharucha, Desai; JHEP 1811 (2018) 195

One SU(2) x U(1) singlet χ + one SU(2) N-plet ψ

$\mathbb{Z}_2$ stabilises the lightest state

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\overline{\sigma}^\mu D_\mu\psi + i\,\chi^\dagger\overline{\sigma}^\mu\partial_\mu\chi - \left(\frac{1}{2}M\psi\psi + \frac{1}{2}m\chi\chi + \text{ h.c.}\right) + \mathcal{L}_{\rm quartic} + \mathcal{L}_{\rm mix}$$

$$\mathcal{L}_{\rm quartic} = \frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \frac{1}{2}\frac{\kappa'}{\Lambda}\phi^\dagger\phi\psi^A\psi^A$$

Strong limits from DD

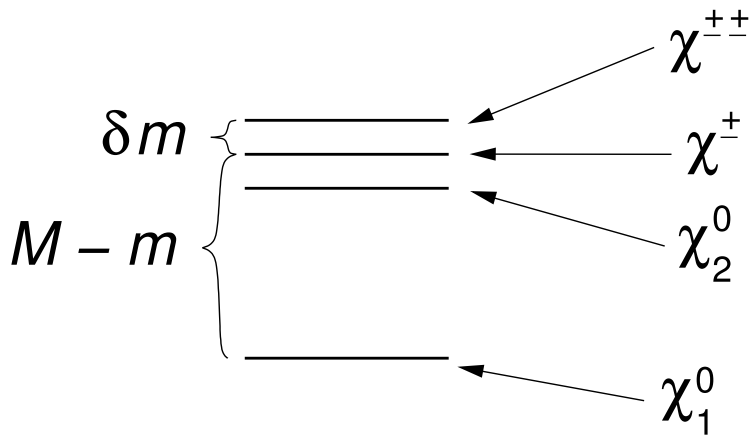
N=3

$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\;\psi^a\chi + \text{ h.c.} \quad\longrightarrow\quad \theta \approx \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

N=5

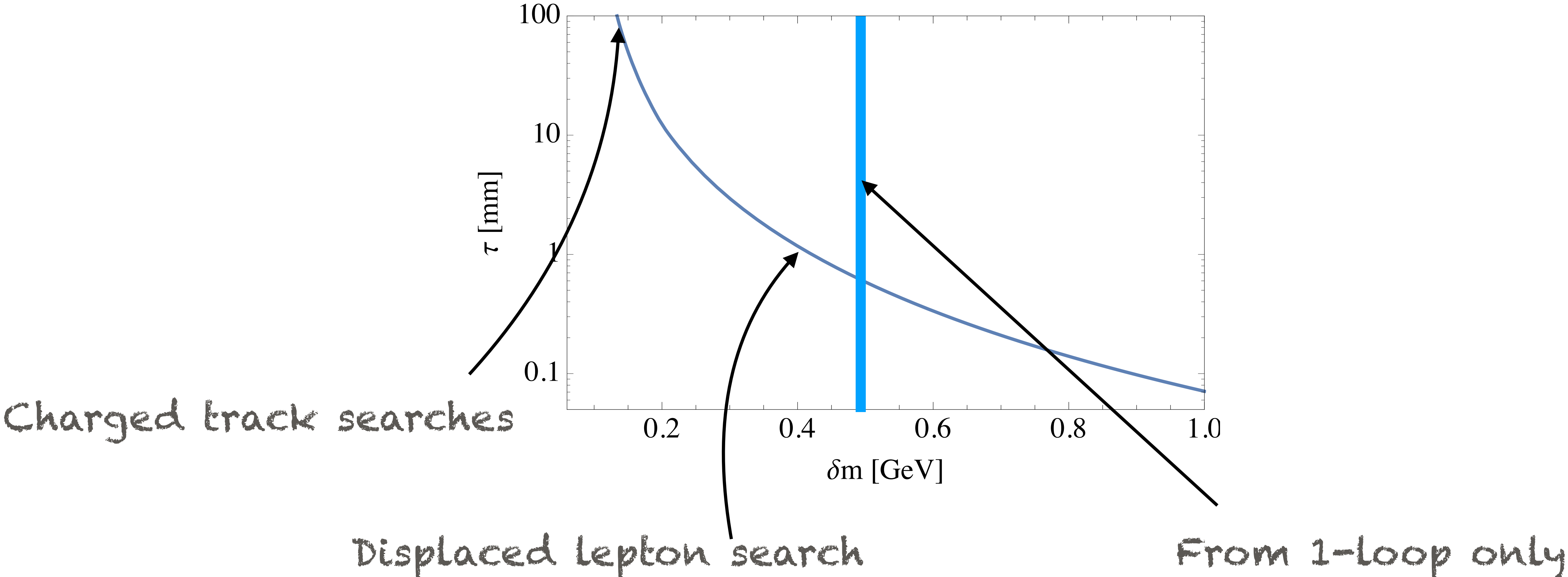
$$\mathcal{L}_{\rm mix} = \frac{\lambda}{\Lambda^3}\,C^{j\ell}_{A\,ik}\;\phi^{\dagger i}\phi_j\phi^{\dagger k}\phi_\ell\psi^A\chi + \text{ h.c.} \quad\longrightarrow\quad \theta \approx \sqrt{\frac{2}{3}}\frac{\lambda v^4}{\Lambda^3(M-m)}\,.$$

Collider searches: Quintuplet model

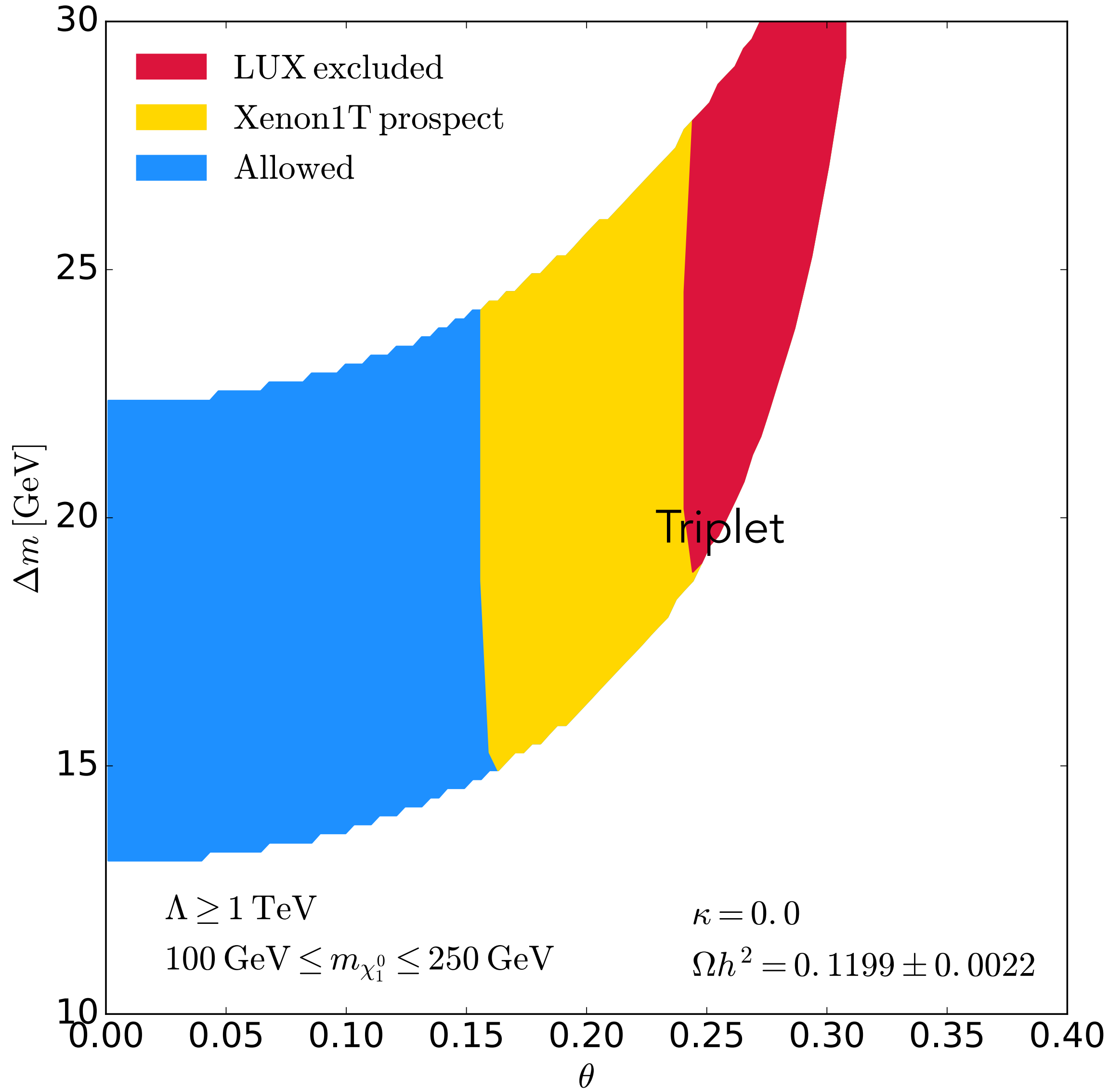


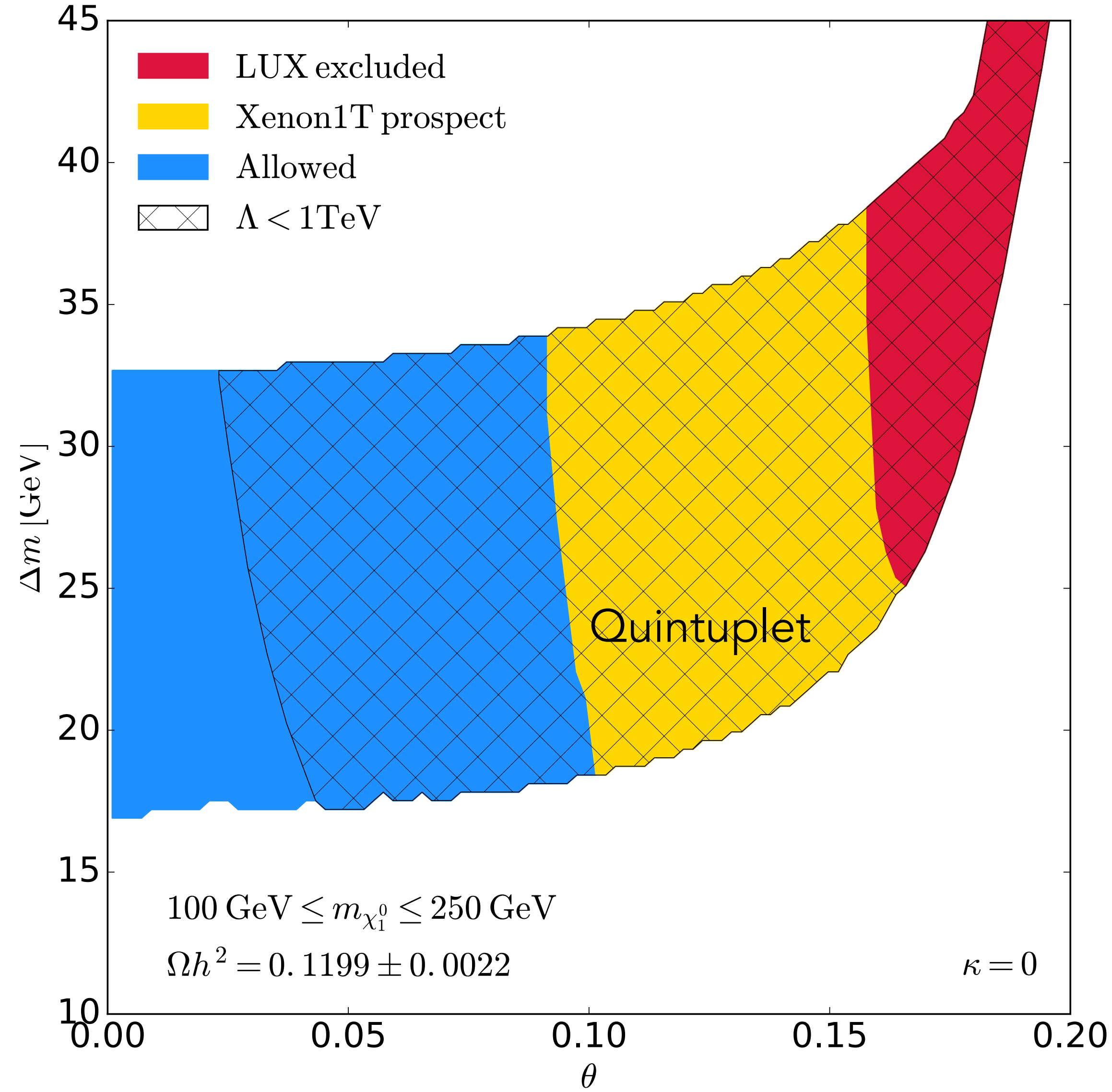
$$\chi^{++} \to \chi^{+}\pi^{+}$$
$$\chi^{+} \to \chi_1^0 W^* \to \ell\nu\chi_1^0$$
$$\chi_2^0 \to \chi_1^0 h^* \to b\bar{b}\chi_1^0$$

Large lifetime for the doubly charged partner



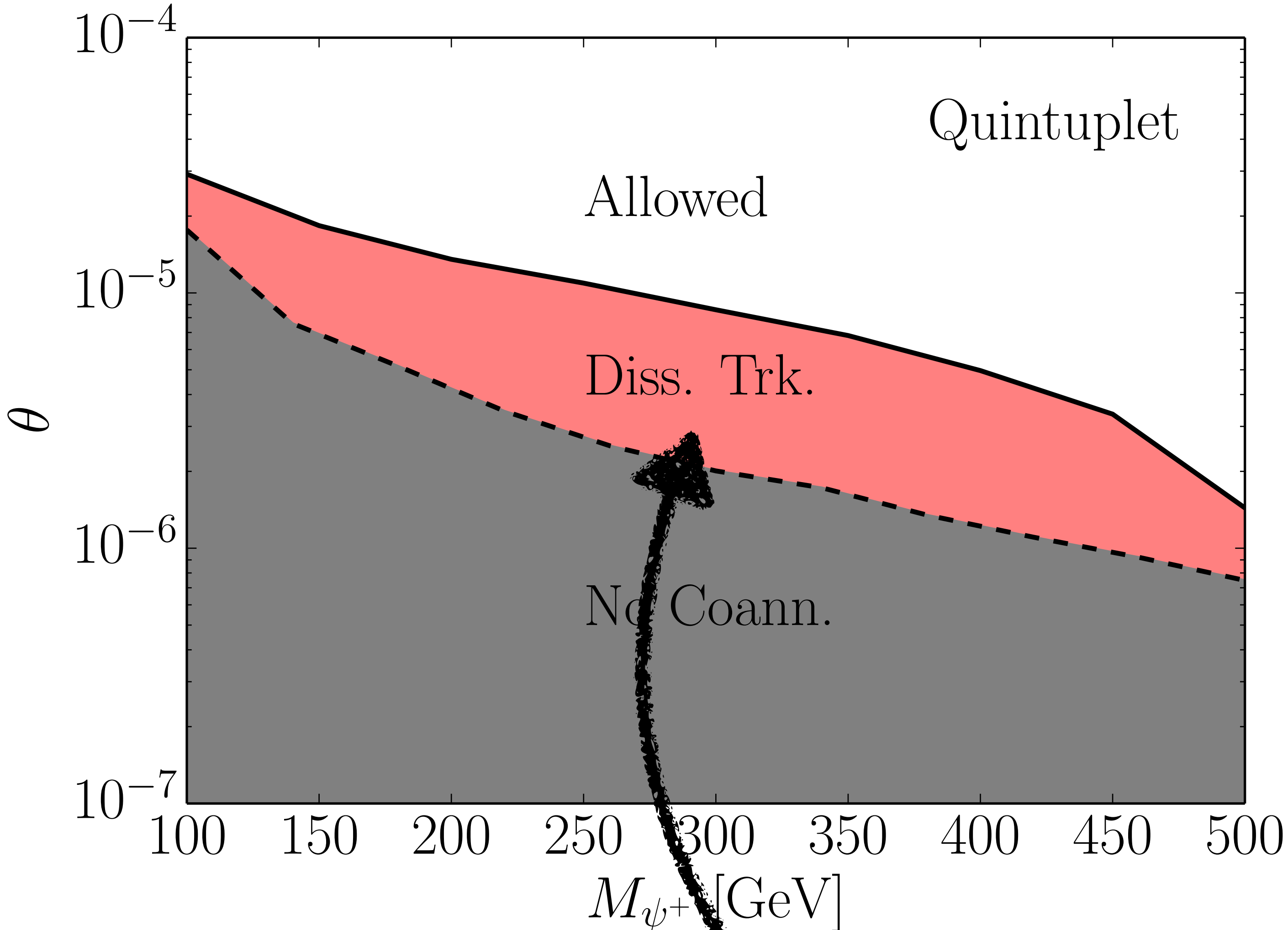
Direct Detection constraints

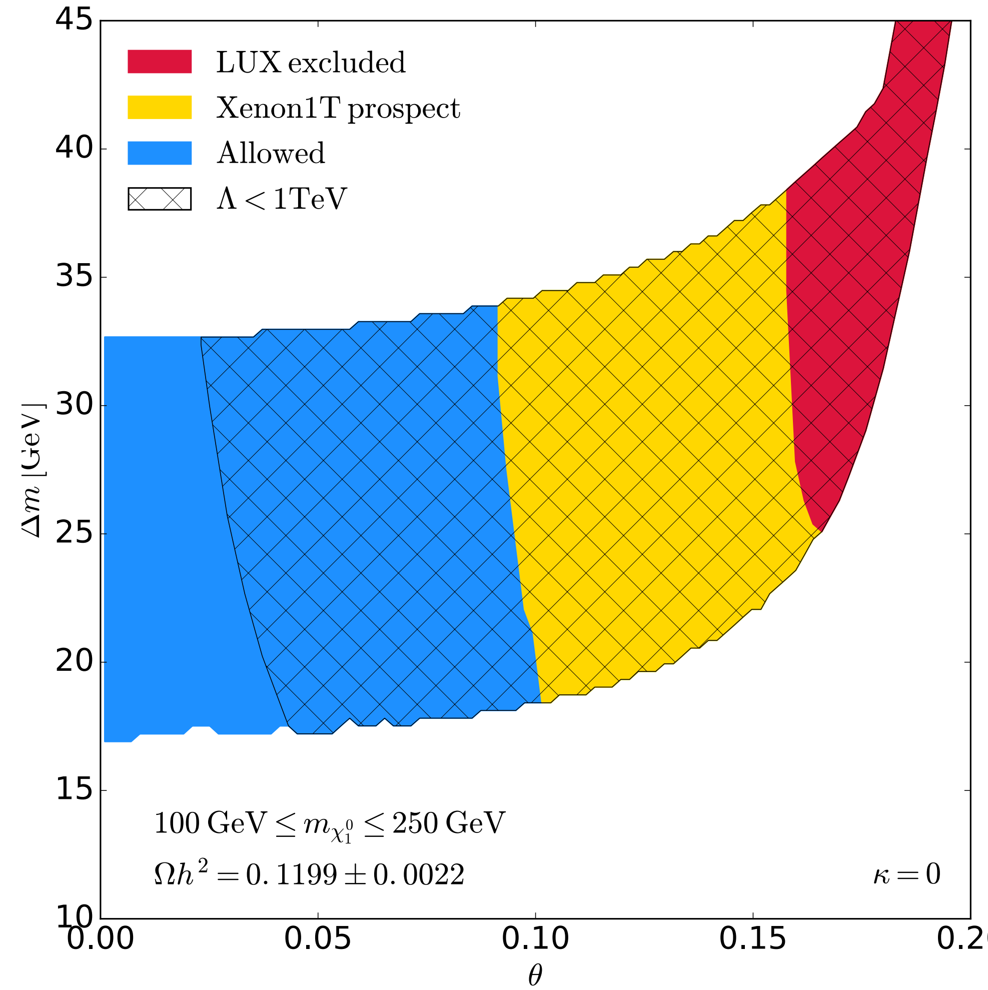




- Look at parameters that gives right relic density
- Low mixing angle gives low DD cross section; however, not a problem at the LHC because production is primarily Drell-Yan!

Limits on mixing angle



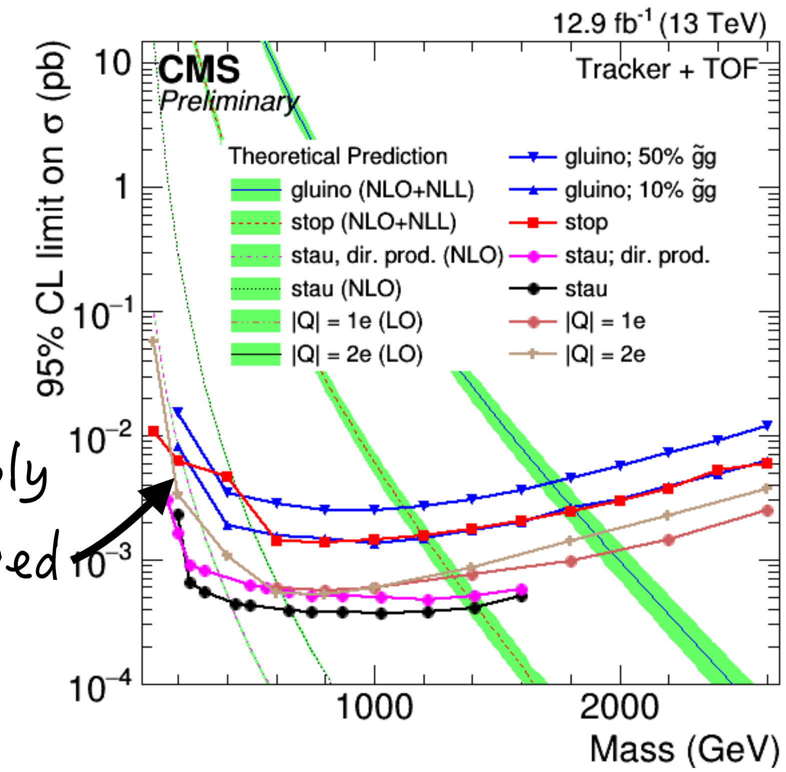


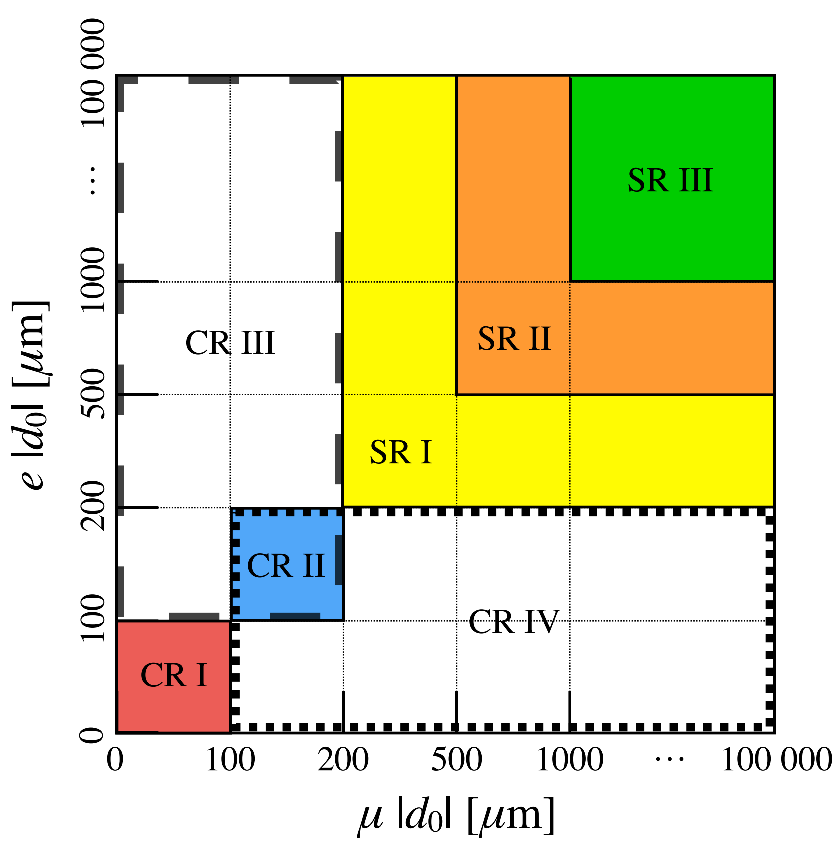
Provides a complementary lower limit on mixing.

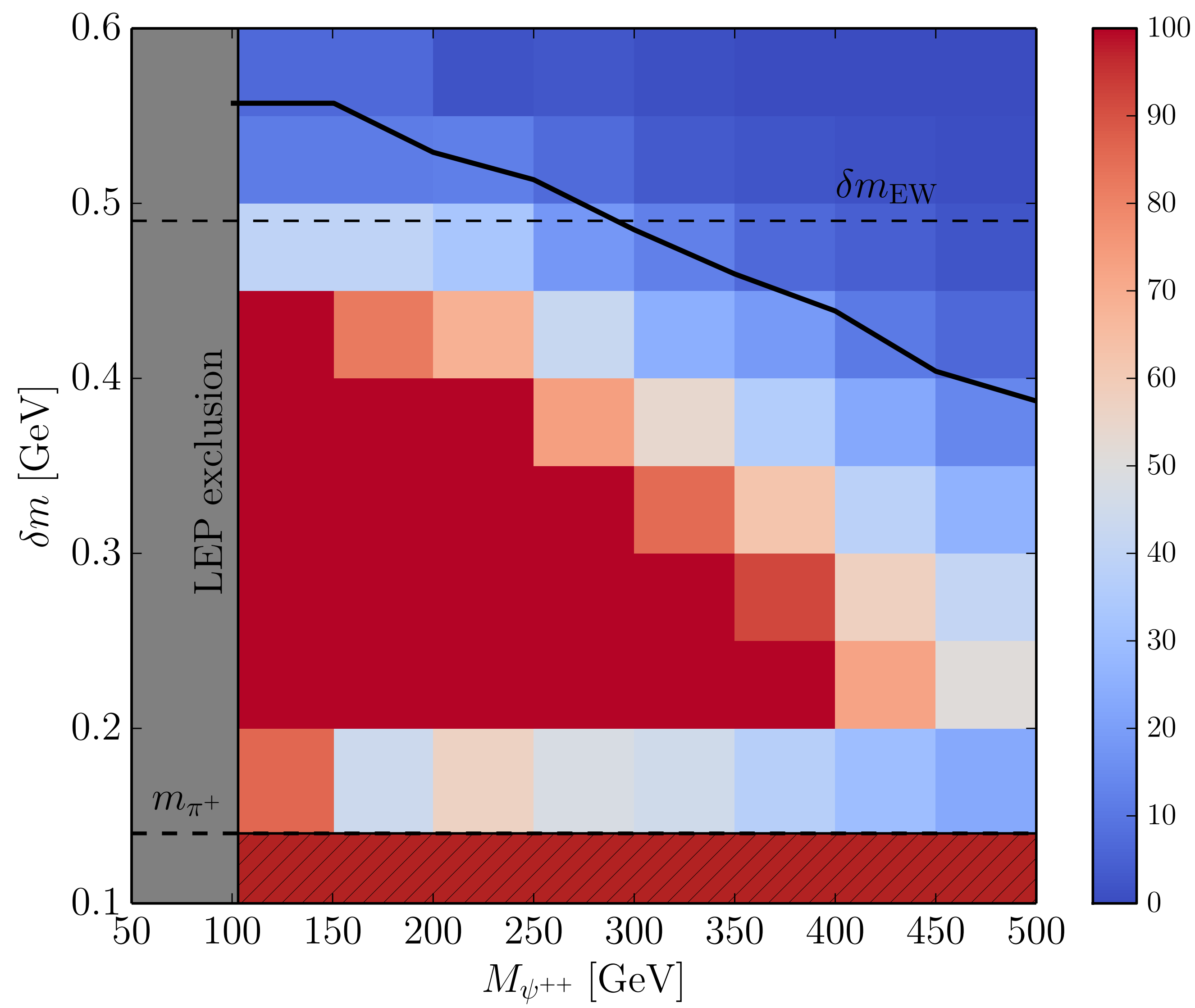
LLP searches can hint at mechanism of DM production

Combination of all searches

Doubly charged







Brümmer, Bharucha, Desai; JHEP 1811 (2018) 195

Comments on Feebly Interacting, DM-motivated LLPs

1. Models currently fall mainly into two categories: models with Yukawa-like couplings (aka t-channel models) and models mediated by small mixing with SM bosons (aka s-channel models)

2. FIMPs + s-channel = cannot be produced at LHC;
   SM > mediator > SM will be seen first.

3. FIMPs + Yukawa = LLP connector with SM charges. Good, almost similar to prompt, coverage (with caveats) for 1st/2nd gen couplings. Possibly good coverage of top.

Comments on Feebly Interacting, DM-motivated LLPs

4. T-channel FIMP models often fall into HCSP region with robust limits (irrespective of flavour)

5. Couplings to b/τ problematic for current searches because of low multiplicity of tracks coming out of secondary vertex.

6. Not really FIMPy, but same models in co-annihilation regime also predict soft + displaced decay products which are not well covered.

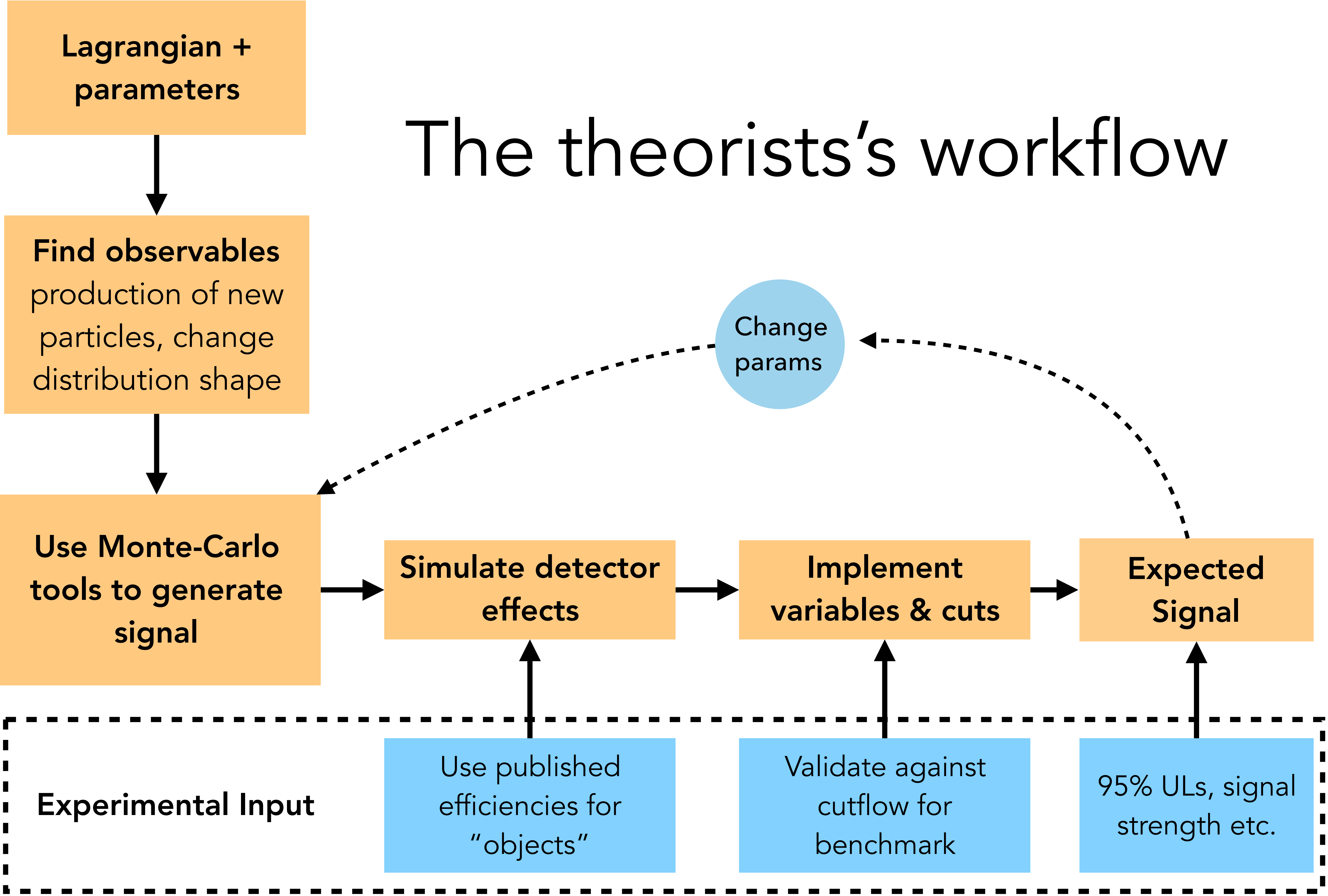
Goal of this talk

1. Introduce a collider friendly freeze-in model (straightforward generalisation to 3rd gen)

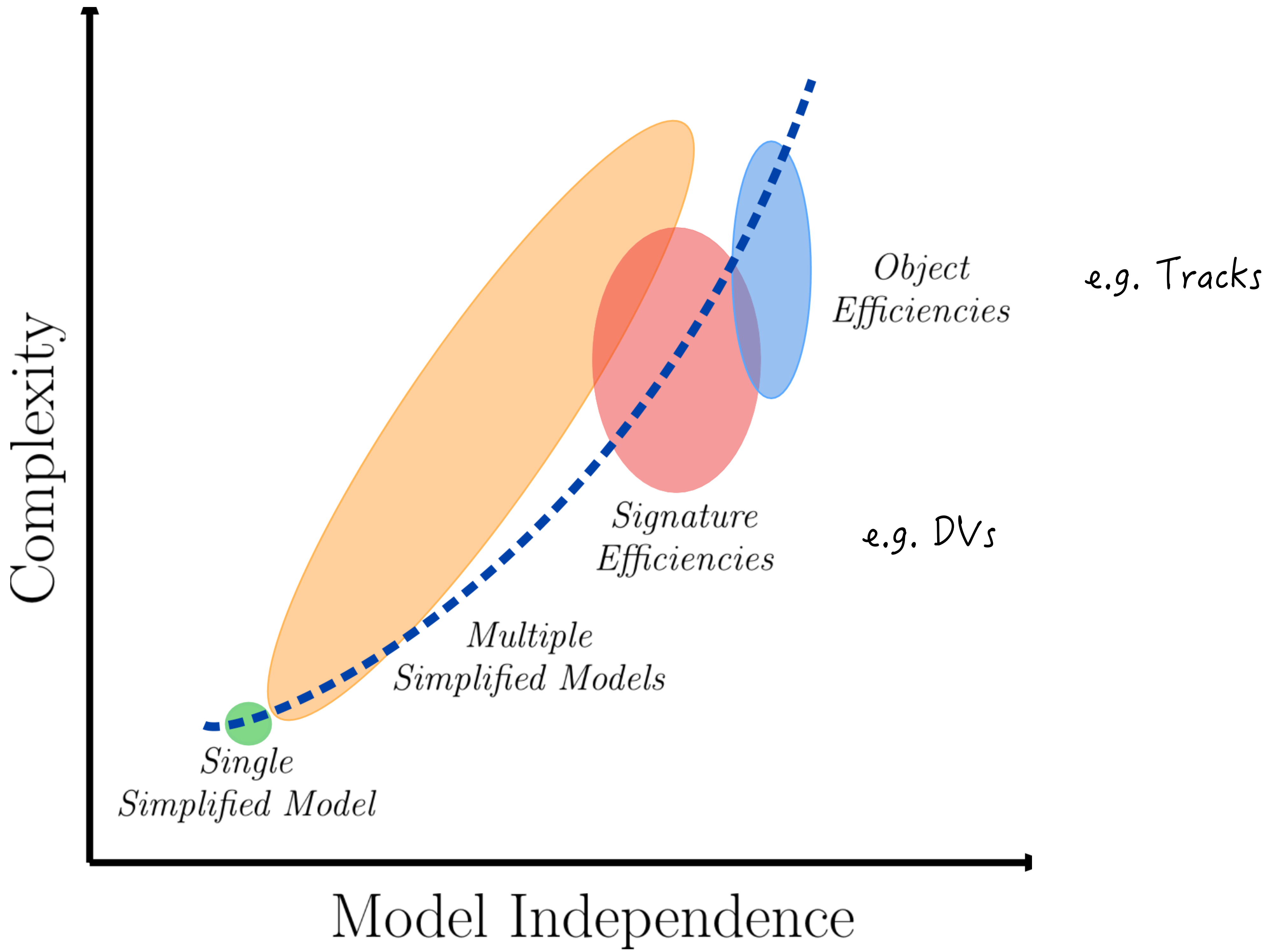
2. Give an overview of models with similar (identical?) signatures but different motivations

3. Some thoughts about how to pick benchmark models when trying to do 3rd generation and LLPs together

The theorists's workflow



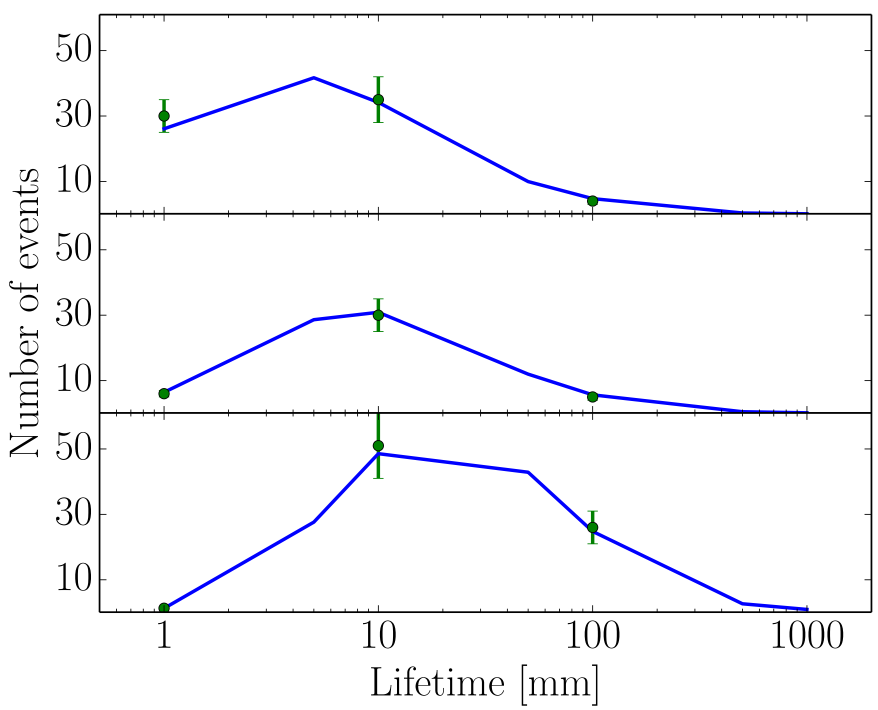
Providing efficiencies



Problem with benchmark for DL search?

The decay stop > b l necessarily gives displaced b-jets

Leptons from B decay and will populate signal and control regions. Was this taken into account? (I think not because impossible to replicate the nice agreement when not using truth leptons)



List of cuts

Preselection
Event passes standard FilterOutScraping cuts
One good primary vertex
generator electron coming from stop
generator electron with $\eta < 2.5$
generator electron with v0 < 4 cm
generator electron with vz < 30 cm
generator electron with pT > 25 CMS.GeV

Better to use a cleaner benchmark ~t-> dl/sl ?

How to provide data for reinterpretation?

1. Use a simplified model that has only one, unambiguous source of signal*
2. Use more than one simplified model, each with different topology (also useful to know about unconscious assumptions)
3. Tell us what happens if there is extra prompt stuff in the event (e.g. isolation cuts, jet or lepton vetoes)
4. Provide signal cutflow for your simplified model for more than one mass benchmark
5. As far as possible, provide efficiencies in terms of objects rather than generator-level particles*.

* May fail when doing 3rd generation