Collider signatures of minimal freeze-in models

Dipan Sengupta

with

G. Belanger, N.Desai, A. Goudelis, J. Harz, A. Lessa, J.M No, A. Pukhov, S.Sekmen, B.Zaldivar, J.Zurita

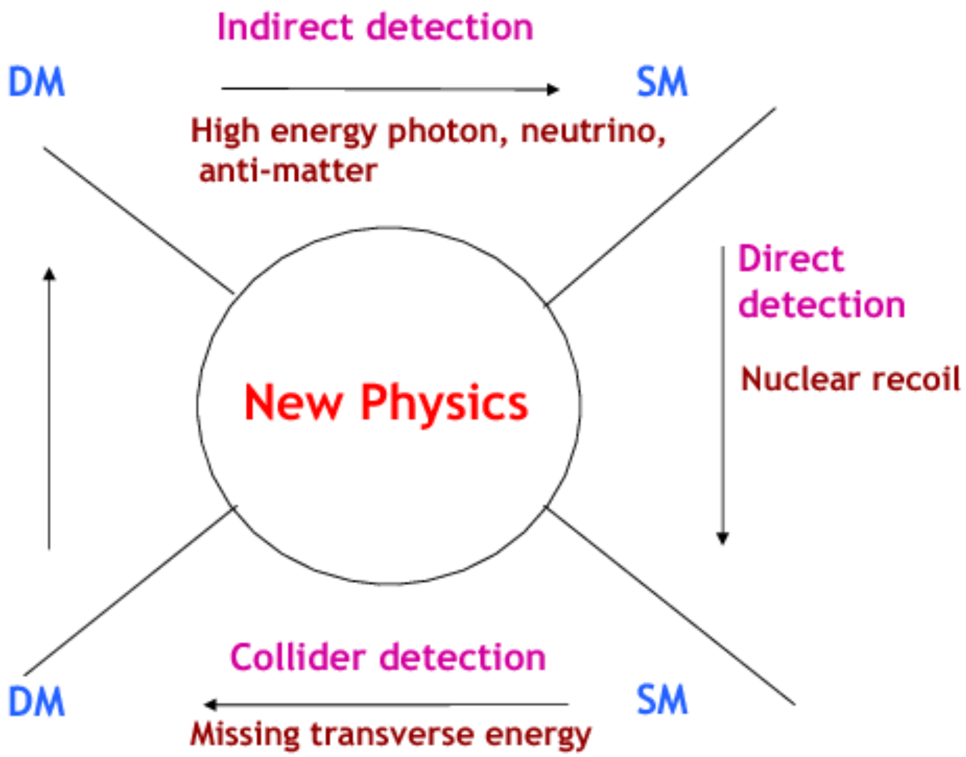
based on

JHEP 1902 (2019) 186, [arXiv:1811.05478]

Outline

- Freeze-in: general framework (reminder?)
- FIMPs and conventional dark matter searches
- Next-to-minimal freeze-in models
- Charged parent models: cosmology *vs* colliders

Weakly Interacting Massive Particle(WIMPs)



DM in thermal equilibrium with bath particles in early universe

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi =< \sigma v > [n_\chi^2 - n_{eq}^2]$$

→ **Boltzmann equation for DM**

$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle (x) = \frac{4x}{K_2(x)^2} \int_1^{+\infty} d\overline{s} \quad \sqrt{\overline{s}} \cdot (\overline{s} - 1) \cdot K_1(2x\sqrt{\overline{s}}) \cdot \sigma_{\rm ann}$$

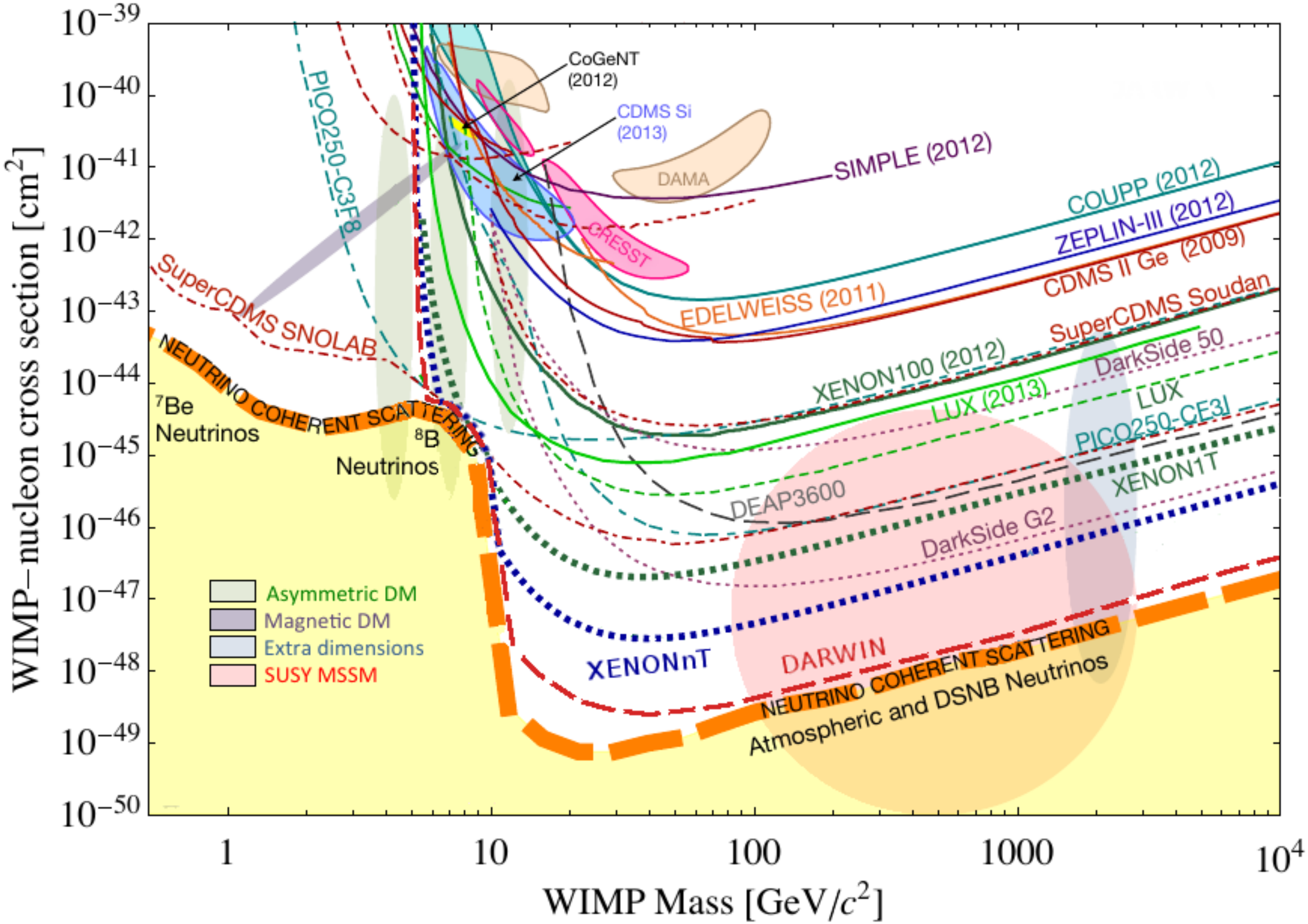
$$x \equiv \frac{M_X}{T}$$

$$\Omega_X \equiv \frac{\rho_{X,0}}{\rho_{\rm crit,0}} = \frac{M_X n_{X,0}}{3M_{\rm pl}^2 H_0^2} = \frac{M_X N_{X,0} s_0}{3M_{\rm pl}^2 H_0^2} = M_X N_X^\infty \frac{s_0}{3M_{\rm pl}^2 H_0^2}$$

$$\Omega_\chi h^2 = 0.1 \frac{x_f}{28} \frac{\sqrt{g_{eff}}}{10} \frac{2.10^{-26} cm^3 s^{-1}}{< \sigma_{\chi\chi} v_{ann} >}$$

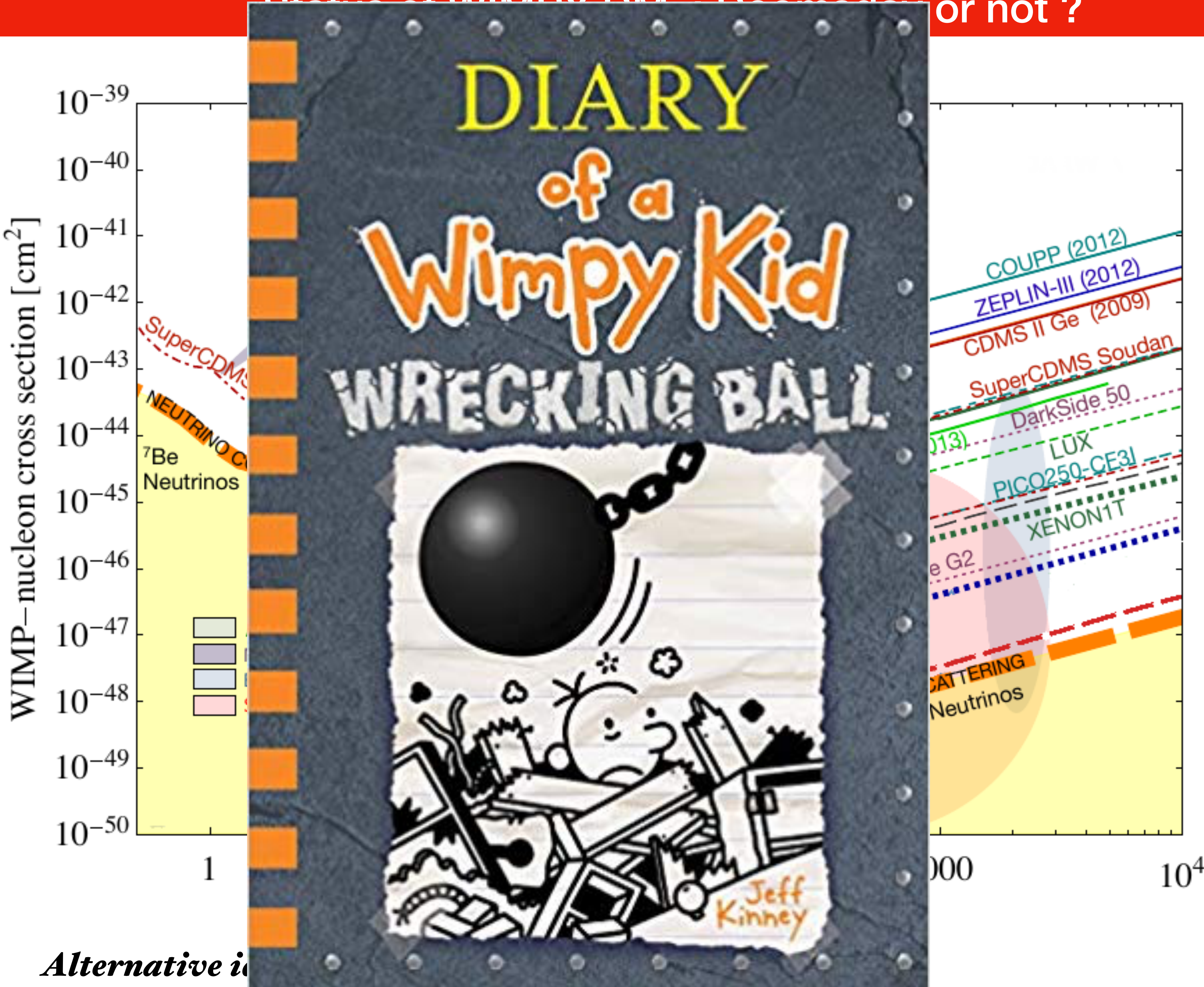
Interaction Strength : Weak Scale -> A BSM theory that also solves Hierarchy problem

Status of WIMPY DM : Doomsday or not ?



Alternative ideas ?

or not ?

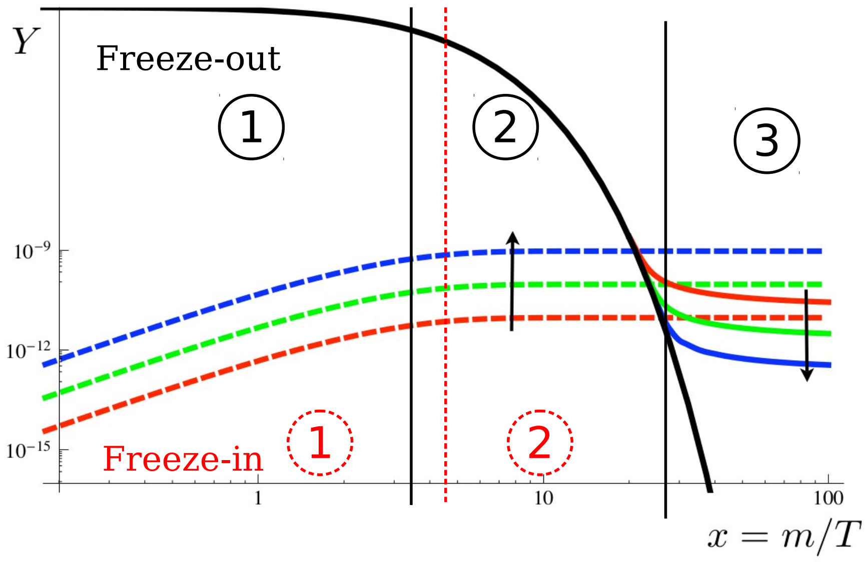


Alternative

Freeze-in: general idea

arXiv:hep-ph/0106249
arXiv:0911.1120
arXiv:1706.07442...

Tweaked from arXiv:0911.1120



Two basic premises :

- DM interacts *very* weakly with the SM.
- DM has a negligible initial density.

Assume that in reaction $A \to B$, ξ_A/ξ_B particles of type χ are destroyed/created.
Integrated Boltzmann equation :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B} (\xi_B - \xi_A)\mathcal{N}(A \to B)$$

$$\mathcal{N}(in \to out) = \int \prod_{i=in} \left(\frac{d^3 p_i}{(2\pi)^3 2E_i} f_i \right) \prod_{j=out} \left(\frac{d^3 p_j}{(2\pi)^3 2E_j} (1 \mp f_j) \right) \times (2\pi)^4 \delta^4 (\sum_{i=in} P_i - \sum_{j=out} P_j) C_{in} |\mathcal{M}|^2$$

1. DM produced from decays/annihilations of other particles.
2. DM production disfavoured → Abundance freezes-in

Freeze-in vs freeze-out

Naively, the freeze-in BE is simpler than the freeze-out one. However :

Initial conditions:

· FO: equilibrium erases all memory.

· FI: Ωh^2 depends on the initial conditions.

Heavier particles:

· FO: pretty irrelevant (exc. coannihilations/late decays).

· FI: their decays can dominate DM production.

Need to track the evolution of heavier states

In equilibrium? Relics? FIMPs?

Need dedicated Boltzmann eqs

Relevant temperature:

· FO: around $m_\chi/20$.

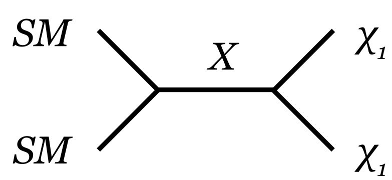
· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on nature of underlying theory.

- Statistics/early Universe physics can become important.

Model-building issues

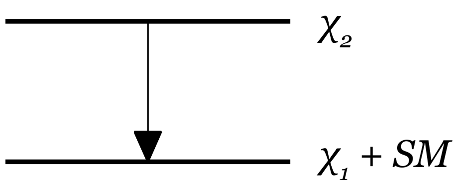
What kind of couplings do we need for successful freeze-in?

Annihilation:



· Requires $\lambda_1 \lambda_2 \sim 10^{-10} - 10^{-12}$

Decay:



· Requires $\lambda \sim 10^{-13} \text{ x } (m_{\chi 2}/m_{\chi 1})^{1/2}$

How can we justify such small numbers?

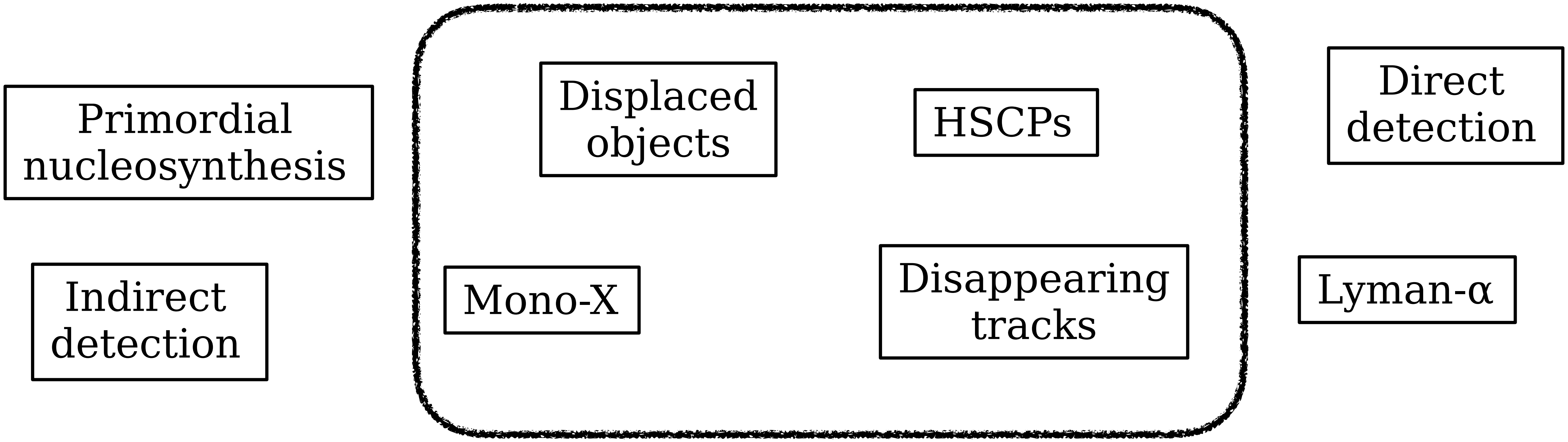
Two main ways so far:

- Scale suppression **UV dominated**
- Symmetries **Potentially IR dominated**

How to dynamically and "naturally" generate such small couplings with order 1 numbers ?

Clockworking: A. Goudelis, K. Mohan , D.S **JHEP 1810 (2018) 014**

· Can we test freeze-in? Certainly not in full generality, but there are actually numerous handles.



Freeze-in can motivate an exciting EXP search programme

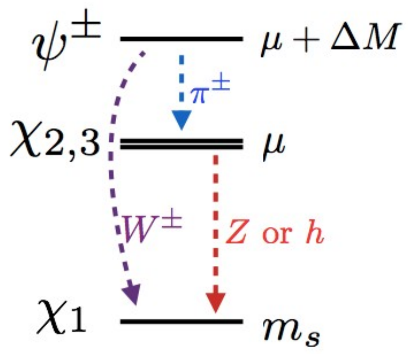
An example: the singlet-doublet model

Consider the singlet-doublet fermion model: SM + 2 Weyl (**2, ±1/2**) fermions ψ_u, ψ_d + a (**1, 0**) fermion ψ_s

arXiv:hep-ph/0510064

$$-\mathcal{L} \supset \mu\, \psi_d \cdot \psi_u + y_d\, \psi_d \cdot H\, \psi_s + y_u\, H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\, \psi_s \psi_s + h.c.$$

· DM can be *e.g.* produced through



arXiv:1805.04423

· Collider signatures:

- ψ± decays (disappearing tracks)
- displaced h/Z + MET
- Promptly (although: not for freeze-in)
- Mono-X (large decay lengths)

An example: the singlet-doublet model

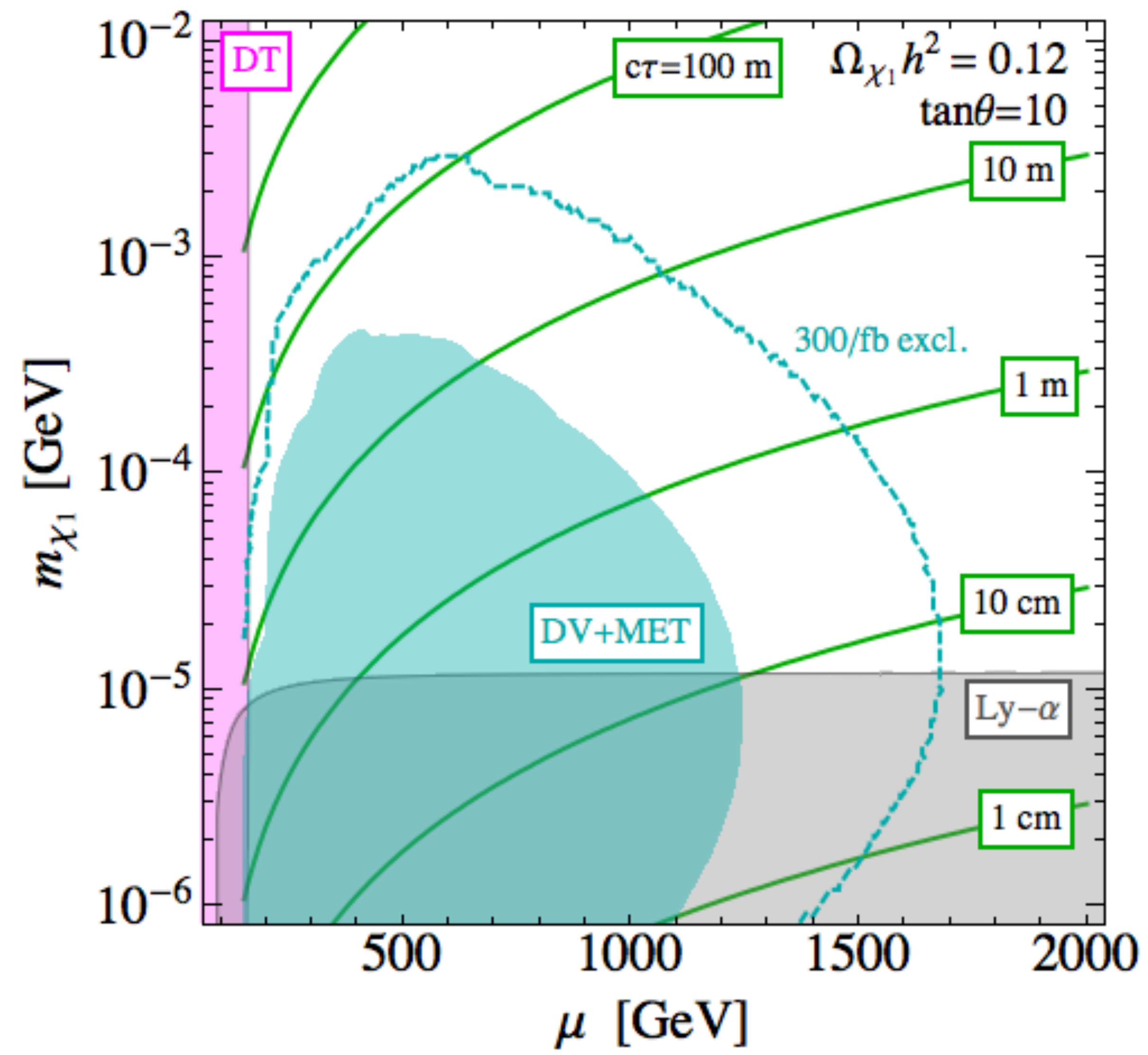
Consider the singlet-doublet fermion model: SM + 2 Weyl (**2, ±1/2**) fermions ψ_u, ψ_d + a (**1, 0**) fermion ψ_s

arXiv:hep-ph/0510064

$$-\mathcal{L} \supset \mu\ \psi_d \cdot \psi_u + y_d\ \psi_d \cdot H\, \psi_s + y_u\ H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\ \psi_s \psi_s + h.c.$$

arXiv:1805.04423

· Combination of all constraints :



Freeze-in with a charged parent

Consider an extension of the SM by a Z_2-odd real singlet scalar *s* (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion *F* (parent).

contribution in arXiv:1803.10379
and arXiv:1811.05478

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

Distinguish three cases:

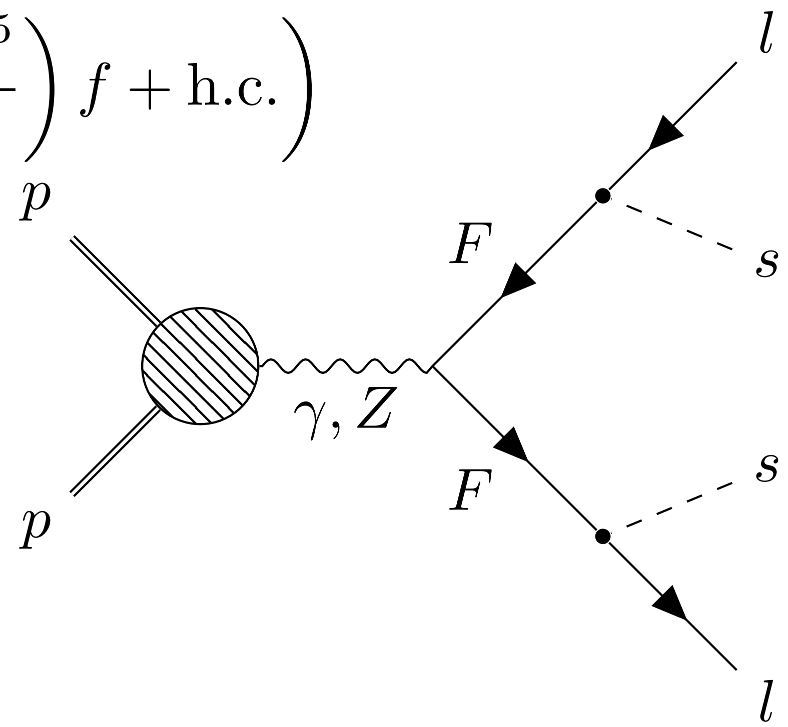
- $f = \{e, \mu, \tau\} \rightarrow F$ transforms as (**1, 1, -1**)
  "Heavy lepton"
- $f = \{u, c, t\} \rightarrow F$ transforms as (**3, 1, -2/3**)
  "Heavy *u*-quark"
- $f = \{d, s, b\} \rightarrow F$ transforms as (**3, 1, 1/3**)
  "Heavy *d*-quark"

Freeze-in with a charged parent

Consider an extension of the SM by a Z_2-odd real singlet scalar s (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion F (parent).

contribution in arXiv:1803.10379
and arXiv:1811.05478

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



For simplicity :

· Study three cases separately.

i.e. add a single pair of F fermions at a time

· Only couple F to the first two generations.

The collider pheno of 3rd generation fermions is a bit more tricky

· Set Higgs portal to zero → Only relevant coupling: y_s^f.

Non-LLP constraints: earth-bound

Focus on the first two models (heavy lepton, heavy u-quark).

Heavy lepton model

- LEP2: $m_F > 104$ GeV

  Actually slightly weaker, depending on lifetime

- No EWPT constraints

  arXiv:1404.4398

- Muon lifetime: $\mu \to ess$

  Checked, irrelevant

- LFV processes, in particular $\mu \to e\gamma$

$$Br(\mu \to e\gamma) \sim \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3m_F^4 (16\pi)^2} \sim 10^{-46}$$

i.e. tiny

Heavy quark model

- Direct collider bounds subleading

  Require prompt jets

- Running of α_s : $m_F >$ few hundred GeV

- Rare decays, e.g. $K^+ \to \pi^+ ss$

  NA62 can reach down to $y_s \sim 10^{-5}$

- Meson mixing: similarly to $\mu \to e\gamma$, tiny

Globally: still lots of room for interesting phenomenology

Parent particle lifetime and cosmology

Assuming that DM is mostly populated by F decays, we can relate the relic abundance with the parent particle lifetime:

$$c\tau \approx 4.5\,\mathrm{m}\,\xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right]$$

Freeze-in favours long lifetimes, unless

- Dark matter is very light
- The reheating temperature is low

Cosmological constraints

- **Big-Bang Nucleosynthesis**

  we consider 1cm < cτ < 10^4m → T~150 MeV
  → heavy fermions decay well before onset of BBN

- **Lyman-α forest**

$$m_{\rm DM} \gtrsim 12\ \mathrm{keV}\left(\frac{\sum_i \mathrm{BR}_i \Delta_i^\eta}{\sum_i \mathrm{BR}_i}\right)^{1/\eta} \gtrsim 12\ \mathrm{keV}$$

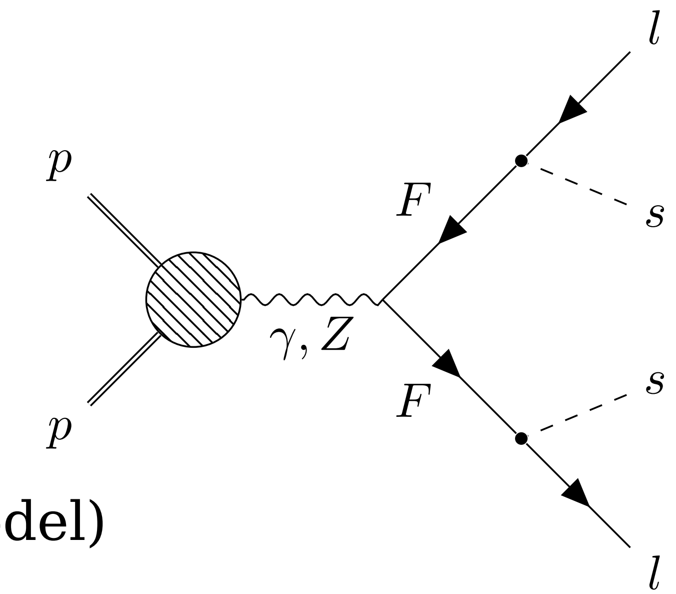
$$\eta = 1.9$$

$$\Delta_i = 1 - m^2_{X^i_{\rm SM}}/m^2_Y$$

Boulebnane, Heeck, Nguyen, Teresi, 1709.07283

Signatures at the LHC

So what are the model's signatures at the LHC?



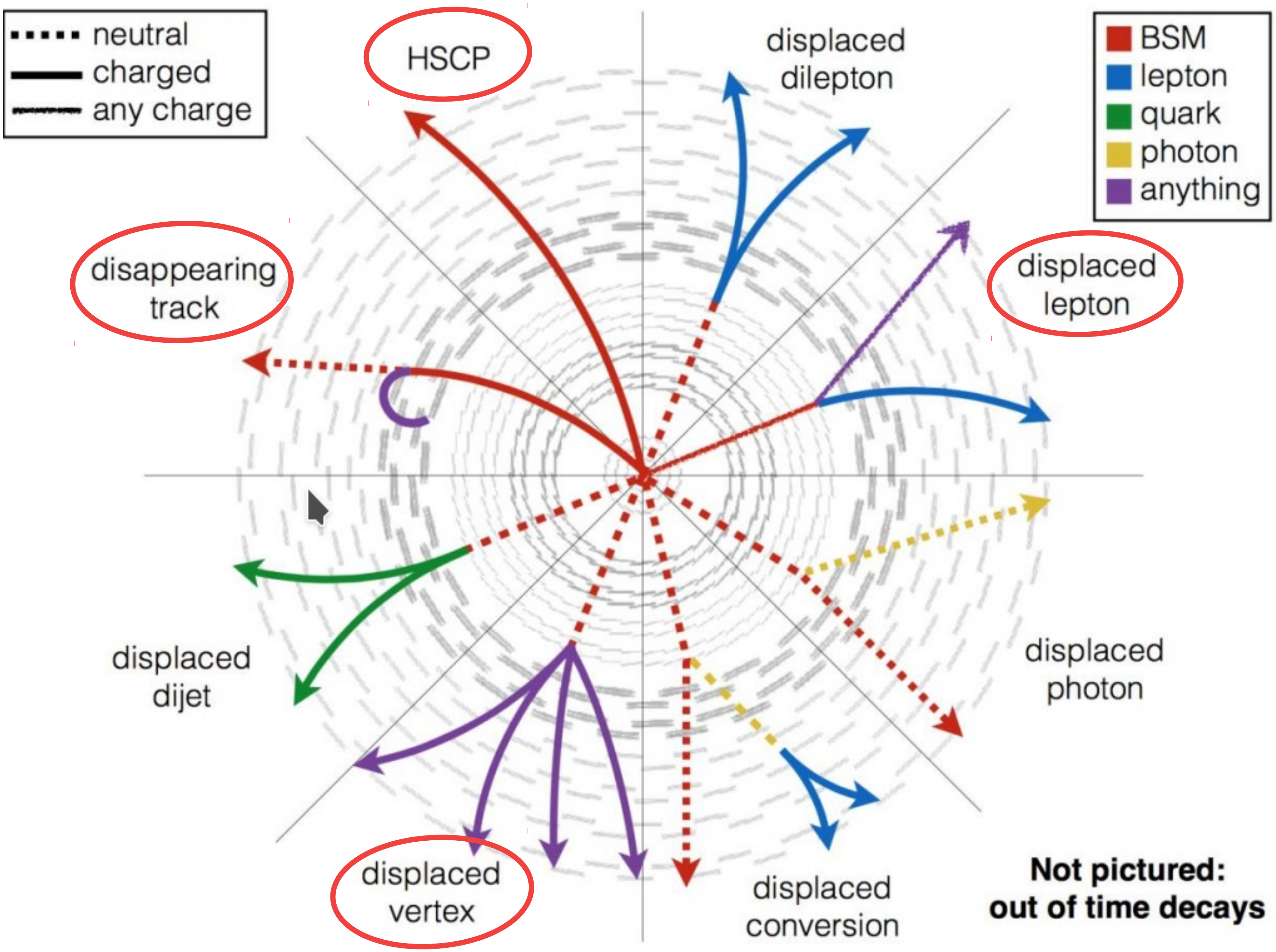
· First of all, production through :

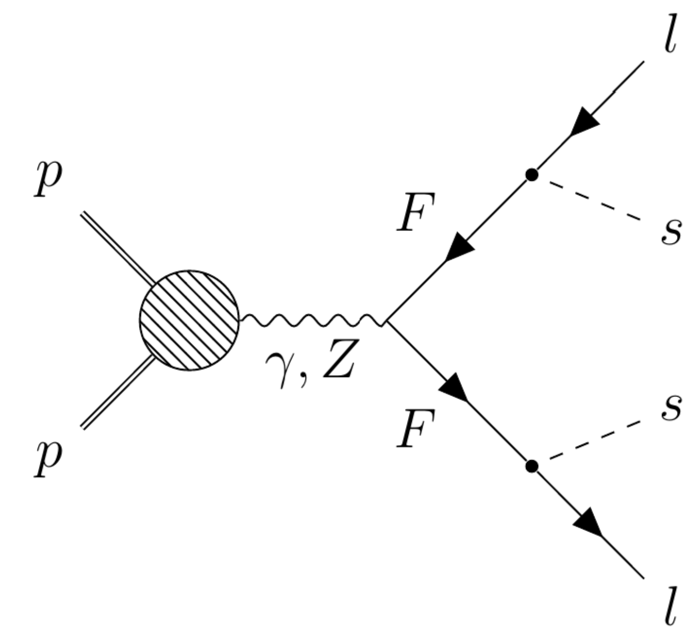
- Drell-Yan (lepton model)
- Drell-Yan +QCD (quark model)

· Several search strategies, depending on the lifetime of the parent particle, i.e. which part of the detector it mostly decays at (if at all).

- Long lifetimes → Heavy Stable Charged Particles (HSCPs)
- Intermediate lifetimes (for lepton model) → Disappearing/kinked tracks
- Short lifetimes → Displaced leptons/vertices

Collider constraints





HSCP searches

General idea: look for a “heavy muon” or “heavy hadron”.

Heavy lepton model	**Heavy quark model**
· Some V-L leptons survive through the tracker and leave an ionising track Different than SM e/μ	· V-L quarks will hadronize and give rise to charged and neutral hadrons (“*R-hadrons*”)
· If they also survive past the muon chambers, one can measure their time-of-flight (TOF) Typically larger than for μ’s	· Limit depends on number of produced charged hadrons Hadronisation as in arXiv:1305.0491
· Two analyses: tracker-only, tracker + TOF	· Interactions in the calorimeter may cause R-hadrons to flip charge → neutral R-hadrons may appear

+ Take into account finite lifetime effects

- comparison with upper limits obtained by production of **staus (leptonic model)** or **stops (hadronic model)** in a gauge mediated SUSY breaking model
- F has smallish life time → **re-scale the efficiency** of particles that surpasses the tracker (L = 3m) / detector (L = 11 m)

$$\sigma_{eff} = \sigma \times f_{LLP}(L, \tau)$$

CMS Coll., Searches for long-lived charged particles in pp collisions at √s=7 and 8 TeV, JHEP 07 (2013) 122, [arXiv:1305.0491]
CMS Coll., Search for heavy stable charged particles with 12.9 fb−1 of 2016 data, CMS-PAS-EXO-16-036 (2016).

Disappearing tracks (lepton model)

General idea:

· The heavy leptons F are produced promptly → they leave a track in the tracker.

· A theorist's view: if F decays before the end of the tracker, we'd observe a "kinked" track.

· But the outgoing lepton can typically *not* be reconstructed.

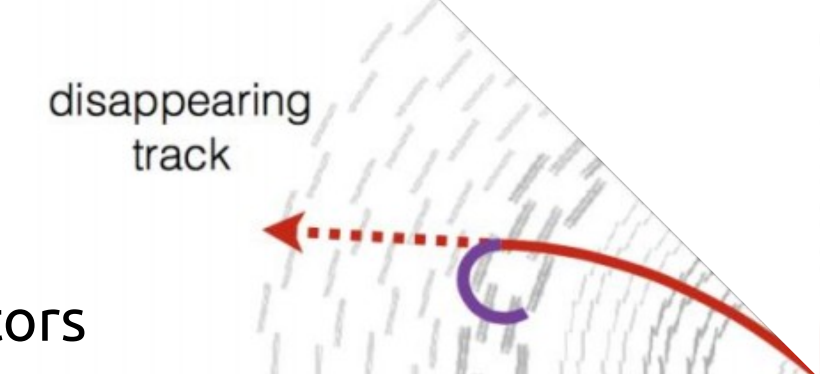
→ Experimentally, the track "disappears"

Non-trivial to assess how often the track *actually* disappears, here assume it always does so → limits rather aggressive

· Limits will differ from one experiment to the other: different hardware.

e.g. as of Run 2 ATLAS can reconstruct tracks as short as 12 cm, while CMS ~25 cm

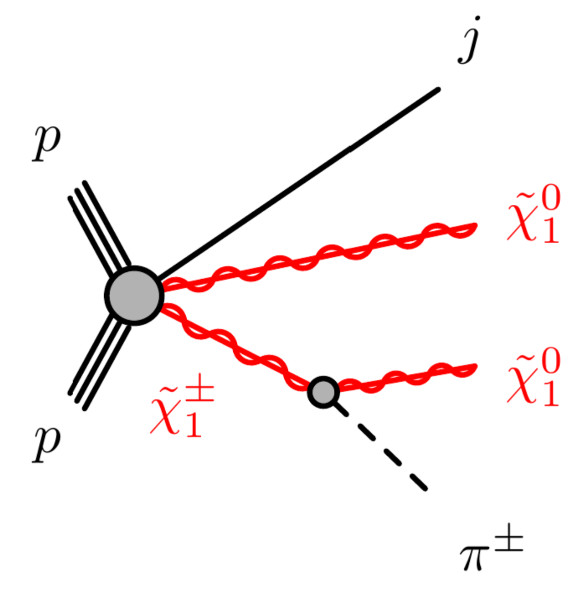
2 Disappearing Tracks (DT)



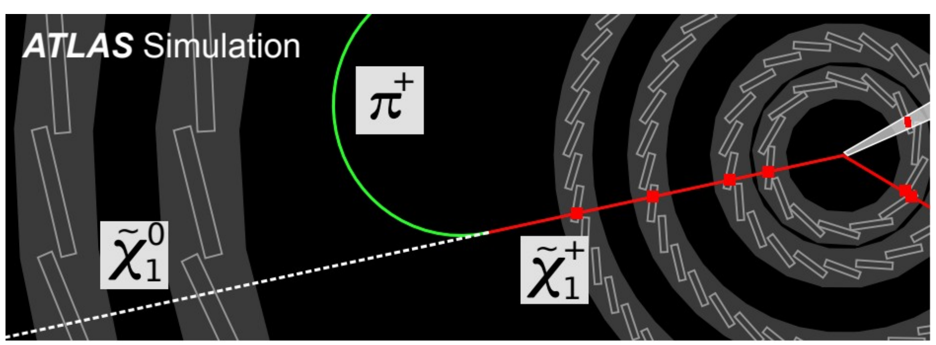
- **isolated track** reconstructed in the pixel and strip detectors without any hit in the outer tracker (CMS) or a track with only pixel hits (ATLAS)

- ATLAS can reconstruct tracks down to 12 cm (new innermost tracking layer); CMS 25-30 cm
- CMS has better coverage for longer life times cτ > 1m

- **AMSB** motivated scenario with mass **degenerate lightest chargino** and **neutralino**



(a) $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0 j$



13 TeV ATLAS analysis 36.1 fb^{-1}
13 TeV CMS analysis 138.4 fb^{-1}

ATLAS Coll., Search for long-lived charginos based on a disappearing-track signature in pp collisions at √s= 13TeV with the ATLAS detector, JHEP06(2018) 022, [arXiv:1712.02118]

CMS Coll., Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at √s=13 TeV, arXiv:1804.07321

- Recasting of two analyses of ATLAS and CMS

$$\mathcal{N} = \sigma_{\mathrm{pp}\to\mathrm{F}\bar{\mathrm{F}}} \times \varepsilon(m,\tau) \times \mathcal{L}$$

Displaced leptons/vertices

Heavy lepton model

· For shorter F lifetimes, the SM lepton track can be reconstructed

· Look for displaced opposite-charge $e+\mu$ (one of each/event)

· Note: in principle possible to reconstruct both $c\tau_F$ and m_F.

→ Assuming s is all of DM, for a given m_s we can infer T_R

Meaning of comment to be explained shortly

Heavy quark model

· Look for displaced jets + MET

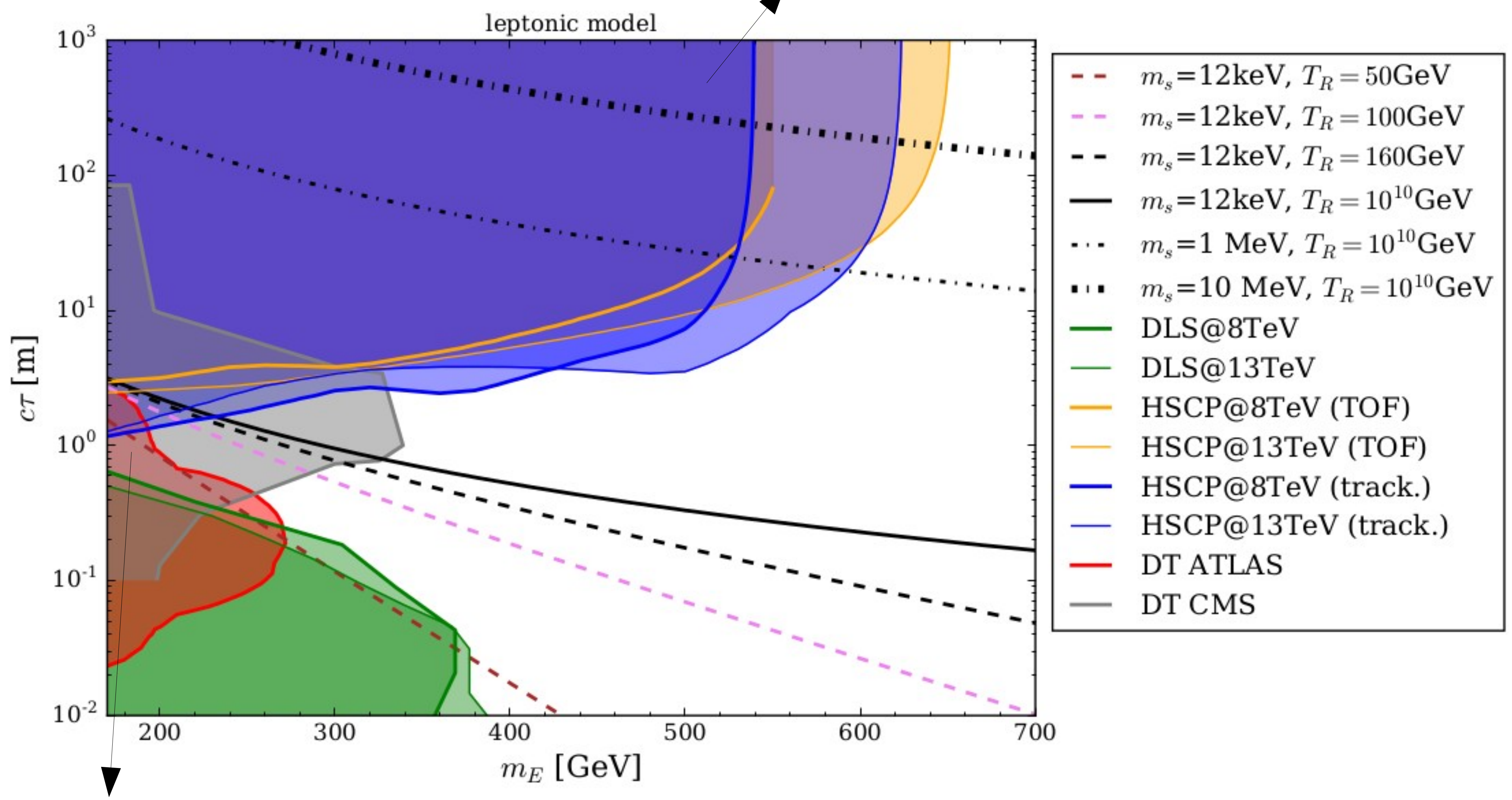
· Performing the analysis from scratch requires very sophisticated detector simulation

→ Instead use parametrised efficiencies provided by ATLAS

ATLAS Coll., Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$= 13 TeV pp-collisions with the ATLAS detector, Phys. Rev.D97(2018), no. 5 052012, [arXiv:1710.04901]

Results: lepton model

HSCP: Tracker + TOF analysis more powerful for larger lifetimes, tracker-only for shorter ones.

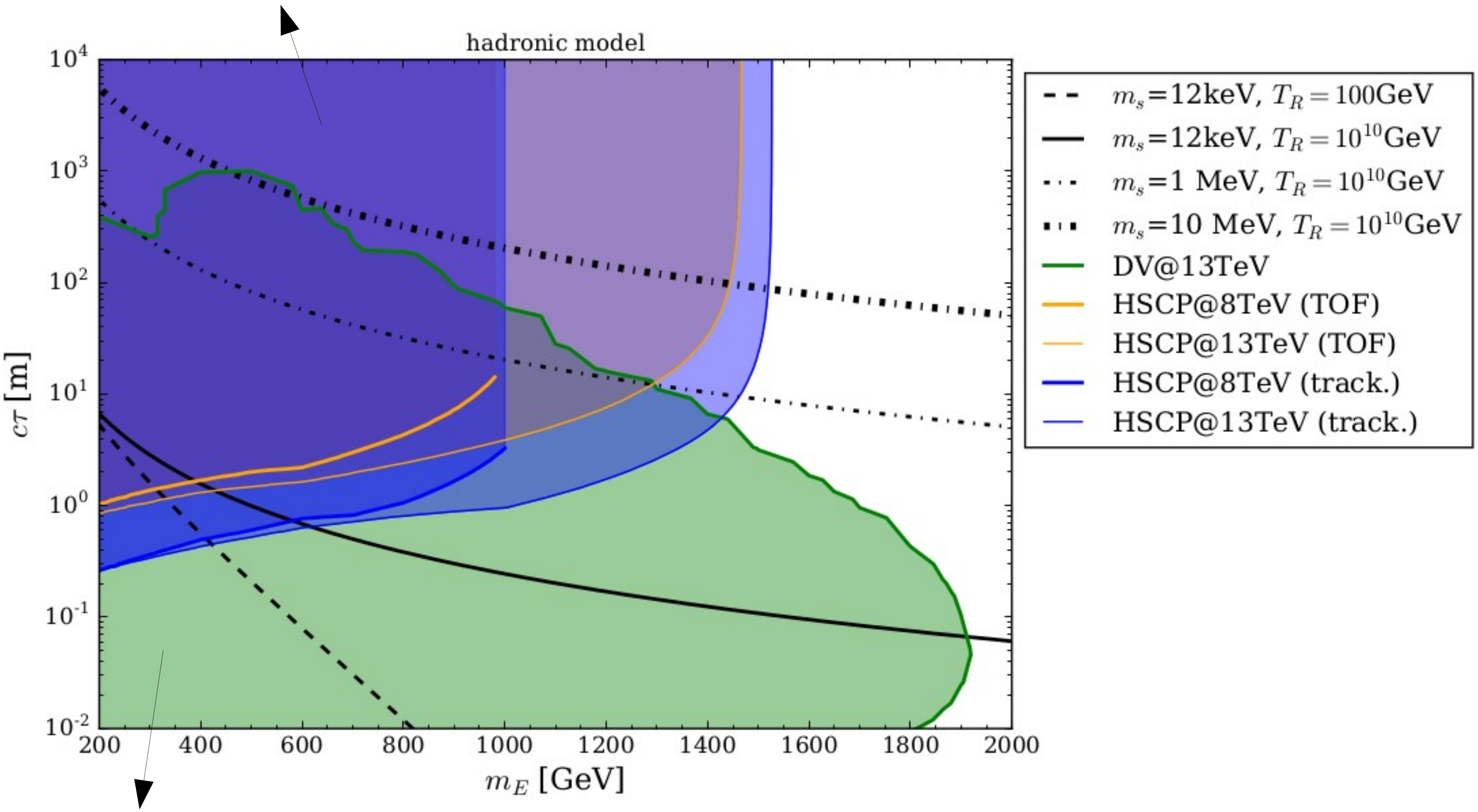


DT: Order-of-magnitude difference in peak sensitivity between ATLAS/CMS

More accurate estimates require extensive input from EXP collaborations

Results: quark model

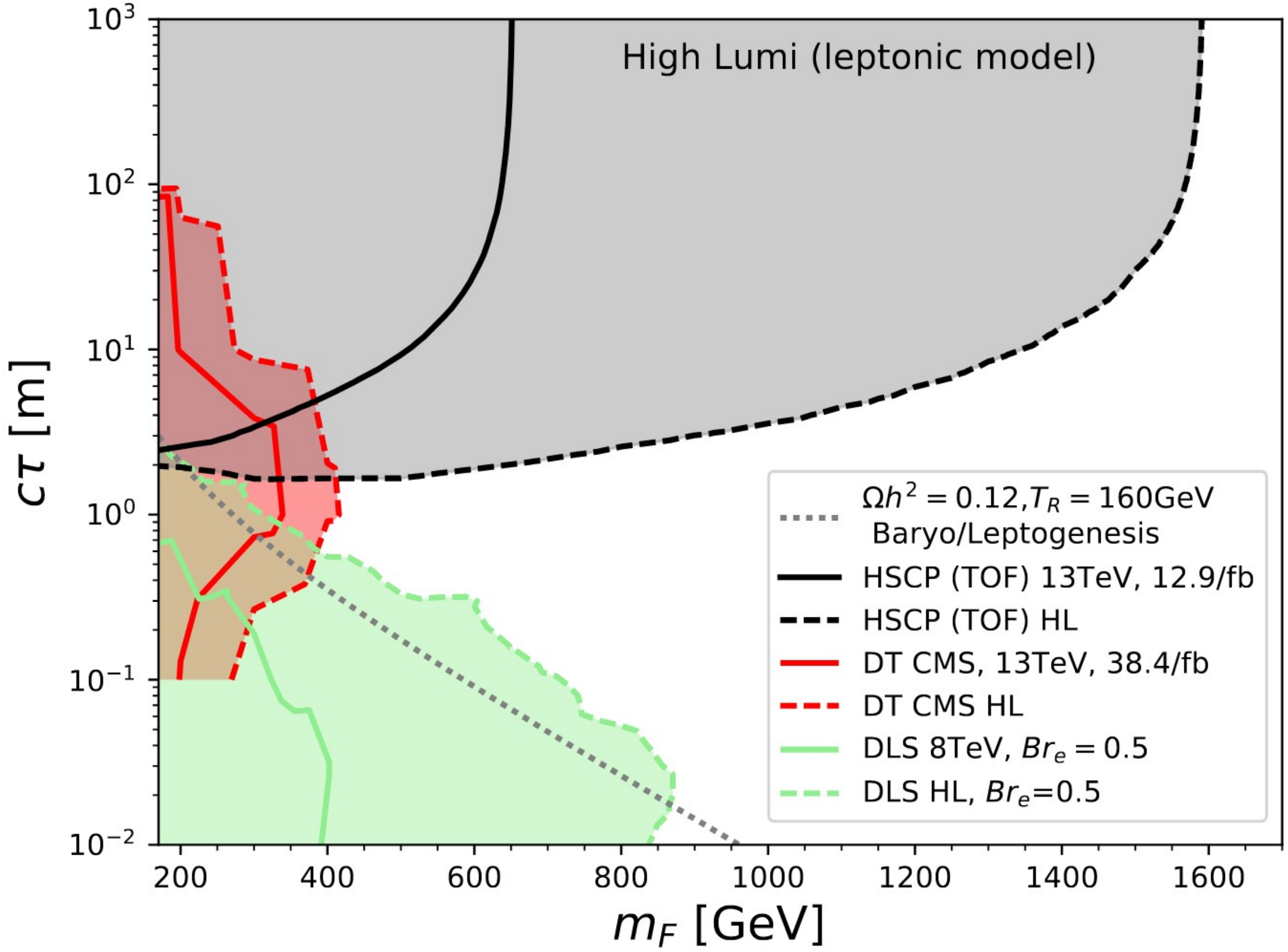
HSCP: Tracker-only analysis always more powerful, neutral R-hadrons fail tracker + TOF selection.



DV: Impressive reach as high as $c\tau_F \sim 100$ m

Clear complementarity between different LHC searches

Extrapolation to High Luminosity LHC



High Lumi LHC could almost close the parameter space in which baryogenesis models would be in tension in case of a discovery

An interplay with baryo/leptogenesis ?

An upshot:

· In E/W baryogenesis and leptogenesis, the reheating temperature must in general be larger than both the EW phase transition temperature (T_{EW}~160 GeV) and the sphaleron freeze-out one (T^*~132 GeV).

· Assume s makes up all of dark matter.

If it doesn't, argument even stronger!

· Assume we manage to measure $c\tau_F$ and $m_F \rightarrow$ 2 free parameters: m_s and T_R.

· Difficult to access $m_s \rightarrow$ take the lowest value allowed from Lyman-α.

If it's heavier, argument even stronger!

If measurements point to $T_R < T_{EW}, T^*$, we can falsify baryogenesis models that rely on efficient sphaleron transitions

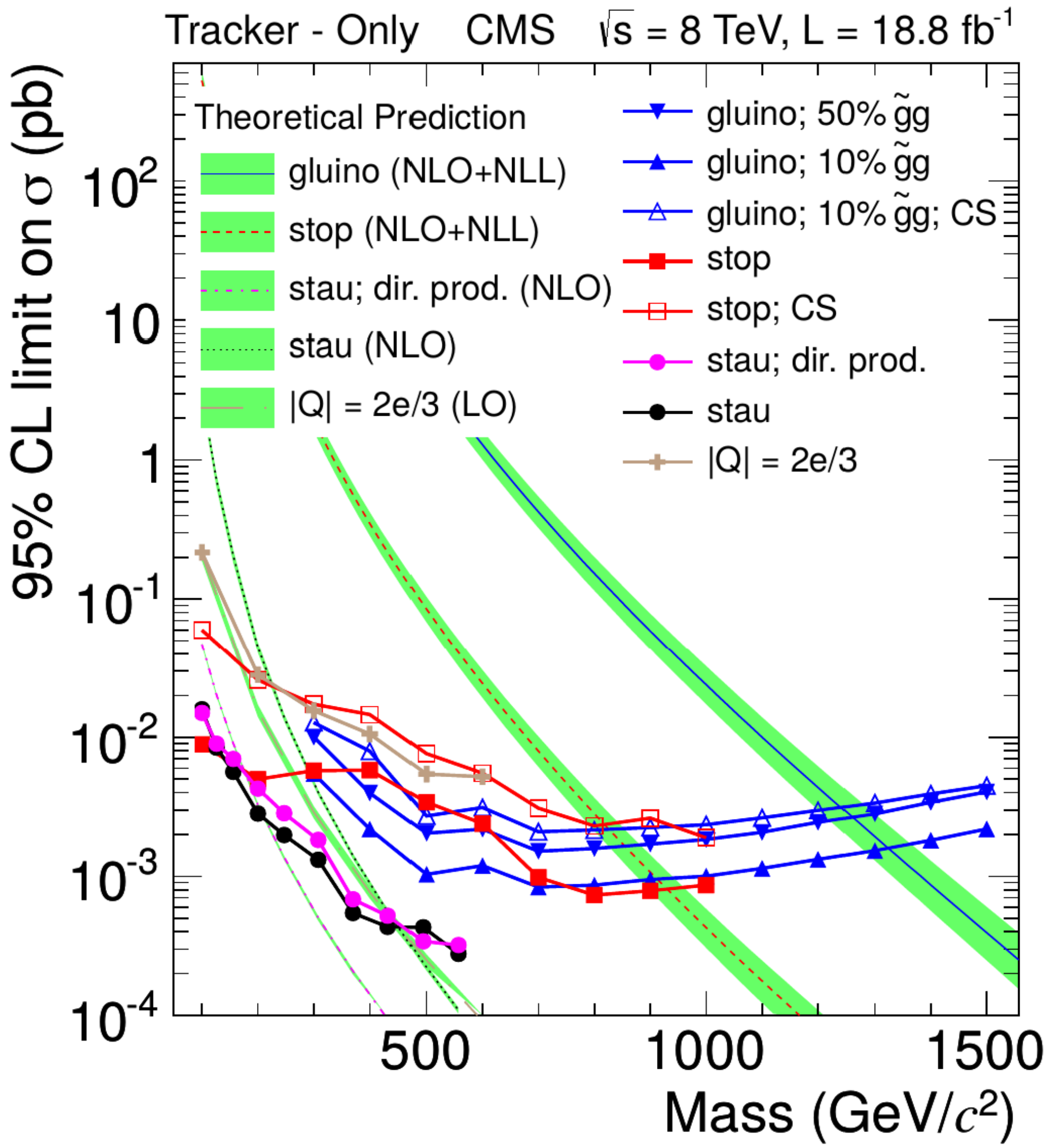
Conclusions

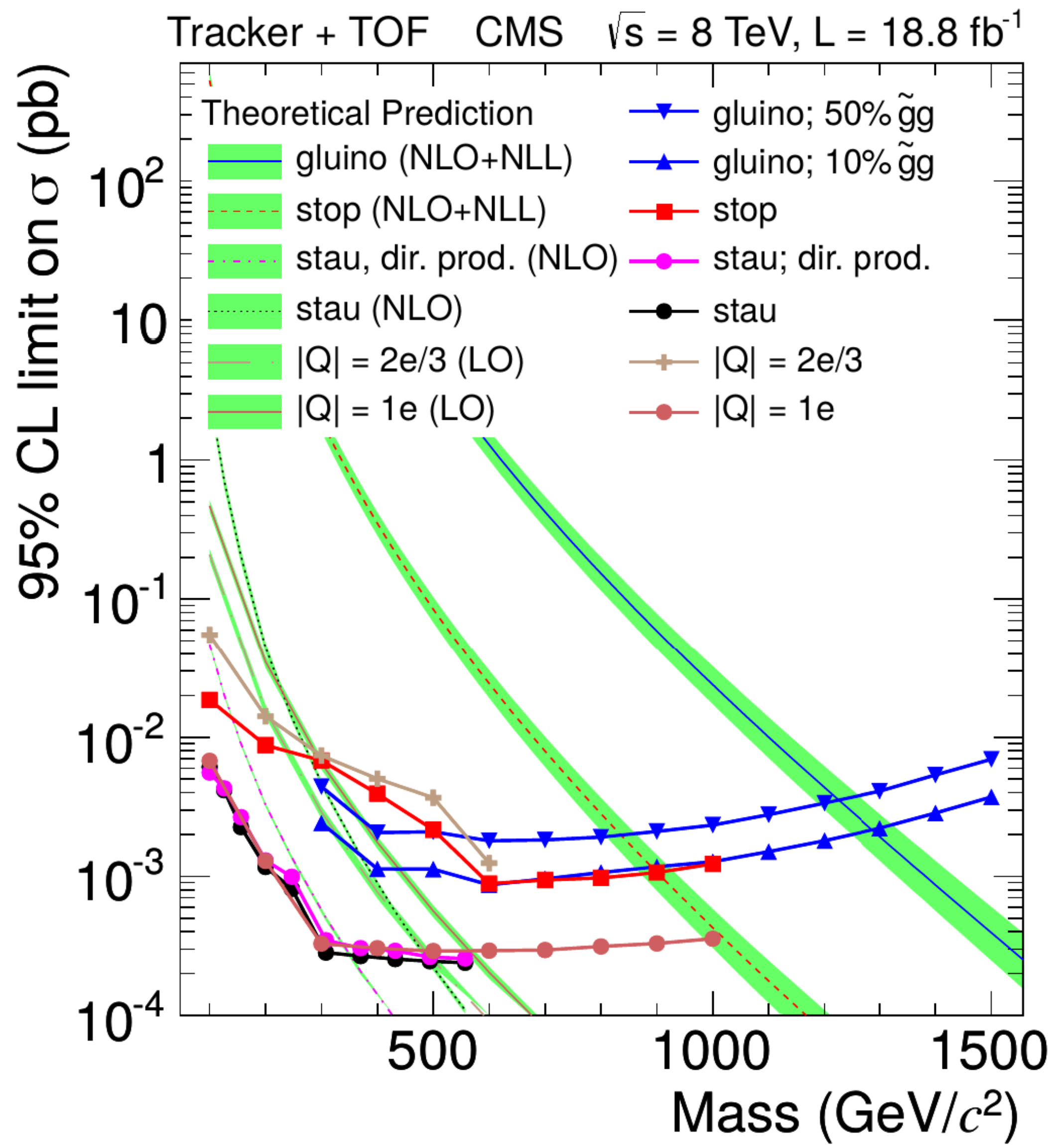
- **Although not in full generality, but freeze-in can be tested at colliders**
- **Simple freeze-in models have predictive and falsifiable signatures**
- **Leads to a wide array of exotic signatures at the LHC and beyond.**
- **Such scenarios also have interesting cosmological implications, in particular baryogengesis and BBN**

We argue for experimentalists to actively look for such signatures

Thanks to Julia and Andreas for some slides

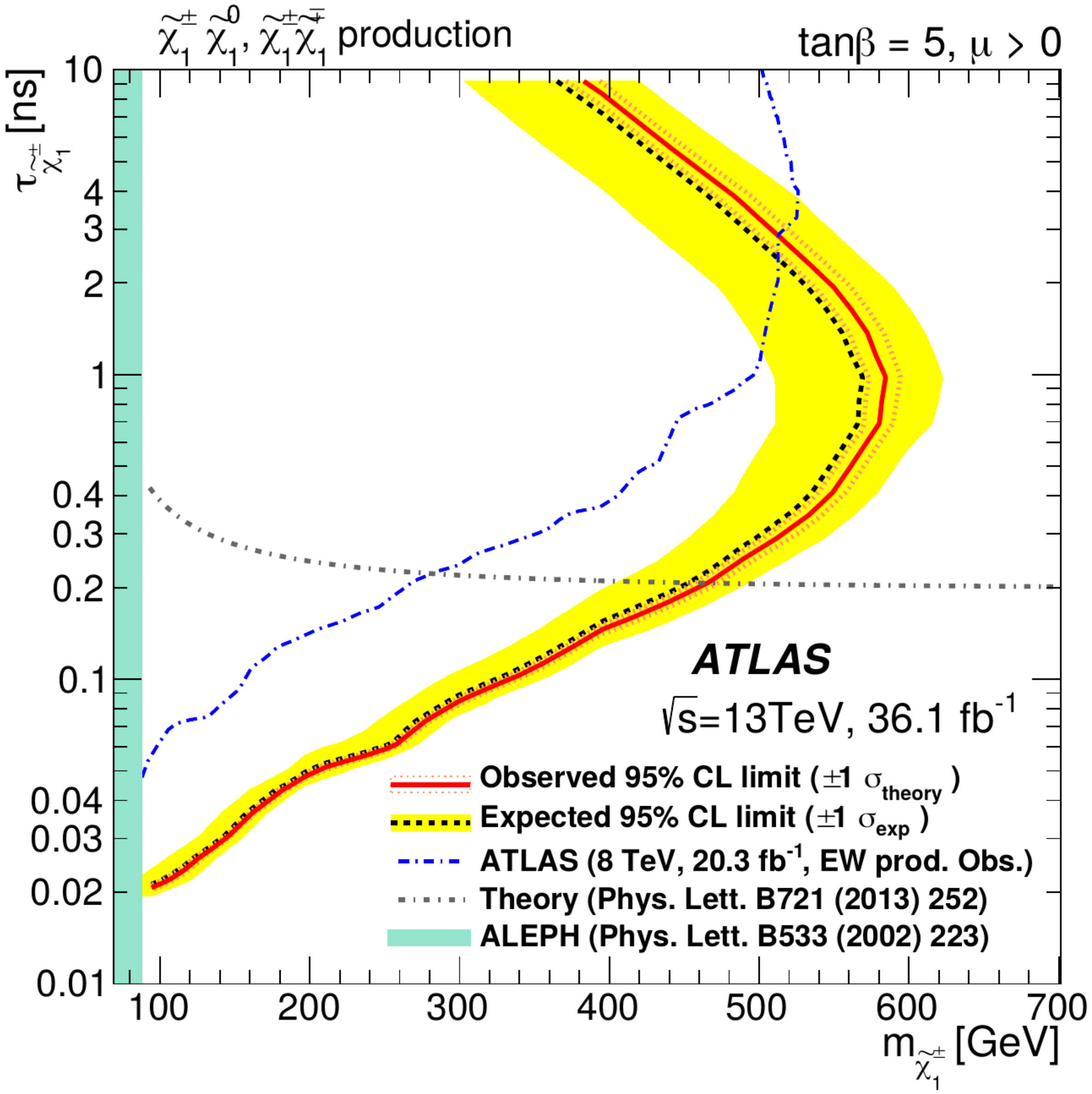
1 Heavy Stable Charged Particles (HSCP)

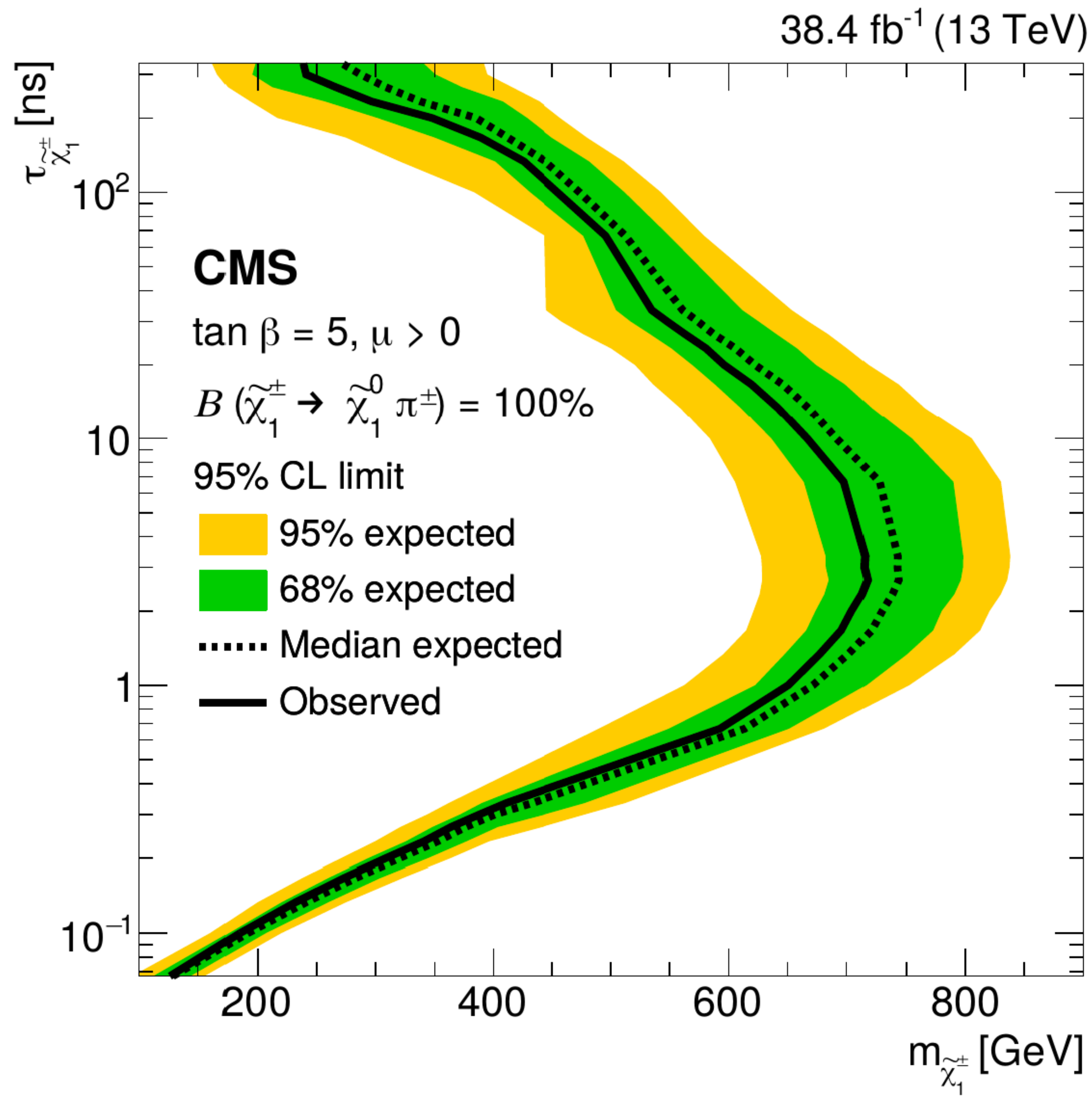




CMS Coll., Searches for long-lived charged particles in pp collisions at √s=7 and 8 TeV, JHEP 07 (2013) 122, [arXiv:1305.0491]
CMS Coll., Search for heavy stable charged particles with 12.9 fb−1 of 2016 data, CMS-PAS-EXO-16-036 (2016).

2 Disappearing Tracks (DT)



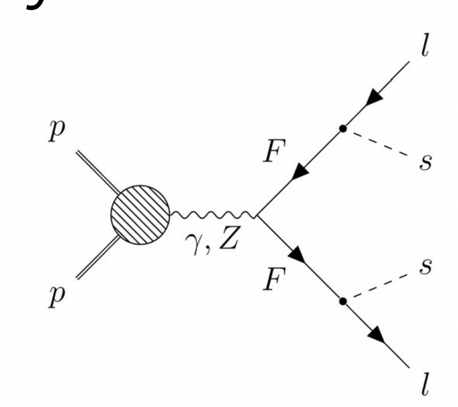


ATLAS Coll., Search for long-lived charginos based on a disappearing-track signature in pp collisions at √s= 13TeV with the ATLAS detector, JHEP06(2018) 022, [arXiv:1712.02118]

CMS Coll., Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at √s=13 TeV, arXiv:1804.07321

3 Displaced leptons (DL) / Vertices (DV) + MET

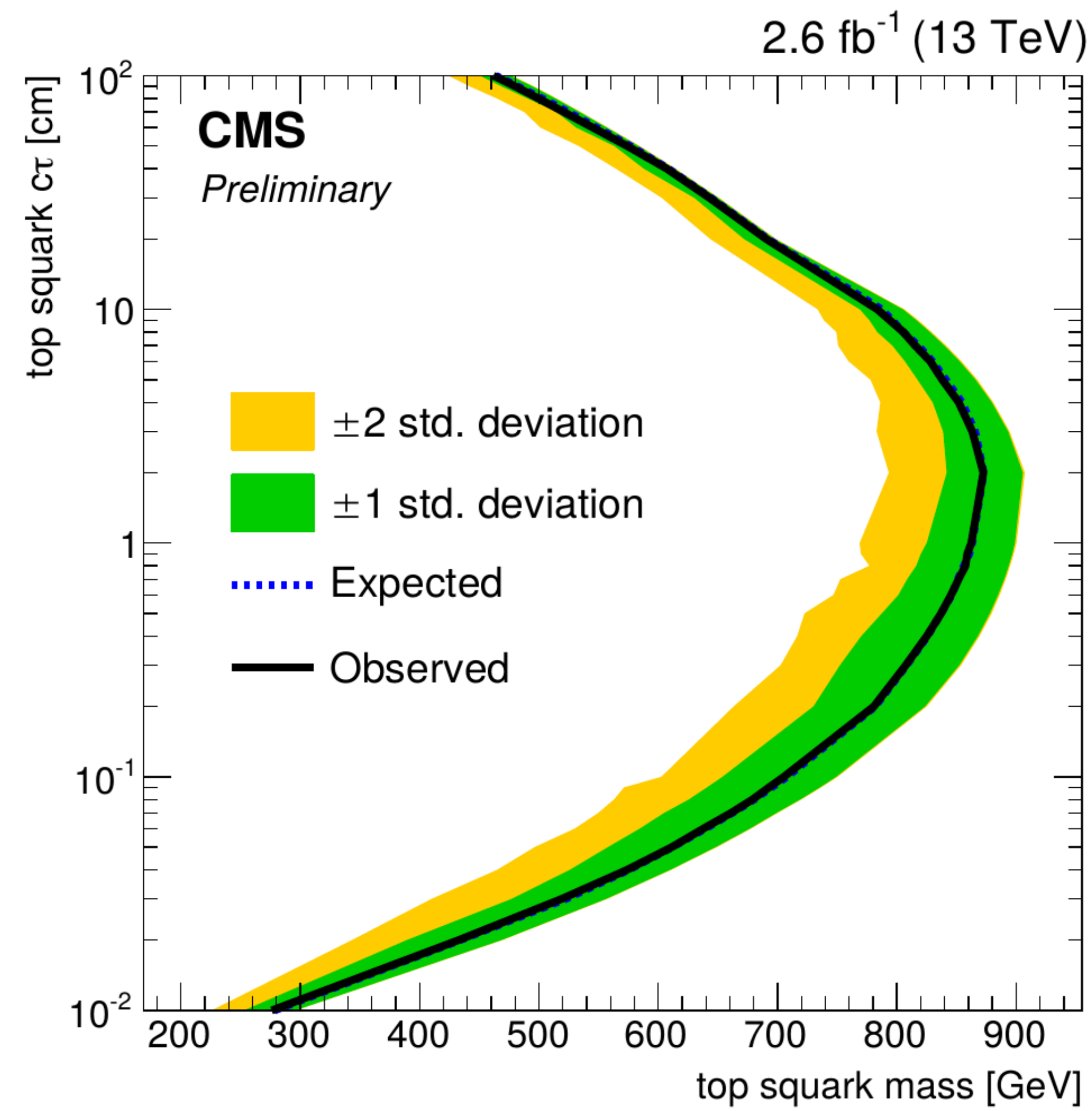
- F can decay into **both muon and electron**



- CMS search for **non-prompt RPV violating SUSY decays** into **e/μ** final state

$$\tilde{t}_1 \to b\ell$$

- search optimized for lifetimes **longer** than prompt searches, but **shorter** than long-lived BSM signatures



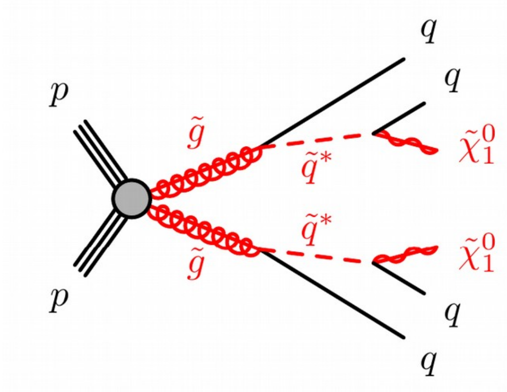
8 TeV CMS analysis 19.7 fb^{-1}
13 TeV CMS analysis 2.6 fb^{-1}

CMS Coll., Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters, Phys. Rev. 1240 Lett. 114 (2015), no. 6 061801, [arXiv:1409.4789]

CMS Coll., Search for displaced leptons in the e-mu channel, CMS-PAS-EXO-16-022 (2016).

3 Displaced leptons (DL) / Vertices (DV) + MET

- F can decay and **hadronize into R-hadrons**



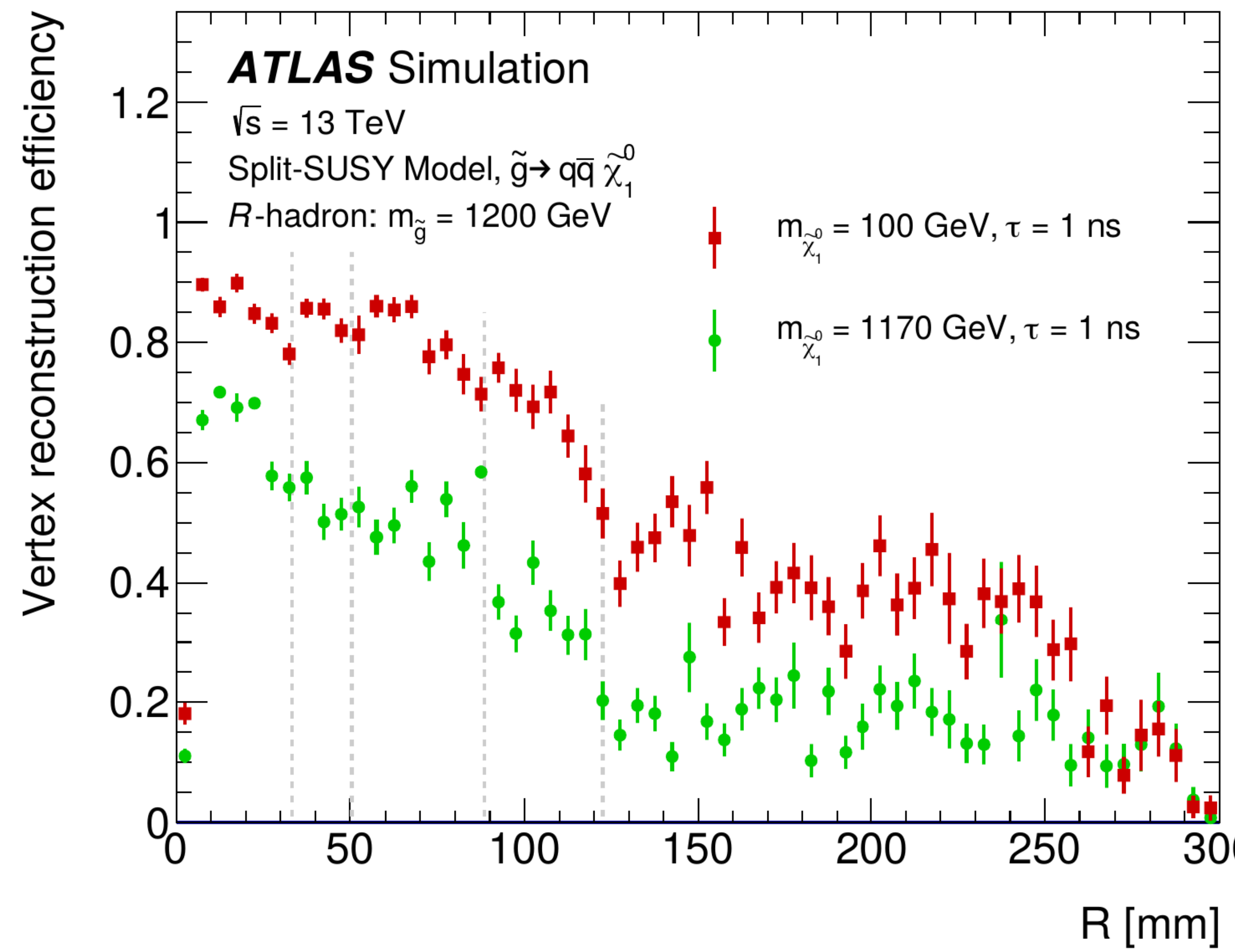
- ATLAS search for a simplified **Split-SUSY model**

$$\tilde{g} \rightarrow \overline{q} q \tilde{\chi}_1^0$$

- Pythia 8 hadronization + 50k MC events per given mF-cτ combination

- prompt multi-jet + MET CMS 13 TeV 35.9 fb-1 analysis weaker

13 TeV ATLAS analysis 32.8 fb^{-1}



ATLAS Coll., Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in √s= 13 TeV pp-collisions with the ATLAS detector, Phys. Rev.D97(2018), no. 5 052012, [arXiv:1710.04901]