LHC searches at the lifetime frontier

motivations, models and gaps

Nishita Desai • 19 March 2021

What does long lifetime signify?

Three ways to get a long-lived particle:

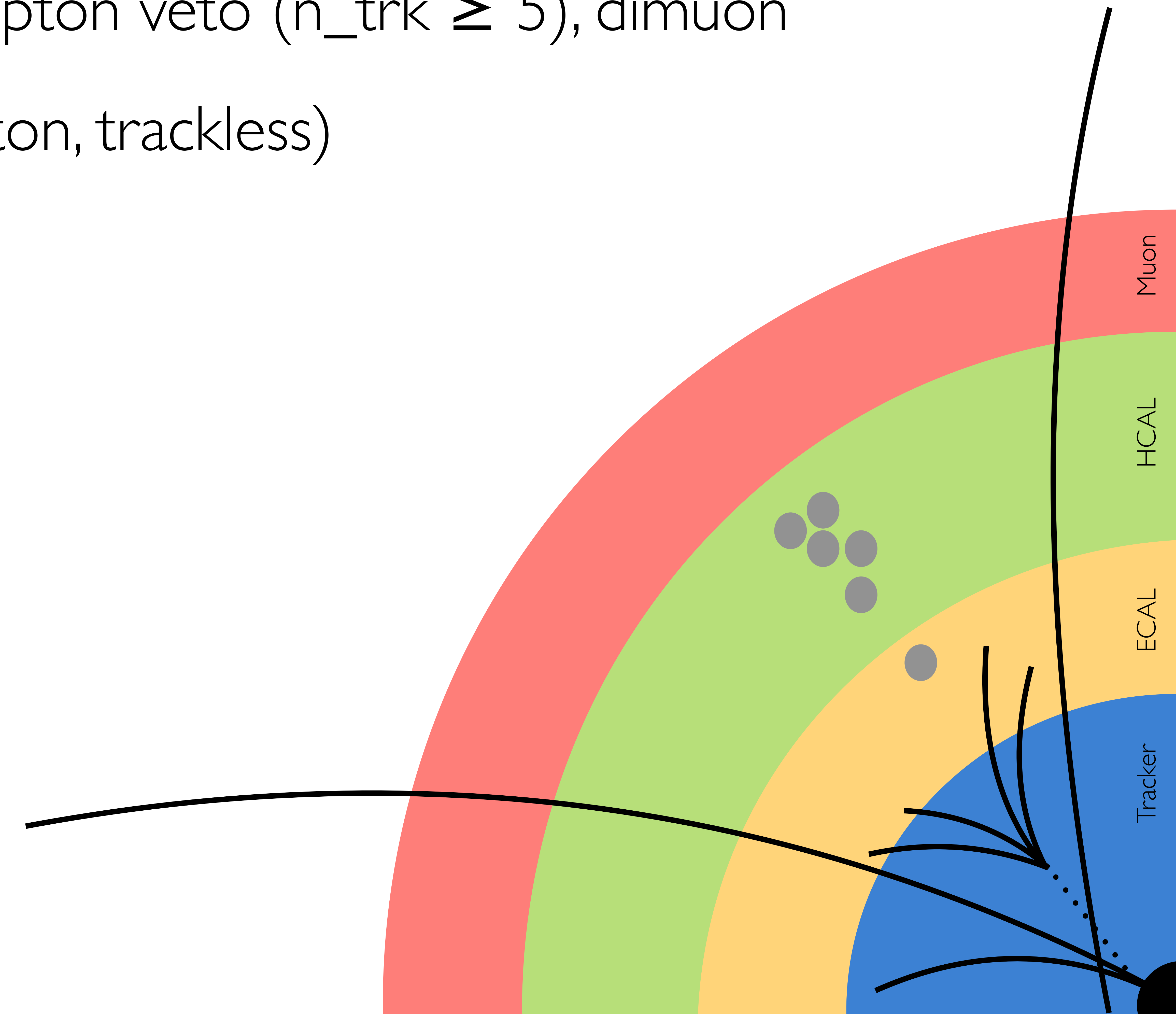
1. Small couplings
2. Heavy intermediate particle (e.g. most meson decays in SM)
3. Compressed spectrum (e.g. new SU(2) Triplet fermion)

Ways to produce a particle at the LHC:

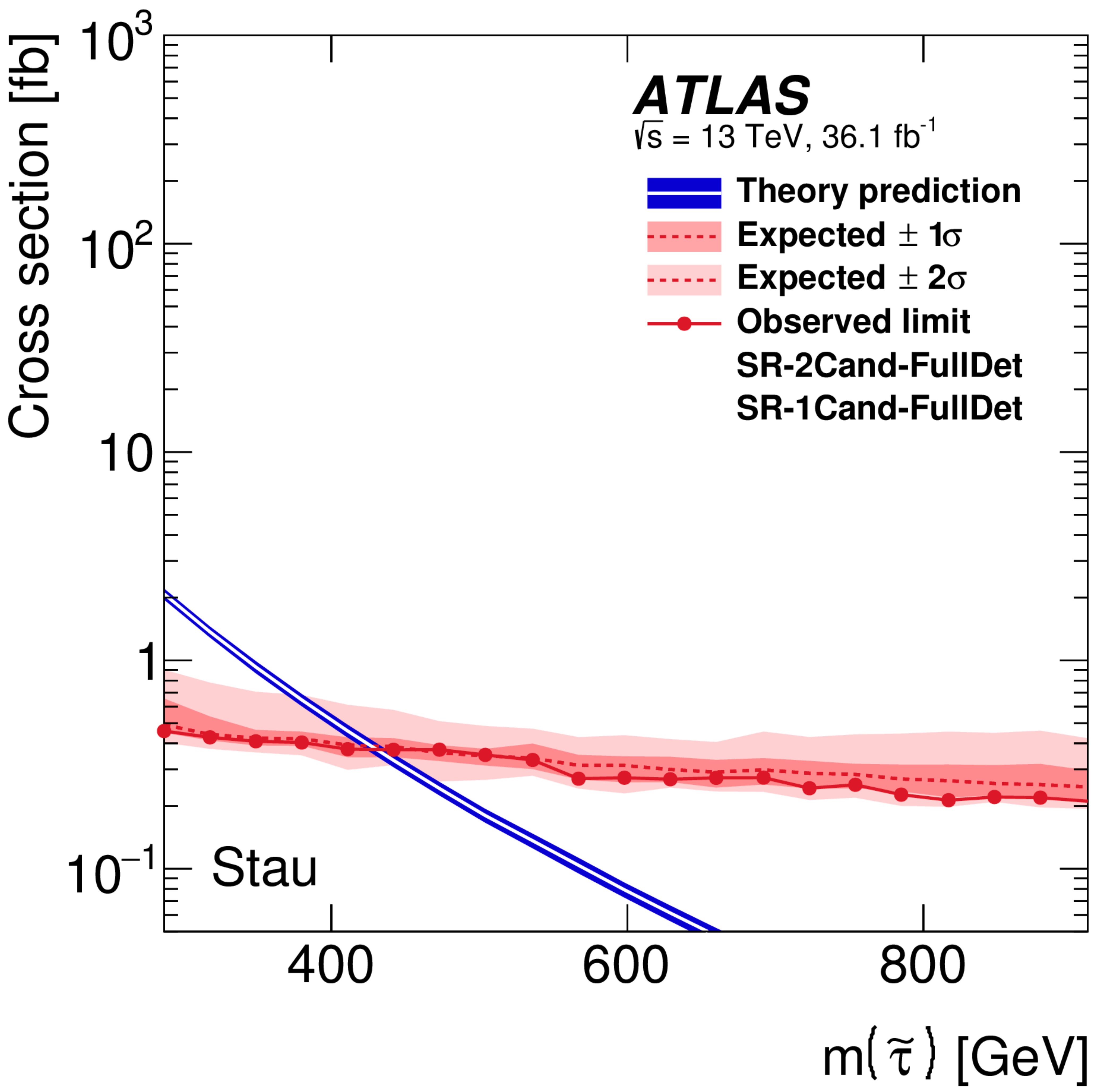
1. Needs to have colour/EW-charge to be produced directly
2. Can be produced in decays of a "mediator" if it does not have SM charges

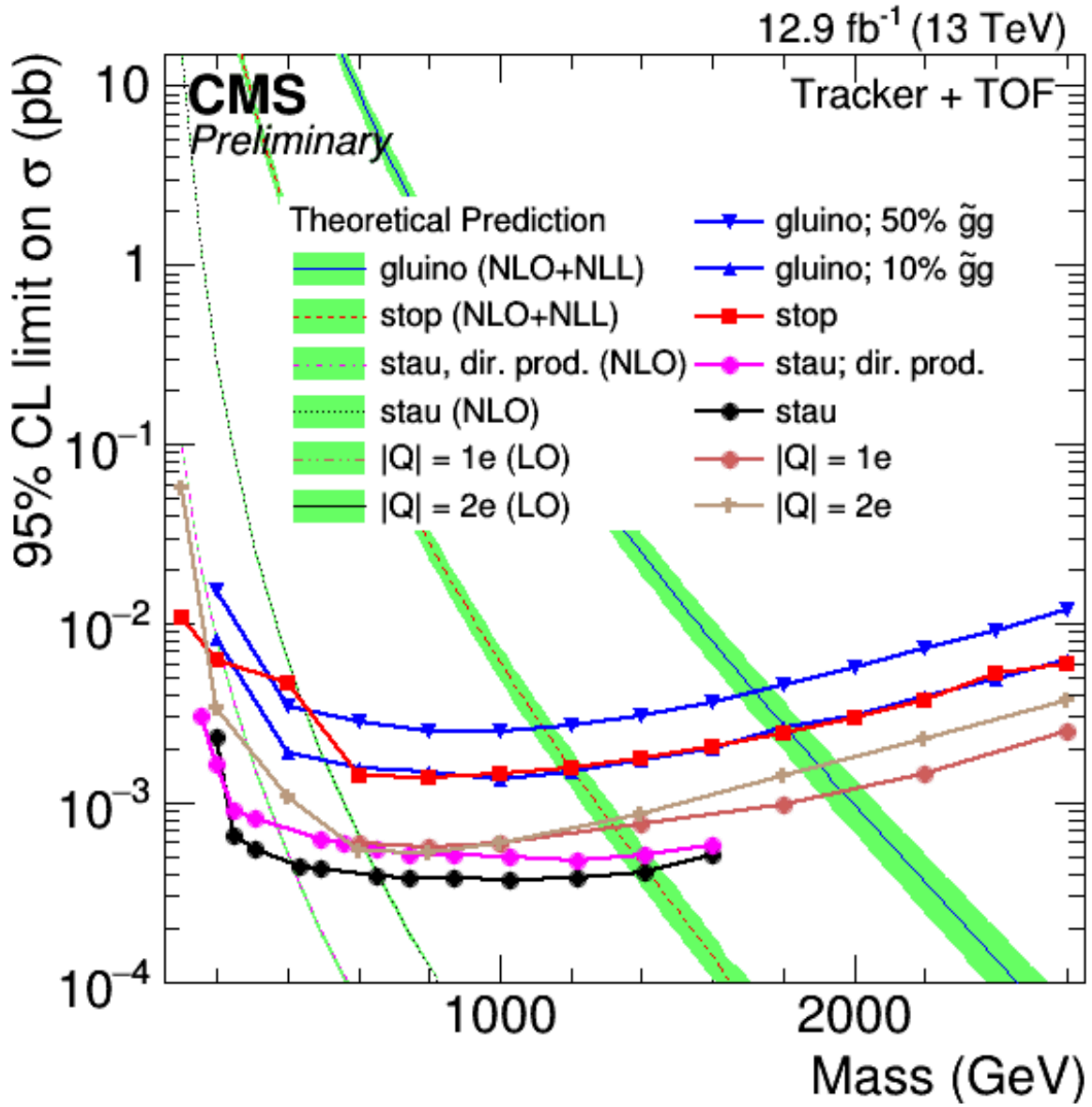
LLP Signature vocabulary

Displaced	Leptons	eμ, μμ
	Vertices	with muons, lepton veto (n_trk ≥ 5), dimuon
	Jets	(emerging, lepton, trackless)
"Prompt"	Heavy charged track	
	Disappearing track	
One-off	SUEP	

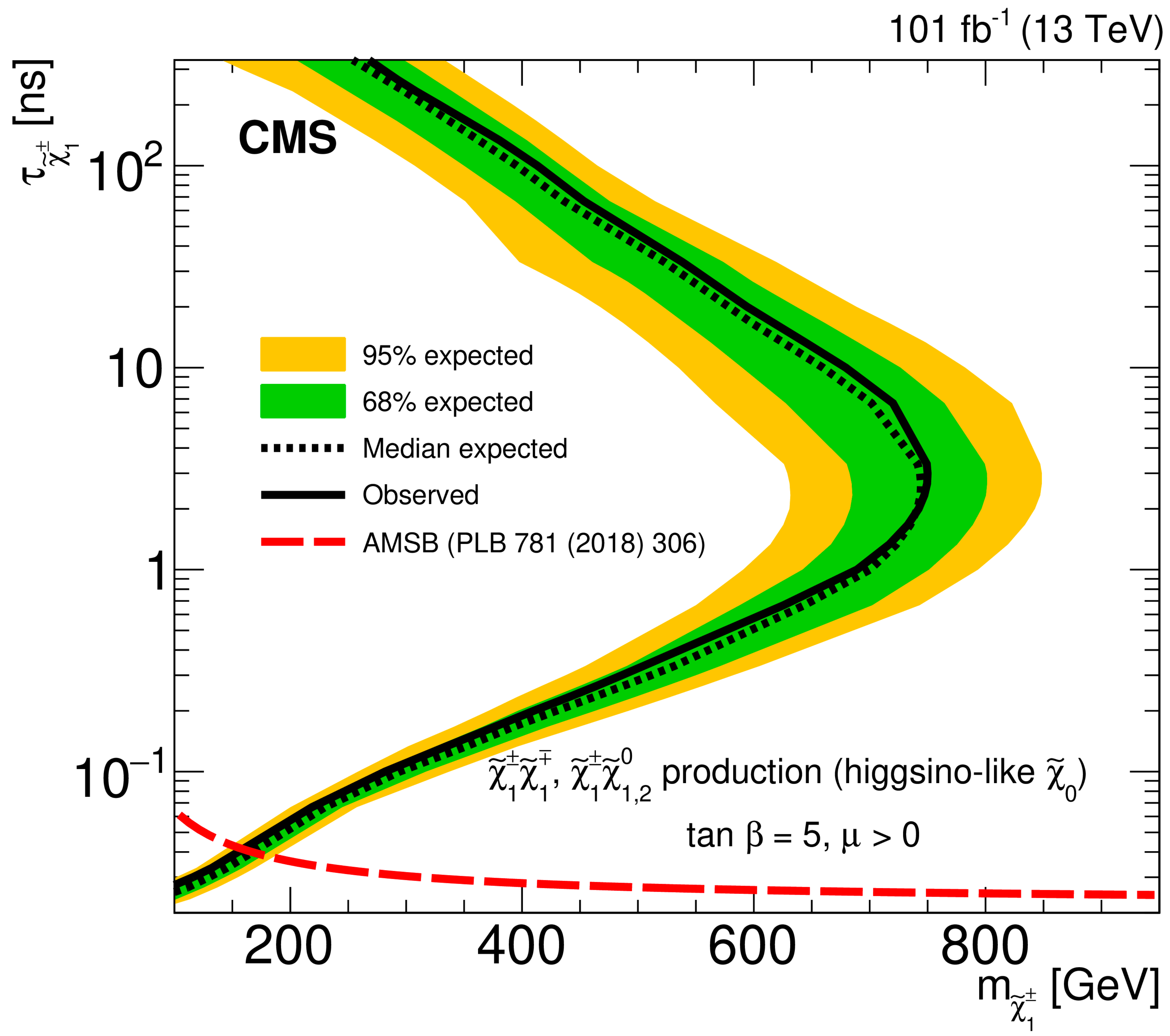


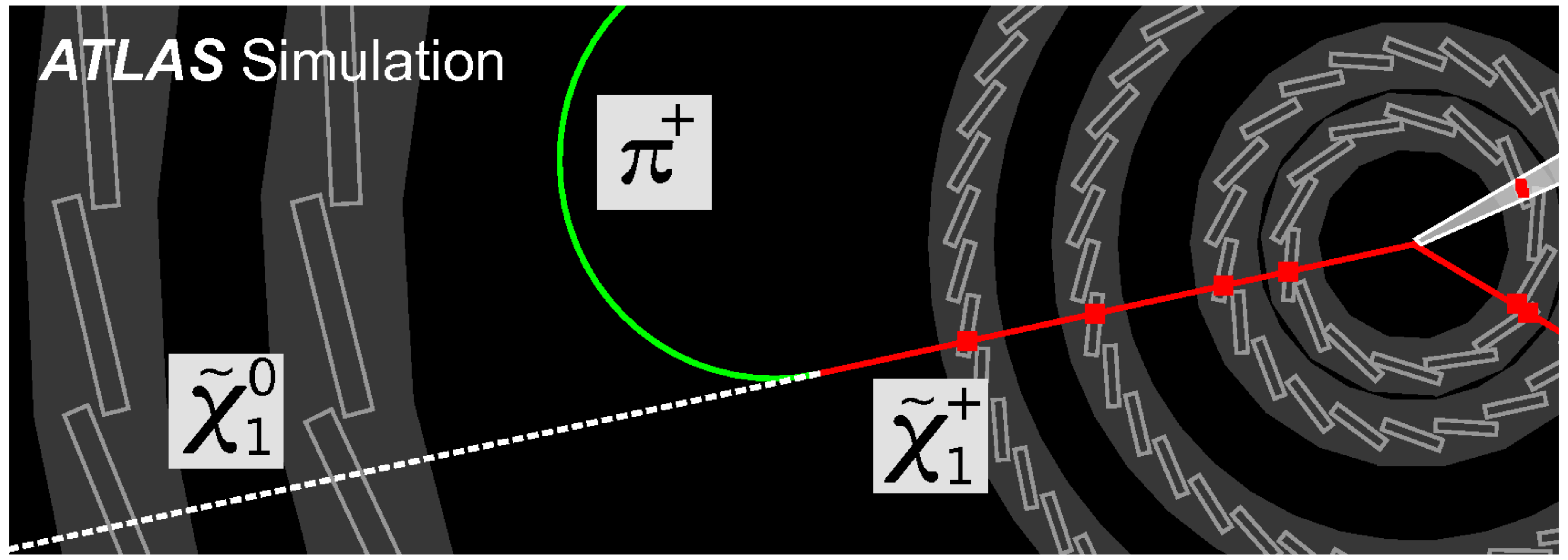
Simplest idea: Heavy charged tracks

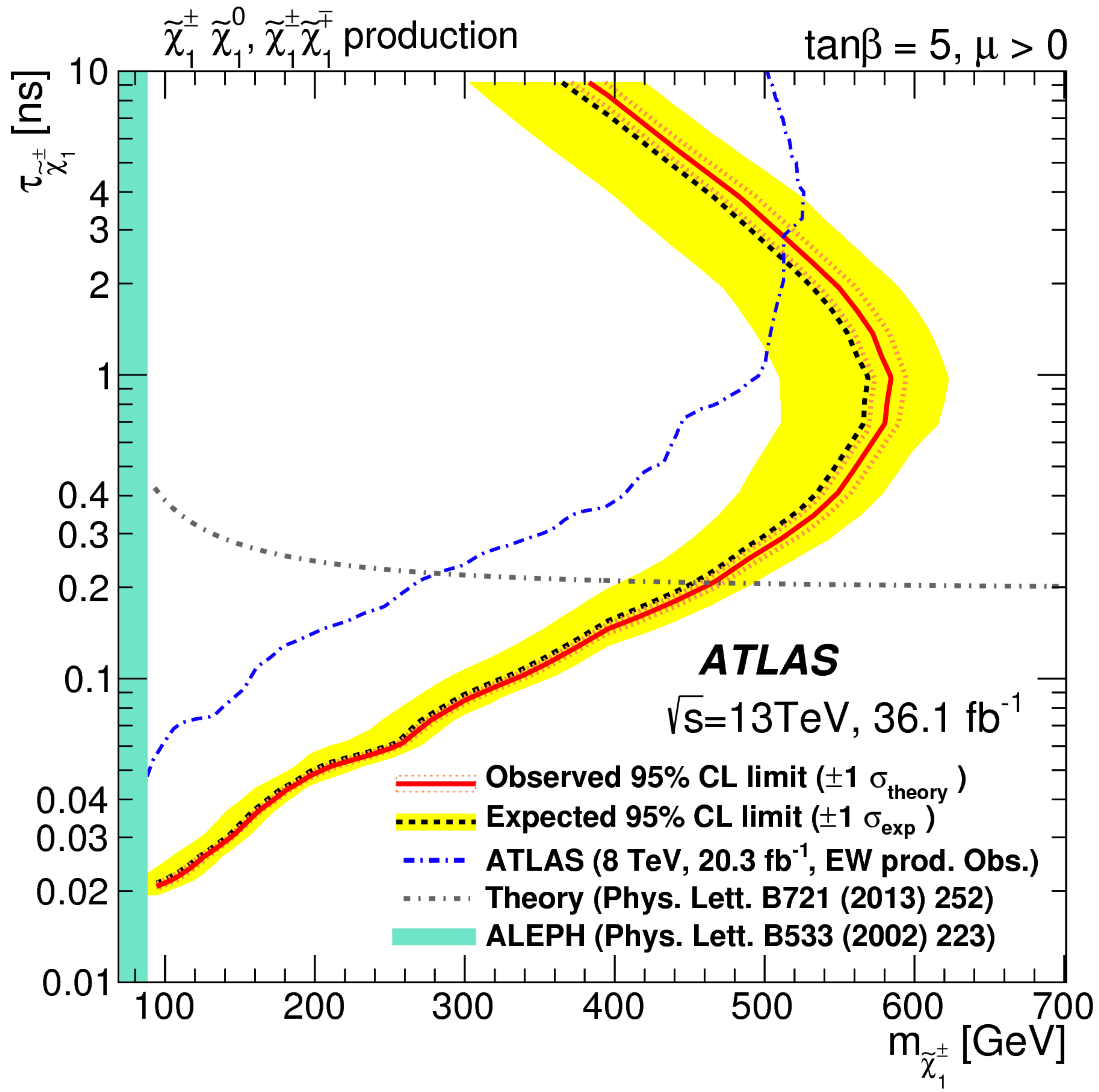




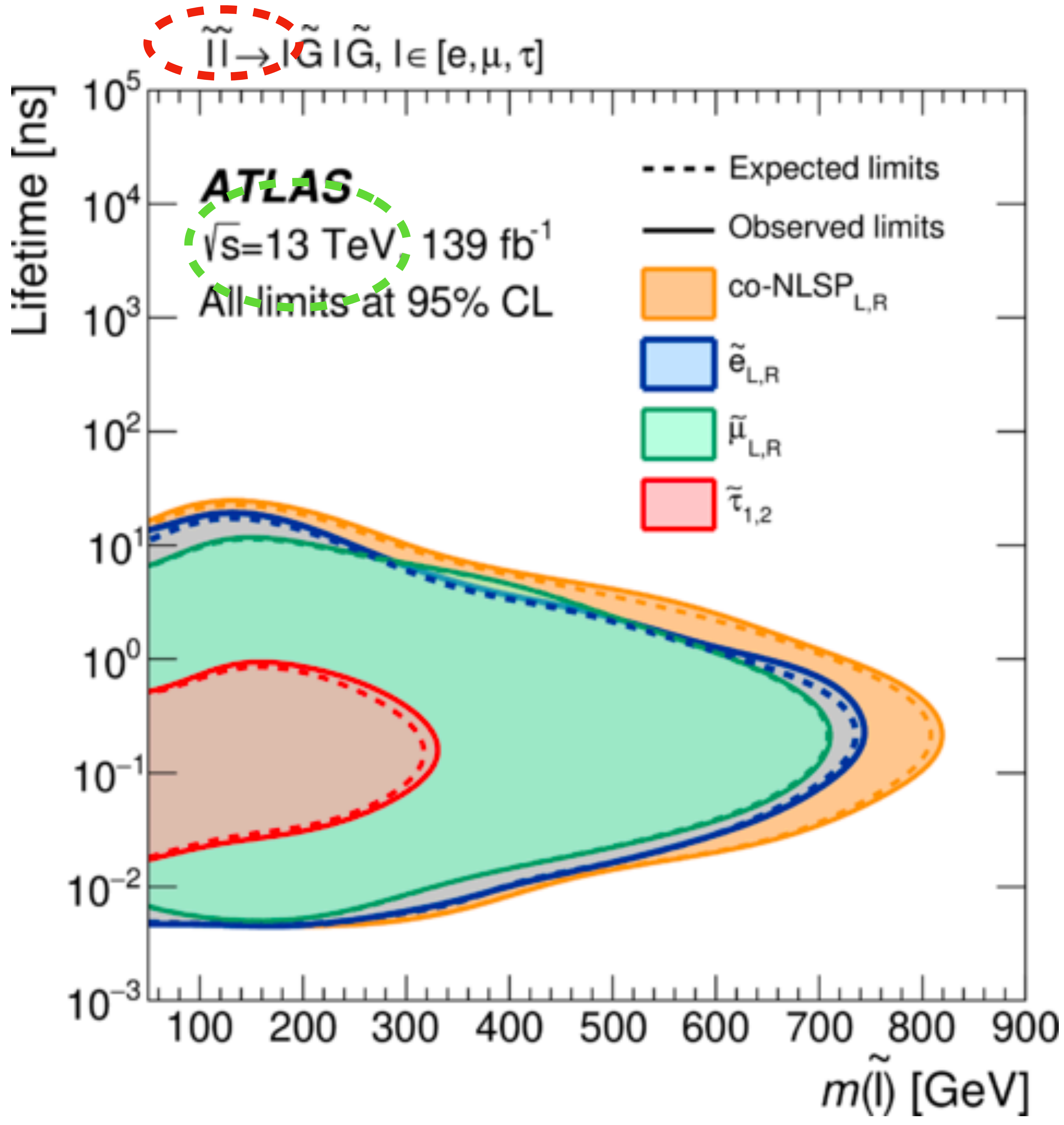
Disappearing track

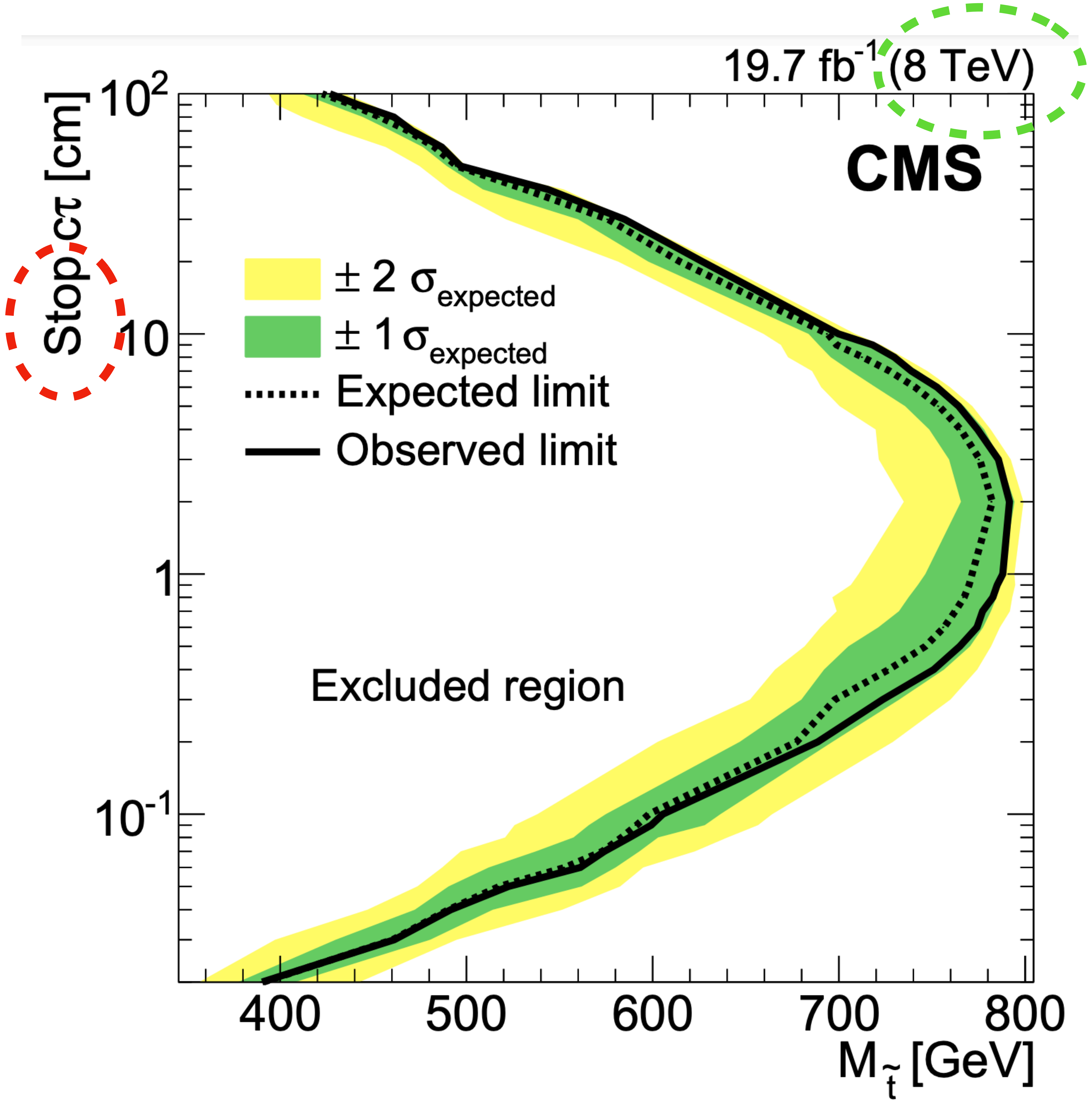




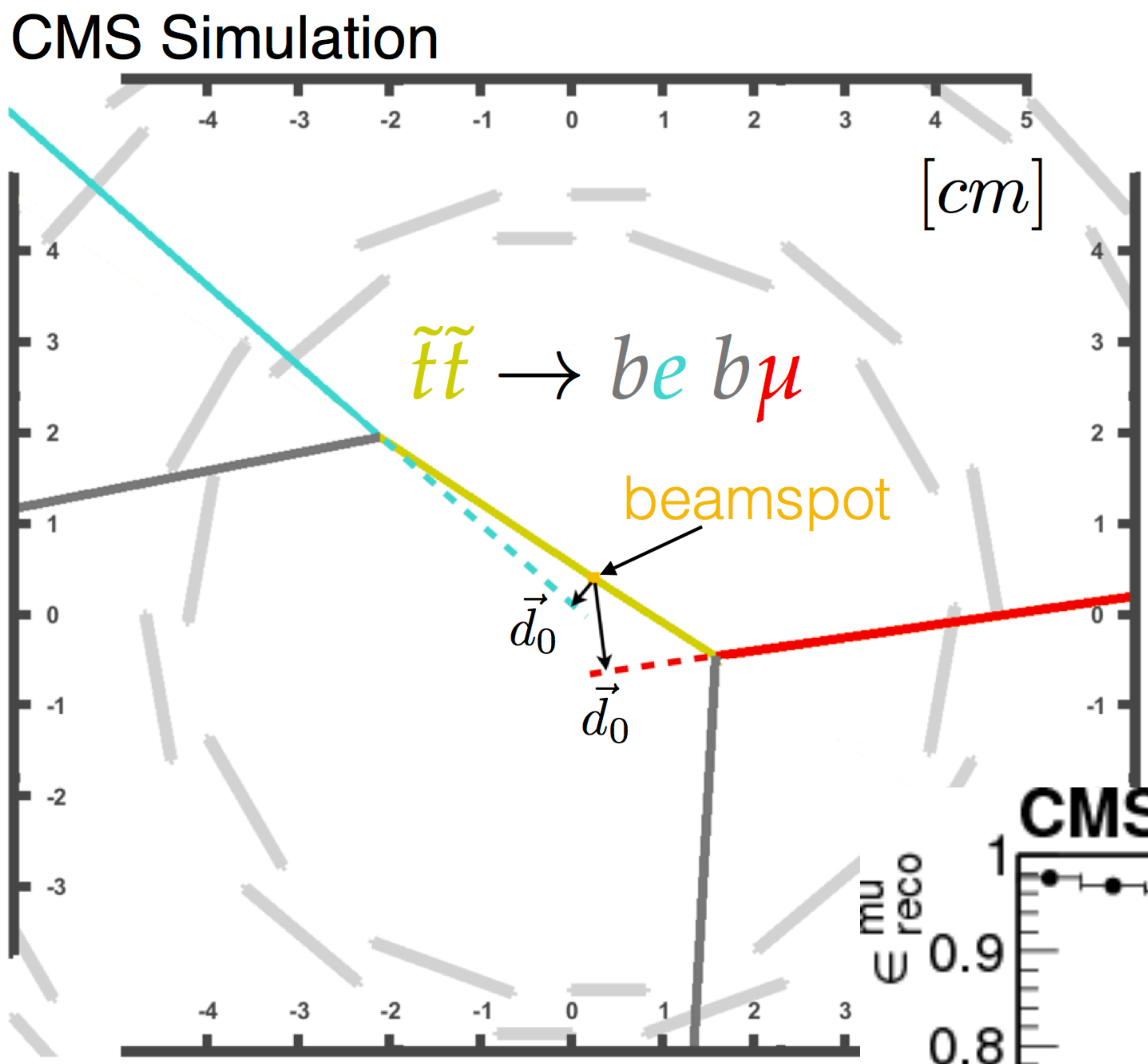


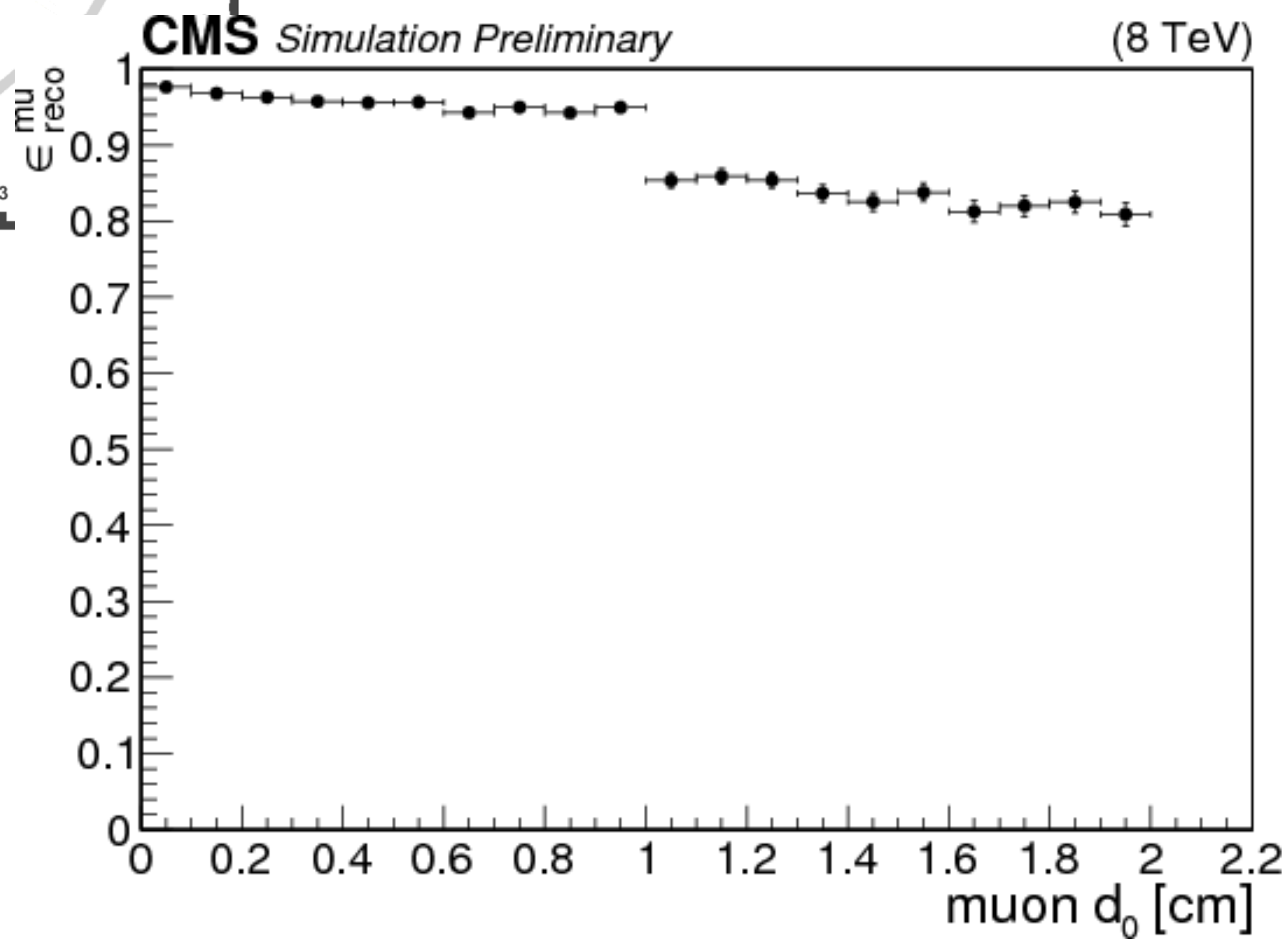
Displaced leptons, production modes matter

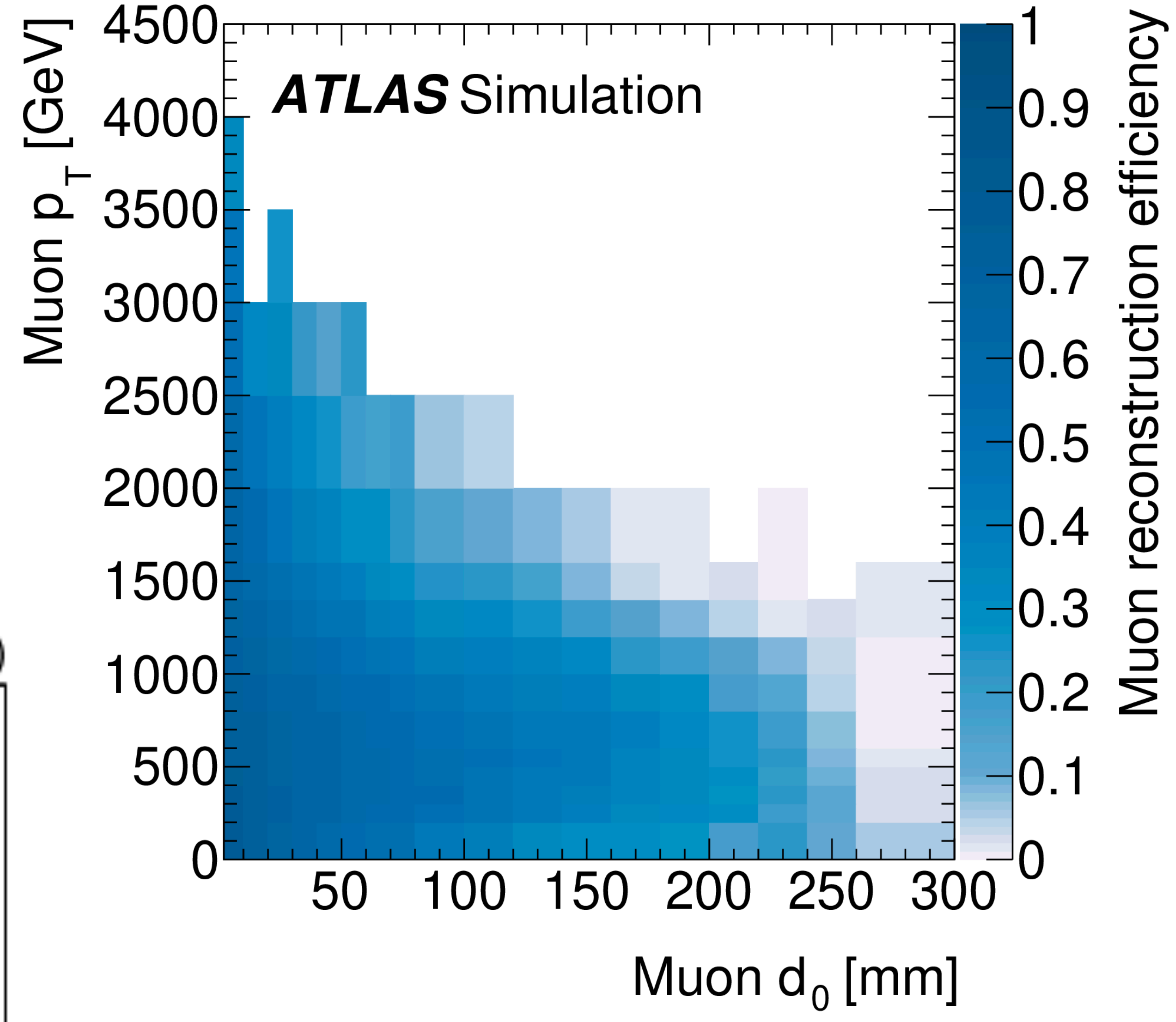




New efficiencies come into play







Motivation for LLPs: Dark Matter

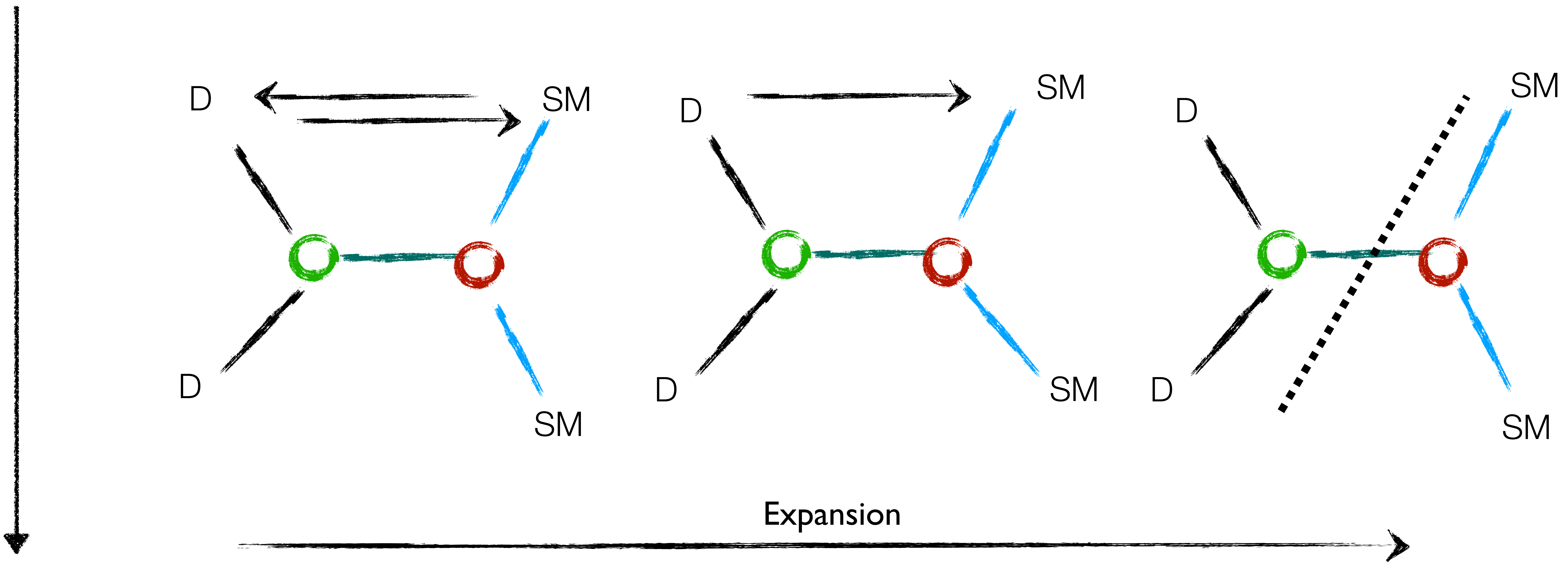
Dark Matter model building relies on obtaining the right observed DM density

Ways to get LLPs:

1. Large couplings but high compression (thermal co-annihilation)
2. Small couplings with heavy mediators + medium compression (thermal co-scattering)
3. Feeble couplings with heavy mediators (non-thermal Freeze-in)

What we know about calculating DM density is changing

1970s



2020s

Particle naming : SUSY/non-SUSY

Warning: Particles with same quantum numbers as those predicted by SUSY are named with SUSY conventions even when not talking about SUSY.

squarks or sleptons = spin-0 with same SM charges as quarks or charged leptons; but NOT necessarily with Yukawa coupling determined by gauge couplings like SUSY

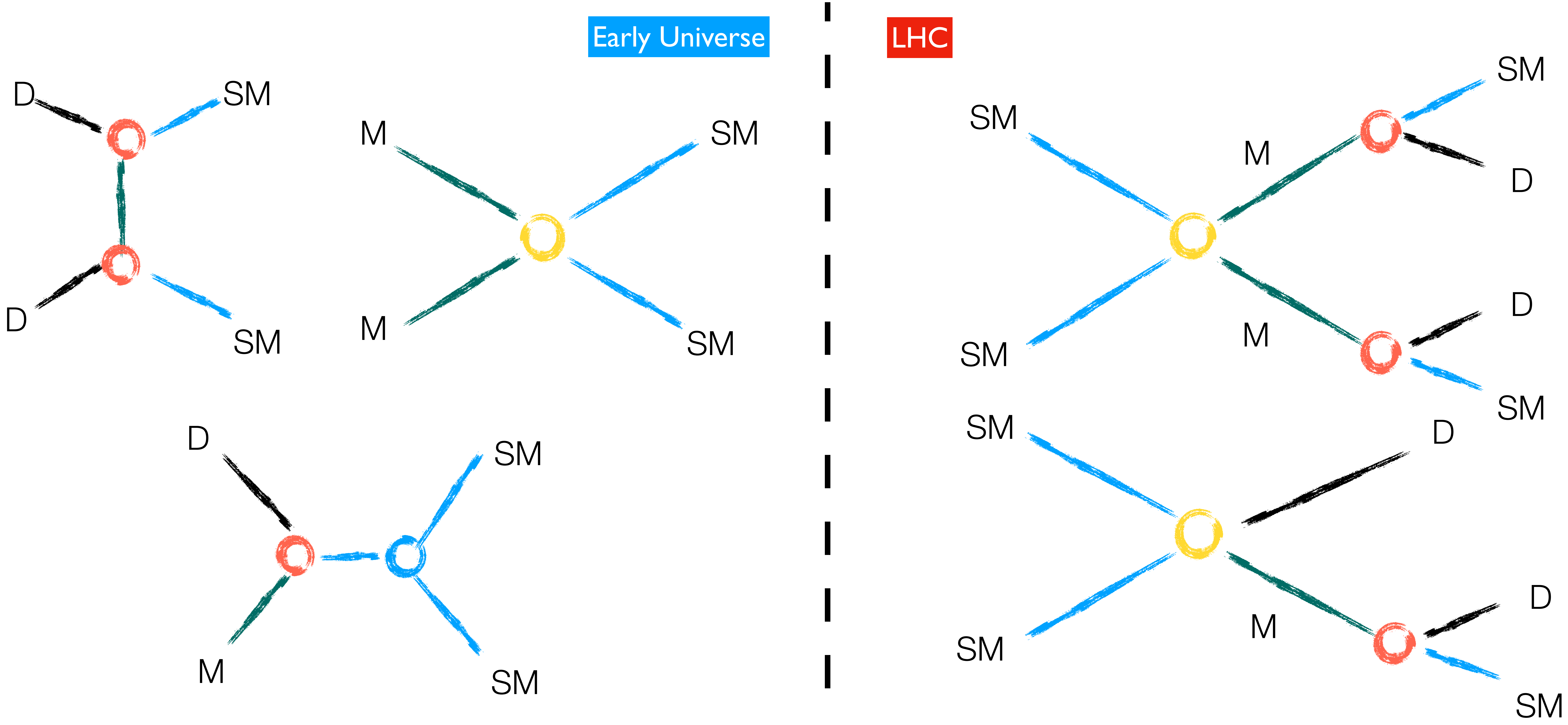
E.g. stau, sbottom

Wino = vector-like fermion, triplet under SU(2)

Bino or singlino = Majorana fermion, scalar under SM

Motivation for LLPs: Dark Matter

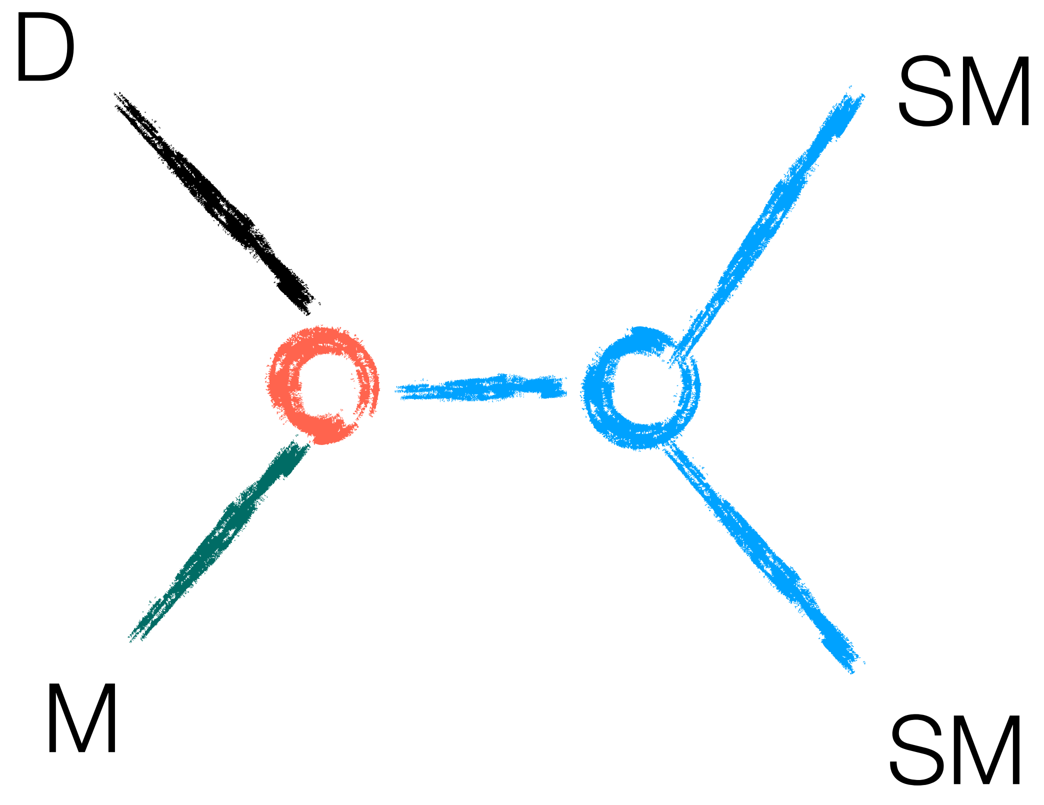
Co-annihilation + extreme compression : slepton/squark co-annihilation, pure-Wino

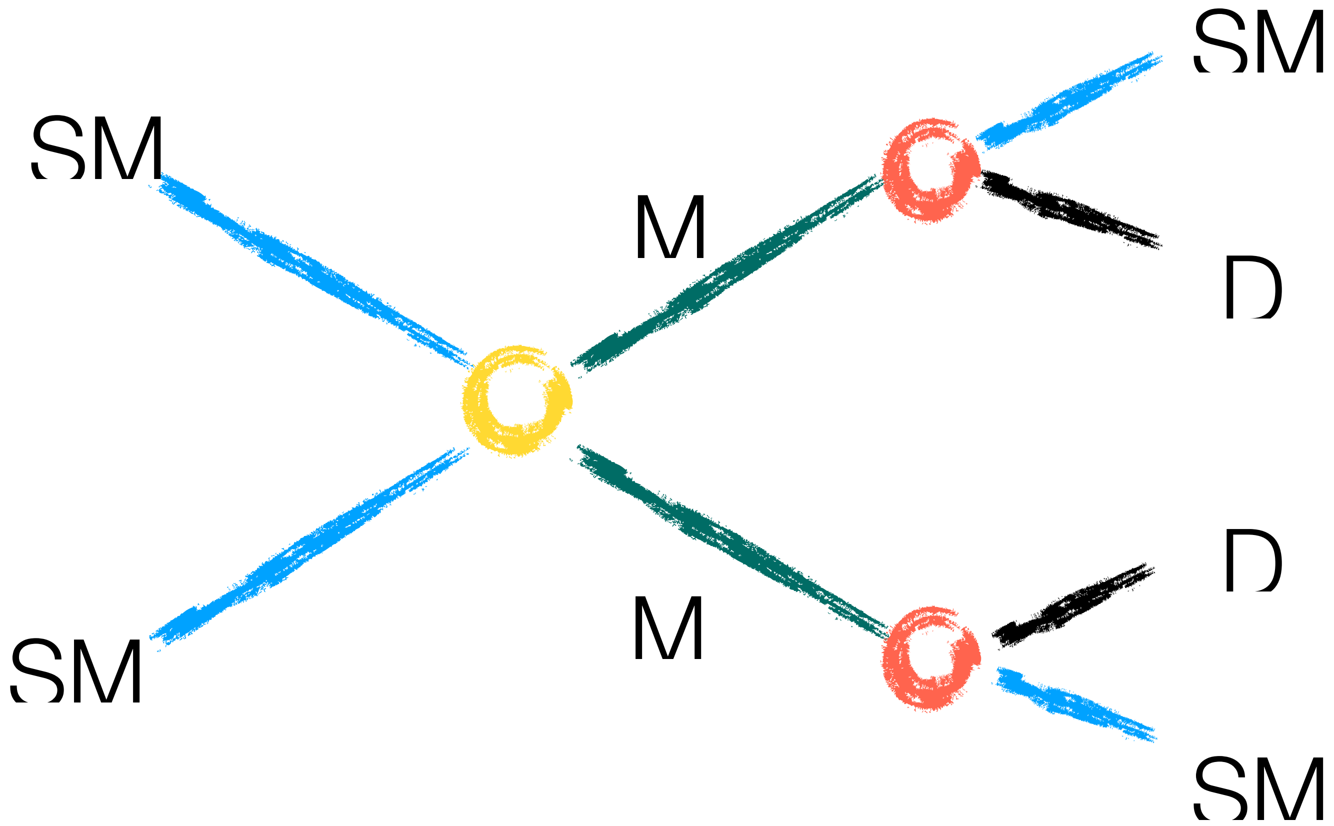


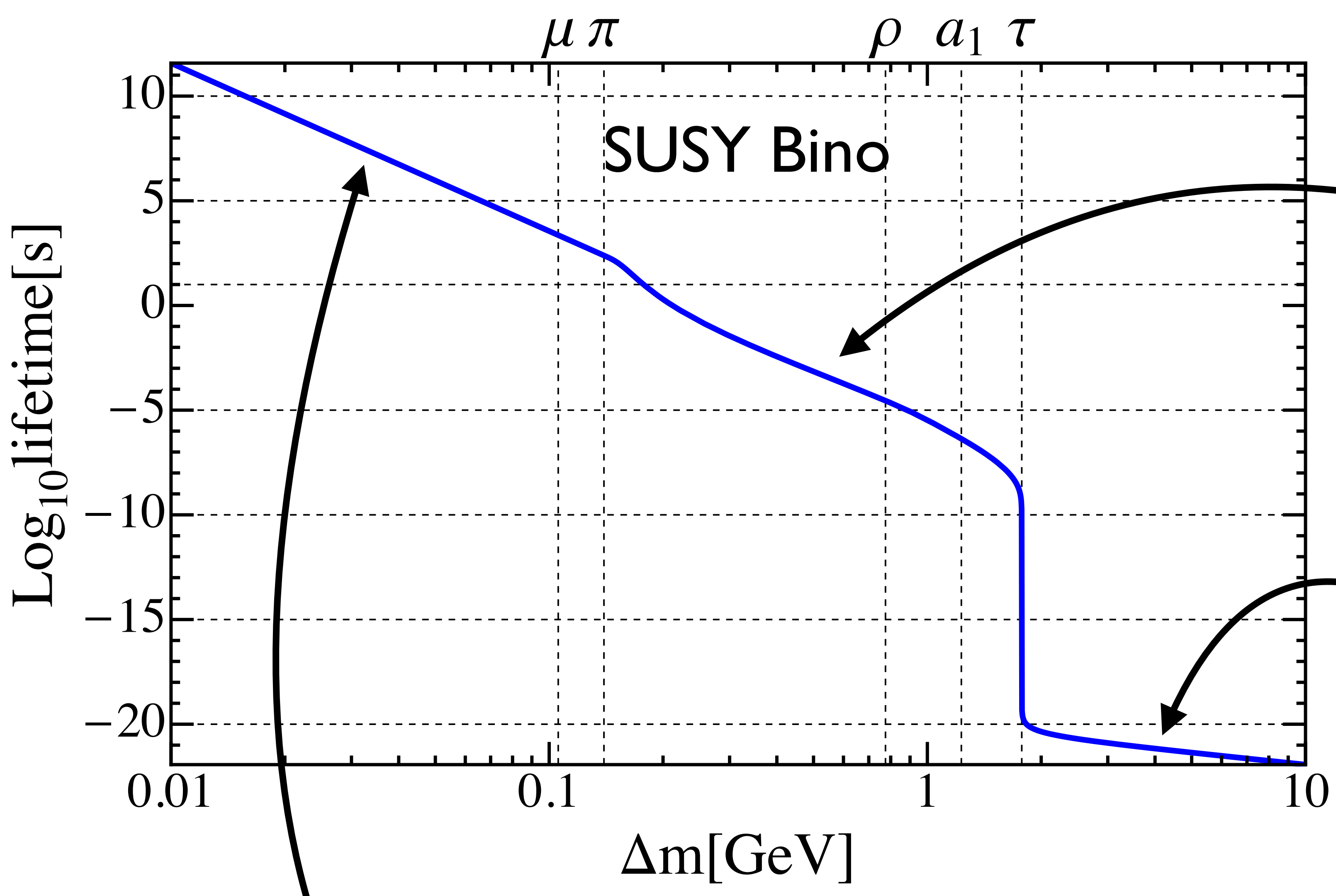
Motivation for LLPs: Dark Matter

Co-annihilation + extreme compression : stau co-annihilation

$$\mathcal{L} \supset \tilde{\tau}^*(\chi\tau_R) + h.c.$$







$$\tilde{\tau}_1^- \to a_1^- \nu_\tau \chi$$
$$\tilde{\tau}_1^- \to \rho^- \nu_\tau \chi$$
$$\tilde{\tau}_1^- \to \pi^- \nu_\tau \chi$$

Disappearing track

$$\tilde{\tau}_1^- \to \tau^- \chi.$$

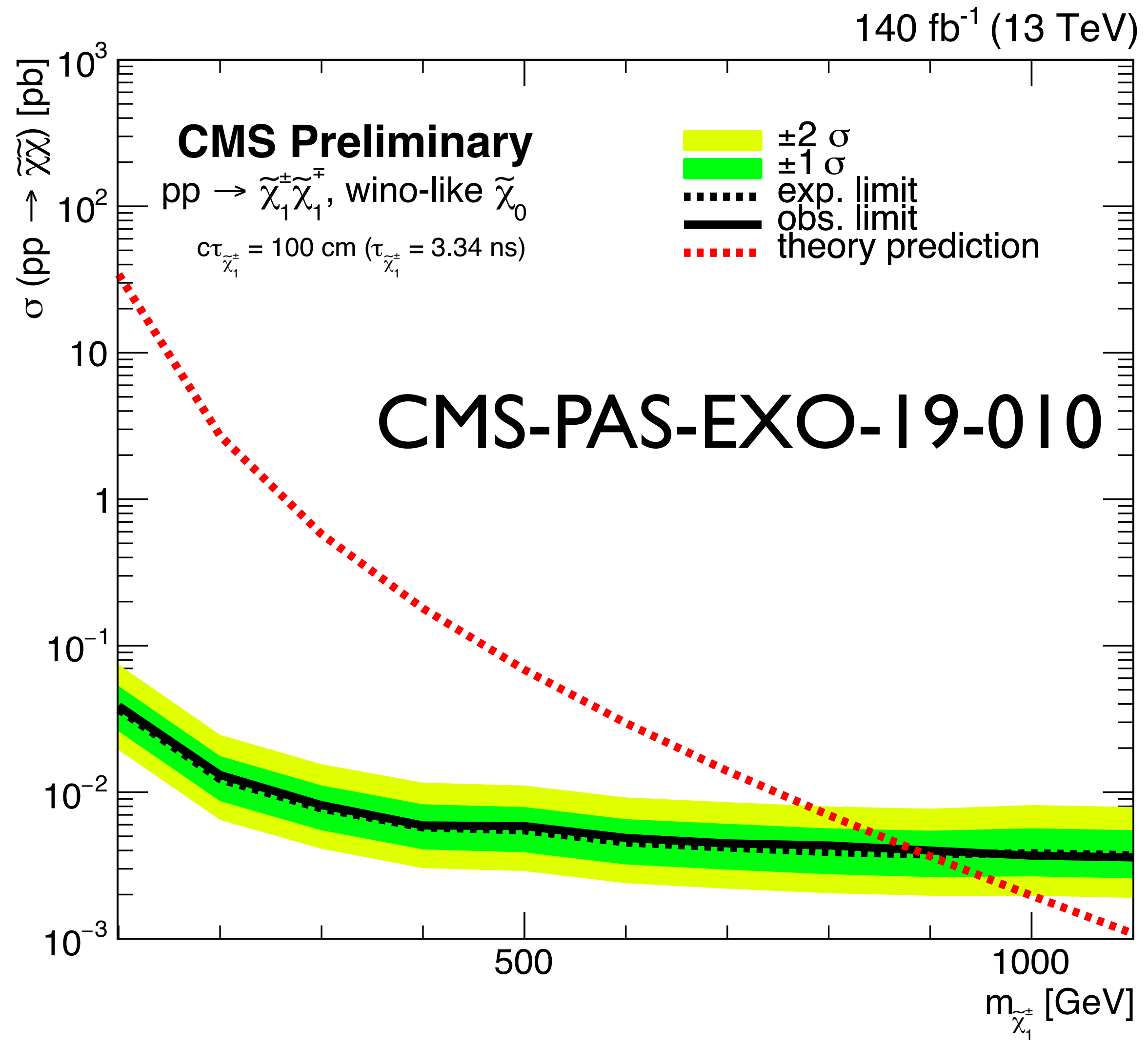
$$\tilde{\tau}_1^- \to e^- \bar{\nu}_e \nu_\tau \chi$$
$$\tilde{\tau}_1^- \to \mu^- \bar{\nu}_\mu \nu_\tau \chi.$$

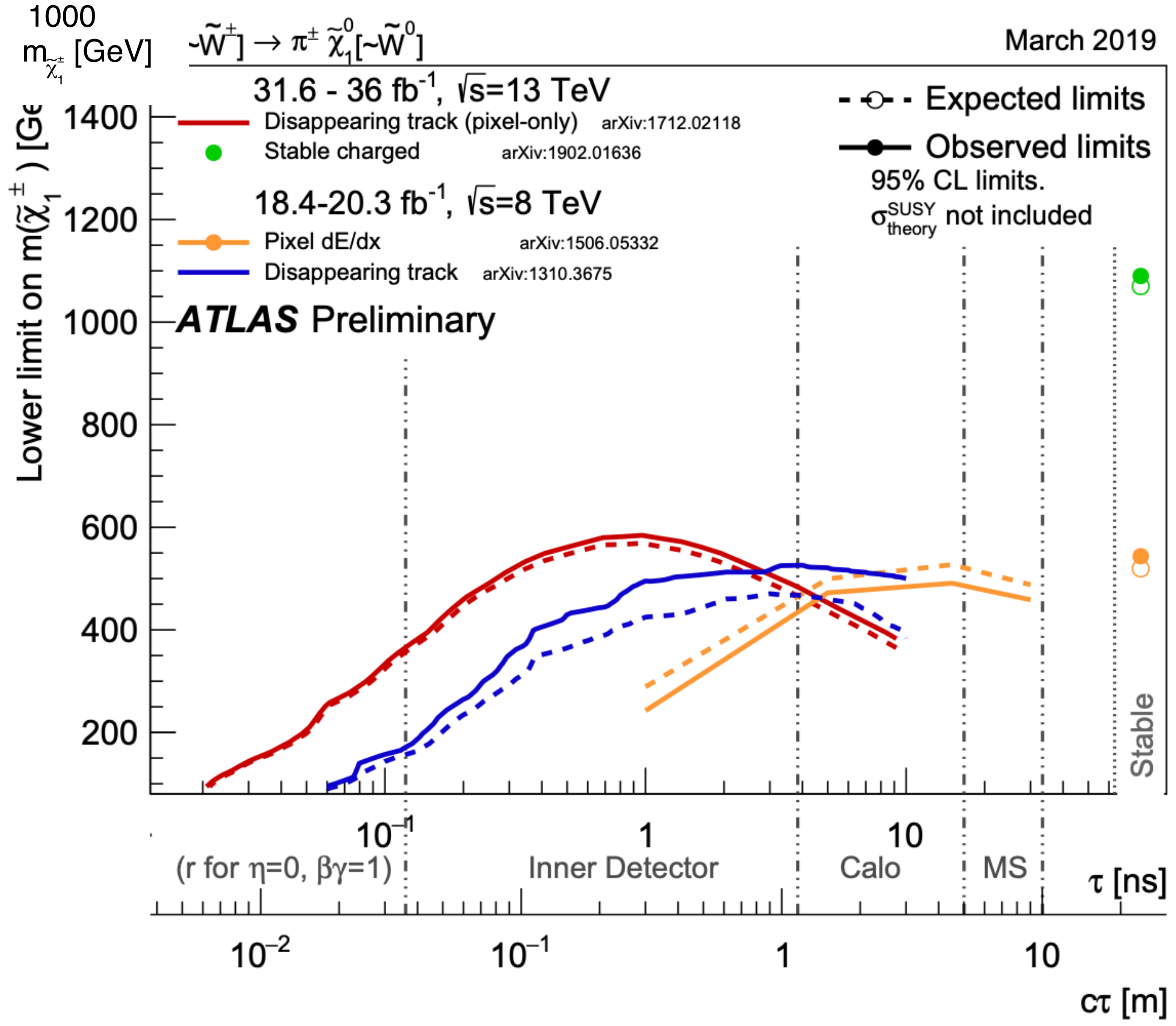
Heavy charged track

(non-SUSY) Khose et al. 1702.00750
(SUSY) Desai et al. 1404.5061

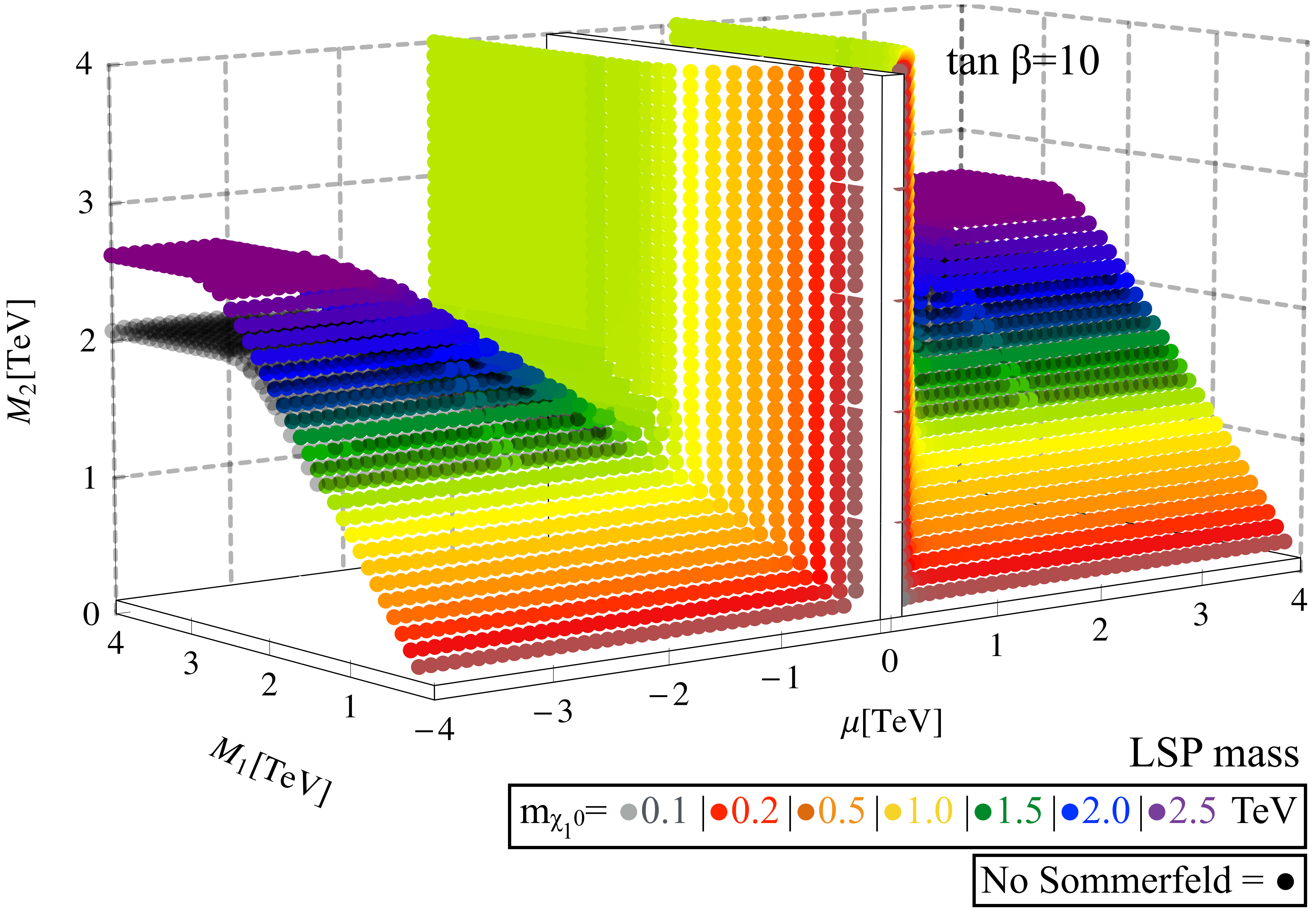
Motivation for LLPs: Dark Matter

Co-annihilation + extreme compression : pure Wino





Pure Wino from DM: 2.7 TeV



Bramante, ND, et al 1510.03460

Cirelli et al 1407.7058

Low and Wang 1404.0682

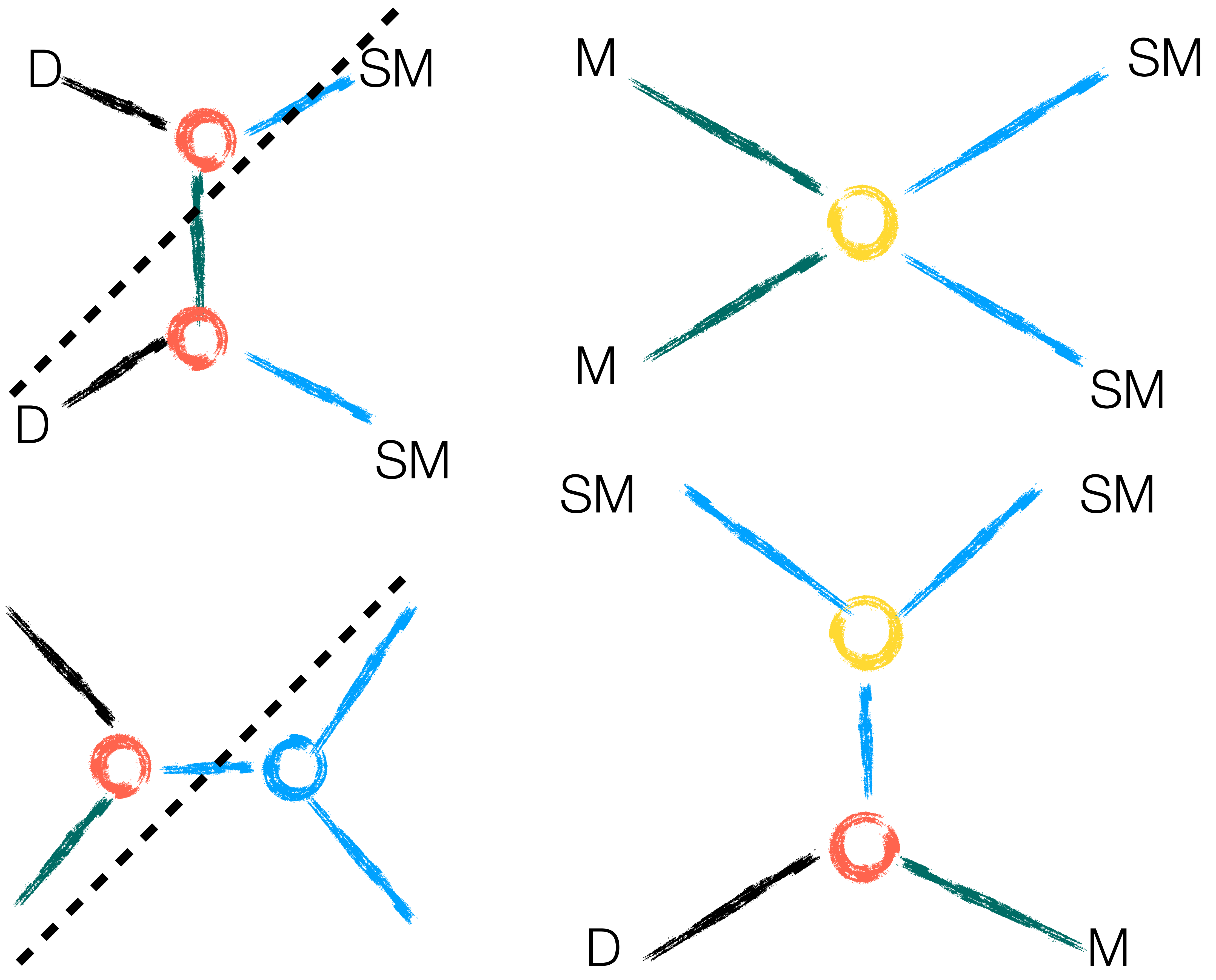
Motivation for LLPs: Dark Matter

Co-scattering = small coupling + some compression:

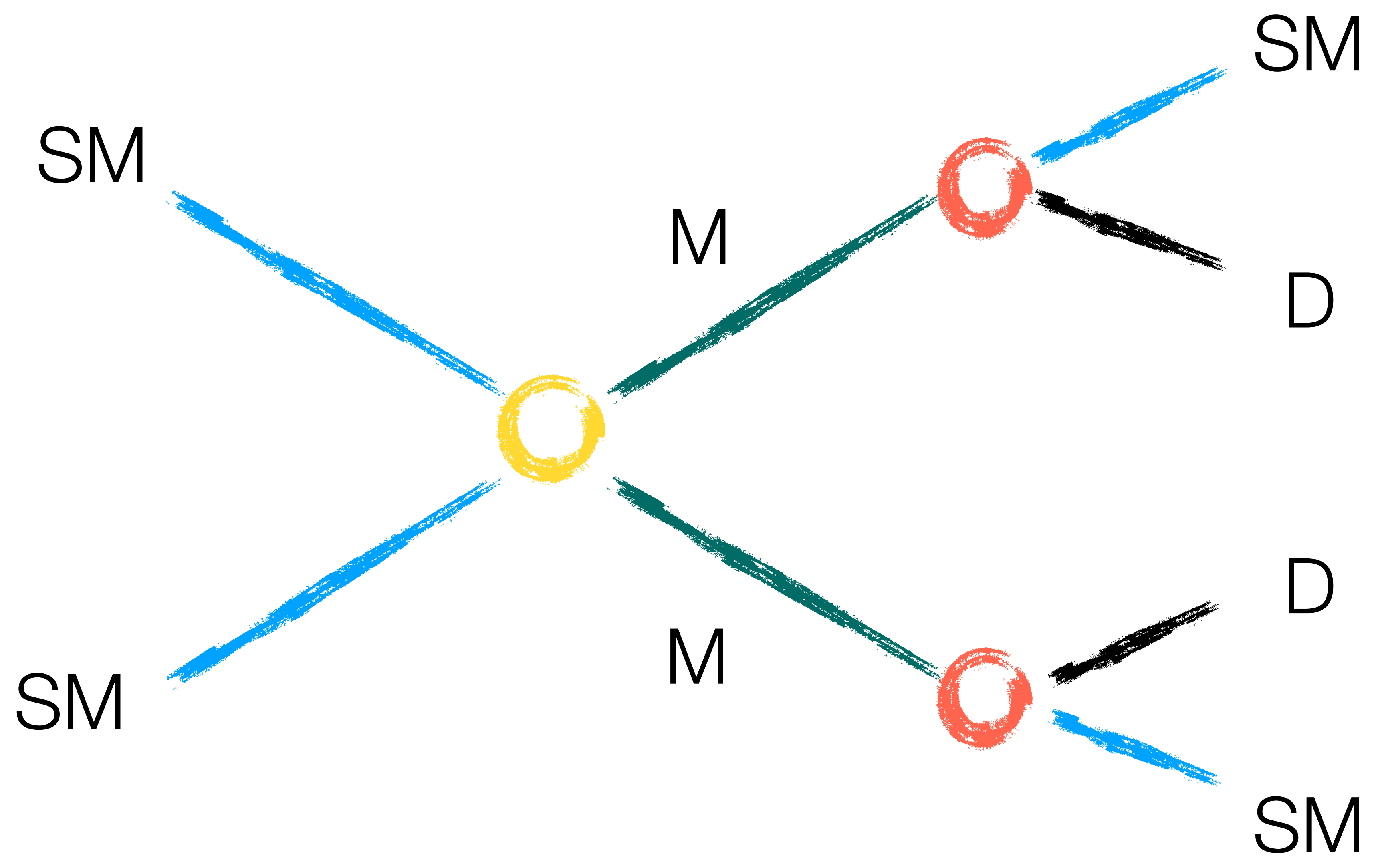
D'Agnolo et al. 1705.08450

Garny et al. 1705.09292

Early Universe

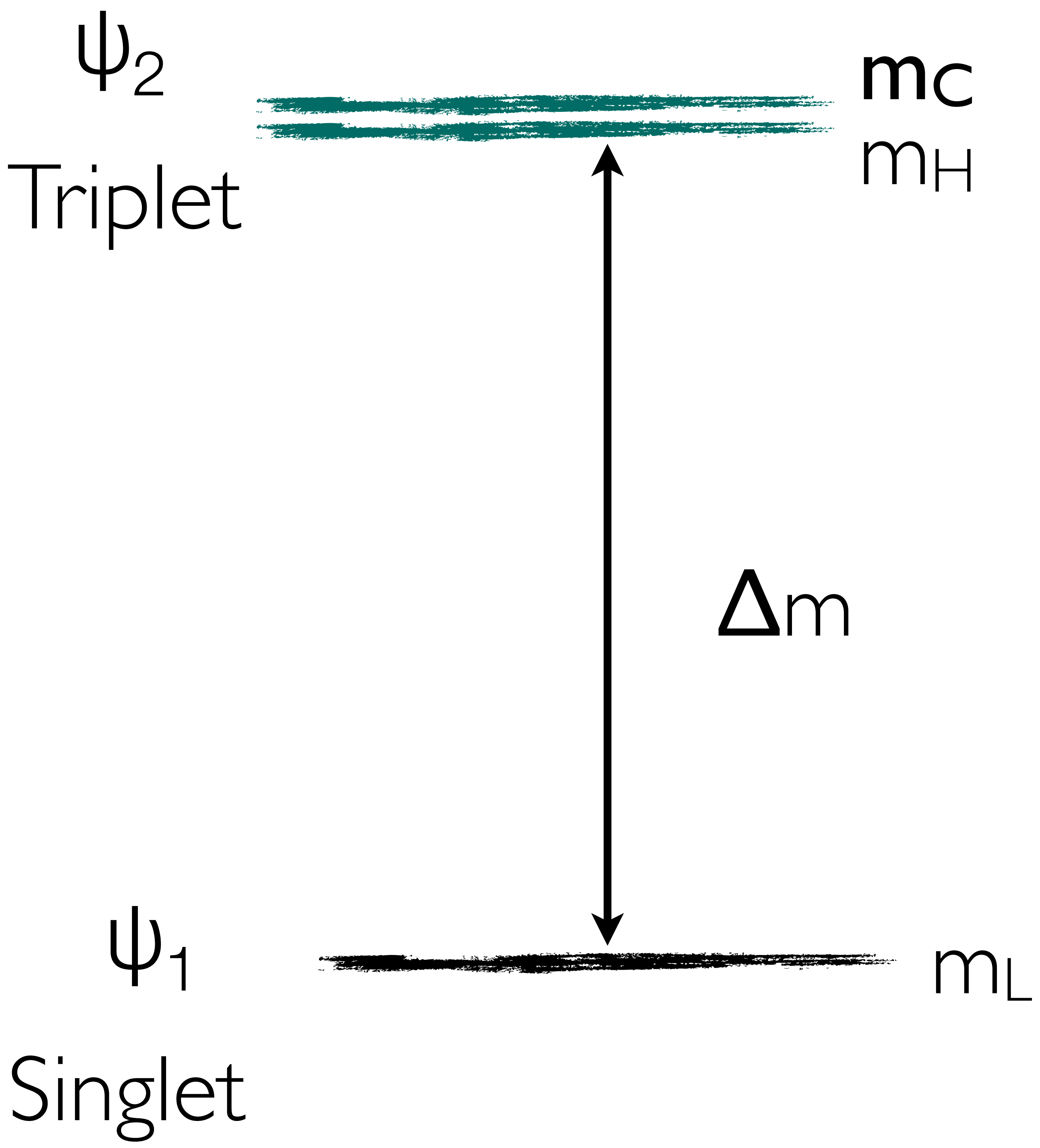


LHC



Motivation for LLPs: Dark Matter

Co-scattering = small coupling + some compression: singlet-triplet (Bino-Wino) model



$\psi_C \rightarrow \psi_L + W^*$ Long-lived because θ is small

$\psi_C \rightarrow \psi_H + \pi^+$ Long-lived because compressed

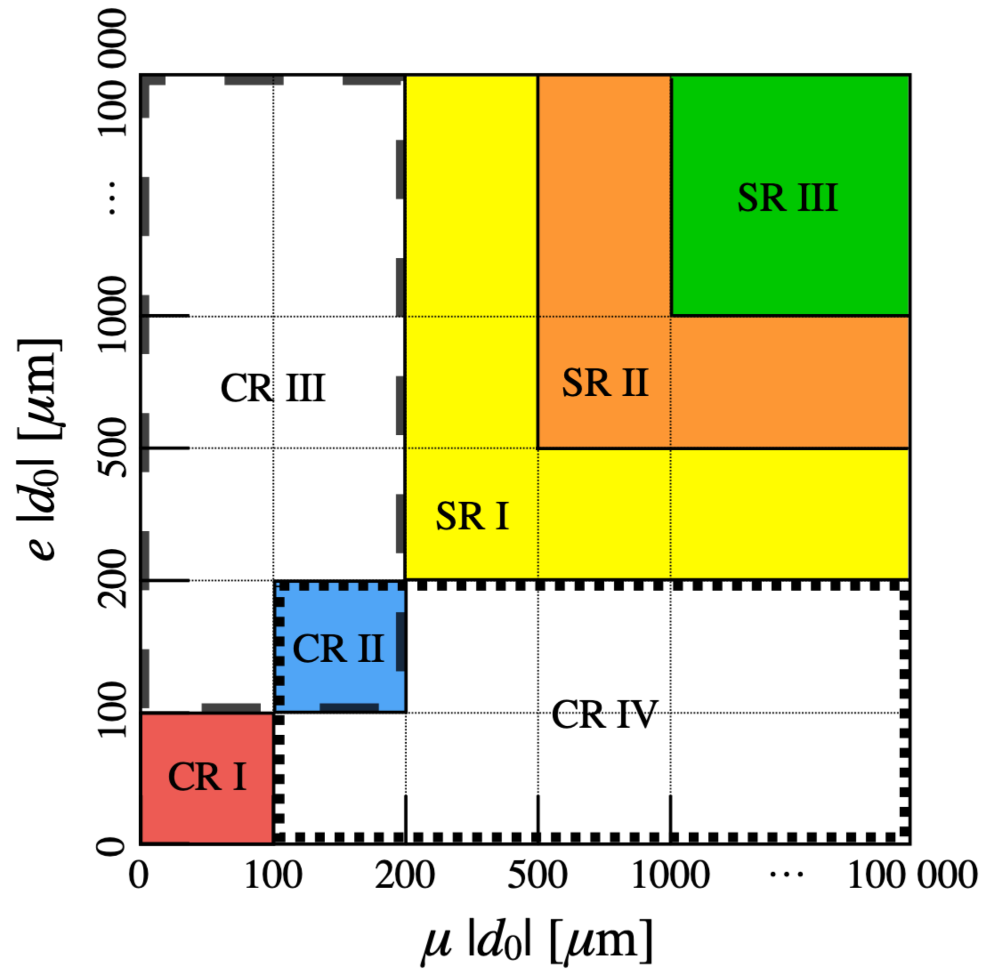
$$\psi_L = \cos\theta\ \psi_1 + \sin\theta\ \psi_2$$
$$\psi_H = -\sin\theta\ \psi_1 + \cos\theta\ \psi_2$$

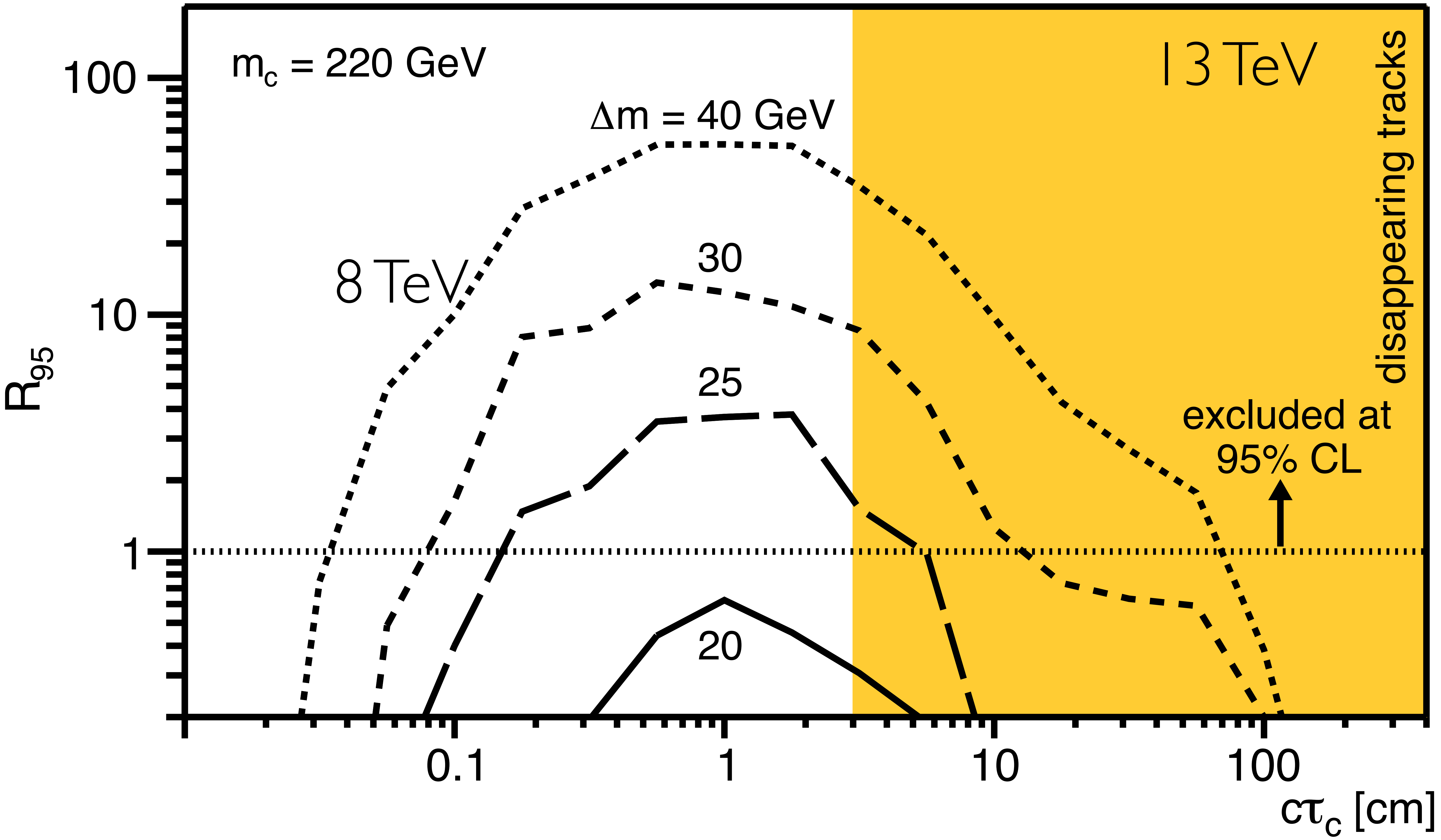
Bharucha et al. 1703.00370

Filimonova, Westhoff 1812.04628

Gaps in coverage: example of displaced leptons

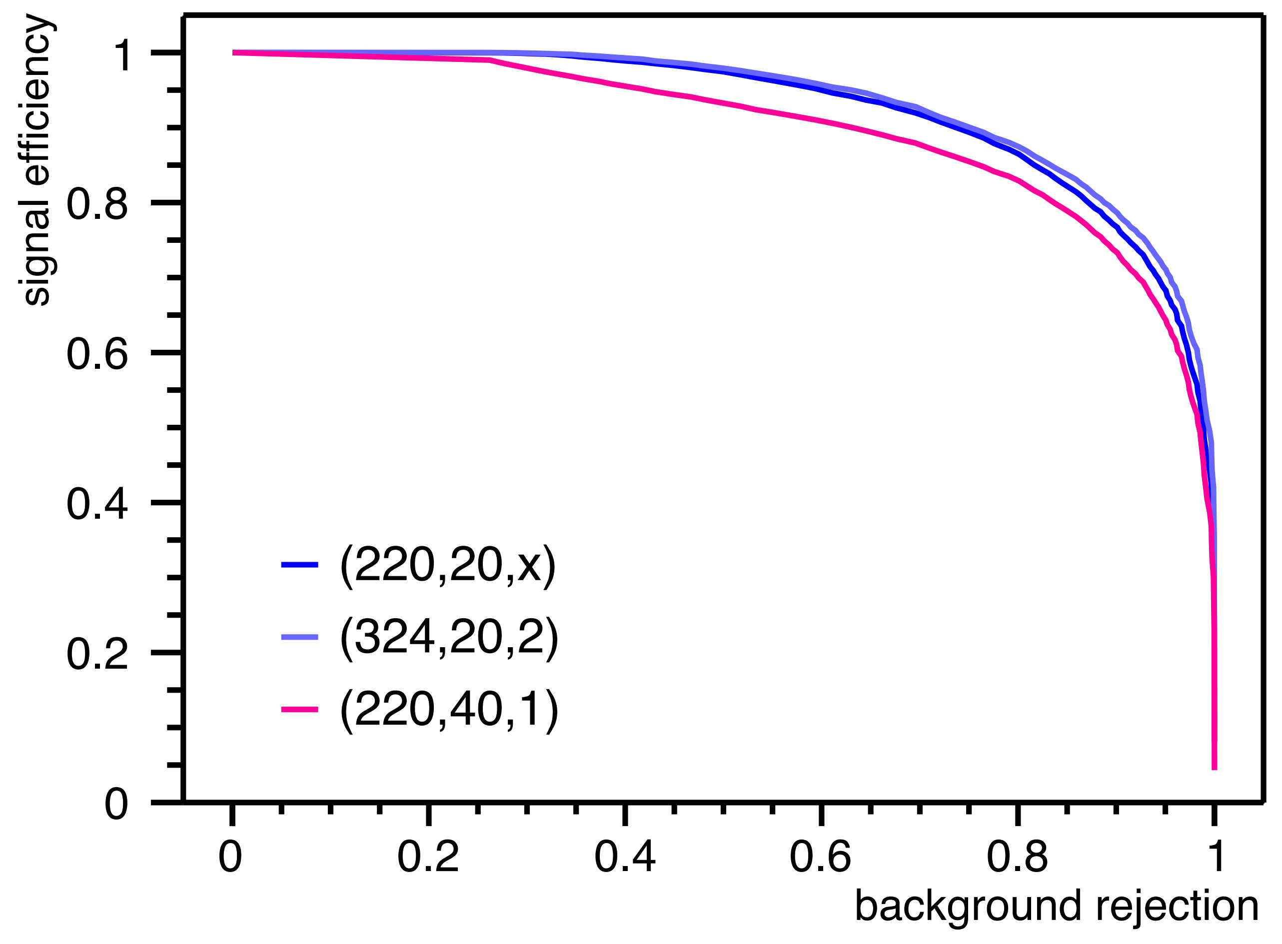
CMS-PAS-EXO-16-022

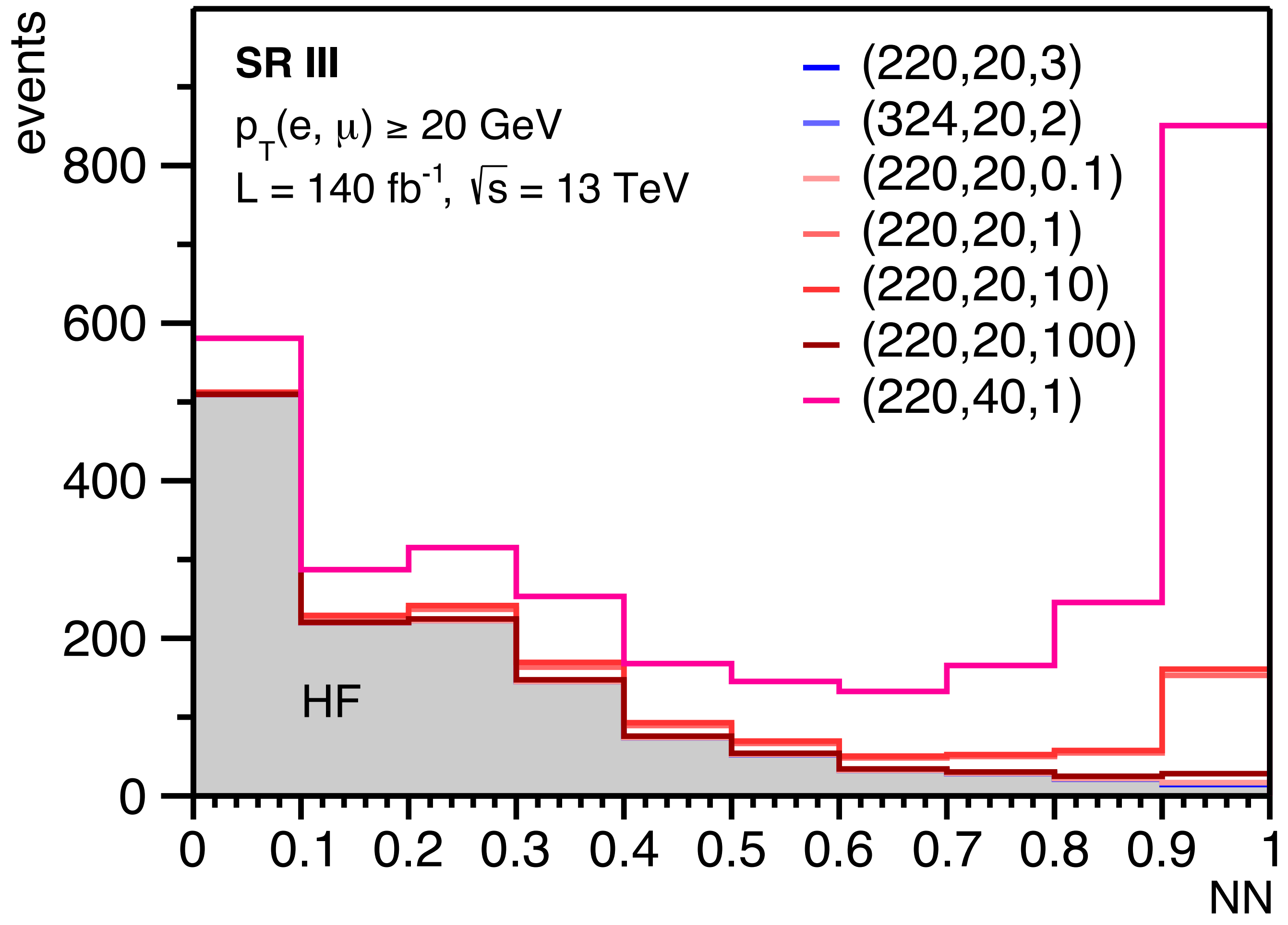


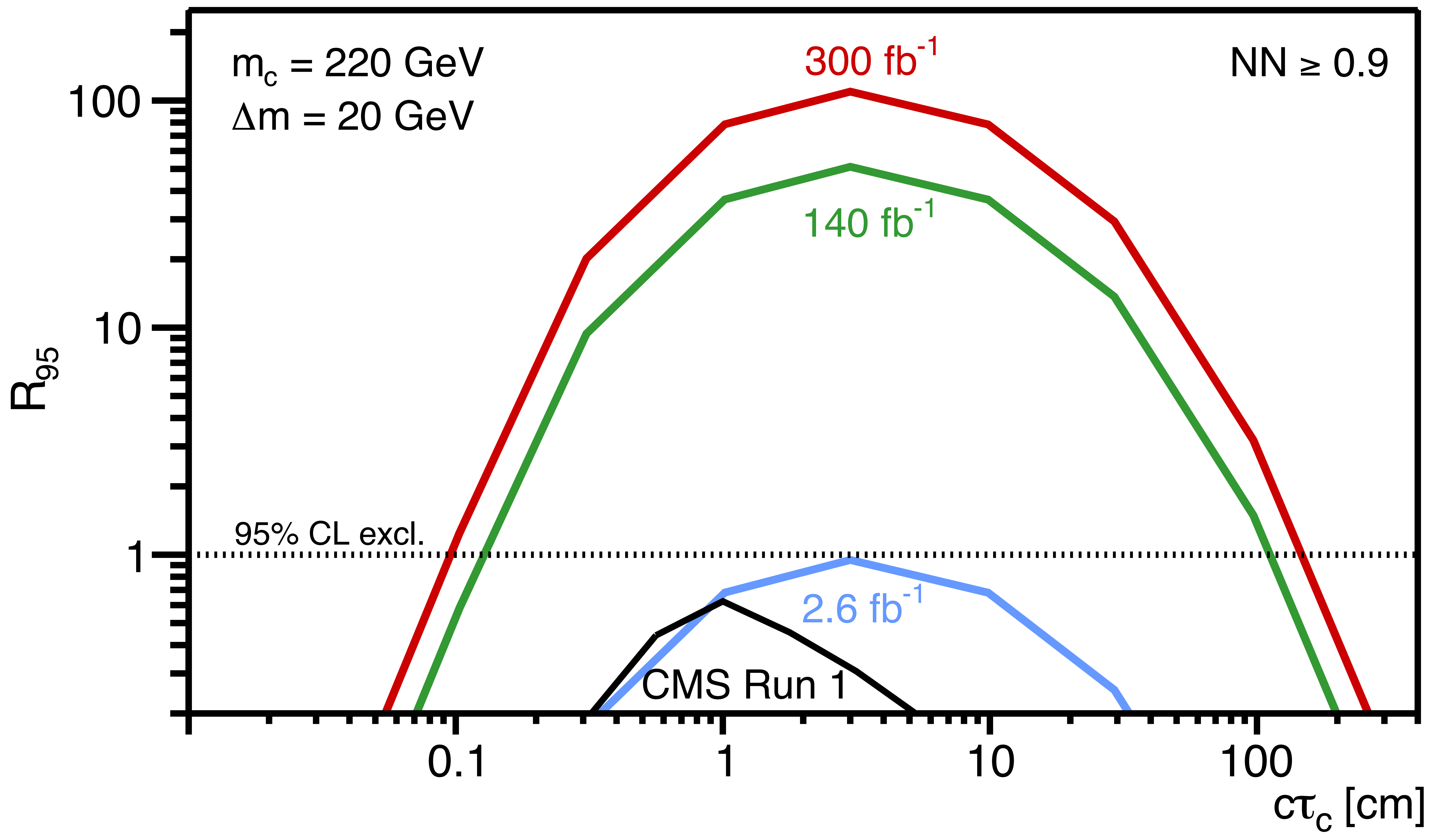


No disappearing track limit from 13 TeV search for **Δ**m < 40 GeV

Gaps can be fixed with dedicated searches





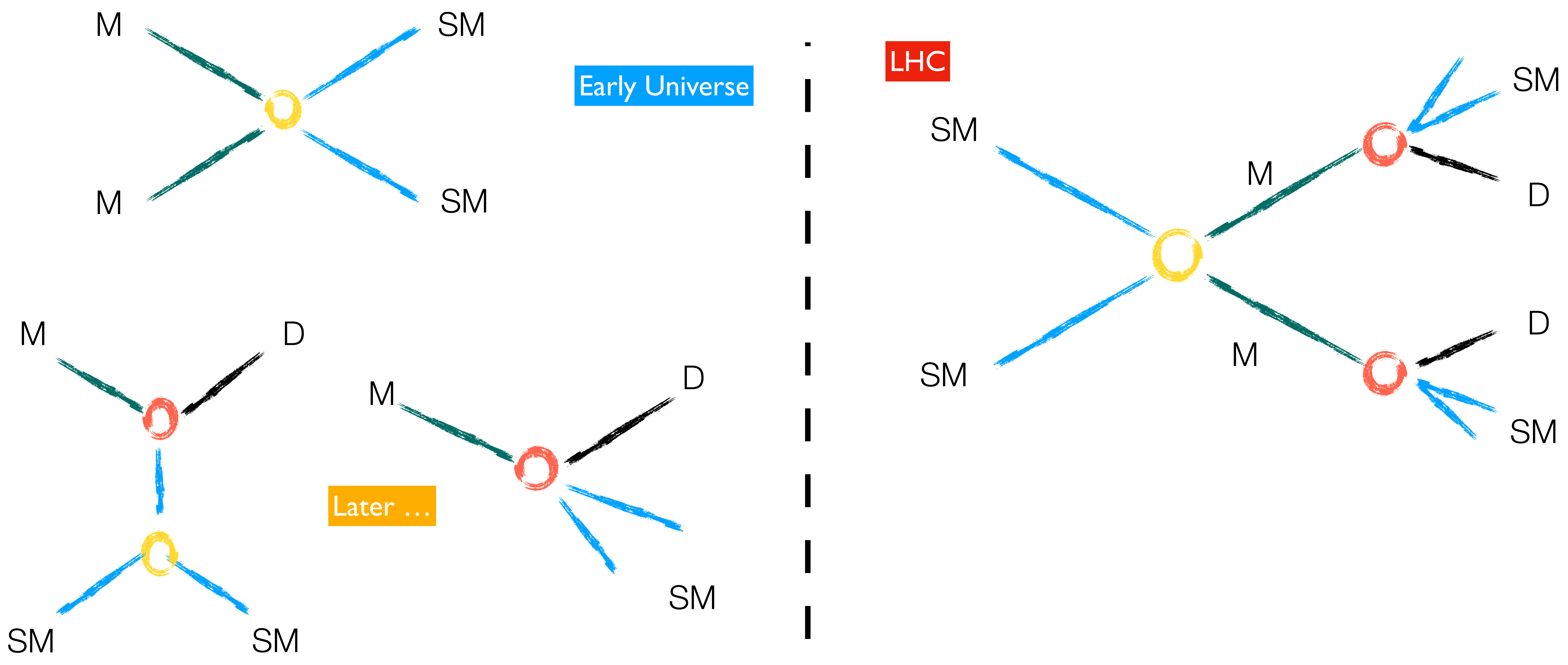


Blekman, ND, et al. 2007.03708

Motivation for LLPs: Dark Matter

Hall et al. 0911.1120

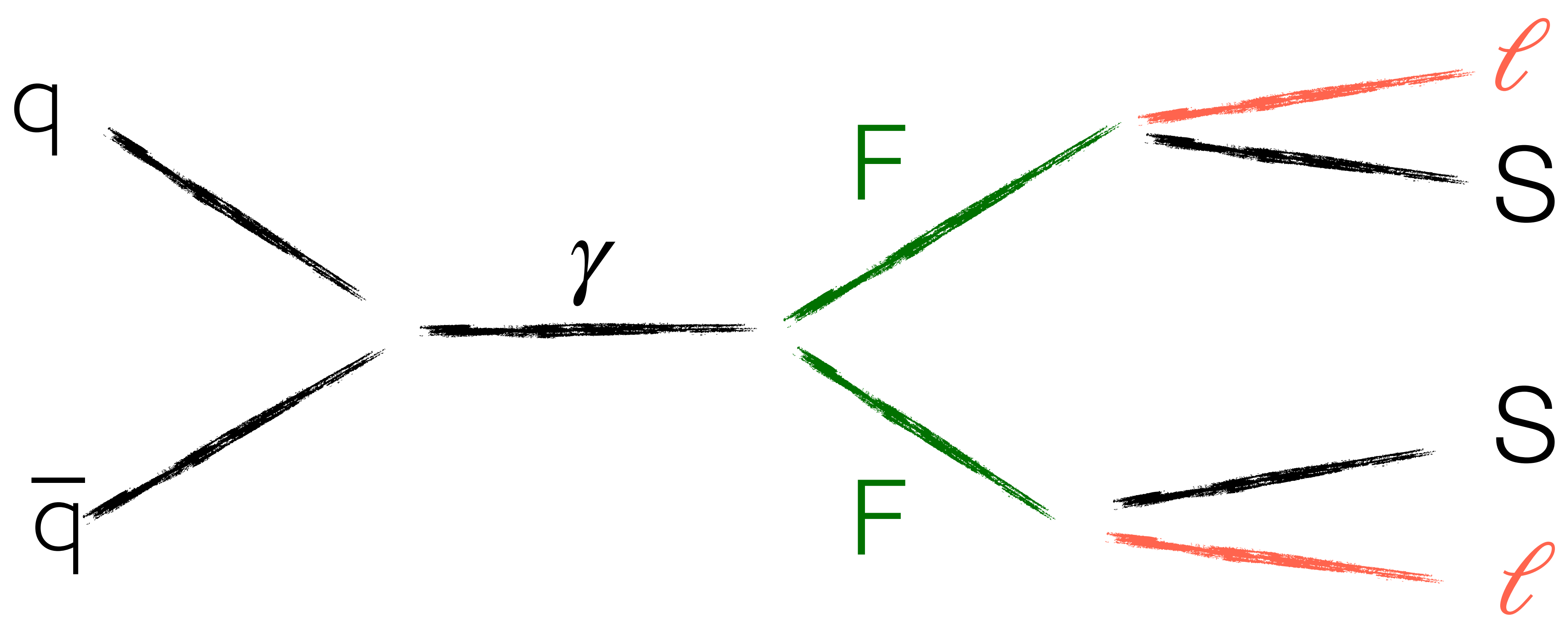
Freeze-in: start with zero DM density, populate later via mediator decay/interactions

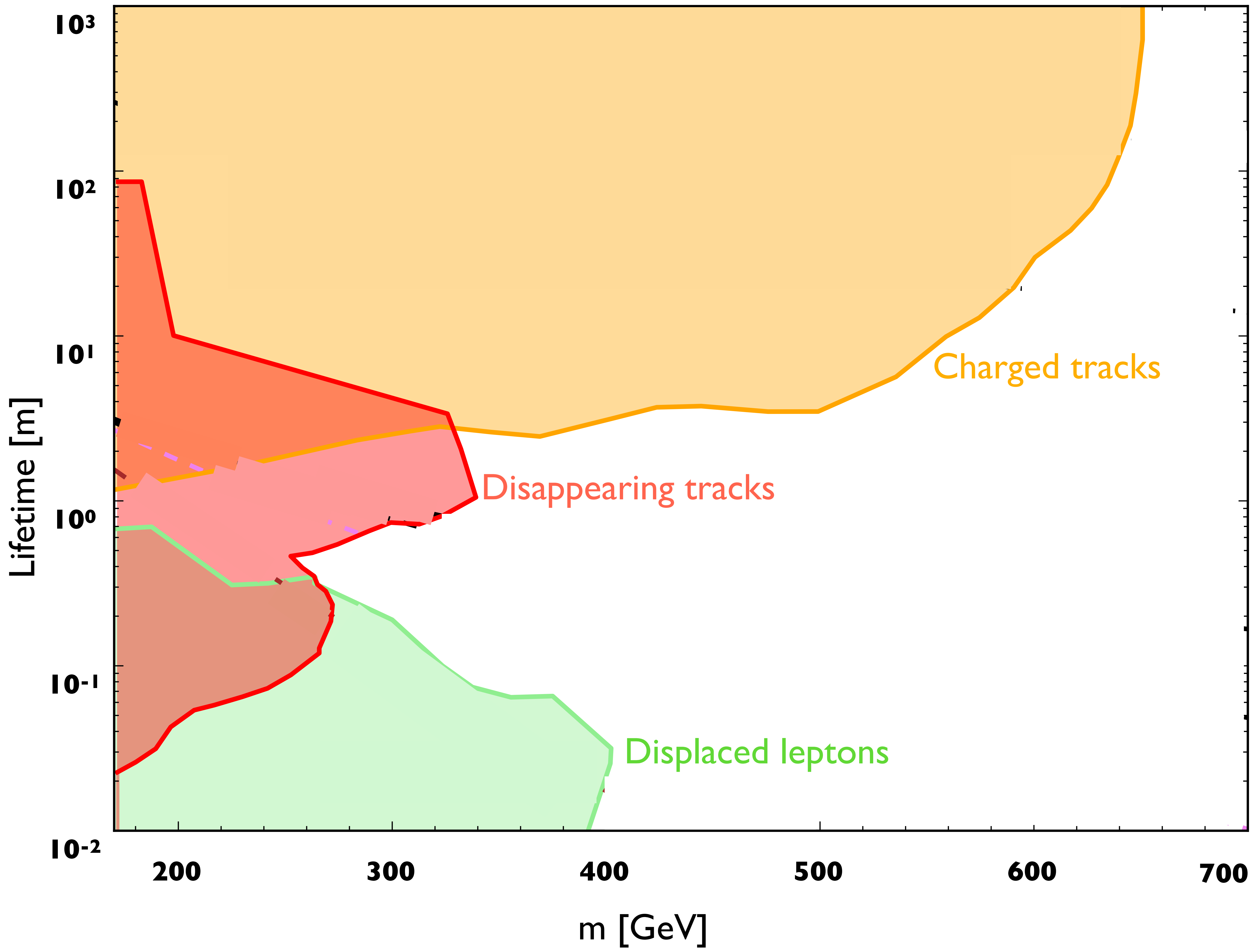


Complementarity of different searches: freeze-in

Scalar DM (S) + Vector-like fermion (F)

$$\mathcal{L} \supset -y_L S \bar{F} \ell_R + \text{h.c.}$$



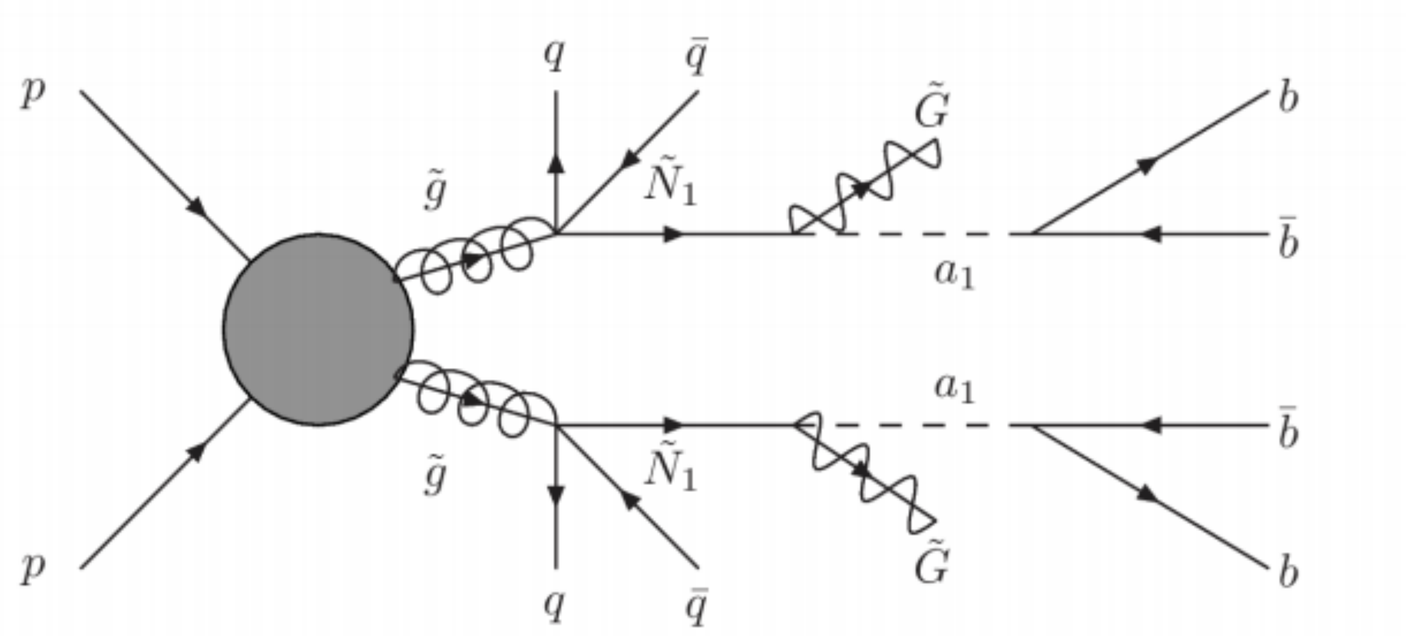


Belanger, ND, et al. 1811.05478

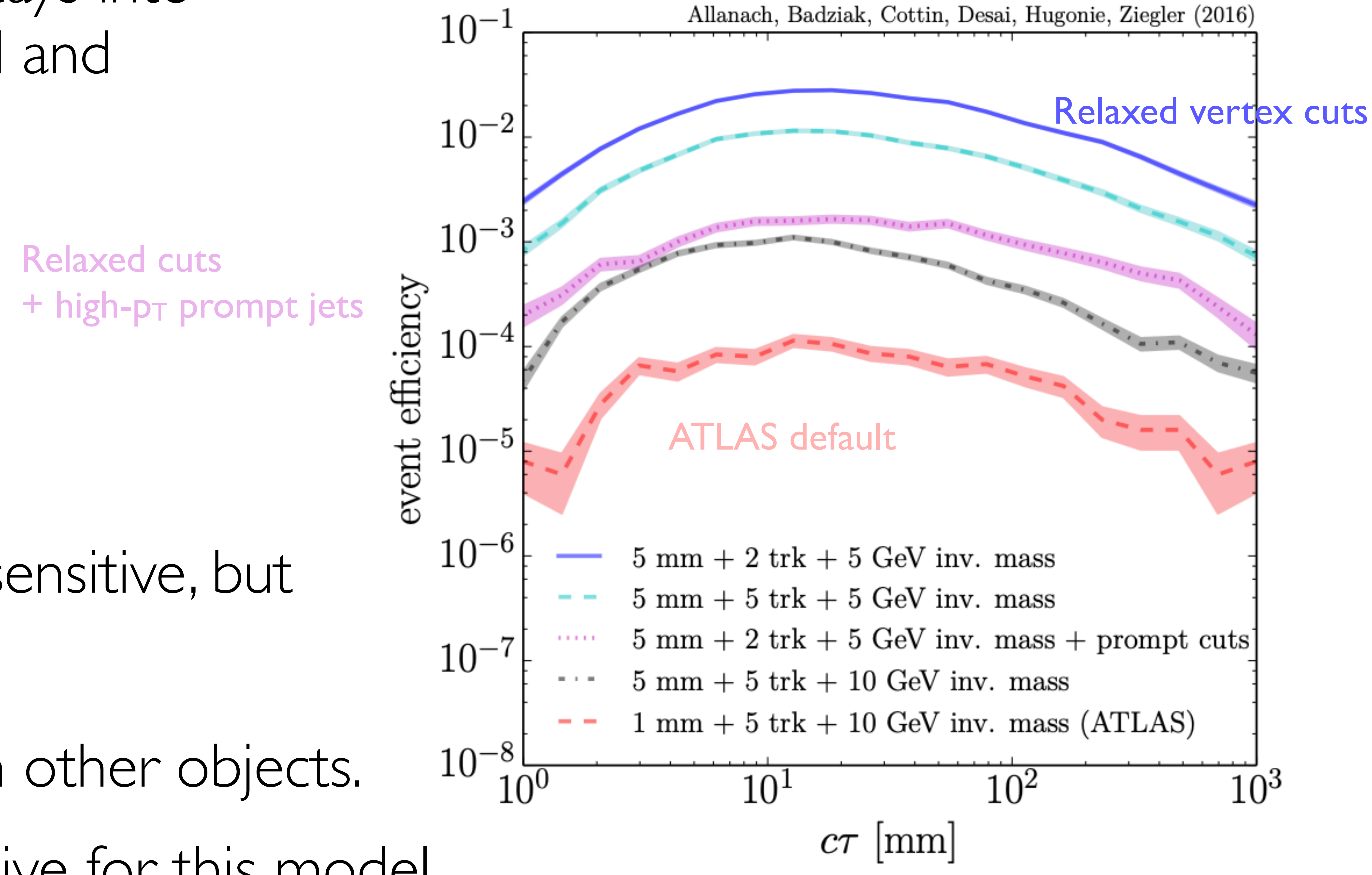
Motivation for LLPs: Naturalness (NMSSM)

(1) NMSSM for Higgs mass, (2) GMSB for SUSY breaking

Main ingredient: NLSP is Bino which decays into gravitino + singlet scalar a; a is long-lived and decays via a → bb



Allanach, ND et al. 1606.03099

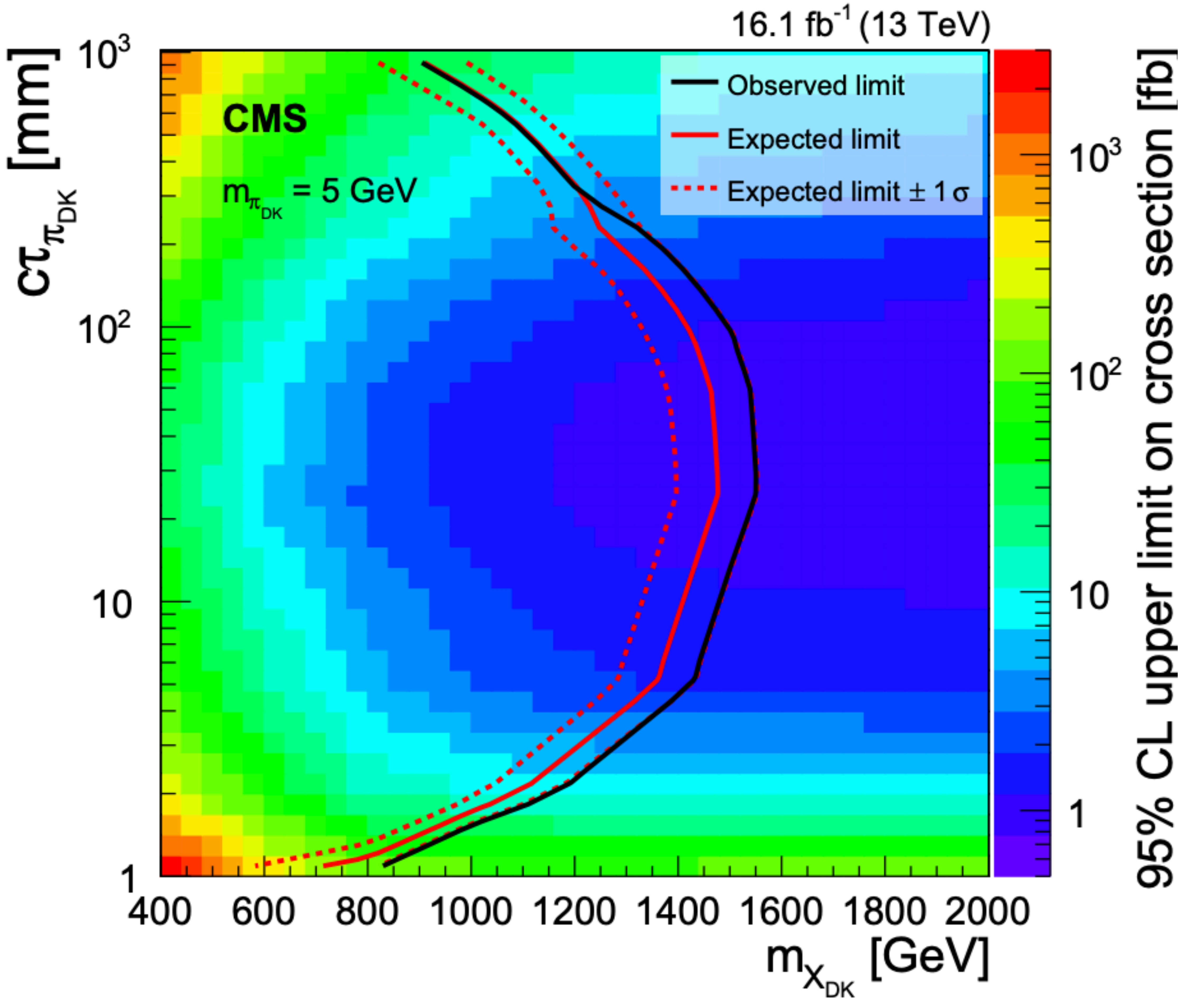


Displaced vertex searches are potentially sensitive, but current cuts too strong.

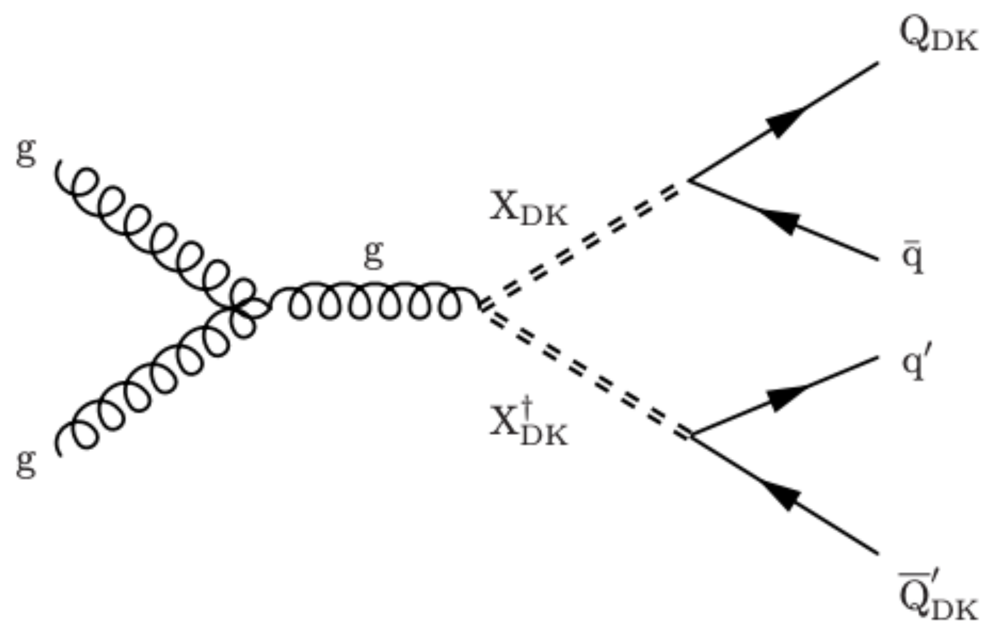
Loose cuts = more background ⇒ cuts on other objects.

Less "model independent" but more sensitive for this model.

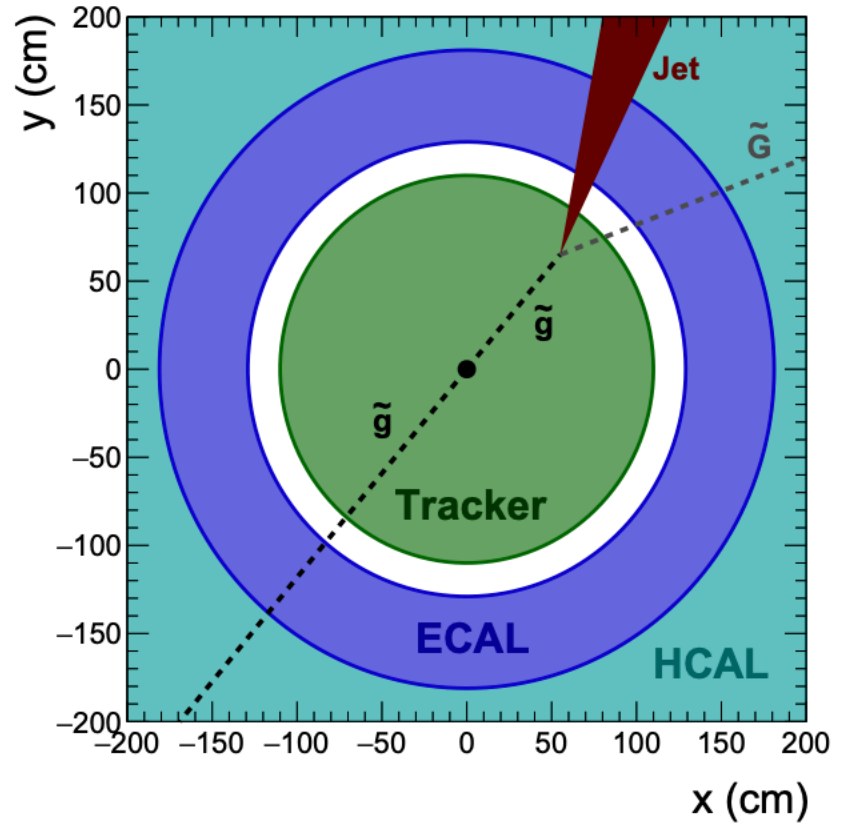
Motivation for LLPs: Naturalness + DM (hidden SU(N)s)

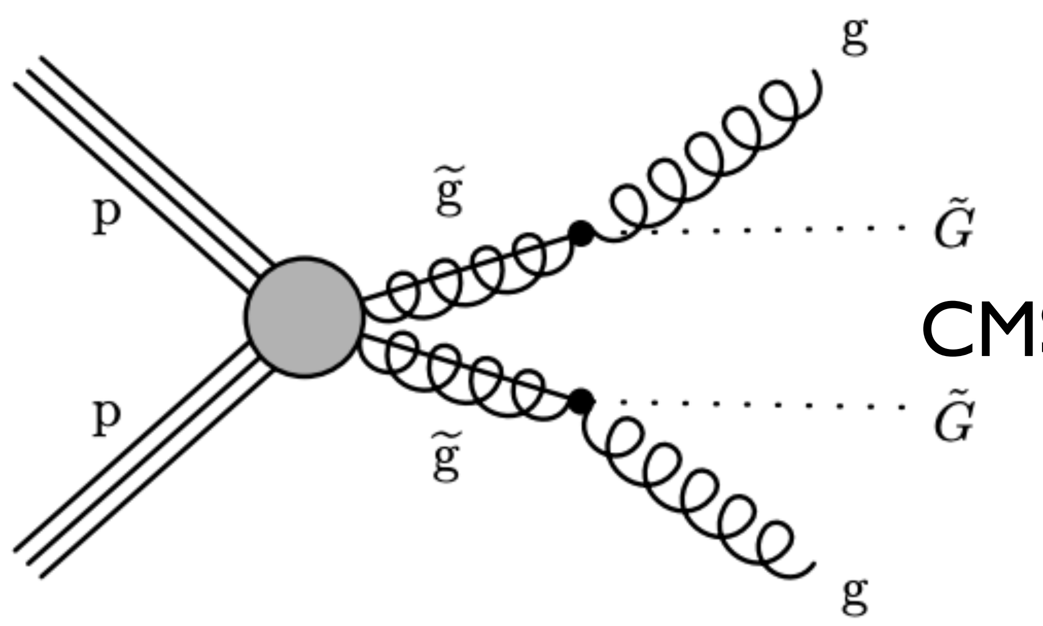


Emerging jets: Schwaller et al, 1502.05409



CMS 1810.10069





CMS-PAS-EXO-19-001

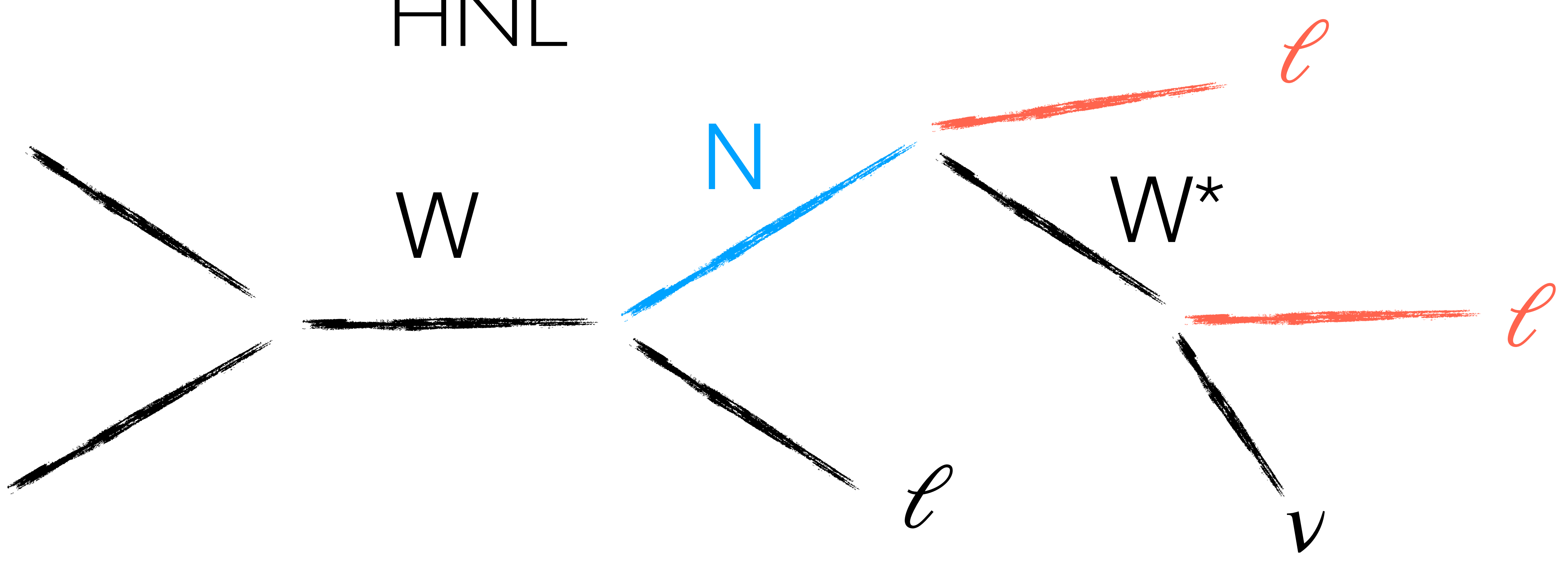
A lot of very recent work:

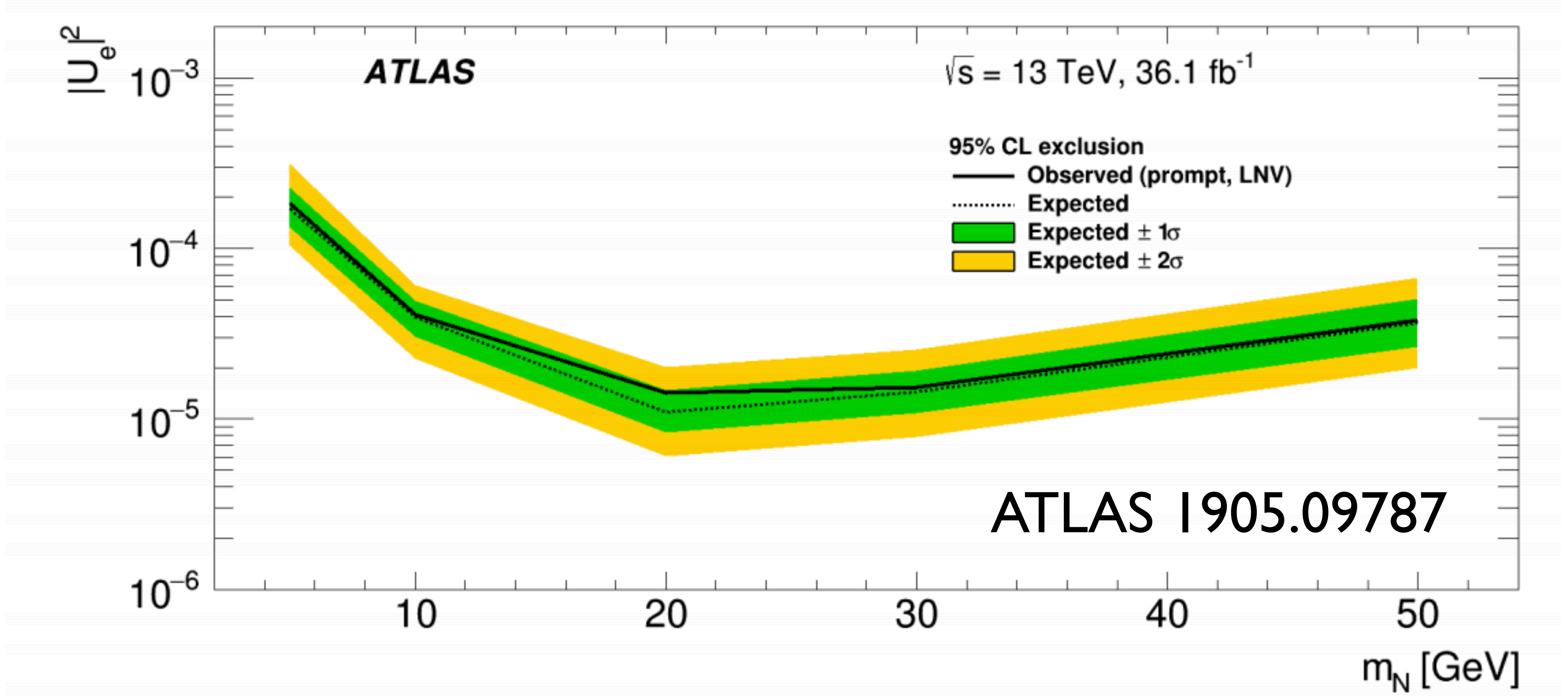
NN for dark jets: Bernreuther et al 2006.08639

Dark jet substructure: Cohen et al 2004.00631

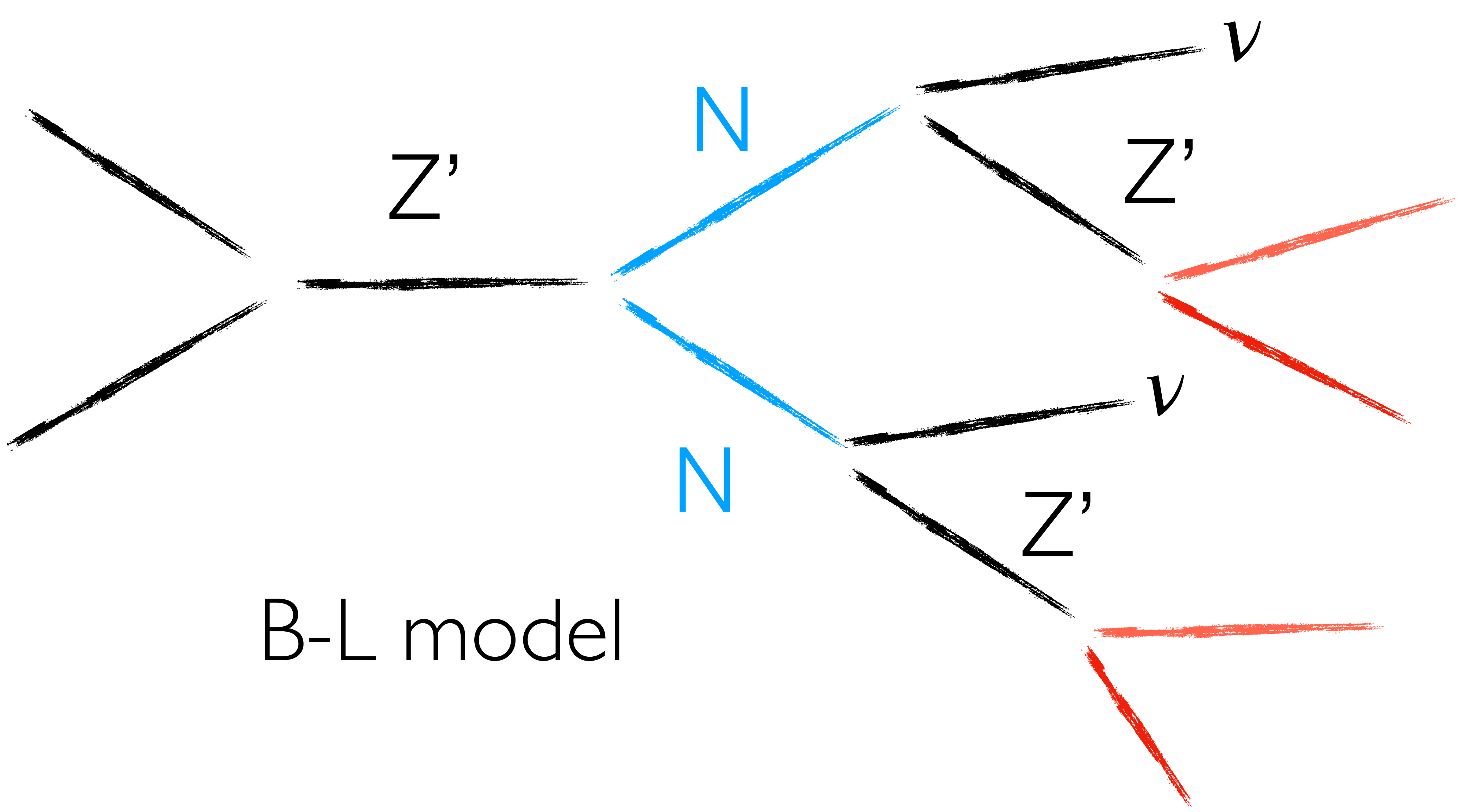
Motivation for LLPs: Neutrino mass

HNL

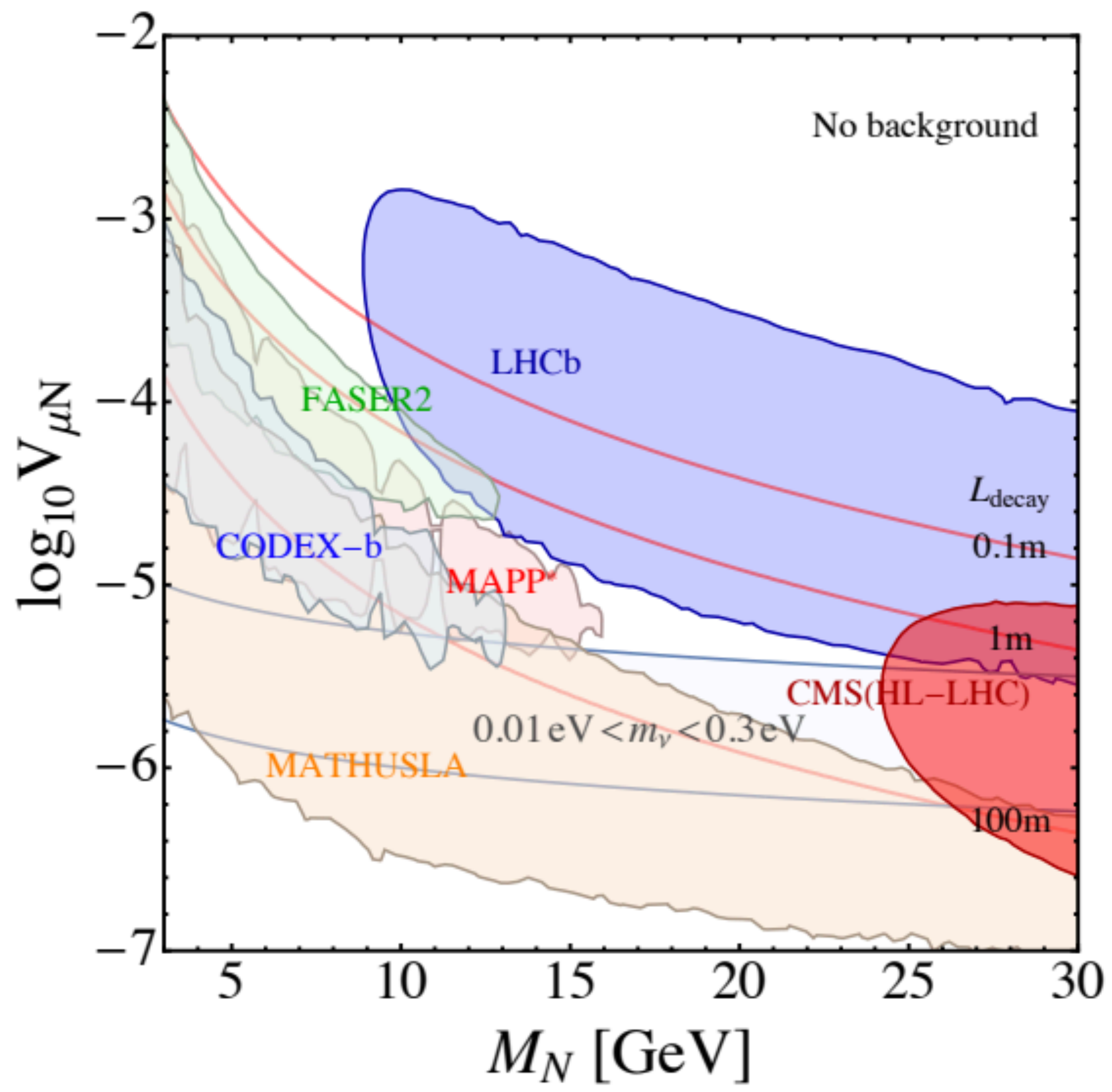




ATLAS 1905.09787



B-L model



Deppisch et al. 1905.11889

Top-down or bottom-up

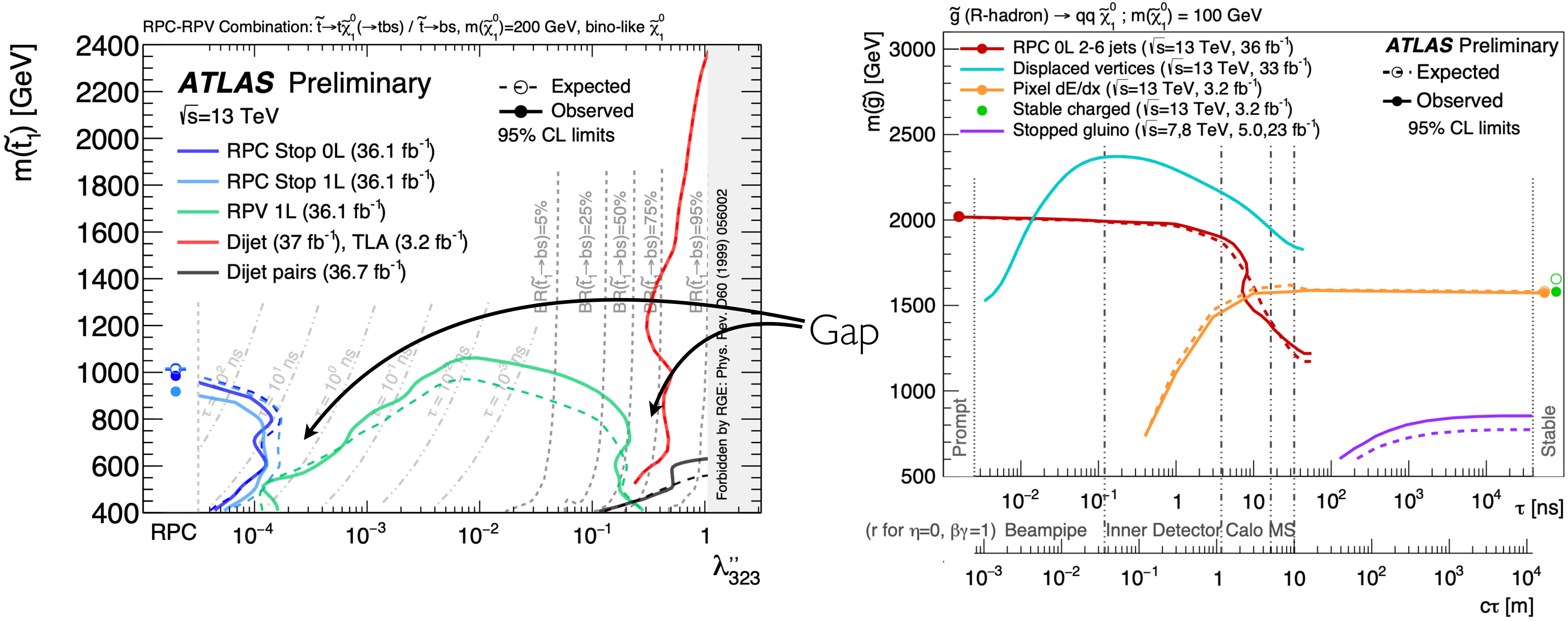
Top-down	Bottom-up
Good physics motivation	Less prejudiced by "theory"
New signatures no one has though of	Good for coverage/overlaps of different signatures (simplified models)
Covers "weird" pockets of phase space that behave differently from typical expectations	May not be sensitive to "weird" pockets because model is too simple.
May bias search strategies	Better for future reinterpretation

Avenues for exploration

Coverage in lifetime

Pick a (simplified) model, investigate sensitivity in multiple searches.

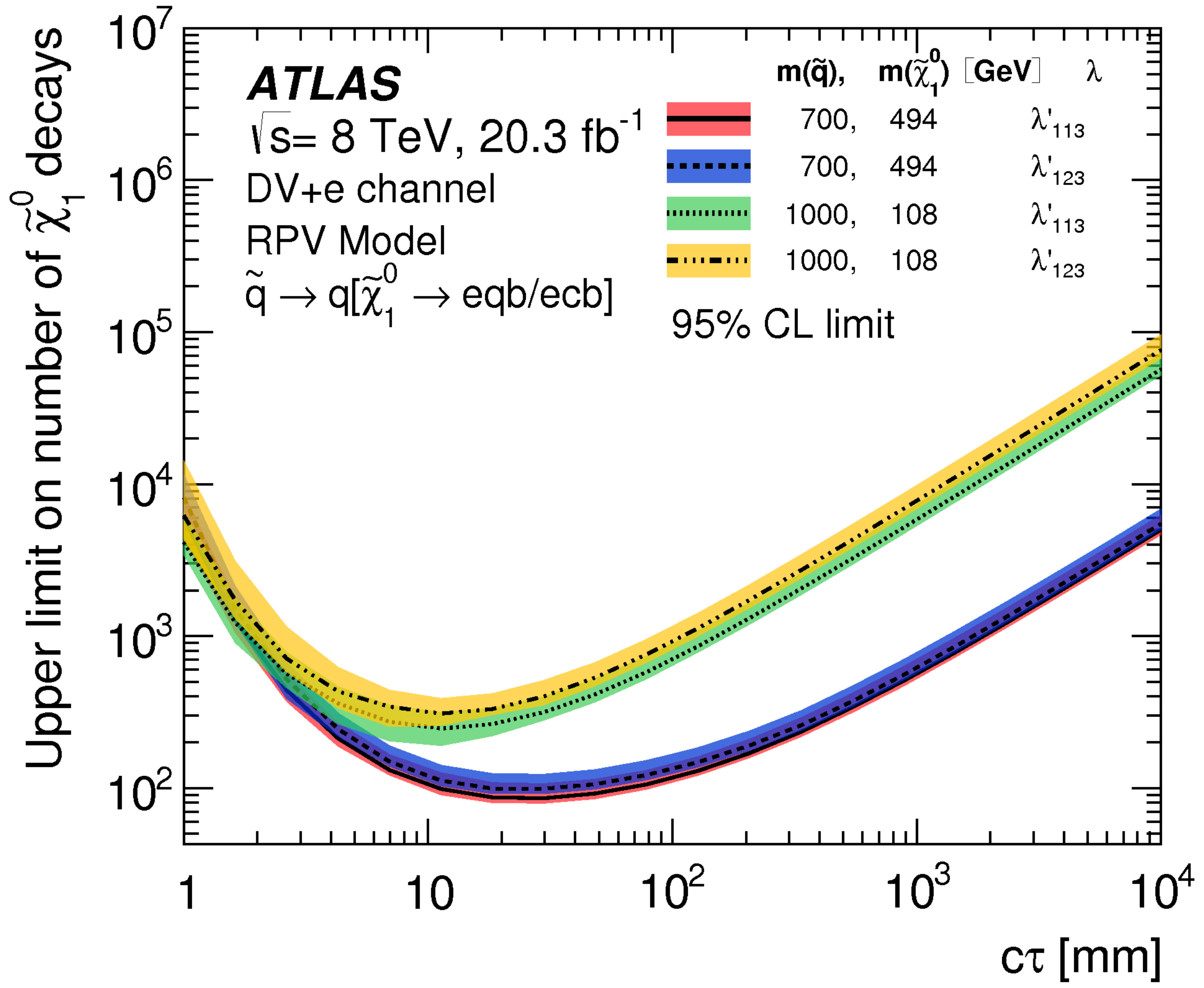
Example here "RPV meets RPC" talk by Karri Folan DiPetrillo in Third LHC LLP Workshop (2018)



Avenues for exploration

Coverage gaps: displaced b/tau

No specific b-tagged searches
so far only search I found was



8 TeV ATLAS 1504.05162

	$\sqrt{s} = 8$ TeV N	$\sqrt{s} = 13$ TeV N
All events	100000	100000
DV jets	96963	98306
DV reconstruction	16542	16542
DV fiducial	16459	16460
DV material	16146	16210
$N_{\rm trk}$	584	544
$m_{\rm DV}$	4	3

"[T]he primary cause for this is failure to satisfy the requirements Ntrk ≥ 5 and the vertex mass cut mDV > 10 GeV … is due to the fact that the displaced jets are mainly b−jets."

Allanach, ND et al. 1606.03099

Displaced tau tagging would be useful e.g. low mass scalars that decay to tau pair, say h→aa→4τ

Avenues for exploration

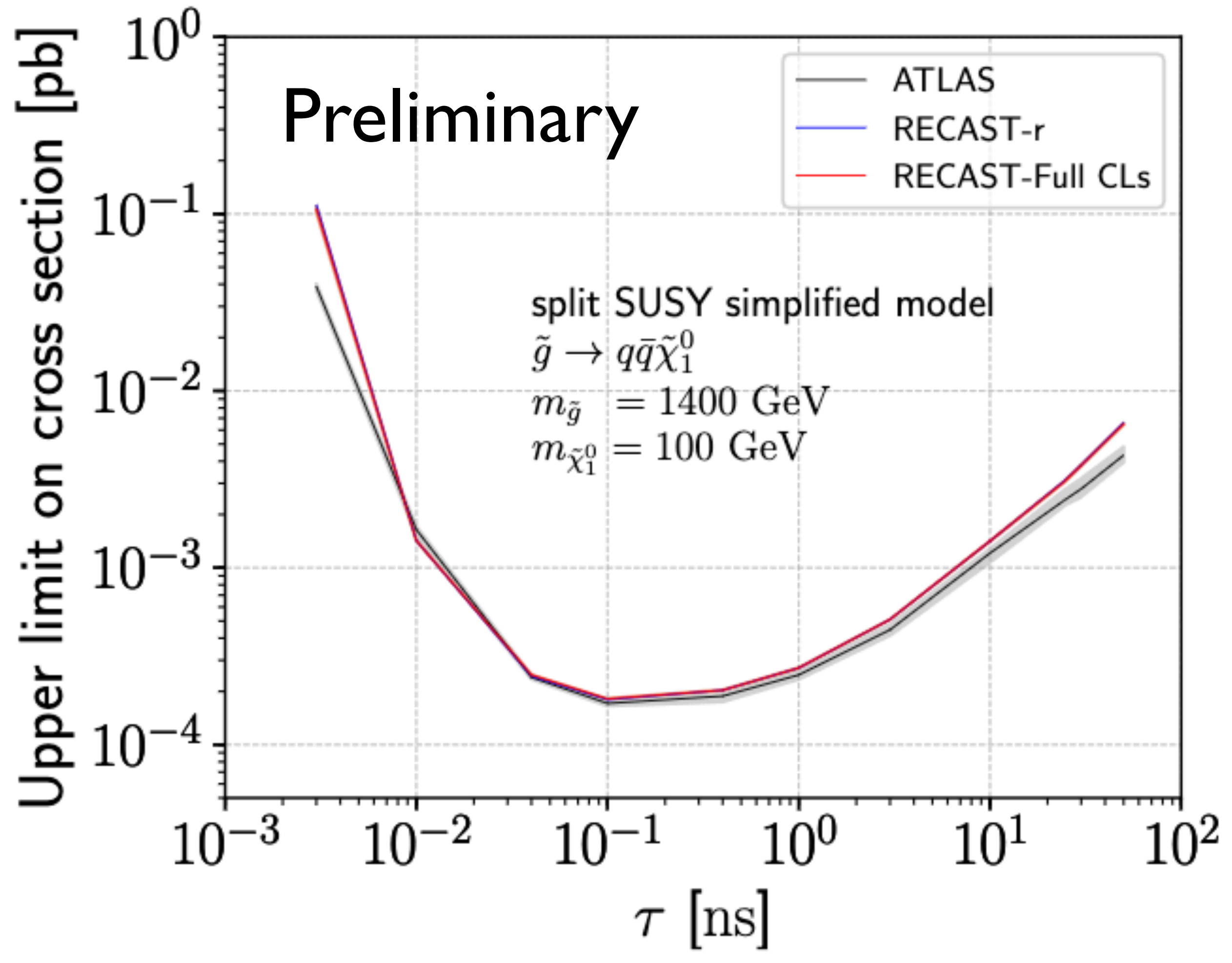
More ideas:

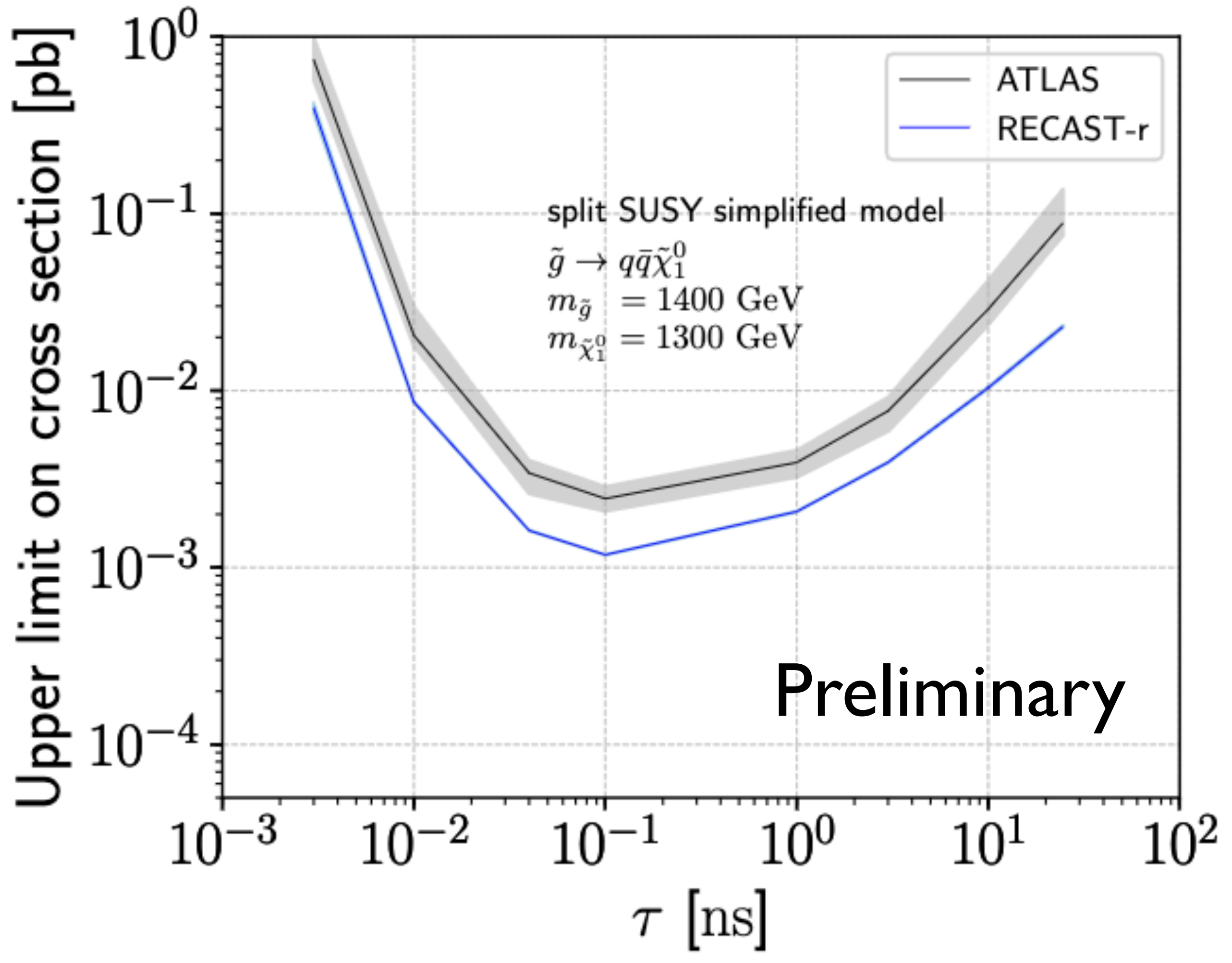
- Kink tracks: predicted for charged mediator that decays to lepton/pion
- Soft decay products from displaced decays (e.g. soft emerging jets, soft leptons)
- Special triggers for signatures other than mono-jet or MET; maybe use multiple objects in trigger to lower thresholds
- …

Another important hurdle for theorists: reinterpretation

Over the years, we have identified all information required to re-interpret SUSY searches. Jet algorithms are standard, smearing functions are published, lepton efficiency is given in terms of momentum, cut flow tables, …

LLP searches are fairly new and there isn't a standard list of objects or an agreed-upon method of communicating efficiencies etc. that can be used for reinterpretation.





Recast of ATLAS DV search 1710.04901

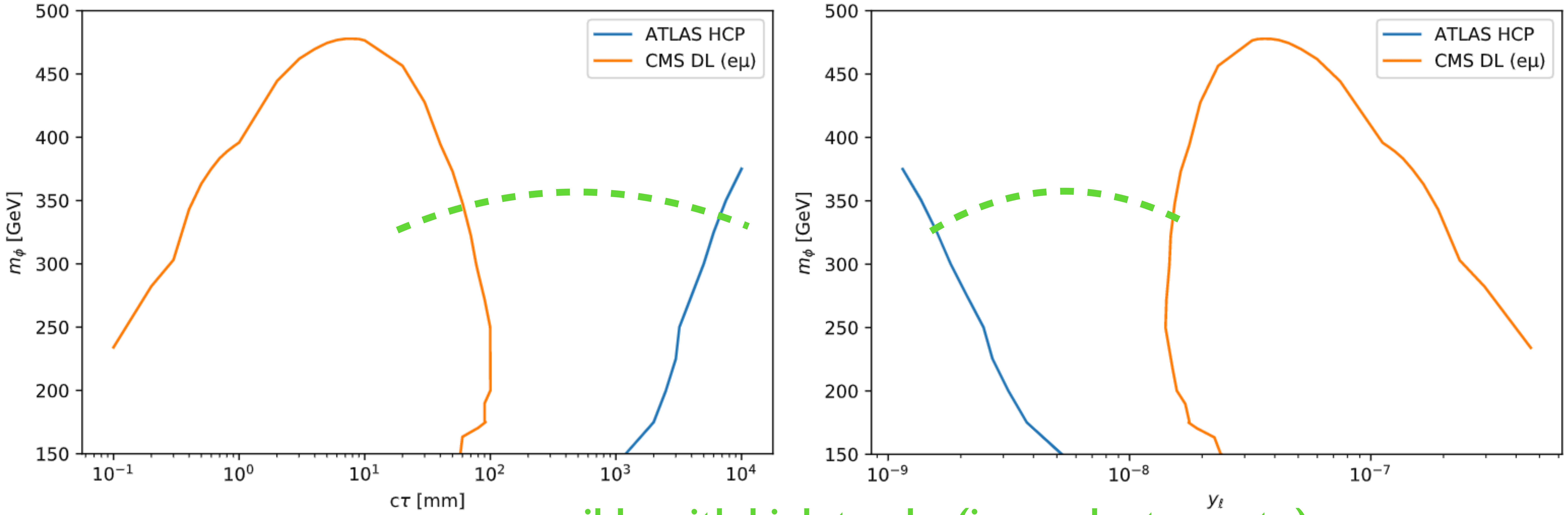
Even when efficiencies are available, they do not always work

CheckMATE coll. to appear

Electroweak LLP

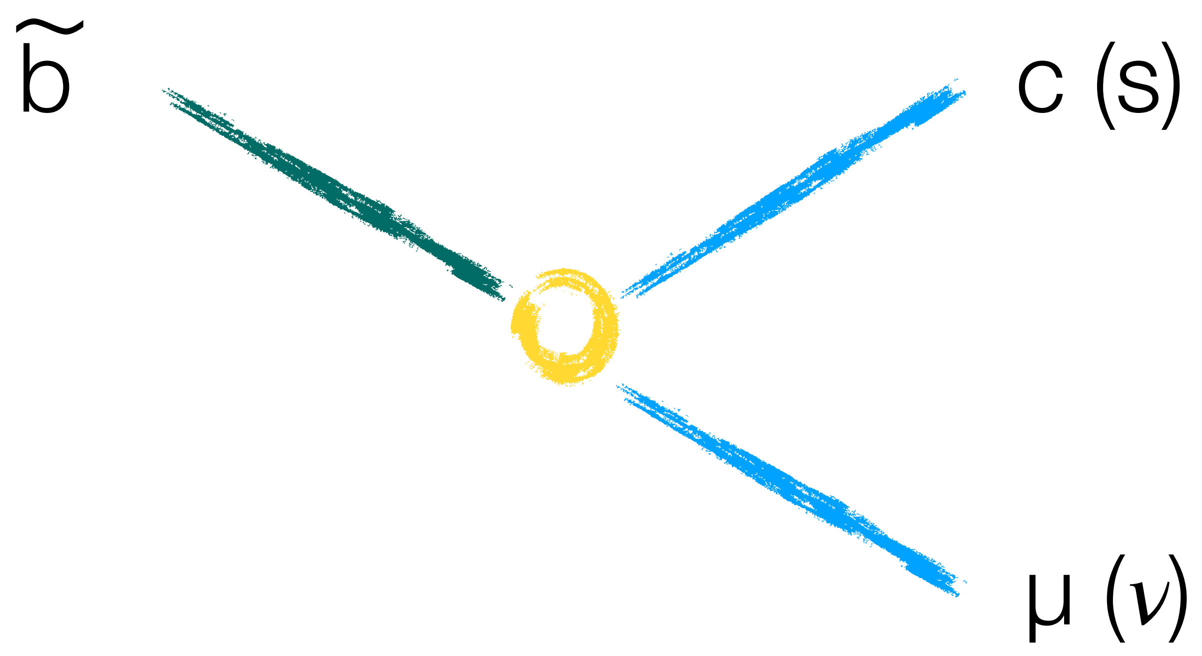
CheckMATE coll. to appear

$$\mathcal{L} = \frac{1}{2}D_\mu\phi D^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \bar{\chi}(i\gamma^\mu\partial_\mu)\chi - m\bar{\chi}\chi - \sum_\ell (y_\ell\phi\bar{\chi}\ell_R + \text{h.c.})$$

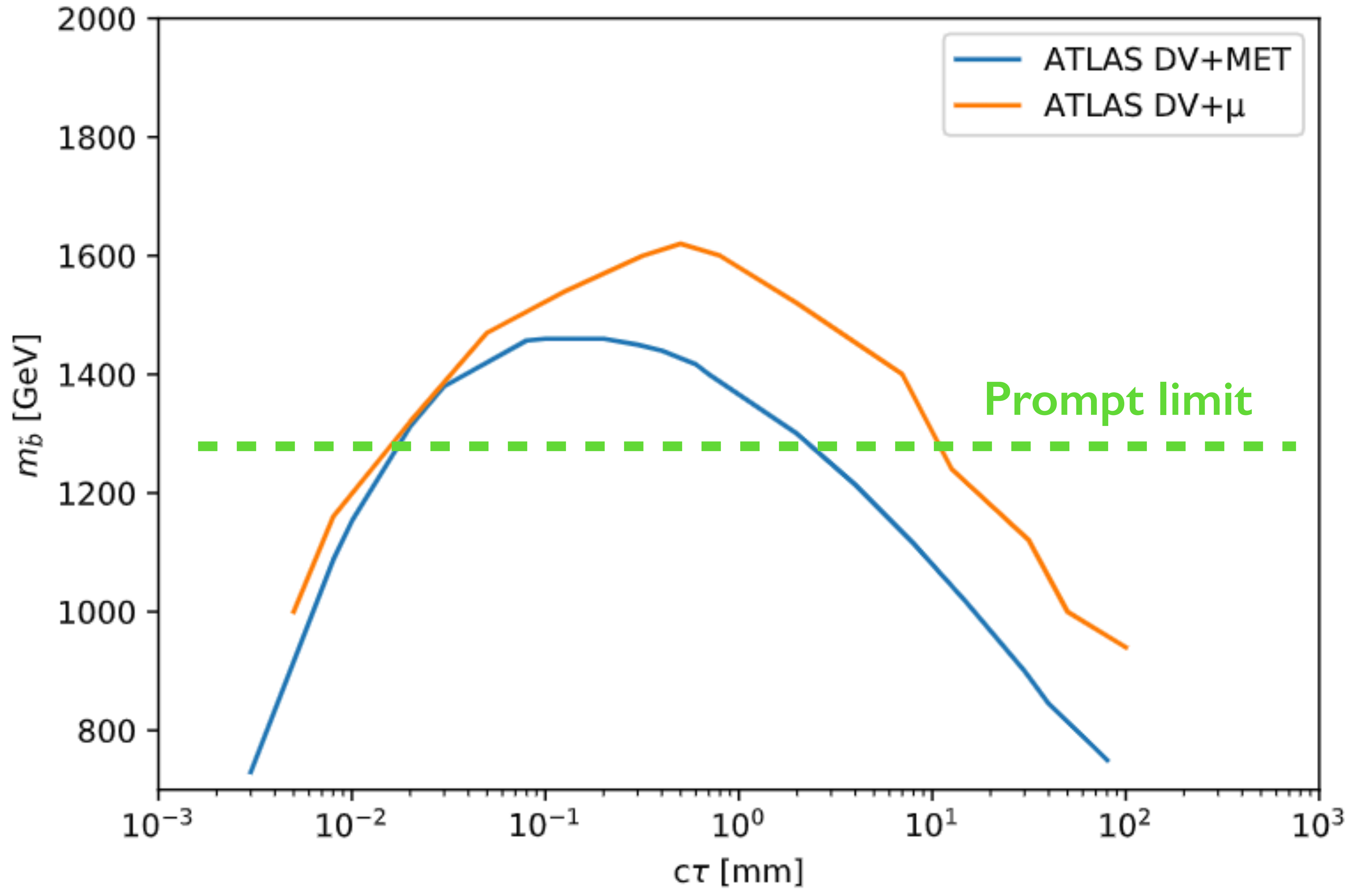


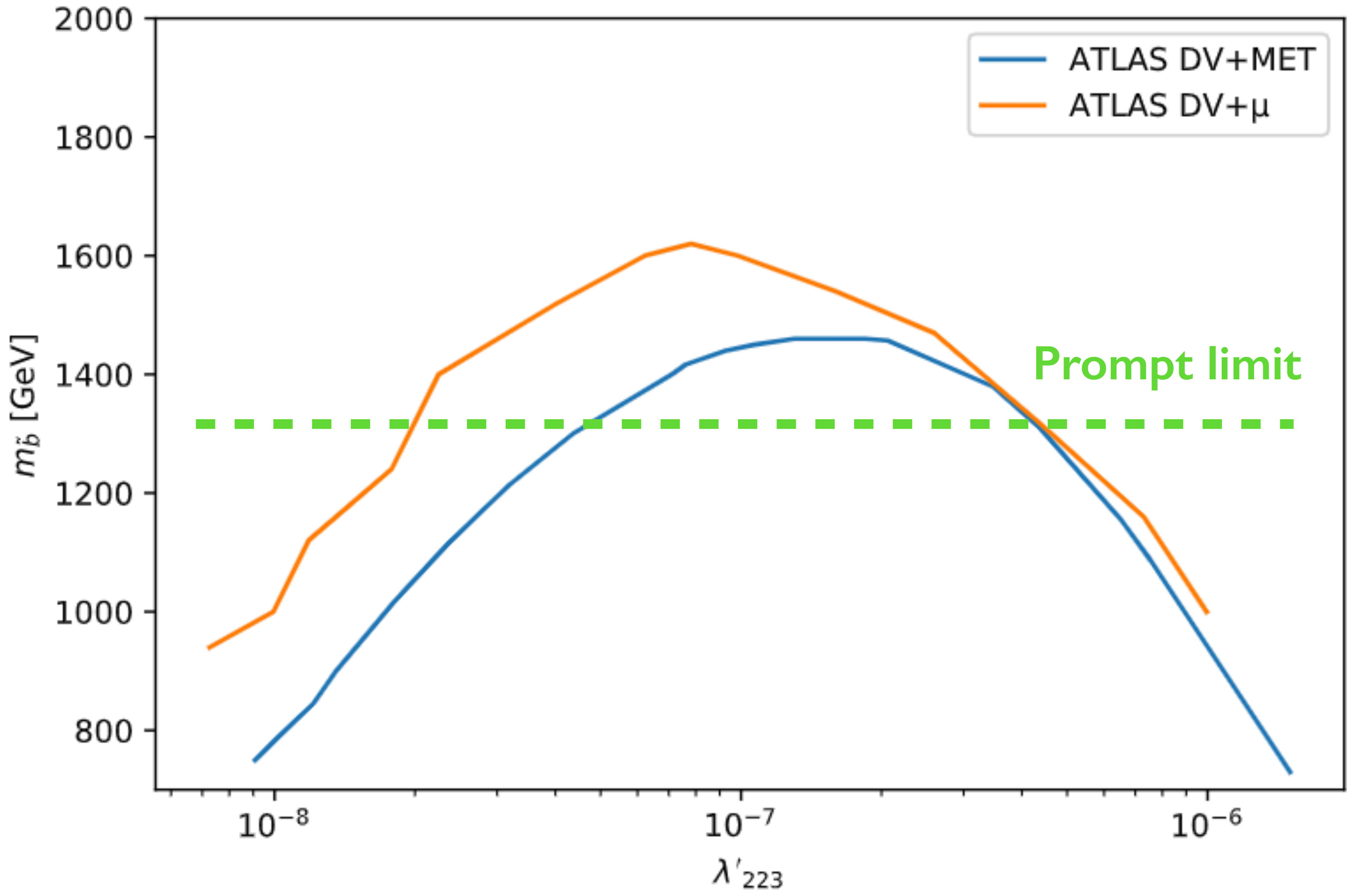
possible with kink tracks (i.e. no lepton veto)

Strong LLP



CheckMATE coll. to appear





Summary

- Multiple motivations to look for LLPs, studies ongoing at least since 2013
- Dark Matter models with LLPs typically predict charged, long-lived mediators which can be seen in track searches and in displaced lepton/jet searches
- Neutrino mass motivations give Heavy Neutral Leptons, signatures can be displaced di-leptons, displaced vertices
- Lots of new activity in dark showers/emerging jets (Hidden valley, twin higgs, etc.)
- Many gaps remain, in signatures as well in lifetime coverage
- We need to work out how to best preserve the result for future use (reinterpretation).