*LLP Theory overview**

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**actually, my own biased pheno POV…*

Long-Lived Particles and the Third Generation, Edinbourgh, 20.11.2019

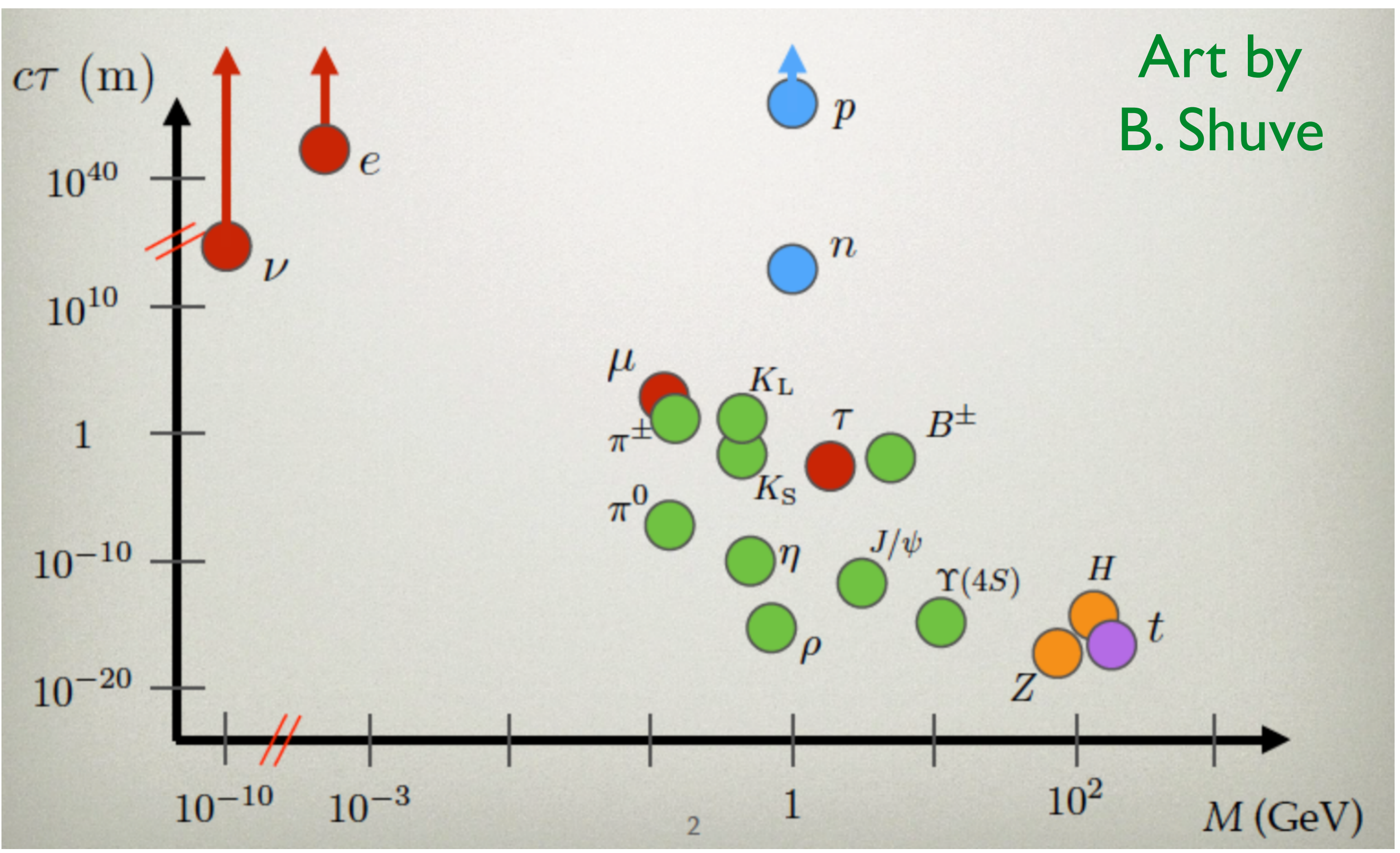
The Quest for New Physics

- Electroweak naturalness problem solved by New Physics (NP) at the TeV scale.
- Other fundamental questions (dark matter, CP asymmetry, neutrino masses, flavor, etc) can also be solved if the NP scale, Λ_{NP} is around the TeV scale.
- No New Physics at the LHC yet (modulo flavour anomalies…)
  - 1) *collider-phobic* (axions, dark photons, sub-GeV dark matter, sterile neutrinos, …): "we'll need <another kind of experiment> " (e.g: FASER, MATHUSLA, ADMX, DUNE)
  - 2) Λ_{NP} higher than expected:
    - → "let's build a new collider!" [BSM-doer, energy]
    - → "let's compute more loops!" [QCD-doer, precision]
  - 3) $\Lambda_{NP} \sim$ 0.1-1 TeV, but it operates in *stealth mode:* heavy mediators, tiny couplings, compressed spectra, sequestered sectors, large backgrounds, …)
  - LLPs in all of them!!! (note that #1 might need a collider as a source!)

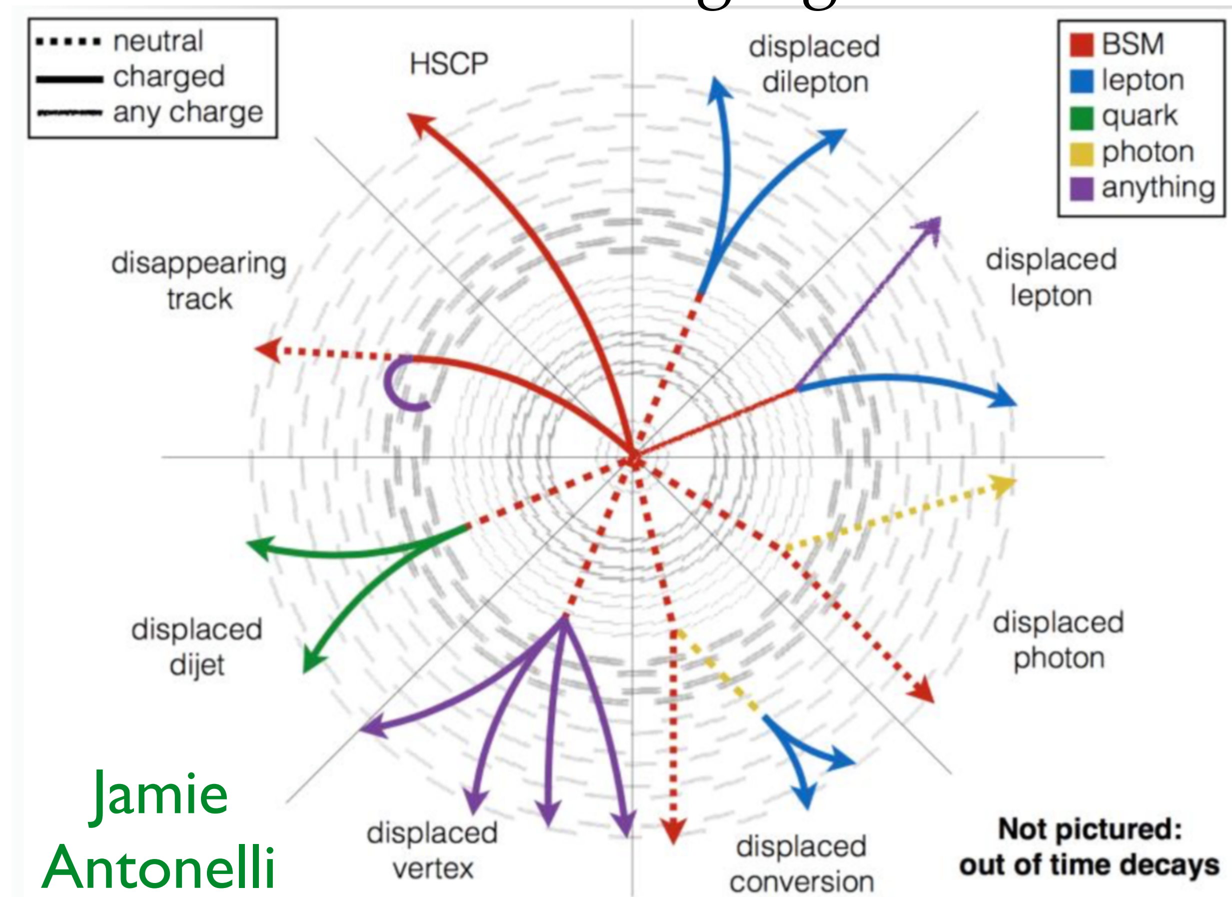
Long-Lived Particles

- LLPs: BSM states with macroscopic lifetimes (ns), theoretically well motivated.

Exist in the SM!



A lot of interesting signatures!



large cτ, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

BSM Models: RH neutrinos, dark QCD, stealth SUSY, Neutral Naturalness, Higgs Portal, Z′ Portal, Hidden Valleys, …

Models ⟷ **Signatures**

MATHUSLA Physics case
Curtin et al, 1806.07396

LLP@LHC White Paper:
Alimena et al, 1903.04497

LLP lessons from the SM

3 ways to get large cτ / small Γ (correlated with LHC limitations)

- Large mass hierarchies / off-shell mediator ⟶ heavy E scale

$$c\tau(\mu \to e\nu) = \frac{1.2\ \mathrm{fm}}{g_X^4}\left(\frac{m_e}{m_\mu}\right)^4\left(\frac{1\ \mathrm{TeV}}{m_\mu}\right) \sim 1\ \mathrm{cm}$$

$m_e = 10\mathrm{GeV}, \mathrm{m}_\mu = 100\ \mathrm{GeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-7}$ RH neutrinos

$m_e = 10\ \mathrm{GeV}, \mathrm{m}_\mu = 1\ \mathrm{TeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-3}$ Hidden Valleys

- Compressed spectra ⟶ Object reconstruction, thresholds

$$c\tau(n \to pe\nu) \sim \frac{1.2\ \mathrm{fm}}{g_X^4}\left(\frac{m_p}{m_n - m_p}\right)^4\left(\frac{1\ \mathrm{TeV}}{m_n - m_p}\right) \sim 1\ \mathrm{cm}$$

SUSY

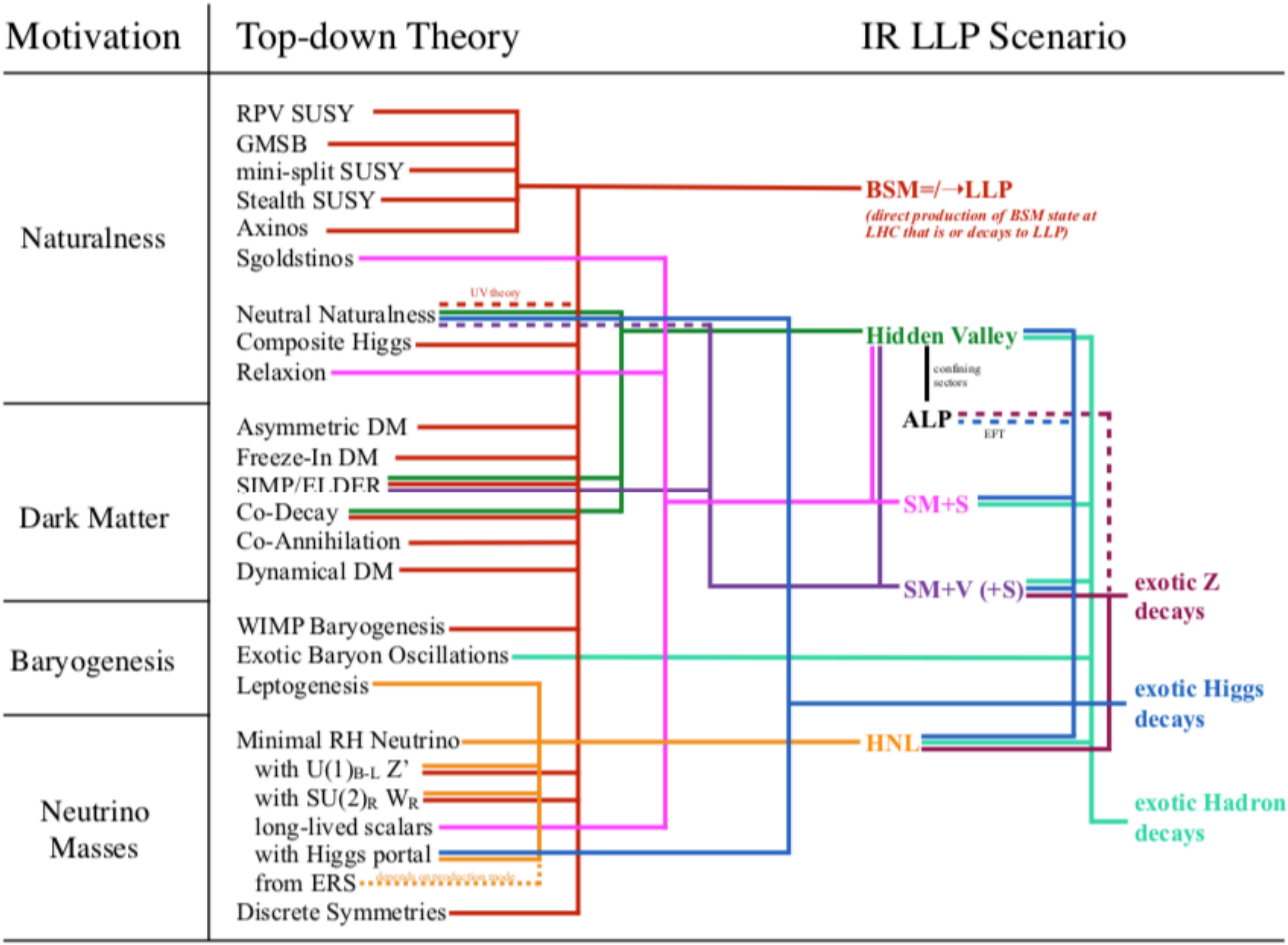
$m_n = 101\ \mathrm{GeV}, \mathrm{m}_\mathrm{p} = 100\ \mathrm{GeV}, \mathrm{g}_\mathrm{X}^4 = 10^{-2}$

- Small coupling ⟶ Low rates

$$c\tau(Z \to \nu\nu) \sim \frac{0.02\ \mathrm{fm}}{g_Z^4}\left(\frac{1\ \mathrm{TeV}}{m_Z}\right) \sim 1\ \mathrm{cm}$$

$m_Z = 1\ \mathrm{GeV},\ \mathrm{g}_\mathrm{Z}^2 = 10^{-12}$ $\mathrm{Z_D}$ models

From theories to signatures



Curtin et al, 1806.07396

What's in the WP?

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Any exp. search using them?

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Closer look in next slide

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Impact of LLP Community

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Any exp. search using them?

Closer look in next slide

Impact of LLP Community

Ask Nishita or Giovanna for details!

Gaps in coverage

1. All-hadronic LLP decays
   - Associated-object triggers (especially motivated by Higgs-like VBF and VH production modes) need to be more comprehensively used to improve sensitivity to low-p_T objects
   - Improvements are needed in sensitivity at lower masses & lifetimes (e.g., for LLPs produced in Higgs decays)
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   - The prospects for dedicated searches for displaced hadronic taus need to be investigated, since no dedicated searches currently exist. By the same token, it would be interesting to explore the possibility to flavor-tag displaced jets (b-displaced jets, c-displaced jets, etc).
2. Leptonic
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   - Searches need to be done for different combinations of charge and flavor of displaced leptons (e.g., same-sign vs. opposite-sign, opposite-flavor vs. same-flavor)
   - Searches need to be done for tau leptons in LLP decays, in particular if they come from the ID; an unanswered question remains as to whether displaced-jet triggers can be used
3. Semi-Leptonic
   - Searches do not exist and need to be done for masses below or about 30 GeV, theoretically well motivated by Majorana neutrinos.
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4. Photonic
   - There is currently no coverage for LLPs decaying into $l\gamma$, $j\gamma$, or without missing energy, and searches urgently need to be performed for this decay topology
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   - There is currently no coverage for softer non-pointing or delayed photons, and searches need to be performed here
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5. Other exotic long-lived signatures
   - Disappearing tracks with $c\tau \sim$ mm are very hard to probe, and new ideas and detector components are needed to extend sensitivity to this potential discovery regime. It's unclear if the ATLAS insertable B-layer will be present in HL-LHC run and how sensitivity to the disappearing track topology will improve with the replacement of the current inner detector with the new ITk (Inner Tracker), or whether new tracking layers very close to the beam line can be added. It's an open question as to what is the lowest distance at which new layers (or double layers) can be inserted. Another open question that needs to be answered is whether there are any prospects for disappearing tracks at LHCb with an upgraded detector.
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(red outline) = What about taus?

(green outline) = lighter and softer objects

LLPs in concrete BSM scenarios

LLPs and Electroweak baryogenesis

- Assume 2 neutral WIMPs that freeze out. One of them works as dark matter via the standard WIMP miracle, and the other one is metastable and decays after freeze-out, triggering baryogenesis [Cui, Sundrum, 1212.2973]

- Baryogenesis better happens before BBN, then

$$1\ \mathrm{cm}\left(\frac{100\ \mathrm{GeV}}{\mathrm{m}_\chi}\right)^2 \lesssim c\tau \lesssim 10^8\ \mathrm{m}$$

- Interestingly, this span various orders of magnitude! If a neutral particle lives too long (more than a few meters) it will escape the detector unscathed and will only appear as missing energy, but then it can be studied with a dedicated detector, such as MATHUSLA, FASER, etc…

LLPs and Dark matter (I): EW multiples (minimal DM)

- Assume DM candidate is the neutral component of one EW multiplet.
- Then EWSB (W,γ-loops) split charged components from the DM candidate. Charged lifetime pretty much independent of DM mass!

$$c\tau \approx 0.7\,\mathrm{cm} \times \left(\frac{\Delta m}{340\,\mathrm{MeV}}\right)^{3} + O(m_Z^2 / m^2)$$

- Lifetimes of 6.6 mm (n-even, Y=1/2), 6.0 cm (n-odd, Y=0).
- Above cases correspond to pure Higgsino and pure Wino if DM is fermion.
- Main search: disappearing tracks (more to discuss in Nishita's talk Thursday)
- Note:mixing with additional states (e.g: singlets) can shorten the lifetime.

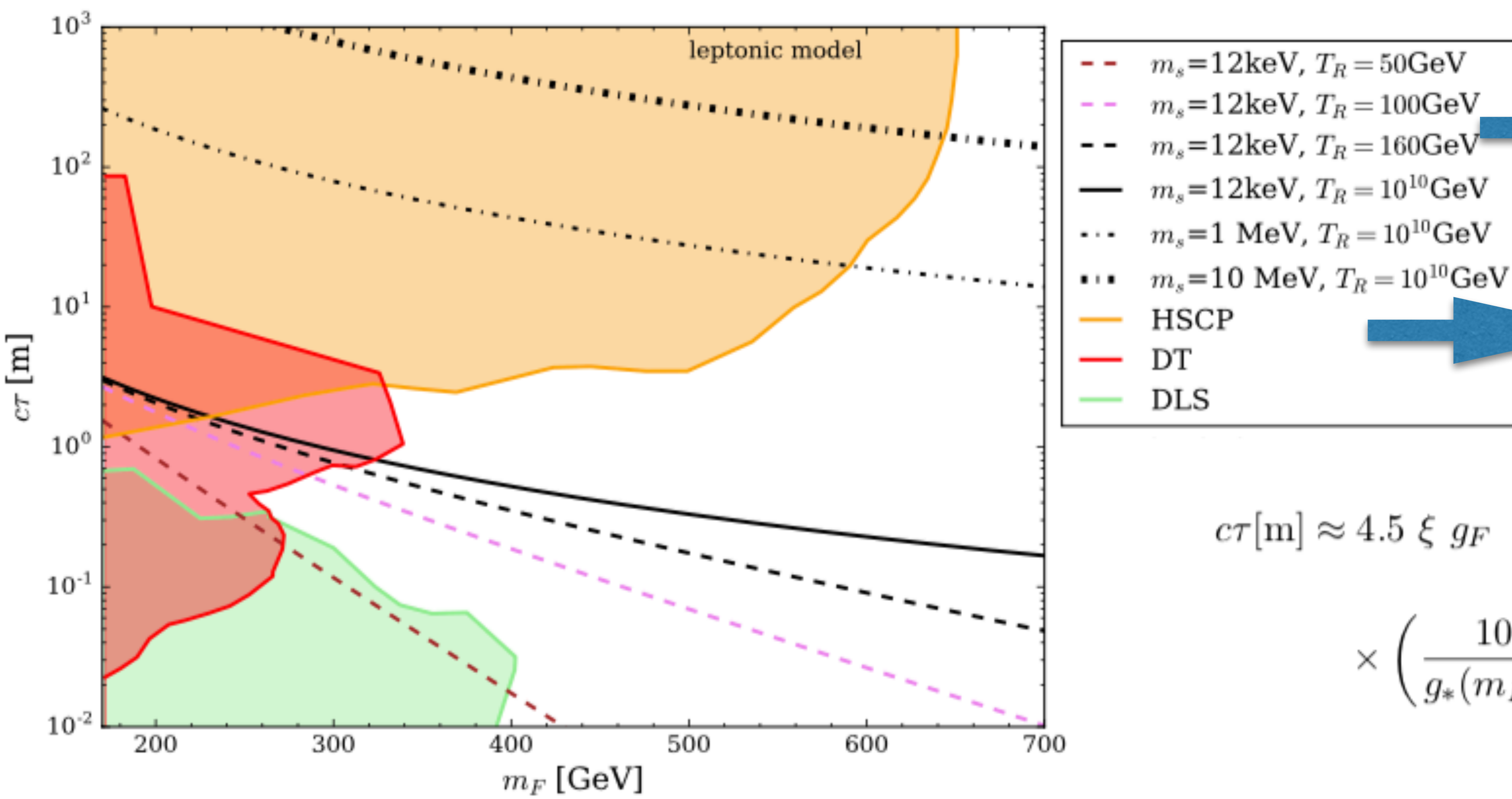
LLPs and Dark matter (II): freeze-in (FIMP DM)

tiny Y: DM never in thermal equilibrium. Slowly produced, reaches measured relic.

New fields: scalar DM (s) + VL-fermion (F).

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\left(i\not{D}\right)F - m_F \bar{F} F - \sum y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

→ Details in Nishita's talk on Thursday (right before tea…)



A positive LLP signal gives information on early Universe physics (T_R).

Different LLP searches probe different regions of parameter space.

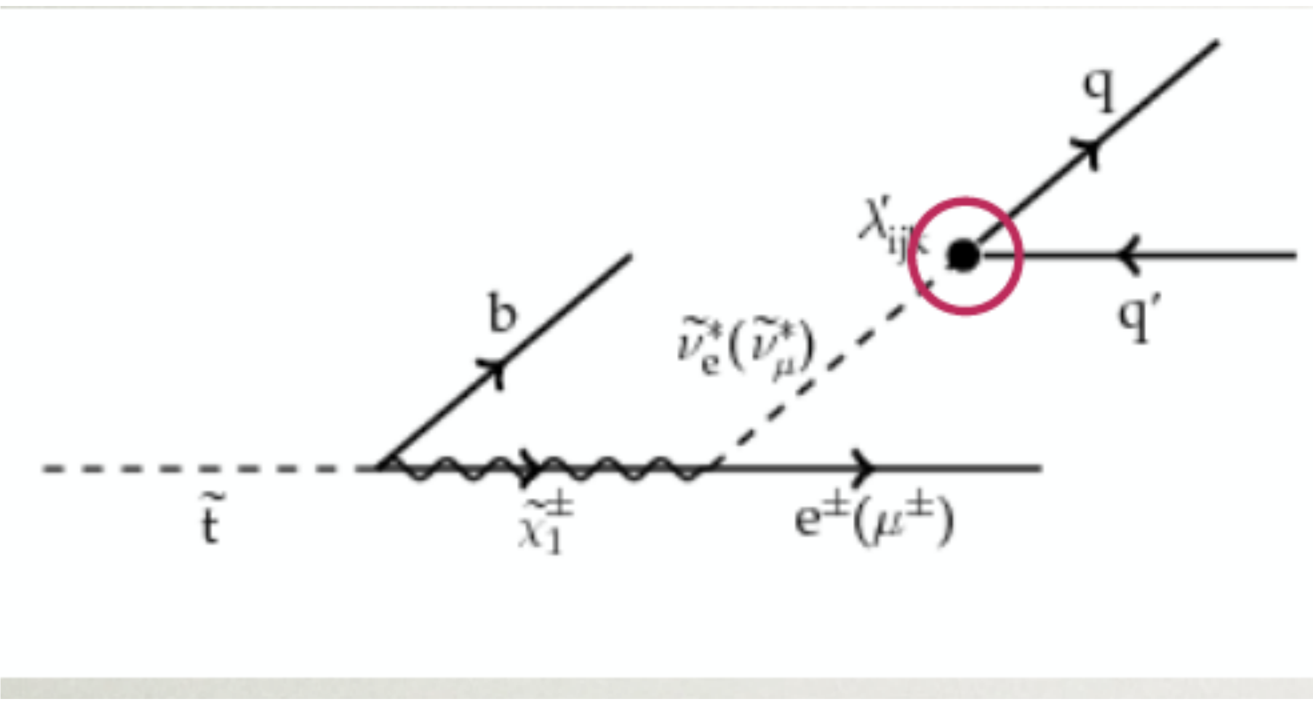
$$c\tau[\mathrm{m}] \approx 4.5\, \xi\, g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \mathrm{keV}}\right)\left(\frac{200\ \mathrm{GeV}}{m_F}\right)^2 \times \left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\, x^3 K_1(x)}{3\pi/2}\right],$$

Belanger, Desai, Goudelis, Harz, Lessa, No, Pukhov, Sekmen, Sengupta, Zaldivar, JZ, 1811.05478, 1910.00117.

See also: Co, D'Eramo, Hall, Pappadopulo, 1506.07532; Evans, Shelton: 1601.01326; Calibbi, Lopez-Honorez, Lowette, Mariotti, 1805.04423, Junius, Lopez-Honorez, Mariotti 1904.07513, No, Tunney, Zaldivar 1908.11387

LLPs and Hierarchy Problem (I): RPV SUSY

- Spontaneous breaking of a symmetry naturally generates a small coupling: symmetry gets restored if the coupling vanishes (technical naturalness)
- RPV operators induce proton decay, hence the coupling must be bounded. Indeed, $|\lambda'| \lesssim 10^{-8}$ (rough estimate)
- RPV SUSY also explain null results in MET + X searches!



For details:

Z. Liu, B. Tweedie 1503.05923;
C. Csaki, E. Kuflik, S. Lombardo, O. Slone, T. Volansky, 1505.00784

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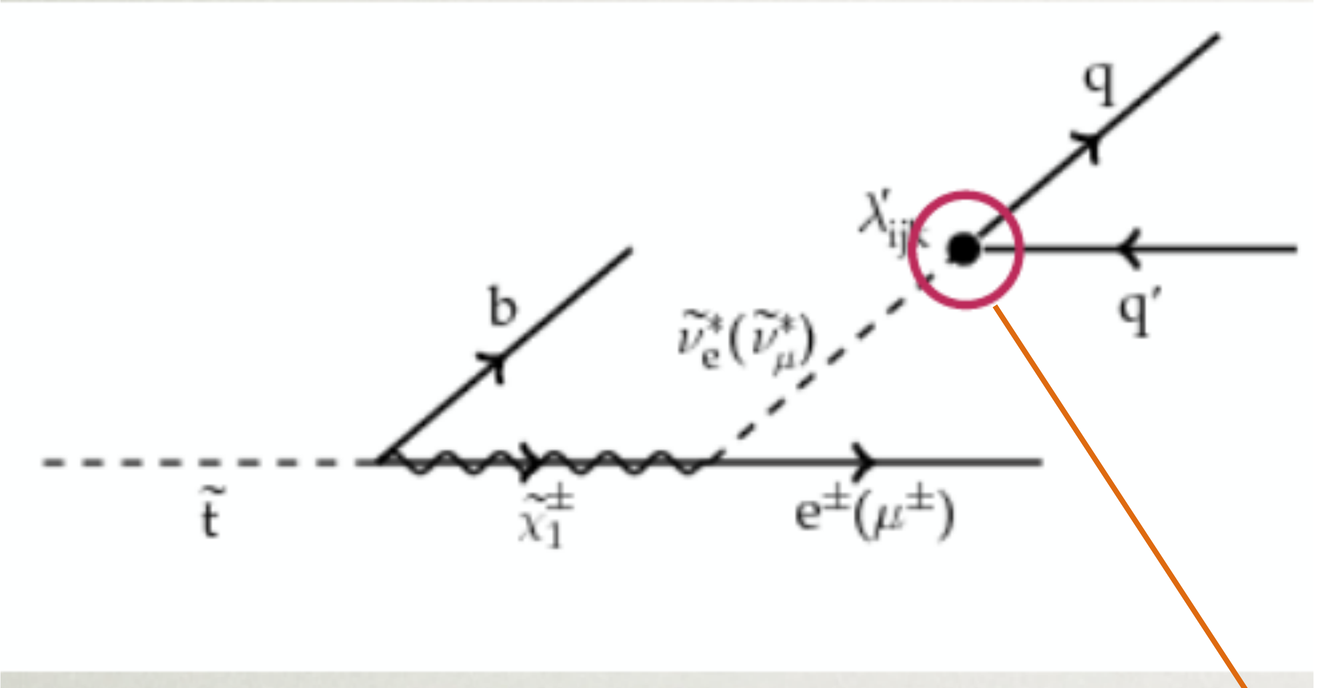

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Flavor structure of λ_{ijk} is arbitrary!

LLPs and Hierarchy Problem (I): Neutral Naturalness

- Expected "*supersymmetric*" LHC outcome: produce coloured particles (stops, gluinos), then electroweak ones (charginos, neutralinos) and finally the Higgs (because it goes via a dimension 5 operator).

- However, the particles canceling the top loops could simply be uncoloured (Twin Higgs, Orbifold Higgs, Quirky Little Higgs, Folded SUSY) or even fully SM singlets: Hyperbolic Higgs [Cohen, Craig, Giudice, McCullough, 1803.03647], Top Siblings [Cheng, Li, Salvioni, Verhaeren, 1803.03651].

- In all cases, glueballs are present and tend to be the leading signal

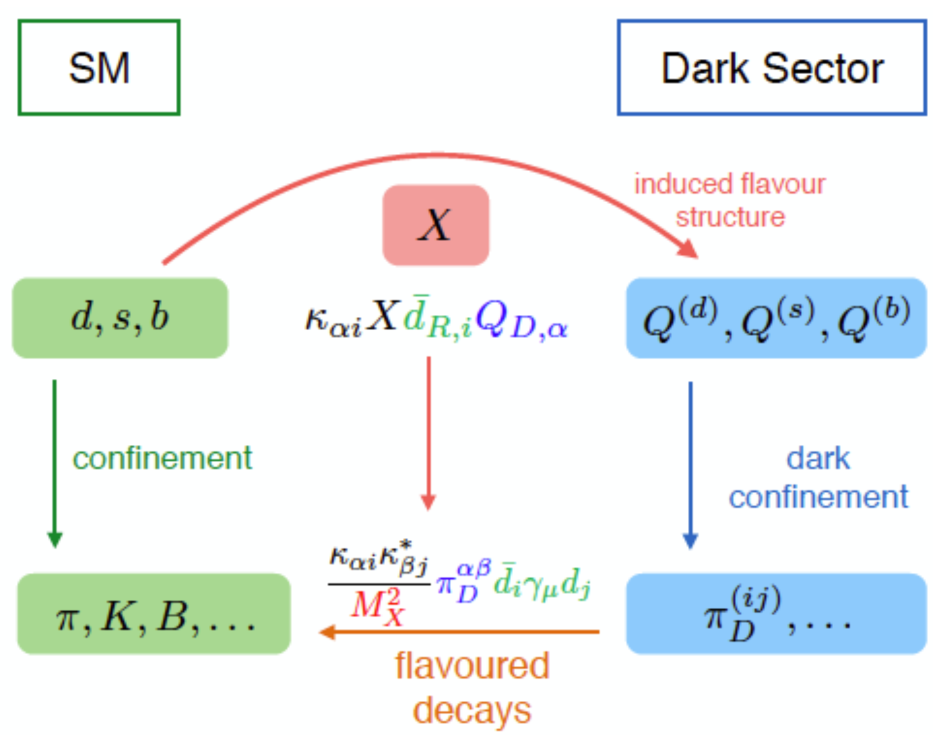
$$\tau \sim 4 \cdot 10^{-13}\,\mathrm{s} \left(\frac{5\,\mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^{9} \left(\frac{m_{\tilde{s}^c_\Delta}}{300\,\mathrm{GeV}}\right)^{4}$$

Cheng, Li, Salvioni, Verhaeren, 1803.03651

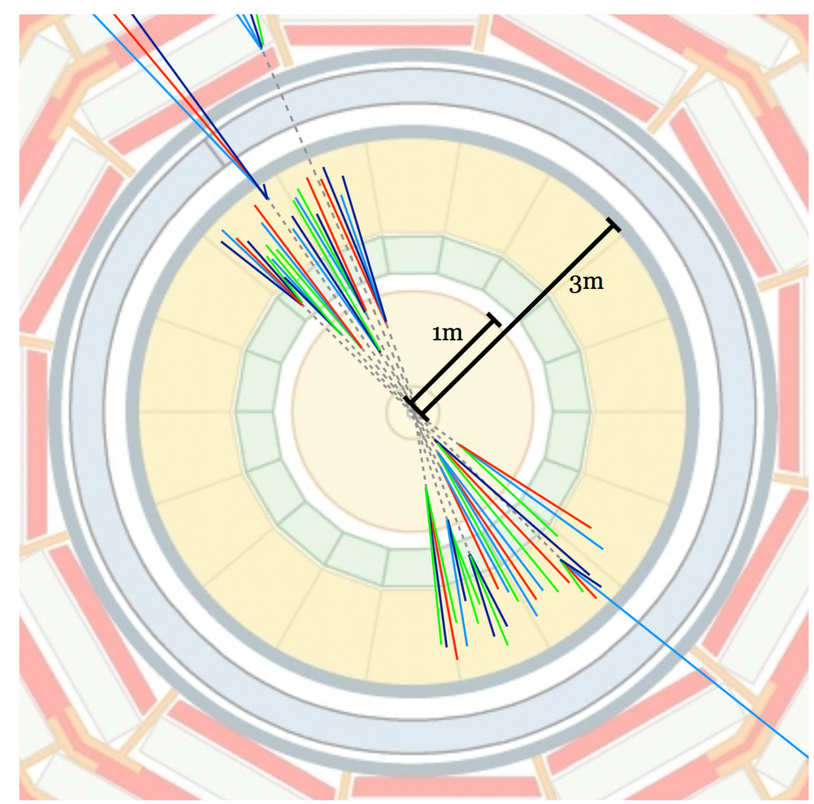
Very sensitive to precise values of $\Lambda_{QCD(B,C)}$ and m_Δ !

LLPs and … String Theory: Hidden Valley models

- String theory models live in 10+1 dimensions with larger gauge groups: SO(32), E8xE8,… so there is plenty of room to have in those constructions some SU(N) confining subgroup (helps to think in terms of QCD).
- The lightest HV meson will drive the pheno (pions if QCD):



Schwaller, Renner 1803.08080

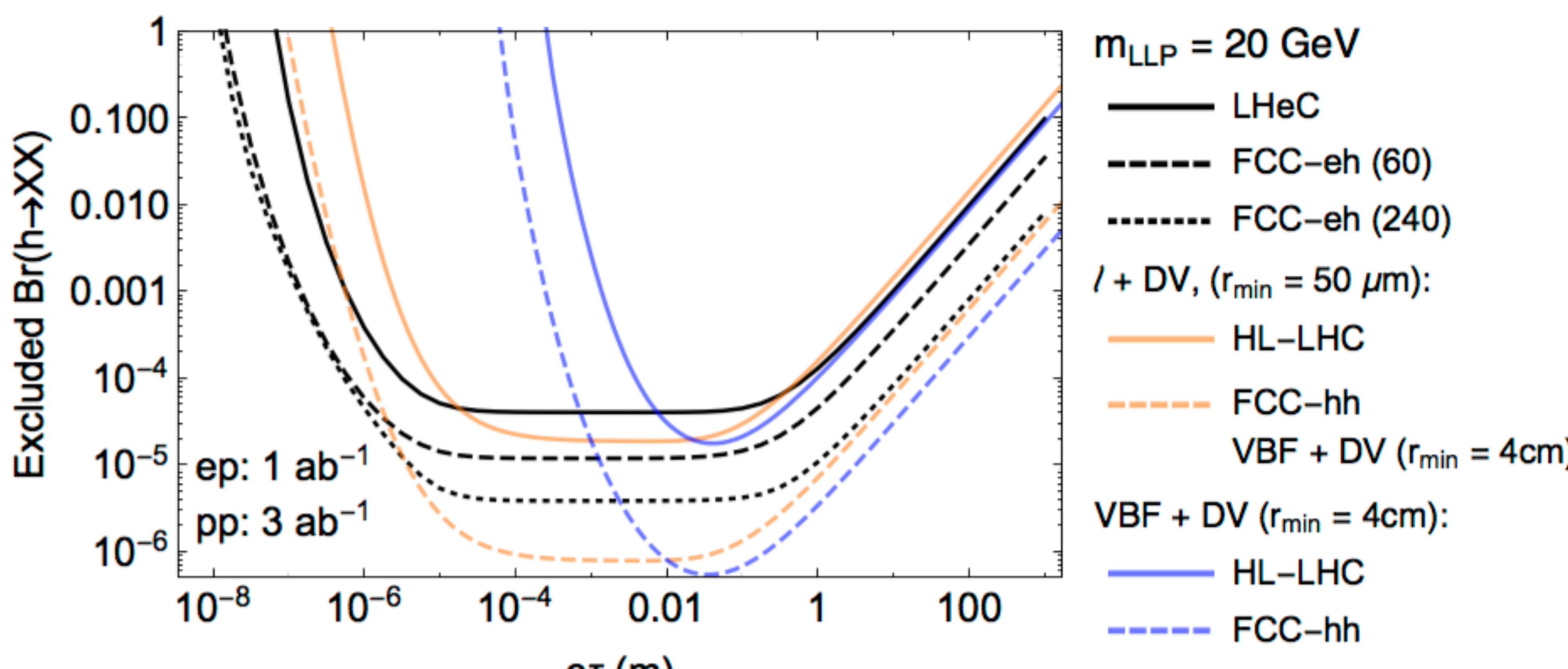


Schwaller, Stolarski, Weiler 1502.05409

- Dark sector can have extra U(1) bosons: current benchmark for displaced jets.

LLPs and …electron-proton colliders

- Electron-proton colliders provide the clean environment of an e^+-e^- machine with a CME larger by $(Ep/Ee)^{1/2}$ but lower by same amount than p-p machine.
- Hence their window of opportunity is narrow: they can only compete for physics cases where the high pile-up of a p-p collider affects the search, and the energy is on the high side e^+-e^- machine.
- Incredible useful to test O(μm) lifetimes; competes with p-p machines!



Curtin, Deshpande, Fischer, JZ:1712.07135

A few open issues

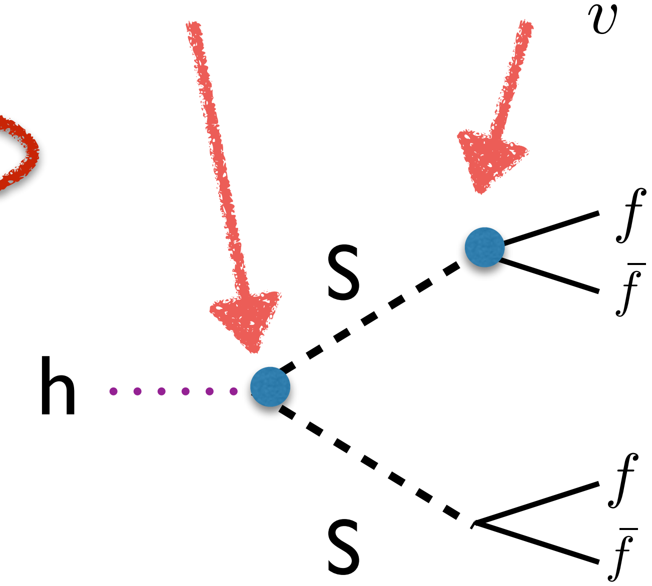
(with a slight preference for 3rd gen solutions)

Disclaimer

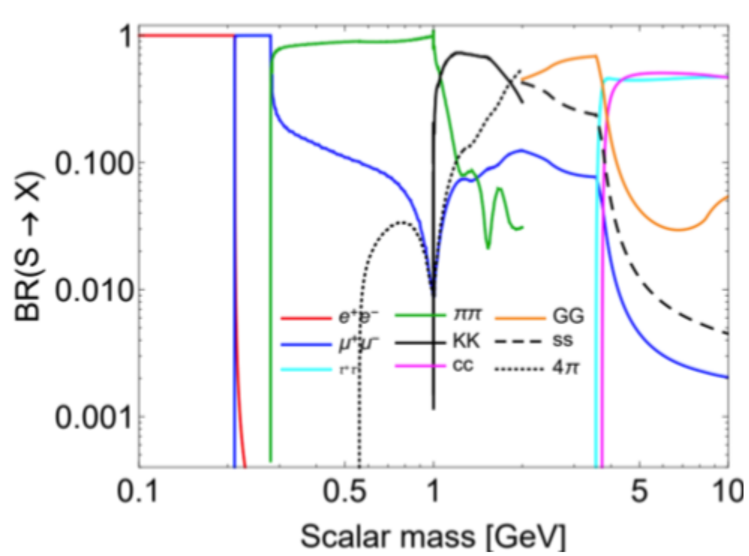
- This part is largely based on my own opinions and ideas, plus interesting discussions with many colleagues.
- I do not intend to point fingers and show a clear and concrete direction, but rather share my own musings… hoping they can trigger some spark!
- Always willing to take any discussion offline!

Why is the 3rd gen special?

$$\mathcal{L} \supset -\lambda_{SSh} h S^2 - \sin\theta \frac{m_f}{v} S\bar{f}f$$



- It could be the discovery mode:
  In "Higgs-like" theories (Higgs portal, HAHM) with minimal flavour violation, new scalars couple strongly to tt, bb, $\tau^+\tau^-$.
  SM Higgs decays 66% into 3rd gen!



I. Boiarska, K. Bondarenko, A. Boyarsky, V. Gorkavenko, M. Ovchynnikov, and A. Sokolenko, *Phenomenology of GeV-scale scalar portal*, arXiv:1904.10447.

S with $2m_\tau < m_S < 2m_b$ decays 1:1 into cc:$\tau^+\tau^-$!

- It is a must for signal characterization, even if we find NP before in 1st/2nd gen, e.g: DV(μ,μ), DV+MET, etc…

1-Displaced flavoured objects?

- Hadronic DVs searches do not identify jet flavour (leptonic DVs can distinguish *e* from *μ*).
- Naively: b-tagging based on B-meson lifetimes (“SM LLPs”). Hence we expect displaced b-jet ID to be a difficult task (particularly if the LLP lifetime lies in the near a SM LLP).
- However, flavour ID can be important in many cases!
- Higgs-like particles couple strongly to b-quarks, tops, tau leptons (if kinematics allow!)

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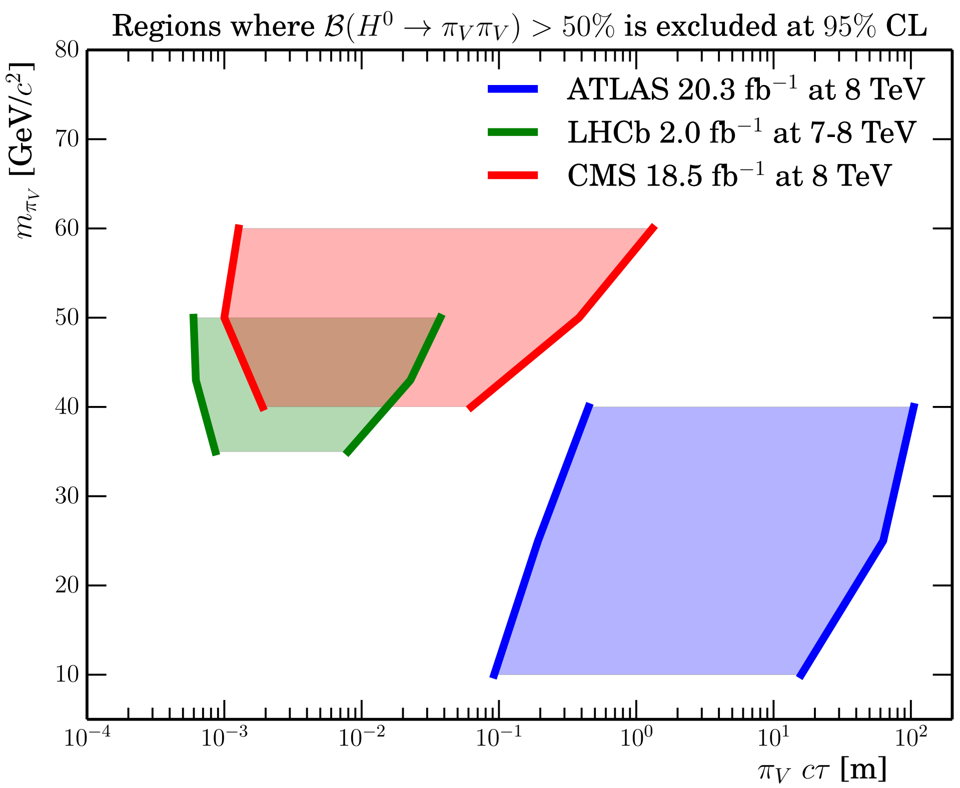
<u>Hadronic DV searches in Hidden Valley Model: Comparison of ATLAS, CMS and LHC.</u>



1) B-tagging on top of b-mesons can be complicated ($c\tau$ ~ 0.15 - 0.45 mm).

2) For larger $c\tau$, all non-b background: properly identifying displaced b-jets can drastically reduce the background while keeping 90% of the Higgs-like signal.

3) Analogous reasoning for H->ττ, 2 $m_\tau < m_H < 2\, m_b$

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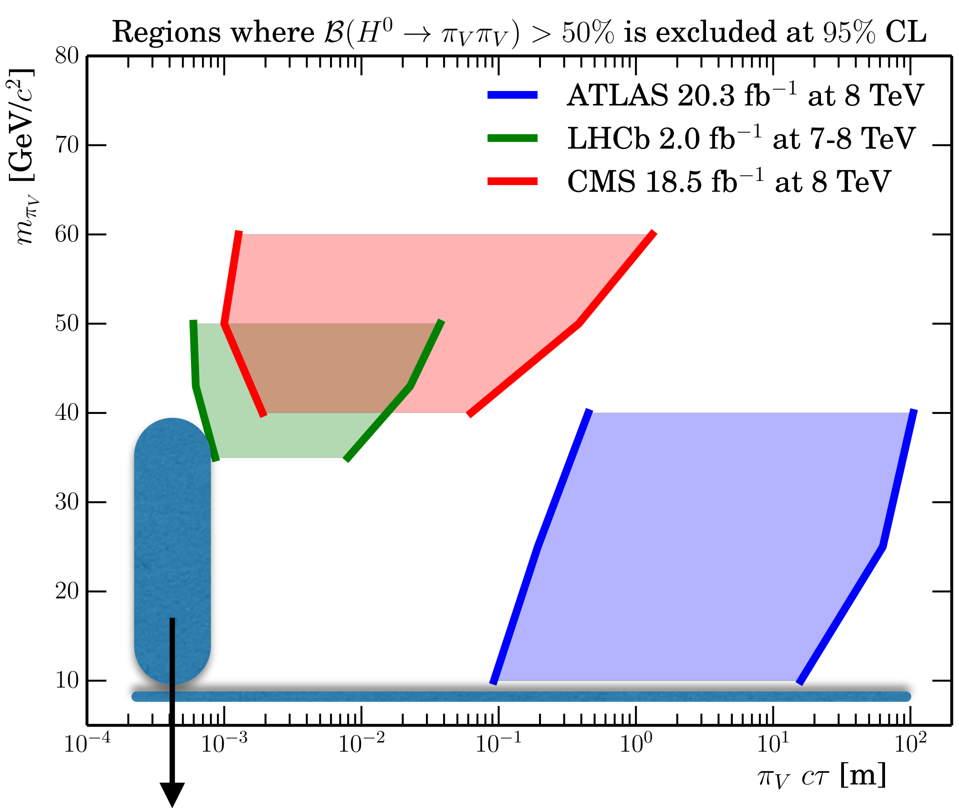
- Higgs-like particles couple strongly to b-quarks, tops, tau leptons (if kinematics allow!)

<u>Hadronic DV searches in Hidden Valley Model: Comparison of ATLAS, CMS and LHC.</u>



1) B-tagging on top of b-mesons can be complicated ($c\tau$ ~ 0.15 - 0.45 mm).

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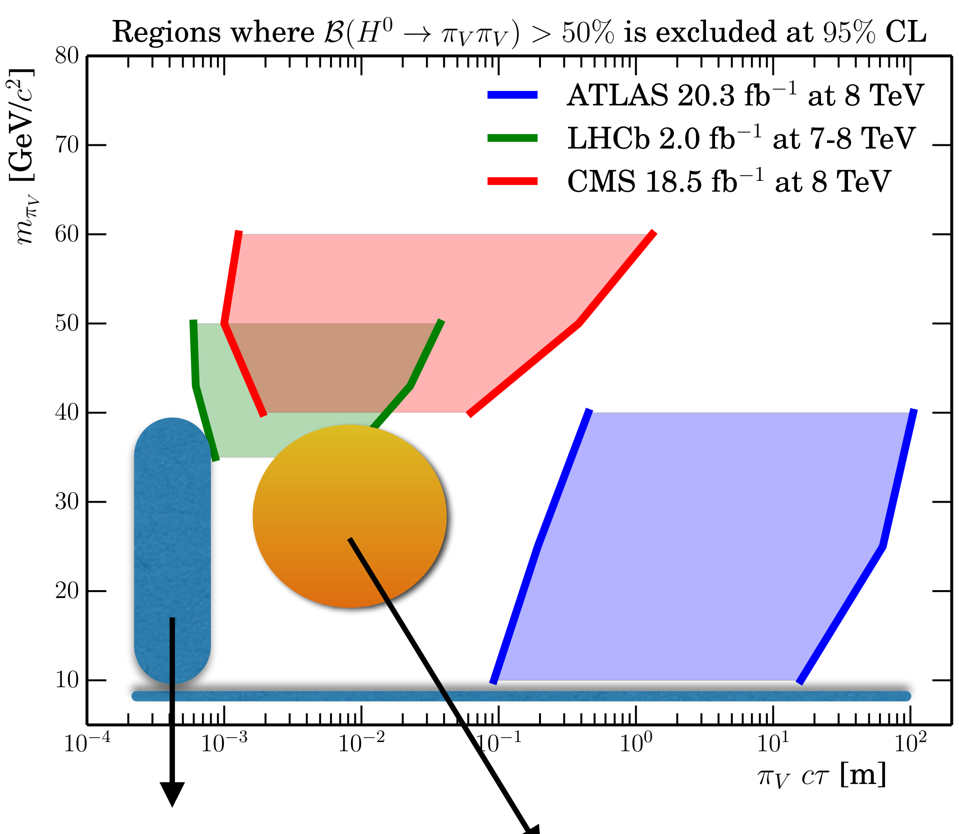

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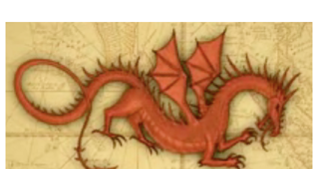


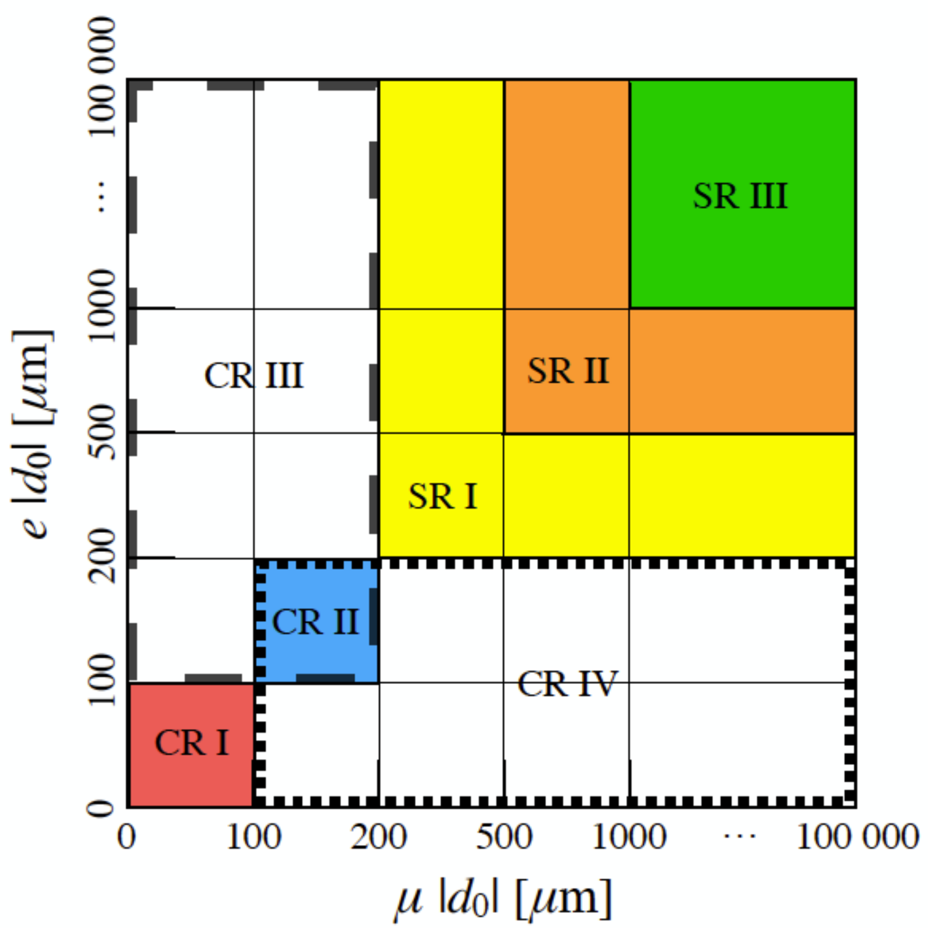
BR(H^0->bb) ~ 90%. Bgd: non-b mesons.
How well can we reject light displaced jets?

2-Soft displaced leptons?

Based on CMS Displaced e-μ search, EXO-16-022-pas

The CMS Displaced Lepton search (DLS) uses exactly 1e and 1μ.

What about τs?



The plot is valid for pT(e, μ) > 40 GeV.

To have LLPs with Δ~40 GeV we need tiny couplings (phase space too large!). Indeed the search is benchmarked with RPV stops, but it also works for e.g: freeze-in dark matter Evans, Shelton, 1601.01326, Belanger, Desai, Goudelis, Harz, Lessa, No, Pukhov, Sekmen, Sengupta, Zaldivar,JZ, 1803.10379 + in preparation

If we want to consider a compressed phase space, as the one arising from dark matter models, or theories with new electroweak multiplets:

1) How would this plot look like to pT = 5, 10, 20, 30 GeV?
2) How strict is the d0 < 200 μm region?

LLPs + X:

LLPs and Neutrino Masses

LLPs and Machine Learning

LLPs and Extra U(1)s

LLPs and Dedicated Experiments

LLPs and…

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LLPs+Google images →

Conclusions

- Long lived particles (LLPs) are theoretically well motivated: ubiquitous in models trying to solve fundamental problems of the SM.

- There is no “no-lose” theorem for LLPs (also true for BSM), but concrete incarnations do point to LHC testable mass-coupling ranges.

- From a theoretical perspective is relatively simple to have models that couple preferentially to the 3rd generation (Higgs portal).

- From an experimental perspective 3rd generation displaced objects pose a challenge, but a comprehensive LLP program at the LHC requires dedicated searches for LLPs->3rd gen.

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What about taus???