Workshop summary:

Long-Lived Particles and the Third Generation

Edinburgh PPE Christmas Meeting / 13 December 2019

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Andreas Søgaard, Akanksha Vishwakarma, Estifa'a Zaid

University of Edinburgh

erc
European Research Council
Established by the European Commission

Workshop

- Focused workshop (≈ 20 attendees), held 20–22 Nov. 2019 at the Higgs Centre of Theoretical Physics, co-funded by ERC Grant and the Higgs Centre (Indico page)
- Dedicated to theoretical work on, and experimental challenges facing, collider searches for long-lived particles (LLPs) coupling to 3rd generation fermions, emphasis on τs
- Mainly aimed at theorists, with experimental input from Edinburgh group and a few invited speakers
- Sinéad reported on the workshop at the recent LHC LLP Community Workshop in Ghent

Context

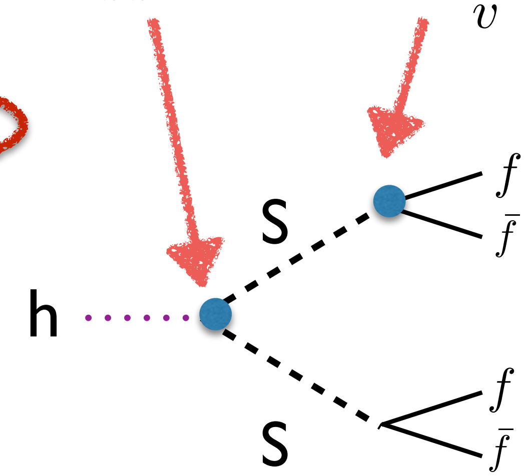
- LLPs are well-motivated
  - **theoretically,** as a broad set of new physics models (*e.g.* dark sector, heavy neutral leptons) give rise to long-lived signatures, and
  - **experimentally,** as prompt searches at ATLAS/CMS have not yielded signs of new physics, but we might be "blind" to unconventional processes *e.g.* involving LLPs

Context

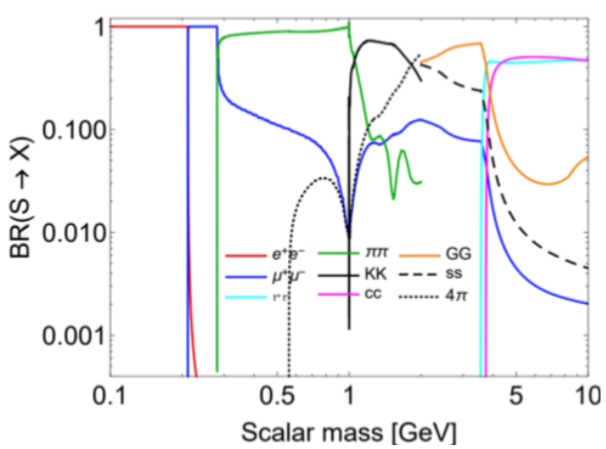
- Much attention (experimentally and theoretically) devoted to LLP decays to 1st and 2nd generation fermions
- Less so to 3rd generation, though it has special reasons to be a significant part of the LLP story
- Sinéad's team in Edinburgh are working on her ERC project (OPEN3GEN), started in 2019, to develop experimental sensitivity to LLPs decaying to τs in ATLAS
- Part of that project is to host theorists at 3 workshops over the 5 year project, to discuss ideas and model benchmarks

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…

Aims of workshop

1. **Identify existing benchmark theoretical models** for LLPs decaying to 3rd generation particles that LHC experiments (and others) should target
2. **Identify areas which are ripe for further work** in theory and/or phenomenological studies
3. **Foster a community** who will meet twice more during the lifetime of Sinéad's ERC grant to discuss the theoretical issues in the search for LLPs decaying to 3rd generation

Outline

1. Overview of five theory talks motivating searches for LLPs coupling to 3rd generation fermions
2. Complementary, signature-focused search approach
3. Experimental challenges
4. Model independence

Point 1

Theory talks searches for LLPs coupling to 3rd generation

1.1 · LLPs as DM co-annihilation partners

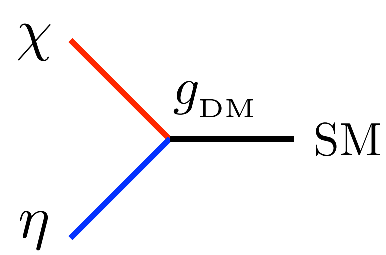
Kazuki Sakurai

Co-annihilation

χ : Dark Matter (DM): → **singlet**

η : Co-Annihilation Partner (CAP): → **coloured or weakly charged**

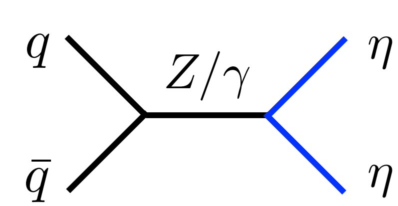
$$\mathcal{L} \supset g_{\rm DM} \cdot \chi \, \eta \, ({\rm SM})$$

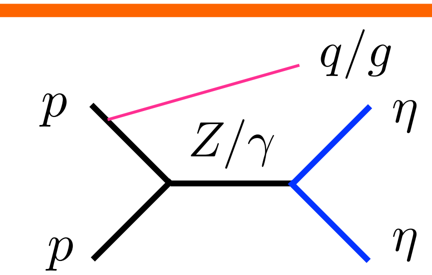


Experimental Signatures

$$\mathcal{L} \supset g_{\rm DM} \cdot \chi \, \eta \, ({\rm SM})$$

- For small $g_{\rm DM}$, the interaction between DM and SM becomes very weak.
- The sensitivities for direct and indirect detections are very low.
- The production rate for direct DM production at the LHC is also very small.
- Since CAP is charged under the SM gauge group, the production rate for CAP is unsuppressed at the LHC.



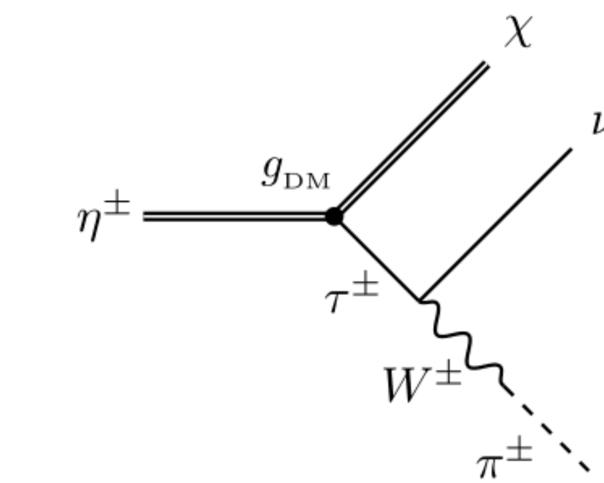


- Co-annihilation partner (CAP) *e.g.* weakly charged as "stau" ($\tilde{\tau}$) coupling to SM τ and DM candidate

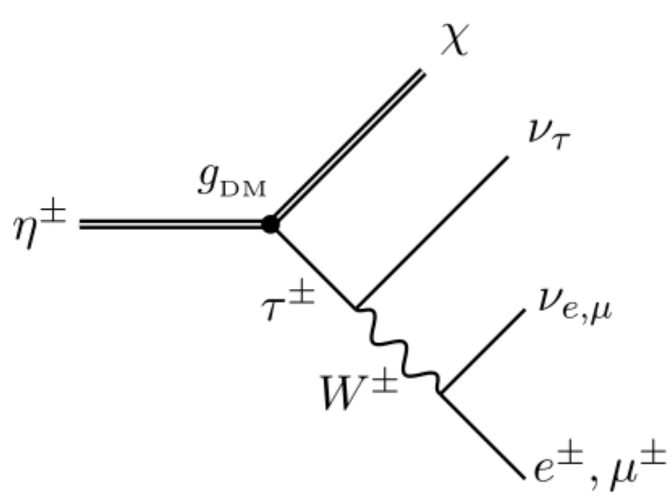
1.1 · LLPs as DM co-annihilation partners

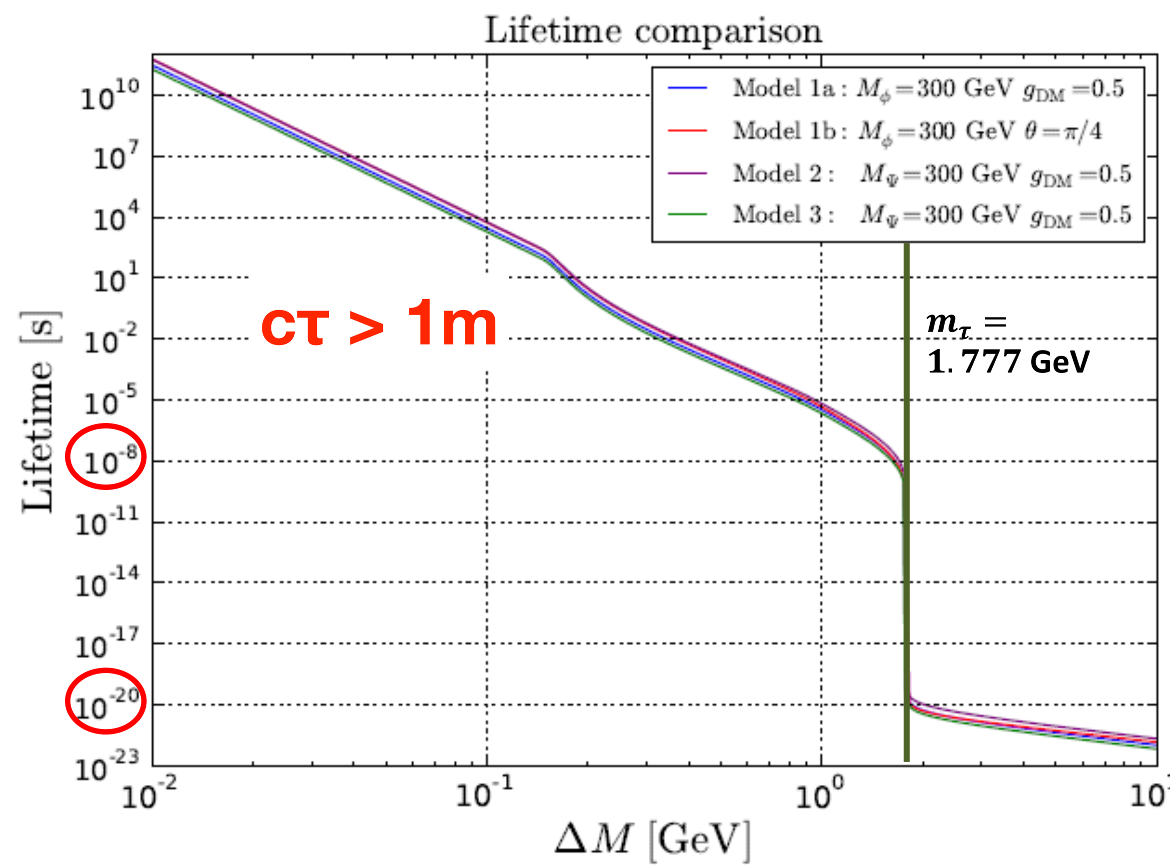
Lifetime in tau-philic models

$$\mathcal{L} \supset g_{\rm DM} \cdot \chi \, \eta \, \tau$$



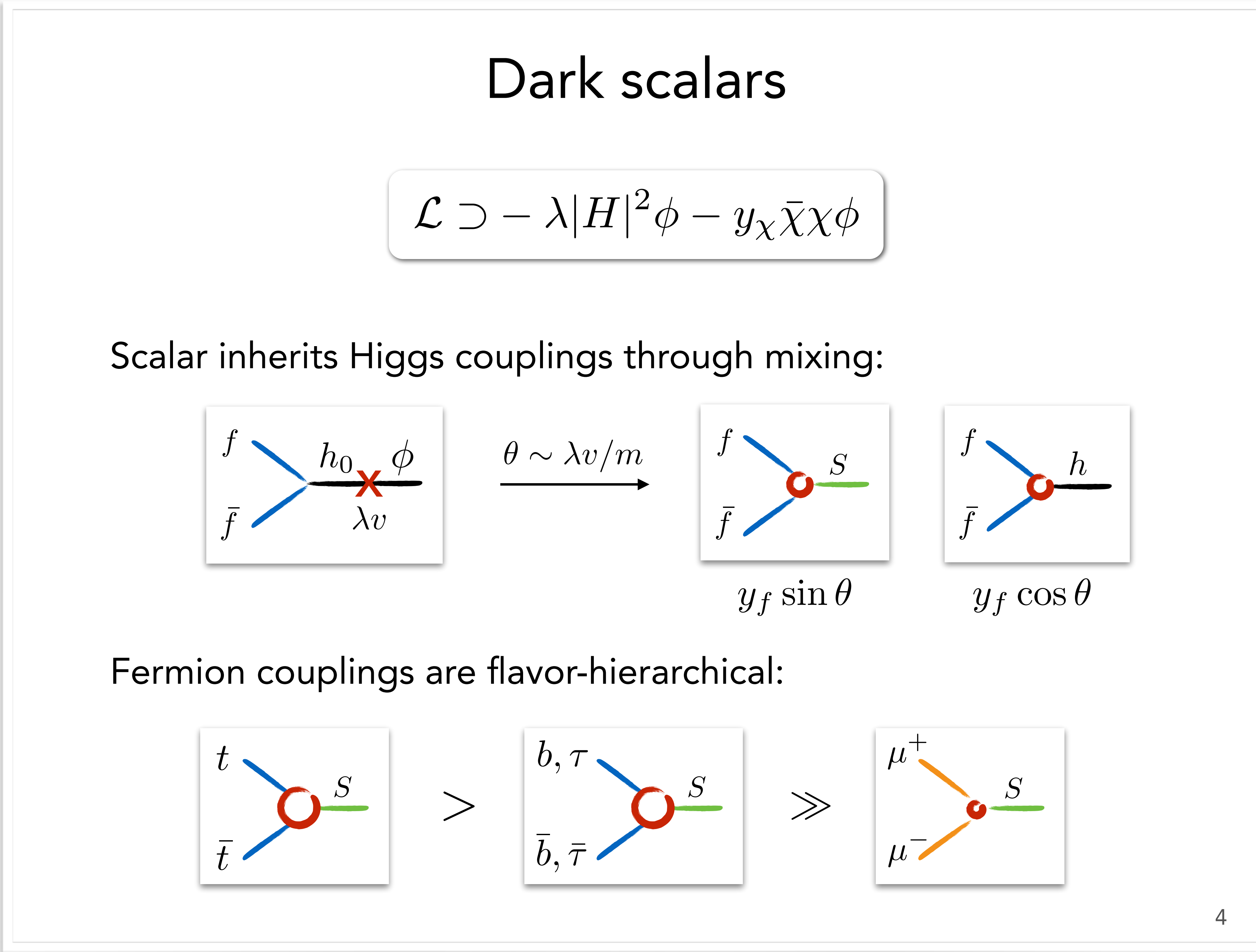
Also ρ and a_1 mesons





- For τ-philic CAPs (η) with $|m_\eta - m_\chi| < m_\tau$, CAP is long-lived
- Pair-produced CAPs each decay to τ + DM (“invisible”)

Susanne Westhoff

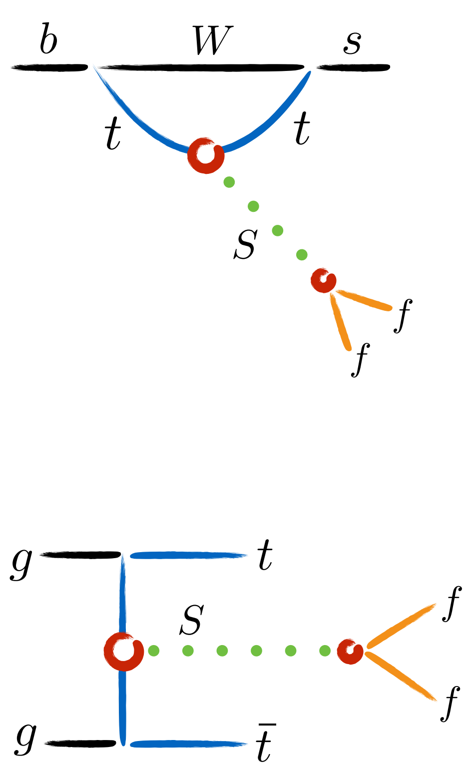


- Dark scalar inherits Higgs' Yukawa-type couplings, $g_{Sff} \sim m_f$
- Favours 3rd gen. fermions, τ for light ($2m_\tau < m_S < 2m_b$) scalar

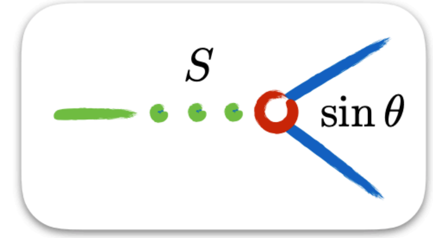
1.2 · LLPs as dark scalars

Susanne Westhoff

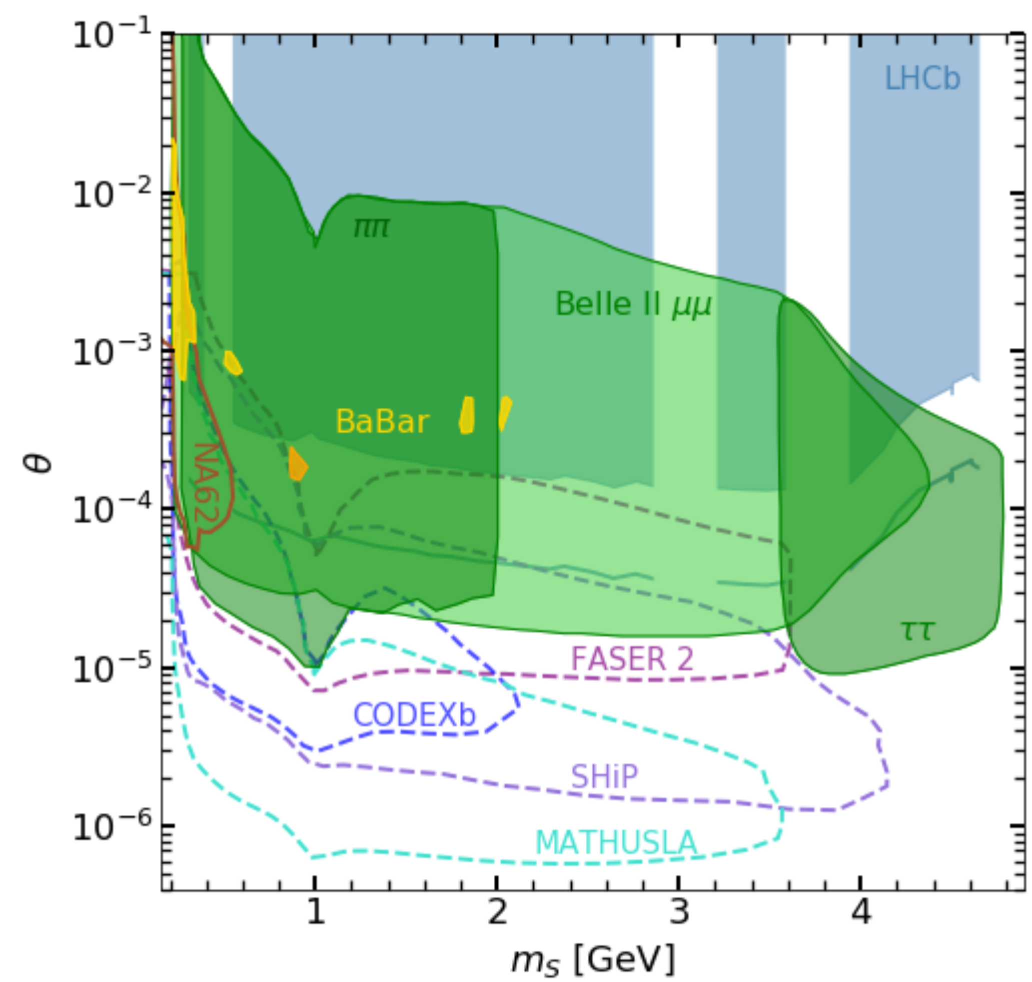
Signatures of long-lived dark scalars



Evans et al. 2017; Winkler 2018



Compare with long-baseline experiments



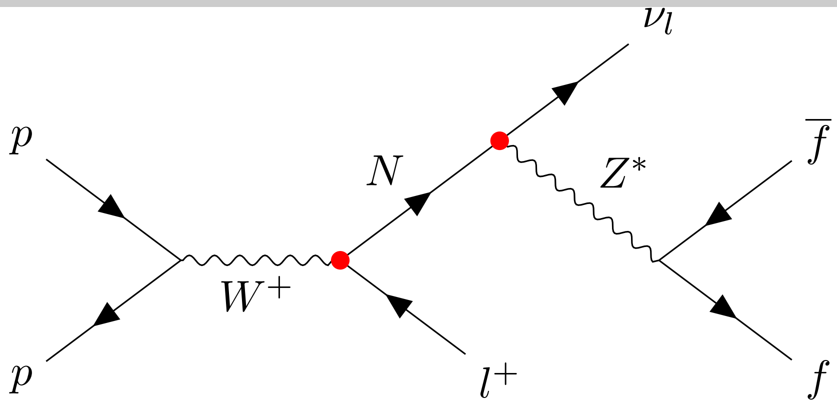
Filimonova, Schaefer, Westhoff 2019 11

- Long-lived dark scalar: small Higgs mixing, θ
- Low direct production rates at *pp* experiments

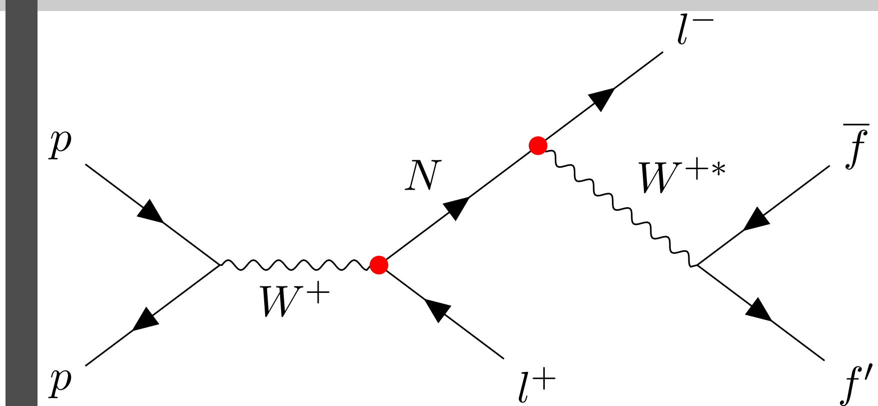
1.3 · LLPs as heavy neutral leptons

Signature

Z-decay



W-decay



Search strategy

- trigger on first lepton
- search for secondary vertex

Displaced vertex reconstruction

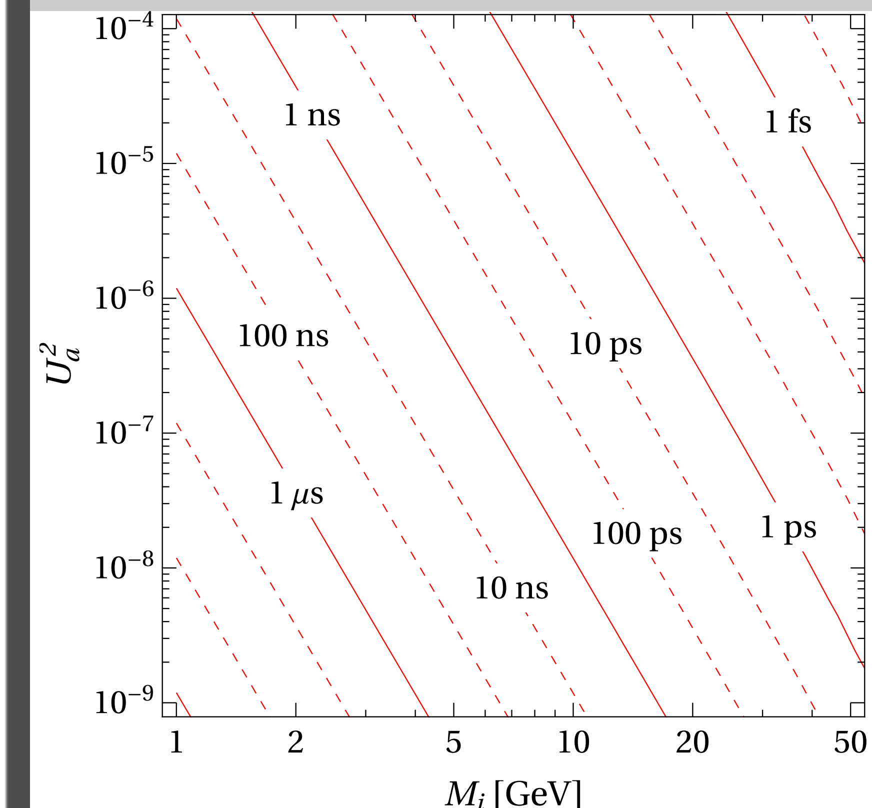
- at least 2 tracks
- invariant mass of 5 GeV (in order to suppress nuclear interactions backgrounds)
- particles must transverse at least half of the tracker
- or the complete muon chamber

Muon chamber [Bobrovskyi et al. 2011; CMS 2015]

- muon chamber reaches farther than tracker
- long lived particles can be search for using only muon chambers

Properties

Lifetime



Decay width for $M \gg 5$ GeV

$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U_a^2 M^5 \,,$$

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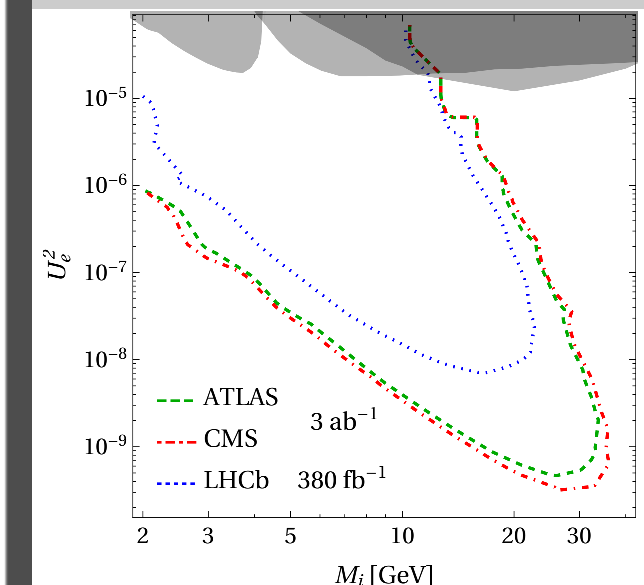
- Neutrino-like interactions; prompt ℓ + displaced ℓ/ν + W/Z
- For low masses, couplings HNLs can achieve large lifetimes

1.3 · LLPs as heavy neutral leptons

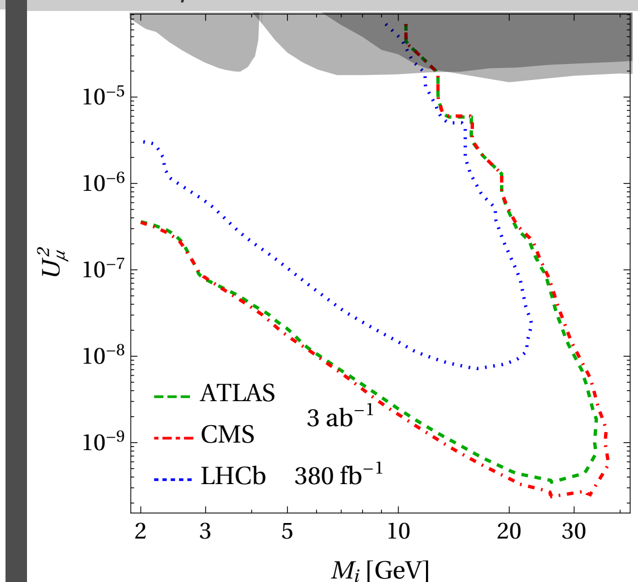
Jan Hajer

Maximal exclusion reach

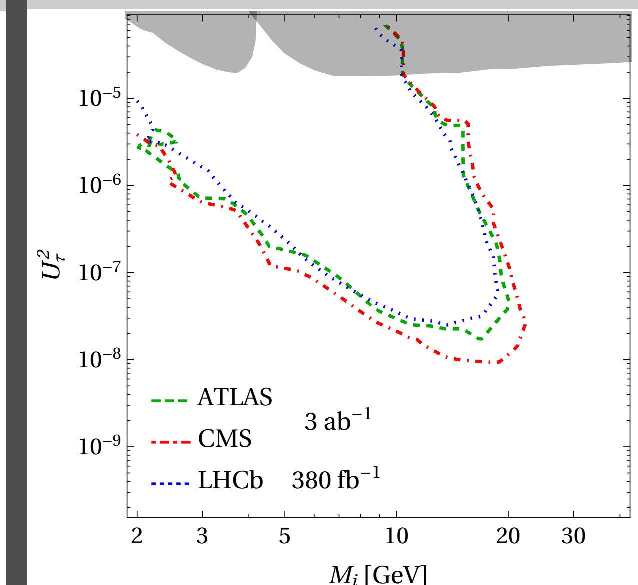
pure U_e^2



pure U_μ^2



pure U_τ^2



p_T^{min} of ATLAS single lepton and lepton pair triggers [ATLAS 2017]

	Single Lepton			Lepton Pair					
	e	μ	τ	e, e	e, μ	e, τ	μ, μ	μ, τ	τ, τ
p_T^{min} [GeV]	27	27	170	18, 18	8, 25 18, 15	30, 18	15, 15 23, 9	30, 15	40, 30

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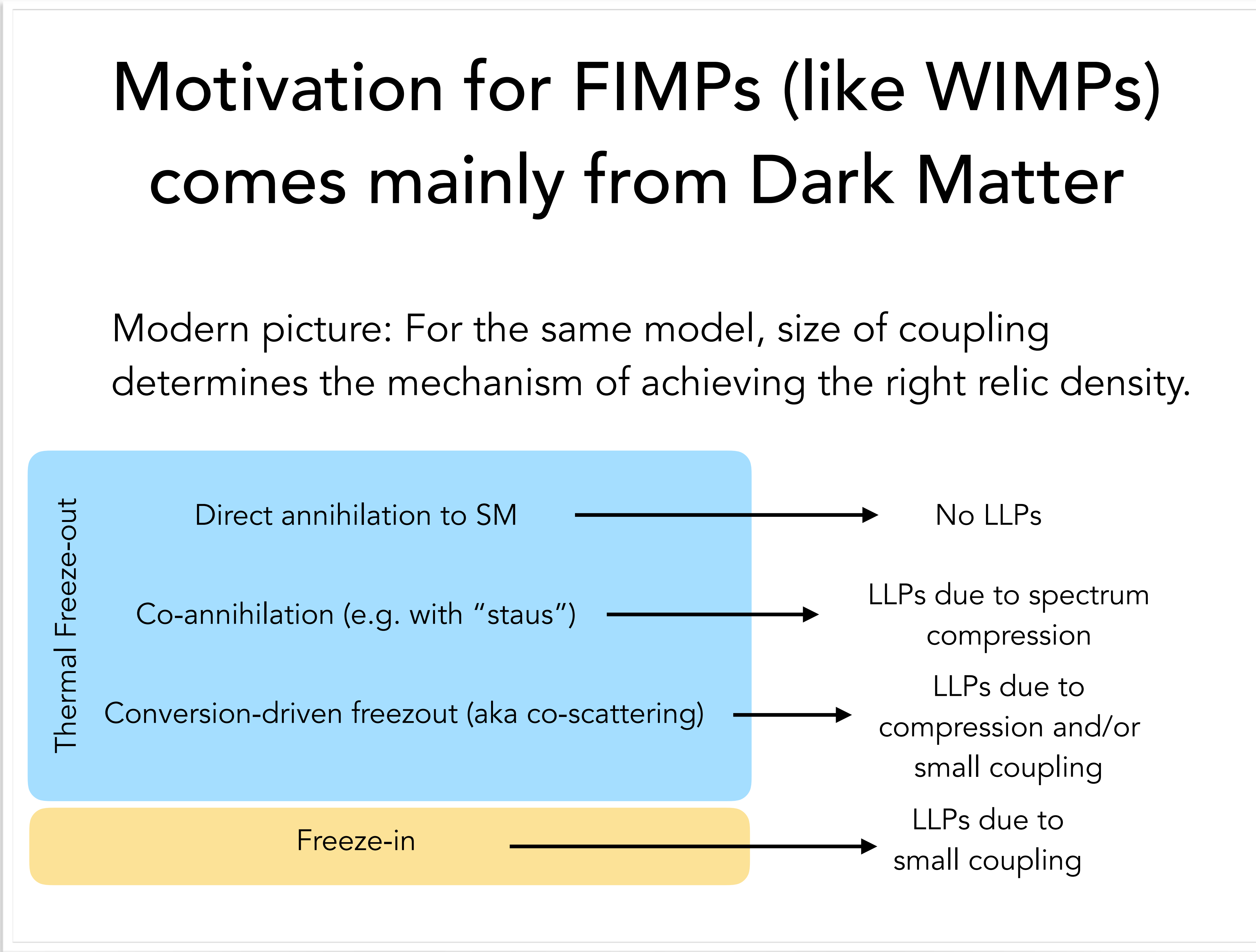
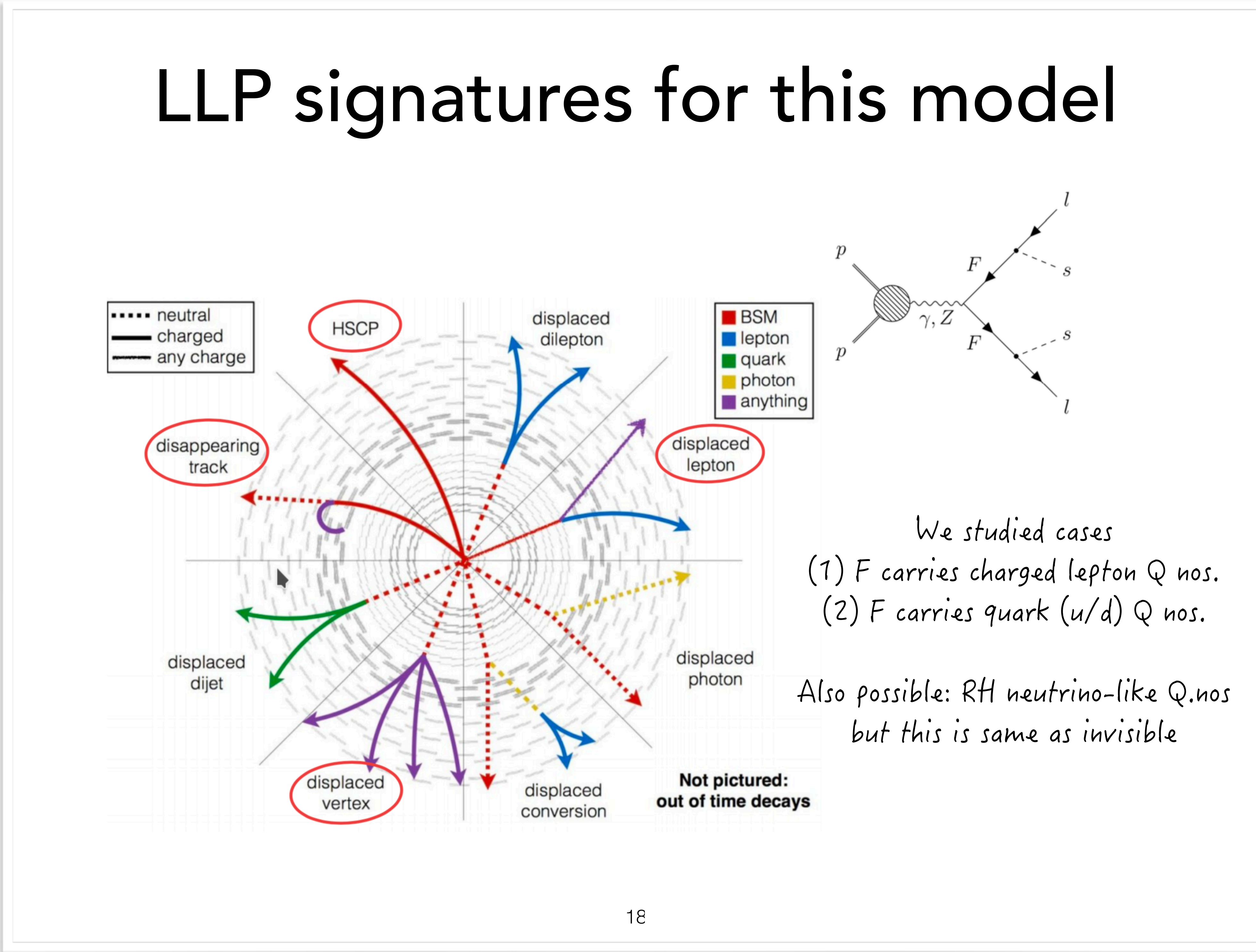
- e/μ-mixing HNL well-constrained by ATLAS/CMS
- Currently quite limited sensitivity to U_τ^2 — potential!



- Feebly interacting massive particles (FIMPs) as DM candidate characterised by tiny couplings to SM

1.4 · LLPs as FIMP mediators

Nishita Desai



- Next-to-minimal FIMP model requires mediator (*F*) with SM quantum nos. (cf. Sakurai), small FIMP coupling → LLP

1.4 · LLPs as FIMP mediators

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/μμ(/ττ) regions for full coverage of model.

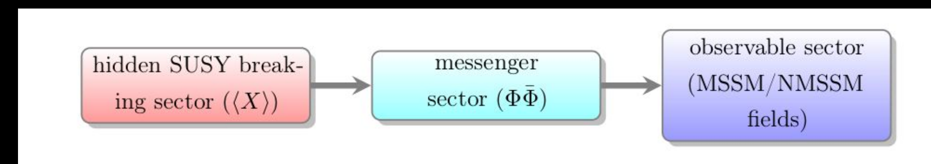
- Models, current displaced lepton searches focused on *e/μ*
- Possible and important to extent coverage to 3rd generation

1.5 · LLPs to *bs* and analysis recasting

Giovanna Cottin

Next-to-minimal Supersymmetry with Gauge Mediation predicts neutral long-lived particles in decay chains ending in b-quarks

A 125 GeV higgs constraints SUSY model building.
Light sparticle spectrum possible in non-minimal models.
In this talk the focus is the DGS Model:



$$W_{\rm NMSSM} = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$W_{\rm GM} = X \sum_{i=1,2} \left(\kappa_i^D \bar{\Phi}_i^D \Phi_i^D + \kappa_i^T \bar{\Phi}_i^T \Phi_i^T \right)$$

$$W_{\rm DGS} = S \left(\xi_D \bar{\Phi}_1^D \Phi_2^D + \xi_T \bar{\Phi}_1^T \Phi_2^T \right)$$

Only 4 free parameters !

$$\lambda,\ \tilde{m},\ \xi,\ M$$

NMSSM +Gauge Mediation+Direct Singlet Messenger Couplings = DGS Model

Delgado, Giudice, Slavich
Phys. Lett. B 653 (2007) 424

In the DGS model, a new contributions to the Higgs mass appears

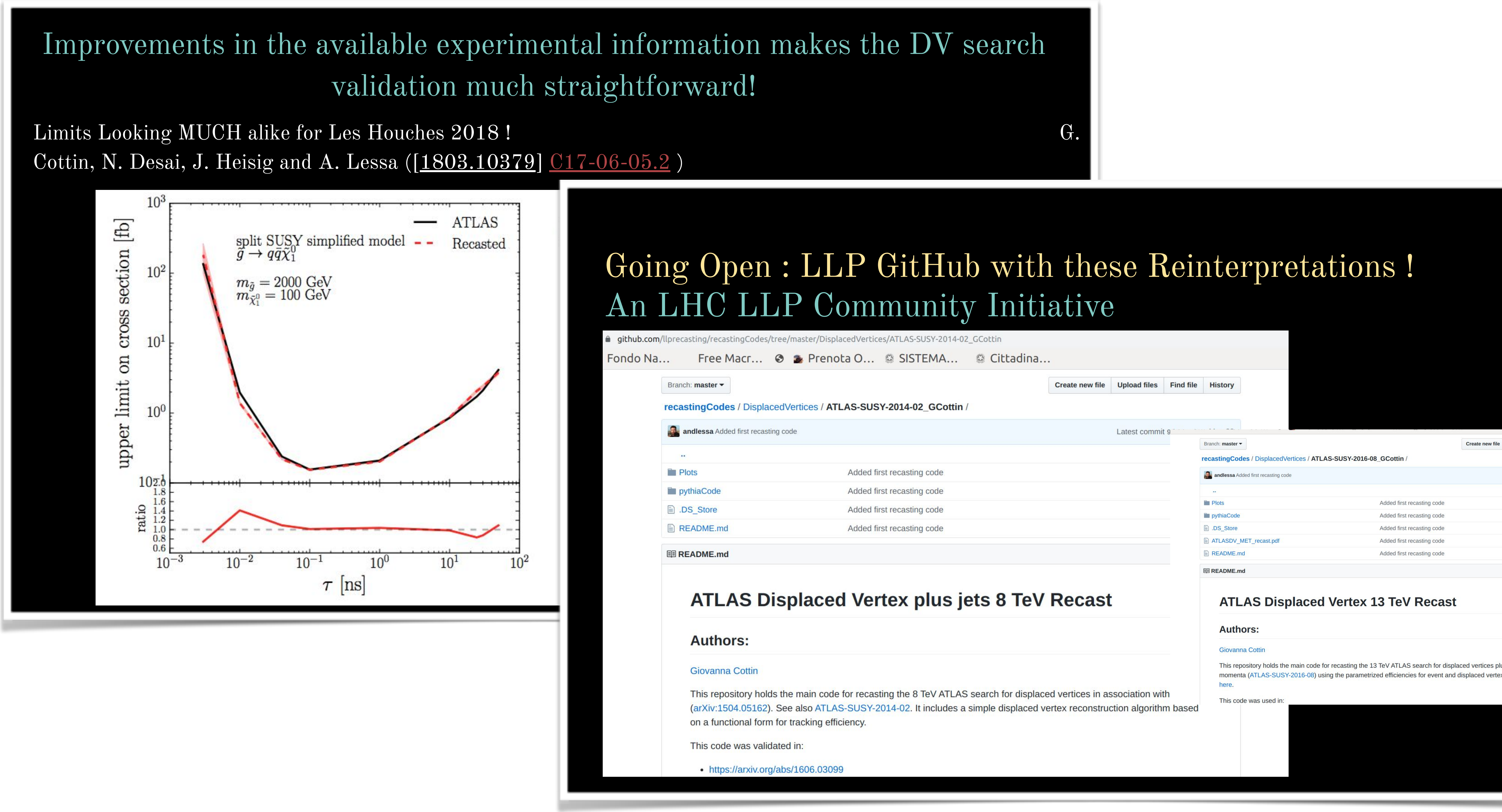
Allanach, Badziak, Hugonie, Ziegler
Phys.Rev. D92 (2015) 1, 015006

This leads to a very light singlet-like pseudo scalar(~20 GeV) and a ~100 GeV singlino NLSP

- Proposed SUSY model results in displaced signatures due to light pseudo-scalar NLSP favouring later generations

1.5 · LLPs to *bs* and analysis recasting

Giovanna Cottin

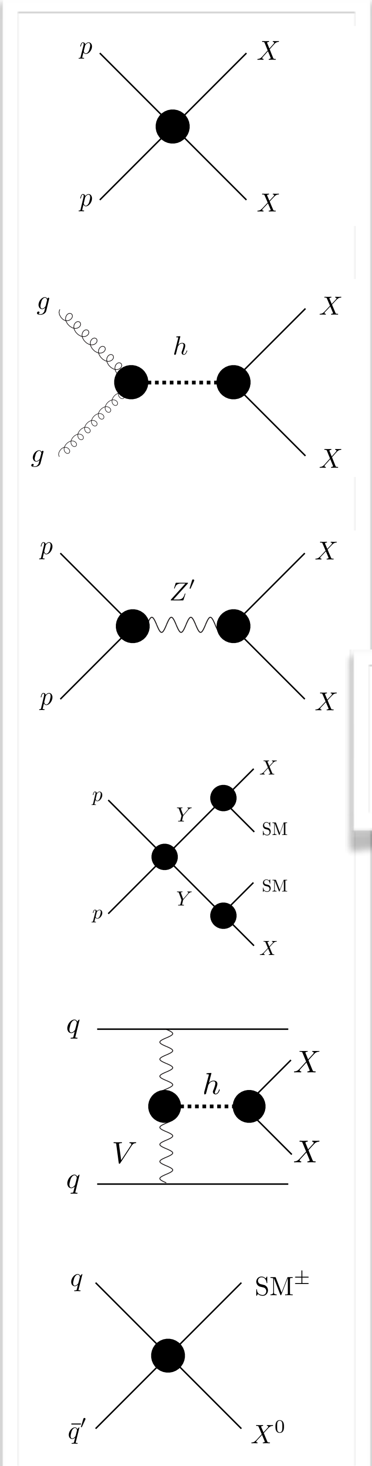


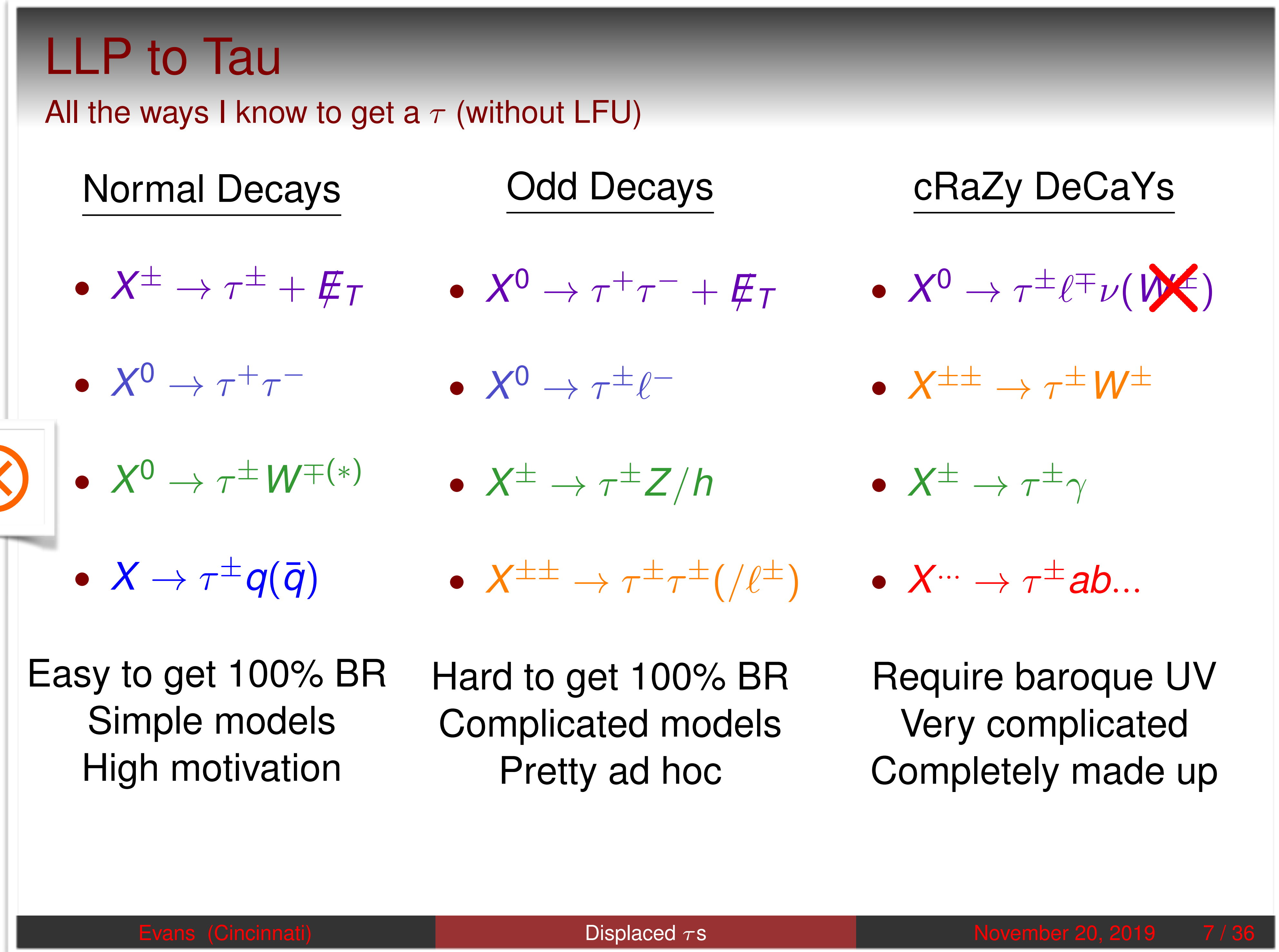
- Better public analysis info. (*e.g.* parametrised signature effs.) making reinterpretations much easier — see GitHub repo

Point 2

Complementary, signature-focused search approach

2 · Signature-focused searches





- Useful to factorise LLP production from decays
- Several simple, well-motivated LLP decays to τs

2 · Signature-focused searches

Summary

- Displaced τs are a challenging (but necessary place) to find BSM
- $X^0 \to W^\pm \tau^\mp$, $X^0 \to \tau^+\tau^-$, and $X^\pm \to \tau^\pm + \not{E}_T$ are well motivated
- Other models (of varying quality) exist
- Sensitivity to $\tilde{\tau}_R$ can be improved in the CMS $e^\pm\mu^\mp$ search
  - Add SFℓ bins
  - Add τ_h bins
  - Lowered p_T thresholds
  - Extend $d_0 > 2$ cm
  - Add SSℓ bins (CR contamination)
  - Allow extra ℓs
  - Relax isolation in high d_0 bins
  - Add high $p_{T,\ell}$ bins (didn't discuss)
- These highlight the value of considering multiple benchmarks
- Motivated $h \to aa \to (\tau^+\tau^-)(\tau^+\tau^-)$ is a big gap at LHC
- A lot of work still needs to be done on displaced τs!

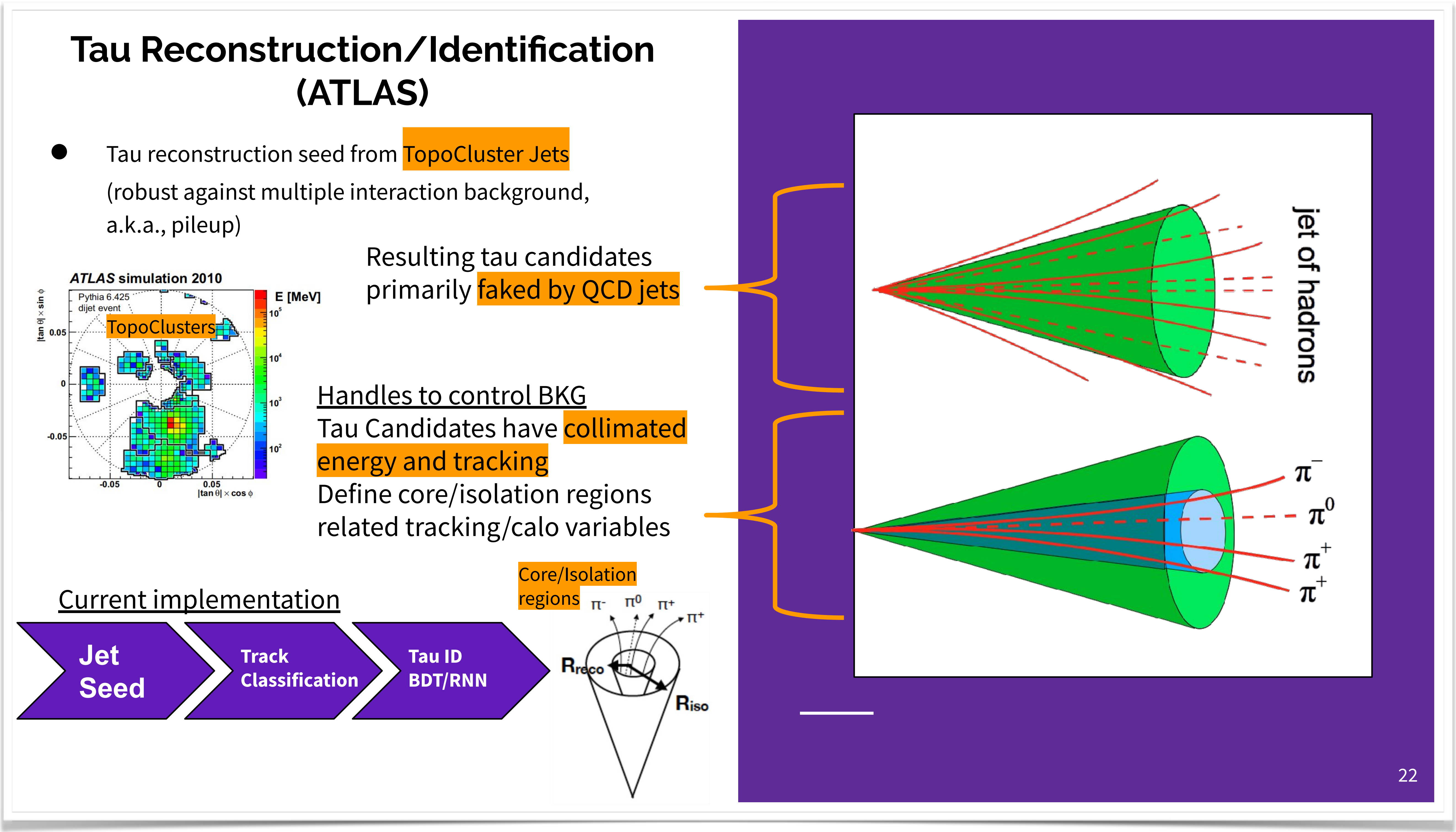
Evans (Cincinnati) | Displaced τs | November 20, 2019 | 36 / 36

- Construct benchmark models from these "LEGO blocks"
- Current LHC searches have limited sensitivity to many of these

Point 3

Experimental challenges

Guillermo Hamity
John Stupak



- Trigger + offline ID for displaced τ decays to hadrons
- ML-based algs. trained on prompt Z/γ; applied "out-of-domain"

Point 4

Model independence

4 · Model independence

UCL

Issues with complex variables & algorithms

- BDTs, Machine Learning &c
- Can they be referred back to a model independent particle-level object? *e.g.*
  - Efficiency = *(truth pass) AND (reco pass)* / *(truth pass)*
  - How do we (can we) evaluate "truth pass"?
  - How model independently can we do that?
- NB: In principle, there can be "truth level" backgrounds.

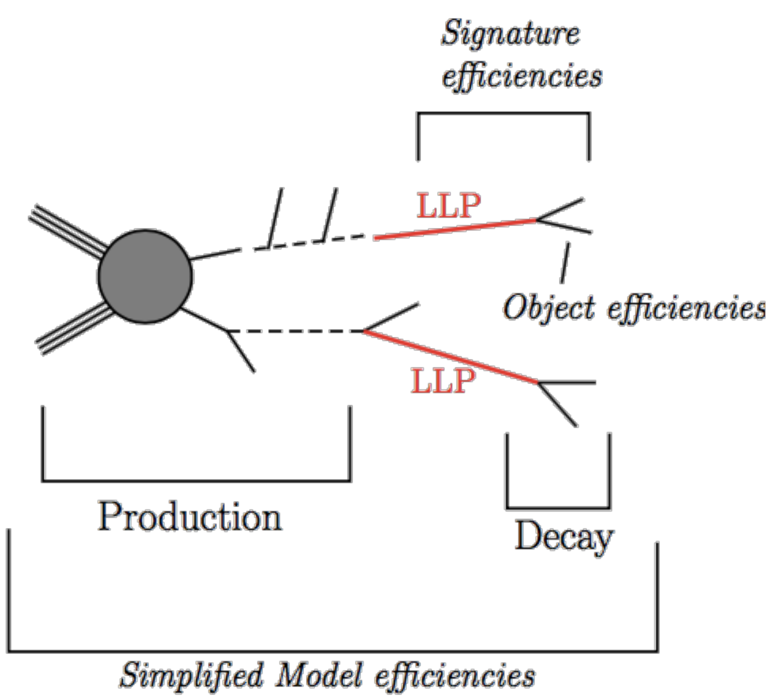
Nov 2019

- Use of "black box" methods (NNs) complicates reinterpretation
- Still, possible to parametrise efficiency for particle-level objects

4 · Model independence

Factorising effiencies?

- Event selection efficiency
  - Can be independent of LLP decay
  - Will be dependent on LLP production model
- Tau efficiency (vs d0, p_T etc)
  - Can be independent of LLP production model (within some fiducial kinematic region)
- Final-state particle efficiency (vs d0, p_T etc)
  - Won't tell you about event efficiency
  - Can be used to build efficiencies for many models; ideal for reinterpretation?



arXiv:1903.04497

Nov 2019

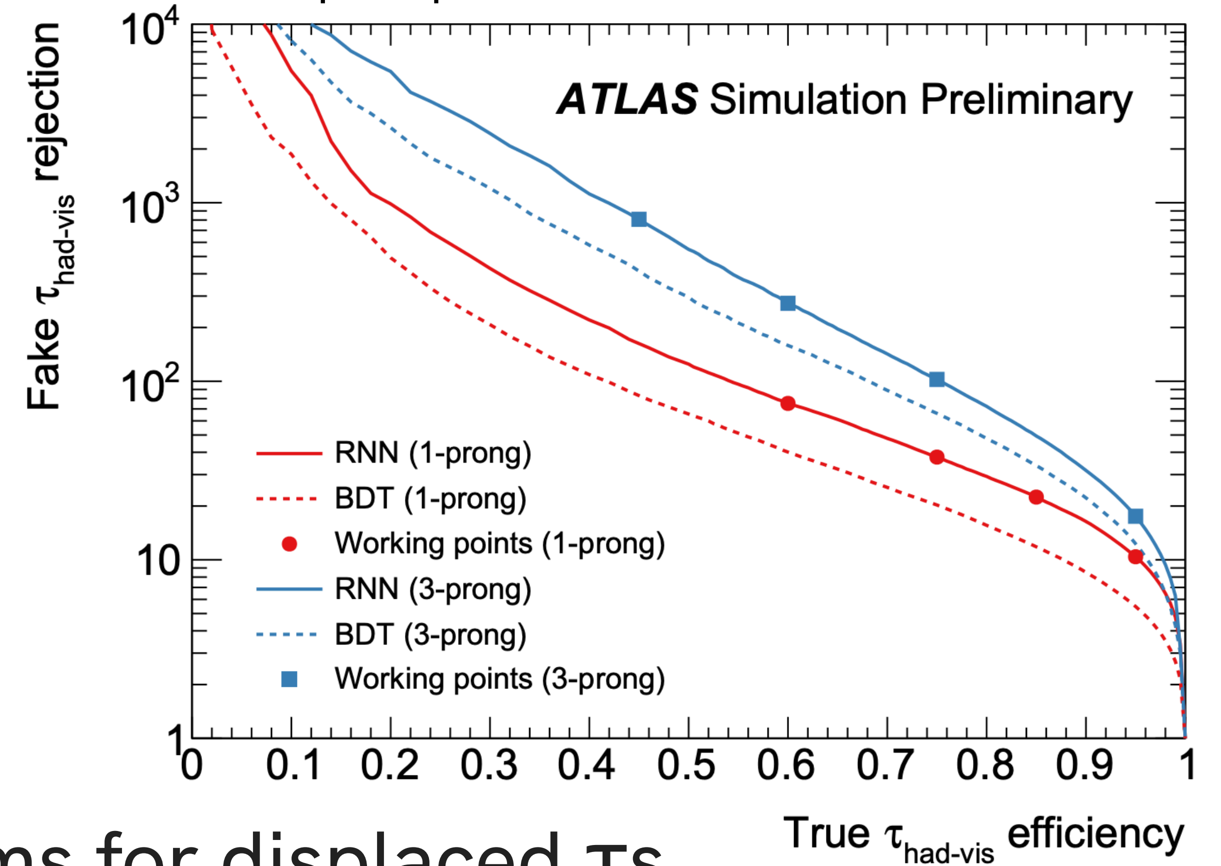
- Factorising LLP benchmark prod. and decay → same for effs.
- Good for reinterpretation; requires mutual independence

Summary

- Several models predict LLPs that favour decays to the 3rd generation. We explored several, some of which
  - need extensions to 3rd generation — work to be done
  - include 3rd generation as "just another fermion"
  - have 3rd generation preference embedded (generally because of Yukawa-like structures)
- Well-motivated, unexplored $H \rightarrow aa$ to be followed-up
- Benchmarks established; model-independent methods explored

Outlook

ATLAS prompt τ ID: ATL-PHYS-PUB-2019-033



- **Core challenge:** trigger and ID algs. designed for prompt τs →
- In the group, have **thoroughly characterised performance** of ATLAS τ triggers and ID algorithms for displaced τs
  - Have identified how to **extend these to LLPs**
- Therefore, will be working on:
  - Improving track reconstruction and classification
  - **Re-optimising** existing, track-based τ ID algorithms
  - Developing **new, calorimeter-focused** τ ID algorithms
- Currently having datasets reprocessed that will enable us to re-train τ ID and trigger