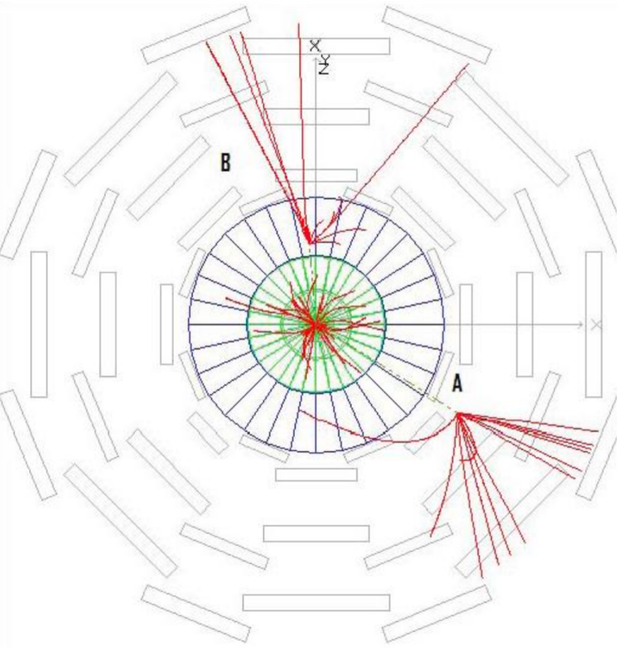
Long-Lived Particles and the Third Generation

PPE Christmas Meeting – 11th December 2020

Sinéad Farrington, Jack Gargan, Guillermo Hamity, Victoria Parrish,
Akanksha Vishwakarma, Estifa'a Zaid

Long-Lived Particles (LLPs)

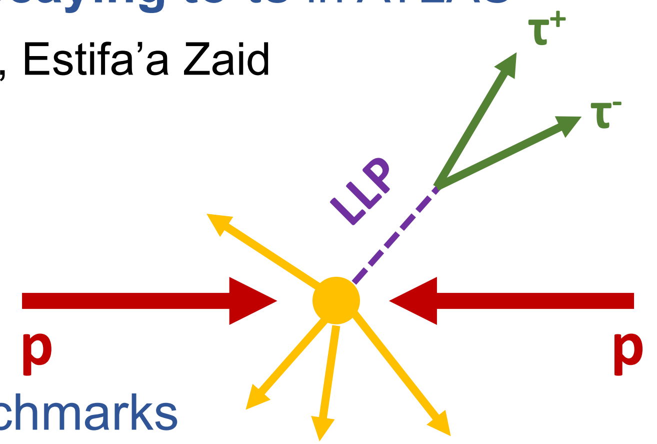
- Quest for New Physics
  - SM ~ 5%; a lot left to learn about (dark matter)
- LLPs are well motivated
  - by broad set of models such as dark sector, heavy neutral leptons which give rise to long-lived signatures
  - prompt searches at ATLAS/CMS not yet yielded signs of new physics, might be "blind" to unconventional processes *e.g.* involving LLPs



- Much attention (experimentally and theoretically) 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

Edinburgh Team

- Sinéad's team is working on ERC project (OPEN3GEN), started in 2019, to develop experimental sensitivity to **LLPs decaying to τs** in ATLAS
    - Jack Gargan, Guillermo Hamity, Victoria Parrish, Estifa'a Zaid
    - Akanksha Vishwakarma (Train@Ed Fellowship)
    - Sara Alderweireldt (will join soon)



- Part of the ERC project is to host workshops with theorists to discuss ideas and model benchmarks
    - 1st one held in November 2019 (Indico page)

- Aim of the workshop
    - Identify existing benchmark theoretical models
    - Identify areas which are ripe for further work
    - Foster a community who will meet twice more to discuss the theoretical issues in the search for LLPs decaying to 3rd generation

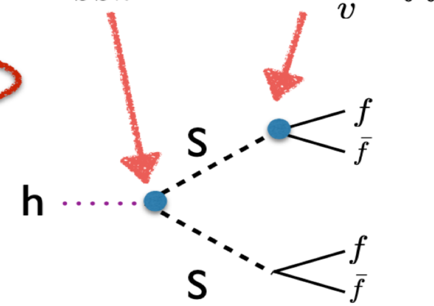
Why Is 3rd Generation Special

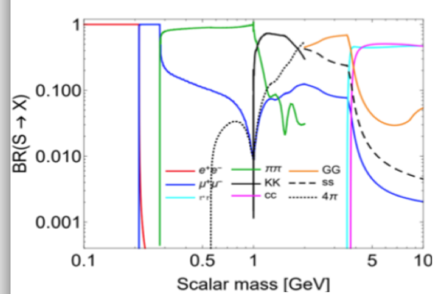
- Motivated search for new physics with mass-dependent couplings (many models predict some mixing with Higgs, hence mass-dependent)

José Zurita

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

- 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:$\tau^+\tau^-$!

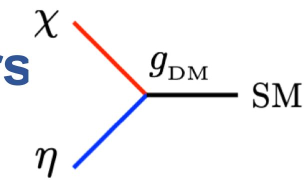
- It is a must for signal characterization, even if we find NP before in 1st/2nd gen, e.g: DV(μ,μ), DV+MET, etc…

- Hadronic tau decays give polarisation information to access spin/dynamics of LLPs if discovered!

Theories Motivated for 3rd Generation Searches

Kazuki Sakurai

- **LLPs as DM co-annihilation partners**

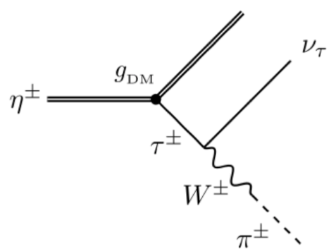


χ : Dark Matter (DM): → **singlet**

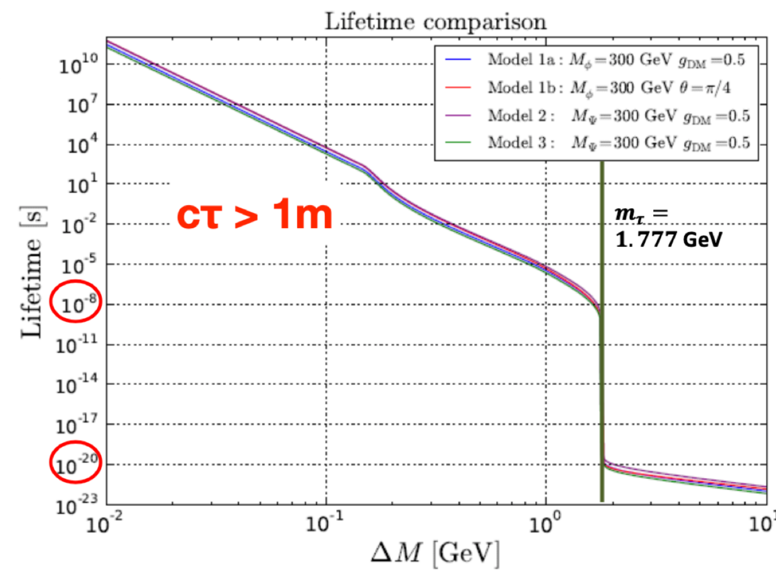
η : Co-Annihilation Partner (CAP): → **coloured or weakly charged**

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

- Since CAP is charged under the SM gauge group, the production rate for CAP is unsuppressed at the LHC



- For τ-philic CAPs (η) with $|m_\eta - m_\chi| < m_\tau$, CAP is long-lived



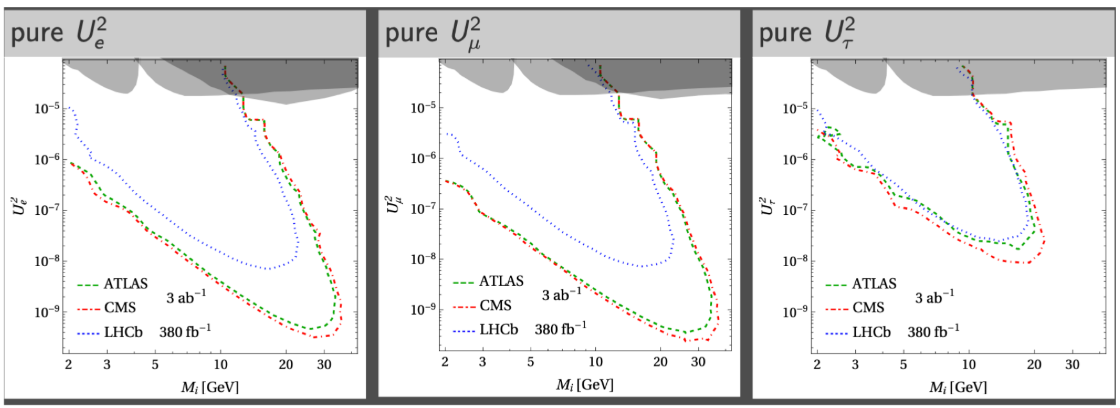
- **LLPs as dark scalars**

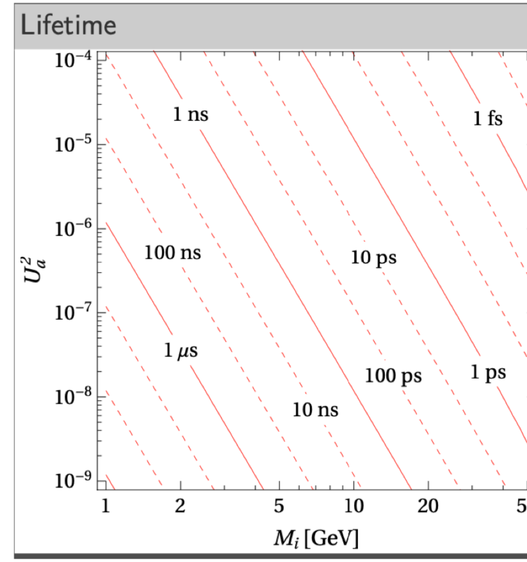
Susanne Westhoff

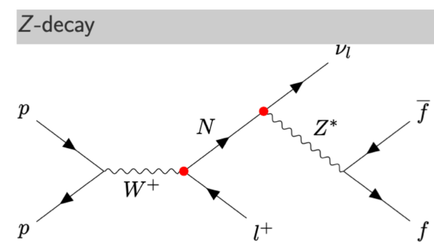
  - Dark scalar inherits Higgs' Yukawa-type couplings
  - Favours 3rd gen. fermions, τ for light ($2m_\tau < m_S < 2m_b$) scalar

Theories Motivated For 3rd Generation Searches

- **LLPs as heavy neutral leptons** Jan Hajer
  - For low masses, couplings HNLs can achieve large lifetimes
  - *e*/*μ*-mixing HNL well-constrained by ATLAS/CMS
  - Currently quite limited sensitivity to U_τ^2 — potential!





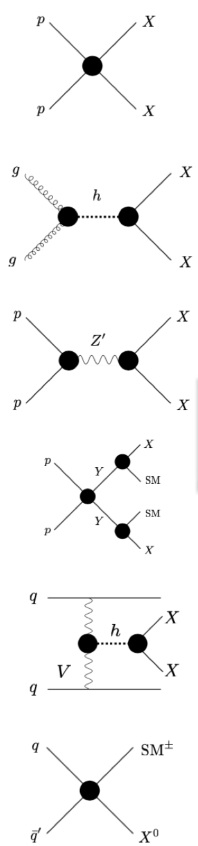


- **LLPs as FIMP mediators** Nishita Desai
  - Feebly interacting massive particles (FIMPs), coupling → LLPs
  - Models, current displaced lepton searches focused on *e*/*μ*
  - Possible and important to extent coverage to 3rd generation

Signature Based Searches

LHC LLP White Paper
Jared Evans

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



Normal Decays	Odd Decays
• $X^{\pm} \to \tau^{\pm} + \not{E}_T$	• $X^{0} \to \tau^{+}\tau^{-} + \not{E}_T$
• $X^{0} \to \tau^{+}\tau^{-}$	• $X^{0} \to \tau^{\pm}\ell^{-}$
• $X^{0} \to \tau^{\pm}W^{\mp(*)}$	• $X^{\pm} \to \tau^{\pm}Z/h$
• $X \to \tau^{\pm}q(\bar{q})$	• $X^{\pm\pm} \to \tau^{\pm}\tau^{\pm}(/\ell^{\pm})$
Easy to get 100% BR Simple models High motivation	Hard to get 100% BR Complicated models Pretty ad hoc

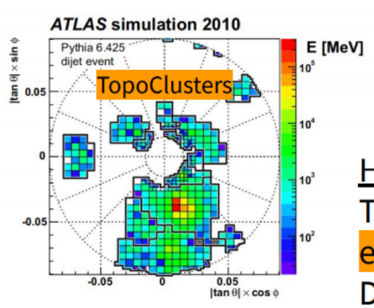
- Construct benchmark models from these signatures
- Current LHC searches have limited sensitivity to many of these

Experimental Challenges

Guillermo Hamity

- Tau reconstruction and identification for the prompt hadronic taus
  - Challenging as they look like jets
- ML-based algs. trained on **prompt *Z/γ***

- Tau reconstruction seed from TopoCluster Jets (robust against multiple interaction background, a.k.a., pileup)



Resulting tau candidates primarily faked by QCD jets

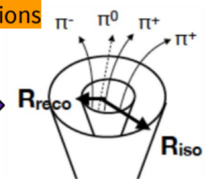
Handles to control BKG

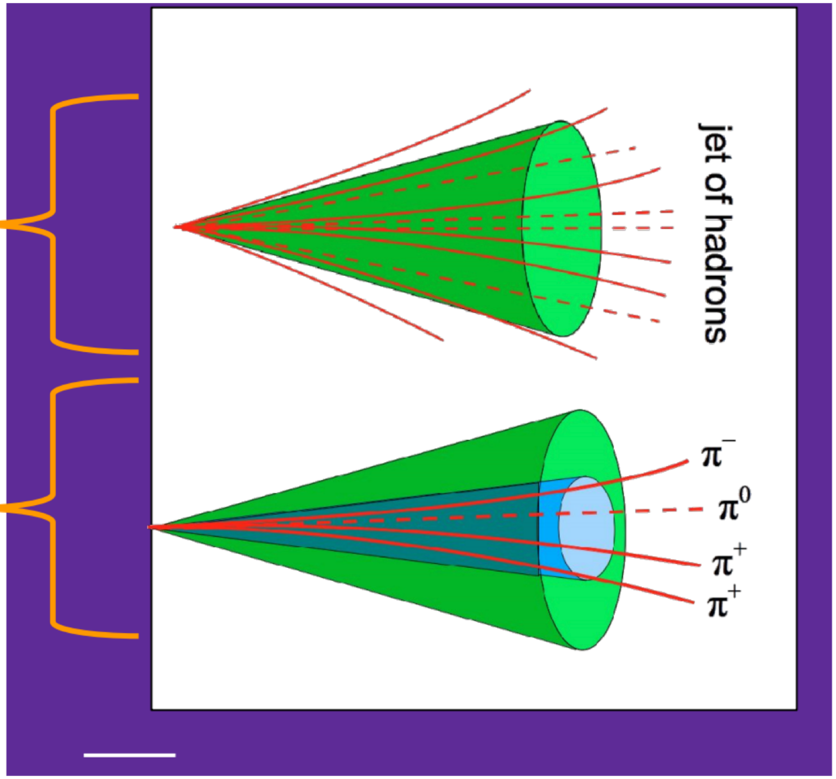
Tau Candidates have collimated energy and tracking

Define core/isolation regions related tracking/calo variables

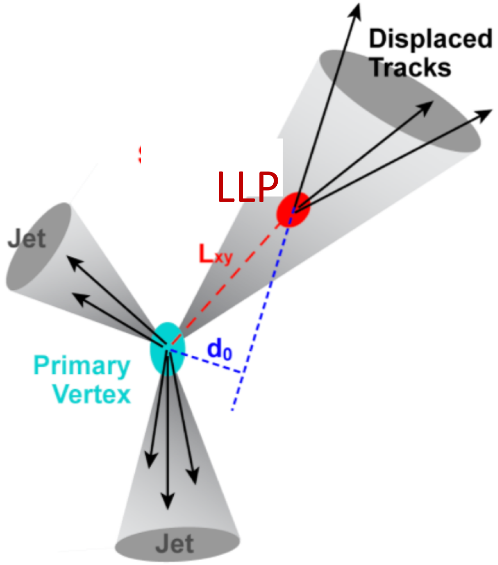
Current implementation

Core/Isolation regions





Experimental Challenges



- Taus from LLPs
  - Displaced jets
- Trigger
- Track Reconstruction

} Work to allow looser d_0 requirement needed

- Tracks not suitable for large decay radius
  - approach: to use Large Radius Tracking (LRT)

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

- ID for displaced τ decays to hadrons
  - ML-based algs. trained on prompt *Z*/ɣ; **characterize performance** for displaced τs

Summary and Outlook

- Several models predict LLPs that favour decays to the 3rd generation
- Benchmarks established; model-independent methods explored
- Third generation LLP sensitivity requires new solutions in
  - --Trigger --Tracking --Tau ID

- Trigger and ID algs. designed for prompt τs
  - **thoroughly characterised performance** for displaced τs
- Working on:
  - Trigger studies and re-optimizing existing, online τ ID for Run3
  - Re-optimizing and improving offline tau ID for implantation in Run2 analysis
    - New samples available with LRT: re-train τ ID
  - Developing analysis framework in parallel

Simulation task

- Detector simulation consumes most CPU
  - Many ongoing efforts to provide GPU accelerated particle transport
- Focus on electromagnetic calorimeter
  - computationally dominant part of Geant4 simulation
  - Relatively tractable number of processes
- ATLAS Electro-Magnetic End Cap (EMEC) calorimeter has a novel and complex structure
  - Not derived from standard Geant4 geometry shapes
  - Accordian shape for the absorbers and electrodes
  - Called "custom solid"
  - Makes it difficult to port the code to new advancements
  - Trying to rebuild the structure from G4 shapes