Theory Overview:
Long-Lived Particles
Why Long-Lived BSM Particles? Supersymmetry

- R-Parity-Violating, small B/L-violating couplings
  \[ c\tau_{RPV} \sim 1 \text{ m} \left( \frac{100 \text{ GeV}}{\tilde{m}} \right) \left( \frac{10^{-8}}{\lambda_{RPV}} \right)^2 \]

- Gauge mediation—suppressed couplings via SUSY breaking scale
  \[ c\tau_{GMSB} \sim 10 \text{ m} \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^5 \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \]

- Mini-split spectrum—suppressed couplings through “decoupled” heavy particles
  \[ c\tau_{\text{milli-split}} \sim 1 \text{ mm} \left( \frac{\text{TeV}}{m_{\tilde{g}}} \right)^5 \left( \frac{m_{\tilde{q}}}{\text{PeV}} \right)^4 \]

- Pure Wino/Higgsino—nearly degenerated, disappearing track
Why hidden sector?

Generic DM physics can invoke hidden sectors:
• Rich interaction structure
• Rich mass spectrum
• Can be unified with us at a higher scale
Hidden Sector Messengers

Categorization of messenger fields*:

- Scalar messenger $s$
  - $\epsilon \Lambda (H^+ H)s$
  - $\epsilon (H^+ H)(s^+ s)$
- Vector messenger $A'_\mu$
  - $\epsilon F^{\mu \nu} F'_{\mu \nu}$
  - $\epsilon J'^{\mu}_{SM} A'_\mu$
- Neutrino messenger $N$
  - $\epsilon (LH)N$
- Axion messenger $a$
  - $\frac{a}{f_a} \left( \frac{\alpha_3}{8\pi} G \tilde{G} + \frac{\alpha_2}{8\pi} W \tilde{W} + \cdots \right)$

*This also form the basis for many discussions of low energy, high intensity experiments. Collider will provide crucial/unique complementary information in the GeV realm.
Heavy Axion

Mass of the axion is a robust prediction

\[ V^{QCD}(a) \approx -f_\pi^2 m_\pi^2 \cos(\theta + \frac{a}{f_a}) \]

New contributions to the potential and the mass in general will not be aligned with the QCD potential

\[ V(a) = V^{QCD} + \frac{f_a^n}{\Lambda^{n-4}} \cos(\theta' + \frac{a}{f_a}) \]

Rubakov, 97'
Hook, 14'
Dimopoulos, Hook, Huang, Marques-Tavares, 16'
Gherghetta, Nagata, Shifman, 16'
Argarwal, Howe, 17'
Argarwal, Howe, 17'
Hook, Kumar, ZL, Sundrum, 19'
Csaki, Ruhdorfer, Shirman, 19'
Gherghetta, Khoze, Pomarol, Shirman, 20’
Challenge: light, rarely produced, hadronic states;

Big open windows for well-motivated heavy Axions

Opens a new direction of singly produced long-lived particles.

A lot more to explore.

\[
\frac{\alpha_s}{8\pi} \left( \theta + \frac{a}{f_a} \right) \tilde{G} G + \ldots
\]
Composite Neutrino

- elementary $\nu_e$ → composite $\nu_R$ → elementary $\nu_e$
- elementary-composite mixing
- $L$-number violation

$\mathcal{L}_{UV} \supset \mathcal{L}_{CFT} + \frac{\lambda}{M^{\Delta-3/2}} \bar{L} \tilde{H} O_N + \frac{\mu}{M^{\Delta_2-4}} O_{2N}$

CFT deformation generates

$\mathcal{L}_{IR} \ni -m_N \bar{N} N - (\lambda \bar{L} \tilde{H} N_R + \mu N_L^2 + h.c.)$

$A \text{ shower of Sterile Neutrinos...}$

$\nu \approx \mu \left( \frac{\lambda v_{EW}}{M_N} \right)^2$

Inverse Seesaw, Mohapatra, Valle, 86’


Chacko, Fox, ZL, Harnik, to appear
DM Coannihilation and LLP

SUSY fully covered, any lifetime?

(infamous)
Compressed SUSY

Easily long-lived

8 TeV result by ZL, B. Tweedie, 1503.05923
Coannihilation and LLP

Mono-jet + (soft) displaced tracks will cover this well motivated region, making direct DM and coannihilator discovery.

For stau coannihilation, the pheno challenges is with soft and prompt tau leptons.

Monojet+(soft) displaced tracks will cover this well motivated region, making direct DM and coannihilator discovery.
Delay is a universal feature of Long-Lived Particles*

Liu, ZL, Wang, 1805.05957

*except for those hyper-boosted $\gamma \geq 7$
Late comers will be spotted easily

Delayed Jet analysis carried out by CMS

Displaced jet at 13 TeV

More to come:
CMS MTD upgrade
ATLAS HGTD upgrade
Ecal, Muon system, Hcal, timing information to be used

Liu, ZL, Wang, 1805.05957
8 TeV results, ZL, Tweedie, 1503.05923
More ideas: High granularity detectors

HL upgrade:
Directional resolution milli-radian,
Temporal resolution 30 ps (for pT > 30 GeV):

Allowing jet & shower substructure reconstruction:
Infor passed to low level triggers
Perfect for LLPs

https://galleryziheng.wordpress.com/2018/03/08/cms-hgcal-event-display/
HGCAL potential

For HGCAL non-pointing photon w ML, see Alimena, Iiyama, Kieseler 2004.10744
Summary

• Theory & Experimental landscape
  • Large class of motivated models for LLPs, mainly classified into SUSY and Hidden sector dynamics

• Challenges and Opportunities
  • Exciting LHC program ahead
  • High Quality Axion (low mass hadronic LLP)
  • HNL shower (semi-leptonic LLP shower)
  • DM & Coannihilation (soft visible energy LLP)
  • Timing in all subdetectors (new dimensions of information greatly boost LLP program, trigger & analysis level)
  • Highly Granularity (new dimensions of information greatly boost LLP program, trigger & analysis level)
  • More Trigger ideas (Bhattacherjee, Mukherjee, Solanki, 2003.03943; Dildick et al, talk link; more at the recent CERN LLP workshop)

Thank you!
LLP coverage: basics
LLP coverage: basics

Geometrical acceptance $P_{in}$

$$d = c \tau \gamma \beta$$

- For short lifetime: the closer the better;
- For long lifetime: the larger decay volume the better (CMS/ATLAS is 5-10 m)
- For any lifetime: angular coverage the large the better (CMS/ATLAS is $4\pi$)

But the challenges are in the triggers and background suppression.
For general purpose LLP detectors, one should consider at least these two representative production modes:

1. **Resonant**
   - Higgs-like via VBF
   - Heavy resonance (RES)
   - Charged Current (CC)

2. **Non-resonant**

- Factorize production and decay;
- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;
Expanding the LHC program

MATHUSLA
Codex-B
AL3X
ANUBIS
FASER
SHiP
NA62
SeaQuest
...
MoEDAL
MilliQan

Central/Hard LLPs
Forward/lighter LLPs
Beamdump experiments
monopole
millicharged particles

Search for LLPs

Forward Spectrometer
Backup
For instance, for Sterile Neutrinos

Atre, Han, Pascoli, Zhang, 0901.3589
+ recent LHC results
+ recent LHC results
+ ES physics briefing (PBC) 1910.11775
More ideas: displaced lepton

Digging hard and use the control region studies to propose new searches on sterile neutrinos.

ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020
New searches and new insights!

Beam halo small
Core and satellite bunches small but one shall try to improve by precision timing
Cosmics small (for this analysis, no need to do cosmic veto yet but there are many ways) and scale with time but not luminosity

Lot of theory & experimental activities:
- L1 trigger under development
- Delays in all subdetectors under development
- Pheno studies on mass reconstruction
- Pheno studies on jet substructure
- Pheno studies on delayed dark photons
- ...

<table>
<thead>
<tr>
<th>Background</th>
<th>Prediction</th>
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<tbody>
<tr>
<td>Beam halo</td>
<td>$0.02^{+0.06}<em>{-0.02}$ (stat) $^{+0.05}</em>{-0.01}$ (syst)</td>
</tr>
<tr>
<td>Core and satellite bunches</td>
<td>$0.11^{+0.09}<em>{-0.05}$ (stat) $^{+0.02}</em>{-0.02}$ (syst)</td>
</tr>
<tr>
<td>Cosmics</td>
<td>$1.0^{+1.8}<em>{-1.0}$ (stat) $^{+1.8}</em>{-1.0}$ (syst)</td>
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