Long-lived particles at the LHC

- Why Long Lived Particles?
Long-lived particles at the LHC

- Why Long Lived Particles?
- Well, duh:

![Diagram showing bar graphs for prompt and long-lived particles with label for no discoveries here yet and let's look over here.]
Why long-lived particles?

- But this is a major oversimplification!

- 1 prompt search ≠ 1 displaced search:
  - great power of LLP searches: intrinsically low SM background
    - SM: $b$-quark lifetime ~ 500 microns
  - displaced searches often relatively insensitive to details of decay
  - typically powerful, relatively inclusive searches
Why long-lived particles?

- Thus it is actually **easier** to make sweeping statements about displaced SUSY than prompt SUSY:

[Liu, Tweedie]
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Why long-lived particles?

- Moreover, lack of prompt signals can predict displaced signals.
- Perhaps SUSY is a little bit tuned:
  
  $$100 \mu m \times \left( \frac{m_{\tilde{q}}}{1000 \text{ TeV}} \right)^4 \left( \frac{\text{TeV}}{m_{\tilde{g}}} \right)^5$$

- **Mini-split:** lifetime suppressed by high sfermion scale.

[Arvanitaki, Craig, Dimopoulos, Villadoro; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski]
Why long-lived particles?

- Moreover, lack of prompt signals can predict displaced signals.
- Perhaps SUSY is a little bit tuned:
  - **GMSB**: high SUSY-breaking scale suppresses gravitino couplings.

\[ c\tau \approx 100\mu m \times \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \left( \frac{100 \text{ GeV}}{m\tilde{g}} \right)^5 \]

[Giudice, Barbieri; ...]
Why long-lived particles?

- Moreover, lack of prompt signals can **predict** displaced signals

- Perhaps SM partners curing hierarchy problem are **neutral**:

  - **Neutral naturalness**: composite states decay via higher-dimension operators, small Higgs mixing

[Chacko, Goh, Harnik; Craig, Howe; Craig, Knapen, Longhi, Strassler; ...]
Why long-lived particles?

- And independently, there are many cosmological reasons to look for LLPs

- For instance, baryon number:
  
  - avoiding washout of baryon number in early universe requires baryon-violating RPV couplings small
Why long-lived particles?

- And independently, there are many cosmological reasons to look for LLPs
- Or dark matter relic abundance:
  - freeze-in of DM requires very small coupling to SM. If this occurs during reheating-like era, required coupling size can give collider-scale signatures

[Co, D’Eramo, Hall, Pappadopulo]
LLPs at the LHC

- LLP searches are not easy! Using detectors off-label
- **nonstandard reconstruction** poses challenges
  - for experimentalists: triggering, efficiencies, backgrounds
  - also for theorists: painstakingly built toolbox for understanding/reusing prompt searches does not apply
- ➞ Very important to assess coverage of current/planned program, identify opportunities and fill in gaps
  - also: make searches easy to reuse in future
LLPs at the LHC

- LLP searches are not easy! Using detectors off-label poses challenges for experimentalists: triggering, efficiencies, backgrounds also for theorists: painstakingly built toolbox for understanding/reusing prompt searches does not apply.

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Simplified model program for LHC LLP searches: ongoing!

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LLPs at the LHC

- Gaps: which objects at what lifetimes

[Evans, JS]
LLPs at the LHC

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limits on long-lived staus

excellent sensitivity to detector-stable charged LLPs

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- newly instituted search, room for optimization
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- border of prompt searches is too uncertain to show!

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[Evans, JS]
LLPs at the LHC

- Gaps: which objects at what lifetimes

all of these analyses use prompt triggers \(\Rightarrow\) missing low \(p_T\) physics

excellent sensitivity to detector-stable charged LLPs

large uncertainties: search very targeted to a different model

newly instituted search, room for optimization

border of prompt searches is too uncertain to show!

limits on long-lived staus

[Evans, JS]
LLPs at the LHC

- Exotic Higgs decays:
  - high HT requirement in trigger limits sensitivity at low mass, short lifetime
  - requirement of 2 DVs limits sensitivity at long lifetime

[Csaki, Kuflik, Lombardo, Slone]
LLPs at LHC Run II

- Two essential strategies to increase reach:
  - combine prompt + displaced objects for more triggering strategies at short lifetimes, low masses
  - extend acceptance with new searches using less restrictive ID criteria

[Csaki, Kuflik, Lombardo, Slone; Coccaro, Curtin, Lubatti, Russell, JS]
LLPs at the LHC

- Extending sensitivity means:
  - adding and maintaining trigger options
    - non-standard reco means limited options for directly triggering on displaced objects: combine prompt, displaced
  - confronting backgrounds
    - (weird SM physics) x (weird detector response): cannot model from first principles
  - background will increasingly be an issue for formerly background-free searches as luminosities increase
Exotic Higgs decays are one of the more challenging signals:

- low-mass signal
- dominantly produced in gluon fusion, i.e., with no characteristic accompanying prompt objects

thus: limited options for triggering, background estimation
Example: Higgs decay to $XX$

- To get better sensitivity to long lifetimes, single-vertex search in muon system. Not background-free!

- Can’t compute background from first principles $\Rightarrow$ estimate from data

- ...but even getting the needed control sample on tape can be challenging

[Coccaro, Curtin, Lubatti, Russell, JS]
Notable gains in sensitivity at long lifetime:

Projected 13 TeV 2DV search, assumed background free

Our estimate for 1DV search sensitivity

[Coccaro, Curtin, Lubatti, Russell, JS]
Beyond this single example

- In MS, not sensitive to detailed properties of decay
  - common but not universal for displaced signatures

- Categorization of possible signals based on production mode: can notably streamline simplified model basis
  - finite set of possible production modes: characteristic prompt objects, cross-sections
  - e.g. Higgs portal: ggF, VBF, VH

- Expanded basis of models helps reinterpretability but aren’t strictly needed for discovery
Proposed surface detector for very long-lived particles: MATHUSLA

Ask these people about pesky details like cost and design

[Chou, Curtin, Lubatti; Curtin, Peskin]
And even further beyond

- Extends sensitivity out to cosmologically interesting lifetimes:

- Physics case in preparation (eds. Curtin, McCullough, Meade, Papucci, JS)

[Chou, Curtin, Lubatti]
Conclusions

- Displaced decays of BSM states are a major discovery opportunity at LHC Run 2 and beyond
  - Technically challenging searches, areas of unexplored territory
- Extending sensitivity means contending with backgrounds, opening new search regions
  - even data-driving background predictions can require new techniques
- Need for concerted experimental/theory effort to evaluate gaps, usability
  - development of simplified model program underway