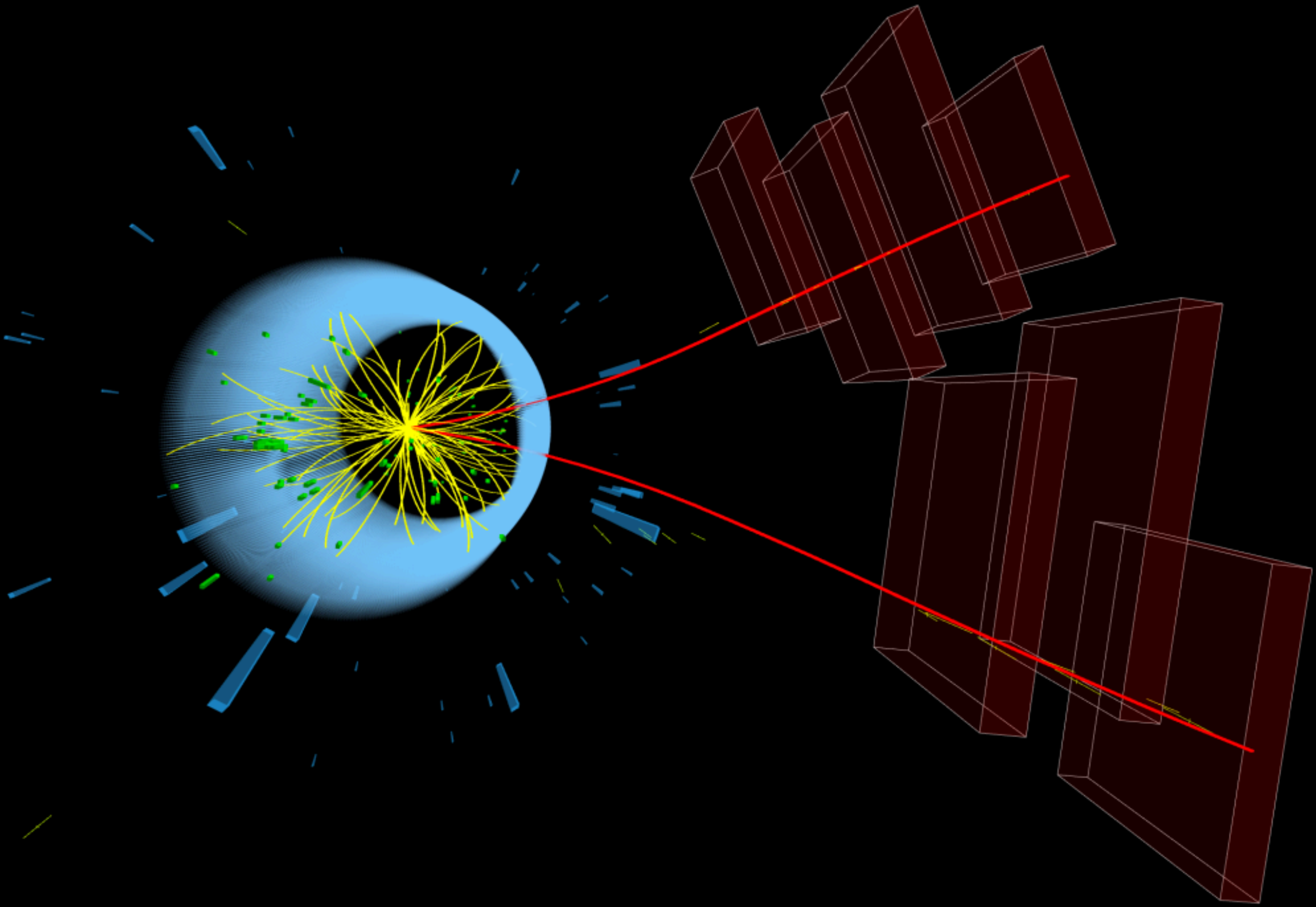
Long lived particles theory for snowmass



Simon Knapen
CERN

Caveats & boundary conditions

Assignment: Theory priors for LLPs and how they could inform snowmass

LLP = Something which does not decay “prompt” and is not MET

Half of this talk are just my opinions…

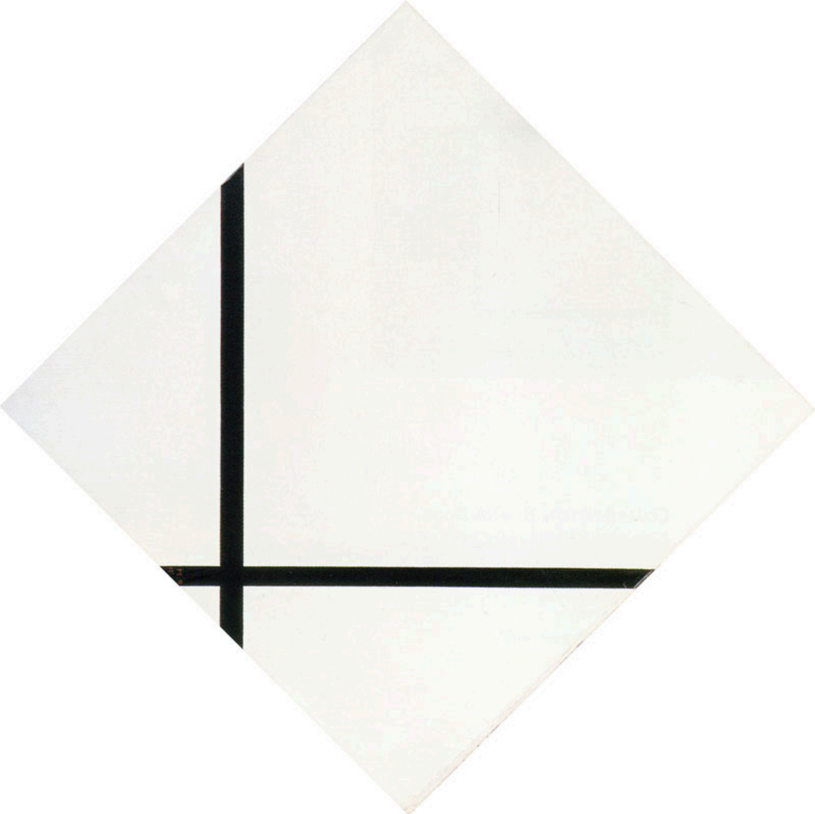
… the other half is likely obvious

There will be a lot of this

Credit, if any, is to be shared with Simone Pagan Griso, Zhen Liu, Diego Redigolo and Jose Zurita
Blame is all on me

Two schools

“Minimalism”



Tries to systematically study simplest extensions of the SM

Aka “simplified models” or “portals”

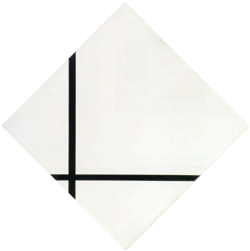
“Realism”

Tries to address problems with the SM, sometimes in great detail

e.g. hierarchy problem, Dark Matter, …

Both are a form of theory prior

Two schools



✔ Relatively few options (~ hundreds)

✔ Simple

✔ Great for benchmarking

✗ Great for benchmarking

✗ "Who ordered this?"

Needed for

- Legacy (data preservation)
- Comparing "existing" experiments
- Searching for holes in coverage

✔ Tell a story (e.g. Dark Matter)

✔ Predictive

✗ Large number of options

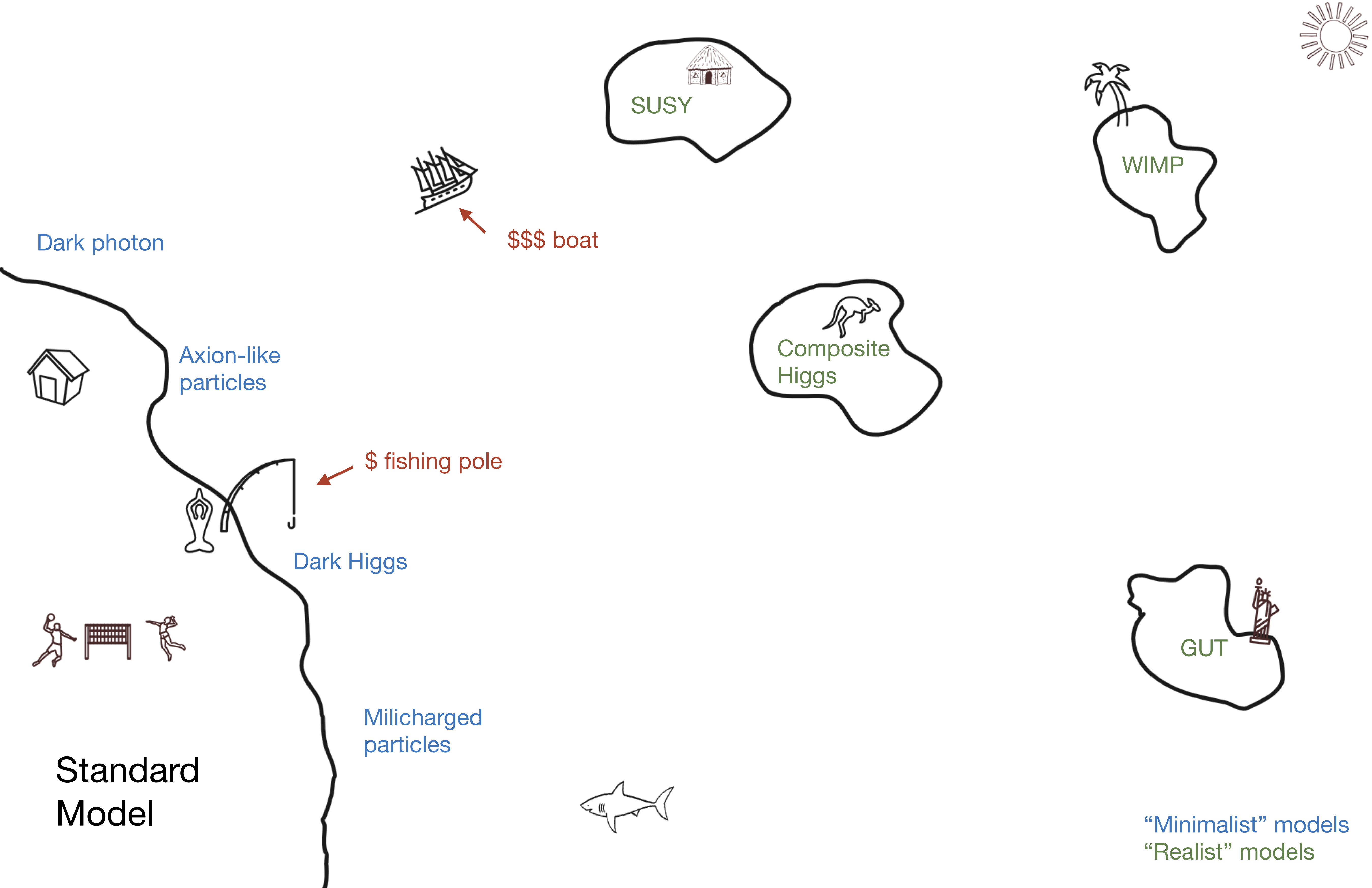
✗ Multi-dimensional parameter space: difficult to falsify

Needed for

- Big directions
- Unexpected new signatures
- Say something qualitative about Nature

I think we need to choose the right mindset for the problem at hand

Journey Beyond the Standard Model



SUSY

WIMP

$$$ boat

Dark photon

Composite
Higgs

Axion-like
particles

$ fishing pole

Dark Higgs

GUT

Milicharged
particles

Standard
Model

“Minimalist” models
“Realist” models

Long Lived particles

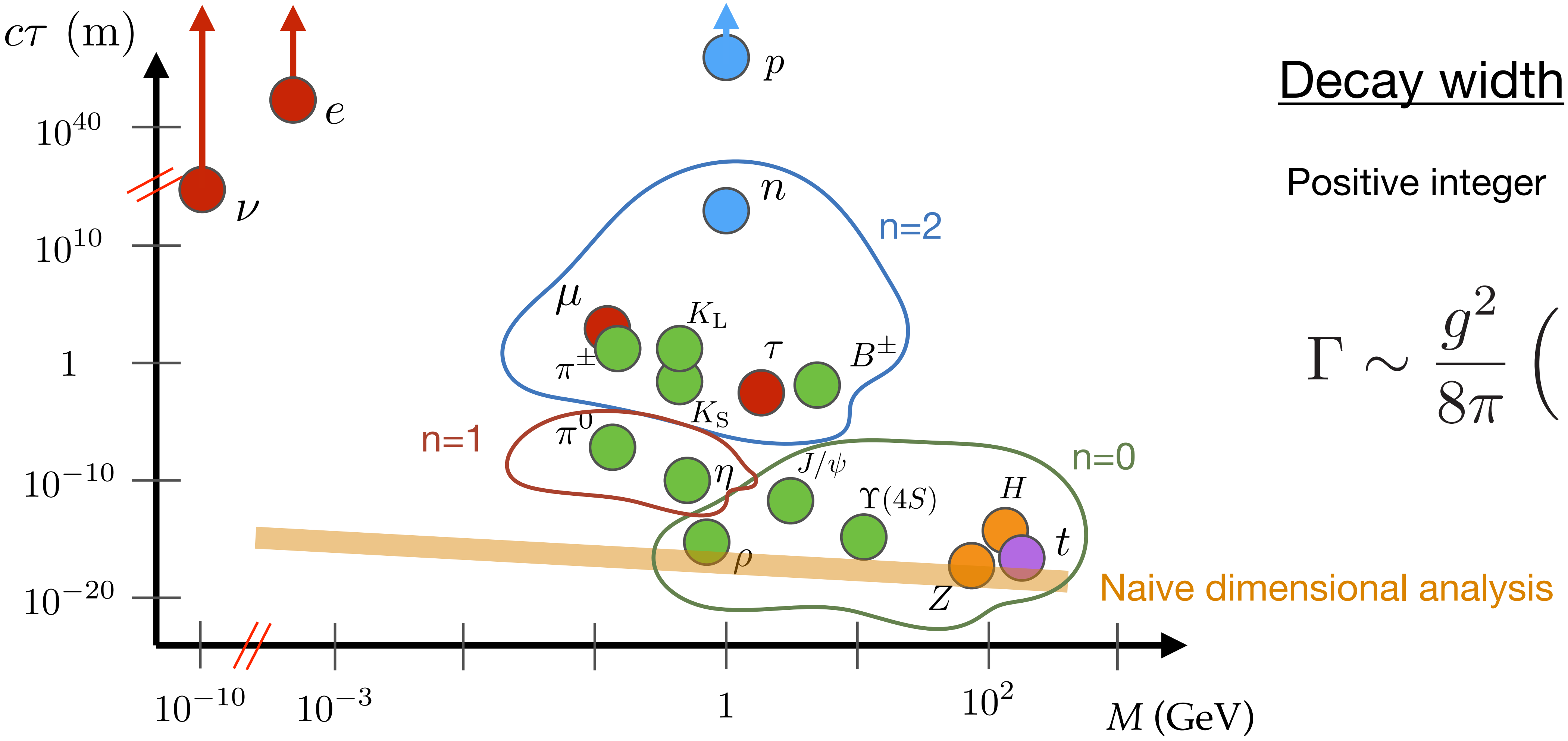


Image by B. Shuve

Decay width

Positive integer

Particle mass

$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

Heavy mass (m_W, Λ_{QCD},…)

BSM examples

Model	n
Dark photon	0
Dark Higgs*	0
ALP	1
Heavy neutral lepton	2
Long lived gluino	2
Dark glueball	3

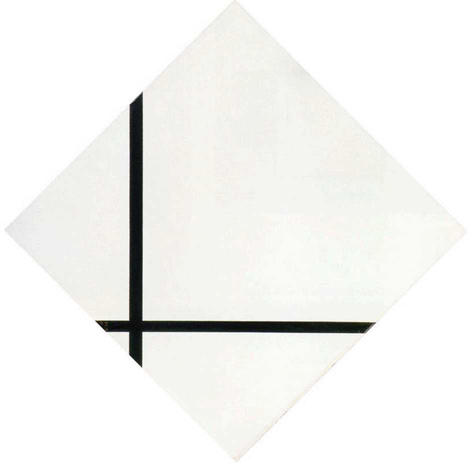
* additional Yukawa suppression

https://indico.cern.ch/event/863077/contributions/3850699/attachments/2044003/3423877/LHC_LLP_Craig.pdf
https://indico.cern.ch/event/714087/contributions/2985914/attachments/1650488/2641192/LHC-LLP_Shuve.pdf

Two categories of LLP’s

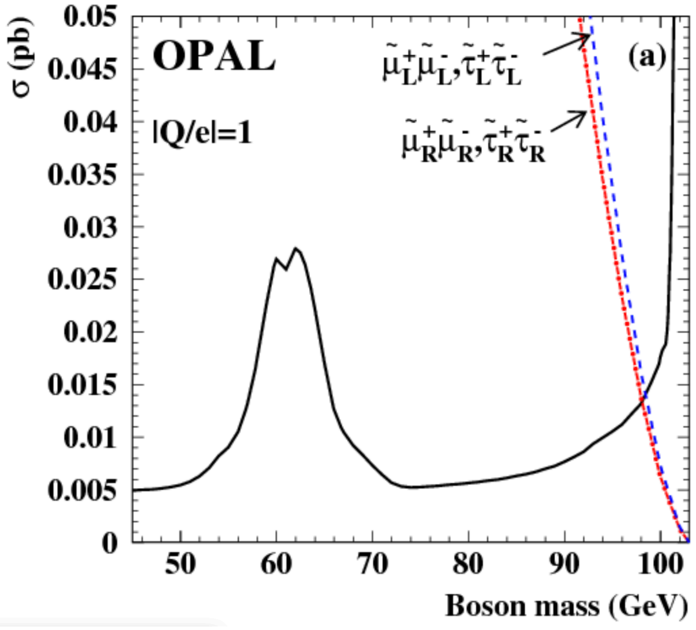
m < 100 GeV

- Only allowed LLPs are neutral displaced decays
- M >> m: Displaced decay is often expected, purely from bottom-up considerations



Largely existing facilities / *relatively* minor upgrades

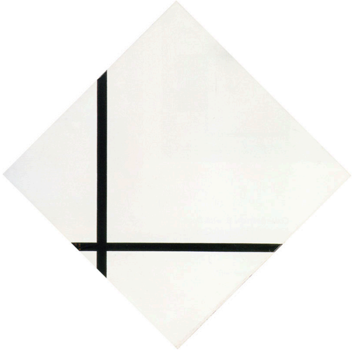
Because LEP II



$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

m > 100 GeV

- Disappearing tracks, kinked tracks, HCSPs etc
- M ~ m is possible: No bottom up prior on the lifetime



ATLAS, CMS &
future high energy colliders

What are we trying to achieve?

1. How do we achieve “comprehensive” coverage with current accelerator facilities?

2. How do we prioritize future collider options?

3. Once a future collider is chosen, how do we inform the detector design for LLP coverage?

Approaching these questions purely from an LLP point of view here

What are we trying to achieve?

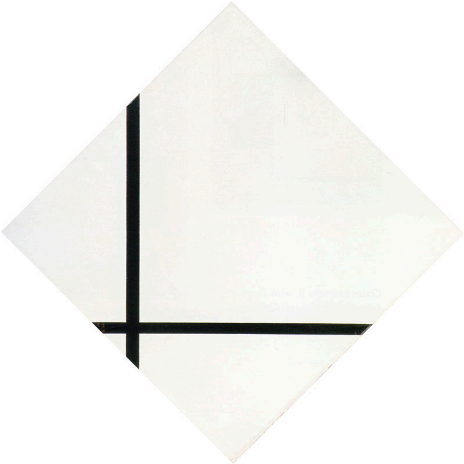
1. How do we achieve “comprehensive” coverage with current accelerator facilities?

Currently the gold standard is LLP white paper: arXiv 1903.04497

- Building simplified models aka using the “Lego set”: factorize production + decay
- Many options can be imbedded in SUSY, Abelian Higgs model and heavy neutral leptons
- Dark showers are different beast (LLP white paper & upcoming work with J. Shelton)

Others have thought much more about this than I have

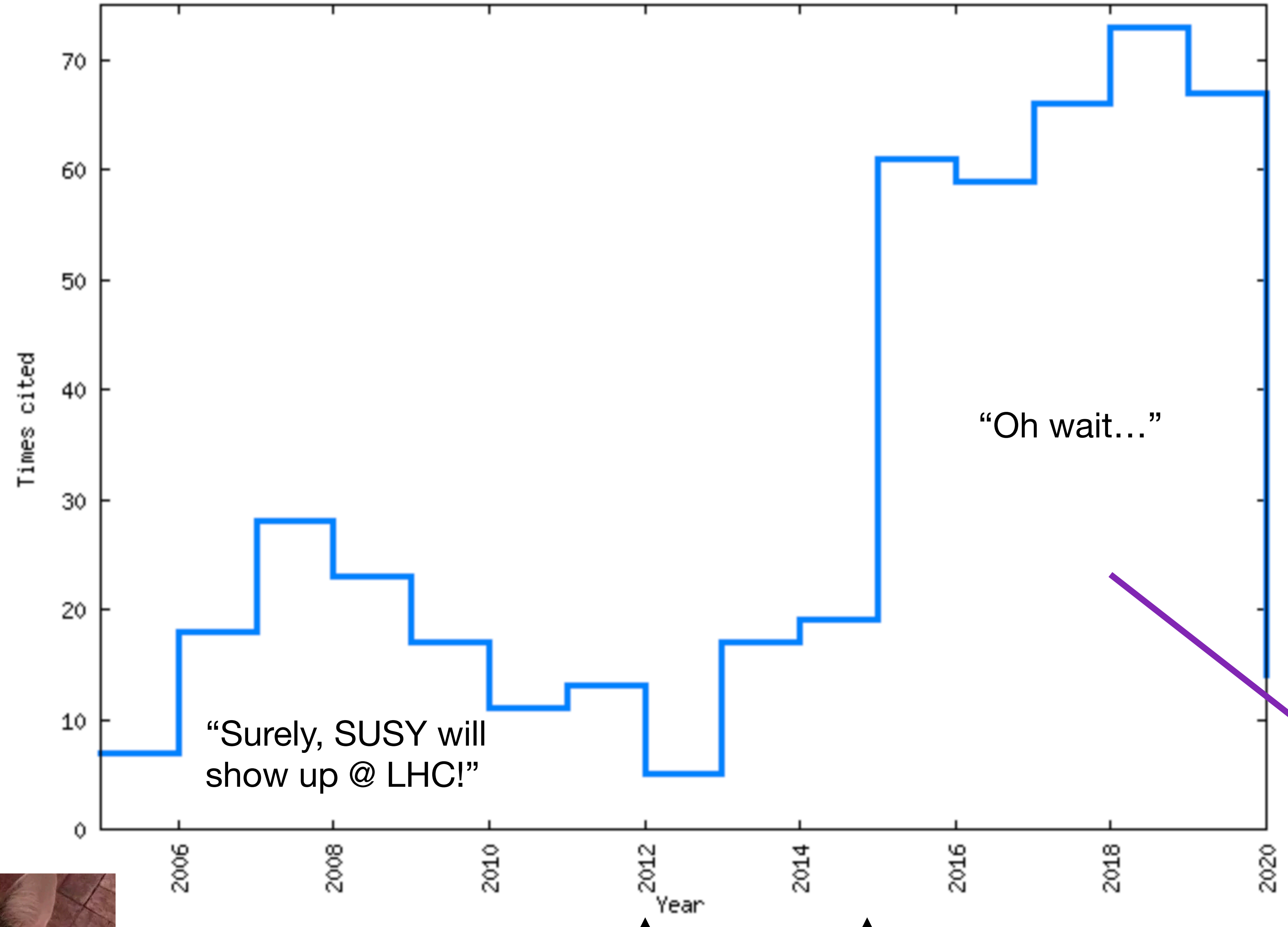
It seems sensible to me to prioritize a “minimalist” approach, but let’s not forget about “realist” models entirely…



Many important experimental aspect to this e.g. triggers (!) but focusing just on theory here

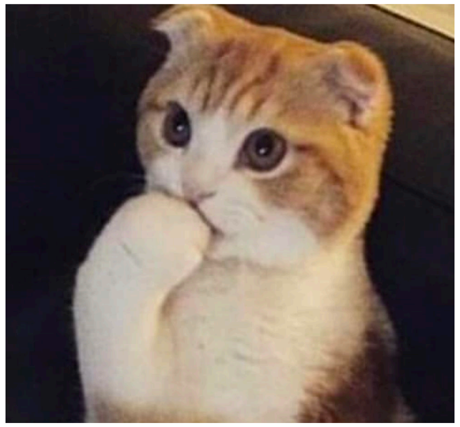
Example: Twin Higgs

Citation history:



"Surely, SUSY will show up @ LHC!"

"Oh wait…"



A lot of this was LLP work

Higgs discovery

25 fb^{-1}

Z. Chacko, H. Goh, R. Harnik: arXiv 0506256

What are we trying to achieve?

2. How do we prioritize future collider options?

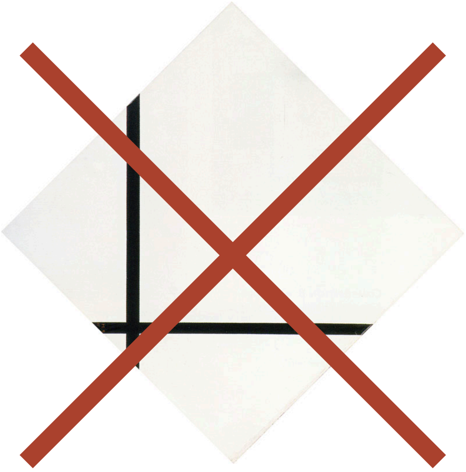
For a “general explorations” working group, it seems to me that exercising some degree of restraint may be appropriate on this question.

An investment of this magnitude is ideally driven by a big question: EW symmetry breaking, dark matter, etc

Question to fellow theorists: Can we compile a list of “big question” motivations which are not covered by the other working groups? Maybe form a study team?

I do not think the “minimalist” approach is useful for this question

e.g. reach of various colliders for the dark photon simplified model is not relevant in my opinion



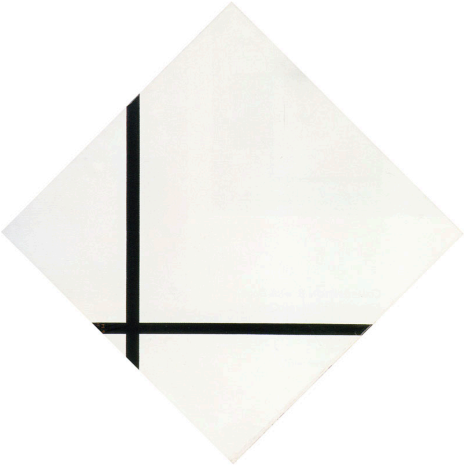
What are we trying to achieve?

3. Once a future collider is chosen, how do we inform the detector design for LLP coverage?

My 0th order sense: the combo ATLAS, CMS & LHCb is pretty great!

A few points/lessons though:

- Track reco/vertex resolution is important (obviously)
- Tracking close to the IP is important for kinked/disappearing tracks
- Muon chambers are VERY useful
- Bigger = better
- Trigger systems are crucial
- …



What are we trying to achieve?

3. Once a future collider is chosen, how do we inform the detector design for LLP coverage?

Example questions:

- Are heavily shielded detectors e.g. Mathusla etc needed in a relatively low background lepton collider? (high $c\tau$ DV)
- Are asymmetric beams (alla Belle) useful for short-lived LLPs? (low $c\tau$ DV, disappearing track)
- dE/dx measurements possible? (HCSP)
- How well can the detector reconstruct displaced objects? (DV, disappearing track)
- What are trigger constraints? E.g. out-of-time objects (HCSP, DV)

Proposal to proceed

1. How do we achieve “comprehensive” coverage with current accelerator facilities?

   LLP community (e.g. white paper) has given a lot of thought about this
   Update and condense findings from white paper?

2. How do we prioritize future collider options?

   Form a study team of theorists to survey and summarize “non-standard” theory motivations for the energy frontier? Generalize beyond LLPs?

3. Once a future collider is chosen, how do we inform the detector design for LLP coverage?

   Form a study team of experimentalists and a few theorists to

   (1) Establish list of qualitative detector features valuable for LLPs

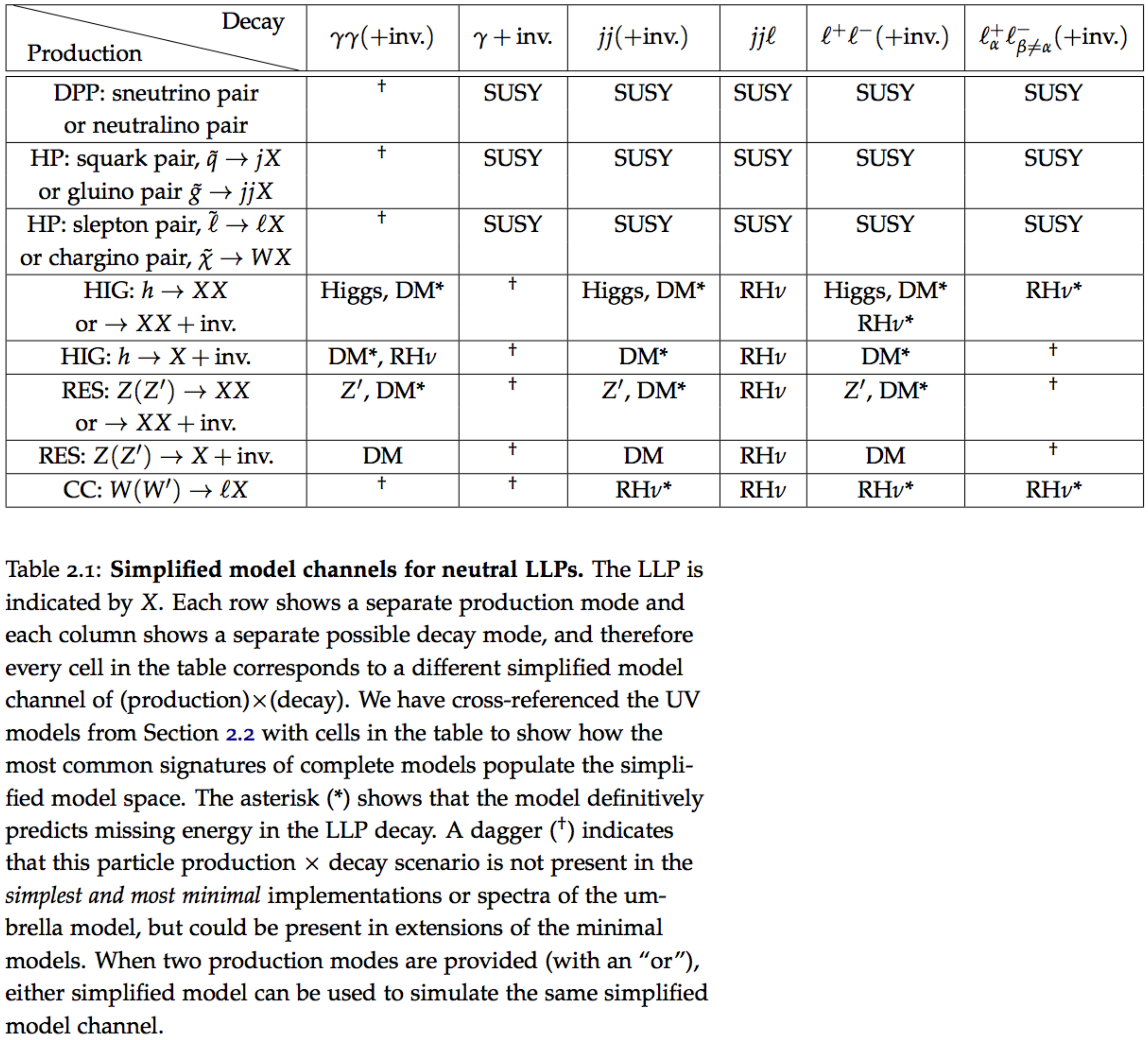
   (2) Based on this list, compile a short list of simplified benchmark models, specifically designed to test these features (e.g. HCSP, disappearing track, displaced vertex, …)

   (3) Invite the collaborations to test their designs with these benchmarks

   (4) Resist the temptation to view the relative reach as favoring one option over another

Back-up slides

From LLP white paper



Decay Production	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

Table 2.1: **Simplified model channels for neutral LLPs.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)×(decay). We have cross-referenced the UV models from Section 2.2 with cells in the table to show how the most common signatures of complete models populate the simplified model space. The asterisk (*) shows that the model definitively predicts missing energy in the LLP decay. A dagger (†) indicates that this particle production × decay scenario is not present in the *simplest and most minimal* implementations or spectra of the umbrella model, but could be present in extensions of the minimal models. When two production modes are provided (with an "or"), either simplified model can be used to simulate the same simplified model channel.

arXiv 1903.04497