Long-Lived Particle WG

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for the LLP WG

Introduction

- Looking for Long-lived particles requires additional tricks and methods.

- But also offers reduced backgrounds (sometimes)

- We are close to releasing a White Paper that summarizes the current status, future prospects and makes suggestions for future research.

- We are not just focused on ATLAS & CMS, we also cover LHCb, VELO, NA62, SHiP, MATHUSLA, FASER, CODEX-b and MoEDAL

Motivation???

- Just because they can be there?

- But perhaps we deserve a less sadistic view: Baryogensis

  - One of the Sakharov's conditions for a successful baryogenesis is that the Universe is out of equilibrium during this process.

  - Take a weak scale particle: when it is about to decay

$$H \sim T^2/M_{\rm Pl} \sim M_X^2/M_{\rm Pl} \sim (c\tau)^{-1}$$

  - Typical ct is of order 1mm for M~1TeV and longer for lighter states

- Not the only motivation and not the only answer: consider deviations from the regular thermal histories.

Higgs and LLPs

- Higgs boson is one of the Standard Model portals

- As a result it deserves its own category

- Higgs portal comes at a price: it is relatively light

  - LLPs are light: we need to rely on tracking

  - LLPs are heavy: we suffer in production rate

Higgs (HIG): The LLP is produced through its couplings to the SM-like Higgs boson. This case has an interesting interplay of possible production modes. The dominant production is via gluon fusion, which features no associated objects beyond initial state radiation (ISR); owing to its role in electroweak symmetry breaking, however, the Higgs has associated production modes (VBF, VH), each with its own characteristic features. The best prospects are for LLP masses below $m_h/2$, in which case the LLPs can be produced on-shell in SM-like Higgs boson decays. LLPs with heavier masses can still be produced via an off-shell SM-like Higgs, albeit at lower rates. The LLP can be pair produced or singly produced through the Higgs portal depending on the model, and may also be produced in conjunction with missing energy. The cross section (or, alternatively, the Higgs branching fraction into the LLP) is a free parameter of the model. The Higgs mass can also be taken as a free parameter: there exist many theories that predict new exotic scalar states (such as the singlet scalar extension to the SM [64]), and these new states can be produced through the same production modes as the SM Higgs.

White Paper

(i) Recommended simplified models

(ii) Experimental coverage

(iii) Trigger and detector upgrades

(iv) Reinterpretations and recommendations for the presentation of results

(v) Dark Showers, Quirks

Simplified Models

Desiderata:

i. Minimal, but sufficient set of models to cover the space of possible UV models

ii. Provide a MC signal generation framework: All of these models will be (by the time the white paper is finished) stored in a repository.

iii. Be able to expand when necessary

iv. Have a single map between models and signatures

v. Provide a way to reinterpret searches by providing efficiencies on a set of benchmark models

Simplified Models

Production

Direct Pair Production

Heavy Parent

Higgs

Heavy Resonance

Charged Current

X

Decays

Diphoton

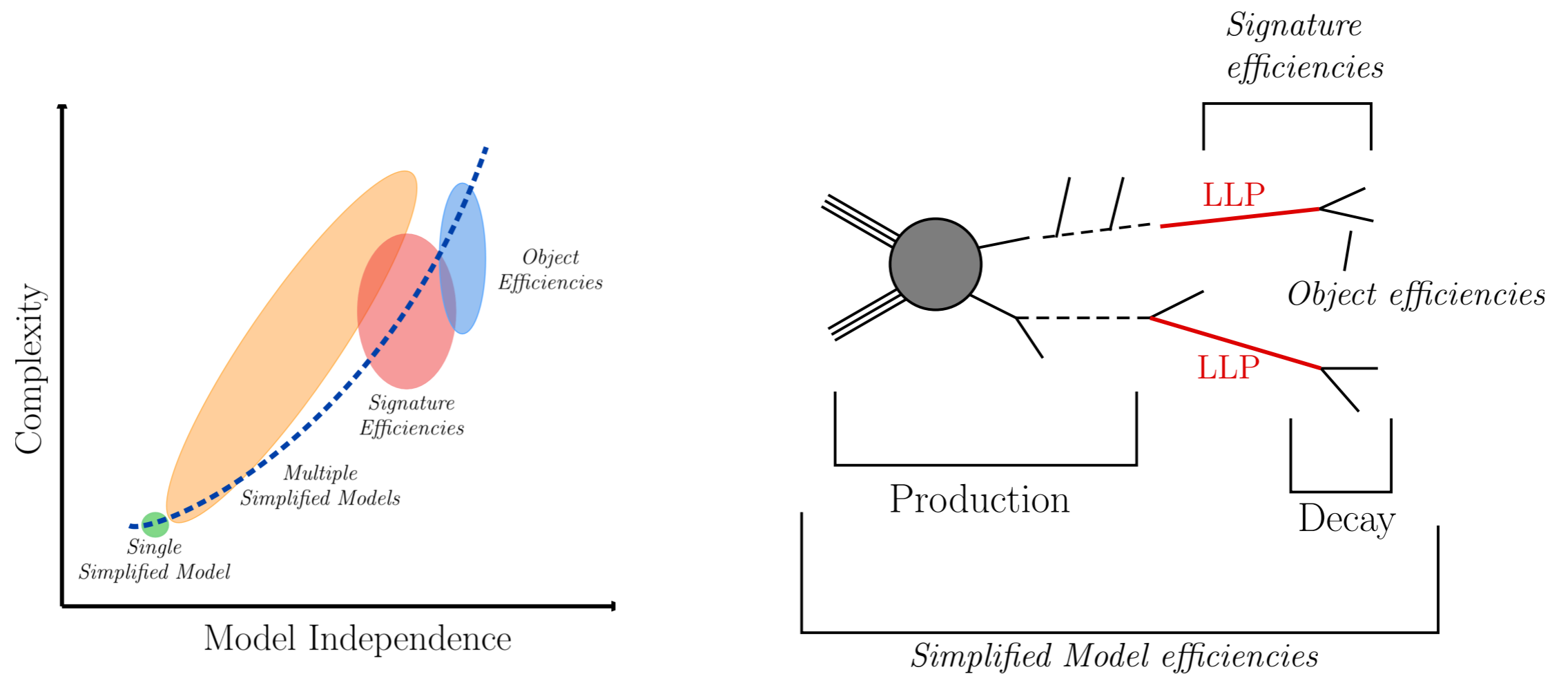Single Photon

Hadronic

Semileptonic

Leptonic

Flavored Leptonic

*Can always come with MET

Simplified Models

Example: Neutral LLP

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell_\alpha^+ \ell_{\beta\neq\alpha}^-(+\text{inv.})$
DPP: sneutrino pair	†	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*	†
ZP: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
ZP: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

8

Reinterpretation and Presentation of Results

Complicated Topic: but there is convergence and recommendations for each decay channel

FIG. 4. Summary plot showing all the most important applicable constraints. Our results are shown in the upper solid red line ("this work"), which corresponds to the green line of Figure 3 (left). In black solid/dashed (for the lines) the monojet constraints are shown. The other constraints are: atmospheric, XQC and RRS experiments and sub[...] the Majorana neutrino underground experiments (orange line), CMB+Lyman-α (black dashed).

Experimental Coverage

This group summarized the current experimental coverage and identified the blind spots

V. CONCLUSION

In this work we have considered further the possibility that DM may be made (partially or totally) of particles with strong interactions with ordinary matter. These so-called SIMPs, for strongly interacting massive particles, are much less considered than their more popular siblings, the WIMPs, but they are regularly considered in the literature in order to address some astrophysical issues. While they are challenged by many observations, again mostly astrophysical, they are not completely excluded. Furthermore, little work has been done on possible constraints from colliders. Extending on previous works, in particular [19], we have studied in more details the possibility of observing trackless jets at the LHC, taking into account realistic simulations of the QCD background and the response of the detectors. Most notably, we show that the charged content of jets is a powerful discriminator to suppress dijet backgrounds at LHC, thus enhancing the sensitivity to a potential SIMP signal. Our analysis shows that SIMPs with mass up to $m_\chi \sim 400$ GeV could lead to an observable signal, provided its interaction cross section with ordinary matter is about 10% of that of ordinary nucleons. Most of our work is dedicated to the forecast for the experimental search of SIMPs at the LHC. To do so, we

1. All-hadronic

- Use associated object triggers (especially motivated by Higgs like VBF and VH)
- Try to push to lower masses & lifetimes
- Online reconstruction of hadronic displaced objects
- Exclusion limits for displaced hadronic taus. Opportunity for CMS displaced triggers?

2. Leptonic

- Intermediate region between low-mass (lepton-jets) and high-mass (resolved ATLAS/CMS searches)
- Continue to push to go to lower masses, p_T thresholds
- Tau leptons in LLP decay, in particular if they come from ID. Opportunity for CMS displaced triggers?

3. Semi-Leptonic

- Low masses (like Majorana neutrino)
- Making sure to cover all flavor combinations (for example, one CMS search only covers $e^\pm \mu^\mp$), as well as same-sign vs. opposite sign leptons
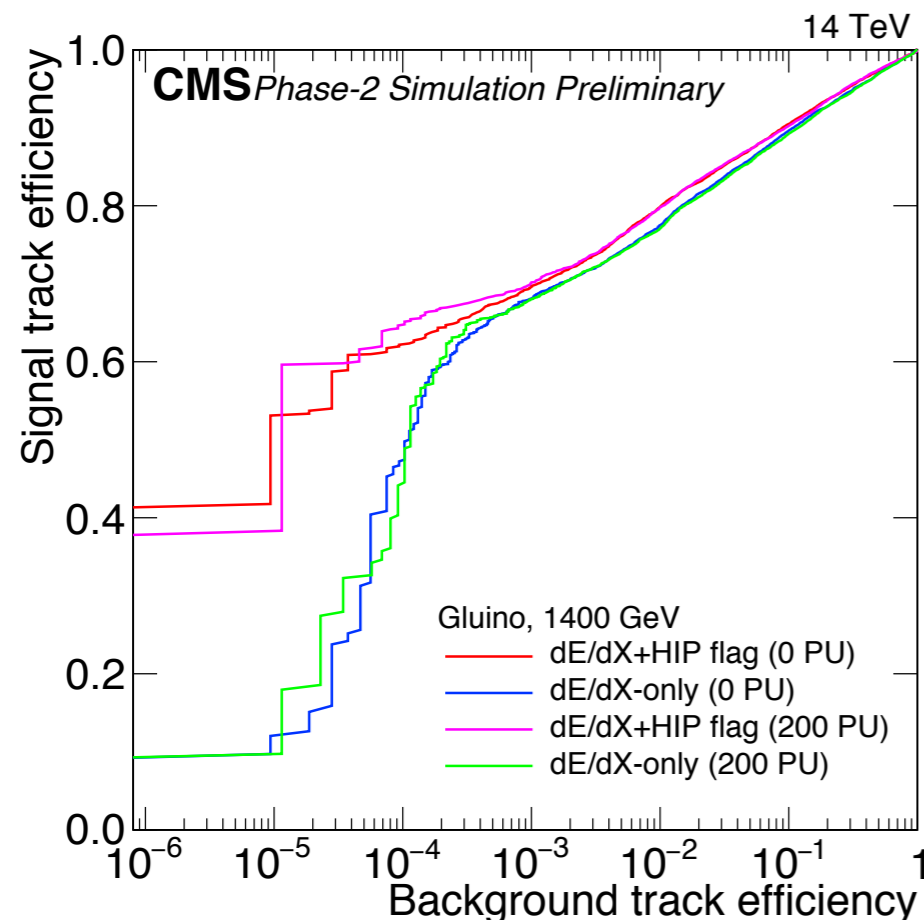- Trigger on associated objects or use dilepton trigger if there are two LLPs?

4. Photonic

- No coverage for LLPs decaying into $l\gamma$, $j\gamma$ or without E_T^miss.
- Poor coverage (non-dedicated search) for single γ, only if two jets are present, needs recasting of CMS delayed photon study [186].
- Prompt photons searches useless, as they veto "non-standard" photons.
- No coverage for softer photons.

5. Other exotic long-lived signatures

- DTs: $c\tau \sim$ mm are very hard to probe. Unclear if ATLAS IBL will be present in HL-LHC run. What is the lowest distance new layers (or double layers) can be inserted at?

Detector & Trigger Updates

CMS *Phase-2 Simulation Preliminary*

14 TeV

Signal track efficiency vs Background track efficiency

Gluino, 1400 GeV
- dE/dX+HIP flag (0 PU)
- dE/dX-only (0 PU)
- dE/dX+HIP flag (200 PU)
- dE/dX-only (200 PU)

**heavy stable particle:
use the fact they are
not minimally ionizing**

- LLP searches rely on all detector subsystems

- Appearance (or disappearance) of particles mid-flight poses additional challenge to the trigger system

- Track triggering is of interest

- Pile-up is a constant enemy.

Dark Showers

- Disclaimer: This is my subgroup: so I may spend more time on this…

- The showers may come from:

  - Strongly coupled group SU'(N)

  - Hierarchical splittings

- Finally, the dark sector needs to decay back into SM

Standard Model

Dark Sector
Hidden Valley

…
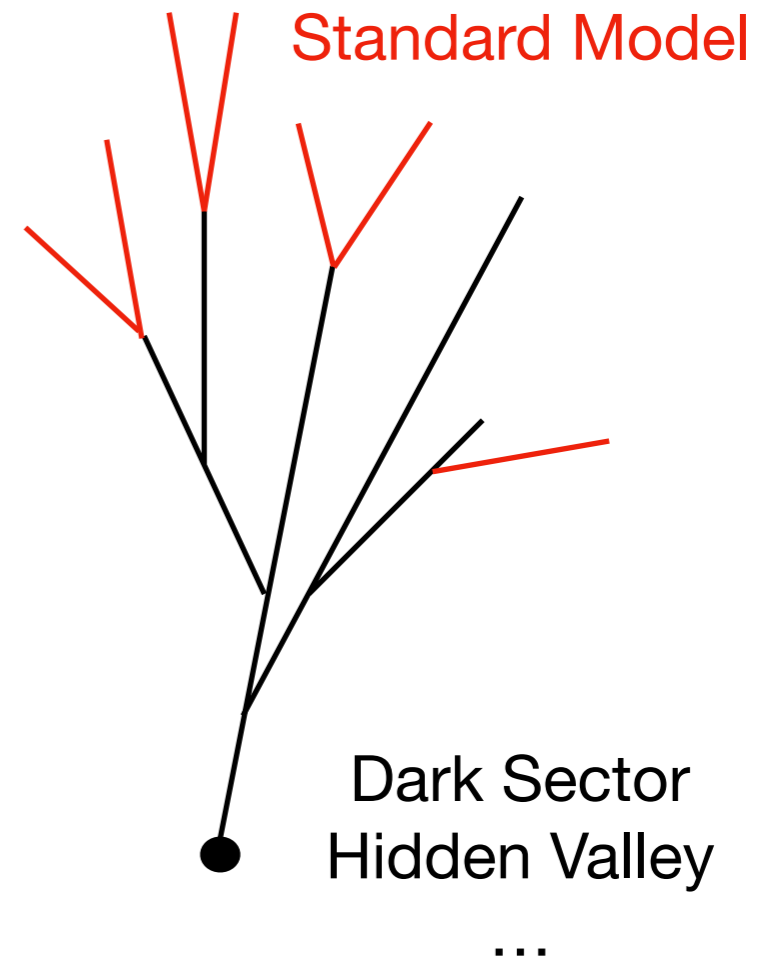
Dark Showers

- Interesting models:

    i. Lepton-jets

    ii. Emerging jets

    iii. SUEPs (Soft Unclustered Energy Patterns)

    iv. Semi-visible jets

    v. Photon-jets

    vi. …

Standard Model

Dark Sector
Hidden Valley

…
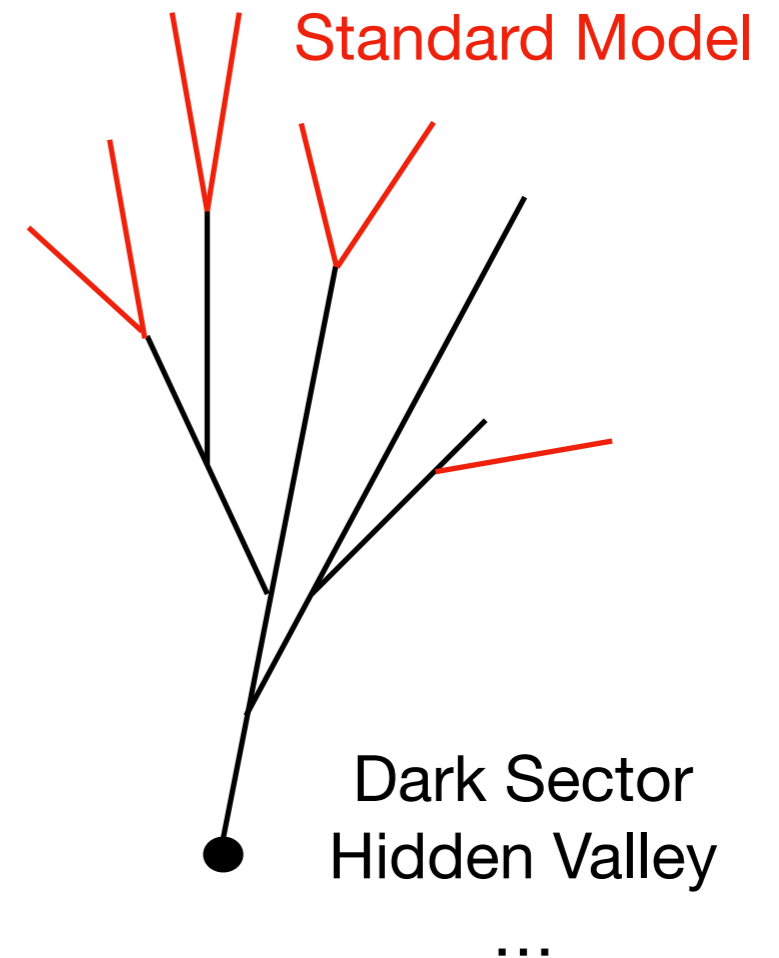
Dark Showers

Experimental Challenges:

- Suddenly there are many displaced vertices: the reconstruction becomes complicated

- Collimated particles tend to fail the typical isolation requirements: Not just for electrons and photons, also muons.

- High sphericity events spread their energy evenly over the detector: not much to trigger on.

Dark Showers

- What are reasonable benchmark models?

- How does one create a reliable simulation of showers?

  - Current showering software is very good for QCD, which is dominated by nearly-collinear radiation.

  - Even using different showering prescription VINCIA, we still saw a lack of coverage of large sphericity events.

  - Use different models to achieve theoretical coverage of such signatures.

Dark Showers

16
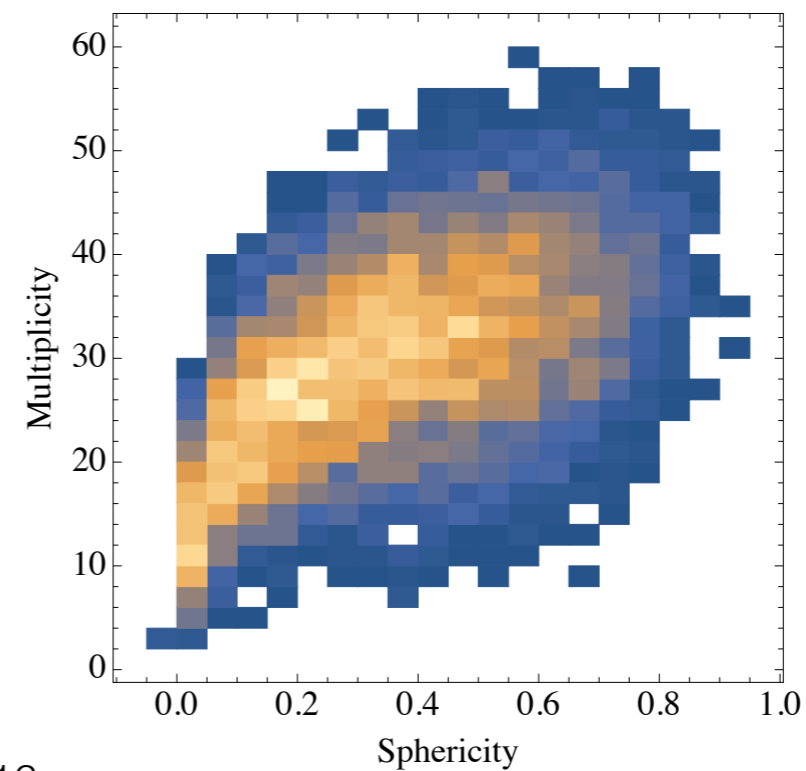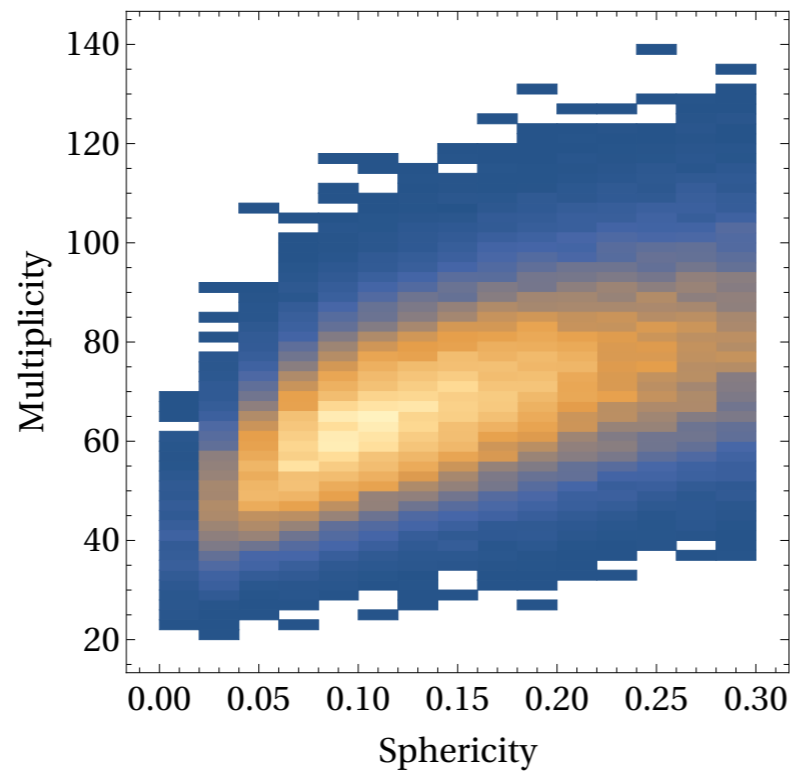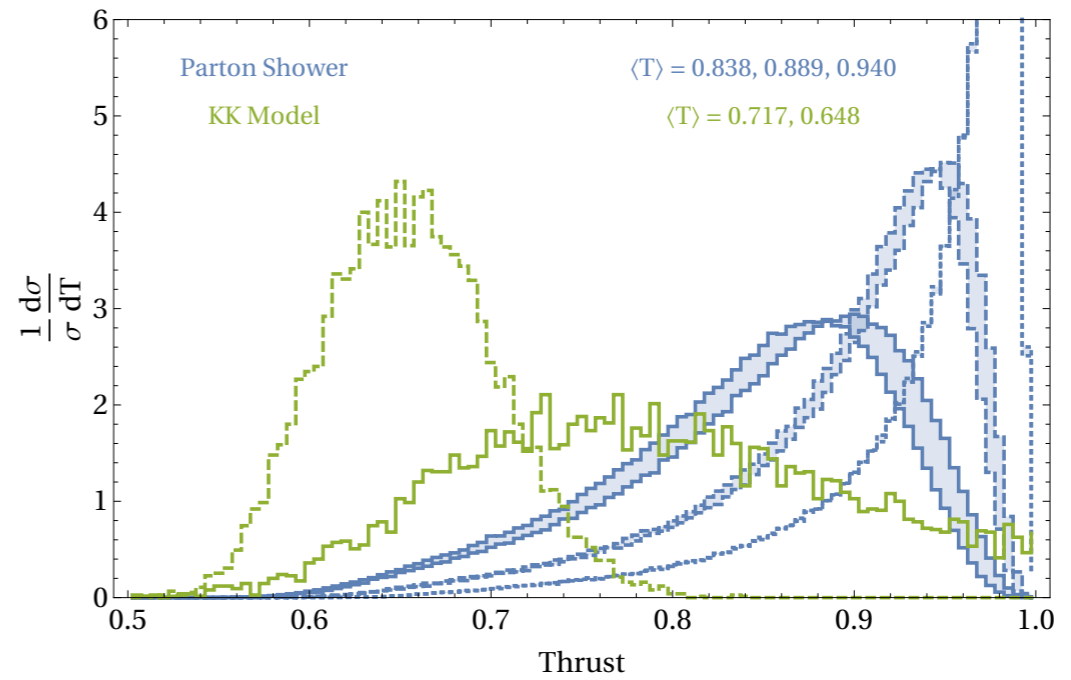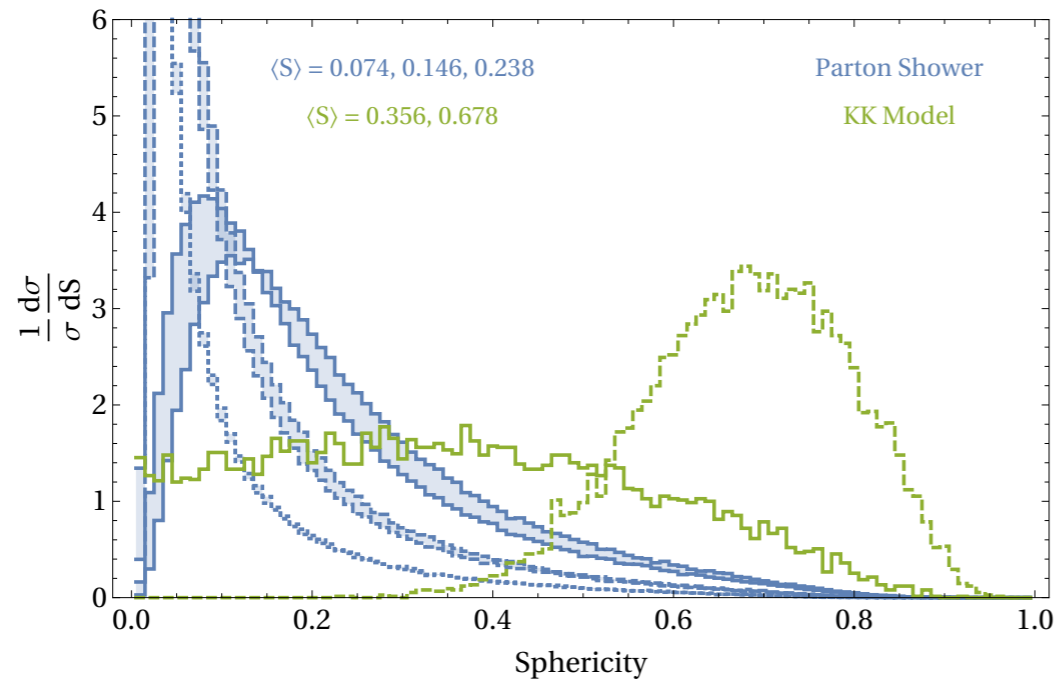
Conclusion

- Higgs is an important portal to new physics.

- Understanding Higgs production is an important input: Associated production objects can be very useful for NP searches.

- LLPs are challenging, but "motivated" and fun.

- We are on our way towards the White Paper: it will be a good read.