

# EF09 Highlights

– BSM general exploration –

Tulika Bose, Zhen Liu, Simone Pagan Griso

[https://snowmass21.org/energy/bsm\\_general](https://snowmass21.org/energy/bsm_general)

EF workshop,  
Brown University, March 28<sup>th</sup> 2022



# Introduction

- The objective of EF09 is to collect input on future opportunities for BSM exploration based on a wide range of models, ranging from “standard candles” to exotic signatures, as well as “model-agnostic” searches
- The current state of particle physics leads to a very wide spectrum of possibilities for where the next ground-breaking discovery might be and for what’s the best way to maximize our opportunities to find it

# EF09 Focus Questions

representative,  
not comprehensive.

- Are there **new interactions** or **new particles** around or above the electroweak scale? To what extent can future experiments probe this?
- **Long-lived** and **feebly-interacting** particles represent an alternative paradigm with respect to traditional BSM searches. To what extent can future detectors and accelerators probe such particles ?
- How do we conduct searches in a more **model-independent** way ?
- What's the origin of the origin of the **flavor structure** of the SM ? Is **lepton flavor universality** violated ? What do we learn from searches at the energy frontier ?

# EF09 - BSM general exploration

To explore these questions, EF09 has been organizing activities around four areas

## Heavy Bosons

- Explore new interactions
- Standard candles for EF machines ( $Z'$ ,  $W'$ ,  $q^*$ , ...)

## New Fermions

- New matter content
- Heavy neutral leptons, Vector-like quarks, ...

## Long-Lived Signatures

- Heavy vs Light new LL particles
- Interplay with detector design

## Other exotica

- Inclusive BSM searches
- AI-powered anomaly detection method
- ...

Identify benchmarks, explore new collider options, focus on the physics messages.

Synergy with other EF groups, as well as other frontiers (RPF, NF, ...)

# Snowmass community input

At the start of Snowmass, gauged interests through expression-of-interests (Eol) and letters-of-interests (Lol)

- 66 Eol, 73 Lol (large overlap)

After the snowmass pause, estimated ~50 Lols still ~active state

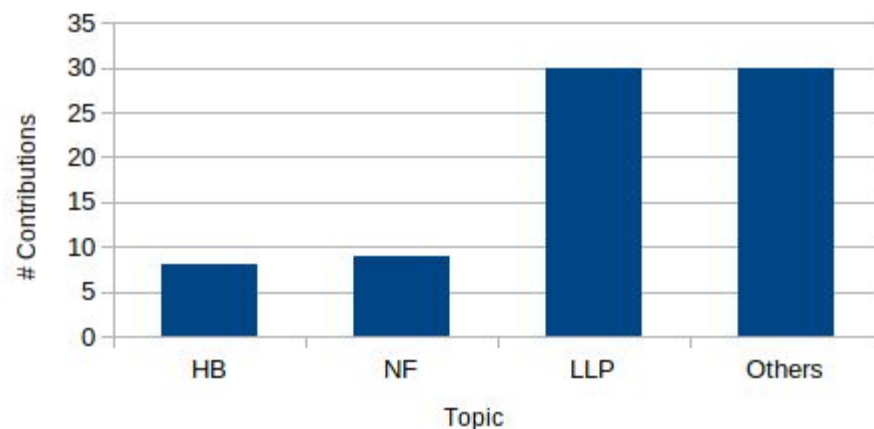
- 22 (44%) submitted as a contributed paper or published to a journal and communicated directly to us

Overall received 25 direct snowmass submissions to EF09.

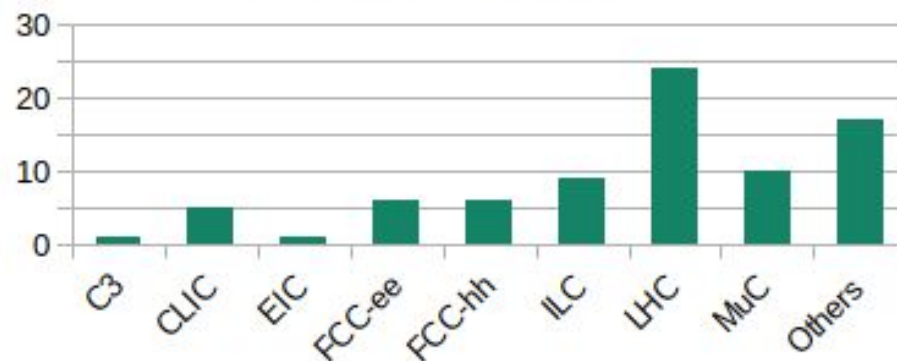
63 contributions (snowmass sub. or journal) identified as having material directly relevant to EF09

- Including 10 contrib. papers from other EF groups or other frontiers

Contributions by topic



Contributions by Collider



# BSM Snowmass report

Snowmass BSM report will include sections on the four main EF09 areas.

We invited, after an open call, experts in three key areas to help scrutinize available literature, snowmass inputs, and draft specific sections. Largest number of contributions expected in these areas.

## Heavy Bosons

Robert Harris,  
Felix Yu

## New Fermions

Julie Hogan,  
Ian M. Lewis

## Long-Lived Signatures

Juliette Alimena,  
Simon Knapen

They will also lead discussions during EF09 parallel session this week.

- One additional expert invited to guide the discussion on other exotica

## Other exotica

Lingfeng Li  
To lead discussion @ EF ws

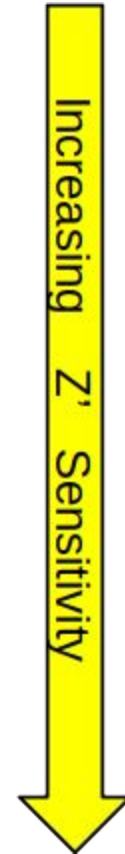
In the following slides, just a flavor of the breadth of contributions received

# New bosons and heavy resonances

- Focus on the many Snowmass results for  $Z'$  bosons
  - Summarized future colliders proposals by  $Z'$  sensitivity
- $Z'$  bosons provide a **standard candle** for BSM physics
  - Allows simultaneous focus on both model and machine space
  - It's a benchmark minimally characterized by mass, production coupling and decay coupling
    - In many new physics models featuring new bosons, the collider phenomenology can typically be distilled into these three new physics parameters
- Also explore a **diversity** of models and channels
  - Diverse signatures, from resonance models exploring complementary physics of unification, flavor, dark matter, compositeness, etc..
    - $W'$ , axion-like particles (ALP), dijet resonances,  $t\bar{t}$  and multi-jet
  - “Over-simplify” only to the necessary extent

# Machines ordered by $Z'$ sensitivity

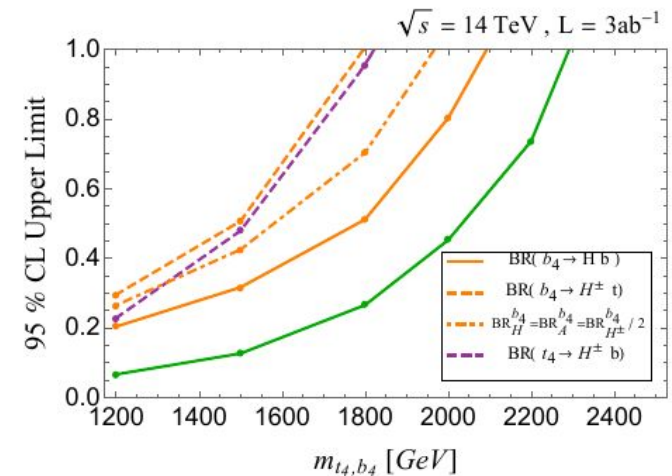
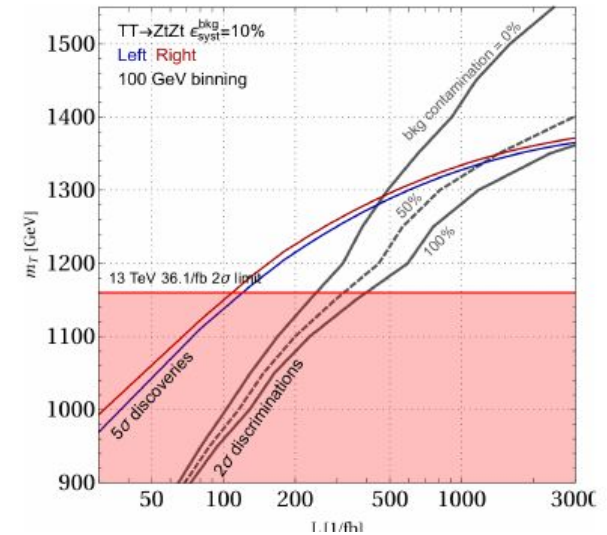
Machine	Type	$\sqrt{s}$ (TeV)	$\int L dt$ (ab <sup>-1</sup> )	Source	$Z'$ Model	$5\sigma$ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	R.H.	$Z'_{SSM} \rightarrow \text{dijet}$	4.2	<b>5.2</b>
				ATLAS	$Z'_{SSM} \rightarrow 1^+ 1^-$	6.4	<b>6.5</b>
				CMS	$Z'_{SSM} \rightarrow 1^+ 1^-$	--	<b>6.8</b>
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>6</b>
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	4.9	<b>7.7</b>
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>7</b>
HE-LHC/ FNAL-SF	pp	27	15	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>11</b>
				ATLAS	$Z'_{SSM} \rightarrow e^+ e^-$	12.8	<b>12.8</b>
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	8.3	<b>13</b>
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>13</b>
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>19</b>
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_Z'=0.2)$	10	<b>20</b>
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \rightarrow f^+ f^-$	14	<b>22</b>
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>21</b>
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>24</b>
FCC-hh	pp	100	30	R.H.	$Z'_{SSM} \rightarrow \text{dijet}$	25	<b>32</b>
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	<b>35</b>
				EPPSU	$Z'_{SSM} \rightarrow 1^+ 1^-$	43	<b>43</b>
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_Z'=0.2)$	42	<b>70</b>
VLHC	pp	300	100	R.H.	$Z'_{SSM} \rightarrow \text{dijet}$	67	<b>87</b>
Coll. in the Sea	pp	500	100	R.H.	$Z'_{SSM} \rightarrow \text{dijet}$	96	<b>130</b>



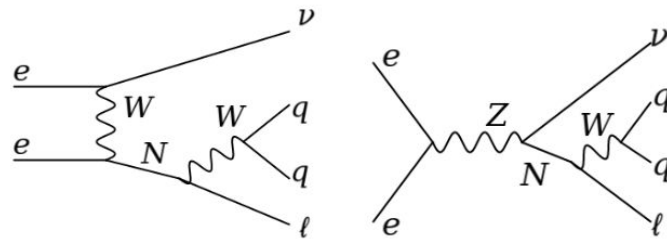


# Vector-like quarks

- Conventional searches:
  - QCD pair production and decays into Standard Model bosons:  $pp \rightarrow TT \rightarrow ZtZt$
  - Projections for HL-LHC [[CERN-2019-007](#)]
- Unconventional decays: [[2203.07270](#), [2203.03852](#)]
  - Standard Model extended by vector-like quarks and a second Higgs doublet
  - Vector-like quarks can decay into heavy Higgs:  $T \rightarrow Ht, T \rightarrow H^\pm b, B \rightarrow Hb, B \rightarrow H^\pm t$
- Unconventional production modes from chromomagnetic moments:  $pp \rightarrow Tt, pp \rightarrow Bb$  [[2107.12402](#), [1908.08964](#), [1803.06351](#)]

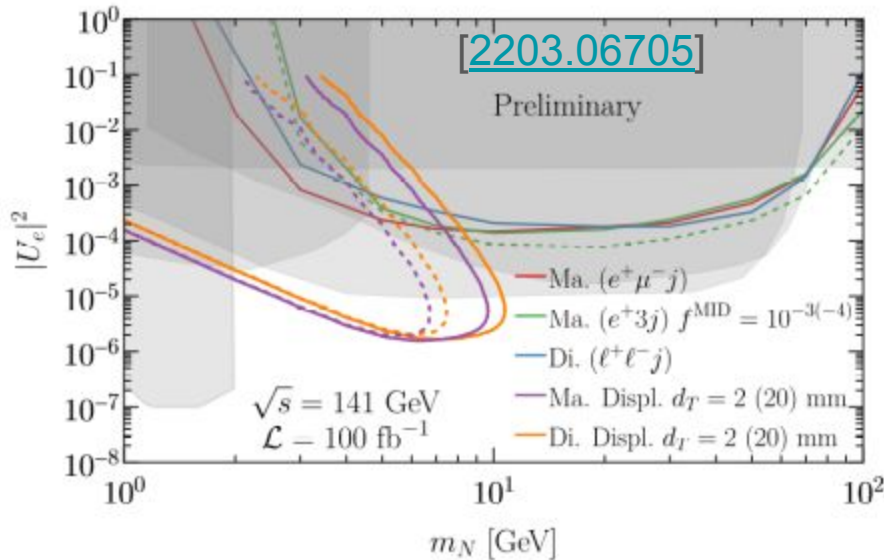


# Heavy-Neutral Leptons

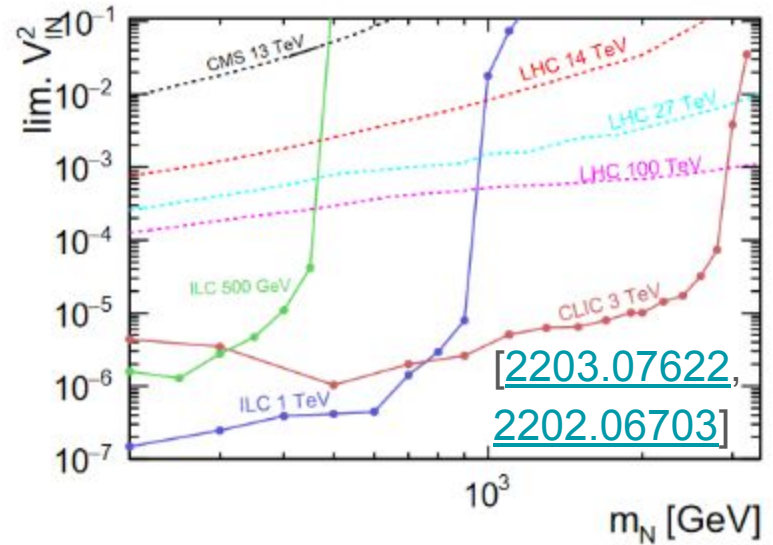


[2203.06703]

- **Type-I seesaw:** heavy right-handed Dirac or Majorana neutrinos
  - strong limits EIC (low), ILC/CLIC (med), pp@100 TeV (high)



[2203.06705]



[2203.07622, 2202.06703]

- **Type-III seesaw:** triplet of Majorana fermions (LHC, ILC [2203.07622])
- **Z'/νSMEFT:** complementary searches at DUNE & other experiments [2203.06131]
- “The Present and Future Status of Heavy Neutral Leptons” summary whitepaper submitted to NF3, including high- $p_T$  constraints [2203.08039]
- Prompt or long-lived signatures depending on mixing parameter

# Heavy Long-lived particles

Strong community interest in LLPs (~30 contributions received on the topic)

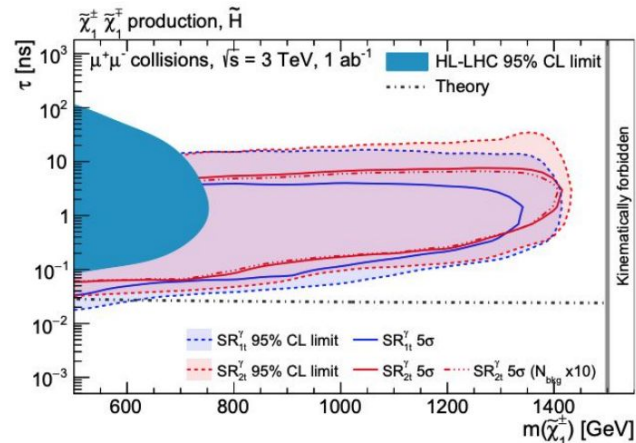
Heavy long-lived particles are now considered part of the core-program of multi-purpose experiments at colliders.

Projections require detailed full-simulation studies or careful pheno studies

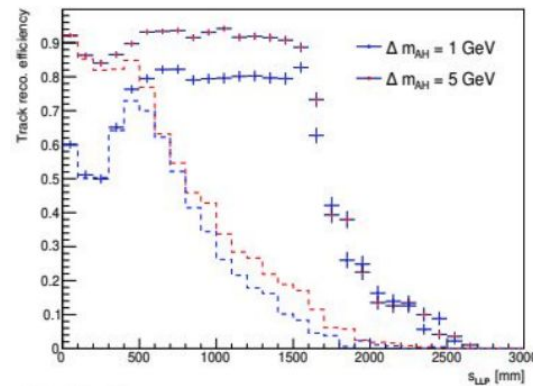
Muon collider, Disappearing Track

ILC, Heavy scalar decays

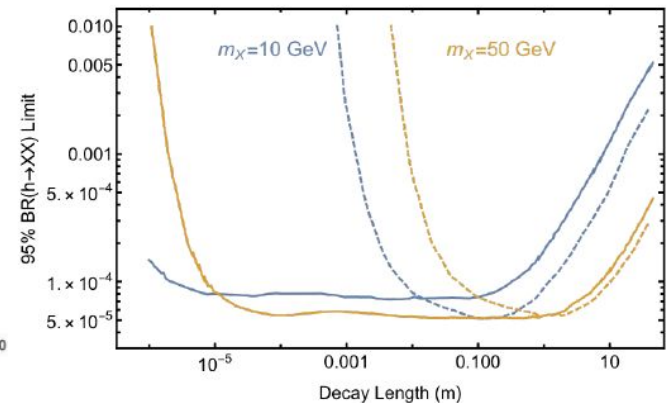
FCC-ee, Exotic Higgs decays



[2203.07261]



[2203.07622]



[2203.05502]

Good coverage across collider options for Disappearing Track projections\*.

More sparse projections for other possible common benchmarks.

Overall in quite some need for a few more results to make good summary plots.

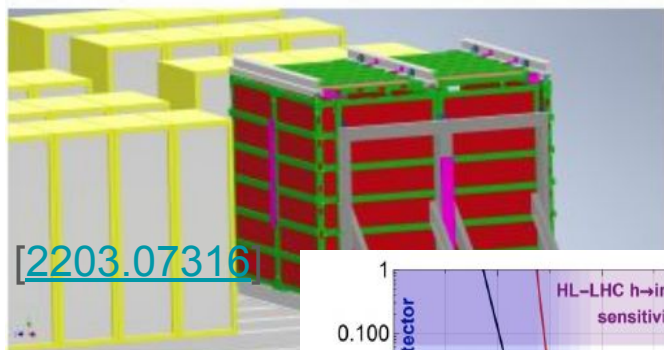
# Light Long-lived particles

Interest in short-term exploration especially via satellite experiments

- Also exploiting possibilities in future colliders (ILC, MuC, FCC-ee, ...)
- Important synergy with the RF6 group (dedicated talk on Fri morning)

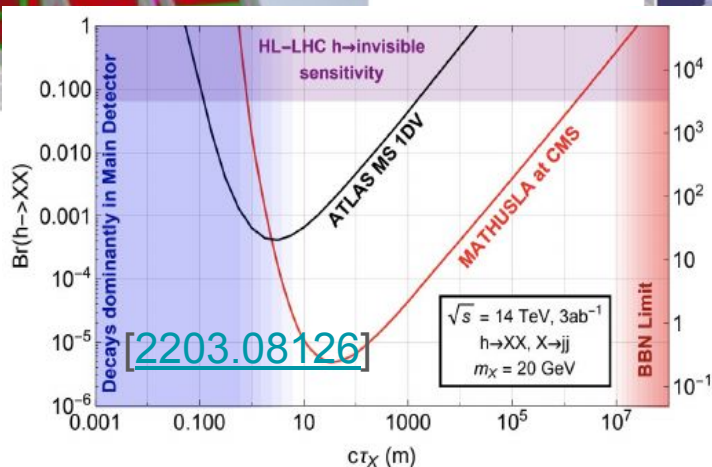
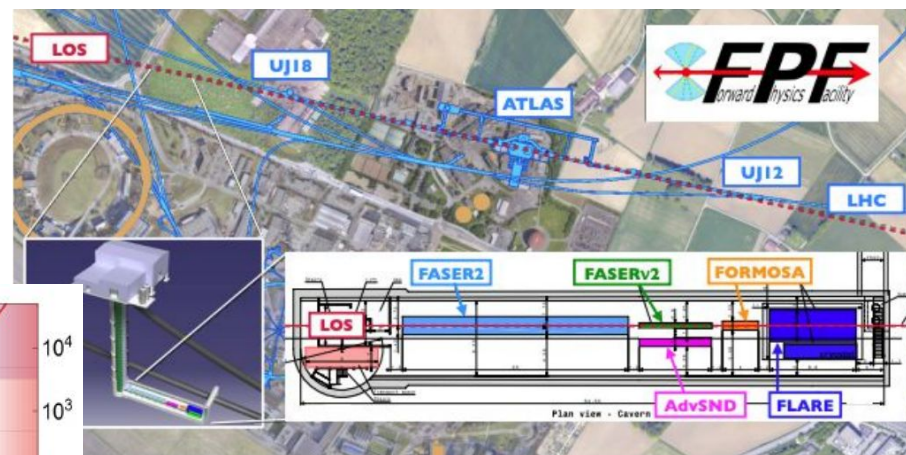
Now it's the time to act to make these proposals impactful for HL-LHC!

## CODEX- $\beta$



[2203.07316]

[2203.05090, 2109.10905]



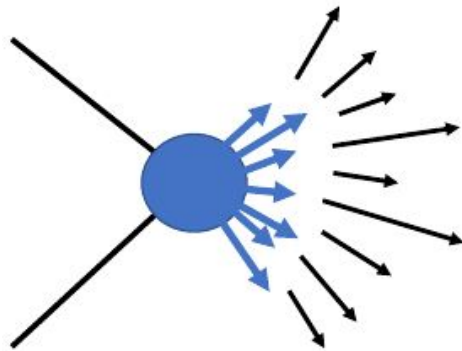
... and much more!



# Other (Exotic)<sup>2..N</sup>a

Extraordinary dynamics possible from a strongly-coupled dark sector

- dark showers, “soft bombs”



Comprehensive summary and view in dedicated snowmass effort. [2203.09503](https://arxiv.org/abs/2203.09503)

See also Friday BSM session:

Topical Group Plenary Discussions: BSM Physics (EF08+EF09+EF10)

10:00 AM

**WIMPs & dark sectors: the Snowmass dark showers project**

Speaker: Suchita Kulkarni

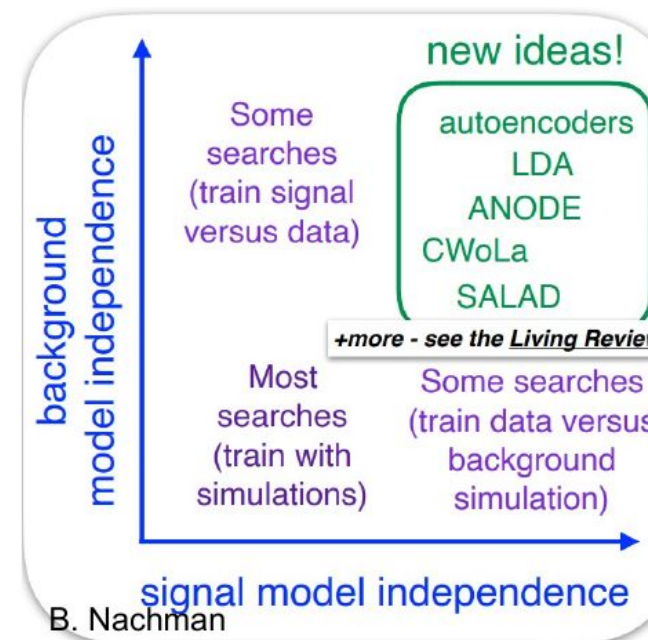
10:10 AM

**WIMPs & dark sectors: dark matter in dark showers discussion**

Speaker: Suchita Kulkarni

Machine Learning techniques without having specific signal samples:

- Unsupervised Learning (No labels)
- Weakly Supervised Learning (Noisy/blurred labels)
- Semi Supervised Learning (“Bkg only” labels)

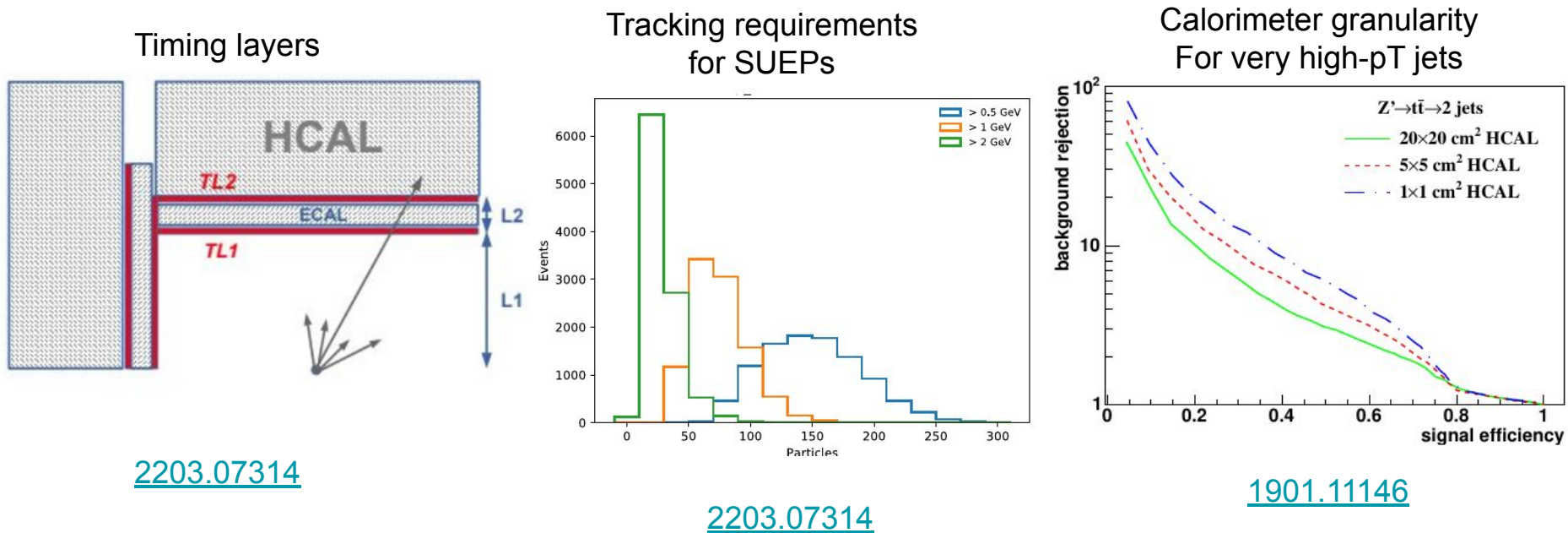


[2101.08320](https://arxiv.org/abs/2101.08320),  
[2111.12119](https://arxiv.org/abs/2111.12119),  
[2108.13451](https://arxiv.org/abs/2108.13451)

# Interplay with detector development / requirements

Several contribution highlighting how key detector R&D are tied to physics goals.

Interplay between detailed simulation studies and flexible rougher estimates.



And many more in performance-dedicated sections of future collider contributed papers submissions by the collaborations!

# [EF09] Plans for this EF workshop

## Tuesday @ 11AM:

Challenges and opportunities for BSM at future colliders (panel)

- Big-picture of BSM landscape to shape report's main points: panel discussion

## Wednesday @ 10AM:

Parallel EF09 session

- Detailed discussion per-area of summary plots and contributions received

### Parallels: EF09 Parallel Session

10:00 AM	<b>Introduction</b> <b>Speakers:</b> Simone Pagan Griso (Lawrence Berkeley National Laboratory), Tulika Bose (University of Wisconsin-Madison), Zhen Liu (University of Minnesota)	🕒 10m
10:10 AM	<b>New Bosons - summary and discussion of critical points</b> <b>Speakers:</b> Felix Yu (JGU Mainz), Felix Yu, Robert Harris (Fermilab)	🕒 15m
10:40 AM	<b>New Fermions - summary and discussion of critical points</b> <b>Speakers:</b> Ian Lewis (University of Kansas), Julie Hogan (Bethel University), Julie Hogan (Bethel University), Julie Hogan (Bethel University)	🕒 15m
11:10 AM	<b>LLP - summary and discussion of critical points</b> <b>Speakers:</b> Juliette Alimena (CERN), Simon Knapen (Lawrence Berkeley National Lab and UC Berkeley)	🕒 15m
11:40 AM	<b>Other Exotica - summary and discussion of critical points</b>	🕒 10m

## Thursday @ 3:30PM and Friday @ 10AM:

BSM plenary session (EF08+EF09+EF10)

- Talk on synergy with RF6 with focus on light long-lived particles (S. Gori)
- Summary of discussions in EF09-parallel (early-career speaker: S. Homiller)
- Panel discussions: including  $g_{\mu}-2$ , pMSSM, WIMP, dark sector, ...

## Friday 3:30PM:

Includes a brief summary and closing remarks from EF09



# Conclusions

- Overall, **large interest and breadth** of topics submitted to or relevant for EF09
  - 25 snowmass papers to EF09 + many large papers relevant to all EF
  - ~63 submitted or published and communicated to us, with content relevant to the group activities (+ many more published in the last two years but not directly communicated to us)
- Effort during snowmass to have discussions on **common benchmarks** for making summary plots easier to produce and understand
  - Successful in some areas, but might lack important contributions in others
- Please **join us for the many opportunities this week** to inject your view on the main messages that will build the bones of the upcoming BSM report and **shape BSM particle physics** in the near and farther future!

# BACKUP

Contributions by topic:

- HB: 8 submitted, 1 unknown
- NF: 9 submitted, 2 unknown
- LLP: 30 submitted, 3 unknown
- G: 30 submitted

Contributions by collider:

- C3: 1
- CLIC: 5
- EIC: 1
- FCC-ee: 6
- ILC: 9
- FCC-hh: 6
- LHC: 24
- MuC: 10
- Others/generic: 17

Contributions include big/generic papers. One contribution can be listed in multiple categories above.

Some Stats, some to put into plots:

Eols: 66

Lols: 73

- 50 Lols still somewhat active after snowmass pause
- 22 submitted/published, 7 unknown, 3 late, 18 withdrawn

93 total potential contributions identified relevant to EF09

- 63 actually submitted or published to journal and provided to us
  - 10 from other EF groups or other frontiers
  - 25 actually submitted to EF09 as snowmass proceedings
  - Remaining: submitted to journal, generic EF relevant for EF09
- 12 waiting(3)/unknown(9)
- 18 withdrawn