

FPF Whitepaper Status: BSM – LLPs

Ahmed Ismail
Oklahoma State University

4th Forward Physics Facility Meeting
February 1, 2022



BSM at the FPF: overview

MC tools

Long-lived particles

- vectors

- scalars

- fermions

- axion-like particles

- non-minimal models

	CONTENTS	4
140	I. Latex Template	6
143	II. BSM Physics	7
144	A. MC Tools for BSM	7
145	1. FORSEE: Forward Experiment SEnsitivity Estimator	7
146	B. LLPs: Vectors	10
147	1. Overview on New Vector Particles	10
148	2. Dark Photon	11
149	3. $B - L$ Gauge Boson	14
150	4. $L_e - L_\mu$ Gauge Bosons	15
151	5. $B - 3L_\mu$ Gauge Bosons	18
152	6. B Gauge Boson	20
153	7. $U(1)_{F3R}$ Gauge Boson [Blaskar Dutta, Jason Kumar, Sumit Ghosh]	23
154	8. Production via Proton Bremsstrahlung [Saeid Foroughi-Ahari, Adam Ritz]	30
155	9. Additional Production Modes [Peter Reimitz, Simon Plaetzer, Aislin Masouminia]	32
156	10. Decays of Light Vector Particles [Peter Reimitz, Renata Zukanovic Funchal, Ana Luisa Foguel de Silva]	33
157	11. Secret Neutrino Interaction [Pouya Bakhti, Moshak Rajaei]	36
158	C. LLPs: Scalars	42
159	1. Dark Higgs / Singlet Scalar Elina Fuels, Gilad Perez, [others ???]	42
161	2. Laboratory and Astrophysical Probes [Dev, Fortin, Harris, Sinha, Zhang]	43
162	3. Inflaton at the FPF [Nobuhiko Okada, Digesh Raut]	46
163	4. Motivation from freeze-in DM [Andrzej Hrycenk, Maciej Laletin]	49
164	5. Rich dark sector and complementarity with indirect searches [Krzysztof Jodkowski, Leszek Roszkowski, Sebastian Trojanowski]	51
165	6. Muon-philic and Up-philic scalar [Ahmed Ismail et al]	52
167	7. 2HDMs [Shufang Su, Wei Su, Felix Kling, Shualong Li, Huayang Song]	52
168	8. Chiral Dilatons [Ameen Ismail et al]	54
169	D. LLPs: Fermions	57
170	1. Light Long-lived Sterile Neutrino [Herbi Dreiner, Zeren Simon Wang, Jordy de Vries, Guanghui Zhou, Julian Y. G\u00fcter]	57
172	2. HNL mixing with the tau sector in neutrino mass models [Martin Hirsch and Juan Carlos H\u00e9lo Herrera]	60
174	3. Tree-level Decays of $O(\text{GeV})$ Supersymmetric Neutralinos from D and B Mesons [Herbi K. Dreiner, Zeren Simon Wang, Jordy de Vries, Guanghui Zhou, Julian Y. G\u00fcter]	64
176	4. Radiative Decays of sub-GeV Supersymmetric Neutralinos from Light Mesons [Herbi K. Dreiner, Doniaki K\u00f6hler, Saurabh Nangia, Zeren Simon Wang]	67
178	E. LLPs: ALPs and Pseudoscalars	69
180	1. Charming ALPs [Adrian Caramona, Christiane Scherb, Pedro Schwaller]	69
181	2. Bremining Enhanced ALP Productions and FPF Sensitivity [Zhen Liu, Kunfeng Lyu]	72
182	F. LLPs: Non-Minimal Models	75
184	1. Dynamical Dark Matter [Pei Huang, Keith Dienes, Brooks Thomas, Jonathan Feng, Max Fieg, Seung J. Lee]	75

186	2. Secondary Production in BSM and Neutrino Interactions [Krzysztof Jodkowski, Felix Kling, Leszek Roszkowski, Sebastian Trojanowski]	77
187	3. Light dark sector going through chain decay [Yazaman Farzan et al]	75
188	4. Dark Axion Portal at FASER [Hye-Sung Lee, Patrick deNiverville]	79
189	5. Z' to RH neutrinos [Deppeich, Kulkarni, Liu]	82
190	6. Fermion portal effective operators [Darine, Ellis, Yon]	85
191	7. search for sterile neutrino with light gauge interactions [Pyungwon Ko, Yongsoo Jho, Jonguk Kim]	88
192	8. beyond the minimal model of dark photon/extra gauge boson, and lepton flavor violation [Takashi Shimomura et al]	91
193	9. Light dark scalars through Z' / EFT [Enrico Bertuzzo, Marco Taoso]	95
194	10. Freeze-in sterile neutrino DM [Arindam Das, Srubabati Goswami, Vishwadev K. N., Tannay Kumar Poddar]	99
195	11. The $\nu\mu e$ -philic dark photon [Garv Chauhan, Xun-Jie Xu]	102
196	12. Imprints of scale invariance and freeze-in dark matter at FPF [Basabendu Barman, Anish Ghoshal]	103
197	13. Bound state formation and LLPs [Dipan Sengupta, Julia Harz, Mathias Becker, Emanuele Copello, Kirtimaan Mohan]	105
198	G. Dark Matter Scattering at the FPF	111
199	1. Dark photon mediator models	112
200	2. Hadrophilic DM Models	115
201	3. Dark matter search in the Advanced SND@LHC detector [Alexey Boyarsky, Alex Mikolajenko, Maksym Ovchynnikov, Lesya Shevtshka]	117
202	4. Dark states with EM form factors [Jui-Lin Kuo et al]	121
203	H. Milli-charged Particles at the FPF [Matthew Citron, Subir Sarkar, Yu-Dai Tsai]	126
204	1. Others	127
205	1. Quirks [Junaid Li, Junle Pei]	127
206	2. BSM with Maos	131
218	Acknowledgments	133
219	References	134

DM scattering \rightarrow talk by Sebastian Trojanowski

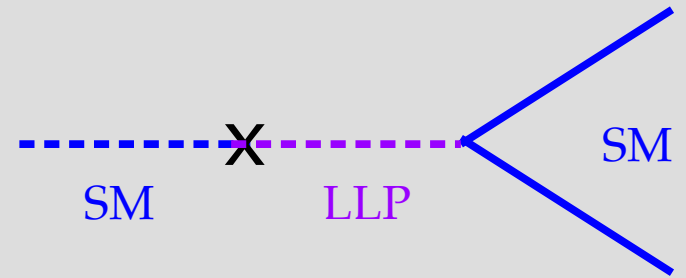
Millicharged particles \rightarrow talk by Yu-Dai Tsai

Long-lived particles at the FPF

General idea: produce LLP from SM pp collisions

For small momentum transfer, LLP beam is well collimated at high rapidity

LLP decays downstream (FASER2)



Limited set of renormalizable portals

$$S^2 H^2 \quad F^{\mu\nu} F'_{\mu\nu} \quad LHN$$

Different phenomenology in more complicated models

Monte Carlo: FORESEE

Github

Kling, Trojanowski

Built-in meson spectra for decays to, mixing with LLPs

The screenshot shows a Github repository interface. At the top, it indicates 'main' branch, '2 branches', and '0 tags'. The repository name is 'KlingFelix MCP Higher Stats', with a commit hash 'f71168a' on 'Dec 10, 2021' and '37 commits'. A list of files and folders is shown, including 'files', 'src', '.gitignore', 'README.md', and several tutorial notebooks like 'Tutorial-ALP-W.ipynb' and 'Tutorial-DarkHiggs.ipynb'. Below the file list, the 'README.md' content is visible, starting with the title 'FORESEE: FORWARD Experiment SENSitivity Estimator' and the authors 'By Felix Kling and Sebastian Trojanowski'.

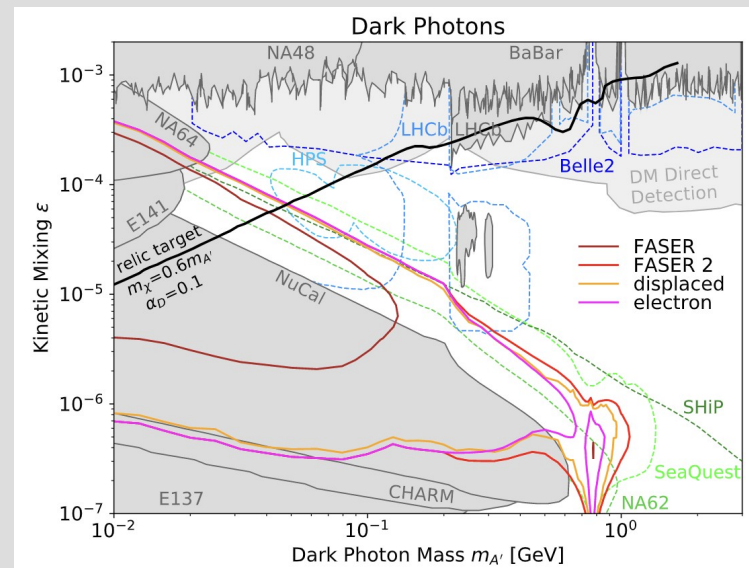
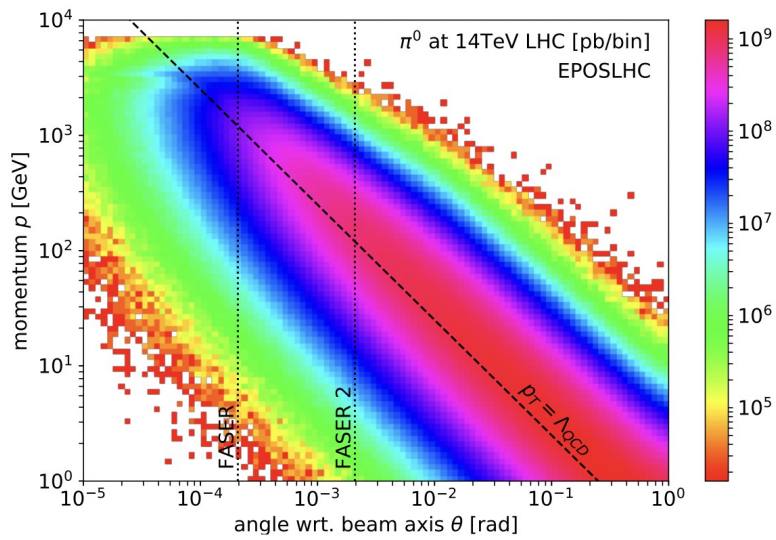
FORESEE: FORWARD Experiment SENSitivity Estimator

By Felix Kling and Sebastian Trojanowski

arXiv: 2105.07077

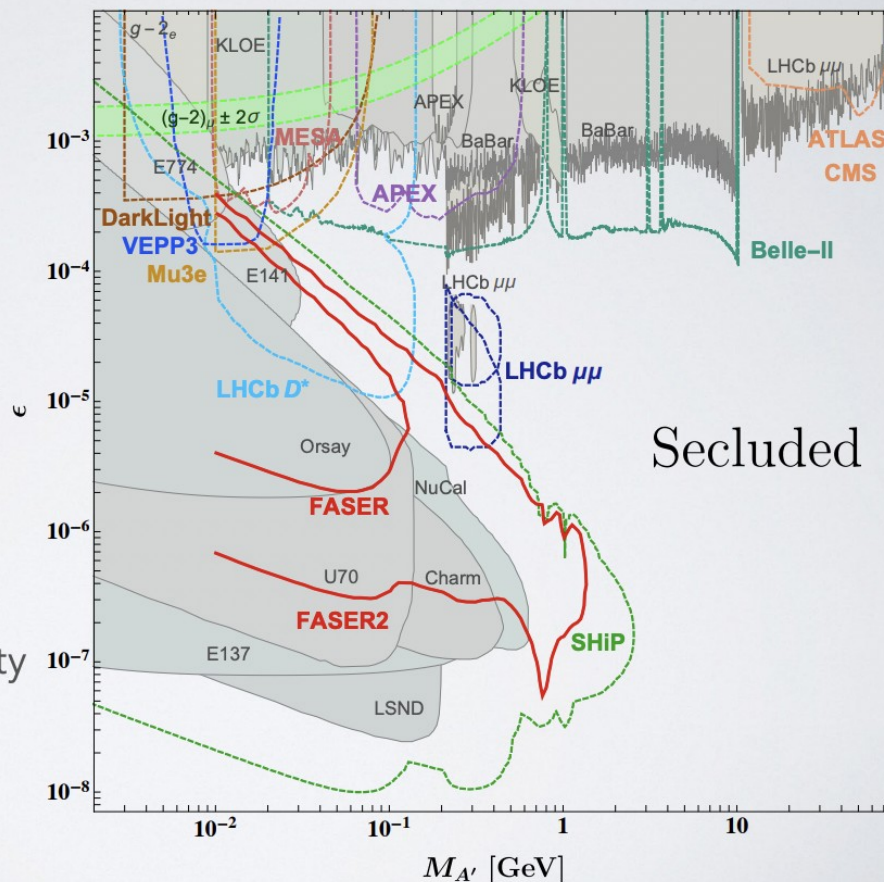
Introduction

We present the numerical package **FOR**ward **SEE** to simulate the expected sensitivity reach of exper- interaction point. We also provide a compre-



SECLUDED $U(1)_X$

- Minimal secluded $U(1)_X$ model for $J_\mu^X = 0$ (only kinetic mixing)
- A' produced in EM processes like bremsstrahlung, radiative return and meson decays
- FASER(2) will be able to search for A' in visible decays and push sensitivity significantly



Dark photons

$$\epsilon F^{\mu\nu} F'_{\mu\nu}$$

talk by
Foldenauer

New gauge bosons

B – L, $L_i - L_j$, B – 3 L_i (Foldenauer)
 B (Foguel et al.), T3R (Dutta et al.)

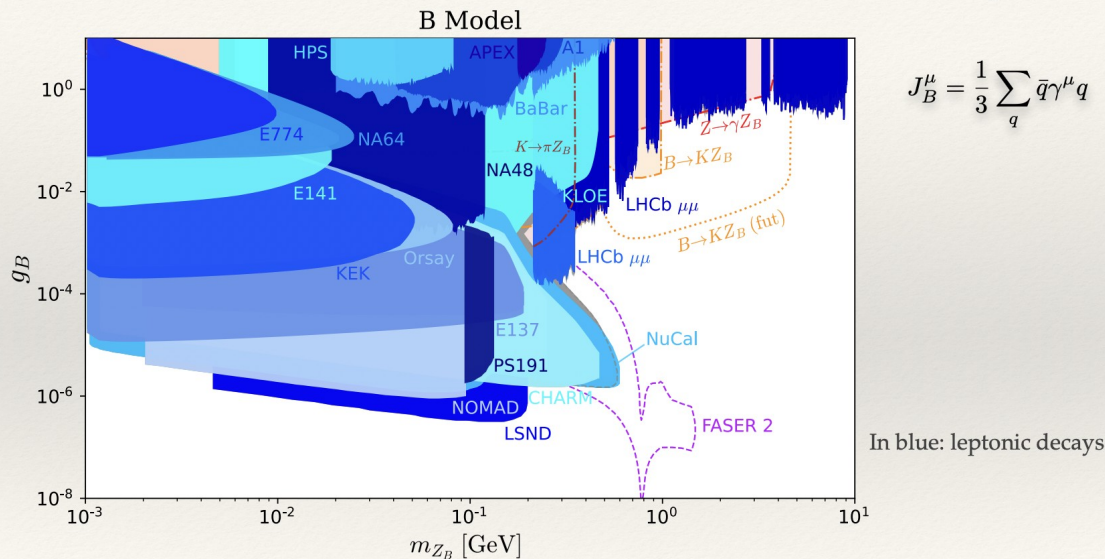
Bremsstrahlung
 calculations
 (Foroughi-Abari et al.)

Production
 (Masouminia et al.)

Decays (Reimitz et al.)

talk by Reimitz

B model



Higgs portal scalar

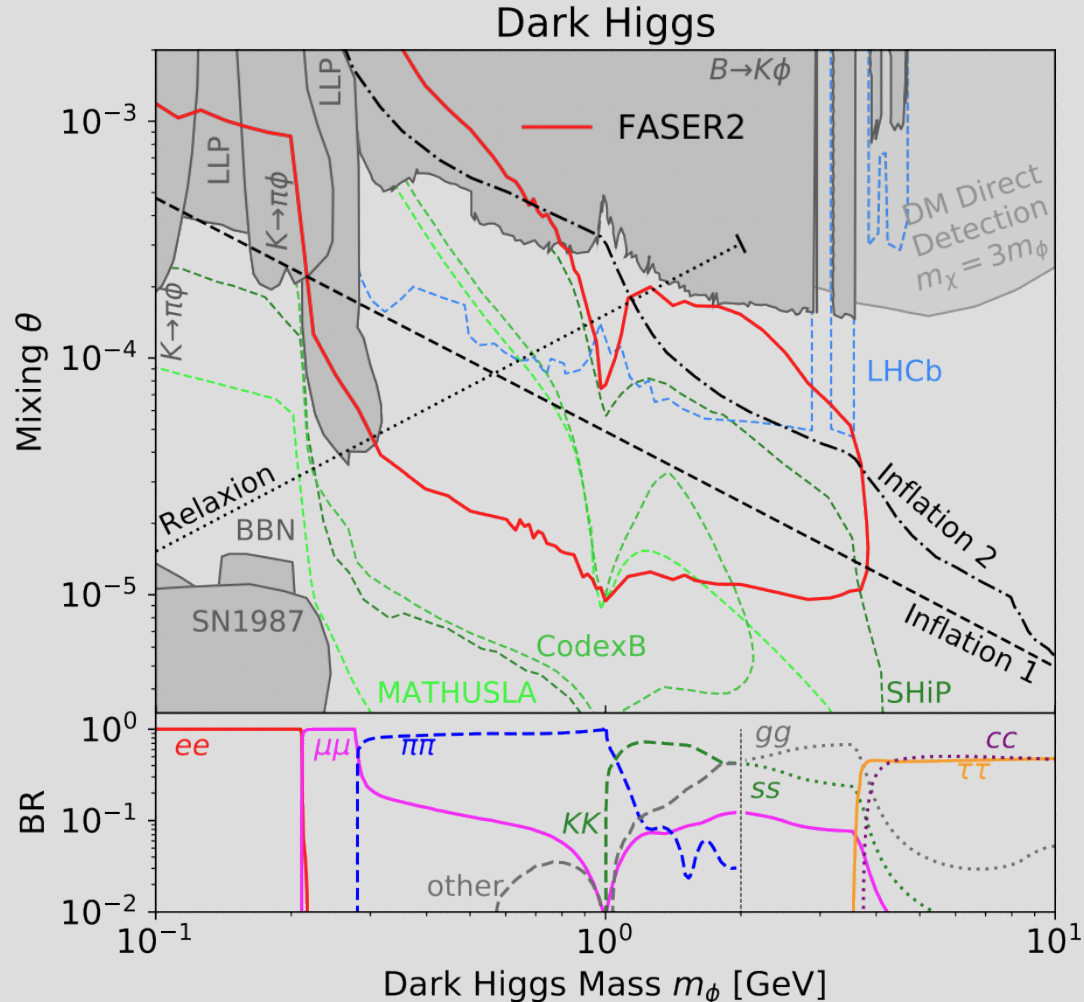
$$\sin \theta \frac{m_f}{v} \phi \bar{f} f$$

Motivations

Dark matter mediator
(Hryczuk et al.,
Jodlowski et al., Barman
et al.)

Inflation (Bramante et
al., Okada et al.)

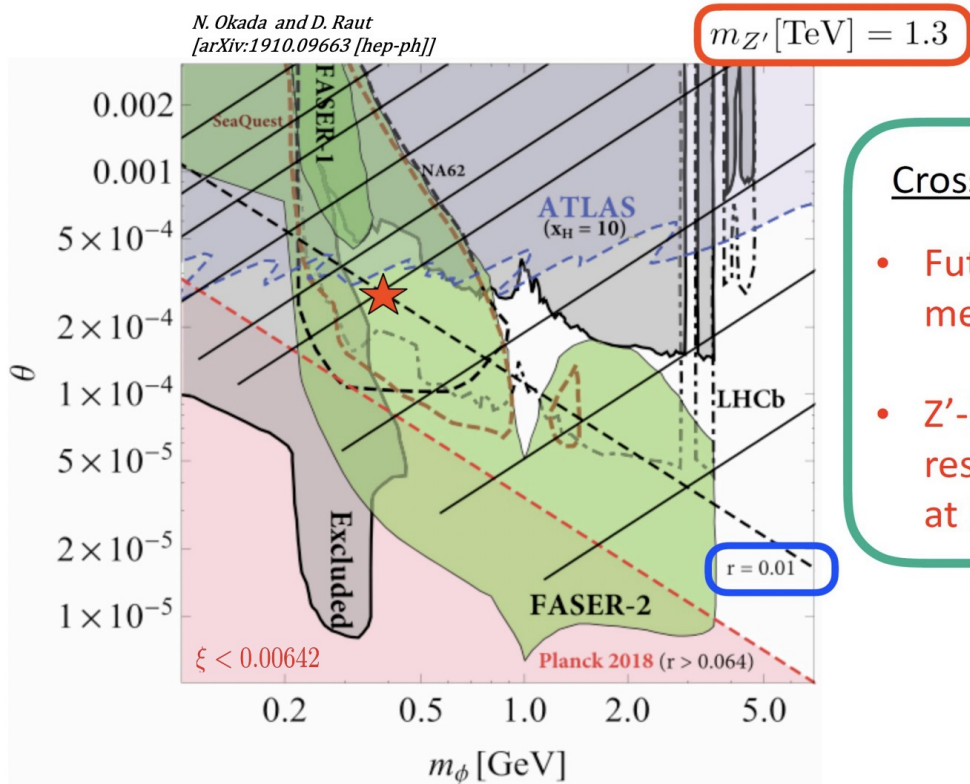
Relaxion (Fuchs et al.,
Winkler et al.)



Higgs portal scalar

Complementarity with Other Searches

N. Okada and D. Raut
[arXiv:1910.09663 [hep-ph]]



Cross checked by

- Future CMB measurements
- Z'-boson resonance search at HL-LHC

Complementarity, e.g.
Planck and Z' searches
(talk by Raut)

Related searches and
models

2HDMs (Su et al.)
Astrophysical probes
(Dev et al.)

Dilatons (Ameen
Ismail et al.)

Heavy neutral leptons

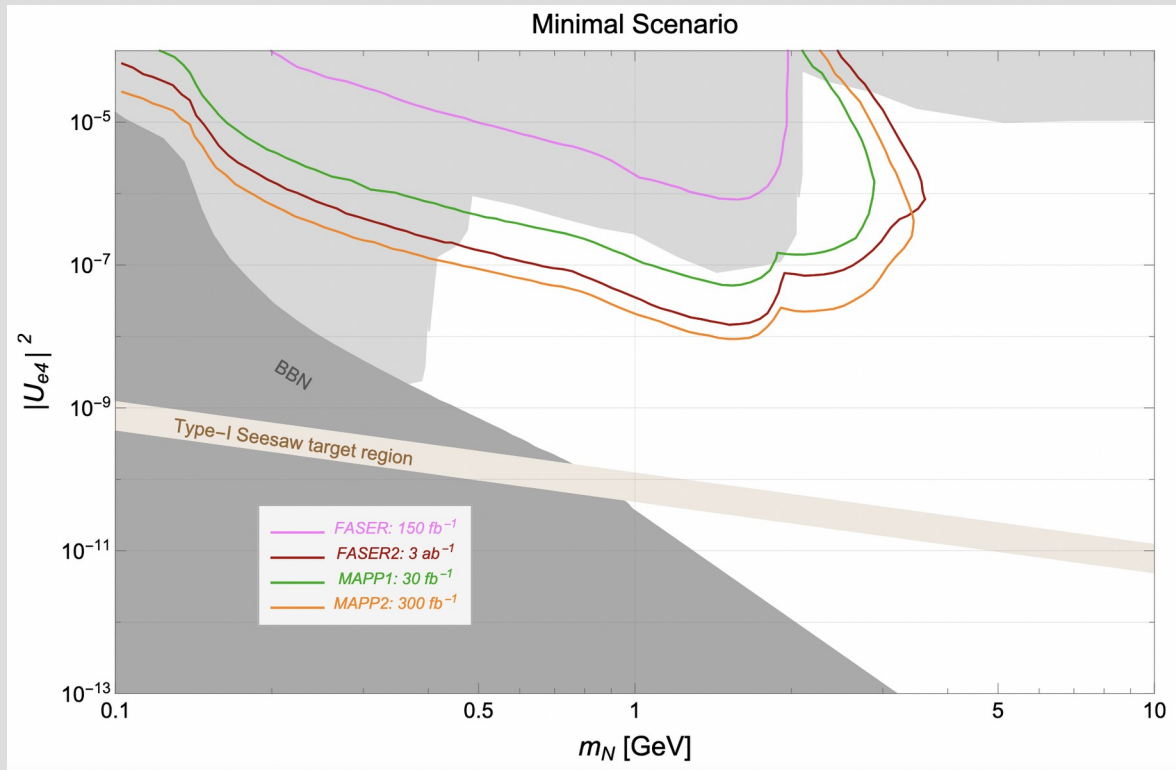
Simplest *LHN* portal \rightarrow mixing of N with active neutrino flavors

Dreiner et al.

Other flavors
(Hirsch et al.)

Effects of extra neutrinos in oscillations: see talk by Timo Karkkainen

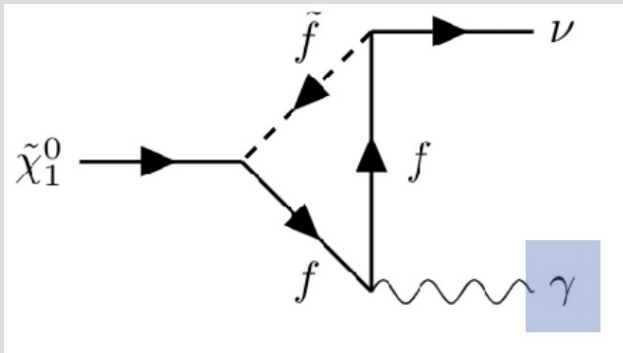
Mixing angle²



Other long-lived fermions

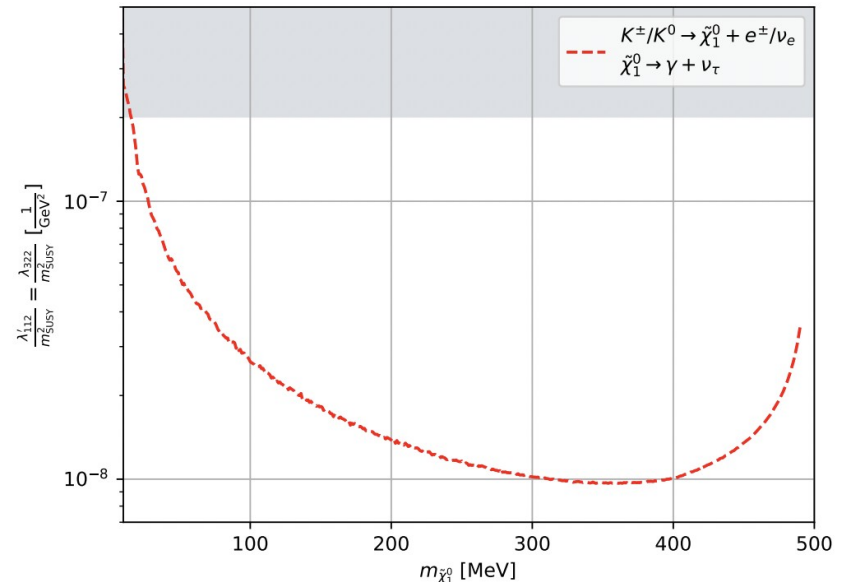
Neutralinos in supersymmetry with R-parity violation

Produce through meson decay, decay to single photon



talk by Kohler

- Probe existing constraints for **wide mass range**
- Production: λ'_{112} (LQD 112)
- Decay: λ_{322} (LLE 322)



Axion-like particles

Motivated by, though not restricted to, solutions to the strong CP problem

Relative strength of gauge boson, fermion couplings model-dependent

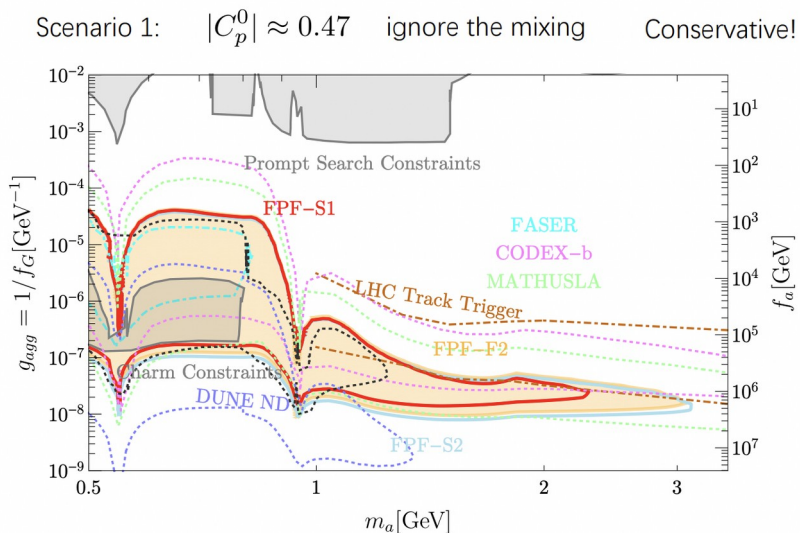
Production: mixing with mesons, flavor-changing decays, Primakoff, brem

$$\frac{g_s^2}{8} g_{agg} a G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$g_{aff} \frac{m_f}{v} a \bar{f} \gamma^5 f$$

Axion-like particles



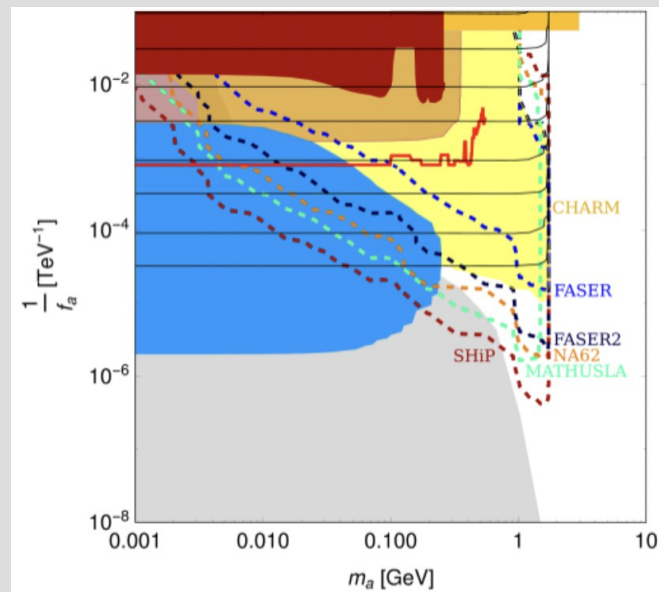
DUNE ND: 2011.05995
FASER: 1806.02348

LHC Track: 1911.12364
FASER2: 1811.12522

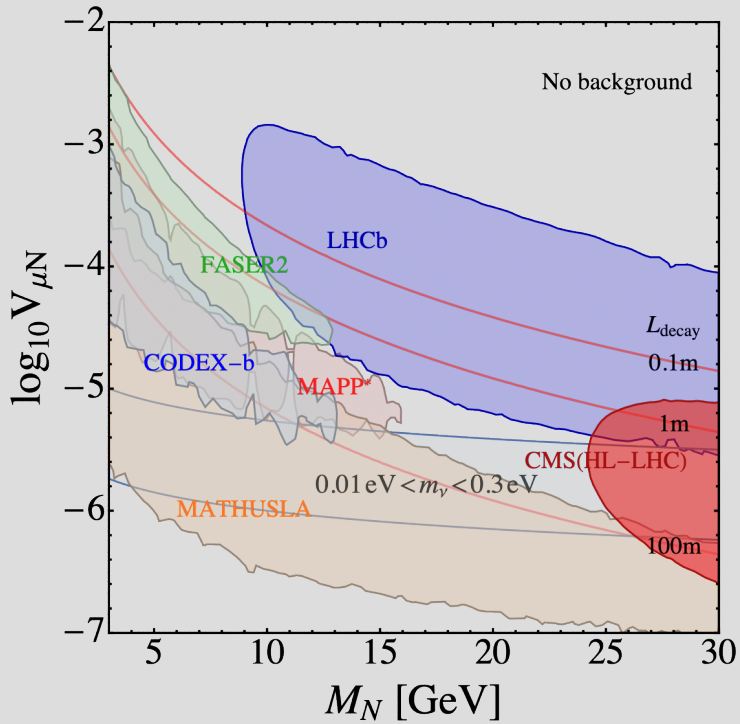
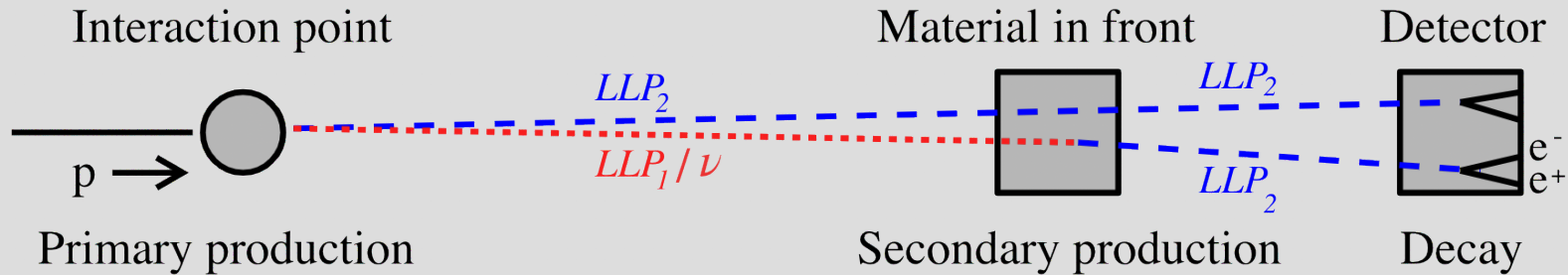
CODEX-b: 1911.00481
MATHUSLA: 1606.06298

Different coupling structures, e.g. charming ALPs (Carmona et al.)

Importance of proton bremsstrahlung when gluon coupling dominates:
talk by Lyu



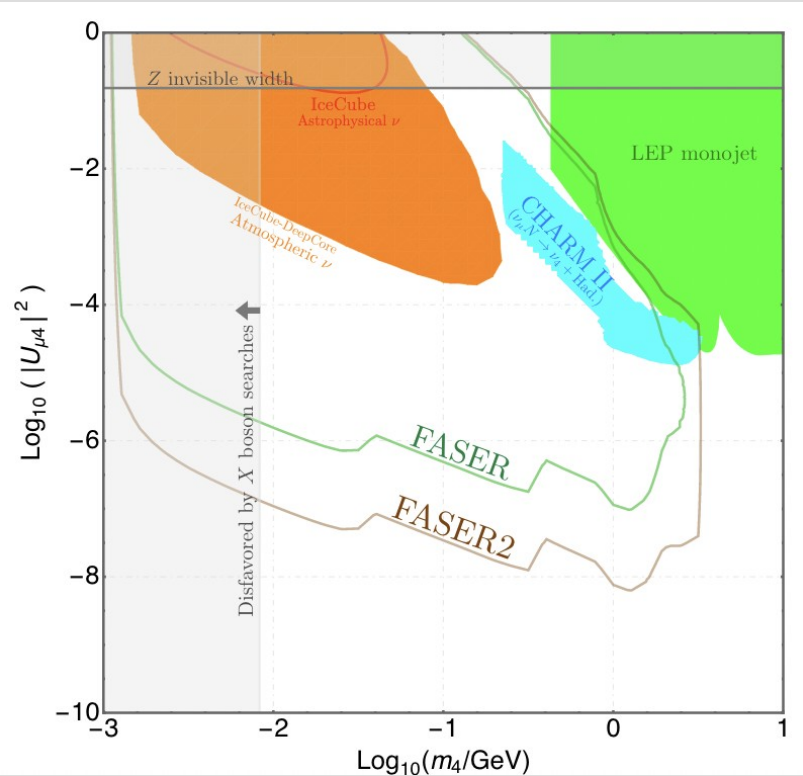
Non-minimal models, briefly



Secondary production with multiple LLPs, Jodlowski et al.

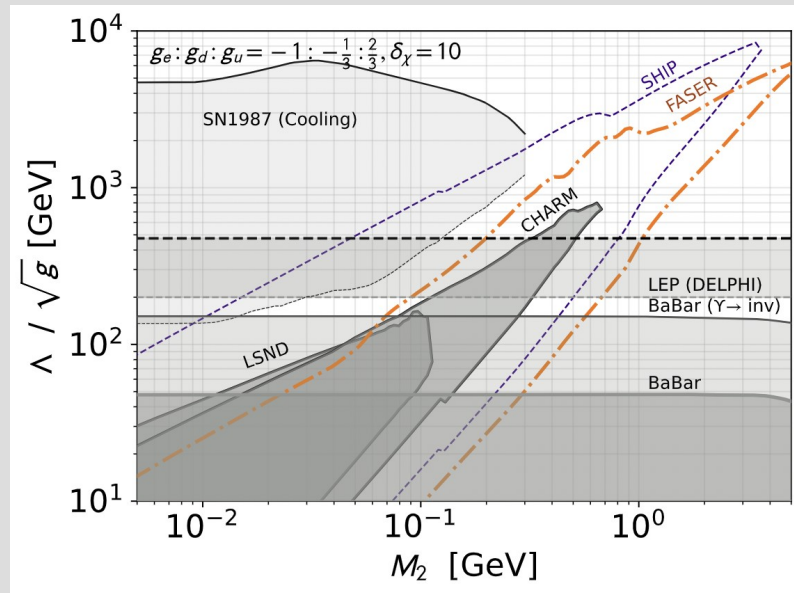
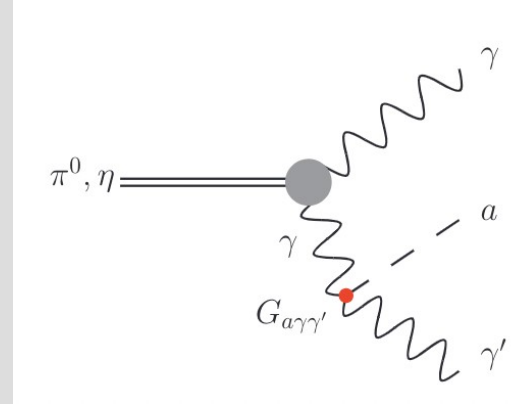
Gauged $B - L$ with RH neutrinos, Deppisch et al.

Many more contributions



Sterile neutrino with Z' , Jho et al.

Dark axion portal, deNiverville et al.



Fermion portal effective operators, Darme et al.

Outlook

4

CONTENTS

6

141

142 I. Latex Template

143 II. BSM Physics

144 A. MC Too

145 1. FOE

146 B. LLPs: V

147 1. Over

148 2. Darl

149 3. B^-

150 4. L_i^-

151 5. B^-

152 6. $B^0 G$

153 7. $U(1)$

154 8. Proc

155 9. Add

156 10. Dec

157 Luis

158 11. Secr

159 C. LLPs: S

160 1. Darl

161 2. Lab

162 3. Infla

163 4. Moti

164 5. Rich

165 Lesz

166 6. Muo

167 7. 2HD

168 8. Cru

169 D. LLPs: F

170 1. Ligh

171 Vrie

172 2. HNL

173 Carl

174 3. Tree

175 [Her

176 Gün

177 4. Radi

178 [Her

179 E. LLPs: A

180 1. Chau

181 2. Bret

182 Lyu]

183 F. LLPs: N

184 1. Dyn

185 Max

5

2. Secondary Production in BSM and Neutrino Interactions [Krzysztof Jodlowski, Felix Kling, Leszek Roszkowski, Sebastian Trojanowski]	75
3. Light dark sector going through chain decay [Yazaman Farzan et al]	77
4. Dark Axion Portal at FASER [Hye-Sung Lee, Patrick deNiverville]	79
5. Z' to RH neutrinos [Deppisch, Kulkarni, Liu]	82
6. Fermion portal effective operators [Darme, Ellis, You]	85
7. search for sterile neutrino with light gauge interactions [Pyungwon Ko, Yongsoo Jho, Jongkuk Kim]	88
8. beyond the minimal model of dark photon/extra gauge boson, and lepton flavor violation [Takahashi Shinomura et al]	91
9. Light dark scalars through Z' / EFT [Enrico Bertuzzo, Marco Taoso]	95
10. Freeze-in sterile neutrino DM [Arindam Das, Srubabati Goswami, Vishnudath K. N., Tanmay Kumar Poddar]	99
11. The ν_τ -philic dark photon [Garv Chauhan, Xun-Jie Xu]	102
12. Imprints of scale invariance and freeze-in dark matter at PPF [Basabendu Barman, Anish Ghoshal]	103
13. Bound state formation and LLPs [Dipan Seugupta, Julia Harz, Mathias Becker, Emannelle Copello, Kirtimaan Mohan]	105
G. Dark Matter Scattering at the PPF	111
1. Dark photon mediator models	112
2. Hadrophilic DM Models	115
3. Dark matter search in the Advanced SND@LHC detector [Alexey Boyarsky, Alex Mikulenko, Maksym Ovchinnikov, Lesya Shchutska]	117
4. Dark states with EM form factors [Jui-Lin Kuo et al]	121
H. Milli-charged Particles at the PPF [Matthew Citron, Subir Sarkar, Yu-Dai Tsai]	126
I. Others	127
1. Quirks [Jinmian Li, Junle Pei]	127
2. BSM with Muons	131
Acknowledgments	133
References	134

Thanks to all the contributors!

Currently at ~100 pages on long-lived particles

Reminder: check name, affiliation, acknowledgments on Overleaf