THEORY UPDATE

FASER 3rd Collaboration Meeting

Jonathan Feng, UC Irvine, 3 September 2020

INTRODUCTION

- Many theory papers exploring the physics potential of FASER and FASERν. A sampling from the last year:

[1] I. Boiarska, K. Bondarenko, A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy, and A. Sokolenko, "Light scalar production from Higgs bosons and FASER 2," *JHEP* **05** (2020) 049, arXiv:1908.04635 [hep-ph].

[2] R. N. Mohapatra and N. Okada, "Dark Matter Constraints on Low Mass and Weakly Coupled B-L Gauge Boson," arXiv:1908.11325 [hep-ph].

[3] N. Okada and D. Raut, "Hunting Inflaton at FASER," arXiv:1910.09663 [hep-ph].

[4] V. Baules, N. Okada, and S. Okada, "Braneworld Cosmological Effect on Freeze-in Dark Matter Density and Lifetime Frontier," arXiv:1911.05344 [hep-ph].

[5] K. Jodłowski, F. Kling, L. Roszkowski, and S. Trojanowski, "Extending the reach of FASER, MATHUSLA, and SHiP towards smaller lifetimes using secondary particle production," *Phys. Rev. D* **101** (2020) no. 9, 095020, arXiv:1911.11346 [hep-ph].

[6] L. Darmé, S. A. Ellis, and T. You, "Light Dark Sectors through the Fermion Portal," *JHEP* **07** (2020) 053, arXiv:2001.01490 [hep-ph].

[7] W. Bai, M. Diwan, M. V. Garzelli, Y. S. Jeong, and M. H. Reno, "Far-forward neutrinos at the Large Hadron Collider," *JHEP* **06** (2020) 032, arXiv:2002.03012 [hep-ph].

[8] N. Okada, S. Okada, and Q. Shafi, "Light Z' and Dark Matter from $\mathrm{U}(1)_X$ Gauge Symmetry," arXiv:2003.02667 [hep-ph].

[9] M. Bahraminasr, P. Bakhti, and M. Rajaee, "Sensitivities to secret neutrino interaction at FASERν," arXiv:2003.09985 [hep-ph].

[10] F. Kling, "Probing light gauge bosons in tau neutrino experiments," *Phys. Rev. D* **102** (2020) no. 1, 015007, arXiv:2005.03594 [hep-ph].

[11] K. J. Kelly, M. Sen, W. Tangarife, and Y. Zhang, "Origin of sterile neutrino dark matter via secret neutrino interactions with vector bosons," *Phys. Rev. D* **101** (2020) no. 11, 115031, arXiv:2005.03681 [hep-ph].

[12] P. Bakhti, Y. Farzan, and S. Pascoli, "Unravelling the richness of dark sector by FASERν," arXiv:2006.05437 [hep-ph].

[13] F. Kling and S. Trojanowski, "Looking forward to test the KOTO anomaly with FASER," *Phys. Rev. D* **102** (2020) no. 1, 015032, arXiv:2006.10630 [hep-ph].

[14] C. Csáki, R. T. D'Agnolo, M. Geller, and A. Ismail, "Crunching Dilaton, Hidden Naturalness," arXiv:2007.14396 [hep-ph].

[15] B. Dutta, S. Ghosh, and J. Kumar, "Opportunities for probing $U(1)_{T3R}$ with light mediators," arXiv:2007.16191 [hep-ph].

[16] Y. Jho, J. Kim, P. Ko, and S. C. Park, "Search for sterile neutrino with light gauge interactions: recasting collider, beam-dump, and neutrino telescope searches," arXiv:2008.12598 [hep-ph].

!! [17] T. Araki, K. Asai, H. Otono, T. Shimomura, and Y. Takubo, "Dark Photon from Light Scalar Boson Decays at FASER," arXiv:2008.12765 [hep-ph]. !!

INTRODUCTION

Here cover a few topics inspired by the following questions:

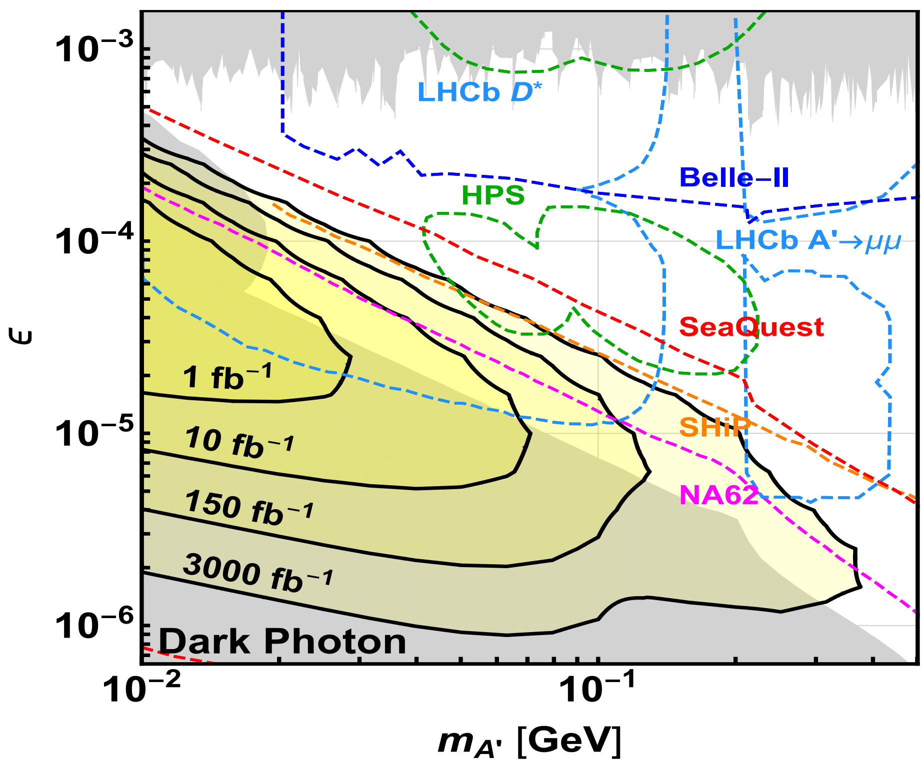
How likely is FASER to discover new physics at Run 3?

What are the prospects for the HL-LHC era?

How likely is FASER to discover new physics at Run 3?

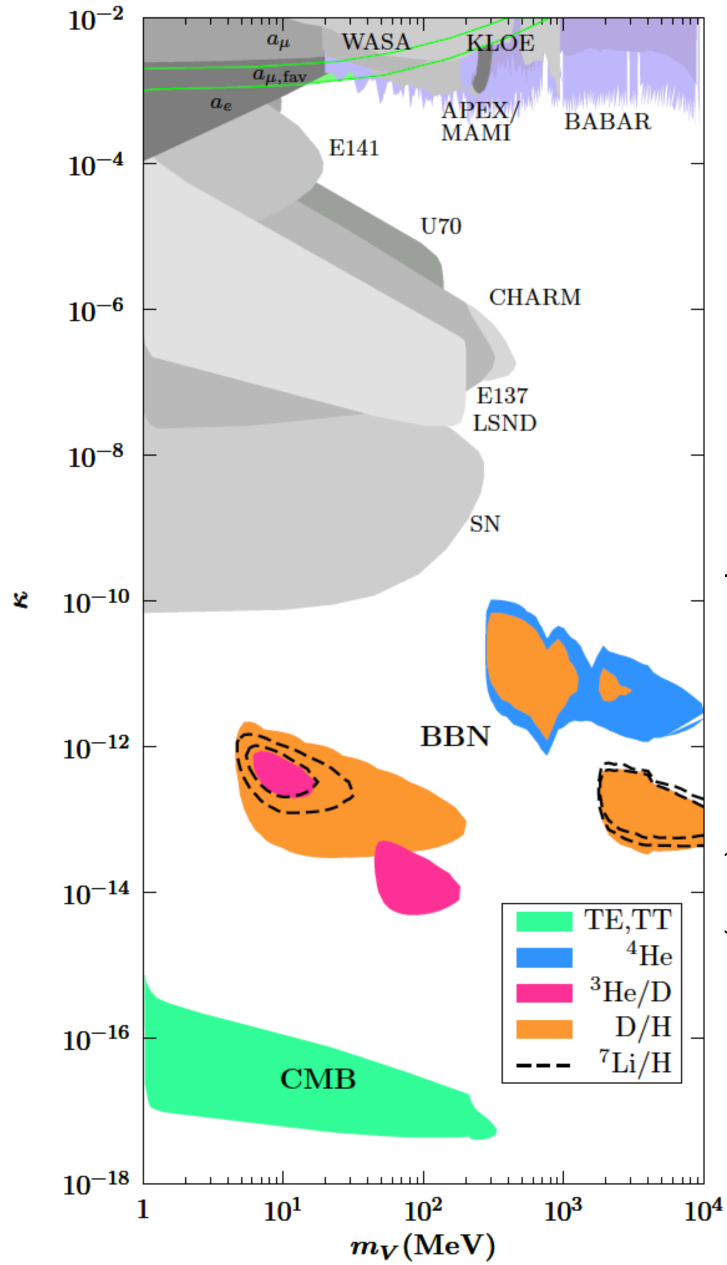
FASER'S DISCOVERY POTENTIAL

- FASER can probe many models. Consider dark photons.
- In Run 3, FASER will start probing new dark photon parameter space with the first fb^{-1}, and extend its sensitivity in the 10 – 100 MeV mass range.
- Is this an interesting part of parameter space?



EXISTING CONSTRAINTS ON DARK PHOTONS

- There is a vast and largely unexplored parameter space.
- "Bump hunts" exclude $\epsilon > 10^{-3}$.
- Fixed target experiments exclude most of the gray region.
- Astrophysics (supernova, BBN, CMB) excludes patches at very low coupling.
- But overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.



Fradette, Pospelov, Pradler, Ritz (2014)

DARK PHOTON MODELS

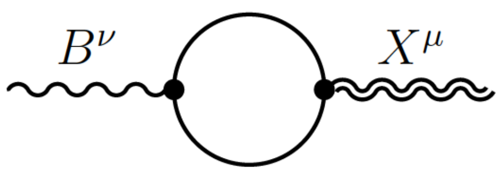
- If the dark photon is a portal particle, coupling arises from kinetic mixing:

Visible Sector
SM, U(1)$_{\text{EM}}$, B^ν

$$\frac{1}{2}\epsilon\, F^{\mu\nu} F_{D\mu\nu}$$

Dark Sector
DM, Dark Forces, X^μ

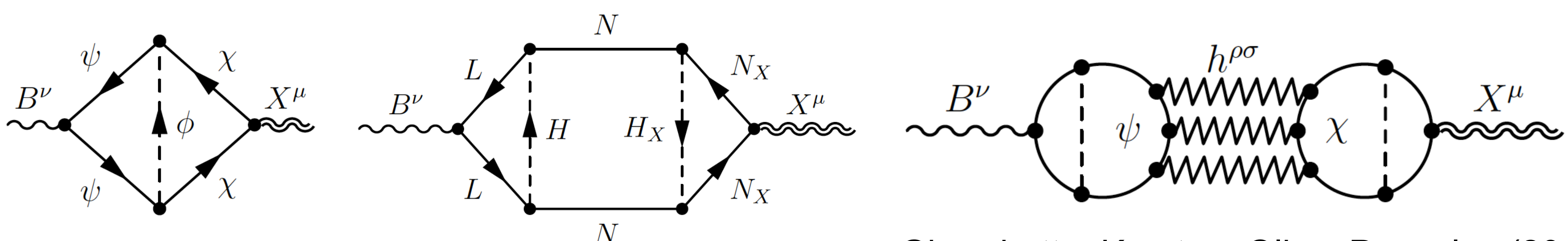
- Mixing can be generated at 1-loop. If 0 at high scale, expect $\epsilon \sim 10^{-3}$



$$\epsilon = -\frac{g' g_X}{16\pi^2} \sum_i Y_i q_i \ln \frac{M_i^2}{\mu^2}$$

Holdom (1986)

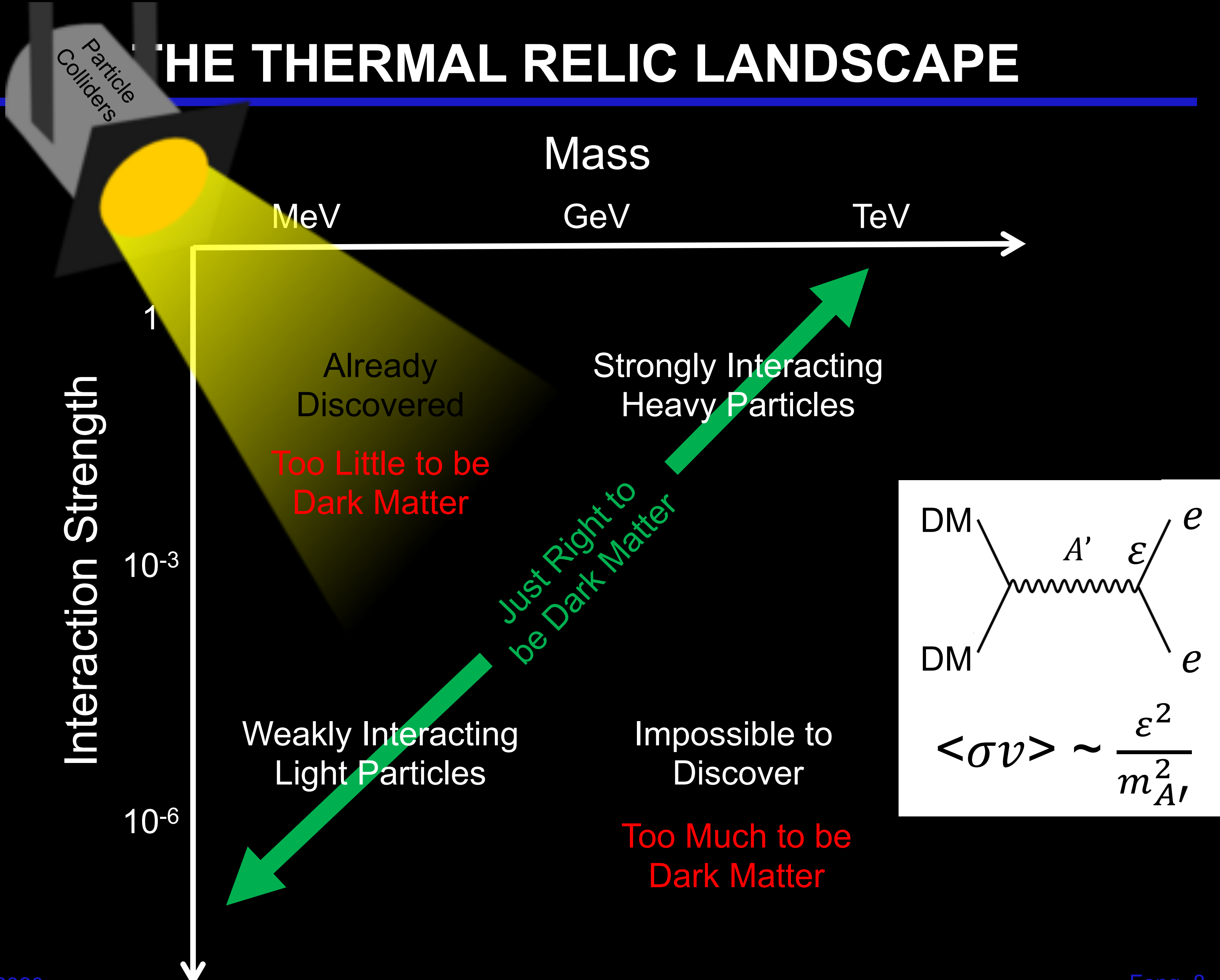
- But there are also theories with mixing generated only at higher loop level



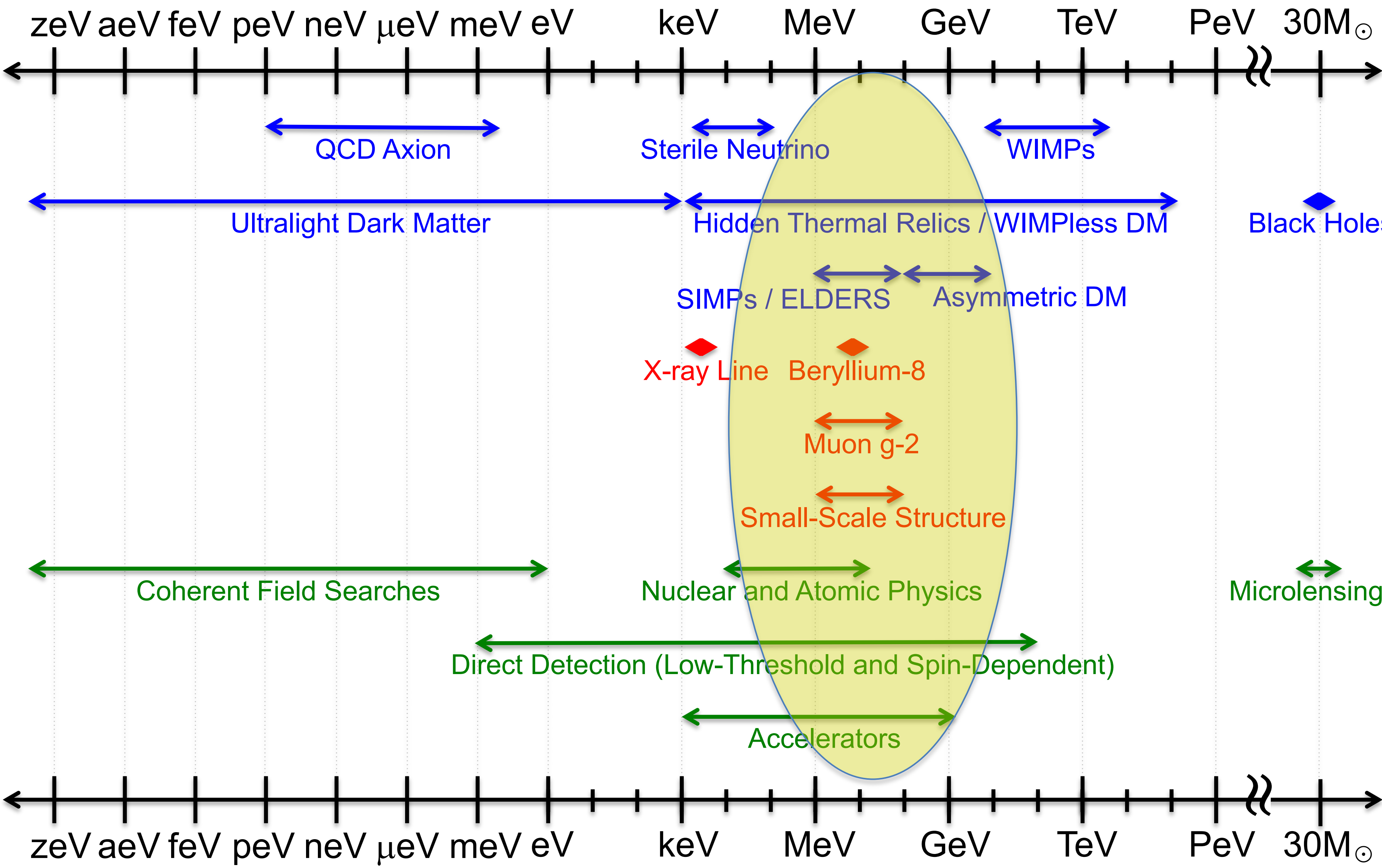
Gherghetta, Kersten, Olive, Pospelov (2019)

- Other than making us feel ok that $\epsilon > 10^{-3}$ is excluded, models don't provide much guidance about the coupling, and none at all about the mass

THE THERMAL RELIC LANDSCAPE



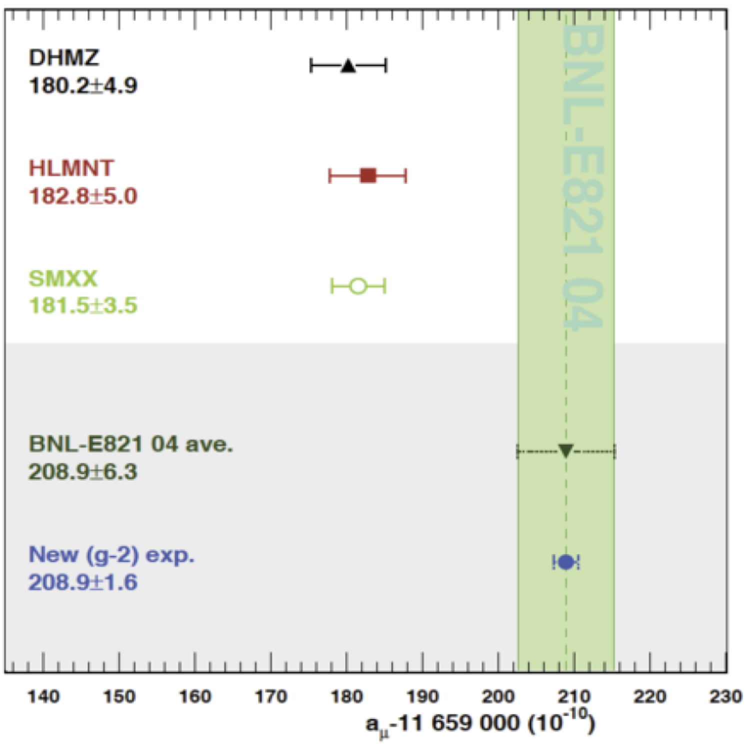
Dark Sector Candidates, Anomalies, and Search Techniques



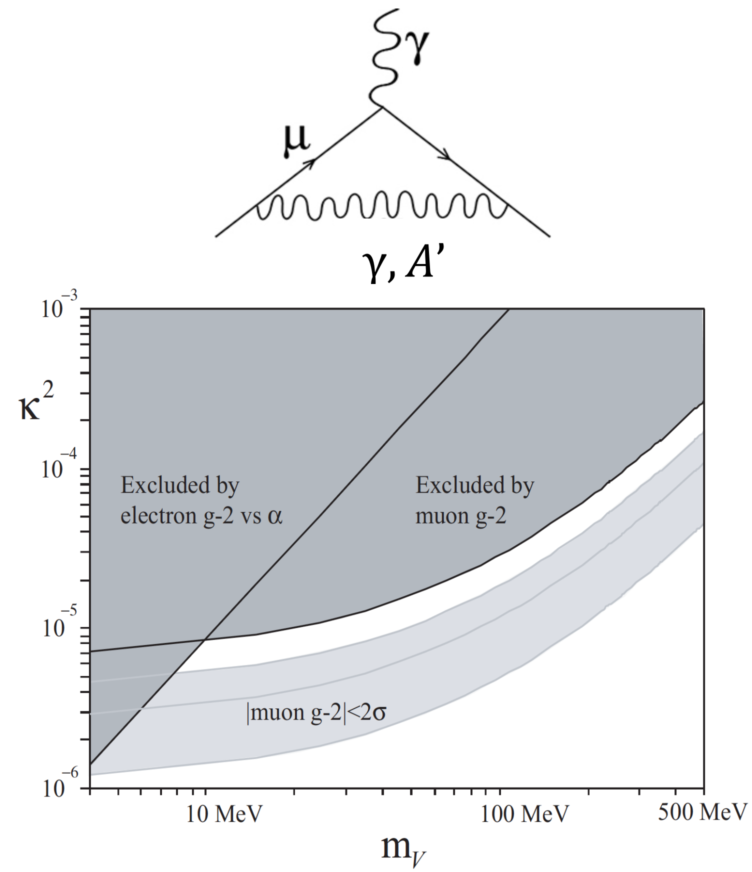
Cosmic Visions Report (2017)

THE MUON'S ANOMALOUS MAGNETIC MOMENT

- The 3.7σ discrepancy between the SM and experiment can be resolved by MeV-GeV particles with $\varepsilon \sim 10^{-3}$. The dark photon is no longer a viable solution, but other particles with similar masses and couplings are.



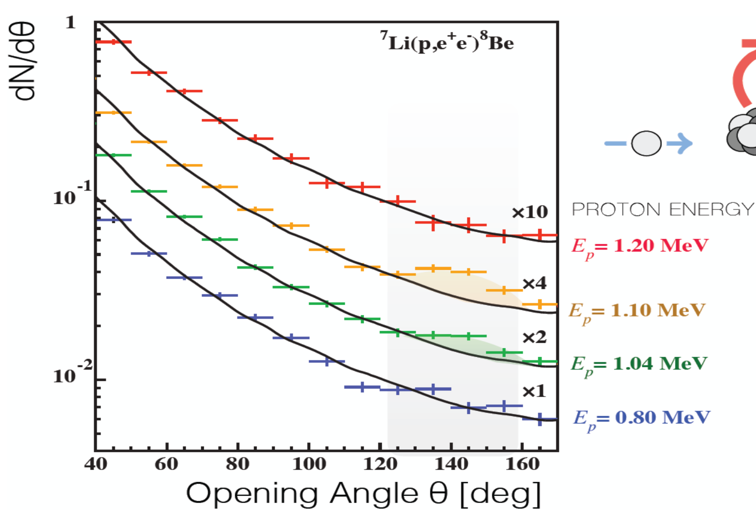
Hagiwara et al. (2017); Aoyama et al. (2020)

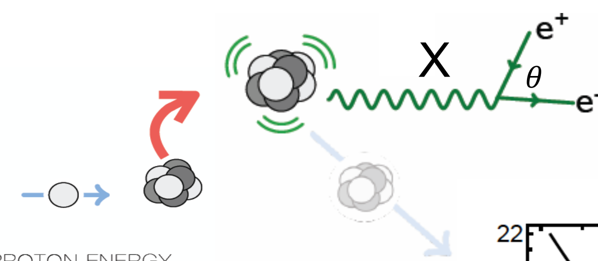


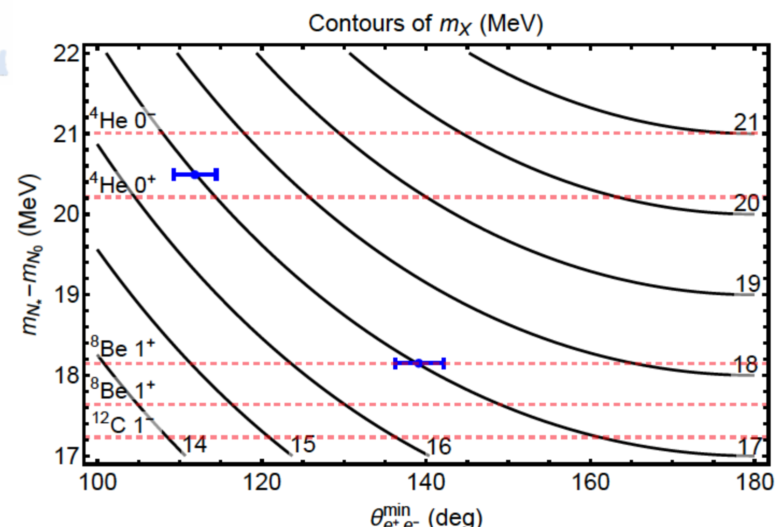
Boehm, Fayet (2003)

THE ^{8}Be and ^{4}He ATOMKI ANOMALIES

- 2016: A 7σ anomaly in the decays of excited ^{8}Be nuclei can be explained by a new particle with mass 17 MeV and couplings ~ 10^{-4} to 10^{-3}.
- 2019: A new 7σ anomaly in the decays of excited ^{4}He nuclei can be explained by the same new particle.







Krasznahorkay et al. (2015, 2019)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)
See also Zhang, Miller (2020)

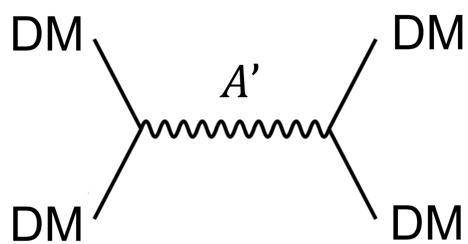
SELF-INTERACTING DARK MATTER

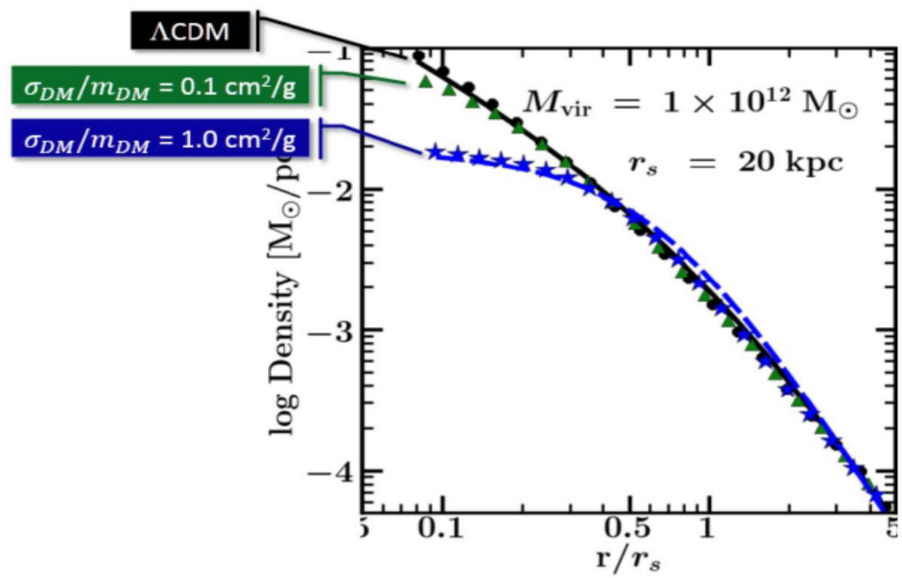
- There are indications from small-scale structure that dark matter may be strongly self-interacting.

- For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted by standard cold dark matter.

- To make a difference, the required self-interaction cross section should be

$$\frac{\sigma}{m} \sim \frac{\mathrm{cm}^2}{\mathrm{g}} \sim \frac{\mathrm{barn}}{\mathrm{GeV}} \sim (100\ \mathrm{MeV})^{-3}$$

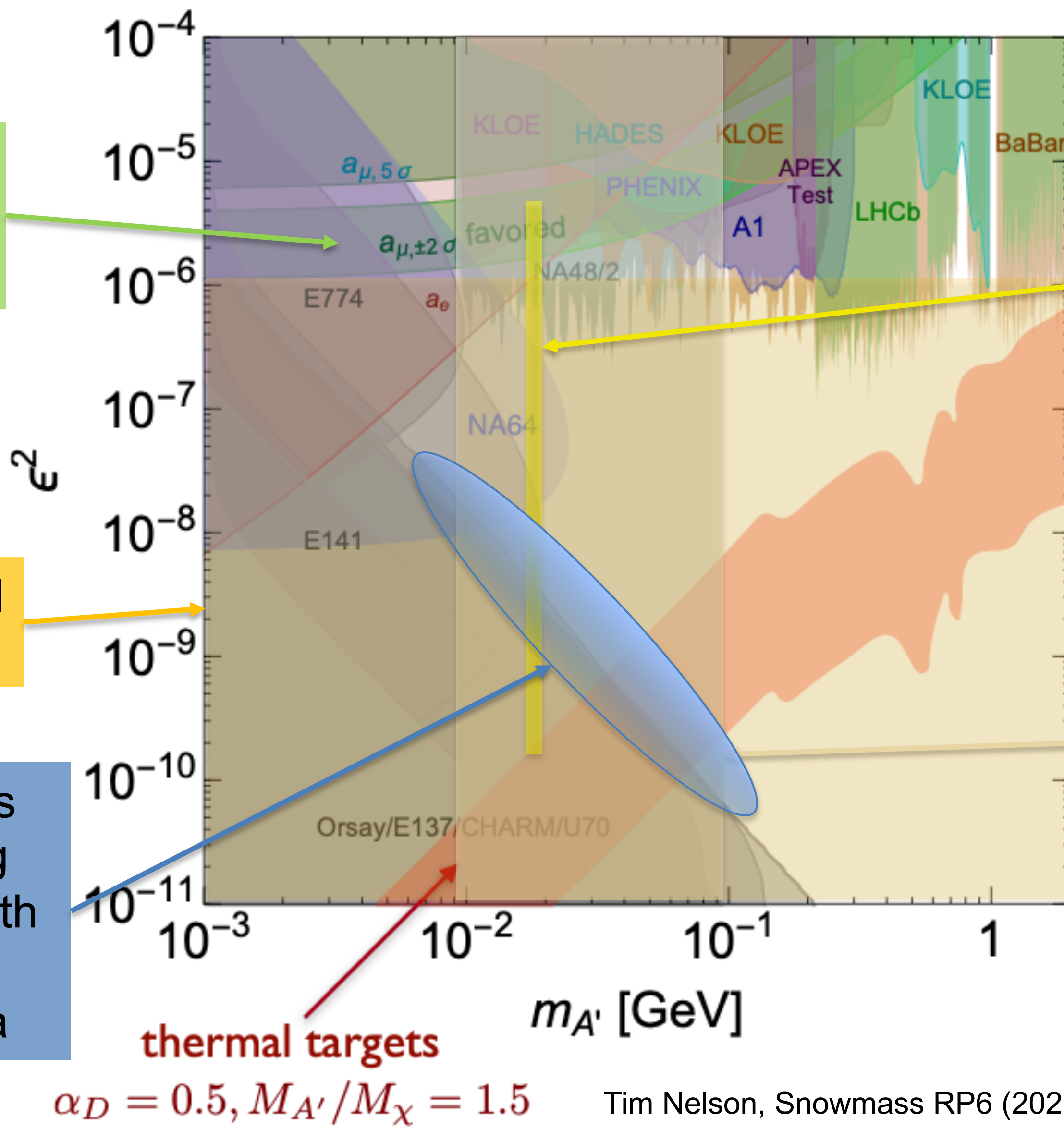




- This can be explained by a characteristic dark sector mass scale of ~ 10-100 MeV.

Tulin, Yu (2017)
Rocha et al. (2012); Peter et al. (2012)
Vogelsberger et al. (2012); Zavala et al. (2012)

TARGETS IN DARK PHOTON PARAMETER SPACE



Muon g-2 Anomaly

^{8}Be and ^{4}He ATOMKI Anomalies

Loop-induced Coupling

Self-interacting Dark Matter

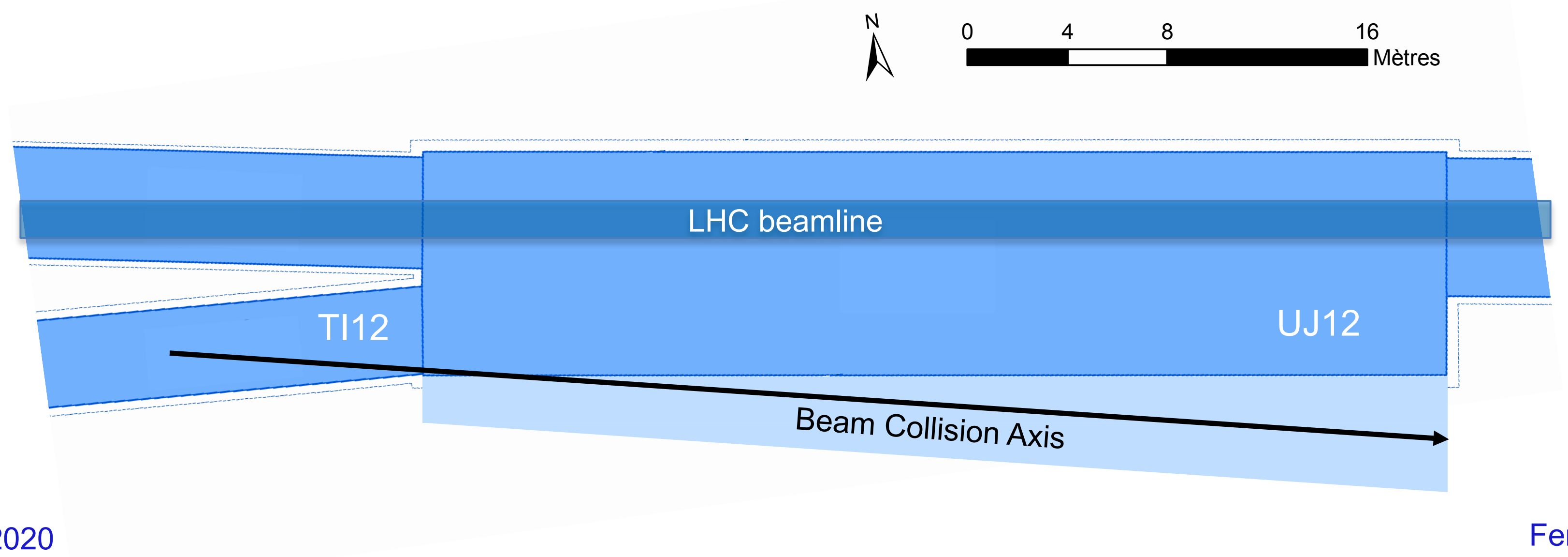
FASER probes an interesting region, even with the 1st fb^{-1} of Run 3 data

Tim Nelson, Snowmass RP6 (2020)

What are the prospects for the HL-LHC era?

FORWARD PHYSICS FACILITY

- FASER, FASERν , and other proposed detectors are currently highly constrained by tunnels and infrastructure that was never designed to support experiments.
- At the same time, it is becoming clear that there is a rich physics program in the far-forward region, spanning long-lived particle searches, neutrinos, QCD, dark matter, dark sector, cosmic rays, and cosmic neutrinos.
- Strongly motivates enlarging UJ12 (or UJ18) to create a dedicated facility to house several far-forward experiments.



NEW PHYSICS SEARCHES AT THE FPF

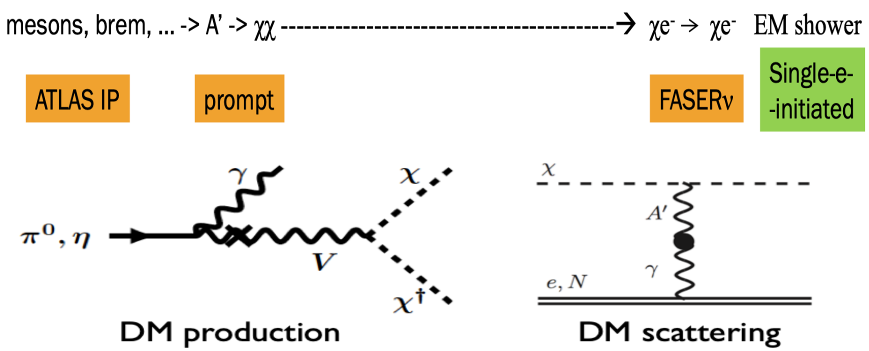
- FASER 2 (R = 1 m, L = 5-20 m) can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other particles.

- Among the PBC benchmark scenarios, FASER2's discovery potential extends to all benchmark scenarios, except BC2 and BC3.

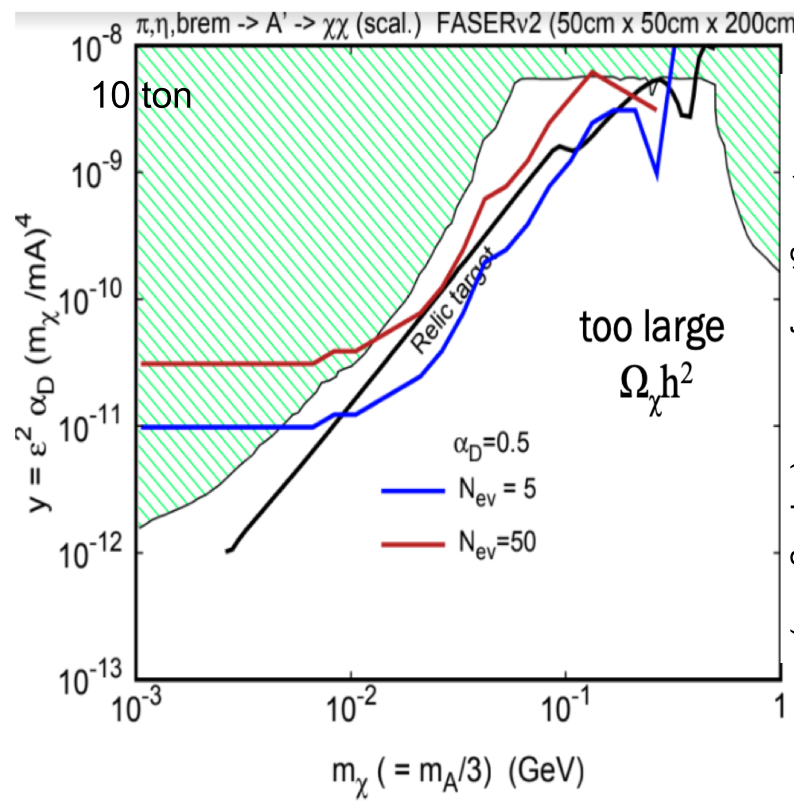
Benchmark Model	FASER	FASER 2
BC1: Dark Photon	√	√
BC1': $U(1)_{B-L}$ Gauge Boson	√	√
BC2: Invisible Dark Photon	–	–
BC3: Milli-Charged Particle	–	–
BC4: Dark Higgs Boson	–	√
BC5: Dark Higgs with hSS	–	√
BC6: HNL with e	–	√
BC7: HNL with μ	–	√
BC8: HNL with τ	√	√
BC9: ALP with photon	√	√
BC10: ALP with fermion	√	√
BC11: ALP with gluon	√	√

BC2: INVISIBLE DARK PHOTONS AT THE FPF

- If $m_{LLP} > 2m_{DM}$, the LLP will typically decay in the dark sector to dark matter, leading to invisible decays.
- Can look for the resulting DM to scatter off electrons at FASERν 2. Dominant background from neutrinos reduced for $1 < E_e < 20$ GeV.



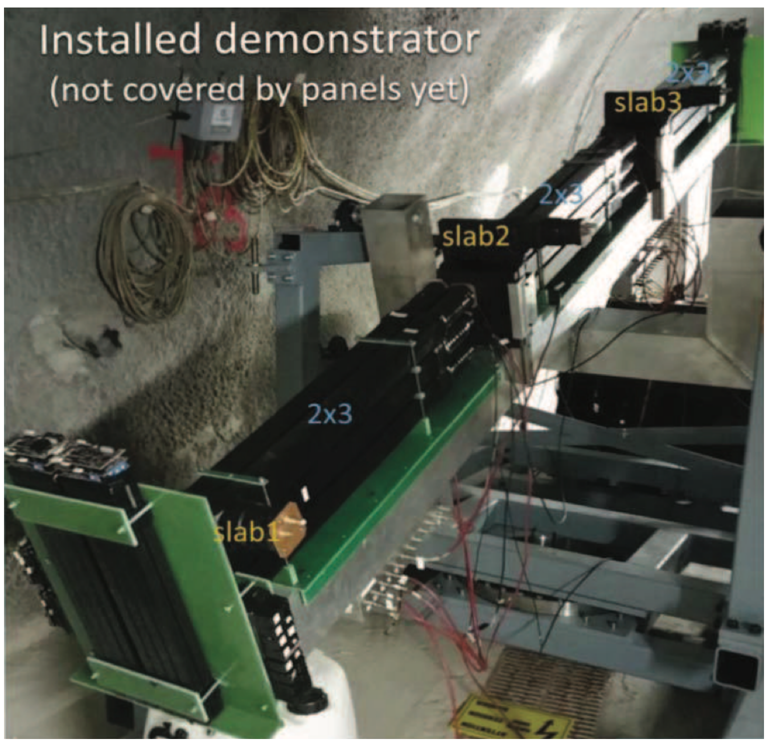
- May be able to probe relic target region. Complementary to dedicated missing energy experiments (e.g., LDMX): these are more sensitive (probe farther into the "too large $\Omega_\chi h^2$" region), but don't detect DM scattering.

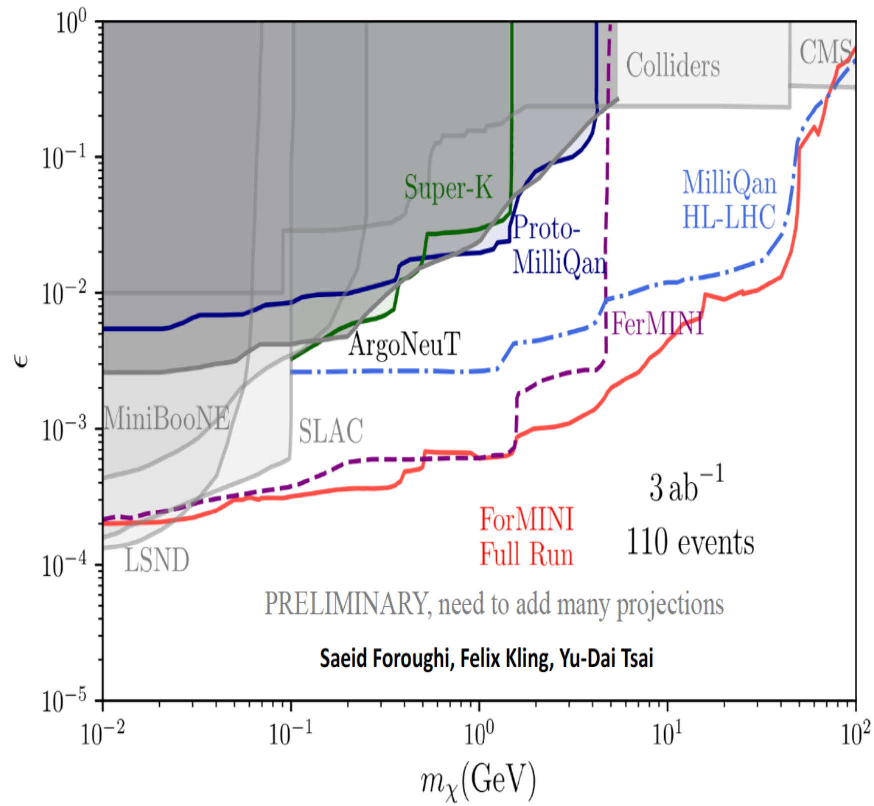


Batell, Feng, Trojanowski (in progress)

BC3: MILLICHARGED PARTICLES AT THE FPF

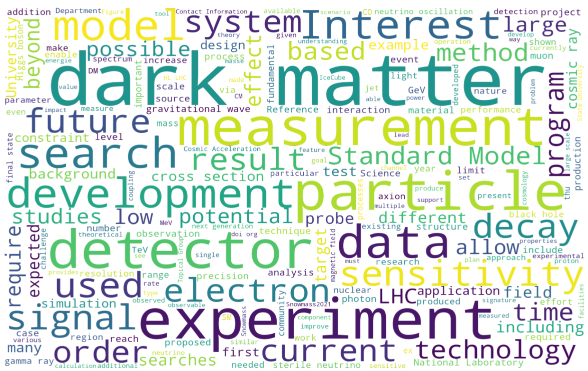
- Currently the target of the MilliQan experiment near the CMS IP.
- MilliQan Demonstrator (Proto-MilliQan) already probes new region. Full MilliQan planned to run in this location at HL-LHC, but it appears that sensitivity can be improved greatly by moving it to the FPF (ForMINI).





FORWARD PHYSICS FACILITY: SNOWMASS LOI

- One of 1578 Snowmass LOIs



- FPF LOI had 240 authors with interest from many communities. An FPF workshop is being planned for the coming months.

Thematic Areas

- (EF05) QCD and Strong Interactions: Precision QCD
- (EF06) QCD and Strong Interactions: Hadronic Structure and Forward QCD
- (EF09) BSM: More General Explorations
- (EF10) BSM: Dark Matter at Colliders
- (NF03) BSM
- (NF06) Neutrino Interaction Cross Sections
- (NF10) Neutrino Detectors
- (RF06) Dark Sector Studies at High Intensities
- (CF07) Cosmic Probes of Fundamental Physics
- (AF05) Accelerators for PBC and Rare Processes
- (UF01) Underground Facilities for Neutrinos
- (UF02) Underground Facilities for Cosmic Frontier

Snowmass 2021 Letter of Interest

Forward Physics Facility

Roshan M. Abraham,[1] Henso Abreu,[2] Yoav Afik,[2] Sanjib K. Agarwalla,[3] Juliette Alimena,[4] Luis Anchordoqui,[5] Claire Antel,[6] Akitaka Ariga,[7] Tomoko Ariga,[8] Carlos A. Argüelles,[9] Kento Asai,[10] Pouya Bakhti,[11] Akif B. Balantekin,[12] Victor Baules,[13] Brian Batell,[14] James Beacham,[15] John F. Beacom,[4,16,17] Nicole F. Bell,[18] Florian Bernlochner,[19] Atri Bhattacharya,[20] Tobias Boeckh,[19] Jamie Boyd,[21] Lydia Brenner,[21] Mauricio Bustamante,[22] Franck Cadoux,[6] Mario Campanelli,[23] David W. Casper,[24] Grigorios Chachamis,[25] Spencer Chang,[26] Xin Chen,[27] Michael L. Cherry,[28] James M. Cline,[29] Ruben Conceição,[30] Andreas Crivellin,[21] Matthew Citron,[31] Andrea Coccaro,[32] Yanou Cui,[33] Mohamed R. Darwish,[34] Carlos P. de los Heros,[35] Patrick deNiverville,[36] Peter B. Denton,[37] Albert De Roeck,[21] Frank F. Deppisch,[23] Jordy de Vries,[38] Claudio Dib,[39] Caterina Doglioni,[40] Monica D'Onofrio,[41] Liam Dougherty,[21] Candan Dozen,[27] Marco Drewes,[42] Bhaskar Dutta,[43] Tamer Elkafrawy,[44] Sebastian A. R. Ellis,[45] Rouven Essig,[46] Glennys R. Farrar,[47] Yasaman Farzan,[11] Yannick Favre,[6] Anatoli Fedynitch,[48] Deion Fellers,[26] Jonathan L. Feng[a],[24] Didier Ferrere,[6] Patrick Foldenauer,[49] Saeid Foroughi-Abari,[50] Jonathan Gall,[21] Iftah Galon,[51] Maria V. Garzelli,[52] Stefano Giagu,[53] Stephen Gibson,[54] Francesco Giuli,[55] Bhawna Gomber,[56] Victor P. Goncalves,[57] Sergio Gonzalez-Sevilla,[6] Yury Gornushkin,[58] Sumit Ghosh,[43] Claire Gwenlan,[59] Carl Gwilliam,[41] Jan Hajer,[42] Francis Halzen,[12,60] Juan Carlos Helo,[61] Christopher S. Hill,[4] Martin Hirsch,[62] Samuel D. Homiller,[46] Matheus Hostert,[63,64] Shih-Chieh Hsu,[65] Zhen Hu,[27] Pham Q. Hung,[66] Giuseppe Iacobucci,[6] Philip Ilten,[67] Tomohiro Inada,[48] Hiroyuki Ishida,[68] Aya Ishihara,[69] Ahmed Ismail,[1] Ameen Ismail,[70] Sune Jakobsen,[21] Yu Seon Jeong,[21] Yongsoo Jho,[71] Krzysztof Jodlowski,[72] Enrique Kajomovitz,[2] Kevin J. Kelly,[73] Maxim Yu. Khlopov,[74,75,76] Valery A. Khoze,[49] Doojin Kim,[43] Jongkuk Kim,[77] Teppei Kitahara,[78] Felix Kling[a],[45] Joachim Kopp,[21,79] Umut Kose,[21] Piotr Kotko,[80] John Krizmanic,[81] Susanne Kuehn,[21] Suchita Kulkarni,[82] Jason Kumar,[83] Alexander Kusenko,[84] Krzysztof Kutak,[85] Greg Landsberg,[86] Luca Lavezzo,[4] Rebecca K. Leane,[45] Hye-Sung Lee,[87] Helena Lefebvre,[54] Benjamin V. Lehmann,[88] Lorne Levinson,[89] Ke Li,[65] Shirley W. Li,[45] Shuailong Li,[90] Benjamin Lillard,[91] Jinfeng Liu,[27] Wei Liu,[92] Zhen Liu,[93] Steven Lowette,[94] Chiara Magliocca,[6] Brandon Manley,[4] Danny Marfatia,[83] Ioana Maris,[95] Josh McFayden,[21] Sam Meehan,[21] Sascha Mehlhase,[96] David W. Miller,[97] Dimitar Mladenov,[21] Vasiliki A. Mitsou,[62] Rabindra N. Mohapatra,[93] Mitsuhiro Nakamura,[98] Toshiyuki Nakano,[98] Marzio Nessi,[21] Friedemann Neuhaus,[79] Kenny C. Y. Ng,[99] Koji Noda,[48] Satsuki Oda,[100] Nobuchika Okada,[13] Satomi Okada,[13] Yasar Onel,[101] John Osborne,[21] Hidetoshi Otono,[8] Carlo Pandini,[6] Vishvas Pandey,[102] Hao Pang,[27] Silvia Pascoli,[49] Seong Chan Park,[71] Brian Petersen,[21] Alexey A. Petrov,[103] Tanguy Pierog,[104] Francesco Pietropaolo,[21] James L. Pinfold,[105] Markus Prim,[19] Michaela Queitsch-Maitland,[21] Meshkat Rajaee,[11] Digesh Raut,[106] Federico L. Redi,[107] Peter Reimitz,[108] Mary Hall Reno,[101] Filippo Resnati,[21] Adam Ritz,[50] Thomas Rizzo,[45] Tania Robens,[109] Christophe Royon,[110] Jakob Salfeld-Nebgen,[21] Osamu Sato,[98] Paola Scampoli,[7,111] Kristof Schmieden,[21] Matthias Schott,[79] Pedro Schwaller,[79] Manibrata Sen,[112] Dipan Sengupta,[113] Anna Sfyrla,[6] Qaisar Shafi,[106] Takashi Shimomura,[114] Seodong Shin,[115] Savannah Shively,[24] Ian M. Shoemaker,[116] Carlos V. Sierra,[117] Torbjörn Sjöstrand,[118] Yotam Soreq,[2] Huayang Song,[90] Jordan Smolinsky,[102] John Spencer,[65] David Stuart,[31] Shufang Su,[90] Wei Su,[119] Antoni Szczurek,[120,121] Dai-suke Takahashi,[100] Yosuke Takubo,[122] Ondřej Theiner,[6] Serap Tilav,[106] Charles Timmermans,[117,123] Eric Torrence,[26] Sebastian Trojanowski,[124] Yu-Dai Tsai,[73] Serhan Tufanli,[21] Paolo Valente,[125] Benedikt Vormvald,[21] Carlos E. M. Wagner,[97,126] Di Wang,[27] Zeren S. Wang,[127] Tao Xu,[128] Tianlu Yuan,[12,60] Tevong You,[21] Shigeru Yoshida,[69] Dengfeng Zhang,[27] Gang Zhang,[27] Yue Zhang,[129] and Yi-Ming Zhong[130]

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