Big Ideas 3

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RF6 Organizational Plans for Whitepapers

Letters of Intent

- Community driven — LOIs are informal documents to express interests/proposals for projects/studies as part of the Snowmass exercise

Contributed Whitepapers Due March 15th

- Community driven — anyone interested in dark sector physics can contribute a whitepaper on their topic of interest (does not require LOI)

Solicited Whitepapers Due April 15th

- Summarize the Contributed Whitepapers
- Synthesize the motivations for dark sectors and associated physics opportunities at high intensity experiments
- This is how we move the message up a level

Slide from Stefania Gori

RF6 "Big ideas" solicited papers

- Organization around science goals/questions.
- Arrange the breadth of RF6 science so that all the main techniques have a chance to shine.
- Span ≳95% of white-paper interests

1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.
Editors: Gordan Krnjaic, Natalia Toro — **Jan. 20, https://indico.fnal.gov/event/52857/**

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.
Editors: Brian Batell, Chris Hearty —**Jan. 27, today's meeting**

3. New Flavors and Rich Structures in Dark Sectors.
Editors: Phil Harris, Philip Schuster, Jure Zupan — **Feb. 3**

4. Experiments/facilities/tools
Editors: Phil Ilten, Nhan Tran —**Feb. 10**

More details: https://docs.google.com/document/d/1R0O23wjGLxRzsc93a4pJIFn17yW9TCTq (in our google drive folder, https://drive.google.com/drive/folders/_1sMn1cWI2ddqzu46Yi4TcMIX7Cm2GUxO_)

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Focus Today

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L / \mu-\tau / B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. $\sin\theta$ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. $\sin\theta$* [λ=0] *m_S vs. $\sin\theta$* [λ=s.t. Br(H→φφ ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	e/μ/τ a la1709.07001?	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasoanble flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* (separate?) Think more about reasoanble coupling relations including $f_{W/Z}$	FV axion couplings

\+ Neutron portal? Hidden valleys (or are these out-of-scope?)? See e.g. 2003.02270

Big Idea 3

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
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Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ϕϕ ~10^{-2})]?	Dark Higgssstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
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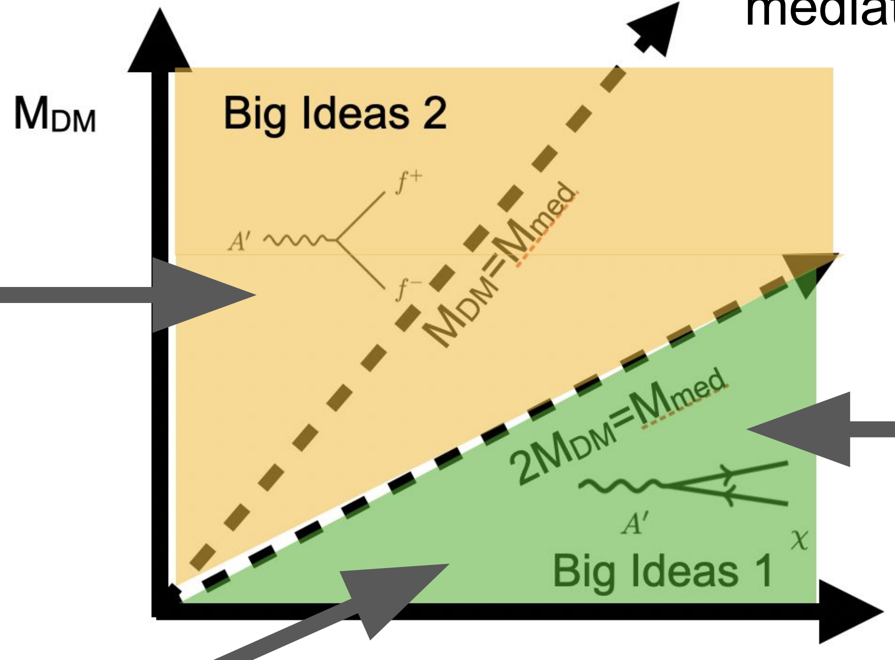
What distinguishes Big Idea 3 from the rest?

- ***Framing Big Idea 3:*** Even if dark sectors have non-minimal structures, either in couplings to the standard model, or the dark sector spectra of states, they can still be efficiently searched for in high intensity experiments.
- ***Framing Big Idea 1:*** Dark matter particles can be observably produced at intensity-frontier experiments, and opportunities in the next decade will explore important parameter space motivated by thermal DM models, the dark sector paradigm, and anomalies in data.
- ***Tentative Framing of Big Idea 2***: Light, weakly coupled mediators to a dark sector can be copiously produced in high-intensity experiments and detected through their decays to Standard Model particles. Existing, planned, and proposed experiments offer great potential to discover the mediator and discern the pattern of its interactions with ordinary matter.

Visualizing The Big Ideas

For a give model we can vary dark matter mass (M_{DM}) and mediator mass (M_{med})

Big idea 2
Over here we look for visible decays from the dark matter



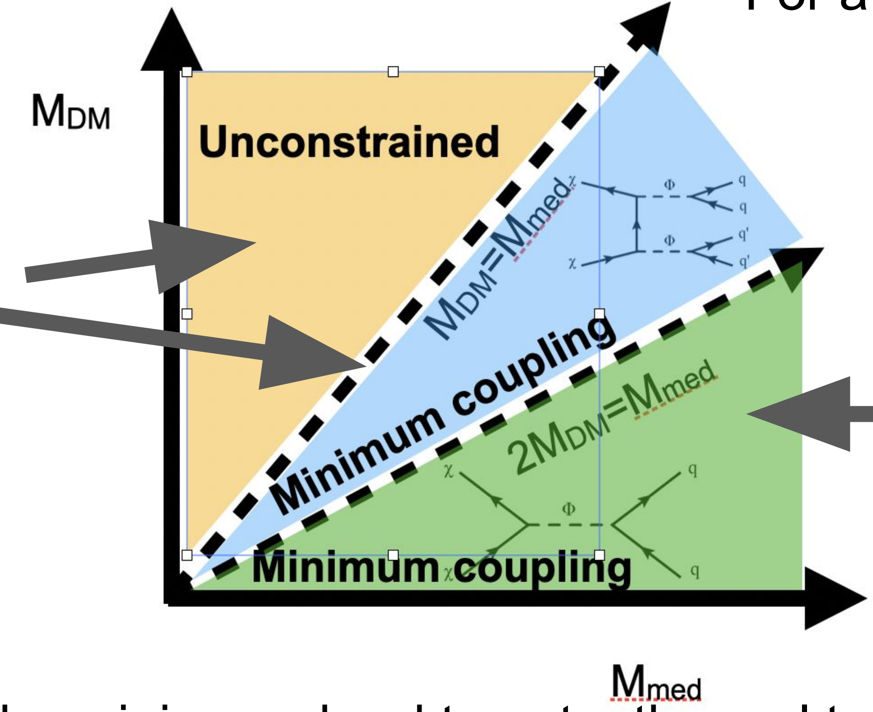
Big idea 1
Over here we look for invisible decays or DM scatters

We still get visible states here(sometimes suppressed), also big idea 2

Motivating The Big Ideas

For each model we can
compute the minimal coupling
For a thermal relic target

Big idea 2
For DM that is lighter than the mediator mass
Can find a minimum coupling otherwise no minima



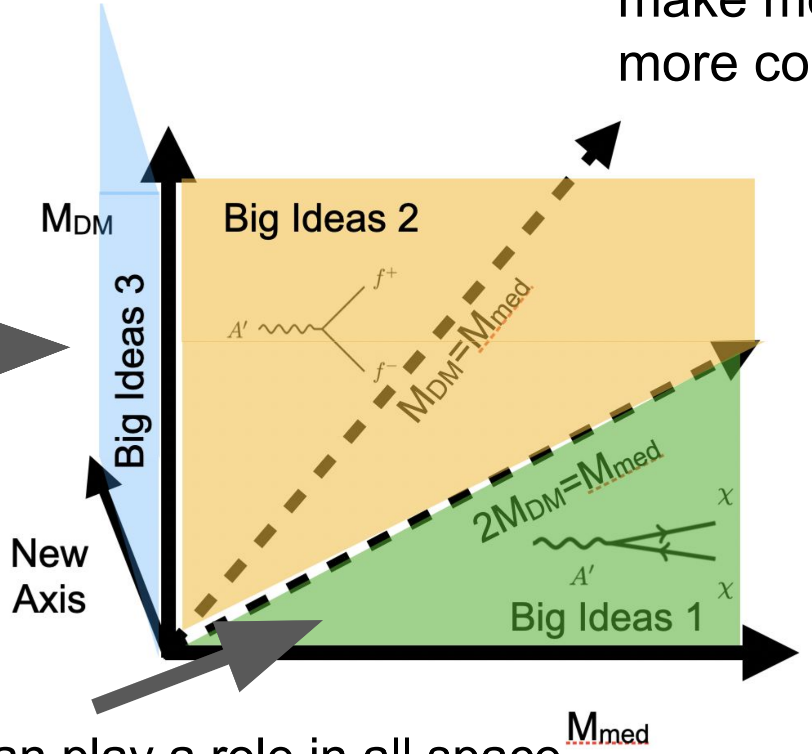
Big idea 1
Minimum coupling present (usually take $⅓=M_{DM}/M_{med}$

Below the minimum, hard to get a thermal target

Big Idea 3

With Big Idea 3 we aim to make models that are **slightly** more complicated

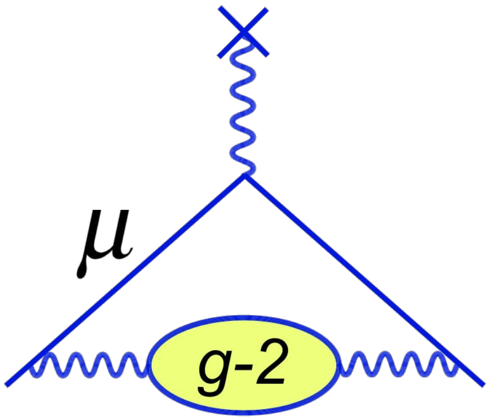
Big idea 3
What is another way to extend the model to enhance the physics performance



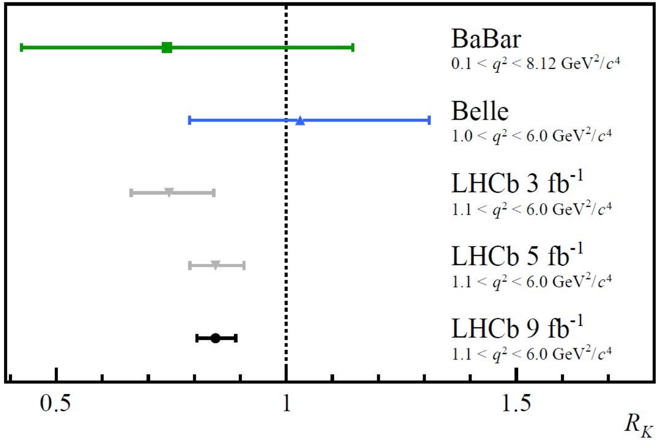
Motivations
The extensions of the models need to be well motivated to ensure lack of simplicity

Visible and Invisible can play a role in all space once model is more complciated

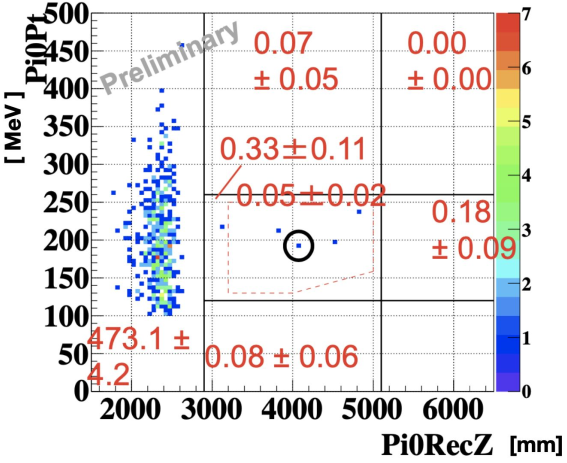
Big Idea 3: Data-driven Motivations



g-2 Excess



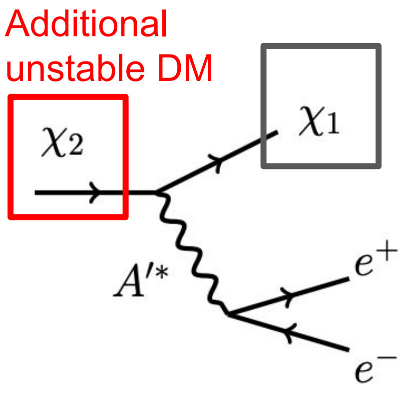
B-physics anomalies



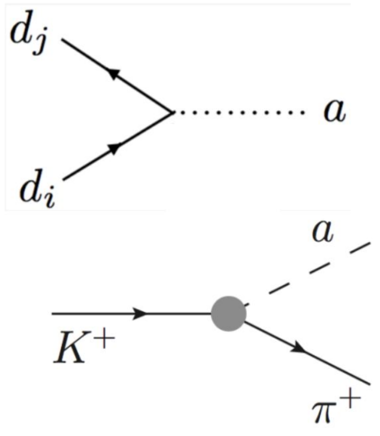
KOTO excess ….

Motivation for Big Ideas 3 can come from observed anomalies

Big Idea 3: Theory Motivations

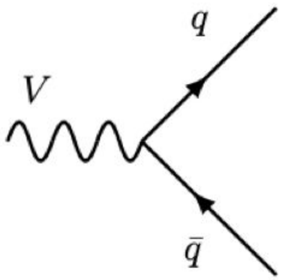


Inelastic DM
(Simple
extension)



Flavor violating
Axions for strong CP

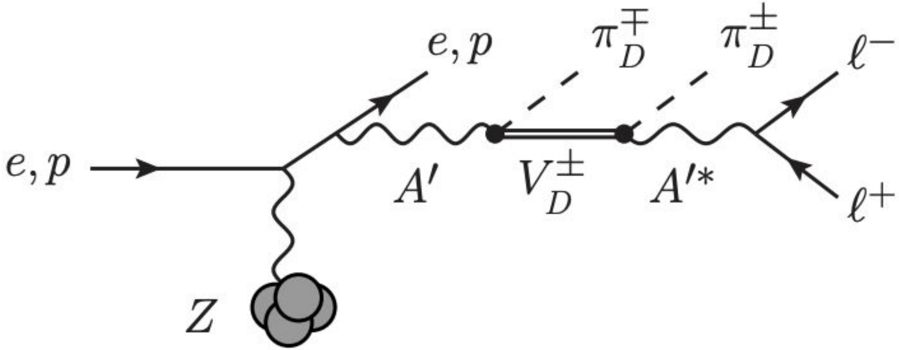
$V \to \text{hadrons}$

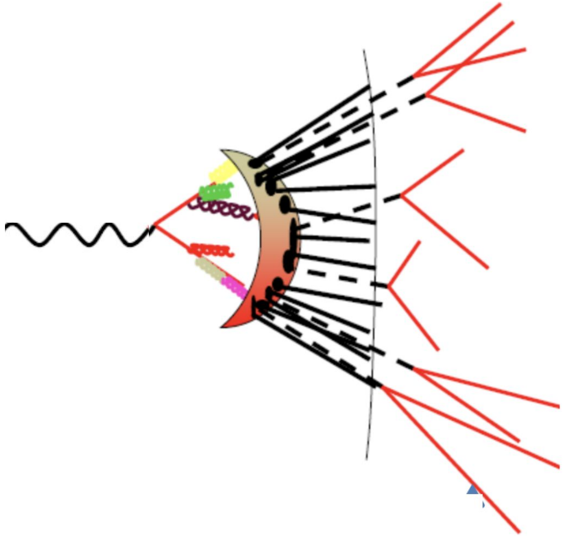


Hadrophilic DM
To avoid existing bounds

Additionally theoretical motivations to make things more complicated

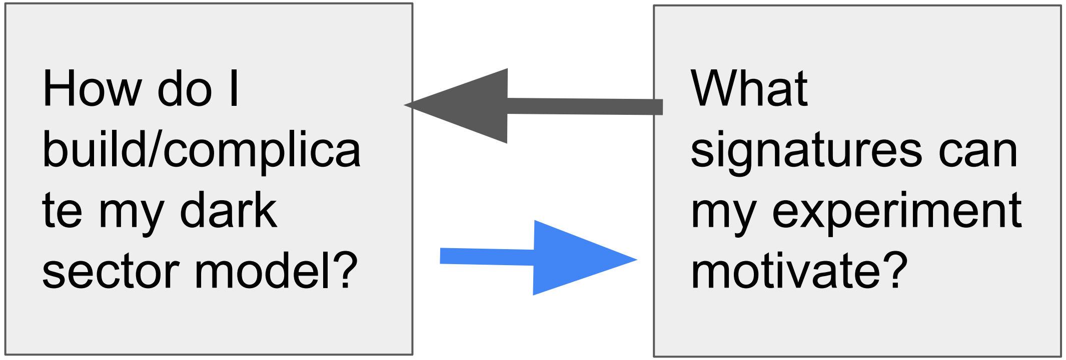
Big Idea 3: Theory Motivations





Or just a full on question
what happens when things get complicated?
Are we covering all signatures?

Additional Backdrop



Small extensions of models can lead to many new signatures at experiments

Being experimentally prepared for well motivated extensions should be goal of next generation experiments

Proposed Outline of the paper

- Framing of Big Idea 3 amongst the other Big Ideas
- Big Idea 3 Motivations and Scope
  - Extended Dark Sector
  - Physics Anomalies
  - Additional Motivations
- Benchmark Models and Motivations
  - Review of the LOIs and how they fit into their papers
- Mapping of models to Experimental Approaches
  - Full discussion of experimental approaches will go in Big Ideas 4

Motivating Models for Big Idea 3

- Extended/non-minimal dark sectors
  - Minimality is good but may not correspond to reality (example: SM)
- Which models to present?
  - Strongly motivated theoretically (example: flavor violating QCD axion)
  - Highlighting experimental reach:
    - What do we learn about a model if nothing is found (example: closing the prompt decaying ALP window below kaon mass)
- Finding Benchmarks for all models can be a challenge
  - A key point of the Big Ideas 3 is to collect the motivations for extension
  - Allows us to have a benchmark

Data Anomalies that help promote Big Idea 3

- $(g-2)_\mu$
- B Physics anomalies
  - RK and other flavor anomalies
- Xenon 1T
- MiniBoone Excess
- Beryllium
- Neutron lifetime anomaly
- KOTO

Discussion: How complicated a model is needed to motivate these?

How complicated a detector is needed to find these models?

Examples

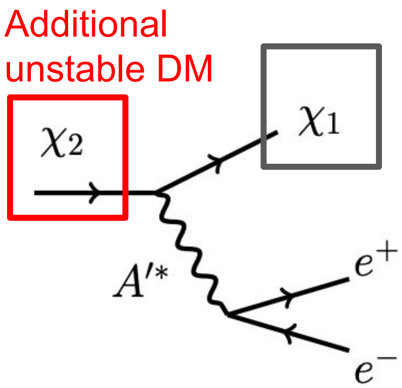
Questions to keep in mind for discussion

How do we prepare ourselves for newer, more complicated models?

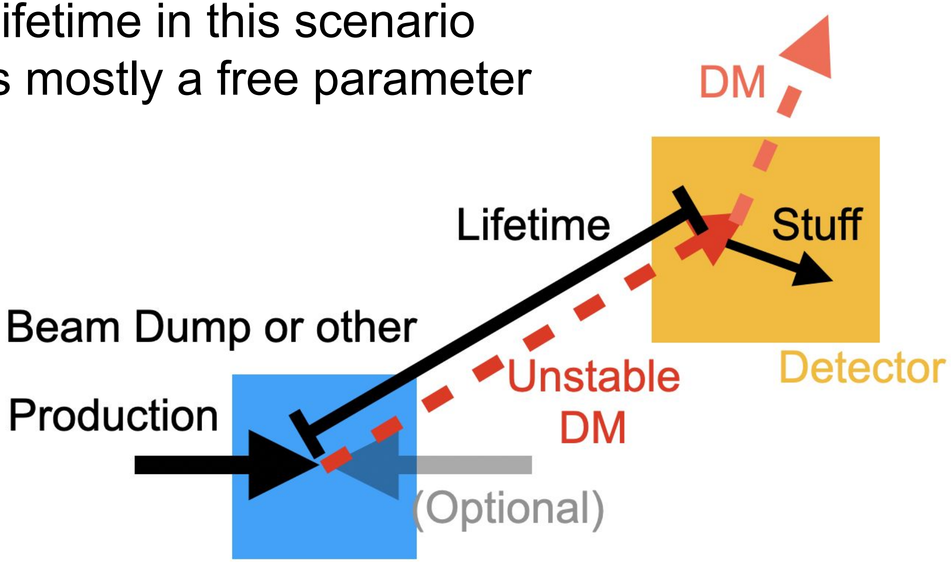
Discussion: What do we define as complete or adequate signature coverage?

Inelastic DM: Example of a minimal extension

- Strategy start with one of our usual portals:
  - Modify the Dark Matter to have an unstable candidate



Lifetime in this scenario
Is mostly a free parameter

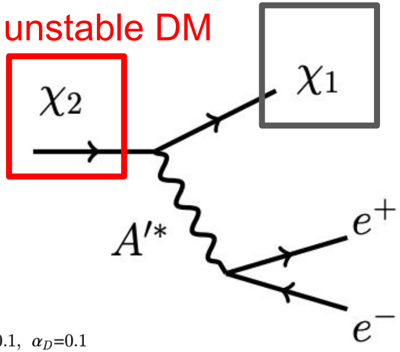


Inelastic DM generally does not change the relic bounds, but adds new signatures

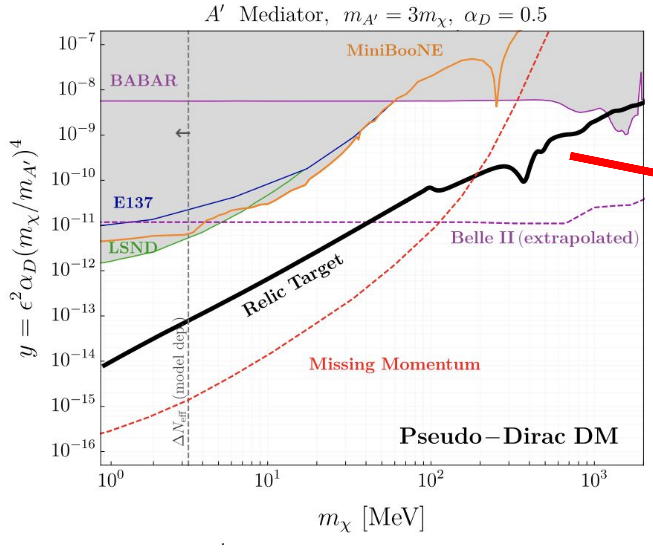
Inelastic DM: Example of a minimal extension

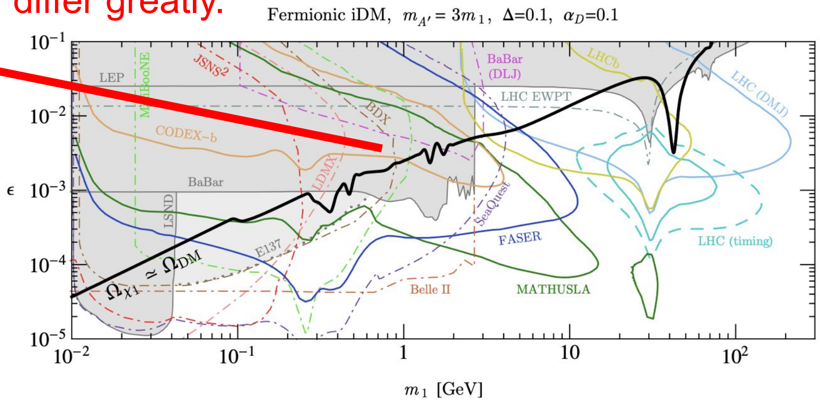
- By adding new signatures we make it easier to detect
    - Simple extension of the model changes bounds a lot
    - A case where many detectors can play a role

Additional unstable DM



Relic Targets are roughly the same. However bounds from experiments differ greatly.





Long Lived particles as an extension of dark sector

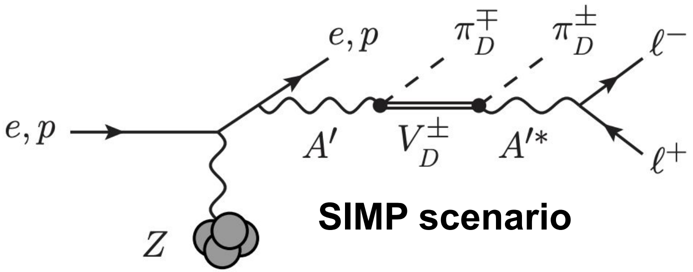
- Adding an unstable DM is a simple extension to dark sector
  - Leads to a wealth of other new final states
- More flexibility of signatures than just portals with small couplings

Related LOIs that cover this

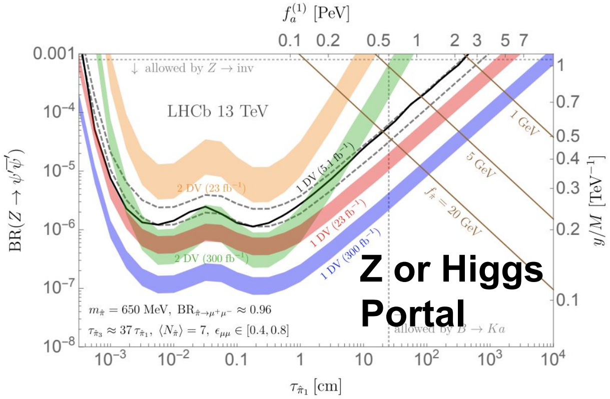
- BDF/SHiP facility AF5_AF0-RF6_RF0-163
- LLP at Energy Frontier EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201
- LLP at FCC-ee EF8_EF9-RF6_RF0_Rebeca_Gonzalez_Suarez-147
- New light particles at ILC main beam dump EF9_EF0-RF0_RF6-086.
- Codex-b EF9_EF0-RF6_RF0-034
- Electron fixed target spectrometer : HPS RF6_RF0_Nelson-078
- Proton fixed target spectrometer : DarkQuest RF6_RF0_Nhan_Tran-025

More complex Dark sector: Dark Pion

- Dark Pions, Dark Vector Mesons as a further extension
  - More complicated Dar Sector Scenario
  - Broad range of complex decays many of them can be long lived



SIMP scenario



Z or Higgs Portal

Related LOIs

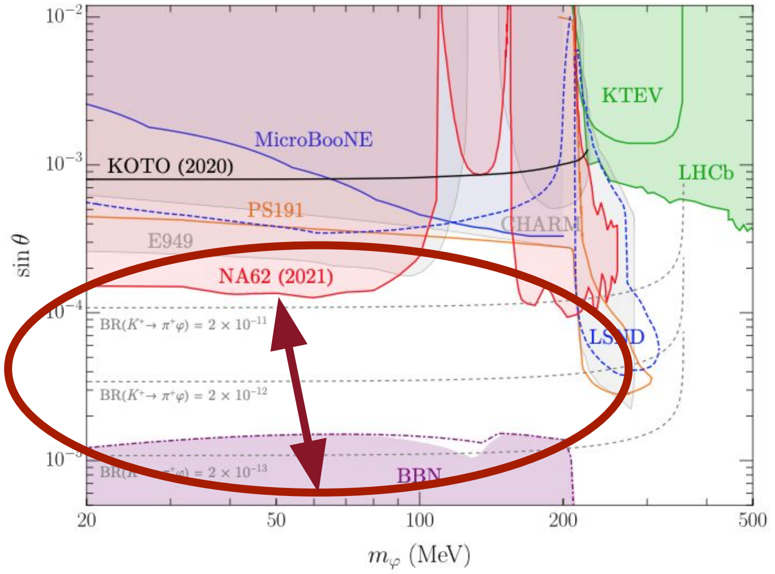
- Dark Pion Searches at LHC and High Intensities EF9_EF0-RF6_RF0-075
- LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104
- Electron fixed target spectrometer : HPS RF6_RF0_Nelson-078
- Proton fixed target spectrometer : DarkQuest RF6_RF0_Nhan_Tran-025

Connecting Portals with bounds: Higgs mixed scalar

Higgs Portal : one of the minimal portals (Big Idea 1 and 2)

Next generation(s) of charged kaon experiments can close low mass allowed region

2201.07805

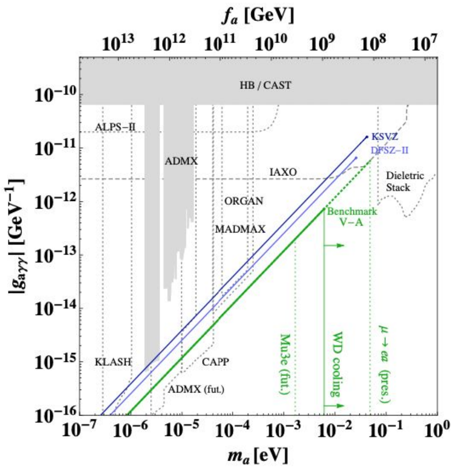


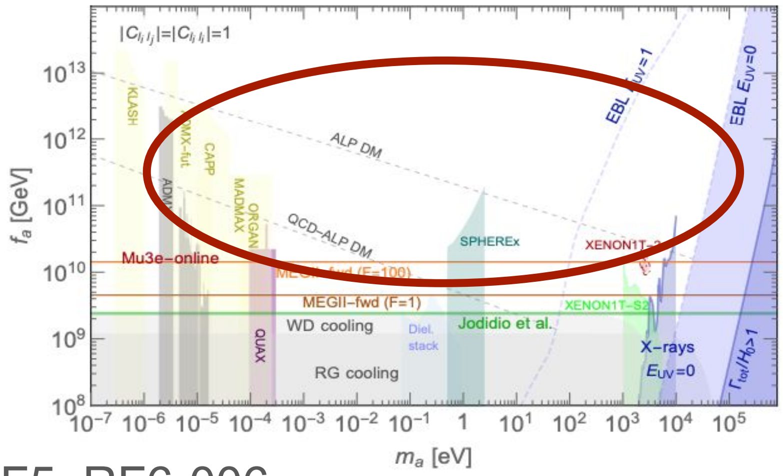
Bridge the gap with next generation Kaon experiments

Lepton flavor violating ALP as dark matter candidate

- If light enough ALP can be a DM candidate
  - If flavor violating couplings, can probe very high scales
  - For instance, for LFV couplings $\mu \rightarrow e\ a$
  - Could be the QCD axion

2006.04795





ALP couplings to quarks

- Flavor violating couplings can translate to drastically different bounds on the parameters of the model
- Example: bounds on fa for ALPs

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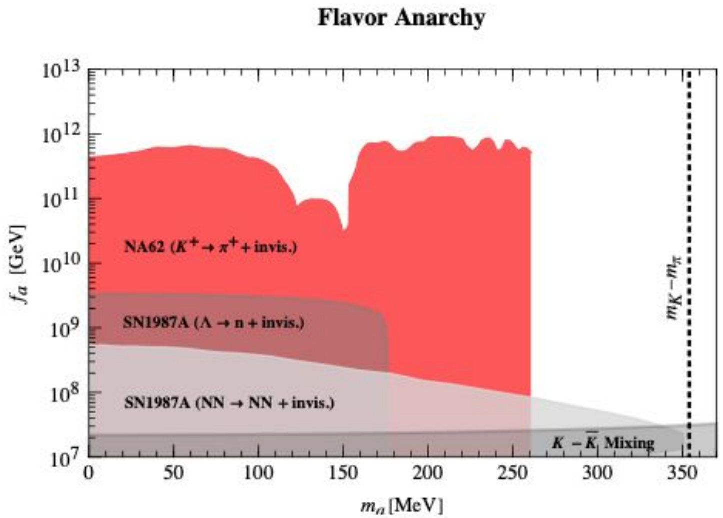
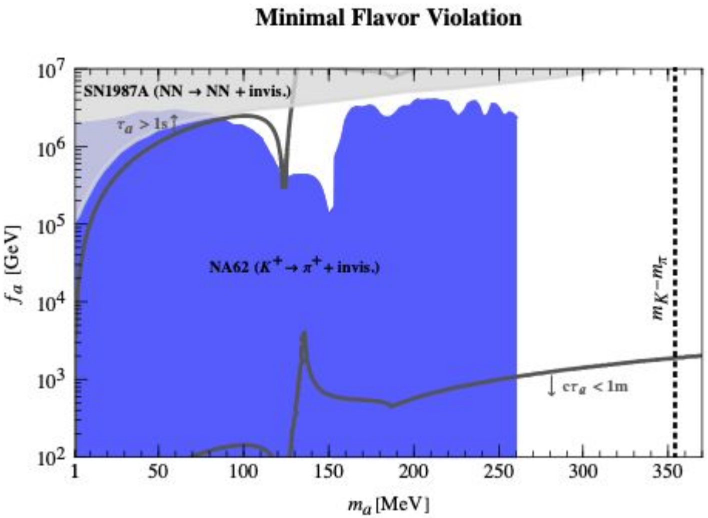
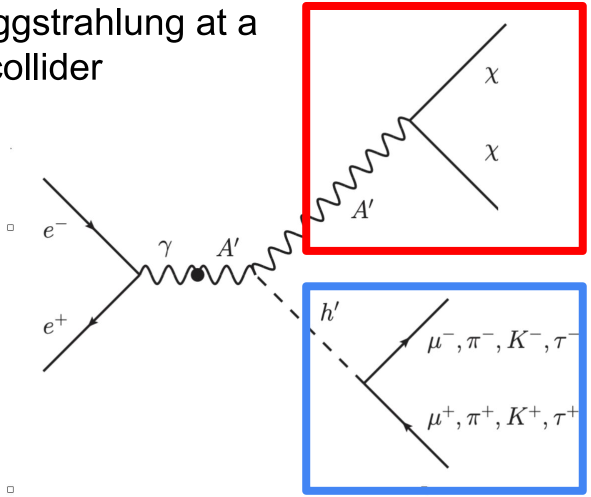




Adding Both a Dark Higgs and a Dark Photon

- Dark Higgs is one way to give the dark photon a mass
- The addition of the Dark Higgs introduces lots of other possibilities
    - Effectively yields both light scalar and vector interactions
- Now have the possibility of multi light boson production

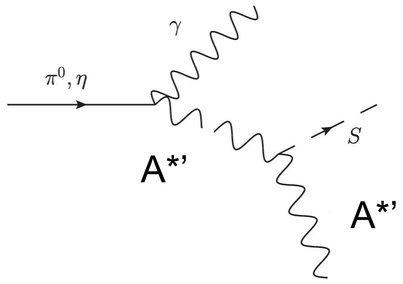
Dark higgstrahlung at a lepton collider



Dark Photon that can decay either visibly or *invisibly*

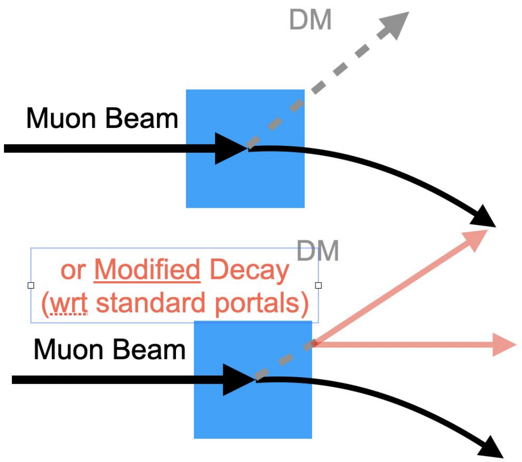
Dark Higgs with yukawa enhanced decays

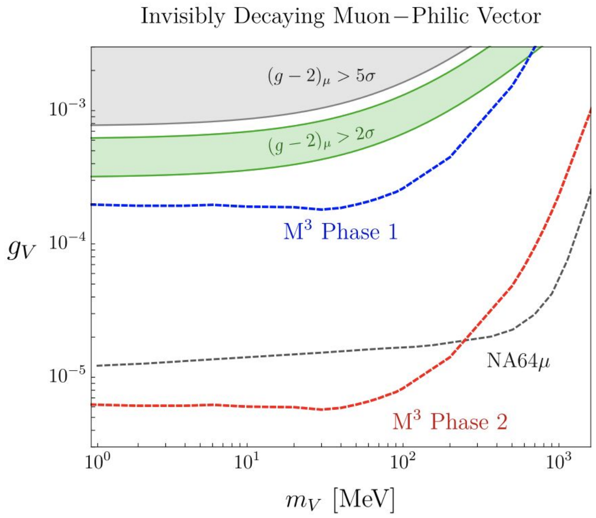
Dark higgstrahlung in meson decays



Models motivated by Physics anomalies

- $(g\text{-}2)_\mu$ is a major motivation for modified physics models
- Overall Strategy is to modify existing portal models
- Commonly used model for this is $U(1)_{\mu\text{-}\tau}$
- Collection of other possible models will go in paper





Motivated by anomalies

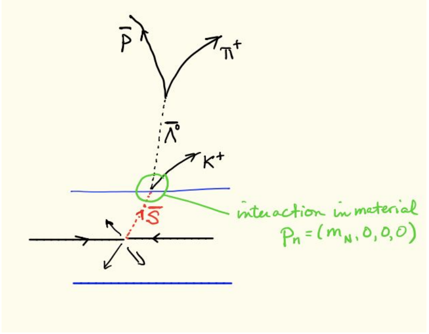
- A number of LOIs focus on modified models to explain g-2
- Additionally there is interest in models that are motivated by heavy flavor
- Another, motivated modification of the couplings also exist
  - Baryophilic
  - Hadrophilic
  - …

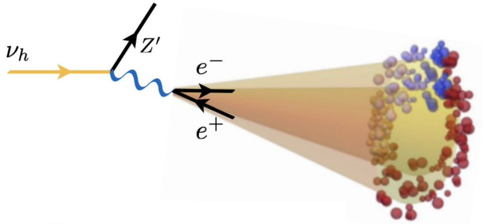
Related LOIs

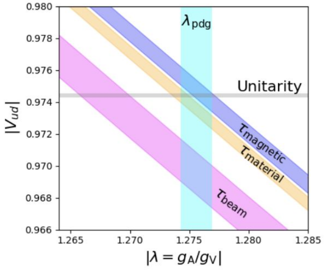
- Light mediators and flavor anomalies (theory) RF6_RF1_Alakabha_Datta-01
- LFV at FCCee RF6_RF4-EF3_EF4_Mogens_Dam-119

Other Models

- Sexaquark Dark Matter
  - Using Quarks to motivate Dark Matter, Distinct, rare signatures
  - **LOI:** Delayed electroweak phase transition (theory) CF1_CF0-EF7_EF10- RF3_RF6_Glennys_Farrar-198
  - **LOI:** Accelerator search for color-flavor-spin singlet uuddss bound state DM CF1_CF0-EF7_EF10- RF3_RF6_Glennys_Farrar-198
- Non minimal HNL models
  - Modified HNL which can potentially explain excess like MiniBoone
  - **LOI:** NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041
- Neutron Portal Dark Matter
  - **LOI**: $\Delta B = 2$ RF4_RF6-NF3_NF10-TF2_TF5_Joshua_Barrow-105
  - **LOI:** Sterile neutrons at ORNL and ESS RF6_RF3_Joshua_Barrow-115



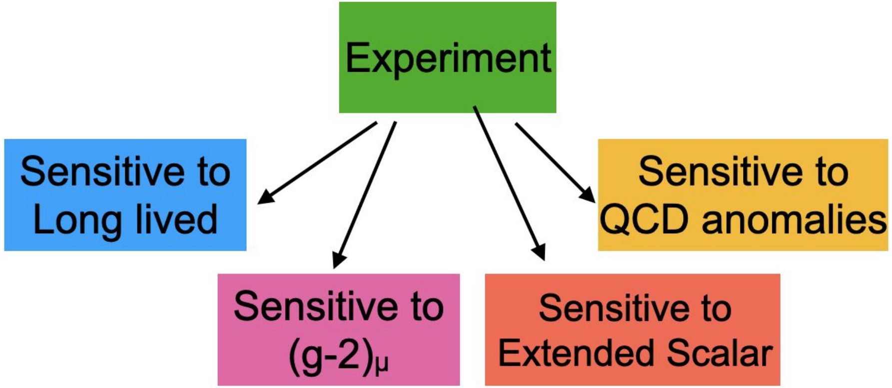




Experimental Signatures (and Motivations)

General View of Experimental Connections

- When trying to construct a model or explain an anomaly
  - Certain experiments are emphasized over other experiments
- This can help to further motivate a specific experimental emphasis
- For Big Idea 3, we would like to highlight these extended motivations
  - And as a consequence, further highlight certain final states



- The full details of the experiments is left for Big Idea 4

Beam Dump LOIs

Photon : Photon beam experiments RF6_RF0-112

Neutrino beams : SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148

Electron : LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104

Electron fixed target spectrometer : HPS RF6_RF0_Nelson-078

Muon : Muon missing momentum RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-111

Proton fixed target spectrometer : DarkQuest RF6_RF0_Nhan_Tran-025

Proton :1GeV proton beam dump at Fermilab RF6_RF0-NF2_NF3-AF2_AF5-099

Proton: 10GeV proton beam dump at Fermilab RF6_RF0-NF3_NF0-AF5_AF0-084

Kaon : Dark Sectors at NA62 & KLEVER — RF6_RF0-011

Kaon: Dark Sectors at KOTO — RF6_RF0_KOTO-050

Kaon: Dark sectors at kaon factories (theory) — RF6_RF0-034

Eta: Redtop RF2_RF6-IF6_IF3_REDTOP_Collaboration_-_new-083

Eta: Eta-Eta’ factories RF6_RF2_Sean_Tulin-117

Beam Dump LOIs

Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

Photon : Photon beam experiments RF6_RF0-112

Neutrino beams : SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148

Electron : LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104

Electron fixed target spectrometer : HPS RF6_RF0_Nelson-078

Muon : Muon missing momentum RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-111

Proton fixed target spectrometer : DarkQuest RF6_RF0_Nhan_Tran-025

Proton :1GeV proton beam dump at Fermilab RF6_RF0-NF2_NF3-AF2_AF5-099

Proton: 10GeV proton beam dump at Fermilab RF6_RF0-NF3_NF0-AF5_AF0-084

Kaon : Dark Sectors at NA62 & KLEVER — RF6_RF0-011

Kaon: Dark Sectors at KOTO — RF6_RF0_KOTO-050

Kaon: Dark sectors at kaon factories (theory) — RF6_RF0-034

Eta: Redtop RF2_RF6-IF6_IF3_REDTOP_Collaboration_-_new-083

Eta: Eta-Eta’ factories RF6_RF2_Sean_Tulin-117

Beam Dump LOIs

Photon : Photon beam experiments RF6_RF0-112

Neutrino beams : SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148

Electron : LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104

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Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

Enhanced by Extended Scalar/ Heavy Flavor

Beam Dump LOIs

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Electron : LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104

Electron fixed target spectrometer : HPS RF6_RF0_Nelson-078

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Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

Enhanced by $(g-2)_\mu$ explanation

Enhanced by Extended Scalar/ Heavy Flavor

Enhanced by explanation of QCD Anomalies

High(er) Energy collider LOIs + Long Lived

Electron : LLP at Belle II RF6_RF0_Torben_Ferber-020

Electron : ILC beam dump: EF9_EF0-RF0_RF6-086

Electron: LLP at FCCee EF8_EF9-RF6_RF0_Rebeca_Gonzalez_Suarez-147

Proton : BDF/SHiP facility AF5_AF0-RF6_RF0-163

Proton : Forward Physics Facility : EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2

Proton : Codex-b: EF9_EF0-RF6_RF0-034

FASER : EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2

Mathusla: EF9_EF10-NF3_NF0-RF6_RF0-AF5_AF0-IF3_IF7_MATHUSLA_(David_Curtin)-184

Overview: LLP at EF EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201

High(er) Energy collider LOIs + Long Lived

Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

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Electron: LLP at FCCee : EF8_EF9-RF6_RF0_Rebeca_Gonzalez_Suarez-147

Proton : BDF/SHiP facility AF5_AF0-RF6_RF0-163

Proton : Forward Physics Facility : EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2

Proton : Codex-b: EF9_EF0-RF6_RF0-034

Proton : FASER : EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2

Proton : Mathusla: EF9_EF10-NF3_NF0-RF6_RF0-AF5_AF0-IF3_IF7_MATHUSLA_(David_Curti

Overview: LLP at EF EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201

High(er) Energy collider LOIs + Long Lived

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Proton : Forward Physics Facility : EF9_EF6_EF10_EF5-NF6_NF3_….

Proton : Codex-b: EF9_EF0-RF6_RF0-034

Proton : FASER : EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2

Proton : Mathusla: EF9_EF10-NF3_NF0-RF6_RF0-AF5_AF0-IF3_IF7_MATHUSLA_(David_Curti

Overview: LLP at EF EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201

Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

Enhanced by Extended Scalar/ Heavy Flavor

High(er) Energy collider LOIs + Long Lived

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Proton : FASER : EF9_EF6-NF3_5_AF0_FASER2..

Proton : Mathusla: EF9_EF10-NF3_MATHUSLA_(David_Curti..

Overview: LLP at EF EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201

Enhanced by Dark Mesons/inelastic DM/Neutrino dipole

Enhanced by Extended Scalar/ Heavy Flavor

Enhanced by $(g-2)_\mu$ explanation≈

Discussion Points

- How much can we use existing anomalies to drive this paper?
- How exotic of a model should we include?
    - What is the right level to motivate DM measurements beyond portals
- How do we handle overlap with BI 1 and BI 3
    - It can be good to have some redundancy
- Are we missing something?

Come and Contribute

- Please let us know (by email/…) if we have missed your stuff
- There have been many developments since the LOIs
  - A number of new interesting channels have emerged
  - We are eager to update this with the many ongoing developments
- Please let us know if you plan on contributing to this white paper

Send an email to us with you contribution topic

zupanje@ucmail.uc.edu,schuster@slac.stanford.edu,pcharris@mit.edu

Contributed white papers due by March 15th, 2022

Solicited whitepapers due by April 15th, 2022

Thanks!