Big Ideas 3 :
New flavors and rich structures in dark sectors

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Logistics

- Current draft of the paper is located here :
  https://www.dropbox.com/s/gksd3y43k0vtpyw/Snowmass_RF6_Big_Idea_3.pdf?dl=0

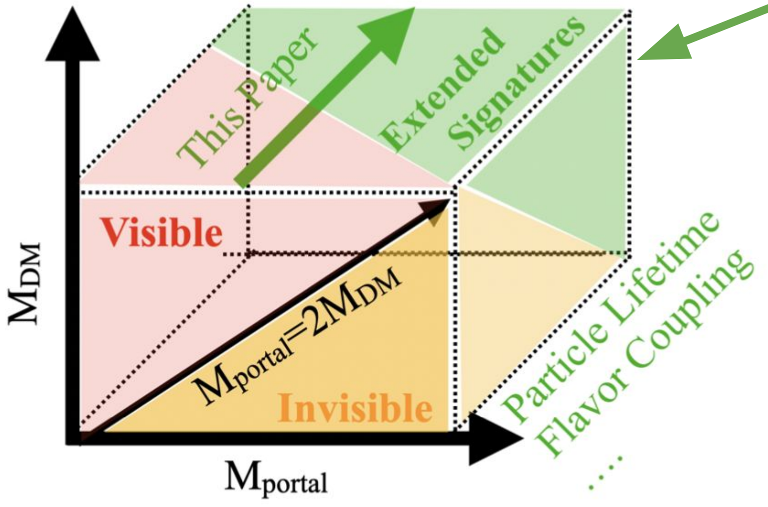
  https://arxiv.org/abs/2207.08990

- Please send any comments to :
  - pcharris@mit.edu schuster@slac.stanford.edu zupanje@ucmail.uc.edu
- In the next set of slides we will review the paper
  - Focus will be on the plots and table
  - You can read the paper if you want to look at the text

- This talk is a summary of what we have finally ended up with

Framing the

- Goal of this paper: emphasize beyond baseline Dark Sectors
- Many reasons to modify the dark sector to resolve other problems



This paper

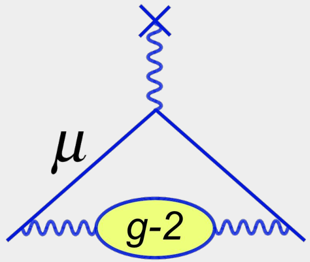
What are ways to modify the Dark Sector?

What do we learn

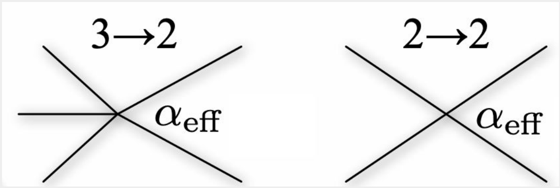
Organization of the paper

- 3 good reasons to motivate an extended dark sector

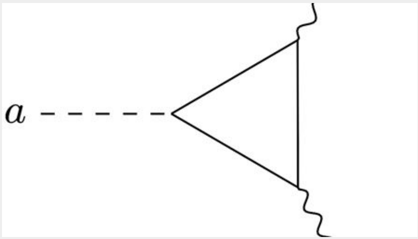
Data Anomalies



Extended Dark Sector



Theoretical Motivated



- Well motivated extensions of baseline dark sector models

Well motivated data anomalies

- There are a number of anomalies that could explain DM
- $(g-2)_\mu$
- B Physics anomalies
    - RK and other flavor anomalies
- Xenon 1T
- MiniBoone/μBoone Excess
- Neutron lifetime anomaly
- KOTO

Our Highlight

How do you search for $(g\text{-}2)_\mu$

Brian Batell

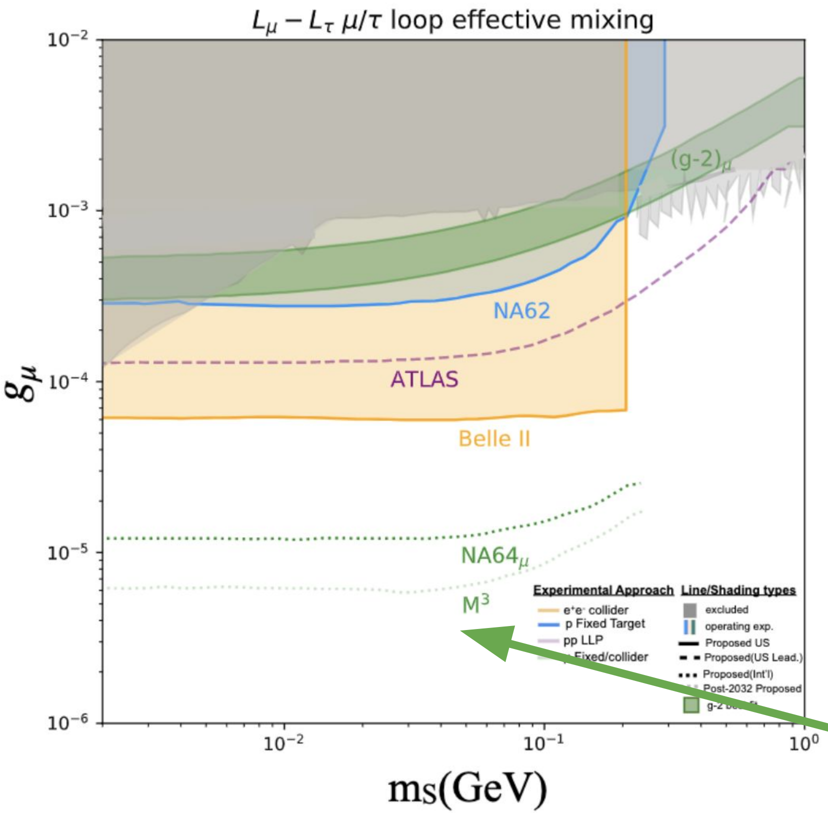
	Invisible			Visible			
Final State/ Mediator	Long-Lived	Neutrinos $(\nu\nu)$	DM $(\chi\chi)$	Photons $(\gamma\gamma)$	Electrons (e^+e^-)	Muons $(\mu^+\mu^-)$	Hadrons $(\pi^+\pi^-)$
Vector	No	Yes	Yes	No	No	Yes $m_V > 2m_\mu$	No

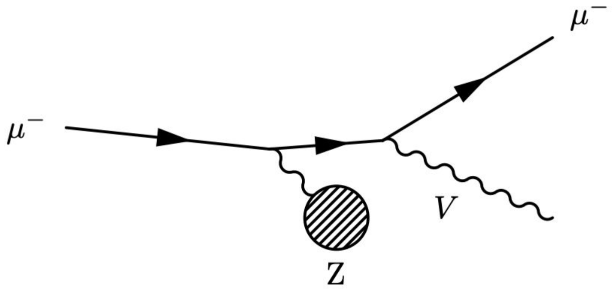
- $L_\mu - L_\tau$ gauge boson: UV complete, automatic coupling to neutrinos, easy to couple to DM.
- Challenging to build viable models with sizable couplings of vector mediator to electrons or hadrons (gauge anomalies, constraints from neutrino physics).

How do you search for $(g\text{-}2)_\mu$

	Invisible			Visible			
Final State/ Mediator	Long-Lived	Neutrinos ($\nu\nu$)	DM ($\chi\chi$)	Photons ($\gamma\gamma$)	Electrons (e^+e^-)	Muons ($\mu^+\mu^-$)	Hadrons ($\pi^+\pi^-$)
Scalar	Yes $m_S < 2m_\mu$	Yes	Yes	Yes $m_S < 2m_\mu$	Yes $m_S < 2m_\mu$	Yes $m_S > 2m_\mu$	Yes $m_S > 2m_\pi$
	• All minimal signatures can be realized in scalar simplified models. • UV complete models require new SM-charged states above weak scale with special flavor structure (such states can in principle also affect $(g-2)_\mu$). • More phenomenological studies needed to chart the parameter space.						
Signature	Missing Energy			Prompt or Displaced Resonance			

Vector mode for $(g\text{-}2)_\mu$

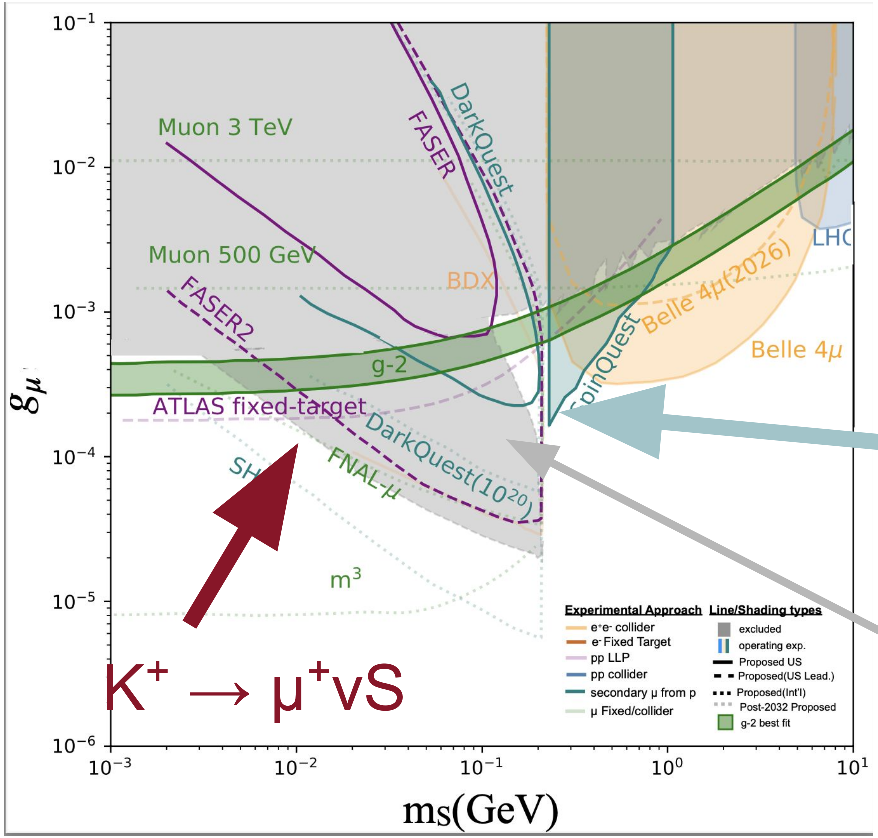


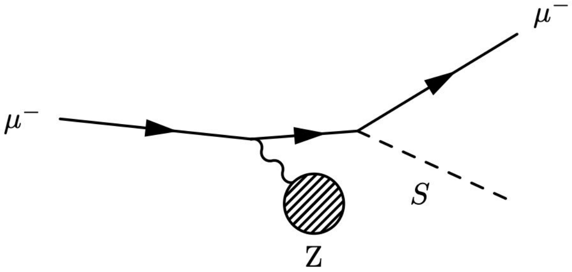


Belle II can close the story by next snowmass

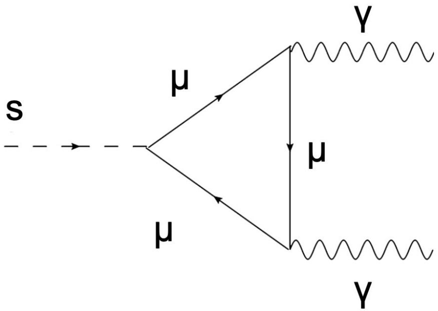
Muon beams drive these searches

Data Motivated Anomalies => $(g\text{-}2)_\mu$





Secondary Muons from proton beam dumps to appear here too

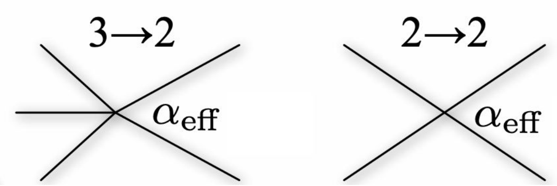


Light mediators
Decay to photons
In a look

Simple extensions of the standard model

SIMP:

+3⟶2 Dark Sector interactions

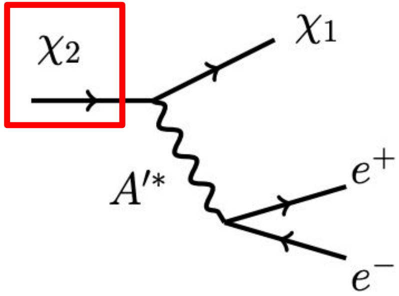


Scenario has dark mesons (rich dark sector)

Light mediator naturally exists w/SIMP for stable cosmology

Inelastic DM

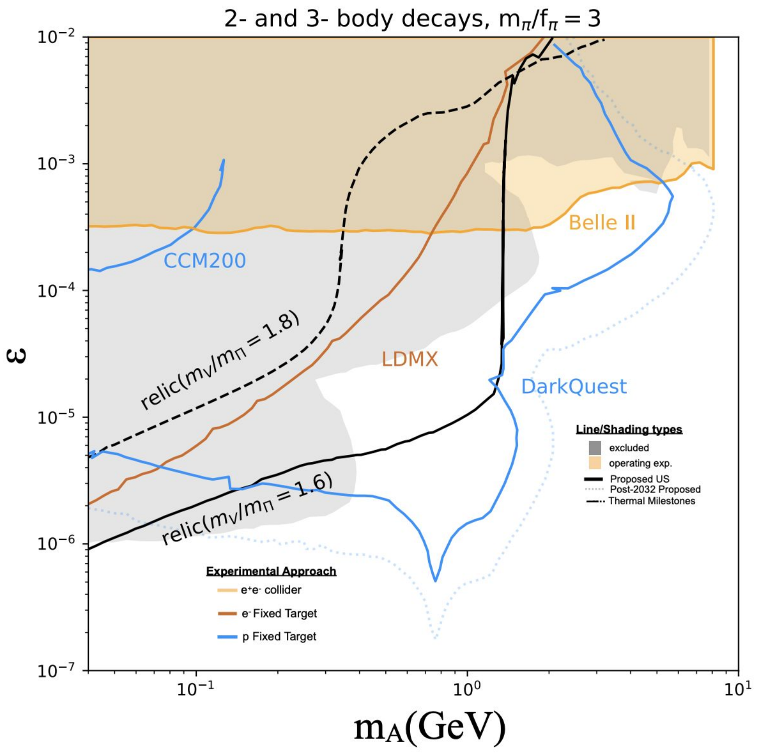
Additional unstable DM

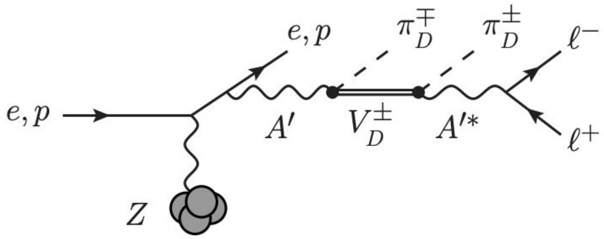


Inelastic DM (Simple extension)

Small mass splitting added for two dark sector particles
Leads to unstable (LL) χ_2

Simple extensions of the standard model: SIMP



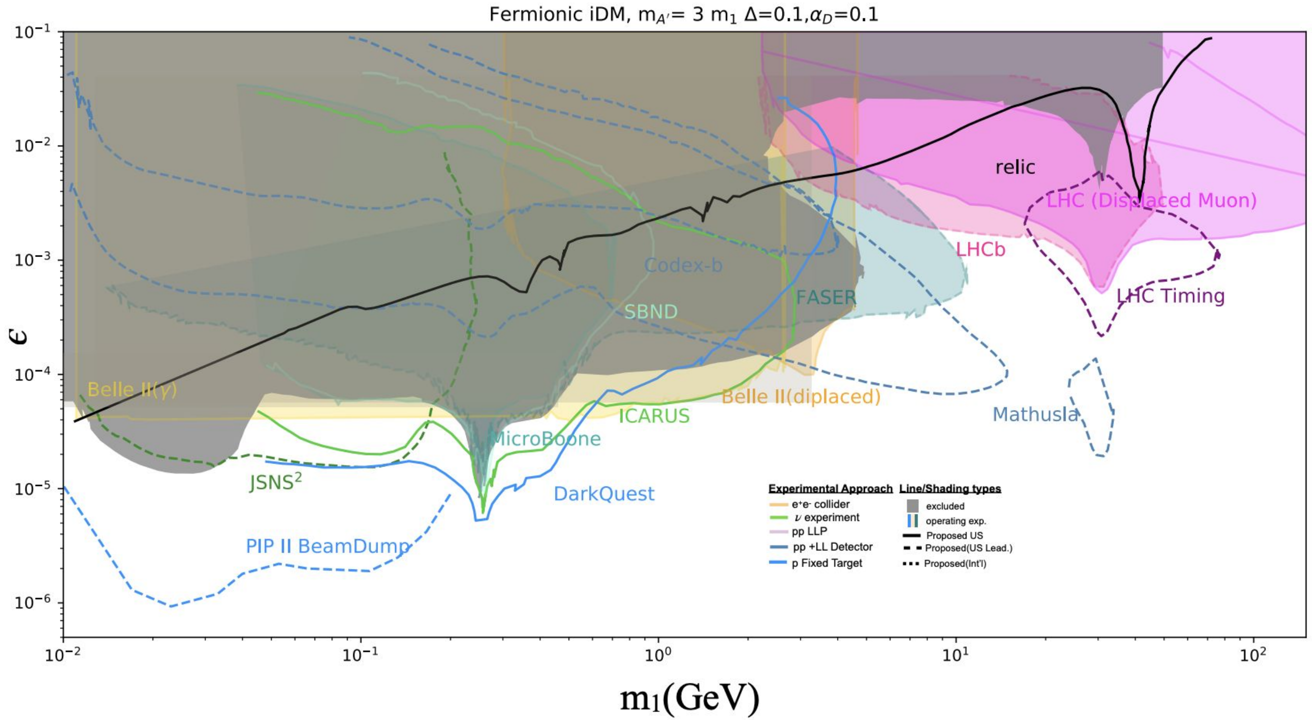


Final state is a displaced dilepton w/intermeidate dark sector particles

SIMP models benefit from small beam dumps (lifetime vs intensity)

Relevant cosmologies are within reach

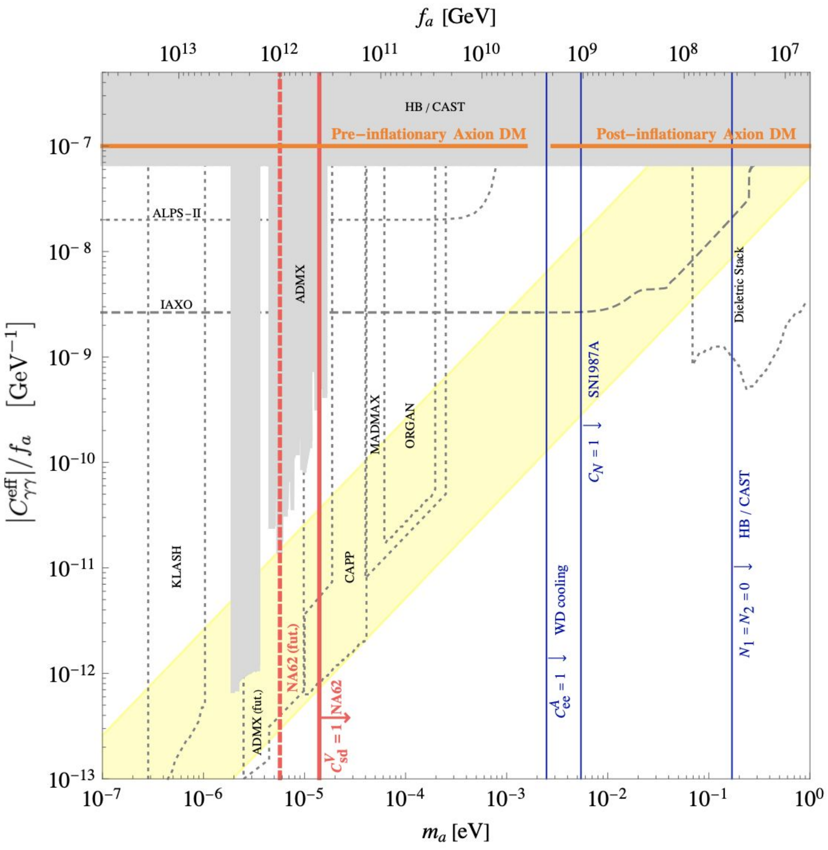
Inelastic Dark Matter



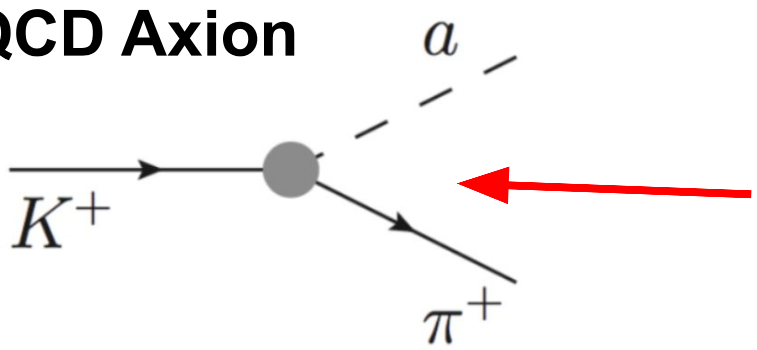
Relic density yields a slightly larger coupling compared to dark photon

Long-lived searches well motivated by inelastic DM (story ends soon)

Theoretical Motivations



QCD Axion



$$\mathcal{L}_{\text{ALP-}f} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5\right) f_j$$

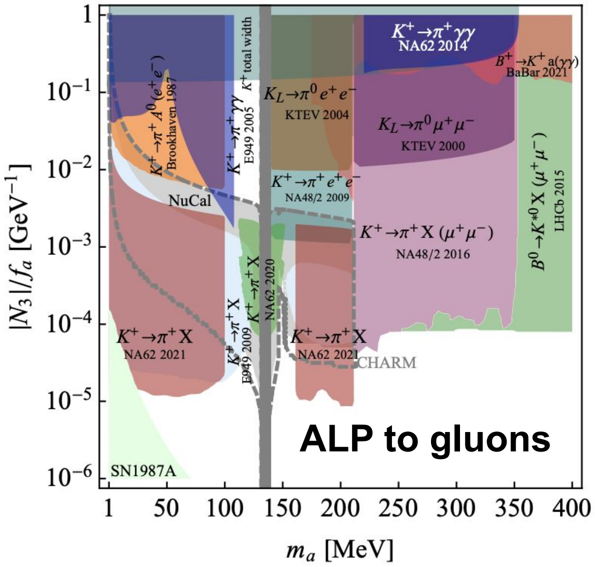
$$C^V_{d_i d_j} - C^A_{d_i d_j} = V^*_{u_k d_i} (C^V_{u_k u_l} - C^A_{u_k u_l}) V_{u_l d_j}$$

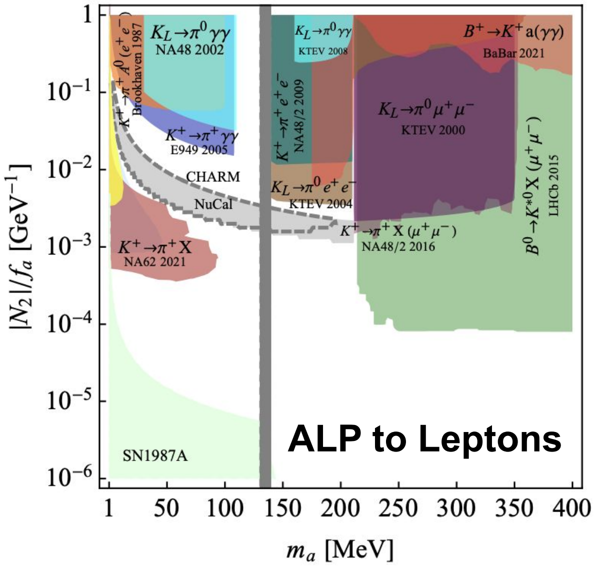
$$V_{u_k u_{d_i}} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \to \text{for} \begin{pmatrix} u \\ d \\ \ell \end{pmatrix}$$

Adding an non-flavor diagonal CKM matrix

More General Axions

$$\mathcal{L}_{\text{ALP-gauge}} = \frac{N_3\alpha_s}{8\pi f_a} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{N_2\alpha_2}{8\pi f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{N_1\alpha_1}{8\pi f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu}$$





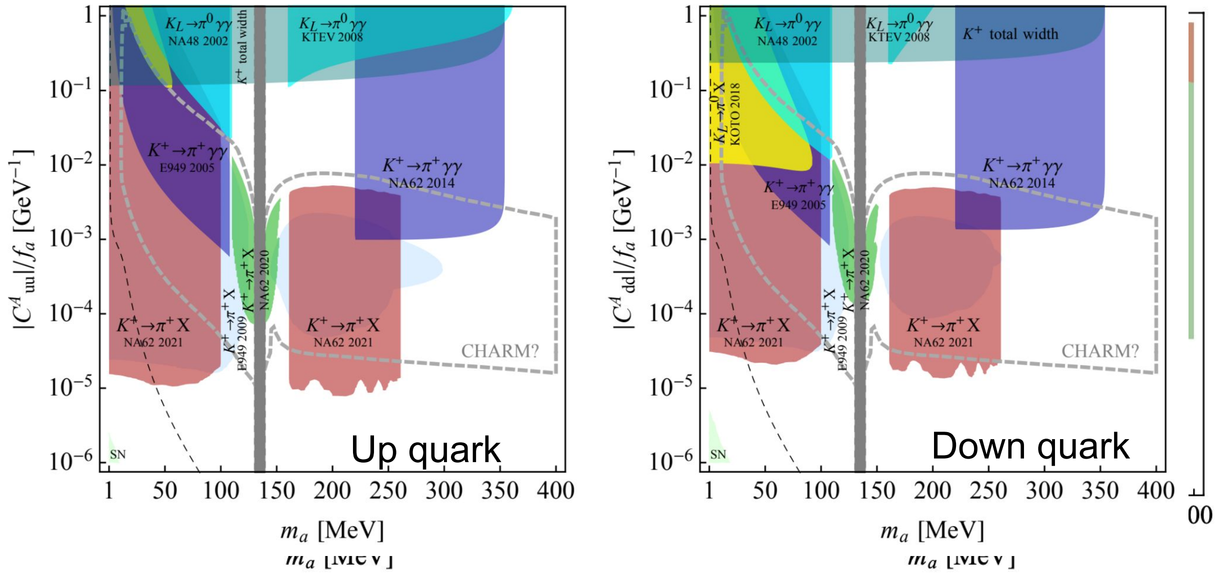
Kaon decays drive the constraints

Probing a scale fo 10 TeV

More General Axions

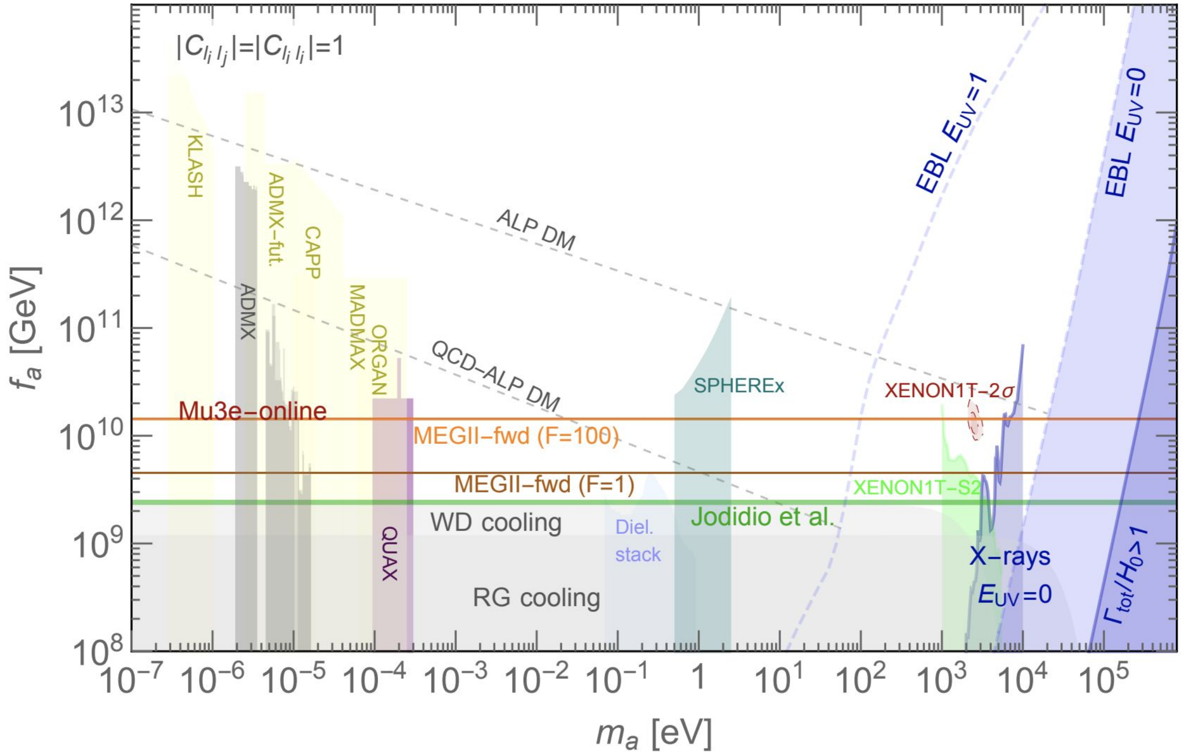
$$\mathcal{L}_{\text{ALP-}f} = \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu\left(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5\right)f_j$$

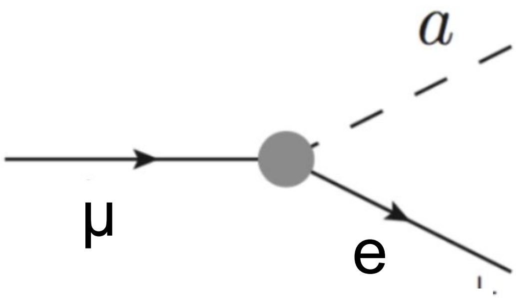
Loop induced di-photon final state



Flavor diagonal bounds on coupling (less constraints)

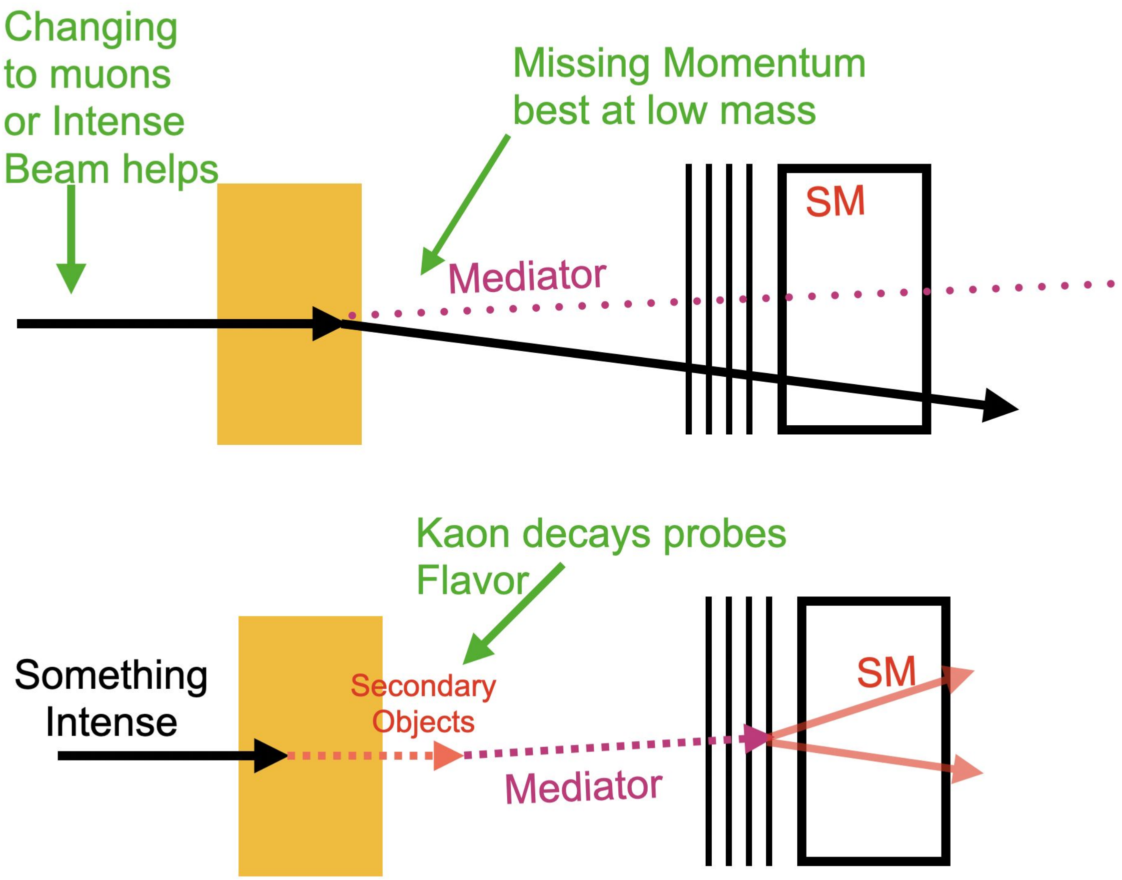
Axions with just lepton couplings



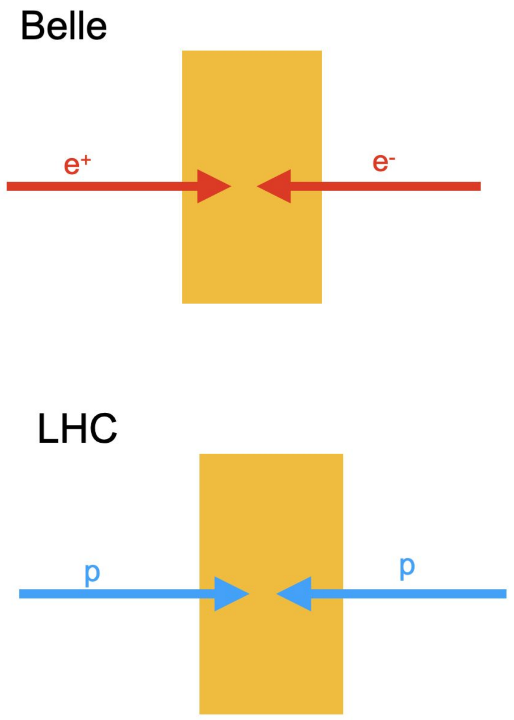


Muon to axion decays

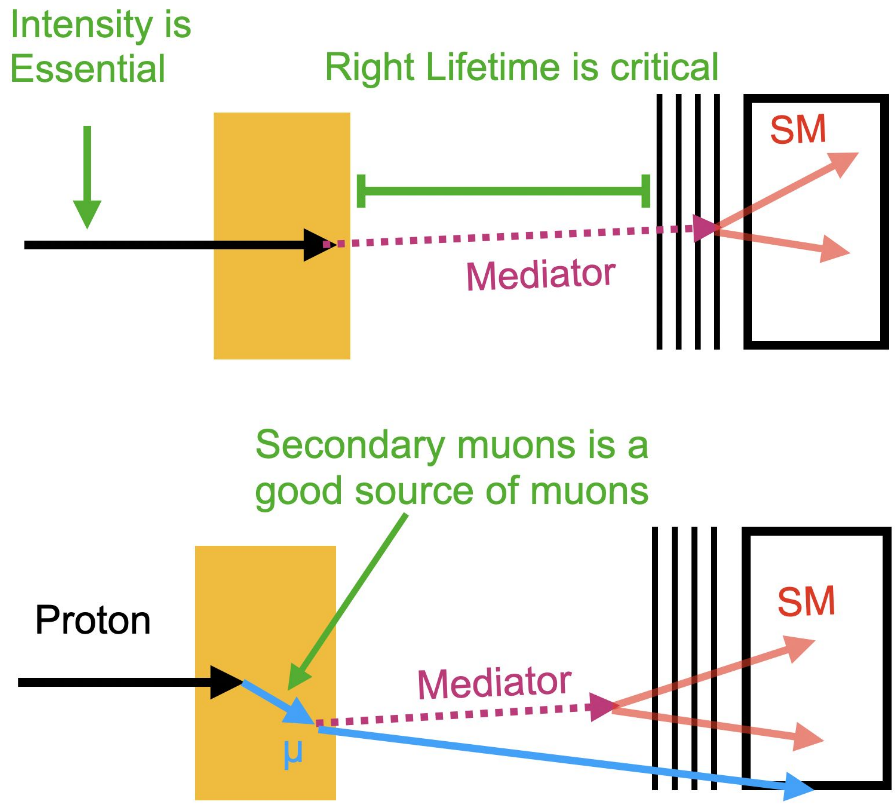
Experimental highlights



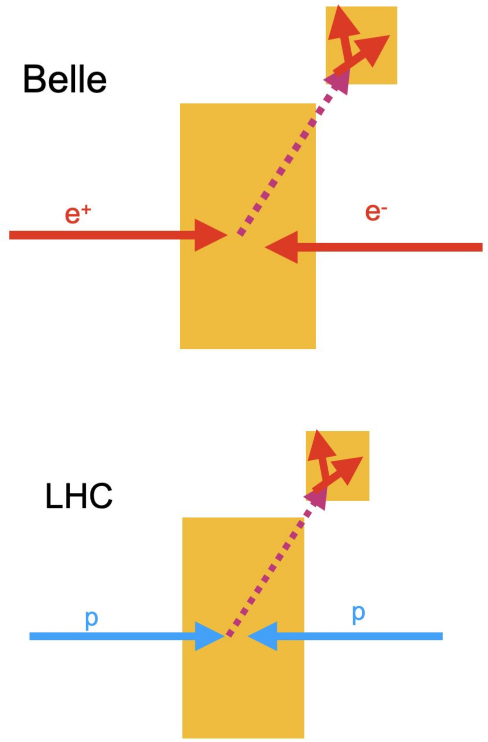
Higher Energy



Experimental highlights

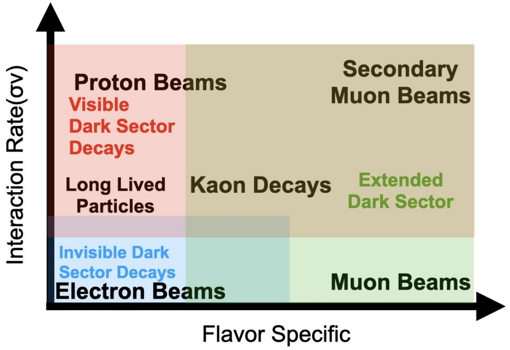


Higher Energy



Conclusions

- Extending the dark sector highlights specific approaches
  - Our focuses:
    - g-2 : (Secondary) Muon beams
    - Extend Dark sector : beam dumps (LLPs)
    - Axions : Kaon decays
- Keep in mind Rich Dark sector
  - Highlights certain tech
- Many opportunities this decade!
  - Modest upgrades probe critical space



Backup

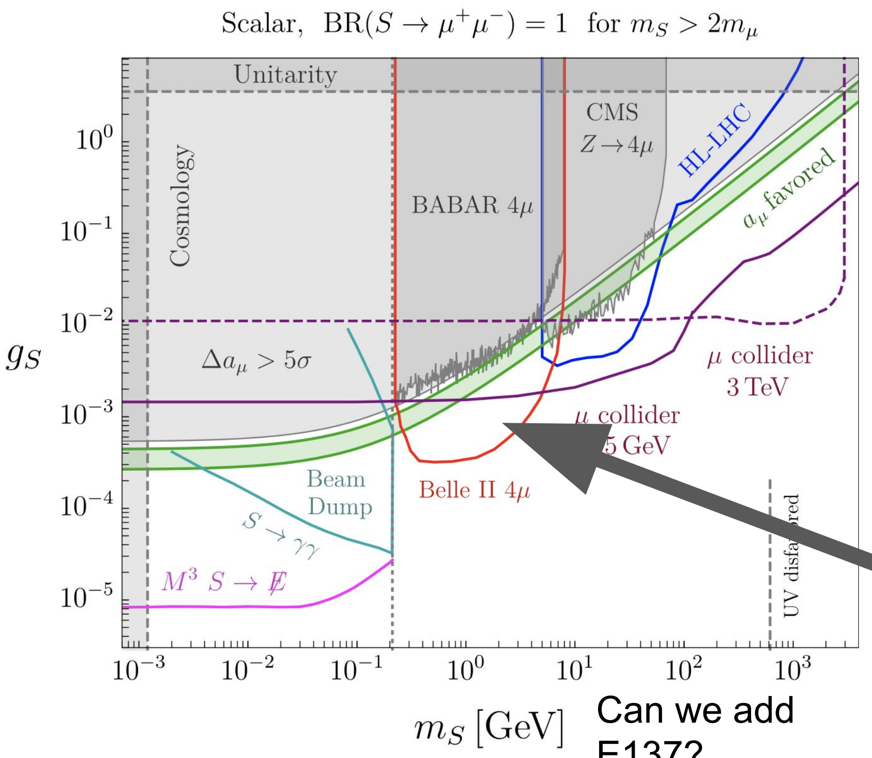
Experimental highlights

- A few general conclusions follow in what is sensitive
  - Long Lived particles enhance these models
    - Beam dump decay size is critical
  - Increased importance of non-resonant processes
  - Importance of muon beams
    - Direct and Secondary enhance rich models
  - Increased importance of Heavy Flavor
    - Kaon decay play an important role

Strategy

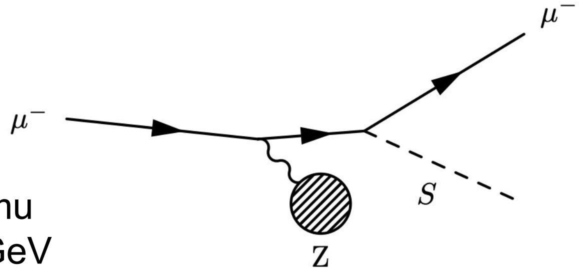
- Aimed to cover 3 major motivations for extended dark sectors
  - Data based anomalies
  - Simple Motivated extensions
  - Theoretical motivations
- Picked a few examples that highlight these
  - No intention of being exclusive
  - Critical point is what we chose to highlight
- We should aim to harmonize plotting styles across papers
  - Not clear which main plots should come from BI3

Data Motivated Anomalies => $(g\text{-}2)_\mu$



Can we add E137?

Add Na64mu
Cut at 20 GeV



General Message, this is where Muon beams shine

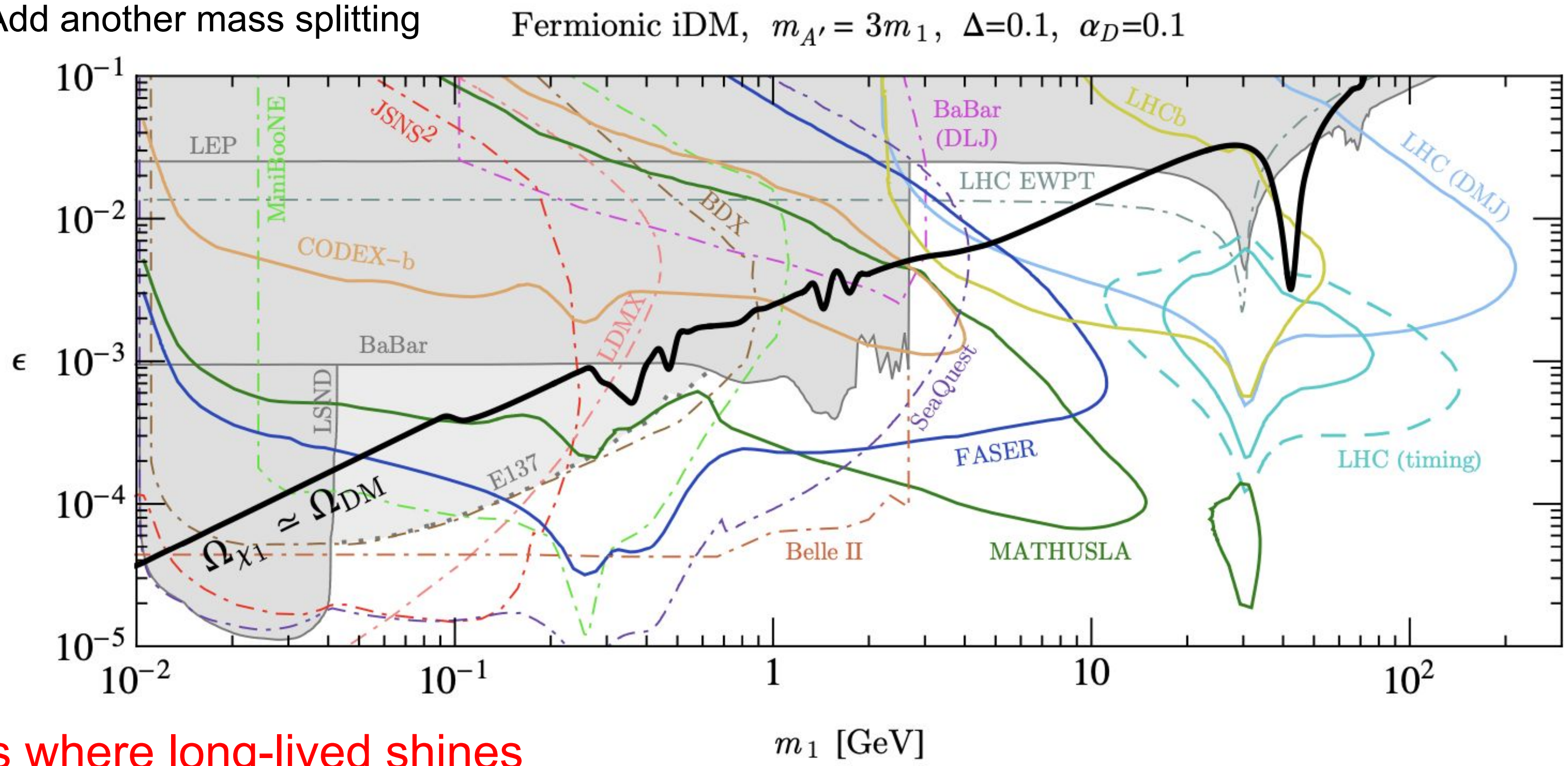
$(L_\mu\text{-}L_\tau)$ in extended

Secondary Muons from proton beam dumps to appear here too

Simple extensions of the standard model

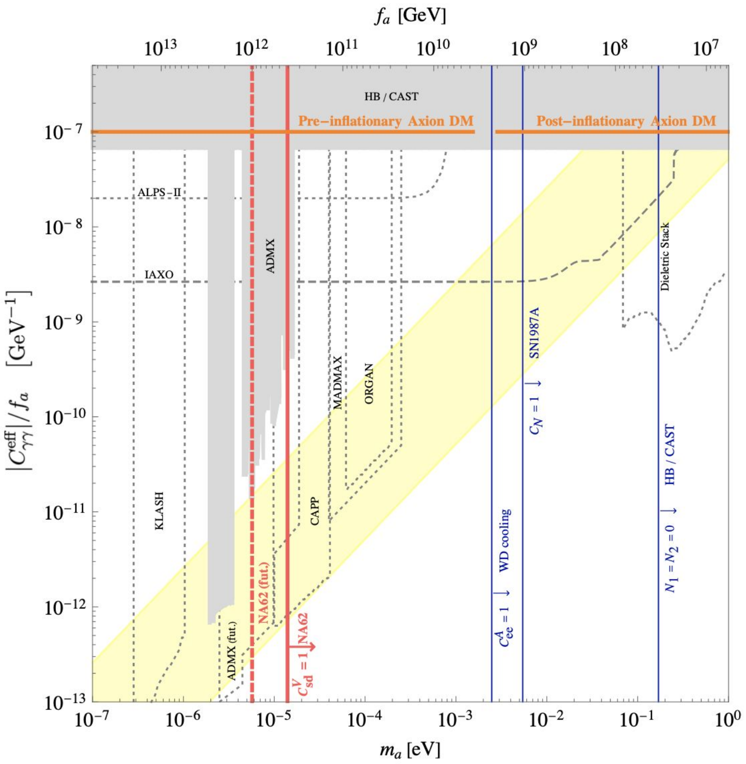
Add g-2?

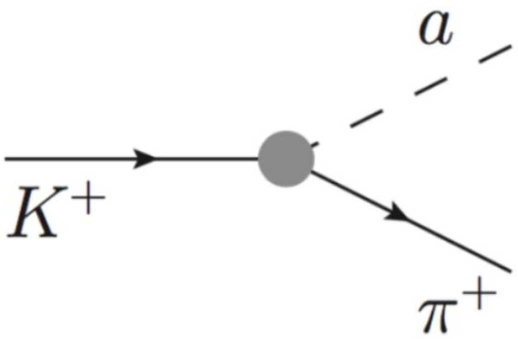
Add another mass splitting



This is where long-lived shines

Theoretical Motivations

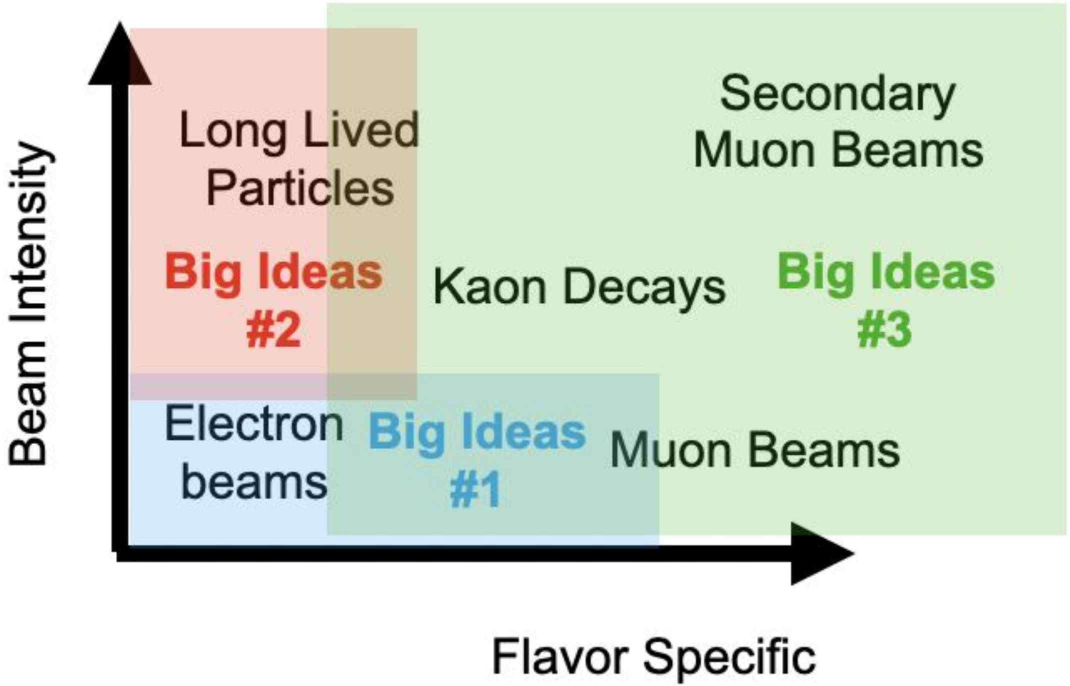


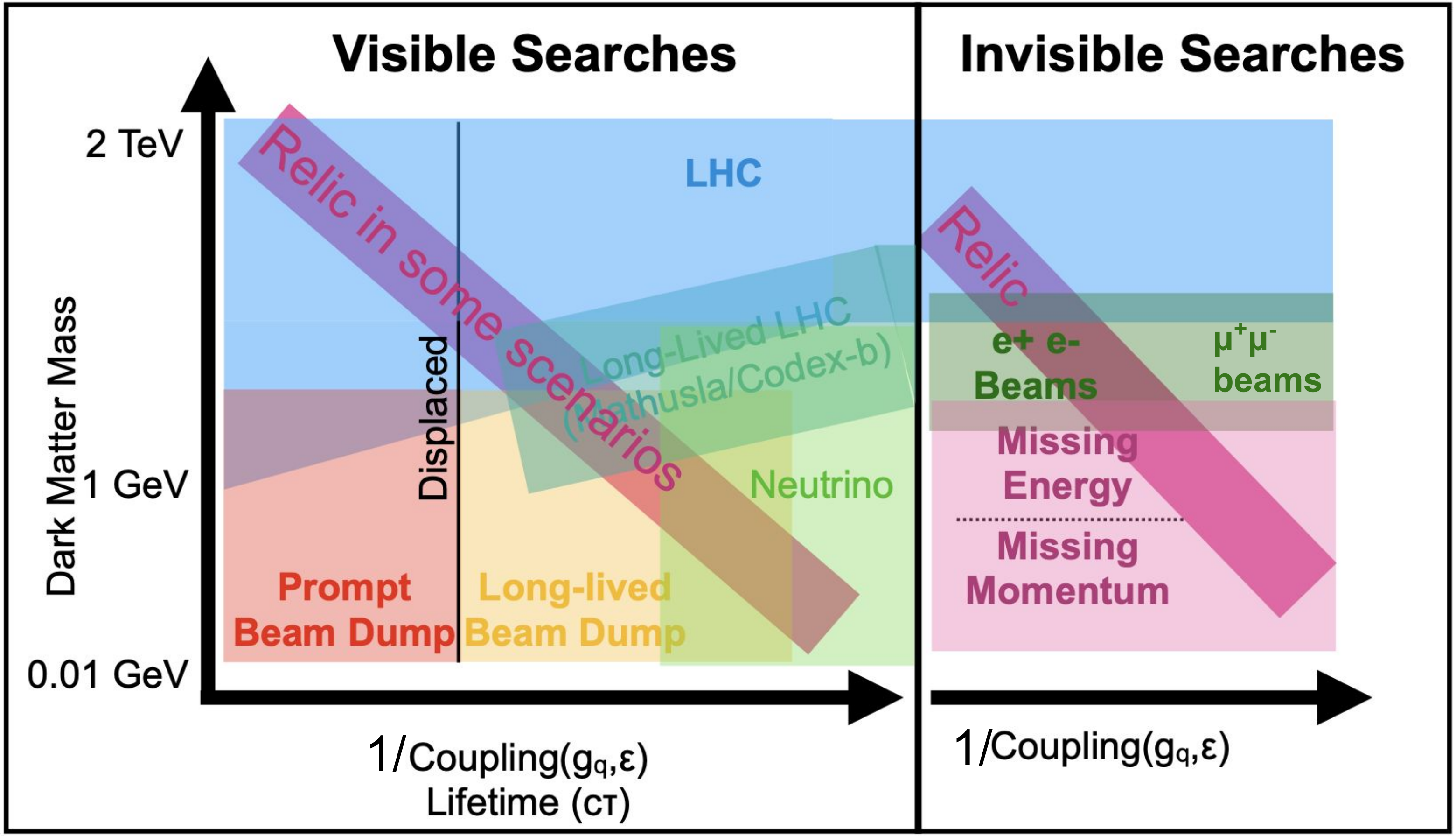


Connecting Kaon decays with the standard Model Axion

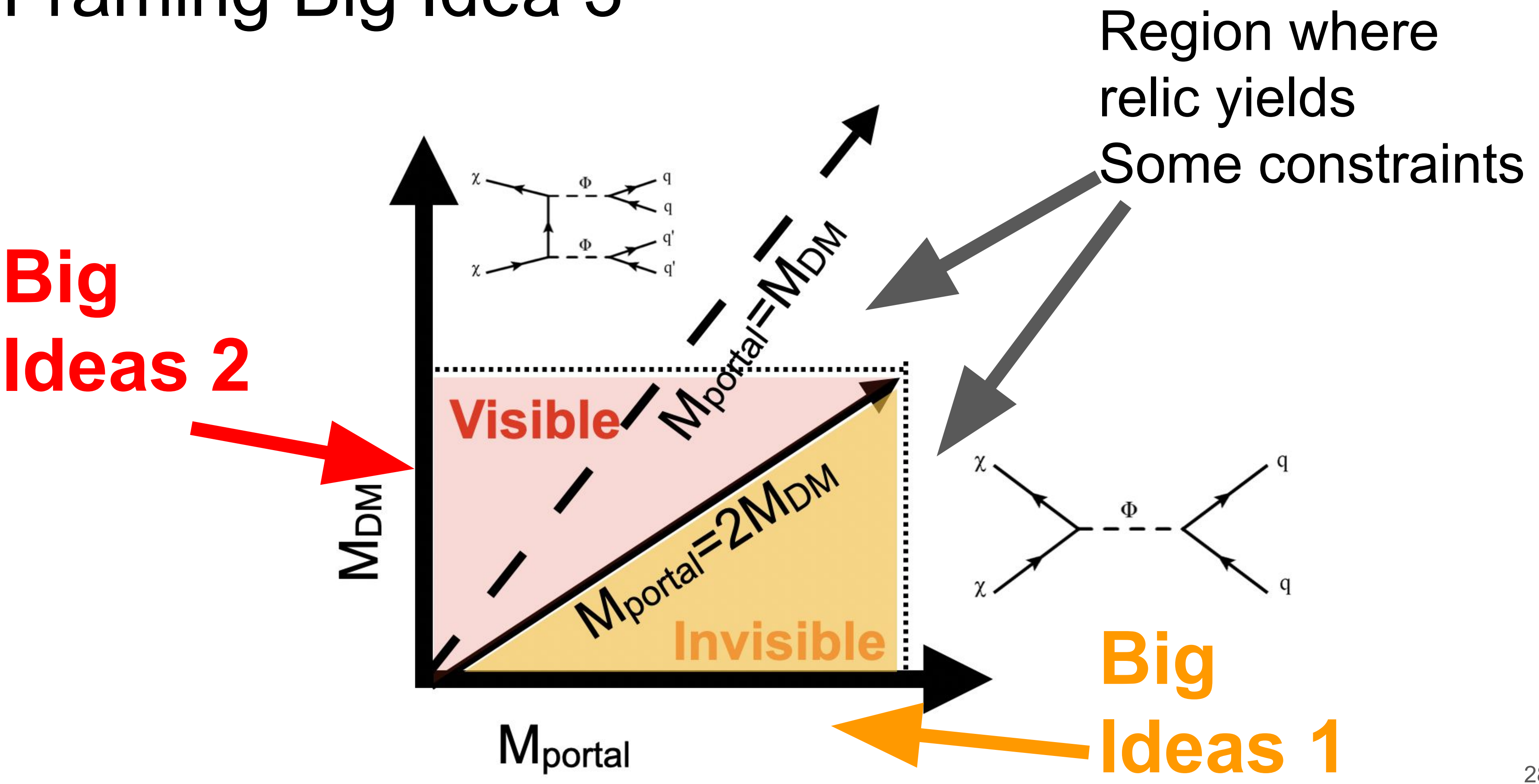
(Not really like the other plots)
Missing a huge number of lines

Experimental Front

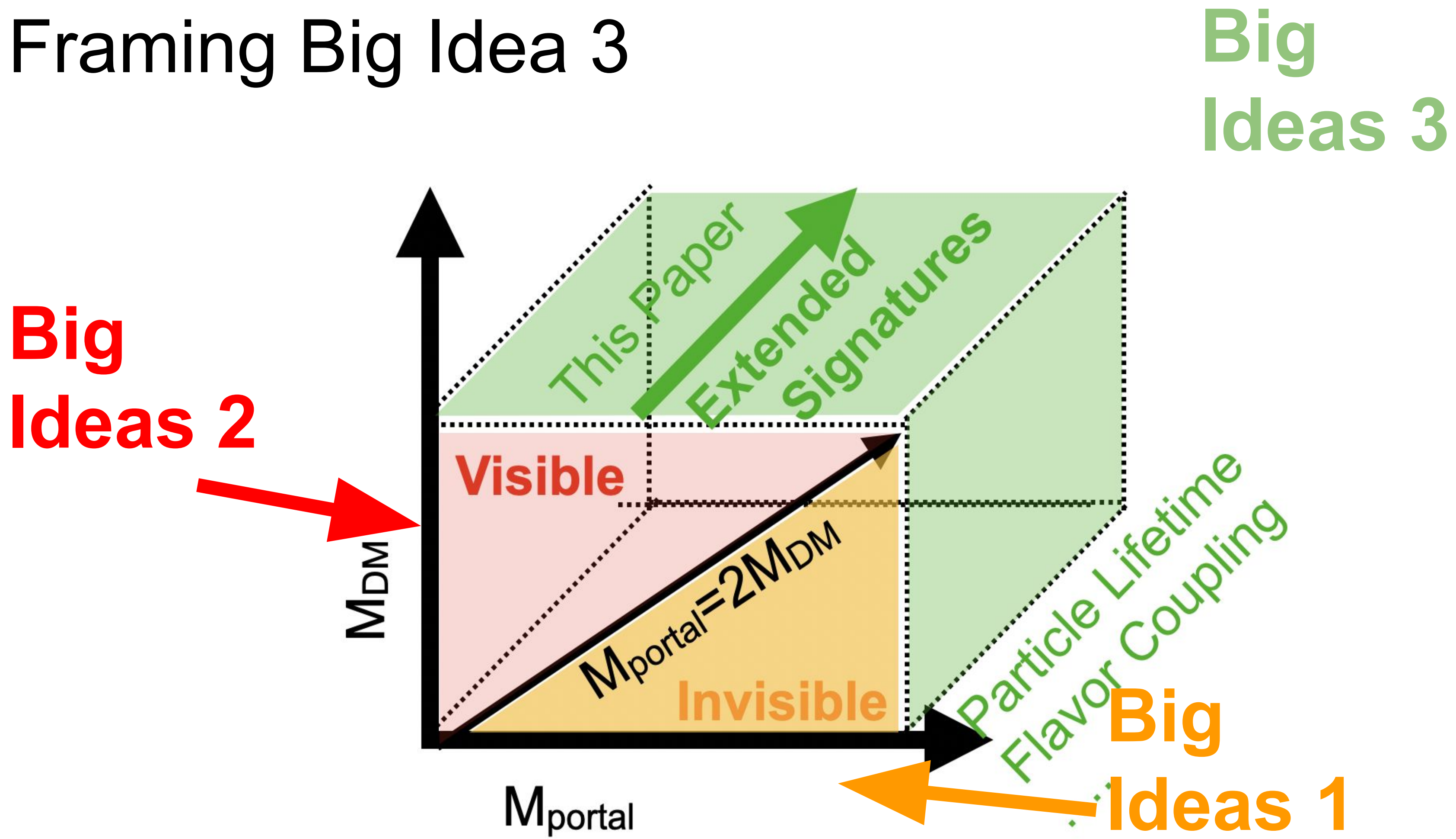



Visible Searches
Invisible Searches
2 TeV
1 GeV
0.01 GeV
Dark Matter Mass
LHC
Relic in some scenarios
Displaced
Long-Lived LHC
(Mathusla/Codex-b)
Neutrino
Prompt
Beam Dump
Long-lived
Beam Dump
1/Coupling(gq,ε)
Lifetime (cτ)
Relic
e+ e-
Beams
μ+μ-
beams
Missing
Energy
Missing
Momentum
1/Coupling(gq,ε)

Framing Big Idea 3



Framing Big Idea 3



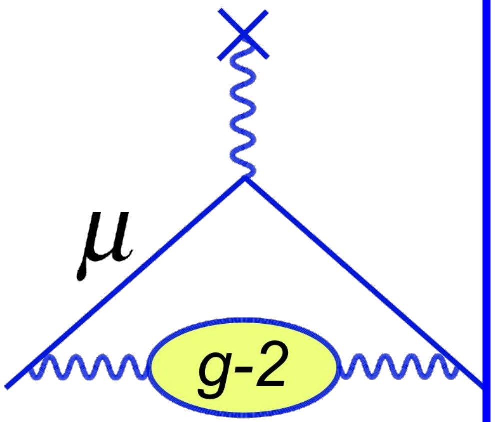
Flavor Violating axions

- One can envision the QCD axion as a dark matter candidate
  - Axion couplings are very sensitive in Kaon decays
  - Can probe a very high scale in axions (Dim 5)
    - Lead to a probe of the QCD Axion
- X

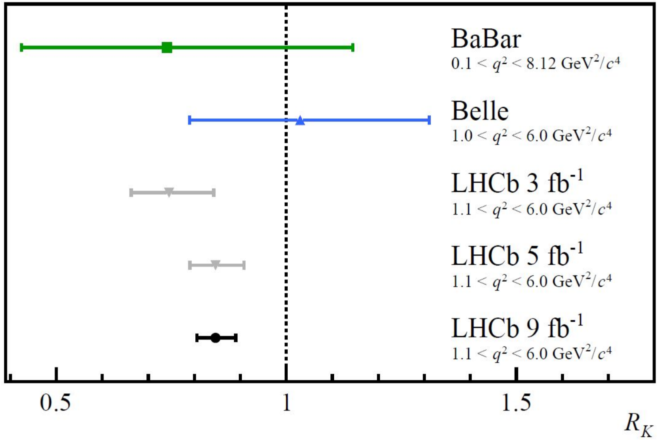
$$\mathcal{L}_{\text{ALP-photon}} = \frac{\alpha}{8\pi f_a} C_{\gamma\gamma}^{\text{eff}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$C_{\gamma\gamma}^{\text{eff}}(m_a) = N_1 + N_2 + \sum_q 6\, Q_q^2\, C_{qq}^A(\mu_0)\, B_1(\tau_q) + 2 \sum_\ell C_{\ell\ell}^A\, B_1(\tau_\ell)$$

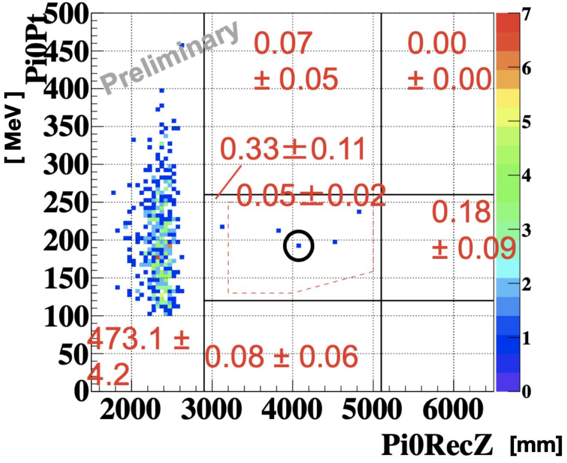
Big Idea 3: Data-driven Motivations



g-2 Excess



B-physics anomalies



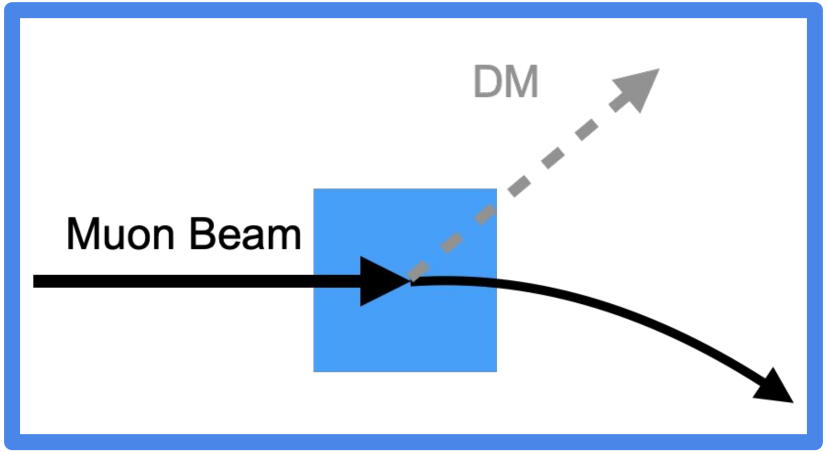
KOTO excess ….

Our Anomaly of choice!

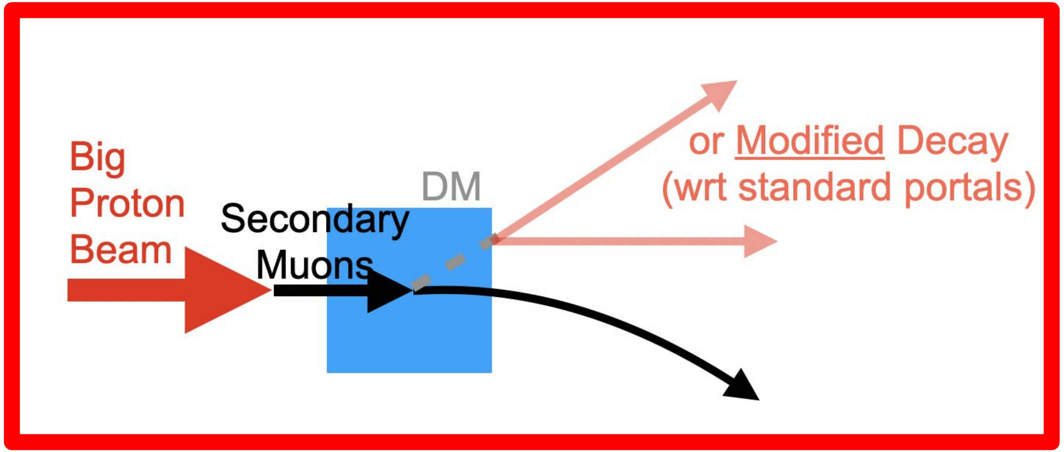
Recent list of many anomalies

How do you explain g-2$_\mu$ excess?

- Safest way to probe g-2$_\mu$ excess is with muons
- 3 Good sources of muons
  - Muon beams, secondary muons, or intense e^+e^- collider(Belle)



Muon+Missing Energy



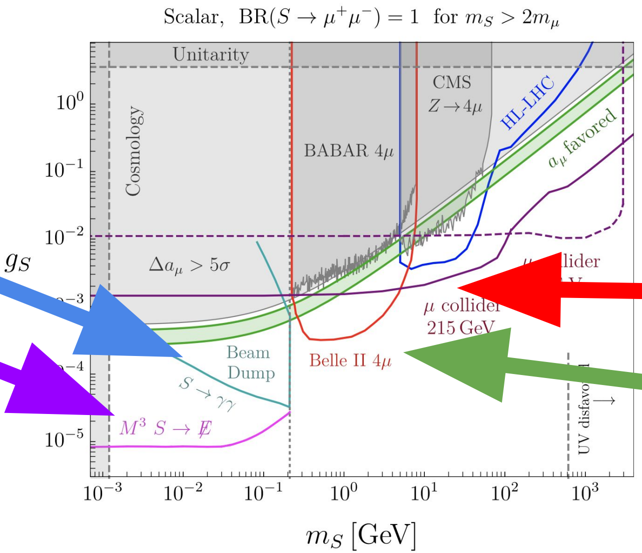
Beam Dumps and the like

How do you explain g-2 excess?

- In minimal scenario consider just a muon coupling
  - Can explain this through a scalar coupling

other Muon beams

M^3 experiment



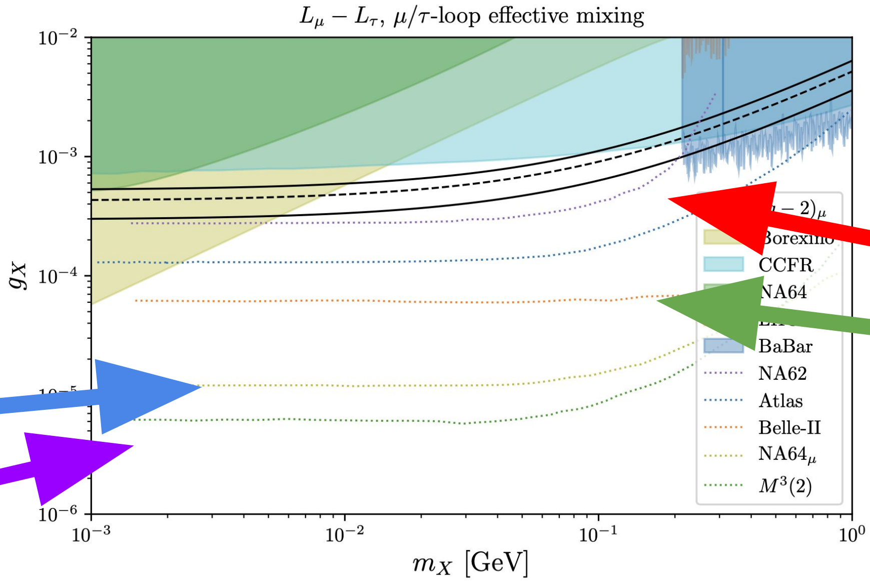
High Intensity

Belle-II 4μ

Secondary Muons From proton beams (Not yet shown)

How do you explain g-2 excess?

- With a more complicated scenario
  - Can consider an explanation with Lμ-Lτ



High Intensity

NA62 π^0

Belle-II

Muon Beams

NA64μ

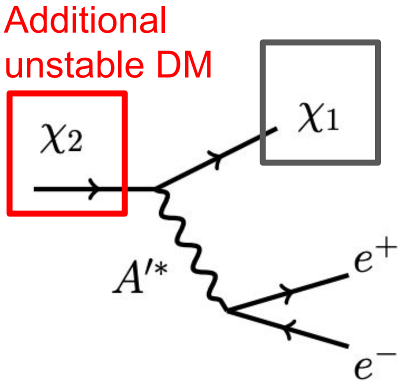
M^3 experiment

Other anomalies that we touched on

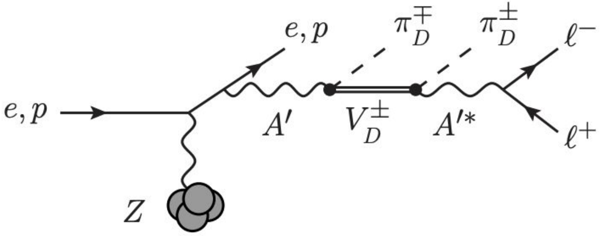
- $(g-2)_\mu$
- B Physics anomalies
  - RK and other flavor anomalies
- Xenon 1T
- MiniBoone Excess
- Beryllium
- Neutron lifetime anomaly
- KOTO

Discussion: Have we missed one? (W mass?)

Big Idea 3: Simple Theory Extensions

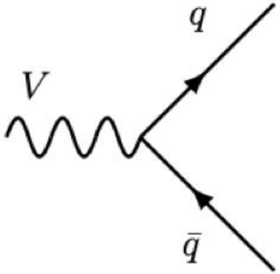


Inelastic DM
(Simple extension)



SIMP Processes
(3 π_D to 2 π_D)

$V \to \text{hadrons}$



Hadrophilic DM
To avoid existing bounds

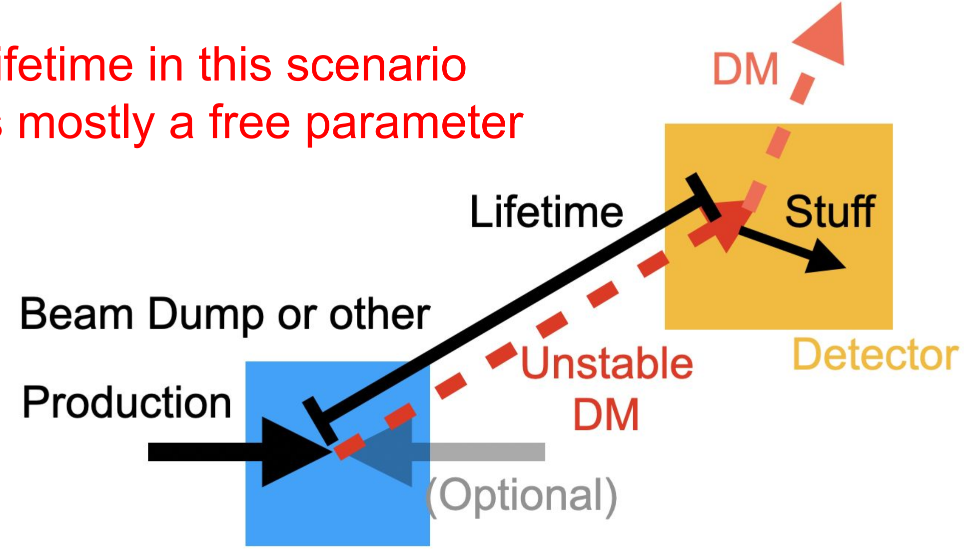
We highlight two models

Strategy is to consider simple well motivated models

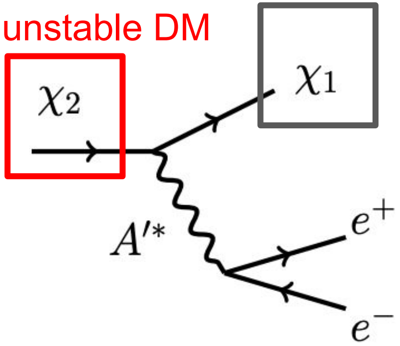
Inelastic DM: Example of a minimal extension

- Start with the usual portal
  - Add an unstable DM candidate

Lifetime in this scenario
Is mostly a free parameter



Additional
unstable DM

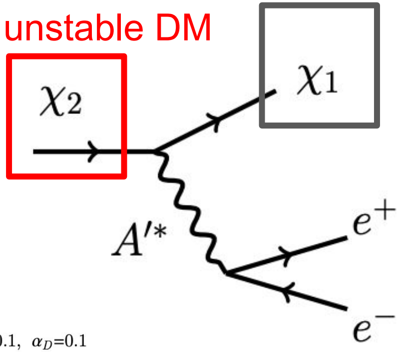


Inelastic DM generally does not change the relic bounds much, but adds new signatures

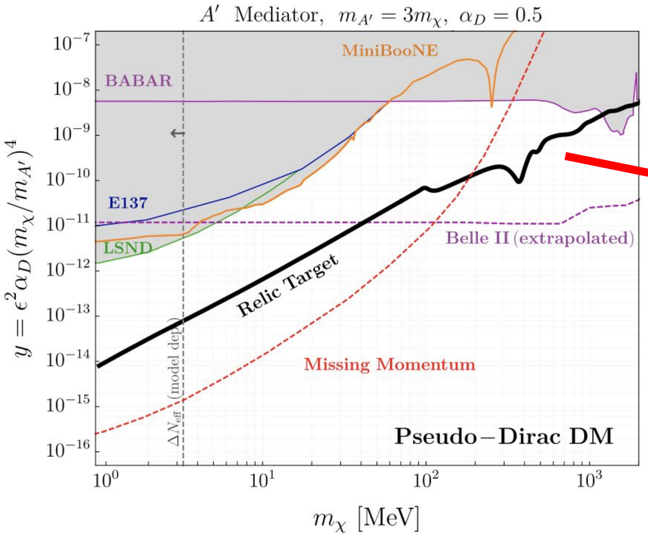
Inelastic DM: Example of a minimal extension

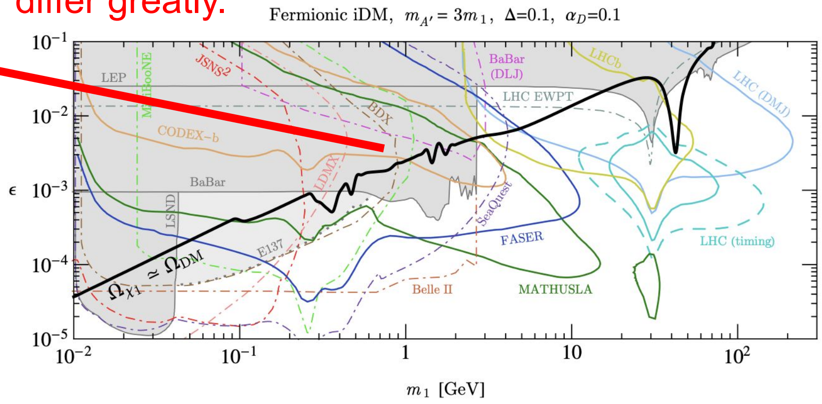
- By adding new signatures we make it easier to detect
  - Simple extension of the model changes bounds a lot
  - A case where many detectors can play a role

Additional unstable DM



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

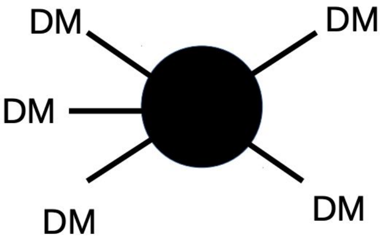


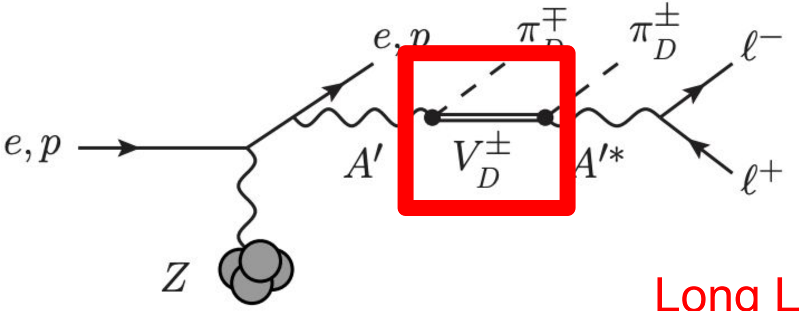


+Strong Bounds from LHC and Beam dump

SIMP DM model

- Strongly Interacting Massive Particle (SIMPs)
  - Dark sector has a SU(N_c) dark that explains DM
    - Yields Dark QCD particles (π_D,V_D) akin to (π,ω,φ,...)
  - Originally motivated by 3 to 2 processes, which gives relic
  - Naturally forces a DM scale of 100 MeV
  - Also motivates long lived signatures naturally from model





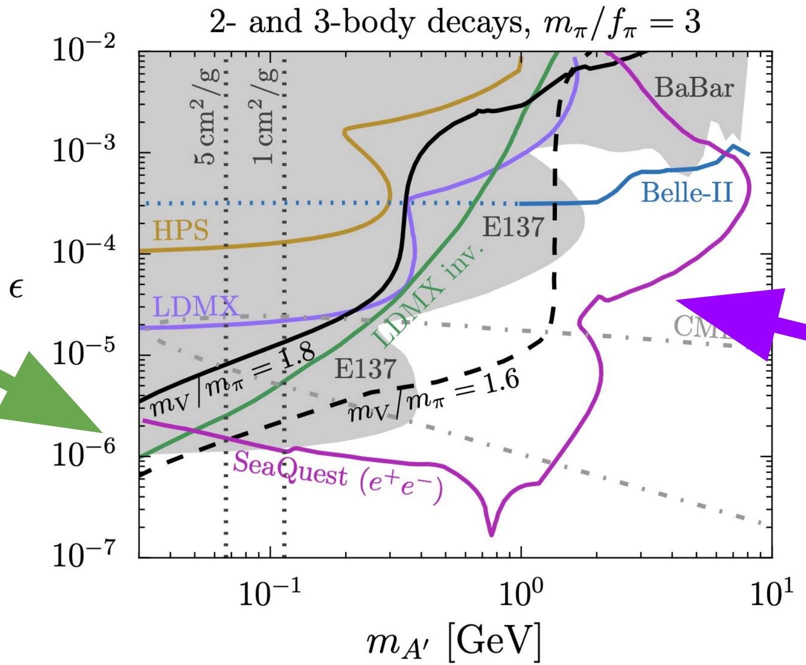
Key Target

Long Lived Signatures

SIMP DM model: Bounds

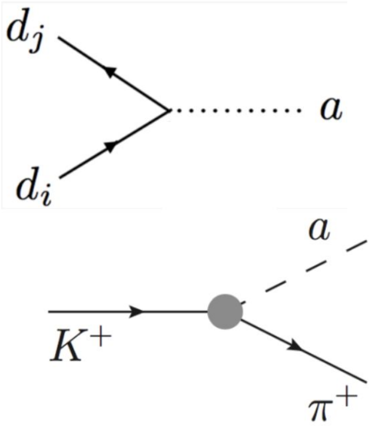
- Core feature is the long lifetime signature
  - Potentially exploration with LHC based searches can help

Invisible searches Are a backup



Long LIved Beam Dump Signatures thrive

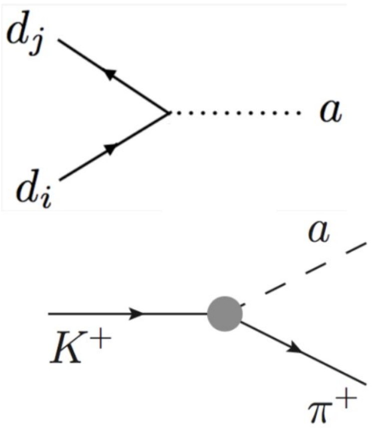
Big Idea 3: Motivated Theory Extensions



Flavor violating
Axions for strong CP

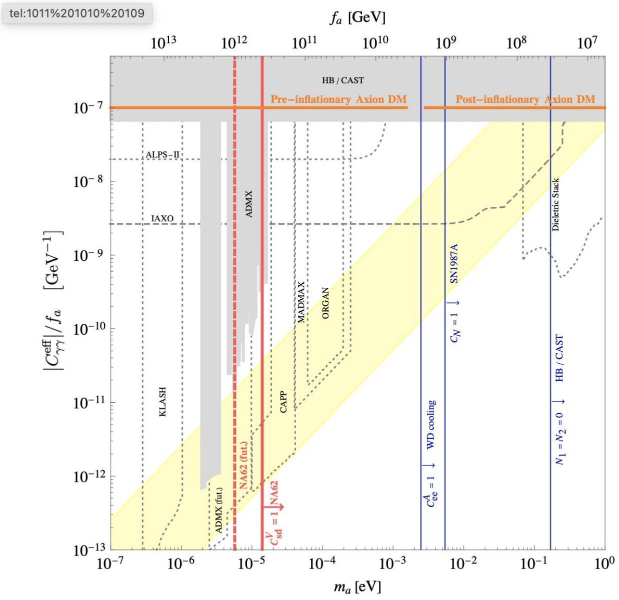
Can we explain core theory features with extended model

Big Idea 3: Motivated Theory Extensions



Flavor violating

Axions for strong CP



$$K \to \pi a$$

Measuring Kaon decays probes flavor structure

Can we explain core theory features with extended model

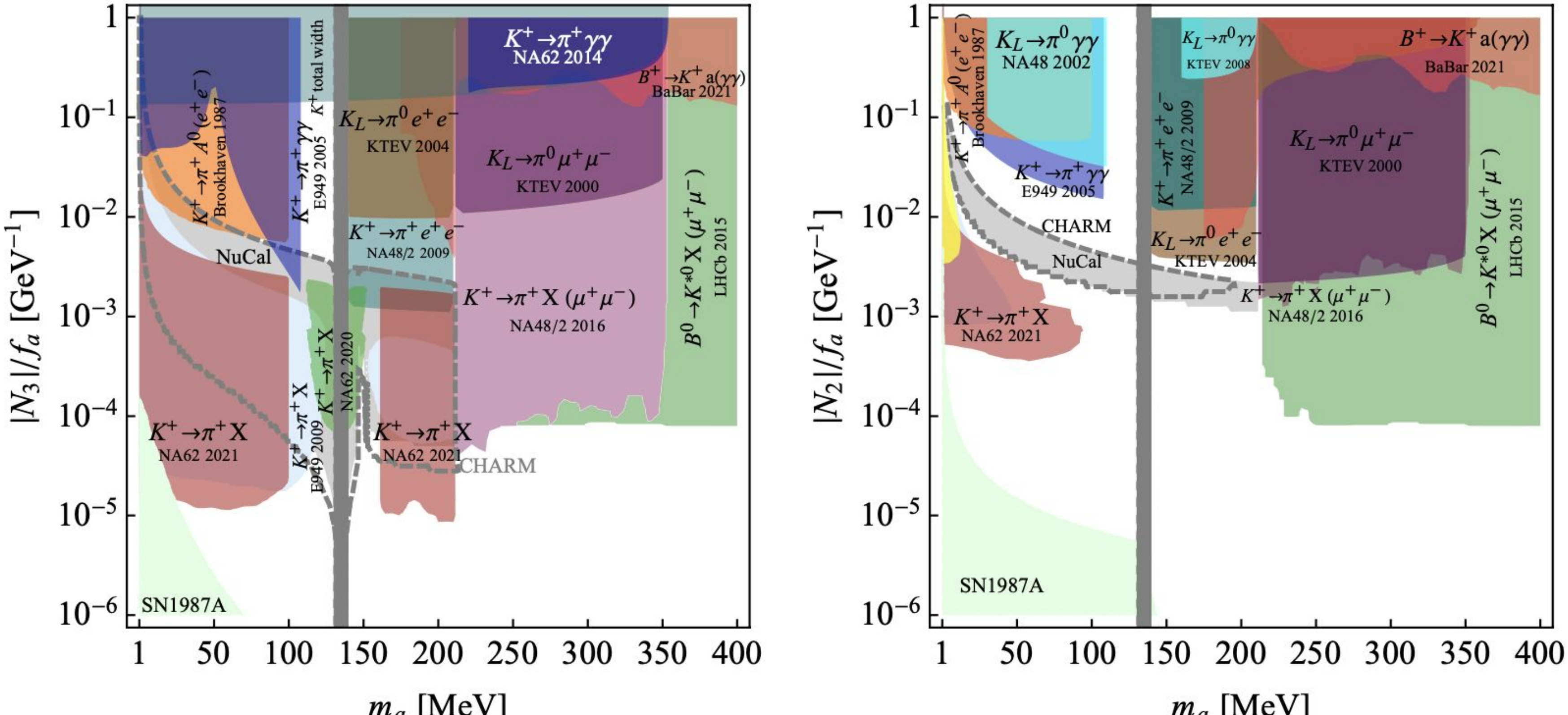
Flavor Violating axions

- One can envision the QCD axion as a dark matter candidate
  - Axion couplings are very sensitive in Kaon decays
  - Can probe a very high scale in axions (Dim 5)
    - Lead to a probe of the QCD Axion
- X

$$\mathcal{L}_{\text{ALP-photon}} = \frac{\alpha}{8\pi f_a} C_{\gamma\gamma}^{\text{eff}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$C_{\gamma\gamma}^{\text{eff}}(m_a) = N_1 + N_2 + \sum_q 6\, Q_q^2\, C_{qq}^A(\mu_0)\, B_1(\tau_q) + 2 \sum_\ell C_{\ell\ell}^A\, B_1(\tau_\ell)$$

More Axions



$|N_3|/f_a$ [GeV^{-1}]
$K^+\to\pi^+\gamma\gamma$ NA62 2014
$B^+\to K^+ a(\gamma\gamma)$ BaBar 2021
K^+ total width
$K^+\to\pi^+ A^0(e^+e^-)$ Brookhaven 1987
$K^+\to\pi^+\gamma\gamma$ E949 2005
$K_L\to\pi^0 e^+e^-$ KTEV 2004
$K_L\to\pi^0\mu^+\mu^-$ KTEV 2000
$K^+\to\pi^+e^+e^-$ NA48/2 2009
NuCal
$K^+\to\pi^+$ X $(\mu^+\mu^-)$ NA48/2 2016
$B^0\to K^{*0}$ X $(\mu^+\mu^-)$ LHCb 2015
$K^+\to\pi^+$X NA62 2020
$K^+\to\pi^+$X E949 2009
$K^+\to\pi^+$X NA62 2021
$K^+\to\pi^+$X NA62 2021
CHARM
SN1987A
m_a [MeV]
$|N_2|/f_a$ [GeV^{-1}]
$K_L\to\pi^0\gamma\gamma$ NA48 2002
$K_L\to\pi^0\gamma\gamma$ KTEV 2008
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$B^0\to K^{*0}$ X $(\mu^+\mu^-)$ LHCb 2015
$K^+\to\pi^+$X NA62 2021
SN1987A
m_a [MeV]

What needs to be done

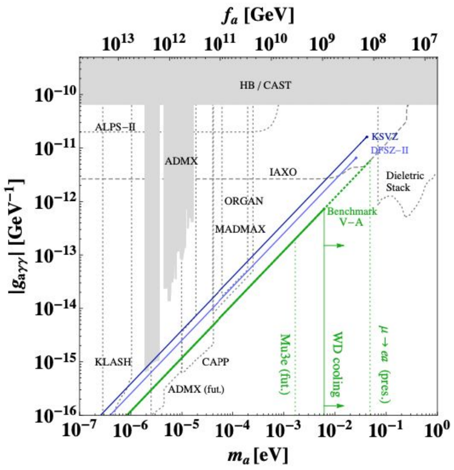
- Add Mike’s messaging suggestions:
  - exploiting capabilities of existing large multi-purpose detectors + near-future upgrades;
  - Investing in specialized small-scale experiments + Investing in facilities that can deliver high-intensity beams;
  - Supporting the theory community to further develop theory of dark sector
- Additional Suggestions from Stefania
  - Is there a way to highlight more BSM physics?
  - Highlight secondary muon beams

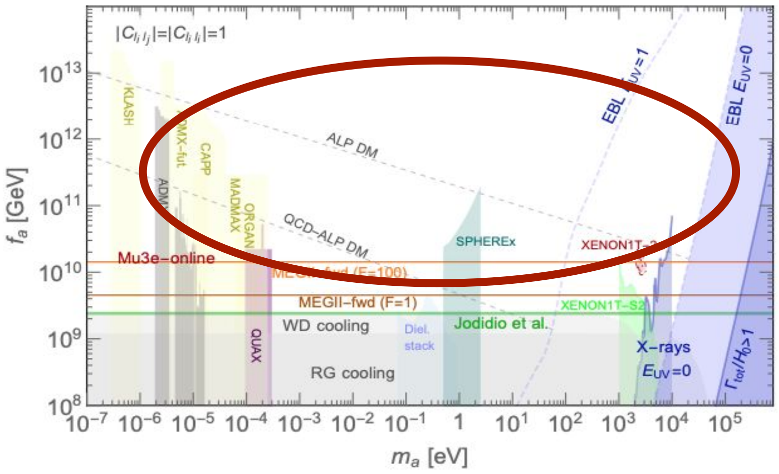
Backup

Lepton flavor violating ALP as dark matter candidate

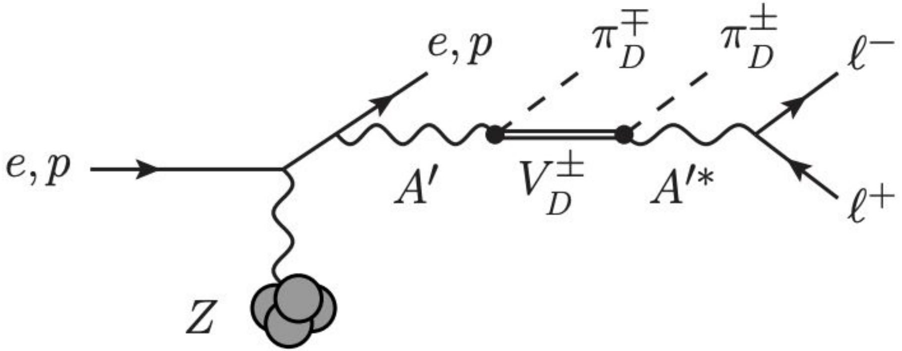
- If light enough ALP can be a DM candidate
  - If flavor violating couplings, can probe very high scales
  - For instance, for LFV couplings $\mu \to e\, a$
  - Could be the QCD axion

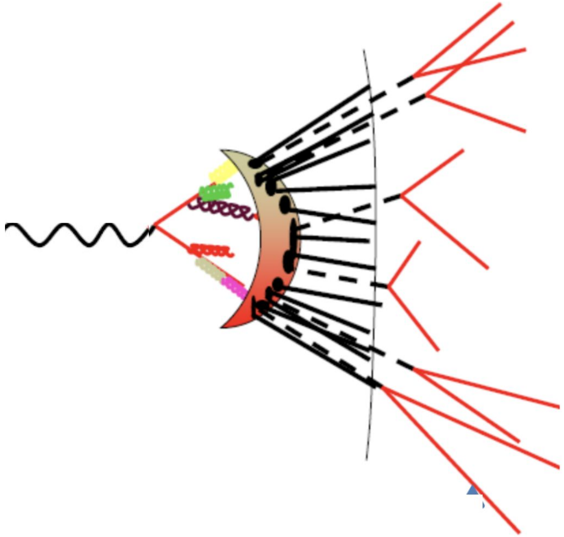
2006.04795





Big Idea 3: Theory Motivations





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

Big Idea 3

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($H\to\phi\phi$ ~10^{-2})]?	Dark Higgssstrahlung (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

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.

Points from Stefania

1. Can we highlight more theory BSM anomalies

2. Point out that SIMPs introduce a scale of 100 MeV naturally

3. Make a stronger statement about iDM

5. SIMP Naturally predct LLPs

6. Highlight secondary muon beams from future proton beam dumps

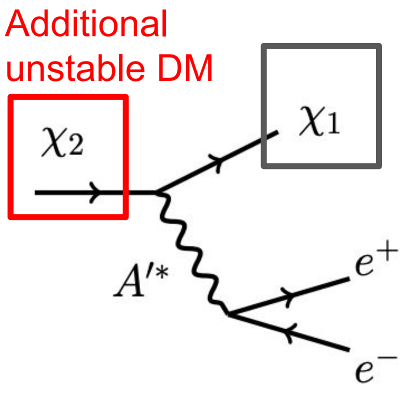
Points from Mike

* exploiting the capabilities of existing large multi-purpose detectors, including near-future upgrades;

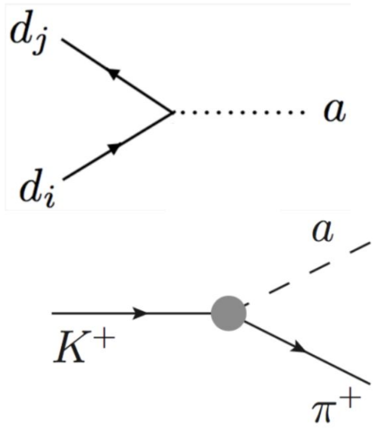
* investing in specialized small-scale experiments, and in facilities that can deliver high-intensity beams;

* and supporting the theory community to further develop the theory of dark-sector physics.

Big Idea 3: Theory Motivations

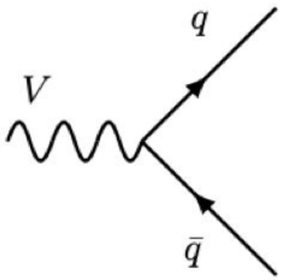


Inelastic DM
(Simple
extension)



Flavor violating
Axions for strong CP

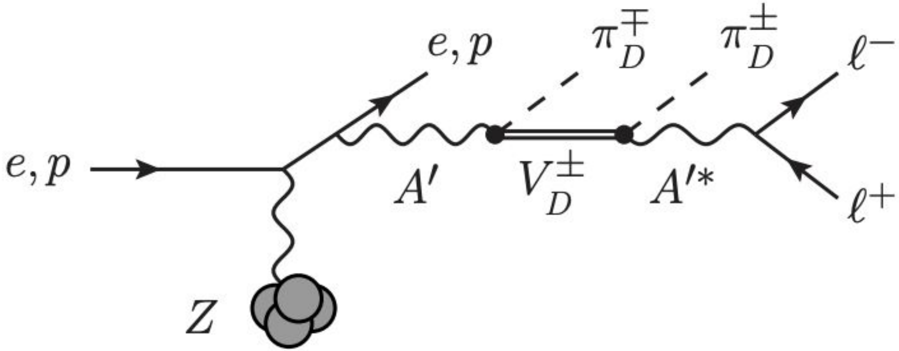
$V \to$ hadrons

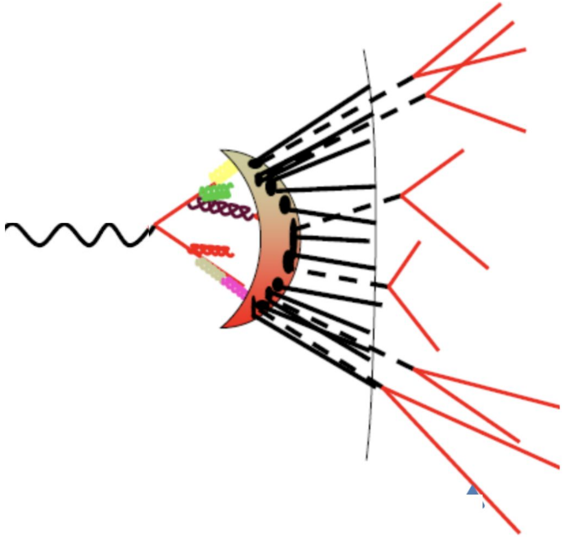


Hadrophilic DM
To avoid existing bounds

Additionally theoretical motivations to make things more complicated

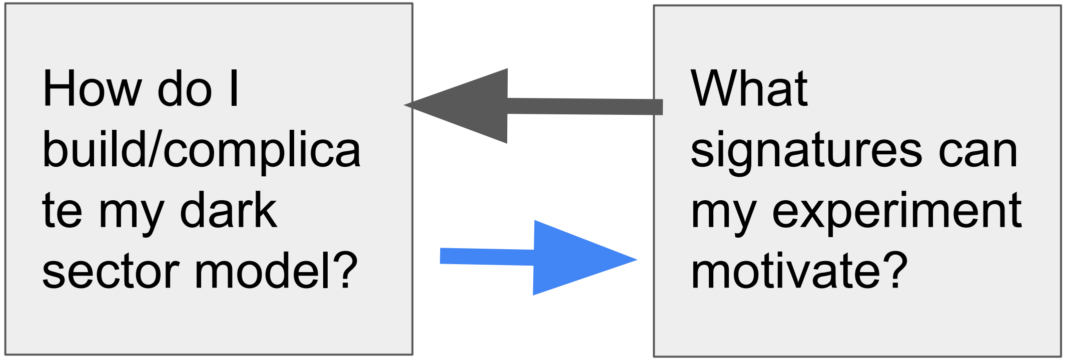
Big Idea 3: Theory Motivations





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

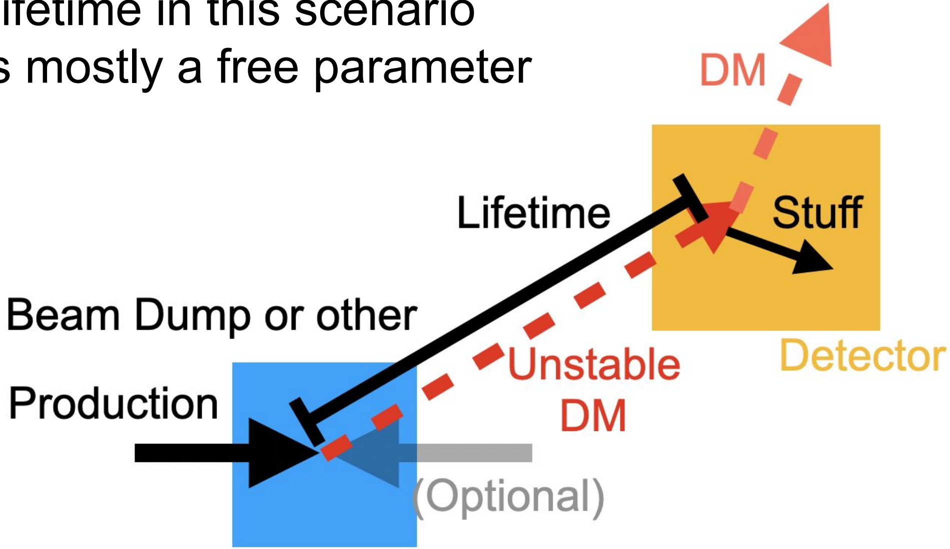
How do we prepare ourselves for newer, more complicated models?

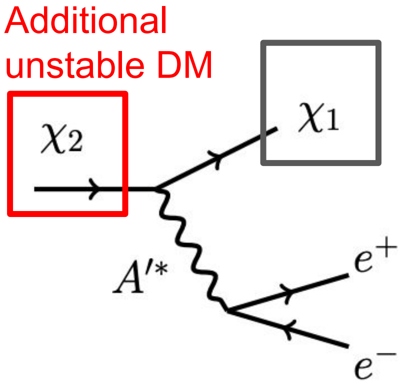
Discussion: What do we define as complete or adequate signature coverage?

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



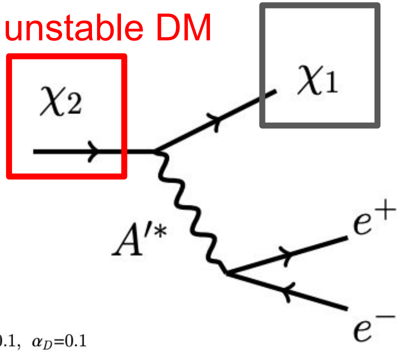


Inelastic DM generally does not change the relic bounds, but adds new signatures

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



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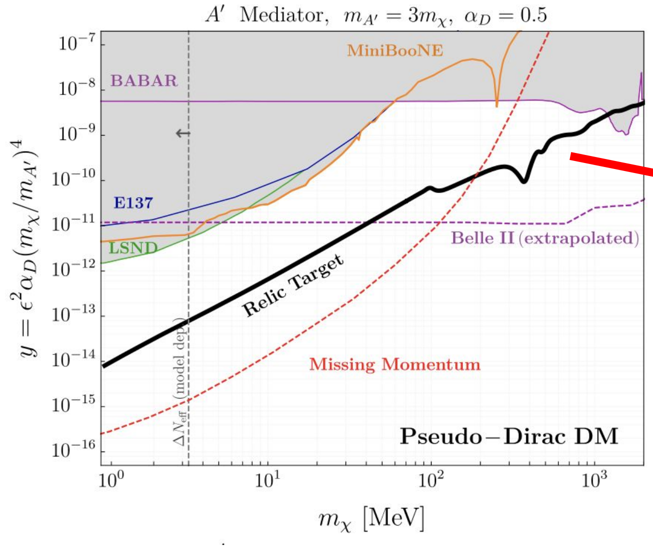
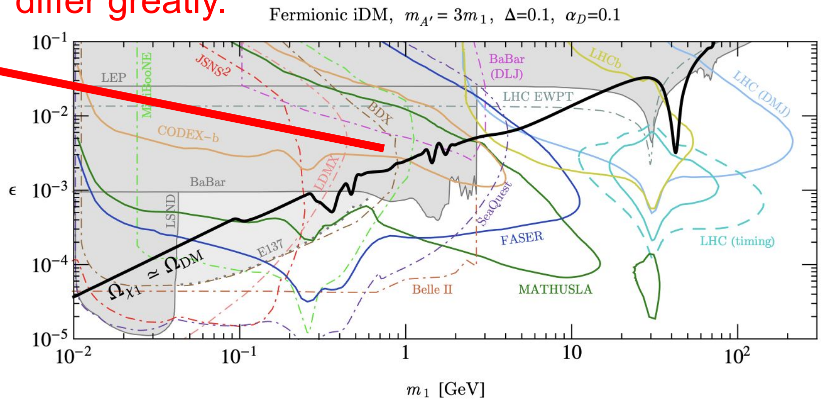




Long Lived particles as an extension of dark sector

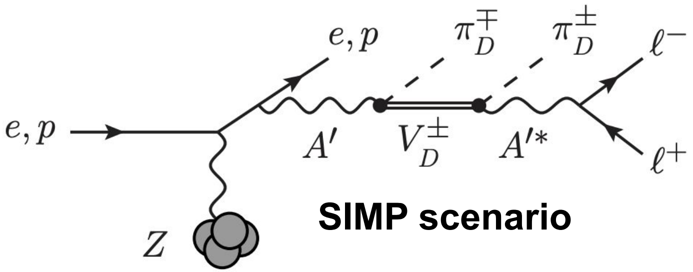
- Adding an unstable DM is a simple extension to dark sector
  - Leads to a wealth of other new final states
- More flexibility of signatures than just portals with small couplings

Related LOIs that cover this

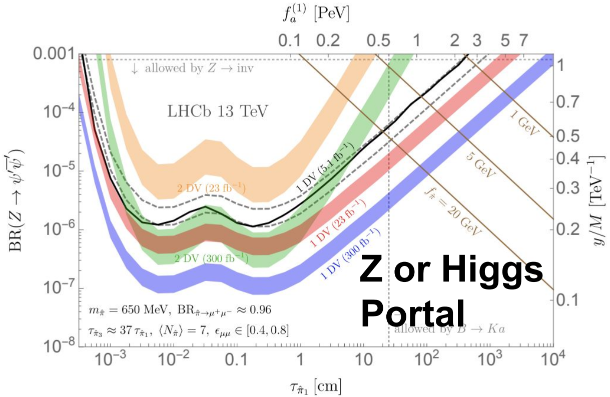
- BDF/SHiP facility AF5_AF0-RF6_RF0-163
- LLP at Energy Frontier EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201
- LLP at FCC-ee EF8_EF9-RF6_RF0_Rebeca_Gonzalez_Suarez-147
- New light particles at ILC main beam dump EF9_EF0-RF0_RF6-086.
- Codex-b EF9_EF0-RF6_RF0-034
- Electron fixed target spectrometer :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

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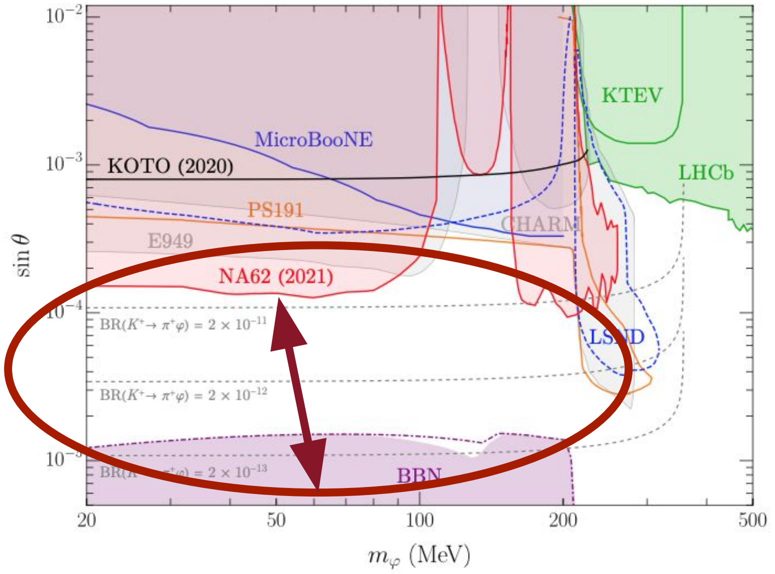

Bridge the gap with next generation Kaon experiments

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 $\mu \to e\, a$
  - Could be the QCD axion

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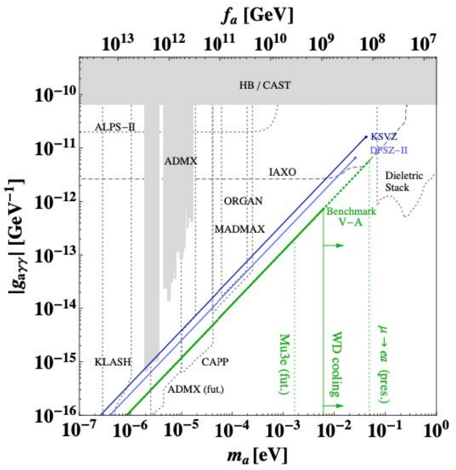

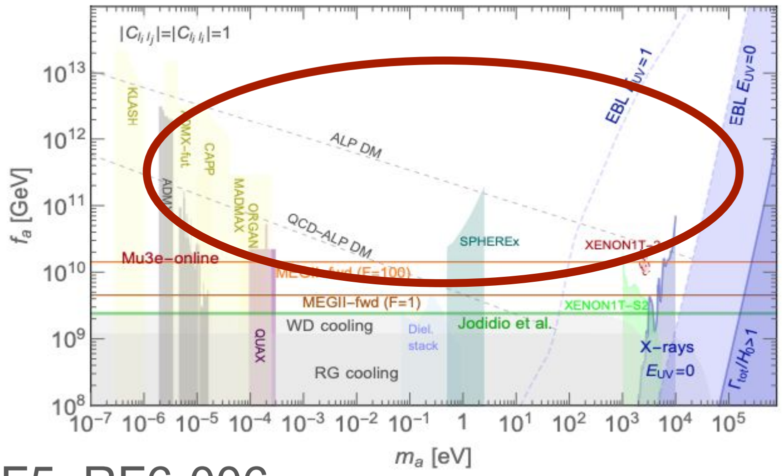

LOI Physics potential with MegII-fwd — RF5_RF6-006

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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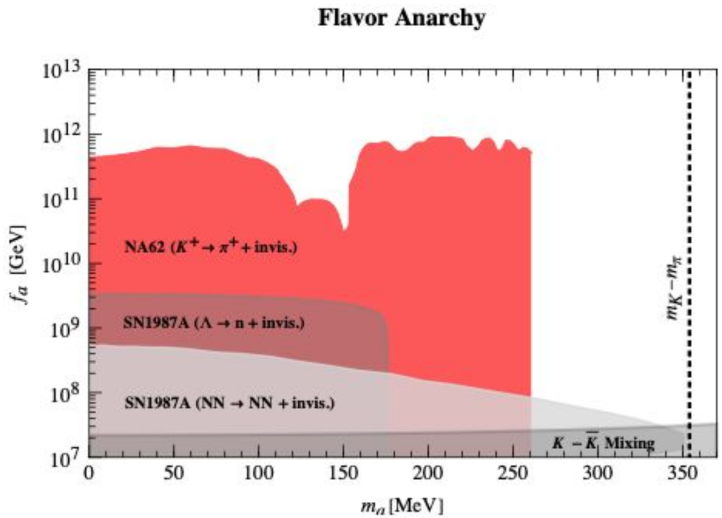
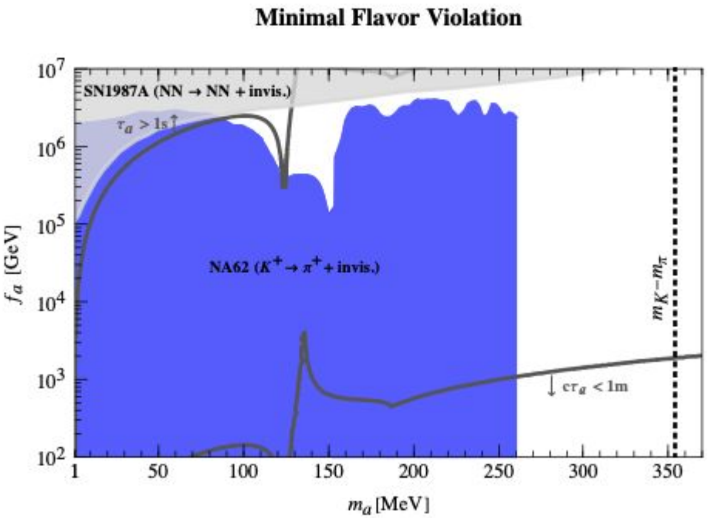
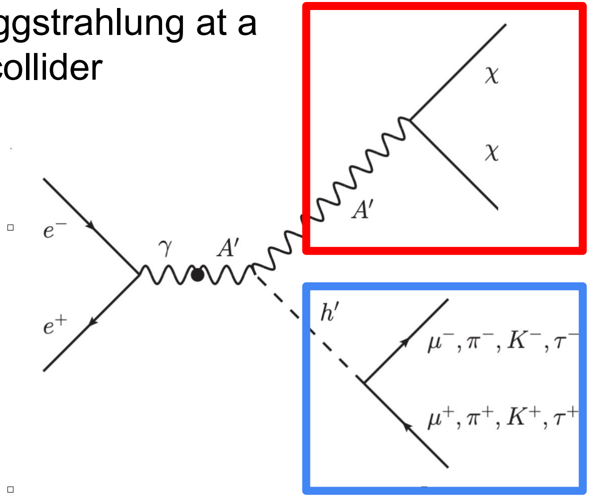




Adding Both a Dark Higgs and a Dark Photon

- 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

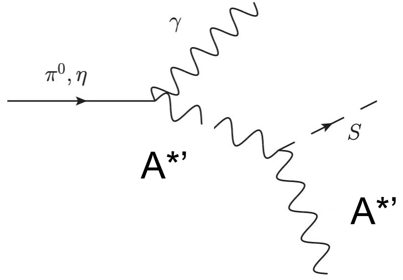
Dark higgstrahlung at a lepton collider



Dark Photon that can decay either visibly or *invisibly*

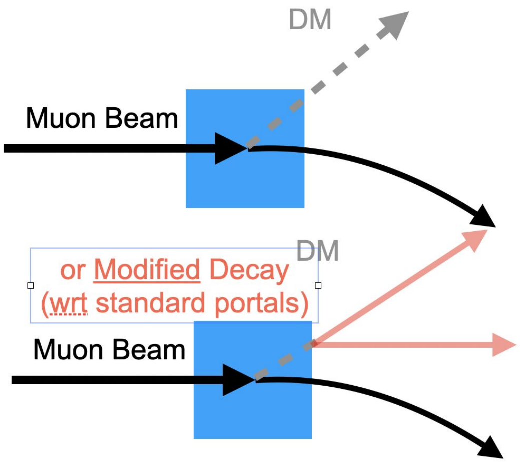
Dark Higgs with yukawa enhanced decays

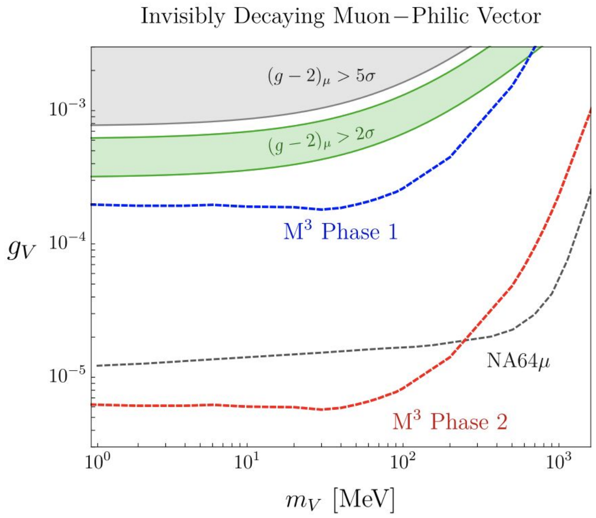
Dark higgstrahlung in meson decays



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

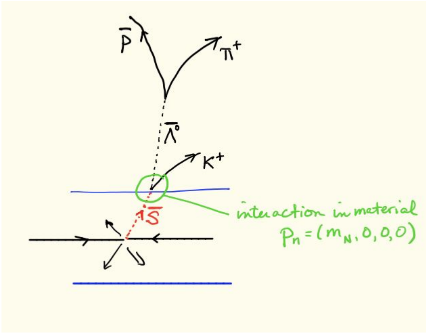
- A number of LOIs focus on modified models to explain g-2
- Additionally there is interest in models that are motivated by heavy flavor
- Another, motivated modification of the couplings also exist
  - Baryophilic
  - Hadrophilic
  - …

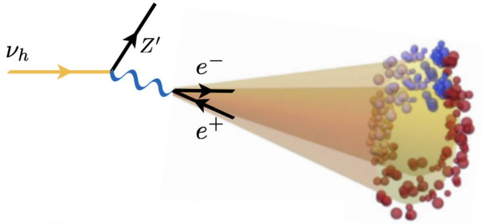
Related LOIs

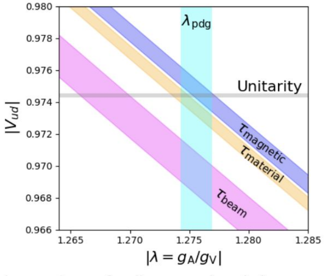
- Light mediators and flavor anomalies (theory) RF6_RF1_Alakabha_Datta-01
- LFV at FCCee RF6_RF4-EF3_EF4_Mogens_Dam-119

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**: ΔB = 2 RF4_RF6-NF3_NF10-TF2_TF5_Joshua_Barrow-105
  - **LOI:** Sterile neutrons at ORNL and ESS RF6_RF3_Joshua_Barrow-115



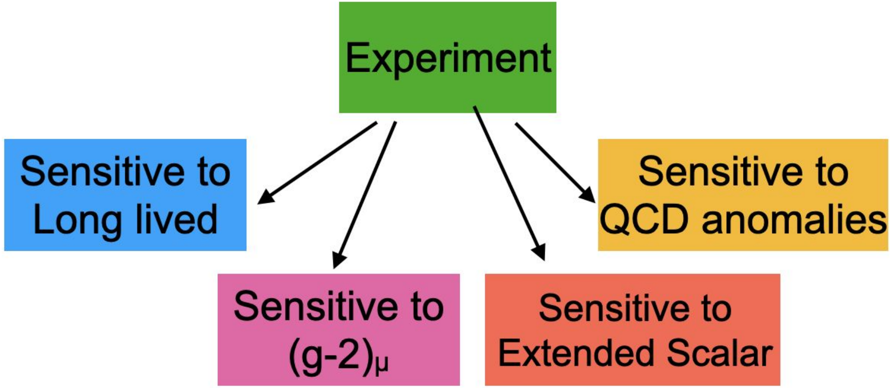




Experimental Signatures (and Motivations)

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

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Electron : LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104

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Enhanced by Extended Scalar/ Heavy Flavor

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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

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Eta: Eta-Eta’ factories RF6_RF2_Sean_Tulin-117

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 : ILC beam dump: EF9_EF0-RF0_RF6-086

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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

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Enhanced by Extended Scalar/ Heavy Flavor

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

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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

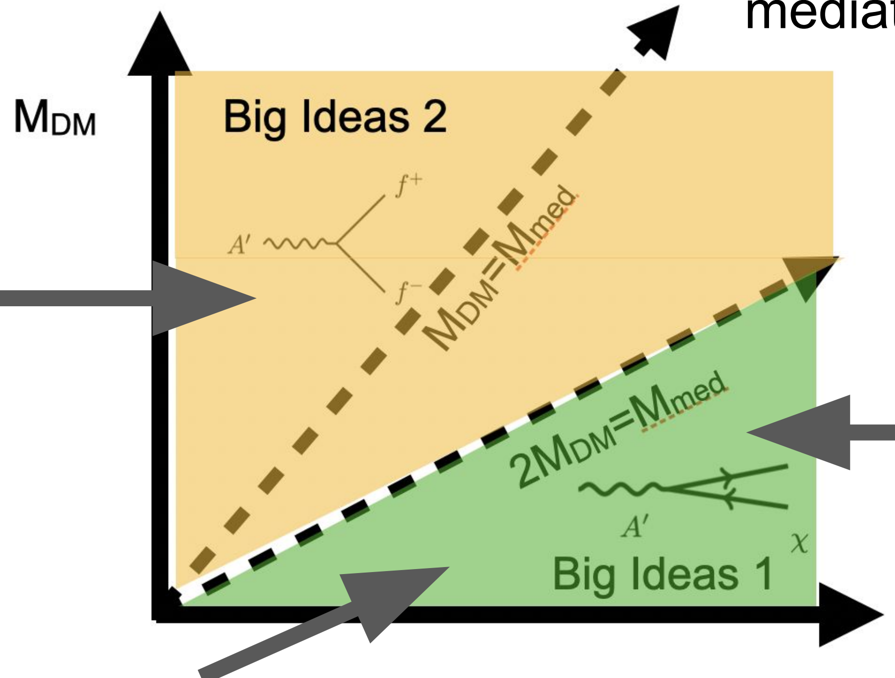
Solicited whitepapers due by April 15th, 2022

Thanks!

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



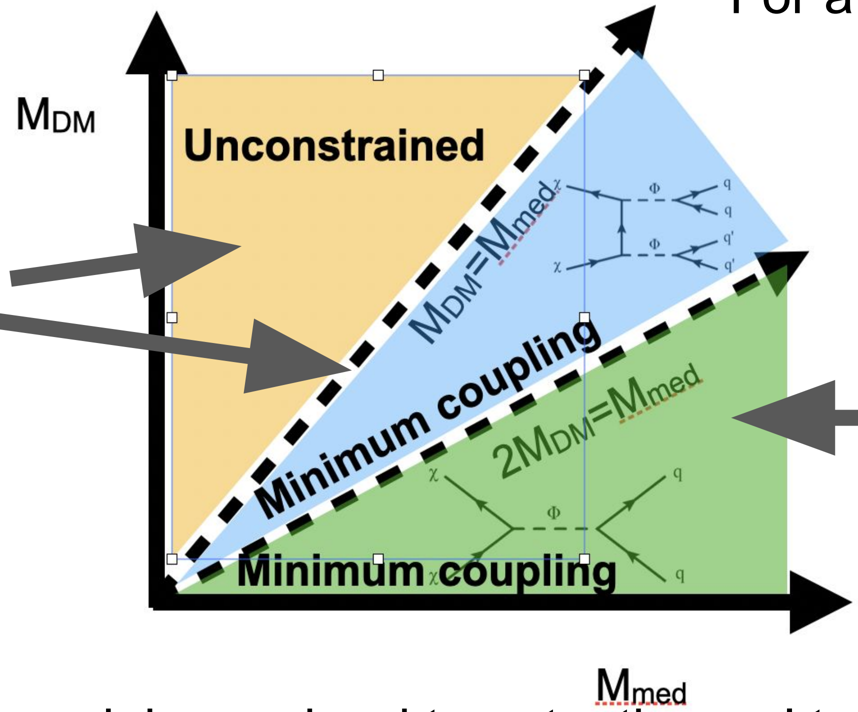
Big idea 1
Over here we look for invisible decays or DM scatters

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



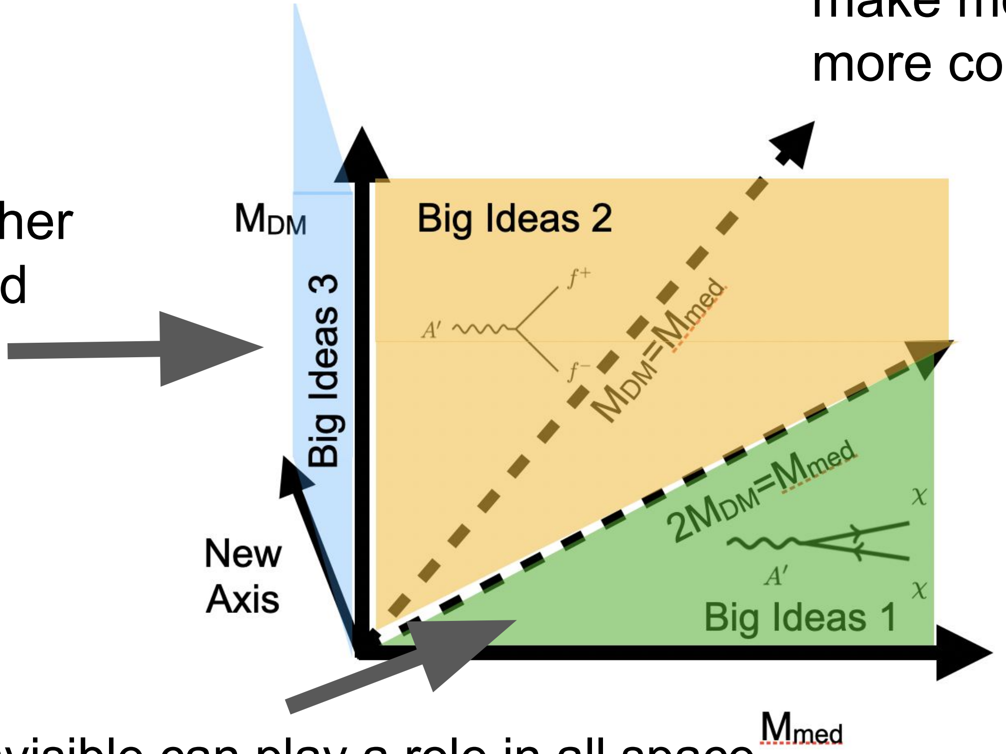
Big idea 1
Minimum coupling present (usually take ⅓=M_{DM}/M_{med}

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