RF6 — Dark Sector Studies at High Intensities
Big Idea 2 Solicited Whitepaper Planning Meeting

Brian Batell (Pitt) and Christopher Hearty (UBC)

January 27, 2022

RF6 Organizational Plans for Whitepapers

Letters of interest (LOIs)

- Community driven — LOIs are informal documents to express interests/proposals for projects/studies as part of the Snowmass exercise
- LOIs were due before the Snowmass pause; we will review RF6 LOIs below.

Contributed whitepapers — due March 15. 2022

- Community driven — anyone interested in dark sector physics can contribute a whitepaper on their topic of interest (does not require LOI)
- Contributed whitepapers will inform the RF6 "Big Ideas" solicited white papers and ultimately the RF6 final repor

4 Solicited "Big Ideas" whitepapers — due April 15. 2022

- Solicited by RF6 conveners (Stefania Gori, Mike Williams) to synthesize the motivations for dark sectors and associated physics opportunities at high intensity experiments
- Contributed whitepapers and direct input from the community (all of you!), along with other recent developments in in the field, will inform these solicited whitepapers
- These solicited whitepapers will be used to inform and guide the final RF6 final report

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/1R0O23wjGLxRzsc93a4pJlFn17yW9TCTq
(in our google drive folder, https://drive.google.com/drive/folders/1sMn1cWl2ddqzu46Yi4TcMIX7Cm2GUxO_)

Deadline: April 15

Today's focus

1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.
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Deadline: April 15

From N. Toro

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] <u>m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}]</u> m_χ vs. m_A [α_D=0.5, y=y_{fo}] ***Millicharge m vs. q***	<u>$m_{A'}$ vs. ϵ [decay-mode agnostic]</u> ***$m_{A'}$ 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. 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 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

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. <u>Underline=CV benchmarks that were not used in BRN</u>

From N.Toro

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Big Idea 2

Proposed Outline of the Whitepaper

- Executive Summary and Framing ~ 3-5 pages
- Big Idea 2 Motivation and Scope ~ 3 pages
- Experimental approaches ~ 3-5 pages
- Benchmark models and broader implications~ 5-10 pages
  - 5-7 benchmark parameter planes?

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.

- Hits the main points: excellent experimental opportunities to detect mediator through visible decays, and determine its couplings to SM particles
- For discussion: more emphasis on "Minimal Portals" and effort to connect with bigger motivations?

Broad Motivations Underlying Big Idea 2

- Effective field theory logic and renormalizable portals

$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Vector Portal
$(A\,S + \lambda\,S^2)\,H^\dagger H$	Higgs Portal
$yNLH$	Neutrino portal

- There are other interesting options for the mediator:
  - Higher dimension portals, e.g. axion-like particle, flavor-specific scalar, …
  - Anomaly free (e.g., $B-L$, $L_\mu - L_\tau$ …) and anomalous (B, …) gauge bosons
  - In some cases, these mediators come with additional motivations (e.g., neutrino masses, heavy QCD axion, solutions to anomalies, …)

For discussion: beyond the three renormalizable portals, where do these other cases fit best? Big Idea 1 (minimal portals), Big Idea 3 (new flavors, rich dark sectors), or both?

Broad Motivations Underlying Big Idea 2

- The "Big Questions" in particle physics
  - Dark Matter - portal couplings can mediate interactions between dark and visible matter
  - Neutrino Masses - new neutral fermions interacting through the neutrino portal can generate small neutrino masses via the seesaw mechanism
  - Implications for other puzzles (baryogenesis, hierarchy problem, …)
- Experimental anomalies
  - Muon g-2, flavor anomalies, MiniBooNE, Xenon1T, …

For discussion: How to best make the connections between minimal portal scenarios and these underlying motivations?

— e.g., Lack of sharp dark matter thermal targets in mass — coupling planes

Big Idea 2 — Scope

- Minimal portal interactions — what do we mean?
  - Three renormalizable portals
  - A selection of simple, motivated higher dimensional portals (e.g., ALP)
  - As mentioned other options *may* fall within Big Idea 1, Big Idea 3, or both.

- Typically assume a single, isolated mediator with a single portal coupling
  - Assume a single coupling dominates
  - No additional structure. In particular, other dark sector states are assumed to be heavier than the mediator, so that its production and decay are governed entirely by the portal coupling
  - Parameter space is simple: mass - coupling plane

Big Idea 2 — Scope

- Narrow focus to $\sim$ MeV $- 10$ GeV mass range
  - This is the domain where high-intensity experiments shine

- Which experiments fall within our scope?
  - To first approximation, anything that can cover new territory in our parameter spaces

For discussion: what about LHC main detectors, future energy frontier colliders?

LOIs & Experimental Approaches

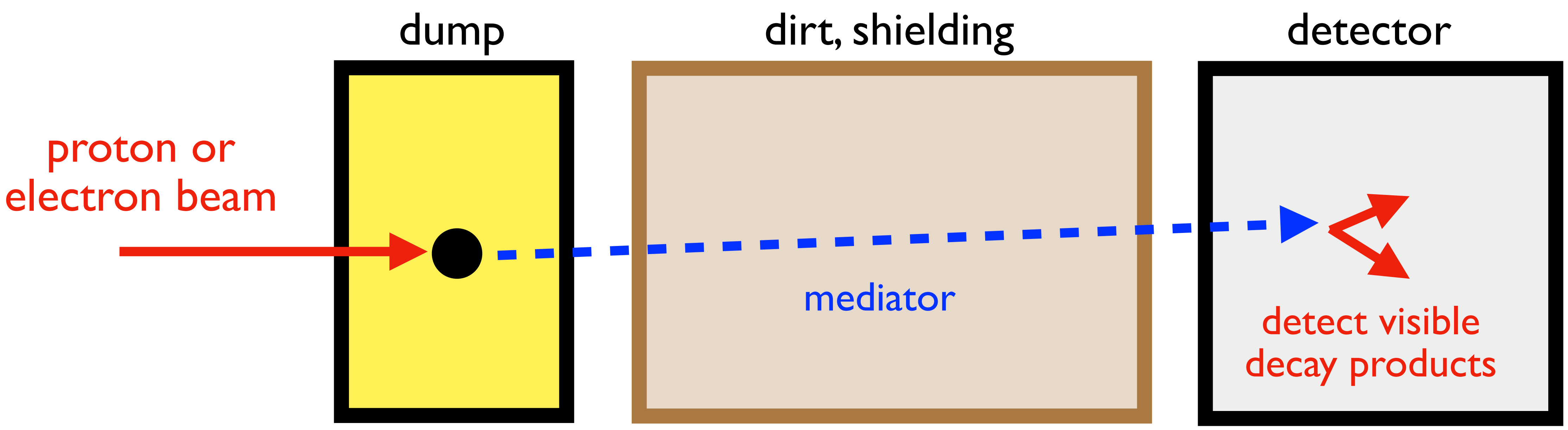
- We have collected the LOIs which overlap with Big Idea 2 scope.
- We will also highlight some associated classes of experiments (note this is not an exhaustive survey!)
- See backup slides for additional LOIs which may fall outside Big Idea 2 scope.

LOIs on Beam Dumps

- Proton beam dumps
  - — BDF/SHiP facility AF5_AF0-RF6_RF0-163
  - — 1GeV proton beam dump at Fermilab RF6_RF0-NF2_NF3-AF2_AF5-099
  - —10GeV proton beam dump at Fermilab RF6_RF0-NF3_NF0-AF5_AF0-084
  - — Dark Sector Studies With Neutrino Beams NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148
  - — HNLs at Accelerator Neutrino Experiments NF2_NF3-RF6_RF0_Athanasios_Hatzikoutelis-160
  - — ALPs at neutrino experiments NF3_NF0-RF6_RF0_Doojin_Kim-028

- Electron beam dumps
  - — BDX RF6_RF0_BDX-076
  - — New light particles at ILC main beam dump EF9_EF0-RF0_RF6-086.

Beam Dumps



- Produce mediator via rare meson decays, bremsstrahlung, secondary collisions (e.g. photon induced Primakoff process)
- Detect visible decay products of mediator
- Leverage relatively higher intensities, longer baselines to probe long mediator lifetimes, small couplings

LOIs on Meson Factories

- e^+e^-, B factories
  - — Dark sectors at Belle II RF6_RF0-028
  - — LLP at Belle II RF6_RF0_Torben_Ferber-020
- Kaon factories
  - — Dark Sectors at NA62 & KLEVER — RF6_RF0-011
  - — Dark Sectors at KOTO — RF6_RF0_KOTO-050
  - — Dark sectors at kaon factories (theory) — RF6_RF0-034
- η, η' factories
  - — Redtop RF2_RF6-IF6_IF3_REDTOP_Collaboration_-_new-083
  - — Eta-Eta' factories RF6_RF2_Sean_Tulin-117

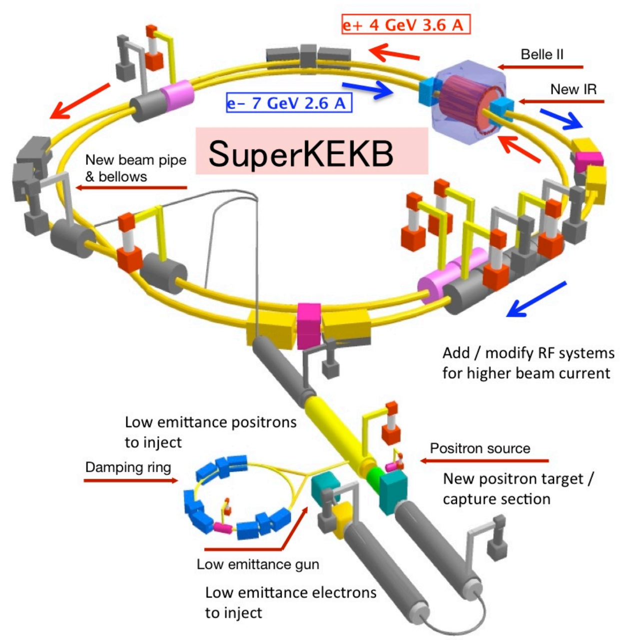
B factories (Belle II)

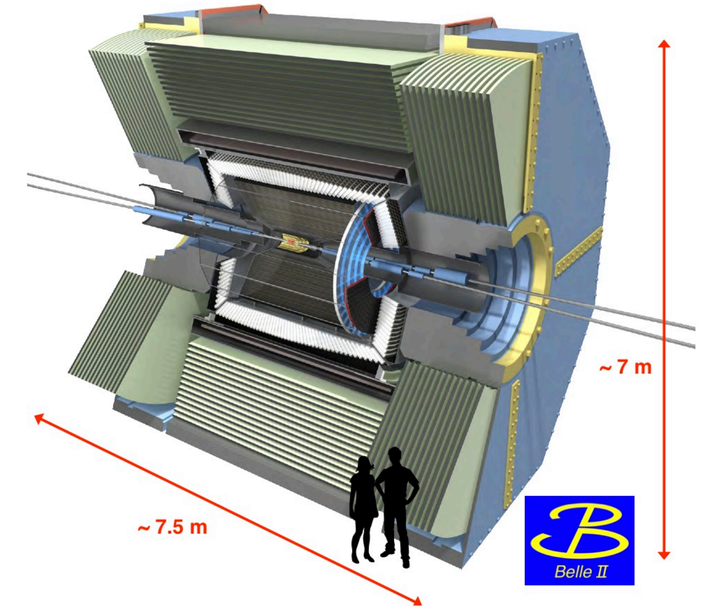
- Medium energy ($E_{\rm CM} \sim 10.5\,{\rm GeV}$), high luminosity e^+e^- collider

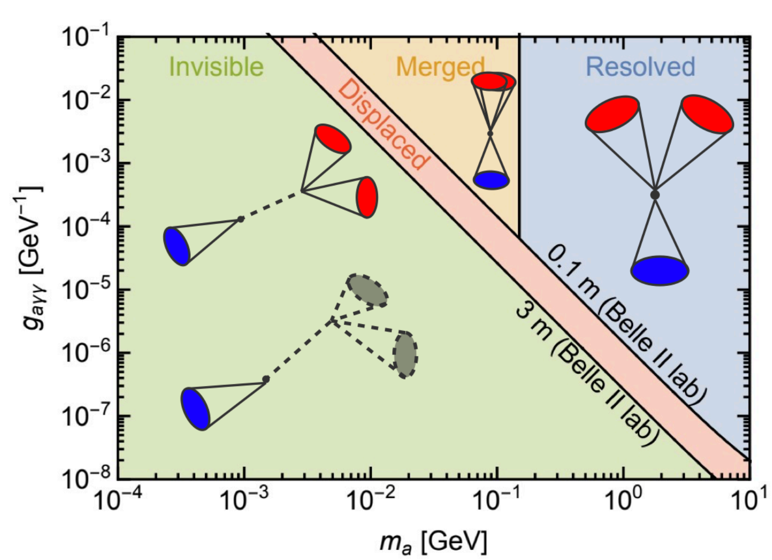
- Hermetic detector, full reconstruction of event kinematics

- Direct production of mediator through electron, photon couplings, or through B meson decays

- Sensitive to a variety of signatures of prompt, displaced, and long-lived mediators







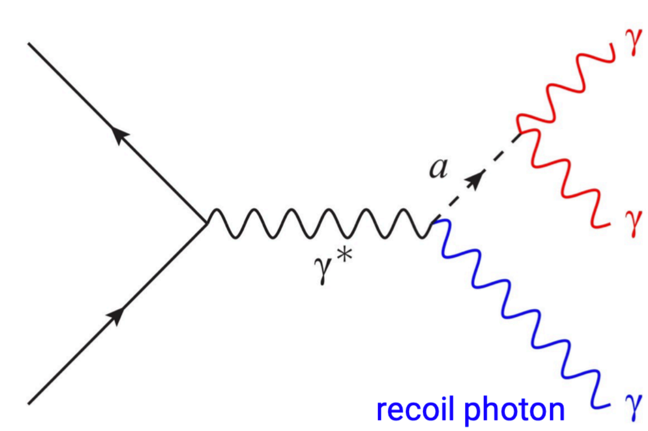
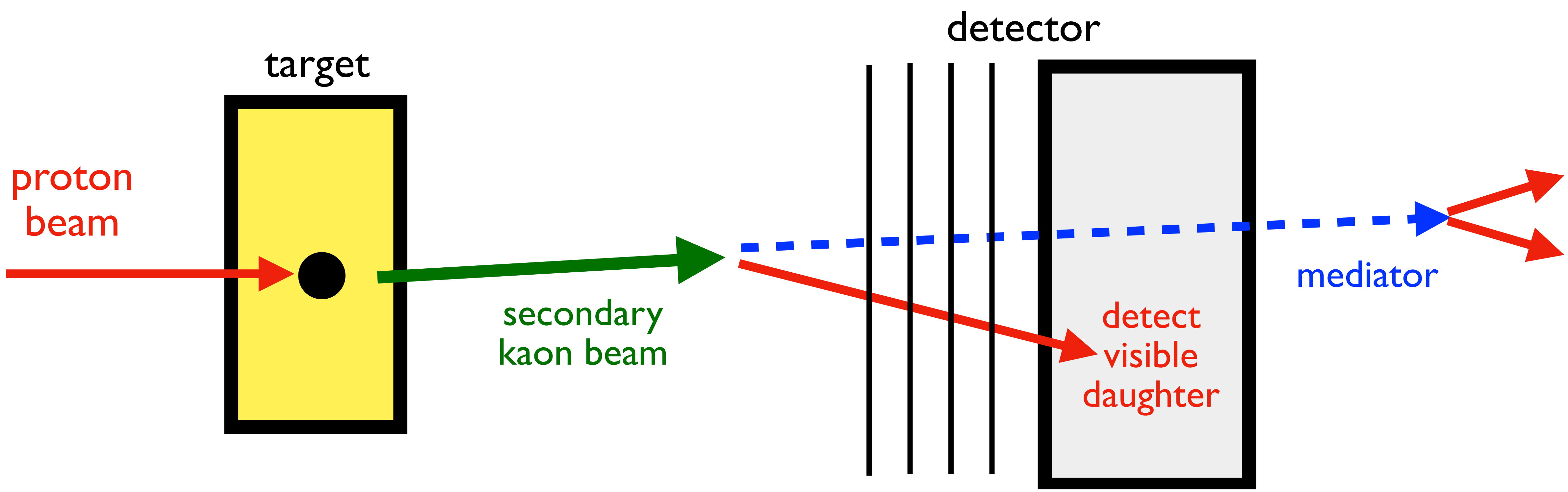
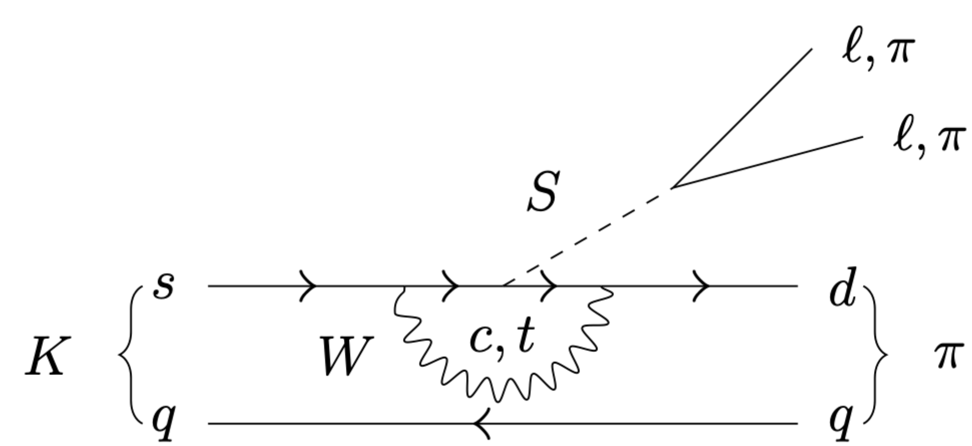


Fig from L. Corona

Kaon Factories



- Produce mediator via rare kaon decays
- Long lived mediators detected via missing mass technique (as above)
- Short lived mediators can be searched for directly by detecting their decay products
- The approach benefits from the narrowness of the Kaons, as well as large datasets



See 2201.07805 for a recent review article

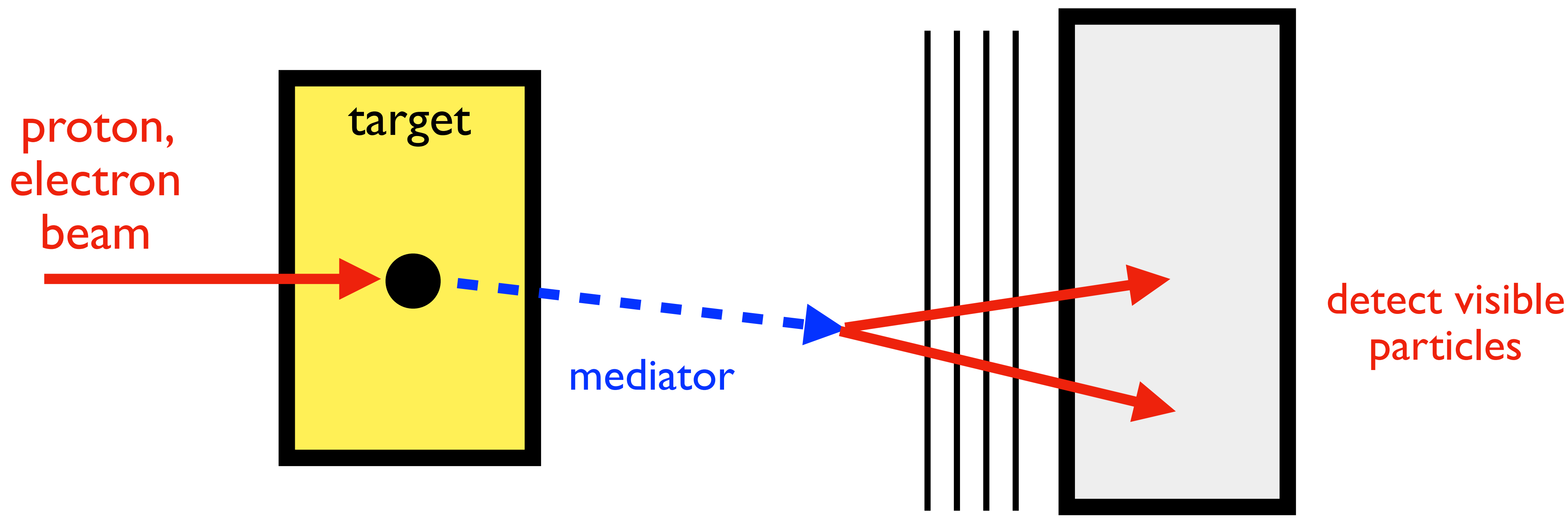
LOIs on Fixed-Target / Spectrometer Detectors

- Fixed Target / Spectrometer
  - HPS RF6_RF0_Nelson-078
  - DarkQuest RF6_RF0_Nhan_Tran-025

- Missing momentum
  - LDMX RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-104
  - Muon missing momentum RF6_RF0-EF10_EF0-CF1_CF0_Andrew_Whitbeck-111

- Photon Beam
  - Photon beam experiments RF6_RF0-112

Fixed-Target / Spectrometer



- Produce mediator via rare meson decays, bremsstrahlung, secondary collisions (e.g. photon induced Primakoff process)
- Detect visible decay products of mediator
- Compact detector geometry, relatively short baseline allows for sensitive probes of moderate mediator lifetimes
- Dedicated missing energy/momentum experiments (NA64, LDMX) can also search for visibly decaying particles in a similar manner

LOIs on LHC LLP detectors

- LLP Detectors at LHC

  — FASER 2 EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2-038

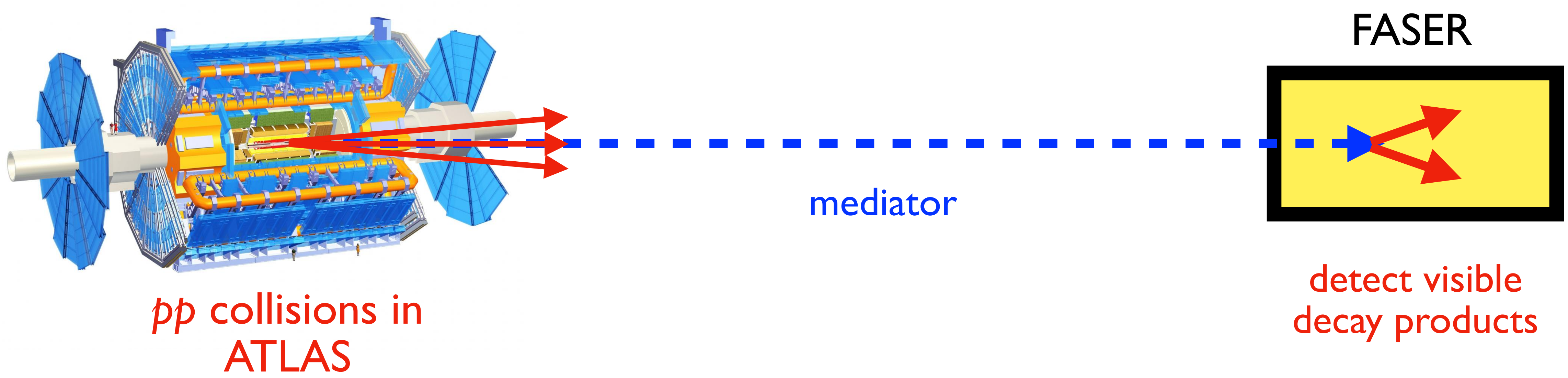
  — Codex-b EF9_EF0-RF6_RF0-034

  —MATHUSLA EF9_EF10-NF3_NF0-RF6_RF0-AF5_AF0-IF3_IF7_MATHUSLA_(David_Curtin)-184

  — Forward physics facility EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0-UF1_UF2_ForwardPhysicsFacility-193

Dedicated LLP Experiments at LHC

Consider FASER for illustration



- Produce mediator in pp collisions via rare meson decays, bremsstrahlung, and secondary interactions downstream
- Detect visible decay products of mediator
- Can harness large forward cross section, large forward boosts of light particles to probe moderate/long lifetimes
- Note that different LLP detectors can have distinct advantages (e.g. MATHUSLA can access mediator production through heavy states such as W,Z,Higgs)

Other LOIs within Big Idea 2 scope

- LLPs at energy frontier colliders
  - — LLP at EF EF9_EF10-RF6_RF0-TF7_TF8_James_Beacham-201
  - — LLP at FCCee EF8_EF9-RF6_RF0_Rebeca_Gonzalez_Suarez-147
- ALPs - other strategies
  - — Passat: A New ALP Detection Strategy NF3_NF0-RF6_RF0-CF1_CF0_Doojin_Kim-016
  - — ALPs at Reactor Neutrino Facilities NF3_NF0-RF6_RF0_Doojin_Kim-056
- Theory
  - — Neutrino Minimal Standard Model NF3_NF1-EF9_EF0-RF4_RF6-CF1_CF3-TF11_TF9-AF5_AF0-195
- Cross-frontier complementarity/synergy
  - — Collider sensitivities to DM / complementarity EF9_EF10-RF6_RF0-CF1_CF3_Boyu_Gao-160
  - — Dark matter complementarity CF2_CF7-EF10_EF0-RF6_RF0-TF9_TF0-150

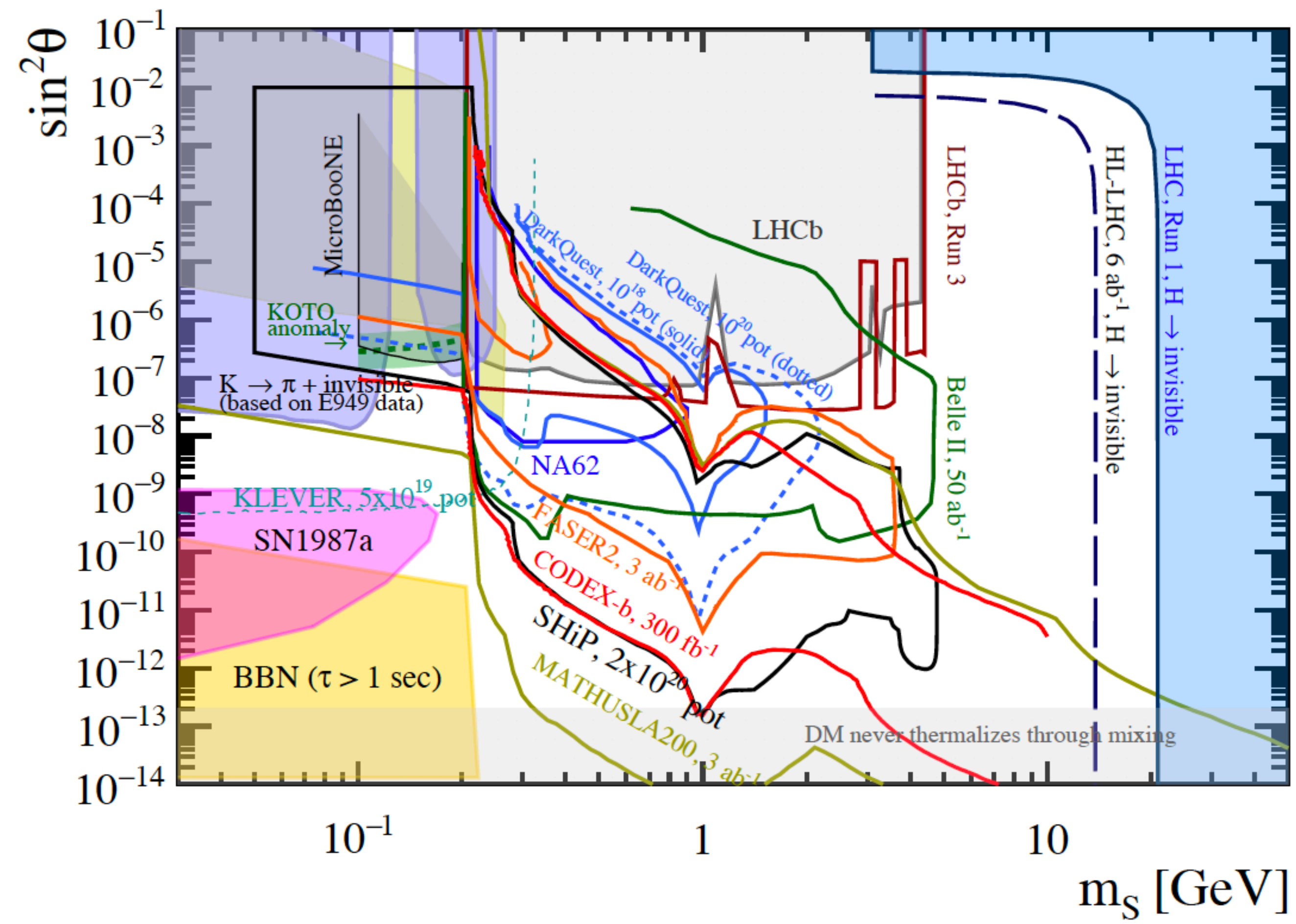
Benchmark Models / Case Studies / Plots

- Higgs Portal Scalar
- Dark Photon
- Heavy Neutral Lepton
  - $(e-, \mu-, \tau-$flavor dominance)
  - For discussion: All three? Choose one? Different flavor hypothesis?
- ALP
  - ALP - photon coupling
  - For discussion: Other ALP couplings?
- For discussion: What else?
  - e.g., B-L gauge boson?

Visibly Decaying Higgs Portal Scalar

$$(AS + \lambda S^2)H^\dagger H$$

- Phenomenology characterized by scalar-Higgs mixing angle, θ, and hSS trilinear coupling
- Like the Higgs, S couples to mass
- Production from flavor-changing meson decays
- Decay width naturally suppressed

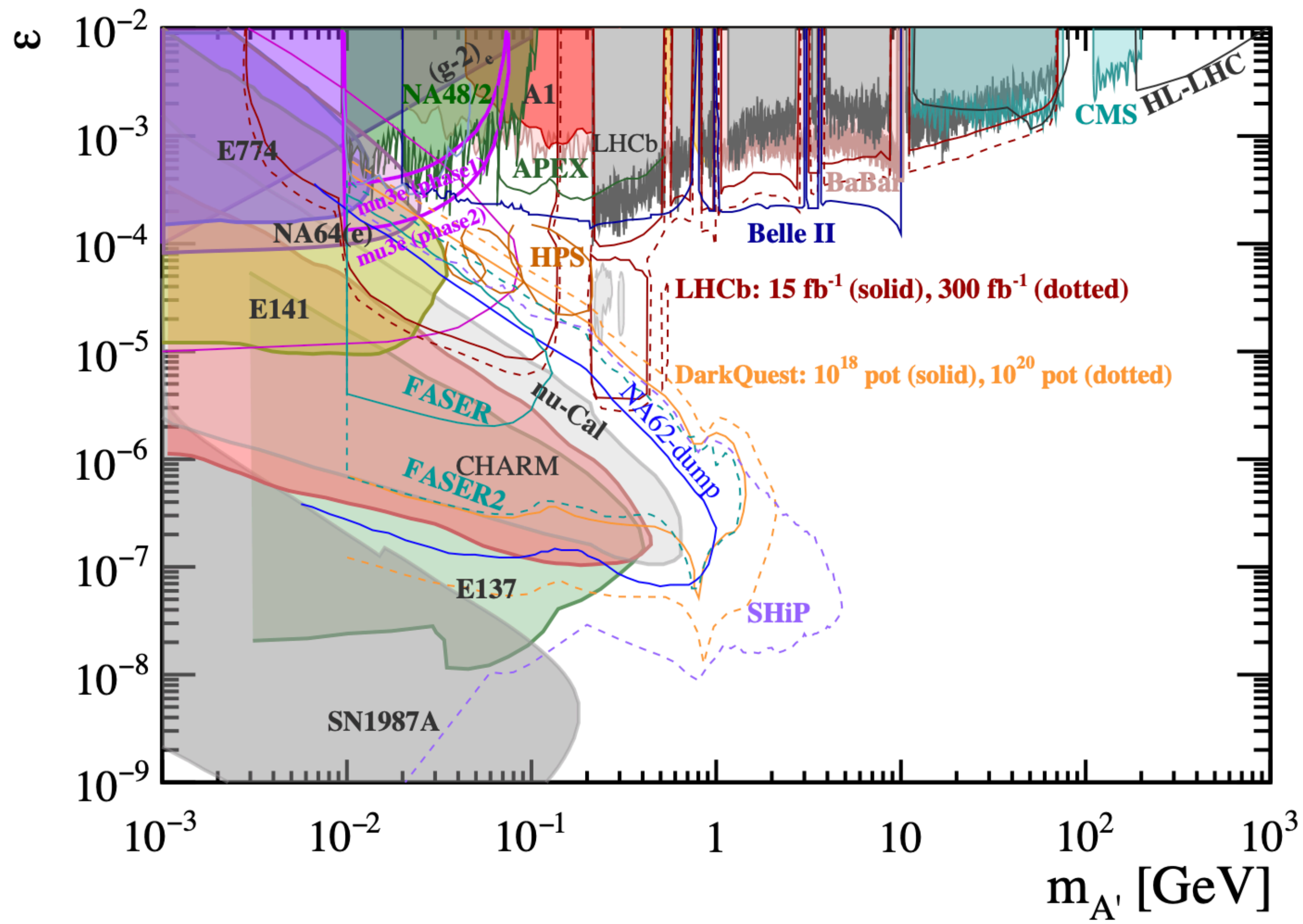


Lanfranchi et al., 2011.02157

Visibly Decaying Dark Photon

$$\frac{\epsilon}{2} F'_{\mu\nu} B^{\mu\nu}$$

- Low mass dark photons couple to electric charge, suppressed by ϵ
- A variety of probes exist, both in leptonic and hadronic systems

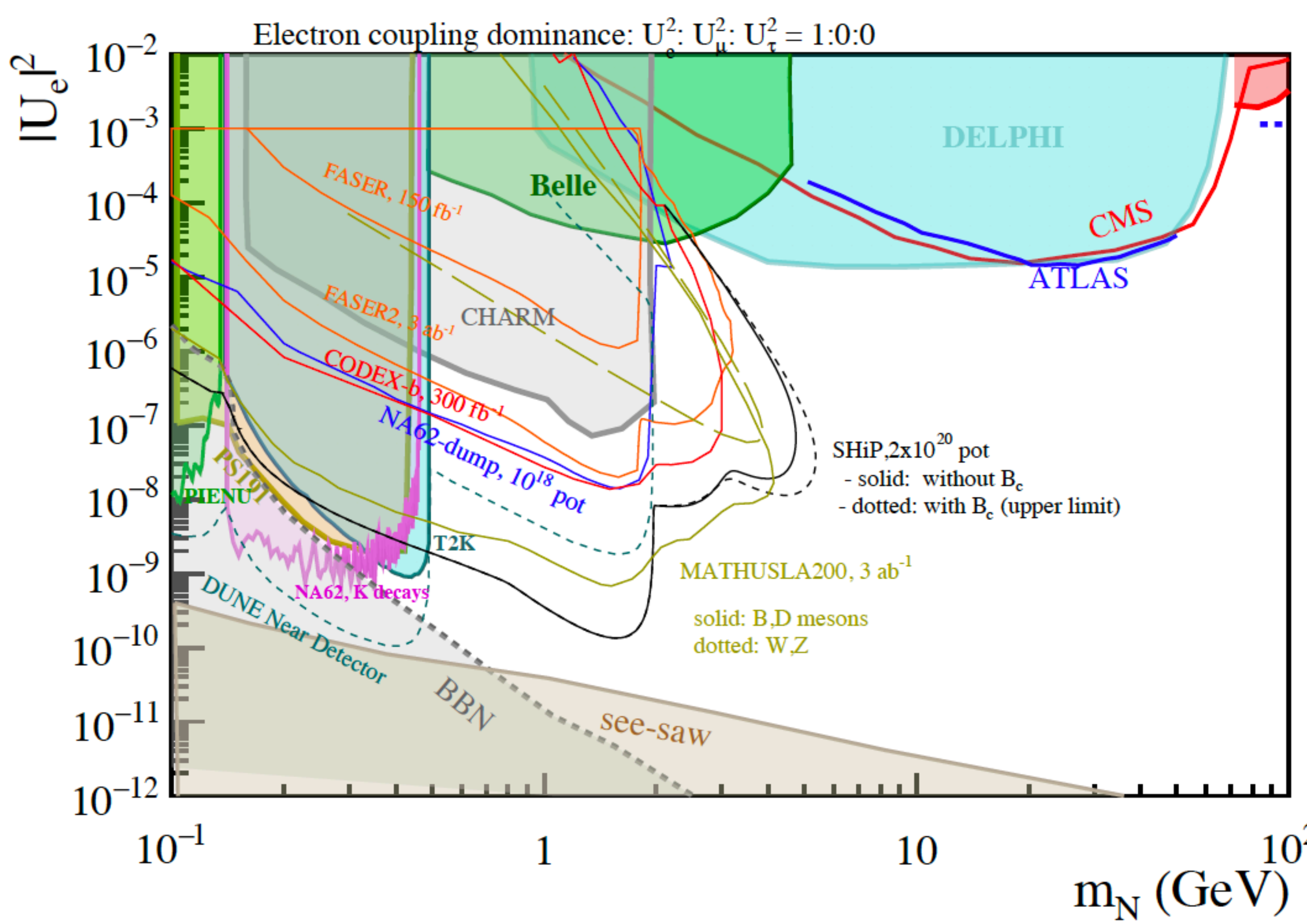


Lanfranchi et al., 2011.02157

Visible decaying HNL, electron dominance hypothesis

yLHN

- Phenomenology dictated by the neutrino-HNL mixing parameter $|U_e|^2$
- HNL inherits the weak interactions of ν_e
- Production dominated by weak decays of mesons
- Decay width naturally suppressed

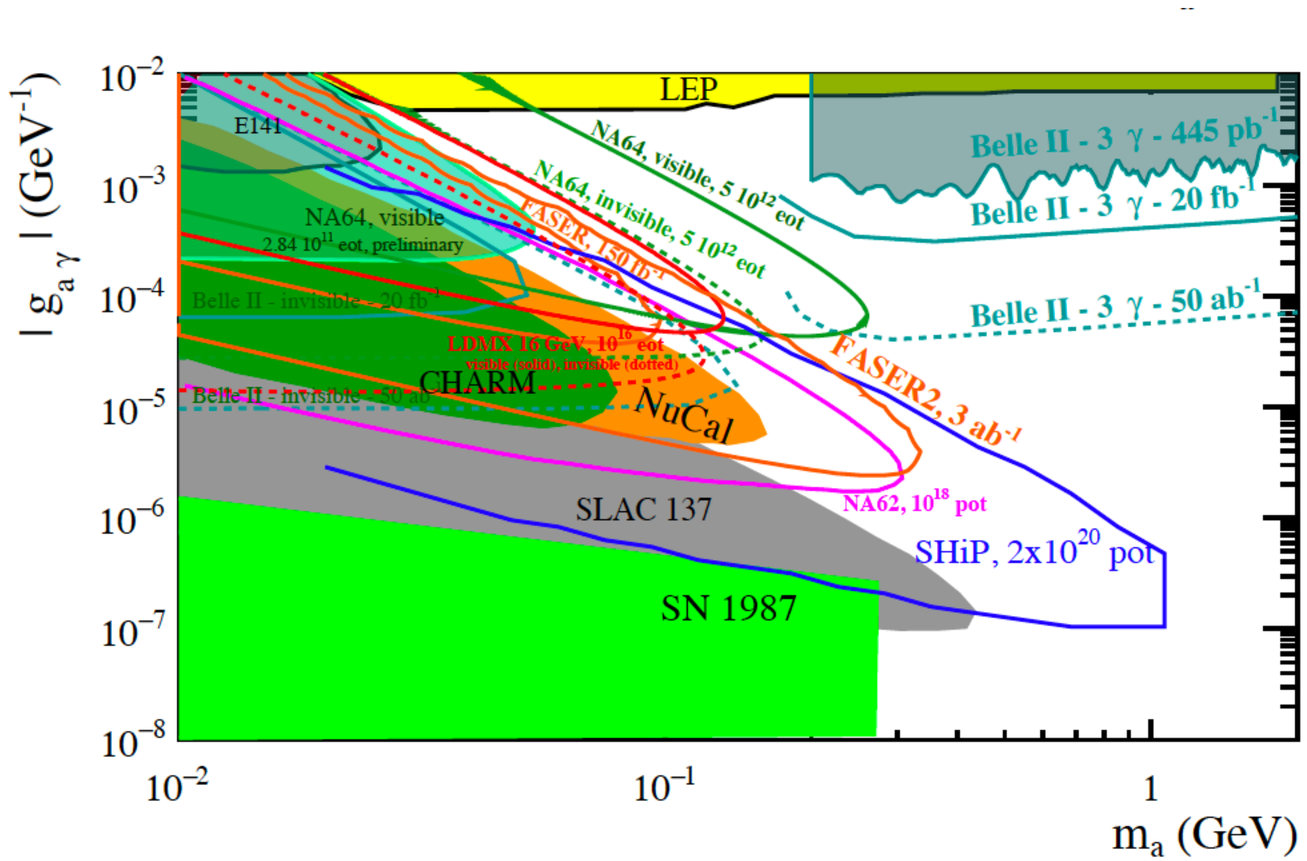


Lanfranchi et al., 2011.02157

ALP - photon coupling

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

- Simplifying assumption, other couplings expected in general
- Production dominated by electromagnetic interactions (e.g., Primakoff production from secondary photons in hadron collisions)



Lanfranchi et al., 2011.02157

Possible Points for Discussion

- Which models to consider, beyond the three renormalizable portals? (discuss/coordinate with Big Idea 3)
- How to treat the case of HNLs?
- How to connect more tightly with the big picture motivations (open puzzles of the SM, dark matter, experimental anomalies,…). Or is that the job of Big Ideas 1,3?
- Do energy frontier probes fall within our scope?
- Minimal Portal benchmarks have been investigated several times in past community studies (e.g., Physics Beyond Colliders). How should this inform our approach? What new ideas or perspectives can be presented in this whitepaper?

Feedback, input, and help on whitepaper from the community is welcomed and encouraged!

- If you have general feedback on our plans, are interested in helping with writing and/or making plots, or would like to sign/endorse the whitepaper, please email us:

batell@pitt.edu

hearty@physics.ubc.ca

- Contributed white papers due by March 15th, 2022
- Solicited whitepapers due by April 15th, 2022

Thank you!

Back-up

Other LOIs

- Dark Matter / Invisible (Big Idea 1)

  — Massless dark photon (theory) RF6_RF0-007

  — DM with positron beams RF6_RF0_Luca_Marsicano-074

  — Low mass dark matter at ICARUS NF3_NF0-RF6_RF0-CF1_CF0_Animesh_Chatterjee-119

  — Dark Matter Searches at the Next-Generation CEνNS and Neutrino Facilities NF3_NF0-RF6_RF0-TF8_TF9_Doojin_Kim-070

  — MIνER CEνNS Experiment NF6_NF10-RF6_RF0_Rupak_Mahapatra-104

- Sexaquark Dark Matter (Big Ideas 1, 3)

  — Delayed electroweak phase transition (theory) CF1_CF0-EF7_EF10-RF3_RF6_Glennys_Farrar-198

  — Accelerator search for color-flavor-spin singlet uuddss bound state DM CF1_CF0-EF7_EF10-RF3_RF6_Glennys_Farrar-198

Other LOIs

- Rich dark sector models (Big Idea 3)

  — Dark Pion Searches at Colliders and High Intensities EF9_EF0-RF6_RF0-075

  — Non minimal HNL models (theory) NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041

- Flavor violation (Big Idea 3)

  — Physics potential with MegII-fwd — RF5_RF6-006

  — Light mediators and flavor anomalies (theory) RF6_RF1_Alakabha_Datta-018

  — LFV at FCCee RF6_RF4-EF3_EF4_Mogens_Dam-119

- Neutron portal, Baryon number violation (Big Idea 3)

  — Sterile neutrons at ORNL and ESS RF6_RF3_Joshua_Barrow-115

  — $\Delta B = 2$ RF4_RF6-NF3_NF10-TF2_TF5_Joshua_Barrow-105

Other LOIs

- Facilities / Experiments (Big Idea 4)

— FNAL booster RF6_RF0_pellico-029

— LANSCE-PSR Short-Pulse Upgrade AF5_AF0-NF2_NF0-RF6_RF0_Vandewater-215

— SLAC LESA AF5_AF0-RF6_RF0_Raubenheimer-122

— Scintillation-based detectors for millicharged particles EF9_EF0-NF3_NF0-RF6_RF0_Matthew_Citron-072

— (Anti)Neutrinos at LBNF NF5_NF6-EF6_EF4-RF1_RF6-122

— Electron-Nucleon Scattering at LDMX for DUNE NF6_NF0-RF6_RF0-TF11_TF0-091

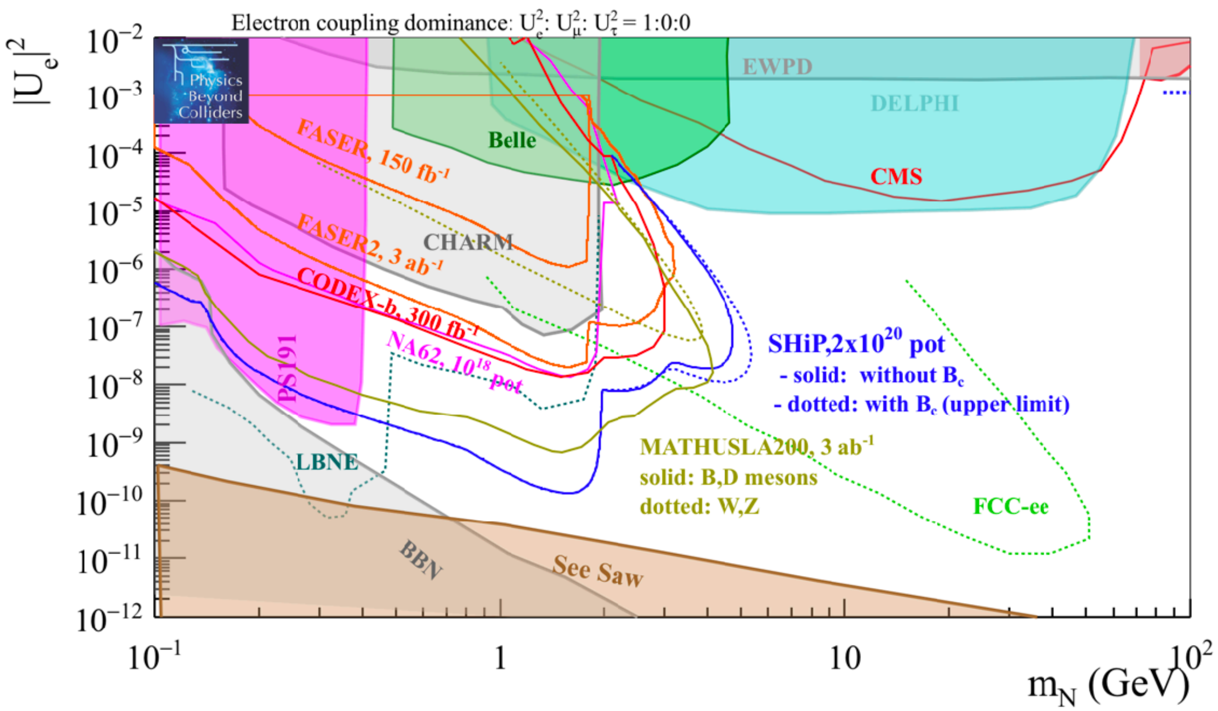
— Mu2e-II Calorimeter EF9_EF6_EF10_EF5-NF6_NF3_NF10-RF6_RF0-CF7_CF0-AF5_AF0 -UF1_UF2_TF10_Calorimeter-193

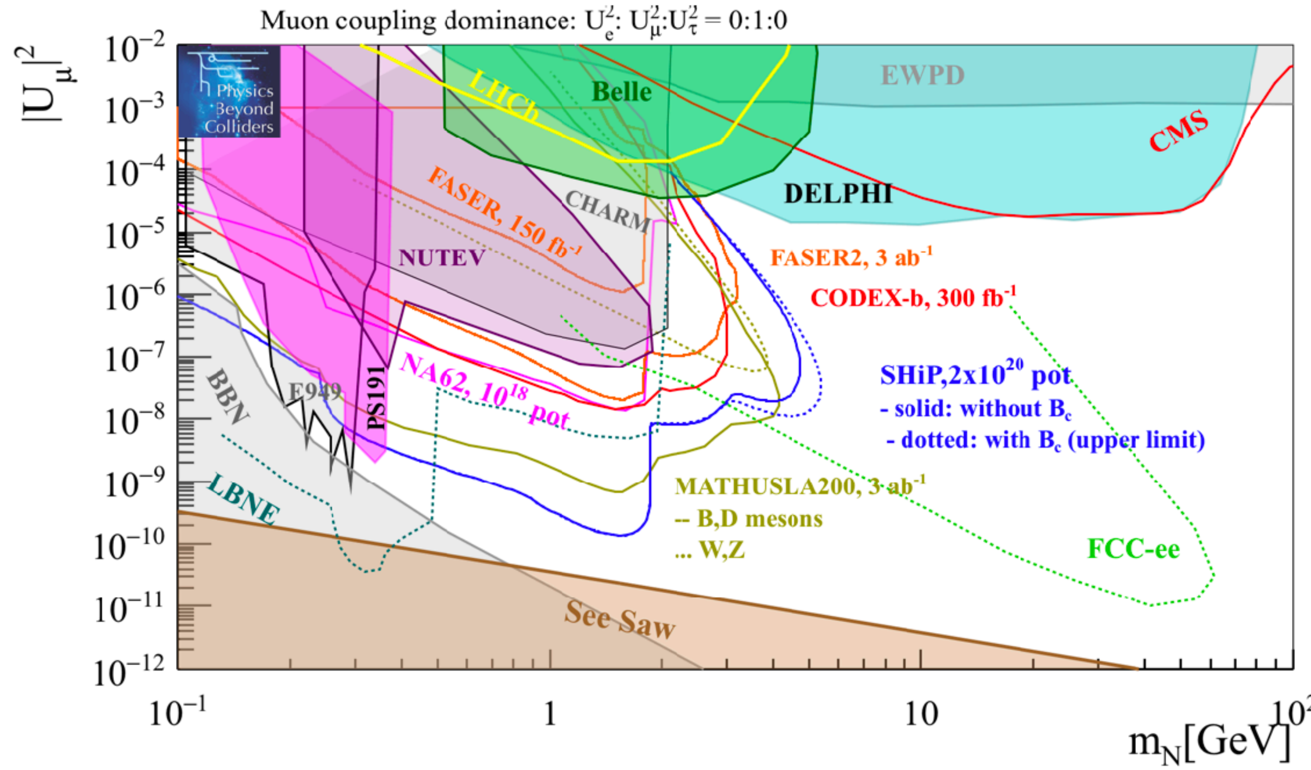
LOIs on Beam Dumps

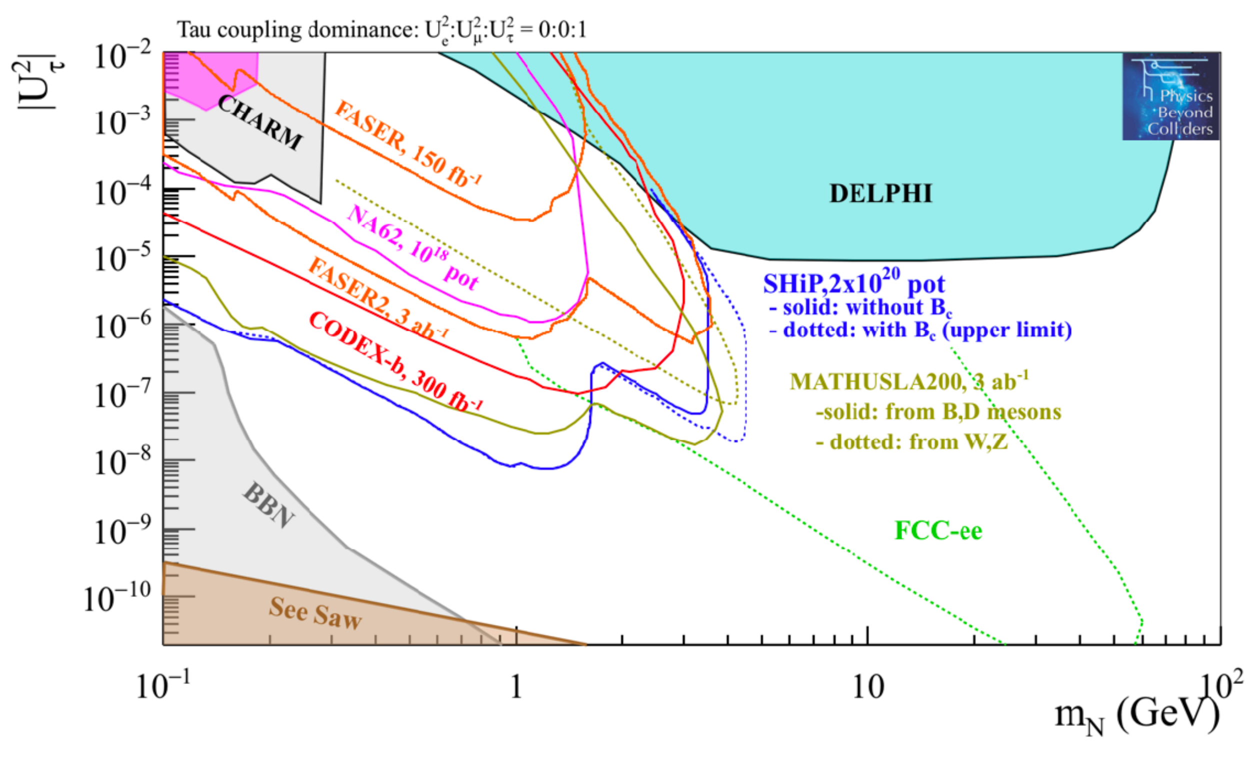
- Proton beam dumps
  - — BDF/SHiP facility AF5_AF0-RF6_RF0-163
  - — 1GeV proton beam dump at Fermilab RF6_RF0-NF2_NF3-AF2_AF5-099
  - —10GeV proton beam dump at Fermilab RF6_RF0-NF3_NF0-AF5_AF0-084
  - — Dark Sector Studies With Neutrino Beams NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148
  - — HNLs at Accelerator Neutrino Experiments NF2_NF3-RF6_RF0_Athanasios_Hatzikoutelis-160
  - — ALPs at neutrino experiments NF3_NF0-RF6_RF0_Doojin_Kim-028

- Electron beam dumps
  - — BDX RF6_RF0_BDX-076
  - — New light particles at ILC main beam dump EF9_EF0-RF0_RF6-086.

HNL flavor dominance scenarios

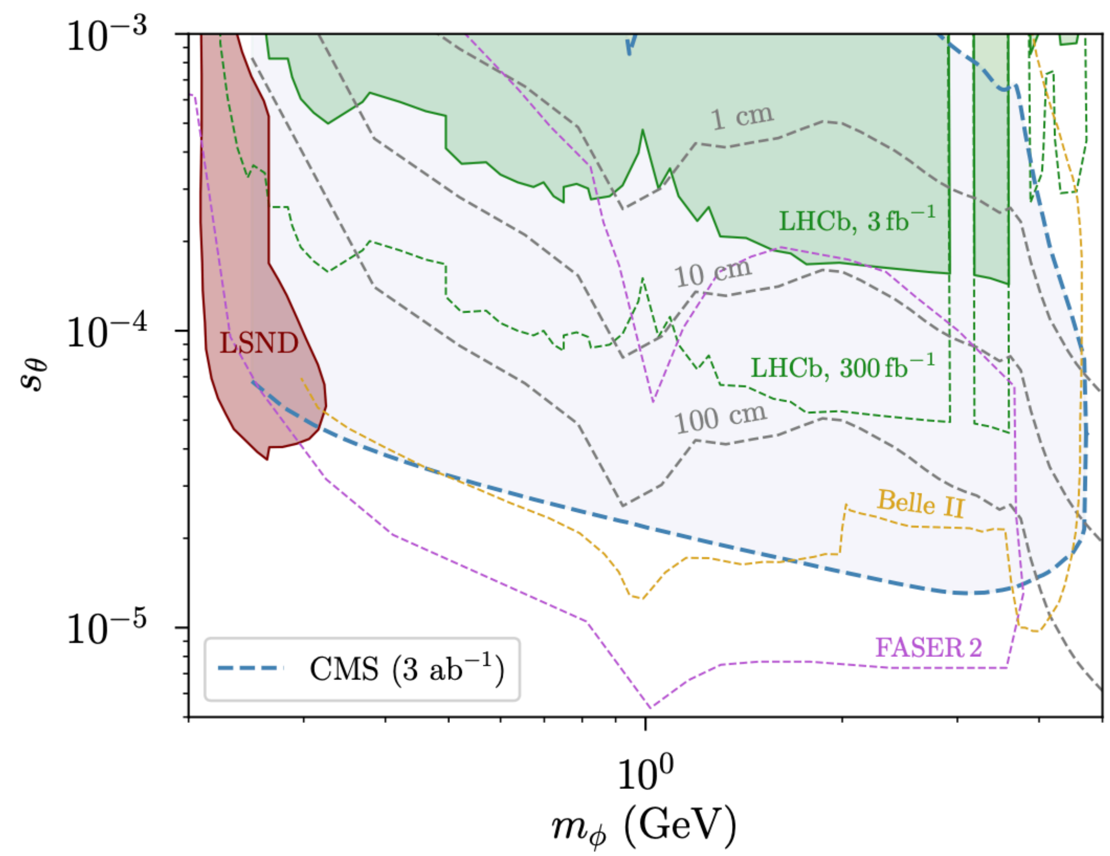




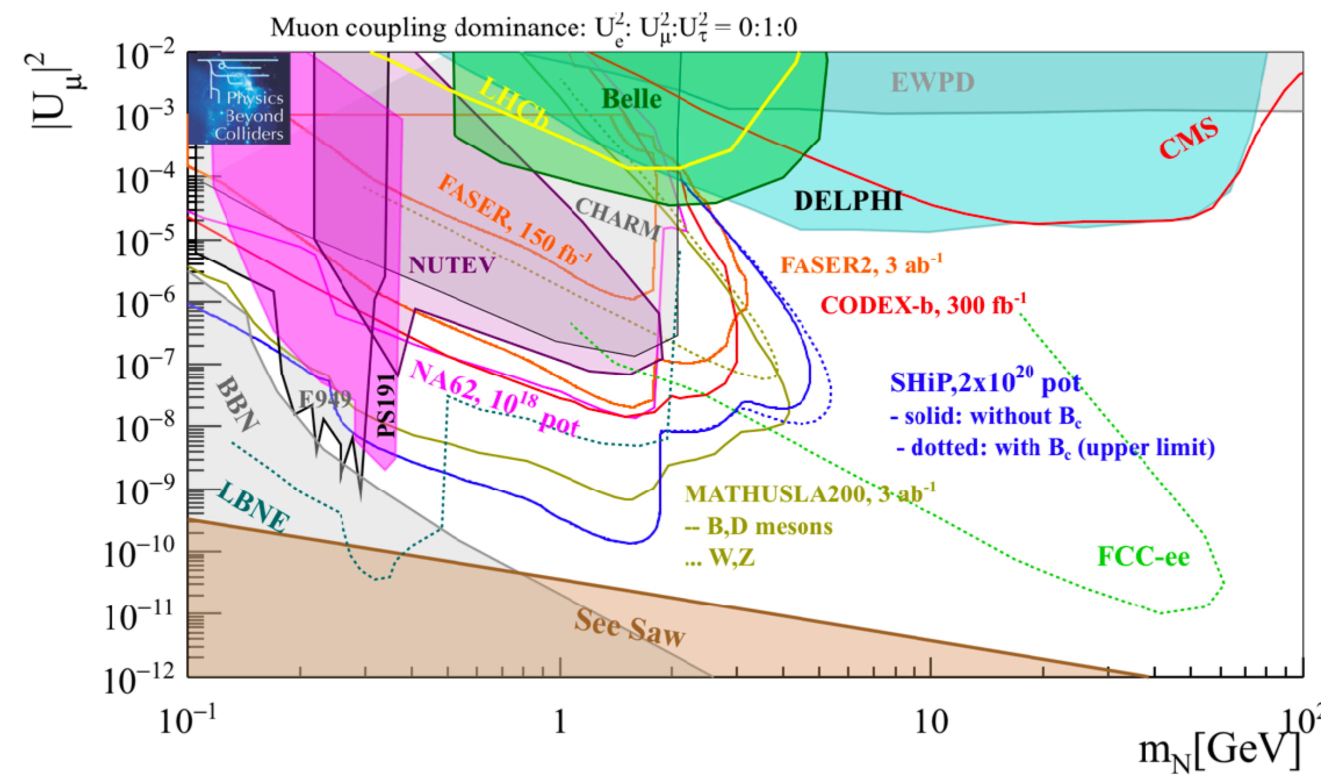


Physics Beyond Colliders Report
CERN-PBC-REPORT-2018-00

Energy frontier probes of GeV-scale state



Evans et al. 2008.06918



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