Captions here

Rare and Precision Frontier

R. Bernstein, Fermilab
for the Frontier

P5 Town Hall 22 March 2023

Marina Artuso
Syracuse U.

Alexey Petrov
Wayne State and U South Carolina

Bob Bernstein
Fermilab

Liaisons

- Invaluable advice and thanks for their contributions!

Josh Barrow	MIT/Tel Aviv/Knoxville	Early Career
Jake Bennett	U. Mississippi	Early Career
Susan Gardner	U. Tennessee	Cosmic Frontier
Sophie Middleton	Caltech	Community Engagement Frontier
Eric Prebys	UC Davis	Accelerator Frontier
Manuel Franco Sevilla	U. Maryland	Energy Frontier

Topical Groups and Subconveners

https://arxiv.org/abs/2210.04765

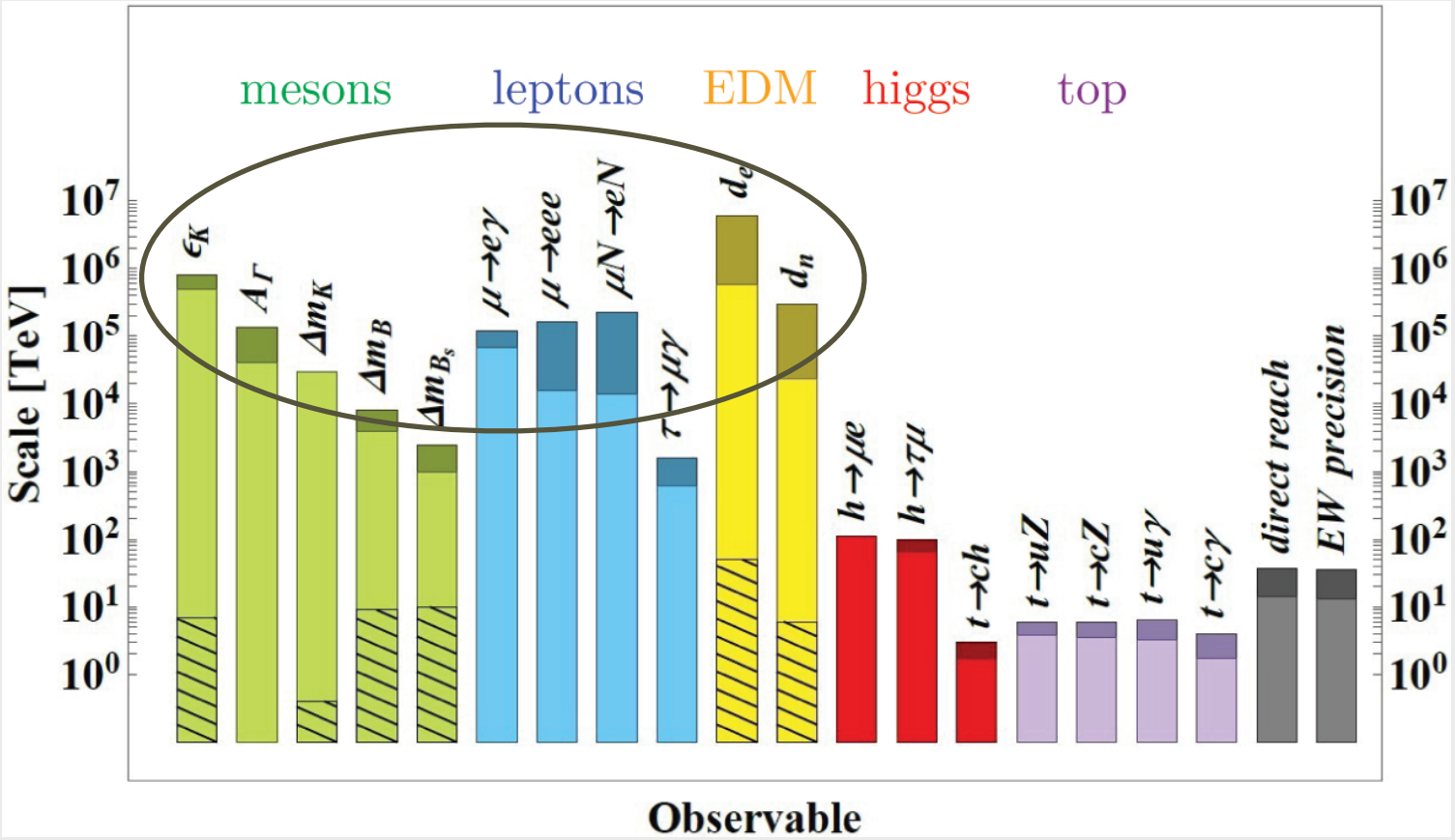
Topical Group	Co-Conveners	
Weak Decays of b and c	Angelo di Canto BNL	Stefan Meinel U Arizona
Strange and Light Quarks	Emilie Passemar Indiana U	Evgueni Goudovski Birmingham
Fundamental Physics and Small Experiments	Tom Blum UConn	Peter Winter ANL
Baryon and Lepton Number Violation	Pavel Fileviez Perez CWRU	Andrea Pocar Amherst
Charged Lepton Flavor Violation	Sacha Davidson IN2P3/CNRS France	Bertrand Echenard Caltech
Dark Sector at High Intensities	Stefania Gori UCSC	Mike Williams MIT
Hadron Spectroscopy	Rich Lebed Arizona State	Tomasz Skwarnicki Syracuse

Physics of RPF

- the origin of quark and lepton flavor, generations, and mass hierarchies;
- the exploitation of flavor (both quark and lepton) as a precision probe of the Standard Model;
- the use of flavor physics as a tool for discovering new physics;
- the origin of the fundamental symmetries and their breakdown mechanisms;
- the origins of Dark Matter and the existence of a dark sector
- *Much of the frontier is "small" and "medium" experiments*
  - *critical to our physics that these thrive in US ecosystem*

RPF Physics Reach

- Precision Experiments probe otherwise inaccessible mass scales



dim-6, coupling ~1 (solid) or MFV suppressed (hatched); Physics Briefing Book, arXiv:1910.11775 **[hep-ex]**

Flavor Driver

- Why are there families and generations? Why do we see the coupling structures we do? The physics of flavor is central to questions across all the Frontiers
- Unifies much of the Frontier:
  - Rare *b* and *c*-decays and precision CKM measurements
  - Lepton flavor/flavor universality violation and lepton number violation
  - CP violation, baryon number violating decays
- A flavor driver would capture and emphasize this physics

RPF Consensus Items

- Agreed on across the Frontier:
  - *b, c* physics at colliders: LHCb/Belle II and their upgrades
  - portfolio of accelerator-based dark matter experiments: starting with the *Dark Matter Small Projects New Initiatives* (DMNI), other ideas across the world

    https://www.osti.gov/servlets/purl/1659757
  - R&D on a new muon program at FNAL
  - The theory efforts that guide and enable these investigations, while not a Project, should be vigorously supported by P5
  - And we need a new driver for flavor physics

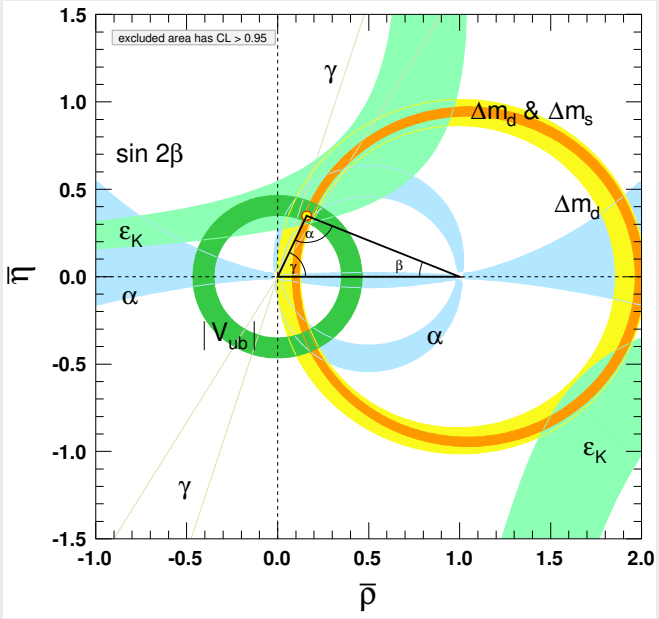
RPF Projects

jargon: srEDM = storage ring proton EDM;
DMNI = dark matter new initiatives;
AMF = Advanced Muon Facility

WG	Experiments	Goals (next decade)	Goals (10-20 years)
RF1: *b* and *c*	LHCb, Belle II	physics and phased upgrades	CKM tests; lepton universality; dark sector; heavy and light NP searches
RF2: light quarks	KOTO, PIONEER, REDTOP (η/η')	R&D	*C,P,T* violation; DM; LFV
RF3: small experiments	storage ring EDMs (srEDM)	Advanced proposal	10^{-29} e-cm, 300 TeV mass scale, 10 μrad CP
RF5: CLFV	Mu2e-II	design of Mu2e-II; R&D for post-Mu2e-II muon program (AMF)	x10 Mu2e at PIP-II; x1000 at AMF
RF6: DM	Dedicated and General-Purpose	select/design experiments; run LDMX	x10-100 progress in range of portals

RF1: Heavy Flavor

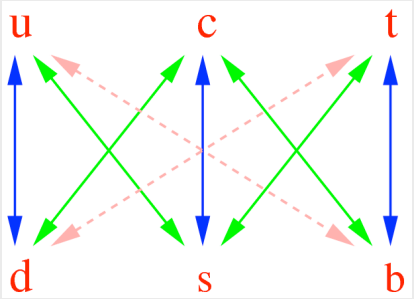
- Precision measurements of weak decays of heavy flavored hadrons:
  - uniquely further our understanding of fundamental interactions
  - try to explain the baryon asymmetry of the universe

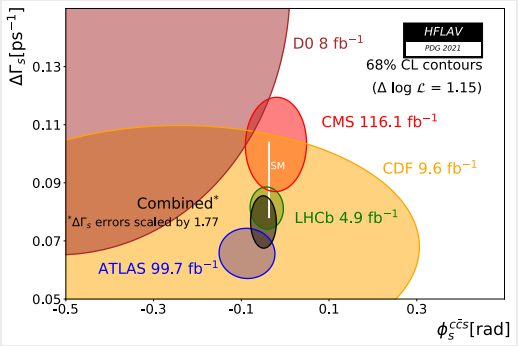


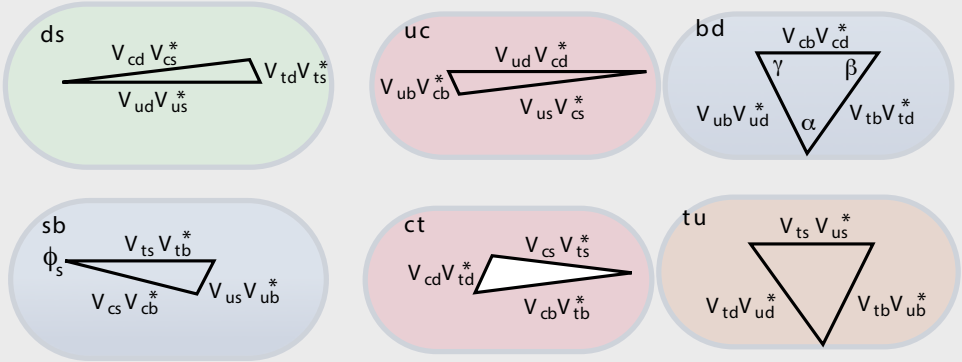
- The next 10-20 years will see the unprecedented development of a highly synergistic program of experiments
  - at both pp and e^+e^- colliders,
  - complemented and inspired by phenomenological and lattice QCD theoretical advances.

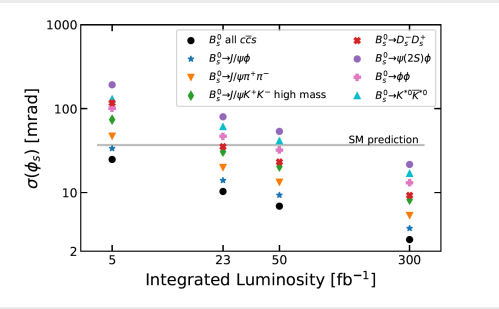
RPF: The CKM Matrix and its triangles

- Rich pattern of charge-changing weak transitions of quarks described by CKM matrix — and the studies cross our topical groups
- The CKM matrix is unitary→6 unitarity triangles
- 4 independent parameters, 3 rotational angles and a phase, η, describing CP violation in the Standard Model









already provide powerful constraints

uncertainties will improve ~x10

RF1: Physics Reach

- Typically x10 across a wide variety of measurements at facilities world-wide!

Observable	Current best	Belle II 50 ab^{-1}	Belle II 250 ab^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	ATLAS 3 ab^{-1}	CMS 3 ab^{-1}	BESIII 20 fb^{-1} (∗)	STCF 1 ab^{-1} (∗)
Lepton-flavor-universality tests									
$R_K(1 < q^2 < 6\ GeV^2)$	0.044 [46]	0.036	0.016	0.017	0.007				
$R_{K^*}(1 < q^2 < 6\ GeV^2)$	0.12 [47]	0.032	0.014	0.022	0.009				
$R(D)$	0.037 [48]	0.008	< 0.003	na	na				
$R(D^*)$	0.018 [48]	0.0045	< 0.003	0.005	0.002				
Rare decays									
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [10^{-9}]	0.46 [49, 50]			na	0.16	0.46–0.55	0.39		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.69 [49, 50]			0.27	0.11	na	0.21		
$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)$ UL [10^{-3}]	2.0 [51, 52]	0.5	na						
$\mathcal{B}/\mathcal{B}_{\rm SM}(B^+ \to K^+\nu\bar{\nu})$	1.4 [53, 54]	0.08–0.11	na						
$\mathcal{B}(B \to X_s\gamma)$	10% [55, 56]	2–4%	na						
CKM tests and CP violation									
α	5° [57]	0.6°	0.3°						
$\sin 2\beta(B^0 \to J/\psi K_S^0)$	0.029 [58]	0.005	0.002	0.006	0.003				
γ	4° [59]	1.5°	0.8°	1°	0.35°			0.4° (†)	$< 0.1°$ (†)
$\phi_s(B_s^0 \to J/\psi\phi)$	32mRad [60]			10mRad	4mRad	4–9mRad	5–6mRad		
$\lvert V_{ub}\rvert(B^0 \to \pi^-\ell^+\nu)$	5% [61, 62]	2%	$< 1\%$	na	na				
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert(\Lambda_b^0 \to p\mu^-\bar{\nu})$	6% [63]			2%	1%				
$f_{D^+}\lvert V_{cd}\rvert(D^+ \to \mu^+\nu)$	2.6% [64]	1.4%	na					1.0%	0.15%
$S_{CP}(B^0 \to \eta' K_S^0)$	0.08 [65, 66]	0.015	0.007	na	na				
$A_{CP}(B^0 \to K_S^0\pi^0)$	0.15 [65, 67]	0.025	0.018	na	na				
$A_{CP}(D^+ \to \pi^+\pi^0)$	11×10^{-3} [68]	1.7×10^{-3}	na	na	na			na	na
$\Delta x(D^0 \to K_S^0\pi^+\pi^-)$	18×10^{-5} [69]	na	na	4.1×10^{-5}	1.6×10^{-5}				
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5} [70]	na	na	3.2×10^{-5}	1.2×10^{-5}				

RF1: Physics Reach Snapshots

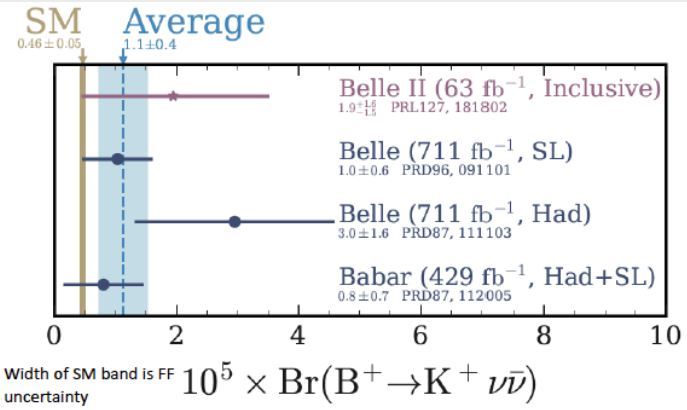
BELLE II

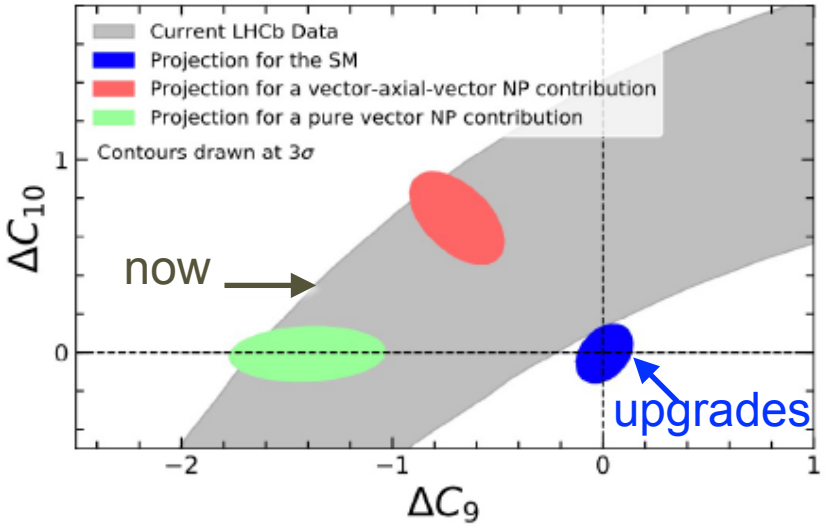
$B \to K\nu\bar{\nu}$

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (2021)

An emerging anomaly ???





4% experimental error on $B \to K^*\nu\bar{\nu}$ with 250ab^{-1}

More than CKM

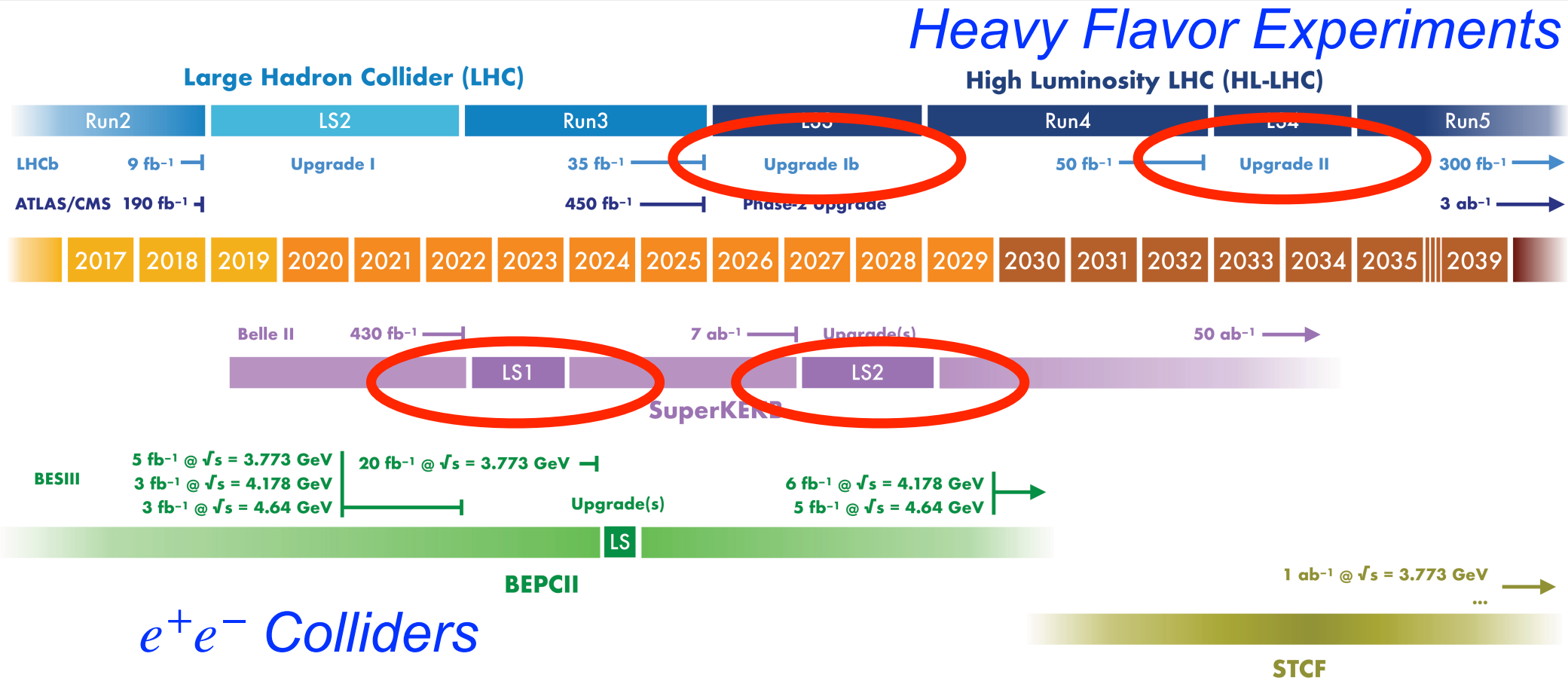
Manuel Franco Sevilla (LHCb): the W-mass and dark photons at LHCb

Jake Bennett (Belle II): searching for new sources of CPV, lepton flavor violation, and dark sector particles in a clean e+e- environment

LHCb

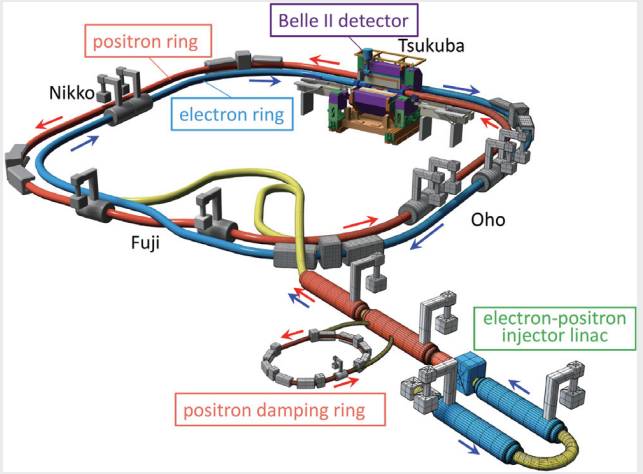
Integrated Luminosity	3 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K and R_{K^*} measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda^{\text{tree generic}}$ [TeV]	40	80	155
$\Lambda^{\text{tree MFV}}$ [TeV]	8	16	31
$\Lambda^{\text{loop generic}}$ [TeV]	3	6	12
$\Lambda^{\text{loop MFV}}$ [TeV]	0.7	1.3	2.5
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\sigma^{\text{stat}}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda^{\text{tree generic}}$ [TeV]	50	75	115
$\Lambda^{\text{tree MFV}}$ [TeV]	10	15	23
$\Lambda^{\text{loop generic}}$ [TeV]	4	6	9
$\Lambda^{\text{loop MFV}}$ [TeV]	0.8	1.2	1.9

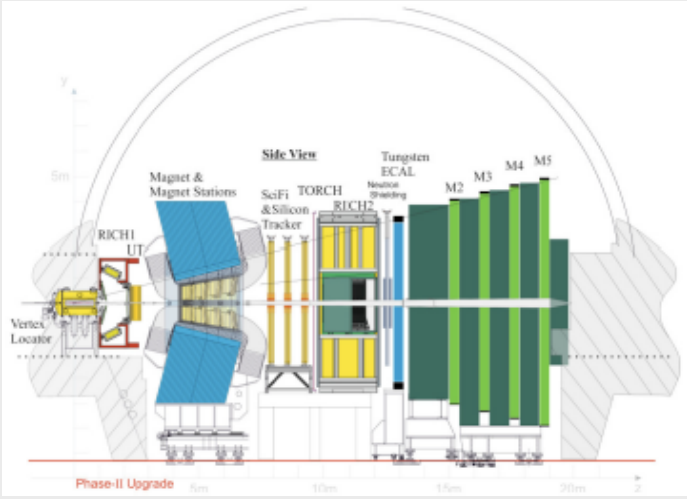
RF1: Heavy Flavor Timeline



RF1: US Contributions

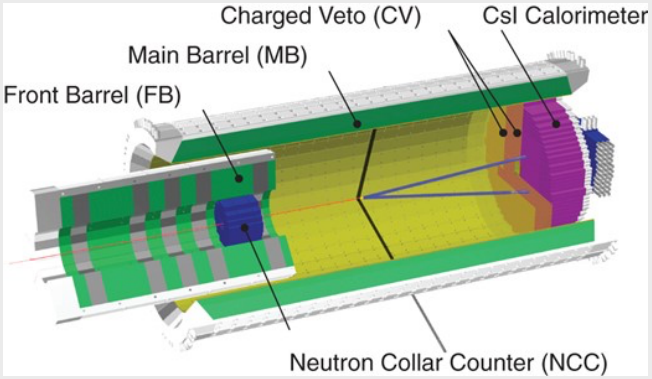
- Belle II
  - particle ID, collaboration leadership;
    many fundamental software and analysis roles
  - we should reap the benefits of our investment!
- LHCb
  - OHEP currently does *not* support LHCb,
    but it is supported by NSF
    - *appreciate and value strong NSF support*
  - the National Lab infrastructure could add value
    - *interest at BNL and US OHEP universities in participating in LHCb upgrades (Sevilla)*





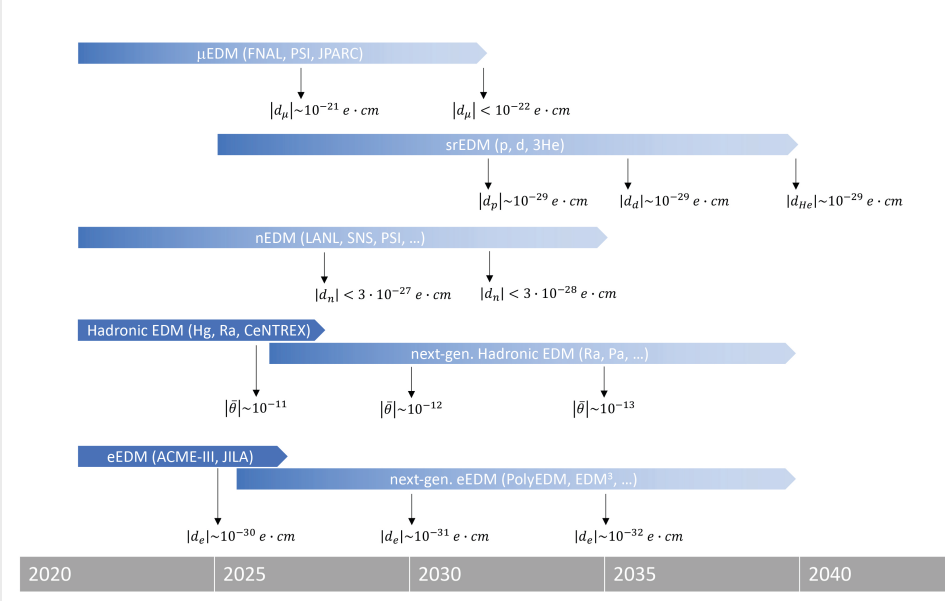
RF2: Strange and Light Quarks

- US is part of J-PARC's KOTO ($K_L \rightarrow \pi^0 \nu \bar{\nu}$)
  - FNAL provided crystals through Chicago
  - Michigan provided trigger and DAQ
  - ASU was funded through Michigan and Chicago subcontracts
  - *maintain U.S. support for KOTO*
- NA62 has an excellent program in the charged mode, including DM
  - US does not participate here



RF3: Fundamental Physics in Small Experiments

- EDMs became the focus
  - sharing intellectual questions with Atomic, Molecular, and Optical (AMO) EDMs
  - storage ring EDM proposal for BNL is a unique HEP contribution



Peter Graham
on "tabletop" experiments

- x1000 enhancement in axion θ_{QCD} , up to 10^3 TeV

$$\mu\text{EDM(FNAL, PSI, JPARC)} \sim d_\mu < 10^{-22} e \cdot \text{cm}$$

$$\text{srEDM}(\ p, d, {}^3He) \sim d_{p,n,{}^3He} < 10^{-29} e \cdot \text{cm}$$

  - similar levels to d_n at LANL, SNS, or PSI

RF3: Fundamental Physics in Smaller Experiments

- We all agree that a portfolio of smaller experiments is a good thing; these cross our topical groups
- Muon g-2 a huge success! (will cover later)

Dave Hertzog

- RF2 has the kaon program and also PIONEER (at PSI)
- RF3 has srEDM, and studied opportunities to collaborate with AMO Ed Stephenson
- We need to support the theory efforts that aid and guide their analyses

RF4 (BLV)
RF7 (hadron spectroscopy)

- RF4 ($0\nu 2\beta$, $n\bar{n}$ oscillations, proton decay) heavily overlaps with Neutrino Frontier; will leave out for lack of time, not lack of interest

- RF7: hadron spectroscopy:
  - "project" part is already being done through existing experiments at colliders
  - wealth of exotic states still being discovered; need support for theory community

top-cited paper for each experiment is an exotics discovery!

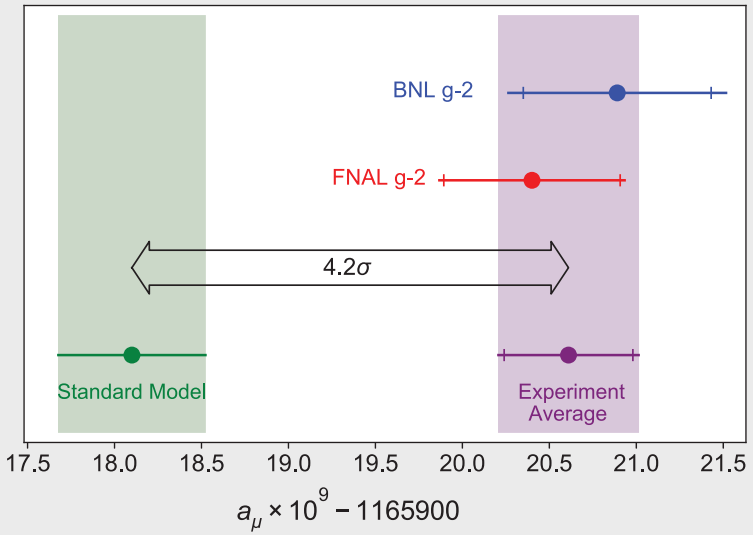
experiment	state	number of cites
Belle	X(3872) exotic	2291
BES III	Zc (charged tetraquark)	1532
LHCb	Pc (pentaquark)	1012

- needed across the Frontier: need to calculate hadronic matrix elements to access fundamental physics, and to understand the architecture of matter

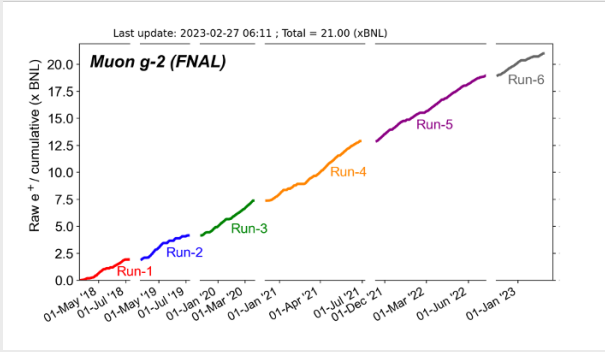
RF5: Current Program

- *P5 in 2014: Complete the Mu2e and muon g-2 projects.*
  - g-2: anomalous magnetic moment of the muon, checking BNL821 result and improving both statistical and systematic errors
  - Mu2e: charged lepton flavor violation at x10,000 current limits
    - in construction with strong FNAL support
- *Examples of the success of the last P5!*

RF5: FNAL g-2



27 Feb: reached goal of x21 BNL!



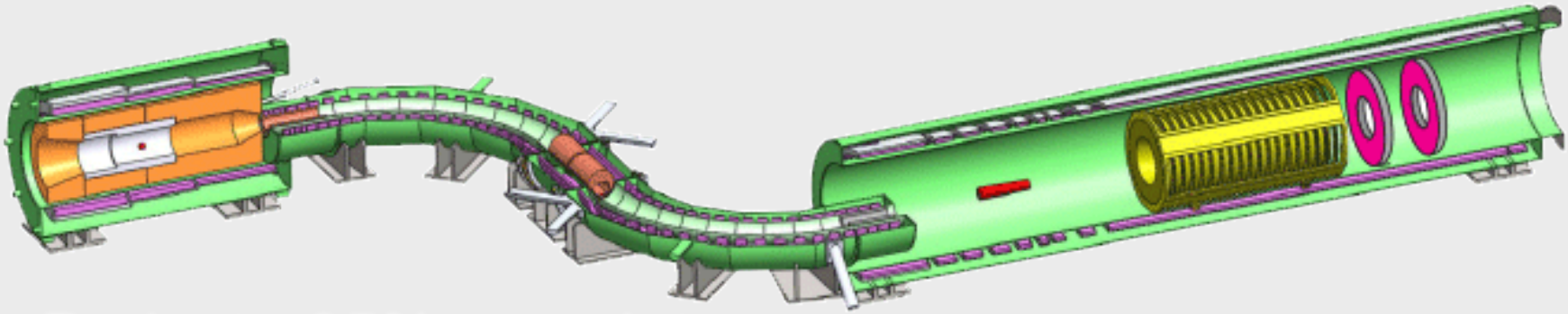
Huge Public Engagement!

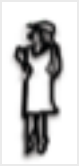
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.141801; >1000 cites!

- Run I was 5% of total statistics
- Analysis of Run 2/3 in progress (x4 Run I)
- Expect x2 reduction in uncertainty (462 to 230 ppb)
- Release expected after June 1

theory status and developments: El-Khadra
J-PARC method: Saito

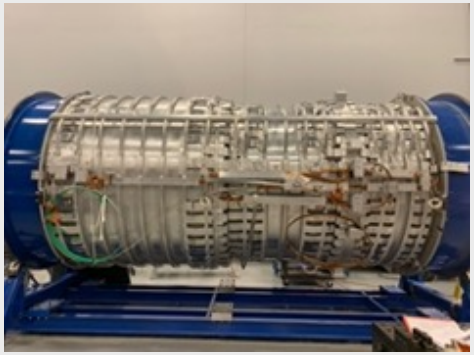
RF5: Mu2e

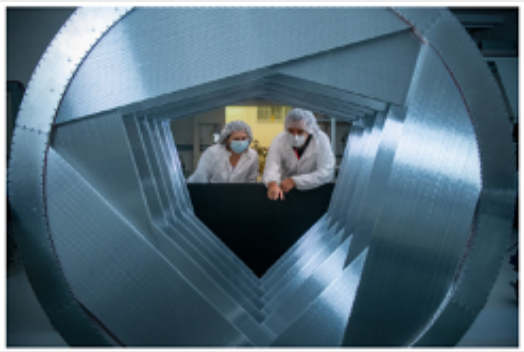


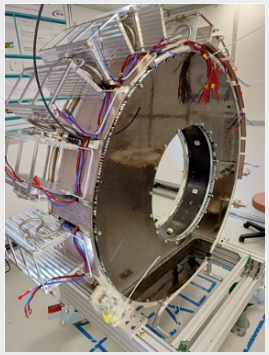


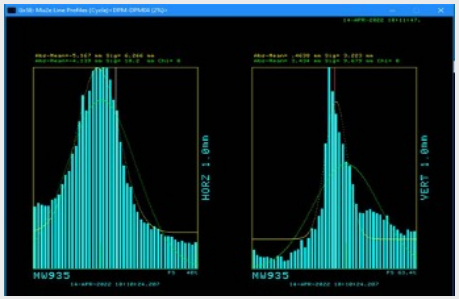
- Project ~85% complete
- Mu2e gearing up for 2026 data at x1000 existing limits with completion around the end of the decade

first beam!









Miller on Mu2e
Kuno on COMET, MEG, Mu3e

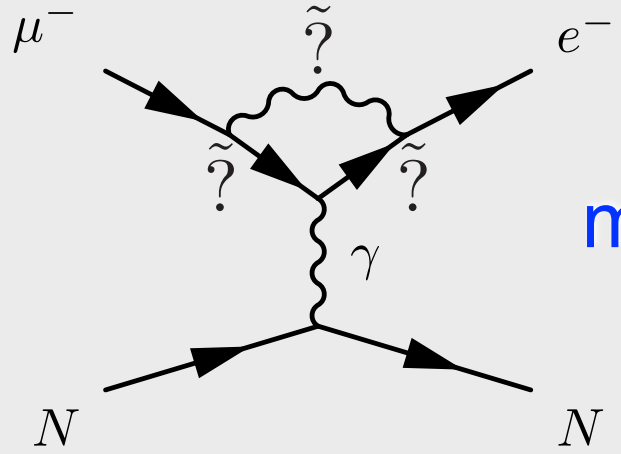
RF5: Charged Lepton Flavor Violation

- Neutrinos and quarks mix; why not charged leptons?
  - *Charged Lepton Flavor Violation (CLFV) is new physics*
  - *many models link Charged LFV to Neutral LFV (oscillations!); for example, see-saws*
- We studied muons, taus, and heavy states
  - many opportunities in $\tau \to (\mu, e)\gamma$ and other τ modes, and collider modes like $H \to l_a l_b$
- I will focus on muon CLFV:
    - three modes: $\mu \to e\gamma$, $\mu \to 3e$, and $\mu^- N \to e^- N$

RF5: De Gouvêa Plot

$$\mathscr{L}_{\mathrm{CLFV}} = \frac{m_\mu}{\Lambda^2}\,\bar{\mu}_R\,\sigma_{\mu\nu}\,e_L\,F^{\mu\nu} \quad + \quad \frac{1}{\Lambda^2}\bar{\mu}_L\gamma^\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

"Loops"



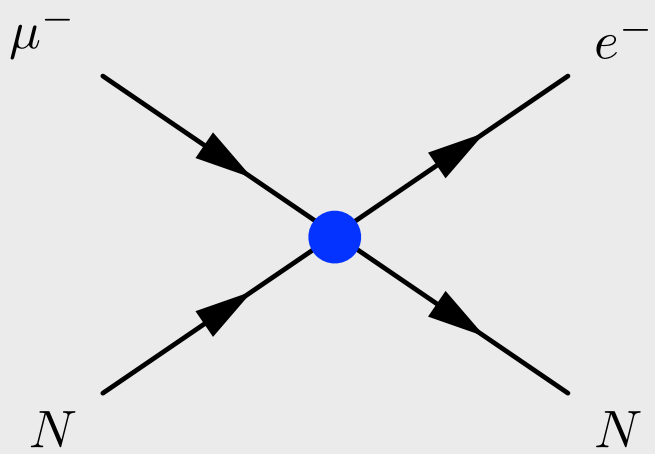
Supersymmetry and Heavy Neutrinos

Contributes to $\mu \to e\gamma$

(just imagine the photon is real)

mass scale Λ

"Contact Terms"

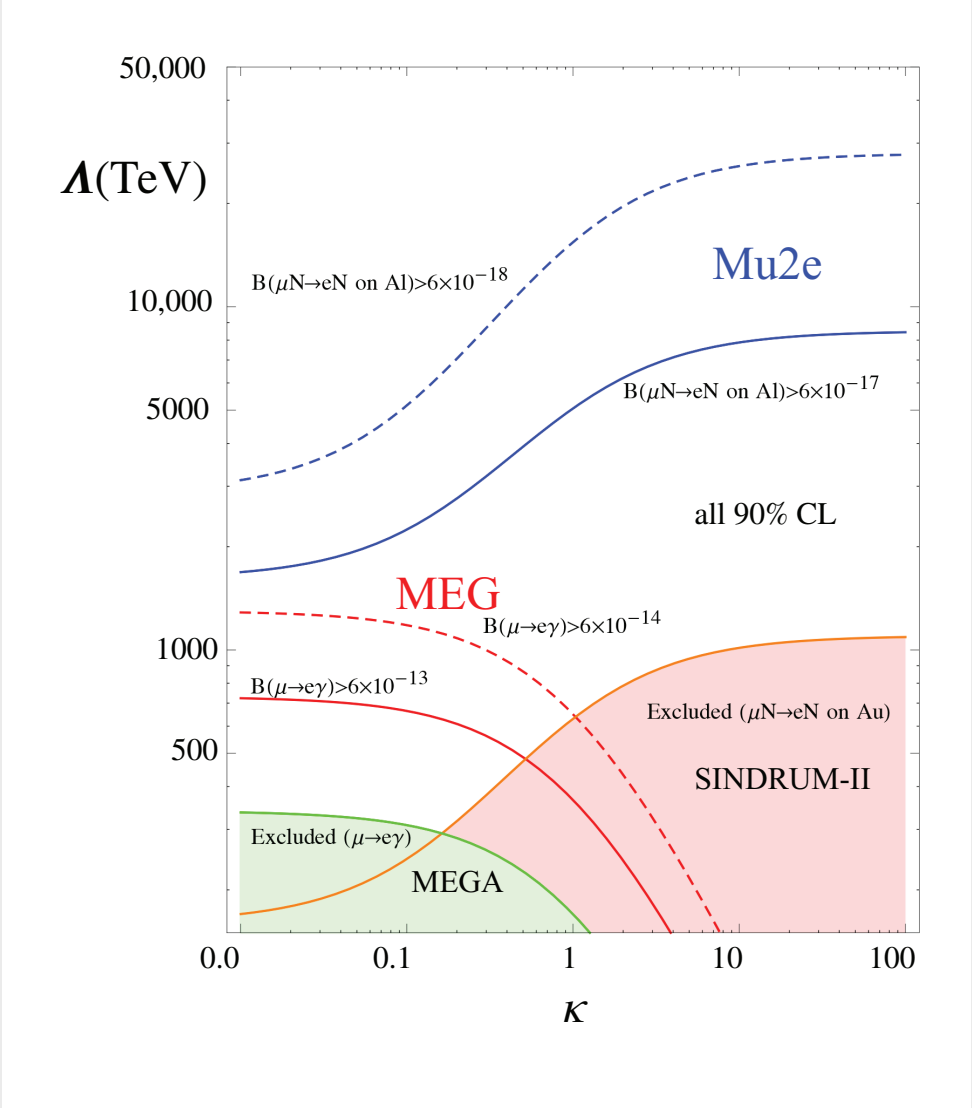


New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Does not produce $\mu \to e\gamma$

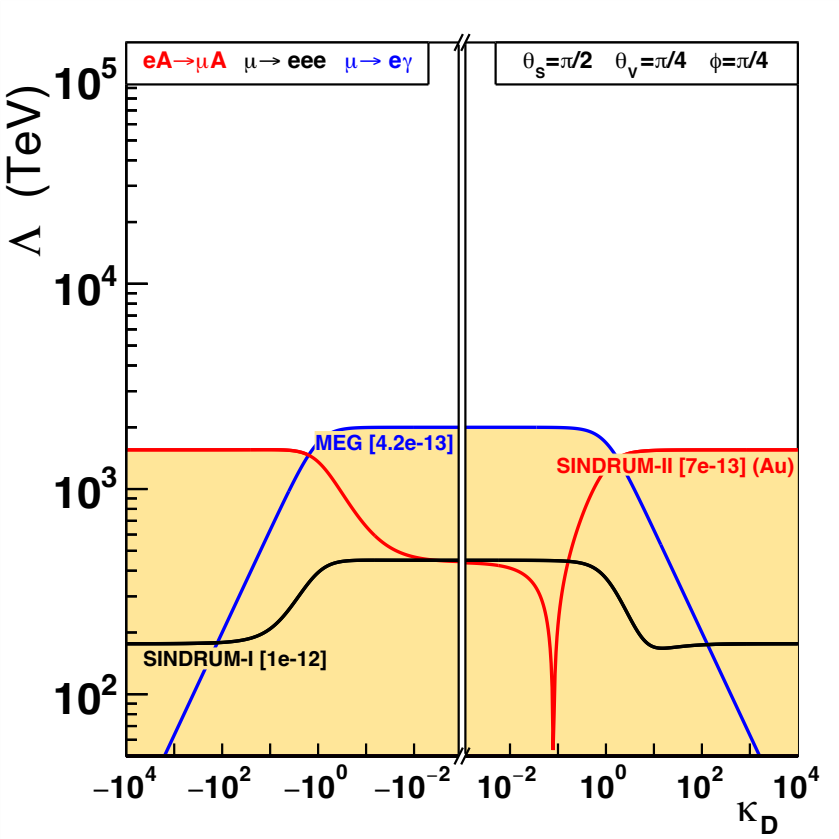
RF5:
$\mu \rightarrow e\gamma$ and $\mu^- N \rightarrow e^- N$

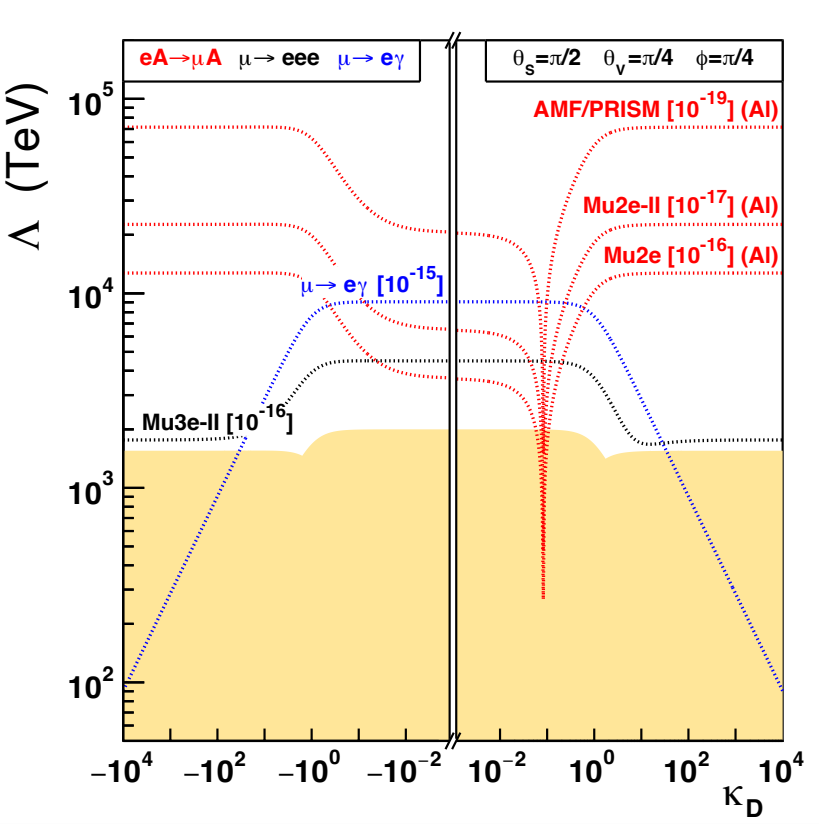
- Demonstrates reach up to 10^4 TeV/c^2 for Mu2e
- Complementarity of muon modes is evident.
- Can we combine PSI and FNAL programs?
- We can create a “big picture” with EFTs



RF5: Comparing muon modes

- $\mu \to e\gamma$ and $\mu \to 3e$ at $\mathcal{O}(10^{-15})$, $\mu^- N \to e^- N$ at $\mathcal{O}(10^{-18})$ are a next-generation target

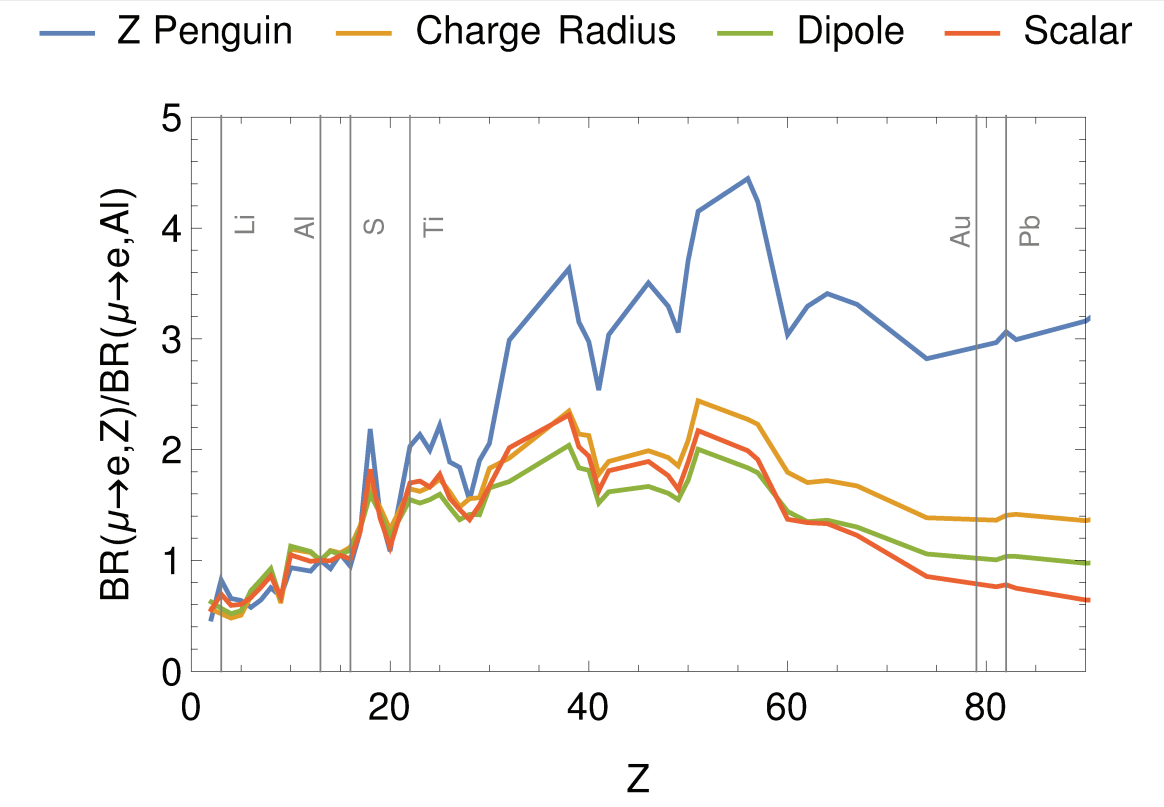




S. Davidson and B. Echenard, 2010.00317 [hep-ph]

RF5: Why Higher Z?

- Model Discrimination and Possibly Larger Signal at high *Z*
- if Mu2e sees a signal, this is the obvious next step
- if not, we should try for another x10-100 better constraints



adapted from V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**

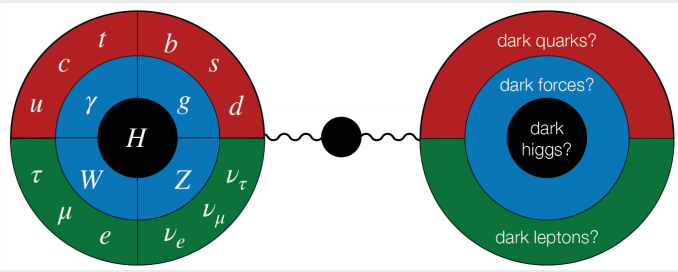
RF5: Future Muon Program at FNAL

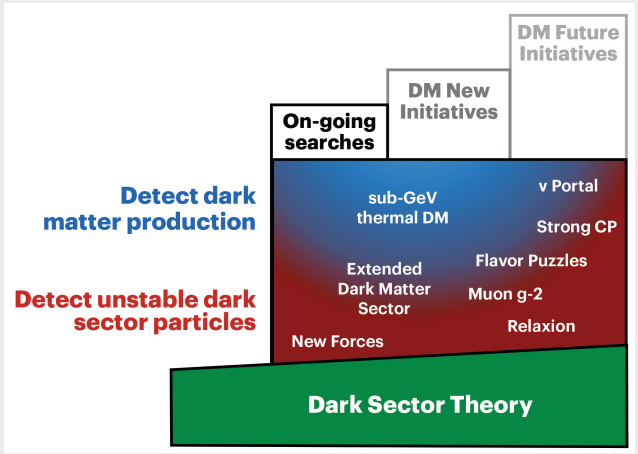
- **Mu2e-II, x10 improvement, go to intermediate-*Z* targets (medium-scale)**
  - relies on intensity provided by PIP-II
  - Mu2e technique has limits precluding high-*Z* materials.
- **An Advanced Muon Facility (AMF) hopes to do *all three* muon modes at next-generation levels and $\mu - e$ conversion at high *Z*, along with the $\Delta L = 2$ processes $\mu^- N \to e^+ N'$, and a muonium program**
  - not asking for approval — asking for endorsement of physics goals and R&D for feasibility. Potential DM experiment as well. R&D is $\mathcal{O}(\text{few})$ FTE's for a few years

    AMF is a "large" project
  - greatly enhanced by upgrades to FNAL complex (ACE)
  - many synergies with Muon Collider, especially high-power targeting in a solenoid; starting collaborative efforts with UK and Japan

RF6: Dark Sectors at High Intensities

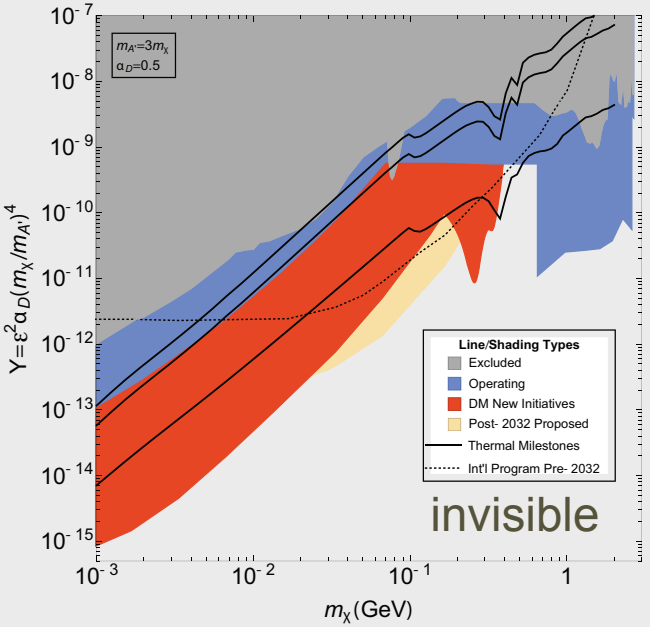
- An explosion of ideas in a major, exciting subfield addressing high priority questions
  - MeV to GeV dark matter and dark sector candidates; you heard about lower mass scales at CF Town Hall, more at BNL
- *Execute Dark Matter New Initiatives (DMNI) as the first step*
  - beyond DMNI: US needs an affordable, unique, and well-planned portfolio across the different portals, coordinated world-wide
- we need a process to determine the US role

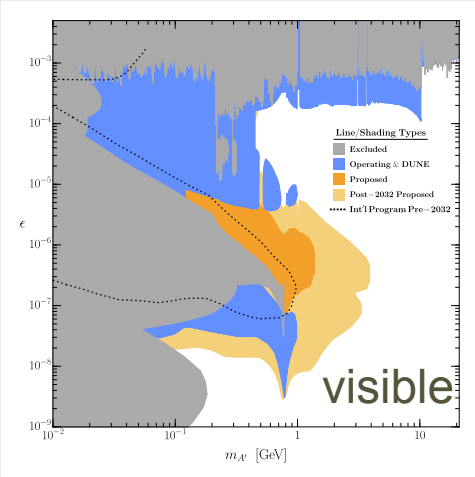




RF6: Portals and Experiments

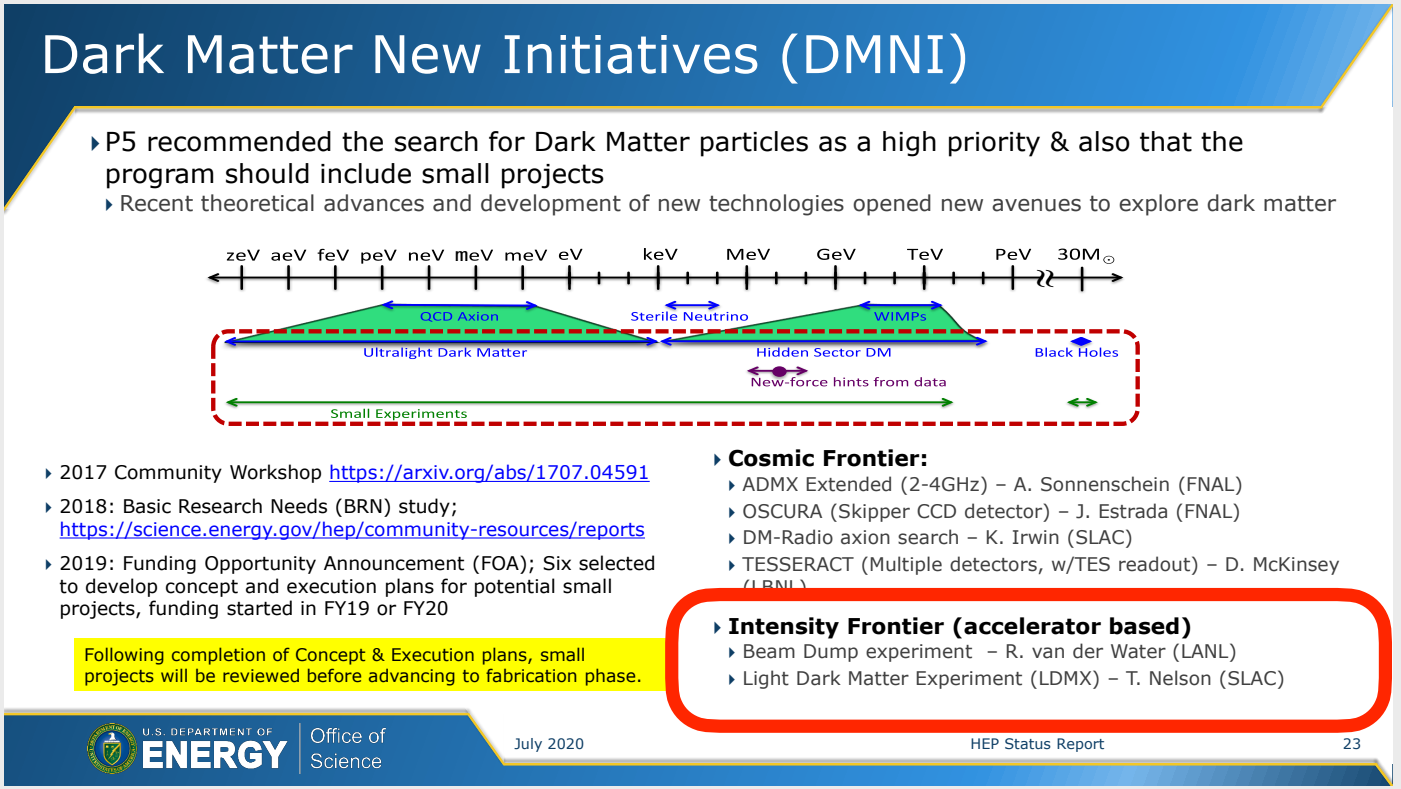
- Variety of “portals”
  - how does DM talk to visible matter?
- Experimentally: many techniques, what does US do?
  - invisible signatures (such as LDMX)
  - visible final states (observe the mediator, e.g. DarkQuest
- Enabled by the beams at SLAC and multiple energy beams at Fermilab (2, 8, 120 GeV)
- LHCb and Belle II also probe the dark sector
  - and CODEX-b or MATHUSLA for long-lived particles





RF6: Where We Are Now

- DOE recognizes the importance of DM and the importance of small projects

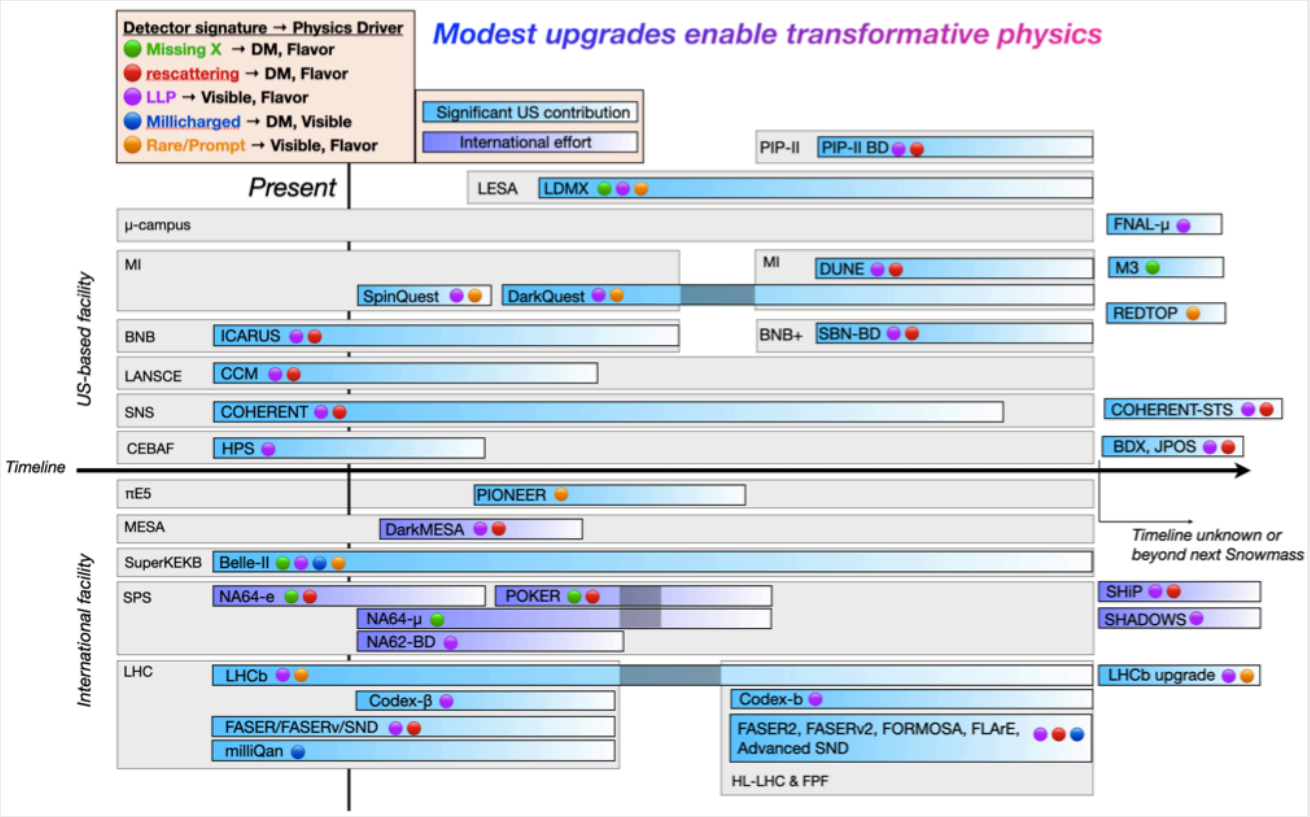


CCM and LDMX

Glen Crawford, https://science.osti.gov/-/media/hep/hepap/pdf/202007/05-Crawford-DOE_Report-HEP_Research_Program_Status.pdf

RF6: Where Next?

- *Our Frontier believes the US should pursue this physics*
- Many choices — we need a process to determine our future program



wide range of experiments at different facilities: more than DMNI!

Opportunity to craft a world-wide program in essential physics with US in a leading role!

Rare and Precision Frontier: Summary

- Three experimental programs:
  - support flavor physics at LHCb/Belle II
  - craft an accelerator-based dark sector program for the MeV to GeV mass range, taking advantage of accelerator upgrades and facilities around the world
  - R&D for a muon program at Fermilab
- Flavor Physics:
  - the physics of flavor and generations crosses all of HEP, and a unifying theme in RPF is flavor physics. A new driver reflects the centrality of this physics and our excitement about it!