Growing Expectations for New Physics

Chris Polly -- Fermilab

13th International Particle Accelerator Conference, Bangkok, Thailand

13 June 2022

Two particle physics Nobel prizes awarded in last 10 years!

- François Englert and Peter W. Higgs
  "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider" (2013)

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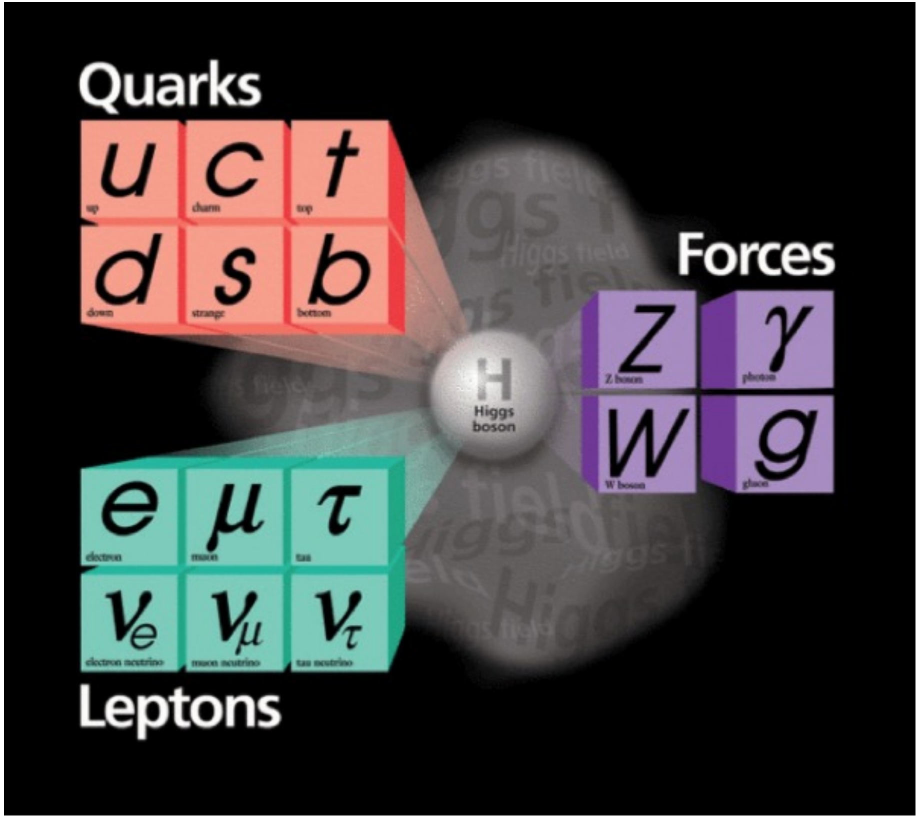
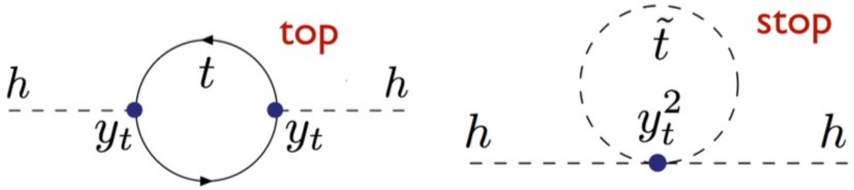
The Higgs motivates the search for new physics



- Higgs itself not new
  - Predicted in 1964
  - Precision EW fits → low mass
  - Conclusive discovery in 2012
- Naturalness puzzle suggests new physics
- Strongly motivates SUSY



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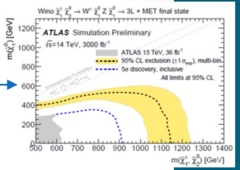
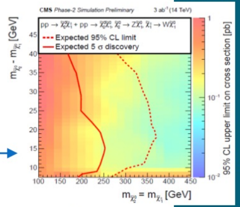
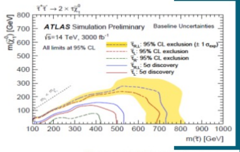
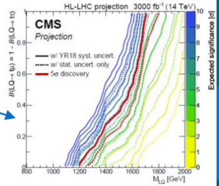
LHC Run 2 and HL-LHC continue to push into the unknown

		Channel	Run-2 Exclusion	HL-LHC Discovery	HL-LHC Exclusion
Wino-like electroweakinos	Wino-like X_1 X^0_2	WZ, Wh (3 leptons)	650 GeV	920 GeV	1150 GeV
	Wino-like X_1 X^0_2	h->bb (1 lep + 2 b-jets)	740 GeV	1080 GeV	1280 GeV
	Wino-like X_1 X_2	W + X^0_1	400 GeV	600 GeV	840 GeV
	Wino-like X_2 X_4	(Compressed higgsino + WW)			900 GeV
	Compressed spectrum. Direct X1 X^0_2 prod.	Dilepton + MET	205 GeV	250 GeV	360 GeV
Stau & Stop	Stau pairs	τ_{had} τ_{had}	120-390 GeV	110-530 GeV	430 -730 GeV
	Stop (Δm near m_{top})		300-630 (small Δm) 1250 GeV	650 (small Δm) - 1250 GeV	850 (small Δm) - 1700 GeV
	Stop (no stop decay to t)	bffX1 or cX1		2400 GeV	2600 GeV
Leptoquarks	Scalar LQ 3rd gen. Single production	τ + b	400 GeV	800 GeV	1130 GeV
	Scala LQ 3rd gen. Pair production	τ + b		1500 GeV	1518 GeV
	Scalar LQ pair prod.	tt -> μ/τ		1.2-1.7 TeV	1.4-1.9 TeV
	2HDMa	4 top		$\sin\theta < 0.35$ m_a<1 TeV m_H=600GeV $\sin\theta > 0.95$ m_a = 350 GeV m_H=1TeV	









https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-018/ATL-PHYS-PUB-2022-018.pdf

- No signs of SUSY yet at the LHC
- HL-LHC will explore significantly higher mass scales
  - Extends mass reach by a factor of 2 or more for many models/channels

Summary presented by Kerstin Hoepfner at recent Snowmass workshop

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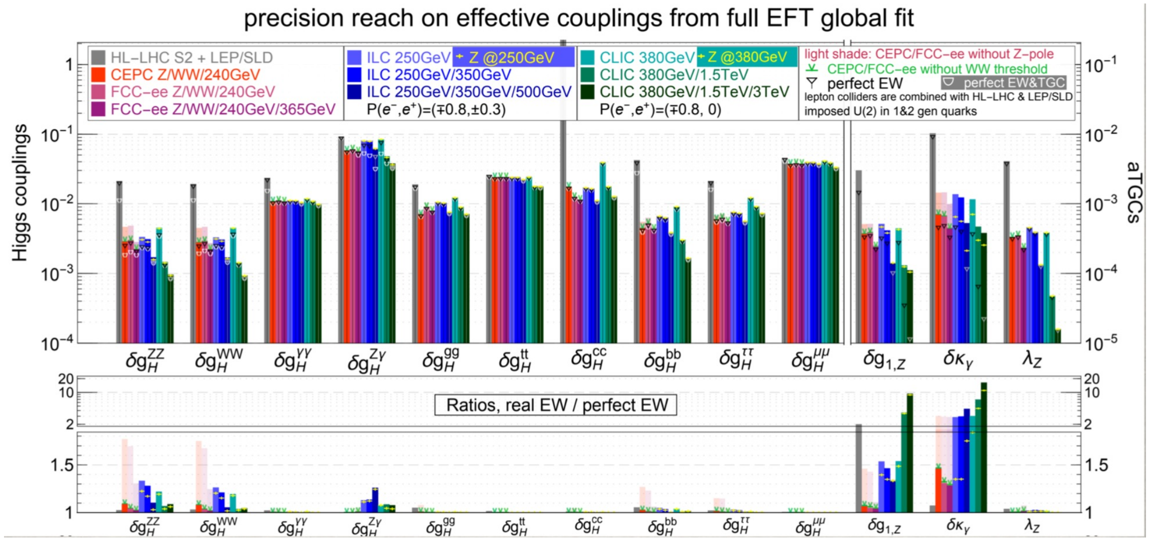
The Higgs opens an unprecedented window in the search for BSM

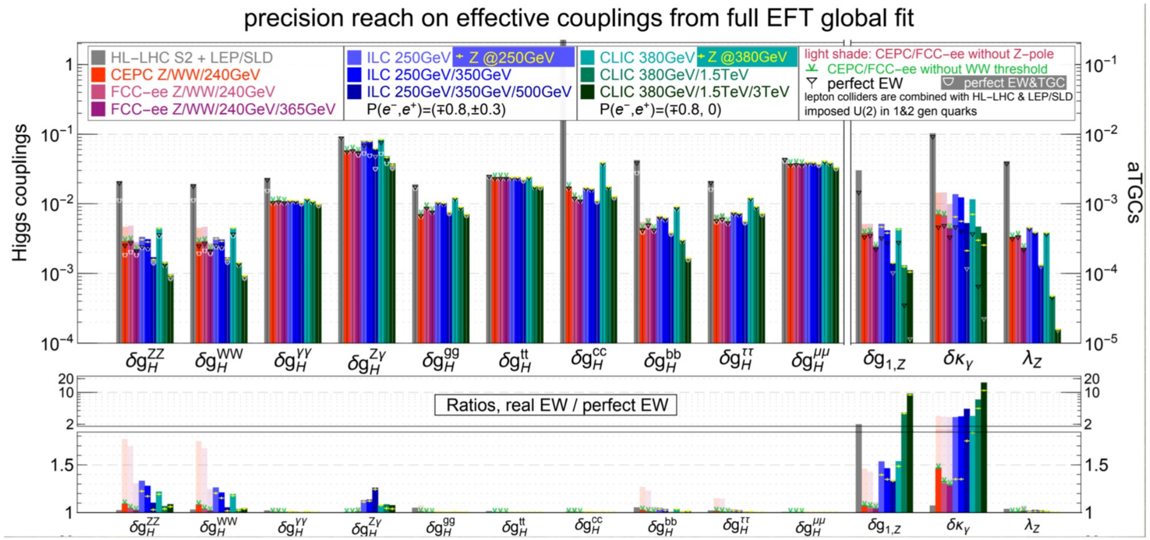


https://arxiv.org/pdf/1907.04311.pdf

- Higgs is extraordinarily unique, imbues mass to other particles
- Unique discovery potential at high precision lepton collider
  - Sub 1% couplings
- Technical questions remain
  - Circular vs linear?
  - Technology?
  - Location?
  - Upgradability?

No question **'must do'** next step for HEP!

The Higgs opens an unprecedented window in the search for BSM



https://arxiv.org/pdf/1907.04311.pdf

8 options actively under study

Name	Nominal COM energy and peak luminosity per IP at nominal energy
FCC-ee	e+e-, $\sqrt{s} = 0.24$ TeV, L= 8.5 $\times 10^{34}$
CEPC	e+e-, $\sqrt{s} = 0.24$ TeV, L= 8.3 $\times 10^{34}$
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.35 $\times 10^{34}$
CCC (Cryo Cooled Collider)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 1.3 $\times 10^{34}$
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.38$ TeV, L= 1.5 $\times 10^{34}$
CERC (ERL ee collider)	e+e-, $\sqrt{s} = 0.24$ TeV, L= 78 $\times 10^{34}$
ReLiC (Linear ERL Collider)	e+e-, $\sqrt{s} = 0.24$ TeV, L= 165 $\times 10^{34}$
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25$ TeV, L= 90 $\times 10^{34}$
XCC FEL-based $\gamma\gamma$ collider	ee $(\gamma\gamma)$, $\sqrt{s} = 0.125$ TeV, L= 0.1 $\times 10^{34}$
MC (Higgs factory)	$\mu\mu$, $\sqrt{s} = 0.13$ TeV, L= 0.01 $\times 10^{34}$

Thomas Roser – EF Workshop

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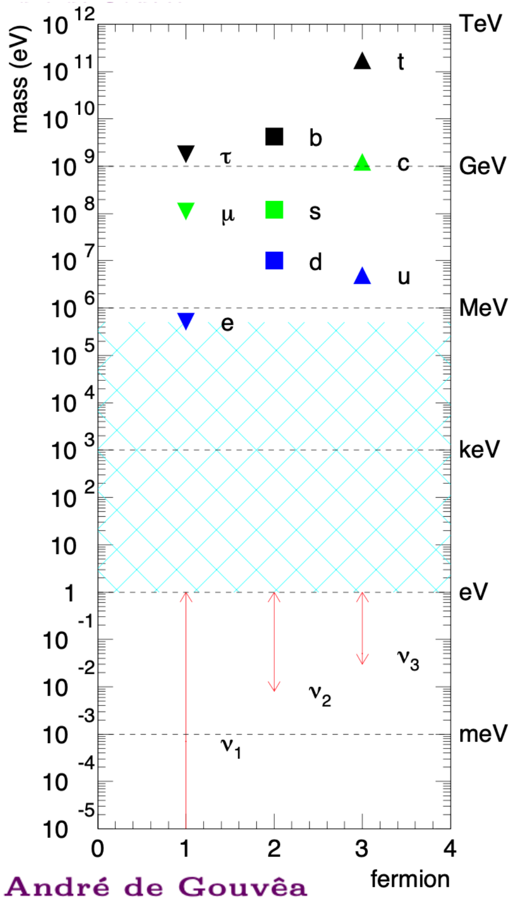
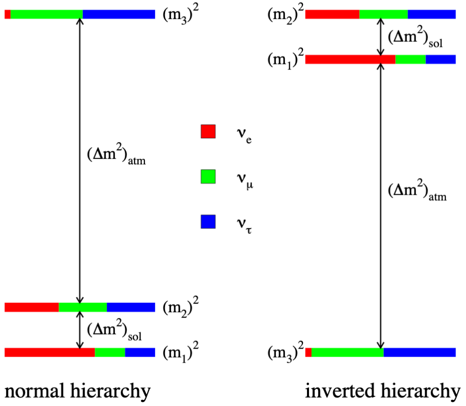


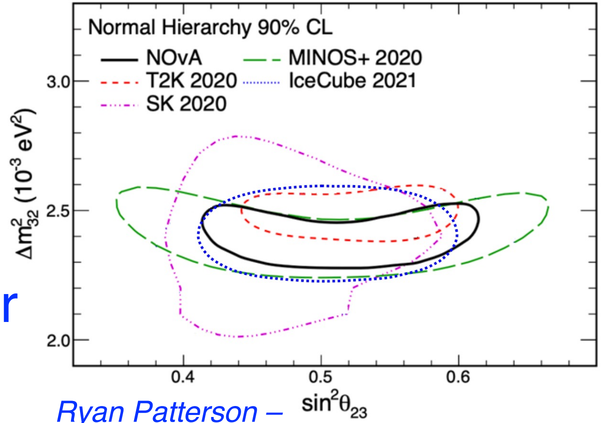
André de Gouvêa

Neutrino mixing is new physics

- Solar ν proved mixing → mass
  - Why so light? Seesaw?
- Accelerator expts, T2K/NOvA and K2K/MINOS, (with reactors) have mapped the PMNS matrix
- More mysteries
  - Hyperfine-like mass splitting inverted or normal?
  - θ_{23} maximal?
- And the big question...

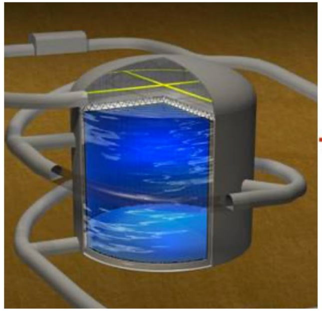
Will CP violation in the ϖ sector provide a clue to the missing antimatter in the universe?

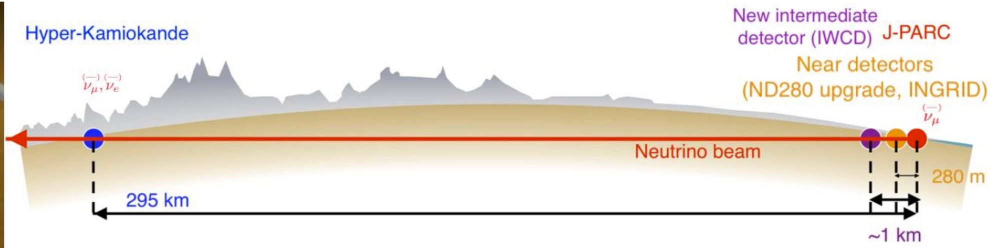


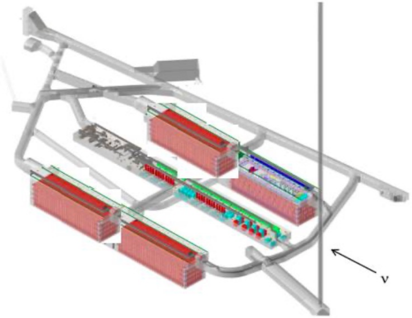


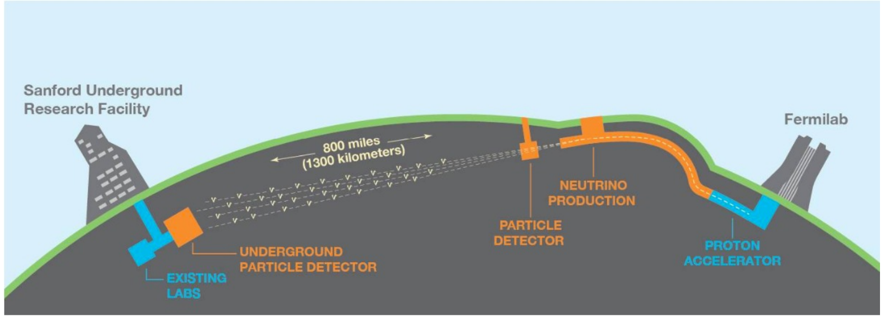
Ryan Patterson – Snowmass Neutrino Colloquium

Next-generation long baseline experiments









Ryan Patterson – Snowmass Neutrino Colloquium

- HyperK and DUNE/LBNF driving upgrades at J-PARC and FNAL
- HyperK water mass and DUNE liquid Ar precision very complementary
- Together, taking ν oscillations into a new era of precision
- Strong possibility of discovering CP violation

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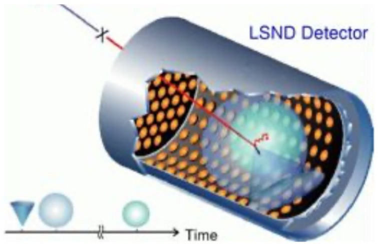
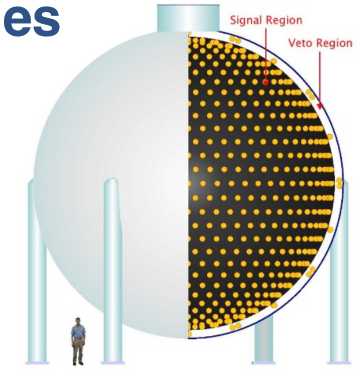
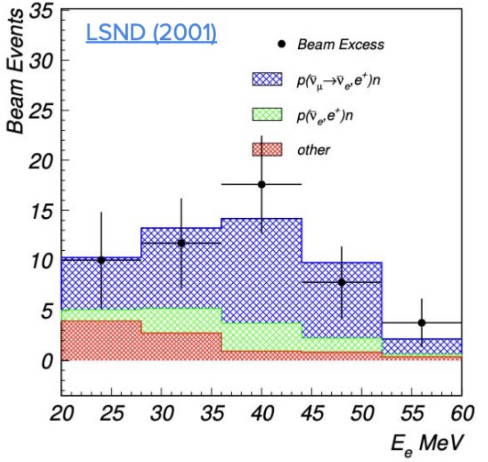
LSND/MiniBooNE Anomalies

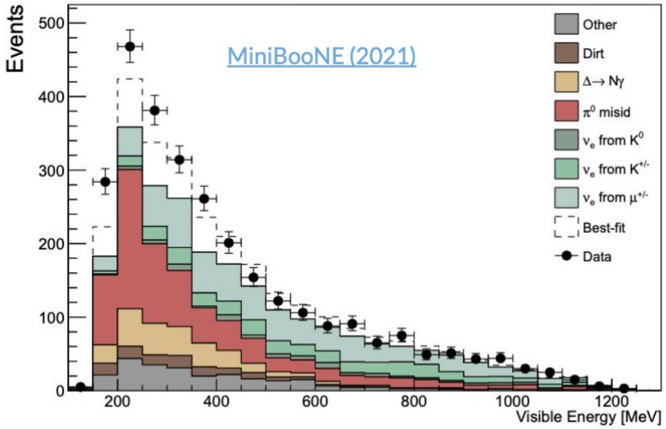




excess $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ dominated beam, 3.8σ

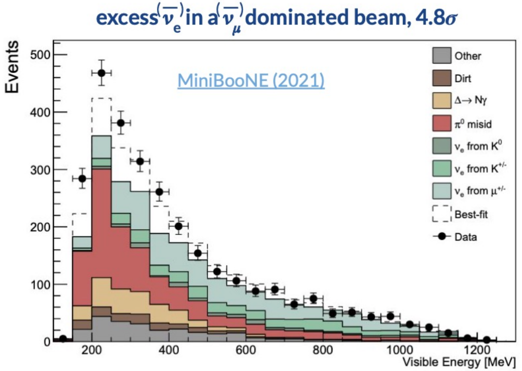


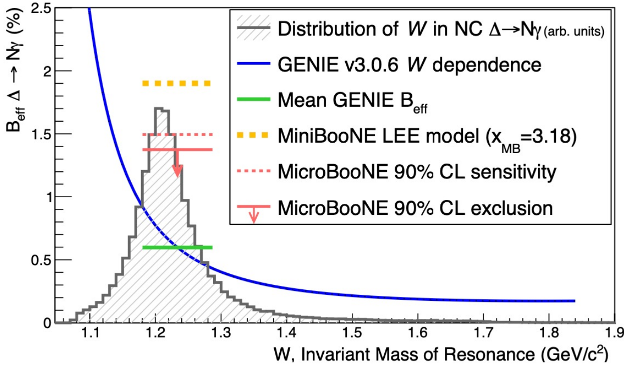
excess $\overset{(-)}{\nu}_e$ in a $\overset{(-)}{\nu}_\mu$ dominated beam, 4.8σ



- LSND and MiniBooNE(MB) observed an excess of ν_e-like events in a ν_μ beam
- Led to the sterile ν hypothesis
- ν_μ disappearance at long baseline expts ruled out simple oscillation models

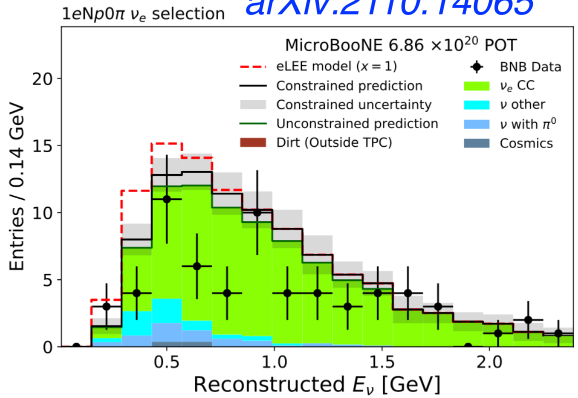
New results from MicroBooNE

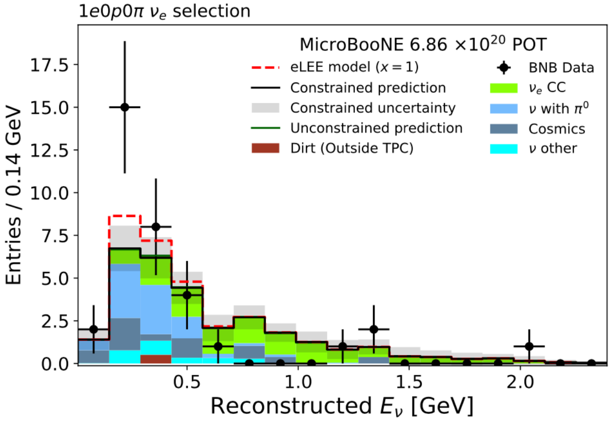




arXiv:2110.00409

arXiv:2110.14065



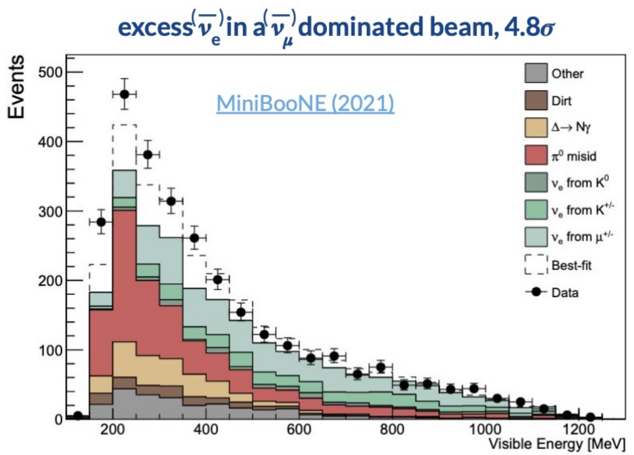


- Built just upstream of MB
  - Pioneered larger LAr TPC and reconstruction
  - Check for low E excess with ability to separate e/γ
- Ruled out Δ→Nγ at 94% CL
- Ruled out e from ν_e at 90% CL
- Question still remains... what is the source of the excess?

Could dark matter be the answer?

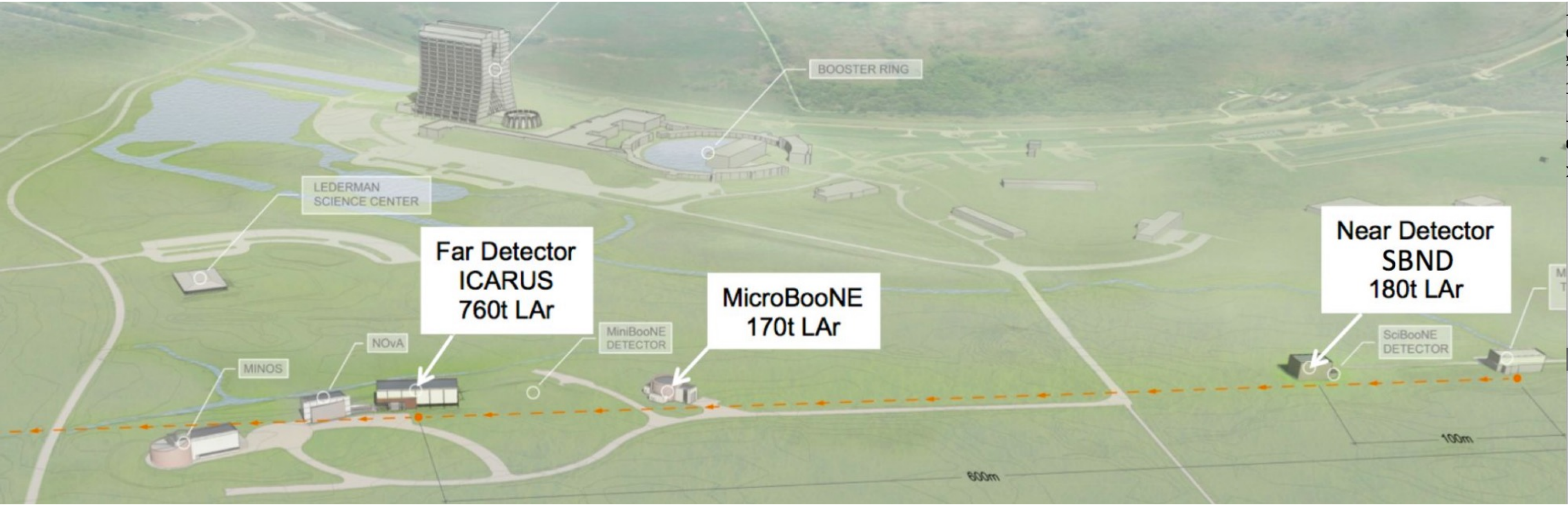
Category	Model	Signature	Anomalies	
			LSND	MiniBooNE
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓
	dark particle-induced inverse Primakoff	γ	✓	✓

Georgia Karagiorgi – Snowmass Neutrino Colloquium



- MB excess likely single γ
  - Misestimated NC π^0?
- Many dark sector models can generate γ in MB
  - Some contribute to LSND

Looking forward to more experimental data



- More analyses from MicroBooNE in progress
- New short-baseline neutrino program just getting started
  - Adding a LAr near detector (SBND) and larger far detector (ICARUS)

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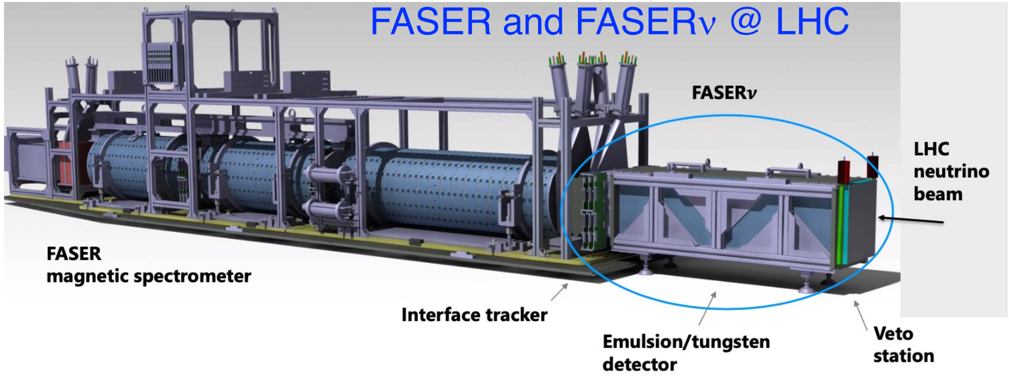
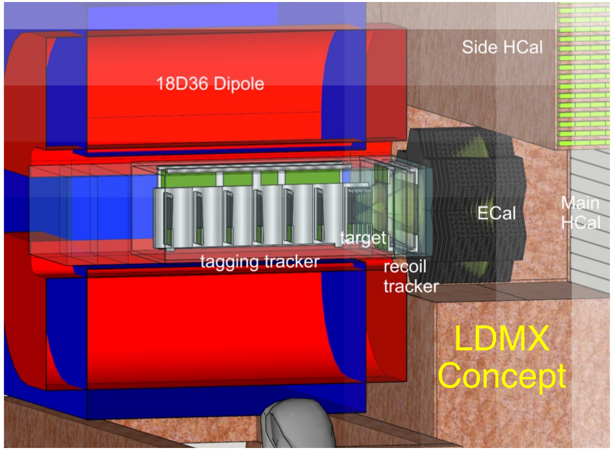
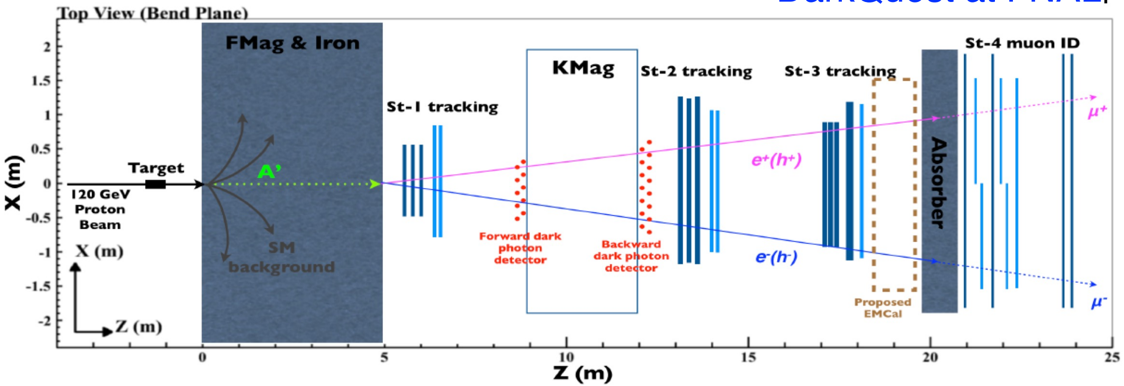
Accelerators are playing an increasingly larger role in DM searches



- Many past parasitic collider and beam dump style experiments
- New generation of proposals tailored to DM portal searches
  - DM rescattering or decay
  - Millicharged
  - Missing momentum



DarkQuest at FNAL.



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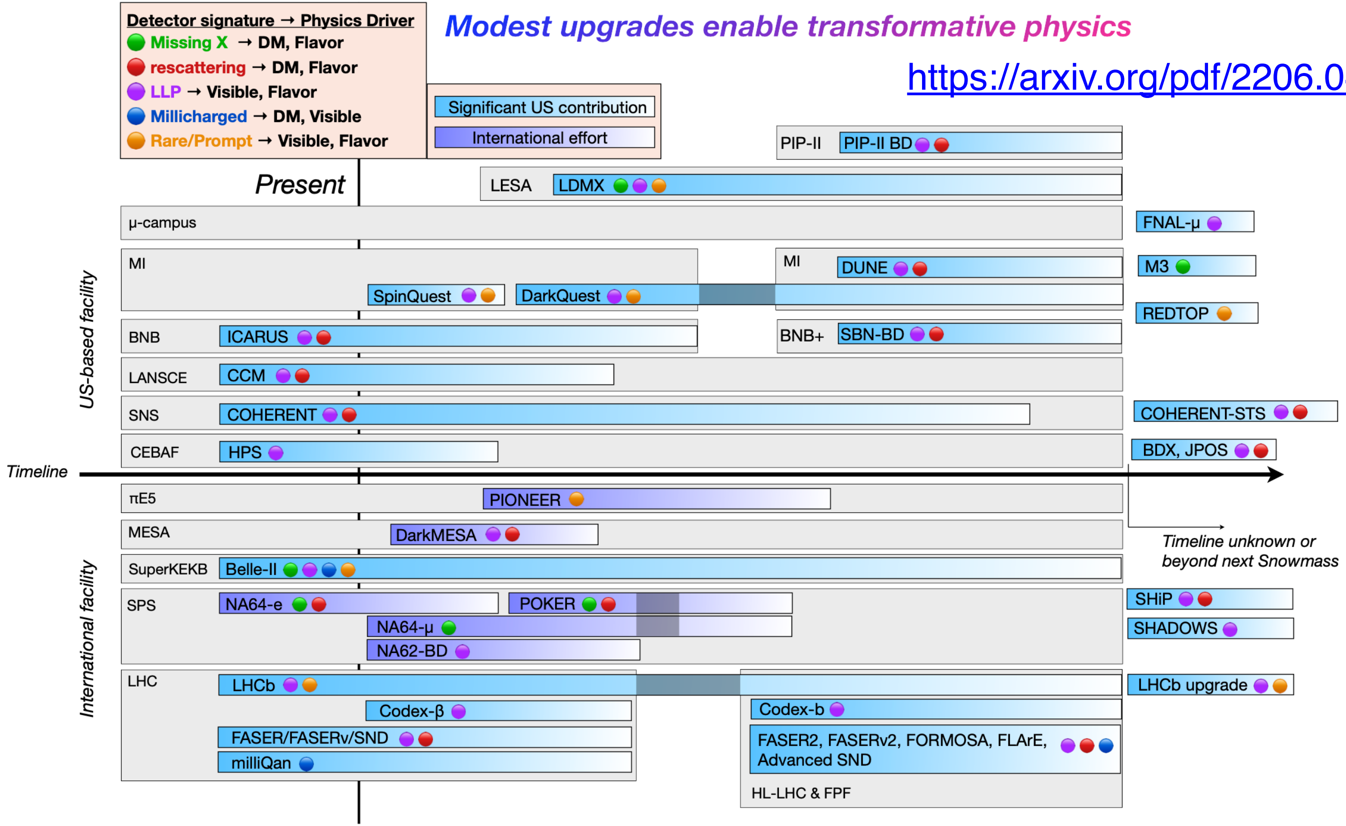
International effort with many current experiments and future proposals

Modest upgrades enable transformative physics

https://arxiv.org/pdf/2206.04220.pdf



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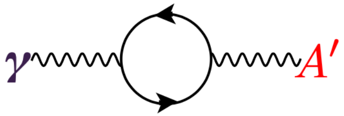
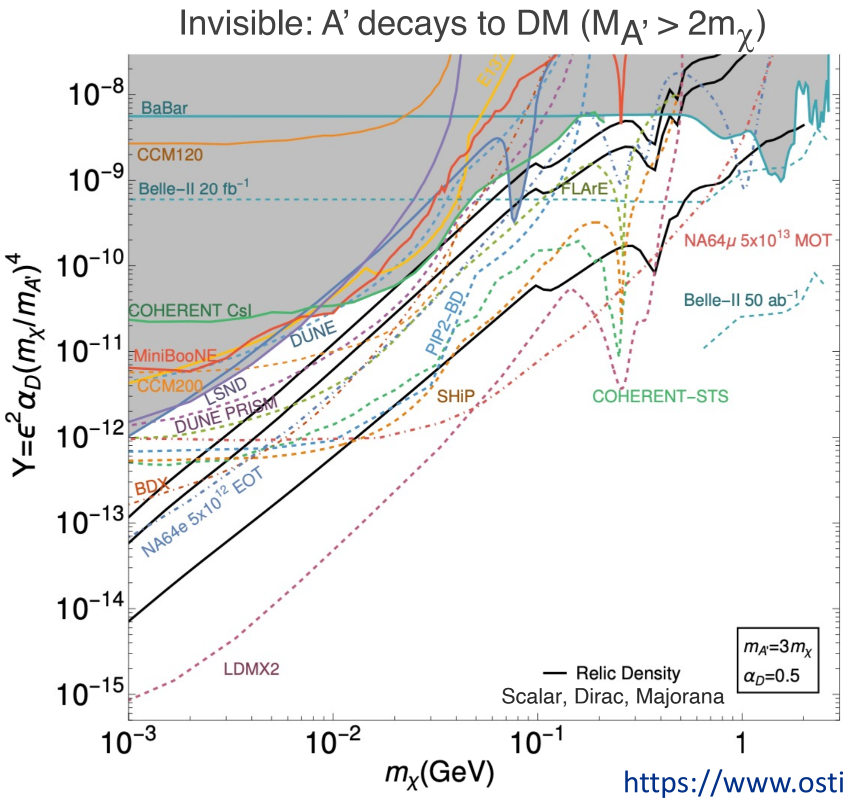
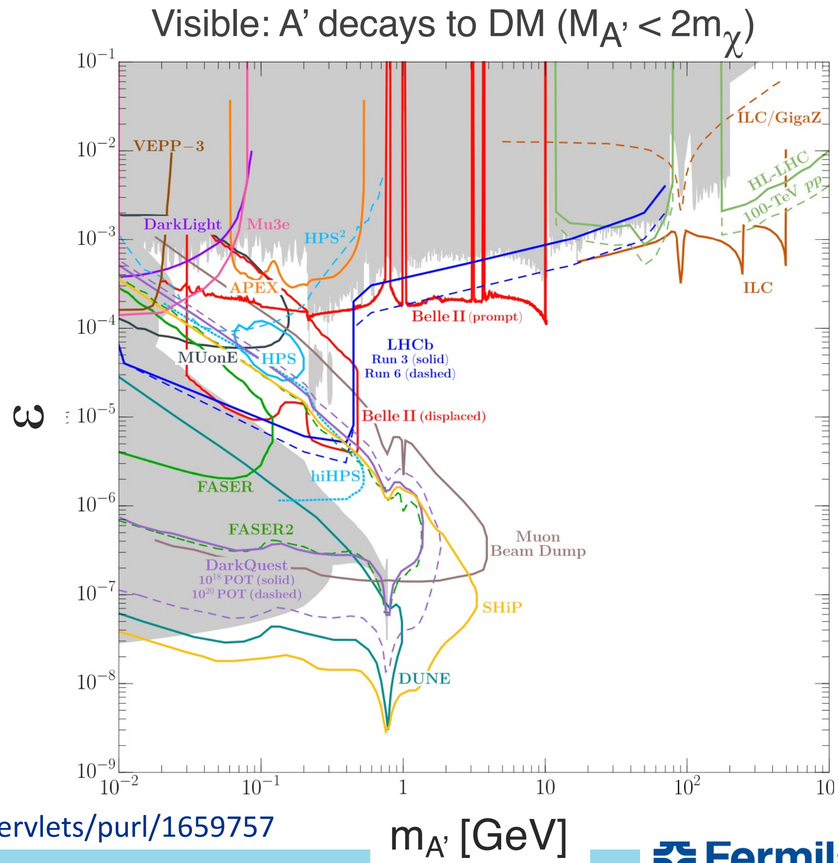
Dark photon vector portal







https://www.osti.gov/servlets/purl/1659757

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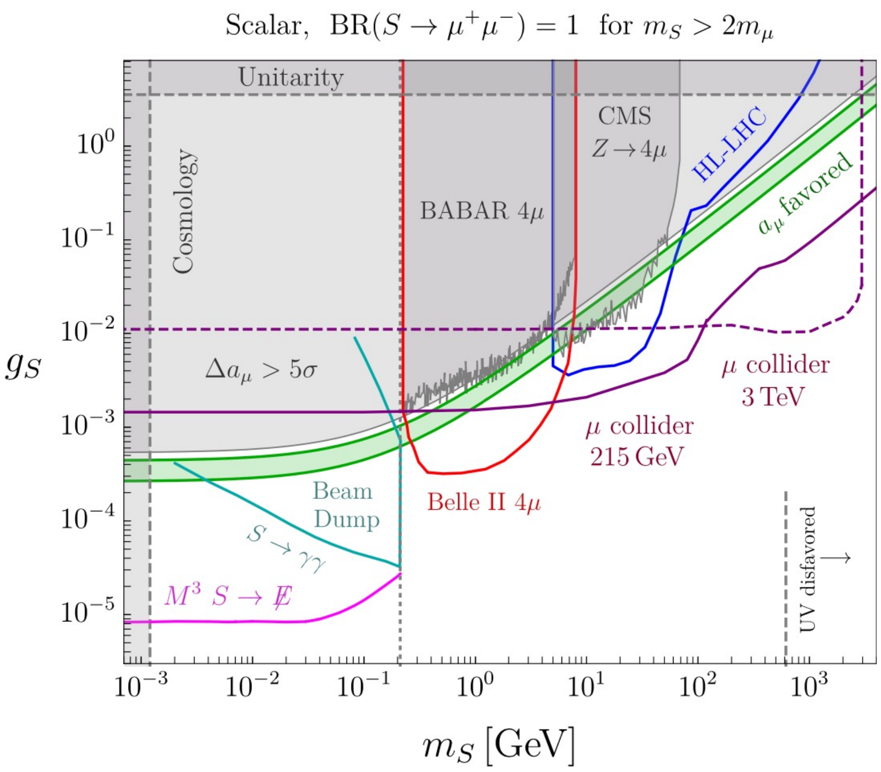
Direct tests of muon-phillic scalar couplings to DM



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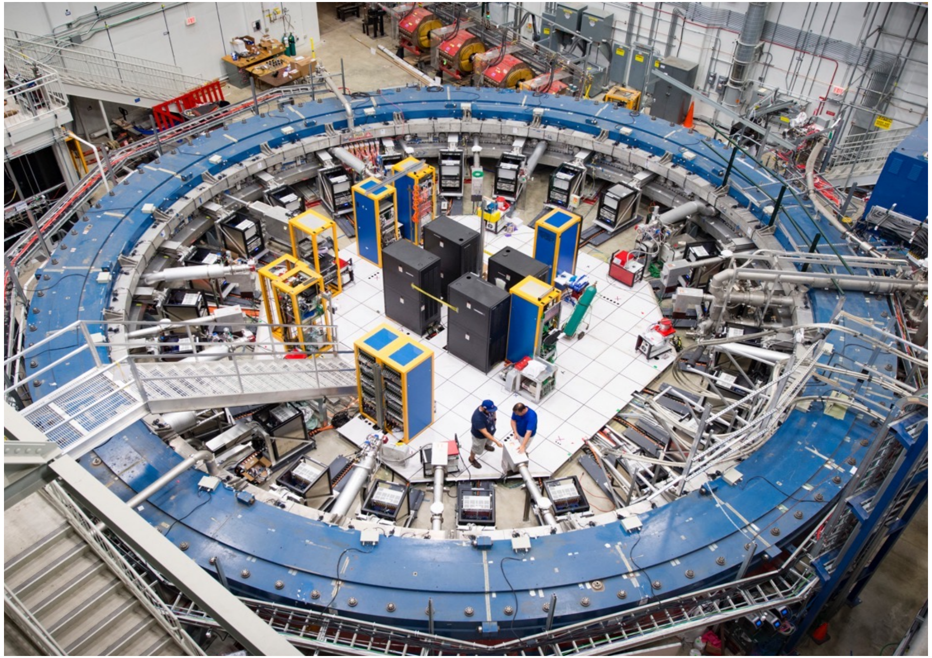
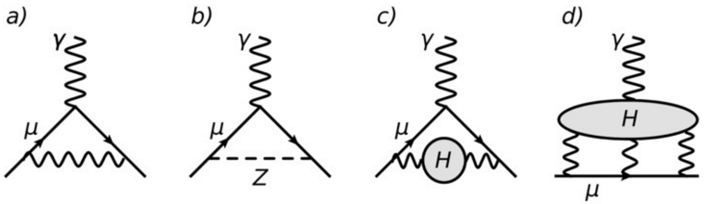
Muon g-2 discrepancy



$$\vec{\mu} = g\frac{e}{2m}\vec{S} \qquad a_\mu = \frac{g-2}{2}$$

- Muon g-2 at FNAL aims to measure the anomalous magnetic moment to 140 ppb (achieved 460 ppb Run 1)
- Sensitive to new particles and forces entering at the loop level
- Interpretation requires a robust SM calculation for comparison

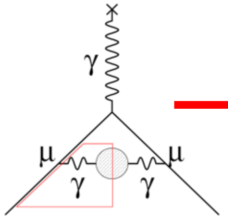
Standard Model calculation of a_μ

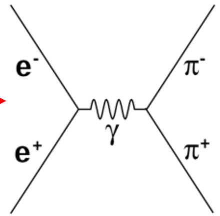


Source	Value (a_μ x 10^{-11})	Error
a) QED	116 584 718.9	0.1
b) EW	154	1
c) HVP	6845	40
d) HLBL	92	18

Muon g-2 Theory Initiative arXiv:2006.04822

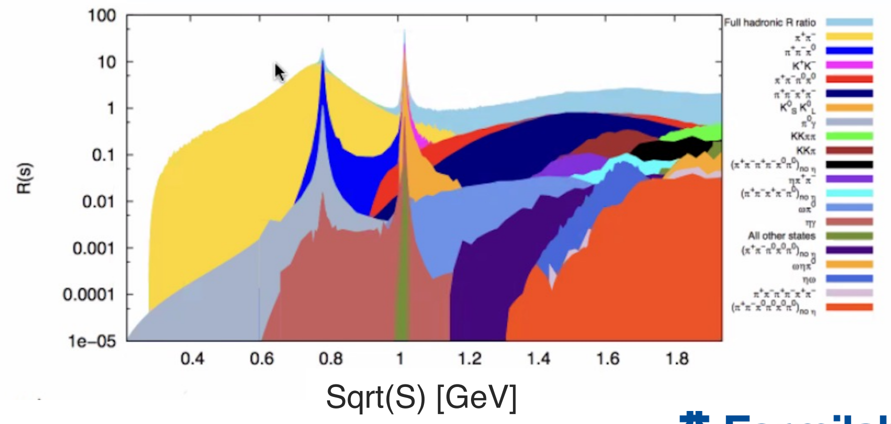
- QED and EW are extremely well known
- Hadronic terms are more difficult due to non-perturbative nature of QCD
  - HVP can be determined from $e^+e^- \rightarrow$ hadrons data





$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$



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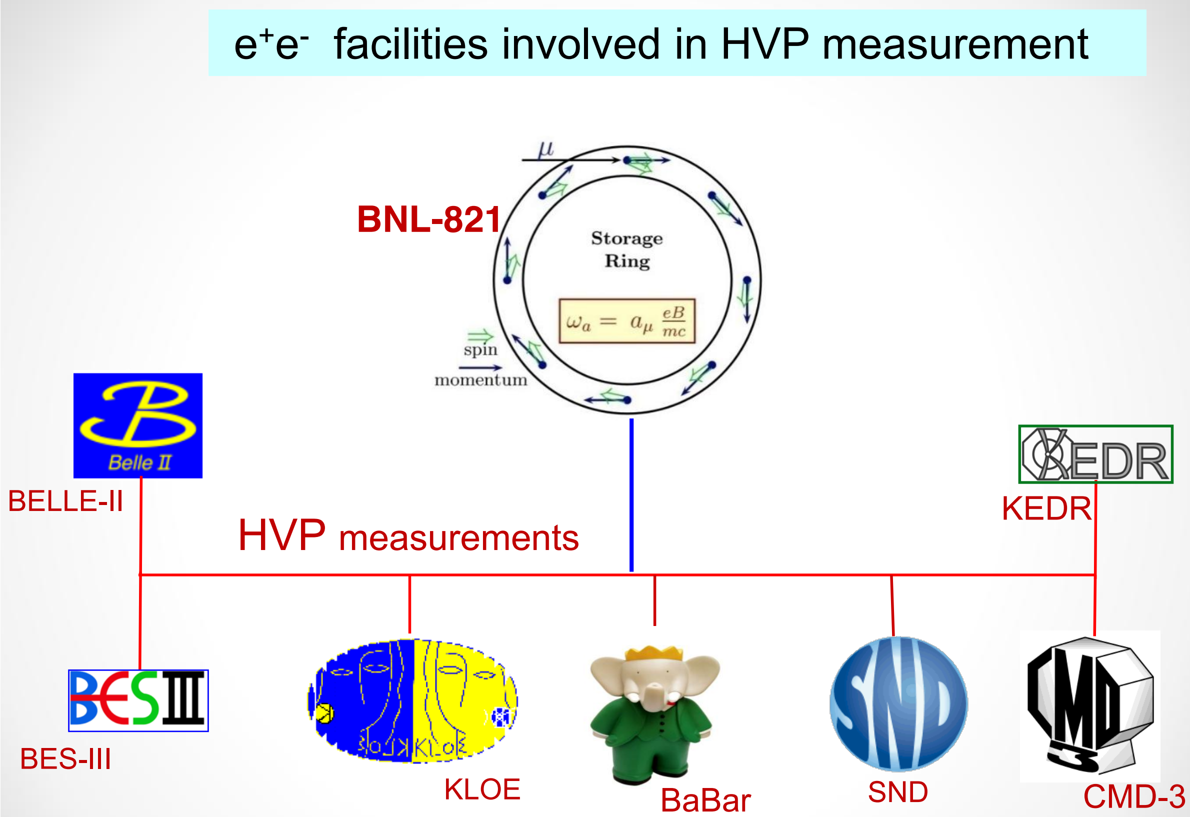
Worldwide effort from colliders for e+e- → hadronic final states



- Upgraded machine and detectors at Novosibirsk to adding more data up to sqrt(s) < 2 GeV, 2π final state particularly important
- B factories providing data on higher multiplicity states

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The FNAL experiment published it’s first result last year!

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, mostly sunny, remaining quite mild for early April, high 67. **Tonight,** partly cloudy, low 48. **Tomorrow,** variably cloudy, a bit cooler, high 62. Weather map, Page B10.

VOL. CLXX .... No. 59,022 — © 2021 The New York Times Company — NEW YORK, THURSDAY, APRIL 8, 2021 — $3.00

Biden Tax Plan Aims to Curtail

Contagious Variant Is Fueling Surge in Infections Across the U.S.

Some states where new cases of the coronavirus are rising have been hit hard by the B.1.1.7 variant. Page A6.

PAIR OF SETBACKS FOR ASTRAZENECA

would have applied to companies with $100 million or more in profits per year.

Continued on Page A18

reached a record high, the Islamic State has trumpeted these battlefield wins to project an image of strength and inspire its support-

researchers.

"As an organization more broadly, ISIS is hurting," said Col-

Continued on Page A11

the pandemic. The effort — a $2.1 billion fund in the state budget — is by far the biggest of its kind in the country and a sign of the

budget deal that was reached on Tuesday, was one of the most contentious points of debate during

Continued on Page A16

in Europe, the safety concerns have delayed inoculations, sunk confidence in the shot and created

Continued on Page A9

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A19

REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

PINEDALE, Wyo. — Kenna Tanner and her team can list the cases from memory: There was the woman who got tired and did not feel like finishing her hike; the campers, in shorts during a blizzard; the base jumper, misjudging his leap from a treacherous granite cliff face; the ill-equipped snowmobiler, buried up to his neck in an avalanche.

All of them were pulled by Ms. Tanner and the Tip Top Search and Rescue crew from the rugged Wind River mountain range in the last year, in this sprawling, remote pocket of western Wyoming. And all of them, their rescuers said, were wildly unprepared for the brutal backcountry in which they were traveling.

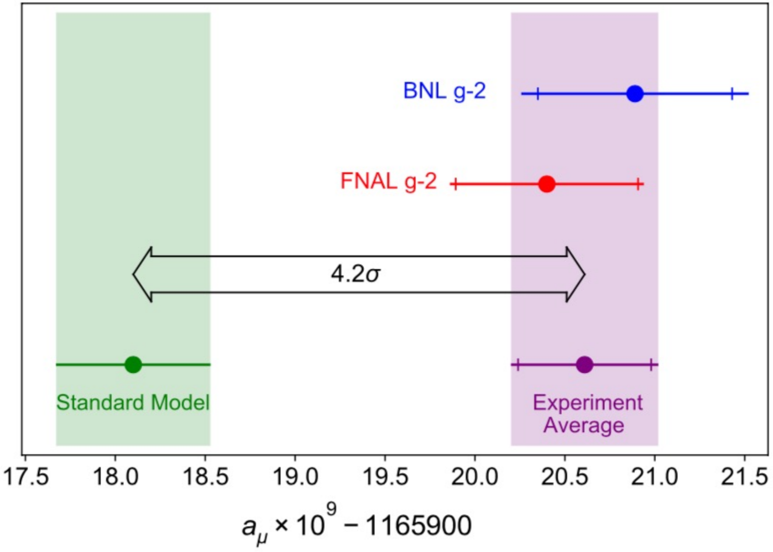
"It is super frustrating," said Ms. Tanner, Tip Top's director. "We just wish that people respected the risk."

In the throes of a pandemic that has made the indoors inherently dangerous, tens of thousands more Americans than usual have flocked outdoors, fleeing crowded cities for national parks and the public lands around them. But as these hordes of inexperienced adventurers explore the treacherous terrain of the backcountry, many inevitably call for help. It has strained the patchwork, volunteer-based search-and-rescue

Continued on Page A17

MAX WHITTAKER FOR THE NEW YORK TIMES

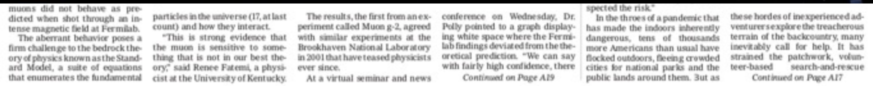
A trail in the Wind River Range in western Wyoming.



- Good agreement with BNL
- Raises tension with SM to 4.2σ

Fermilab

The FNAL experiment published it’s first result last year!



muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

“This is strong evidence that the muon is sensitive to something that is not in our best theory,” said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. “We can say with fairly high confidence, there

Continued on Page A19

spected the risk.”

In the throes of a pandemic that has made the indoors inherently dangerous, tens of thousands more Americans than usual have flocked outdoors, fleeing crowded cities for national parks and the public lands around them. But as these hordes of inexperienced adventurers explore the treacherous terrain of the backcountry, many inevitably call for help. It has strained the patchwork, volunteer-based search-and-rescue

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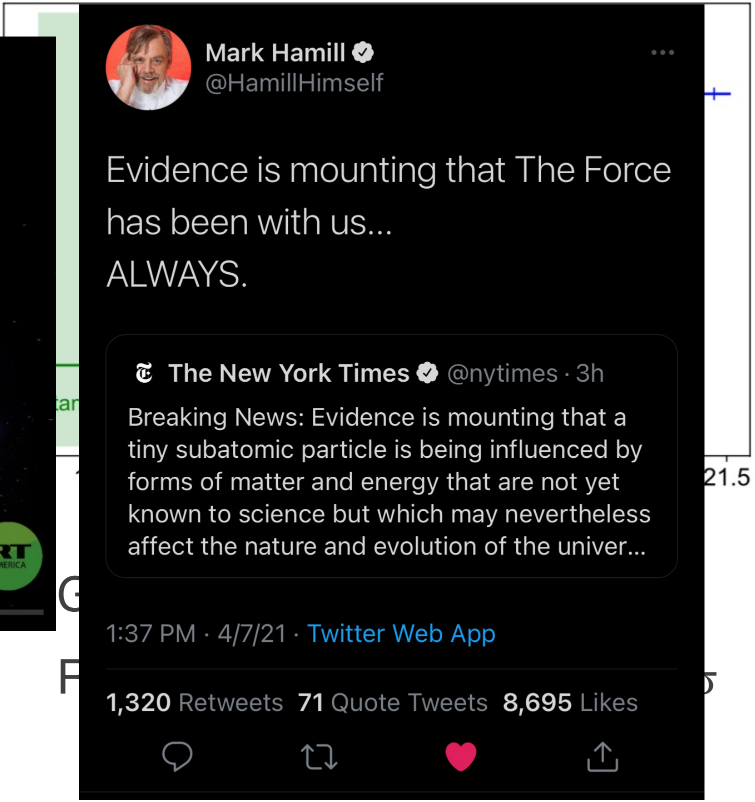
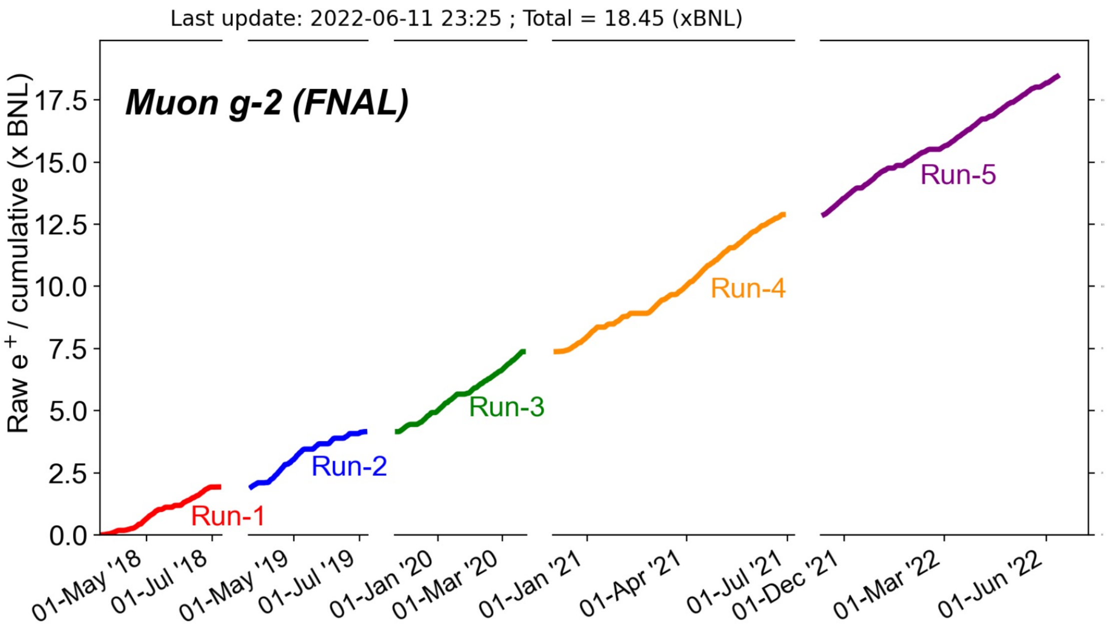


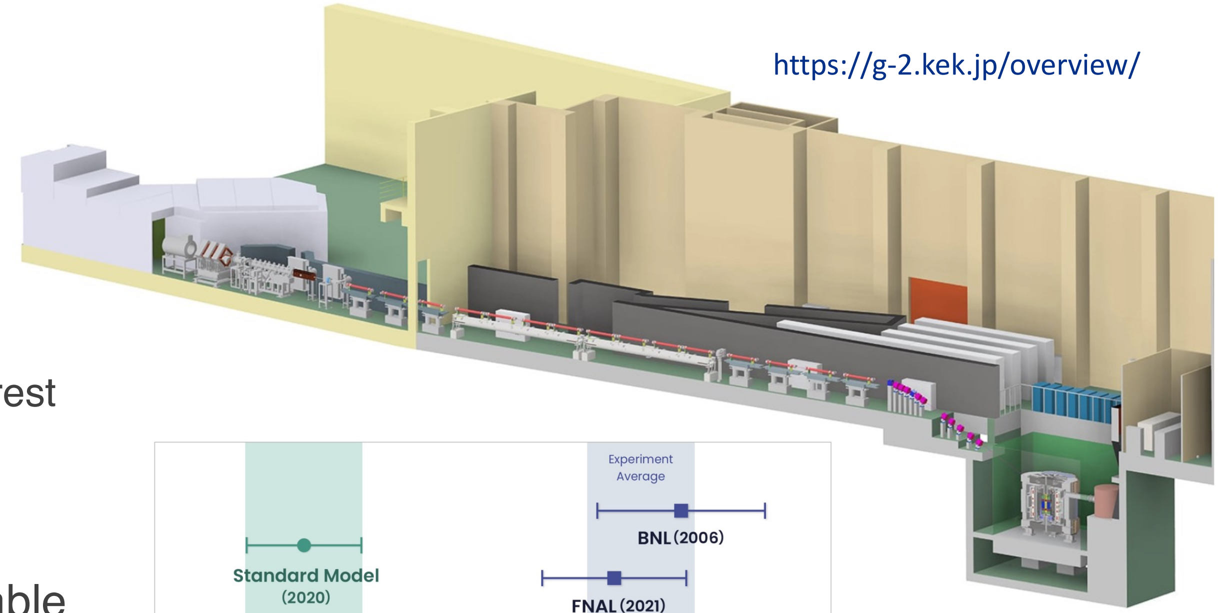
Fermilab

Experimental outlook for Muon g-2



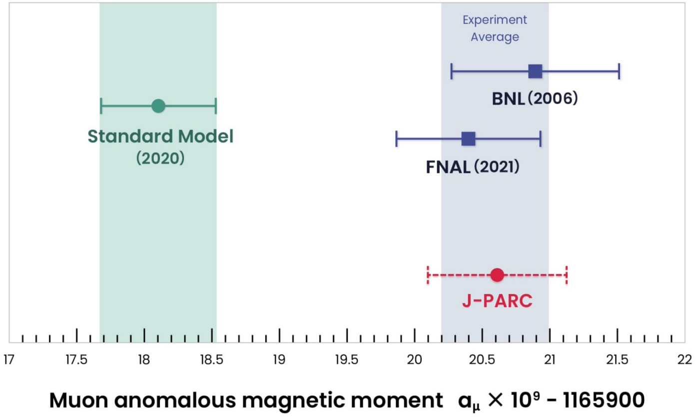
- Run 1 result ~1.2 x BNL
- Aiming for a Run 2/3 publication by spring reducing error by ~2
- Run 5 wrapping up and approaching 20x BNL goal
- Experiment switching to μ- next year

Muon g-2 at J-PARC

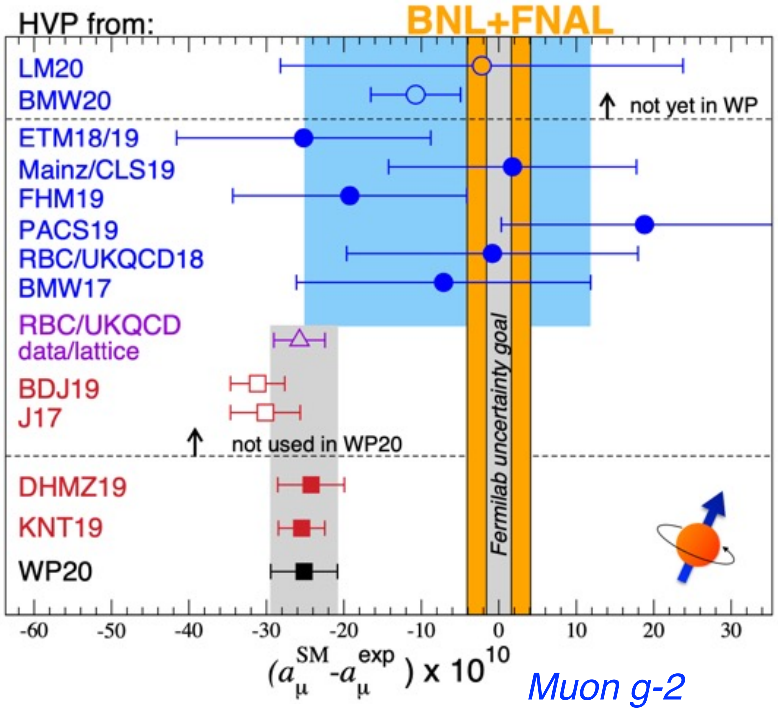


https://g-2.kek.jp/overview/

- Complimentary technique
  - μ beam accelerated from rest
  - no E fields
  - smaller magnet
- Aiming for a result comparable to current results towards the end of the decade

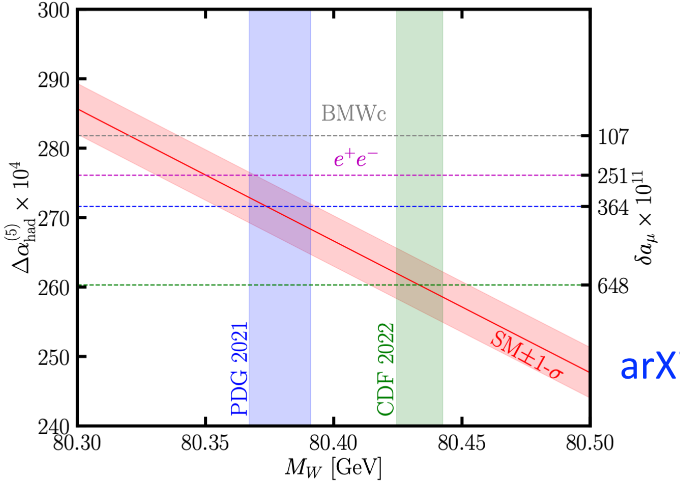


Lattice calculation for Muon g-2 making rapid progress on HVP



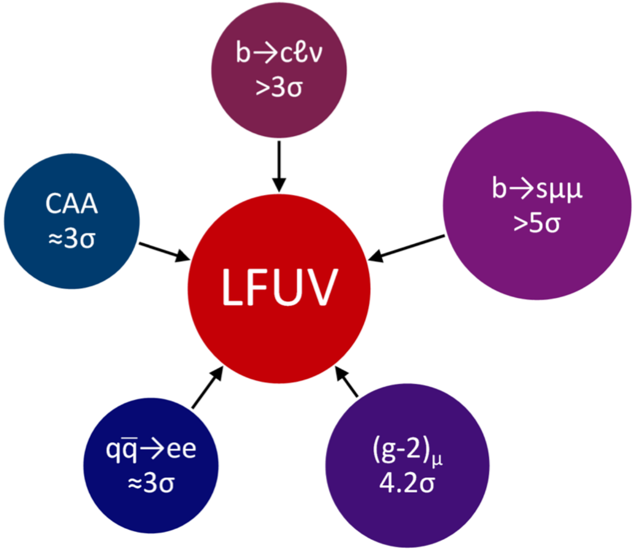
Muon g-2 Theory Initiative

- First result with e+e- competitive error bars came from a hybrid approach (RB/UKQCD)
- Pure lattice calculations trend towards larger quark contributions to a_μ (blue band)
  - Updated BMW20 in ~2σ tension with e+e-
- Increasing quarks moves tension in SM fits



arXiv:2204.03996

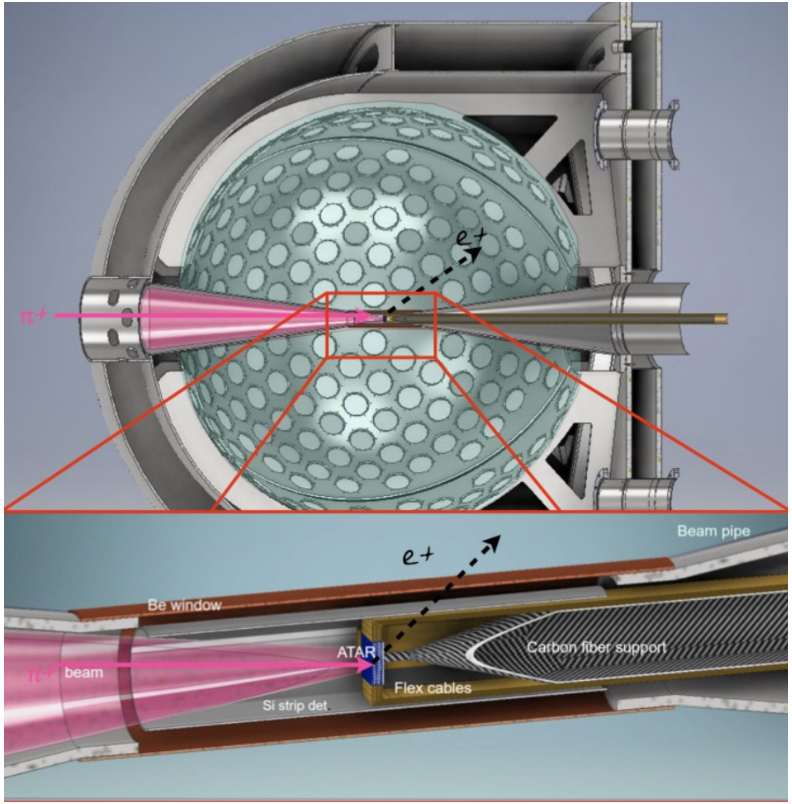
Are we seeing the hints for violation of Lepton Flavor Universality



Mounting Evidence for the Violation of Lepton Flavor Universality
https://arxiv.org/pdf/2111.12739.pdf
(A. Crivellin, M. Hoferichter)

- Many measurements with muons in the final state are starting to show tension with SM predictions
  - B factory anomalies R(D), R(D*), R(K), R(K*) are becoming particularly strong
  - Many of these have avenues for continued improvement
- New efforts to test lepton universality being proposed

The PIONEER Experiment



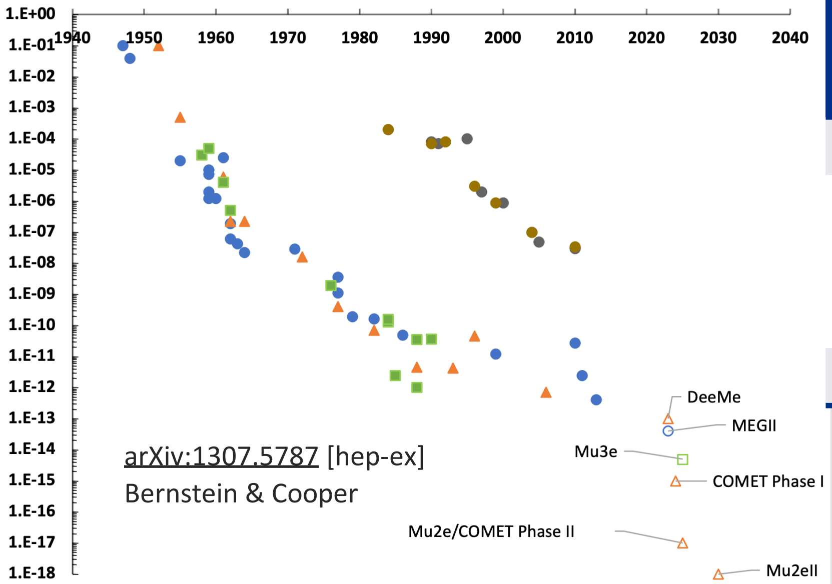
- Primary goal is to improve $R_{e/\mu}$, the charged pion branching ratio to electrons vs muons, by an order of magnitude
  - $R_{e/\mu}$ thy uncertainty ~15x smaller than current exp (PIENU)
- Secondary goal to study pion beta decay

$$\pi^+ \to \pi^0 e^+ \nu(\gamma)$$

  and improve V_{ud} by an order of magnitude for theoretically clean CKM unitarity test
- Recently rate a high priority by the PSI PAC

PIONEER PSI Proposal (arXiv:2203.01981)
PIONEER Snowmass (arXiv:2203.05505)

Searches for Charged Lepton Flavor Violation (CLFV)



Mode	Current Limit (at 90% CL)	Future Proposed Limit	Future Experiment/s
$\mu^{\pm} \rightarrow e^{\pm}\gamma$	4.2 x 10^{-13}	6 x 10^{-14}	MEG II
$\mu^{-} N \rightarrow e^{-} N$	7 x 10^{-13}	10^{-14} 10^{-15} 10^{-17} 10^{-18}	DeeMe COMET Phase-I Mu2e & COMET Phase-II Mu2e-II
$\mu^{+} \rightarrow e^{+}e^{+}e^{-}$	~10^{-12}	10^{-15} ~ 10^{-16}	Mu3e

Sophie Middleton – RPF Workshop

- Given all the other anomalies in the muon sector, CLFV is a promising avenue of exploration
- SM branching ratio is 10^{-54} → any signal is a definitive sign of new physics
- New μ CLFV experiments at PSI, J-PARC and CERN

Fermilab

Conclusion

- Accelerators have played a major role in discovering recent new physics
- Many anomalies abound – some will fade but some might just prove to be new cracks in the Standard Model
- International roadmap of accelerator-based experiments paving the way to discovery short and long-term
- Looking forward to a very colorful future!!!

Catuchak Weekend Market