



# Future flavor physics

Chris Polly, Fermi National Accelerator Laboratory

# Outline

- Muon  $g-2$  outlook
  - Not Snowmass timescale, but results inform next generation theory and experimental endeavors
- Other anomalies in flavor physics
  - Multiple anomalies in flavor sector pointing towards new physics
- Motivates future efforts
  - Flavor physics at B factories
  - Dedicated CLFV experiments
  - Lepton universality at PIONEER

# The results heard round the world!

- Worldwide press coverage
  - Over 3000 media outlets covered the story
  - Total estimated media reach of those outlets > 6 billion people! (Pop. Earth 7.7 billion)



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

By DENNIS OVERBYE

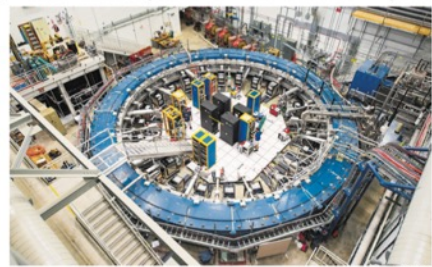
Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

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 least 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 Fatahi, 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

was a discrepancy," said Dr. Polly.

Continued on Page A19

## Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

PINEDALE, Wyo. — Kenna Tanner and her team can't let the cavers from memory: There was the woman who got tired and did not feel like finishing her hike; the camper, 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 widely unprepared for the brutal backcountry in which they were traveling.

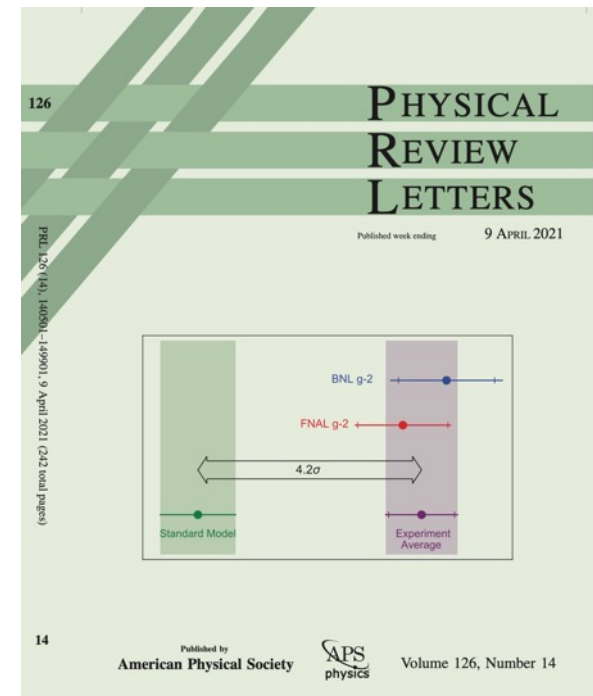
"It is super frustrating," said Ms. Tanner, Tip Top's director. "We just wish that people respected the risk."

In the throes of a pandemic that has made the outdoors inherently dangerous, tens of thousands more Americans than usual have flocked outdoors, leaving crowded cities for national parks and public lands around them. But as



the se herders of inexperienced adventures 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



# The results heard round the world!

- Worldwide press coverage
  - Over 3000 media outlets covered the story
  - Total estimated media reach of those outlets > 6 billion people! (Pop. Earth 7.7 billion)



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

By DENNIS OVERBYE

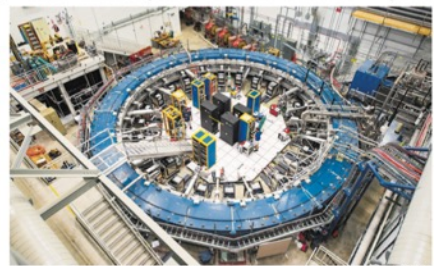
Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

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 least 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 Fatahi, 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 A15

## 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 camper, 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 widely 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 outdoors inherently dangerous, tens of thousands more Americans than usual have flocked outdoors, leaving crowded cities for national parks and public lands around them. But as



the se herders of inexperienced adventures 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





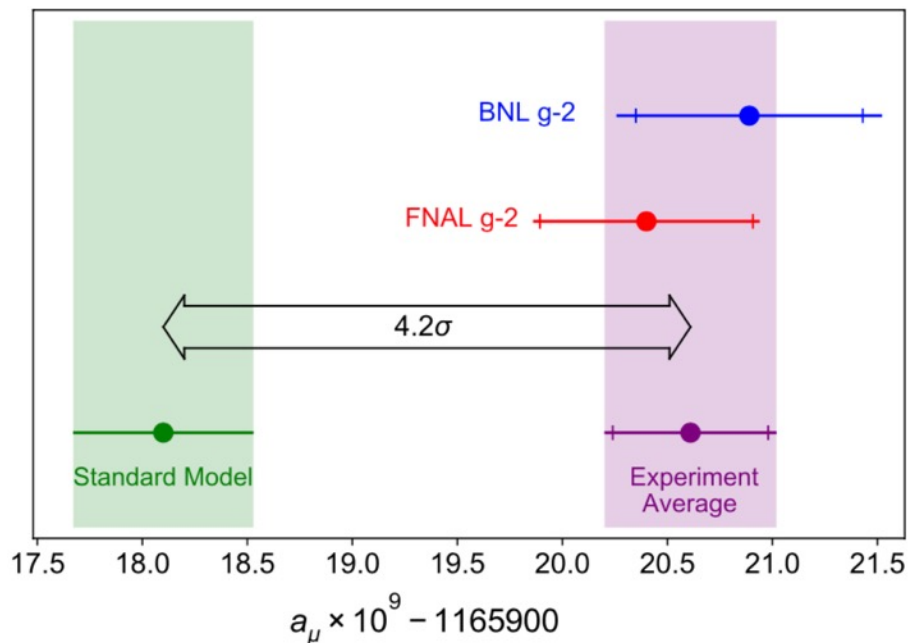
# The results heard round the world!

9 Apr 2021



<http://latenightfeud.com/video/biden-goes-after-ghost-guns-physics-may-be-a-lie-the-daily-social-distancing-show/> (g-2 bit starts at 2:03)

# First FNAL Muon g-2 major takeaways

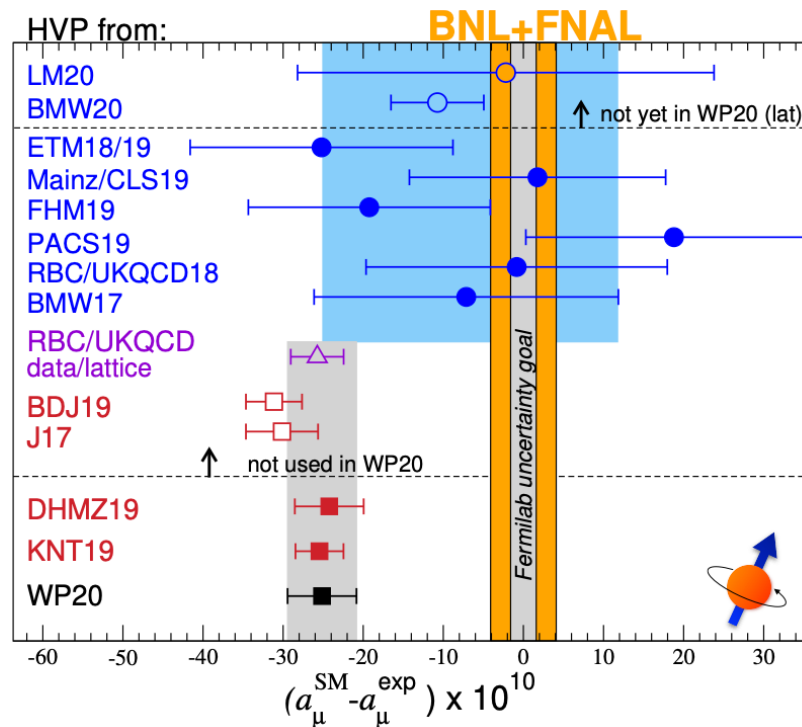


- First result comes from Run 1 “engineering run”
  - 6% of data on tape today
- FNAL error 15% < BNL and in excellent agreement
- Combination increases tension with Theory Initiative to  $4.2\sigma$ !

	BNL	FNAL	Exp Combined	SM Theory
$a_\mu \times 10^{-11}$	116592089(63)	116592040(54)	116592061(41)	116591810(43)
$\delta a_\mu$ (ppb)	540	463	350	368

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 251(59) \times 10^{-11}$$

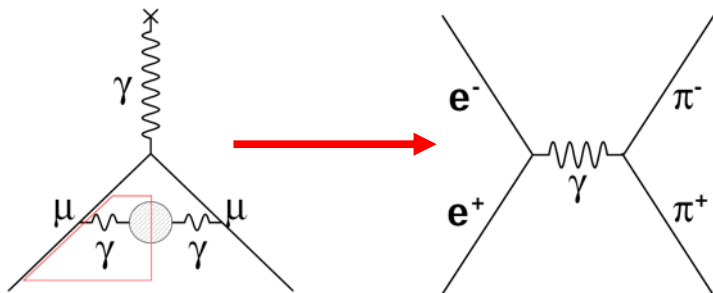
# Hadronic vacuum polarization from lattice



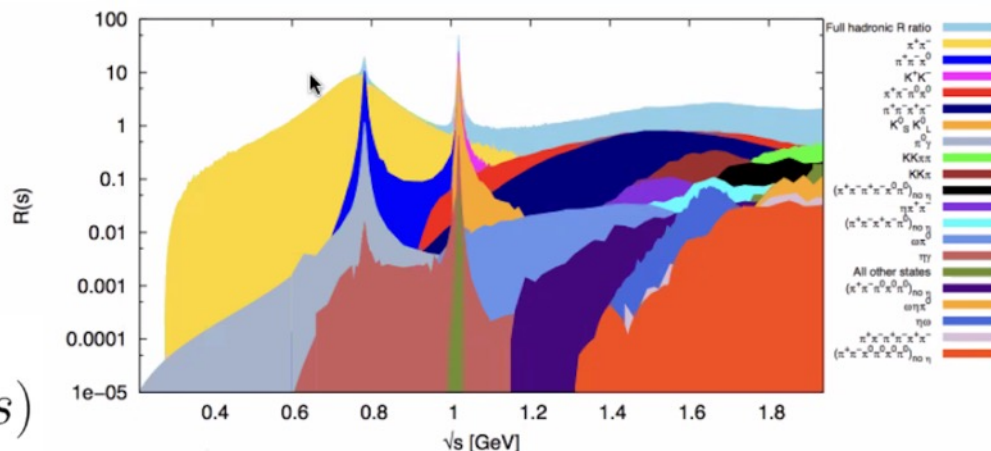
- Lattice calculations of quark contribution to Muon g-2 making enormous progress!
- New results from BMW approach precision of direct  $e^+e^- \rightarrow \text{hadrons}$  measurements (40% larger)
- BMW central value would reduce discrepancy by  $144 \times 10^{-11}$  ( $\sim 60\%$ )

# Solving g-2 with quarks is not so simple

- Quark contributions are calculated through a dispersion integral over measured  $e^+e^- \rightarrow \text{hadrons}$  cross sections



$$a_{\mu}^{\text{LO HVP}} = \frac{1}{4\pi^3} \int_{s_{th}}^{\infty} ds K(s) \sigma_{\text{had}}(s)$$



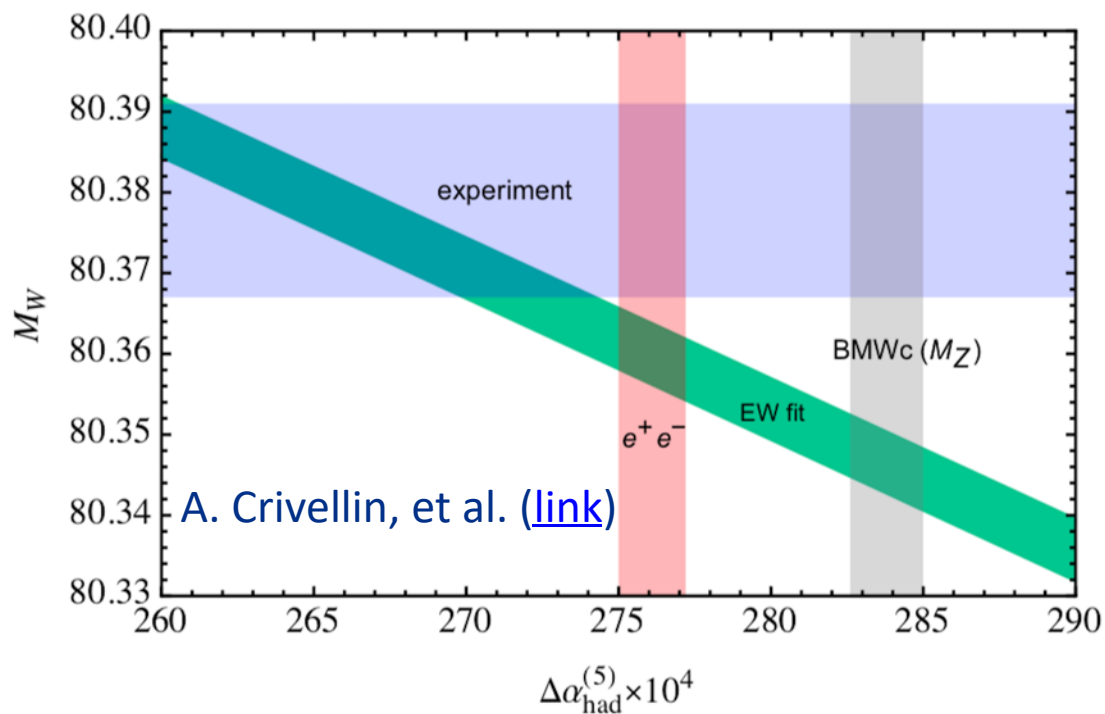
- Same measured cross sections used for calculating the fine structure constant  $\rightarrow$  impacts precision EW fits

$$\Delta\alpha_{\text{had}}^{(5)}(q^2) = -\frac{q^2}{4\pi^2\alpha} \text{P} \int_{m_\pi^2}^\infty \frac{\sigma_{\text{had}}^0(s) \, \text{d}s}{s - q^2}$$



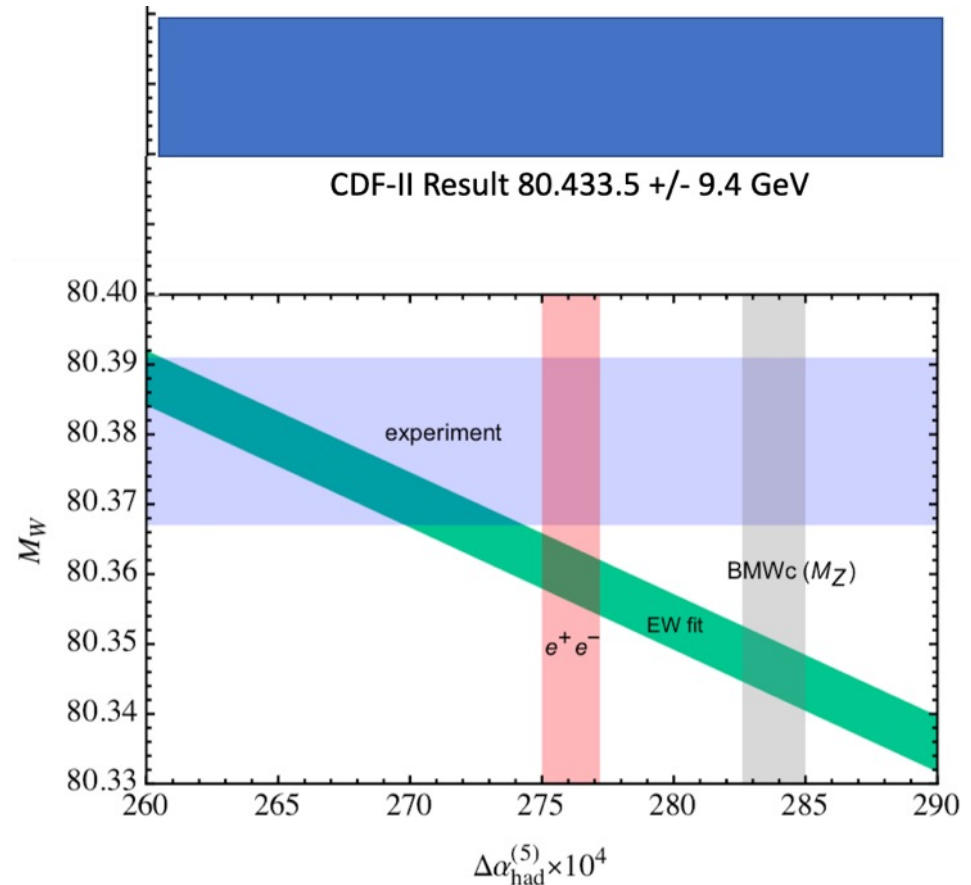
# Increases tension in other precision EW fits

- One example shown here for  $M_W$
- Other tension also increases in other SM predictions

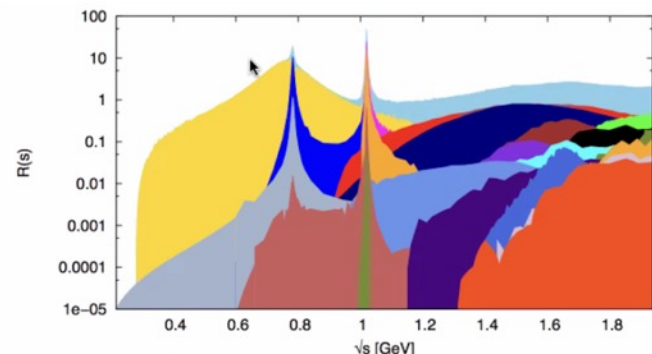
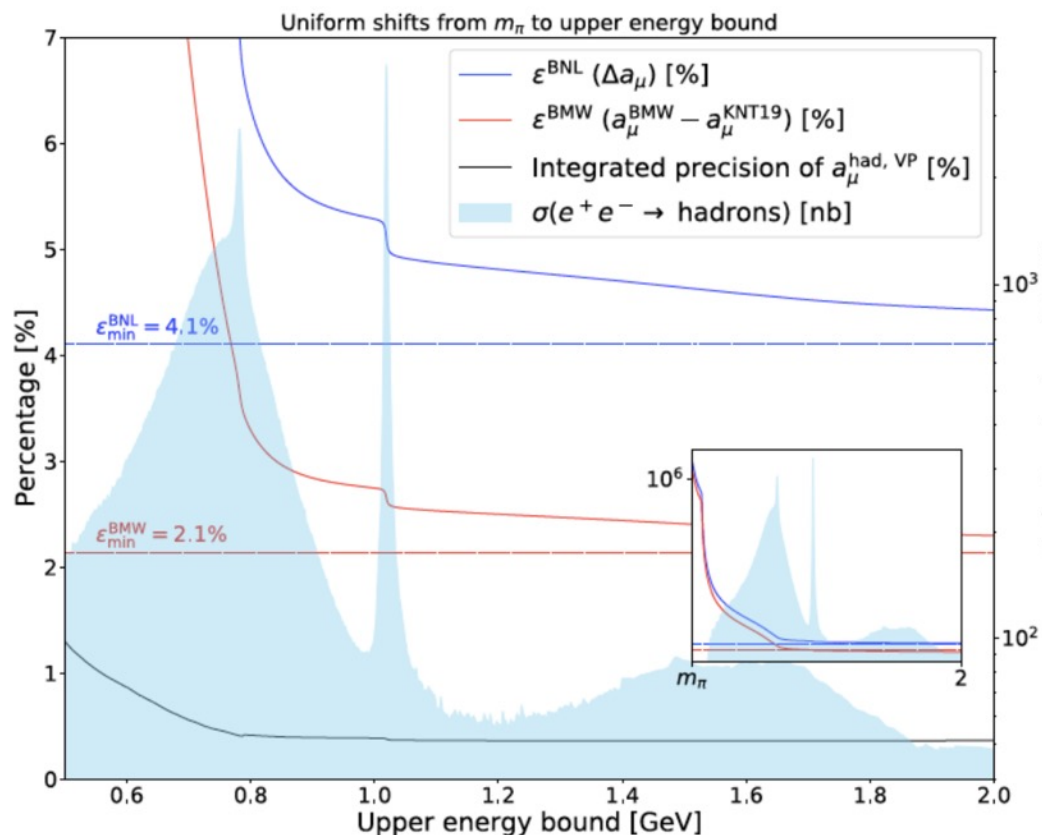


# Increases tension in other precision EW fits

- One example shown here for  $M_W$
- Other tension also increases in other SM predictions
- Recent CDF result pulls fit the wrong way



# Direct tension with e+e- data

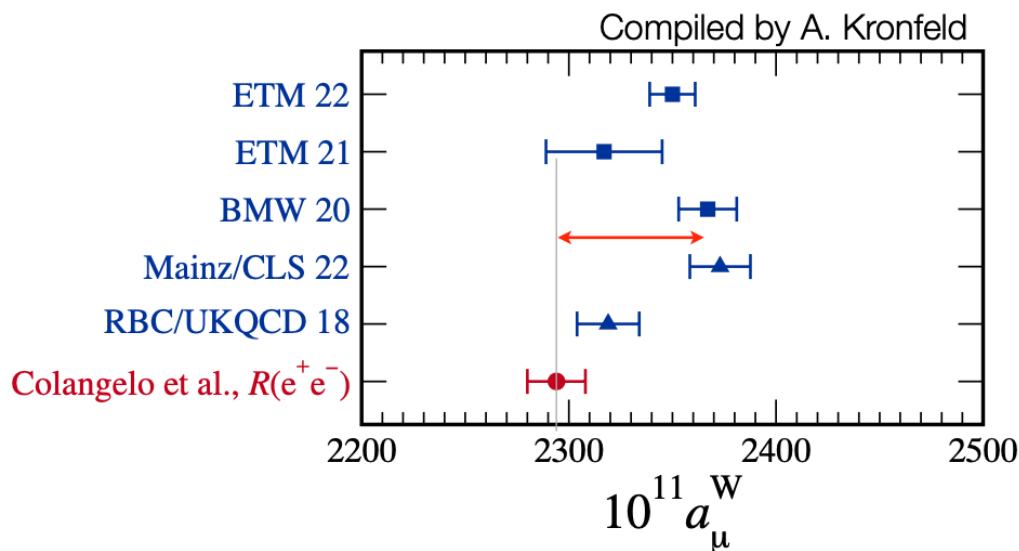
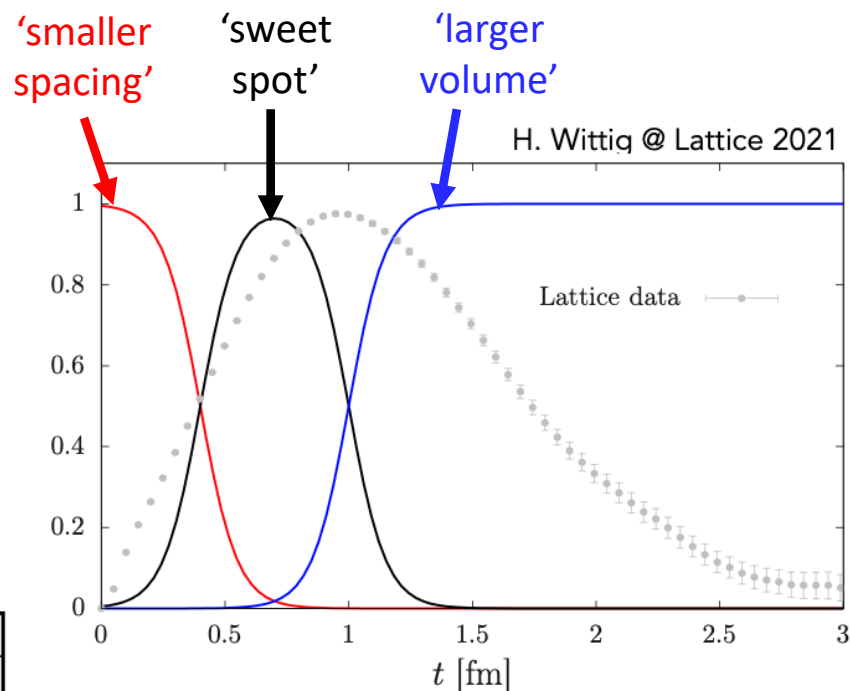


- Over all  $\sqrt{s}$  need 2.1% larger xsec to explain BMW and 4.1% for BNL
- If error is in dominant  $2\pi$  channel, need 3% (BMW) or 6% (BNL)
- Tough to accommodate since these are xsec are all known to sub 1%

Keshavarzi, Marciano, Passera and Sirlin, *Phys.Rev.D* 102 (2020) 3, 033002

# Window approach improves understanding

- Windows method allows lattice to study short, middle, and long range contributions in Euclidean time
- Can convert e+e- data into same space for direct comparisons

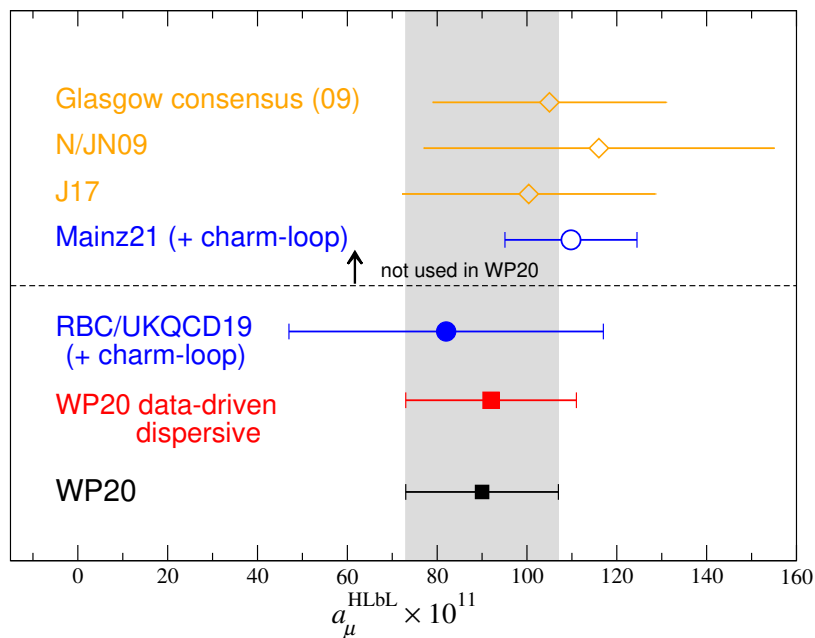
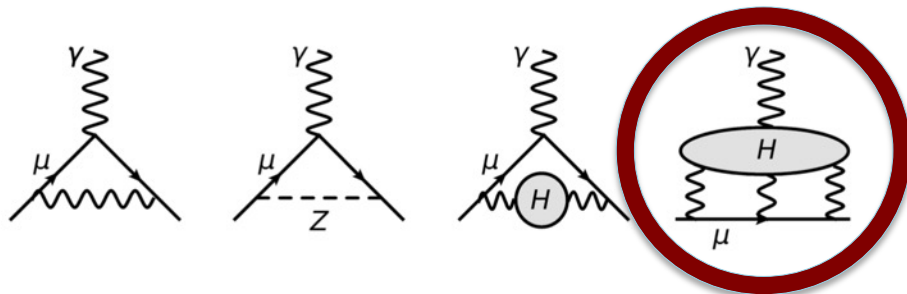


- About  $90 \times 10^{-11}$  of BMW diff comes from intermediate range
- Averaging over lattice groups reduces overall  $250 \times 10^{-11}$  discrepancy by about  $\sim 20\%$

Aida El-Khadra (Fri AM) *Prospects for precise predictions of  $a_\mu$  in the Standard Model*



# Theory conclusion



- TI urges caution interpreting lattice as they make spectacular progress
- (I'm) confident in a few years we will sort differences and be in a situation much like HLbL
- In the meantime, we need the best measurement we can achieve
  - We might resolve part of the  $g-2$  discrepancy with quarks, but very unlikely it can explain all

# Experimental outlook

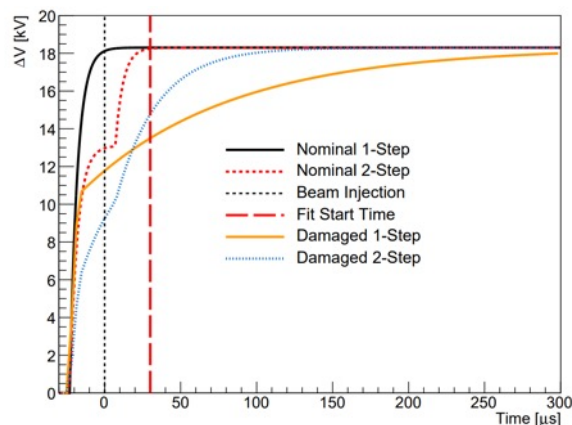
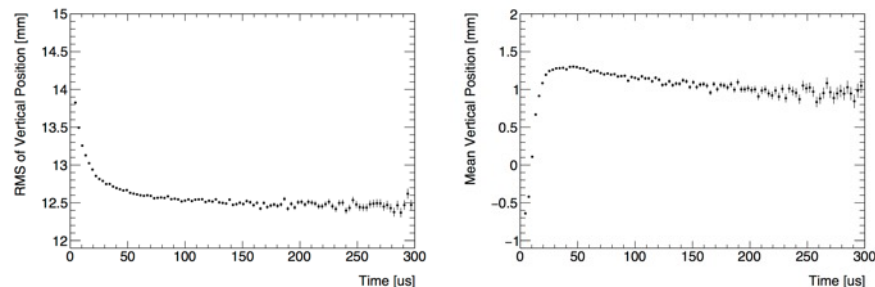
- Run 1 result was dominated by statistical error
  - 434 ppb stat vs 157 ppb syst

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
$\omega_a^m$ (statistical)	–	434
$\omega_a^m$ (systematic)	–	56
$C_e$	489	53
$C_p$	180	13
$C_{ml}$	-11	5
$C_{pa}$	-158	75
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$	–	56
$B_k$	-27	37
$B_q$	-17	92
$\mu_p'(34.7^\circ)/\mu_e$	–	10
$m_\mu/m_e$	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

- Original TDR goal:
  - Control systematics at 100 ppb
  - Run experiment until stat error matched at 100 ppb  $\rightarrow$  20 x BNL
- Did not quite achieve 100 ppb syst in Run 1
- Two dominant errors

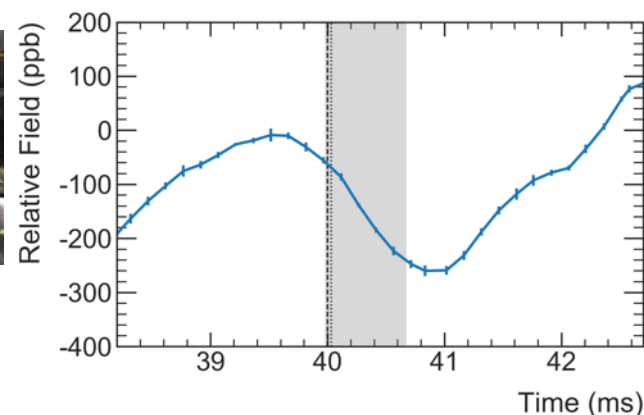
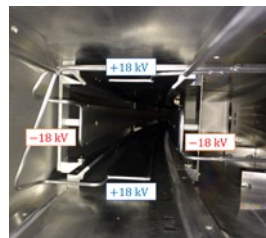
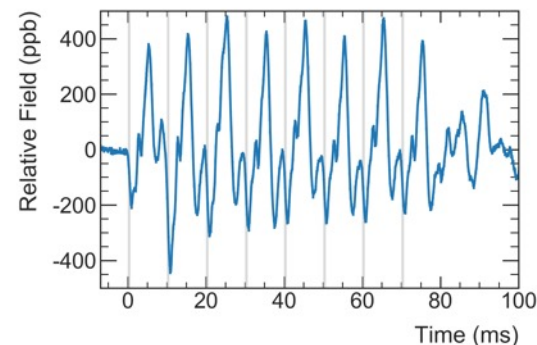
# Reducing the two dominant errors

$C_{PA}$  = phase acceptance correction



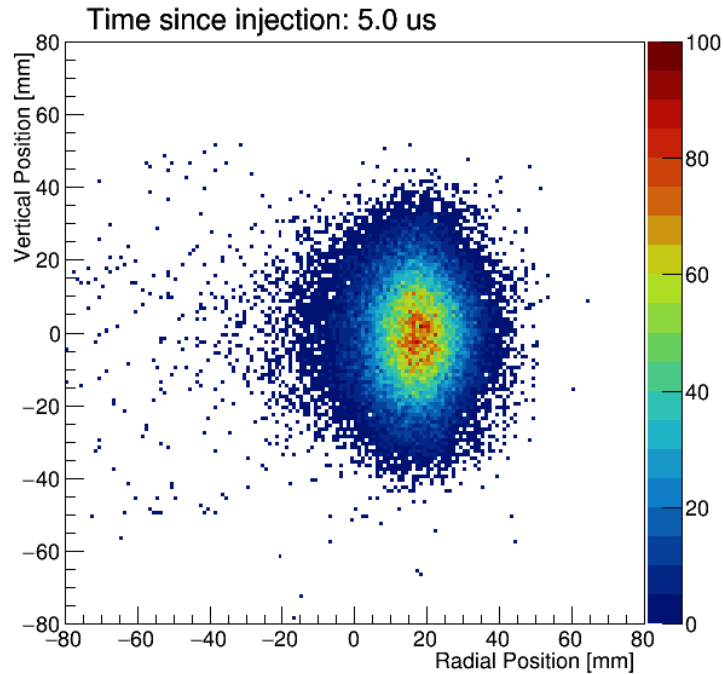
- Failed resistors in Run 1 → beam instabilities → time-dependent g-2 phase in accepted e+
- Resistors fixed by Run 2

$B_Q$  = quad transients

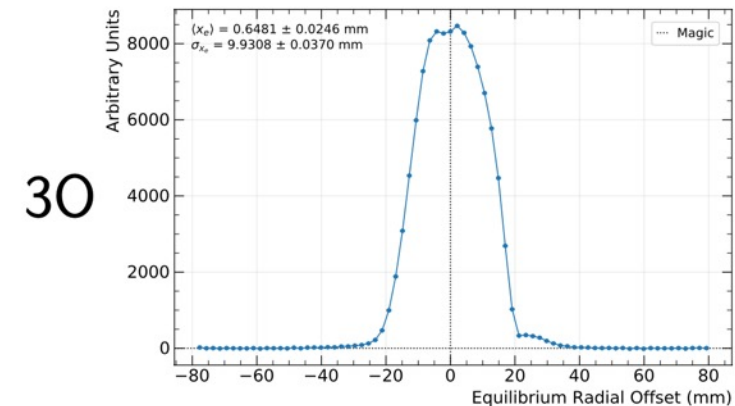
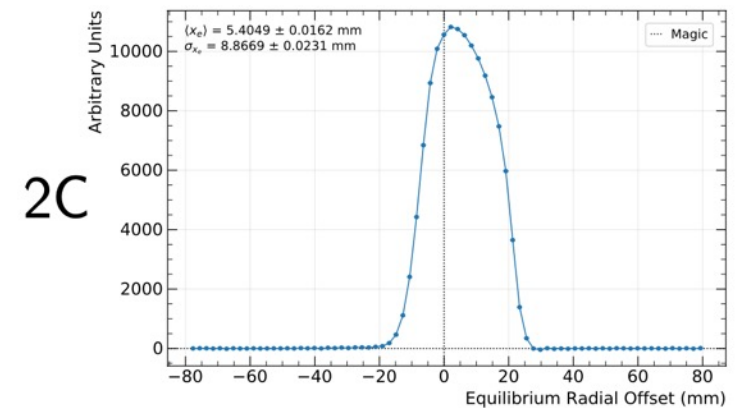
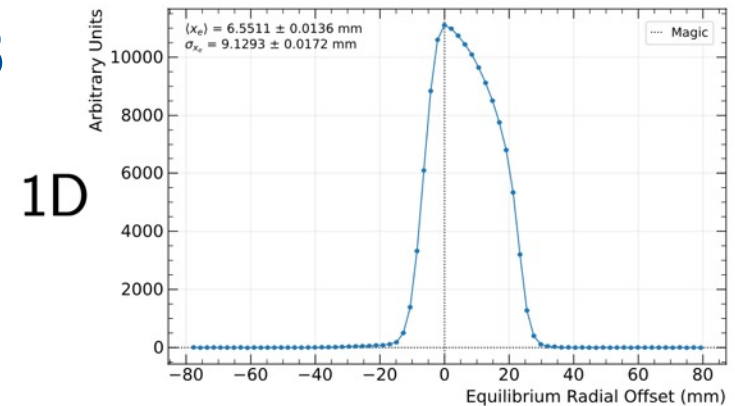


- Pulsed quads → mech vibrations → time-dependent field perturbation
- Mapped in increasing detail with newly-constructed NMR probes starting by Run 2 and continuing through subsequent runs

# Major kicker upgrade by Run 3



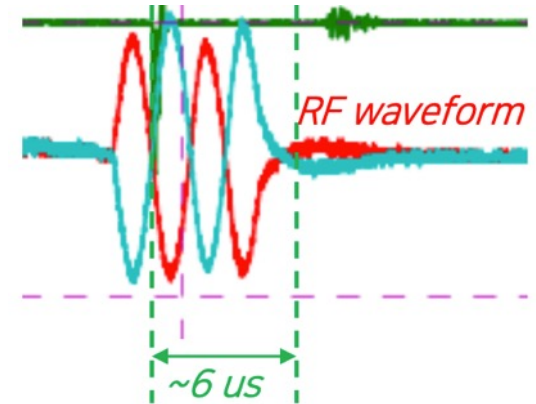
- Run 1 kick insufficient to center beam
  - Increased rate 30%
  - Reduced equilibrium orbit from 6mm to 0.6mm off ideal
  - Reduced CBO amplitude at injection from 13mm to 5mm
- Improves many other non-dominant systematics



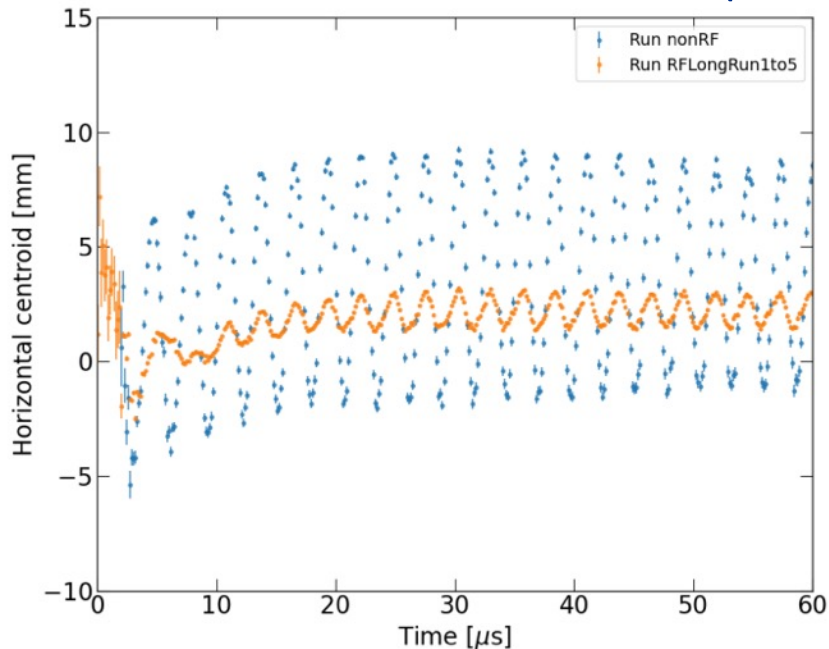


# RF system added for Run 5

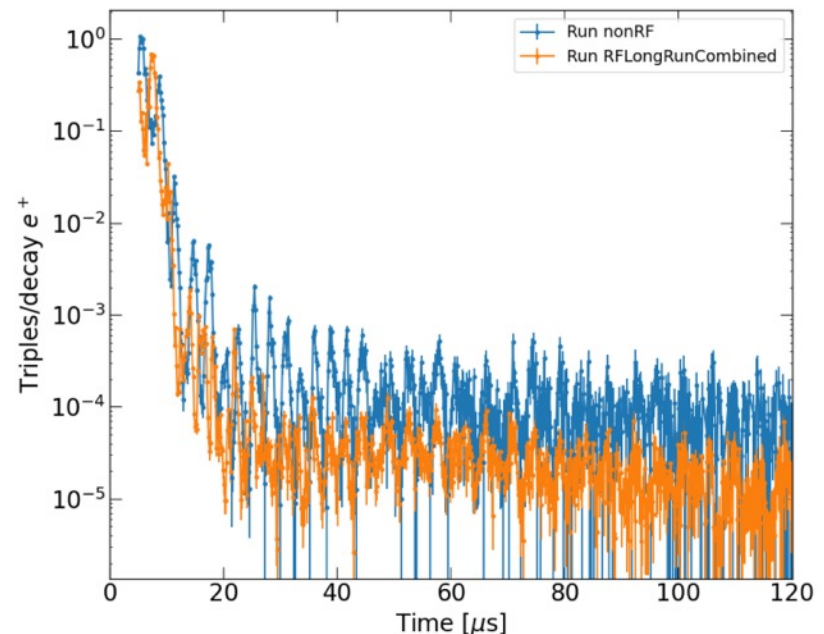
- Apply horizontal dipole electric field, near CBO frequency,  $\sim 1$  kV to inner and outer quad plates, for  $6 \mu\text{s}$  after injection.
- Reduced CBO amplitude from 6mm to  $<1\text{mm}$ , reduced muon losses by  $\times 7$



## Coherent betatron oscillations (CBO)



## Muon loss rate



# Experimental outlook

* = Prelim	Run 1	Run 2/3	Run 4/5
Stat error	434	202*	119*
Syst error	157	95*	86*
Total error	462	223*	147*

Not cumulative

- Run 2/3 and Run 4/5 being analyzed as sets, all numbers preliminary based on our current understanding
  - Could still discover new source of systematics
  - Still working hard to control systematics at 70-80 ppb
    - Installed new det system in June to reduce new dominant error
    - Higher stats often reduce data-driven systematics
- Will be exceeding TDR systematic goal starting with Run 2/3
- Aiming to publish Run 2/3 by Spring 2022, Run 4/5 in 2025

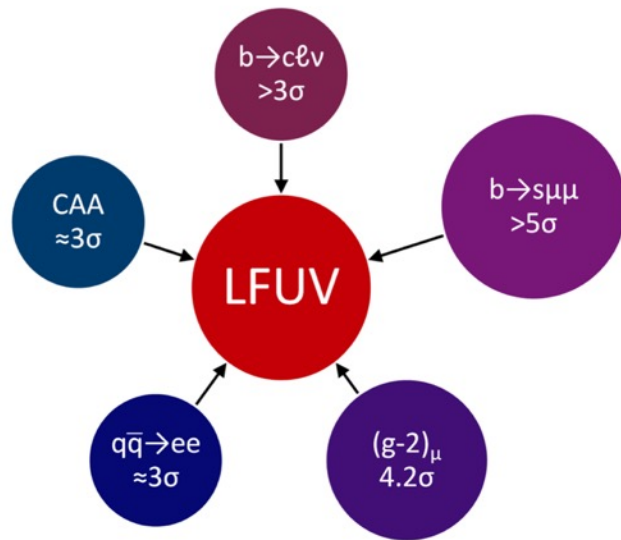
# Experimental outlook

* = Prelim	Run 1	Run 2/3	Run 4/5
Stat error	434	202*	119*
Syst error	157	95*	86*
Total error	462	223*	147*

Not cumulative

- Controlling systematics better than TDR projections → experiment is still statistics limited
- Run 6 is still a question mark
  - Had planned to run  $\mu^-$  this coming year
    - Factor of 2 less rate, but access to CPT/LV analyses, 4xBNL  $\mu^-$
    - Recently cancelled to divert lab resources to higher priorities
  - Still proposing to run  $\mu^+$  for a 30% increase in total stats and hoping to hear positive news
- With current projections need 30 x BNL to hit systematic floor, could be 40 if 70 ppb syst error achieved

# Many anomalies hinting at LFUV



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

See RP talks by:

Angelo Di Canto (Tues AM) *Weak decays of b/c quarks: summary*

Rafael Silva Contino (Thurs AM) *Flavor anomalies overview*

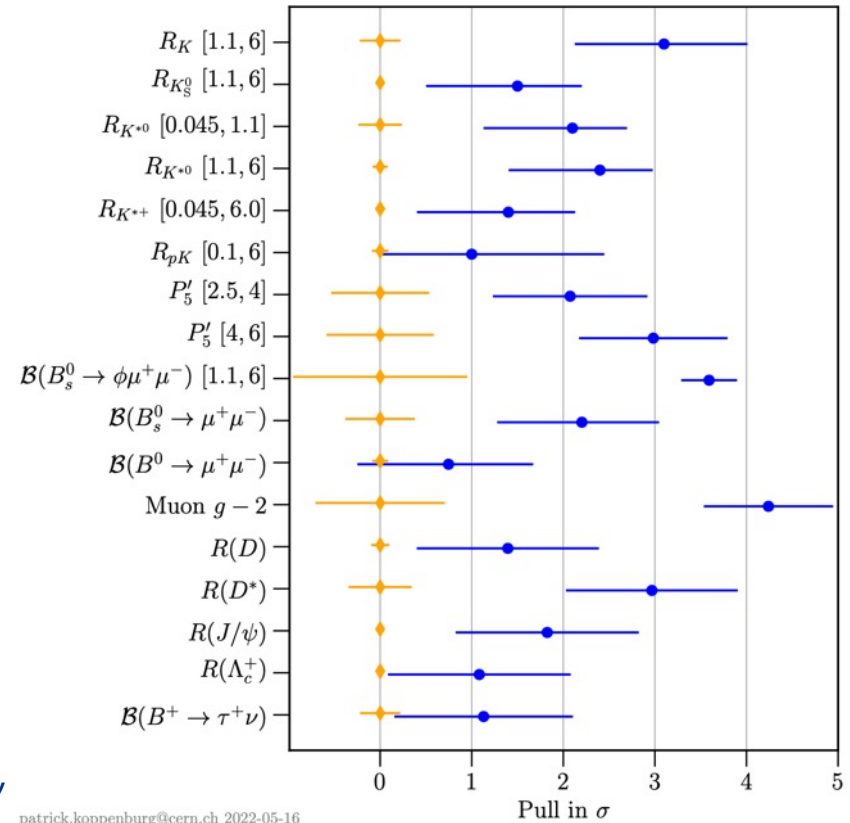
Wolfgang Altmannshofer (Thurs AM) *New physics models for flavor anomalies*

Peter Stangi (Thurs AM) *CLFV in heavy quark decays - interplay between LFV and LFUV*

Phillip Urquijo (Thurs PM) *SM precision tests & new physics in heavy flavour: Examples from the RP frontier*

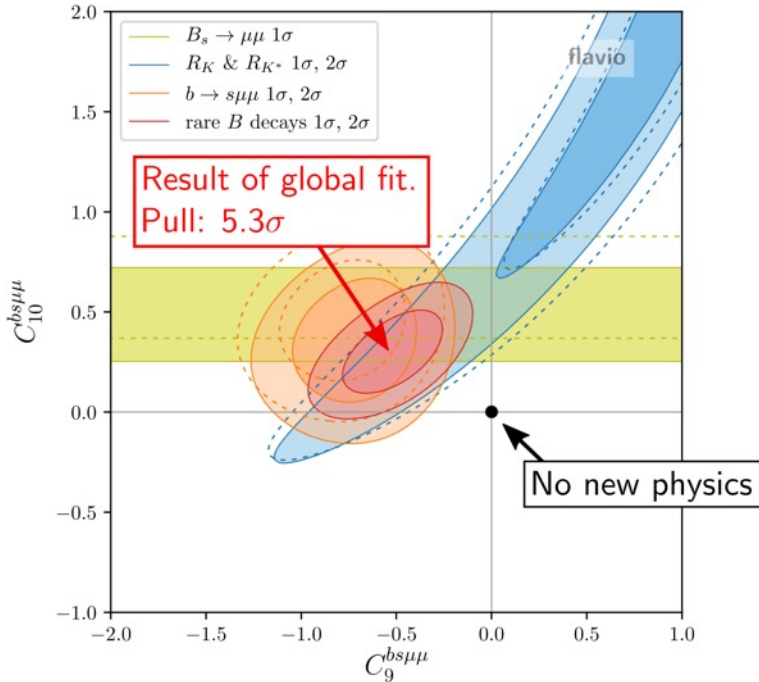
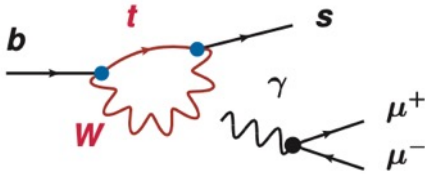
Vincenzo Cirigliano (Thurs PM) *Searching for new physics with rare processes and precision measurements ( $0\nu\beta\beta$ , LFV, and Cabibo Angle Anomaly)*

Several other talks touching on LFUV and LFV

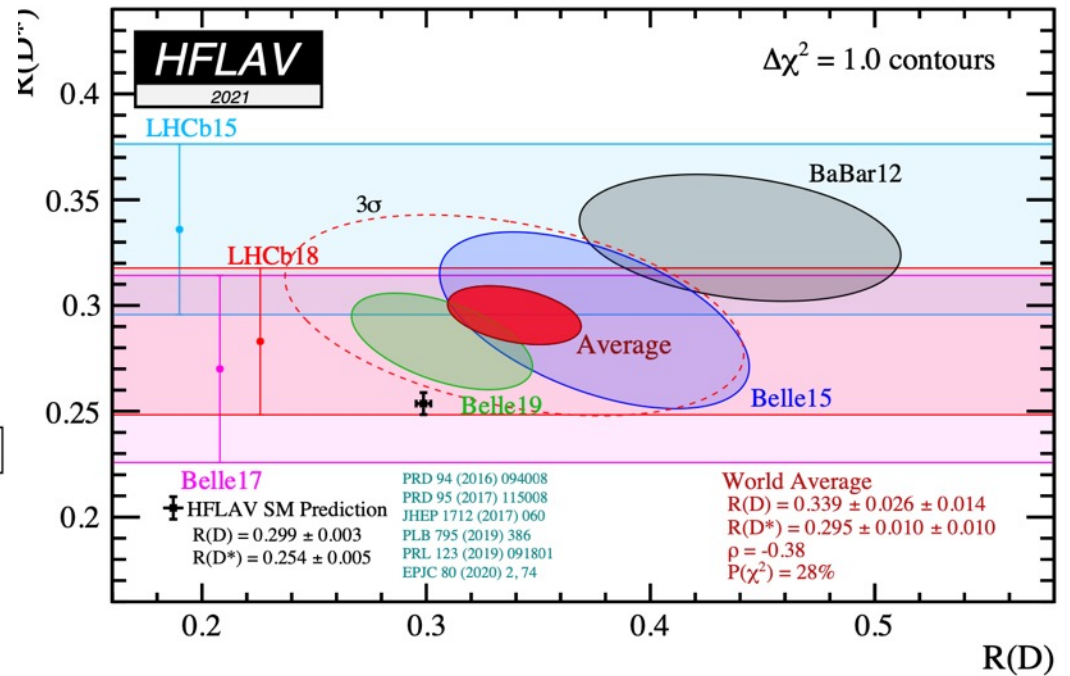
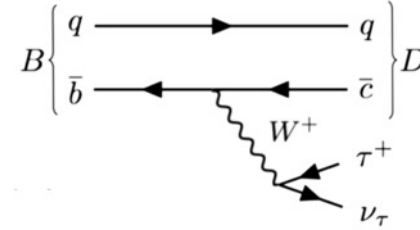




# B anomalies



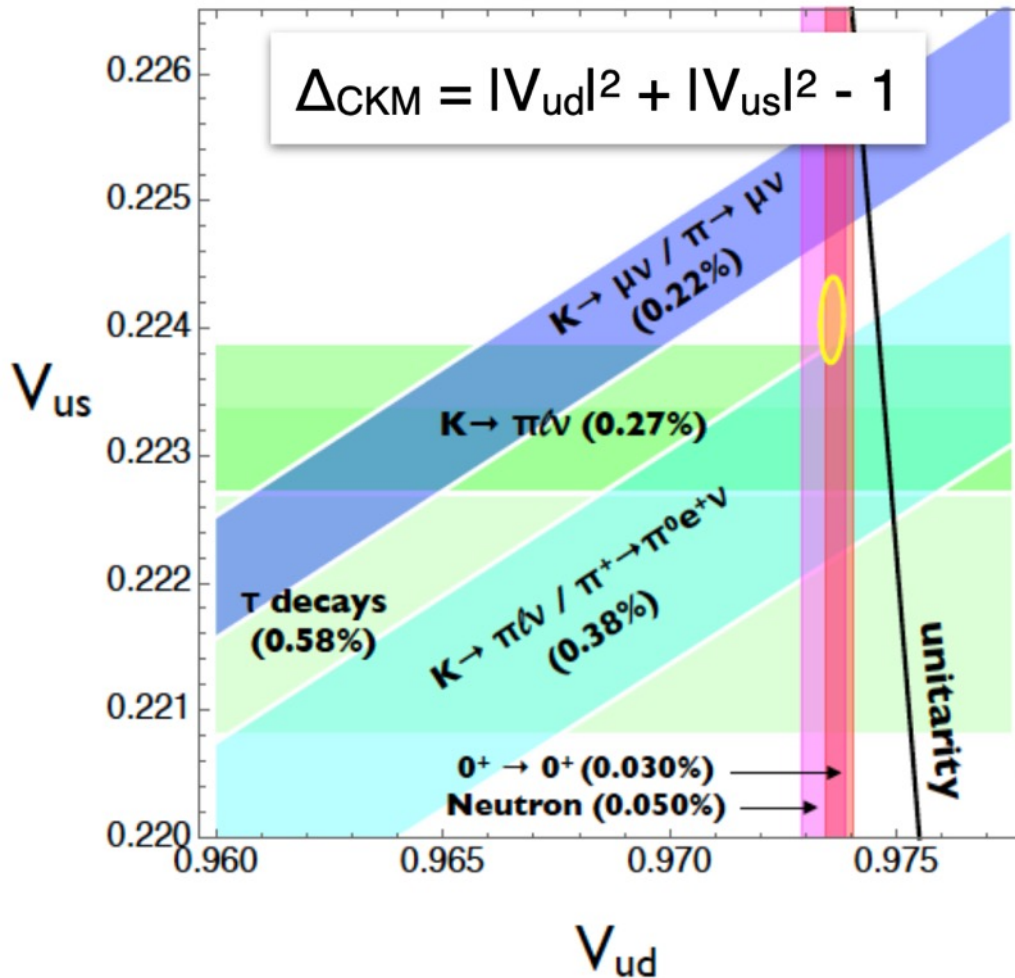
W. Altmannshofer, P. Stangl arXiv:2103.13370



- Both analyses hint at LUV through  $R(K)$ ,  $R(K^*)$ ,  $R(D)$ , and  $R(D^*)$  ratios

# Cabibo angle anomaly

Bryman, VC, Crivellin, Inguglia 2111.05338, ...



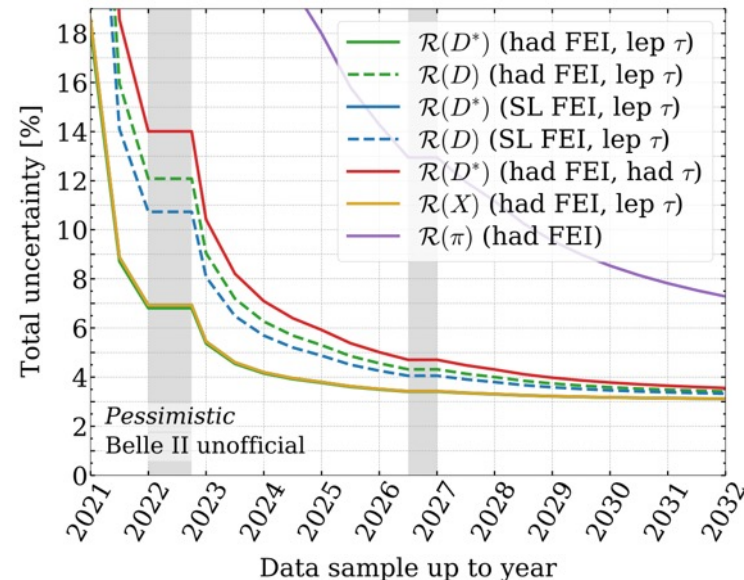
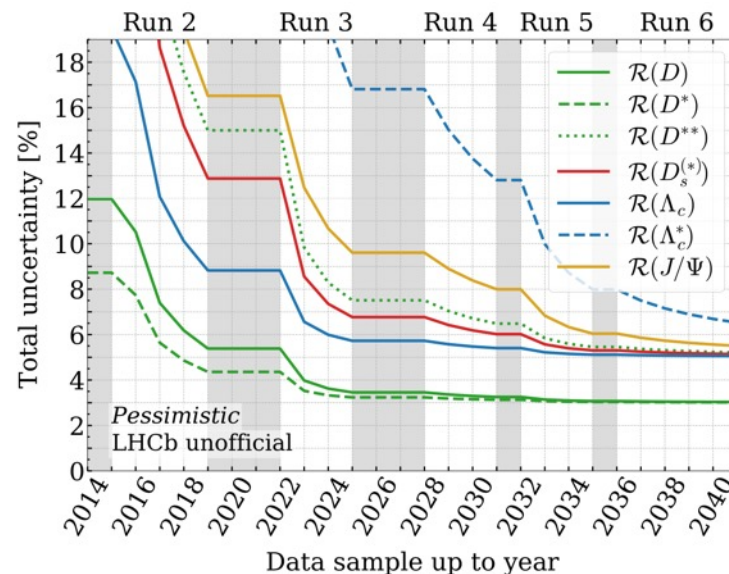
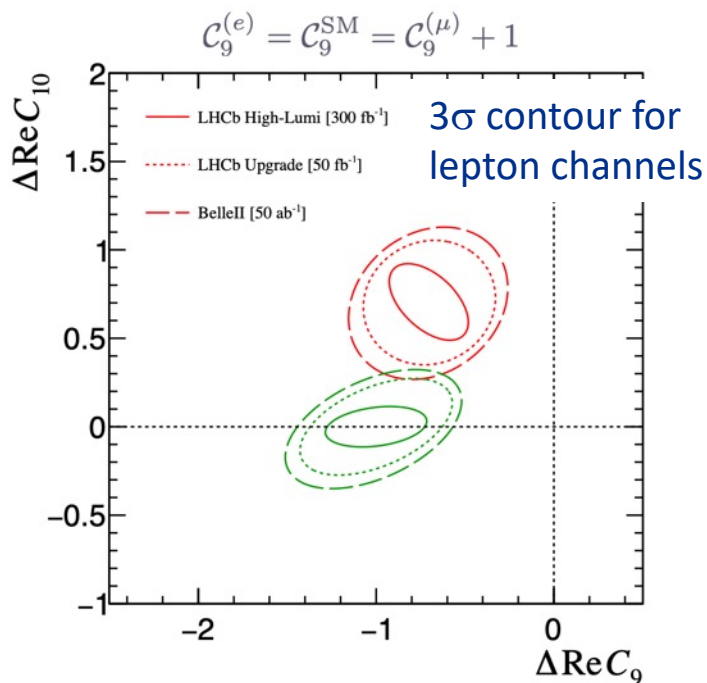
- Approaching  $4\sigma$  tension in top row global fit of CKM unitarity
- Remains  $3\sigma$  just looking at meson sector or dropping nuclear decay from fit

Vincenzo Cirigliano (Thurs PM) *Searching for new physics with rare processes and precision measurements ( $0\nu\beta\beta$ , LFV, and Cabibo Angle Anomaly)*

# Flavor anomalies motivate future upgrades

- LHC and b-factory upgrades will improve precision searches for LFUV

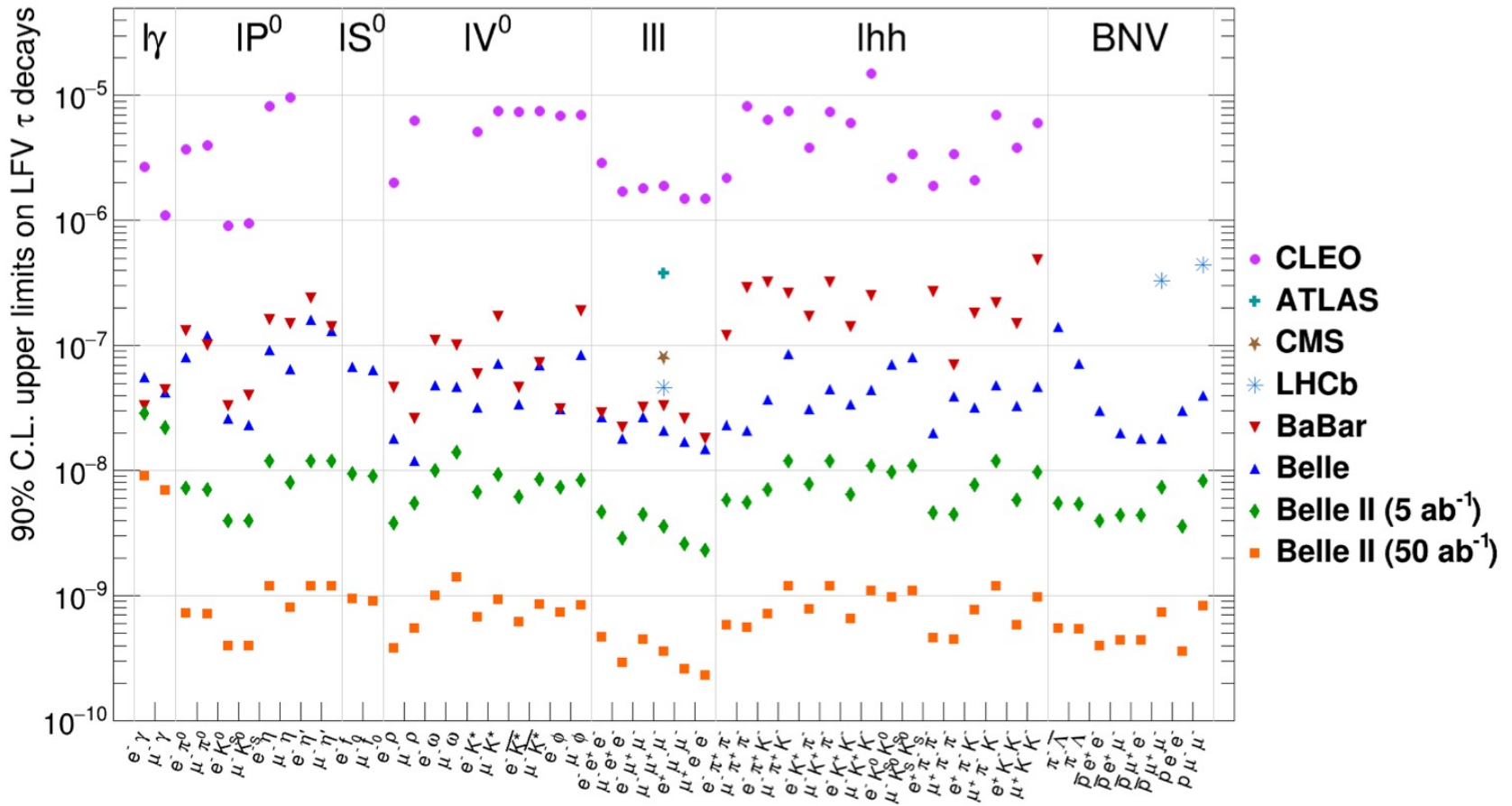
[LHCb, arXiv:1808.08865, Belle II physics book]



Rafael Silva Contino (Thurs AM) –  
*Flavor anomalies overview*

## Also motivates searches for CLFV

arXiv:2207.06307



- Compilation plot shows nearly 2 order of magnitude increase in sensitivity to  $\tau$  lepton violating across all channels at Belle II

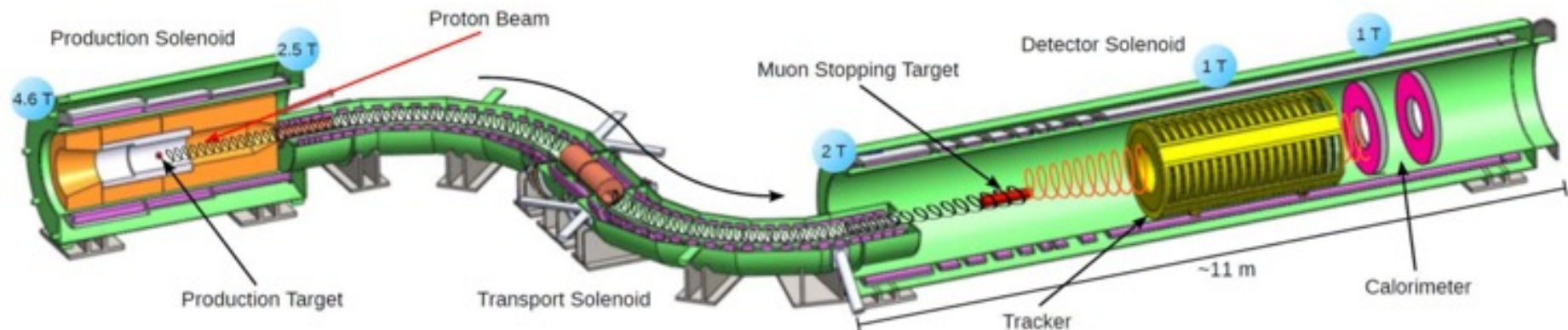
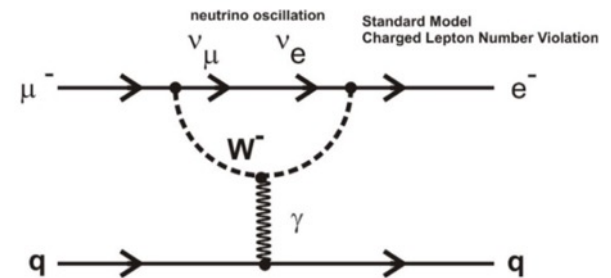
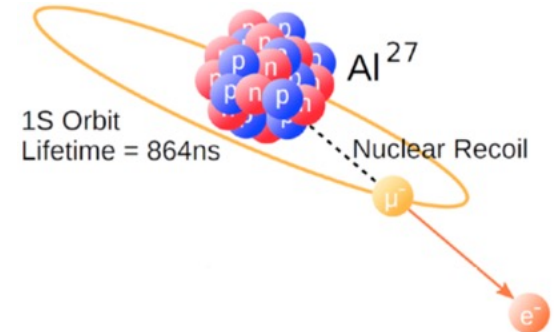


# Mu2e and Mu2e-II experiments

- Mu2e is searching for muons spontaneously converting to electrons in the field of a nucleus

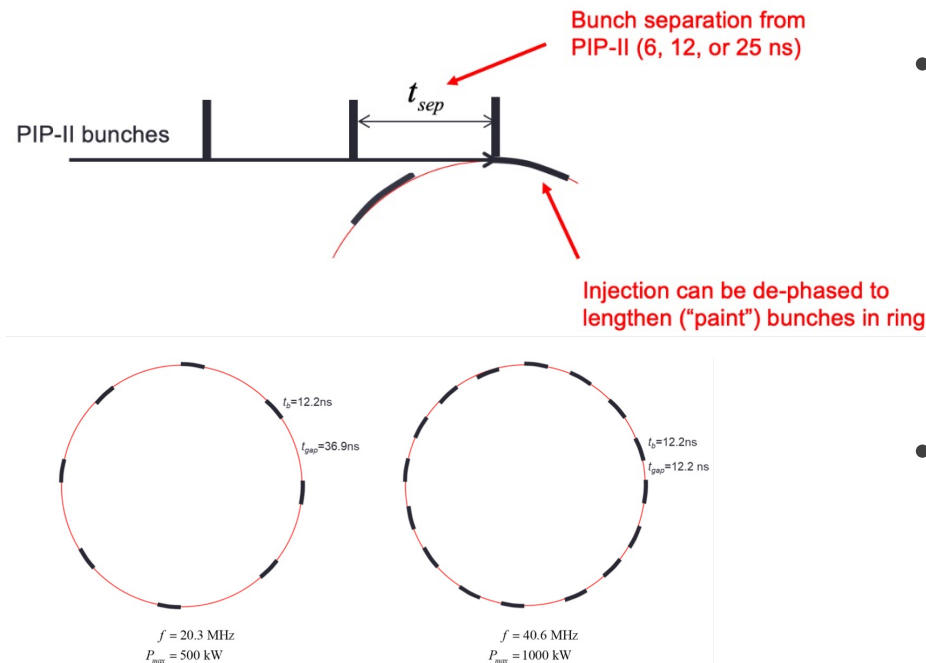
$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}$$

- Goal of the experiment is to reach a sensitivity to branching ratios of  $3 \times 10^{-17}$ 
  - 4 order of magnitude improvement over last experiment (SINDRUM II)
- Upgrades for Mu2e-II to be fed by new PIP-II beam can improve rates by another x10



# Future CLFV – Advanced Muon Facility (AMF)

- Current worldwide effort with Mu2e@FNAL, COMET@J-PARC, and MEG-II/Mu3e@PSI
- Advanced Muon Facility propose to use the new MW capable PIP-II beam to mount a program for next generation muon CLFV

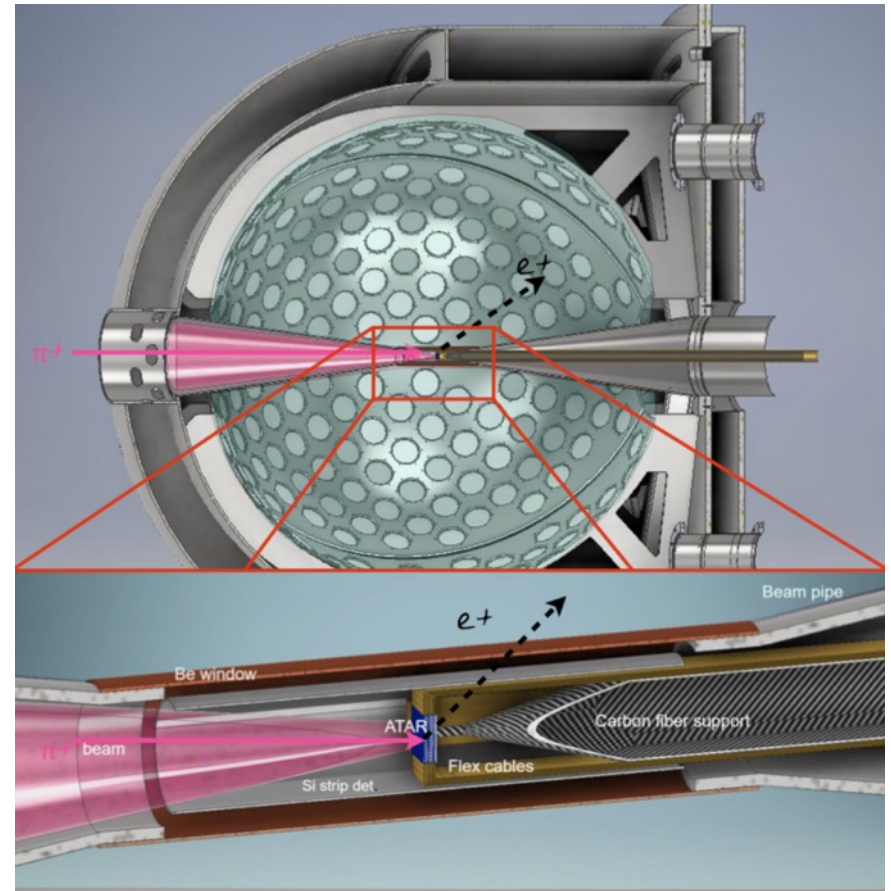


- Much R&D required
  - Compressor ring to consolidate beam power into bunches
  - High power targetry
  - Experimental design
- Potential to advance muon CLFV by 2-3 more orders of magnitude

Bob Bernstein (Fri AM) *Pioneer: A new muon program at Fermilab*

# 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  $\sim 15\times$  smaller than current exp (PIENU)
- Second phase goal to study pion beta decay
$$\pi^+ \rightarrow \pi^0 e^+ \nu(\gamma)$$
and improve  $V_{ud}$  by an order of magnitude for theoretically clean CKM unitarity test
- Recently rate a high priority by the PSI PAC

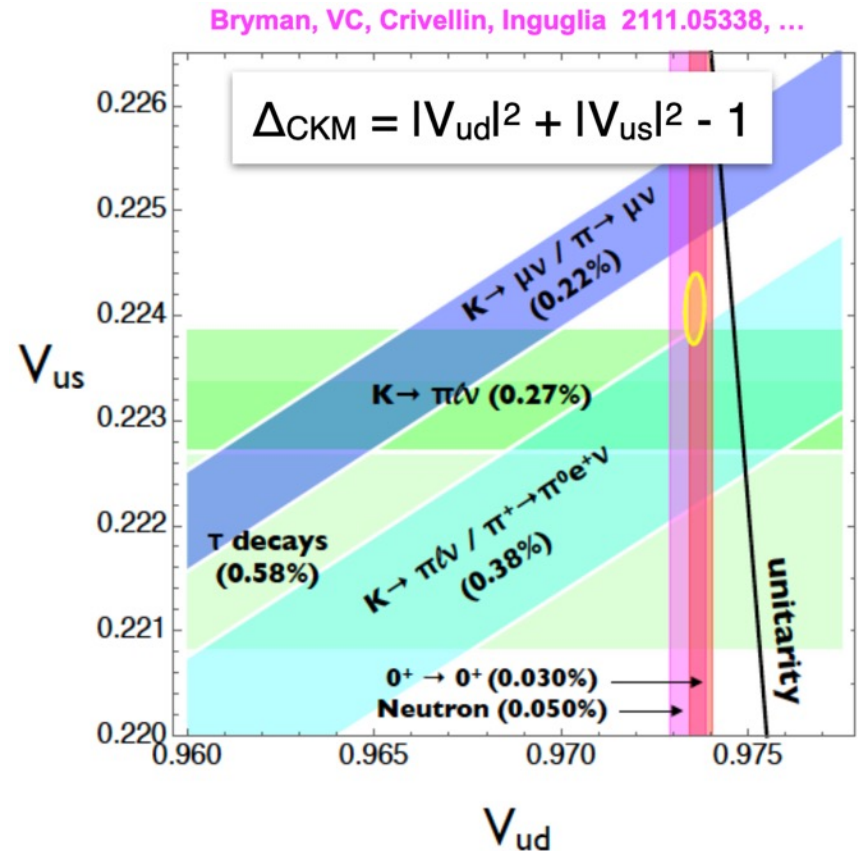
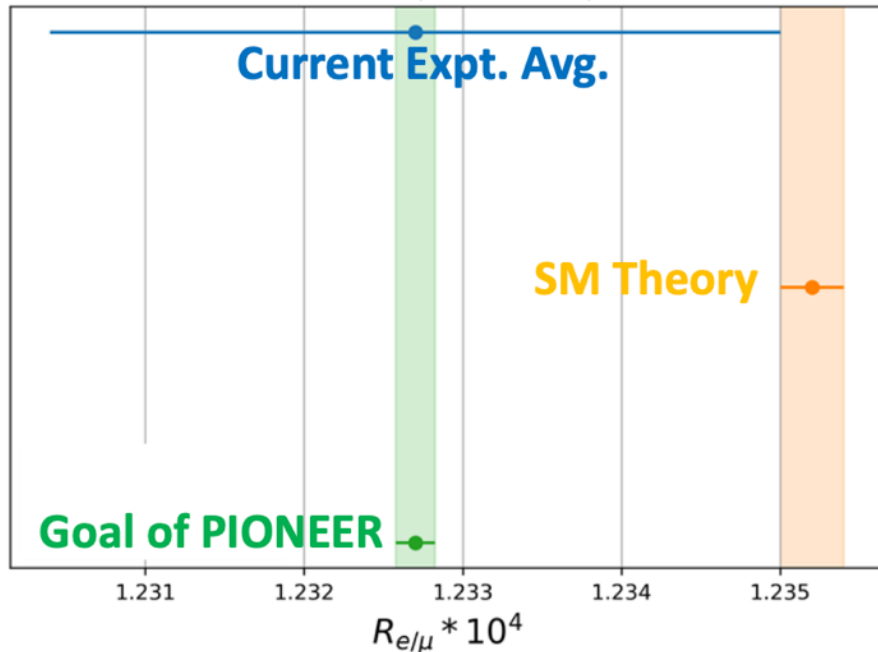


PIONEER PSI Proposal (arXiv:2203.01981)

PIONEER Snowmass (arXiv:2203.05505)

David Hertzog (Tues AM) *Pioneer: A next-generation rare pion decay experiment*

# PIONEER Experiment



- Just what the field needs...a small to mid-size experiment that can produce compelling physics within the decade
  - Large window for new LFUV to appear
  - Theoretically clean determination of  $V_{ud}$

# Conclusion

- Muon  $g-2$ 
  - Results confirm BNL and raise tension with SM prediction
  - Theory and experiment making rapid progress over next few years
- Other flavor anomalies abound
  - B anomalies and Cabibo angle anomaly have all reached a level of significance that merits further study
- Highly motivates future flavor physics experiments and supporting theory calculations
  - LHC and b-factory upgrades
  - Rare muon CLFV searches
  - Other probes of LFUV like PIONEER
- RP is requesting the Snowmass community call out exploration of the flavor sector as one of the key science drivers in the next era