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)


"All the News That's Fit to Print"
The New York Times
Late Edition
VOL. CLXX .... No. 59,022 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.

PAIR OF SETBACKS

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

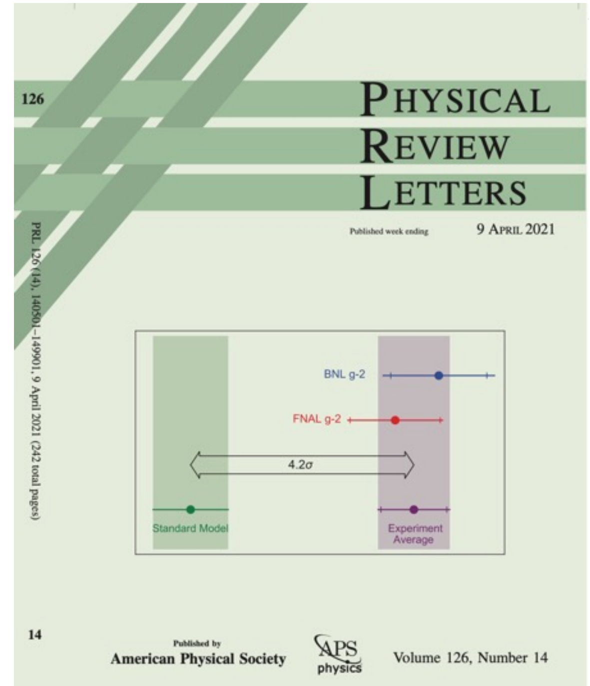
By DENNIS OVERBYE

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

A trail in the Wind River Range in western Wyoming.



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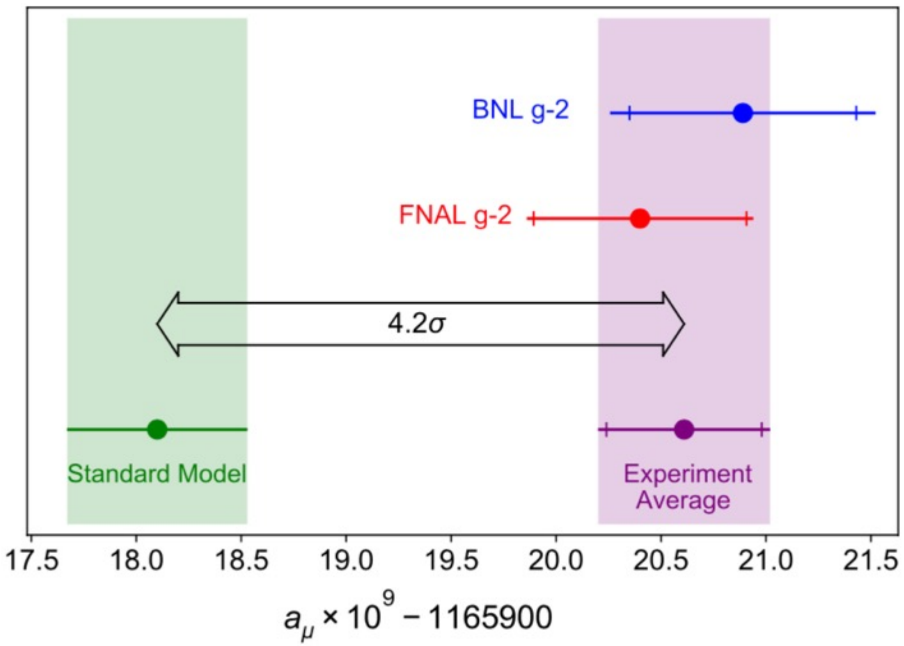
Fermilab

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

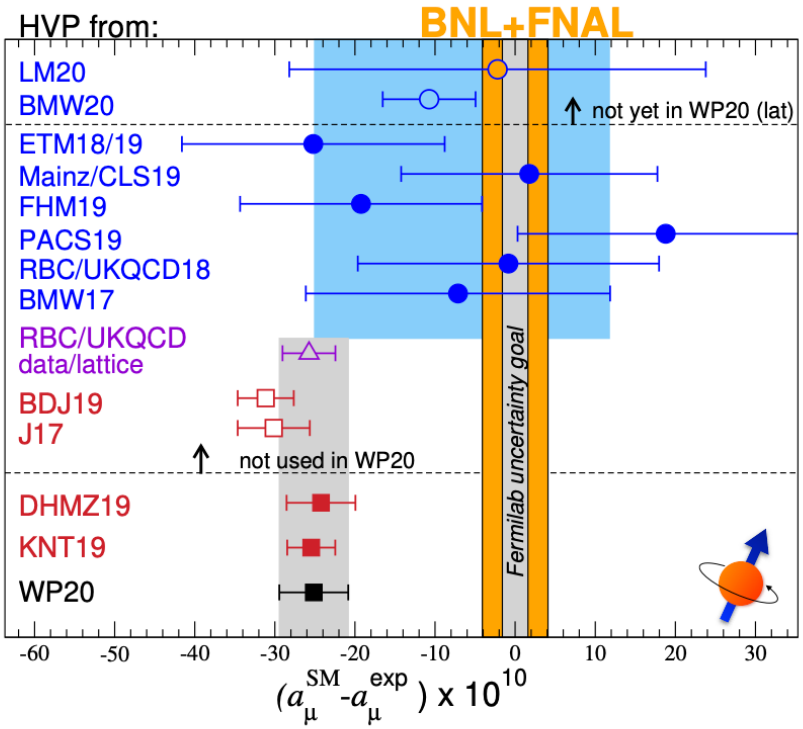


- First result comes from Run 1 "engineering run"
  - 6% of data on tape today
- FNAL error 15% < BNL and in excellent agreement
- Combination increases tension with Theory Initiative to 4.2σ!

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

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

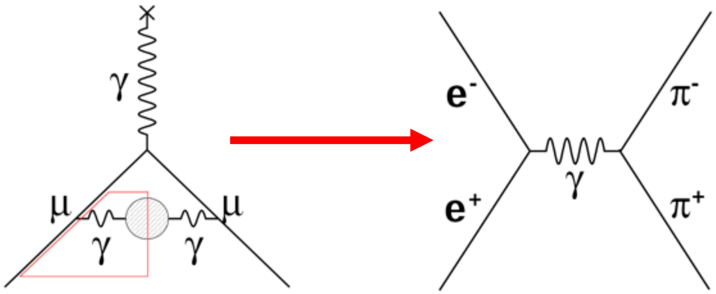
Hadronic vacuum polarization from lattice

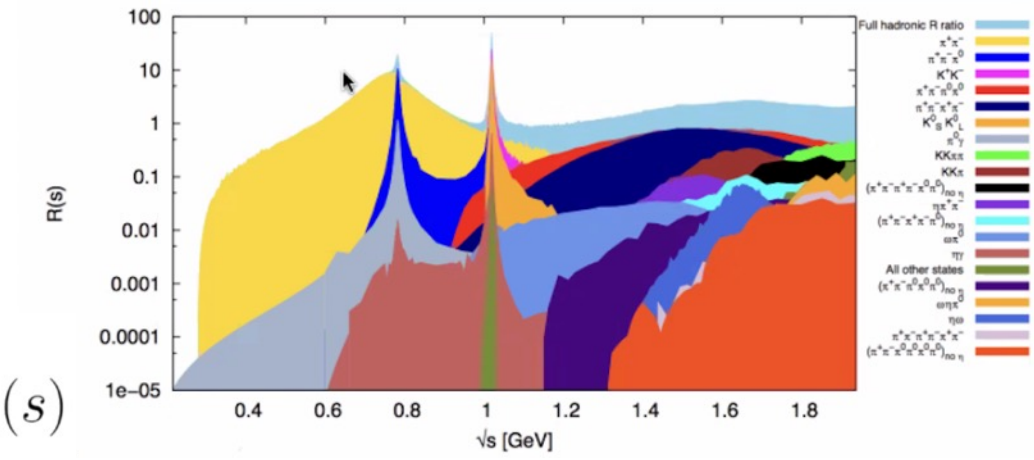


- Lattice calculations of quark contribution to Muon g-2 making enormous progress!
- New results from BMW approach precision of direct e+e- → hadrons measurements (40% larger)
- BMW central value would reduce discrepancy by 144 x 10^{-11} (~60%)

Solving g-2 with quarks is not so simple

- Quark contributions are calculated through a dispersion integral over measured e+e- → hadrons cross sections





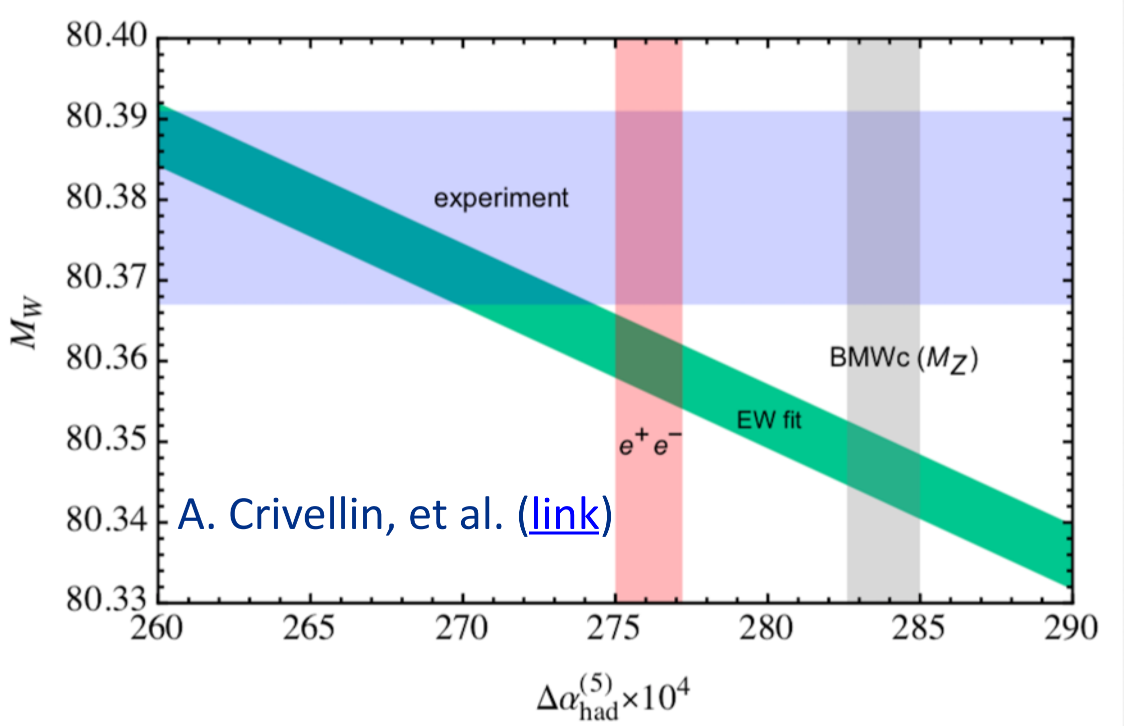
$$a_\mu^{\mathrm{LO\,HVP}} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} \mathrm{d}s\, K(s)\,\sigma_{\mathrm{had}}(s)$$

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

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

Increases tension in other precision EW fits

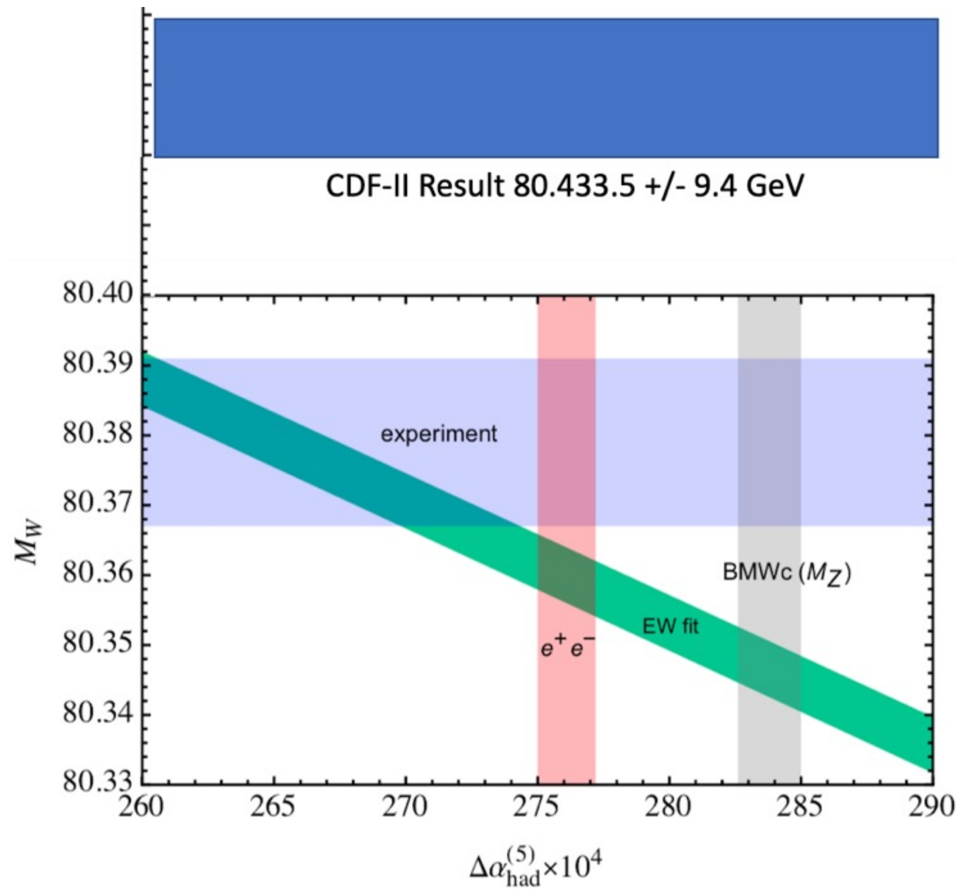
- One example shown here for M_W
- Other tension also increases in other SM predictions



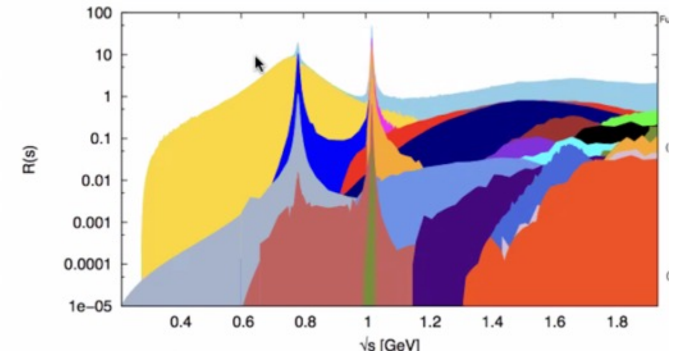
A. Crivellin, et al. (link)

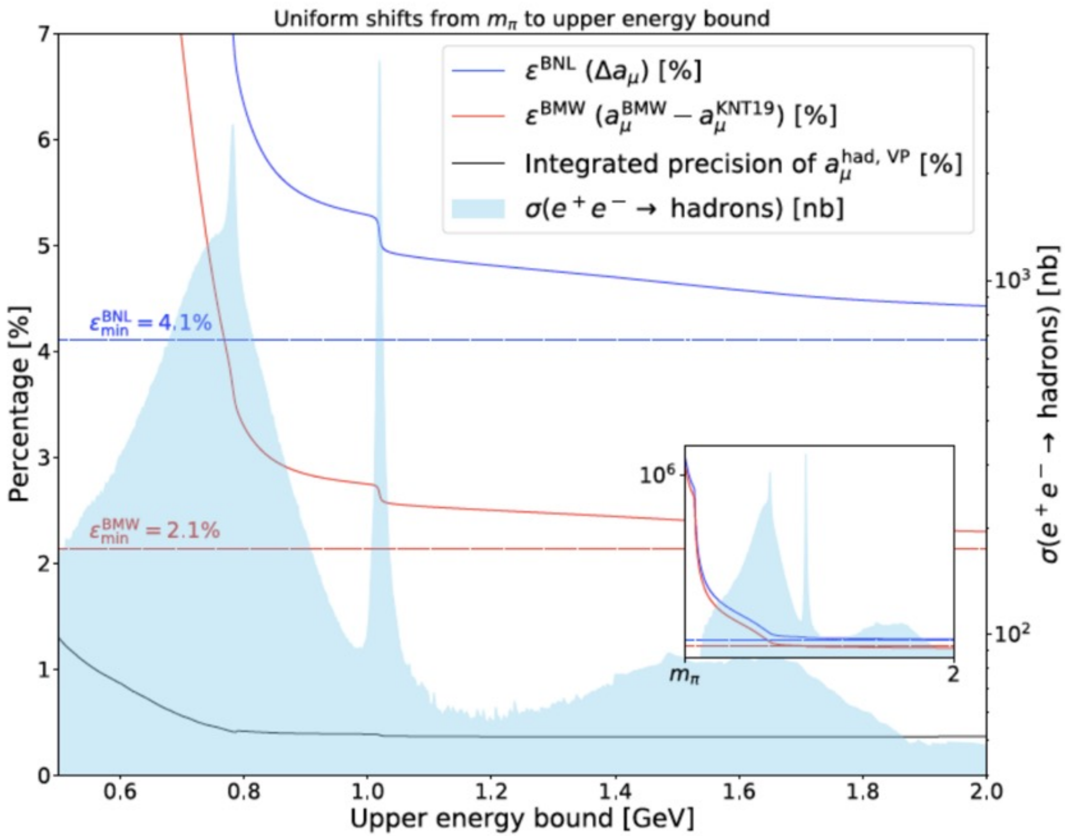
Increases tension in other precision EW fits

- 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



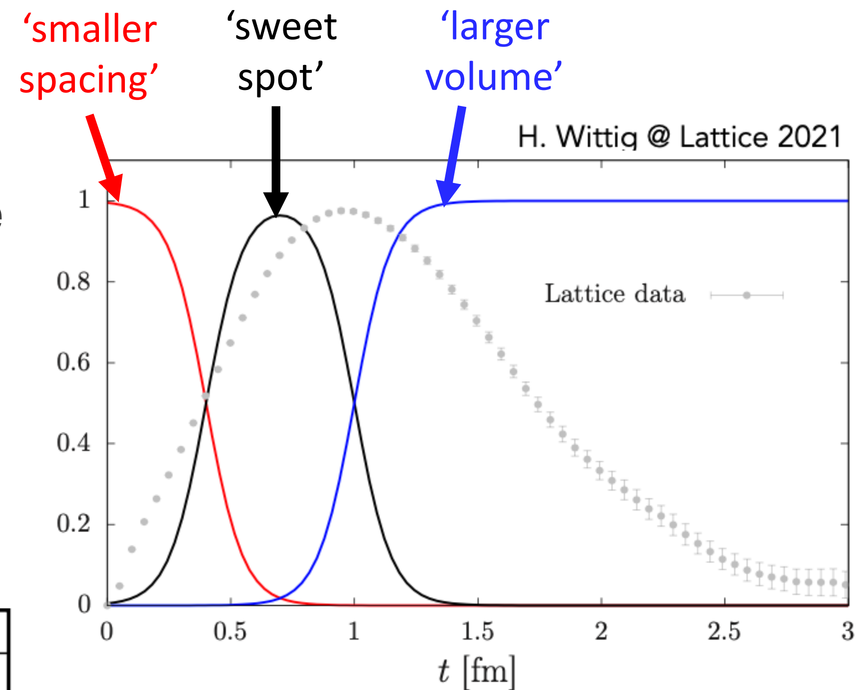


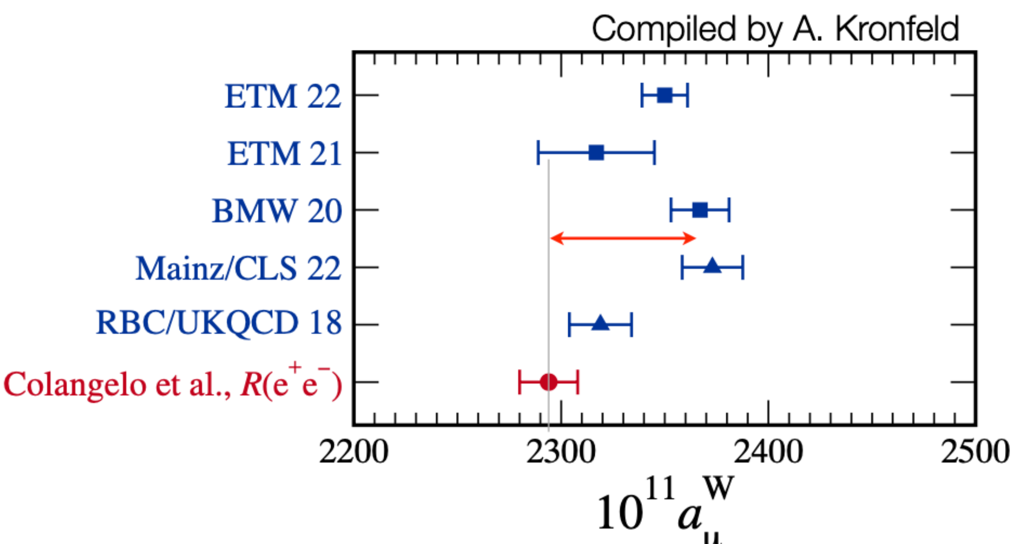
Keshavarzi, Marciano, Passera and Sirlin, *Phys.Rev.D* 102 (2020) 3, 033002

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

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

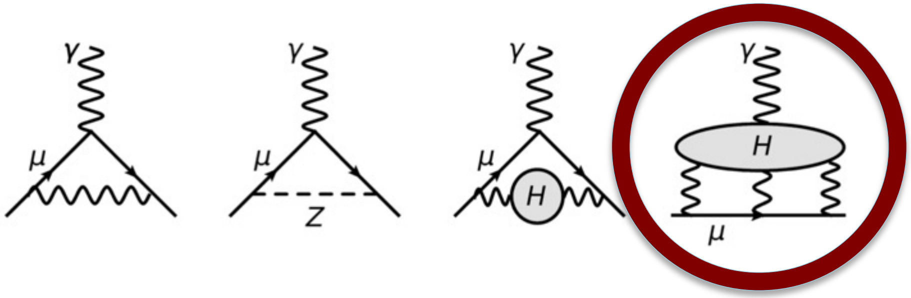


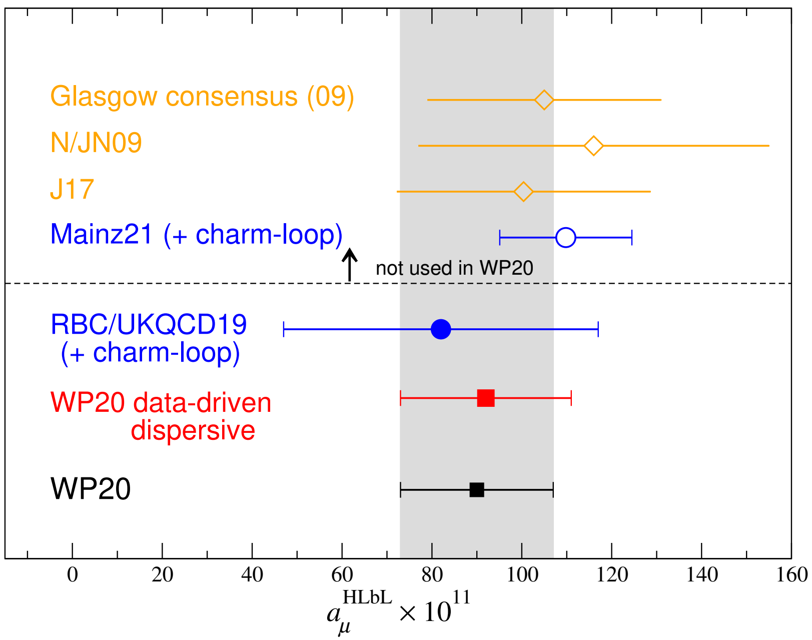


- About 90 x 10^{-11} of BMW diff comes from intermediate range
- Averaging over lattice groups reduces overall 250 x 10^{-11} discrepancy by about ~20%

Aida El-Khadra (Fri AM) *Prospects for precise predictions of aμ 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

Fermilab

Experimental outlook

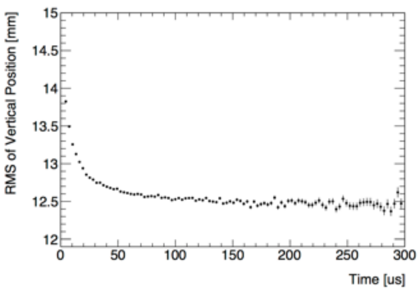
- Run 1 result was dominated by statistical error
  - 434 ppb stat vs 157 ppb syst

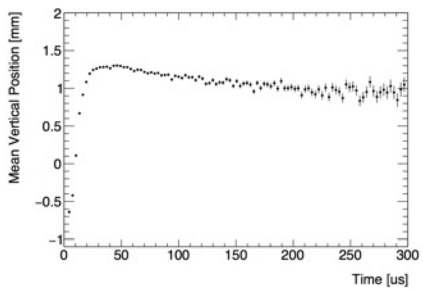
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\rm calib}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu_p'(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total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

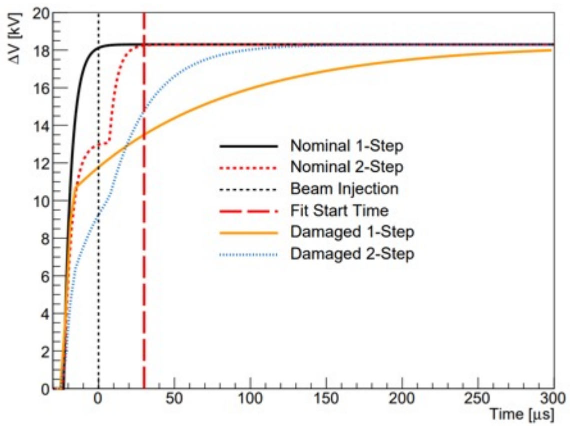
- Original TDR goal:
  - Control systematics at 100 ppb
  - Run experiment until stat error matched at 100 ppb → 20 x BNL
- Did not quite achieve 100 ppb syst in Run 1
- Two dominant errors

Reducing the two dominant errors

C_{PA} = phase acceptance correction

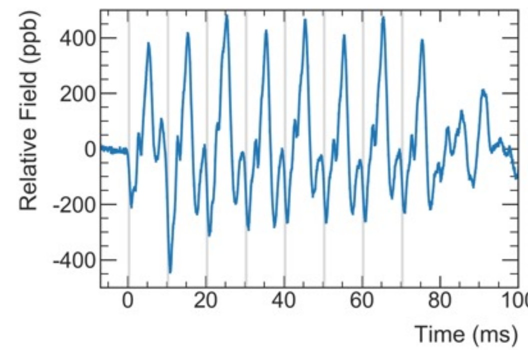


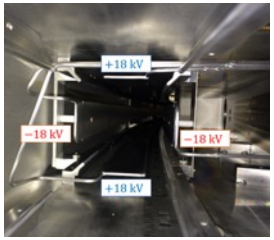


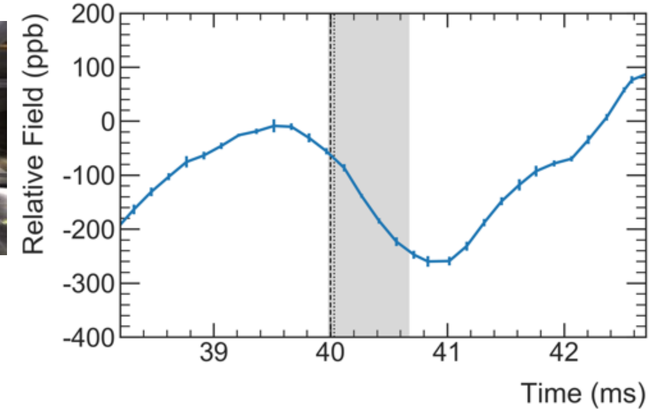


- Failed resistors in Run 1 → beam instabilities → time-dependent g-2 phase in accepted e+
- Resistors fixed by Run 2

B_Q = quad transients



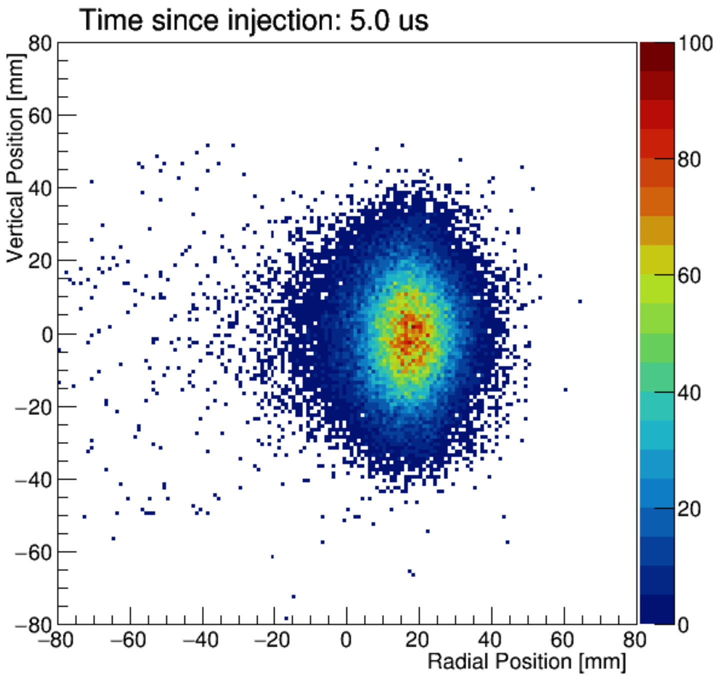




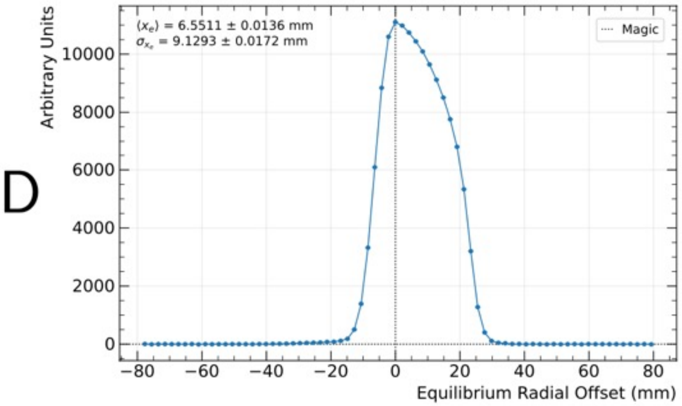
- Pulsed quads → mech vibrations → time-dependent field perturbation
- Mapped in increasing detail with newly-constructed NMR probes starting by Run 2 and continuing through subsequent runs

Fermilab

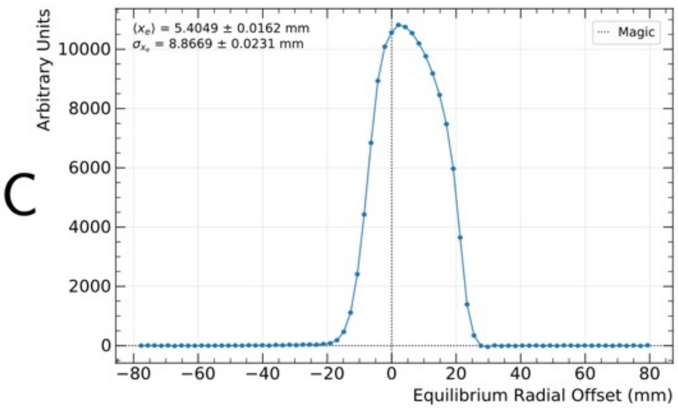
Major kicker upgrade by Run 3



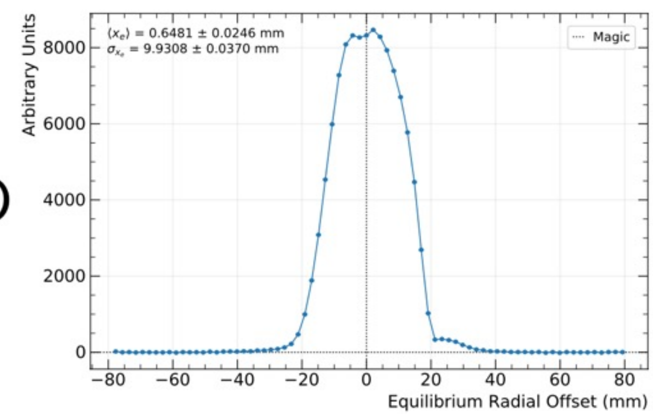
1D



2C



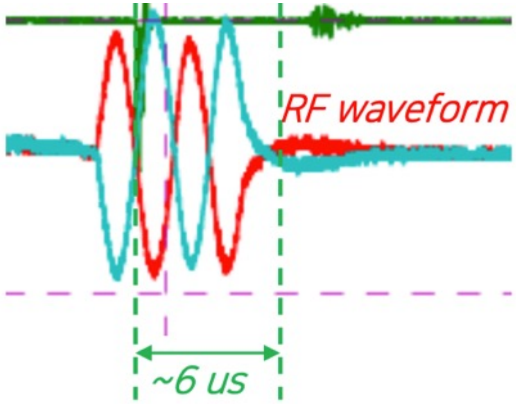
3O

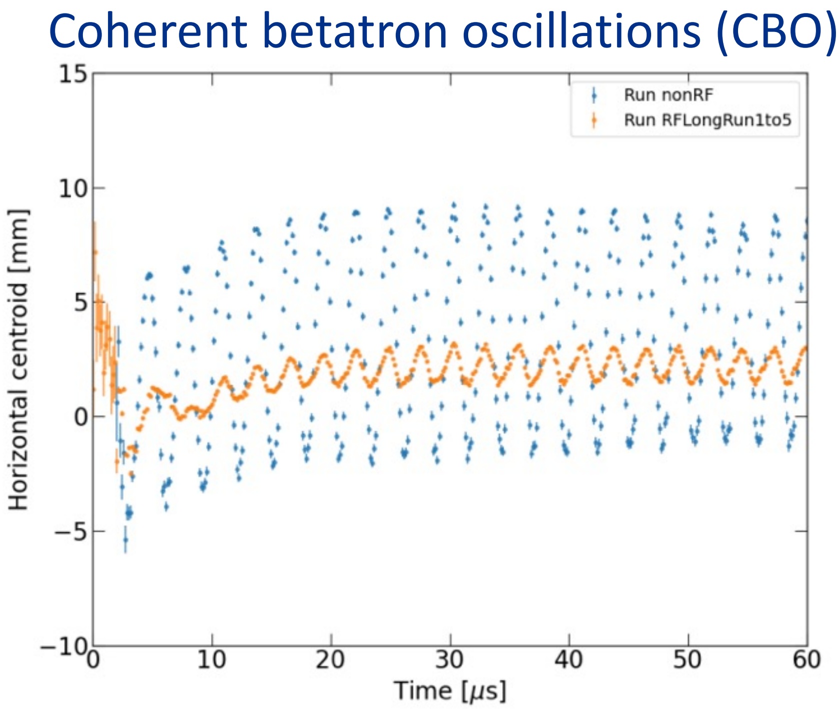


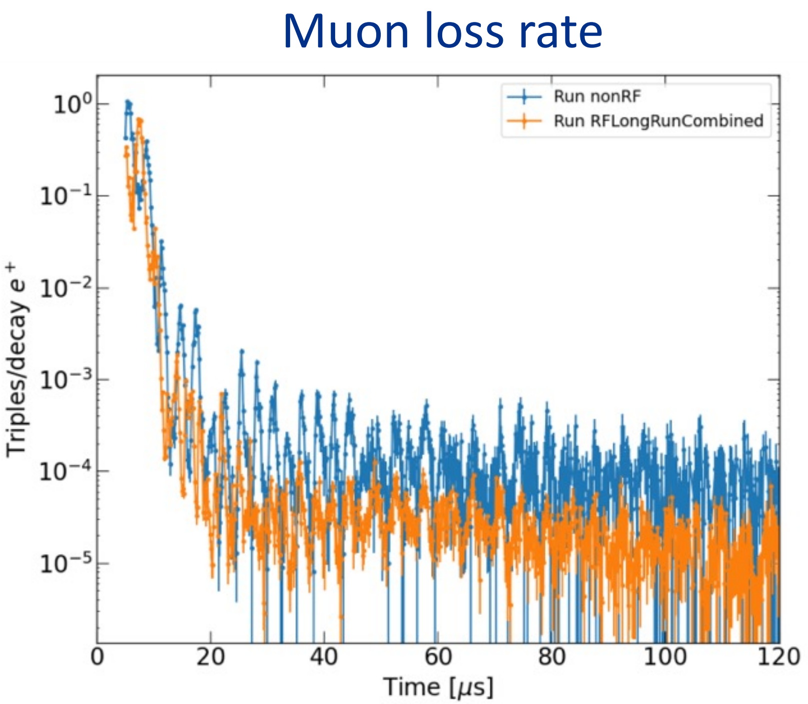
- Run 1 kick insufficient to center beam
  - Increased rate 30%
  - Reduced equilibrium orbit from 6mm to 0.6mm off ideal
  - Reduced CBO amplitude at injection from 13mm to 5mm
- Improves many other non-dominant systematics

RF system added for Run 5

- Apply horizontal dipole electric field, near CBO frequency, ~1 kV to inner and outer quad plates, for 6 µs after injection.
- Reduced CBO amplitude from 6mm to <1mm, reduced muon losses by x7







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

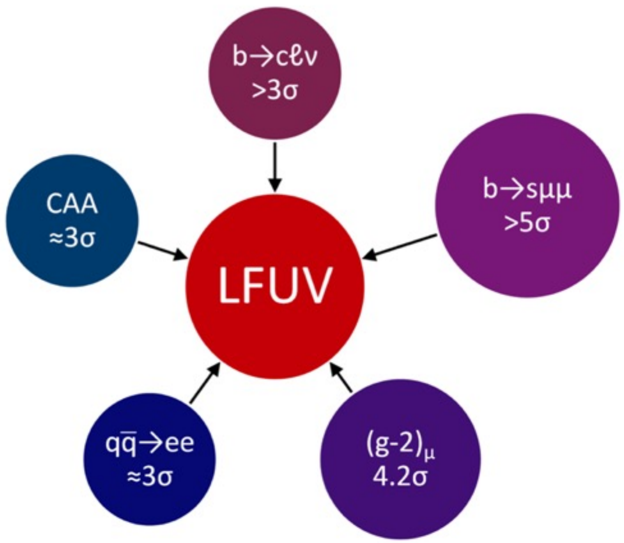
Experimental outlook

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

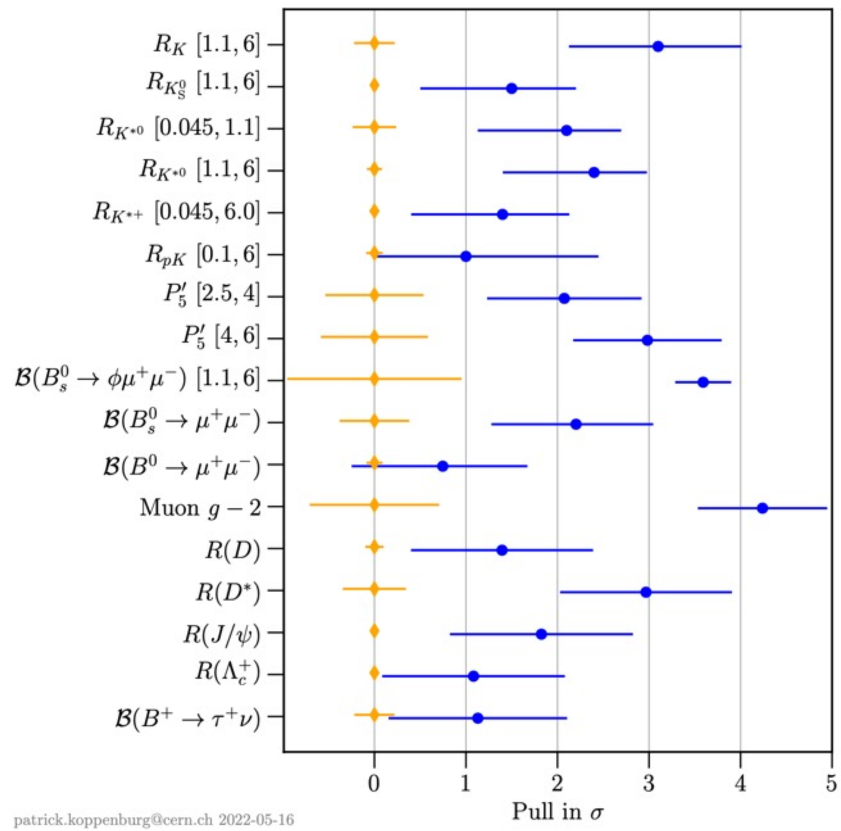
Not cumulative

- Controlling systematics better than TDR projections → experiment is still statistics limited
- Run 6 is still a question mark
  - Had planned to run μ- this coming year
    - Factor of 2 less rate, but access to CPT/LV analyses, 4xBNL μ-
    - Recently cancelled to divert lab resources to higher priorities
  - Still proposing to run μ+ 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

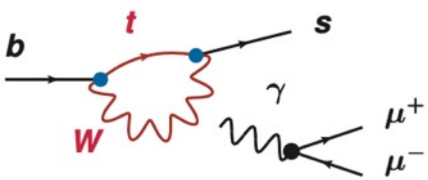


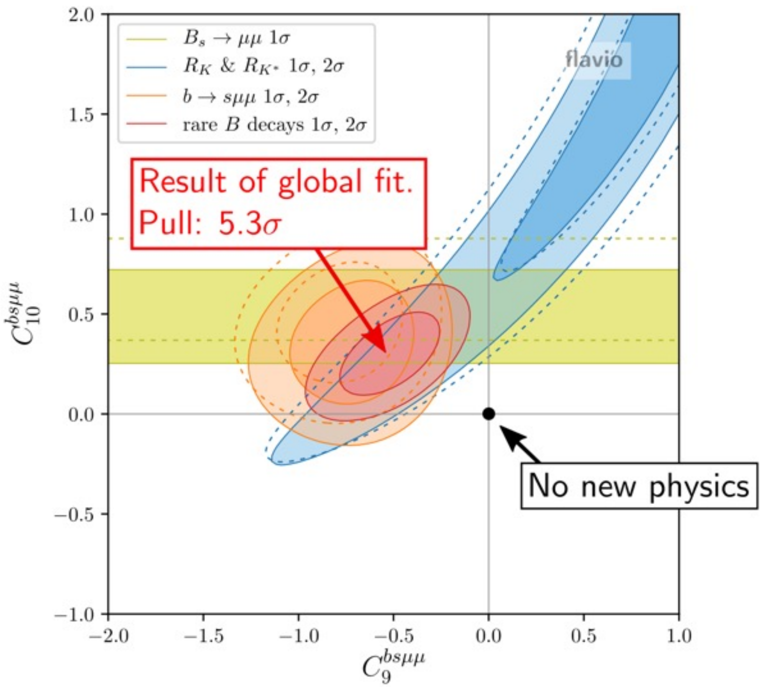
Mounting Evidence for the Violation of Lepton Flavor Universality
https://arxiv.org/pdf/2111.12739.pdf (A. Crivellin, M. Hoferichter)



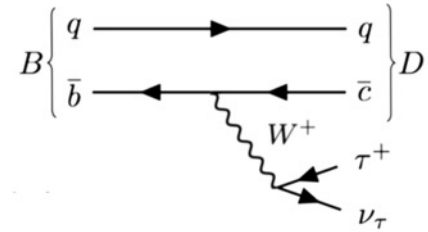
See RP talks by:
Angelo Di Canto (Tues AM) *Weak decays of b/c auarks: summary*
Rafael Silva Contino (Thurs AM) *Flavor anomalies overview*
Wolfgang Altmannshofer (Thurs AM) *New physics models for flavor anomalies*
Peter Stangi (Thurs AM) *CLFV in heavy quark decays - interplay between LFV and LFUV*
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* (0νββ, LFV, and Cabibo Angle Anomaly)
Several other talks touching on LFUV and LFV

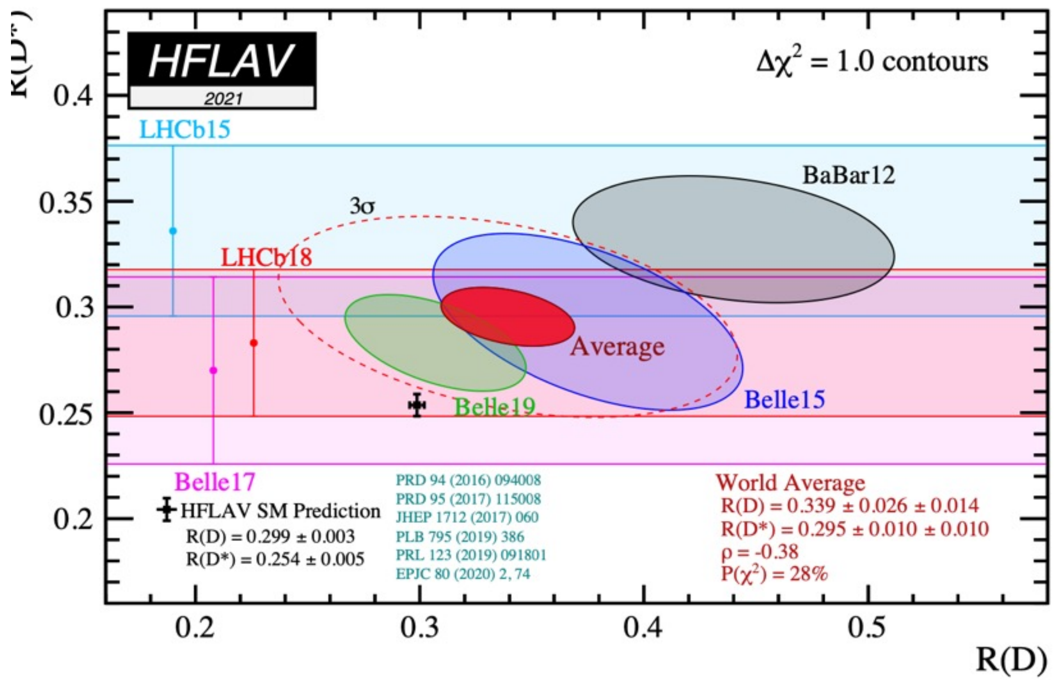
B anomalies





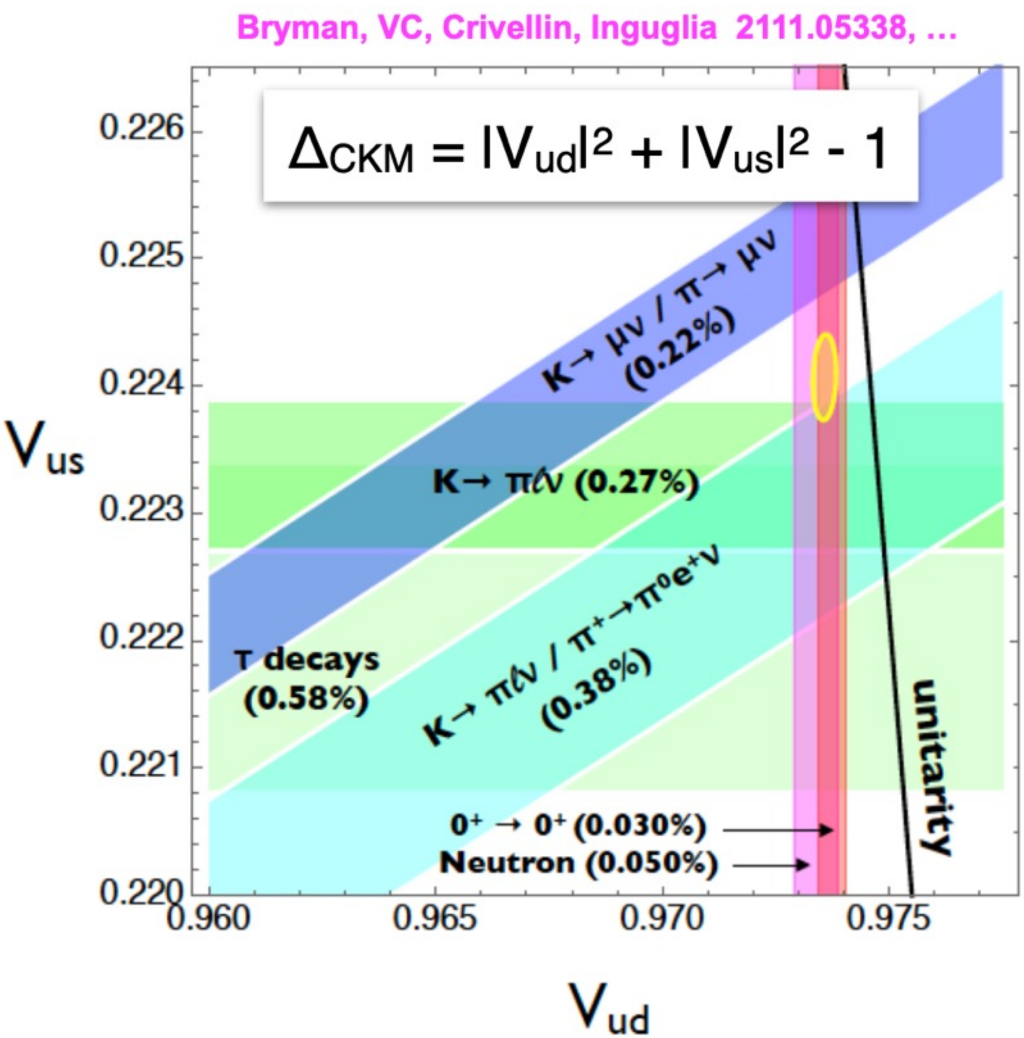
W. Altmannshofer, P. Stangl arXiv:2103.13370





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

Cabibo angle anomaly



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

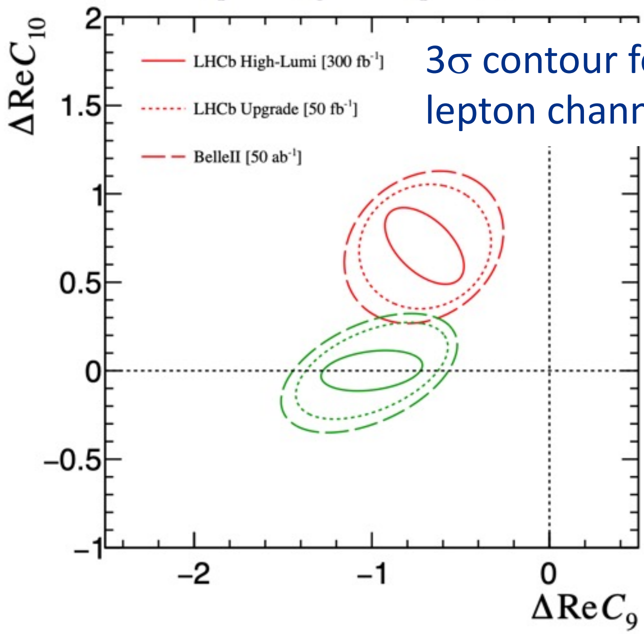
Vincenzo Cirigliano (Thurs PM) *Searching for new physics with rare processes and precision measurements* (0νββ, LFV, and Cabibo Angle Anomaly)

Flavor anomalies motivate future upgrades

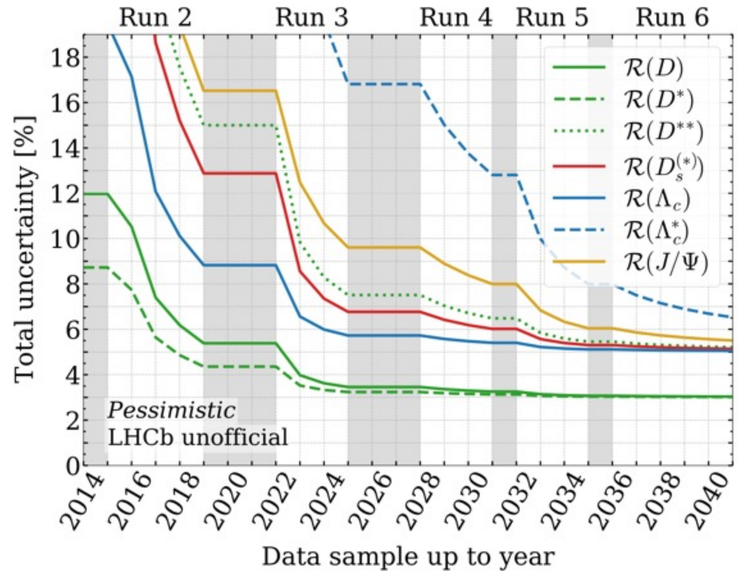
- LHC and b-factory upgrades will improve precision searches for LFUV

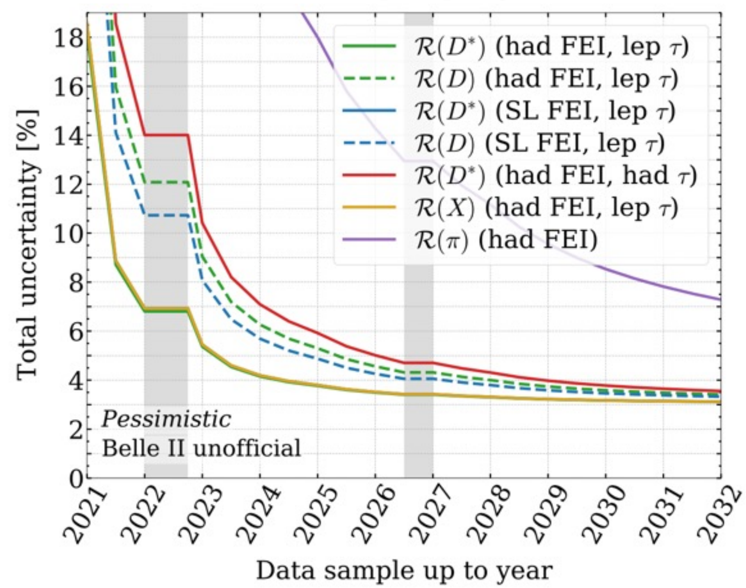
[LHCb, arXiv:1808.08865, Belle II physics book]

$$\mathcal{C}_9^{(e)} = \mathcal{C}_9^{\mathrm{SM}} = \mathcal{C}_9^{(\mu)} + 1$$



3σ contour for lepton channels

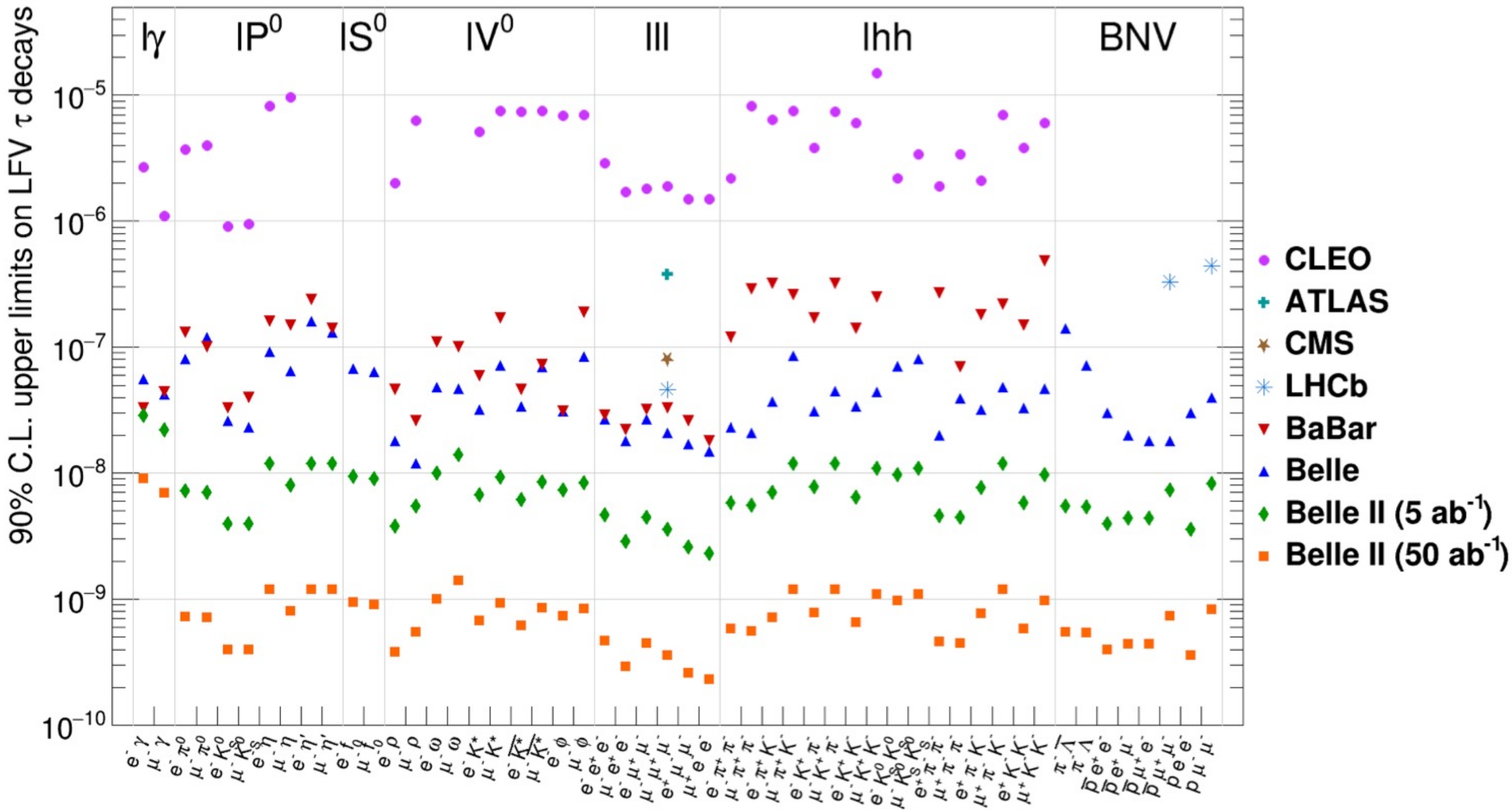




Rafael Silva Contino (Thurs AM) –
Flavor anomalies overview

Also motivates searches for CLFV

arXiv:2207.06307



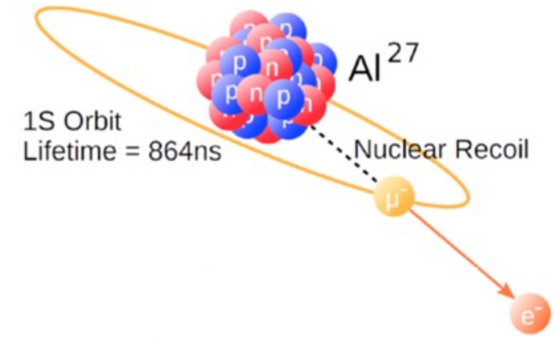
- Compilation plot shows nearly 2 order of magnitude increase in sensitivity to τ lepton violating across all channels at Belle II

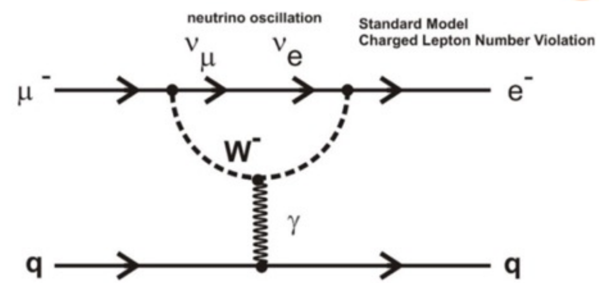
Mu2e and Mu2e-II experiments

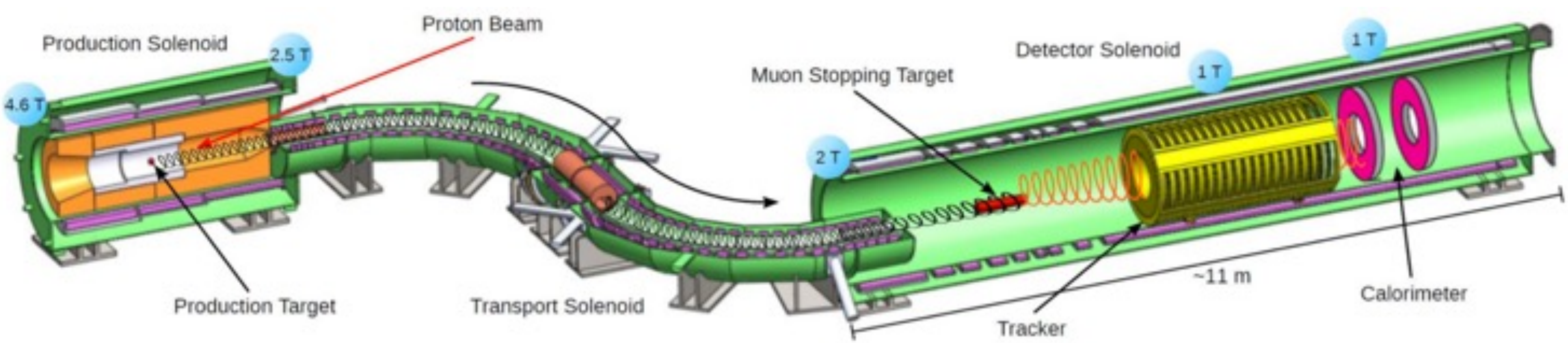
- Mu2e is searching for muons spontaneously converting to electrons in the field of a nucleus

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

- Goal of the experiment is to reach a sensitivity to branching ratios of $3\text{x}10^{-17}$
  - 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

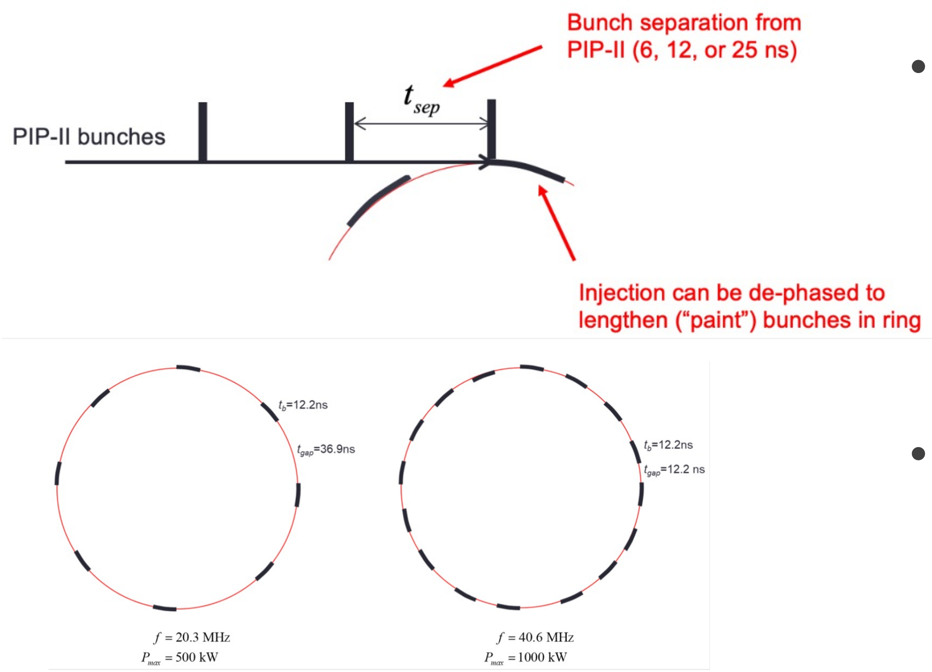






Future CLFV – Advanced Muon Facility (AMF)

- 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

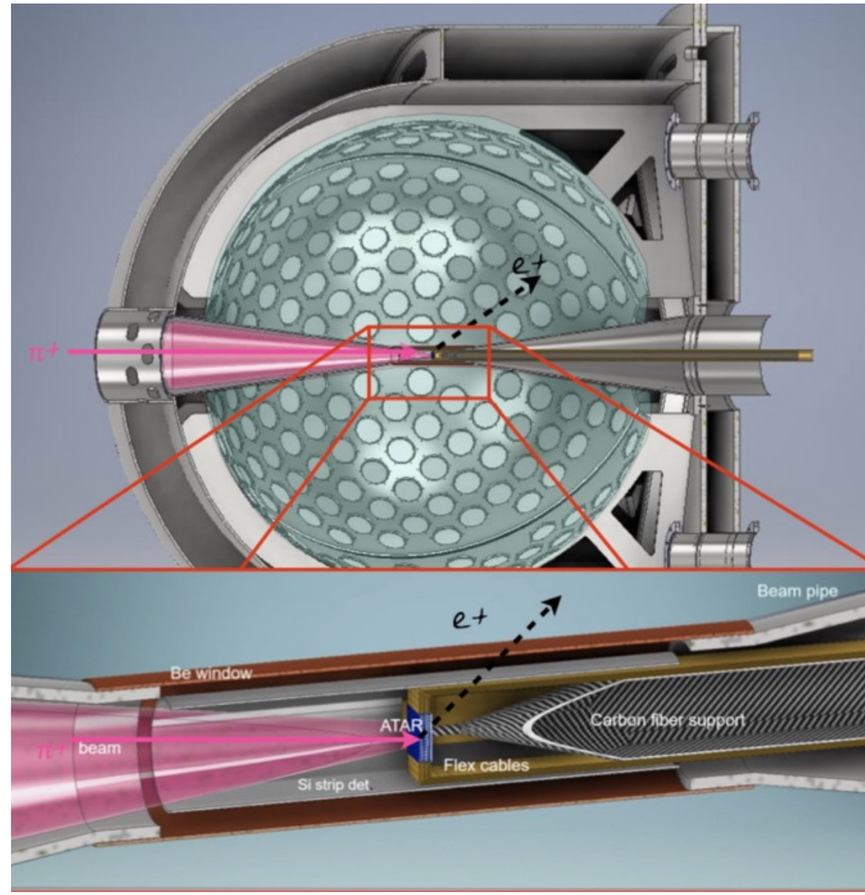
Bob Bernstein (Fri AM) *Pioneer: A new muon program at Fermilab*

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 ~15x smaller than current exp (PIENU)
- Second phase goal to study pion beta decay

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

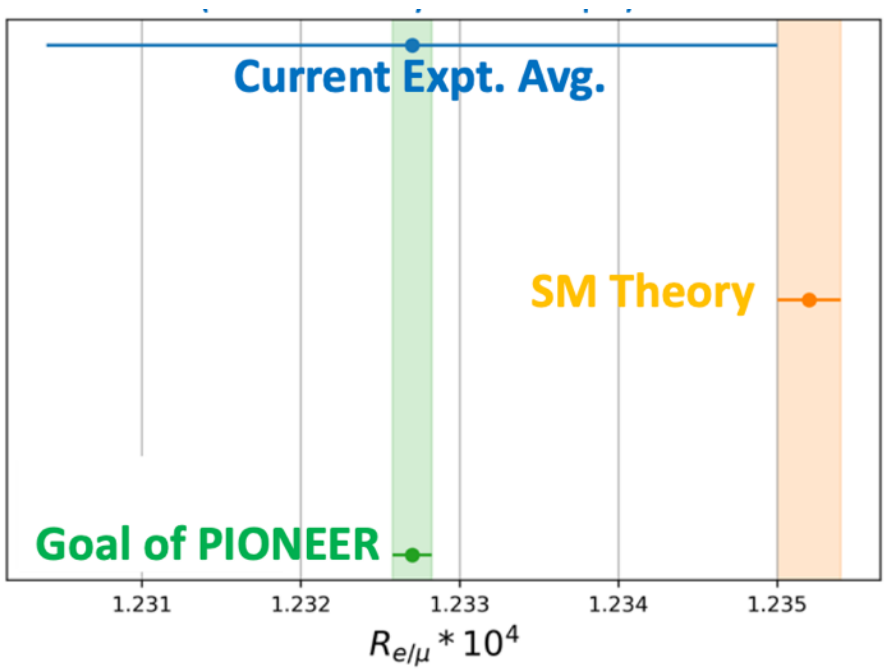
  and improve V_{ud} by an order of magnitude for theoretically clean CKM unitarity test
- Recently rate a high priority by the PSI PAC

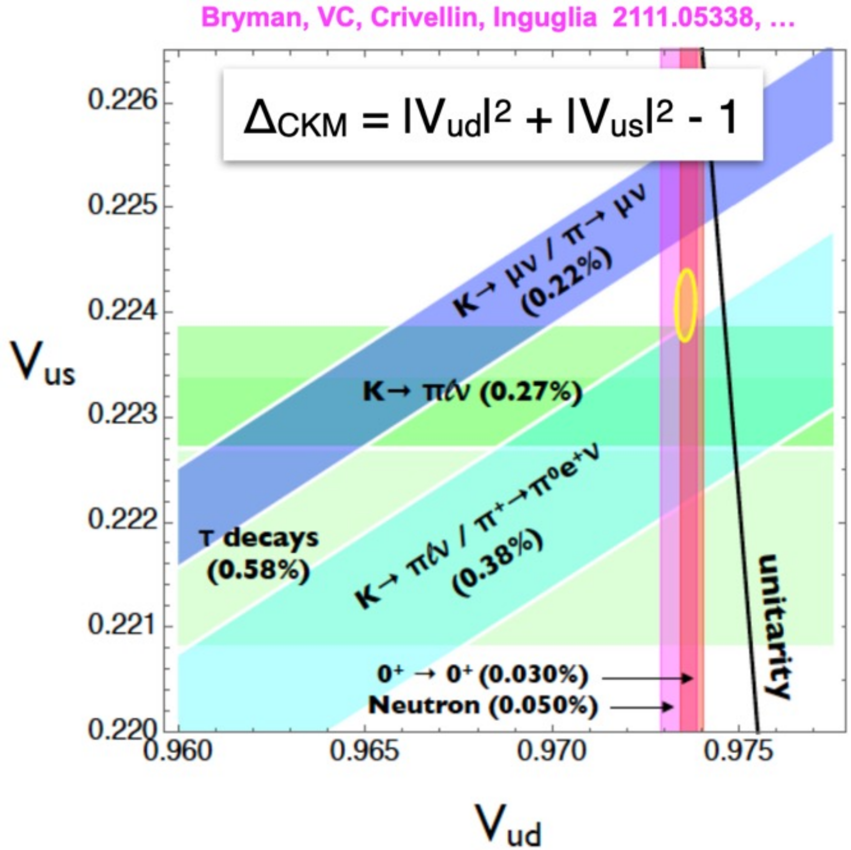


PIONEER PSI Proposal (arXiv:2203.01981)
PIONEER Snowmass (arXiv:2203.05505)

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 Vud

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