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)
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The results heard round the world!

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!

<table>
<thead>
<tr>
<th></th>
<th>BNL</th>
<th>FNAL</th>
<th>Exp Combined</th>
<th>SM Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_\mu \times 10^{-11})</td>
<td>116592089(63)</td>
<td>116592040(54)</td>
<td>116592061(41)</td>
<td>116591810(43)</td>
</tr>
<tr>
<td>(\delta a_\mu) (ppb)</td>
<td>540</td>
<td>463</td>
<td>350</td>
<td>368</td>
</tr>
</tbody>
</table>

\[ a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 251(59) \times 10^{-11} \]
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 $144 \times 10^{-11}$ (~60%)
Solving g-2 with quarks is not so simple

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

$$\Delta \alpha_{\text{had}}^{(5)}(q^2) = \frac{q^2}{4\pi^2} P \int_{m^2}^{\infty} \frac{\sigma^0_{\text{had}}(s)}{s - q^2} ds$$

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

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

Aida El-Khadra (Fri AM) *Prospects for precise predictions of $\alpha_\mu$ 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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Correction Terms</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>$\omega^m_a$ (statistical)</td>
<td>–</td>
<td>434</td>
</tr>
<tr>
<td>$\omega^m_a$ (systematic)</td>
<td>–</td>
<td>56</td>
</tr>
<tr>
<td>$C_e$</td>
<td>489</td>
<td>53</td>
</tr>
<tr>
<td>$C_p$</td>
<td>180</td>
<td>13</td>
</tr>
<tr>
<td>$C_{ml}$</td>
<td>-11</td>
<td>5</td>
</tr>
<tr>
<td>$C_{pa}$</td>
<td>-158</td>
<td>75</td>
</tr>
<tr>
<td>$f_{\text{calib}}(\omega_p(x, y, \phi) \times M(x, y, \phi))$</td>
<td>–</td>
<td>56</td>
</tr>
<tr>
<td>$B_k$</td>
<td>-27</td>
<td>37</td>
</tr>
<tr>
<td>$B_q$</td>
<td>-17</td>
<td>92</td>
</tr>
<tr>
<td>$\mu_p'(34.7^\circ)/\mu_e$</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td>$m_\mu/m_e$</td>
<td>–</td>
<td>22</td>
</tr>
<tr>
<td>$g_e/2$</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Total systematic</td>
<td>–</td>
<td>157</td>
</tr>
<tr>
<td>Total fundamental factors</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Totals</td>
<td>544</td>
<td>462</td>
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- Original TDR goal:
  - Control systematics at 100 ppb
  - Run experiment until stat error matched at 100 ppb \(\rightarrow 20 \times \text{BNL}\)
- Did not quite achieve 100 ppb syst in Run 1
- Two dominant errors
Reducing the two dominant errors

\[
C_{PA} = \text{phase acceptance correction}
\]

\[
B_Q = \text{quad transients}
\]

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

- 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, ~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

Coherent betatron oscillations (CBO)  Muon loss rate
Experimental outlook

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<th>Run 2/3</th>
<th>Run 4/5</th>
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<tr>
<td>Stat error</td>
<td>434</td>
<td>202*</td>
<td>119*</td>
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<tr>
<td>Syst error</td>
<td>157</td>
<td>95*</td>
<td>86*</td>
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<td>462</td>
<td>223*</td>
<td>147*</td>
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- 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

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- 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

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

20 07/23/2022 Chris Polly -- Snowmass 2022
B anomalies

Both analyses hint at LUV through R(K), R(K*), R(D), and R(D*) ratios.
Cabibo angle anomaly

\[ \Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1 \]

- 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 (0νββ, LFV, and Cabibo Angle Anomaly)*
Flavor anomalies motivate future upgrades

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

[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 $\sim 15x$ 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

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

\[ \Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1 \]
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