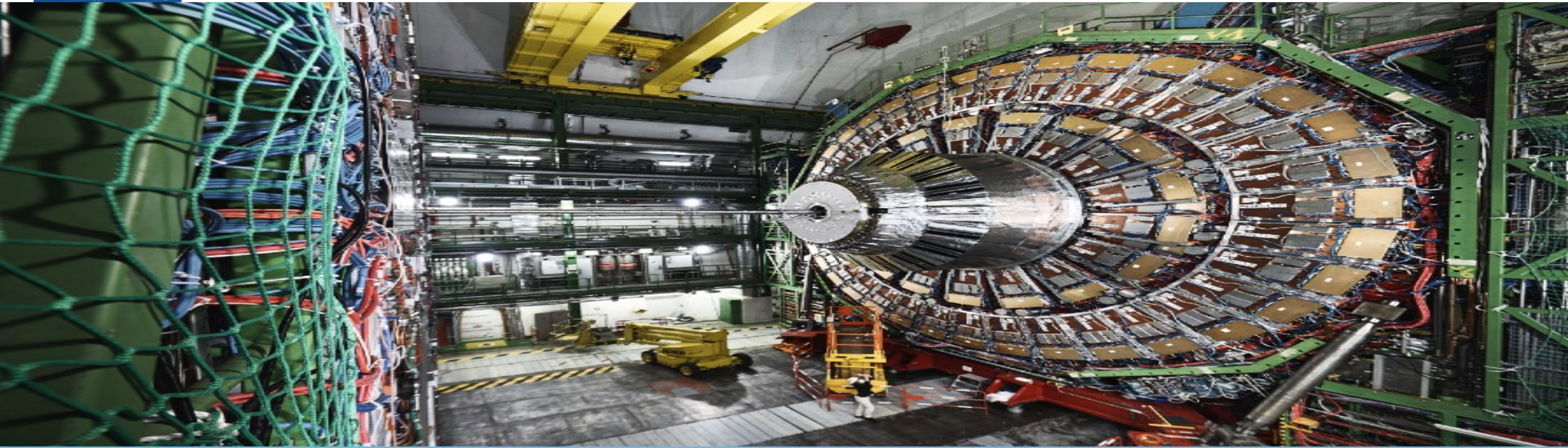


WP21 - JRA3: Precision Tests of the Standard Model

Coordinators: Misha Gorshteyn (JGU Mainz), Andrzej Kupsc (Uppsala U.)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

JRA 3: Precision tests of SM in electroweak sector

Work package number	21															
Work package acronym	PrecisionSM															
Work package title	JRA3-Precision Tests of the Standard Model															
TASKS/Subtasks	**Year 1**				**Year 2**				**Year 3**				**Year 4**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Hadronic effects in precision tests of the weak sector of the Standard Model																
1.1 Extraction of WMA from PVES and Vud from β-decay						1										
1.2 Determination of neutrino properties with short baseline neutrino scattering														3		
2. Hadronic effects in precision tests of the electromagnetic sector of the Standard Model								2						4		

Weak sector:

Neutral Current - weak mixing angle from a measurement of hadronic weak charges with parity-violating electron scattering

Charged Current - V_{ud} and V_{us} from beta decays of free&bound neutron, pions, kaons

Neutrinos: hadronic background for energy reconstruction

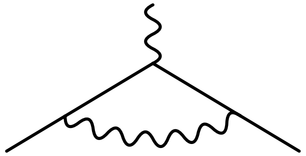
Electromagnetic sector:

Hadronic vacuum polarization correction to muon g-2 within data-driven approach across timelike and spacelike regimes

$(g-2)_\mu$ Global Effort
Experiment/Theory Tension reaches 4.2σ

Schwinger, 1948: anomalous moment of a lepton

$$a_\mu = \frac{(g-2)_\mu}{2} = \frac{\alpha}{2\pi} = 0.001161$$



Since then: theory advanced by 4 o.o.m.

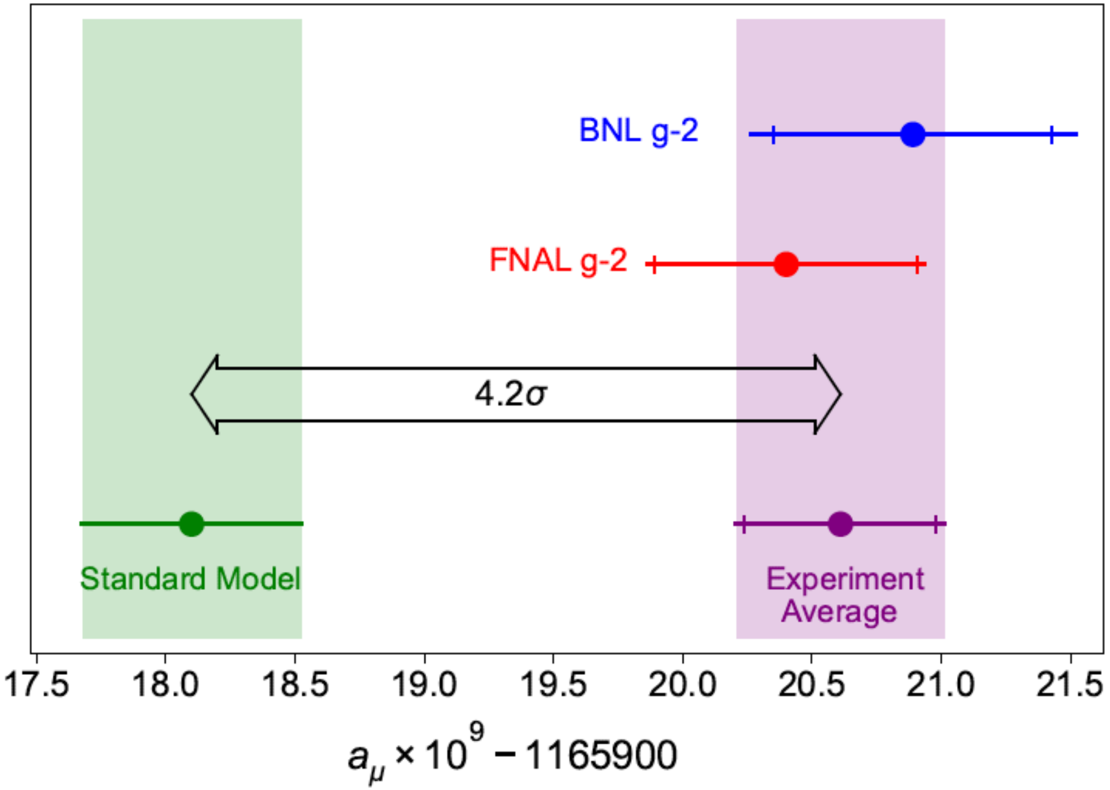
April 7: Release of the first result of the Muon g-2 Collaboration

Enormous interest from the international community

First results after ~20 years.

Confirms BNL result; stronger tension with SM (4.2σ)

$(11\,659\,181.0 \pm 4.3) \cdot 10^{-10}$ $(11\,659\,206.1 \pm 4.1) \cdot 10^{-10}$



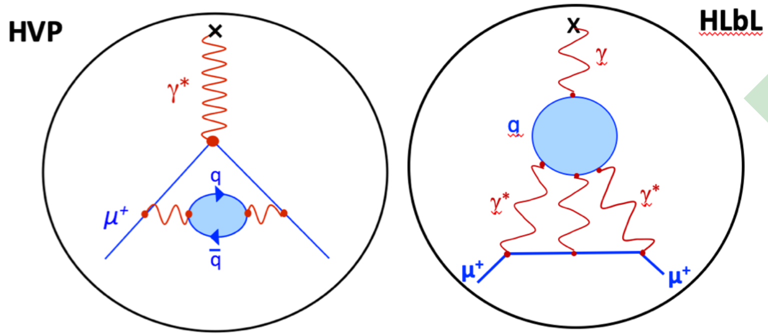
B. Abi et al., Muon g-2 Coll. Phys. Rev. Lett. 126, 141801 (2021)

$(g-2)_\mu$ Global Effort
Experiment/Theory Tension reaches 4.2σ

Theoretical precision equally important as experimental!

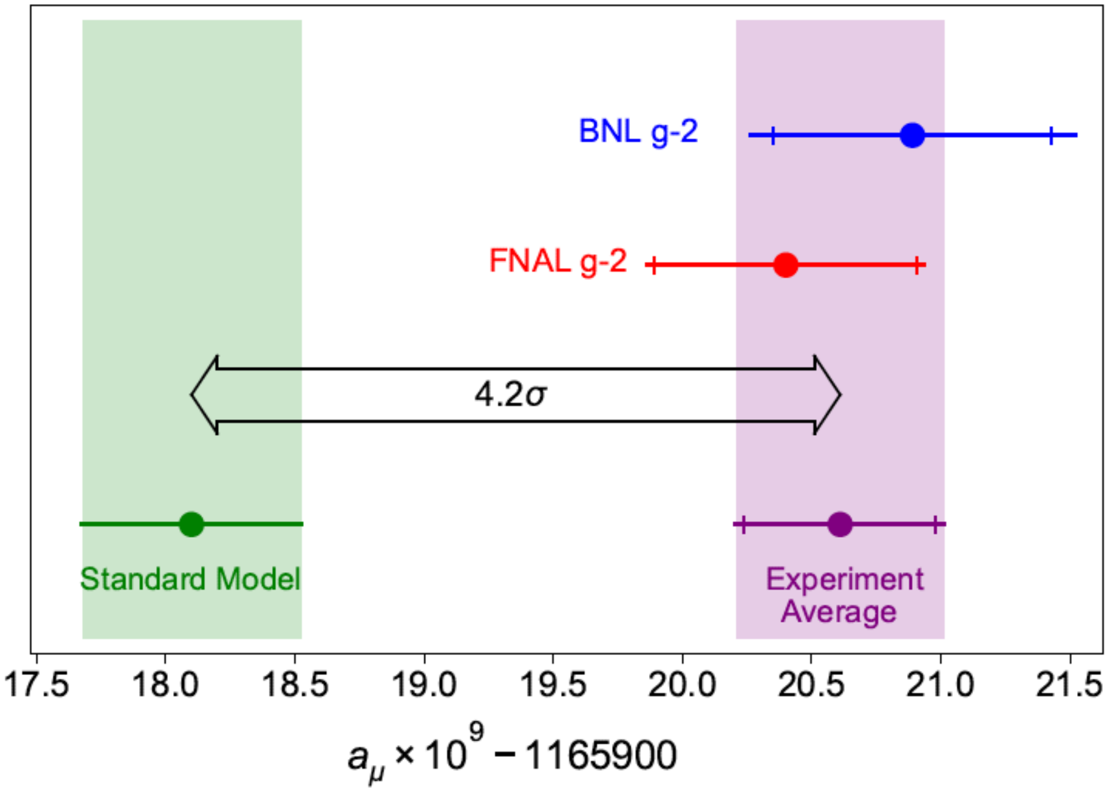
Theo uncertainty: entirely from hadronic contributions

Best approach so far: dispersion theory + data



$(693.1 \pm 4.0) \cdot 10^{-10}$ $(9.2 \pm 1.8) \cdot 10^{-10}$

$(11\,659\,181.0 \pm 4.3) \cdot 10^{-10}$ $(11\,659\,206.1 \pm 4.1) \cdot 10^{-10}$



Extremely important activity within WP21

(database e+e—-> hadrons, theory, MUonE)

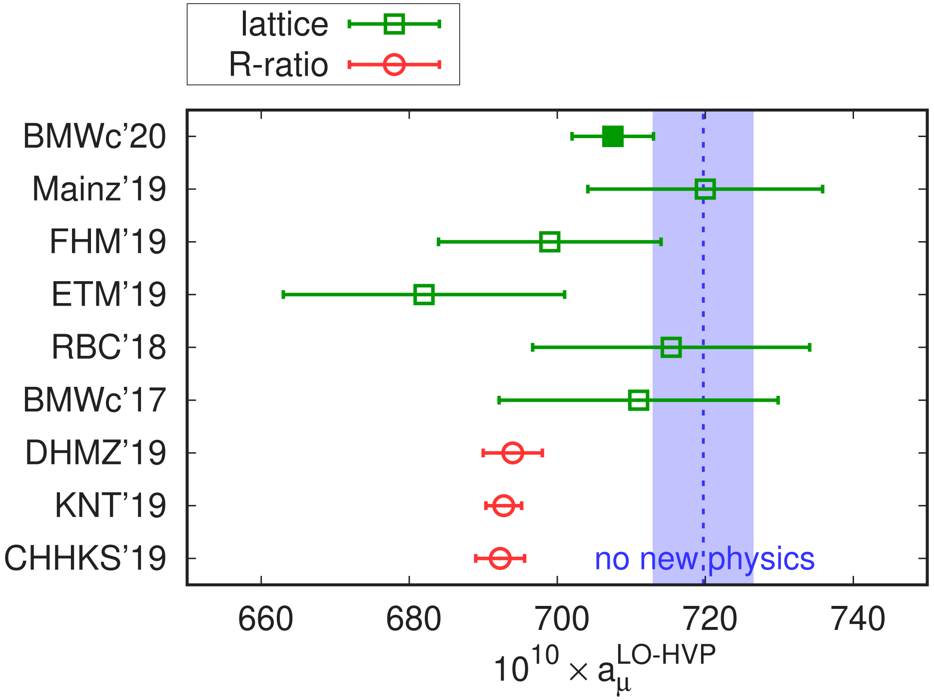
$(g-2)_\mu$ Global Effort

Experiment/Theory Tension reaches 4.2σ

Unexpected tension between

- data-driven HVP (within JRA 3) and

- new lattice result by BMW collaboration



Muon g-2 Theory Initiative Whitepaper

Physics Reports 887 (2020) 1-166

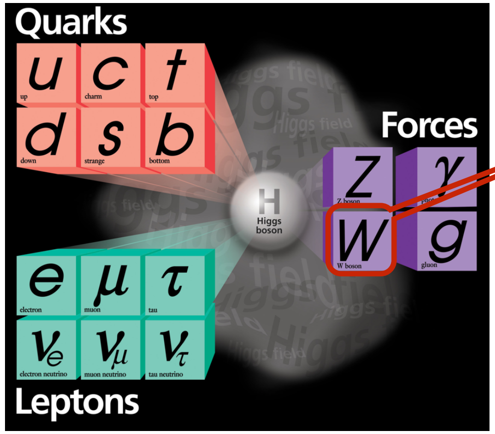
The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

WP21 (JRA 3) provided results and methods that are major players in the test of SM with muon (g-2)

Top-Row CKM unitarity anomaly: Confirmed and Sharpened



Charged current interaction - β-decay

$$\mu \to e + \nu_\mu + \bar{\nu}_e, \;\; n \to p + e + \bar{\nu}_e, \;\; \pi^\pm \to \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

Universality of weak interaction:

Same strength in lepton and quark sector

Quark mixing: strength distributed among 3 generations

CKM unitarity - measure of completeness of the SM:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

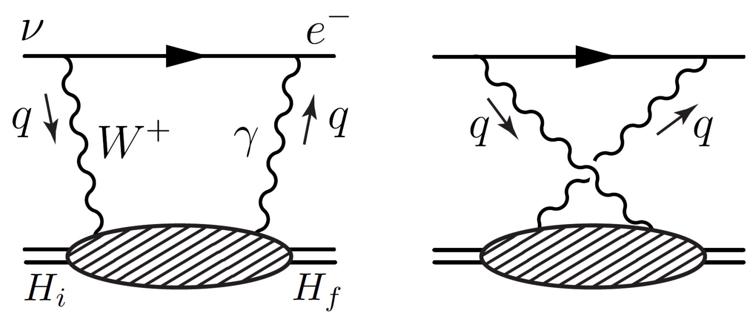
PDG2020: CKM unitarity in the top row $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$ **— 3σ deficit**

PDG 2018: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{V_{ud}}(2)_{V_{us}}$

CKM unitarity anomaly established within this JRA!

Top-Row CKM unitarity anomaly: Confirmed and Sharpened

Main change: reevaluation of the γW-box
Bottleneck for precision improvement since 40 years
Major improvement (factor 2) due to new framework



Dispersion relations (DR) for EW boxes

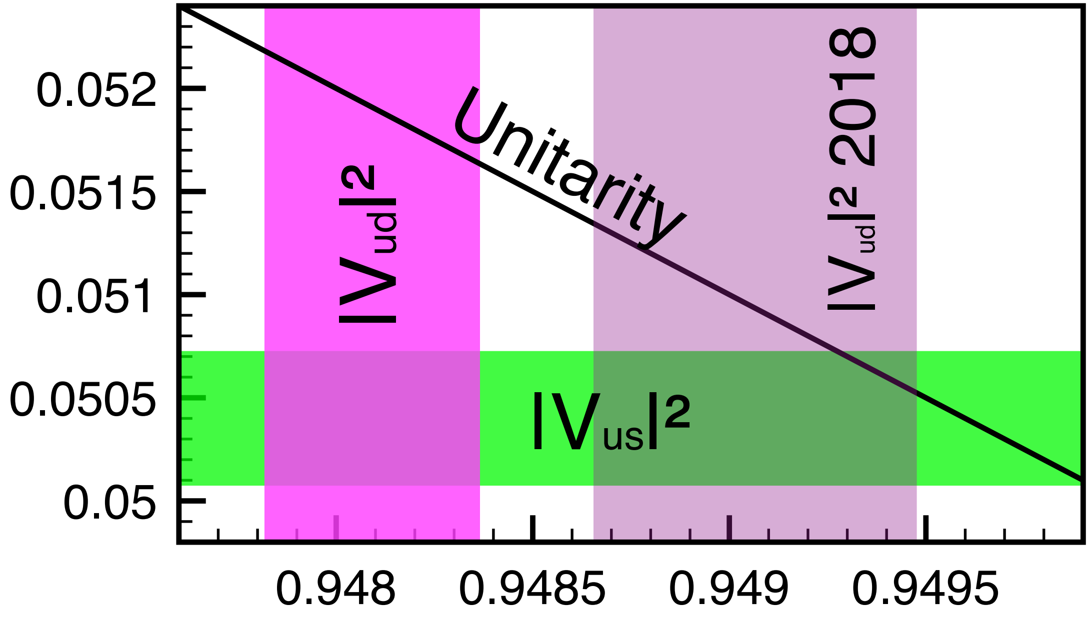
C-Y Seng, MG et al., Phys.Rev.Lett. 121 (2018) 24, 241804;
C-Y Seng, MG, M.J. Ramsey-Musolf, Phys.Rev. D 100 (2019) 1, 013001

Nuclear corrections from DR

C-Y Seng, MG, M.J. Ramsey-Musolf, Phys.Rev. D 100 (2019) 1, 013001;
MG, Phys.Rev.Lett. 123 (2019) 4, 042503;

Combined DR + lattice QCD + phenomenology

X. Feng, MG et al, Phys.Rev.Lett. 124 (2020) 19, 192002
C-Y Seng, X. Feng, MG, L-C Jin, Phys.Rev. D 101 (2020) 11, 111301;



Top-Row CKM unitarity anomaly: Confirmed and Sharpened

The framework further applied to

Dispersion analysis of radiative corrections to g_A for neutron β decay

MG, C-Y Seng, JHEP 10 (2021) 053

Important for: extracting V_{ud} from neutron decay; comparing g_A from experiment and lattice QCD

Combined DR + lattice QCD + ChPT for RC to semileptonic kaon decays

C-Y Seng, X. Feng, MG, L-C Jin, U.-G. Meißner, JHEP 10 (2020) 179
P.-X. Ma, X. Feng, MG, L-C Jin, C-Y Seng, PRD 103 (2021) 114503
C-Y Seng, D. Galviz, MG, U.-G. Meißner, PLB 820 (2021) 136522
C-Y Seng, D. Galviz, MG, U.-G. Meißner, 2103.04843

Important for: extracting V_{us} from Kl3 decays; establishing the Kl2-Kl3 discrepancy

Complete change of landscape in SM tests with CKM unitarity in the past 2 years
New method developed; wide range of applications to previously unaccessible corrections

Deliverables & Milestones

Deliverables (brief description and month of delivery)
D21.1-Electroweak MAID (month 18). For weak π,η production will be made accessible on the existing MAID website, and computer code provided for download. This deliverable is also the Milestone 1, and will serve as input for Milestone 3, new νπ MC event generator. The formalism will be extended to kaon and multi-pion channels and to nuclear targets, and will be directly applicable to the conditions of the actual short baseline neutrino experiments.
D21.2-Report on spacelike HVP in muon-electron scattering at CERN **vs timelike HVP (month 24).** We will organize a workshop on this topic, the Milestone 2.

D21.2 - Report on HVP was submitted; results incorporated in the Muon g-2 white paper

T. Aoyama et al. [Muon g-2 Theory Initiative] Phys.Rept. 887 (2020) 1-166

Milestone 2: workshop "Spacelike and timelike determination of a_μ^{HLO}" (postponed and changed to virtual due to COVID) **will be held Nov 24-26, 2021**

Deliverables & Milestones

Deliverables (brief description and month of delivery)
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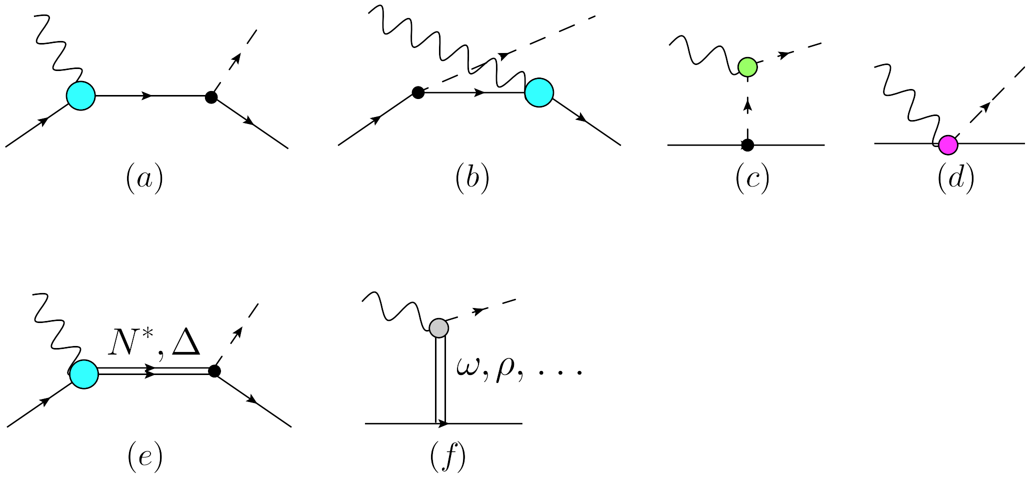
D21.1 & Milestone 1 - Electroweak MAID

Postdoc position filled for 1 year
New unitary isobar model for neutrino pion production is developed
Test website with limited functionality created
Model being implemented on the website (operational - end of November?)
Publication in preparation (end of the year)

Deliverables & Milestones

D21.1 & Milestone 1 - Electroweak MAID



Electromagnetic MAID - unitary isobar model
Direct channel resonances (1 resonance - 1 PW)
Simple low-energy model for background
Strong rescattering via Watson theorem

What's new?

1. Axial vector channel for the first time implemented in the same way
2. Regge-exchange background ensures correct high-energy behavior
3. Resonance-Regge duality implemented on the level of partial waves
4. Website (in preparation) with output options Multipoles, Amplitudes, Observables
5. Work on electromagnetic channels is conducted in parallel

Delay with D21.1

Reasons for the delay:

Active in-person collaboration meetings (Mainz-Tuzla-Zagreb collaboration) would have been beneficial for accelerating the progress on developing the model;

An extended stay (via Mainz-FNAL agreement) at Fermilab was foreseen;
No visits to Fermilab were possible for this whole period

These disruptions impacted the progress, although not dramatically

Summary

Extremely successful developments in precision tests of SM in electroweak sector

Two out of three most significant anomalies at low energies ($> 3\sigma$) established within JRA 3

Muon g-2 (4.2σ) and Cabibbo angle anomaly (top-row CKM unitarity) ($3-5\sigma$) together with B-anomalies are our best shot at BSM at low energies

Slight delay in delivering the fully operative website “Weak MAID” for neutrino pion production
Should be delivered in the next few weeks