STRONG-2020

HORIZON 2020

Annual Meeting 2024

WP21 — JRA3 — Precision tests of the Standard Model

Misha Gorshteyn, Universität Mainz

Low-energy precision tests: complementarity to the LHC

Naively: to feel heavy new particles need to operate at comparable energy

High-precision measurements introduce a new scale (example: EW Observable)

$$\Lambda_{\mathrm{NP}} \sim v_{\mathrm{EW}}\sqrt{\frac{[\mathrm{Obs}]}{\Delta[\mathrm{Obs}]}}$$

Typical reach of modern precision experiments ~ 50 TeV (competitive to colliders)

Low-energy probes work like filters: study a restricted parameter space of New Physics models (complementary to colliders) SMEFT: 2499 6D Op's

JRA3 guides global effort in $(g\text{-}2)_\mu$, CKM unitarity tests, PVES

Highlights since last annual meeting

Reformulation of SM theory of V_{ud} from beta decay
CKM unitarity deficit 2.5σ with nuclear decays
Neutron decay: no unitarity deficit, comparable precision if discrepancies resolved
Revival of interest to nuclear corrections, new synergies (PVES - CKM unitarity)

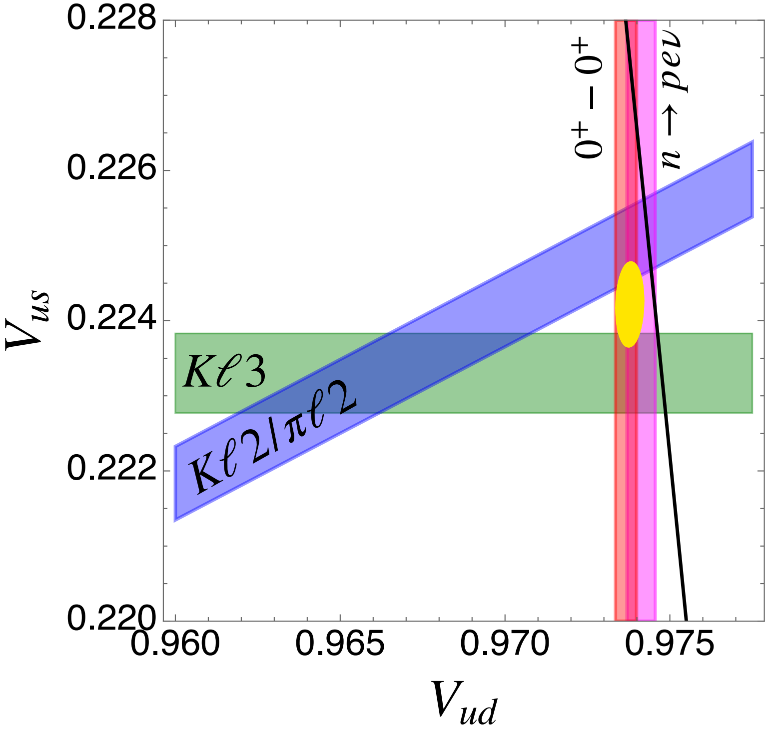
FNAL muon g-2 experiment: Runs 2/3 confirm Run 1 and BNL
5.1σ discrepancy with SM theory that uses world-data driven HVP
but just 1σ when SM theory uses lattice QCD or CMD-3 low-energy data

MUonE experiment test run
study of HVP in spacelike alternative and complementary to R-ratio

CKM unitarity in the top row

Cabibbo unitarity: deficit observed; discrepancies?

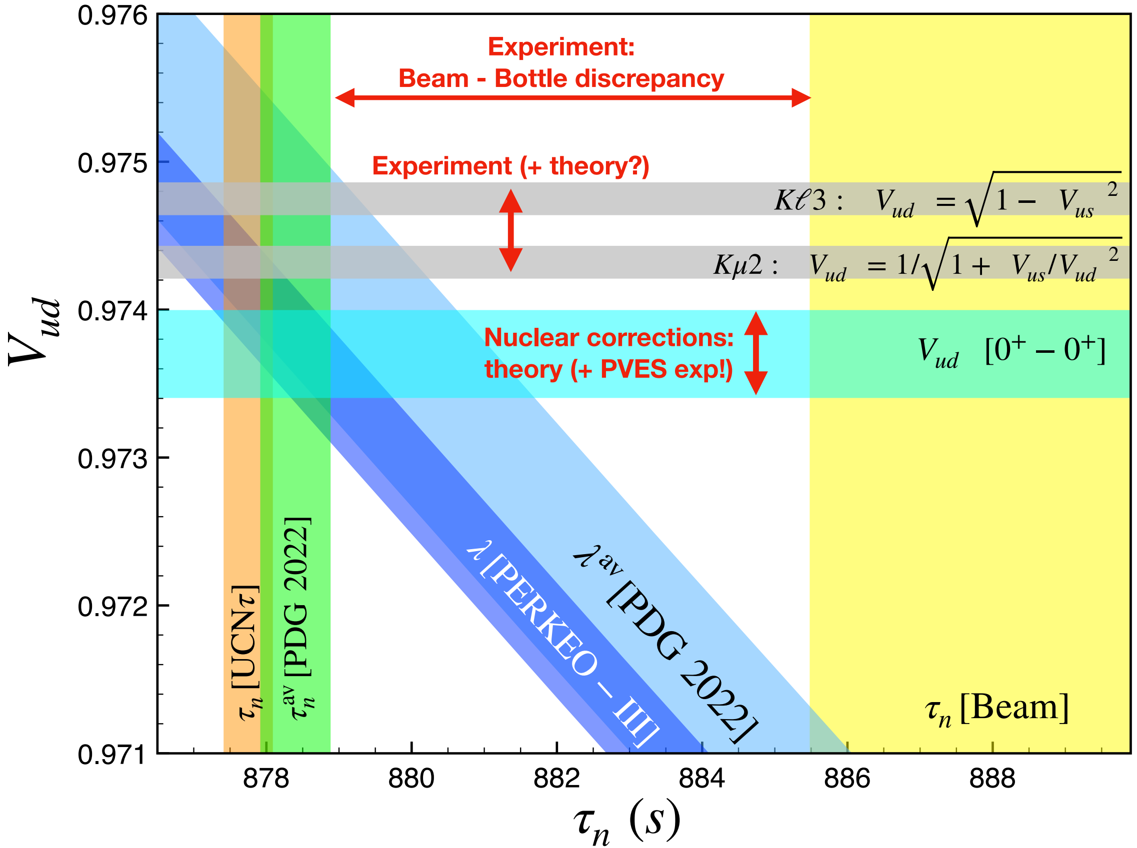
$$\underbrace{V_{ud}}_{\sim 0.95}{}^2 + \underbrace{V_{us}}_{\sim 0.05}{}^2 + \underbrace{\cancel{V_{ub}}}_{\sim 10^{-5}}{}^2 - 1 = -0.0015(6)_{V_{ud}}(4)_{V_{us}}$$



Superallowed nuclear decays:
Nuclear theory uncertainties increased

Cold neutrons live longer than UCN

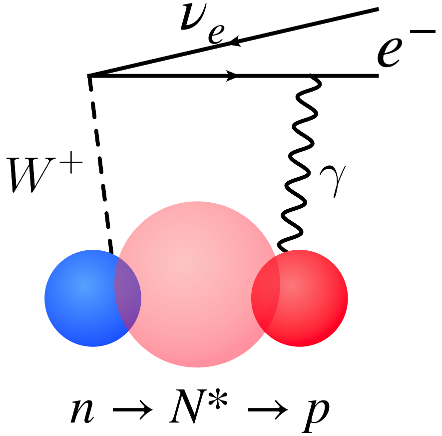
Kl2 and Kl3 disagreement (via Vud)



Universal correction Δ_R^V

Equally affects free and bound neutron decay

$$\Delta_R^V = \frac{\alpha}{2\pi}\left\{3\ln\frac{M_Z}{M_p} + \ln\frac{M_Z}{M_W} + \tilde{a}_g\right\} + \delta_{\rm QED}^{HO} + \mathbf{2\,\Box_{\gamma W}}$$



γW-box: main source of theory uncertainty since 40 years

JRA3: γW-box from dispersion relations (DR) + lattice

Marciano, Sirlin 2006: $\Delta_R^V = 0.02361(38)$ —> $V_{ud} = 0.97420(10)_{Ft}(18)_{RC}$

DR (Seng et al. 2018): $\Delta_R^V = 0.02467(22)$ —> $V_{ud} = 0.97370(10)_{Ft}(10)_{RC}$

Confirmed by **first ever direct LQCD calculation**

LQCD on pion + pheno: $\Delta_R^V = 0.02477(24)_{\rm LQCD^\pi + pheno}$

LQCD on neutron: $\Delta_R^V = 0.02439(19)_{\rm LQCD^n}$

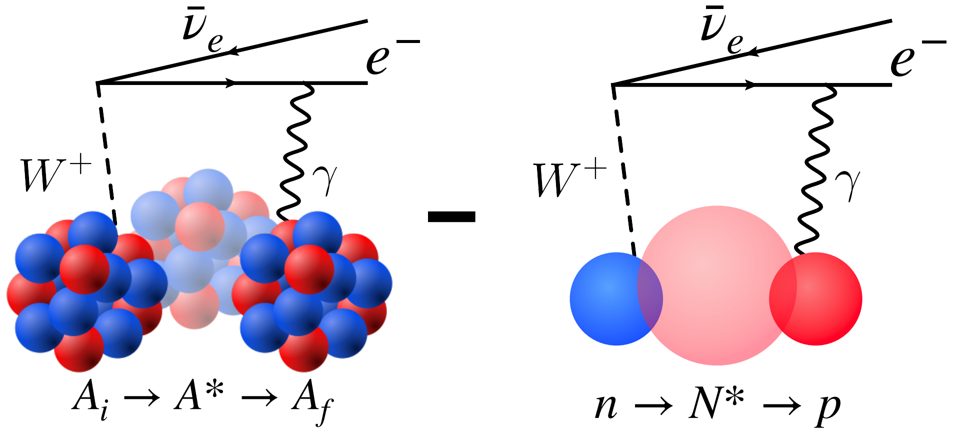
Seng, MG, Feng, Jin, 2003.11264
Yoo et all, 2305.03198

Ma, Feng, MG et al 2308.16755

Nuclear structure correction $\delta_{\mathrm{NS}} = 2[\,\Box_{\gamma W}^{\mathrm{VA,\,nucl}} - \Box_{\gamma W}^{\mathrm{VA,\,free\,n}}\,]$

Nuclear environment, nuclear excitation spectrum, …

Until 2024: only calculated in nuclear shell model;
Free-n box subtraction implicit, uncertainties ad-hoc



2024: **First ab-initio** calculation of δ_{NS}

First case study: ${}^{10}C \to {}^{10}B$ in No-Core Shell Model (NCSM)

Many-body problem in HO basis with separation Ω and up to $N = N_{max} + N_{Pauli}$

Nuclear interactions from chiral EFT (NN-N^{4}LO+3N$_{\mathrm{lnl}}$,NN-N^{4}LO+3N$^*_{\mathrm{lnl}}$)

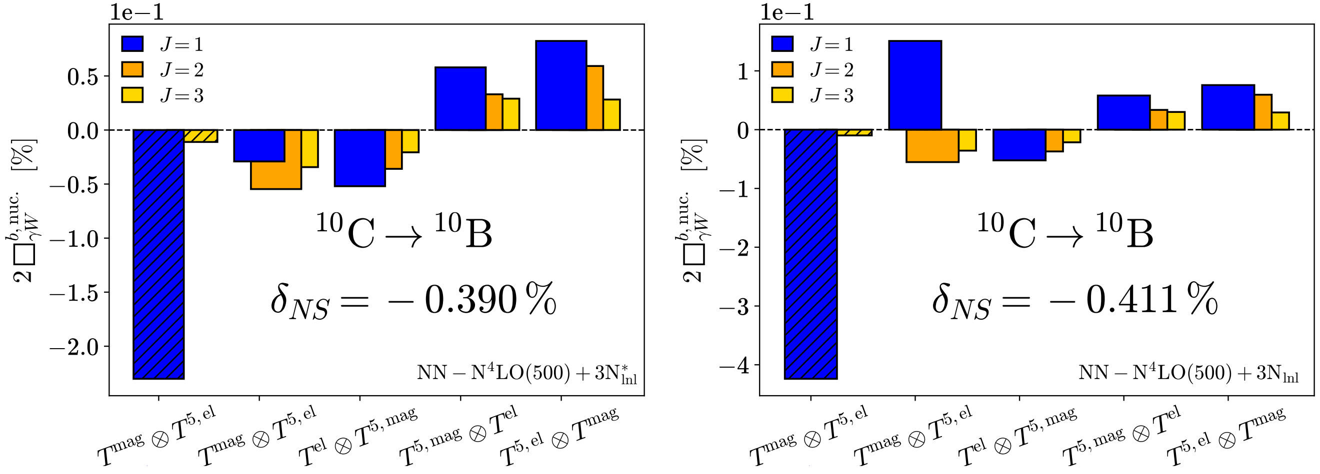
DR formalism to make the free-n box subtraction explicit

M. Gennari, M. Drissi, MG, P. Navratil, C.-Y. Seng, arXiv: ***2405.19281***

Nuclear structure correction δ_{NS}: numerical results

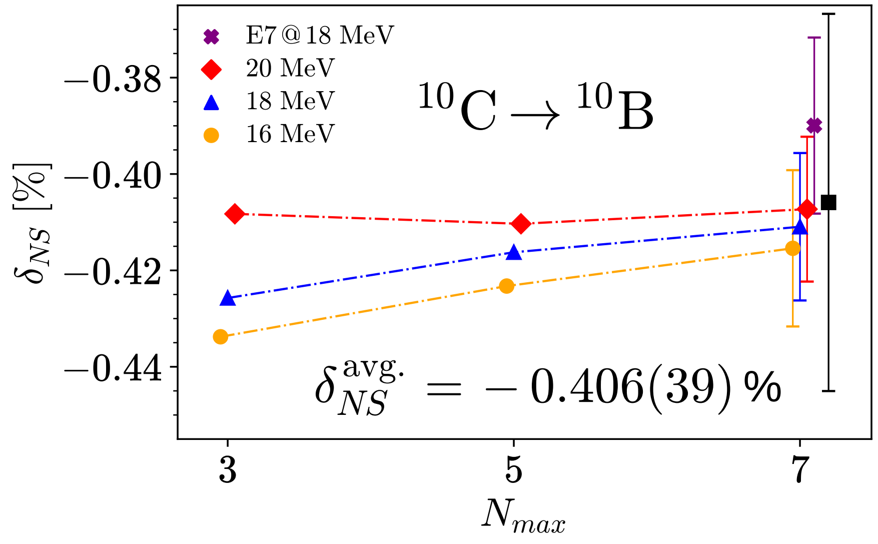
Systematic uncertainty:
compare different nuclear forces

Convergence (basis size) OK



Ab-initio result for $^{10}C \rightarrow {}^{10}B$:

$$\delta_{\mathrm{NS}} = -0.406(39)\,\%$$ *arXiv:* ***2405.19281***



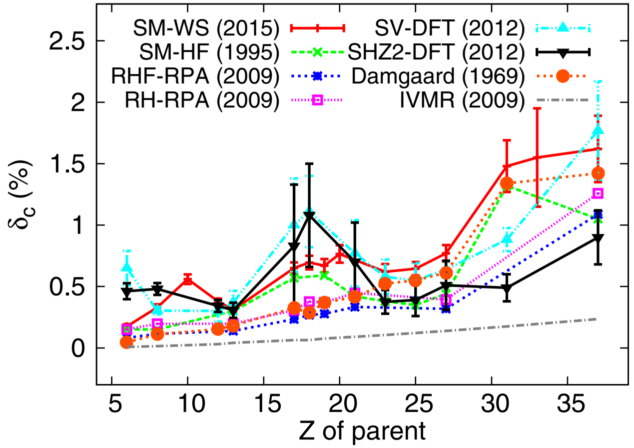
Compare to Hardy-Towner (old-fashion SM)

$$\delta_{\mathrm{NS}} = -0.347(35)\,\%$$ (2014)

$$\delta_{\mathrm{NS}} = -0.400(50)\,\%$$ (2020)

Isospin-breaking correction δ_C

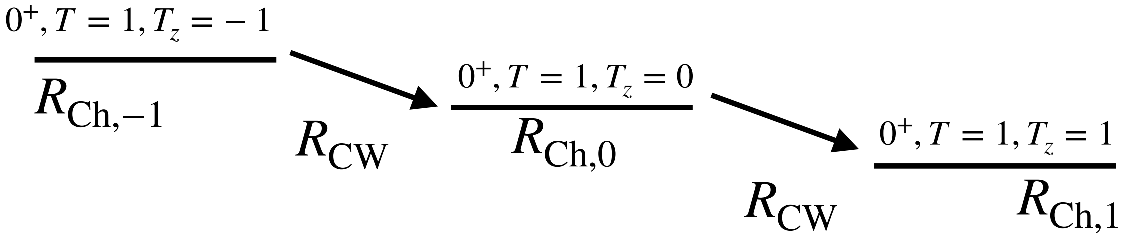
Coulomb repulsion of protons, but not neutrons
—> isospin symmetry broken (0.1-1%)
Until now purely theoretical, but model dependence



JRA3: data-driven approach! Relate δ_C to nuclear radii: known or measurable

Seng, MG ***2208.03037; 2304.03800; 2212.02681***

Superallowed decays within iso-triplet
Isospin symmetry connects 3 charge radii,
transition CC radius and neutron skins



$0^+, T = 1, T_z = -1$

$R_{\mathrm{Ch},-1}$

R_{CW}

$0^+, T = 1, T_z = 0$

$R_{\mathrm{Ch},0}$

R_{CW}

$0^+, T = 1, T_z = 1$

$R_{\mathrm{Ch},1}$

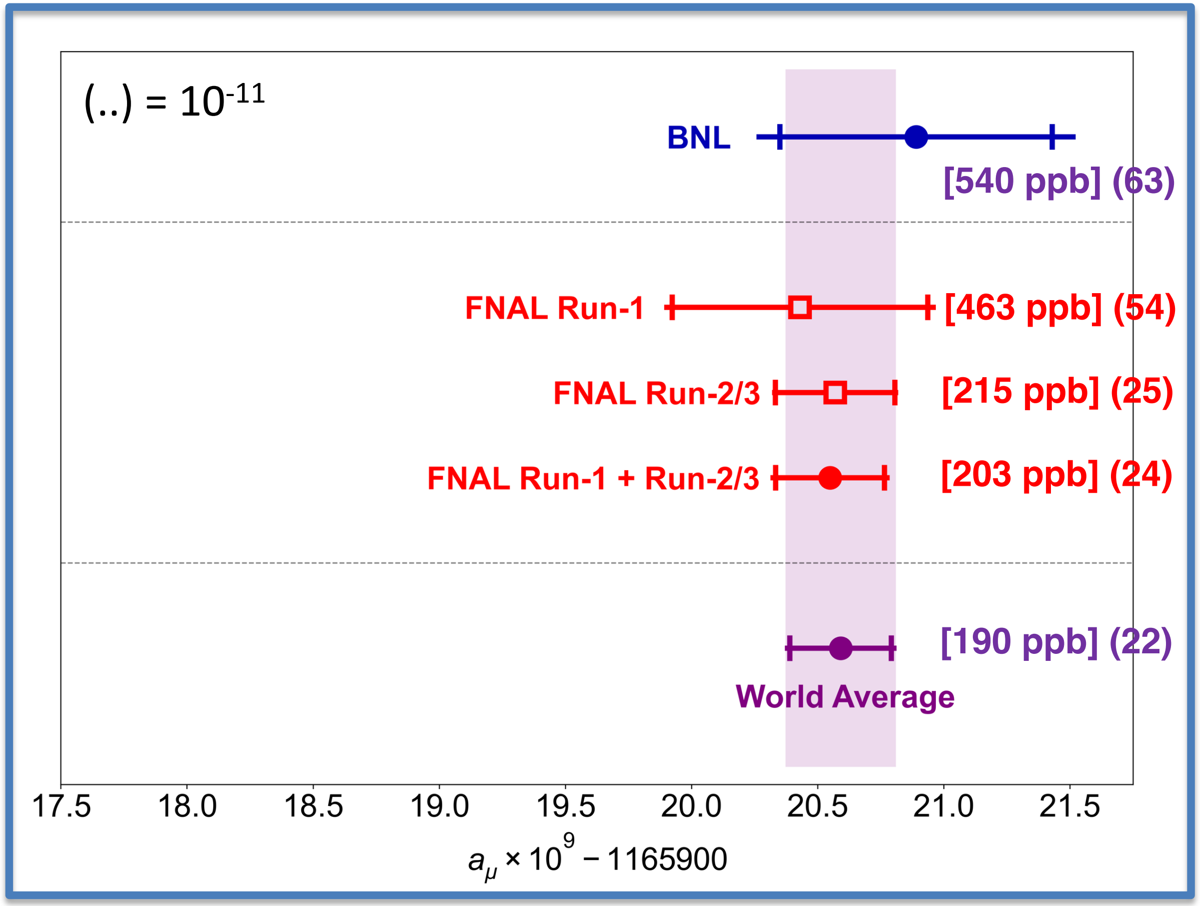
Experimental plans:
neutron skins of stable 0+ isotopes ^{26}Mg, ^{54}Fe, … at MESA (synergy with nuclear EoS)
Charge radii with μ atoms (^{9,10}Be, ^{26}Al,Mg, ^{40,41}K) at PSI (MuX, QUARTET)

Muon g-2

FNAL E-989 $(g\text{-}2)_\mu$ experiment runs 2-3

a_μ(FNAL) = 116 592 055(24) x10^{-11} [203 ppb]

Talk by Graziano Venanzoni on Wednesday



- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

Systematic uncertainty:

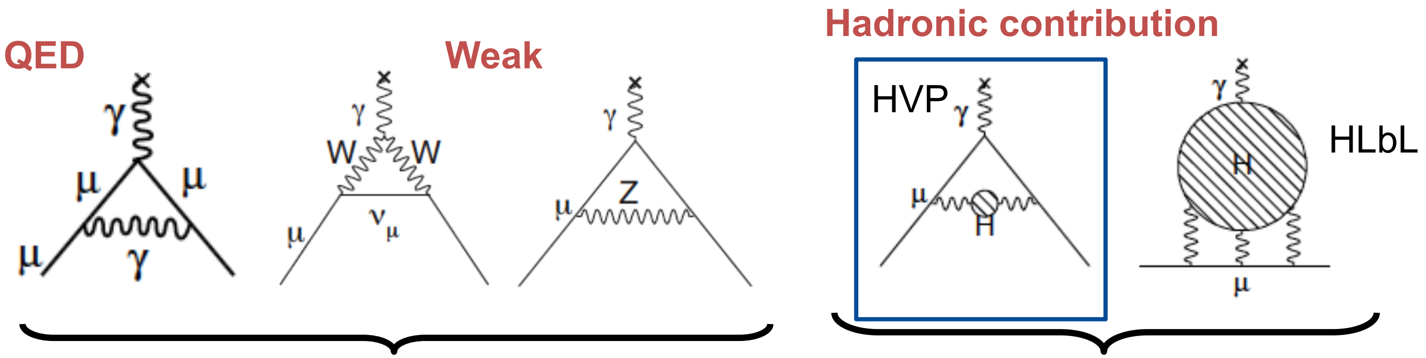
70 ppb exceed
100 ppb in the proposal

a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

(g-2)$_\mu$ SM theory and the role of JRA3

SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$

Muon g-2


QED

Weak

Hadronic contribution

Precisely known

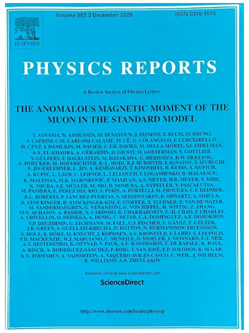
Large uncertainty

$$a_\mu(\text{SM}) = 116\,591\,810(43) \times 10^{-11} \quad (0.37\,\text{ppm})$$

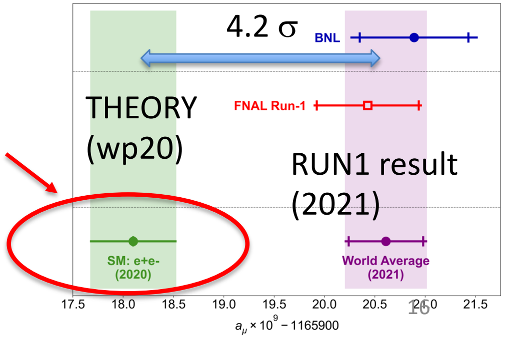
SM Prediction in 2020

Theory Initiative **(wp20):**
T. Aoyama et al. Phys. Rept. 887 (2020)

HVP based on e+e- hadronic cross section data


PHYSICS REPORTS

THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL



G. Venanzoni, Hadron WS, LNF 19 June 2024

JRA3 and the
Muon g-2 Theory Initiative:

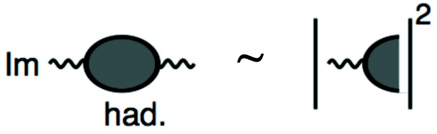
Coordinated the global effort for the SM prediction

Especially important in view of
- conflicting data sets
- conflicting calculations
- necessity to define theory uncertainty

Data-driven HVP for $(g\text{-}2)_\mu$

Muon g-2

- Calculated from data for $\sigma(e^+e^- \to \text{hadrons})$



Analyticity & Unitarity

$$a_\mu^{\text{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{K(s)}{s}\boxed{R(s)}ds$$

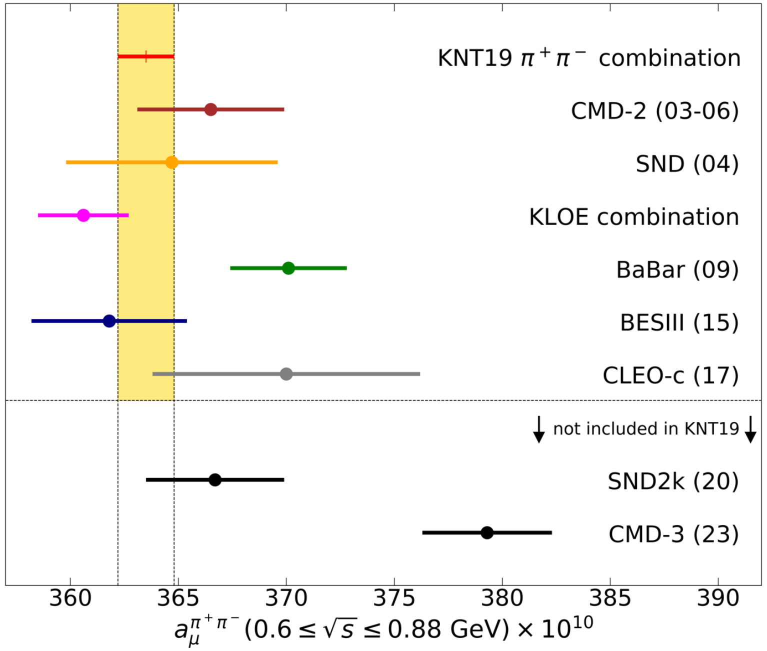
Hadronic R-ratio
(Data Driven)

K(s) ~1/s

- Uses **data** from different experiments from **20+ years**
- 1/s weights low energy strongly: 73% from **$\pi^+\pi^-$ channel**

$$\mathbf{R(s)} = \frac{\boldsymbol{\sigma^0(e^+e^- \to \gamma \to \text{hadrons})}}{\boldsymbol{4\pi\alpha^2/3s}}$$

Keshavarzi, Nomura, Teubner: Priv. Comm.



inc. in
wp20

NOT inc.
in wp20

- Data from **CMD-2, SND, KLOE, BaBar, BESIII** and **CLEO-C** were included in wp20

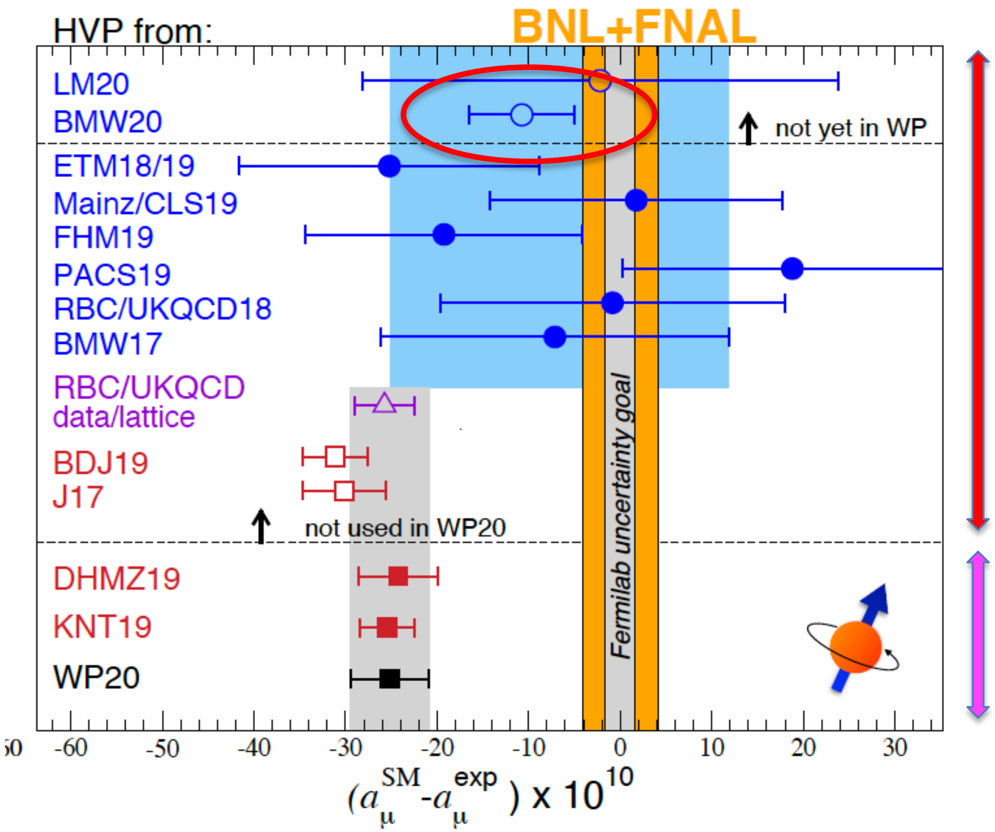
$$\boxed{a_\mu^{HVP;LO} = 6931\,(40) \times 10^{-11}(0.6\%)\ \ (\text{wp20})}$$

- New results from **SND2k** and **CMD-3** after wp20
- **CMD-3 is different from all the other data**

Lattice QCD HVP for $(g\text{-}2)_\mu$

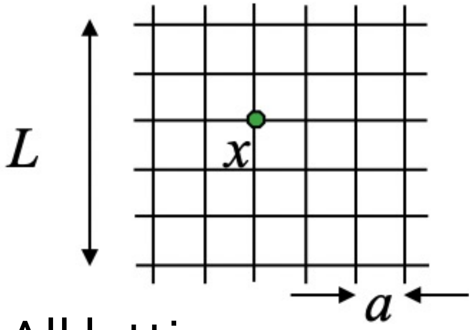
- ***Ab-initio*** calculation of HVP on lattice

G. Colangelo et al.
https://arxiv.org/pdf/2203.15810.pdf



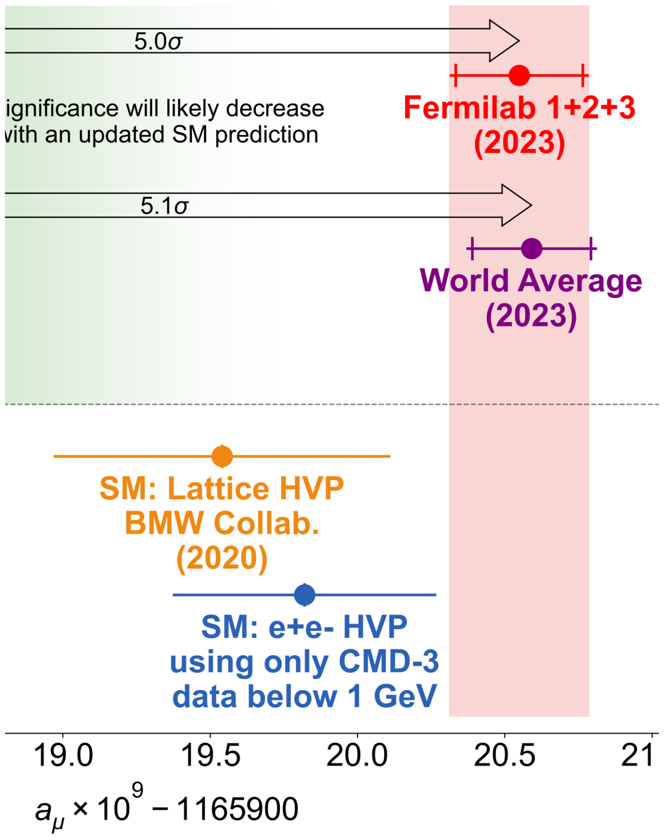
NOT inc. in wp20

inc. in wp20



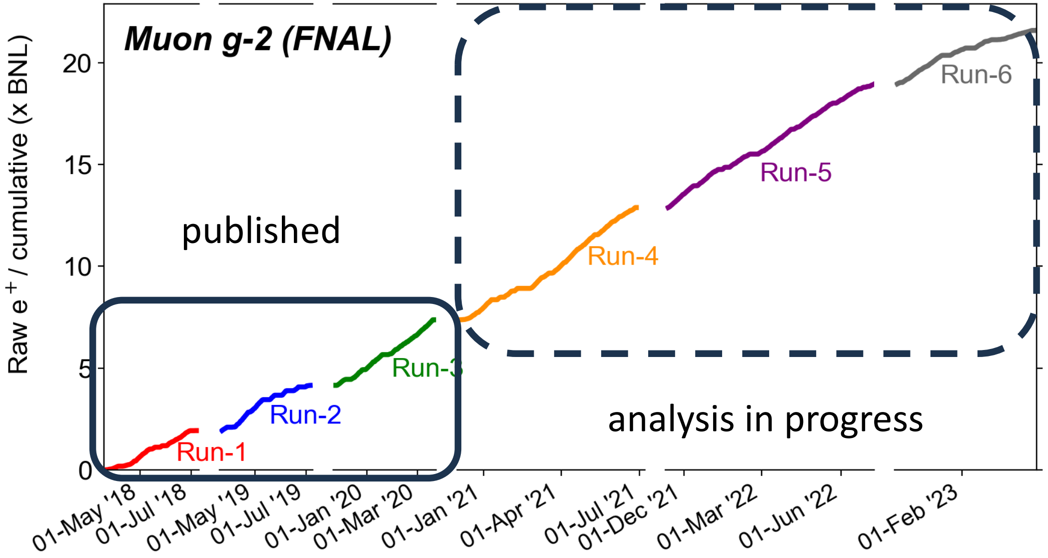
- All lattice calculations were not included in wp20
- **BMW** is only high precision calculation: closer to exp. Result

CMD-3, BMW HVP alone:
~ no anomaly



Prospects for $(g\text{-}2)_\mu$

Experiment: all data taken



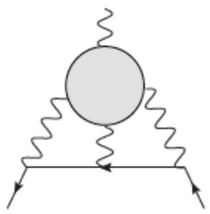
~25% of total statisics

~75% of total statisics

Full analysis in 2025 with 1/2 statistical error for 140 ppb total uncertainty

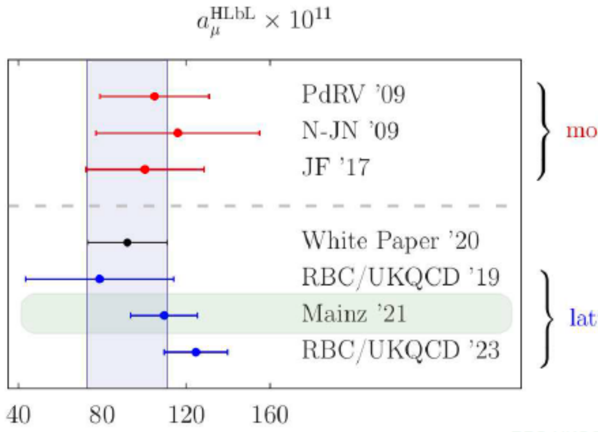
Theory: further effort on HLBL

QCD contribution: HLbL



Two main approaches:

- Dispersion relations
- Lattice simulations



$a_\mu^{\rm HLxL} = 92(19)\cdot 10^{-11}$ [WPsummary]

$a_\mu(\mathrm{SM}) = 116\,591\,810(43)\times 10^{-11}$

(wp2020)

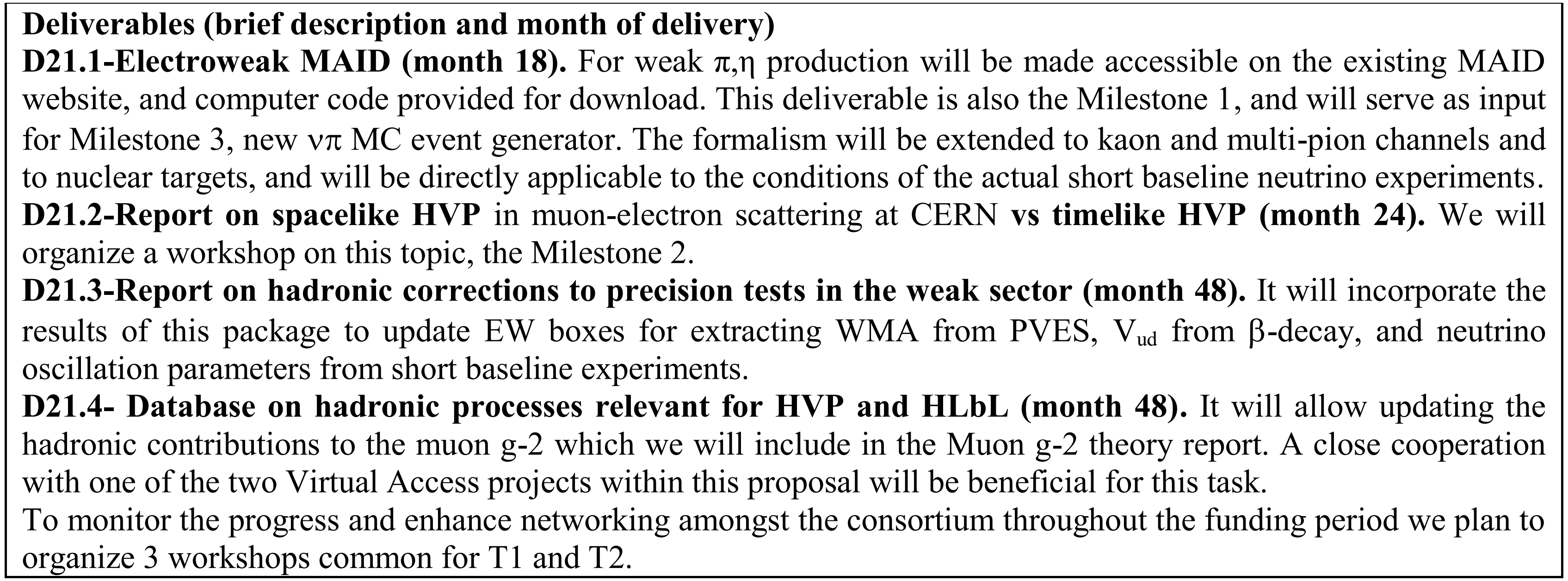
RBC-UKQCD 19: PRL 124, 132002 (2020)
Mainz 21: Eur. Phys. J. C 81, 651 (2021); C 82, 664 (2022)
RBC-UKQCD 23: arXiv:2304.04423

WP update: expect (cf. lattice results) some upward shift of central value, precision < 15%

Deliverables, Milestones

What we promised

Deliverables



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.

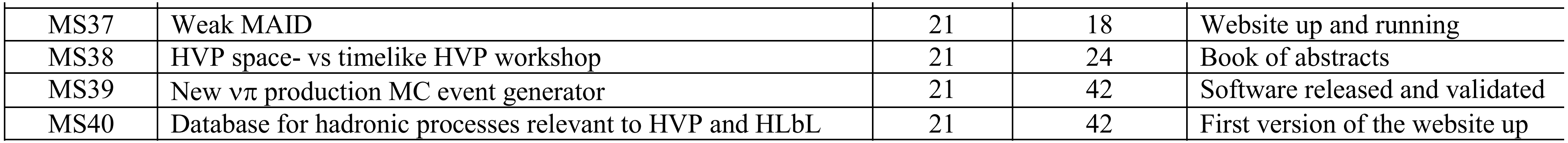
D21.2-Report on spacelike HVP in muon-electron scattering at CERN **vs timelike HVP (month 24).** We will organize a workshop on this topic, the Milestone 2.

D21.3-Report on hadronic corrections to precision tests in the weak sector (month 48). It will incorporate the results of this package to update EW boxes for extracting WMA from PVES, V_{ud} from β-decay, and neutrino oscillation parameters from short baseline experiments.

D21.4- Database on hadronic processes relevant for HVP and HLbL (month 48). It will allow updating the hadronic contributions to the muon g-2 which we will include in the Muon g-2 theory report. A close cooperation with one of the two Virtual Access projects within this proposal will be beneficial for this task.

To monitor the progress and enhance networking amongst the consortium throughout the funding period we plan to organize 3 workshops common for T1 and T2.

Milestones



MS37	Weak MAID	21	18	Website up and running
MS38	HVP space- vs timelike HVP workshop	21	24	Book of abstracts
MS39	New νπ production MC event generator	21	42	Software released and validated
MS40	Database for hadronic processes relevant to HVP and HLbL	21	42	First version of the website up

What we delivered

Deliverables

Deliverable No	Deliverable Name	Nature	Delivered Month	Link/Reference
D21.1	WeakMAID Website	Website	36	https://wwwth.kph.uni-mainz.de/weakmaid/
D21.2	Report on Spacelike HVP in MuonE at CERN vs timelike HVP	Report	13	*Phys.Rept.887 (2020) 1-166*
D21.3	Report on hadronic corrections to precision tests of SM in weak sector	Report	53	*Universe* 9 (2023) 422 *Ann.Rev.Nucl.Part.Sci.* 74 (2024) 23-47
D21.4	Database on hadronic processes relevant for HVP and HLbL	Website	42	https://precision-sm.github.io/

Milestones

Milestone No	Deliverable Name	Delivered	Means of verification
MS37	WeakMAID Website	YES	Website up and running
MS38	HVP space- vs timelike HVP workshop	YES	Book of abstracts
MS39	New $\nu\pi$ production MC event generator	NO	(Software validated and released)
MS40	Database on hadronic processes relevant for HVP and HLbL	YES	First version of website up https://precision-sm.github.io/

Summary

JRA3: significant progress in precision tests of EW sector of SM

Overachieved in several tasks

One objective had to be dropped (insufficient manpower)

Outlook for next call:
Current discrepancy in HVP has to be resolved to interpret $(g-2)_\mu$ exp.
Precise determination of weak mixing angle and neutron skins
Rich program in beta decay, Vud, Vus and CKM unitarity
Improved experimental precision requires coordinated theory support