JRA3-Precision Tests of the Standard Model

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(University and INFN Pisa)
on behalf of JRA3 working group

STRONG-2020 ANNUAL MEETING

17, 18 and 19 October 2022, in Paris, France

INTRODUCTION

LOW ENERGY FRONTIER

comprises:

TASK 1 — MUON PHYSICS

TASK 2 — WEAK SECTOR

Precise determination of the muon anomalous magnetic moment (g-2)μ; the CKM matrix element Vud from beta decay, and the weak mixing angle from parity-violating electron scattering. Associated novel constraints (or discovery) of physics beyond the SM.

Is part of

JRA3-PrecisionSM

http://www.strong-2020.eu

Spokespersons:

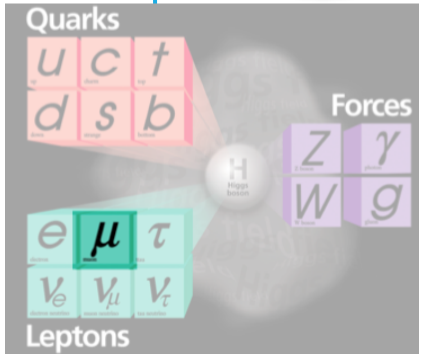
Andzrej Kupsc (UU)
Mikhail Gorshteyn (JGU)
Graziano Venanzoni (INFN)

Collaborators:

Muon Sector ~ 20 people
Weak Sector ~ 15 people

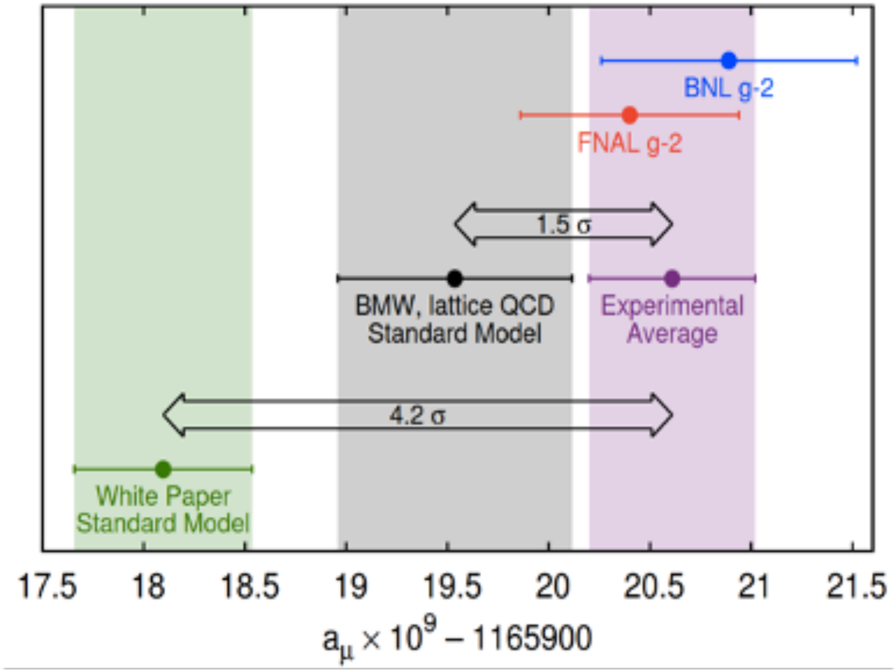
TASK 1

Muon g-2 anomaly discrepancy



- **Muon:** elementary particle with spin-1/2 and magnetic moment proportional to spin through the **g-factor**: $\vec{\mu} = \mathbf{g}\frac{q}{2m_\mu}\vec{S} \quad \Rightarrow \quad \boxed{a_\mu = \frac{g-2}{2}}$ **muon anomaly**

➡ Comparison between theoretical value and experimental measurement allows for a precise test of the Standard Model and to look for new physic



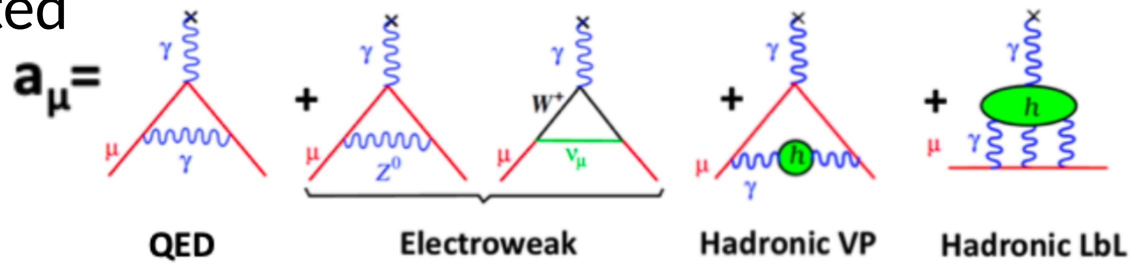
- New measurement from FNAL Muon $g-2$ Exp. Run-1 data in 2021 confirmed result from BNL:

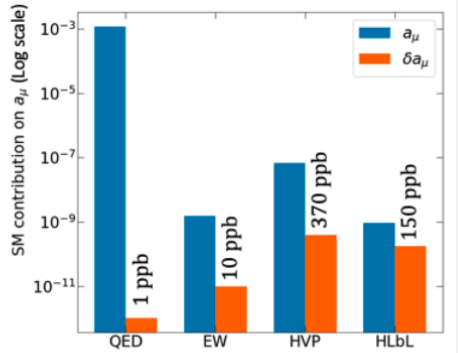
$$\mathbf{a}_\mu(\mathbf{FNAL}) = 116592040(54) \cdot 10^{-11} \text{ (460ppb)}$$
$$\mathbf{a}_\mu(\mathbf{BNL}) = 116592089(63) \cdot 10^{-11} \text{ (540 ppb)}$$
$$\mathbf{a}_\mu(\mathbf{Exp}) = 116592061(41) \cdot 10^{-11} \text{ (350 ppb)}$$

- Theory:
  - **a$_\mu$(BMW,SM)** calculation with LatticeQCD
  - **a$_\mu$(WP,SM)** calculation recommended by the Theory Initiative based on e^+e^- data

Muon g-2 theoretical calculation

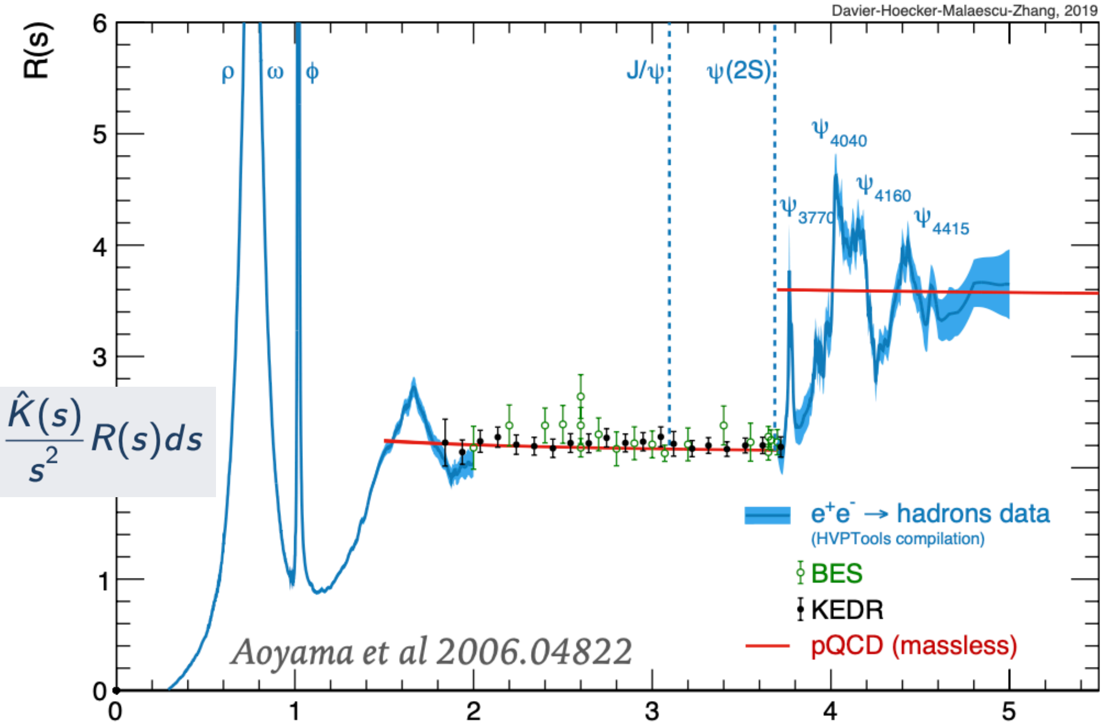
- Calculation is continuously updated
- Largest contribution but lowest uncertainty from QED
- EW terms are also well known
- Uncertainty dominated by QCD contributions:
  - mainly from **Leading Order Hadronic Vacuum Polarization:** virtual loops with hadrons calculated with two approaches:
    - data-driven: experimental data plus dispersion theory (used by WP20)
    - direct calculation with latticeQCD: recent result (BMW20) in tension with data-driven HVP





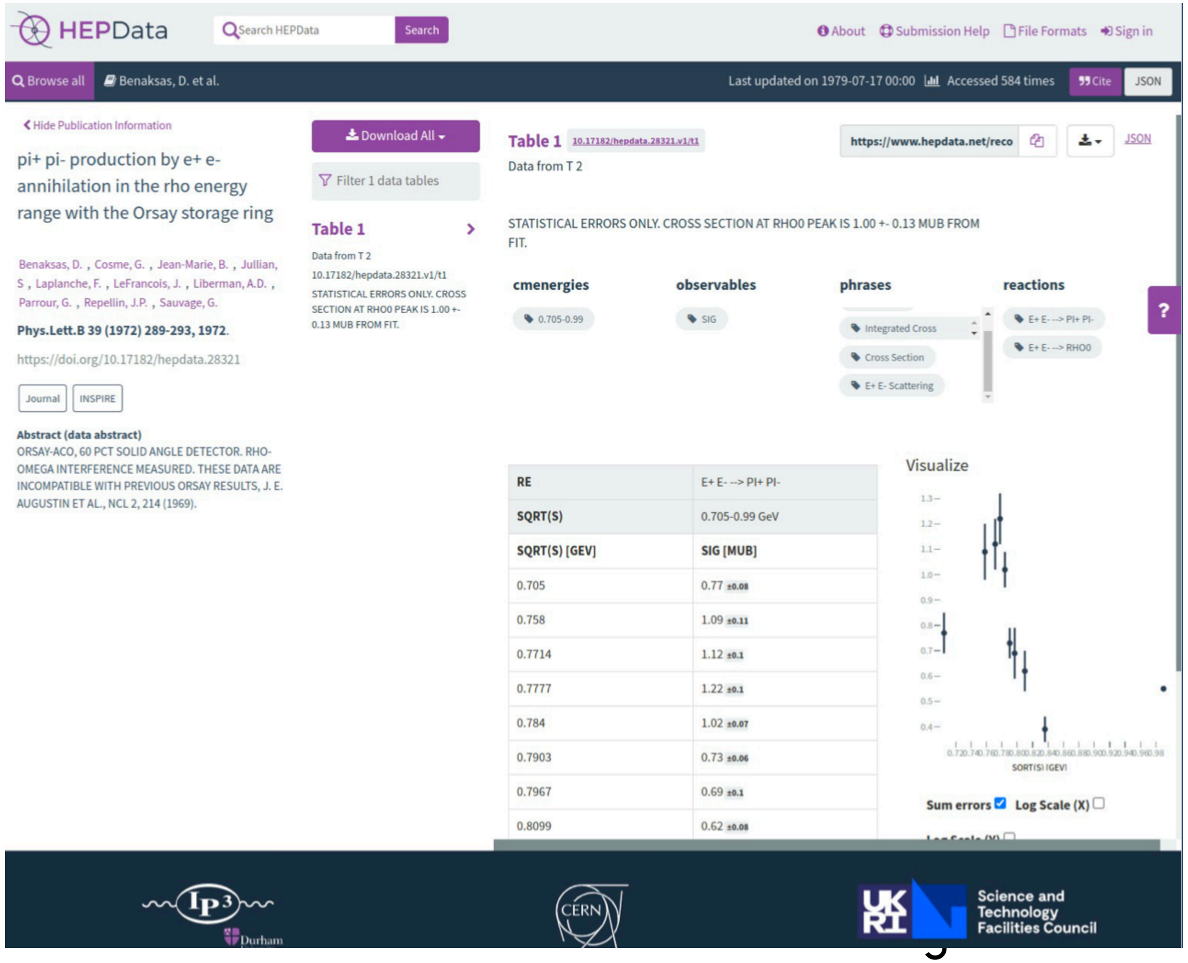
$$R(s) = \frac{\sigma^0(e^+e^- \to \text{hadrons}(\gamma))(s)}{\sigma^0(e^+e^- \to \mu^+\mu^-(\gamma))(s)}$$

$$a_\mu^{\text{HVP,LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{\hat{K}(s)}{s^2} R(s) ds$$



Precision SM Activities for Muon g-2

- **Goal:** compile an annotated database for low-energy hadronic cross sections in e^+e^- collisions
- **Activities:**
  - collect in HEPDATA low energy hadronic cross-section measurements



- HEP data public storage web site with well defined submission data format
- Submissions done only by authorized contact persons of collaborations

Precision SM Activities for Muon g-2

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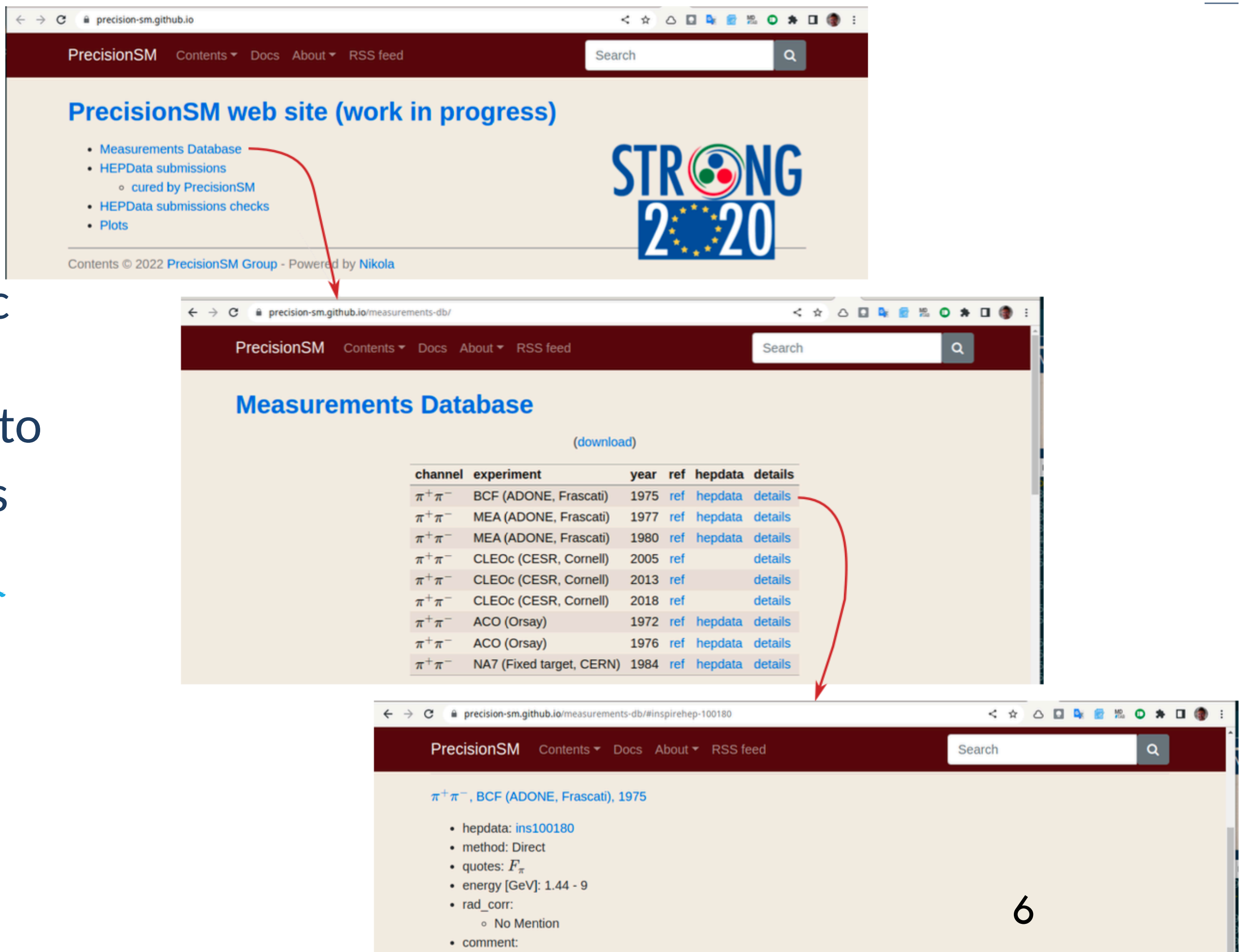
  - maintain annotated database of hadronic cross-section measurements for computation of the LO HVP contribution to a_μ on dedicated web site, with hyperlinks



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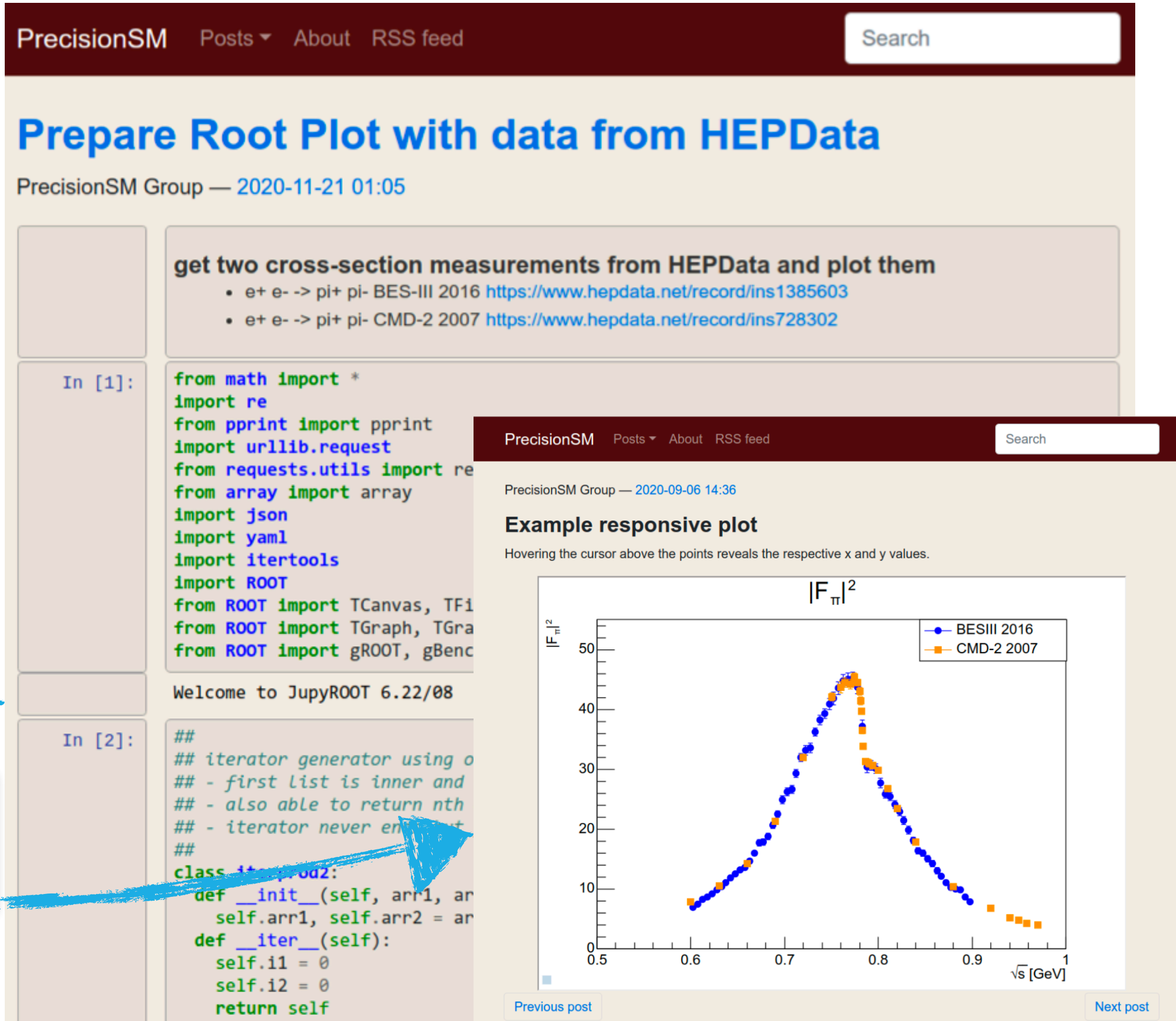
  - document, with examples, how to use measurements stored in HEPDATA
  - responsive plots of measurements of hadronic cross-sections



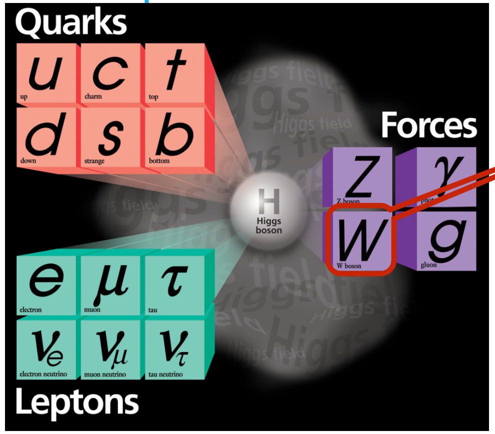
Status, Next Steps & Workshops

- **Status:**
  - Defined procedure and completed infrastructure for the database
  - In completion: collection in HEPDATA and annotation on the web site of the $e^+e^- \to \pi^+\pi^-$ channel
- **Next Steps:**
  - Add the other $e^+e^- \to hadrons$ channels

- **Workshop:**
  - STRONG 2020 Virtual Workshop on "Spacelike and Timelike determination of the Hadronic Leading Order contribution to the Muon g-2" [Nov 24 - 27, 2021]
    - book of abstracts submitted to ArXiv [arXiv:2201.12102]

TASK 2

Top-Row CKM unitarity anomaly



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:

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

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

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**

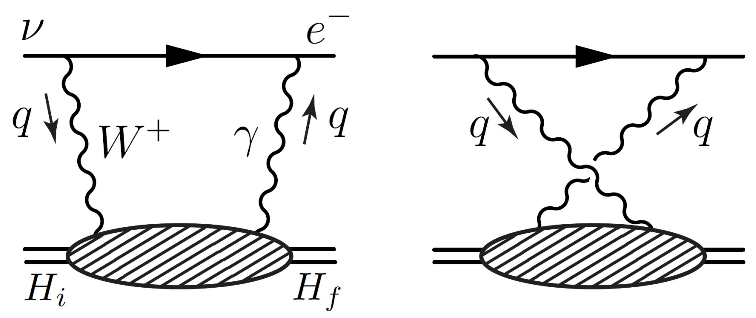
Within this JRA: CKM unitarity anomaly established and sharpened
Methods for new-era high-precision SM calculations developed and applied

Top-Row CKM unitarity anomaly: Confirmed and Sharpened

Main source: 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

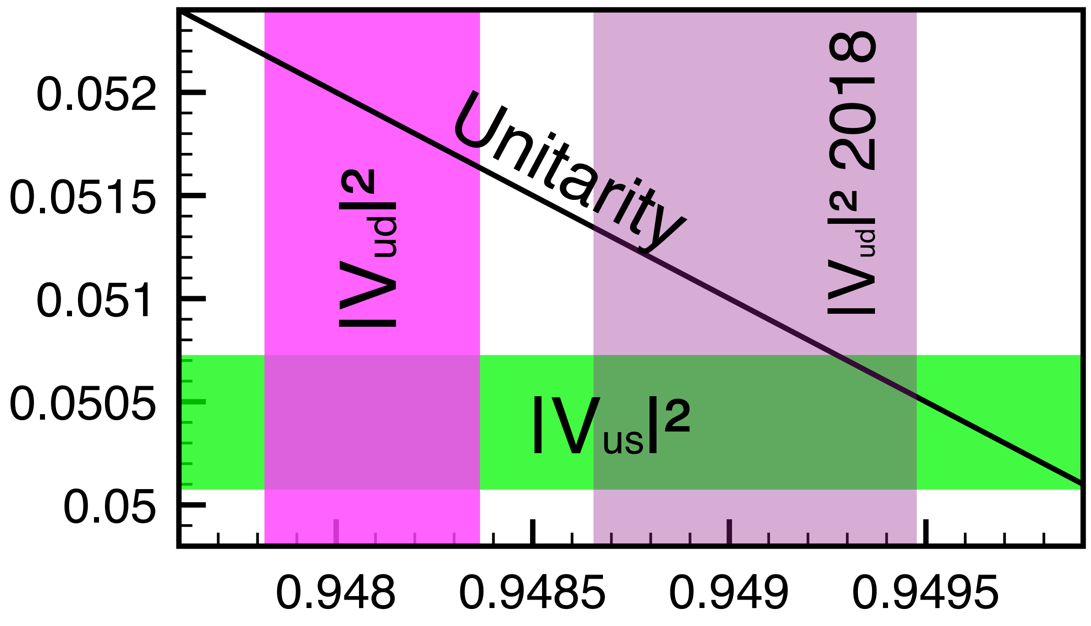
C-Y Seng, MG et al., Phys.Rev.Lett. 121 (2018) 24, 241804;
C-Y Seng, MG, M.J. Ramsey-Musolf, Phys.Rev. D 100 (2019) 1, 013001

DR representation of nuclear corrections

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

Next Steps: Nuclear Corrections

Dispersion analysis of the nuclear structure correction δ_{NS} to V_{ud}

Collaboration with the group of S. Pastore (Green-Function Monte Carlo) and P. Navratil (No-Core Shell Model) started

Data-driven analysis of the isospin-symmetry breaking correction δ_C to V_{ud}

Seng, MG, arXiv: 2208.03037 [nucl-th]

Proposal for next-generation rare pion decay experiment PIONEER

PSI Ring Cyclotron Proposal R-22-01.1 [PIONEER Collaboration] Altmannshofer et al., arXiv: 2203.01981 [hep-ex]

Full involvement in shaping the future of CKM unitarity

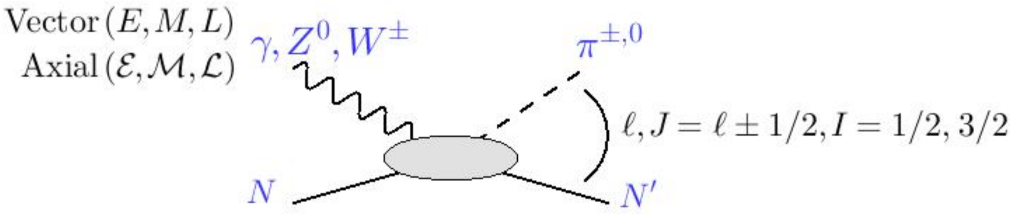
WeakMAID: pion production with neutrinos

Motivation:

Neutrino energy reconstruction for neutrino oscillation experiments (DUNE, T2HK)
Inelastic neutrino scattering in the near detector, with pion production an important channel, is used as a tool to calibrate the flux of neutrinos in each energy bin to ensure a high-precision determination of neutrino oscillation parameters (masses, angles, phases).

Method and Background:

Mainz-based partial-wave analysis MAID is a leading player in the field of electromagnetic pion production. MAID is a unitarized isobar model that accounts for all known N* and Δ resonances. MAID's range of validity $W \leq 2.5$ GeV needs to be extended to 5-6 GeV to cover DUNE's needs. Axial current contribution has to be added.



Realization:

WeakMAID is based on the decomposition of scattering amplitudes for weak pion production into multipoles characterized by angular momentum *l,* total spin J=*l±1/2,* isospin I=1/2,3/2, multipolarity (electric E, magnetic M, and longitudinal L) carried by the electroweak probe. Each multipole is unitarized to account for strong rescattering at low energies, and matched with Regge behavior at high energies. **These two features are new among the existing weak pion production models.**

Website WeakMAID created

https://wwwth.kph.uni-mainz.de/weakmaid/

Users can download tables with multipoles, amplitudes as functions of energy, Q^2, angle, and integrated cross sections as functions of Q^2. At present website being tested, journal publication in preparation. As per MAID collaboration policies: once published and tests concluded WeakMAID will be added to official MAID website

Next Steps

Upon completion of WeakMAID the work on incorporating WeakMAID into MC neutrino events simulators will commence.

Involvement in shaping DUNE program:

Two Snowmass White Papers submitted:
L. Alvarez-Ruso et al, arXiv: 2203.11298 [nucl-ex]
L. Alvarez-Ruso et al, arXiv: 2203.11319 [physics.ins-det]

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Theory Group
Institute for Nuclear Physics

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WeakMAID

Dual Unitary Isobar-Regge Model for Pion Neutrino-Production

Mikhail Gorshteyn, Institut für Kernphysik, Johannes-Gutenberg Universität Mainz

Motivation

Long-base neutrino oscillation experiments, such as DUNE, aim at determining neutrino masses and mixing parameters at an unprecedented level of precision. Born from charged pions decaying in flight, by the time they reach the far detector 1300 km away, the muon neutrinos will oscillate to electron or tau ones. To unravel the oscillation pattern, the energy of the neutrino beam has to be known to a good precision. For this purpose, close enough to the neutrino source - where no oscillation has occurred yet - the near detector is placed to study neutrino interactions with matter. An important mechanism in these interactions is the production of pions. This project is dedicated to developing a state-of-the-art theoretical analysis for weak pion production on the nucleon. Embedded in Monte Carlo simulation codes, it will lead to precise predictions of pion counts in the near detector, resulting in a reliable neutrino energy reconstruction.

Method and Background

Pion production in electromagnetic reactions has a long history. One of the leading efforts is due to the Mainz-based partial wave analysis tool MAID, a unitary isobar model that accounts for all known N* and Δ resonances, single-channel unitarity and over years has proven to be a valuable analysis tool for pion photo- and electroproduction. At present, MAID is further developed by the Mainz-Tuzla-Zagreb Collaboration.

MAID approach is suitable for the invariant mass of the πN-system W < 2 GeV and moderate photon virtualities. The project WeakMAID builds upon its predecessor while extending it in several ways. Firstly, weak interaction contains the axial current, additionally to the vector current readily contained in the electromagnetic case. Secondly, the energy spectrum of neutrinos at DUNE extends to 5-6 GeV, so that a connection to high-energy such as Regge theory is necessary. This can be correctly done by implementing unitarity, analyticity and duality constraints.

Realization

As a partial wave analysis (PWA) tool, WeakMAID is based on the decomposition of scattering amplitudes for weak pion production into multipoles characterized by the angular momentum *l*, total spin J=*l*±1/2, total isospin I=1/2,3/2 *of the πN-system*, as well as the multipolarity (electric E, magnetic *M*, and longitudinal L) carried by the electro-weak probe. Two sets of multipoles describe the interaction with the hadronic vector and axial current. Additionally, two sets of invariant amplitudes *V1-6* for vector and *A1-6* for axial current are introduced, as well as center-of-mass CGLN *F1-6* and *G1-6*, respectively, and helicity amplitudes H*1-6*.

Vector Weak Multipoles (*El±, Ml±, Ll±*)
Vector Amplitudes (*F1-6; V1-6; H1-6*)
Axial Weak Multipoles (El±, Ml±, Ll±)

REQUESTED ADJUSTMENTS

TASK 1

Travels were limited (COVID) for the entire duration of the project

TASK 2

Visits to Fermilab were impossible (COVID) for the entire duration of the project

Until now this impediment was unpleasant but not critical.

The next step envisions the incorporation of the WeakMAID analysis into MC simulators for which a close collaboration with local researchers at Fermilab is crucial.

A cost-neutral 1-year extension is desired.

CONCLUSIONS

Precision tests of the Standard Model require collection, sophisticated analysis and elaboration of large number measurement:

Within the Strong2020 PrecisionSM project we are:

- assembling an annotated database of hadronic cross-section measurements with a web site that also documents how to use the data
- working on reduce uncertainties on EW boxes calculation for precise calculations of the CKM unitarity
- implementing tools to study the pion production with neutrinos