XIV INTERNATIONAL CONFERENCE
ON INTERCONNECTIONS BETWEEN
PARTICLE PHYSICS AND COSMOLOGY
The UNIVERSITY of OKLAHOMA

Rare processes and Precision Measurements @ Snowmass

Frontier for Rare Processes and Precision Measurements

Alexey A. Petrov
Wayne State University

Frontier for Rare Processes and Precision Measurements

SnowMass2021

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- ANNOUNCEMENTS
- SNOWMASS CALENDAR
- ETHICS GUIDELINES
- SNOWMASS REPORT

- Organization

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- SNOWMASS STEERING GROUP
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- THEORY FRONTIER
- ACCELERATOR FRONTIER
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- UNDERGROUND FACILITIES

RARE PROCESSES AND PRECISION MEASUREMENTS

Frontier Conveners

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  - Frontier Conveners
  - Description
  - Topical groups
  - Calendar of meetings
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  - Submitted LOI

Name	Institution	email
Marina Artuso	Syracuse University	martuso[at]syr.edu
Bob Bernstein	Fermi National Accelerator Lab	rhbob[at]fnal.gov
Alexey A Petrov	Wayne State University	apetrov[at]wayne.edu

Description

The Frontier for Rare Processes and Precision Measurements explores fundamental physics with intense sources and ultra-sensitive detectors. It encompasses seeking tiny deviations from Standard Model expectations in properties and transitions of elementary particle and searches for extremely rare processes. The Frontier for Rare Processes and Precision Measurements experiments use precision measurements to probe quantum effects and employ sophisticated theoretical techniques for their interpretations. These experiments typically investigate new laws of physics that manifest themselves at higher energies or weaker interactions than those directly accessible at high-energy particle accelerators. These experiments require the greatest possible beam intensities of electrons, muons, photons or hadrons, as well as large detectors, which provide an opportunity for substantial new discoveries complementary to other Frontier experiments.

https://snowmass21.org/rare/start

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10 Frontiers

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Welcome to Snowmass 2021

The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the

- Timeline:

  31 August 2020: Submission of Letters of Interest (LOIs)
  15 March 2022: Submission of Contributed Papers to arXiv
  30 June 2022: Preliminary reports of the Frontiers
  July 2022: Community Summer Study meeting (UW Seattle)
  30 September 2022: Final Reports

- Currently on hiatus until June 2021 (COVID)

Sincerely,

Young-Kee Kim (DPF Chair), Tao Han (DPF Chair-Elect), Joel Butler (DPF Vice-Chair), Priscilla Cushman (DPF Past Chair)

Glennys Farrar (DAP Rep), Gabriela Gonzales (DGRAV Rep), Yury Kolomensky (DNP Rep), Sergei Nagaitsev (DPB Rep)

DPF Community Planning Process

https://snowmass21.org/start

Frontier for Rare Processes and Precision Measurements

Topical groups

- RF1: Weak decays of b and c quarks (Angelo Di Canto/Stefan Meinel)
- RF2: Weak decays of strange and light quarks (Evgueni Goudzovski/Emilie Passemar)
- RF3: Fundamental Physics in Small Experiments (Tom Blum/Peter Winter)
- RF4: Baryon and Lepton Number Violating Processes (Pavel Fileviez Perez/Andrea Pocar)
- RF5: Charged Lepton Flavor Violation (electrons, muons and taus) (Bertrand Echenard/Sacha Davidson)
- RF6: Dark Sector Studies at High Intensities (Mike Williams/Stefania Gori)
- RF7: Hadron Spectroscopy (Tomasz Skwarnicki/Richard Lebed)

Liaisons with other frontiers:

- Energy Frontier: Angelo Di Canto
- Neutrino Frontier: Bob Bernstein
- Cosmic Frontier: Susan Gardner
- Theory Frontier: Alexey Petrov
- Accelerator Frontier: Bob Bernstein
- Instrumentation Frontier: Marina Artuso
- Computational Frontier: Stefan Meinel
- Community Engagement Frontier: Sophie Middleton

SNOWMASS-RP-FRONTIER@fnal.gov

1. SNOWMASS-RPF-01-HEAVY-QUARKS@FNAL.GOV
2. SNOWMASS-RPF-02-LIGHT-QUARKS@FNAL.GOV
3. SNOWMASS-RPF-03-FUNDAMENTL-SMALL@FNAL.GOV
4. SNOWMASS-RPF-04-BLNV@FNAL.GOV
5. SNOWMASS-RPF-05-CLFV@FNAL.GOV
6. SNOWMASS-RPF-06-DARK-SECTOR@FNAL.GOV
7. SNOWMASS-RPF-07-HADR-SPECT@FNAL.GOV

https://snowmass21.org/rare/start

Frontier for Rare Processes and Precision Measurements

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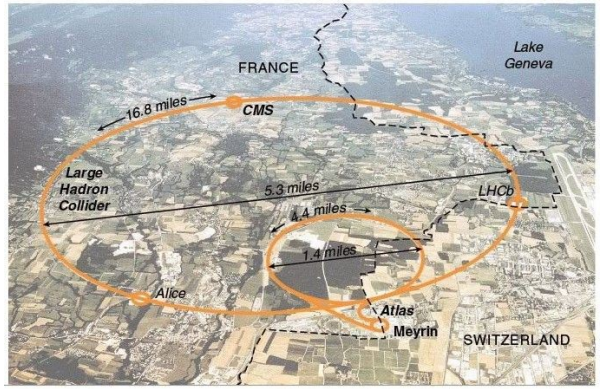
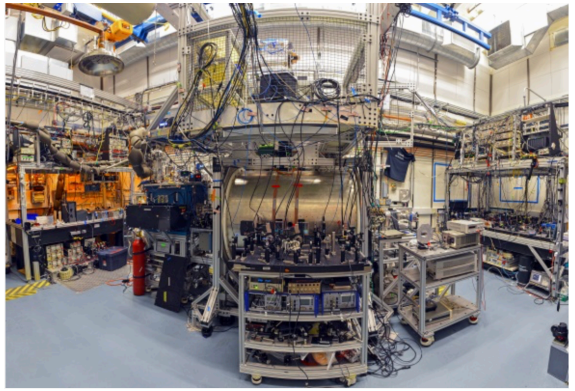


Accelerator-based experiments



"Table-top" experiments

Frontier summary: searches for new (rare) phenomena with precision measurements

Community input

Letters of Interest (submission period: April 1, 2020 – August 31, 2020)

Letters of interest allow Snowmass conveners to see what proposals to expect and to encourage the community to begin studying them. They helped conveners to prepare the Snowmass Planning Meeting that took place on October 5 - 8, 2020 ~~at Fermilab~~ on Zoom. Letters should give brief descriptions of the proposal and cite the relevant papers to study. Instructions for submitting letters are available at https://snowmass21.org/loi. Authors of the letters are encouraged to submit a full writeup for their work as a contributed paper.

Contributed Papers (submission period: April 1, 2020 – March 15, 2022)

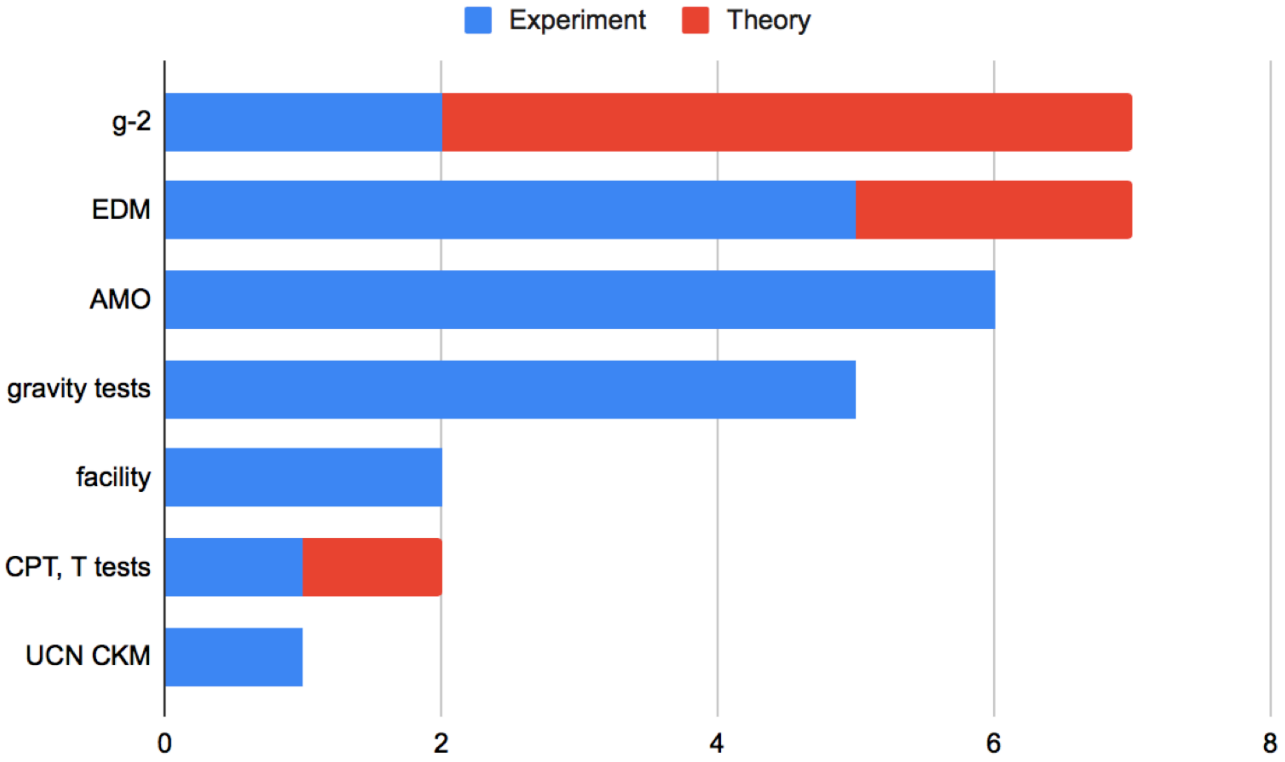
Contributed papers will be part of the Snowmass proceedings. They may include white papers on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities, including those related to community involvement. These papers and discussions throughout the Snowmass process will help shape the long-term strategy of particle physics in the U.S. Contributed papers will remain part of the permanent record of Snowmass 2021. Instructions for submitting contributed papers are available at https://snowmass21.org/submissions/ (both solicited and non-solicited)

Final Product: Snowmass Report (submission: 30 September 2022)

The Town Hall meeting was held in response to Letters of Interest (LOIs) submitted to our Frontier. It offered the submitters of LOIs a chance to make presentations on the topic of their LOIs.

Letters of Interest (LOIs)

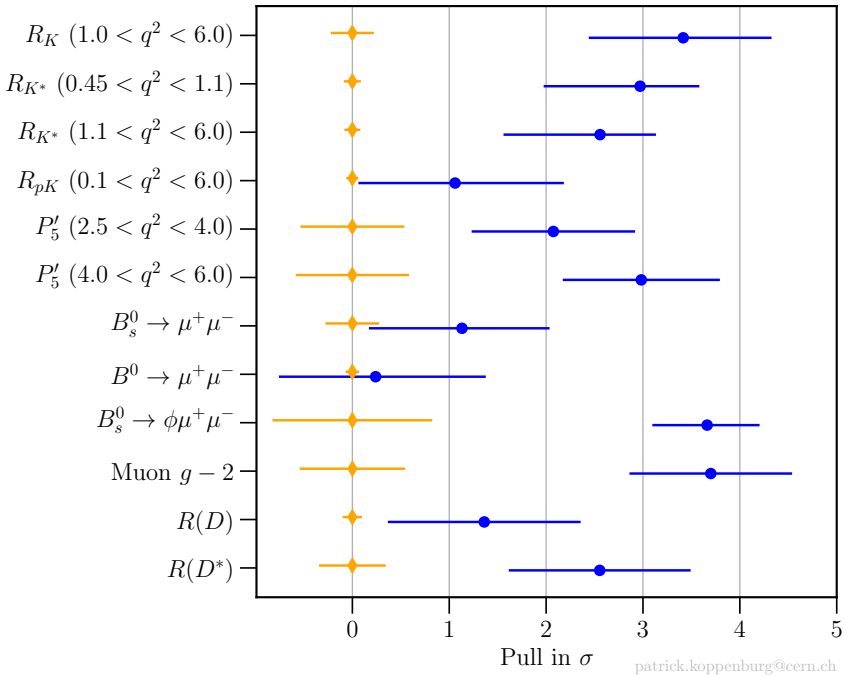
- 214 LOIs submitted to RPF
  - physics, devices/experiments, facilities
  - example distribution for RF3-5:

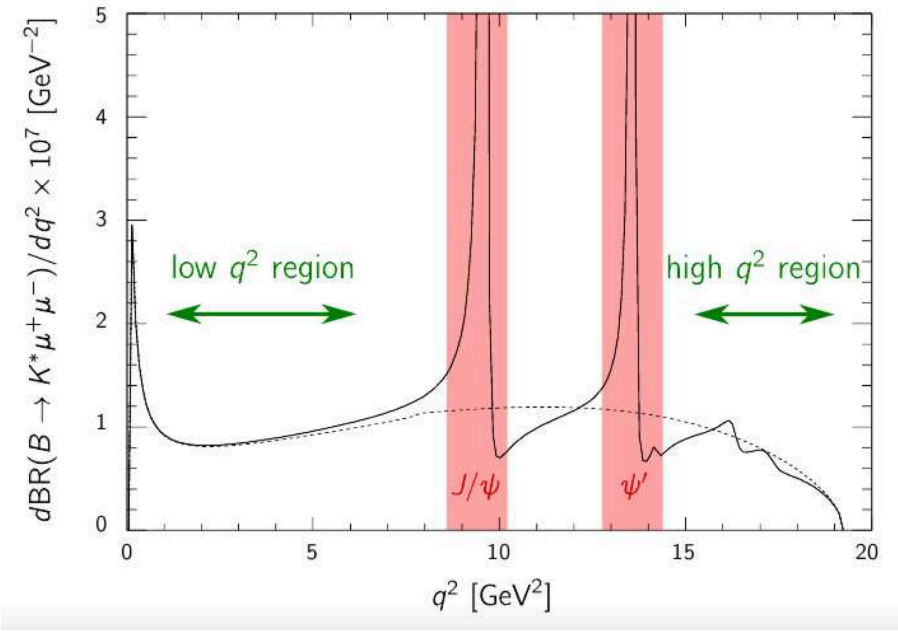


  - exploration of recent experimental (flavor) anomalies: New Physics nearby?

Flavor anomalies and B-decays (RF1)

- Recent anomalies in electroweak rare B-decays (CERN expts)
  - most mediated quark-level $b \to s\ell^+\ell^-$ transitions, also $b \to c\ell\nu_\ell$





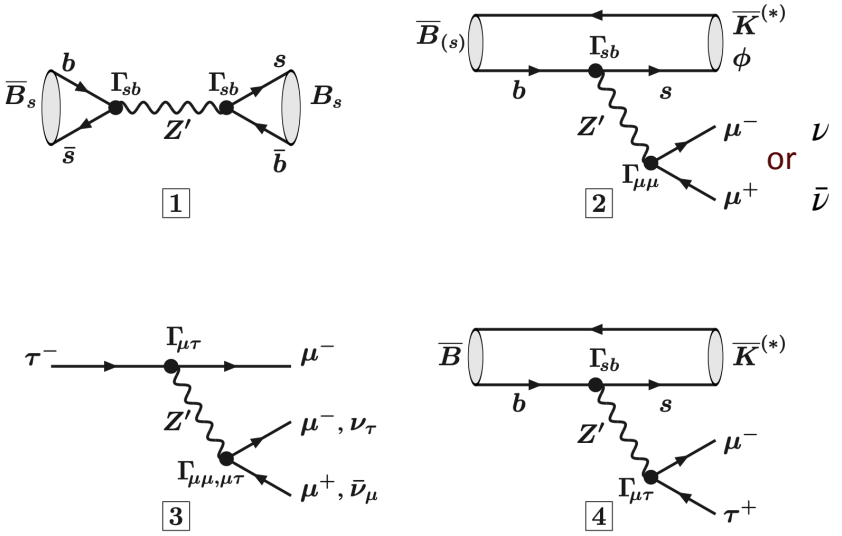
  - anomalies related to lepton-flavor universality (LFU) violations are not easy to explain by SM hadronic effects

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)}, \quad R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$$

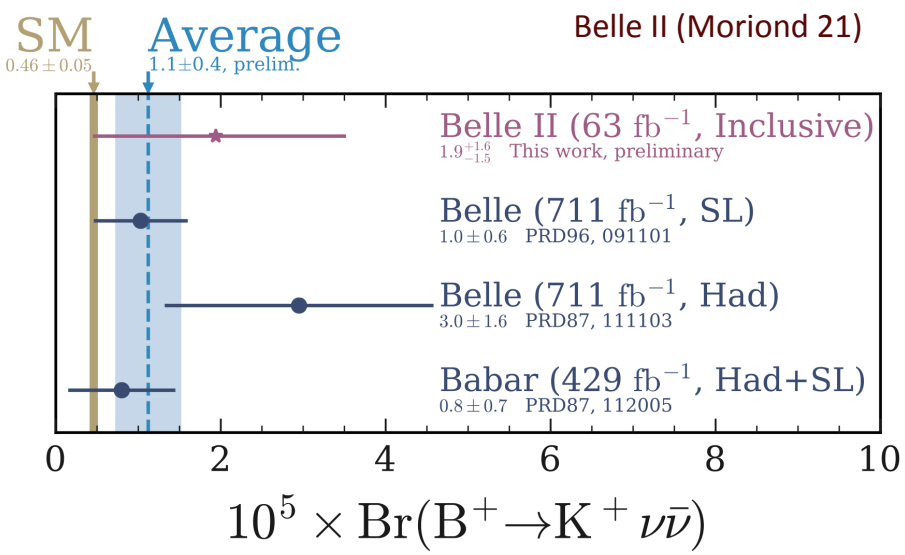
Need independent checks (Belle II)!

Flavor anomalies and B-decays (RF1/RF6)

- Recent anomalies in electroweak rare B-decays (CERN expts)
  - most mediated quark-level $b \to s\ell^+\ell^-$ transitions, also $b \to c\ell\nu_\ell$
  - … if New Physics: can affect other transitions, like $b \to s\nu\bar{\nu}$
  - … perfect modes for Belle II ($B \to K^{(*)}\nu\bar{\nu}$)



Crivellin et al



Belle II (Moriond 21)

Maybe a 1σ excess?

  - $\nu\bar{\nu}$ final state is detected as missing energy: dark sector? $B^+ \to K^+ a$?

What about kaons?

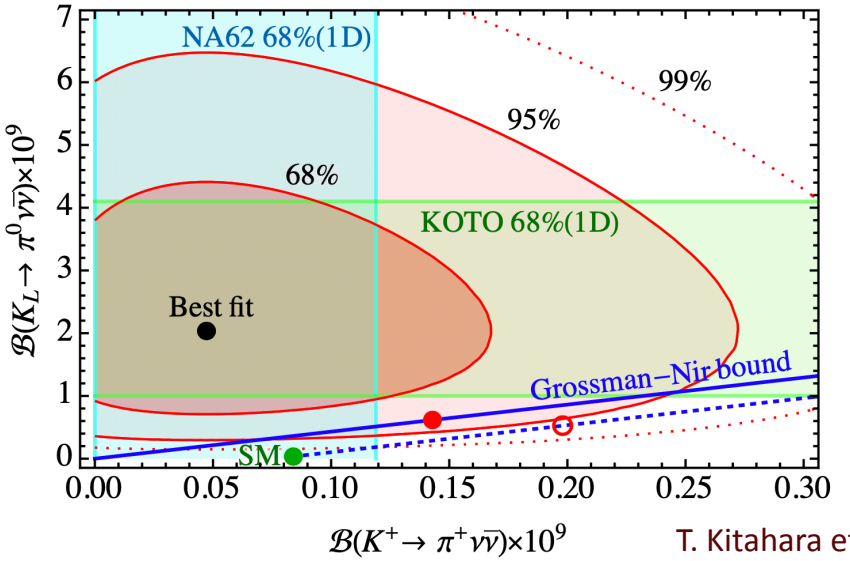
Flavor anomalies and K-decays (RF2/RF6)

- Measurements of $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62) and $K_L \to \pi^0 \nu\bar{\nu}$ (KOTO)

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{NA62} = 0.47^{+0.72}_{-0.47} \ (< 2.44) \times 10^{-10}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu})_{\rm KOTO} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$$

  - KOTO's BR appears to be two orders of magnitude larger than SM
  - appear to violate Grossman-Nir bound (aka "KOTO anomaly")



T. Kitahara et al

GN bound

$$BR(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.3 BR(K^+ \to \pi^+ \nu\bar{\nu})$$

SM predictions

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

  - … which can be arranged if there are light Dark Sector (DS) particles, e.g. $K \to \pi a$

NP/DS particles can affect muon precision observables: (g-2)?

Anomalies and precision muon physics (RF3/RF5/RF6)

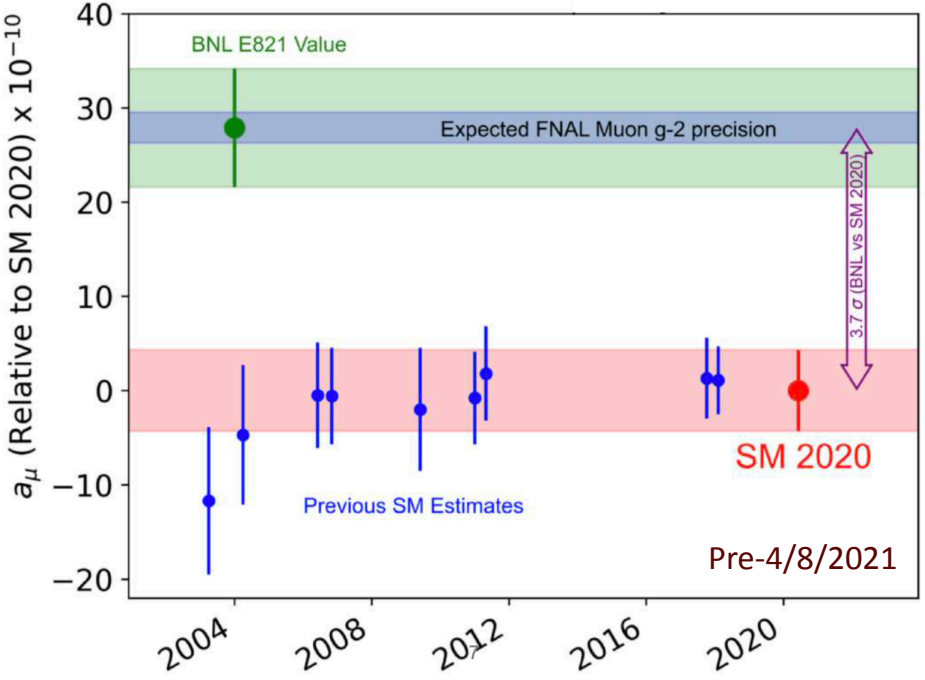
- Muon g-2: look for radiative corrections due to New Physics
  - magnetic moment: $\mathscr{H}_M = -\vec{\mu}\cdot\vec{B}$ with $\vec{\mu} = g\dfrac{e}{2m}\vec{s}$
  - in terms of form-factors: $a_\mu = \dfrac{g-2}{2} = F_2(0)$

$$\langle p_i|j^\mu|p_f\rangle = \bar{u}(p_i)\Gamma^\mu(P,q)u(p_f) = (-ie)\,\bar{u}(p_i)\left[F_1(q^2)\gamma^\mu + \frac{iF_2(q^2)}{2m}\sigma^{\mu\nu}q_\nu\right]u(p_f)$$

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	−98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, *udsc*)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, *uds*)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM}$	279(76)

P. Winter (ANL)

arXiv: 2006.04822
https://muon-gm2- theory.illinois.edu/white-paper/



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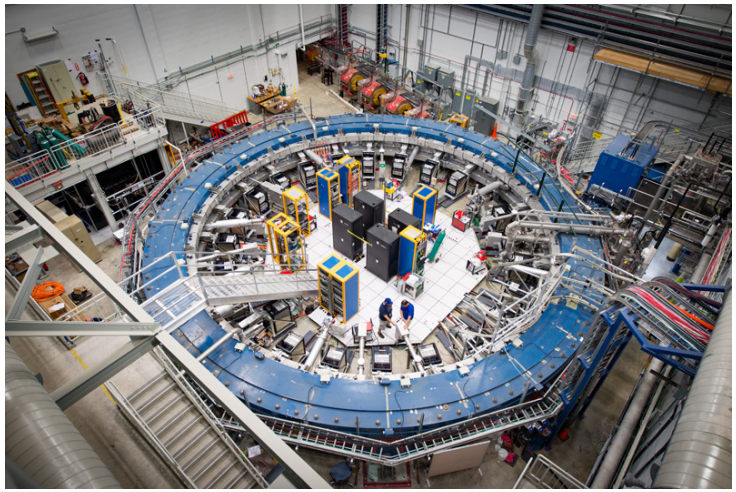
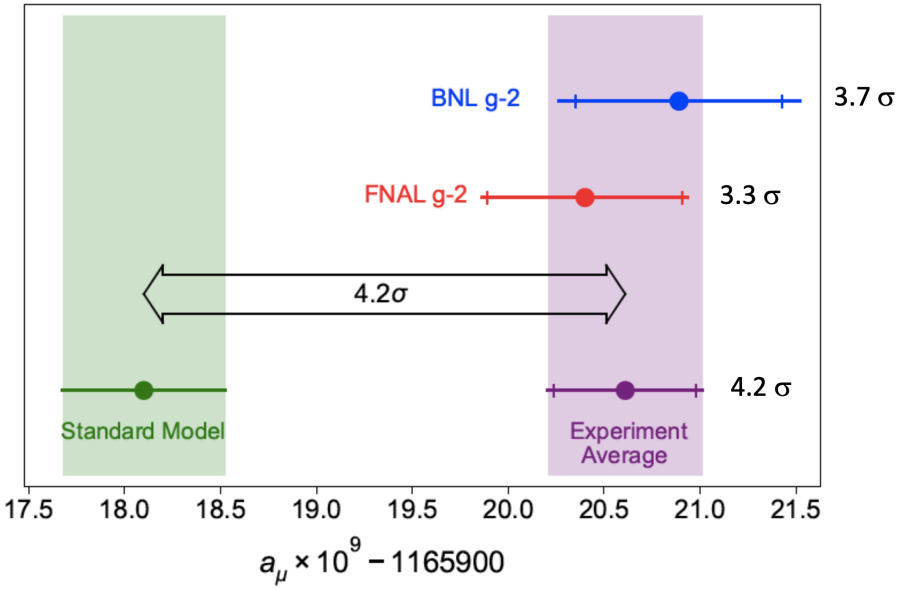


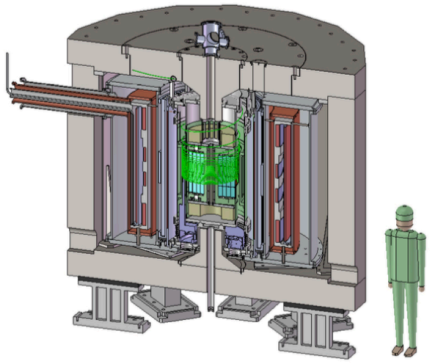


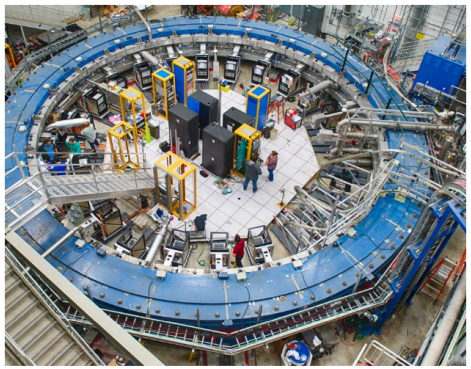
FNAL (g-2): $a_\mu(\mathrm{Exp}) = 116592061(41) \times 10^{-11}$

$a_\mu(\mathrm{Theory}) = 116591810(43) \times 10^{-11}$

$a_\mu(\mathrm{BMW}) = 116591954(55) \times 10^{-11}$

NEW g-2 EXPERIMENTS AIM AT ~140 PPB



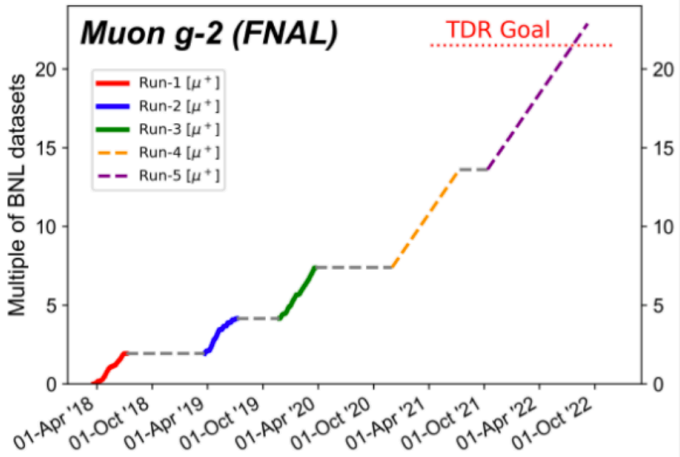


	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/C)
Polarization	P_{max} = 50%	P ≈ 97%
Magnet	MRI-like solenoid ($r_{storage}$ = 33cm)	Storage ring (7m radius)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Electron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	~400 ppb (possibly 100 ppb)	140 ppb

P. Winter (ANL)

Outlook for muon g-2 experiments

MUON g-2 EXPERIMENTS STATUS AND OUTLOOK



- Fermilab Muon g-2 E989 experiment:
  - Ongoing experiment, Runs 1-3 completed
  - First result (~BNL precision) this year
  - Run 4 and 5 will proceed
  - Prospects beyond that:
    - μ^- run (also good for CPT/LV tests)
    - More dedicated muon EDM
- J-PARC E34 g-2/EDM experiment:
  - A lot of ongoing R&D, not fully funded yet
  - Data taking maybe in a few years
  - One limitation is the muonium source (interest for other measurements)
- Muon g-2 theory:
  - Theory initiative will continue
  - Progress especially with LatticeQCD expected
  - Could bring us to 10σ with improved Muon g-2 experimental precision

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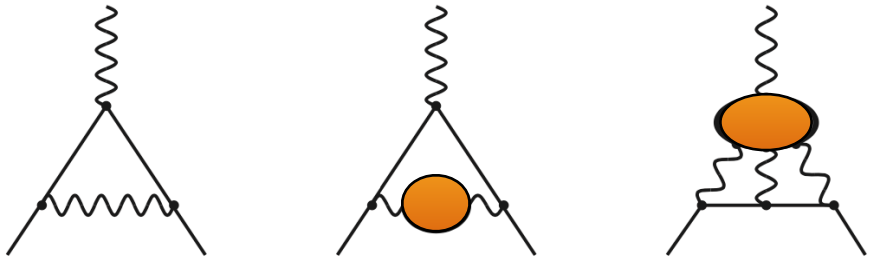
If theoretical issues…

- Independent lattice computations of HVP
- Data-driven estimates of hadronic vacuum polarization (HVP)
  - discrepancy between KLOE and BaBar data used in HVP

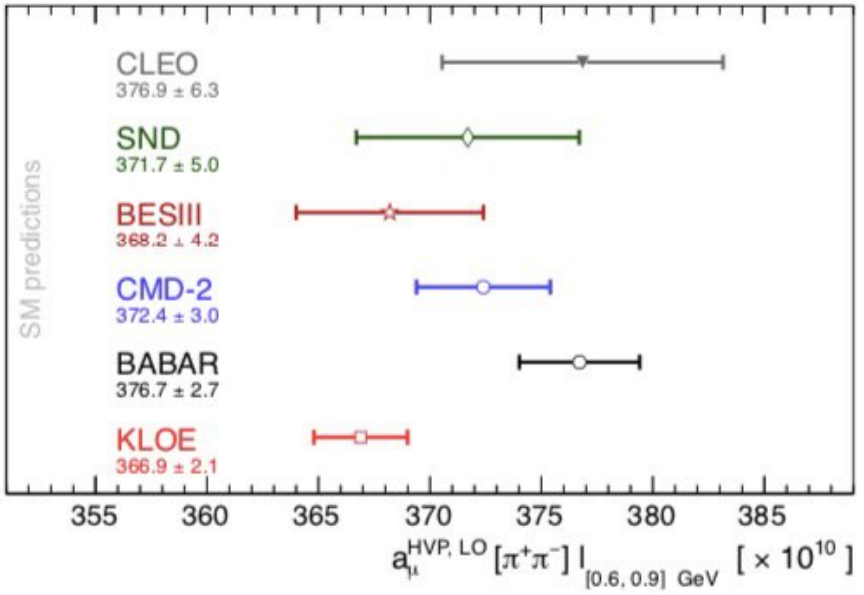


Leading order Vacuum polarization Light-by-light scattering

$$a_\mu^{hvp} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s) R(s)$$

$$\frac{1}{12\pi} R(s) = \frac{1}{12\pi} \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

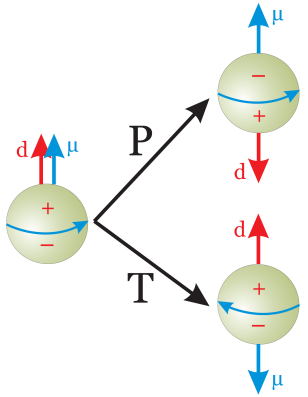
$$K(s) = \int_0^1 dx \frac{x^2(1-x)m_\mu^2}{x^2 m_\mu^2 + (1-x)s}$$

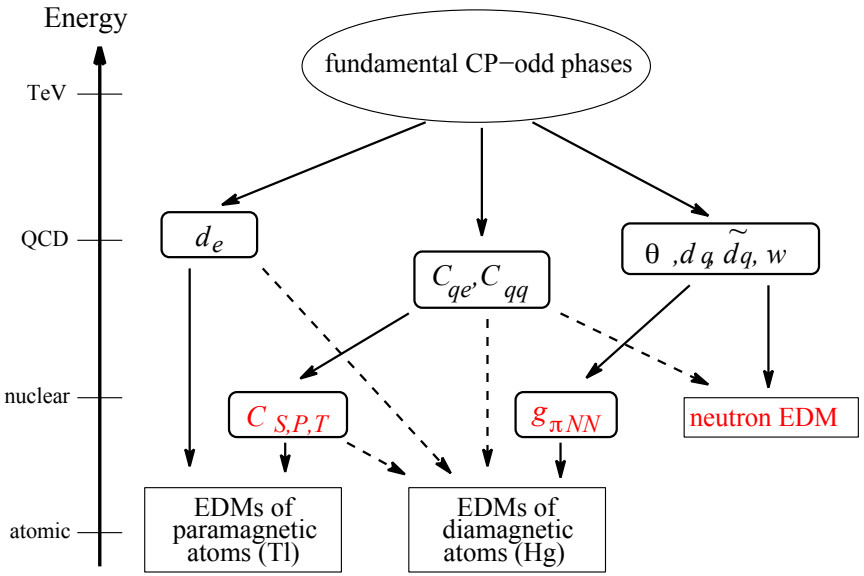


  - need radiative return Belle II data to eliminate the discrepancy
  - τ-decay data is not currently used: Belle II + lattice?

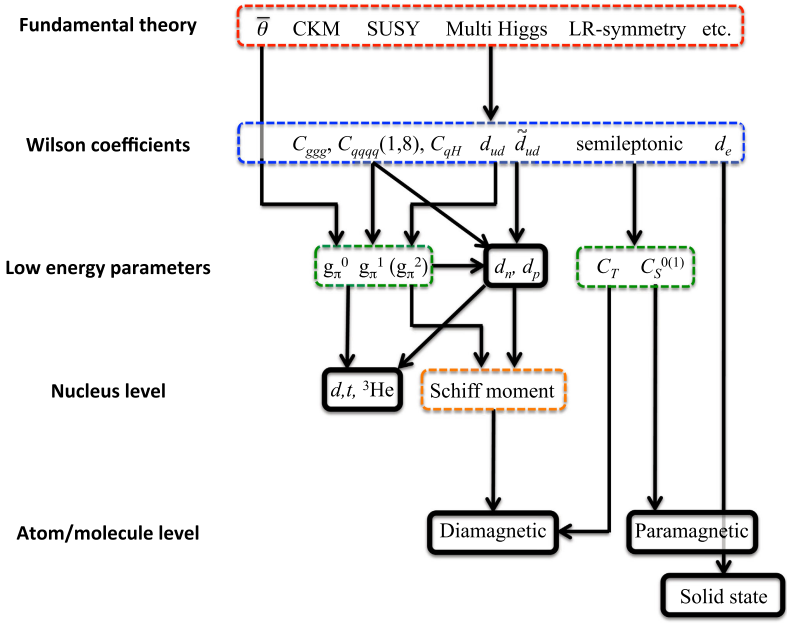
Discrete symmetries: Electric Dipole Moments (RF3)

- Studies of discrete symmetry breaking (C/P/CP/CPT)
  - probe BSM physics (a single source of CPV in the SM)
  - EDMs probe CP-violation
  - different systems sensitive to EDMs of different particles
    - paramagnetic atoms sensitive to (unpaired) electron edm
    - diamagnetic atoms sensitive to nucleus edm and less to e-edm





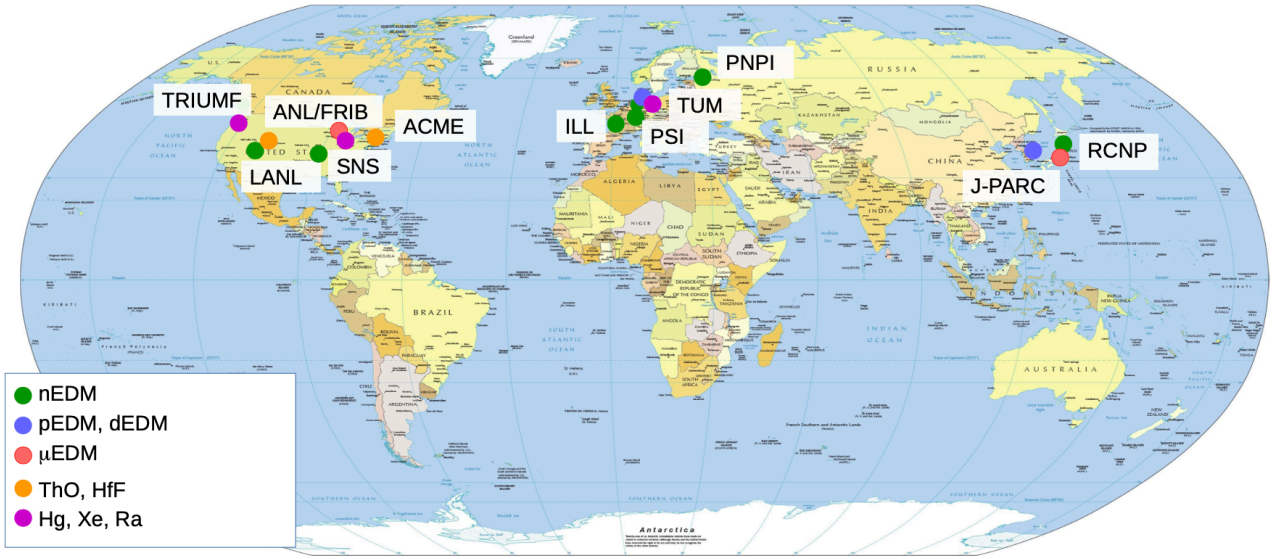
M. Pospelov and A. Ritz, Ann. Phys. 318 (2005) 119.



T. Chupp, et al, RMP 91(2019)

Discrete symmetries: EDM experiments (RF3)

- EDM measurements are done around the world
  - good prospects for improvement of current limits



	Current Limit	CKM prediction
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
n	10^{-26}	10^{-31}
p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
^{129}Xe	10^{-27}	10^{-33}
^{225}Ra	10^{-23}	10^{-33}

EDM experiments

- EDM measurements are done around the world
  - good prospects for improvement of current limits

experiment	sensitivity now	in 5 years	in 10 years
Cs @ Penn State		3×10^{-30}	
Fr @ Riken		1×10^{-30}	
Hg @ Bonn		5×10^{-31}	5×10^{-32}
Ra @ Argonne		$1.4/1.96\times10^{-23}$	3×10^{-27}
Xe @ Heidelberg	$-4.7+-6.4+-0.7\times10^{-28}$	$< 1\times10^{-28}$ @Jülich	$< 1\times10^{-30}$ @Uni Hd
Xe @ PTB		1×10^{-29}	
Xe @ Riken		1×10^{-28}	

experiment	sensitivity now	in 5 years	in 10 years
BaF (NleEDM) @ Groningen/Nikhef		1×10^{-30}	
HfF+ @ JILA	$1.3/1.64\times10^{-28}$	5×10^{-30}	5×10^{-31}
ThO (ACME) @ Yale	$1.1/1.64\times10^{-29}$	1×10^{-30}	
YBF @ Imperial	$1/1.64\times10^{-27}$	1×10^{-30}	1×10^{-31}

T. Blum (UConn)

	Current Limit	CKM prediction
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
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p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
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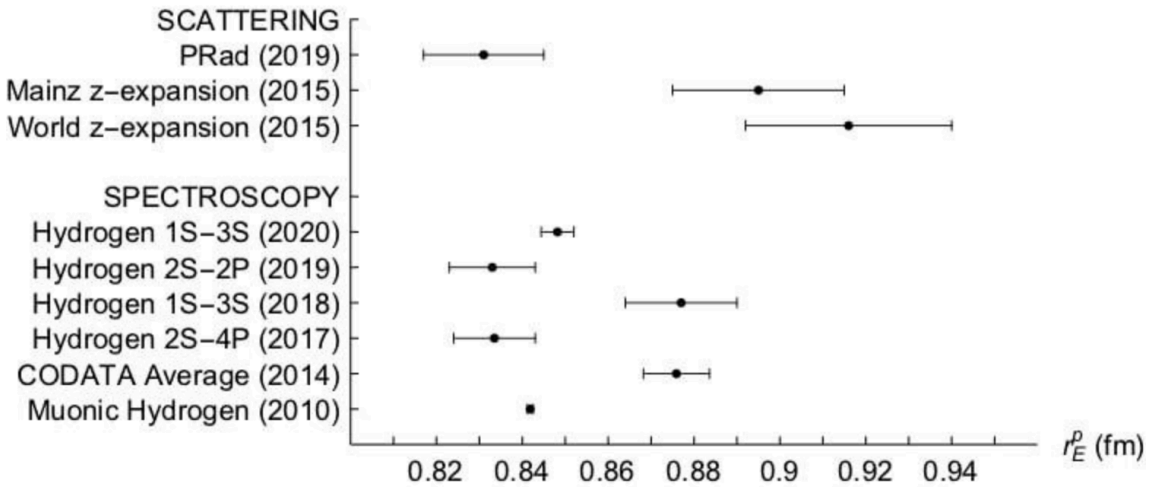
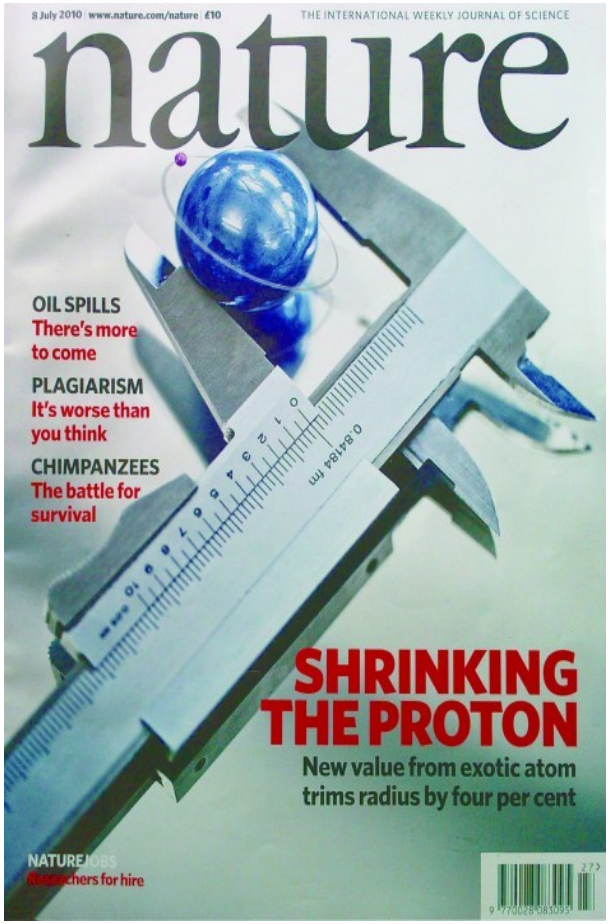
^{225}Ra	10^{-23}	10^{-33}

Other topics: QCD vs New Physics

- Proton's radius from muonic hydrogen: any New Physics?

★ Level splittings (e.g. Lamb shift) are sensitive to the charge radius of the proton





★ They are also sensitive to QED radiative corrections

★ Are there possible light New Physics particles that are responsible for this difference?

Barger et al, PRL 106 (2011) 153001

Remove proton radius issue from the problem: atomic physics with muonium?

Things to take home

- Flavor physics is a very exciting field at the moment
  - B-physics: CKM measurements and B-mixing to constrain NP
  - B-physics anomalies: first glimpse of New Physics or not?
  - Charm physics: CP-violation with up-type quarks (LHCb/Belle II)
  - Lepton flavor physics: bright future (Mu2e/COMET → muon collider)?
- EDMs provide powerful probes of New Physics with more reach than direct searches and provide complimentary information
  - electron EDM down to 10^{-31} e-cm in 10 years
- Magnetic dipole moments (electron, muon) have research timelines that span the next decade
  - muon g-2 results might help to clarify the path forward
- Precise tests of SM in parity violation ongoing (JLab, Mainz)
- AMO techniques help probe the whole spectrum of BSM physics
- Precision hadron spectroscopy: new phenomena in QCD

The Evening Herald
EXTRA!

Effective Lagrangians and CP-violation

$$\mathcal{L}_{\rm CPV}^{d\le 6} = -\frac{g_s^2}{32\pi^2}\bar{\theta} G\tilde{G} \qquad \text{dim=4 QCD } \theta\text{-term}$$

$$-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}(\sigma\cdot F)\gamma_5 q \qquad \text{dim=5 Quark EDM (qEDM)}$$

$$-\frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q g_s \bar{q}(\sigma\cdot G)\gamma_5 q \qquad \text{dim=5 Quark Chromo EDM (CEDM)}$$

$$+ d_w \frac{g_s}{6} G\tilde{G}G \qquad \text{dim=6 Weinberg's 3g operator}$$

$$+\sum_i C_i^{(4q)} O_i^{(4q)} \qquad \text{dim=6 Four-quark operators}$$

B. Yoon

LOI Breakdown

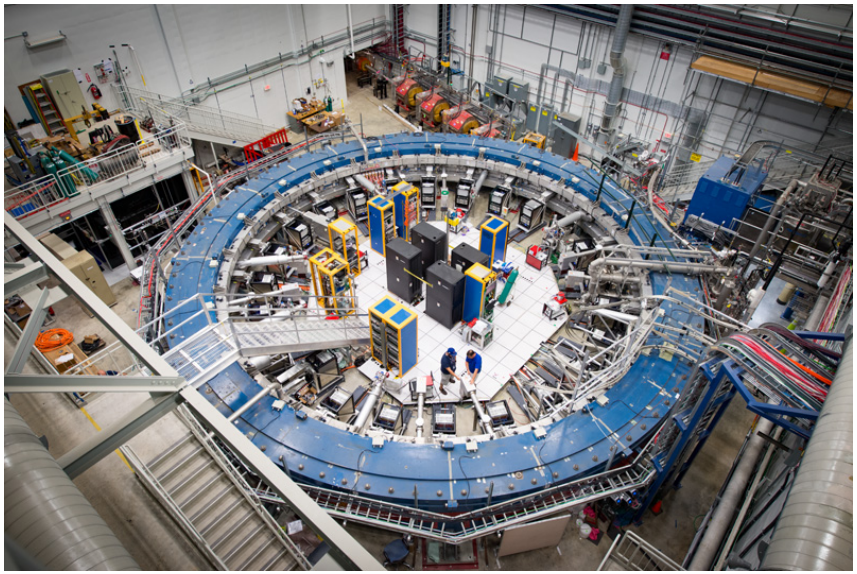
"Fundamental" Physics	
Dedicated Experiment Exploring Gravitational Effects on CP Violation	Gravity-generated / connected CPV
Strong CP and Neutrino Masses: A Common Origin of Two Small Scales	neutron EDM <-> neutrino masses (cross-frontier)
Searches for Exotic Short-range Gravity and Weakly Coupled Spin-Dependent Interactions using Slow Neutrons	Gravity tests with neutrons
Lorentz and CPT Tests with Low-Energy Precision Experiments	L / CPT tests (overview of many opportunities)
NOPTREX:	T violation with neutrons
Muonium Gravity Experiment	Gravity test (antimatter)
Facilities	
Upgraded Low-Energy Muon Facility at Fermilab	Facility (cross-group)
Potential storage ring and Muon Campus experiments	Muon campus / facility use
Dipole Moments	
Using lattice QCD for the hadronic contributions to the muon g – 2	Lattice QCD - HVP
Calculations of nucleon electric dipole moments on a lattice with chiral fermions	Lattice QCD - nucleon EDM
Hadronic contributions to the anomalous magnetic moment of the muon	Lattice QCD - HVP & HLbL
Opportunities and New Physics Implications for (g – 2)e,μ	electron and muon MDM: Theory model (cross frontier)
The Proton Storage Ring EDM Experiment	EDMs (CPV) and axion DM
Test of the Standard Model and Search for Physics Beyond∗ Opportunities for Fundamental Physics using Small-scale Storage Ring Experiments	EDMs storage ring (see other LOI in AF5)

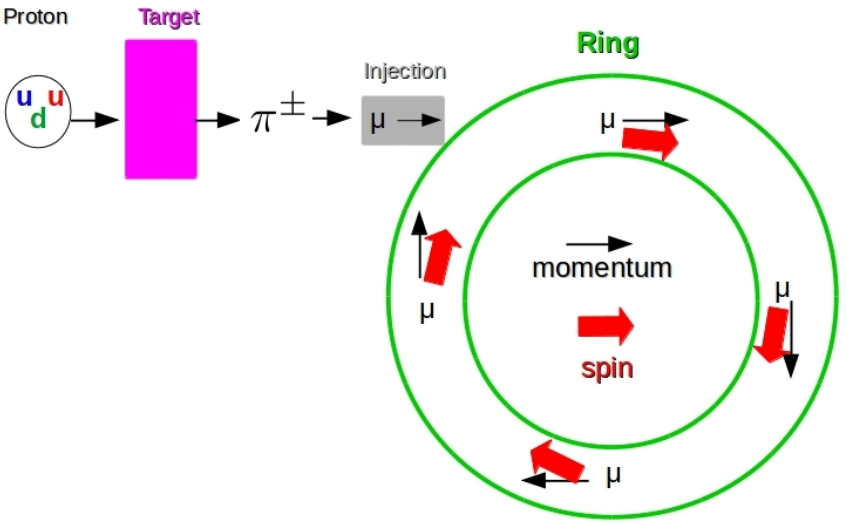
AMO	
Atomic/nuclear clocks and precision spectroscopy measurements for dark matter	Precision clocks and spectroscopy/DM
Optically levitated sensors for precision tests of fundamental physics	Gravity tests (micron-scale) with nanospheres, axion DM
Probing fundamental physics with highly-coherent nuclear spins	EDM (CPV) and axion DM
Th-229 Nuclear Clock	Precision clocks
Mechanical tests of the gravity-quantum interface	Gravity (-quantum) tests
Doped Cryocrystals for Ultrasensitive EDM Measurements: Snowmass LOI	EDMs, facility for cryo-crystals
Searches for new sources of CP violation using molecules as quantum sensors	EDMs (CPV) with molecules

R. Bernstein (FNAL)

Muons: examples of current puzzles

- Muon's magnetic properties: a = (g-2)/2: $\vec{\mu} = g\frac{e}{2m}\vec{s}$
  - there is a >3 sigma discrepancy between the theoretical prediction and exp. measurement





Lindner et al

Are there possible heavy New Physics particles that are responsible for this difference?

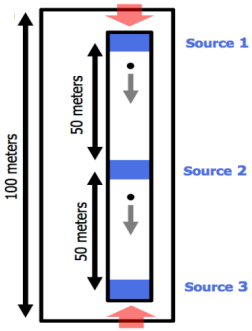
Other BSM searches with AMO

Atom interferometry

BSM searches:
Variation of fundamental constants
Ultralight scalar DM & relaxion searches
Violation of the equivalence principle

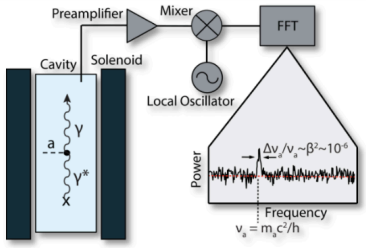
Prototype gravitational wave detectors

MAGIS-100 Fermilab



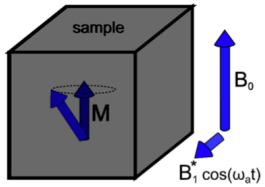
MIGA (France), 150 meters under construction
AION

Axion and ALPs searches



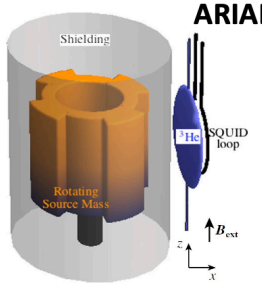
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



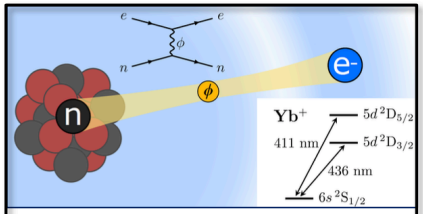
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE



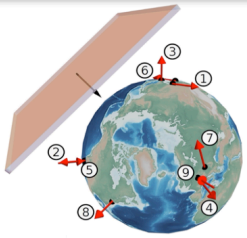
Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches



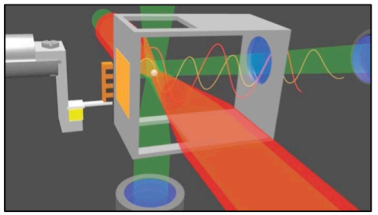
Fifth force searches with precision spectroscopy with atoms and ions

WReSL: Cs spectroscopy



GNOME: network of optical magnetometers for exotic physics

Levitated optomechanics



Also: gravitational wave detection and testing the Newtonian inverse square law

Many other current & future experiments: HUNTER (AMO sterile neutrino search), SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, tests of the gravity-quantum interface, tests of QED, …
See Rev. Mod. Phys. 90, 025008 (2018) for a recent review.

Marianna Safronova (UDel)