Precision Physics at High Intensities

Summary Talk

Conveners: Luchang Jin [1], Sophie Middleton [2], Mark Pitt [3]

4th September 2022

Conference on the Intersection of Particle and Nuclear Physics

[1] University of Connecticut
[2] California Institute of Technology
[3] Virginia Tech.

Our sessions

Our group covers a variety of intensity frontier topics, we tried to include sessions which reflect this:

PPHI: Precision Physics using Muons and Pions (new results and proposed measurements)

PPHI: Understanding the muon g-2 anomaly

PPHI: Anti-hydrogen and n-nbar oscillations

PPHI/DM: Dark Matter at High Intensity experiments (new results and projections)

PPHI/HF: Rare Decays

PPHI/HF: Charged Lepton Flavor Violation/Lepton Universality (new results and projections)

PPHI/EW: Symmetry Tests

PPHI/QCD: Proton Radius

~ 40 talks in total!!

Precision Physics using Muons and Pions

LFU searches using pions at PIONEER
Patrick Schwendimann

Primary Goals of PIONEER
Precision Measurements of Rare Pion Decays [1]

PIONEER

Motivation
Experimental Setup
Conclusion
Backup
Further Reading

Phase I: e/μ Decay Branching Ratio

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$

with a precision $< 0.01\,\%$

Phase II: PiBeta Decay

$$R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+\nu)}{\Gamma(\text{all})}$$

with a precision $< 0.2\,\%$

Pioneer Experiment approved by Paul Scherrer Institute

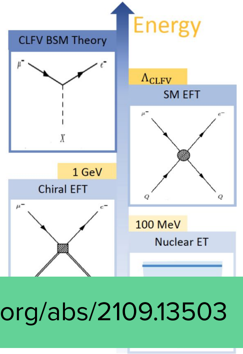
- Proposal: https://arxiv.org/abs/2203.01981
- PSI Website: https://www.psi.ch/en/pioneer

P. Schwendimann (UW) PIONEER CIPANP 2022/8/30 2 / 17

Effective Theories and Muon to Electron Conversion
Evan Rule & Frederic Noel

Summary and Future Work

- Nuclear ET identifies six CLFV response functions + two interference terms probed by elastic $\mu \to e$ conversion
- Publicly-available Python & Mathematica codes for $\mu \to e$ effective theory (see arXiv:2208.07945 for details)
- Matching to quark-level EFTs in progress
- Inelastic $\mu \to e$ conversion probes 4 LECs that elastic cannot



ER, Haxton, and McElvain, arXiv:2109.1350
Haxton, **ER**, McElvain, and Ramsey-Musolf,

See : https://arxiv.org/abs/2109.13503

August 30, 2022 | 14th CIPANP | Evan Rule

Recent results from AlCap
Nam Tran

Summary

- AlCap measures charged and neutral particles from muon capture on aluminum & titanium
- Important photons
  - 347 keV X-rays (Al): $79.8 \pm 0.8\,\%$
  - 1809 keV gammas (Al): $53.8 \pm 2.6\,\%$
  - 932 keV X-rays (Ti): $67.3 \pm 2.2\,\%$
- Interferences:
  - 347 keV X-rays (Al) has interferences from W and Pb
  - 932 keV X-rays (Ti) has interferences from Pb, and stainless steel
  - 1809 keV gammas (Al) is clean

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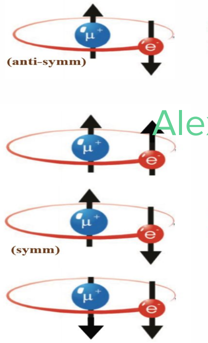
Future experimental searches for muonium-antimuonium oscillations
Alexey Petrov

The simplest bound states: muonium

- Muonium: a bound state of μ^+ and e^-
  - $(\mu^+\mu^-)$ bound state is *true muonium*
- Muonium lifetime $\tau_{M_\mu} = 2.2\ \mu s$
  - main decay mode: $M_\mu \to e^+ e^- \bar{\nu}_\mu \nu_e$
  - annihilation: $M_\mu \to \bar{\nu}_\mu \nu_e$
- Muonium's been around since 1960's
  - used in chemistry
  - QED bound state physics, etc.
  - New Physics searches (oscillations)



Spin-0 (singlet) paramuonium

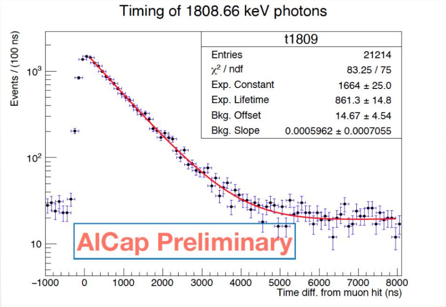
Spin-1 (triplet) orthomuonium

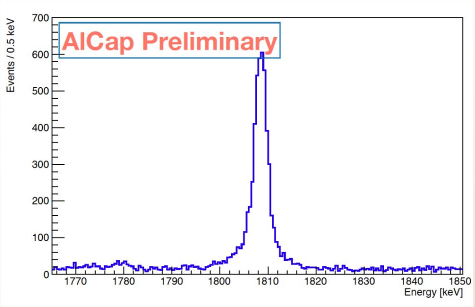
Hughes (1960)

The masses of singlet and triplet are almost the same!

Alexey A Petrov (USC) 18 CIPANP 2022, Orlando

1809 keV gamma line from aluminum



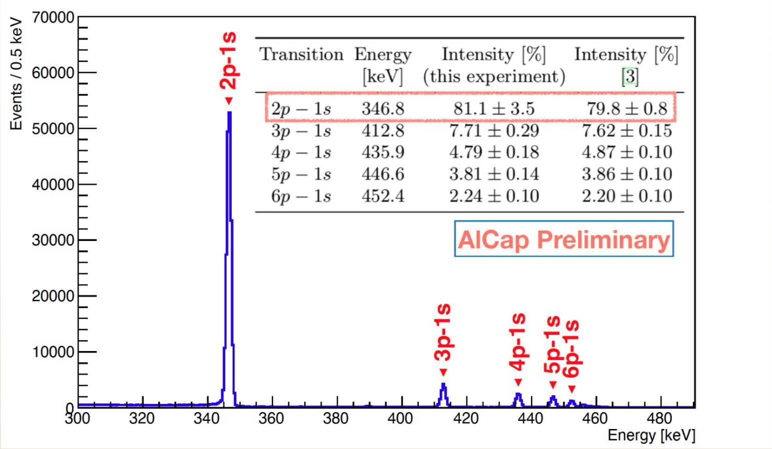


- Fitted lifetime: 861(14) ns
  - Lifetime of muons in aluminum 864(4) ns
- Emission rate: $53.8 \pm 2.6\,\%$ per muon capture
  - Consistent with previous value at $51 \pm 5\,\%$

New results from AlCap

Nam Tran

Muonic X-rays from aluminum



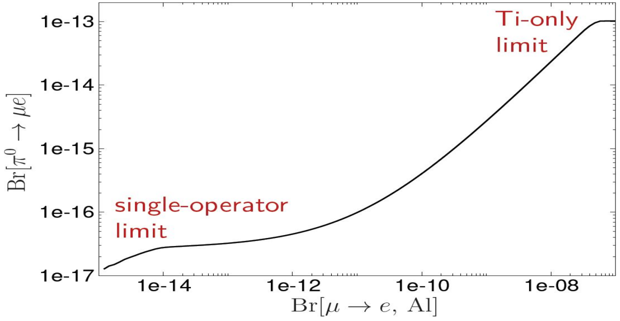
Transition	Energy [keV]	Intensity [%] (this experiment)	Intensity [%] [3]
$2p-1s$	346.8	81.1 ± 3.5	79.8 ± 0.8
$3p-1s$	412.8	7.71 ± 0.29	7.62 ± 0.15
$4p-1s$	435.9	4.79 ± 0.18	4.87 ± 0.10
$5p-1s$	446.6	3.81 ± 0.14	3.86 ± 0.10
$6p-1s$	452.4	2.24 ± 0.10	2.20 ± 0.10

Prediction on pion flavor violating channels based on muon to electron projections that are reachable in next generation of CLFV experiments from Frederic Noel

Outlook

With values from Mu2e or COMET the limits become even stronger

- Combining the limits from Ti and Al we find:



Understanding the muon g-2

The field measurement and systematics in g-2   Kyun Woo Hong

Part 1
Overview of E989

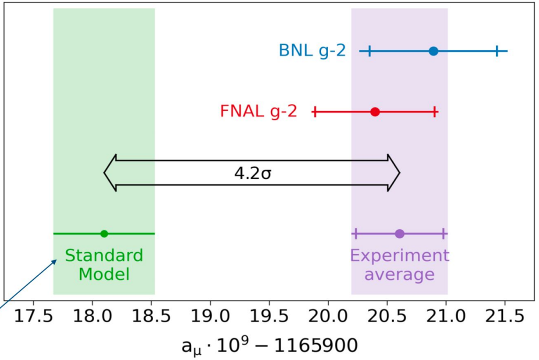
Run 1 Result (2021)

- Result a_μ to 460 ppb
- Confirmed BNL experimental results (20 years later)

a_μ^{SM} = 116 591 810 (43)
a_μ^{EXP} = 116 592 061 (41)

$a_\mu^{EXP} - a_\mu^{SM}$ = (251±59) = 4.2 σ
[unit: 10^{-11}]

The white paper from the theory invitation [https://muon-gm2-theory.illinois.edu/white-paper/]



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Part 3
NMR Technique and Field Measurement

NMR Probes

Trolley Probe

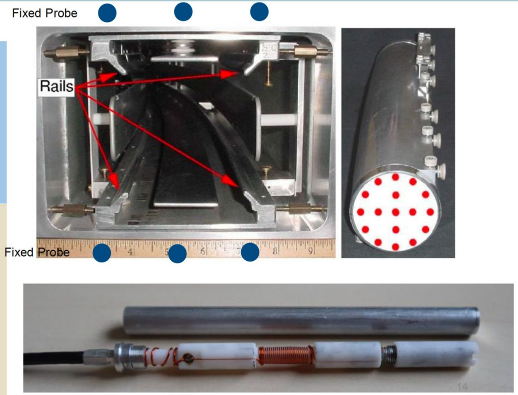
Location:
Total 17 probes carried by trolley

Purpose:
Periodic field maps inside of the ring every 3-5 days

Fixed Probe

Location:
Total 378 probes mounted at fixed locations outside (top and bottom) of the muon orbit

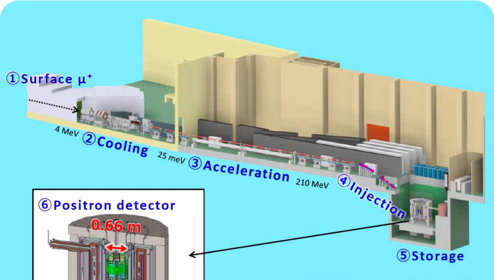
Purpose:
Continuously monitor field drift while muons are present in the ring



J-PARC muon g-2/EDM experiment   Yutaro Sato

J-PARC muon g-2/EDM Experiment 7

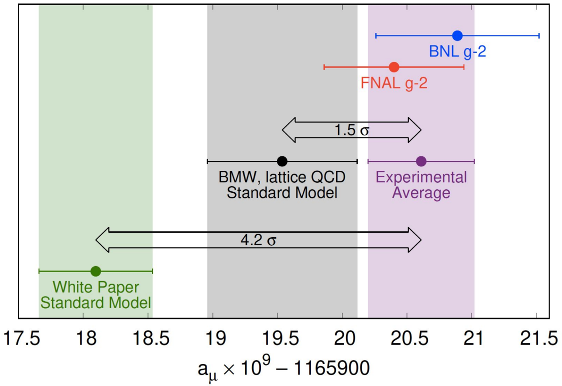
① Muon Beam Line and experimental area
② Thermal muon
③ Muon linac
④ Injection
⑤ Storage
⑥ Detector



	Initial goal	Final goal
g-2	~ 0.45 ppm	→ 0.1 ppm
EDM	~ 10^{-21} e・cm	

Hadron Vacuum Polarization from lattice QCD   Kalman Szabo

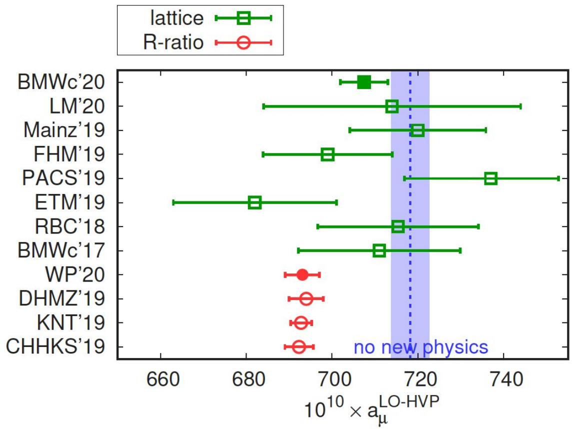
Outline



Kalman Szabo: reported on BMW'20 lattice QCD calculation of the hadronic vacuum polarization term

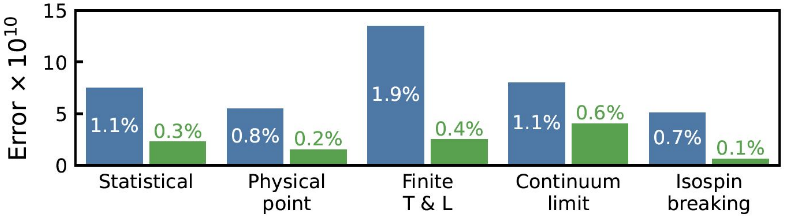
- Several improvements led to significantly reduced uncertainty in lattice-based determination of HPV
- Disagreement with HPV determinations from e^+e^- R value data

Final result



- $a_\mu^{LO-HVP} = 707.5(2.3)(5.0)[5.5]$ with 0.8% accuracy
- consistent with FNAL and 1.5σ away from BNL+FNAL
- 2.0σ larger than [DHMZ19], 2.5σ than [KNT19]

Key improvements



- incorporated recent algorithmic improvements to reduce statistical noise
- physical input is mass Omega baryon with 0.2% error
- dedicated finite-size study in 11 fm box (typical is $\lesssim$ 6 fm), good agreement with model computations
- six lattice spacings and improved approach towards cont.limit
- included all relevant isospin breaking effects

Anti-hydrogen and n-nbar oscillations

Pulsed production of antihydrogen in the AEgIS Experiment

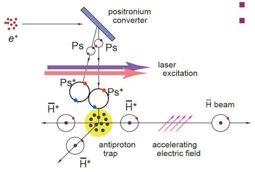
Michael Doser

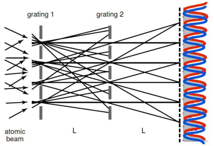
Schematic overview: AEḡIS (Antimatter Experiment: gravity, Interferometry, Spectroscopy)

Physics goals: measurement of the gravitational interaction between matter and antimatter, $\bar{H}$ spectroscopy, antiprotonic atoms ($p\bar{p}$, $\bar{p}Cs$), Ps, …

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

- Anti-hydrogen formation via Charge exchange process with Ps*
  - o-Ps produced in SiO_2 target close to $\bar{p}$; laser-excited to Ps*
  - $\bar{H}$ temperature defined by $\bar{p}$ temperature
- Advantages:
  - Pulsed $\bar{H}$ production (time of flight – Stark acceleration)
  - Narrow and well-defined $\bar{H}$ *n*-state distribution
  - Colder production than via standard process possible
  - Rydberg Ps & $\sigma \approx a_0 n^4 \rightarrow \bar{H}$ formation enhanced





pulsed production of $\bar{H}$*

horizontal beam formation

gratings produce periodic pattern on detector; measure gravity-induced vertical shift of fringes

Friday 26 August 22

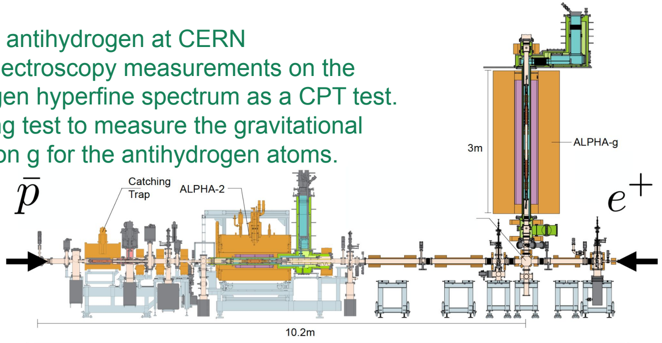
> Demonstrated production of pulsed beam of antihydrogen
> Expect improved rate due to an upgrade in the antiproton deacclerator.

Precision Studies with Trapped Antihydrogen

Will Bertsche

ALPHA as installed, 2022

> Trapped antihydrogen at CERN
> Done spectroscopy measurements on the antihydrogen hyperfine spectrum as a CPT test.
> Preparing test to measure the gravitational acceleration g for the antihydrogen atoms.



MANCHESTER 1824 The University of Manchester

CIPANP, Orlando Florida, 2022

ALPHA

Baryon Number-Violating Amplitudes on a Lattice

Sergey Syritsyn

Summary & Conclusions

- Amplitudes of quark BNV operators computed in lattice QCD with realistic, chirally-symmetric quarks
- Neutron-antineutron oscillation
  - *Amplitudes × (6 … 8) larger than from pheno.models*
  - *Continuum limit study pending*
  - *NEXT: nn→vacuum amplitudes, n→n̄ in nuclear medium*
- Proton decays p→π/K, p→leptons
  - *No topological suppression of nucleon decay found; confirm limits on GUTs*
  - *Finer spacing, larger volume calculations desirable*
  - *Need NLO ChPT for p→π/K : cross-check vs. p→vacuum amplitude*
  - *NEXT: p→ρ→$\pi\pi$, p→K*→πK amplitudes*

Sergey Syritsyn | BNV Amplitudes from Lattice QCD | CIPANP 2022, Aug 31, Orlando, FL

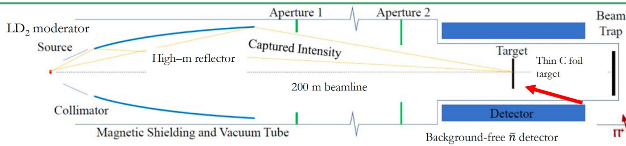
Searches for Neutron Oscillations with HIBEAM and NNBAR

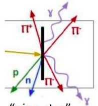
Leah Broussard

The NNBAR Experiment

NNBAR

- NNBAR at ESS: Leverage 3 decades of advances: moderator design, neutronics, detection, reconstruction techniques ×**1000** sensitivity of ILL J Phys G 48 070501 (2021)





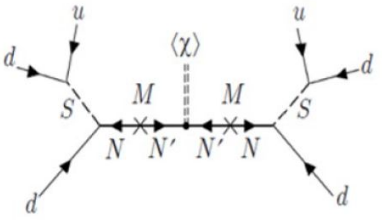
"pion star"

- HighNESS (3M€ EU grant): moderator study, $\bar{n}$ detector prototyping
  - EPJ Web Conf 251 02062 (2021), Sym 14 1 (2022), arXiv:2204.04051
  - Goal: CDR in 2023 for LD_2 moderator, NNBAR
- Staged R&D program ORNL – HIBEAM – NNBAR

Leah Broussard | HIBEAM and NNBAR, CIPANP 2022, 8/29/22 – 9/4/22 | 10

Leah Broussard: Chance coming up at European Spallation Source (ESS) to significantly improve on search for relatively unexplored neutron-antineutron oscillations

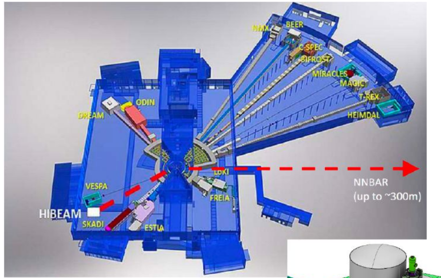
$$n \rightarrow \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$



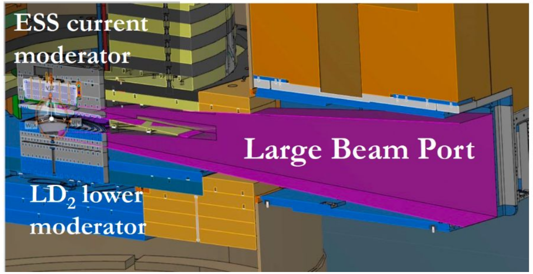
- $n \rightarrow \bar{n}$, dinucleon decays sensitive to BNV-only
- x1000 improvement in $n \rightarrow \bar{n}$ sensitivity on horizon

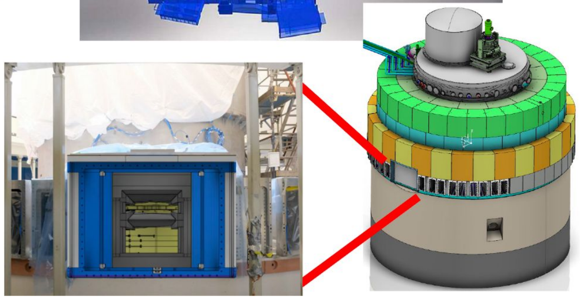
Golden opportunity for $n \rightarrow \bar{n}$ at ESS

- Substantial investment from ESS with $n \rightarrow \bar{n}$ in mind, to maximize FOM: $N\langle t^2 \rangle$
  - "Large Beam Port" now constructed
  - Up to 300 m beamline
- Fundamental Physics leading design of LD_2 lower moderator J Phys G 48 070501 (2021)



Search for n-nbar oscillations in a free neutron beam at the ESS; can reach up to $(2\text{-}3)\times10^9$ sec.





1000 times improved sensitivity search for n-nbar oscillations.

Charged Lepton Flavor Violation

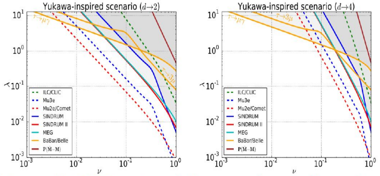
Prospects for CLFV in the Tau Sector from S. Banerjee

New Physics expectations

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons

Low- and high-energy phenomenology of a doubly charged scalar

A. Crivellin et. al. Phys. Rev. D 99, 035004 (2019)



$$\lambda_{ab} \sim (y^l_a y^l_b)^{-1}$$

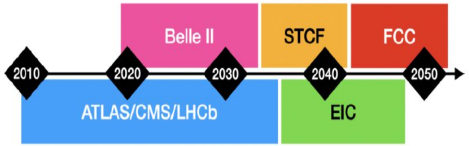
$$\lambda_{ab} = \lambda \begin{pmatrix} \pm 1 & \nu^2 & \nu^3 \\ \nu^2 & \nu^4 & \nu^5 \\ \nu^3 & \nu^5 & \nu^6 \end{pmatrix}$$

- Some models predict LFV up to existing experimental bounds
- eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow$ LFV
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau \to \mu\gamma$ ($\tau \to e\gamma$)
- Neutrinoless 2 and 3 body τ decays have different sensitivity

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-8}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

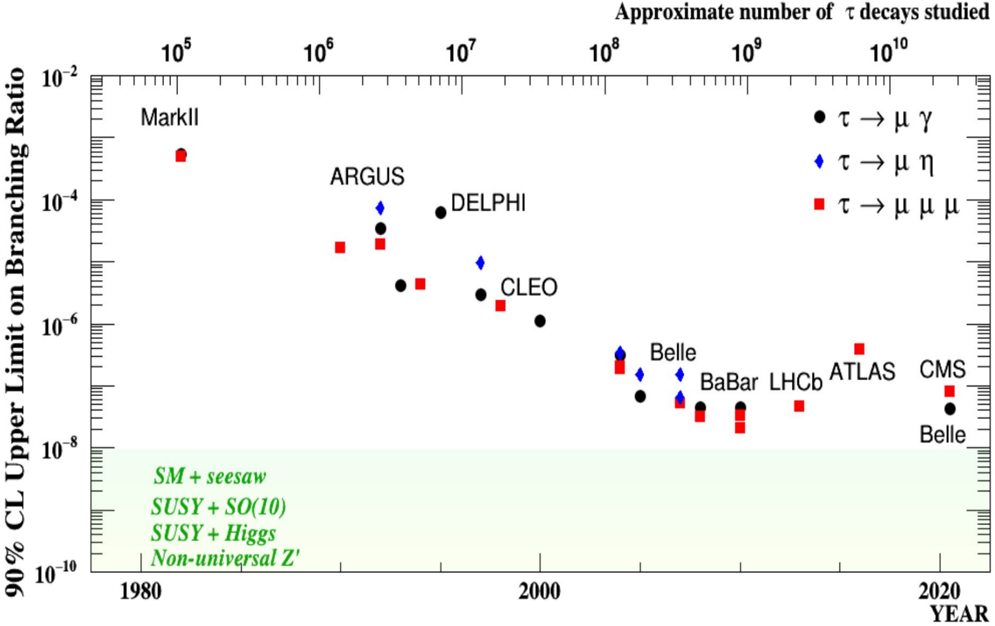
☞ Search for $\tau \to \ell\gamma/P^0$, $\tau \to \ell\ell\ell$, $\tau \to \ell h h'$ decays ($\ell = e, \mu; h = \pi, K$)

Tentative timeline



e-Print: 2203.14919 [hep-ph]

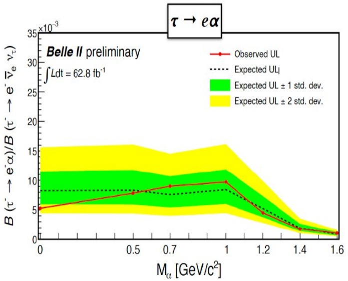
Current status of LFV τ decays ~ 10^{-7}

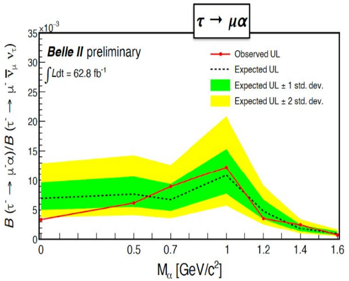


Latest Results on CLFV in the Tau Sector from S. Banerjee

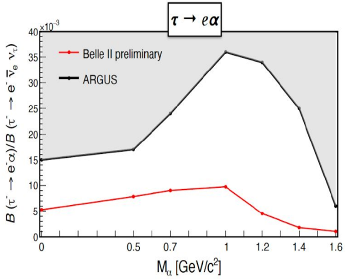
$\tau \to \ell\alpha$ at Belle II

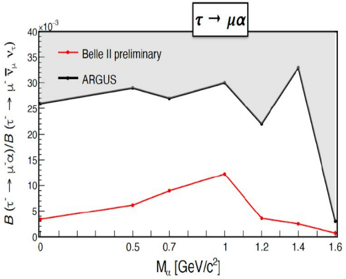
95% C.L. upper limits from Belle II (ICHEP'2022)





Comparison with previous limits from ARGUS (0.472 fb^{-1}) [Z. Phys. C68 (1995) 25]





$\tau \to \mu\mu\mu$ at ATLAS & CMS

- ATLAS limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio (20 fb^{-1} at 8 TeV)

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76 \times 10^{-7} \quad @\,90\%\ \text{C.L.}$$

Eur. Phys. J. C (2016) 76:232

- CMS limit on the $\tau^- \to \mu^-\mu^+\mu^-$ branching ratio (33 fb^{-1} at 13 TeV)

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0 \times 10^{-8} \quad @\,90\%\ \text{C.L.}$$

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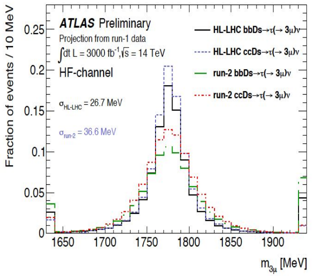
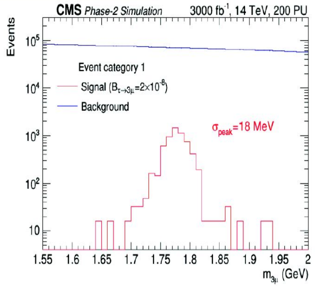
Future prospects using D & B decays (3 ab^{-1} at 14 TeV) :





ATL-PHYS-PUB-2018-032

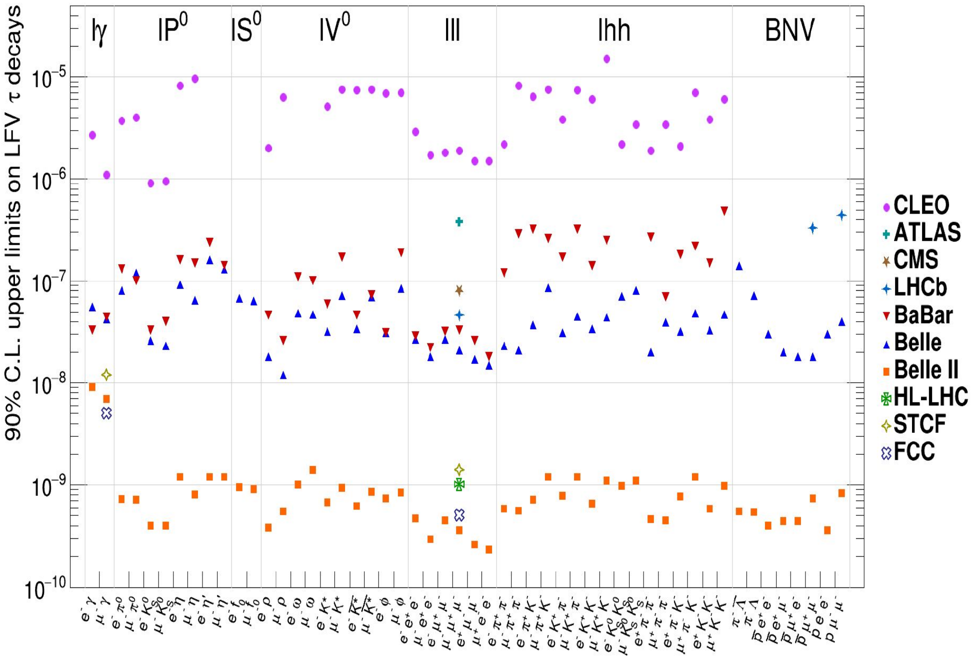
Scenario	$\mathcal{A} \times \epsilon$ [%]	N^{exp}_{bkg}	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
High background	0.88	507.05	6.40
Medium background	0.88	152.12	2.31
Low background	0.88	50.71	1.03

CMS-TDR-016

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4580	3640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}	

Projections for CLFV in the Tau Sector from S. Banerjee

Summary of experimental prospects of τ decays



e-Print: 2203.14919 [hep-ph]

Projections for CLFV in the Muon Sector from R. Bernstein

CLFV Muon Processes

- $\mu \to e\gamma$
  - oldest studied, most powerful limits, and the best experiment so far: MEG at PSI
- $\mu N \to eN$
  - muon to electron conversion: muon converts in field of nucleus, leaving nucleus unchanged

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \text{all muon captures})}$$

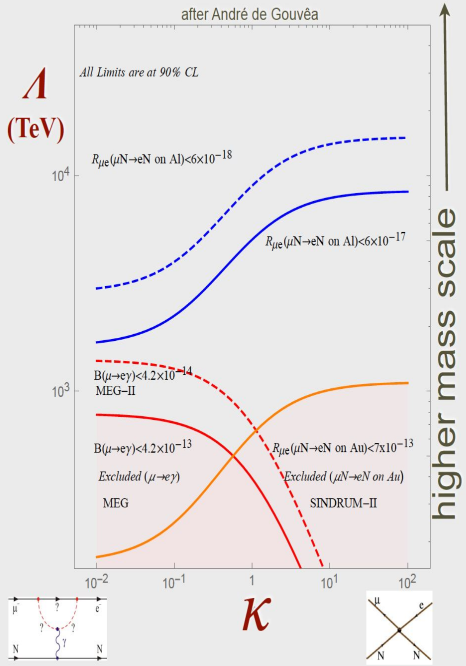
  - two experiments upcoming at FNAL and JPARC
- $\mu \to eee$
  - ambitious and unique, excellent partner to other two (at PSI)

μe Conversion and $\mu \to e\gamma$

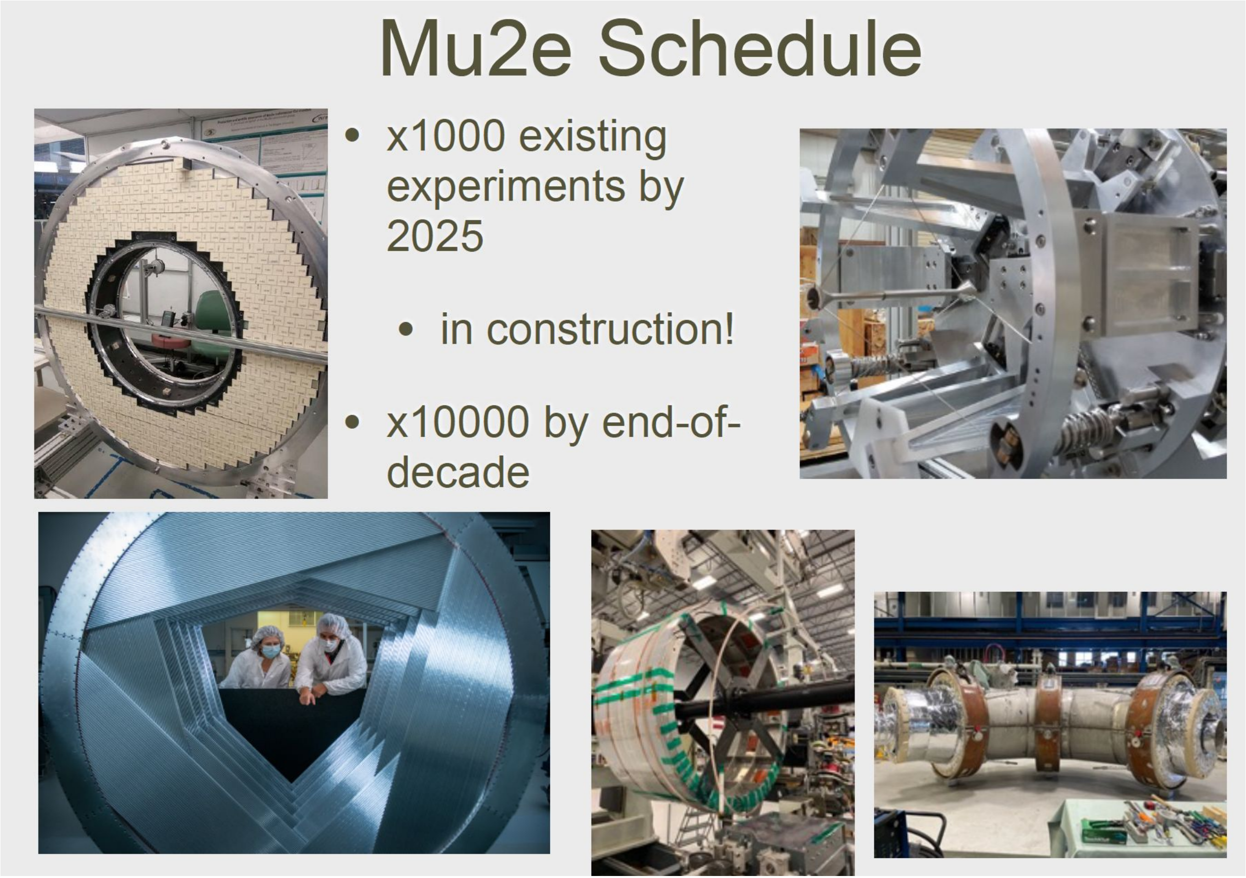
1) *Mass Reach to ~10^4 TeV for unit coupling, x10000 existing experiments*

2) *Mu2e/MEG upgrade complementary in loop-dominated physics.*

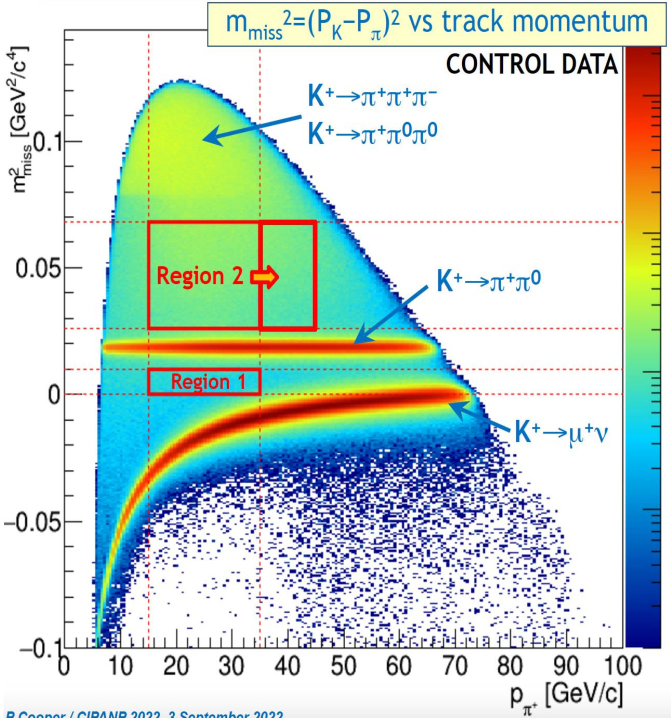
3) *These are discovery experiments*



Status of upcoming searches for CLFV in the Muon Sector from R. Bernstein



NA62: $K_{\pi\nu\nu}$ signal regions



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

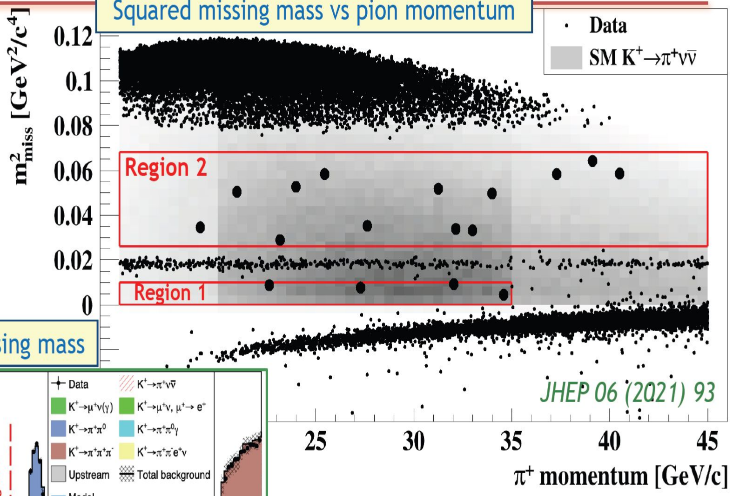
Measured kinematic background suppression:

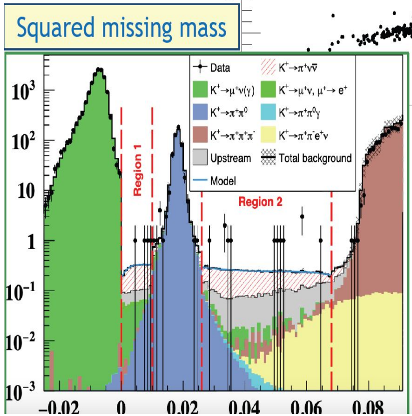
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & RICH): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

Opening the box (2018 data)





Full Run 1 data set:

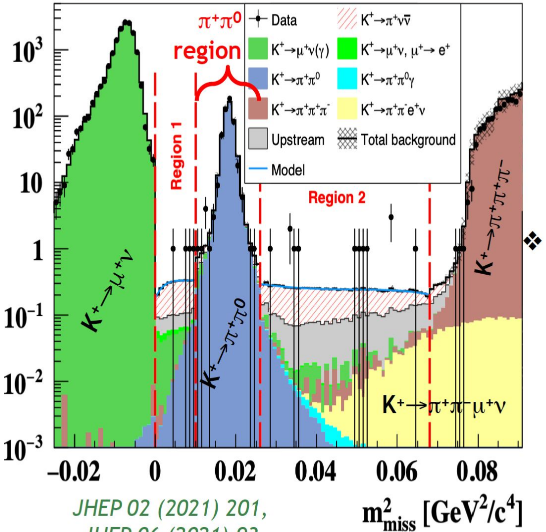
Candidates observed: **20** (17 in 2018 data)

Expected background: $7.03^{+1.05}_{-0.82}$

Expected SM events: $10.01\pm0.42_{syst}\pm1.19_{ext}$

Hidden sectors with $K^+ \to \pi^+ \nu\nu$

Squared missing mass (2018 data)



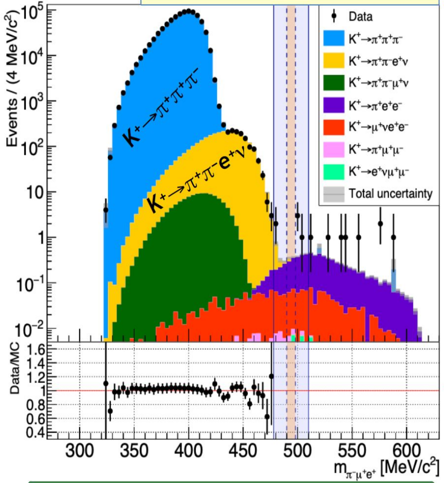
JHEP 02 (2021) 201,
JHEP 06 (2021) 93

- Signal regions **R1**,**R2**: search for $K^+\to\pi^+X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+\to\pi^+\nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0\to$invisible.
  - ✓ SM rate: BR($\pi^0\to\nu\nu$)~10^{-24}.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0\to\gamma\gamma$ background: optimised π^+ momentum range.
  - ✓ Interpretation as $K^+\to\pi^+X$, with m_X between R1 and R2.

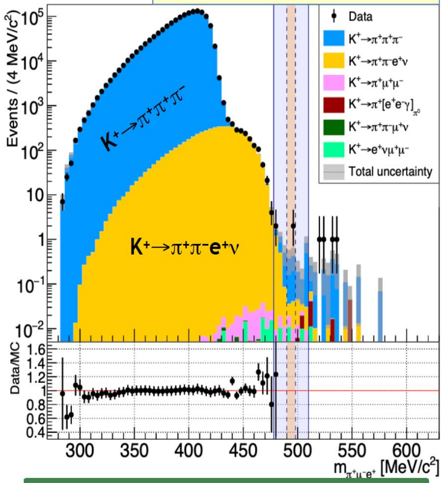
Results from NA62 P. Cooper

Search for $K^+\to\pi\mu e$ decays (Run 1)

LNV decay: $m(\pi^-\mu^+e^+)$



LFV decay: $m(\pi^+\mu^-e^+)$



K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
BR($K^+\to\pi^-\mu^+e^+$)<4.2×10^{-11} at 90% CL

Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
BR($K^+\to\pi^+\mu^-e^+$)<6.6×10^{-11} at 90% CL
BR($\pi^0\to\mu^-e^+$)<3.2×10^{-10} at 90% CL

[PRL 127 (2021) 131802]

Dark Matter Searches with HI

Theory Overview Yu dai Tsai

Benchmark Models for Dark-Sector Searches

Snowmass RF06 Classification

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [m_A/m_χ=3, α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] <u>m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}]</u> m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	<u>$m_{A'}$ vs. ϵ [decay-mode agnostic]</u> ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y** [m_A/m_χ=3, α_D=.5] (anom connection) **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. $\sin\theta$ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. $\sin\theta$* [λ=0] *m_S vs. $\sin\theta$* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_w*	FV axion couplings

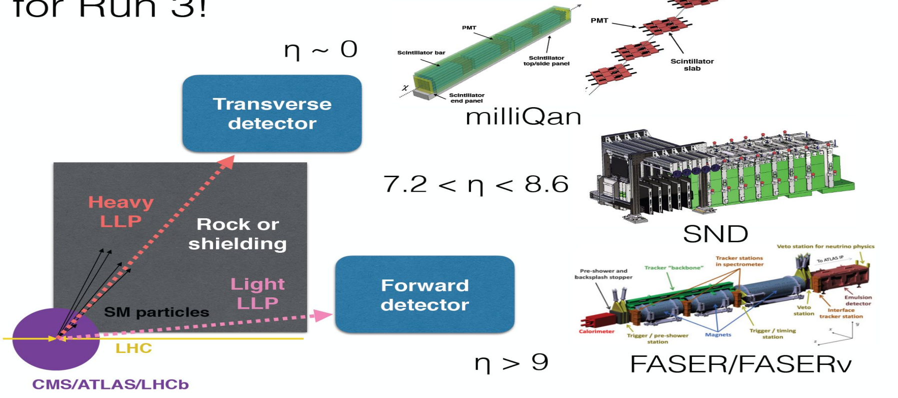
Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. <u>Underline=CV benchmarks that were not used in BRN</u>

PBC: The Physics Beyond Colliders initiative at CERN

Krnjaic, ... **Tsai**, <u>arXiv:2207.00597</u>

CERN Based Experiments Matt Citron

Range of new detectors coming online for Run 3!



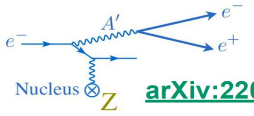
+ Moedal/MAPP

HPS and LDMX Matt Solt

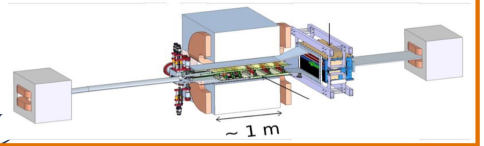
Dark Photon Decays - Complementary Searches

$2m_e < m_{A'} < 2m_{DM}$

Heavy Photon Search
(HPS) at Jefferson Lab

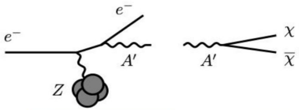


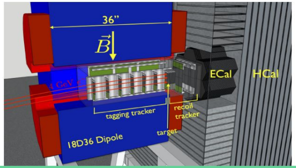
<u>arXiv:2203.08324</u>



$2m_{DM} < m_{A'}$

Light Dark Matter eXperiment
(LDMX) at SLAC

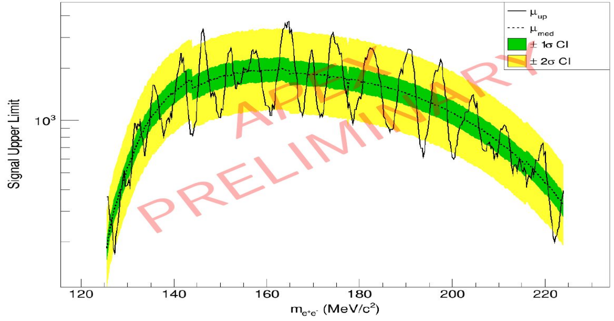




APEX Results Oliver Jevons

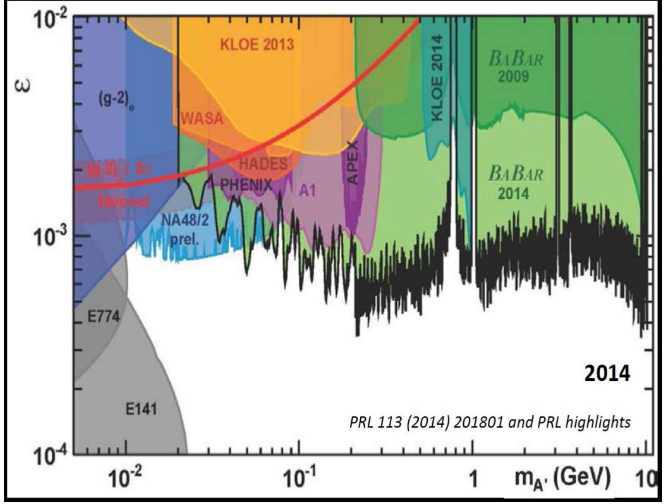
APEX results: blinded data set

Analysis performed on blinded data set; looking at upper limits on signal counts, and 1 and 2σ confidence intervals.



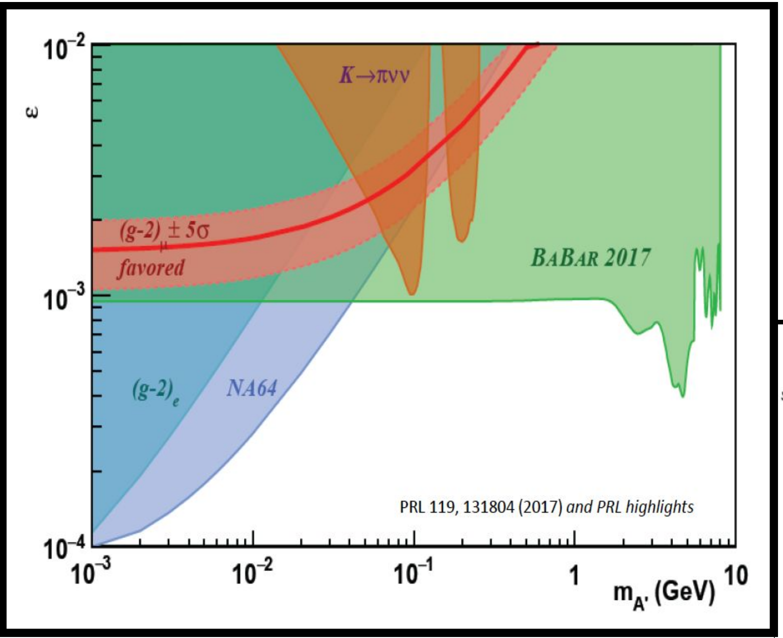
Results from BABAR

Presented by B. Echenard



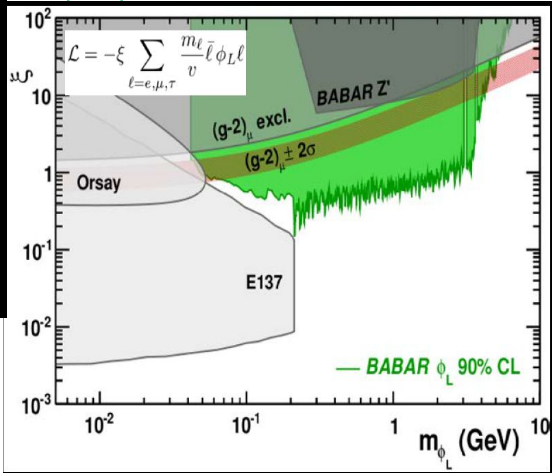
Visible dark photons

Plus many others. Analyses still on going

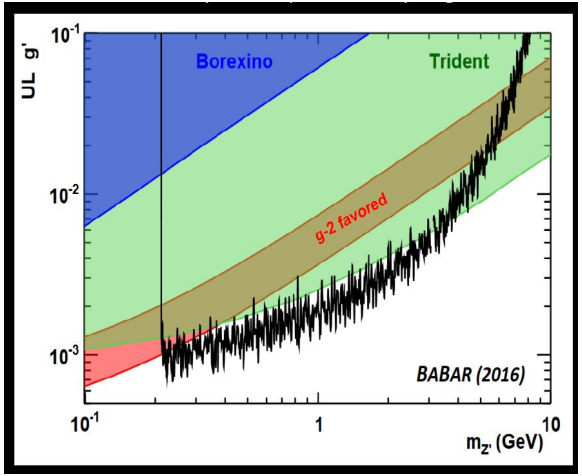


Invisible dark photons

Leptophilic Dark Scalars



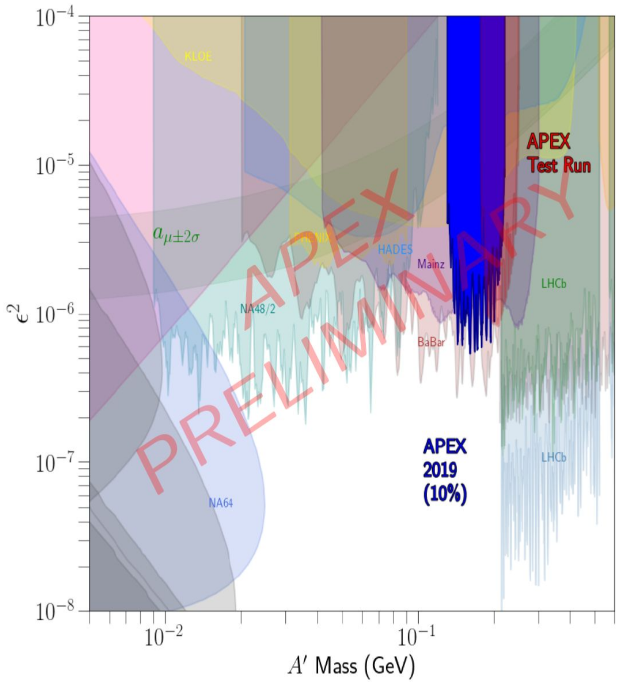
Muonic Dark Forces



Results from Jefferson Lab

APEX results (coming soon) by O. Jevons

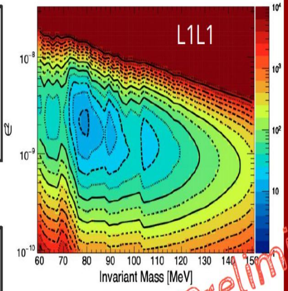
APEX results: blinded data set



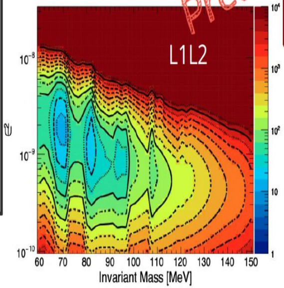
HPS results by M. Solt

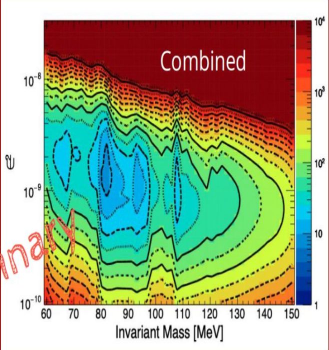
Displaced Vertex Search Final Results

Set limit using the Optimum Interval Method (OIM) ("L1L1")



Repeat analysis procedure for the case in which one of the A' daughters misses L1 of the SVT ("L1L2") . Combine results.





No exclusion to minimal dark photon model for this dataset, however **current datasets with upgrades...**

Symmetry Tests

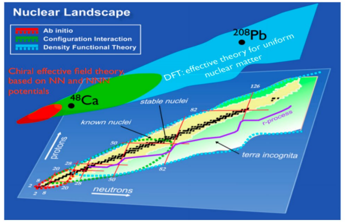
Neutral Weak Form Factor Measurements from the PREX-II and CREX Experiments
Allison Zec

PREX-II & CREX

	PREX-II	CREX
Target	^{208}Pb	^{48}Ca
Target Thick.	0.5 mm	6 mm
Beam Energy	1 GeV	2.2 GeV
$\langle Q^2 \rangle$	0.00616 GeV^2	0.0297 GeV^2
$\langle \theta \rangle$	5°	5°

Predicted asymmetries on the order of 1 ppm!

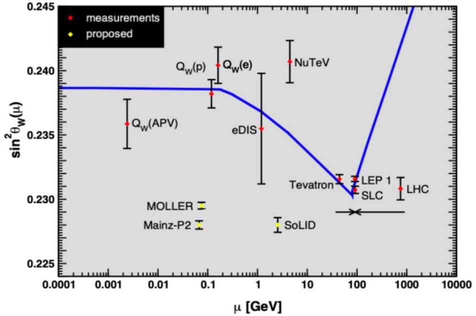
- Two PVES experiments, run at JLab Hall A in 2019-20
- Neutron radius from A_{PV} measurements
- Polarized electron beam on unpolarized high-Z targets
- ^{208}Pb radius: test of uniform nuclear matter
- ^{48}Ca radius: test of different nuclear structure models
- Overall goal: $\approx$3% error on A_{PV}^{208} and A_{PV}^{48}



Parity-Violating Electron Scattering as a Test of the Standard Model
Devi Adhikari

Summary and Outlook

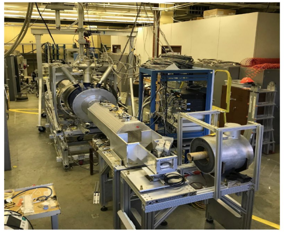
- **PVeS has become a precision tool for:**
  - Beyond standard model searches
  - Neutron skin of a heavy nucleus
  - QCD structure of the nucleon
- **Technical progress over time has enabled unprecedented precision**
- **Complementary to collider measurements**



Neutron Measurements to Probe the Hadronic Weak Interaction
Murad Sarsour

Summary

- HWI is still one of the least understood aspects of nuclear physics. Significant recent theoretical work but still lack a sufficient number of precision measurements to constrain the set of couplings.
- NPDGamma and n^{3}He are the first two recent statistically significant precision measurements in few nucleon systems.
- NSRIII (n^{4}He) provides additional, much needed, significant precision measurement in the NN weak sector.
- NSRIII collaboration has an apparatus nearing readiness for an n^{4}He spin rotation measurement at the level ~$[\pm 1.0(\text{stat}) \pm 1.0(\text{sys})]\times 10^{-8}$ rad/m.
- The critical path items are the LHe pump, LHe target, and radiation shielding
- NIST will announce the details of their restart plan in the next couple of weeks



ZOMBIES: An Experiment to measure nuclear anapole moments
David DeMille

ZOMBIES: an experiment to measure nuclear anapole moments

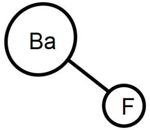
(and more)

- Nuclear anapole moment and hadronic parity violation
- Nuclear spin-dependent parity violation (NSD-PV) in atoms & molecules: nuclear anapole moment + semi-leptonic
- ZOMBIES approach using amplified NSD-PV effect in molecules
- Proof of principle with ^{19}F in BaF molecules
- Outlook

Dave DeMille
University of Chicago & Argonne National Laboratory

Dave DeMille: ZOMBIES: Nuclear spin-dependent parity violation in atoms and molecules (NSD-PV); Measure nuclear anapole moments and more

ZOMBIES I: NSD-PV with BaF



Initial physics goal: NSD-PV with ^{137}BaF

- Odd neutron (vs. ^{133}Cs w/odd proton)
- Heavy → large effect, anapole term dominates
- Large enough natural abundance 11%
- Required lasers = simple, cheap diodes

Completed: proof of principle using ^{138}Ba^{19}F

- Larger natural abundance (~75% vs ~11% for ^{137}Ba)
- Uses same beam source, lasers, magnet, etc. as ^{137}BaF
- $W(^{138}\text{Ba})$ = 0 Hz (no unpaired nucleons = no NSD-PV)
  $W(^{19}\text{F}) \approx$ 0.002 Hz $\approx$ 0 (light, small electron spin density in BaF)
- **Test for practical sensitivity & systematics with known answer**

Final Error Budget with ^{138}Ba^{19}F

Crossing	$W/(2\pi)$ (Hz)	C	d (Hz/(V/cm))	$W_{\text{mol}} = \kappa' W_P/(2\pi)$ (Hz)
A	$0.28 \pm 0.49_{\text{stat}} \pm 0.38_{\text{sys}}$	-0.41	3360	$-0.68 \pm 1.20_{\text{stat}} \pm 0.93_{\text{sys}}$
F	$0.01 \pm 0.51_{\text{stat}} \pm 0.38_{\text{sys}}$	+0.39	3530	$0.03 \pm 1.30_{\text{stat}} \pm 0.97_{\text{sys}}$
Weighted Average	-	-	-	$-0.36 \pm 0.88_{\text{stat}} \pm 0.95_{\text{sys}}$

~170 h data
~6x10^7 molecules total

$$W_{mol} = 2\pi \times (-0.36 \pm 1.29)\ \text{Hz}$$

- Proof of principle experiment in ^{138}Ba^{19}F saw expected null result
- Achieved precision adequate for anapole measurements on many nuclei, including lighter isotopes, with < 10% uncertainty

ZOMBIES: Summary & Outlook

--**New era in NSD-PV:** anapole + $V_e A_N$ measurements beginning

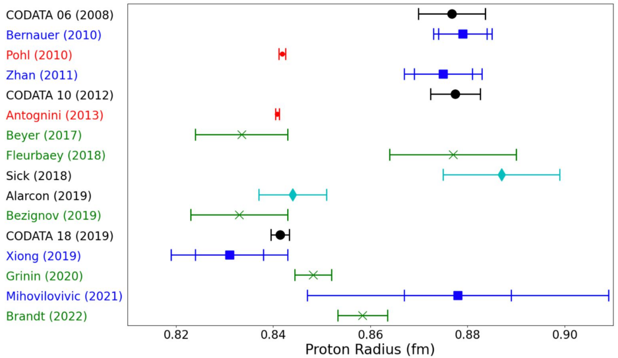
--Sensitivity & accuracy of molecular systems likely to **enable measurements on many nuclei, including lighter isotopes, with <10% uncertainty**

--Complementary to other hadronic PV experiments & SoLID/PVDIS @ JLab

--NSD-PV poised to open new window to unified understanding of hadronic PV & semileptonic neutral-current PV, in strongly-interacting environment, across wide range of scales

Proton Radius

MUSE and the Proton Radius Puzzle — Evangeline Downie



Proton Radius Puzzle Status (2022)

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC

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- MUSE in mixed μ/e/π PiM1 beamline of Paul Scherrer Institute
- Allows direct comparison of μ and e, cross sections, form factors
- Comparison of charge states, μ+/μ-, e+/e-, two photon effects
- Extraction of radii using e and μ in same experiment

MUSE

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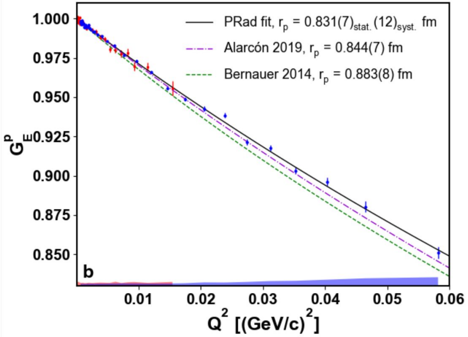
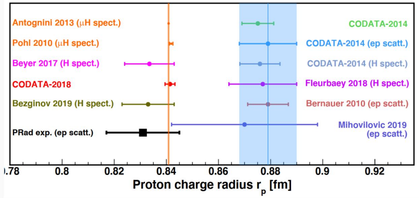
The PRad Experiment and the Proton Radius Puzzle — Tyler Hague



That's only one measurement and many others disagree

It also doesn't explain the disagreeing atomic spectroscopy results



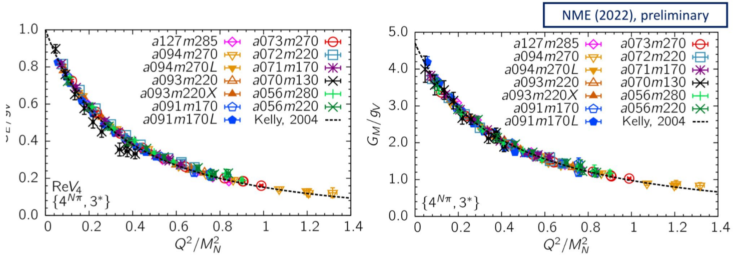
Next: **PRad-II**

Nearly 4x precision!

Lowest Q^2 ever recorded!

Lattice calculation of the proton charge radius — Sungwoo Park

G_E^{u-d} , G_M^{u-d} and Kelly parametrization



- Lattice data agree with the Kelly parametrization of the experimental data
- Errors in lattice data for G_E^{u-d} , G_M^{u-d} much (>10X) larger than experimental data

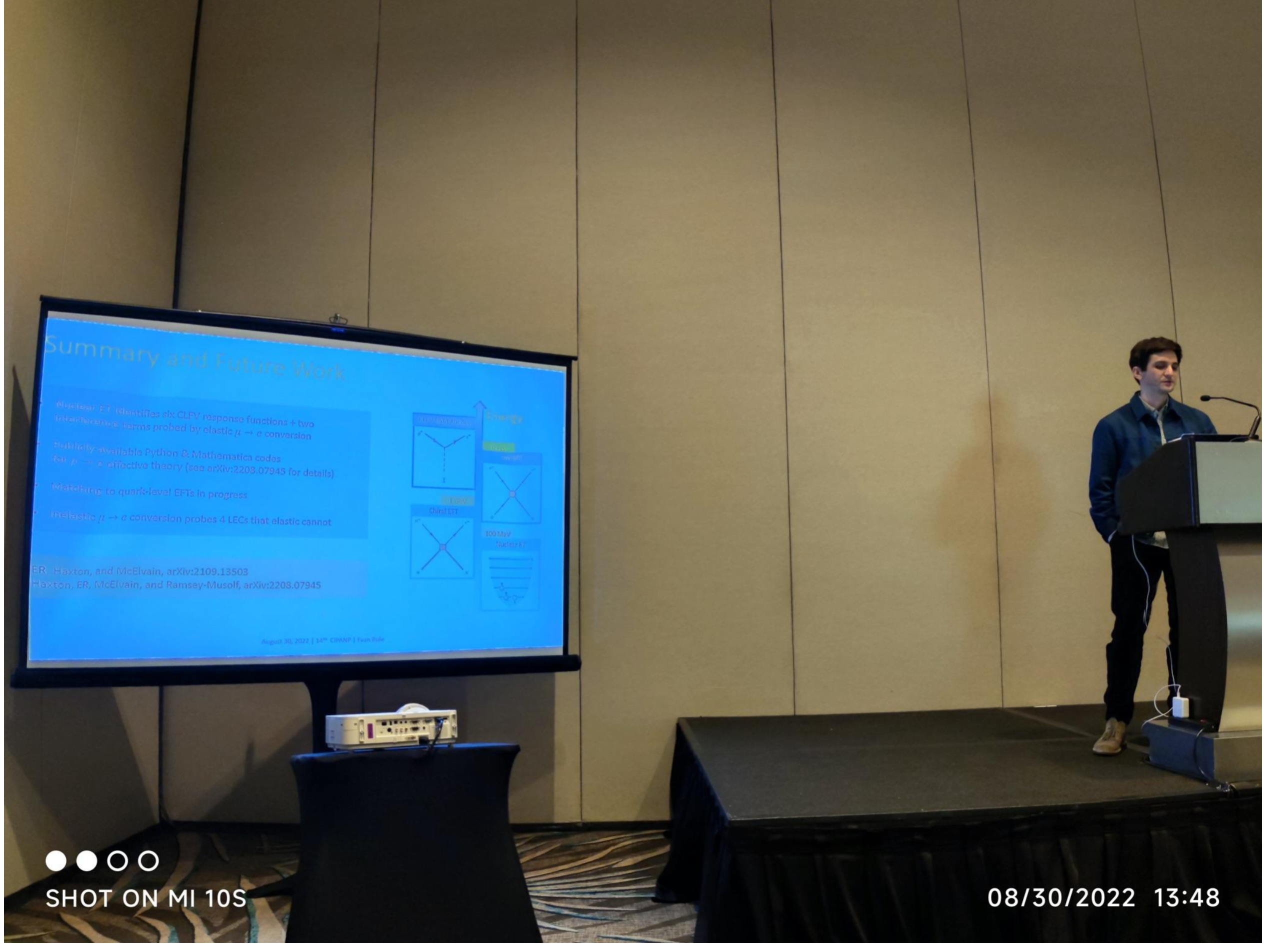
[J.J.Kelly, PRC 70, 068202 (2004)]

13 gauge ensembles generated by the Jlab/W&M/LANL/MIT collaborations with a range of the parameters

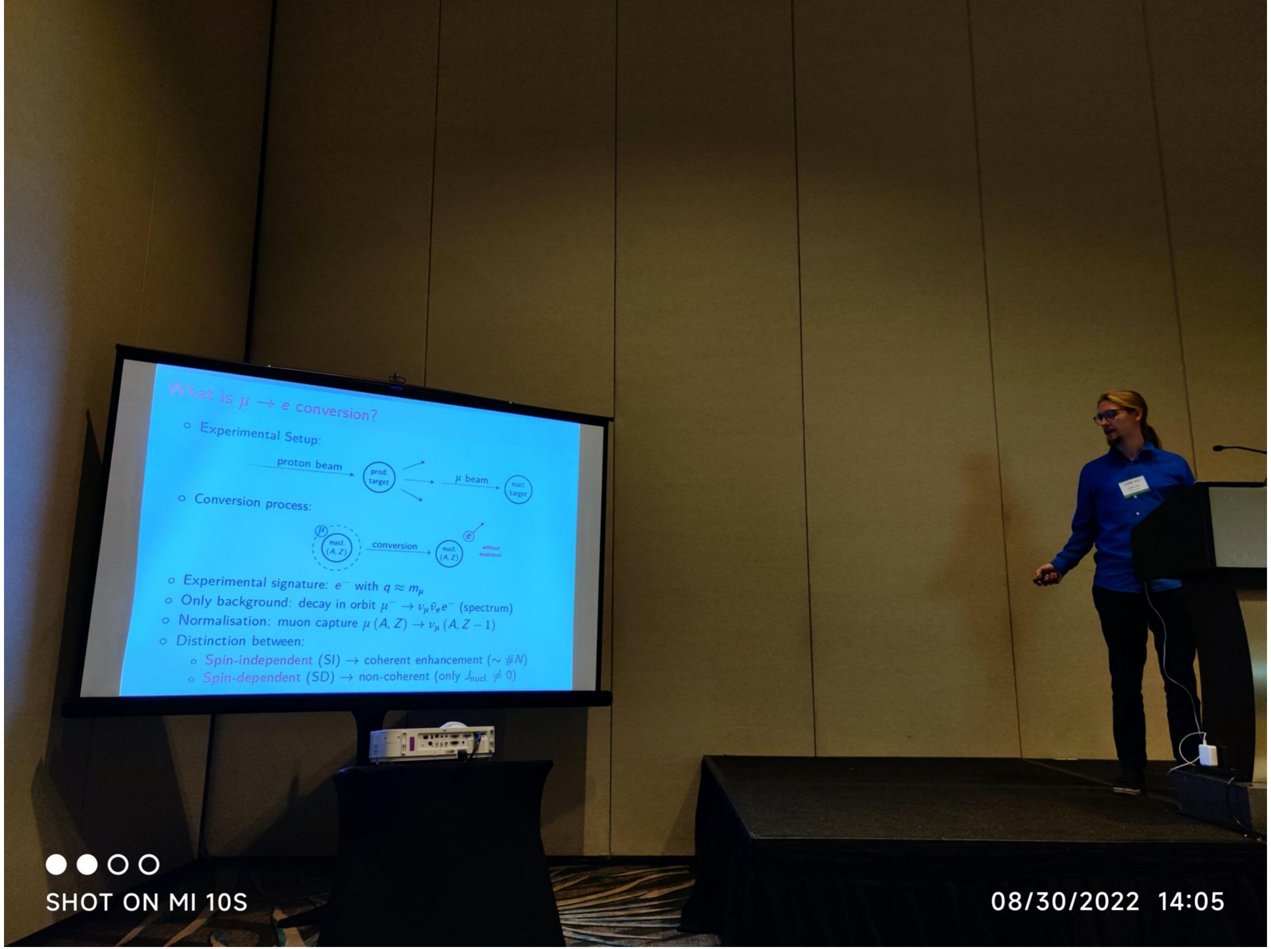
Thanks!

- We would like to thank all our speakers for accepting our invites!
- It has been a pleasure to help organize and convene the PPHI sessions and we thank the organizers for asking us to do that and for organizing the conference despite so much uncertainty, it has been a great success!

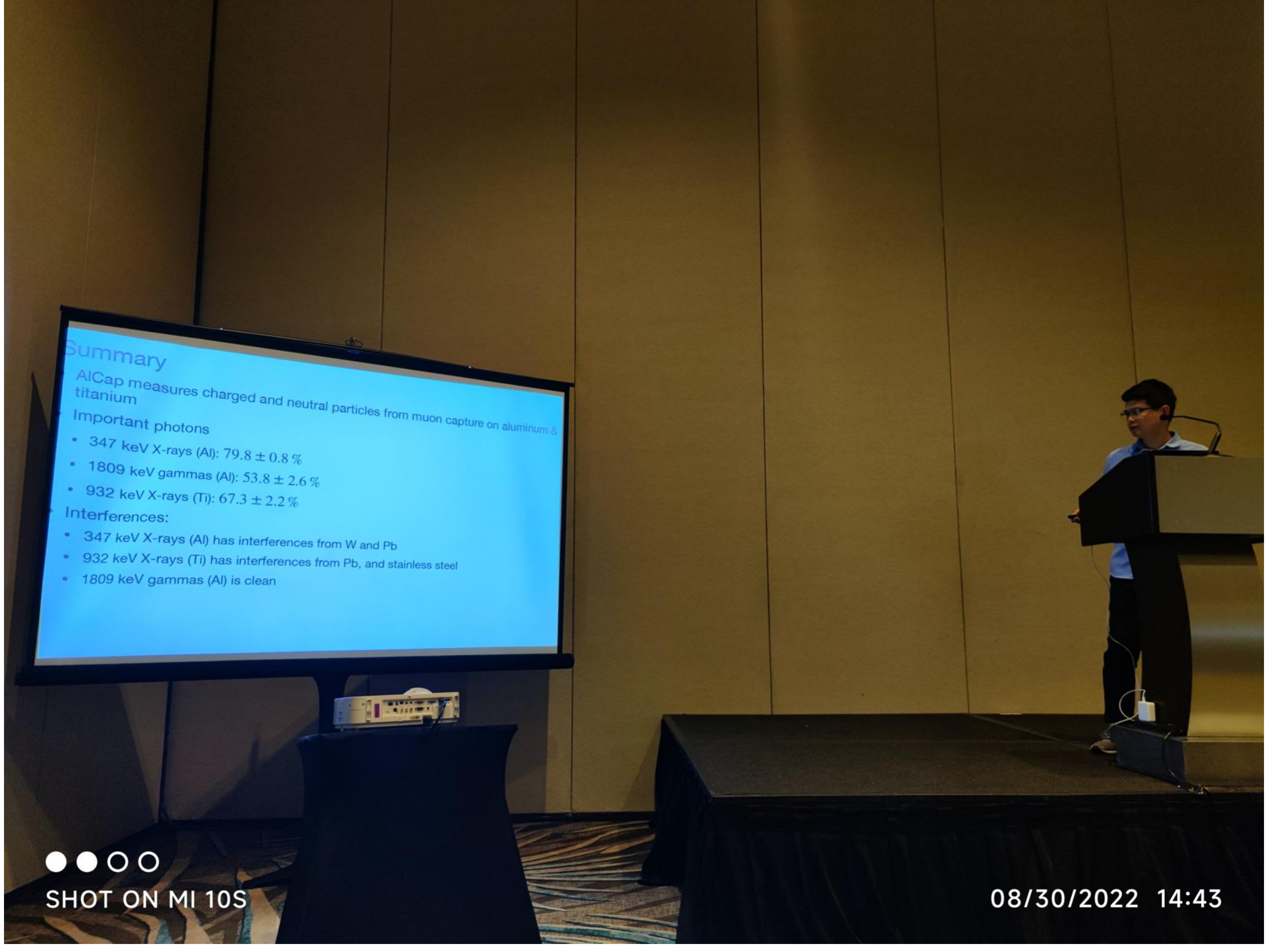
Patrick Schwendimann (University of Washington) - PIONEER: Precision measurements of rare pion decays



Evan Rule (UC Berkeley) - Nuclear Effective Theory of Muon-to-Electron Conversion



Frederic Noël (University of Bern) - Improved limits on lepton-violating decays of light pseudoscalars via spin-dependent mu -> e conversion in nuclei



Nam Tran (Boston University) - Measurements of muonic X-rays and gammas from Al and Ti

Alexey Petrov (University of South Carolina) - Muonium-antimuonium oscillations

Kyun Woo (Chris) Hong (University of Virginia) - E989 muon g-2; The Magnetic Field Measurement and Systematics

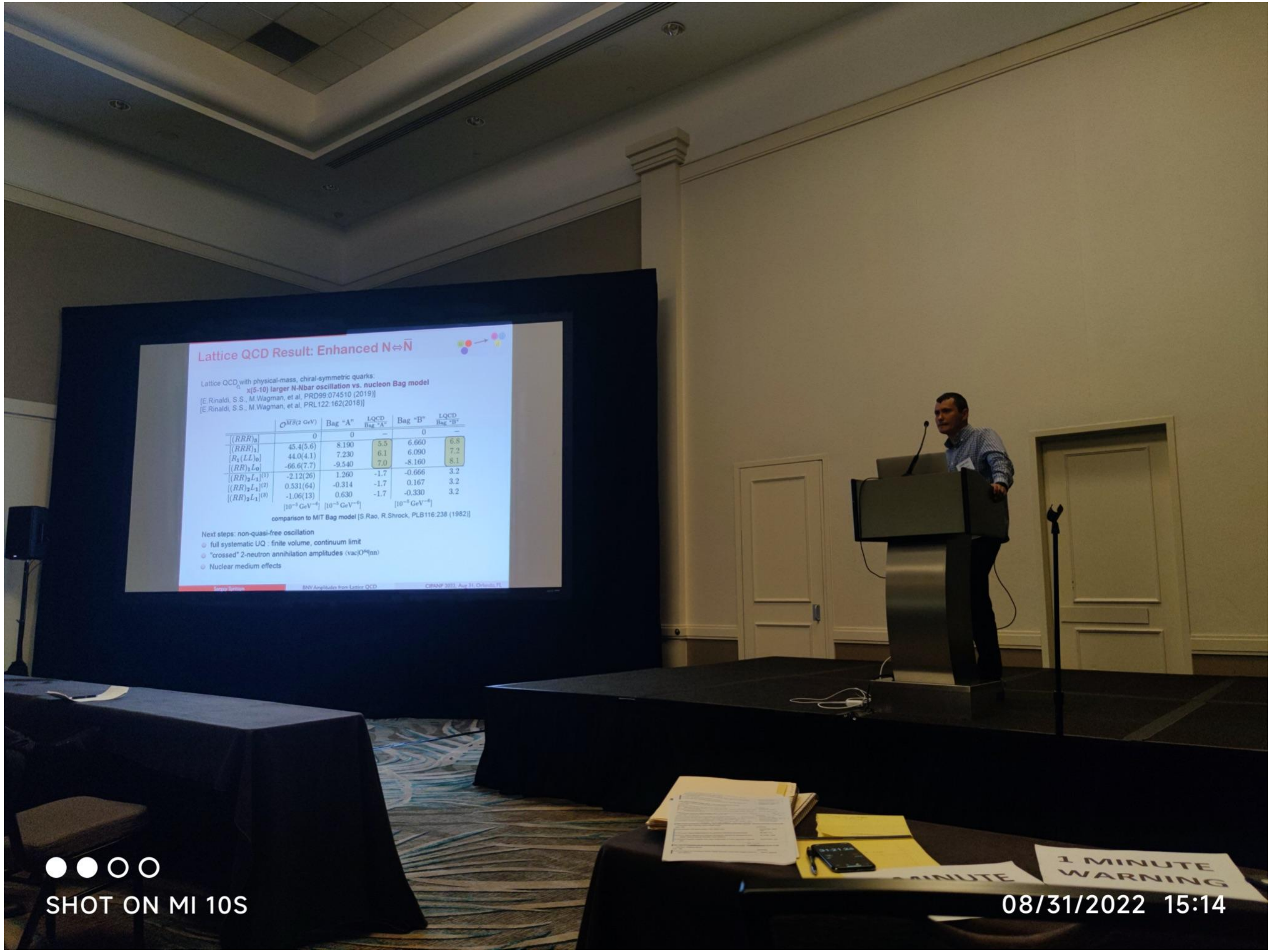
Yutaro Sato (Nigata University) - presented remotely - J-PARC muon g-2/EDM experiment

Kalman Szabo (Forschungszentrum Julich & University of Wuppertal) - Hadron Vacuum Polarizaton from lattice QCD

Michael Doser (CERN) - Pulsed production of antihydrogen in the AEgIS experiment

Will Bertsche (U. Manchester) - Precision Studies with Trapped Antihydrogen

Leah Broussard (ORNL) - Searches for neutron oscillations with HIBEAM and NNBAR



Sergey Syritsyn (Stony Brook U.) - Baryon number-violating amplitudes on a lattice

Matt Citron (UC Santa Barbara) - Future LHC Based Dark Sector Searches

Matthew Solt (University of Virginia) - Dark Matter at Accelerators - The Heavy Photon Search and the Light Dark Matter eXperiment

Bertrand Echenard (Caltech) - Dark Sector Searches at BaBar

Oliver Jevons (University of Glasgow) - APEX: A Dark Matter Search at Jefferson Lab Hall A

Allison Zec (University of New Hampshire) - Neutral Weak Form Factor Measurements from the PREX-II and CREX Experiments

Devi Adhikari (Virginia Tech) - Parity-Violating Electron Scattering as a Test of the Standard Model

Murad Sarsour (Georgia State University) - Neutron Measurements to Probe the Hadronic Weak Interaction

Dave DeMille (University of Chicago and Argonne National Lab) - ZOMBIES: an experiment to measure nuclear anapole moments

Evie Downie (George Washington University) - presented remotely - The MUSE Experiment and the Proton Radius Puzzle

Tyler Hague (Berkeley Lab) - The PRad experiment and the Proton Radius Puzzle

Sungwoo Park (Jefferson Lab) - Lattice calculation of the proton charge radius