Electroweak and Precision Physics: Experimental Review (less EDMs and PVES)

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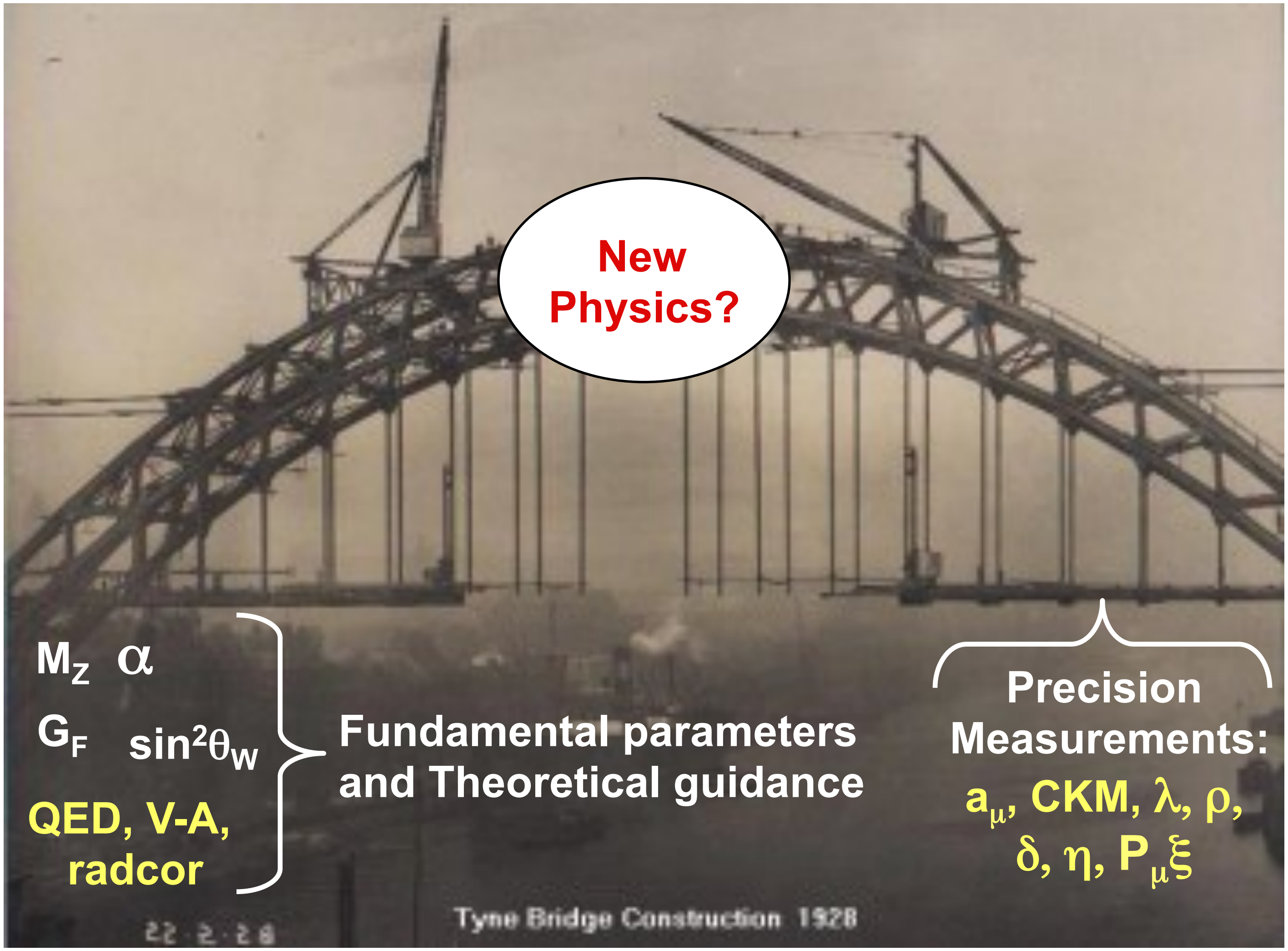
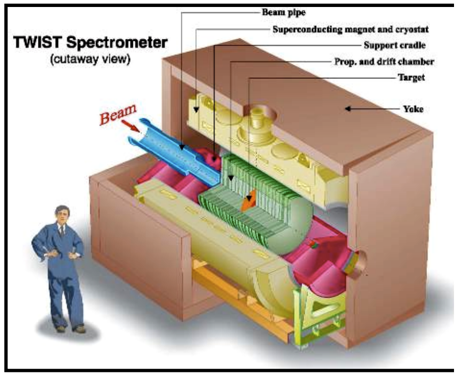
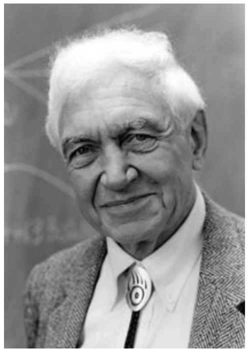


Workshop on Fundamental Symmetries and Neutrinos

very Recent, Present and Future Projects Worldwide

- **Muons**
  - **Lifetime: Fermi constant**
    - **MuLan:** Status: complete $\delta\tau_{\mu}$ = 1.0 ppm; δG_F = 0.5 ppm
  - **Decay: Michel parameters**
    - **TWIST:** Status: complete $\rho, \delta, \eta, P_{\mu}\xi$
  - **Capture: fundamental hadronic parameters**
    - **MuCap (g_P)** Status: complete δg_P = 7%
    - **MuSun (L1a)** Status: data taking
  - **Anomalous magnetic moment**
    - **g-2** Status: ~CD0; design and construction
    - **EDM** Status: parasitic to g-2
  - **Charged Lepton Flavor Violation**
    - **MEG ($\mu \rightarrow e\gamma$)** Status: BR < 10^{-12}; data taking; upgrade plans
    - **Mu2e ($\mu A \rightarrow eA$)** Status: CD-1; design and construction
    - **COMET ($\mu A \rightarrow eA$)** Status: in design, approved for phase 1





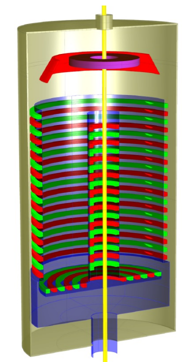
very Recent, Present and Future Projects Worldwide

- **Pions**
  - Lepton universality: $\pi \rightarrow e\nu$
    - PEN Status: data taking complete; analysis in progress
    - PIENU Status: data taking

- **Proton** **(or Deuterons)**
  - EDM in storage ring
    - Julich Status: deuteron pre-cursor proposal to $d_d \sim 10^{-24}$ ecm
    - BNL Status: proton proposal developed to $d_p < 10^{-29}$ ecm

- **Dark Photons**
  - APEX (Hall A) Status: test run published
  - HPS (Hall B) Status: tested with photon beam
  - DarkLight (FEL) Status: test run complete

very Recent, Present and Future Projects Worldwide



- **Neutrons**
  - **Lifetime**
    - NIST – beam technique Status: In progress
    - LANSE – Ultracold traps Status: planning
    - Munich – magneto-grav trap Status: construction
  - **Decay parameters (many efforts)**
    - PERKEO II ("big A") Status: complete (2012) $\delta A/A \sim 5x10^{-4}$
    - UCNA ("big A") Status: complete (2012) and future running
    - aCORN ("little a") Status: in progress
    - N_{ab} ("little a, little b") Status: in construction

- **Nuclei** **(incomplete)**
  - **0+ → 0+**
    - Many new results Status: complete, but new set of nuclei
  - **He-6 System**
    - Lifetime Status: complete $\delta\tau_{He\text{-}6} = 3x10^{-4}$
    - e-ν correlation ("little a") Status: in progress
    - E spectrum ("little b") Status: planning
  - **Paul Trap at ANL**
    - **^{8}B and ^{8}Li** Status: data taking on Li complete. B planning

Precision Physics and Beyond the Standard Model Exploration: An example (of course, quite speculative and not implied as true)

- **We often claim the low-energy observables (both limits and signals) will be part of the conversation and interpretation of, say, LHC results**

Correlation between the Higgs Decay Rate to Two Photons and the Muon $g-2$

Gian F. Giudice[a], Paride Paradisi[a] and Alessandro Strumia[a,b]

arXiv:1207.6393v1

Post Higgs paper
(others exist too)

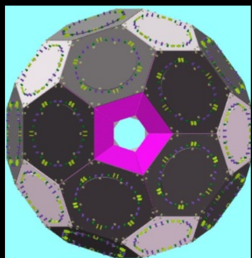
- Observations at the LHC
  - **production rate is too high by ~40-50%**
  - **Higgs rates in ZZ* and WW* are consistent with the SM**

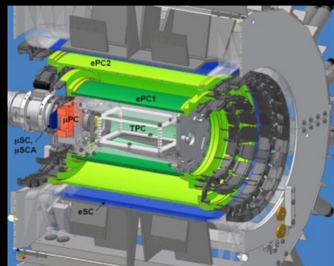
- Theoretical SUSY model that fits observations
  - **light stau with large left-right mixing**
  - **light Bino**
  - **heavy higgsinos**

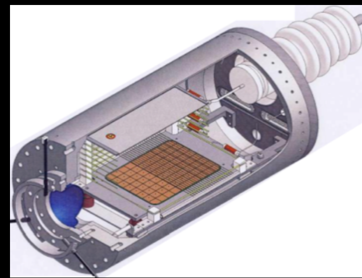
- Other consequences
  - ✓ **Predicts Muon Anomaly exactly** — **Low-energy**
  - ✓ **Compatible with thermal dark matter** — **Low-energy**
  - ✓ **Predicts small deviations in $h \to \gamma Z$ and $h \to \tau\tau$** — **Collider**
  - ✓ **Predicts measureable violations of Lepton Non-Universality in $\tau-\mu$ and τ-e** — **Belle-II**
  - ✓ **Predicts NO violation in the μ-e sector** — **Low-energy**

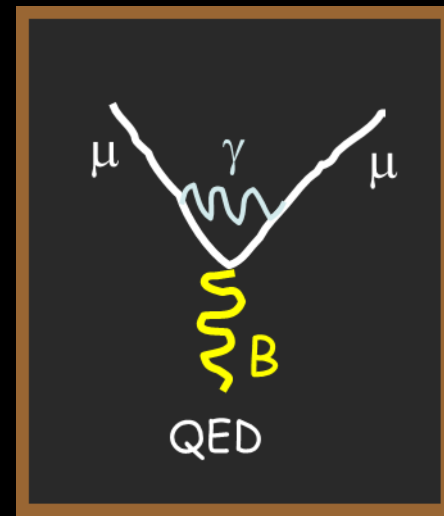
Chapter 1: Muons

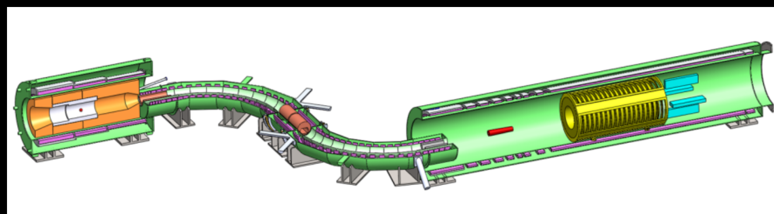
(well) Beyond Schwinger

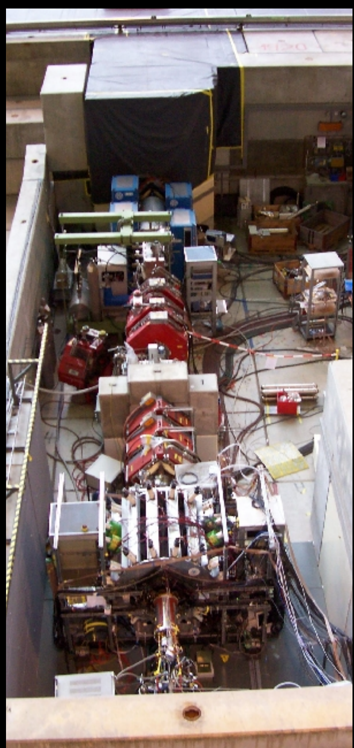










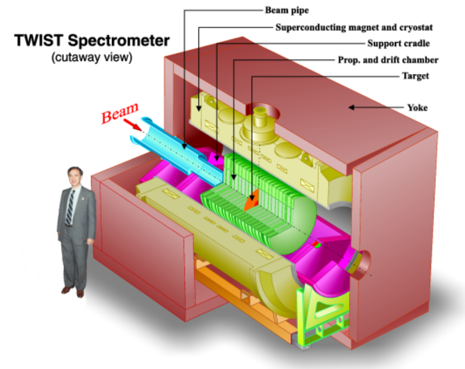


2010: Michel Parameter / Muon Decay: TWIST

ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

$\mathcal{P}_\mu{}^\pi\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)



Results mostly constrain right-handed muon terms

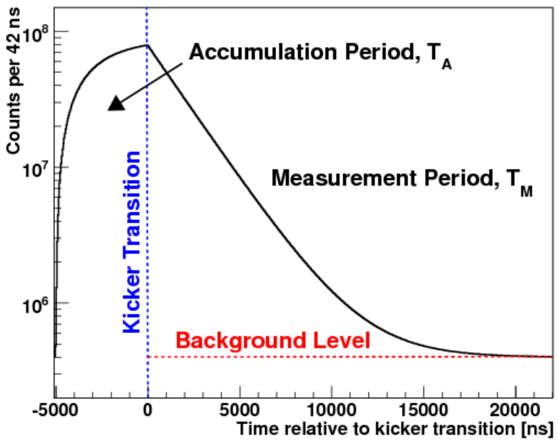
- summary of all terms (pre-*TWIST* in parentheses)

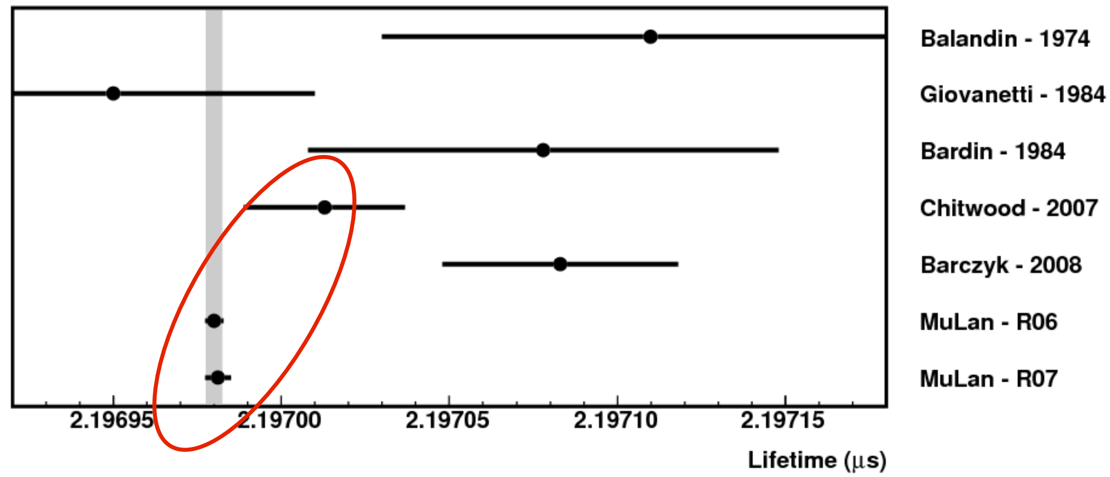
$\lvert g^S_{RR}\rvert < 0.035\ (0.066)$	$\lvert g^V_{RR}\rvert < 0.017\ (0.033)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.050\ (0.125)$	$\lvert g^V_{LR}\rvert < 0.023\ (0.060)$	$\lvert g^T_{LR}\rvert < 0.015\ (0.036)$
$\lvert g^S_{RL}\rvert < 0.420\ (0.424)$	$\lvert g^V_{RL}\rvert < 0.105\ (0.110)$	$\lvert g^T_{RL}\rvert < 0.105\ (0.122)$
$\lvert g^S_{LL}\rvert < 0.550\ (0.550)$	$\lvert g^V_{LL}\rvert > 0.960\ (0.960)$	$\lvert g^T_{LL}\rvert \equiv 0$

$$\begin{aligned} Q^\mu_R &= \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RR}|^2 + |g^V_{LR}|^2 + |g^V_{RR}|^2 + 3|g^T_{LR}|^2 \\ &= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\ &< 8.2 \times 10^{-4} \quad (90\%\text{C.L.}) \end{aligned}$$

A. Hillairet et al., Phys. Rev. D 85, 092013 (2012)

2011: Muon lifetime / Fermi constant: MuLan*





The most precise particle or nuclear or atomic lifetime ever measured

τ(MuLan) = 2 196 980.3 ± 2.2 ps (1.0 ppm)

$\Delta\tau$(R07 – R06) = 1.3 ps

G_F(MuLan) = 1.166 378 75(62) x 10^{-5} GeV^{-2} (0.5 ppm)

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Weak Nuclear Force Is Less Weak

New insights from subatomic particles that fly apart.

Jan 12, 2011

By Phillip F. Schewe
Inside Science News Service

(ISNS) -- The force that governs some of the reactions that keep our sun shining is not quite as weak as scientists had previously thought. As a consequence, our estimation of how energetic the sun actually is just went up by a tiny amount.

The evidence for this weak nuclear force comes from the decay of muons, essentially heavier cousins of the electron, one of the building blocks of atoms.

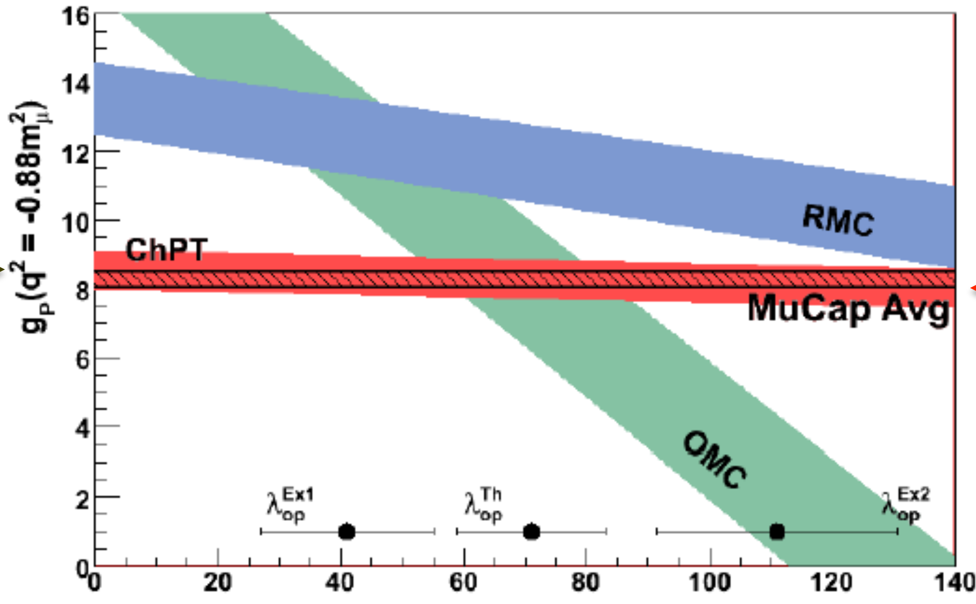
Just as biologists sometimes study the tiniest and most

View full-size image

*US led effort at PSI

2012: Muon Capture on Proton: MuCap*

Measured: $\Lambda_S = (714.9 \pm 5{:}4_{stat} \pm 5{:}0_{syst})\ s^{-1}$



g_P as a function of the molecular transition rate, λ_{op}.

Determined: $g_P\ (MuCap) = 8.04 \pm 0.56$

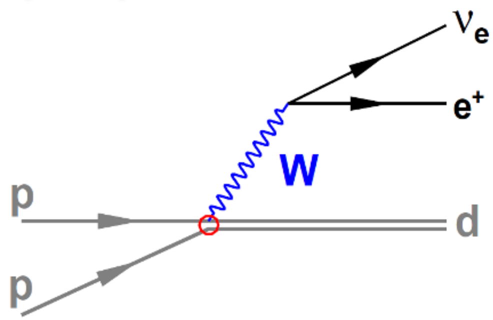
Compare to: $g_P\ (Theory) = 8.26 \pm 0.23$

First unambiguous determination of g_P and clarification of long-standing puzzle between fundamental QCD-based prediction and expt.

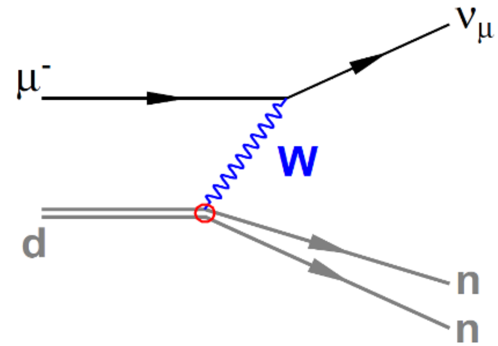
***US led effort at PSI**

2012-14: Muon Capture on Deuteron: MuSun*

$p + p \rightarrow d + e^+ + \nu$



$\mu^- + d \rightarrow \nu + n + n$



Several fundamental astrophysics processes depend on weak interaction in deuterium

Basic solar fusion: $p + p \rightarrow d + e^+ + \nu$

Sudbury Neutrino Observatory: $\nu_e + d \rightarrow p + p + e^-$ (CC)

$\nu_x + d \rightarrow p + n + \nu_x$ (NC)

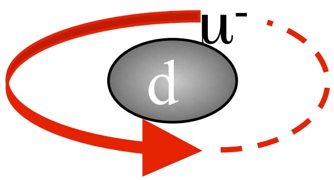
Tiny cross sections, predictions rely on theory

Idea: replace e^- by μ^-, calibrate in muon capture reaction

***US led effort at PSI**

model-independent connection via EFT

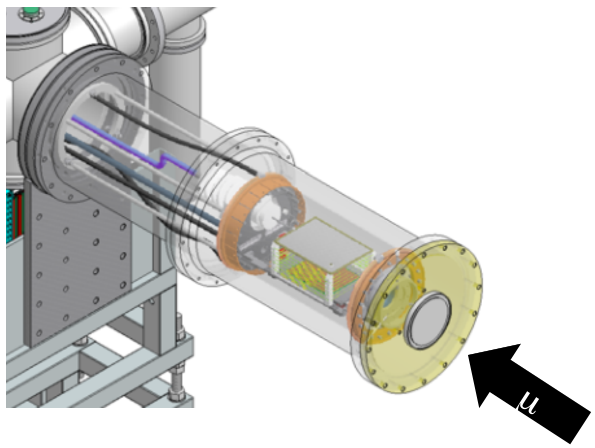
Capture rate is deduced from μ^+/μ^- lifetime difference

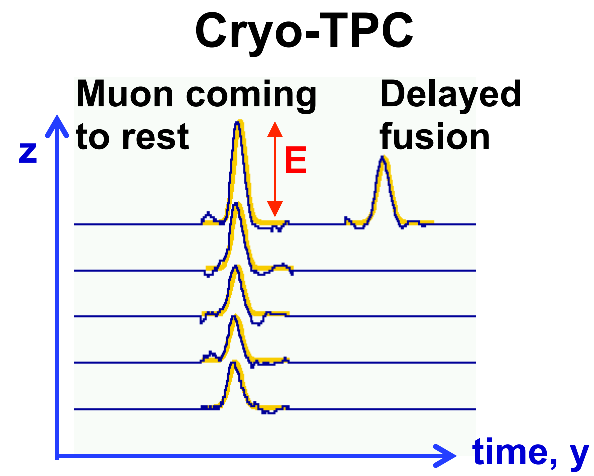


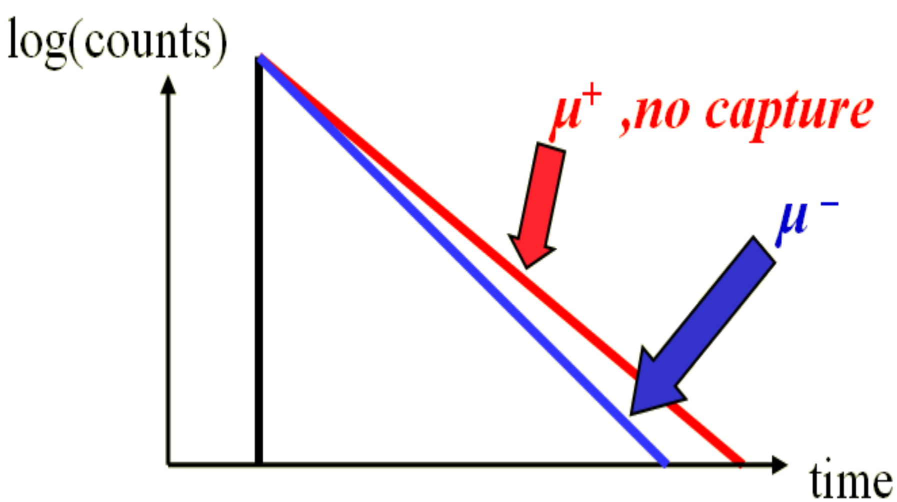
Muon forms atom, overlap with nucleus enhanced.

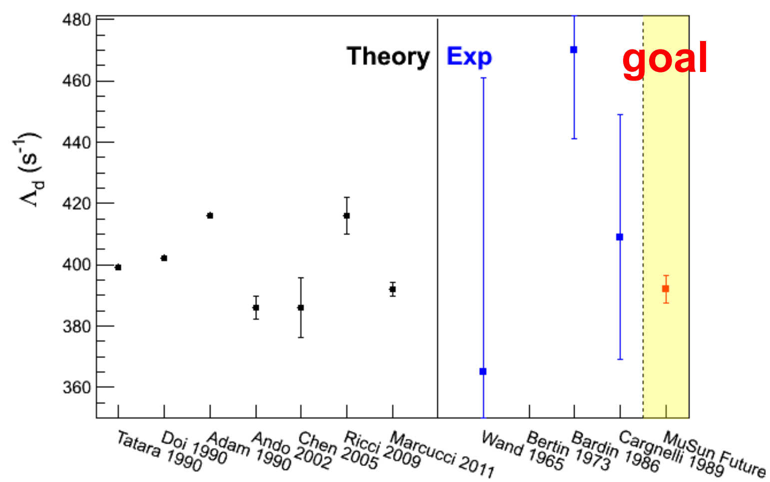
Short range EW interaction leads to small, but **observable** rate.

$\mu^- + d \rightarrow \nu + n + n$ (~0.1% compared to decay)





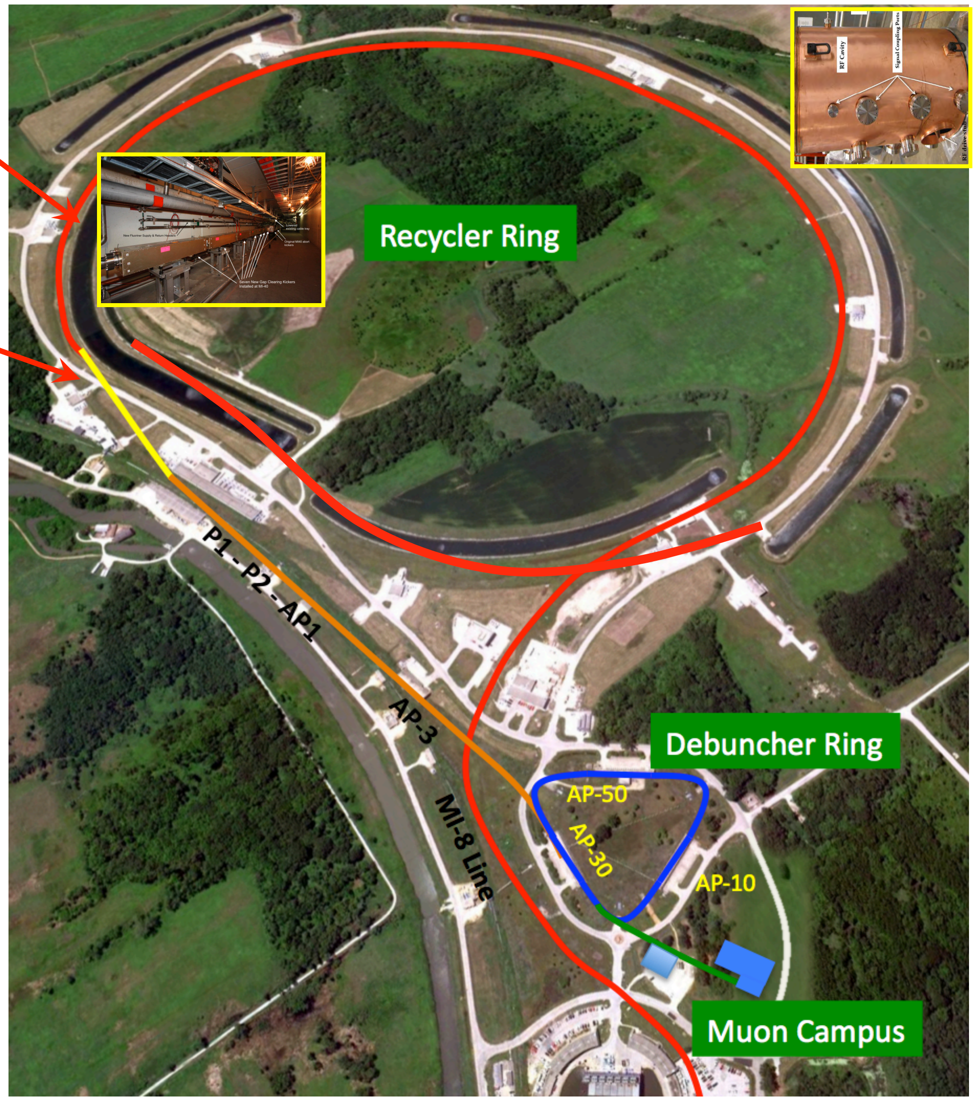




Existing FNAL accelerator complex, with suitable mods, will deliver muons for g-2, Mu2e and EDM

Extraction kicker

Recycler Ring to P1 connection



Newly installed 2.5 MHz RF

For g-2, achieves

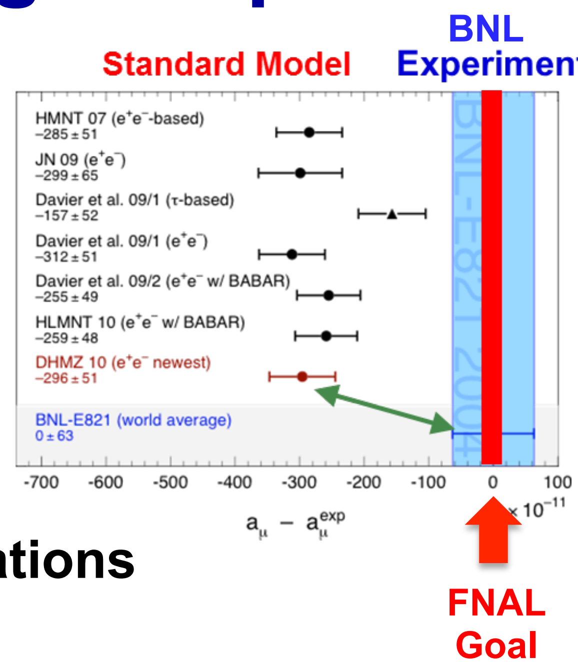
1) LONG decay channel
2) Rapid ring cycle
3) No hadronic flash

For Mu2e, achieves

1) Ideal timing of proton bunches for mu formation
2) High intensity

New customized buildings

2016-19 Muon Anomaly: The g-2 Experiment*



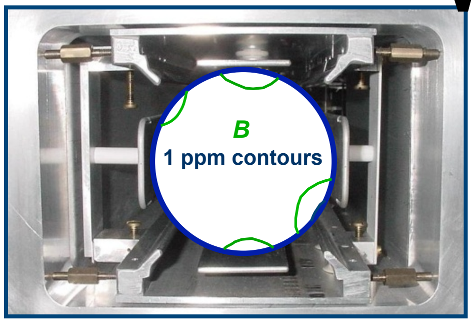
What is nature trying to tell us?

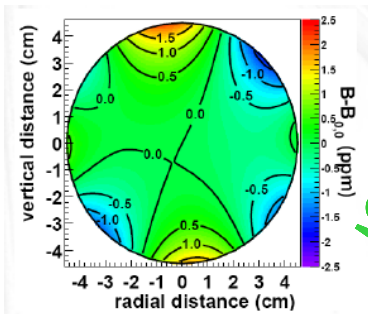
- **Magnitude and sign have important implications**
- **1-D UED models predict "tiny" effects**
- **SUSY models – many predict large contributions as observed**
- **The "Uninvented" – sets a stringent experimental constraints for any new models, together with other low- and high-energy data**

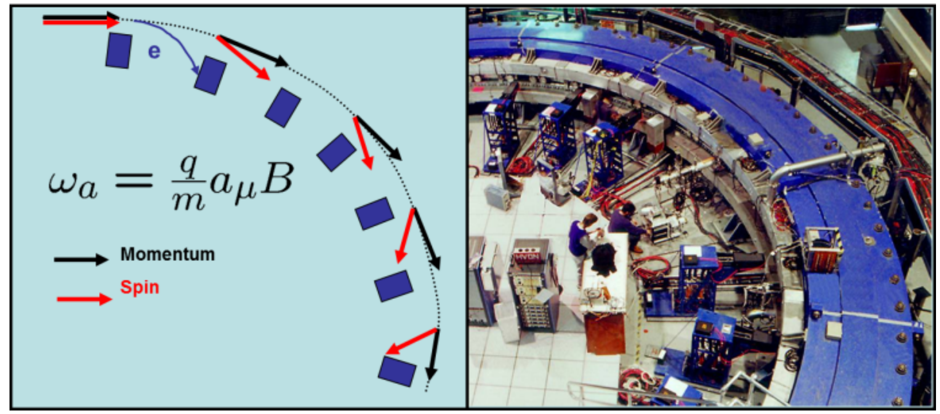
Last g-2 experimental results have > 2000 citations.
It's highly relevant in helping shape the New Standard Model we hope to discover

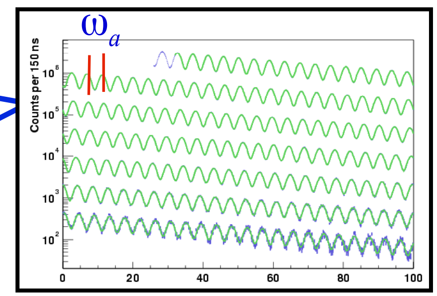
Method*

The anomaly is obtained from three well-measured quantities



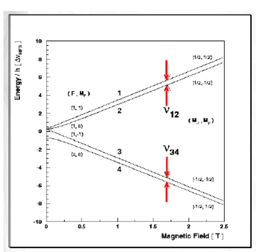






ω_p

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$



μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

***Nuclear / Particle / Atomic / Accelerator collaboration at Fermilab**

Method and Goal

- Build on a proven technique
- Use existing unique storage ring
- Obtain more muons
- Control systematic errors
- New team built from E821 experts, augmented by significant new

GOAL

Experimental uncertainty: 63 → 16×10^{-11}

0.1 ppm statistical

0.1 ppm systematic

Theory uncertainty: 51 → 30×10^{-11}

Future: Δa_{μ}(Expt – Thy) = xx ± 34×10^{-11}

(If xx remains 296, the deviation from zero would be close to 9σ)

U.S. Nuclear Physics & g-2

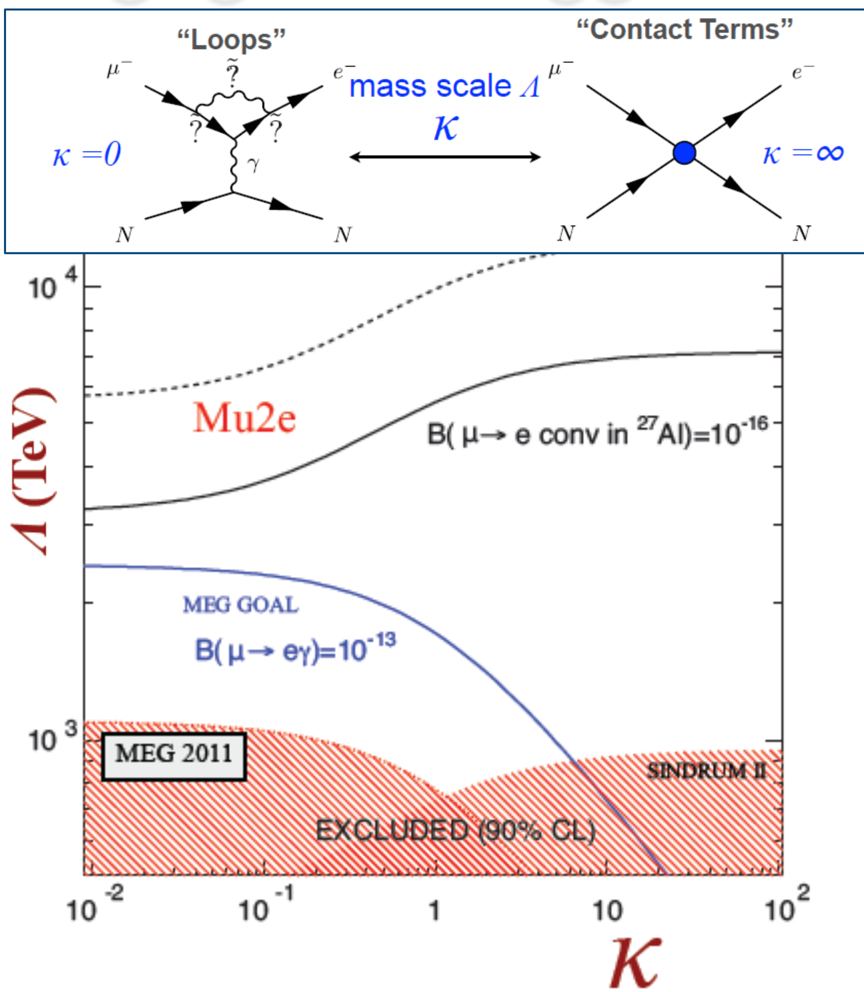
- Boston University
- James Madison University
- Regis University
- Univ. Kentucky
- Univ. Massachusetts
- Univ. Michigan
- Univ. Virginia
- Univ. Washington
- Both co-spokespersons are supported by Nuclear Physics (NSF and DOE)
- Project Manager got his Ph.D. in a NSF nuclear physics funded group

Seeking Nuclear Physics NSF MRI support at about $4M for Detectors, Electronics, DAQ
(basically the ω_a measurement)

2019→? Muon-to-Electron Conversion: Mu2e*

Physics Motivation: If you see this, it's BSM!

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa + 1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

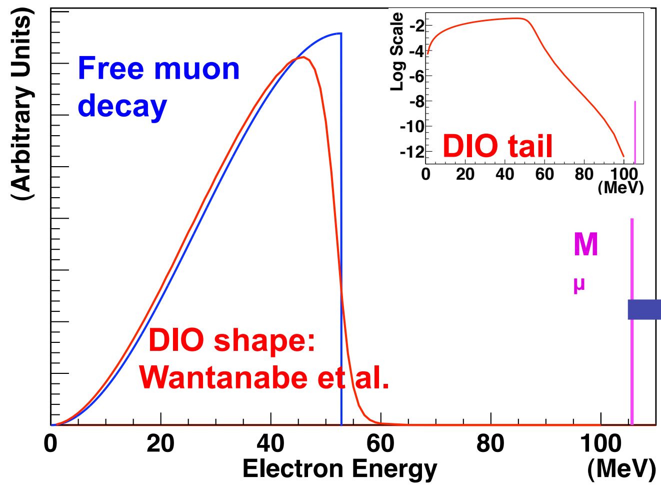


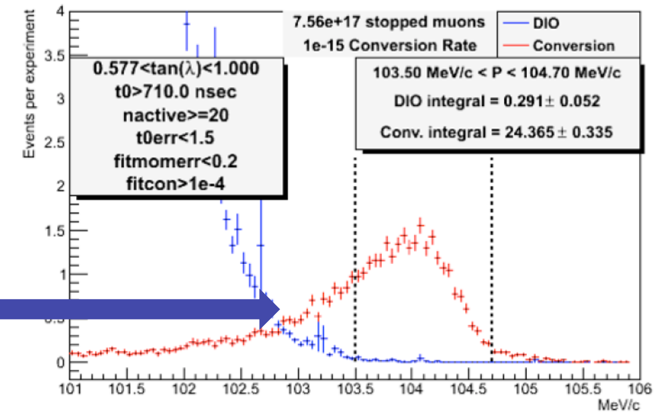
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A, Z-1))}$$

*Nuclear / Particle / Accelerator collaboration at Fermilab

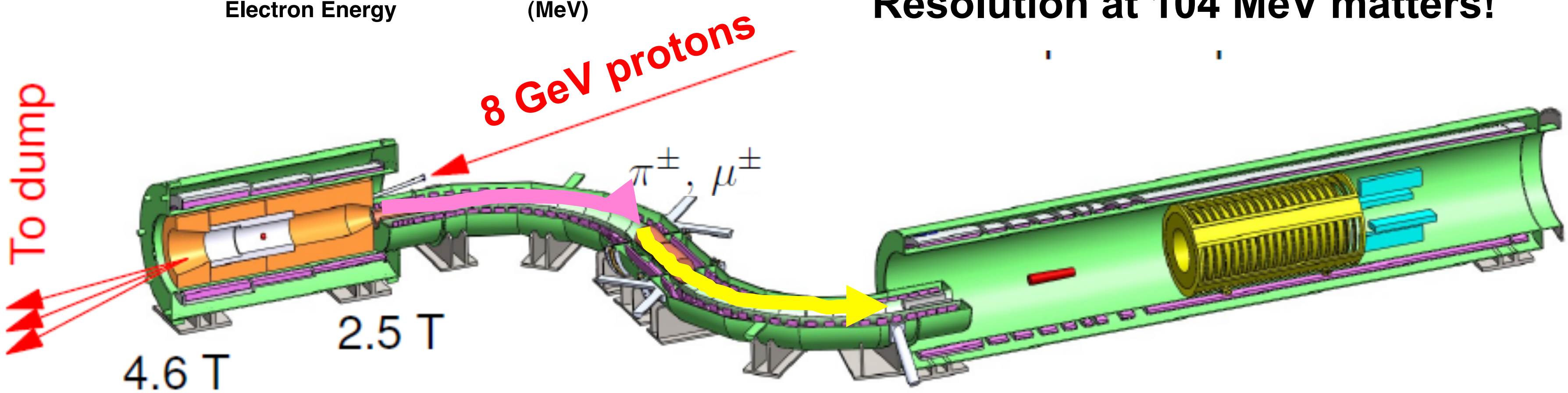
Method and Goal (has CD1)

- Make muonic Al: 40% will decay "in orbit"; 60% will capture (junk emitted)
- Look for mono-energetic e^-, at muon mass
- Avoid backgrounds: Goal single event sensitivity $< 2 \times 10^{-17}$



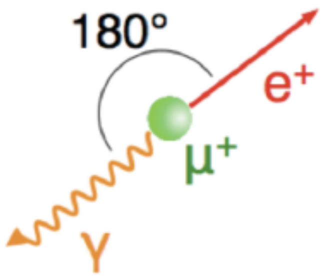


Resolution at 104 MeV matters!



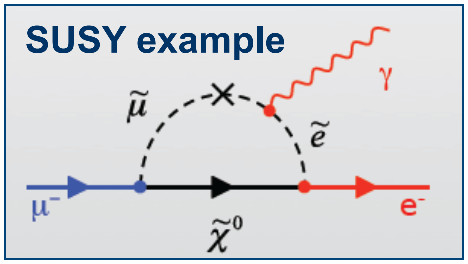
International Competition here …

MEG (PSI): $\mu \rightarrow e\gamma$



2011: BR($\mu \rightarrow e\gamma$) < 2.4 x 10^{-12} @ 90%C.
5 times better than previous

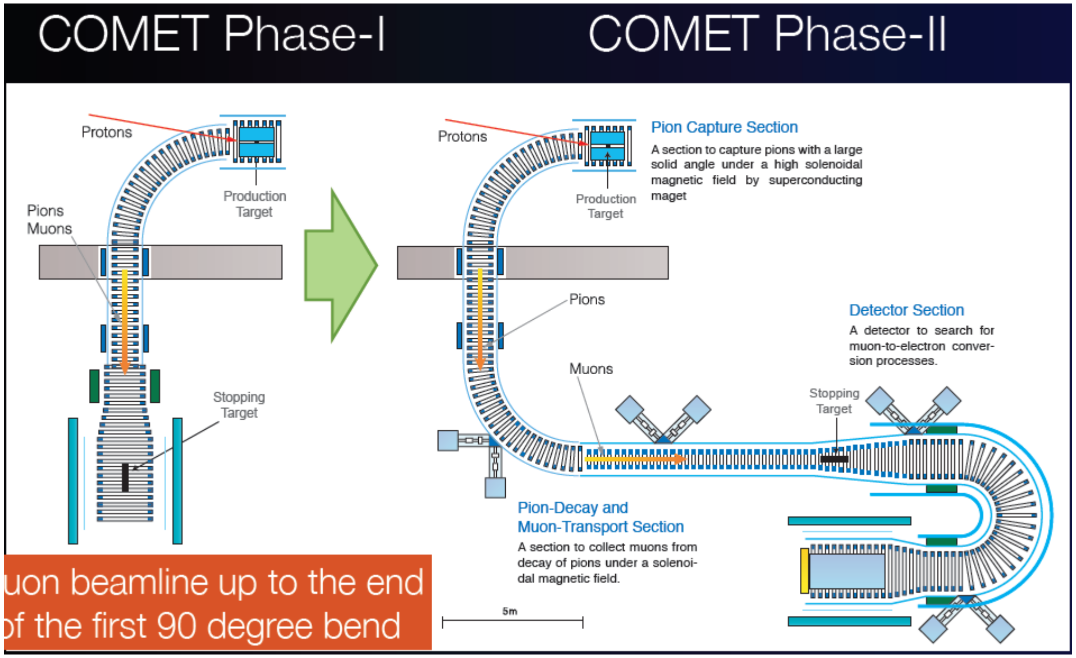
Future: Expect to push 10^{-13}



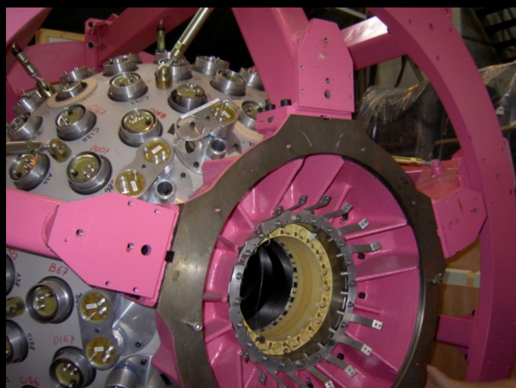
Signal is back-to-back 53 MeV γ and e^+ from muons at rest

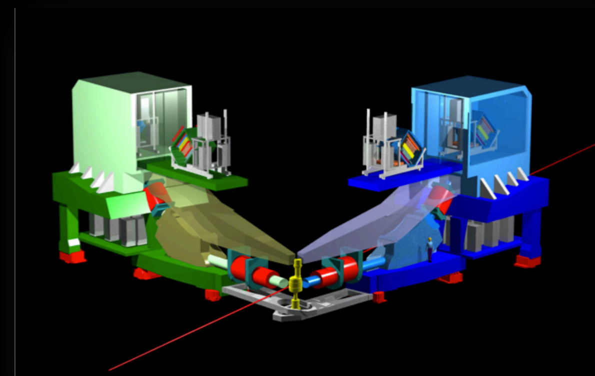
COMET (JPARC): $\mu \rightarrow e$

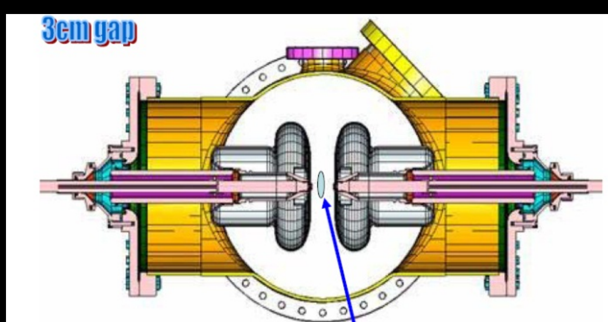
- Similar technique as Mu2e
- Staged approach.
- Approved for Phase-1
  - Sensitivity: < 7x10^{-15}
- Full phase later
  - Sensitivity: 2.6 x 10^{-12}



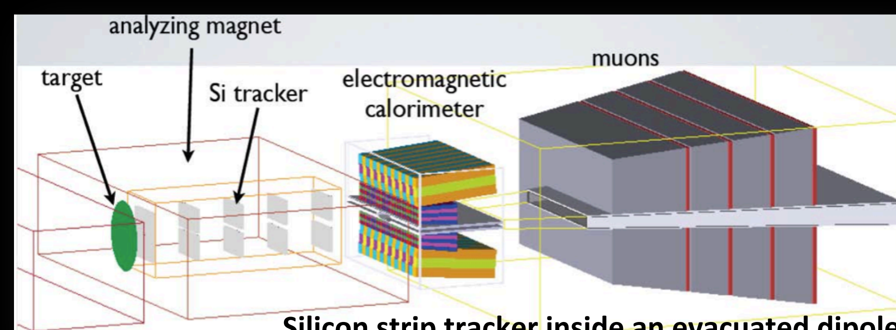
Chapter 2: Pions, Protons and Photons







A' ?



for excellent vtx & mom resolution

2012+ $\pi \rightarrow e\nu$: Lepton Universality: PEN*, PiENu**

$$B_{\text{calc}} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{calc} = \begin{cases} 1.2352\,(5) \times 10^{-4} \\ 1.2354\,(2) \times 10^{-4} \\ 1.2352\,(1) \times 10^{-4} \end{cases}$$

Current Expt. World Avg. $= (1.230 \pm 0.004) \times 10^{-4}$

PEN, PiENu aim at: $\dfrac{\delta B}{B} \simeq 5 \times 10^{-4}$

PEN data taking complete. Analysis in progress

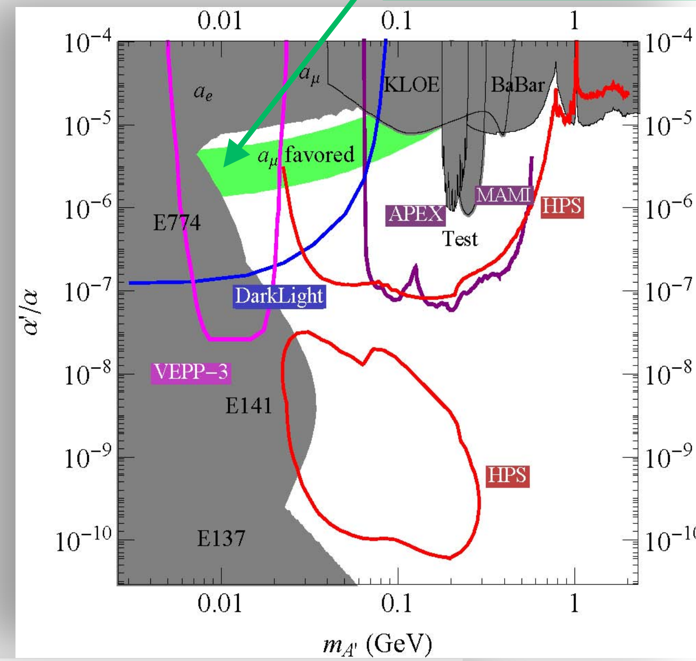
PiENu data taking

***at PSI** ****at TRIUMF**

2010 → … Dark Photon searches: @JLab

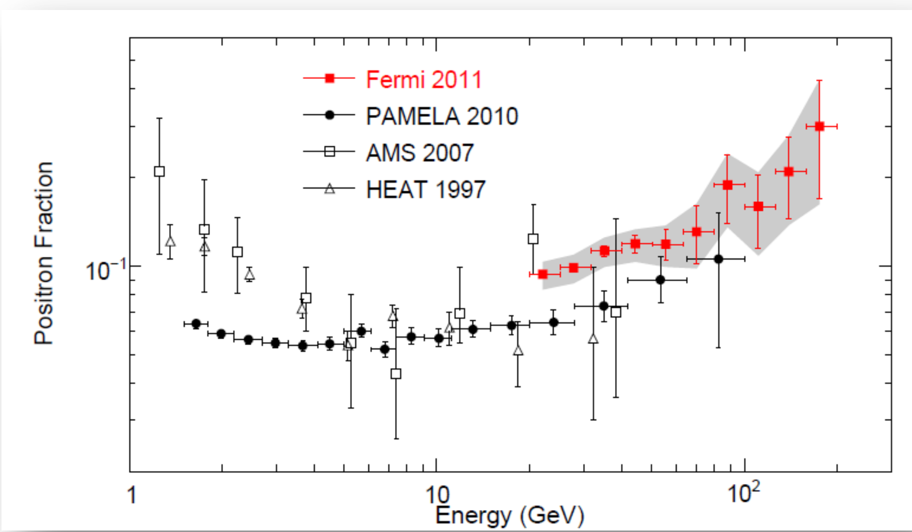
- **A’, a massive neutral vector boson**
  - kinematically mixes with γ
  - $\alpha' = \varepsilon\alpha_{e.m}$ $\varepsilon = 10^{-2} - 10^{-6}$
  - Mass in the **MeV-GeV** region

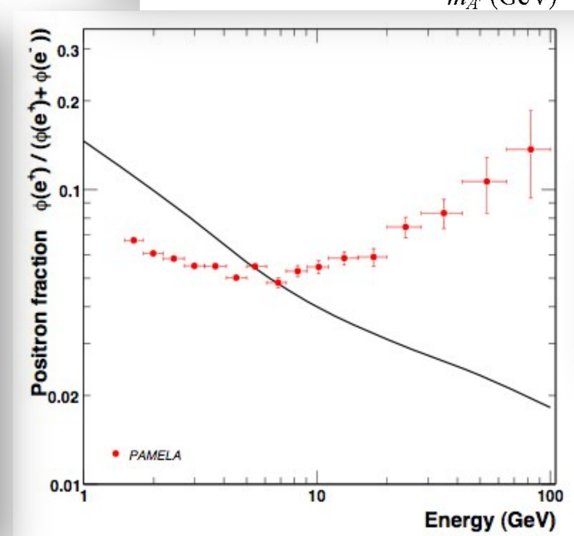
g – 2 preferred

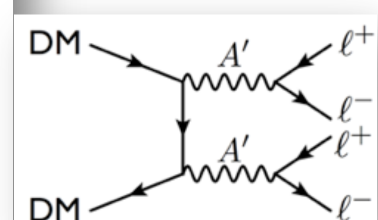


- **Can explain g-2 discrepancy**

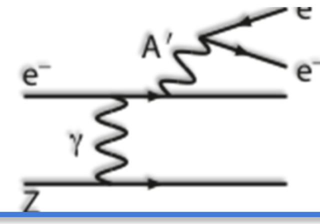
- **Can explain cosmic positron data**



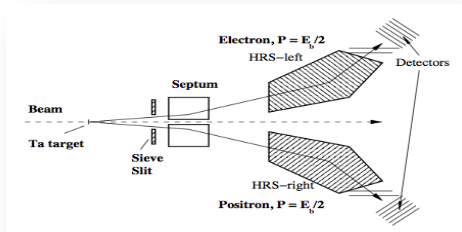


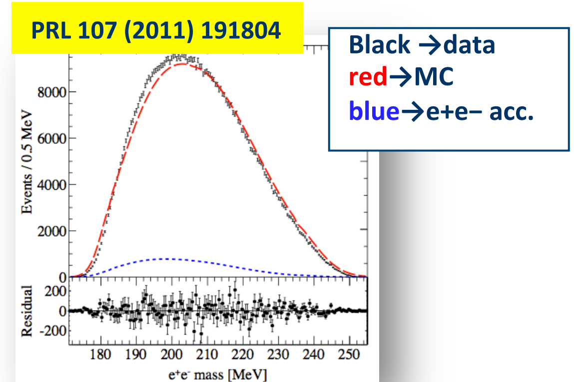


Method: Produce **A'** with electron beam
Detect pair decays (narrow peak above background)



APEX in Hall A





Heavy Photon Search @ Hall B

Physics reach: ε < 10^{-4}; mass 20-800 MeV

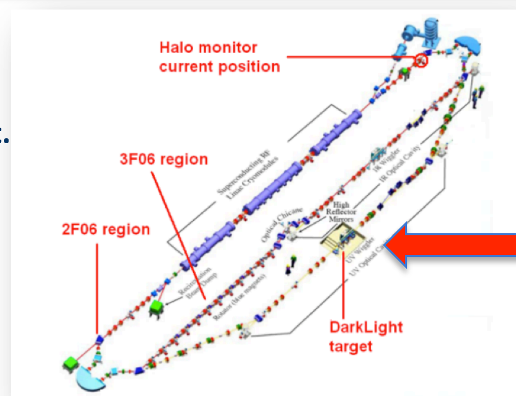
Parasitic test run complete 2012

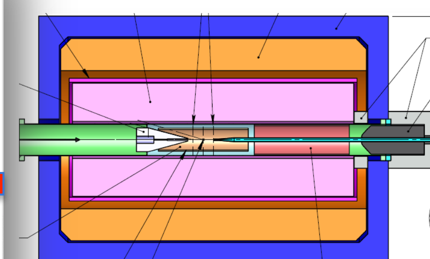
Plan for physics run in 12 GeV era

DarkLight @ the JLab **FEL**

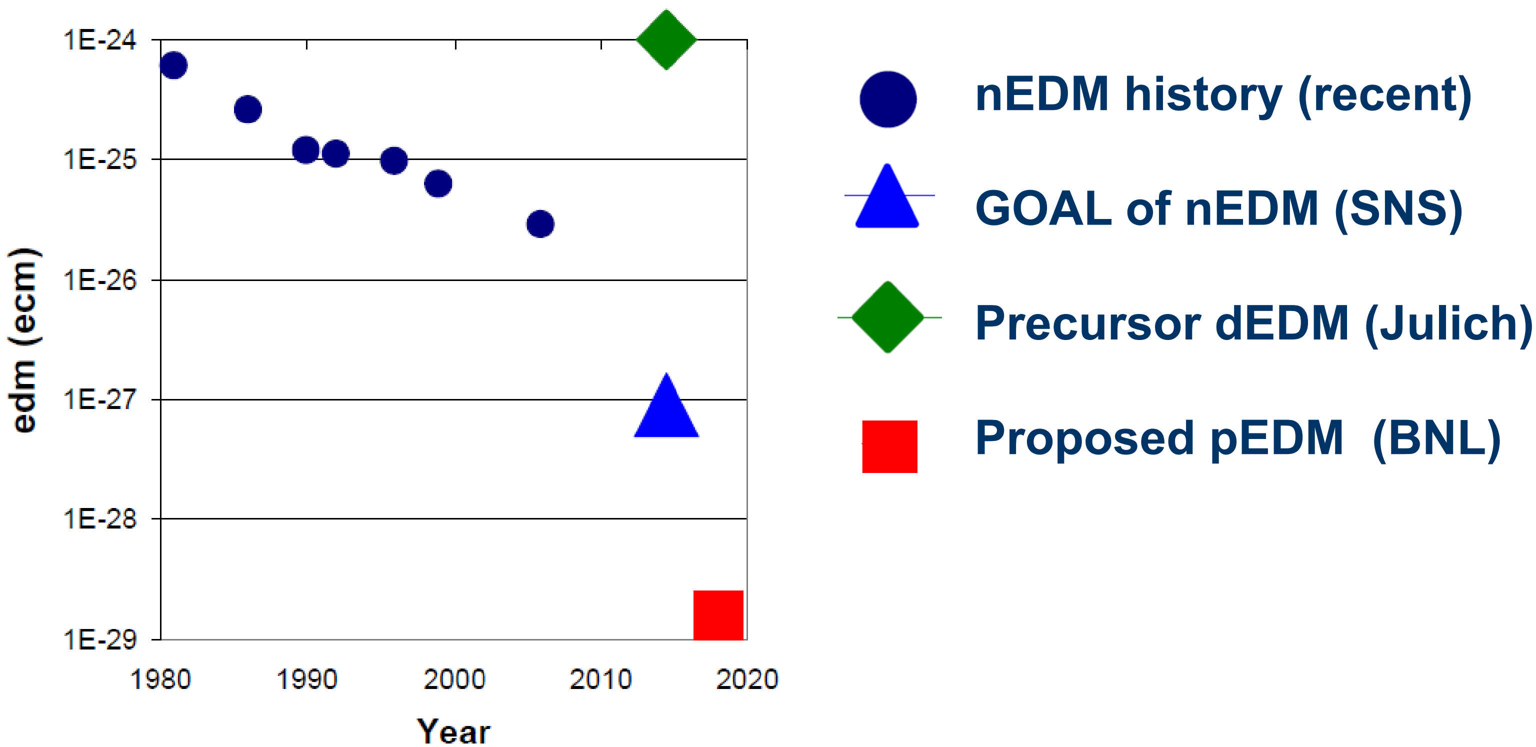
- FEL beam (~1mA, 100 MeV) incident on a H2 gas jet target.
- Collect 1/ab in ~ 60 days of beam time
- High acceptance detector inside a 0.5 T solenoid

Successful Test Run (July 2012)





2020+ Storage Ring EDM: The Proton opportunity



Polarized protons at 10^{11}/shot is relatively easy compared to cold neutrons or trapped atoms

What's the catch? It's charged! So traditional route complicated

ALL-ELECTRIC ring: spin remains aligned with the momentum vector. Is tipped up by non-zero EDM

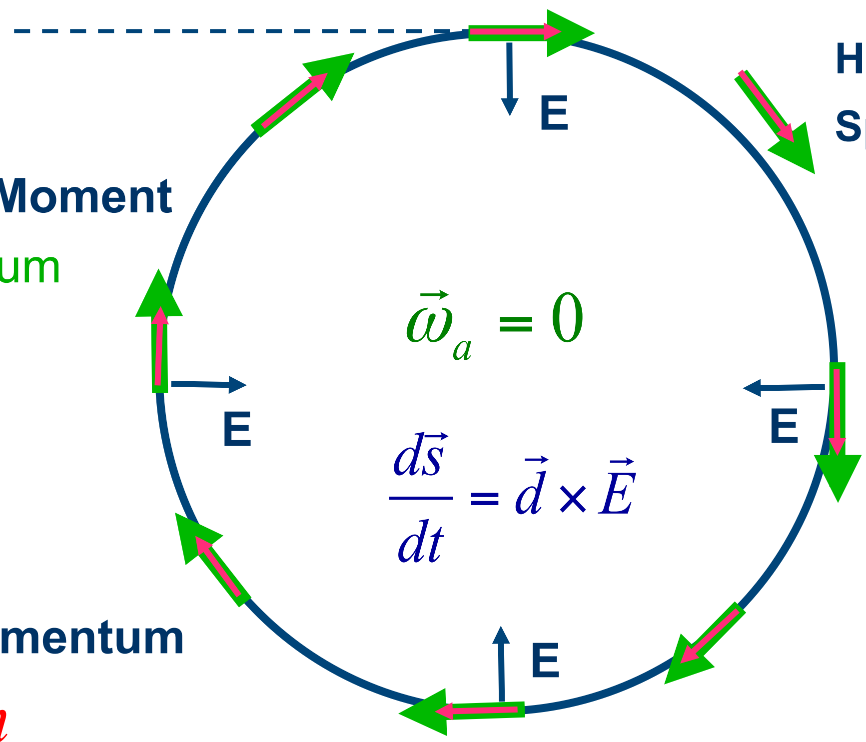
High analyzing power: A>50%

Spin Coherence Time ~1000 s

Freeze Magnetic Moment

Momentum

Spin



At the magic momentum

$$p = \frac{m}{\sqrt{a}}$$

the spin and momentum vectors precess at same rate in an E-field

Systematic Errors Evaluated and Published

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

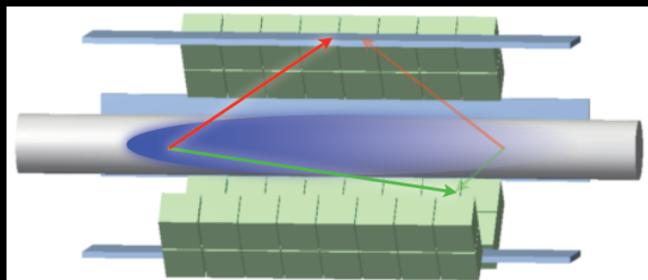
journal homepage: www.elsevier.com/locate/nima

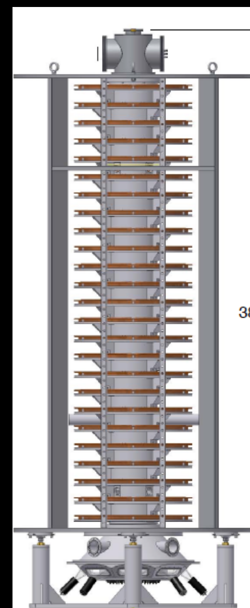
ELSEVIER

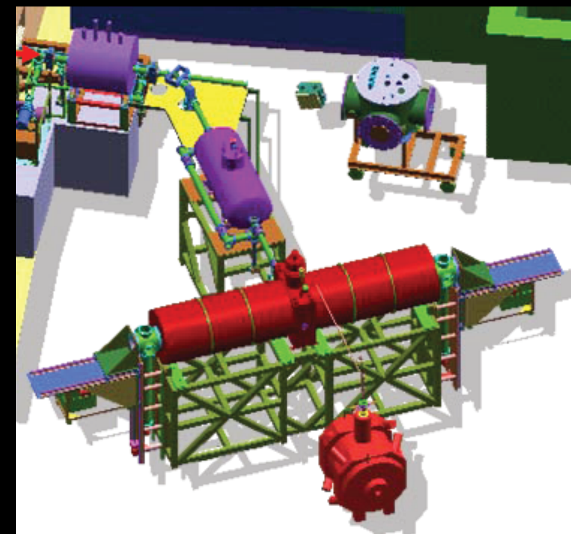
Correcting systematic errors in high-sensitivity deuteron polarization measurements

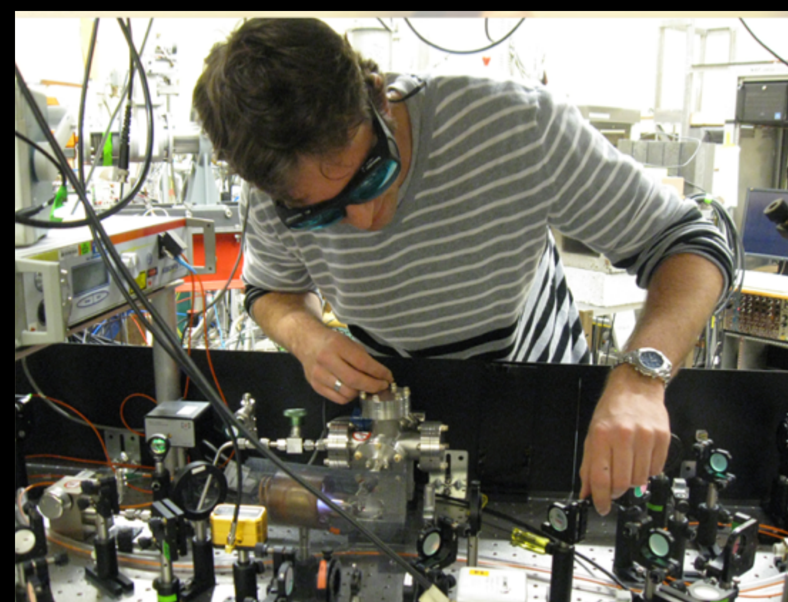
N.P.M. Brantjes[a], V. Dzordzhadze[b], R. Gebel[c], F. Gonnella[d,e], F.E. Gray[f], D.J. van der Hoek[a], A. Imig[b], W.L. Kruithof[a], D.M. Lazarus[b], A. Lehrach[c], B. Lorentz[c], R. Messi[d,e], D. Moricciani[e], W.M. Morse[b], G.A. Noid[g], C.J.G. Onderwater[a], C.S. Özben[h], D. Prasuhn[c], P. Levi Sandri[i], Y.K. Semertzidis[b], M. da Silva e Silva[a], E.J. Stephenson[g,*], H. Stockhorst[c], G. Venanzoni[i], O.O. Versolato[a]

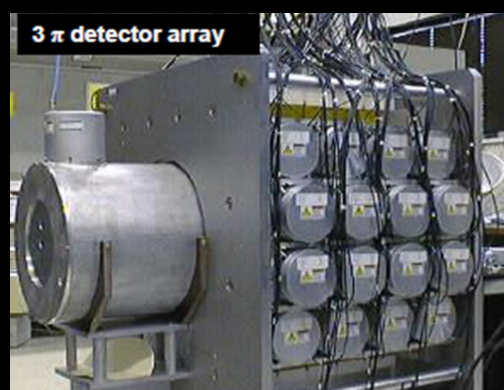
Chapter 3: Neutrons & Nuclei











2012 - 13: Hadronic Parity Violation: NPDGamma

1. ***DDH model*** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

$$f_\pi^1, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\omega^0, h_\omega^1$$

$f_\pi \sim 4.5\text{x}10^{-7}$

- Observables can be written as their combinations

$$A_\gamma \approx -0.11 f_\pi^1$$

$$A = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

2. ***Lattice QCD*** – J. Wasem, PRC C85 (2012)

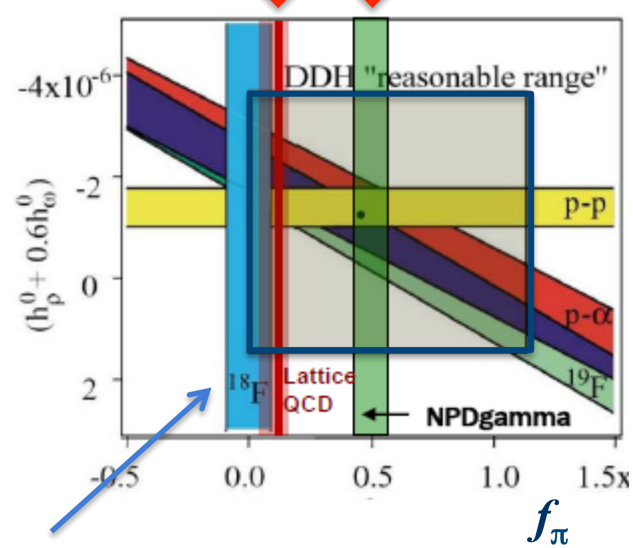
$$f_\pi = 1.099 \pm 0.505 \,^{+0.058}_{-0.064} \; [\text{x}10^{-7}] \quad (m_\pi \sim 589\,\text{MeV})$$

3. ***Effective Field Theory*** (hybrid and pure) – model-independent

- NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low energy coupling constants
  - connect to 5 parity-odd S-P NN amplitudes

$$A_\gamma^{\vec{n}p} \approx -0.27\widetilde{C}_6^\pi - 0.09 m_N \rho_t$$

GOAL



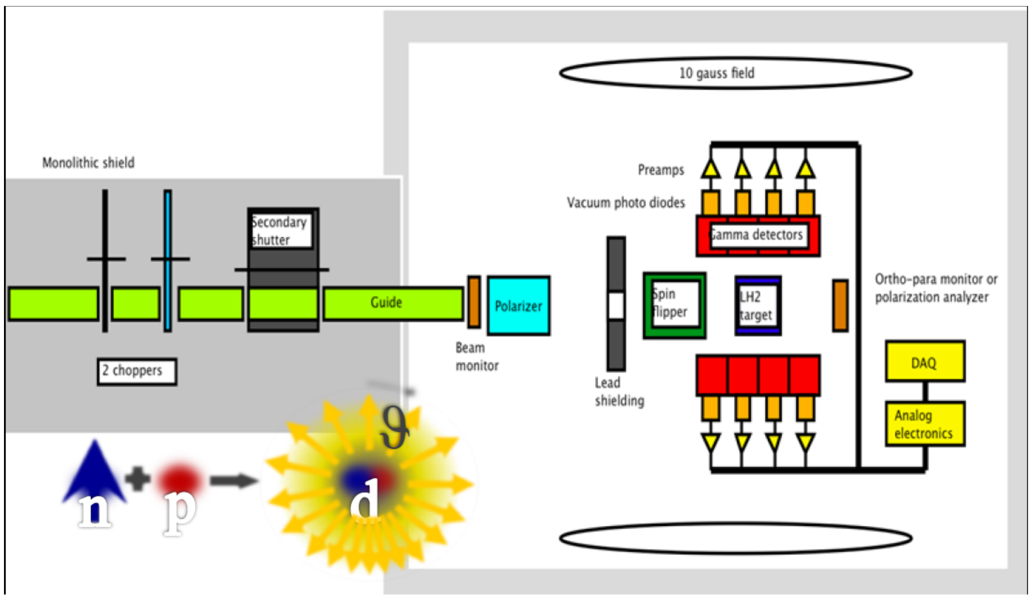
Curious result

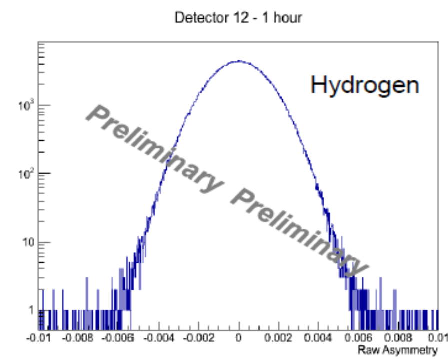
Method and Status: On floor at the FnPB (SNS)

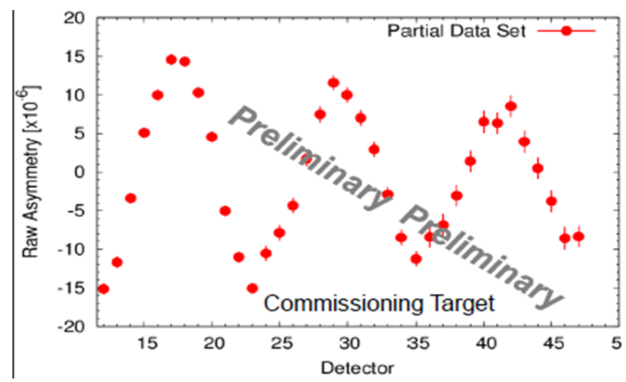
- **Already taken hydrogen data at the 5×10^{-8} A_γ level.**

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

A_γ – directional asymmetry in the gammas emitted from cold neutron capture on protons







- **200 MW-days, starting next month, needed to reach goal of 1×10^{-8}**

The Neutron as a Fundamental Laboratory

Neutron beta decay

$n \rightarrow p^+ + e^- + \nu'_e$

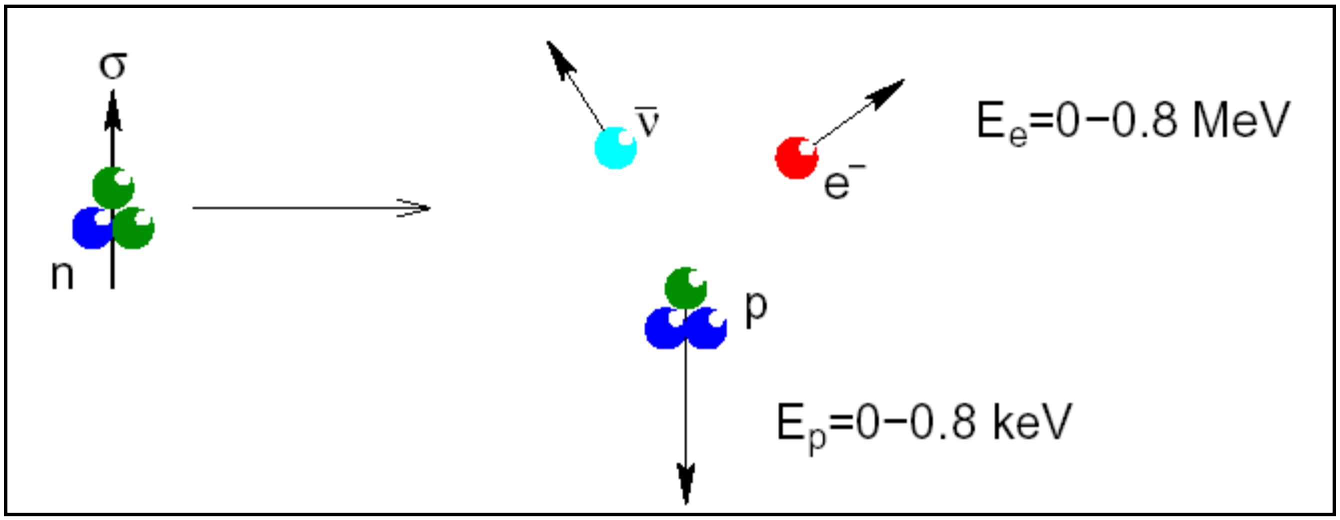
neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV

Only 3 parameters needed: V_{ud}, λ, ϕ

- CKM matrix element V_{ud},
- ratio of c.c. $\lambda = g_A/g_V = |\lambda|e^{i\varphi}$
- relative phase φ

  (T-symmetry: $\varphi = 180^0$)



Correlations in Neutron Decay

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e \cdot E_\nu} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B\frac{\sigma_n \cdot \mathbf{p}_\nu}{E_\nu}\right]$$

$$\tau_n \propto 1/(g_A^2 + 3g_V^2)$$

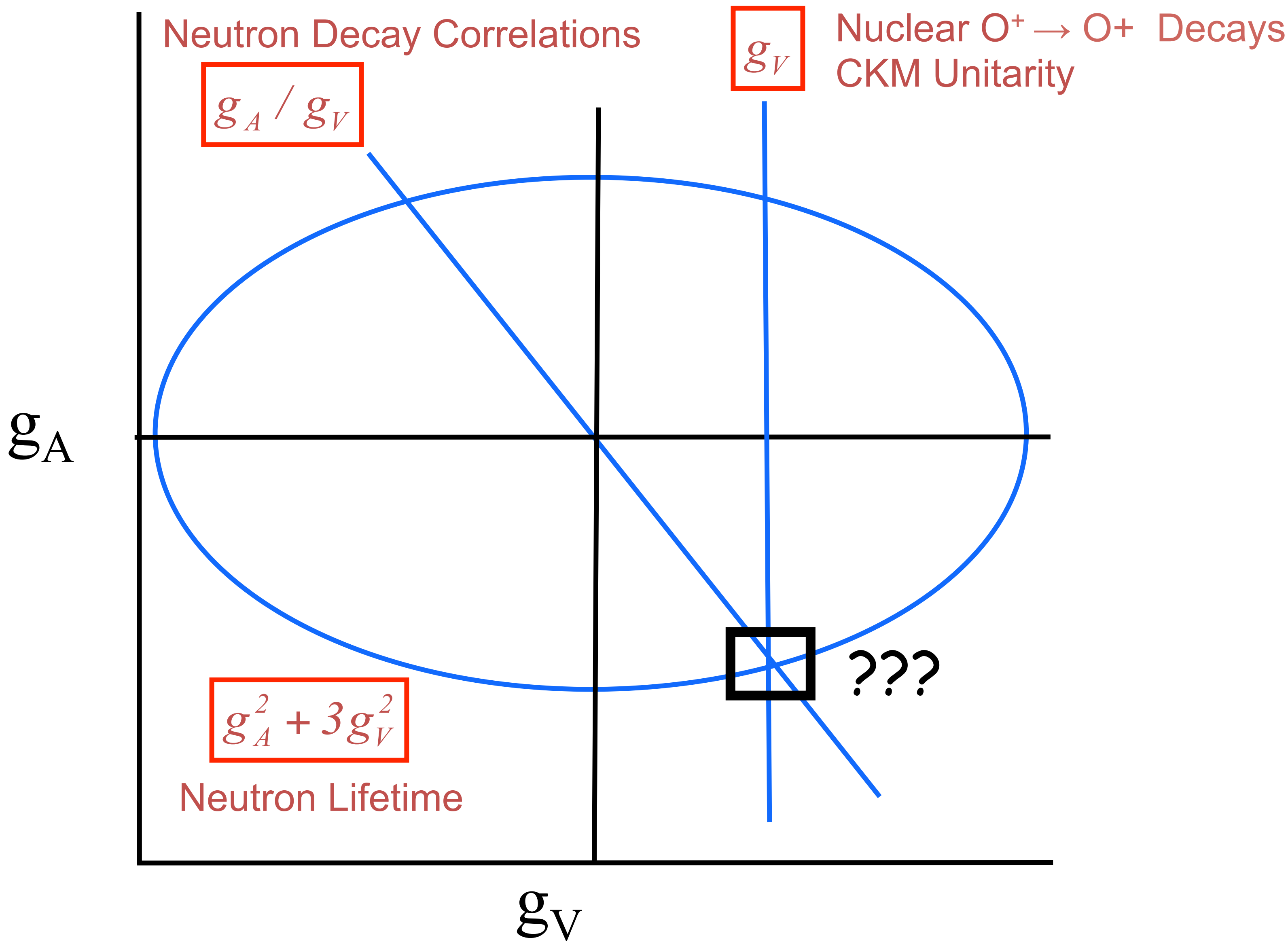
$$a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$b = 0$$

$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

$$B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 - \left(\frac{g_A}{g_V}\right)^2}$$

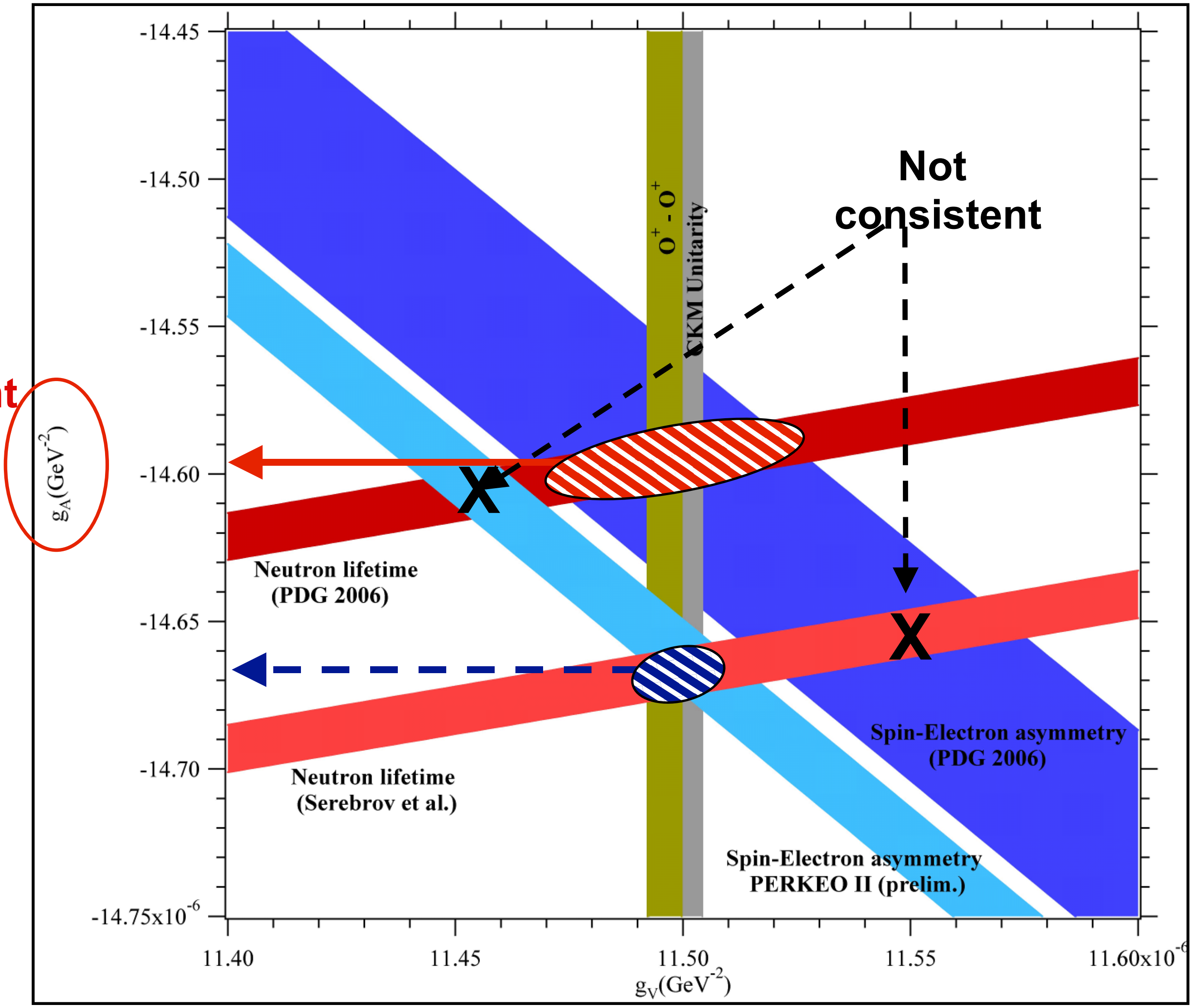
Neutron beta decay measurements give: $(g_A^2 + 3g_V^2)$, g_A/g_V



Neutron Decay Correlations
g_A / g_V
g_V
Nuclear O⁺ → O+ Decays,
CKM Unitarity
g_A
???
$g_A^2 + 3g_V^2$
Neutron Lifetime
g_V

2007 picture: Lifetime and Correlations combine in a confused picture for the physics of g_A or unitarity

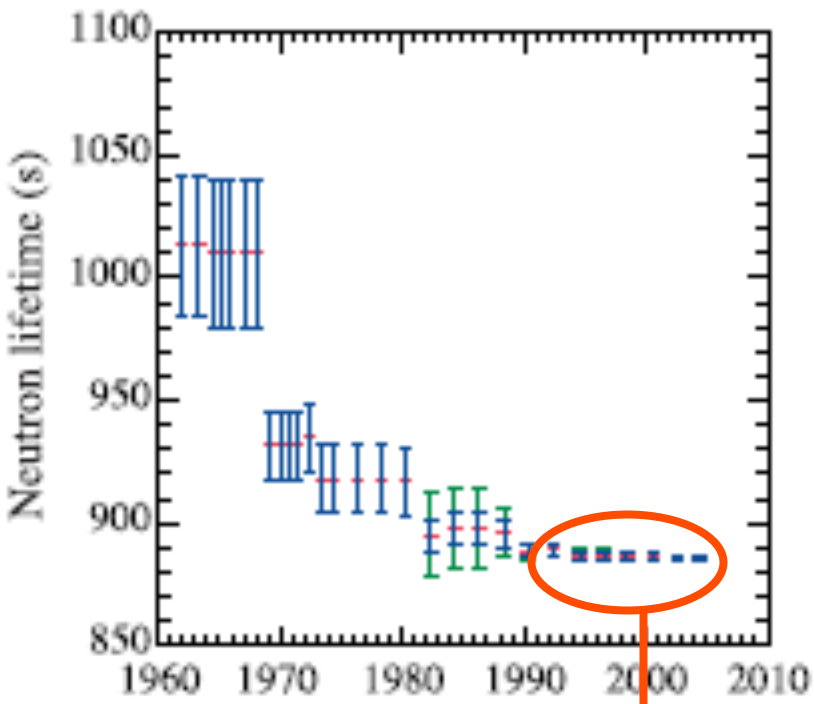
g_A important



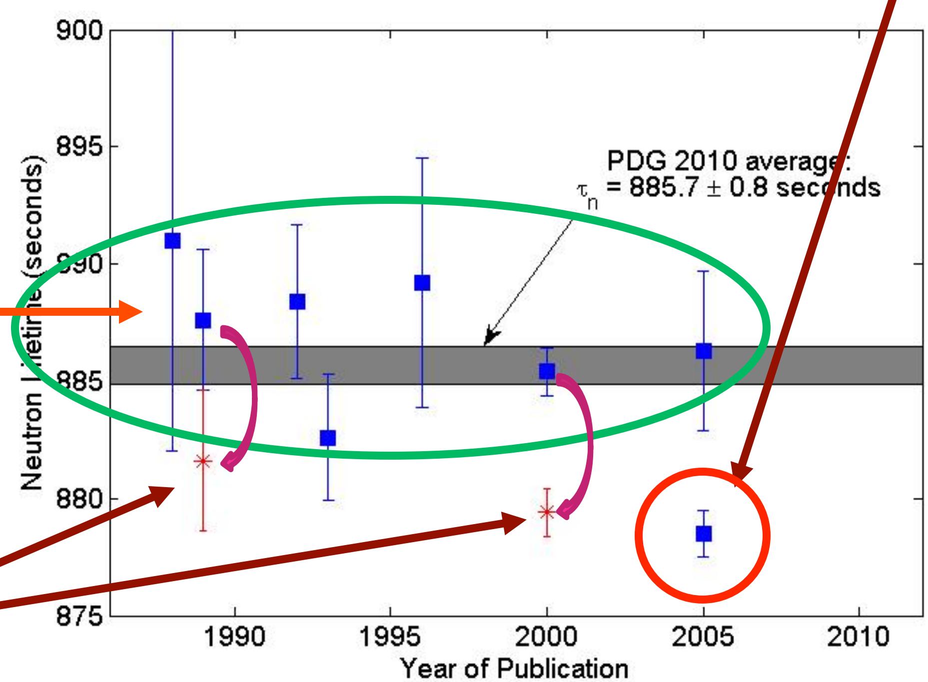
$$g_V \equiv G_F V_{ud} f(0)$$

J. Nico, 2007

This well-known plot of Neutron Lifetime versus Time illustrates just how difficult this measurement is:



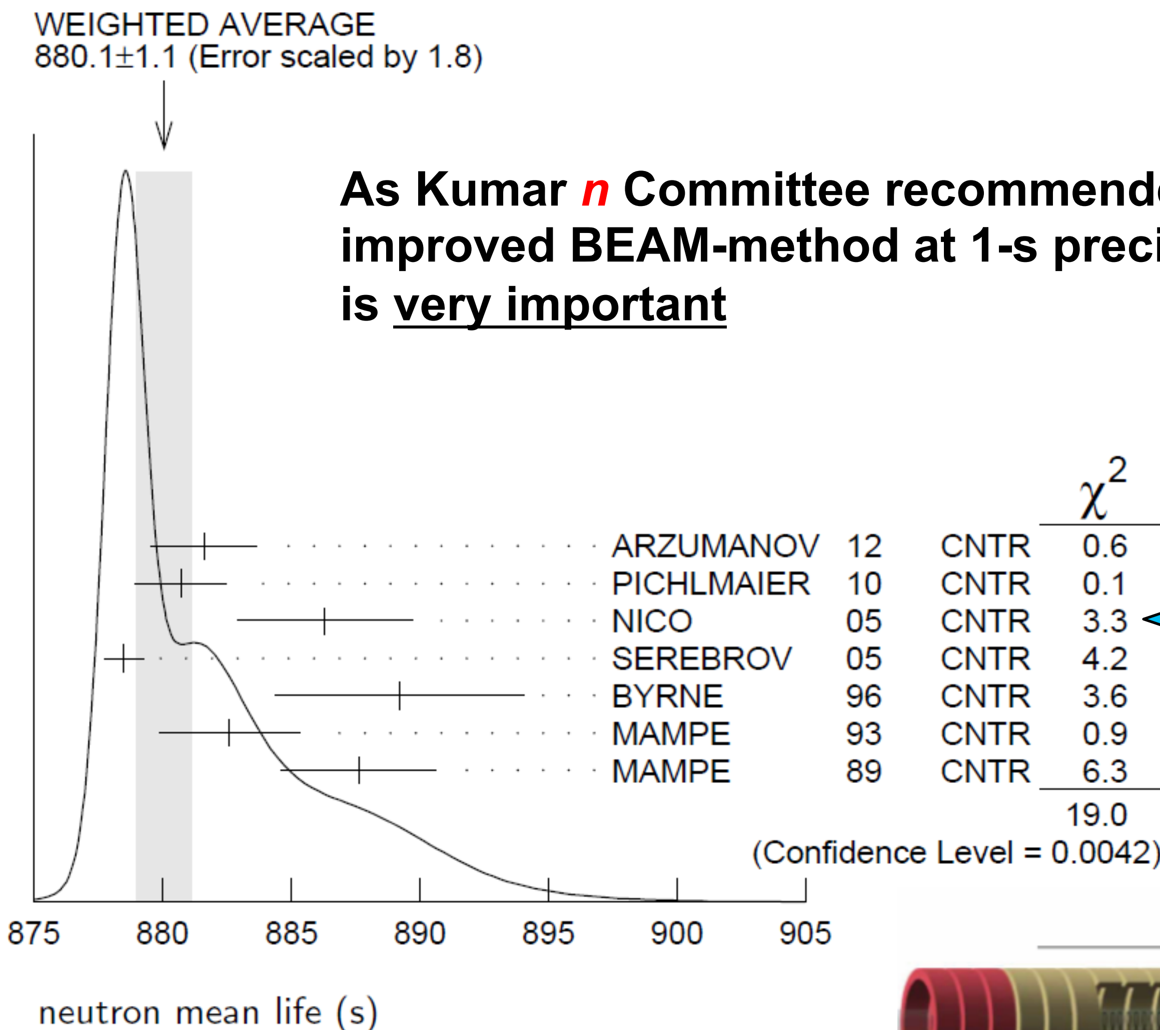
Serebrov *et al.*,
(878.5 ± 0.7 ± 0.3) seconds



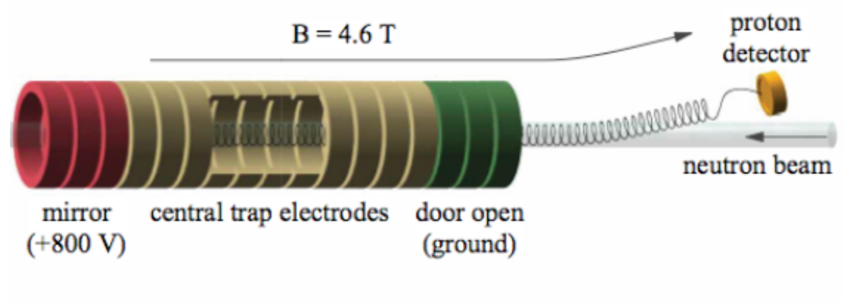
Reanalysis of bottle experiments by Serebrov, et al.

2012: *n* Lifetime Update: PDG

As Kumar *n* Committee recommended, an improved BEAM-method at 1-s precision is <u>very important</u>

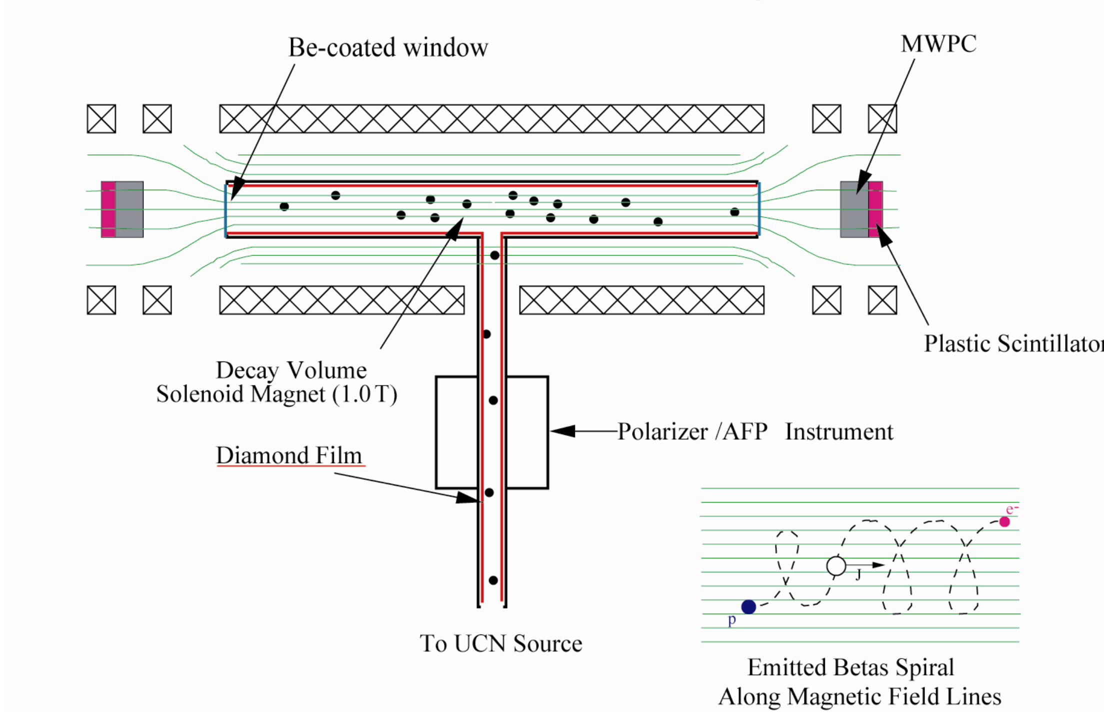


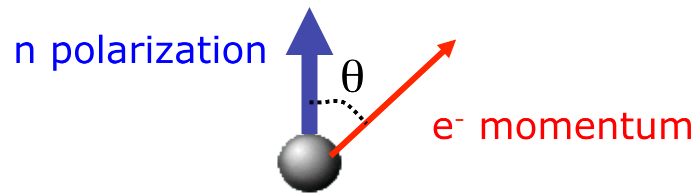
See Nico talk



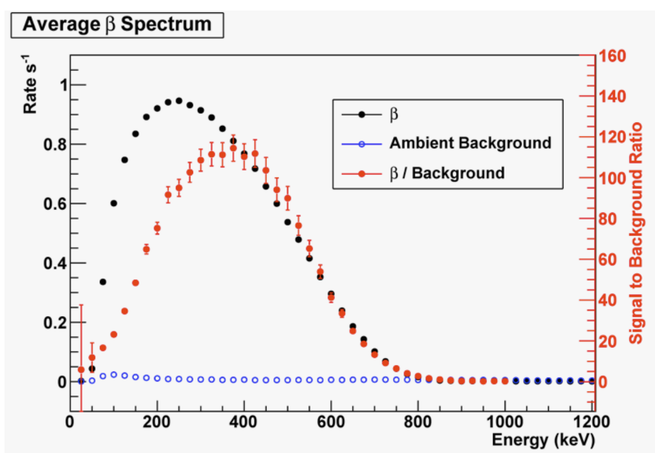
PDG uses latest 7, including corrected and other newer results

2009 - 13 UCNA: big "A" with Ultracold Neutrons



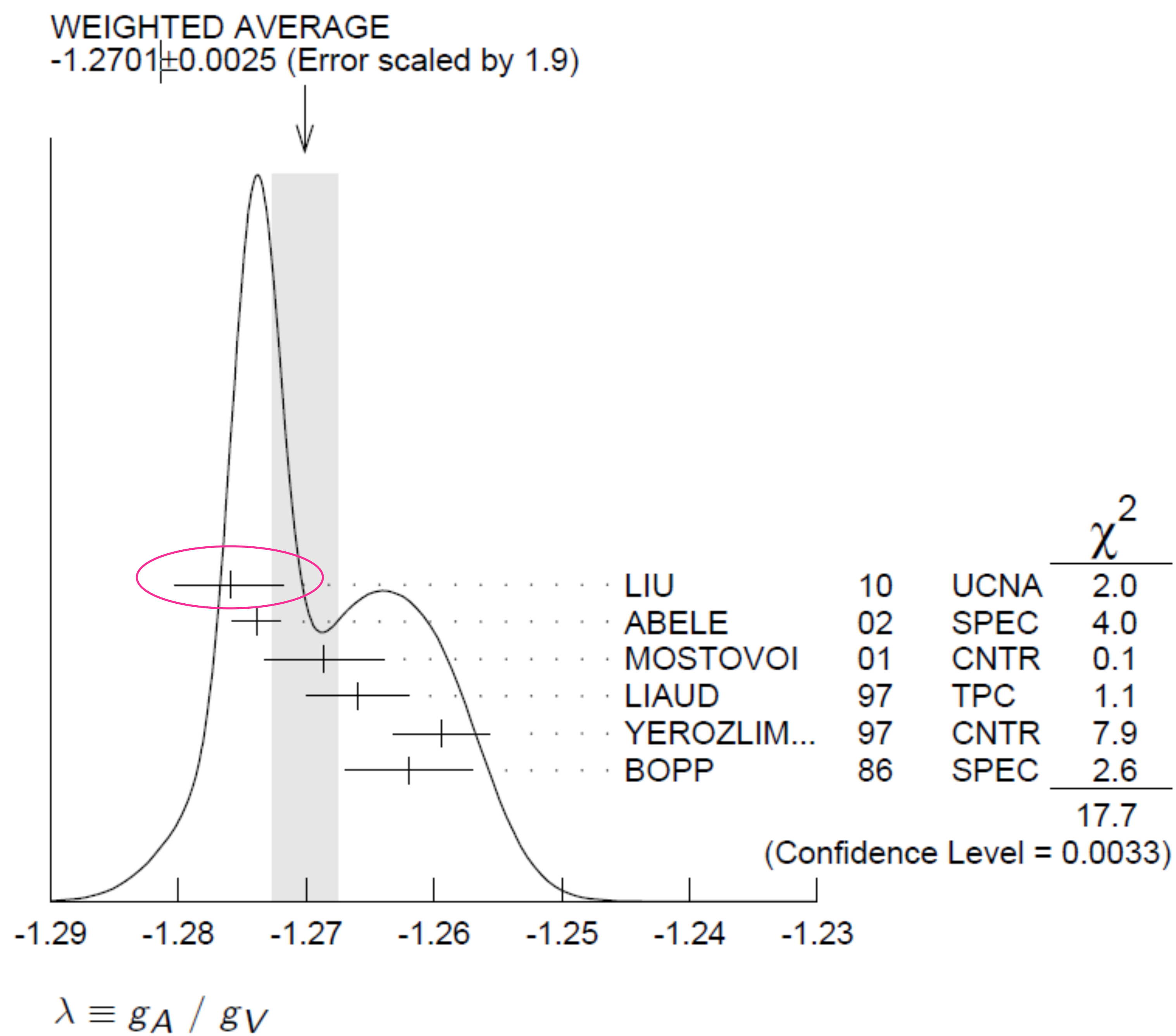


- Only expt. using ultracold neutrons for angular correlation measurements
- Scintillator + MWPC detector package
- Very low background (see plot)



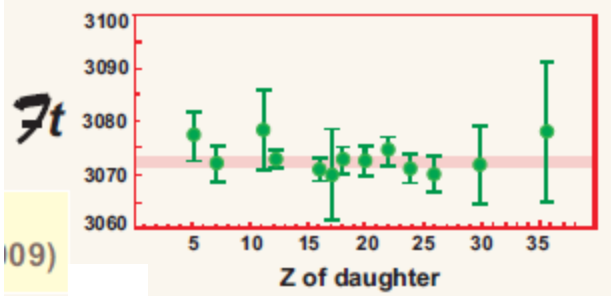
Year	Statistics	δA/A	Published
2007	2 M	4.5%	2009
2008/2009	24 M	1.4%	2010
2010/2011	65 M		

$$R = R_o(1 + (v/c)\, P\, A(E) \cos\theta)$$


WEIGHTED AVERAGE
-1.2701±0.0025 (Error scaled by 1.9)
χ^2
LIU 10 UCNA 2.0
ABELE 02 SPEC 4.0
MOSTOVOI 01 CNTR 0.1
LIAUD 97 TPC 1.1
YEROZLIM... 97 CNTR 7.9
BOPP 86 SPEC 2.6
17.7
(Confidence Level = 0.0033)
-1.29
-1.28
-1.27
-1.26
-1.25
-1.24
-1.23
$\lambda \equiv g_A / g_V$

2009-12: SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

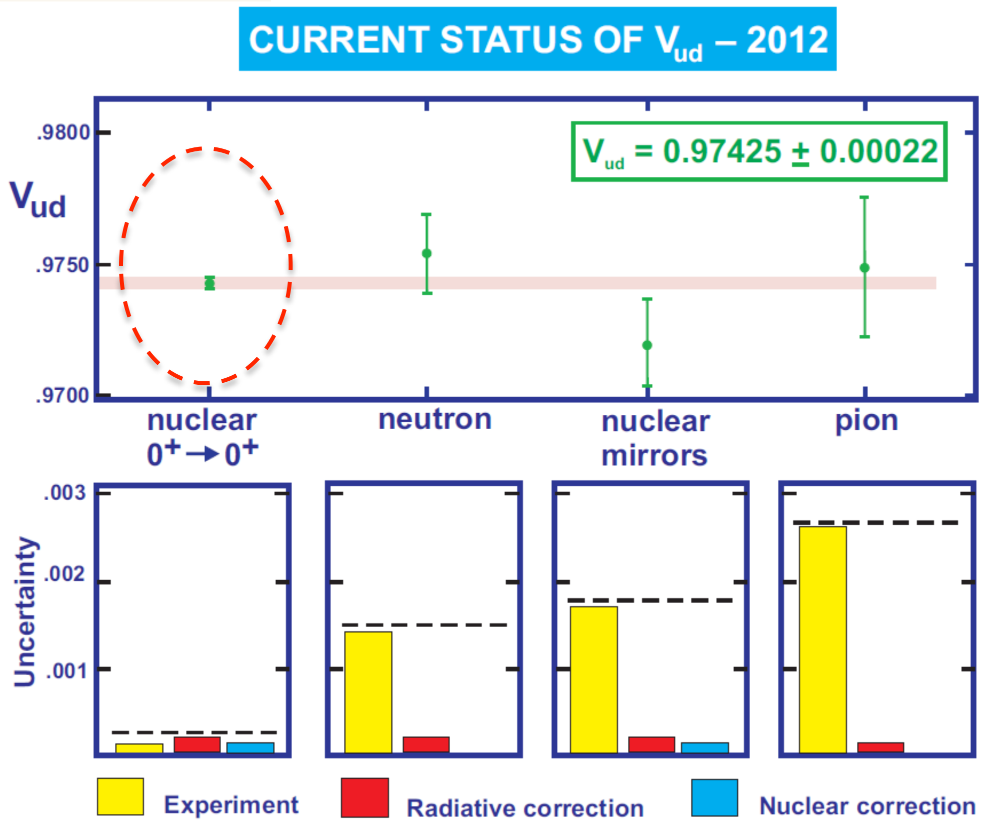
$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$



- CVC verified
- V_{ud} = 0.97425(22)

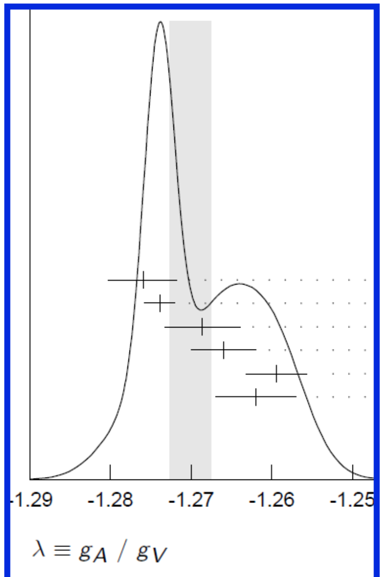
CKM unitarity test:

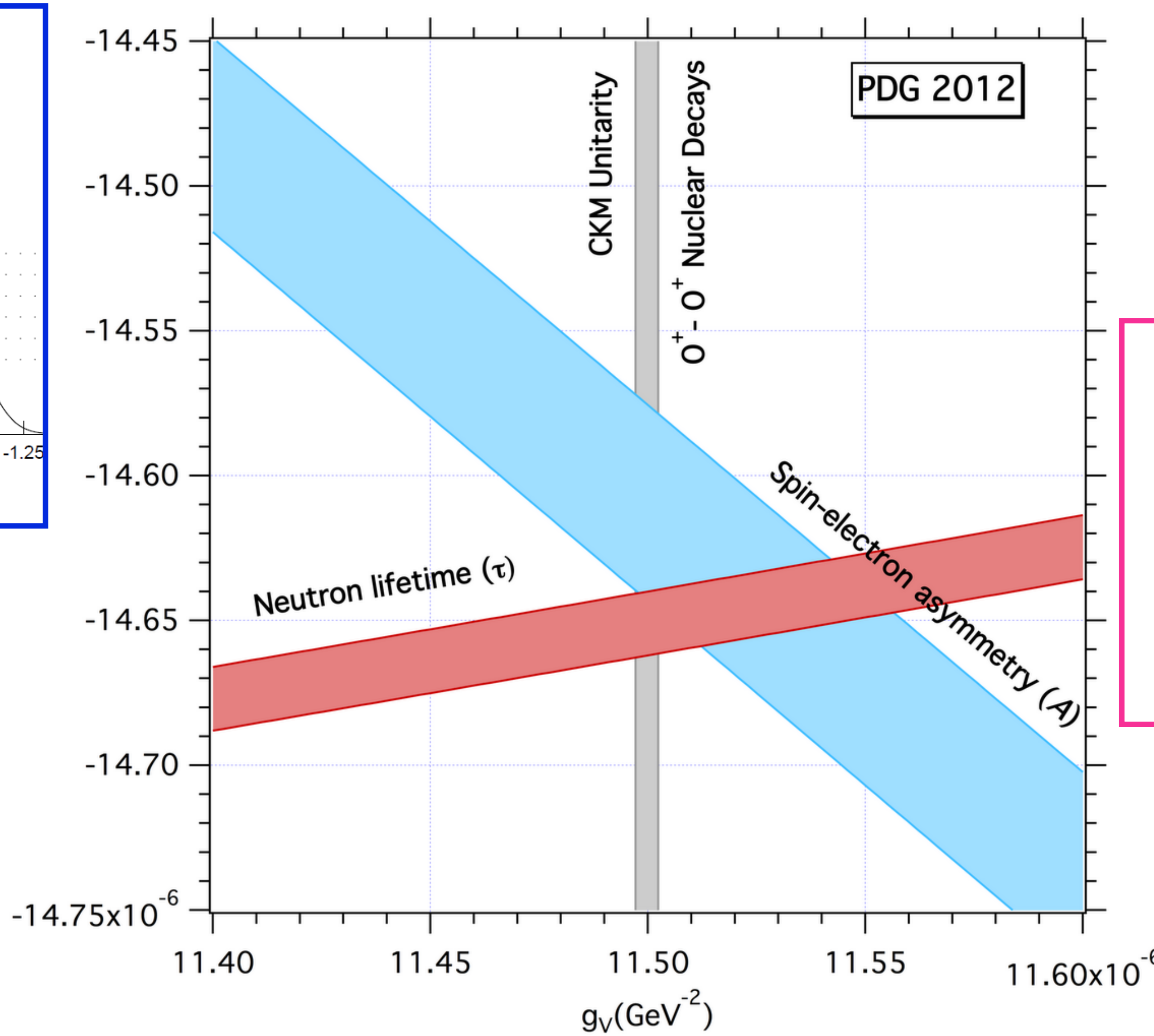
$V_{ud}^2 + V_{us}^2 + V_{ub}^2$
= 0.9999(6)

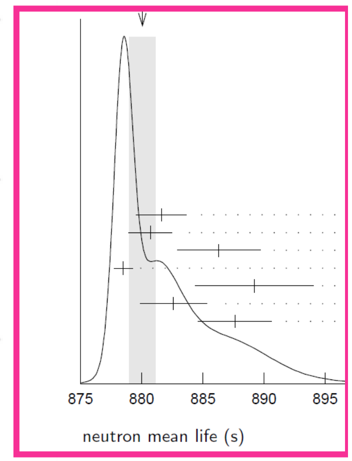


Hardy et al

2012 Picture: Lifetime and Correlations in better shape, but lifetime and Asymmetry still in tension







$$g_V \equiv G_F V_{ud} f(0)$$

J. Nico, 2012

2015- Nab – future and beyond

- Measure the electron-neutrino parameter **a** in neutron decay

  with accuracy of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$ or $\sim$ 50× better than:

current results:	-0.1054 ± 0.0055	Byrne et al '02
	-0.1017 ± 0.0051	Stratowa et al '78
	-0.091 ± 0.039	Grigorev et al '68

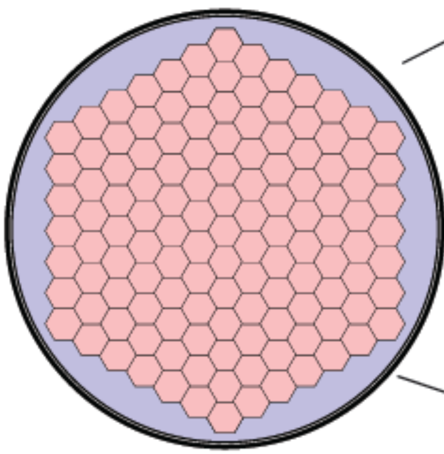
- Measure the Fierz interference term **b** in neutron decay

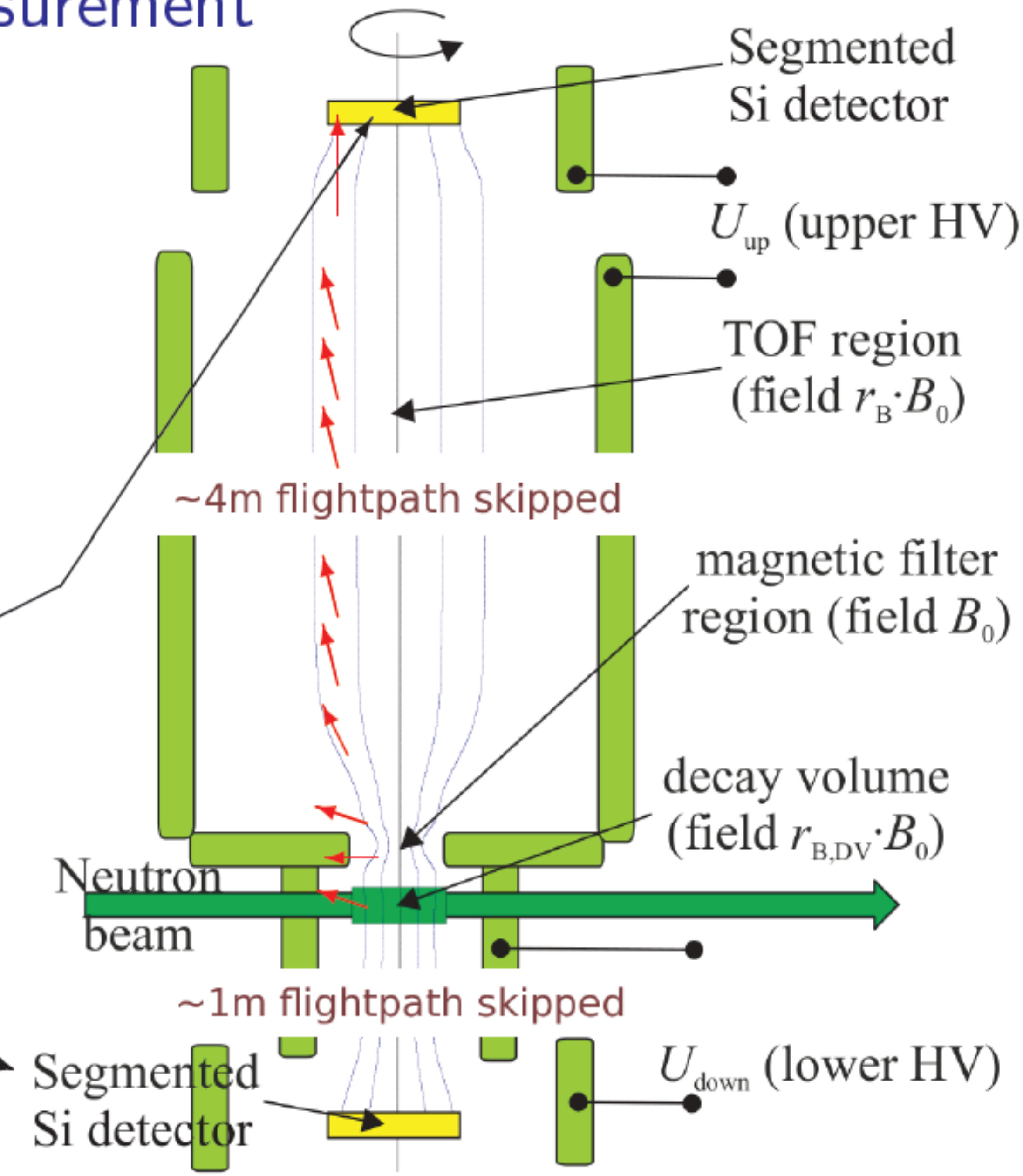
  with accuracy of $\boxed{\Delta b \simeq 3 \times 10^{-3}}$ **Never measured in n decay**

- **Nab** will be followed by the **abBA/PANDA** polarized program to measure **A**, electron, and **B/C**, neutrino/proton, asymmetries with $\simeq 10^{-3}$ relative precision, an independent measurement of λ.

Nab principles of measurement

- Collect and detect both electron and proton from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:





Toward Exotica with Nuclei

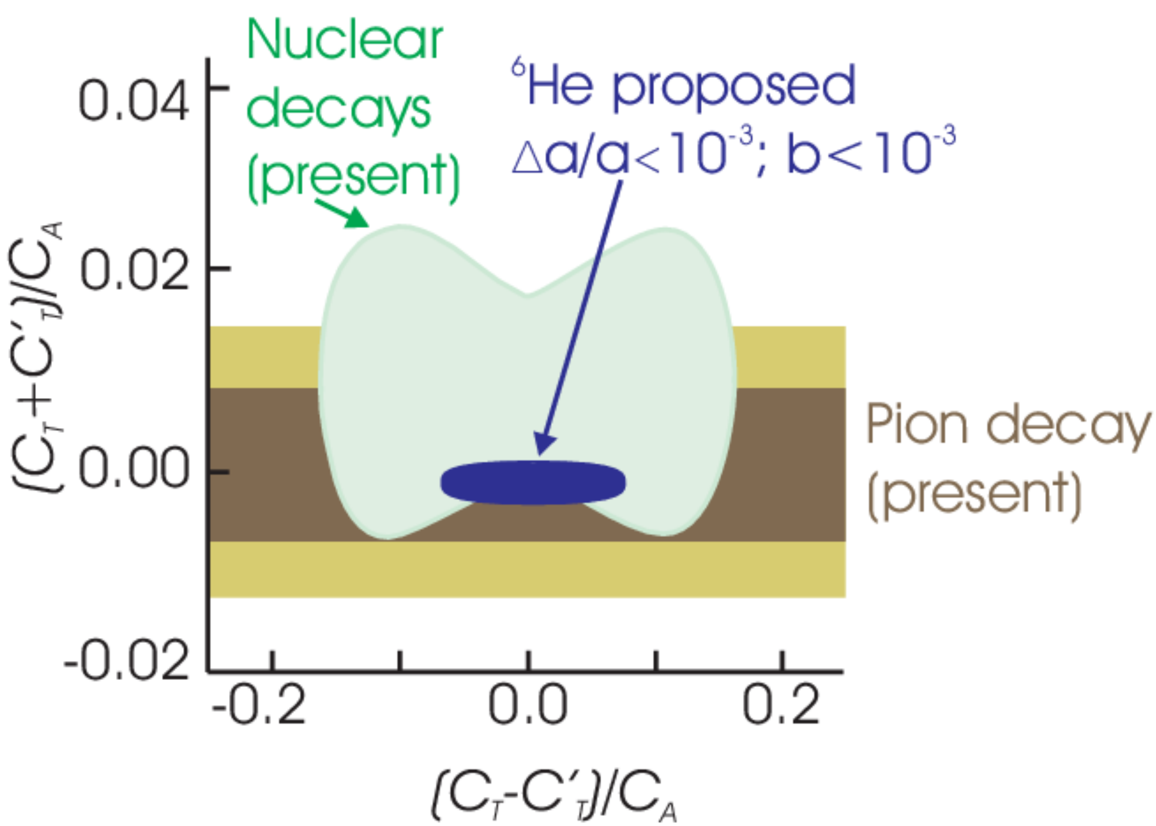
(just a few examples)

2012-13 Searches for tensor currents in ^{6}He decays

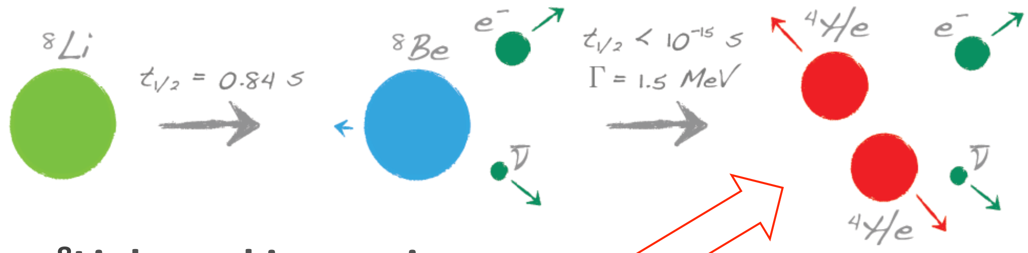
- *a* is sensitive *quadratically* to Tensor currents of either chirality
- *b* is sensitive *linearly* to Tensor currents, but only to those with no left-handed anti-neutrinos (or right-handed neutrinos
- Production of >10^9 atoms/s to a low-background room

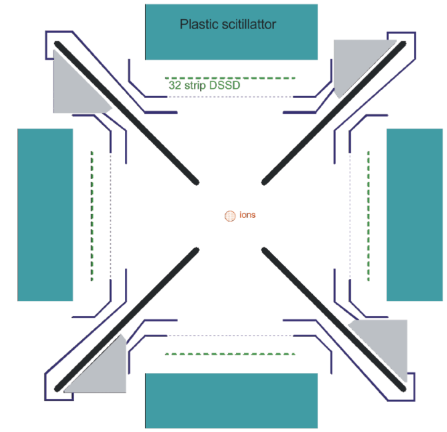
$$a = -\frac{1}{3}\frac{(2|C_A|^2 - |C_T|^2 - |C_T'|^2)}{(2|C_A|^2 + |C_T|^2 + |C_T'|^2)}$$

$$b = \frac{2C_A\,(C_T + C_T')}{(2|C_A|^2 + |C_T|^2 + |C_T'|^2)}.$$



2010 – 2013 Beta Decay Paul Trap for ^{8}Li





Linear Paul trap cross section

^{8}Li decay kinematics

- Pure GT decay
- Characteristic $\beta-\alpha-\alpha$ coincidence

Results from FY 2010 test run

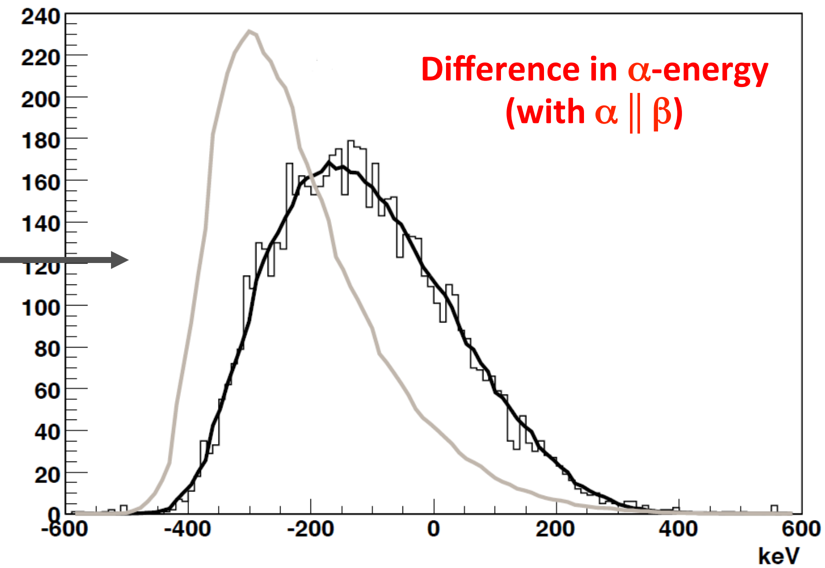
- **Collected ~20,000 $\beta-\alpha-\alpha$ coinc.**
- **~2 % total uncertainty in *a*, consistent with *a* = -1/3**

Final ^{8}Li run (study finished)

- **High statistics run (20X) ran in fall 2011**
- **Analysis ongoing, expect < 0.3% total uncertainty → best tensor limit so far**

Prepare for ^{8}B experiment

- **test of CVC, second class currents - 2013**



Charge (nEDM and PVES added for completeness)

1. What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?
   1. TWIST Michel parameters agree with SM; pushes out W_R
   2. G_F to 0.5 ppm (best EW measured parameter)
   3. g_P measurement confirms theory after more than 40 years controversy
   4. g-2 signal now about 3.5 σ, owing to improved SM theory
   5. *A* in *n* beta decay measured precisely by 2 independent experiments
   6. V_{ud} , when combined with V_{us} and V_{ub} satisfies CKM unitarity to 0.06%.
   7. emiT measures D coefficient n beta decay to $(-0.96 \pm 1.89 \pm 1.01) \times 10^{-4}$

2. What compelling and unique science is to be done in the next 5 years?
   1. g-2 experiment to 0.14 ppm on schedule
   2. f_π from NPDGamma
   3. n lifetime from Beam technique
   4. Qweak result
   5. nEDMs emerging from ?? experiment
   6. Improved n beta decay parameters from neutrons and nuclei.
   7. Perhaps not designed for "5 σ" discovery, but null results at 90% C.L. will constrain exotic theories at sensitive levels

Charge …

3. What science would you expect to pursue in the program in "2020" and beyond?
    1. Mu2e experiment
    2. US nEDM
    3. Moller at 11 GeV
    4. Storage ring EDM of proton

    Big Project for NP Capital Funding (items 2–4)

    5. Smaller efforts that might be proposed: e.g, abBA, n lifetime, muon EDM, …)
    6. **AND, it DEPNDS ON WHAT WE FIND !!**
4. What is the international context, and how does it affect your vision?
    1. Unique Muon Campus at FNAL will dominate on g-2 and Mu2e, but JPARC can be very competitive with COMET and possible little g-2
    2. PSI owns stopping muon experiments (MEG, MuSun, mu → eee, …)
    3. Neutron sources highly competitive
    4. nEDM very intense competition
    5. PVES rather unique in US program
5. Manpower, resources, etc.
    1. Sustaining effort of research groups and enabling travel and detector, electronics, daq purchases essential
    2. Continue to support MRIs for strategic opportunities (recent example: Nab)
    3. Make room for a few "big" projects in the future. This field can defend it.

Summary

- A lot of superb and diverse projects
- Scale from small $ to large $$$
- A wide variety of facilities used.
    - Often nuclear physics does not have to ‘provide the beam’
        - SNS, PSI, Fermilab, Solar Neutrinos; Reactor Neutrinos, just hiding underground and ducking the cosmics rays, … and so on
    - Important science, highly leveraged
- International competition is very active
    - Sometimes they are ahead
    - Sometimes the US is ahead
    - Very often, it’s close and depends on support

This talk featured contributions from MANY people in the field, but I did not cover everything. Apologies

Incomplete list of credits …

- Marshall
- Mu2e documents
- Polly, Roberts
- Pocanic
- Nico
- Garcia
- Hardy
- Savard
- Young
- Alarcon
- Morse et al
- Greene