Electroweak and Precision Physics: Experimental Review

(less EDMs and PVES)

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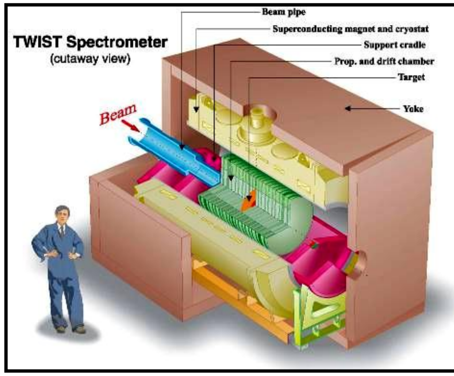
University of Washington

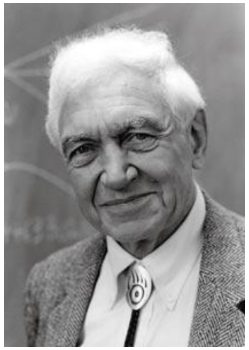
- Focus on **active or approved** experiments, which are in design phases
- Many other efforts are **in development**
- I will try to tell you what each experiment is **designed to deliver**

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 this month; 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



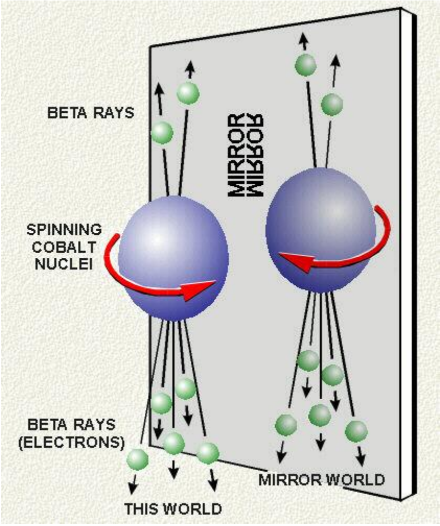
very Recent, Present and Future Projects Worldwide

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

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

- **EDMs → Brad Filippone**

- **PVES → Kent Paschke**



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) $\delta A/A \sim 5\text{x}10^{-3}$
    - UCNA ("big A"; B, b later) Status: complete (2012) and future running
    - aCORN ("little a") Status: in progress
    - N_{ab} ("little a, little b") Status: in construction

- **Nuclei** **(incomplete; mostly covered elsewhere)**
  - **0+ → 0+**
    - Many new results Status: complete, but new set of nuclei
  - **He-6 System**
    - Lifetime Status: complete $\delta\tau_{He\text{-}6} = 3\text{x}10^{-4}$
    - 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]

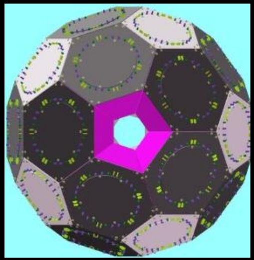
arXiv:1207.6393v1

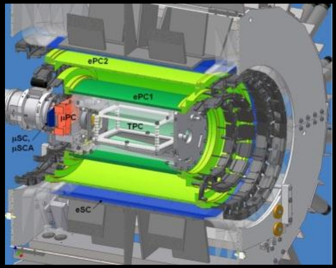
Post Higgs paper
(others exist too)

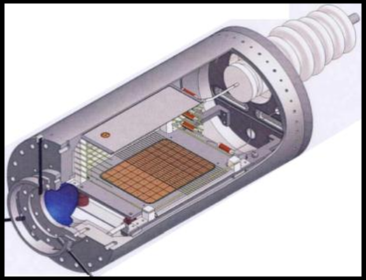
- Observations at the LHC
  - $h \rightarrow \gamma\gamma$ **production rate is too high by ~40-50%**
  - **Higgs rates in ZZ* and WW* are consistent with the SM**
- Theoretical SUSY model that fits observations
  - **light stau with large left-right mixing**
  - **light Bino**
  - **heavy higgsinos**
- Other consequences
  - ✓ **Predicts Muon Anomaly exactly** — **Low-energy**
  - ✓ **Compatible with thermal dark matter** — **Low-energy**
  - ✓ **Predicts small deviations in h → γZ and h → ττ** — **Collider**
  - ✓ **Predicts measureable violations of Lepton Non-Universality in τ–μ and τ-e** — **Belle-II**
  - ✓ **Predicts NO violation in the μ-e sector** — **Low-energy**

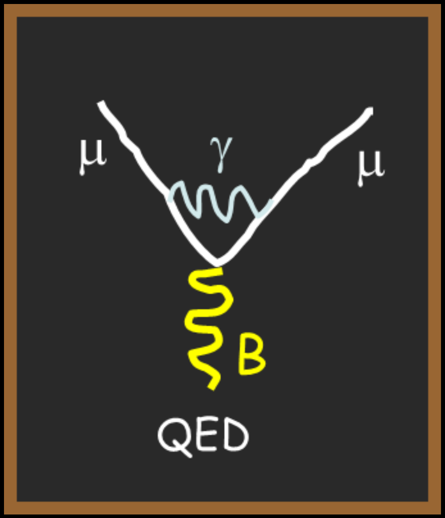
Chapter 1: Muons

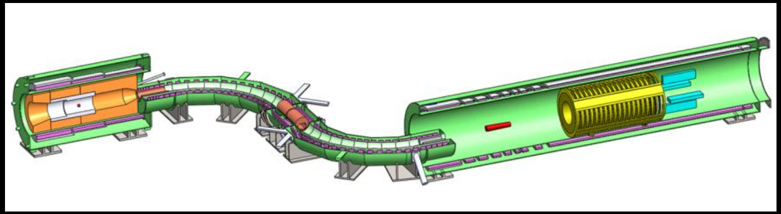
(well) Beyond Schwinger

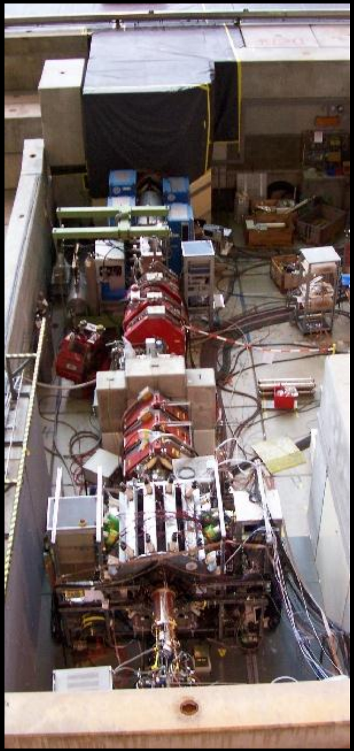


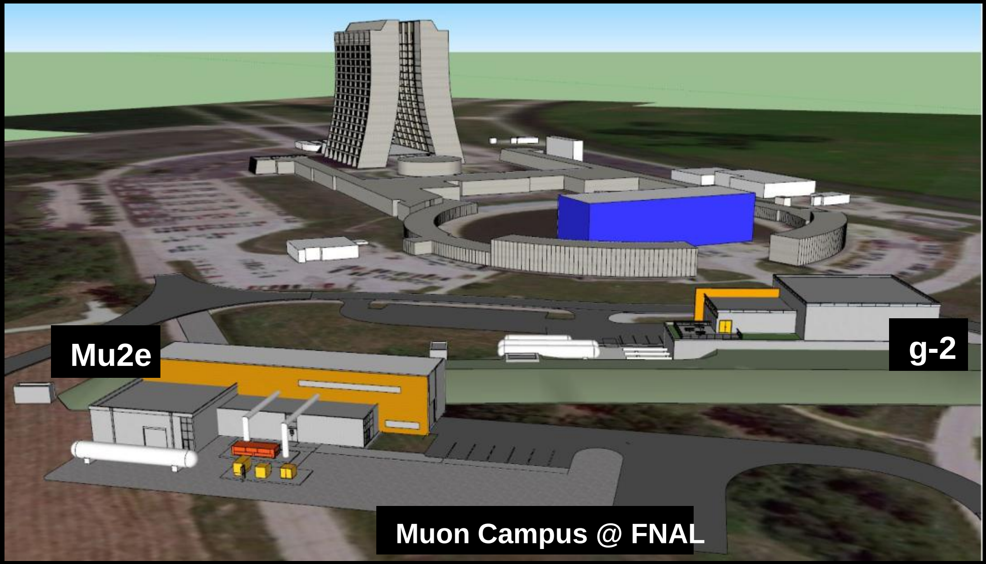










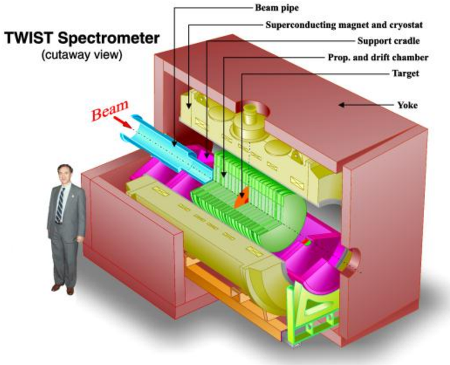


2010: Michel Parameter / Muon Decay: TWIST

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

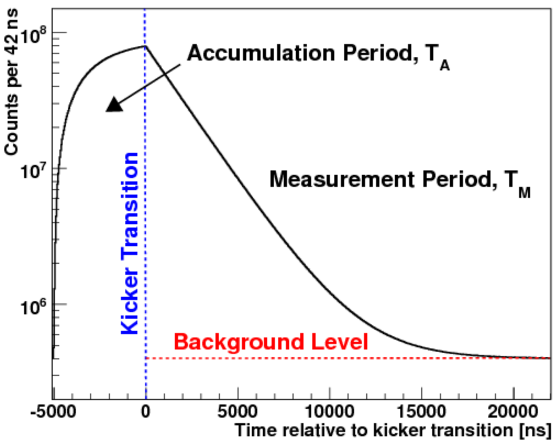
- summary of all terms (pre-*TWIST* in parentheses)

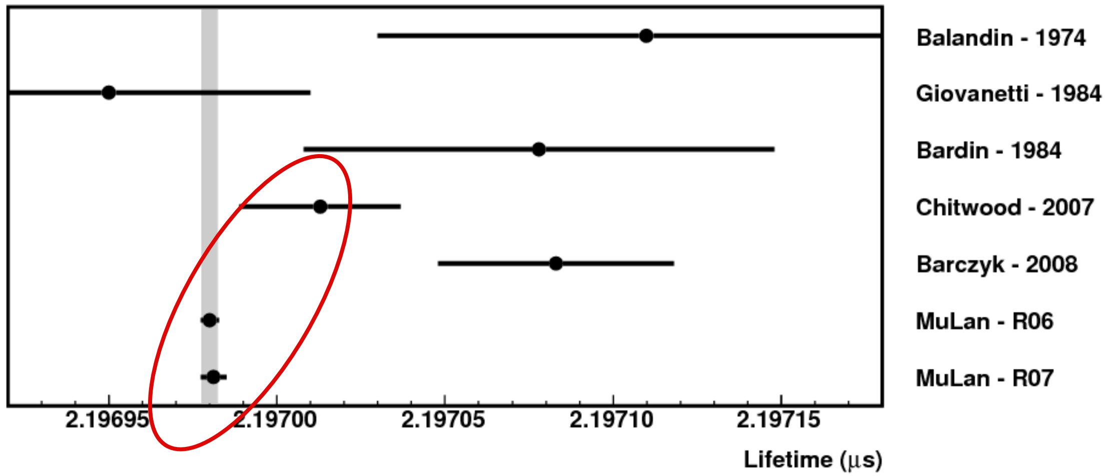
$\lvert g^S_{RR}\rvert < 0.035\ (0.066)$	$\lvert g^V_{RR}\rvert < 0.017\ (0.033)$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.050\ (0.125)$	$\lvert g^V_{LR}\rvert < 0.023\ (0.060)$	$\lvert g^T_{LR}\rvert < 0.015\ (0.036)$
$\lvert g^S_{RL}\rvert < 0.420\ (0.424)$	$\lvert g^V_{RL}\rvert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

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

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)


InsideScience.org
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FEBRUARY 11, 2011
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Research

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.

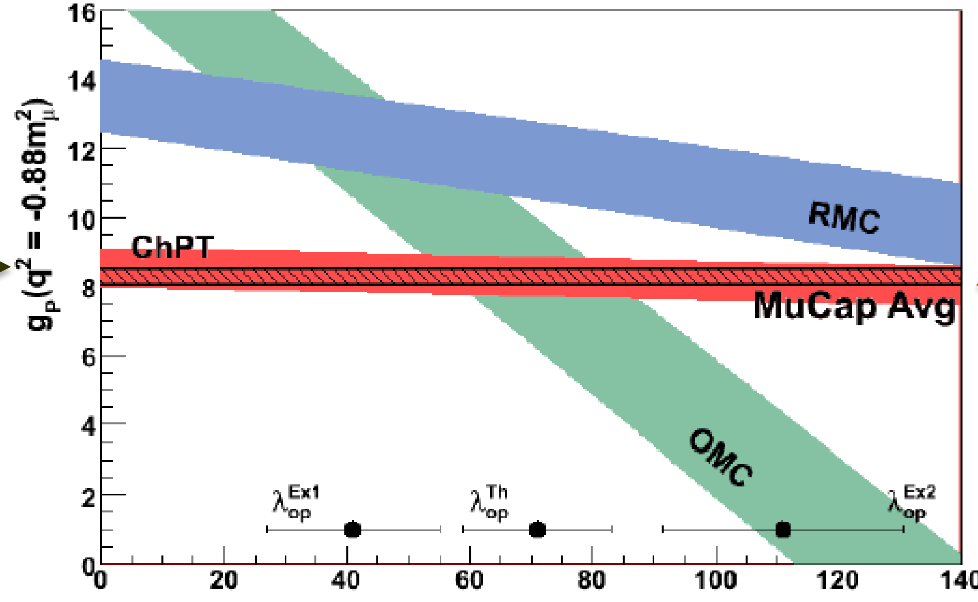
Just as biologists sometimes study the tiniest and most

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: $\mathbf{g_P(MuCap) = 8.04 \pm 0.56}$

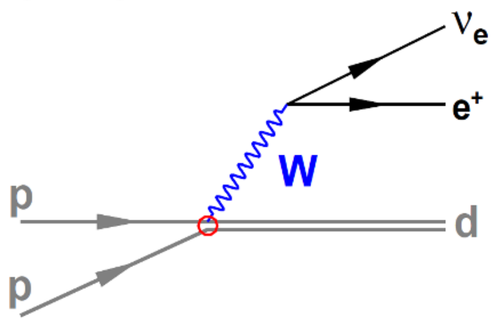
Compare to: $\mathbf{g_P(Theory) = 8.26 \pm 0.23}$

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

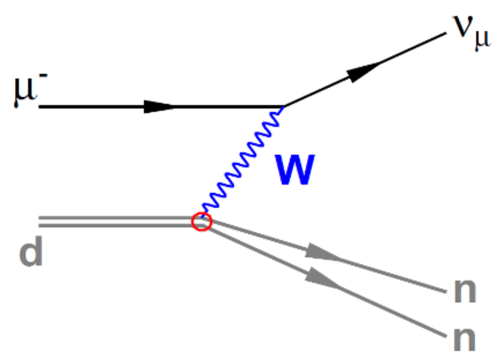
***US led effort at PSI**

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)

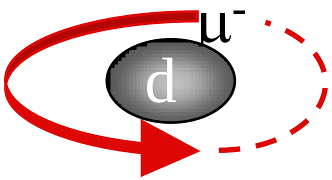
Tiny cross sections, predictions rely on theory

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

***US led effort at PSI**

model-independent connection via EFT

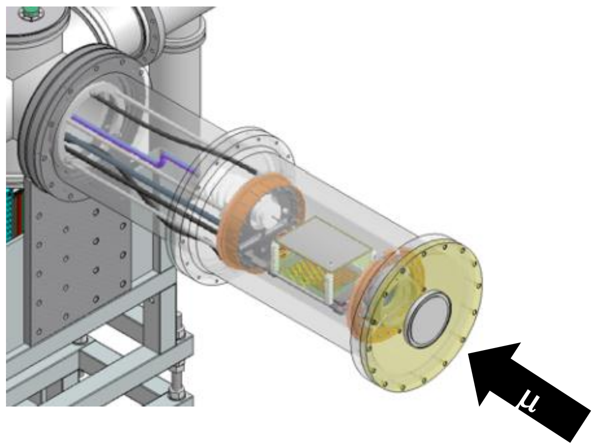
Capture rate is deduced from μ^+/μ^- lifetime difference



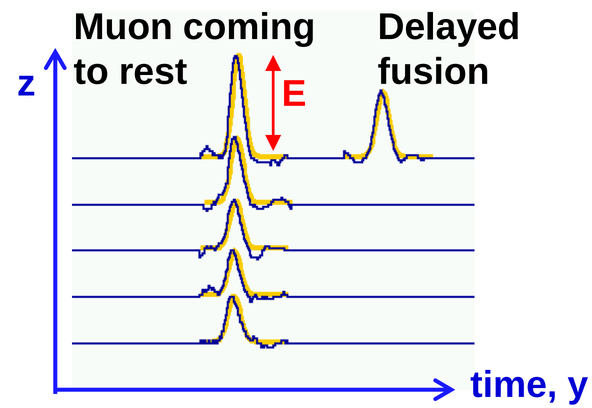
Muon forms atom, overlap with nucleus enhanced.

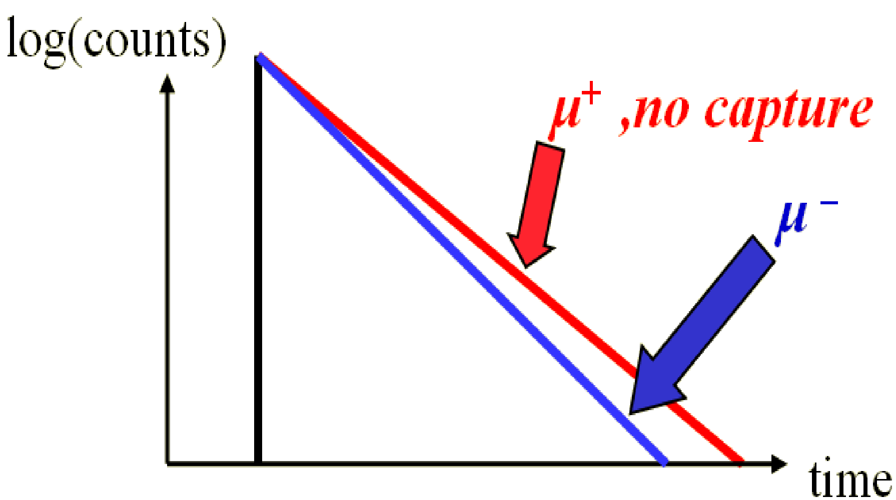
Short range EW interaction leads to small, but **observable** rate.

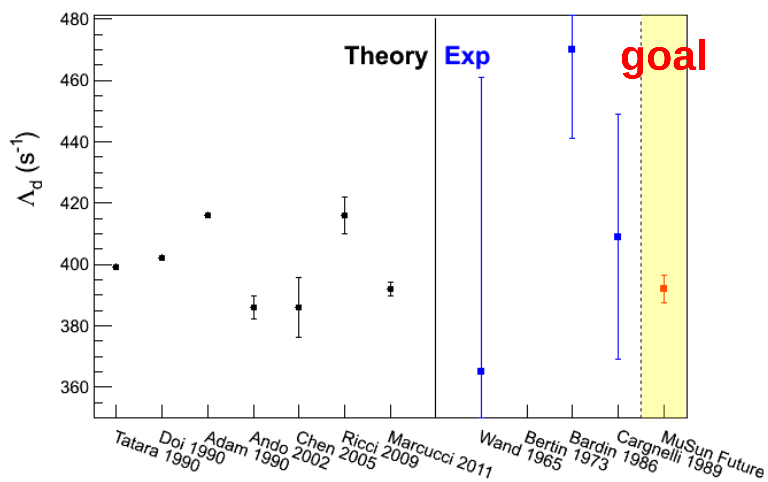
$\mu^- + d \rightarrow \nu + n + n$ (~0.1% compared to decay)



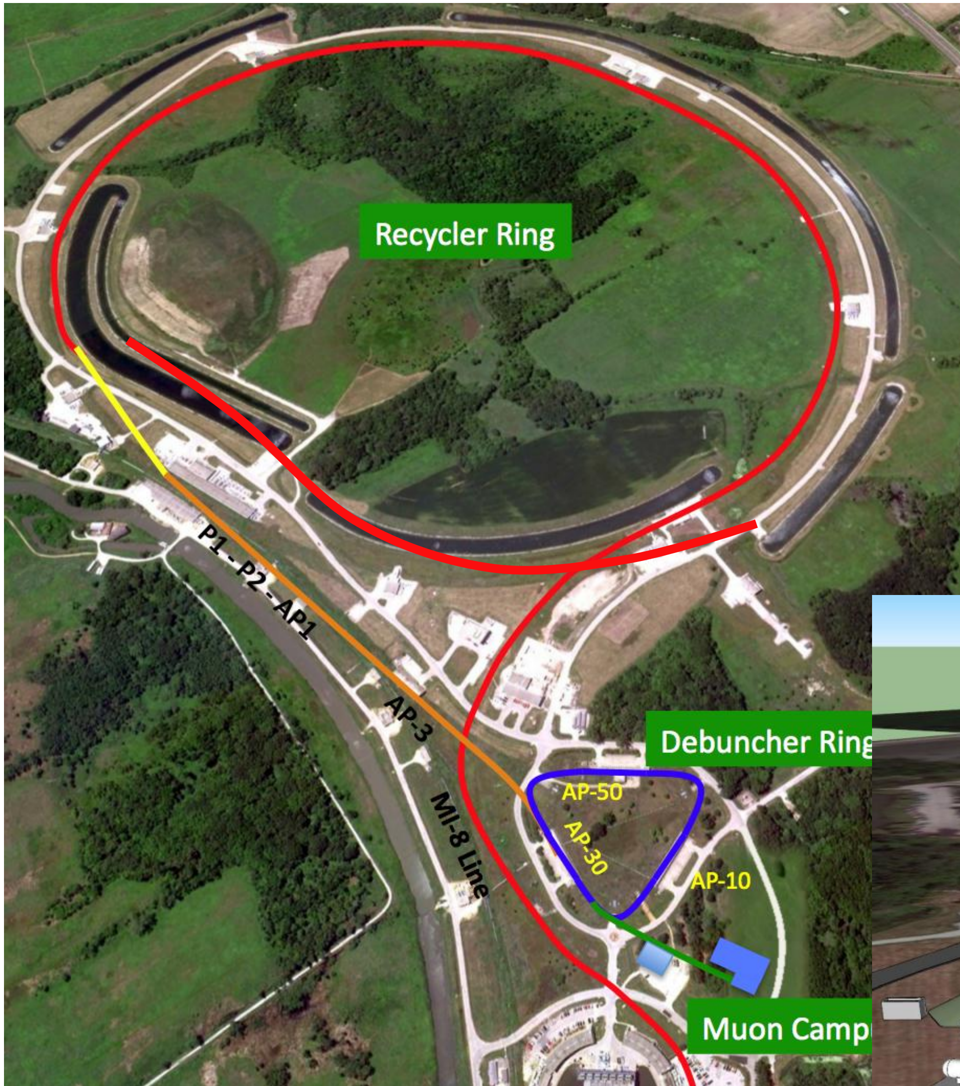
Cryo-TPC







FNAL initiates Muon Campus concept to serve new g-2, Mu2e and parasitic EDM experiments

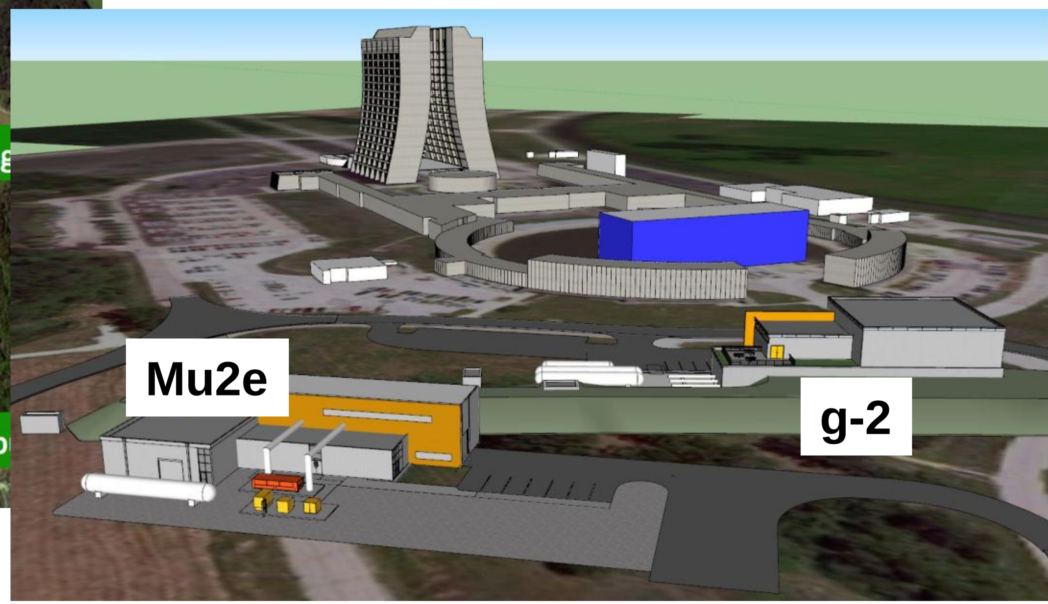


For g-2, achieves

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

For Mu2e, achieves

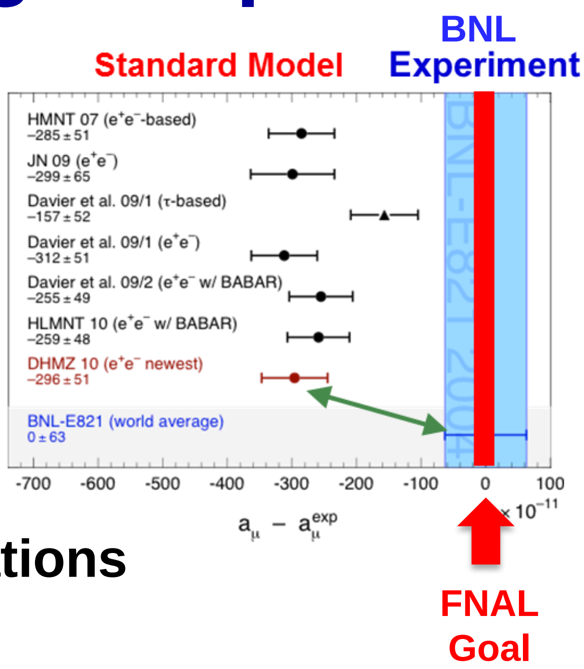
1) Ideal proton bunches for mu formation
2) High intensity / Extinction



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

$$a_\mu(\text{Expt}) - a_\mu(\text{SM}) = (296 \pm 81) \times 10^{-11} \quad (3.6\,\sigma)$$

What is nature trying to tell us?

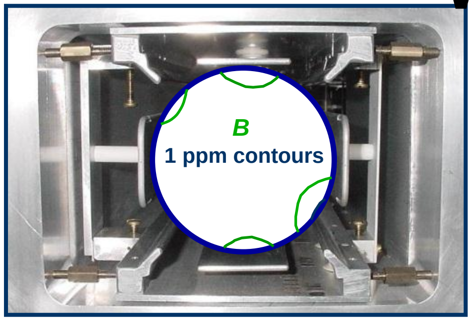


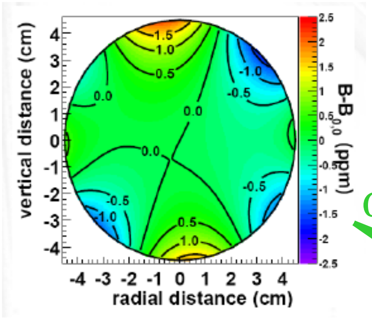
- **Magnitude and sign have important implications**
- **1-D UED models predict “tiny” effects**
- **SUSY models – many predict large contributions as observed**
- **The “Uninvented” – sets a stringent experimental constraints for any new models, together with other low- and high-energy data**

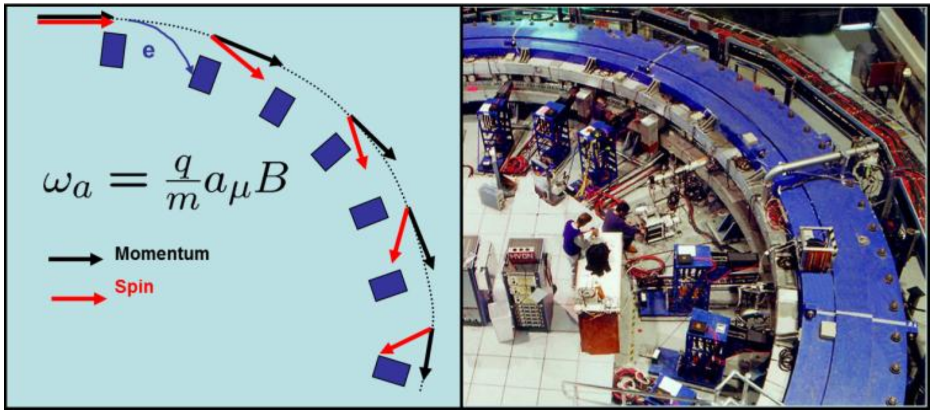
Last g-2 experimental results have > 2000 citations.
It’s highly relevant in helping shape the New Standard Model we hope to discover

Method*

The anomaly is obtained from three well-measured quantities

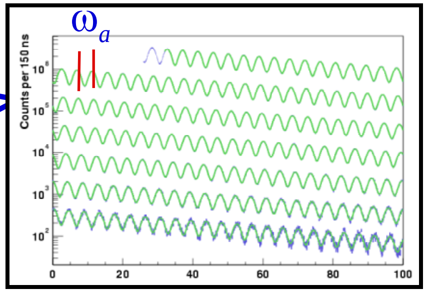




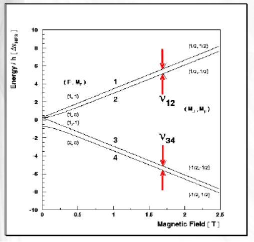


ω_p

ω_a



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



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 strengths**
- **VERY strong Nuclear Physics community effort here**

GOAL

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

0.1 ppm statistical

0.1 ppm systematic

Theory uncertainty: 51 → 30 x 10^{-11}

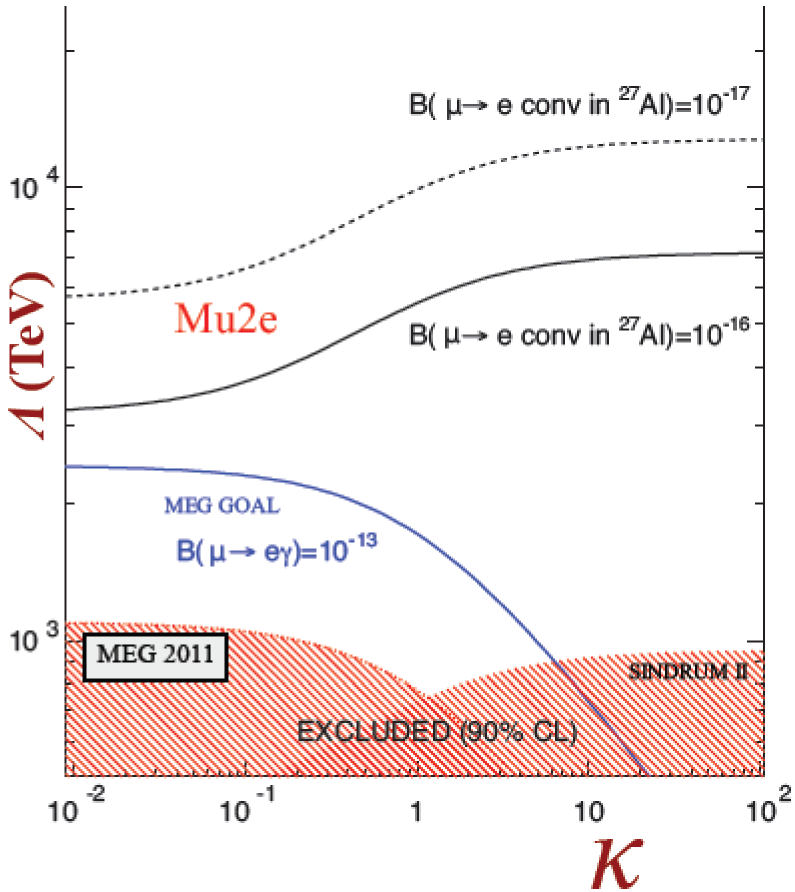
Future: Δa_{μ}(Expt – Thy) = xx ± 34 x 10^{-11}

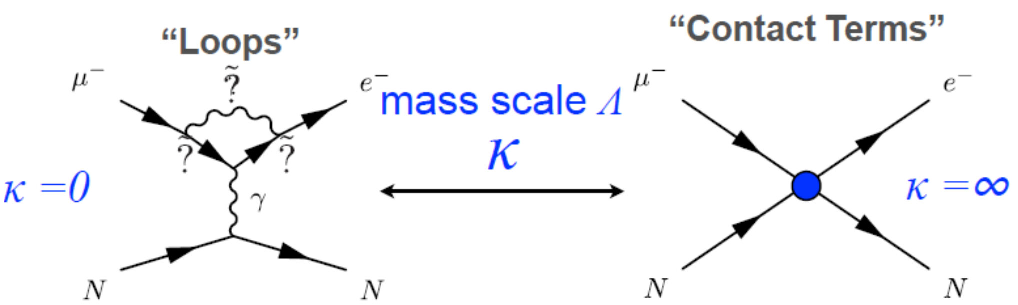
(If xx remains 296, the deviation from zero would be close to 9σ)

Muon-to-Electron Conversion: Mu2e*

The SM theory is clear: It won't happen

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





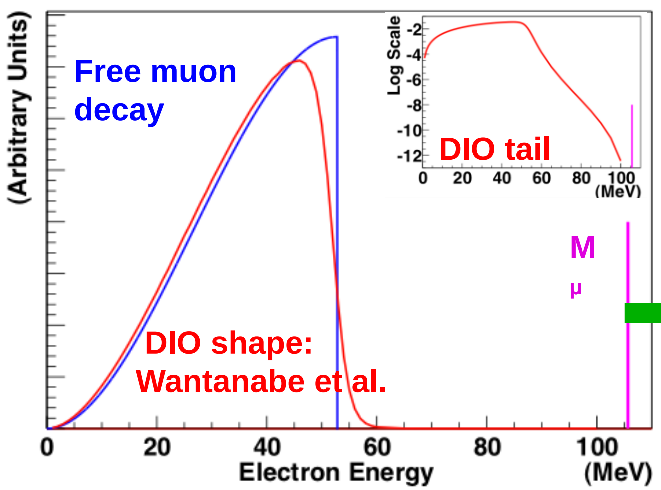
Vertex correction" vs "4-fermion" operator

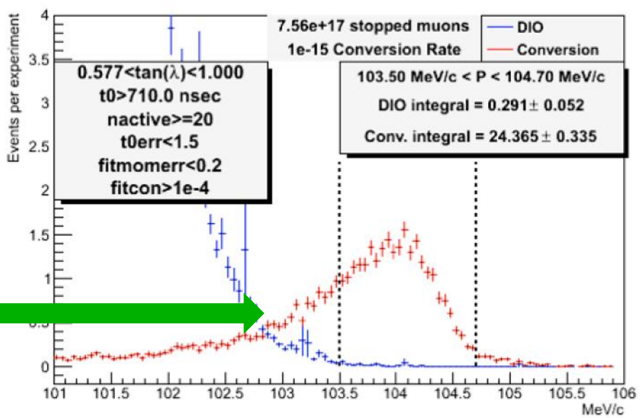
*Nuclear / Particle / Accelerator collaboration at Fermilab

Method and Goal

- Make muonic Al atoms.
  - 40% will decay "in orbit";
  - 60% will capture (junk emitted)
- Look for mono-energetic e^-, at muon mass (~104 MeV)
- Severe high rates implies tracking issues
- Avoid fake backgrounds: Goal single event sensitivity $< 2 \times 10^{-17}$

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



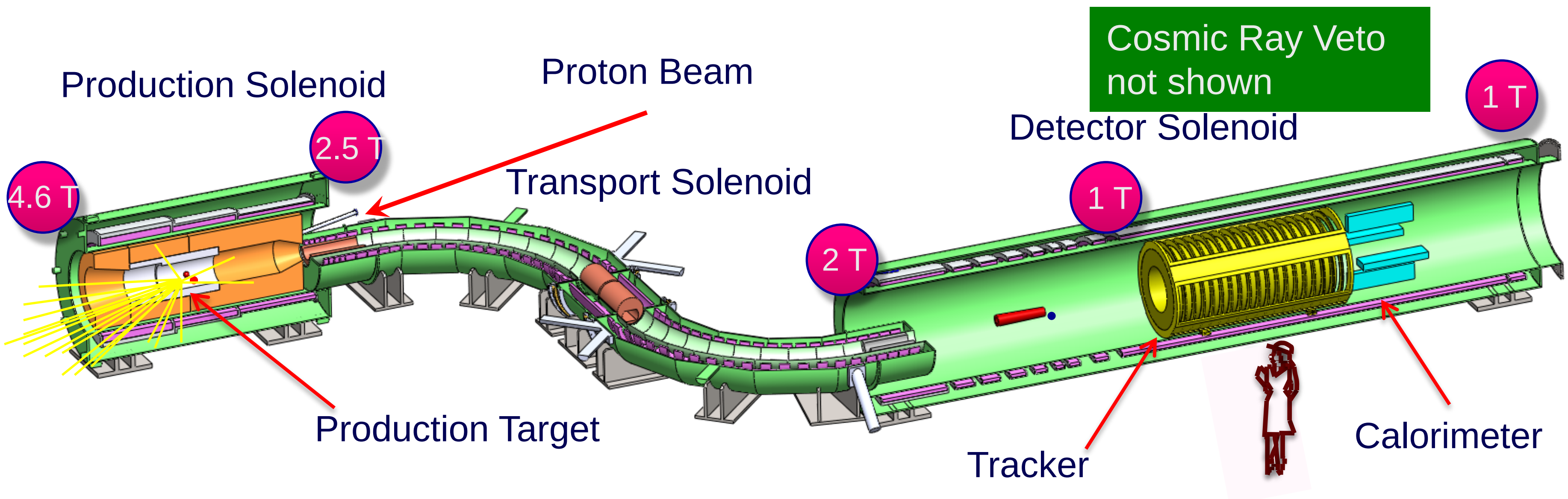


Resolution at 104 MeV matters!

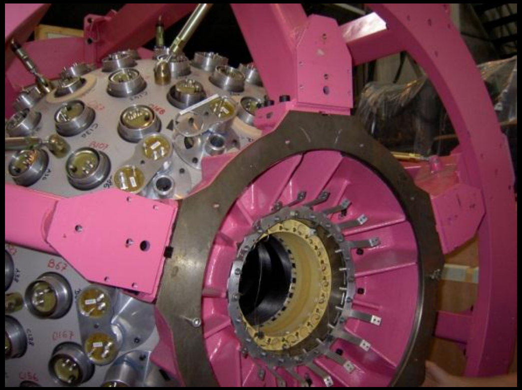
How it is done

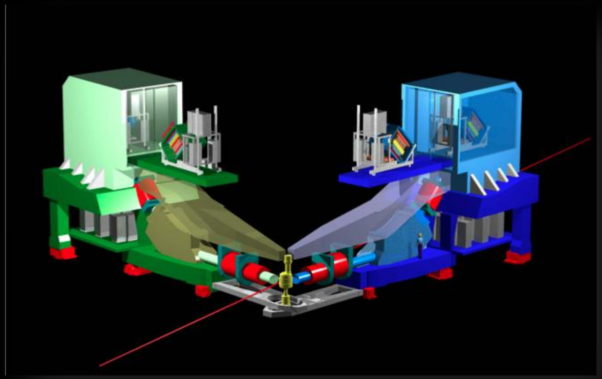
(note: somewhat similar project COMET starting in Japan)

This experiment is in R&D and Pre-Construction Mode with CD1 approval

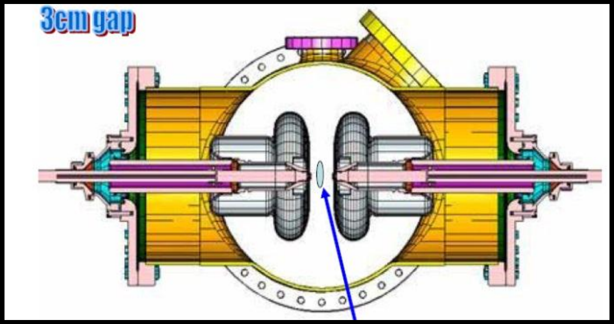


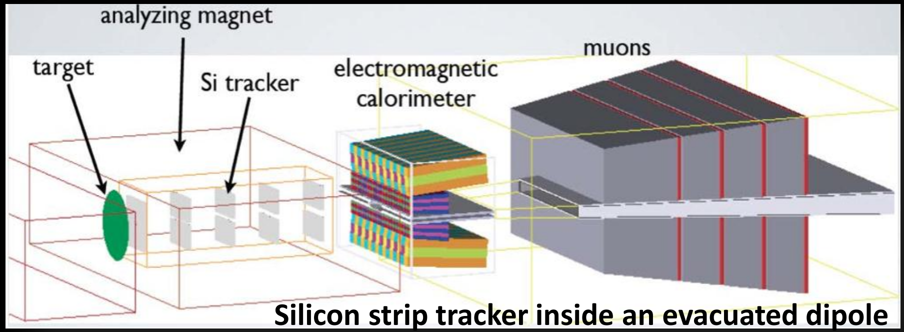
Chapter 2:
Pions & Photons





A' ?





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

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

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

PEN, PiENu aim at: $\frac{\delta B}{B} \simeq 5 \times 10^{-4}$ **x 10 improvement**

PEN data taking complete. Analysis in progress

PiENu data taking

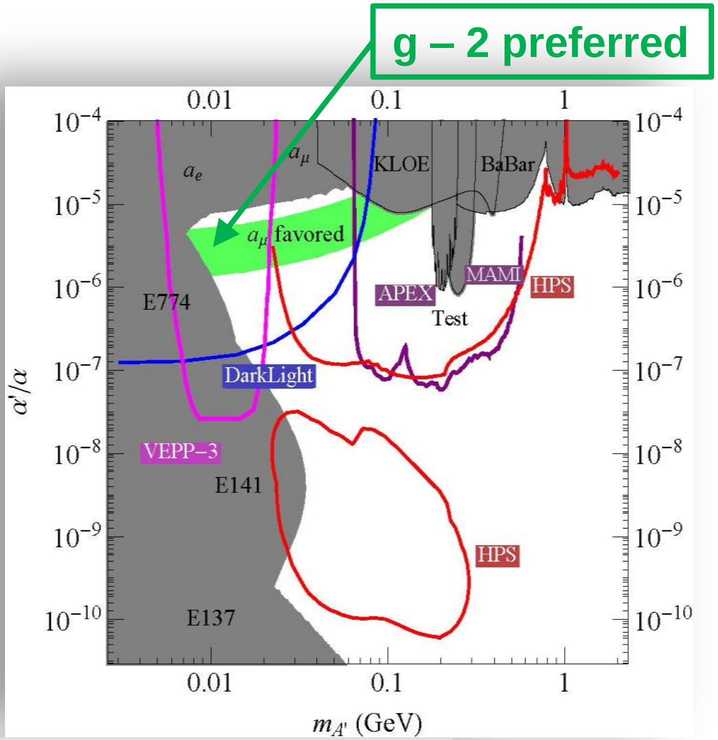
*at PSI **at TRIUMF

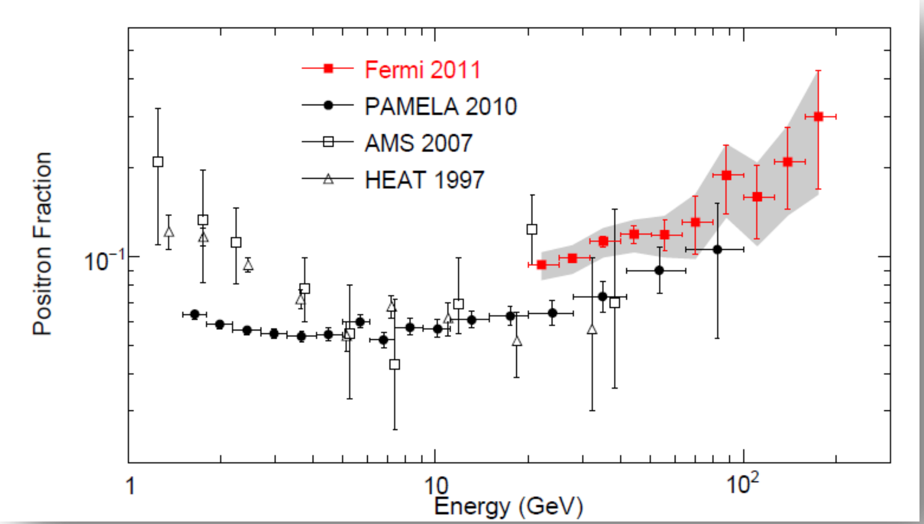
2010 → … Dark Photon searches: @JLab

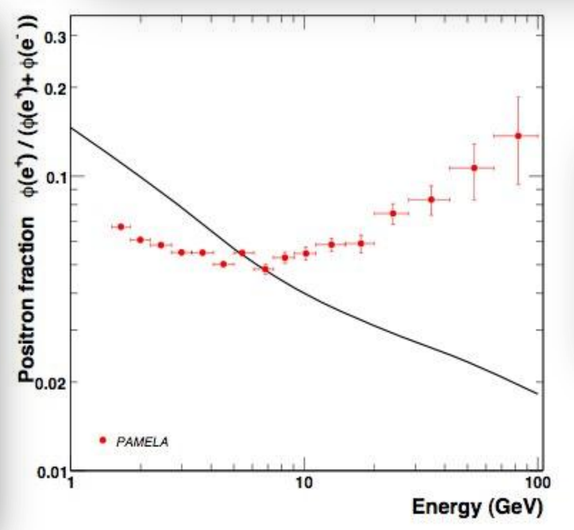
- **A', a massive neutral vector boson**
  - kinematically mixes with γ
  - $\alpha' = \varepsilon\alpha_{e.m}$ $\varepsilon = 10^{-2} - 10^{-6}$
  - Mass in the MeV-GeV region

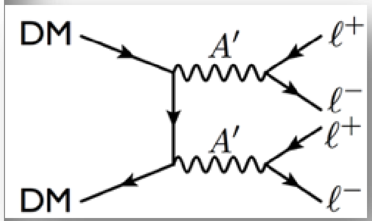
- **Can explain g-2 discrepancy**

- **Can explain cosmic positron data**

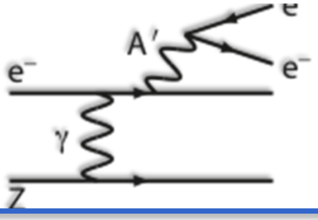




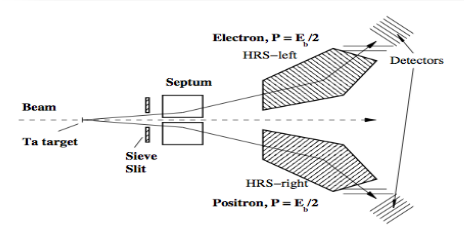




Method: Produce A' with electron beam
Detect pair decays (narrow peak above background)

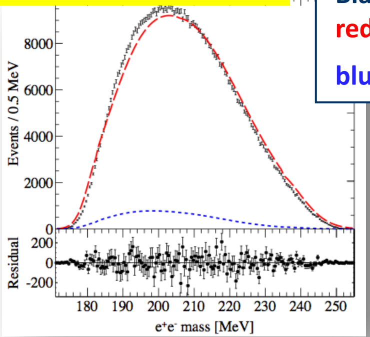


APEX in Hall A



Simplest using existing spectrometers

PRL 107 (2011) 191804



Black →data
red→MC
blue→e+e– acc.

Heavy Photon Search @ Hall B

Physics reach: $\varepsilon < 10^{-4}$; mass 20-800 MeV

Parasitic test run complete 2012

Plan for physics run in 12 GeV era

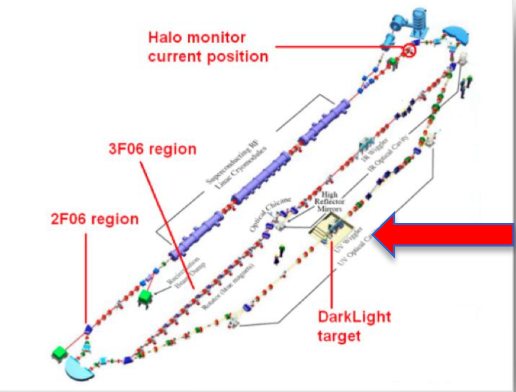
HEP funded

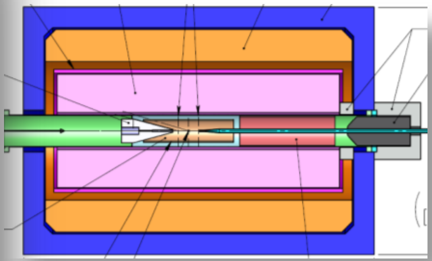
DarkLight @ the JLab FEL

- 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

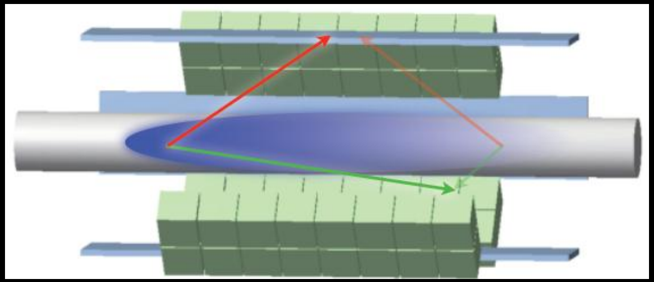
Successful Test Run (July 2012)

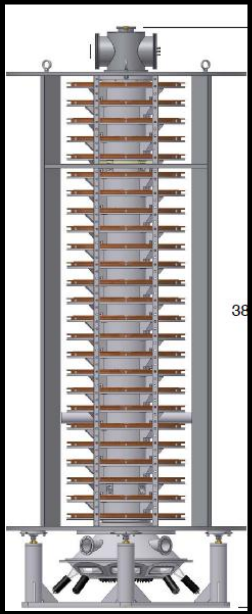
Seeking funding

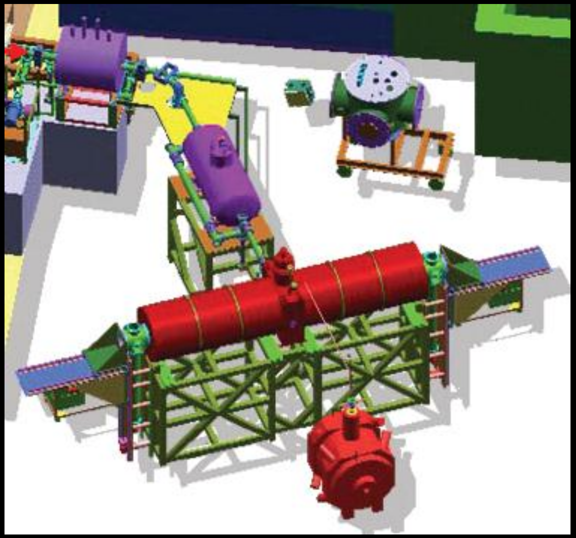


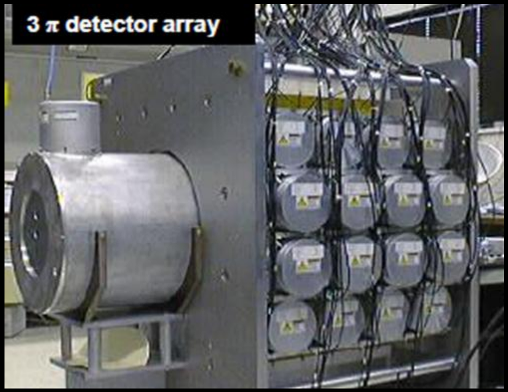


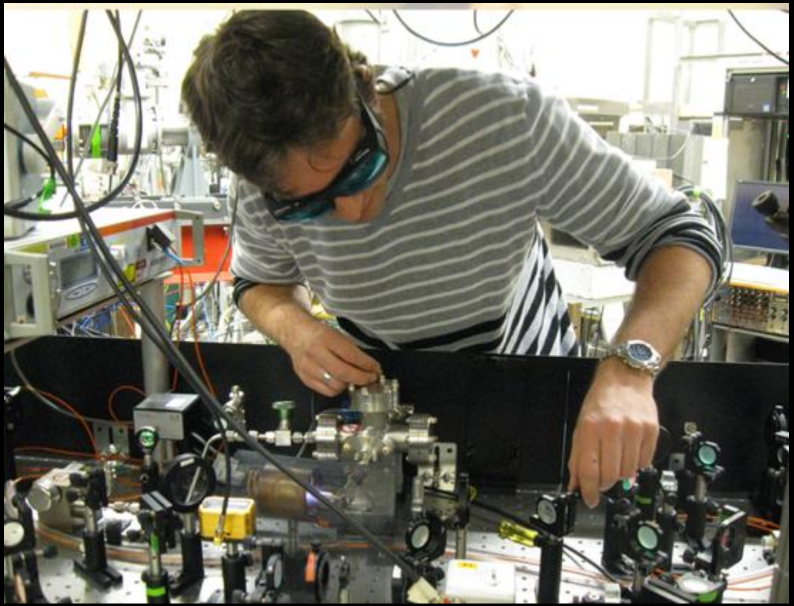
Chapter 3: Neutrons & Nuclei











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

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

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

- 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)

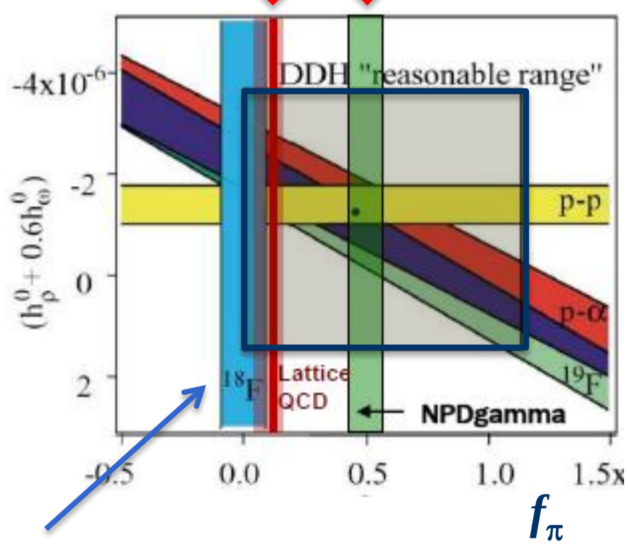
$f_\pi = 1.099 \pm 0.505 {}^{+0.058}_{-0.064}$ [x10^{-7}] ($m_\pi \sim 589 MeV$)

GOAL

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

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



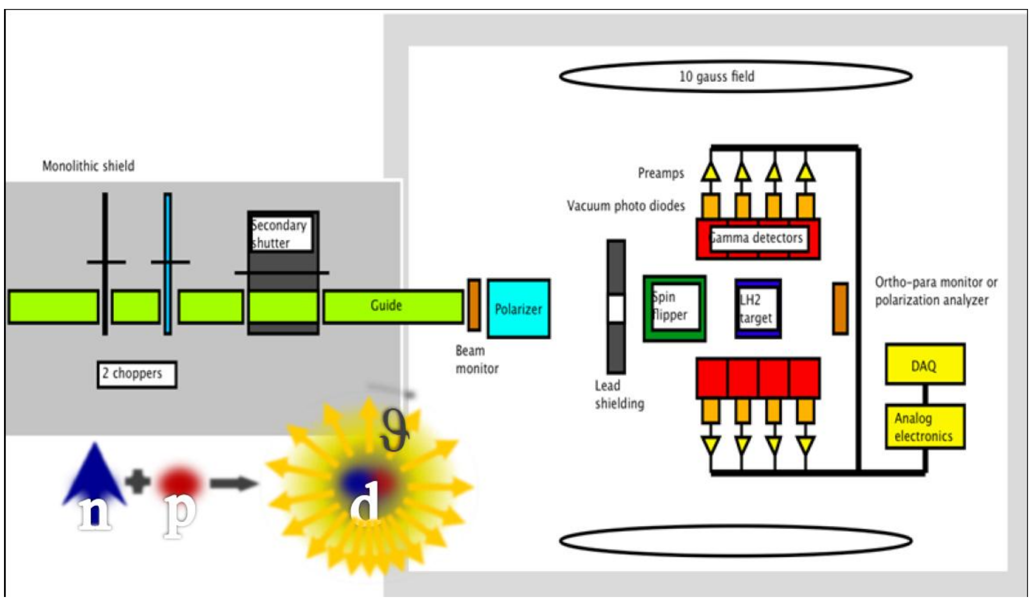
Curious result

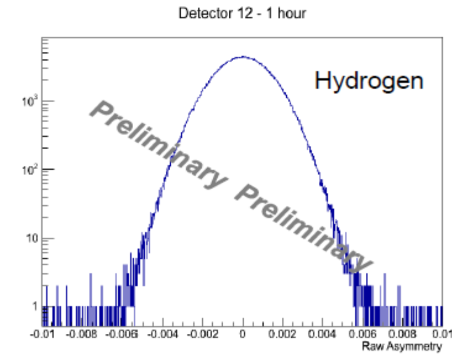
Method and Status: On floor at the FnPB (SNS)

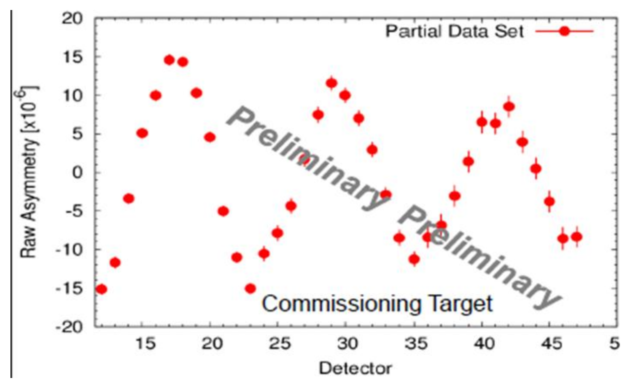
- **Already taken hydrogen data at the 5×10^{-8} A_γ level.**

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

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







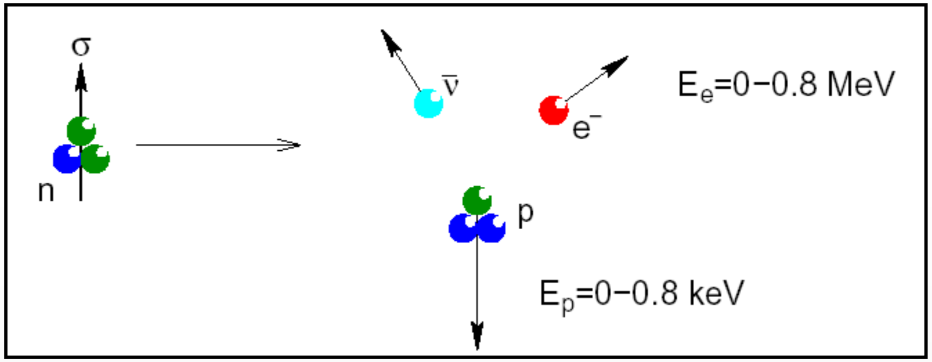
- **200 MW-days, starting next month, needed to reach goal of 1×10^{-8}**

The Neutron as a Fundamental Laboratory

$n \rightarrow p^{+} + e^{-} + \nu'_{e}$

neutron lifetime $\tau \approx 15$ min

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



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

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

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

$$b = 0$$

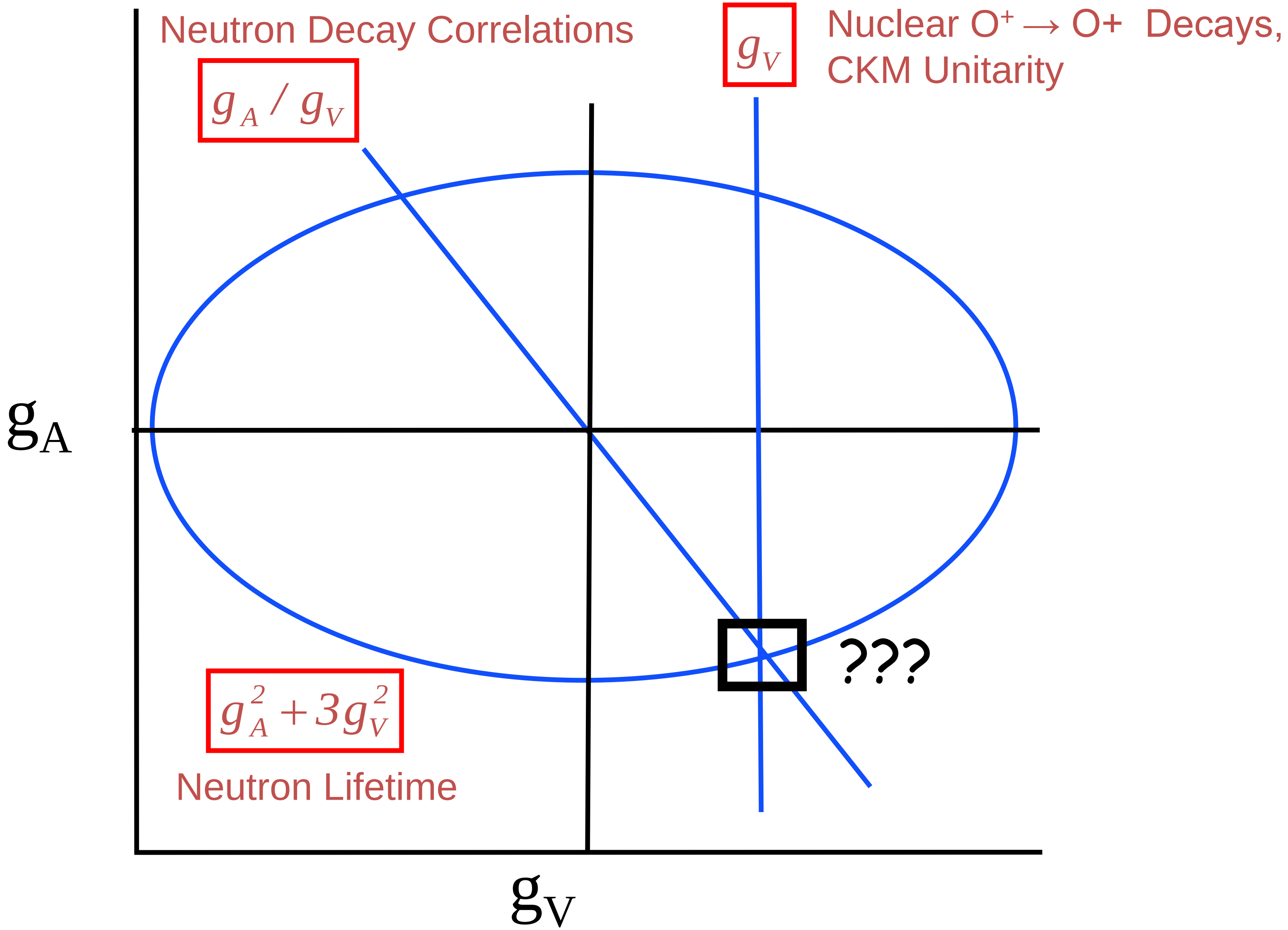
$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

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

Neutron beta decay measurements give:

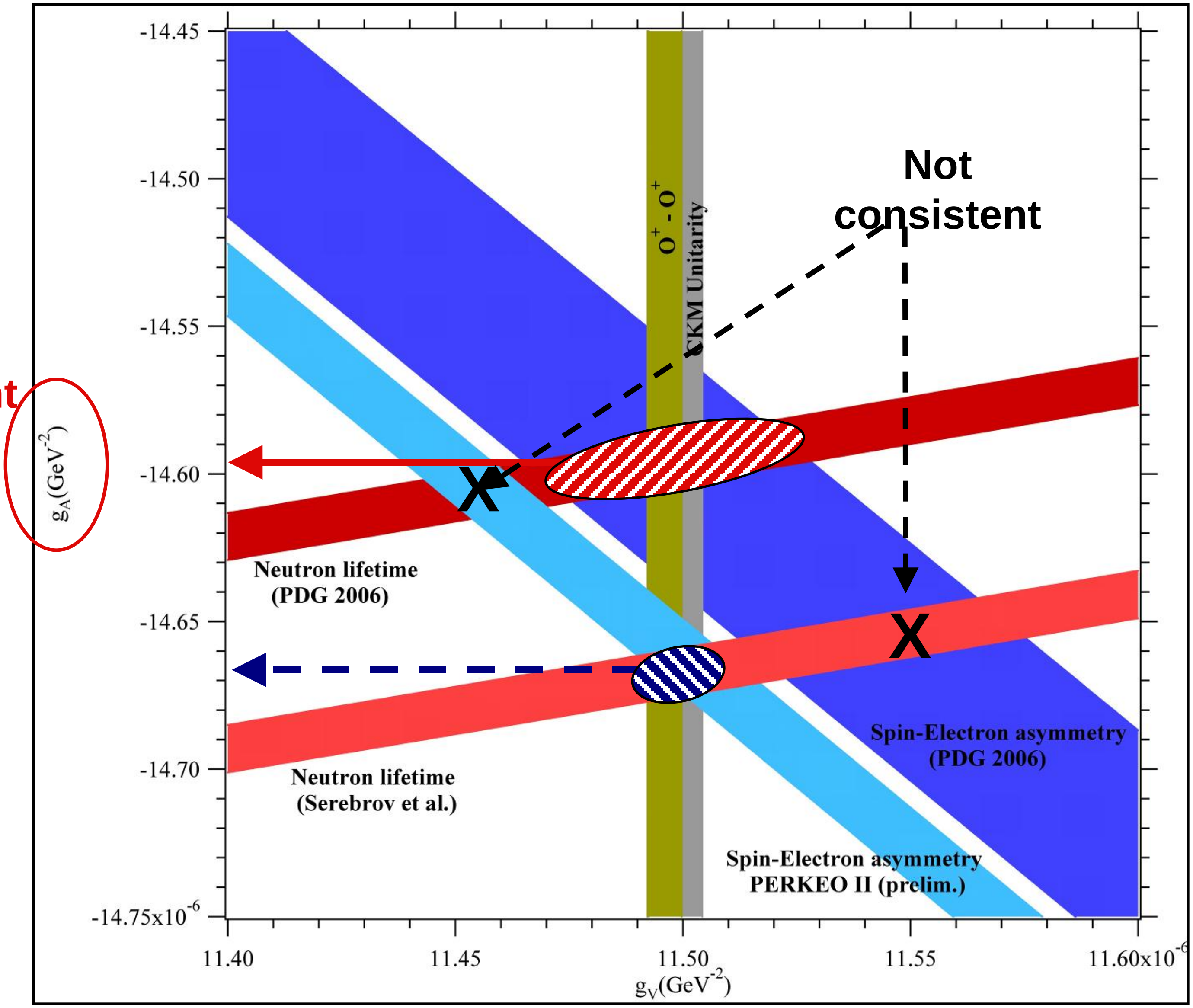
$$(g_A^2 + 3g_V^2)$$

$$g_A / g_V$$


Neutron Decay Correlations
g_A / g_V
g_V
Nuclear $O^+ \to O+$ 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

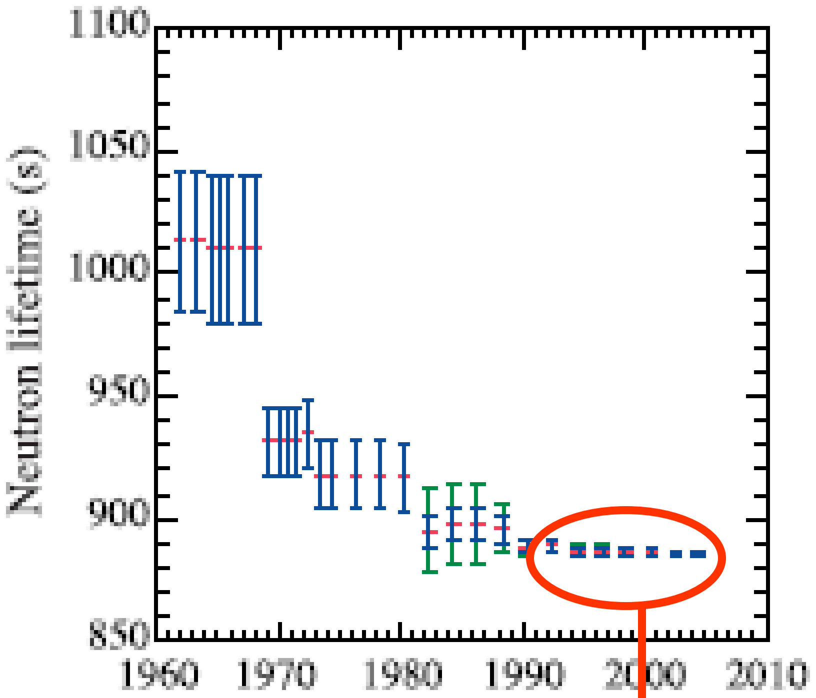
g_A important

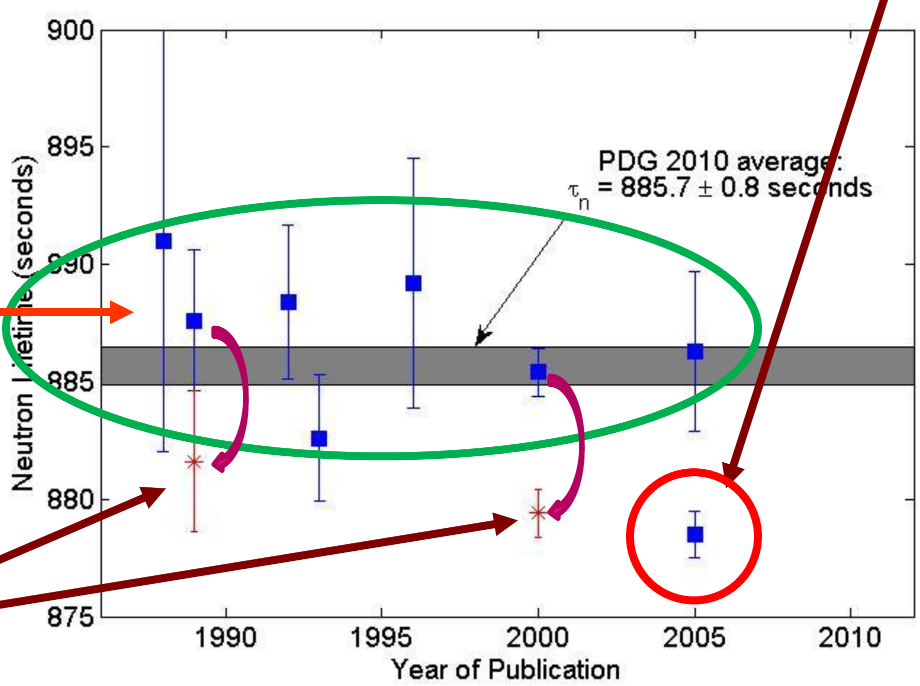


$$g_V \equiv G_F V_{ud} f(0)$$

J. Nico, 2007

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





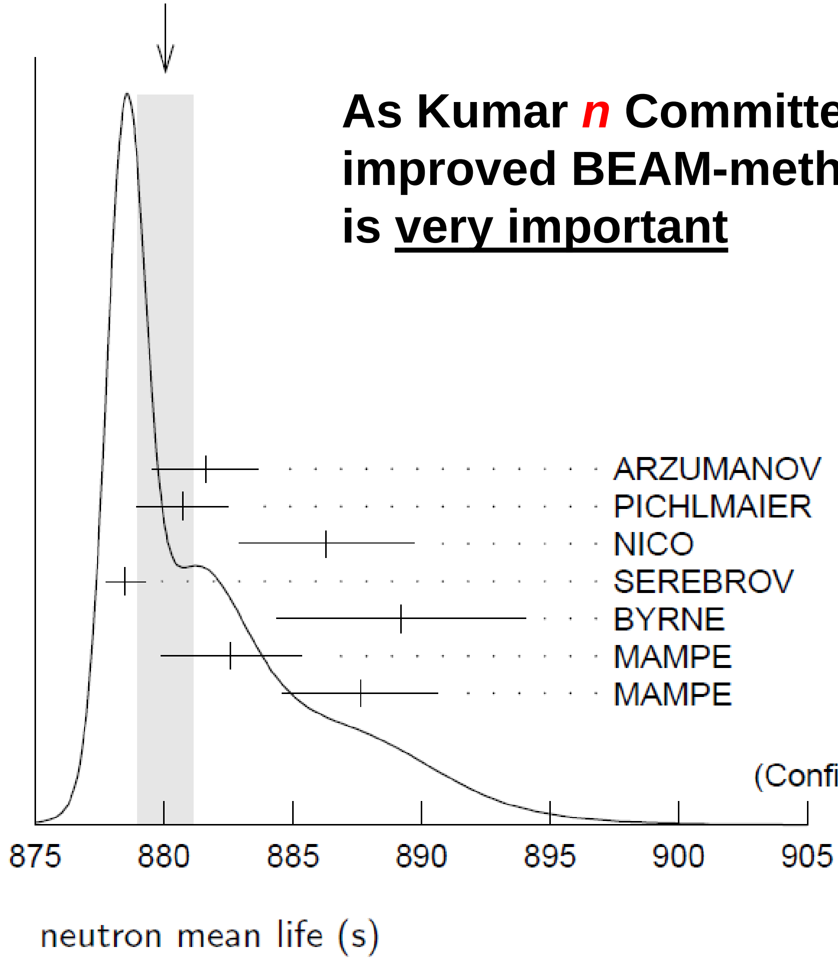
Serebrov et al.,
(878.5 ± 0.7 ± 0.3) seconds

Reanalysis of bottle experiments by Serebrov, et al.

2012: *n* Lifetime Update: PDG

WEIGHTED AVERAGE
880.1±1.1 (Error scaled by 1.8)

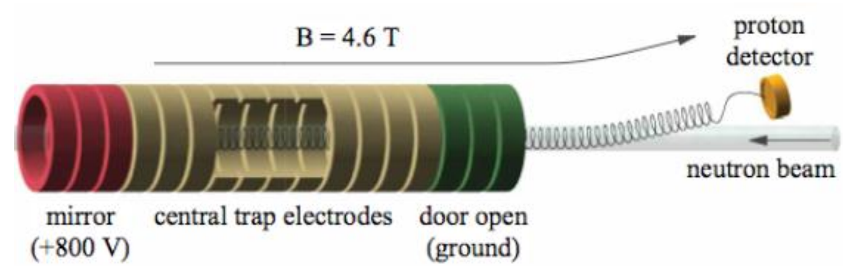
As Kumar *n* Committee recommended, an improved BEAM-method at 1-s precision is <u>very important</u>



			χ^2
ARZUMANOV	12	CNTR	0.6
PICHLMAIER	10	CNTR	0.1
NICO	05	CNTR	3.3
SEREBROV	05	CNTR	4.2
BYRNE	96	CNTR	3.6
MAMPE	93	CNTR	0.9
MAMPE	89	CNTR	6.3
			19.0

(Confidence Level = 0.0042)

NIST beam method



PDG uses latest 7, including corrected and other newer results

J. Nico

Big Bang Nucleosynthesis

Thermal Equilibrium (T > 1 MeV)

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$
$$n + \nu_e \leftrightarrow p + e^-$$

$n/p \sim e^{-Q/T}$

After Freezeout

n/p decreases due to neutron decay

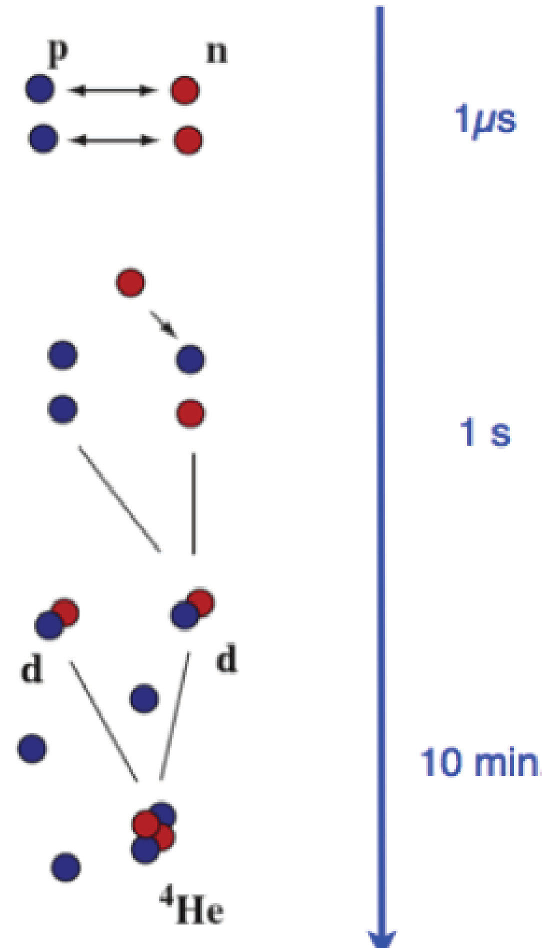
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Nucleosynthesis (T~0.1 MeV)

Light elements are formed.

$$p + n \rightarrow d + \gamma$$
$$d + d \rightarrow {}^4He + \gamma$$

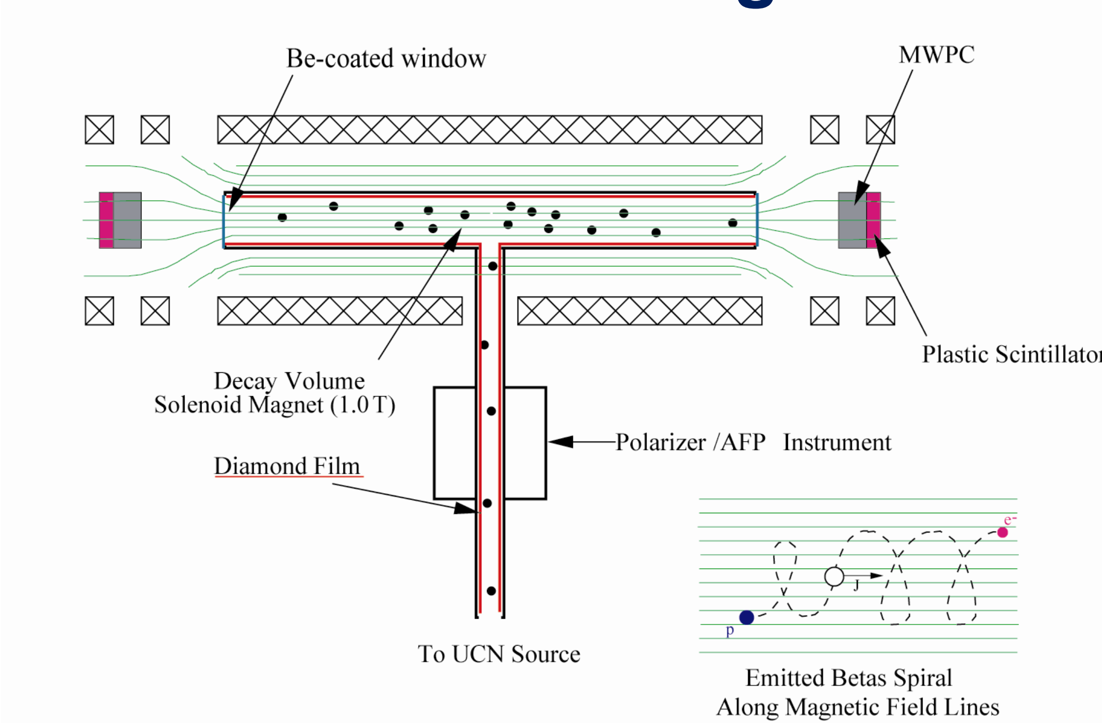
almost all neutrons present $\rightarrow {}^4He$

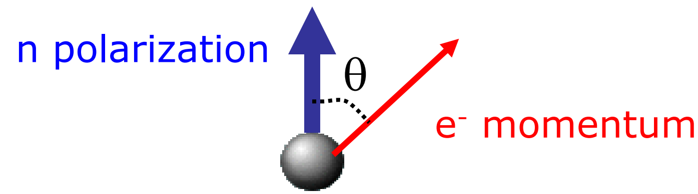


Neutron lifetime dominates theoretical uncertainty in ^{4}He abundance.

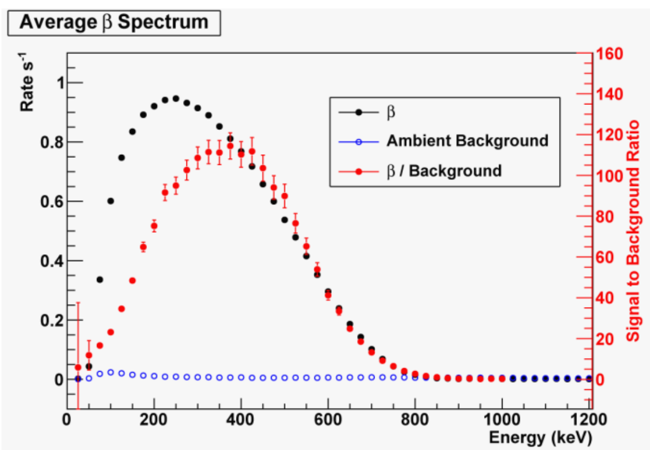
Kolb and Turner, The Early Universe, 1990

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)**



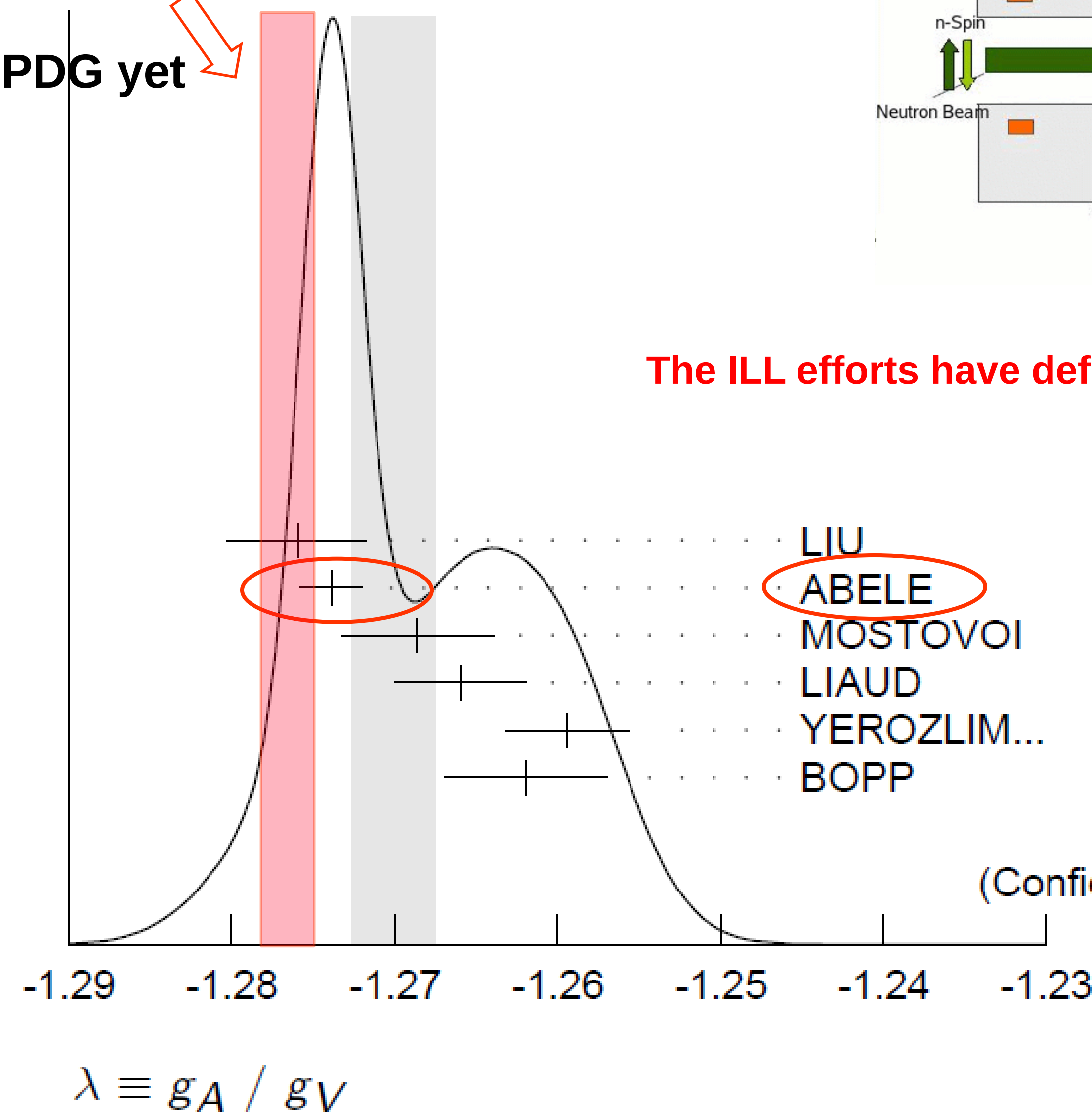
Year	**Statistics**	**δA/A**	**Published**
2007	2 M	**4.5%**	2009
2008/2009	24 M	**1.4%**	2010
2010/2011	**65 M**	**<1%**	**Fall 2012**

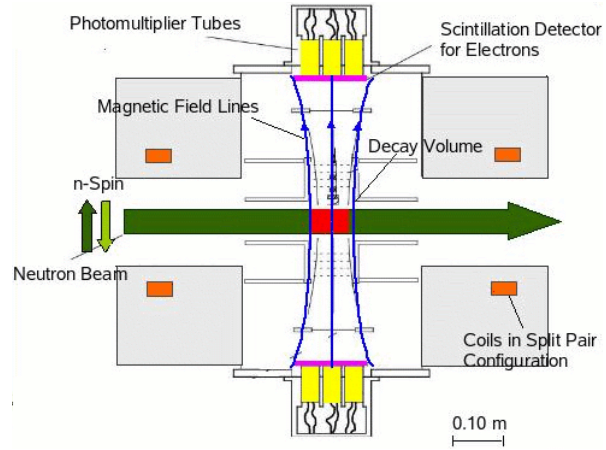
$$R = R_o(1 + (v/c)\, P\, A(E) \cos\theta)$$

WEIGHTED AVERAGE
-1.2701±0.0025 (Error scaled by 1.9)

MUND et al (2012)
= −1.2767(16)

Not in PDG yet





PERKEO II

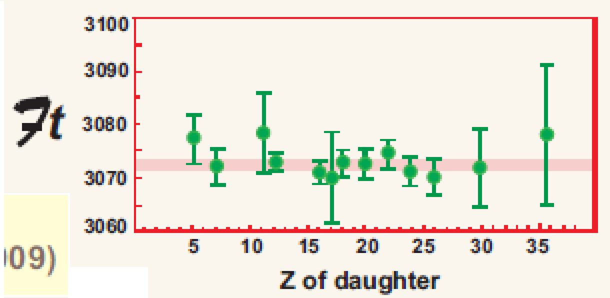
The ILL efforts have defined the field for a long time

			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)

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

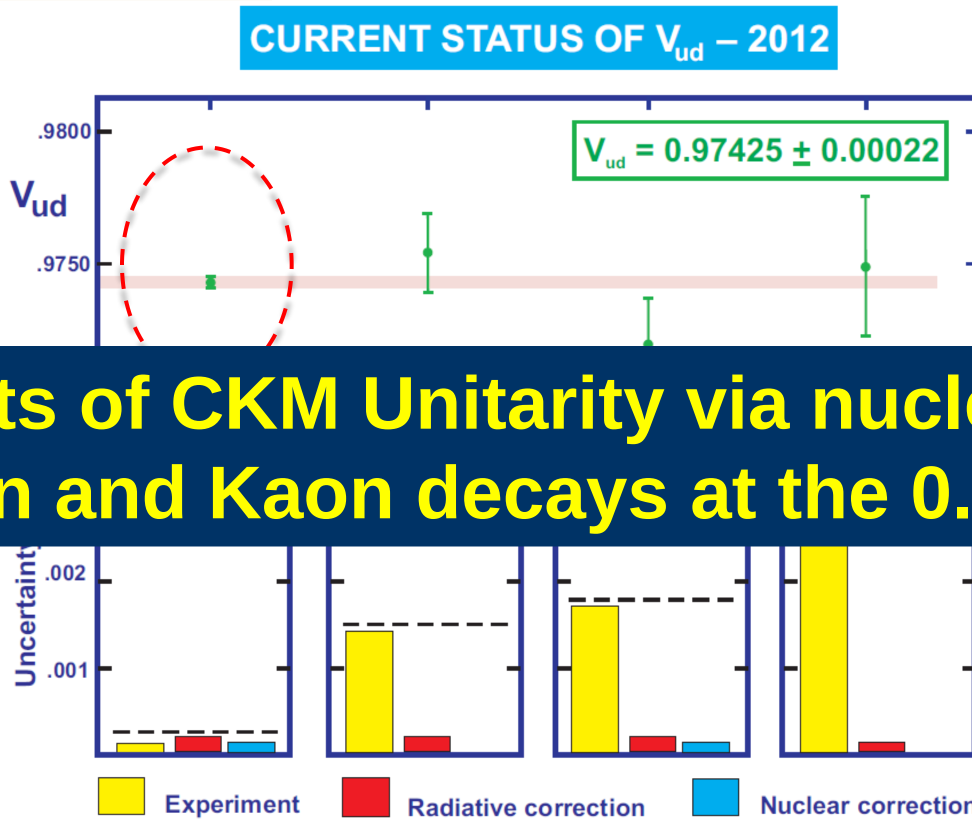
$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$



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

CKM unitarity test:

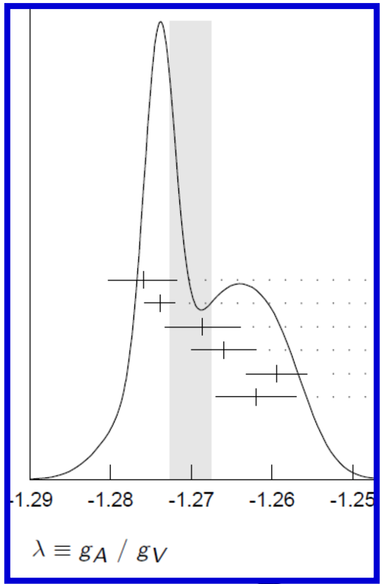
$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9999(6)$

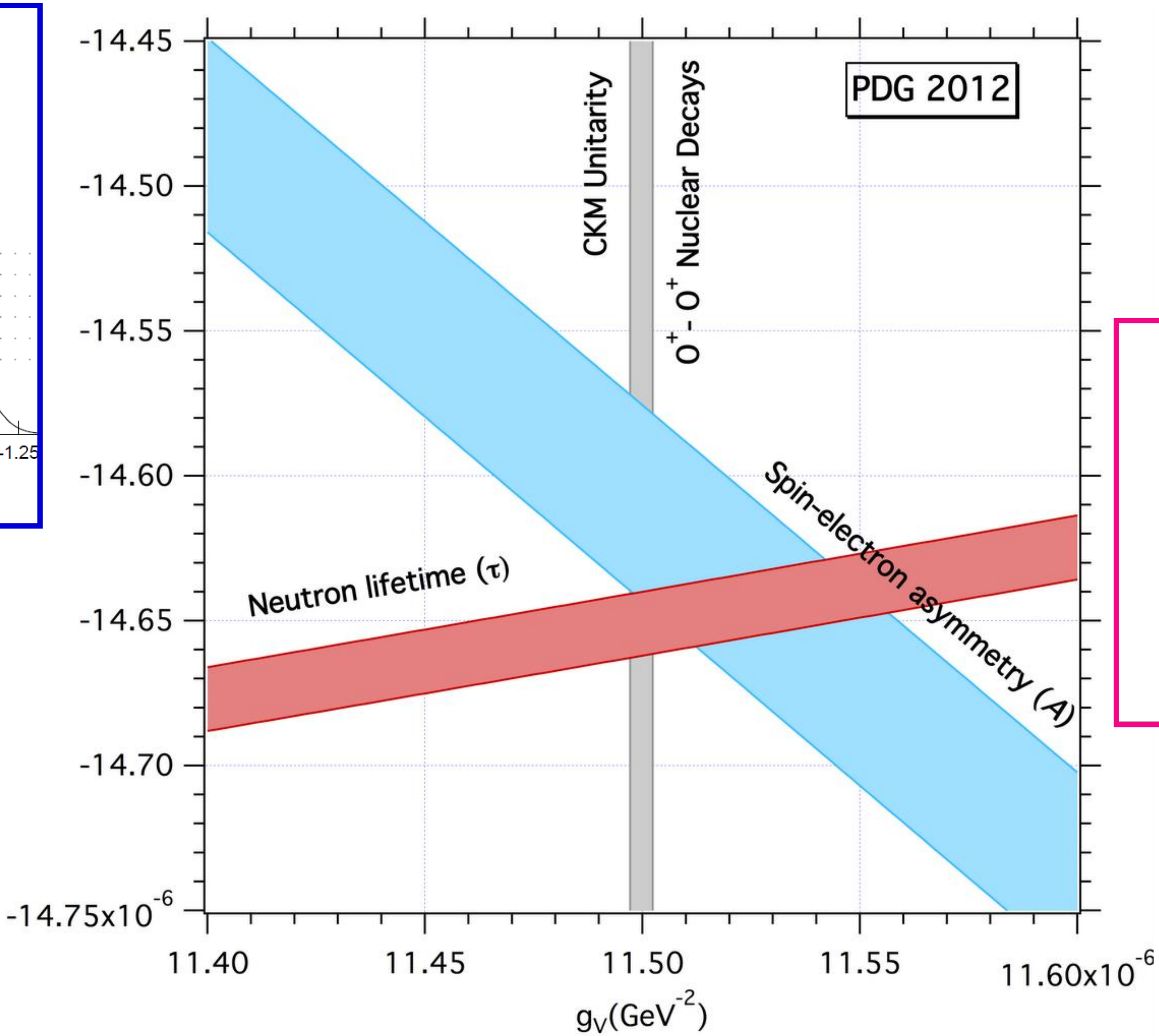


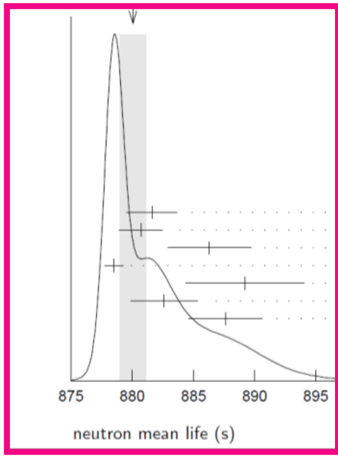
Tests of CKM Unitarity via nuclear beta, muon and Kaon decays at the 0.06% level

Hardy et al

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







J. Nico, 2012

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

2015- Nab – future and beyond

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

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

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

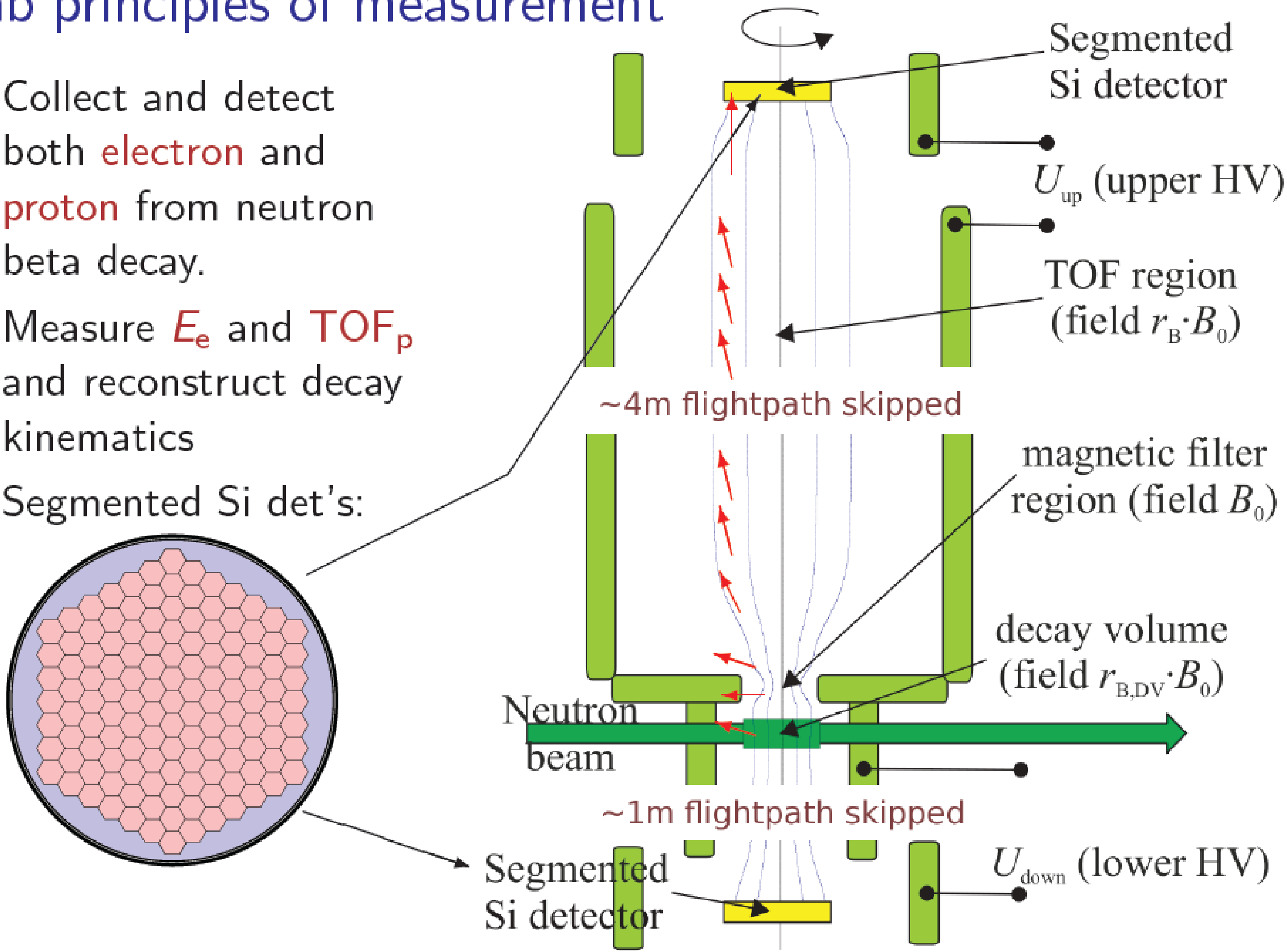
- Measure the Fierz interference term **b** in neutron decay

  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

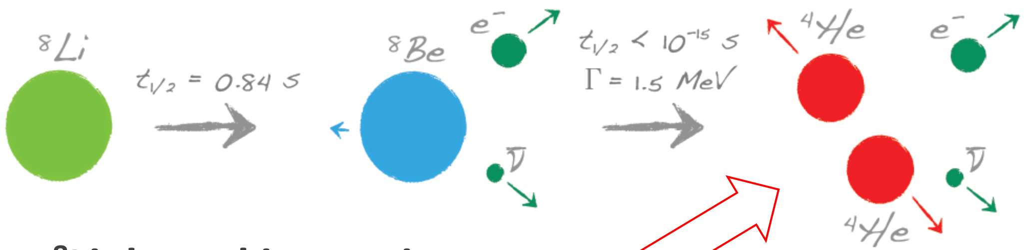
- Collect and detect both electron and proton from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:

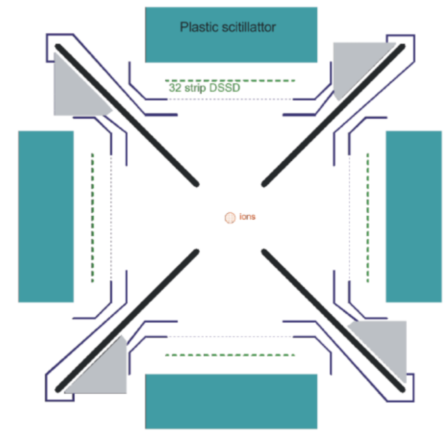


Toward Exotica with Nuclei

(just a few examples)

Argonne





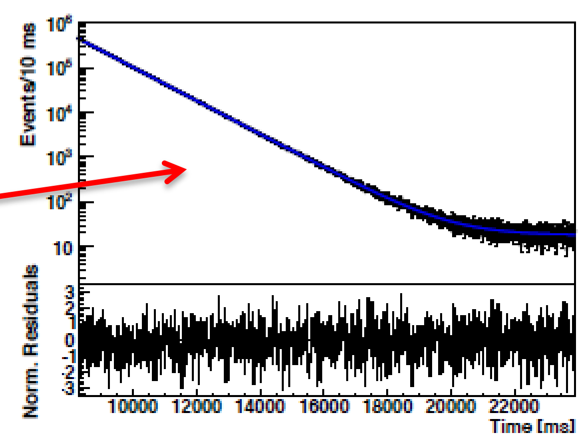
Linear Paul trap cross section

^{8}Li decay kinematics

- Pure GT decay
- Characteristic β–α–α coincidence

Seattle Tandem van de Graaff

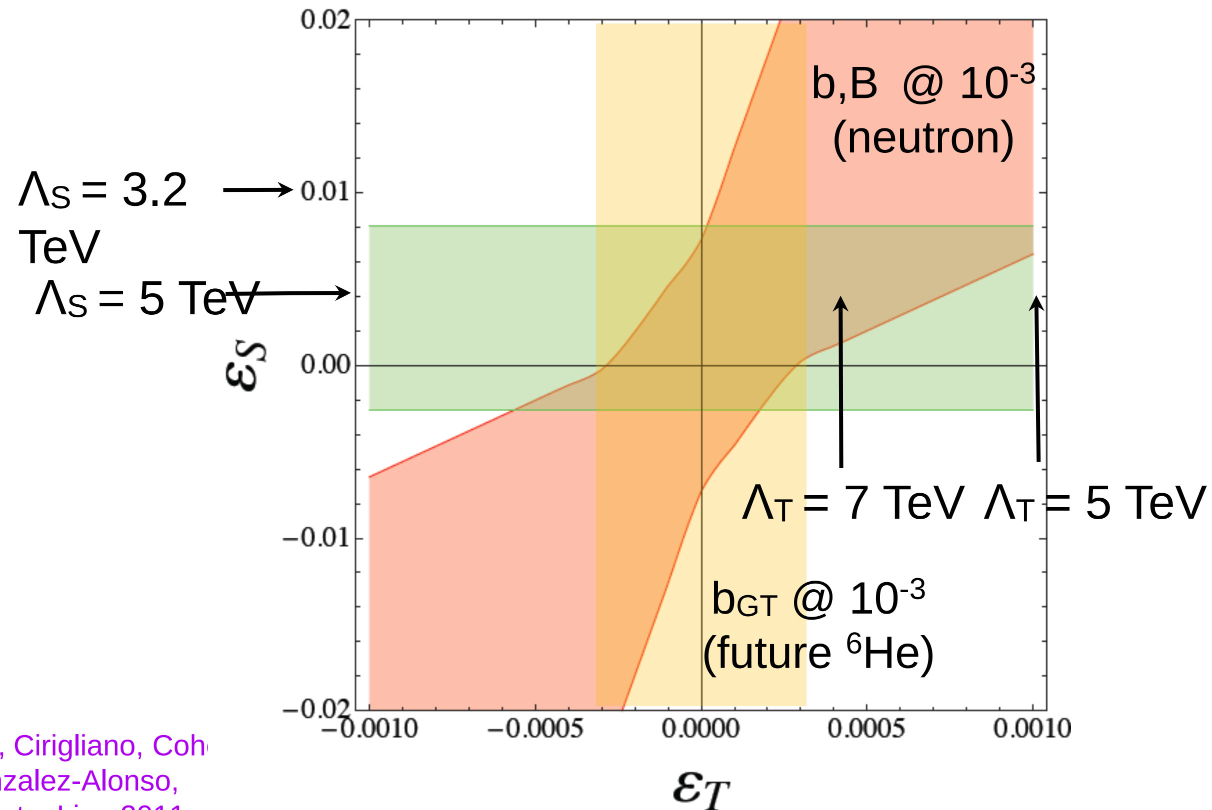
→ 10^9 ^{6}He atoms/s
→ Lifetime
→ Decay correlations with MOT



Probing exotic scalar and tensor CC couplings

$$\mathcal{L}_{\rm CC} \supset -\frac{G_F V_{ud}}{\sqrt{2}}\left[\epsilon_S\ \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \epsilon_T\ \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\right]$$

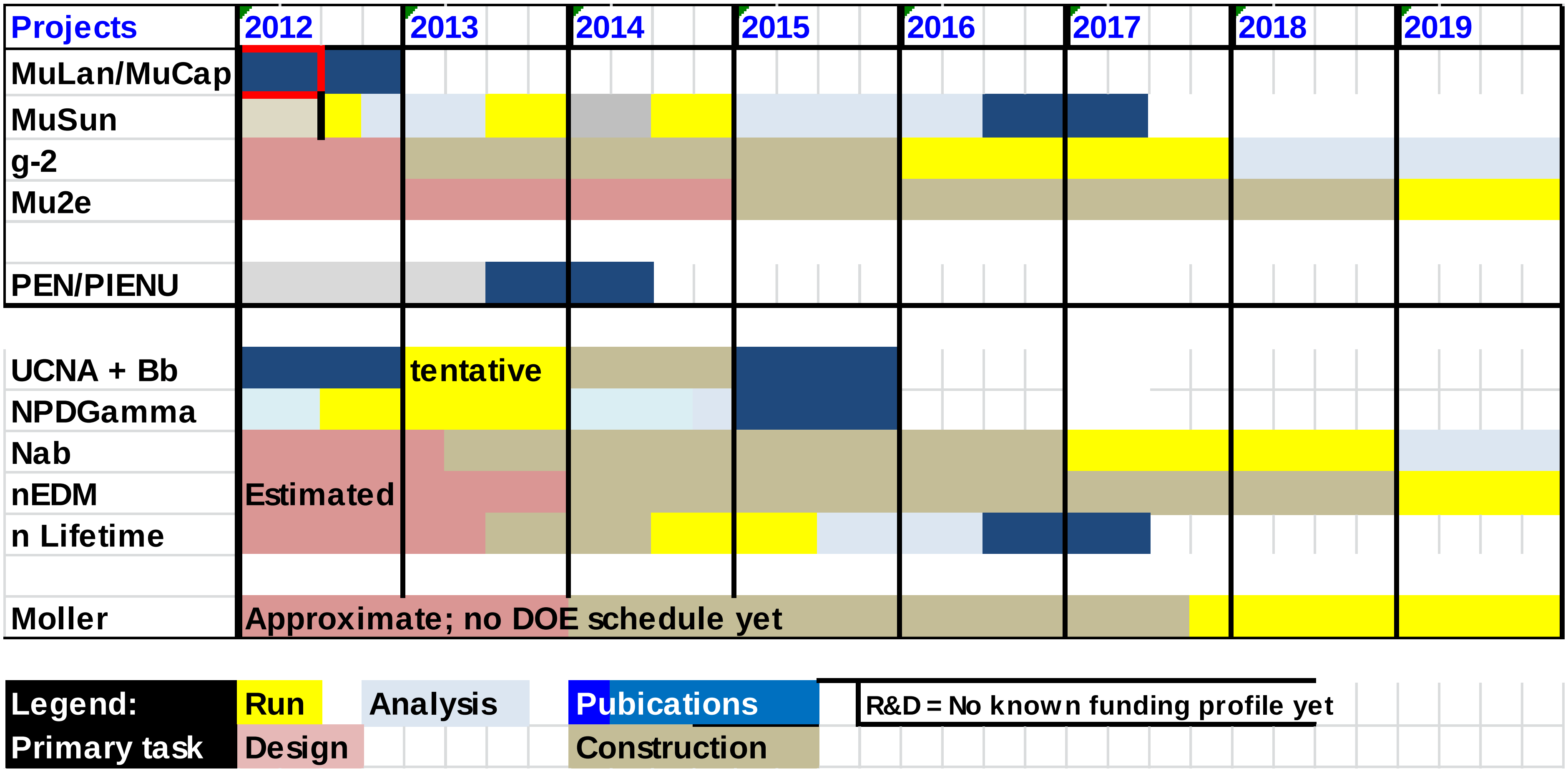
- Current: $0^+ \to 0^+$ (b) constrains ε_S ; $\pi \to e\,\nu\,\gamma$ constrains ε_T [green band]
- Future: neutron b, B @ 10^{-3} level (Nab; UCNB,b, abBA, ...) [red band], ^{6}He (b) [yellow band]



- Plot uses input on scalar and tensor nucleon matrix elements from Lattice QCD
- g_S = 0.8 (4), g_T = 1.05(35)

Bhattacharya, Cirigliano, Coh Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

FS Selected Timelines for major projects



Neutron experiments mostly from Kumar report priorities; others R&D

Many of these are approximate and depend on actual funding profiles

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 1–4)

    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