Fundamental Symmetries: Highlights

David Hertzog
University of Washington

- **Motivation**

- **An interdisciplinary Field**
  – Atomic, High-Energy, Astro- and **Nuclear** Physics communities

- ***Priorities in this Presentation***
  – ***Recent findings***
  – ***Major efforts on the horizon***
  – ***Chapters in thisTalk***
    1. ***EDMs***
    2. ***PVES***
    3. ***Neutrons***
    4. ***Muons***
    5. ***Pions and Photons***

DNP FS/Neutrino Pre-Town Meeting 2012

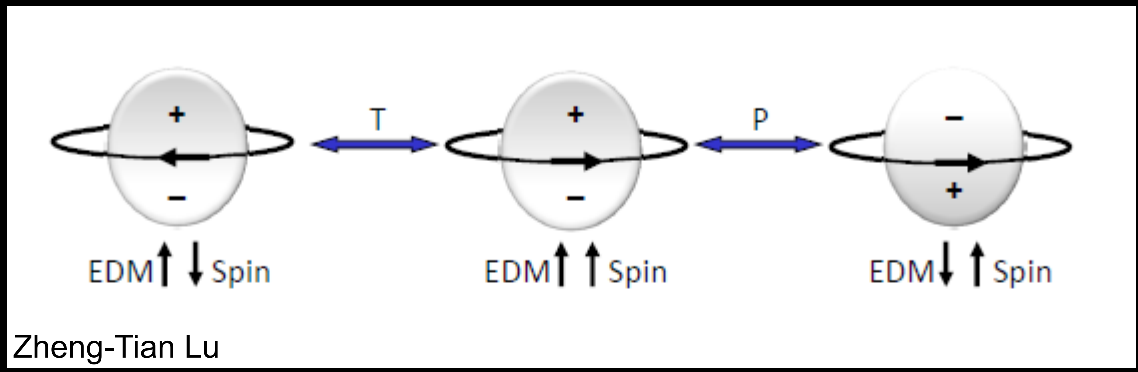
Motivation: I

- Establish SM parameters and laws. Examples:
  - Masses **M_Z, M_W, M_H, m_b, m_t, m_e, m_u, m_ν, …**
  - Couplings: α_{QED}, α_{Strong}, G_F, G_{grav}
  - Structure of interactions $SU(3)_C x SU(2)_L x U(1)_Y$
  - Broad issues
    - Numbers of generations
    - Mixing angles, quarks and neutrinos
    - Lepton number conservation
      - Majorana or Dirac neutrinos
    - CP violation parameters
- The Standard Model as we know it has been built on an enormous experimental foundation involving ***Precision*** and ***Energy*** frontier efforts
- And, some exquisite ***Theory*** !

Motivation: II The burning issues

- Can we sensitively test the SM limitations to help answer key questions:
  - Baryon Asymmetry of the Universe
  - EW symmetry breaking
  - …
- Are the Standard Model predictions complete?
  - What is missing?
  - What extensions are needed?

Chapter 1: Electric Dipole Moments

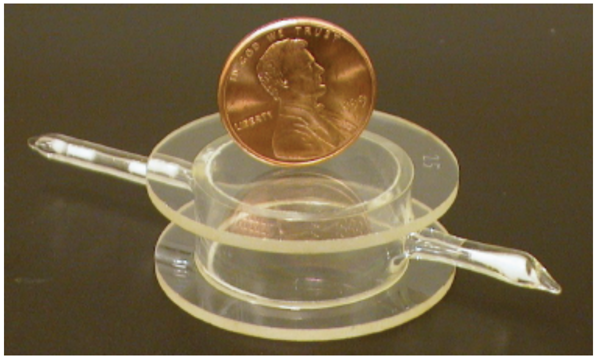


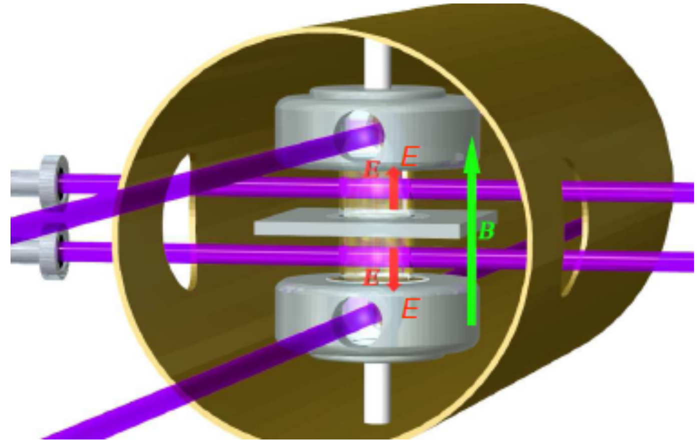
EDM violates T → violates CP

New sources of CP → BAU ?

Experiments are largely the same:
Precess spin in B field with parallel and anti-parallel E
Measure the frequency difference

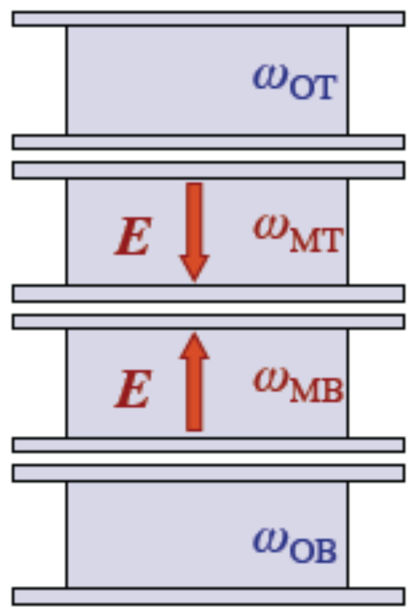
The Seattle ^{199}Hg (atomic) EDM Measurement





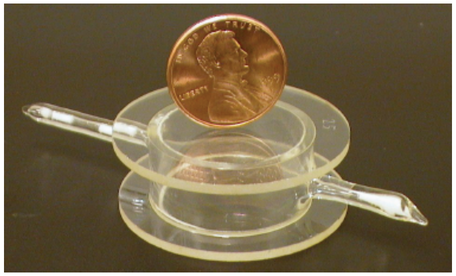
- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: 0.5 – 1 pA
- N_2 + CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

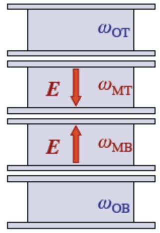
4 mercury vapor Cells:
2 with opposite E fields
2 for B field normalization

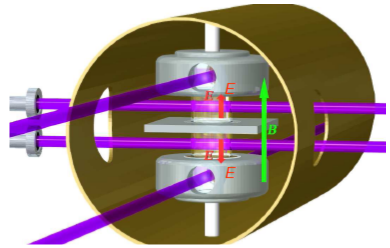


C. Griffith

The Seattle ^{199}Hg (atomic) EDM Measurement







Shielding reduces the effect of the nuclear dipole:

$$d_{atom} \propto d_{nuc} \underbrace{\left[Z^2 \left(\frac{r_n}{a_0} \right)^2 \right]}_{\approx 10^{-3}}$$

Limits and Sensitivities **World's best (absolute) limit**

- Current: < 0.3 x 10^{-28} e-cm Griffith *et al.*, Phys. Rev. Lett. (2009)
- Next 5 years: 0.03 x 10^{-28} e-cm
- 2020 and beyond: 0.006 x 10^{-28} e-cm

C. Griffith

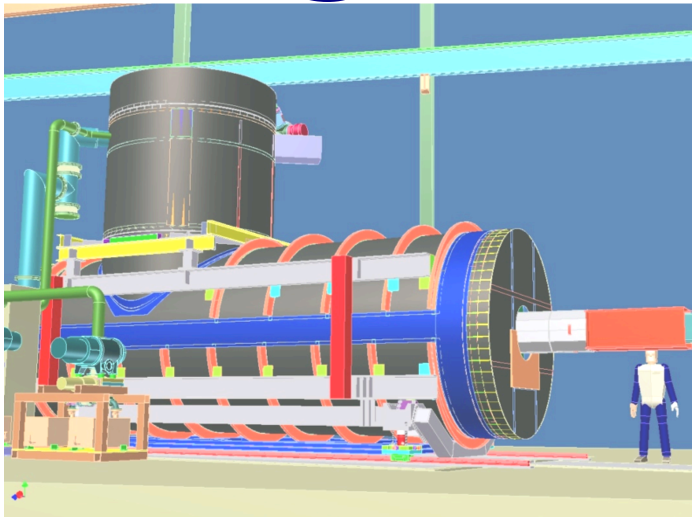
World-wide intense effort on nEDM

Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL CryoEDM	Superfluid ^4He	^4He	Ramsey technique for ω External SQUID magnetometers	Phase1 ~ 50 Phase 2 < 5
PNPI – ILL	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω $\vec{E}$=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & $^3\vec{He}$ magnetom.Possible Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vac.	Under Construction (similar to PSI	< 5
SNS EDM	Superfluid ^4He	^4He	$^3\vec{He}$ capture for ω $^3\vec{He}$ comagnetometer SQUIDS & Dressed spins	< 5
TRIUMF	Superfluid ^4He	Vac.	Phase I @ RCNP	< 10
JPARC	Solid D_2	Vac.	Under Development	< 5
NIST	Crystal	Solid	R & D	~ 5 ?

B. Filippone

Status & Timeline for nEDM@SNS

NSAC Subcommittee on Fundamental Nuclear Physics with Neutrons Report (12/2011)



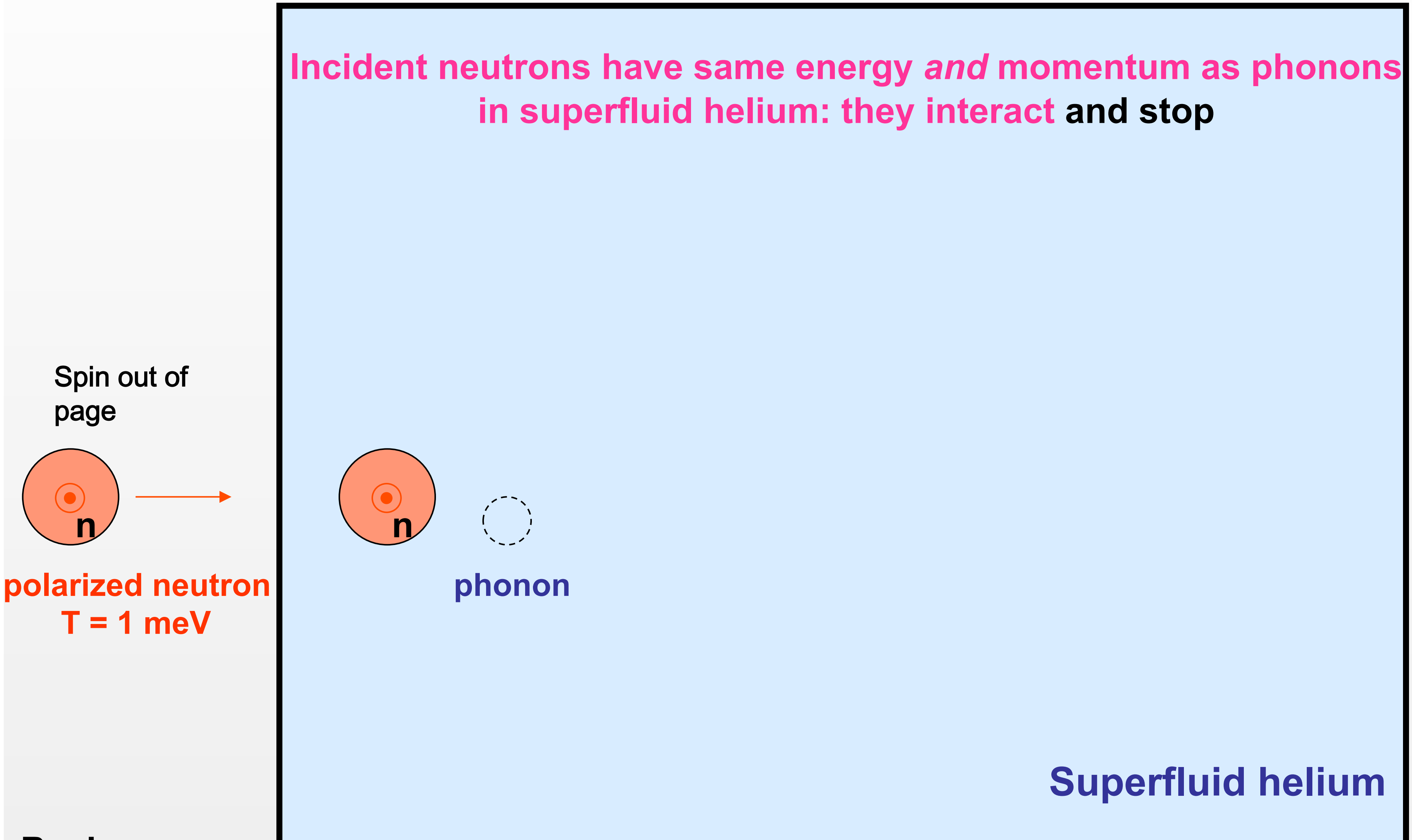
- **Motivation remains strong**
- **Sensitivity remains compelling**

- **Focus now on R&D**
- **Construction after with 4 – 5 year timeline and ~$30M capital**
- **<u>2 minutes to show you why the US idea is special</u>**

Aim: 2 orders of magnitude improvement to < 5 x 10^{-28} level

So clever, it's worth a moment: S. K. *Lamoreaux* and R. *Golub*,

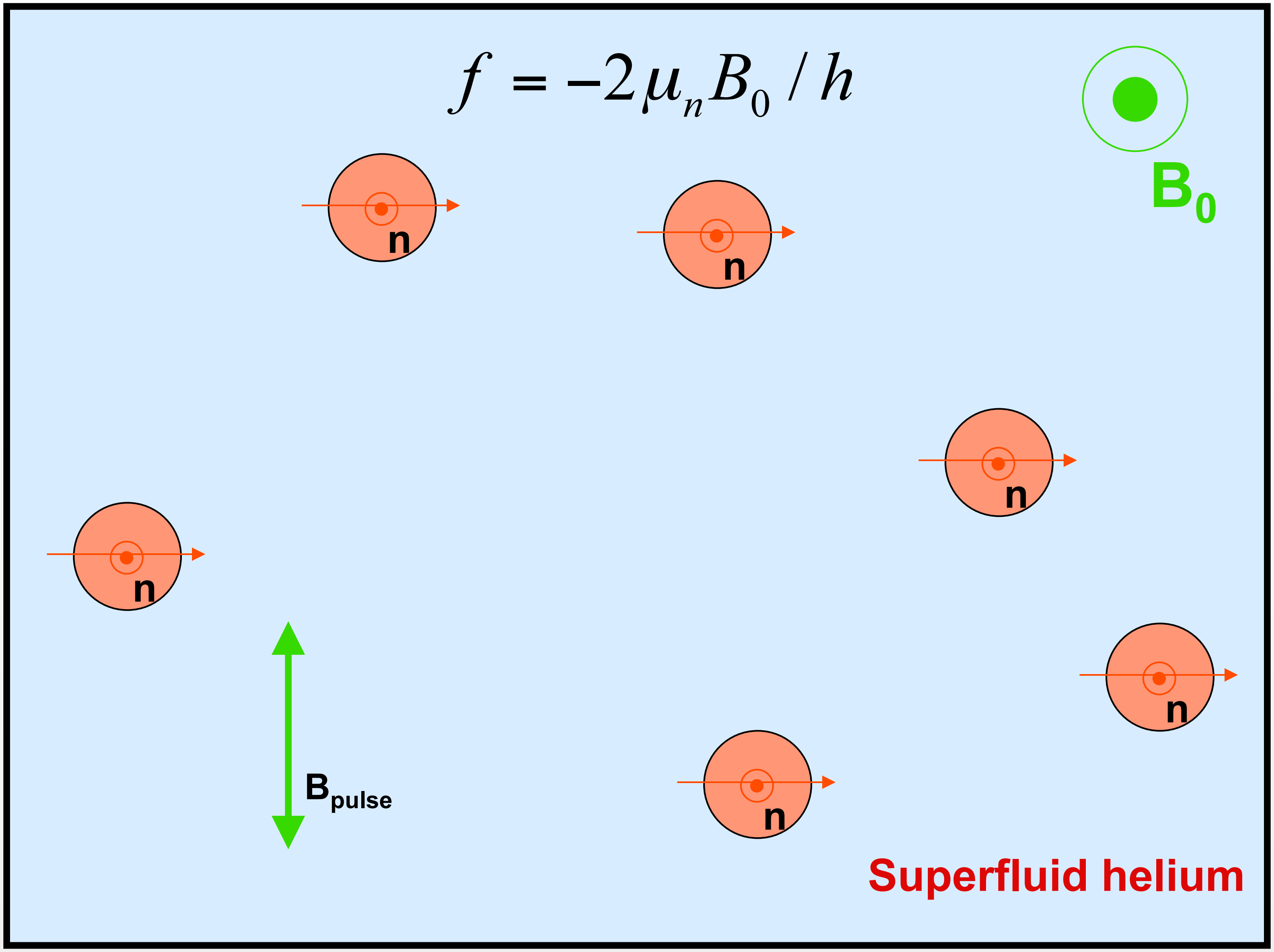
Cold polarized neutrons enter superfluid helium vessel, and get stopped & trapped



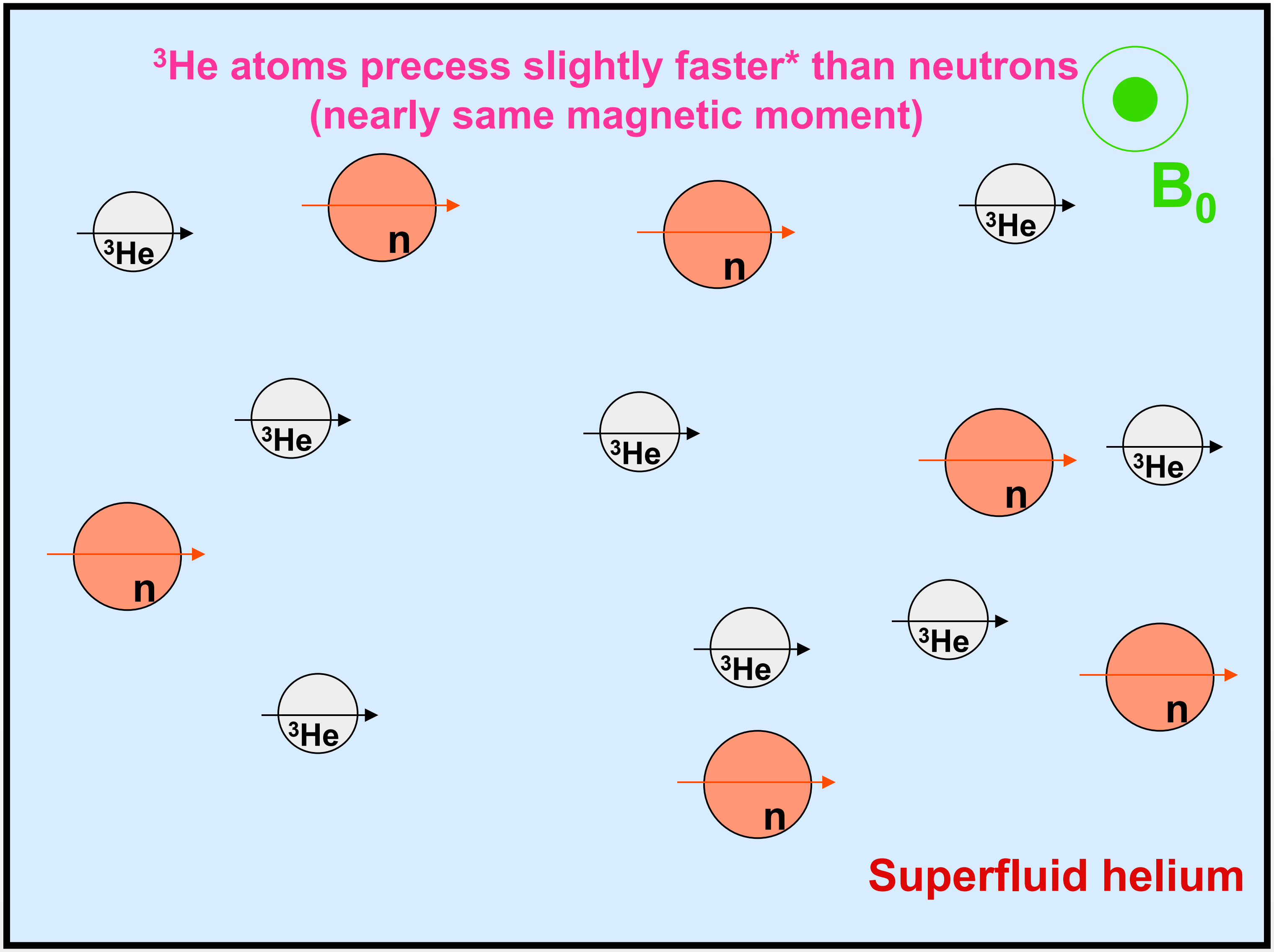
Beck

Neutron spins precess because of external magnetic field

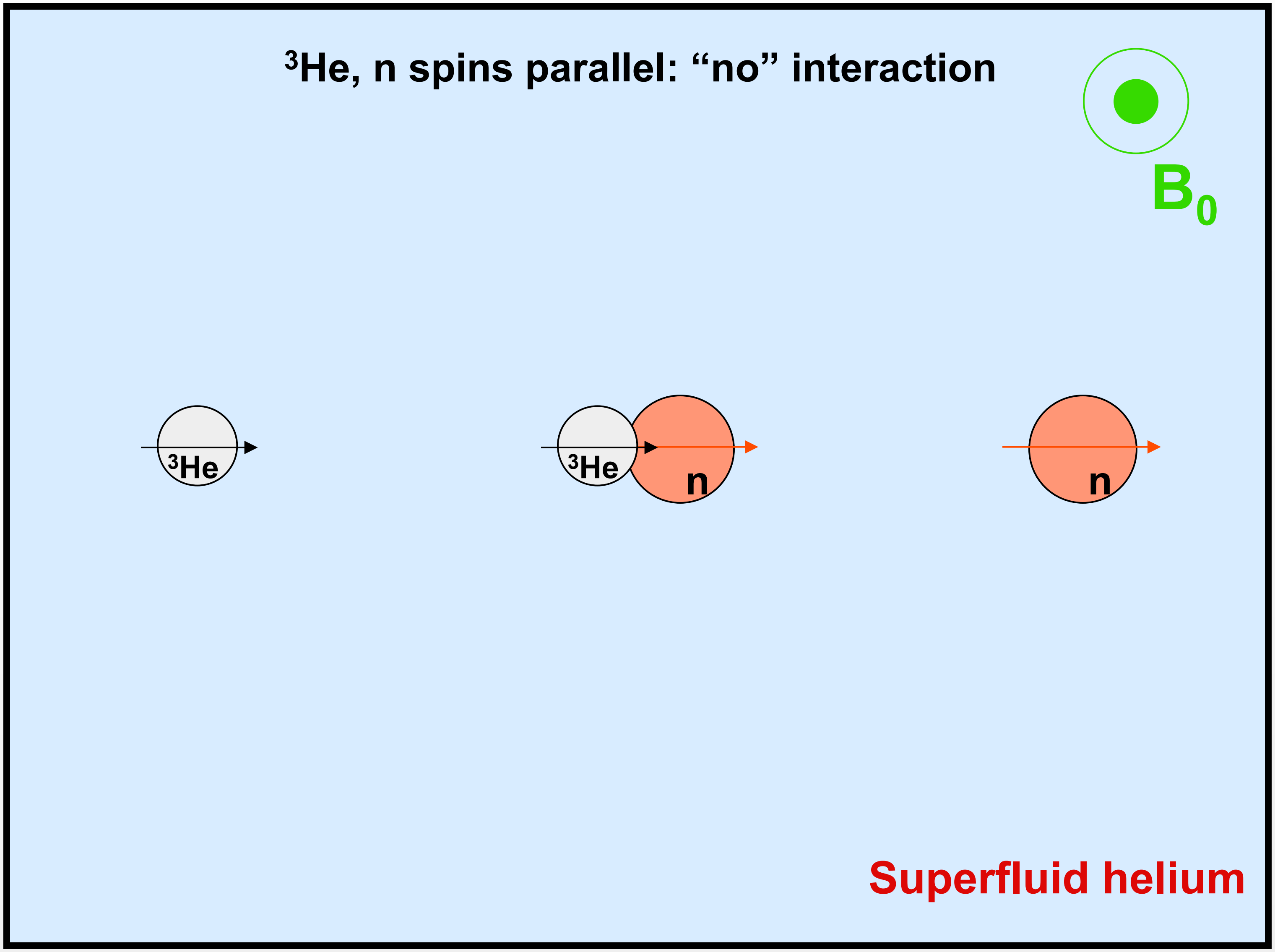
$$f = -2\mu_n B_0 / h$$



So do spins of polarized ^{3}He, which are also brought into the same vessel



When neutrons and ^{3}He collide, interaction depends on relative spin orientations



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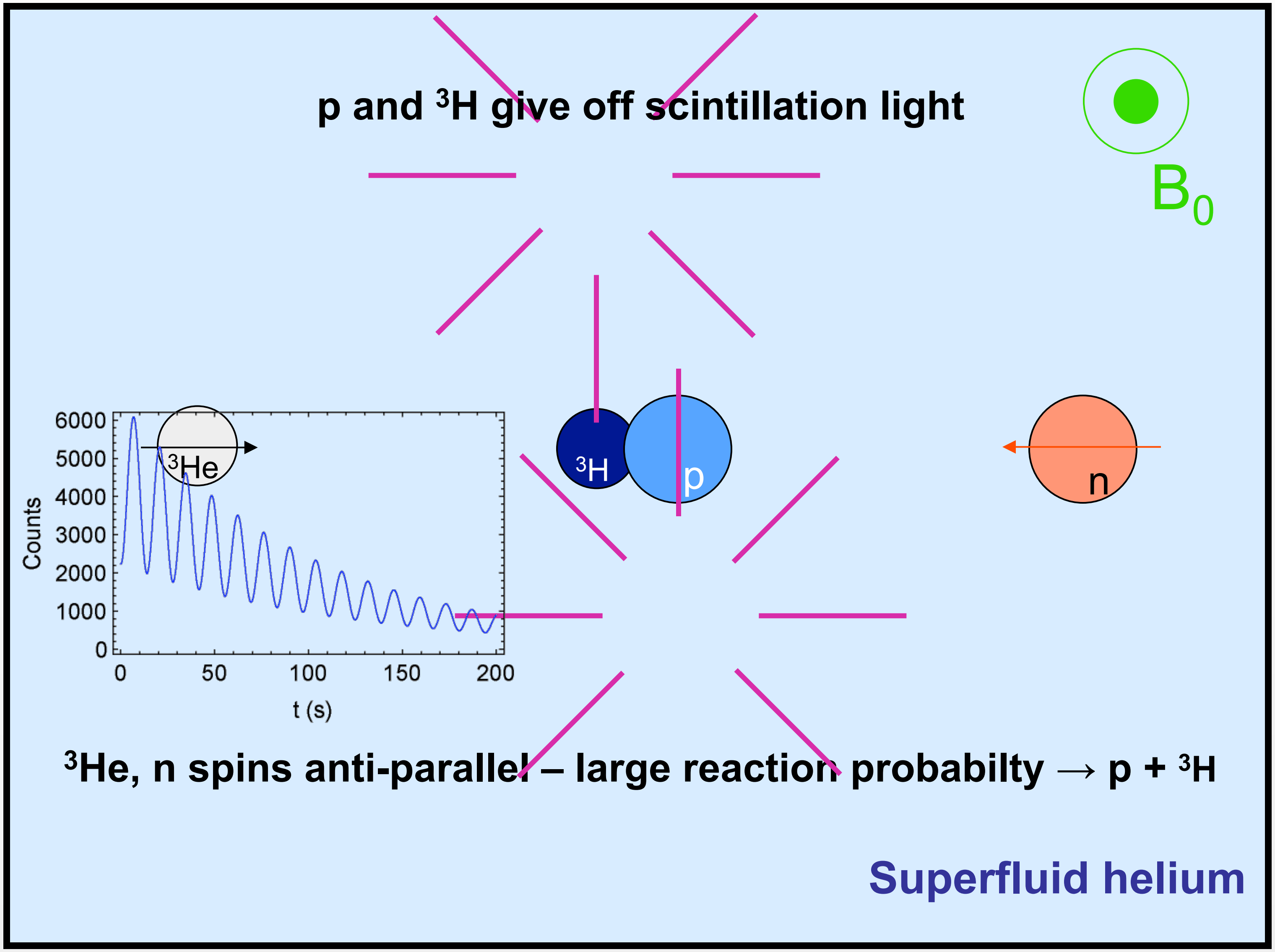
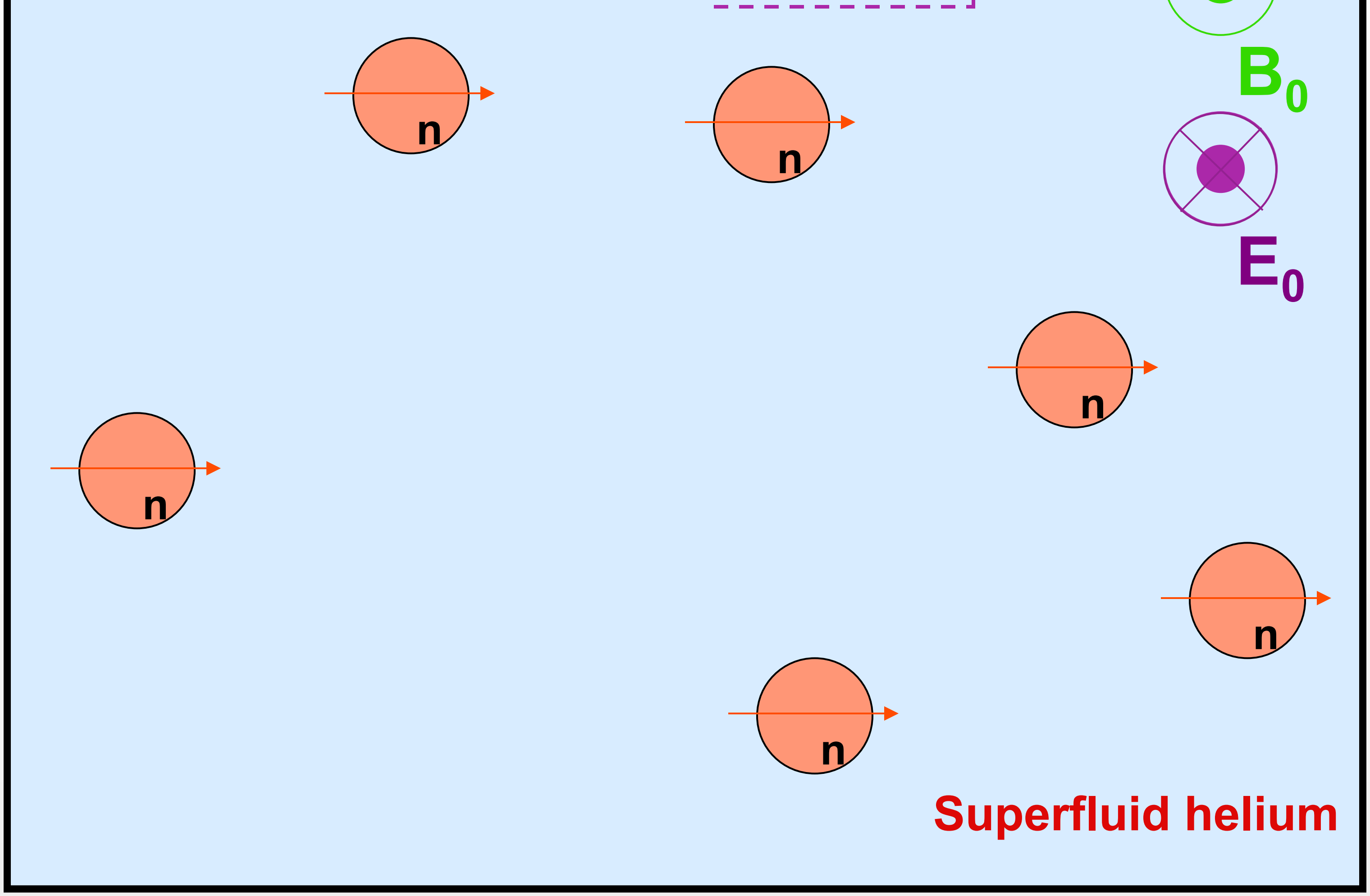
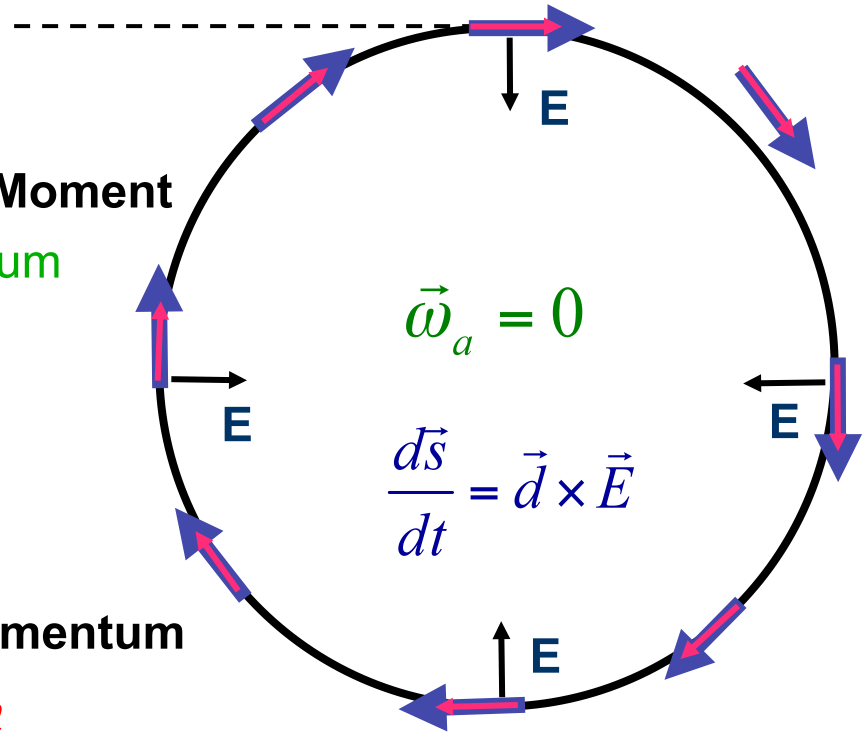


Now, add external electric field: spin rate of neutrons affected if EDM is non-zero

$$f = \left(-2\mu_n B_0 \pm 2d_n E_0\right)/h$$



A new idea: pEDM in all-electric storage ring **and, to a precision of 10^{-29} !**



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

~$100 M effort, but very exciting limit

Systematic Errors Evaluated and Published


Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

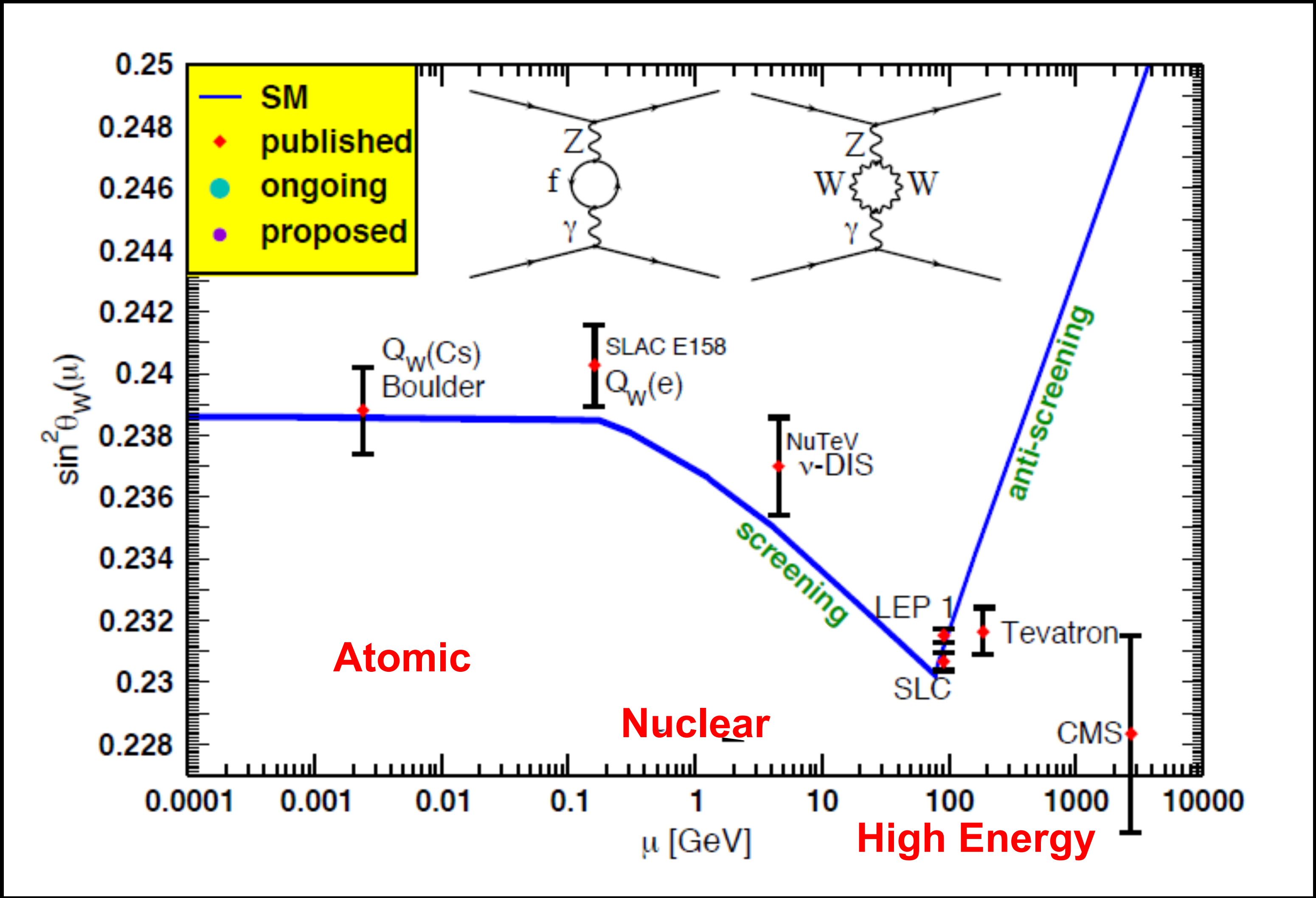
journal homepage: www.elsevier.com/locate/nima

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]

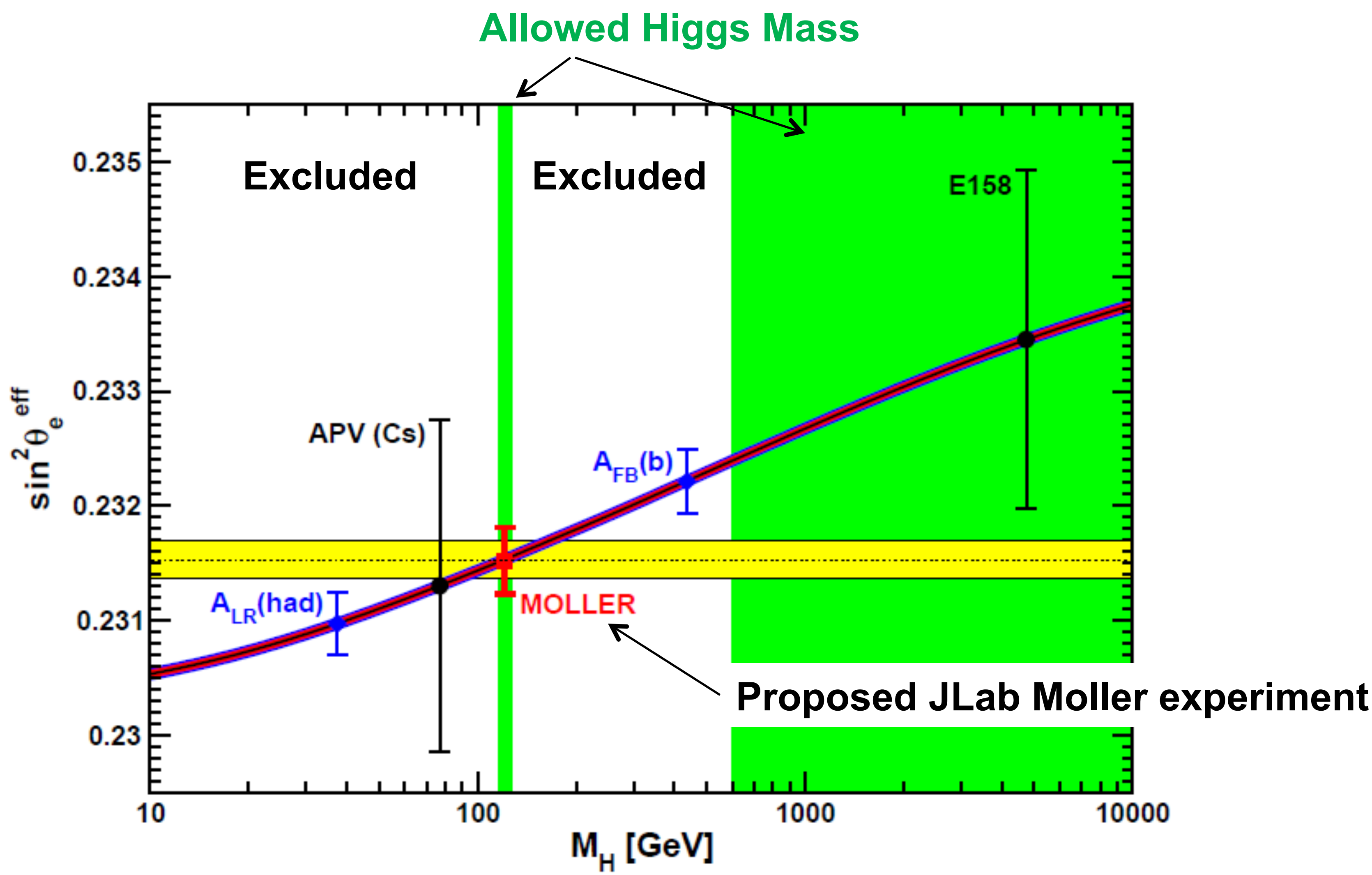
Chapter 2: Parity-Violating e⁻ Scattering



A Broad Community Example

The precision measurement of the Higgs mass updates the story, fixing central value of $\sin^2\theta_W$

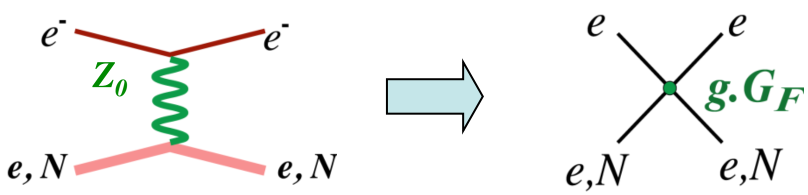
Summer 2012



J. Erler: arXiv:1209.3324v2

Next-Generation experiments will Probe for New Physics

Many new physics models require new, heavy, neutral current interactions

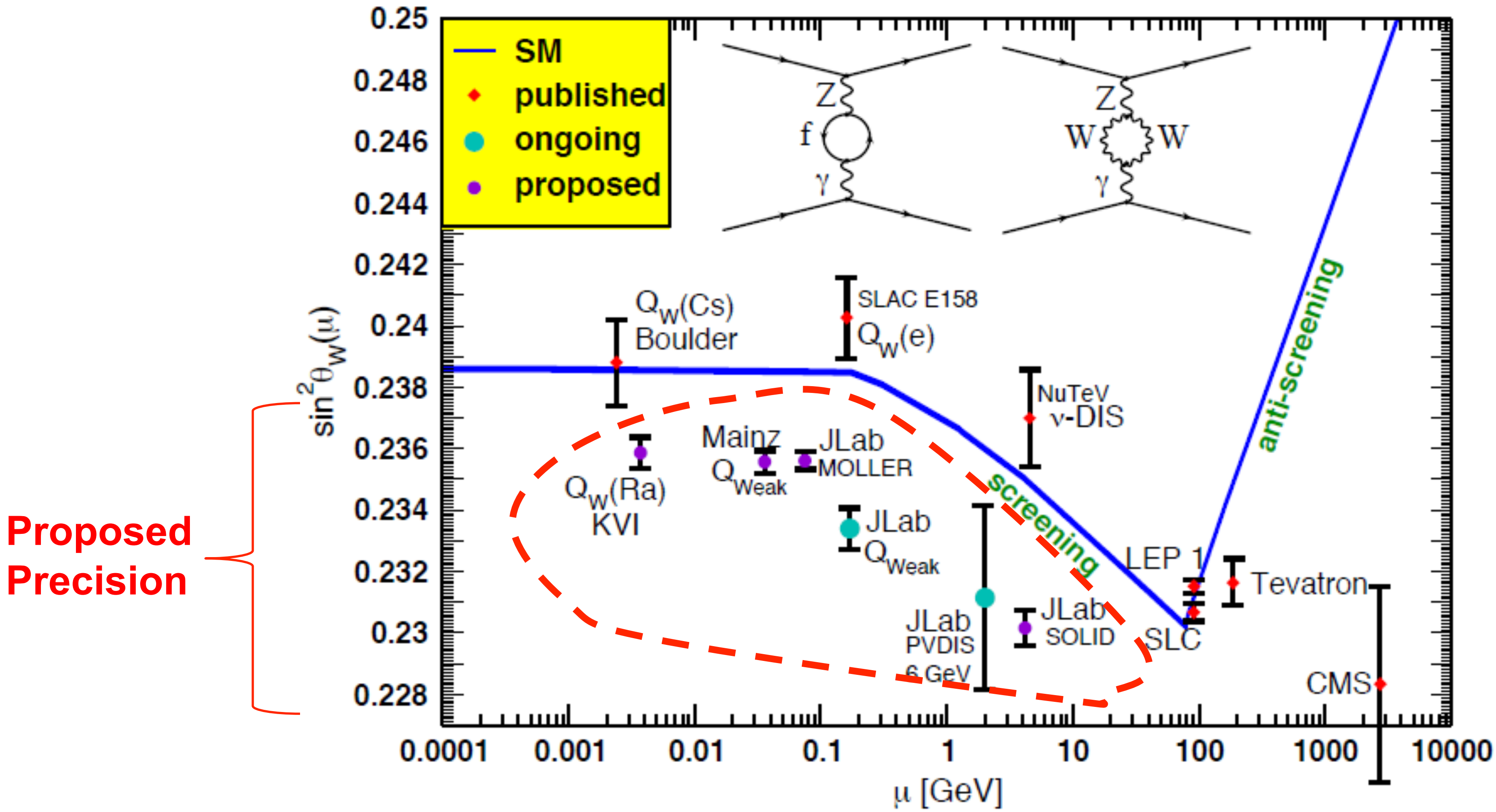


Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Sensitivity to TeV-scale contact interactions if:

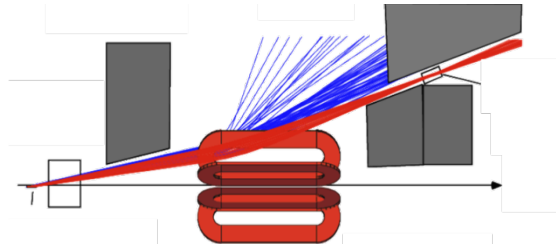
- $\delta(\sin^2\theta_W) \leq 0.5\%$
- away from the Z resonance

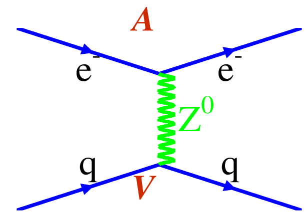
Worldwide proposed efforts



The JLab Suite

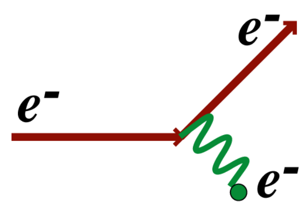
- **QWeak**
  - Completed
  - 1st result today
  - Goal: $\delta Q_W^p = \pm 4\% \;\Rightarrow\; \delta(\sin^2\theta_W) = \pm\, 0.3\%$

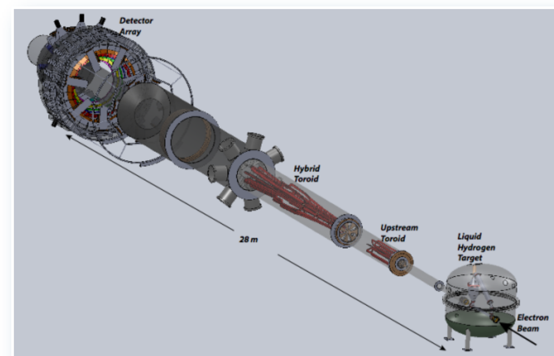




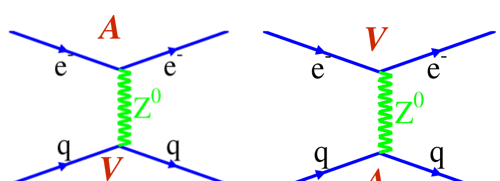
$C_{1i} \equiv 2g_A^e g_V^i$

- **MOLLER@11GeV**
  - Proposed for 2017
  - Goal: $\delta(\sin^2\theta_W) = \pm\, 0.1\,\%$

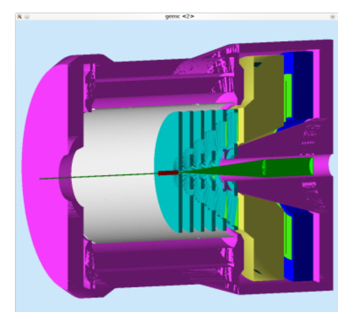




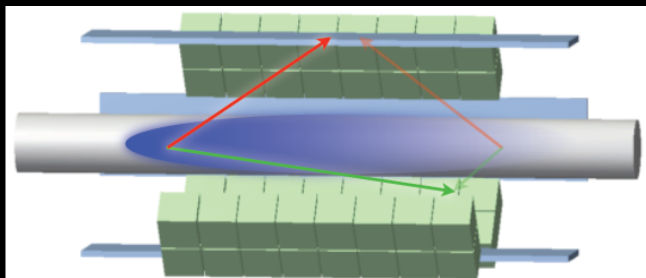
- **SOLID**
  - Deep Inelastic Scattering from ^{2}H
  - Early planning

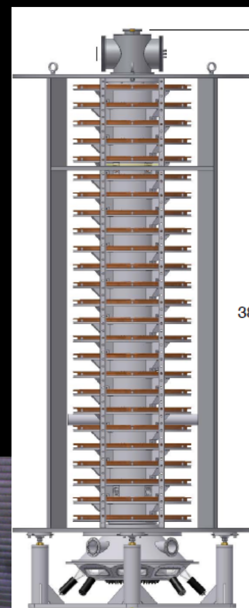


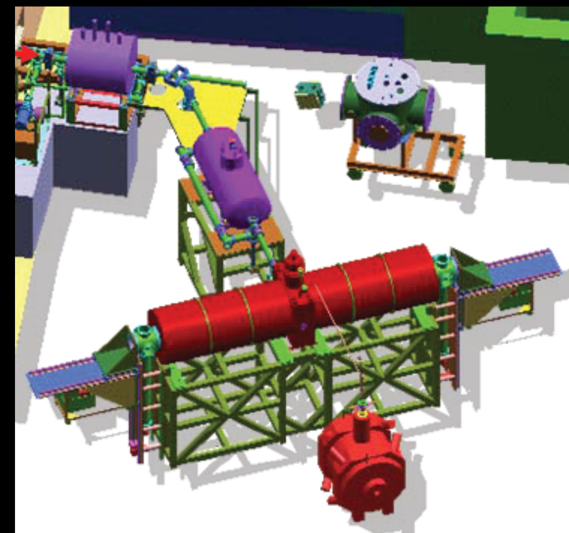
$C_{1i} \equiv 2g_A^e g_V^i$ $\quad C_{2i} \equiv 2g_V^e g_A^i$

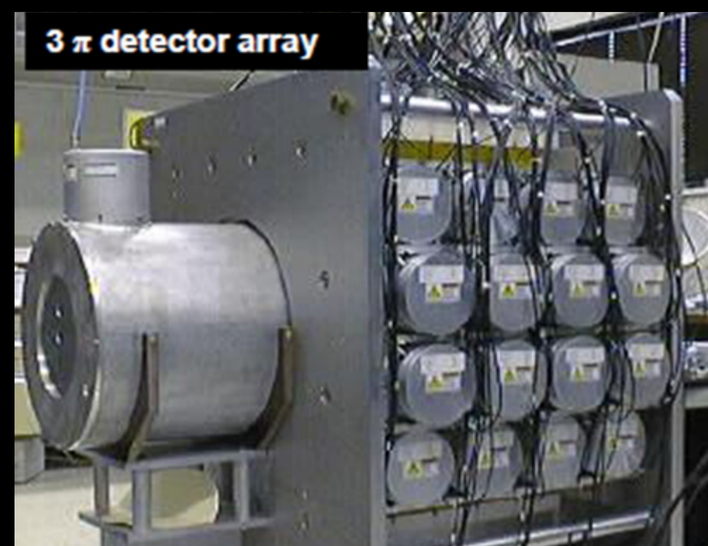


Chapter 3: Neutrons







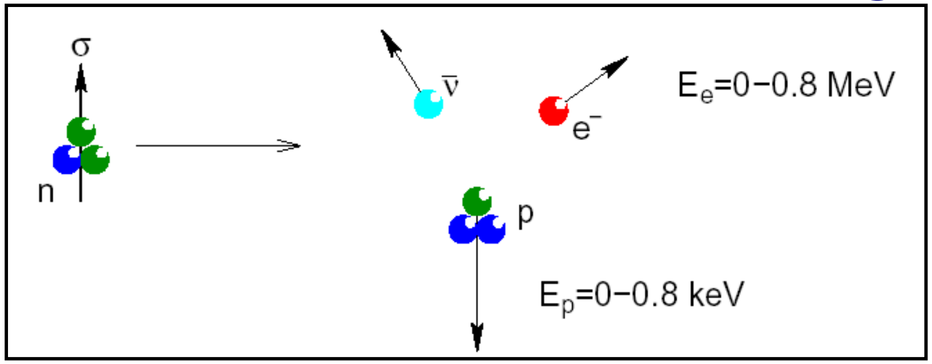


The Neutron as a Fundamental Laboratory

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

neutron lifetime $\tau \approx 15$ min

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



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

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

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

$$b = 0$$

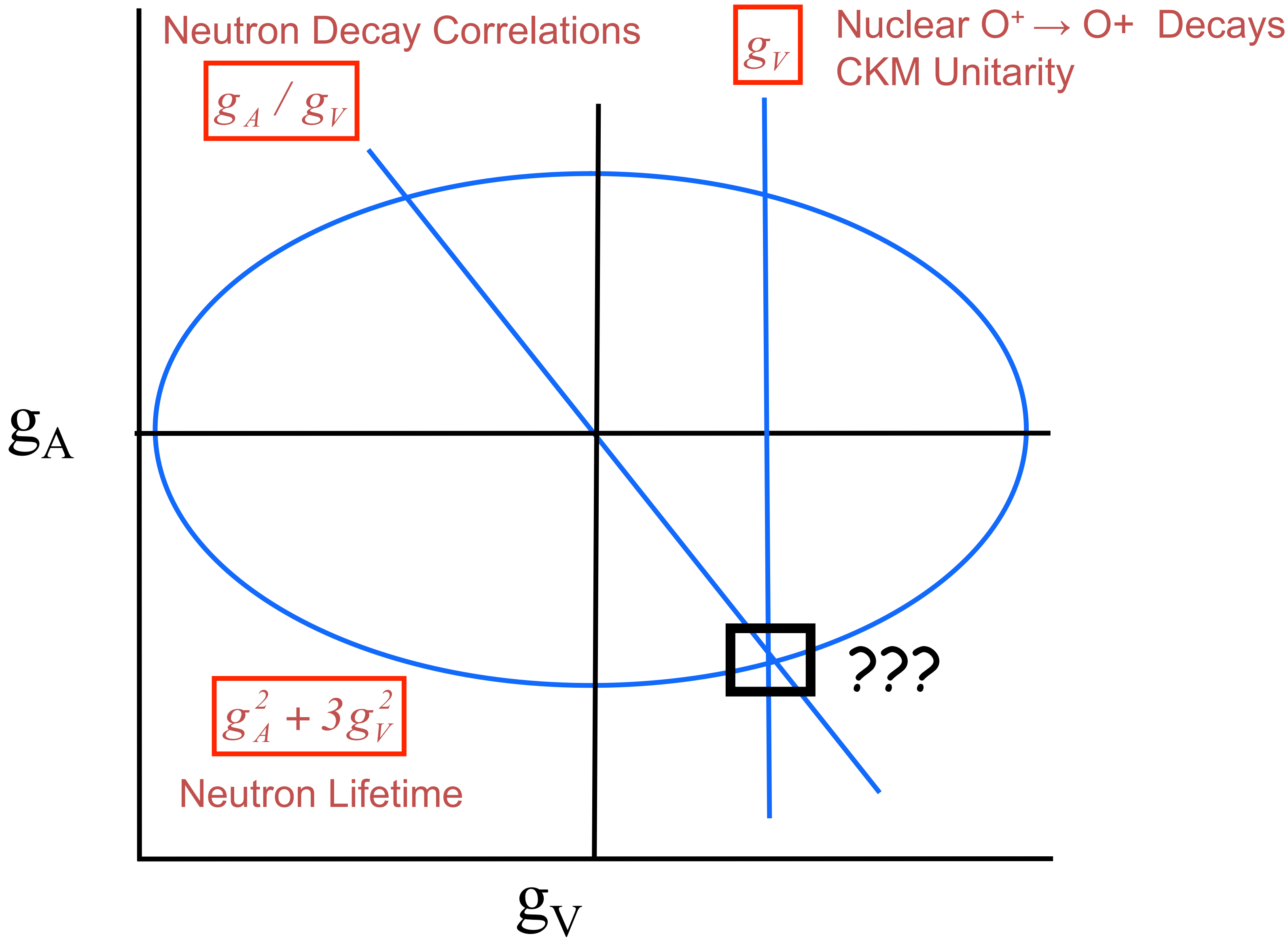
$$A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}$$

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

Neutron beta decay measurements give:

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

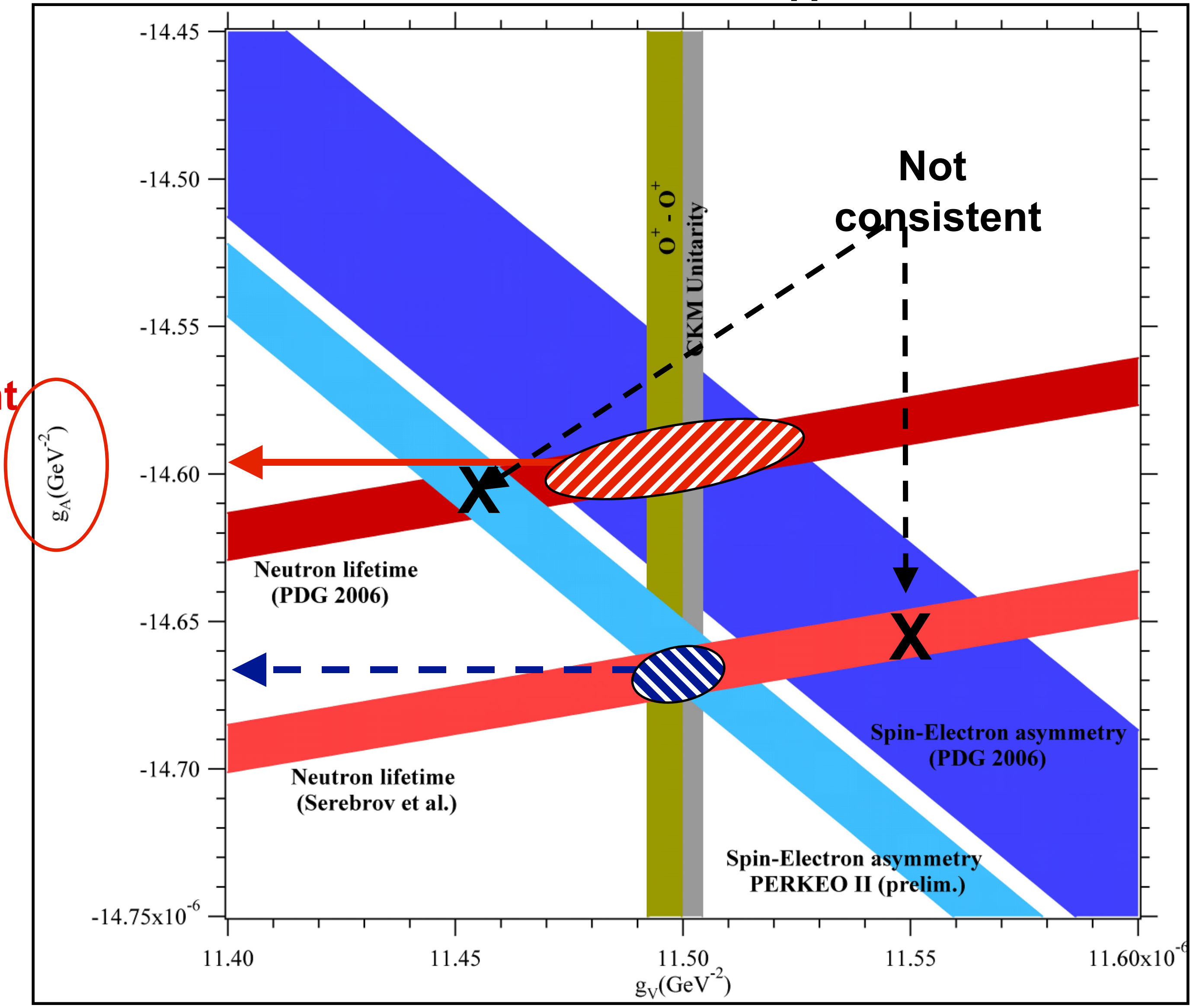
$$g_A / g_V$$


Neutron Decay Correlations
g_A / g_V
g_V
Nuclear O⁺ → 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

Significant updates

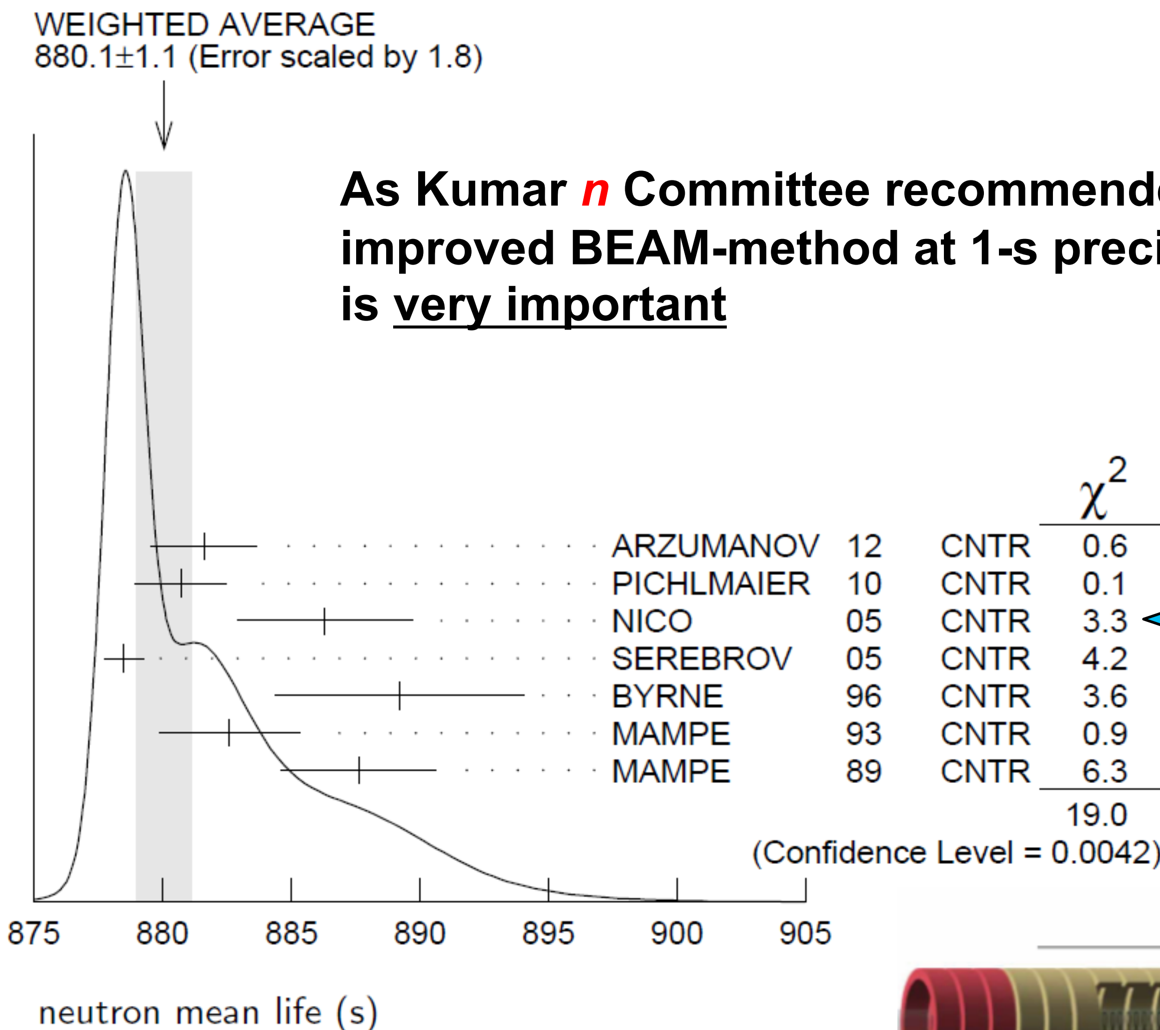
- **Big A: g_A/g_V**
  - UCNA
  - PERKEO II
- **n Lifetime Update**
  - Important to Big Bang Nucleosynthesis
- Precision of $0^+ \rightarrow 0^+$ **superallowed measurements** for unitarity

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

CKM unitarity test:

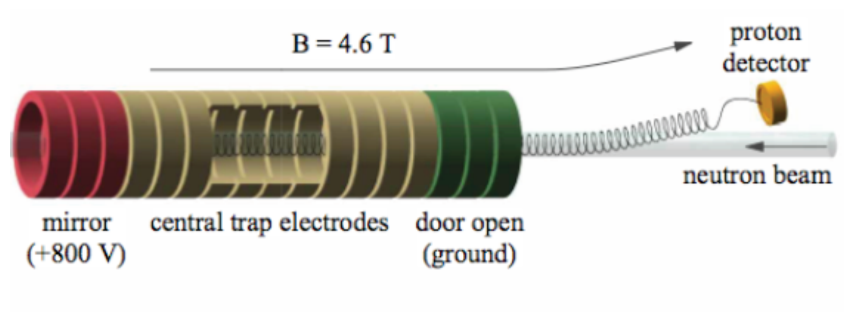
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9999(6)$$

2012: *n* Lifetime Update: PDG



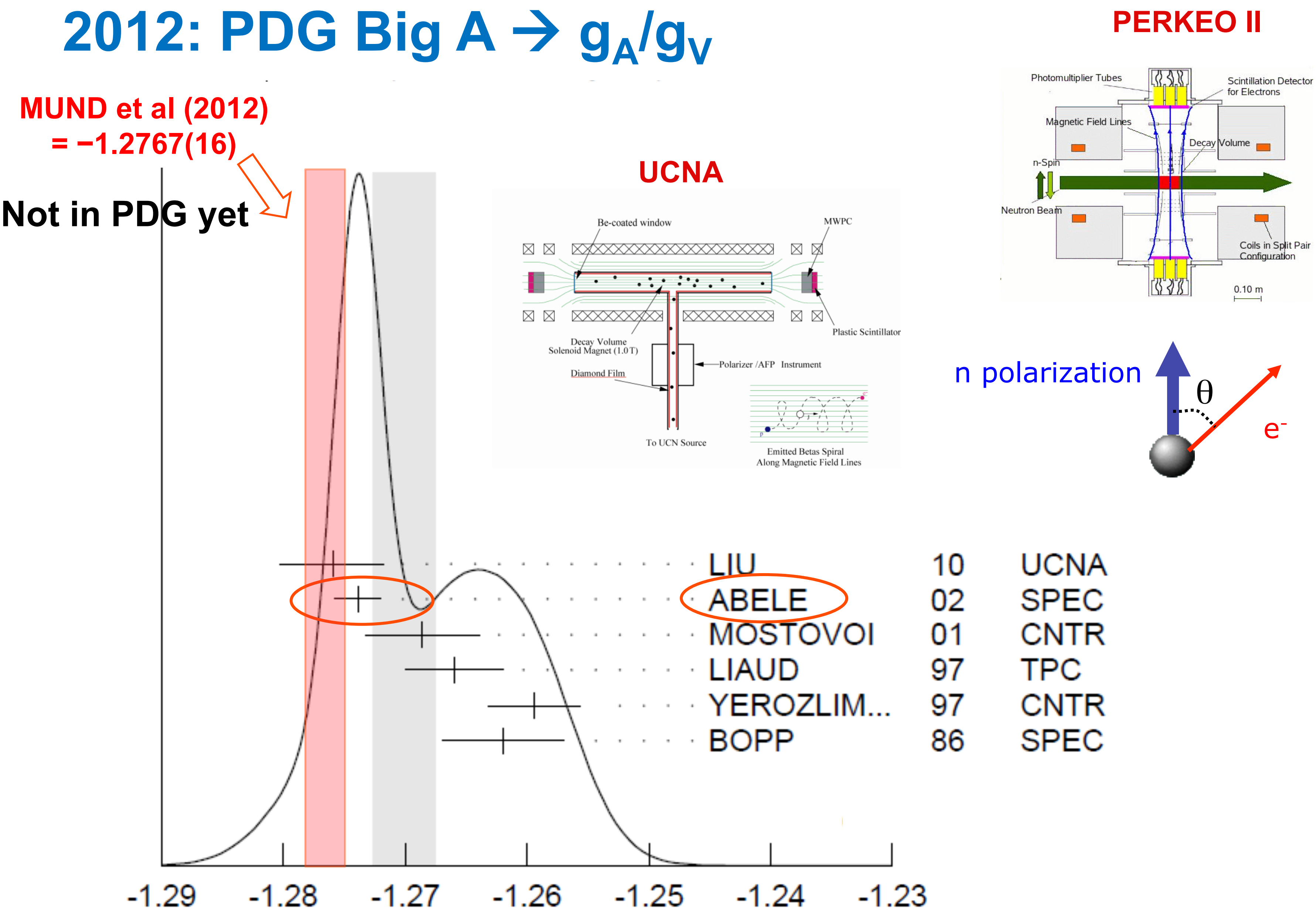
As Kumar *n* Committee recommended, an improved BEAM-method at 1-s precision is <u>very important</u>

NIST beam method



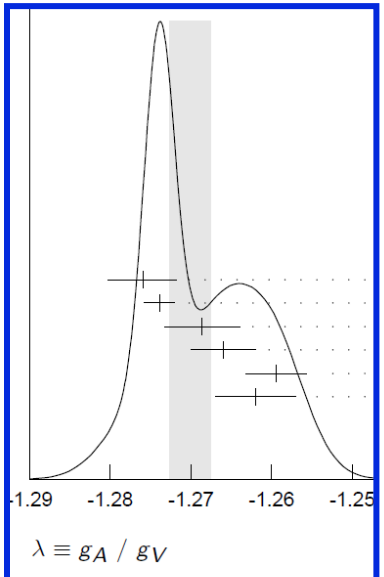
PDG uses latest 7, including corrected and other newer results

2012: PDG Big A → g_A/g_V

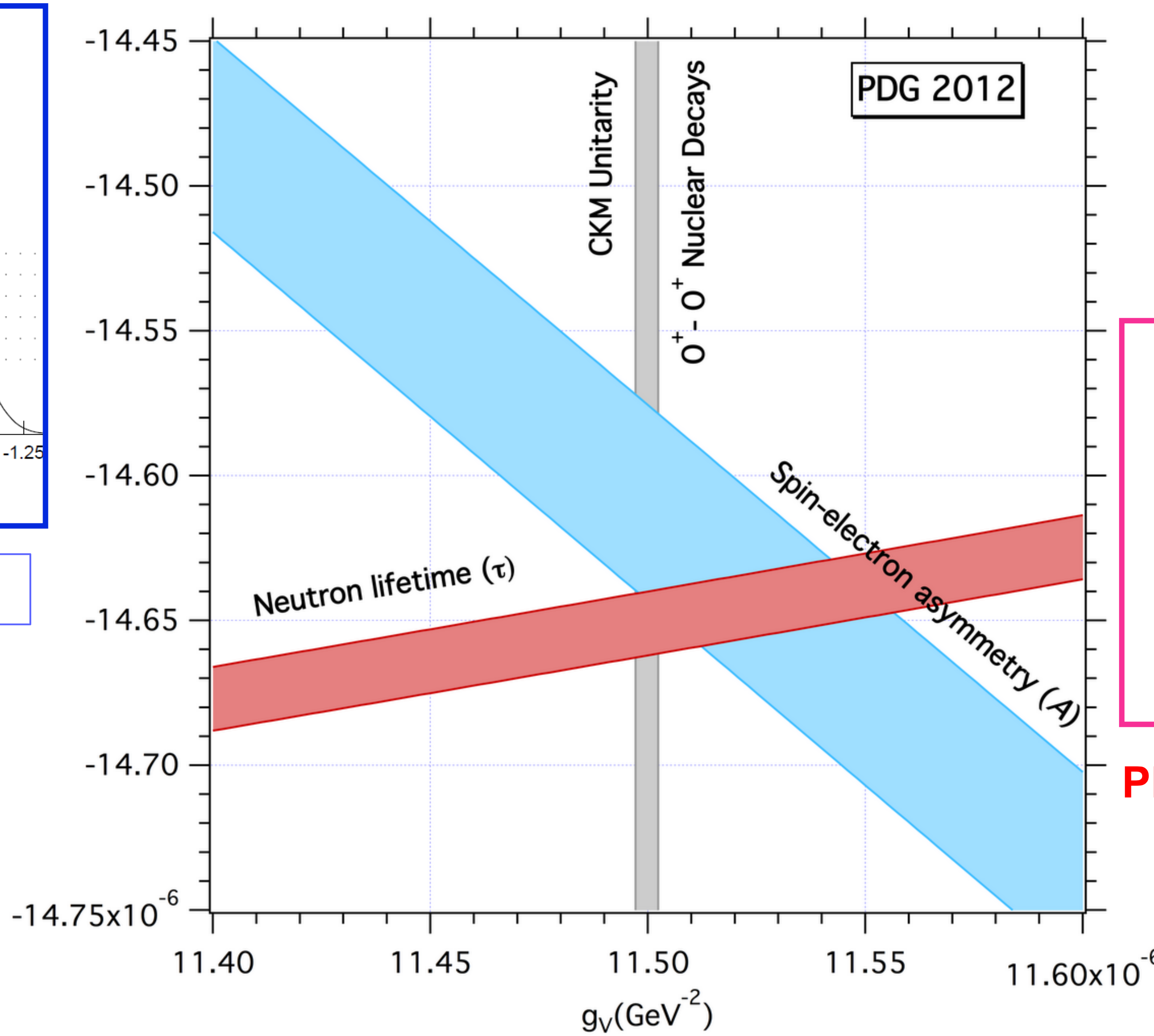


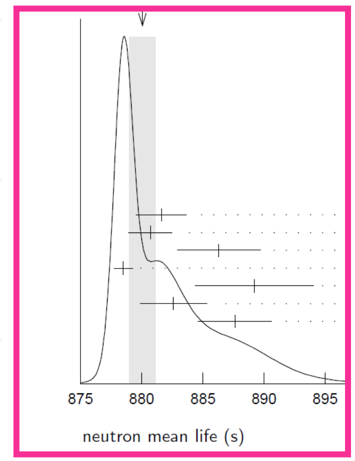
$$\lambda \equiv g_A / g_V$$

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



PDG: g_A/g_V





PDG: Lifetime

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

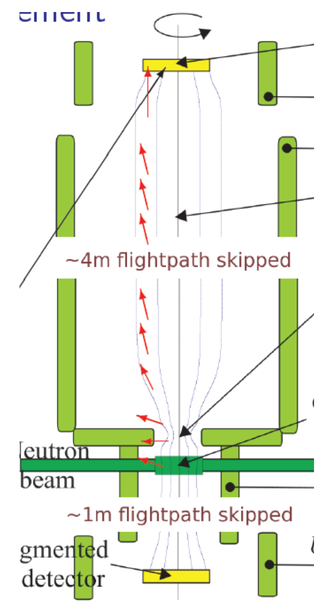
  with accuracy of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$ or $\sim 50\times$ better

- 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

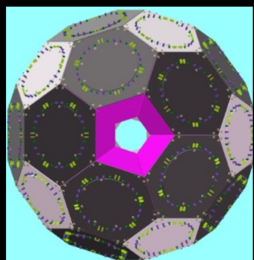
NSF MRI-funded Spectrometer

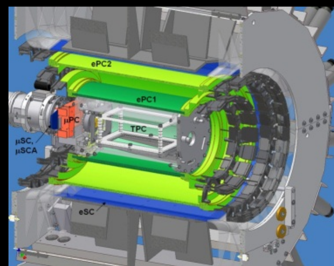


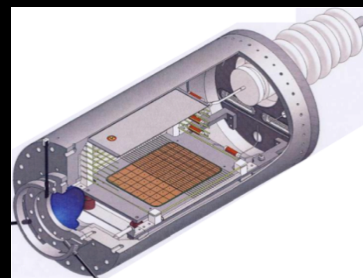
- **Nab** will be followed by the **abBA/PANDA** polarized program to measure **A**, electron, and **B/C**, neutrino/proton, asymmetries with $\simeq 10^{-3}$ relative precision, an independent measurement of λ.

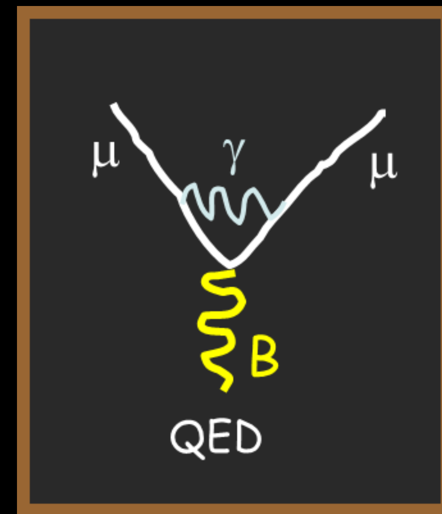
Chapter 4: Muons

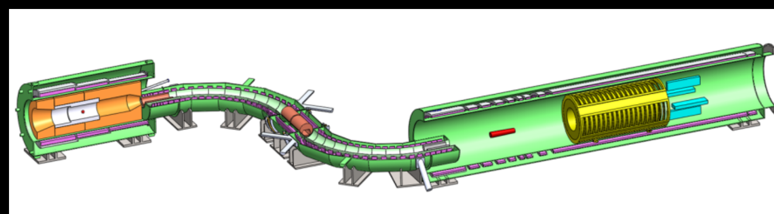
(well) Beyond Schwinger

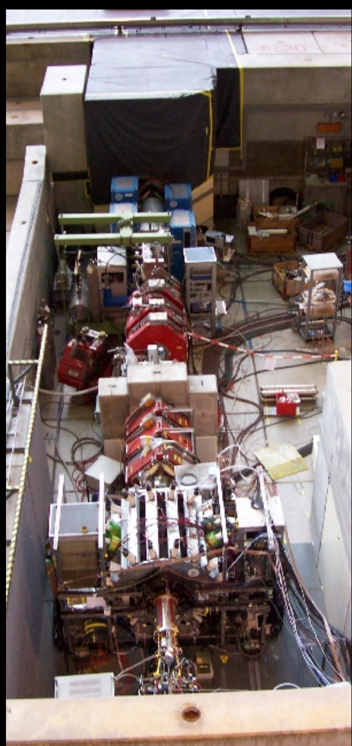


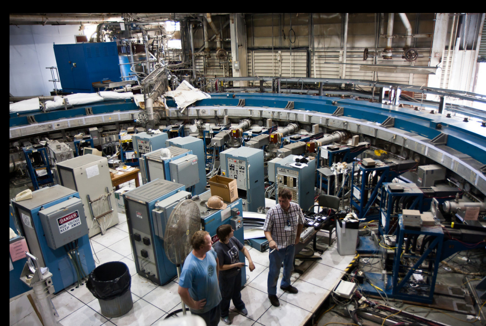


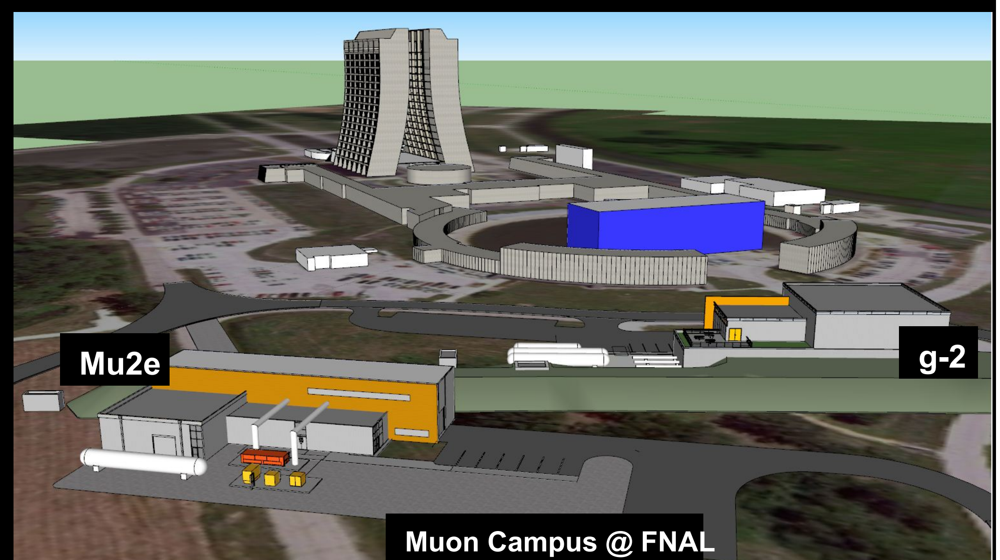










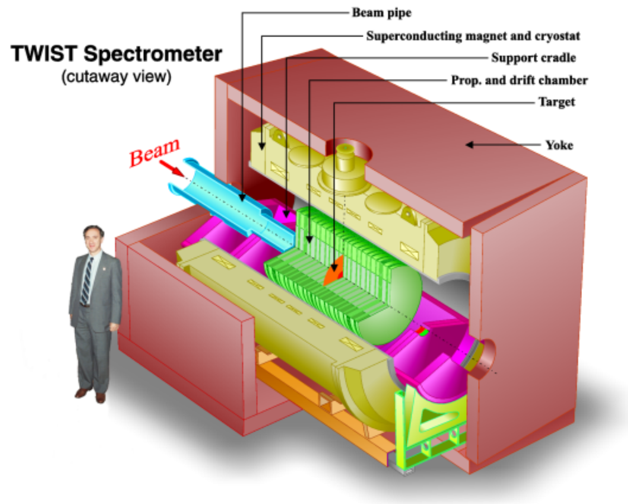


2010: Michel Parameter / Muon Decay: TWIST

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)

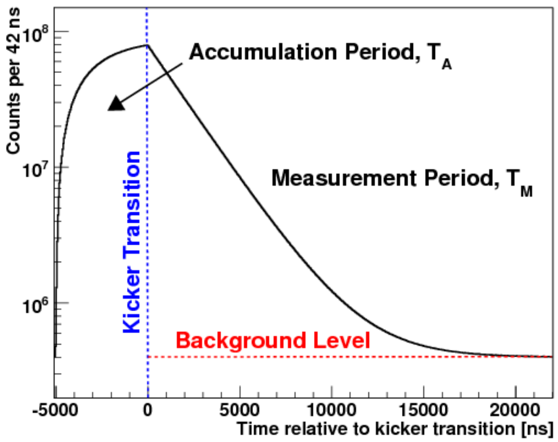


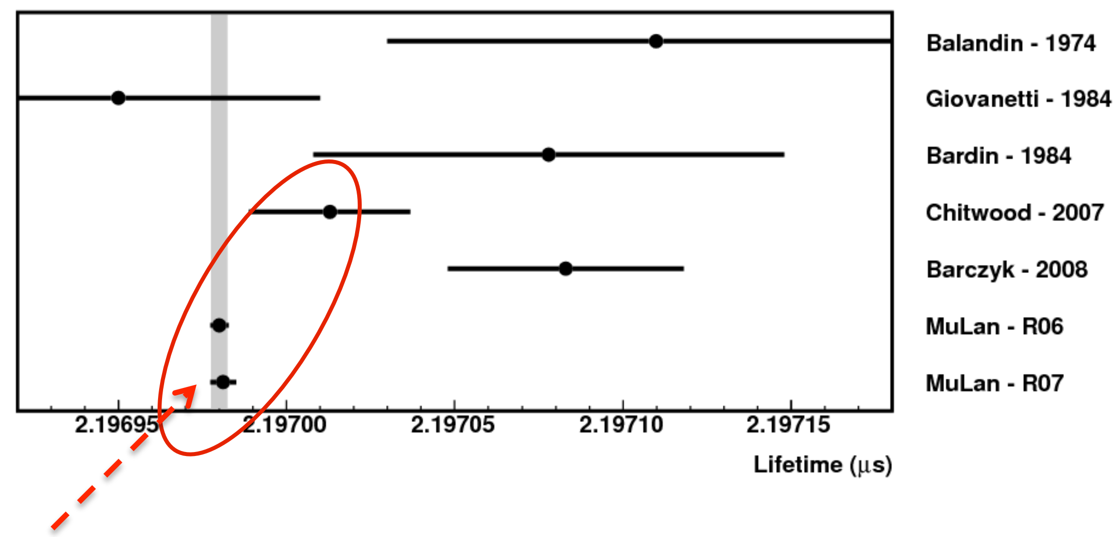
Results mostly constrain right-handed muon terms

$$\begin{aligned} Q_R^\mu &= \frac{1}{4}|g_{LR}^S|^2 + \frac{1}{4}|g_{RR}^S|^2 + |g_{LR}^V|^2 + |g_{RR}^V|^2 + 3|g_{LR}^T|^2 \\ &= \frac{1}{2}[1 + \frac{1}{3}\xi - \frac{16}{9}\xi\delta] \\ &< 8.2 \times 10^{-4} \quad (90\%\text{C.L.}) \end{aligned}$$

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

2011: Muon lifetime / Fermi constant: MuLan*





$\Delta\tau$(R07 – R06) = 1.3 ps

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

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

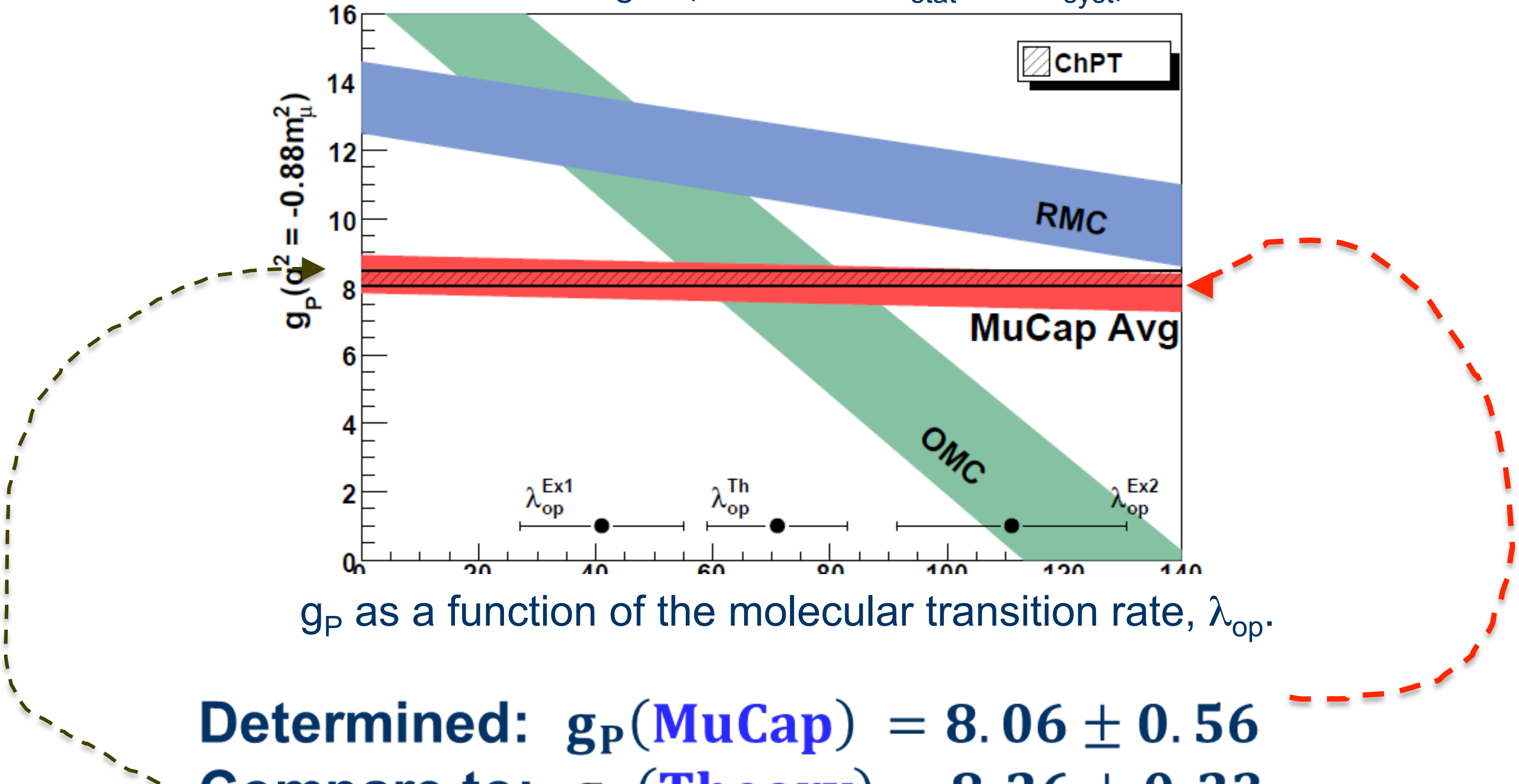
The most precise particle or nuclear or atomic lifetime ever measured
Enables precision muon capture program (next)

***US led effort at PSI**

Webber et al, Phys. Rev. Lett. 106, 041803 (2011).

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: $g_P(\text{MuCap}) = 8.06 \pm 0.56$

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

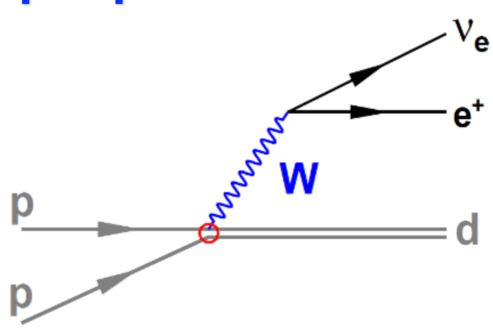
First unambiguous determination of g_P and clarification of long-standing puzzle between fundamental QCD-based prediction and expt.

***US led effort at PSI**

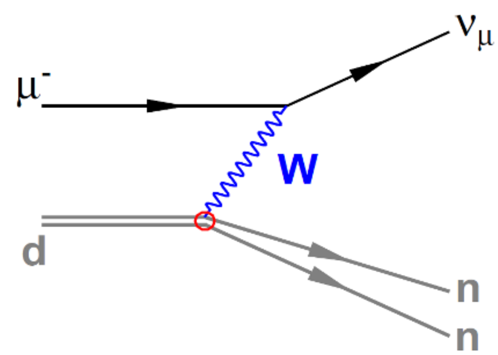
Andreev et al, ArXiv:1210.6545v1; submitted to PRL (today)

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)

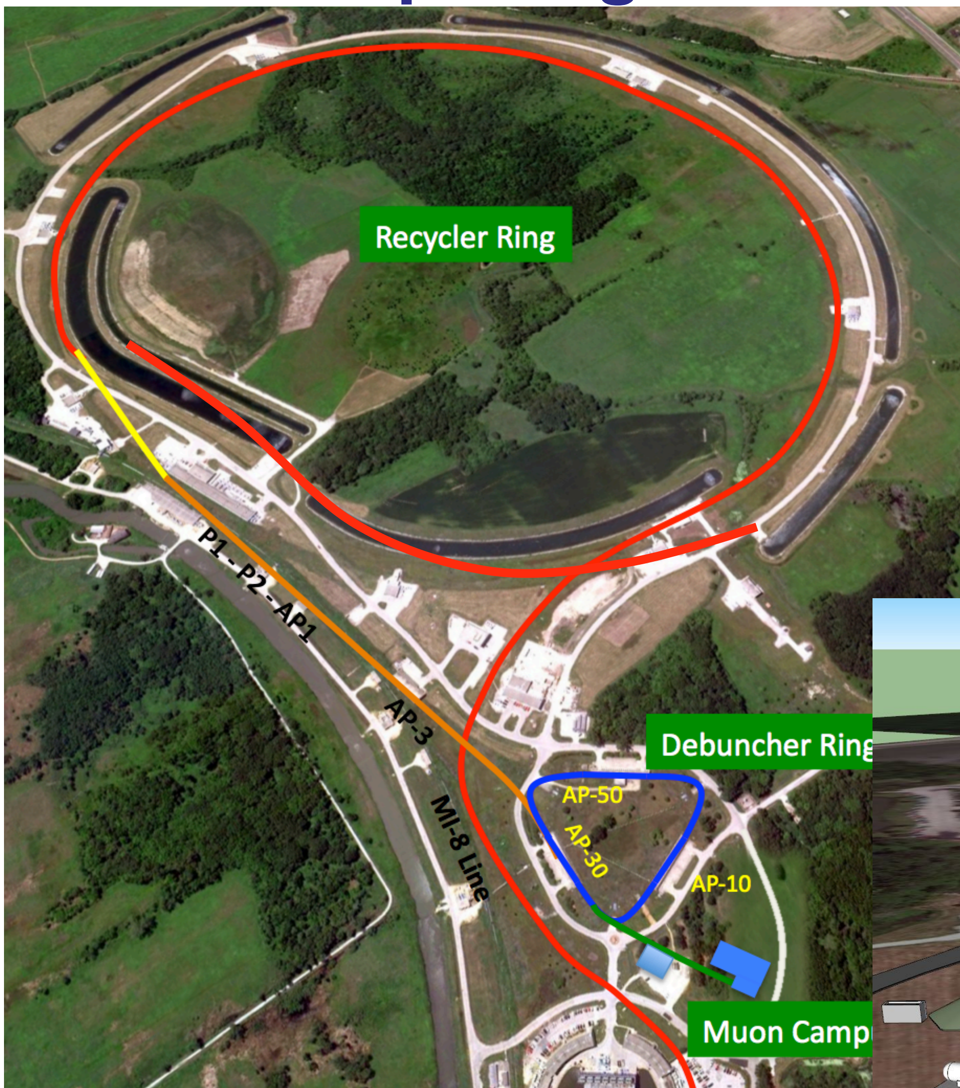
Tiny cross sections, predictions rely on theory

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

***US led effort at PSI**

model-independent connection via EFT

Flagship efforts being mounted at the new Fermilab Muon Campus: g-2 & Mu2e

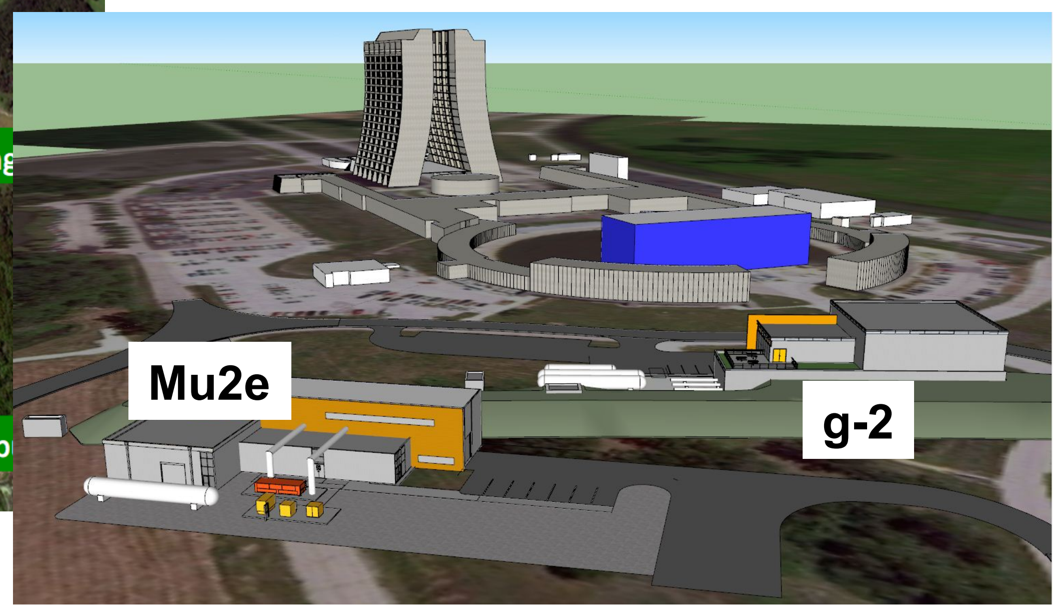


For g-2, achieves

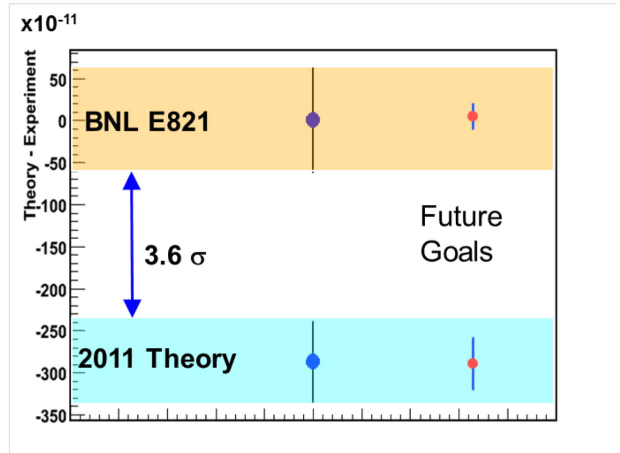
1) Long decay channel
2) Rapid ring cycle
3) No hadronic flash

For Mu2e, achieves

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



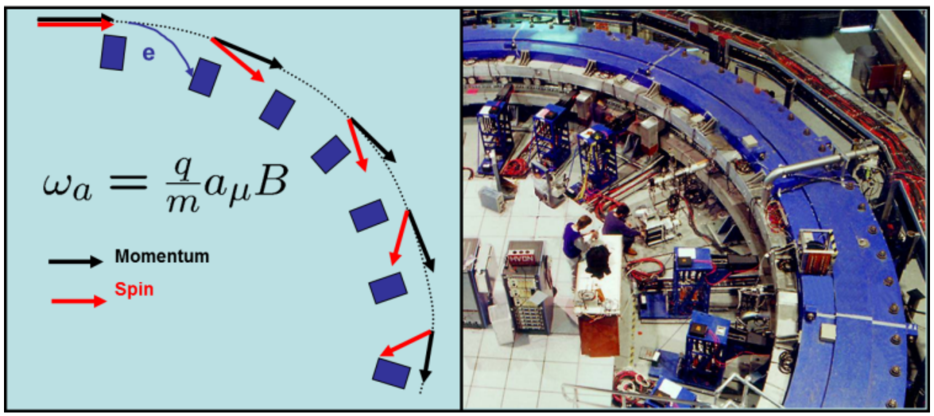
The statistically limited g-2 measurement is 3.6σ from the Standard Model



"Do it better …"

→ More Muons

→ Reduced Systematics



Disassembling Ring at BNL

- Concept sound
- Relocate the storage ring to FNAL
- Build new measuring equipment (NSF & DOE Nuclear invested in this part)

E989 is approved, has CD-0, 24 Institutions, 100+ members, Start: 2016

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
  - $h \to \gamma\gamma$ **production rate is too high by ~40-50%**
  - **Higgs rates in ZZ* and WW* are consistent with the SM**

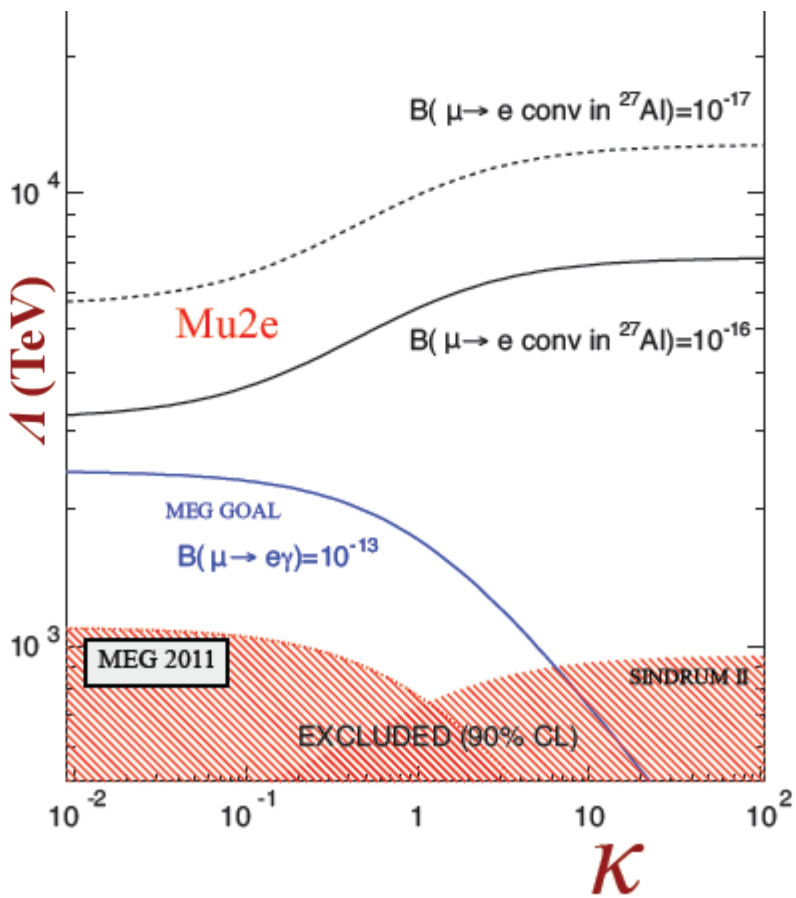
- Theoretical SUSY model that fits observations
  - **light stau with large left-right mixing**
  - **light Bino**
  - **heavy higgsinos**

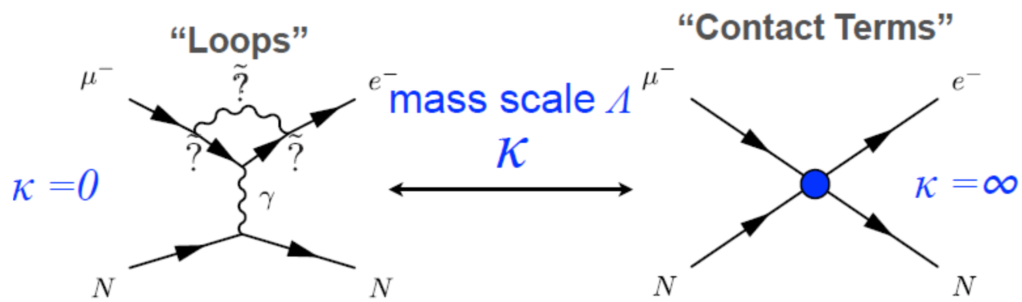
- Other consequences
  - ✓ **Predicts Muon Anomaly exactly** — **Low-energy**
  - ✓ **Compatible with thermal dark matter** — **Low-energy**
  - ✓ **Predicts small deviations in h → γZ and h → $\tau\tau$** — **Collider**
  - ✓ **Predicts measureable violations of Lepton Non-Universality in $\tau-\mu$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

Muon-to-Electron Conversion: Mu2e*

The SM theory is clear: It won't happen

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





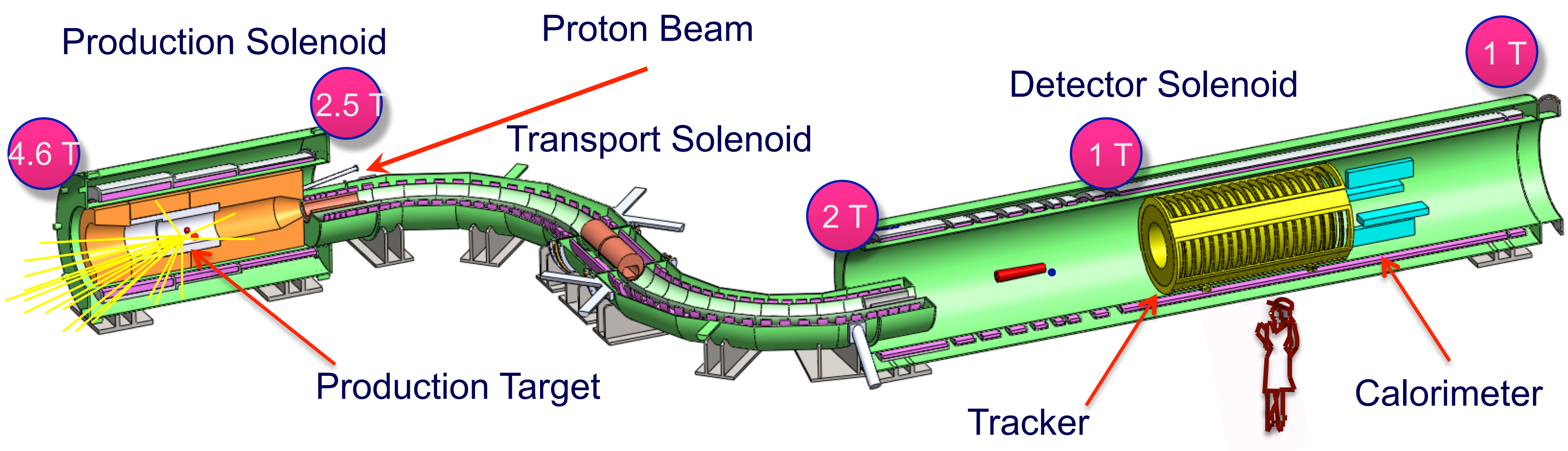
Vertex correction" vs "4-fermion" operator

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

How it is done

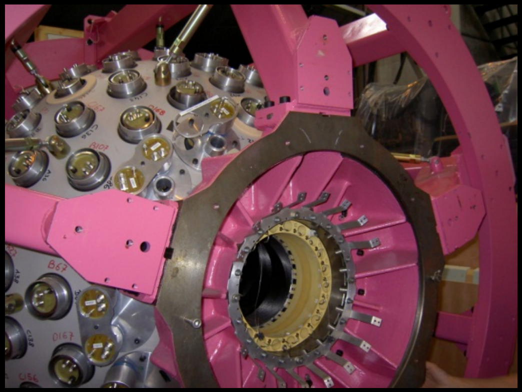
- Make **muonic Al** atoms.
  - 40% will decay "in orbit";
  - 60% will capture (junk emitted)
- Look for **mono-energetic e$^-$,** at muon mass (~104 MeV)

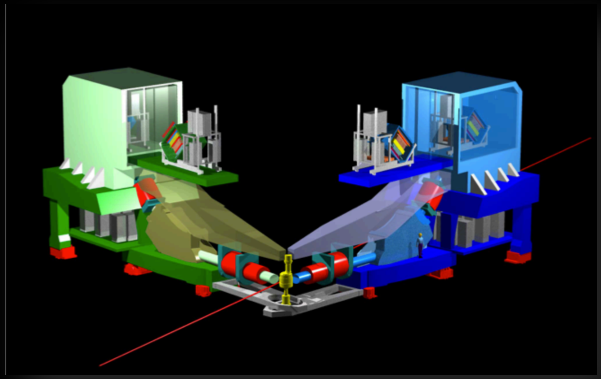
This experiment is in R&D and Pre-Construction Mode with CD1 approval



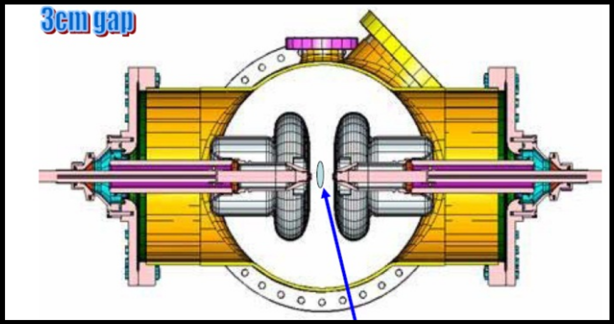
Start date close to 2020

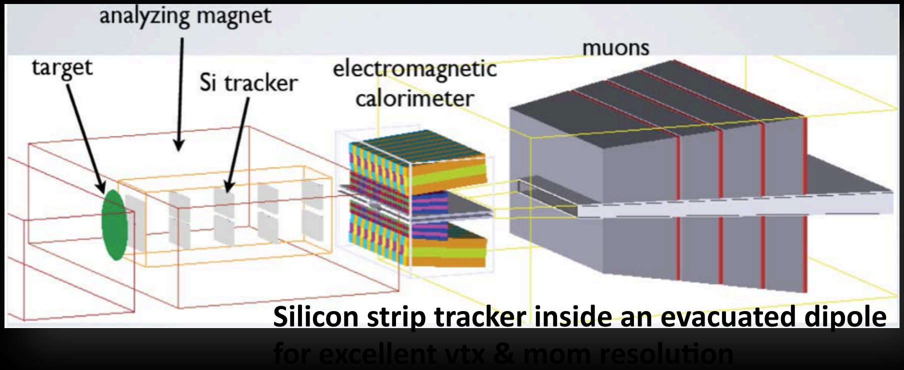
Chapter 5: Pions & Photons





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: $\dfrac{\delta B}{B} \simeq 5 \times 10^{-4}$ **x 10 improvement**

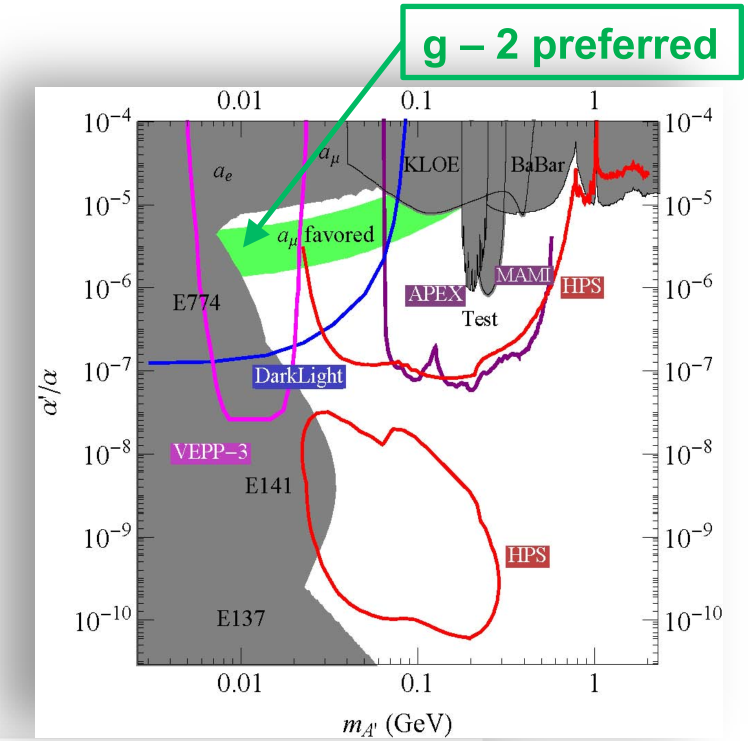
PEN data taking complete. Analysis in progress

PiENu data taking ends in December

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

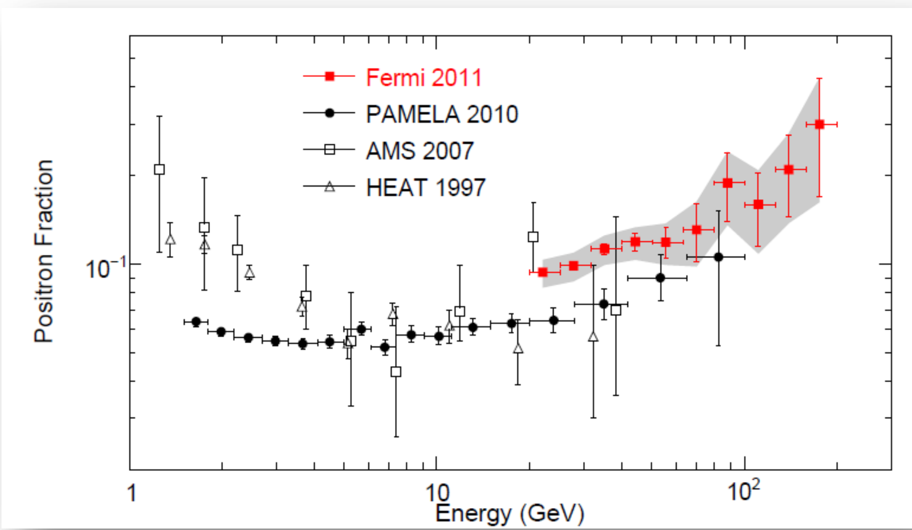
2010 → … Dark Photon searches: @JLab

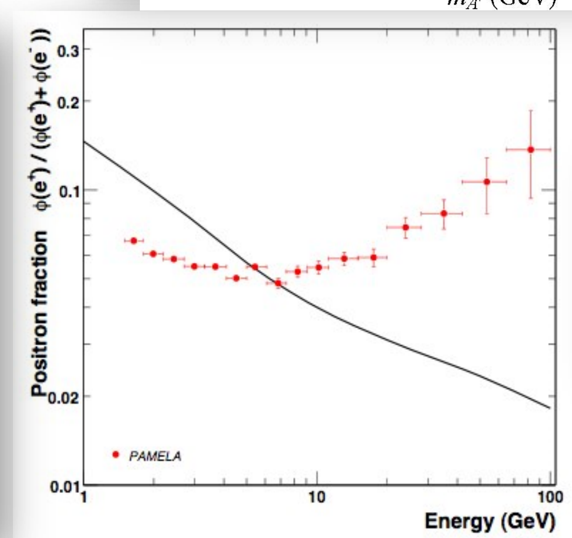
- **A', a massive neutral vector boson**
  - kinematically mixes with γ
  - $\alpha' = \varepsilon\alpha_{e.m}$ $\varepsilon = 10^{-2} - 10^{-6}$
  - Mass in the MeV-GeV region

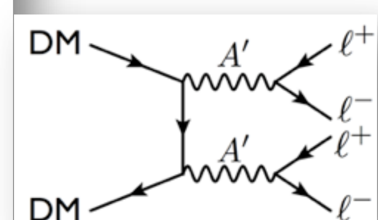


- **Can explain g-2 discrepancy**

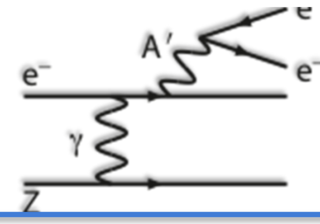
- **Can explain cosmic positron data**



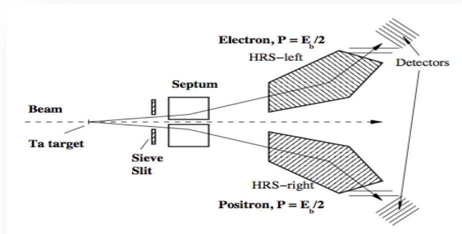




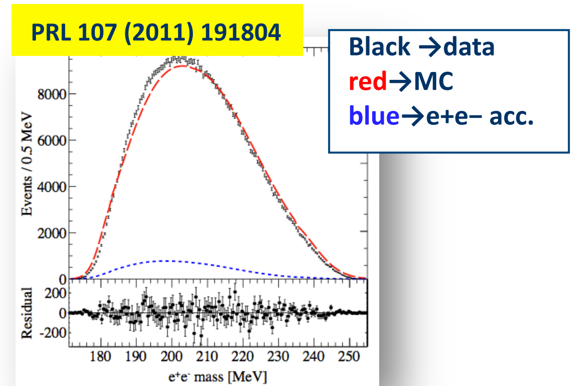
Method: Produce A' with electron beam
Detect pair decays (narrow peak above background)



APEX in Hall A



Simplest using existing spectrometers



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

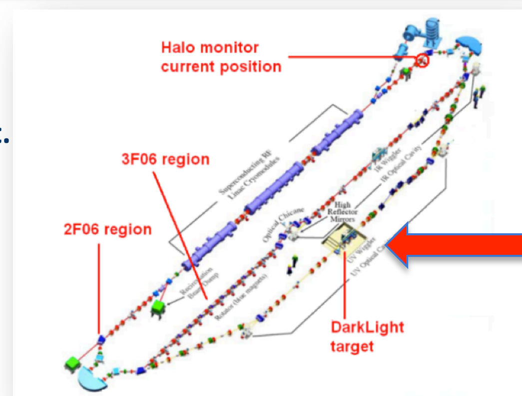
HEP funded

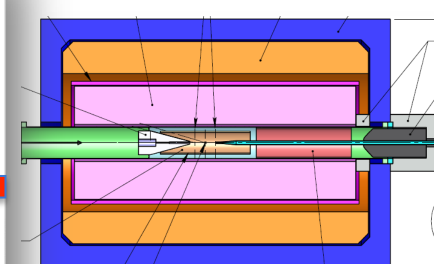
DarkLight @ the JLab FEL

- FEL beam (~1mA, 100 MeV) incident on a H_2 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





Summary: This Field is …

- **Vibrant, Active, Diverse**
- **Discovery-oriented**
- **Directing larger investments to efforts with significant potential payoff**
  - nEDM
  - Moller
  - Equipment request for g-2
- **Incompletely summarized. I omitted:**
  - npdgamma, other EDM efforts, various nuclear beta decay expts., theory efforts, n radiative decay, emiT, new n lifetime ideas, acorn, …