Fundamental Symmetries and Precision Physics

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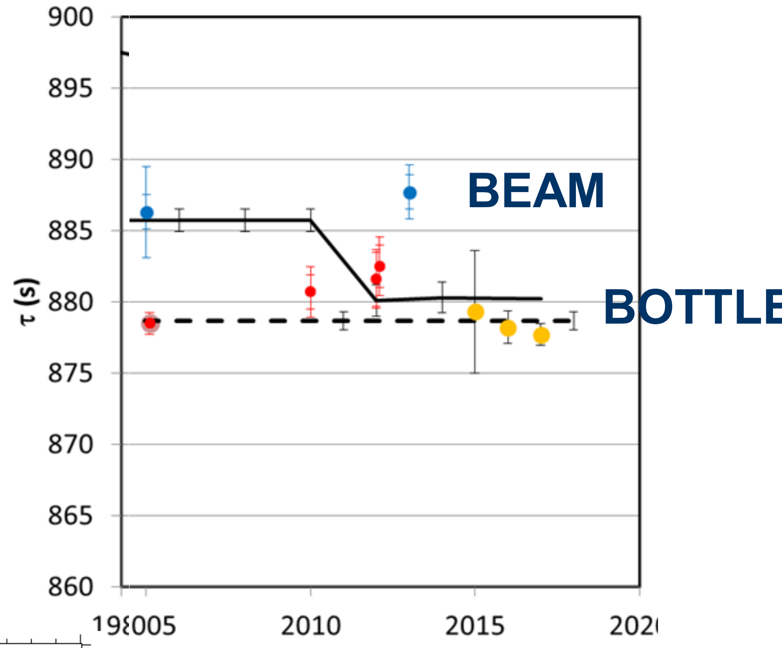
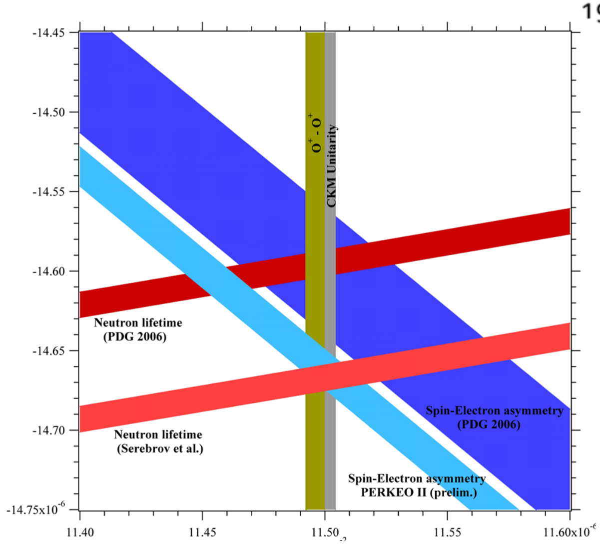
- **Lecture 1**
  - Motivations
  - Symmetries, Parity, and the Weak Interaction
  - The Fermi Constant
  - Muon Decay as a test of V-A theory
  - Neutrons … started …
- **Lecture 2**
  - Neutron beta decay … continued
  - Parity as a tool to probe matter: PVES
  - Highly sensitive low-energy probes of New Physics
  - Start … CPV and Electric Dipole Moments
- **Lecture 3**
  - Charged Lepton Flavor Violation
  - Muon g-2

Last time we finished with …

- Having explained a [new neutron lifetime experiment]
- Having setup the experimental confusion of lifetimes and asymmetry measurements in the 2007 timeframe





The UCN-Tau Annimation

- Load trap for 150 sec
- Clean high-energy ones out for (100-400 sec)
- The Cleaner and Detector (dagger) are raised during the storage time (10 – 1510 sec)
- The Detector is lowered to count remaining UCN

Why else is neutron lifetime important?

Big-Bang Nucleosynthesis (brief)

Time Since Big Bang	Temp	
3 min	10^9K	Nucleosynthesis Begins

Nuclei are now stable against photo disassociation e.g.

$$n + p \to d + \gamma$$

and nuclei are quickly formed. The Universe is now ~87% protons & 13% neutrons

$3\frac{1}{2}$ min	10^8K	Nucleosynthesis Ends

Neutrons are all "used up" making ^{4}He and the Universe is now has ~80% H and ~20% He.

Why else is neutron lifetime important?

Big-Bang Nucleosynthesis (brief)

Some of the Reactions in Big Bang Nucleosynthesis

$$\boxed{\begin{array}{l} n \to p + e + \overline{\nu} \\ p + n \to d + \gamma \end{array}}$$

➡ $N_n = N_0 e^{-t/\tau_n}$

➡ *Disassociation Energy 2.2MeV*

$$p + D \to {}^3He + \gamma$$

$$D + D \to {}^3He + n$$

$$D + D \to T + p$$

Etc.

Cosmic He/H Ratio Depends on 3 quantities:

1. **Cooling rate of the Universe**
2. **Rate at which nuclear interactions occur**
3. **Rate at which neutrons are decaying**
   - **THE NEUTRON LIFETIME**

$$\boxed{Y_p} = 0.264 + 0.023\log\boxed{\eta_{10}} + 0.018(\boxed{\tau_n} - 10.28)$$

Cosmic He abundance

Cosmic baryon density

***n* Lifetime**

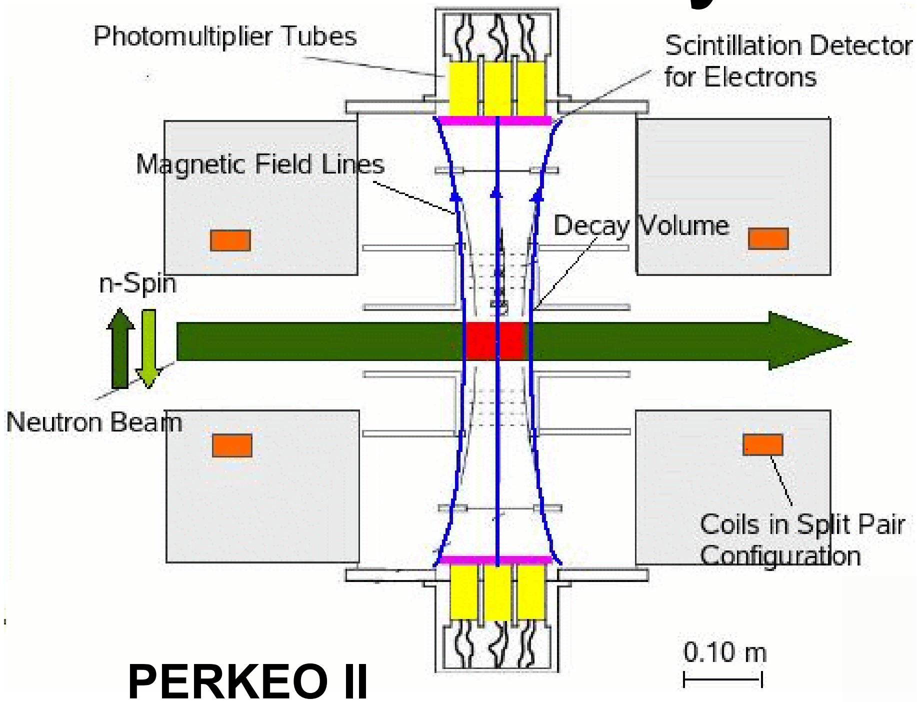
The neutron asymmetry …

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

We'll concentrate on the 2 recent experiment that measured 'big A'

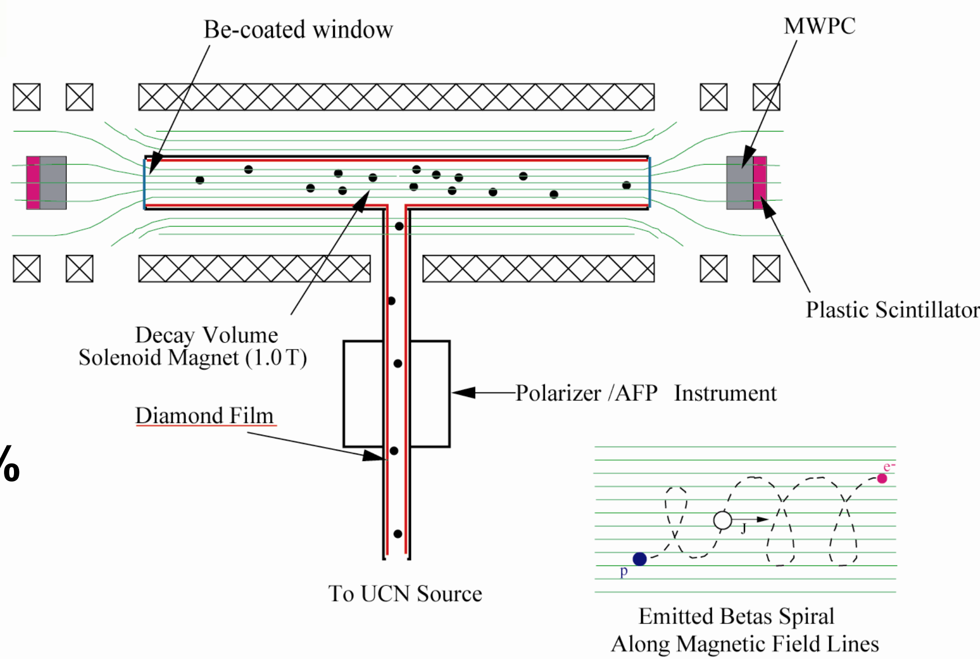
But, note, there is a new major effort being launched nowish to measure "little a" and "little b" … called Nab

Modern Asymmetry Experiments



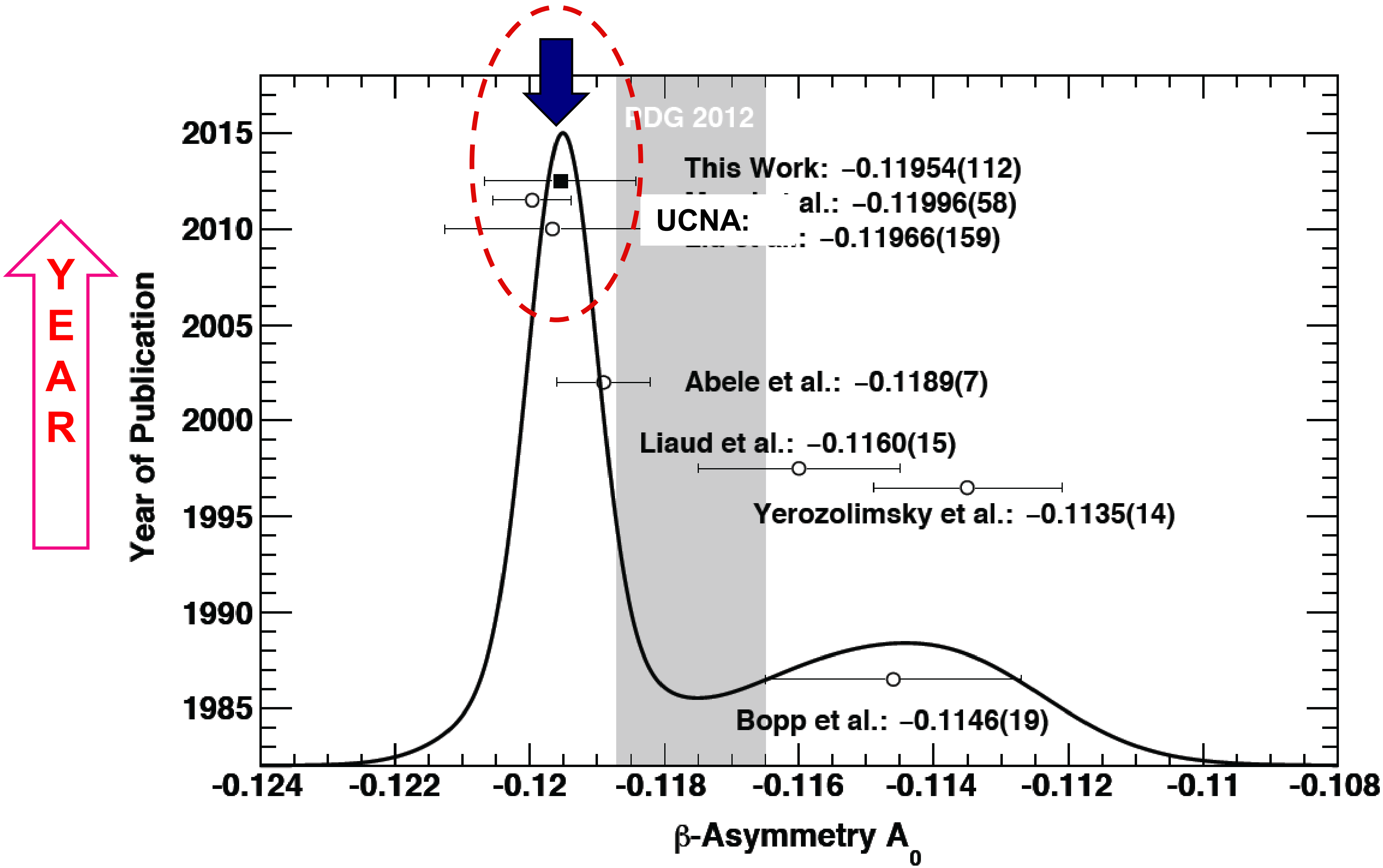
PERKEO II
dλ/λ = 0.11%

$$A = -2\frac{|\lambda|^2 + Re(\lambda)}{1+3|\lambda|^2}$$



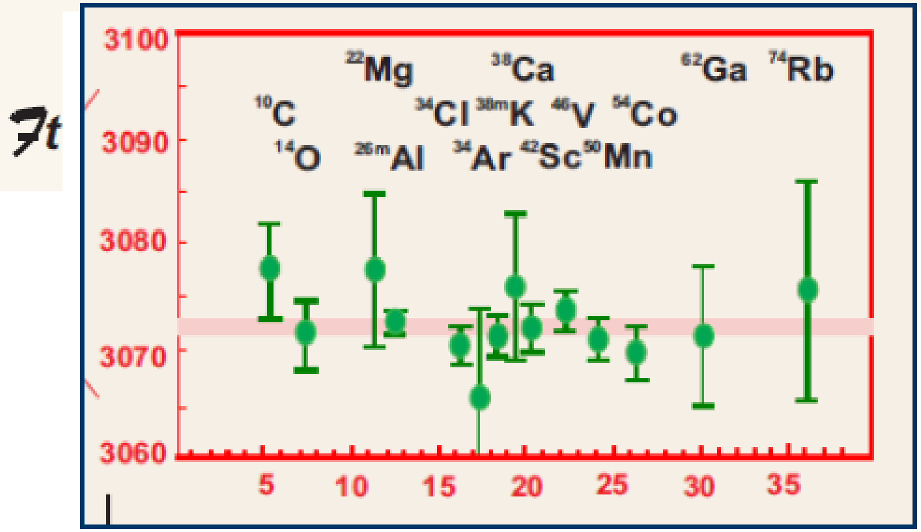
UCNA
dλ/λ = 0.24%

2013 Update on beta decay asymmetry

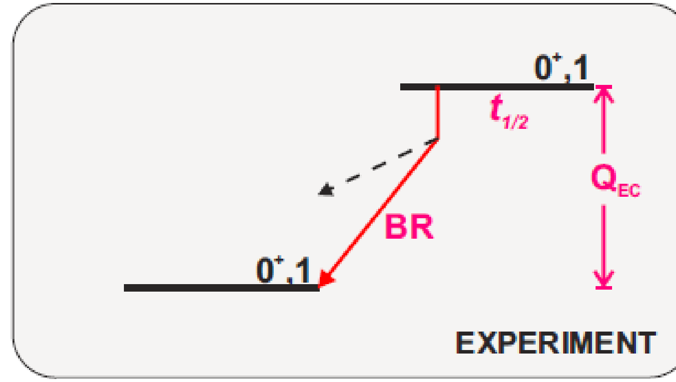


One more thing: Superallowed $0^+ \rightarrow 0^+$ Beta Decays

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



Z of daughter



$$ft = \frac{K}{G_V^{\,2} <\tau>^2}$$

f = statistical rate function: $f(Z, Q_{EC})$

t = partial half-life: $f(t_{1/2}, BR)$

G_V = vector coupling constant

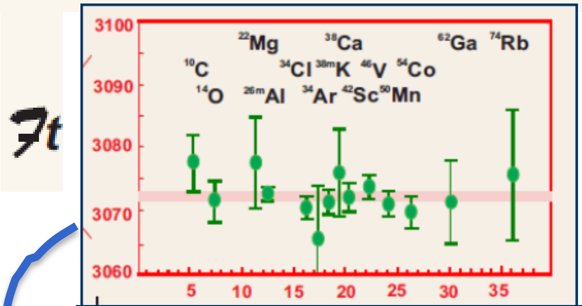
$<\tau>$ = Fermi matrix element

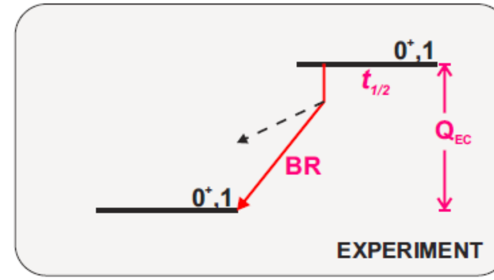
The special case of a transition between isobaric analogue states, where the structure of the final state is very similar to the structure of the initial state, is referred to as "superallowed" for beta decay, and proceeds very quickly.

Forbiddenness	ΔJ	$\Delta\pi$
Superallowed	0	no
Allowed	0, 1	no
First forbidden	0, 1, 2	yes
Second forbidden	1, 2, 3	no

One more thing: Superallowed $0^+ \rightarrow 0^+$ Beta Decays

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





$$ft = \frac{K}{G_V^2 <\tau>^2}$$

Tests of CKM Unitarity via nuclear beta, muon and Kaon decays at the 0.05% level

- Test CVC from many transitions
  - & validate correction terms

G_V constant to ± 0.013%

- Test for Scalar current

limit, $C_S/C_V = 0.0014\ (13)$

Then, *IF* CVC verified:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Precise V_{ud} :

$V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$

- Test CKM unitarity

$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$

J. Hardy

2017 Picture: Lifetime, Correlations, V_{ud} all painting a very consistent picture now IF we use the "precision" results only

$$A = -\frac{2\lambda(\lambda+1)}{1+3\lambda^2}$$

$$|V_{ud}|^2 = \frac{4908.7\text{sec}}{\tau_n\left(1+3\lambda^2\right)}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

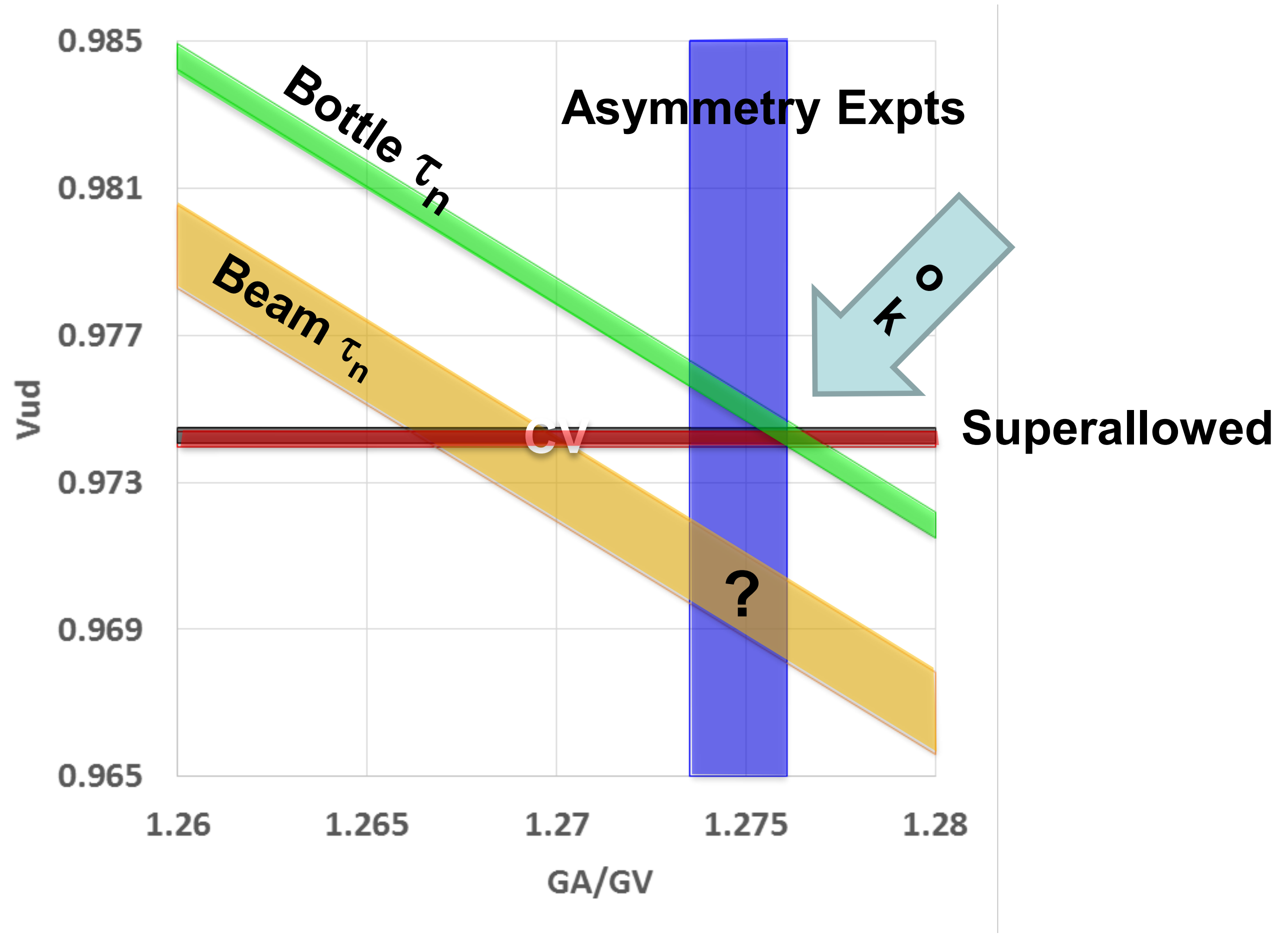
bottle τ_n

beam τ_n

UCN+beam λ

$0^+ \rightarrow 0^+$decays

V_{ud}



Sorry, this plot is turned and arranged differently

How does this story end?

- I draw the conclusion that the SM is pretty well tested and confirmed here, IF, the Beam lifetime experiments were wrong.
- Community of experts needs to resolve this before drawing exotic physics conclusions
- The Lifetime is important on its own

Topic 4

Parity as a Tool to Probe the Nucleon and to search for New Physics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Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

The weak neutral current

CrossMark

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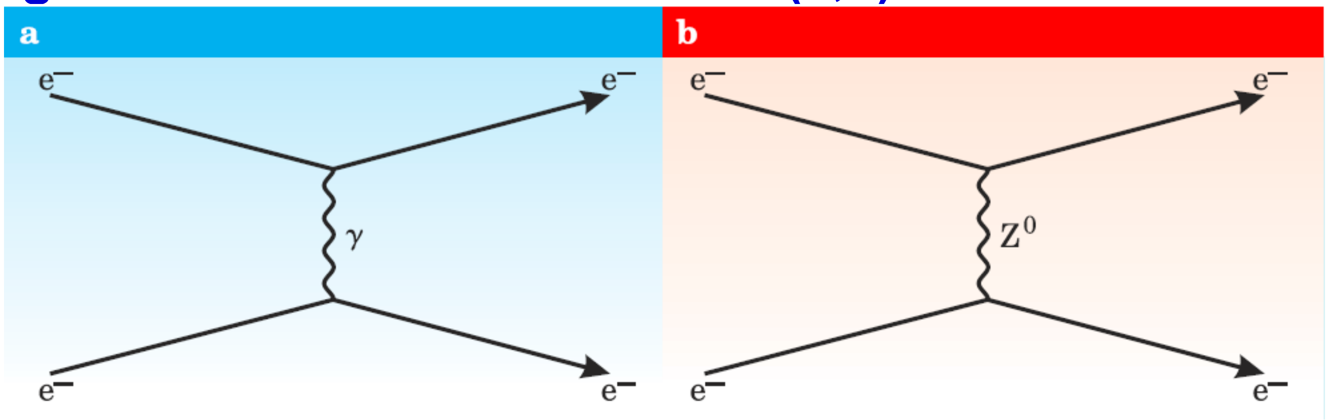
The basic idea is this …

- Compare elastic scattering of Left and Right handed electrons on some target …
  - Target could be a proton (e, p), or a deuteron (e, d), etc.
  - Target could even be an electron (e,e) → "Moller" scattering



Photon has no handedness preference

But Z boson does

Interference of processes a and b causes a tiny difference in cross sections vs incoming polarized electron direction

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim 10^{-4}$$

Image: Physics today

In elastic electron-proton scattering

(diverse physics probed depending on kinematics)

$$A^{PV} = \left[\frac{-G_F M_p^2 Q^2}{\pi\alpha\sqrt{2}}\right]\left[(1-4\sin^2\theta_W) - \frac{\epsilon G_E^{p\gamma}(G_E^{n\gamma}+G_E^s)+\tau G_E^{p\gamma}(G_M^{n\gamma}+G_M^s)}{\epsilon(G_E^{p\gamma})^2+\tau(G_M^{p\gamma})^2}\right] - A_A$$

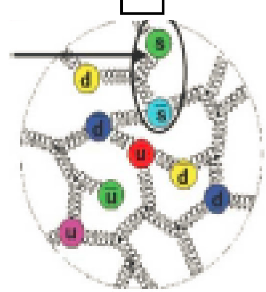
Proportional to the Weak Charge

Our focus

Proportional to the hadronic structure, including strange-quark form factors

Proportional to the neutral weak axial form factor and contains contributions from the anapole moment

This was a major program for years at JLab and elsewhere, looking for strange quark contributions to the proton's electric and magnetic properties



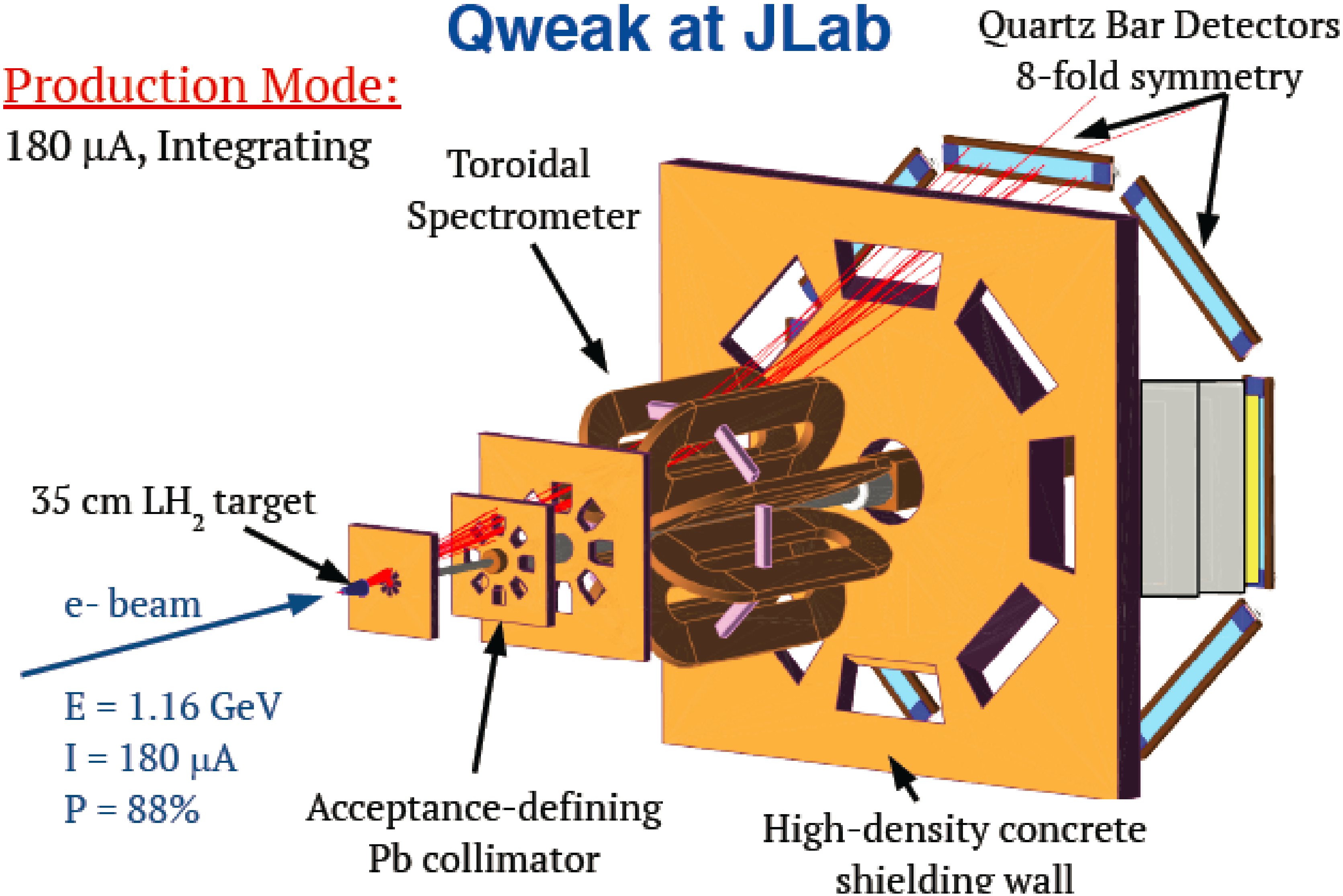
$G_E^s(Q^2)$

$G_M^s(Q^2)$

Qweak at JLab

Production Mode:

180 μA, Integrating

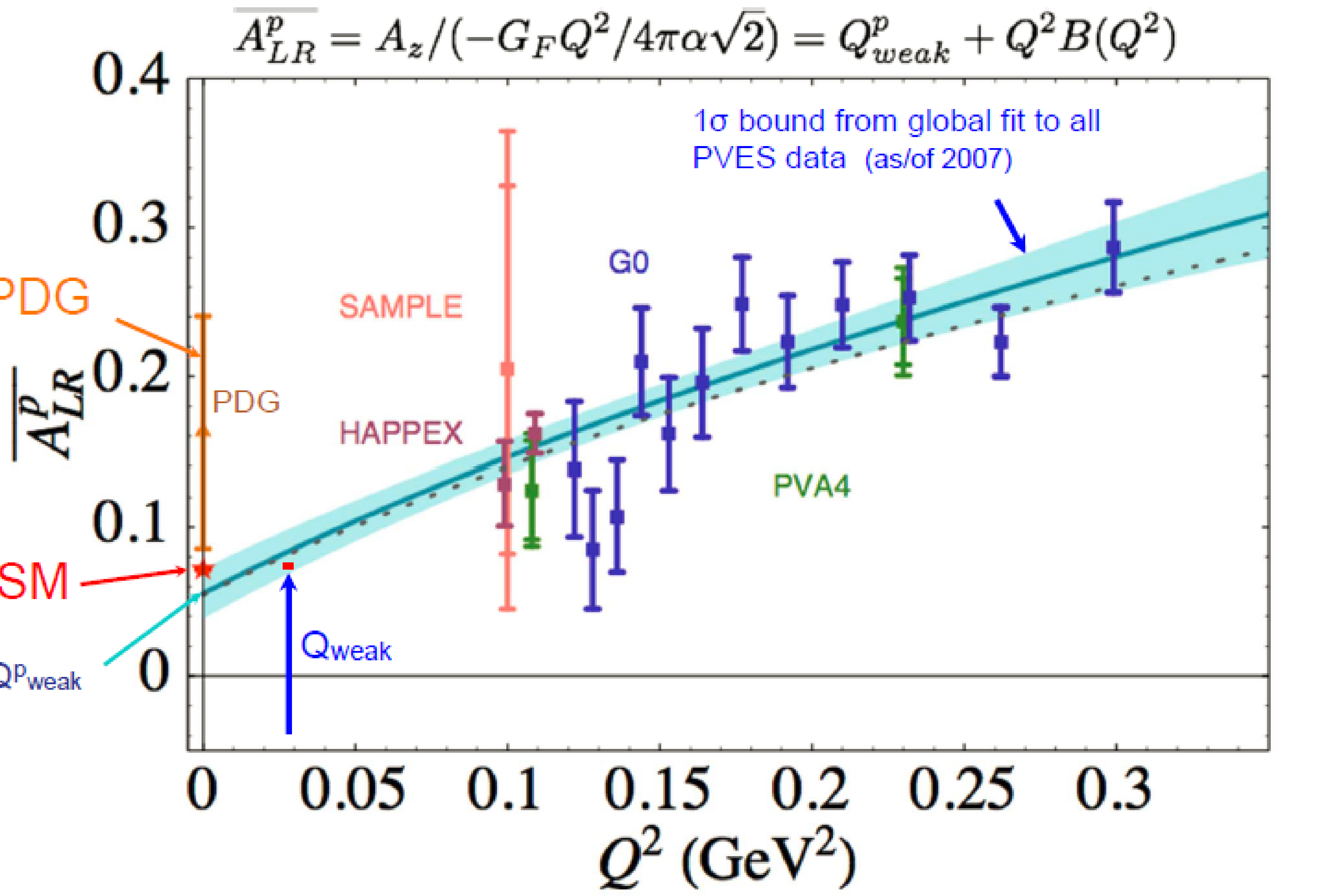


E = 1.16 GeV
I = 180 μA
P = 88%

$$A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 \boxed{Q^p_{weak}} + Q^4 B\left(Q^2\right)\right] \quad Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

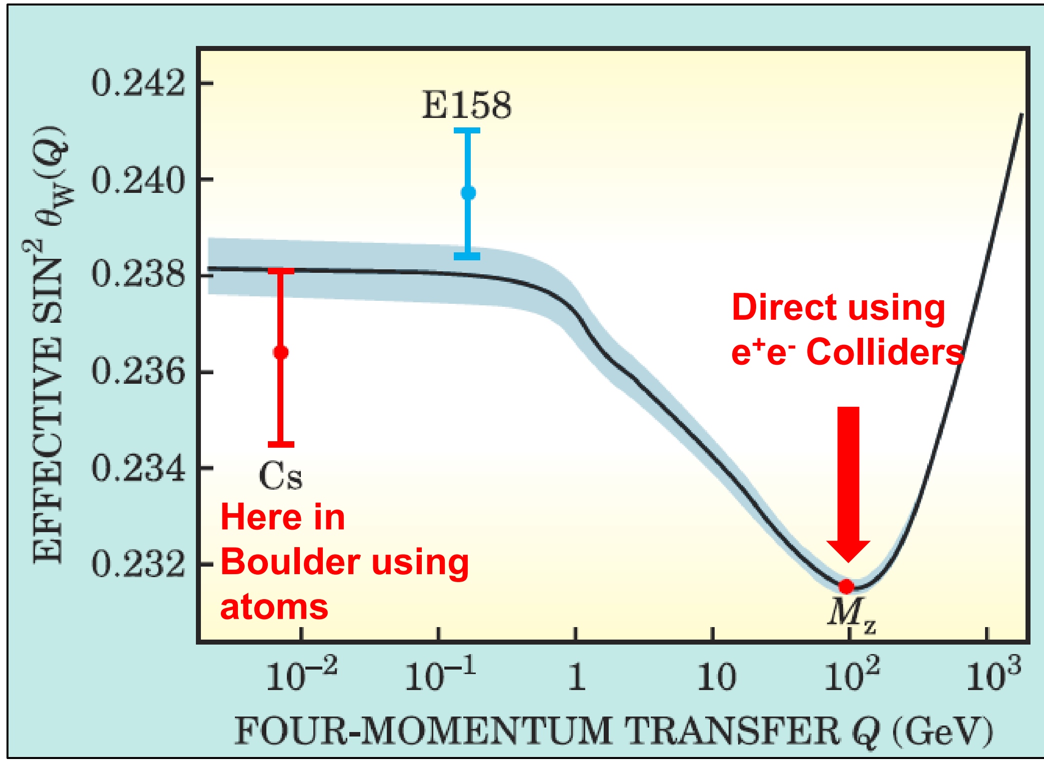
Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007))



The canonical display of the running of $\sin^2\theta_W$ vs 4-momentum transfer Q

New physics sensitivity is deviation from this expected running curve.

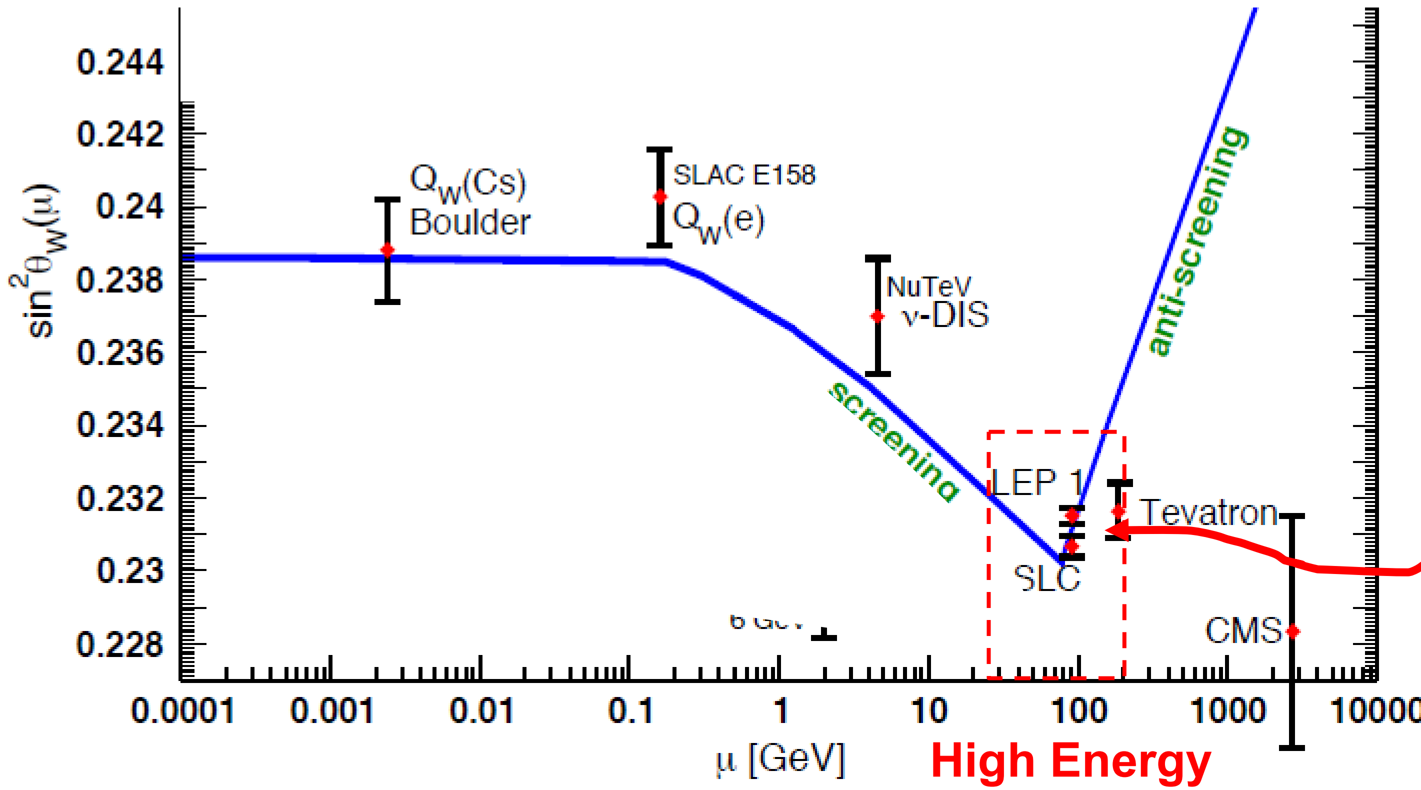


The effective weak mixing angle is the fundamental parameter of parity violation involving the Z boson

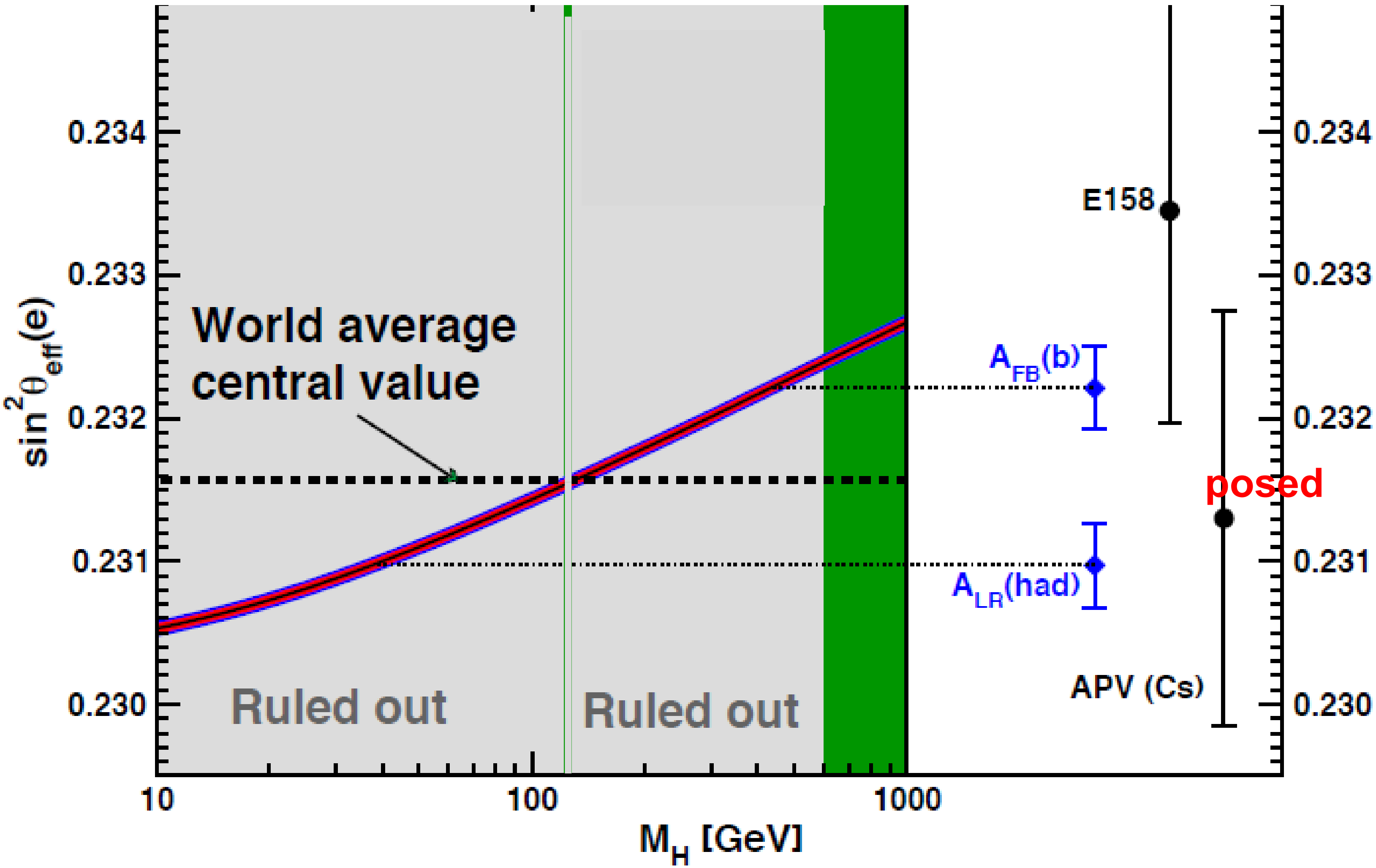
It is expected to vary ('run') depending on the energy scale (E) probed by a given experiment.

Andrzej Czarnecki and William J. Marciano, Nature

Let’s start with some interest at the high energies.



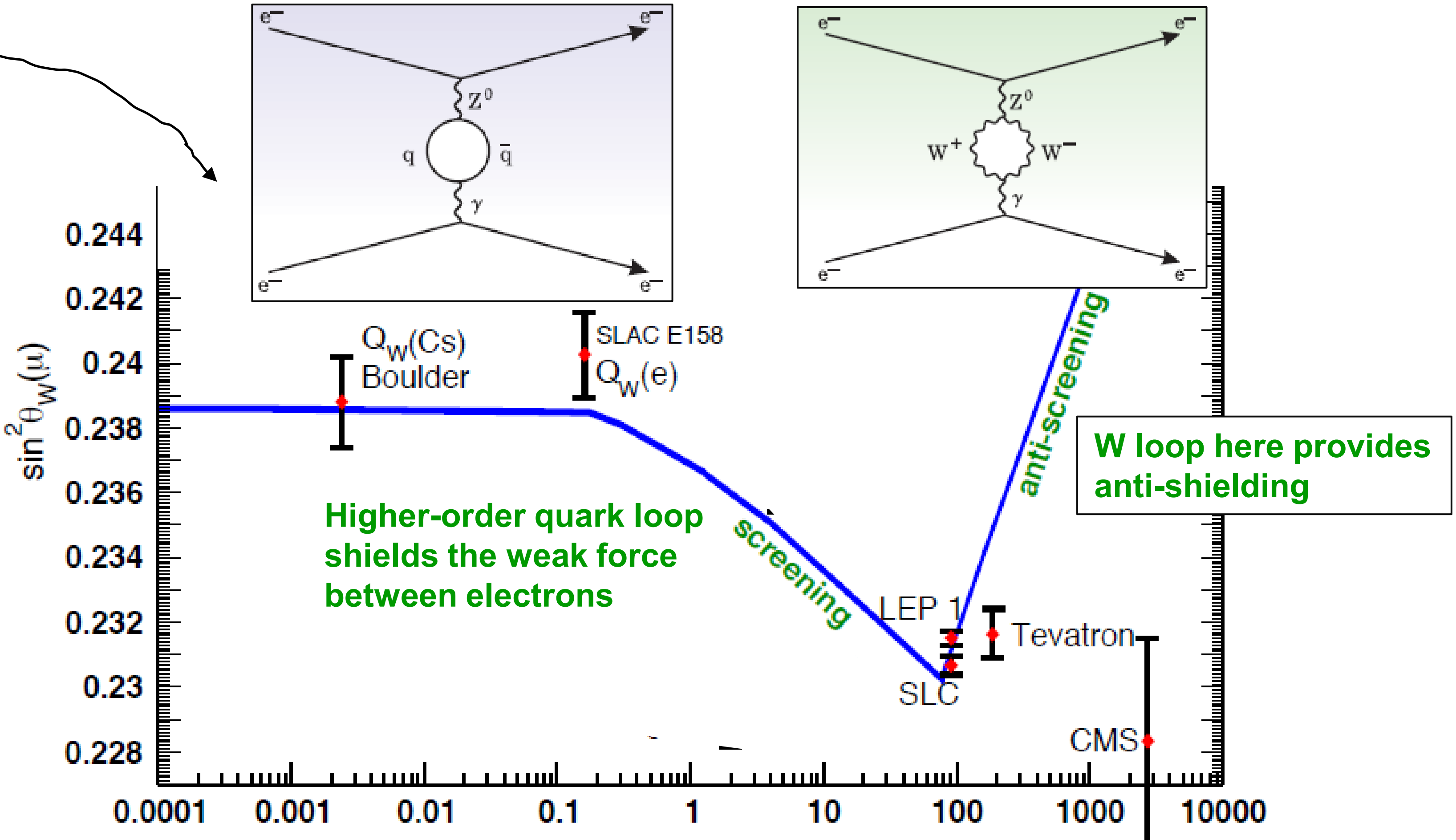
SLAC and CERN are 3 σ apart ! Lots of discussion….
Technicolor? SUSY?
But, then the precision measurement of the Higgs mass fixes the central value of $\sin^2\theta_W$



J. Erler

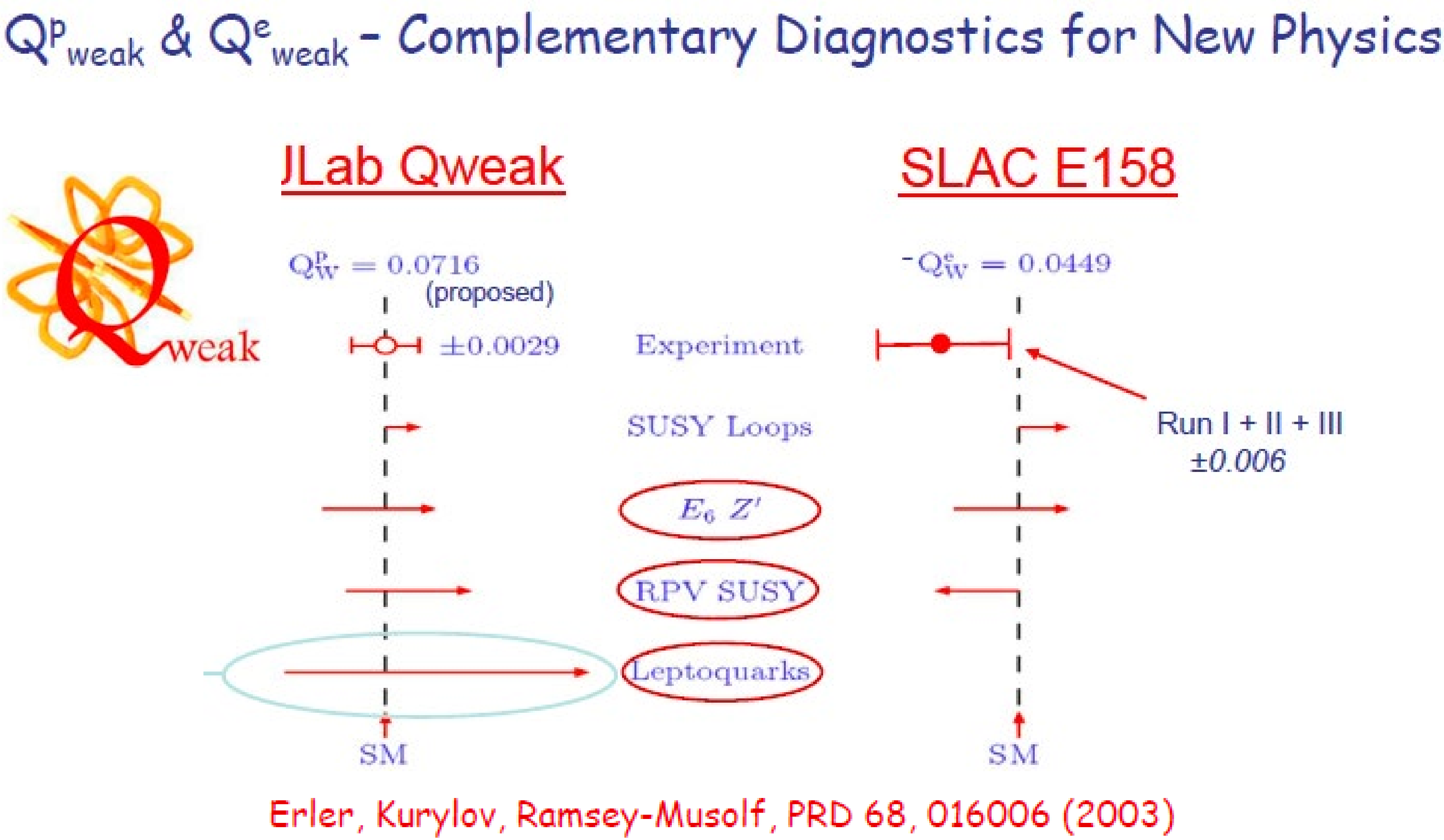
Why is it *running*?

Quantum effects, particularly 'clouds' of quark–antiquark excitations surrounding the electrons at short distances, modify the mixing of the photon and Z boson. This causes the effective weak mixing angle to change slowly as a function of the energy scale probed

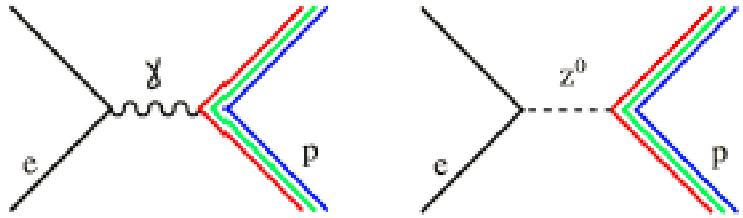


Andrzej Czarnecki and William J. Marciano, Nature

So far, I only showed you (e,e) scattering, but (e,p) very important



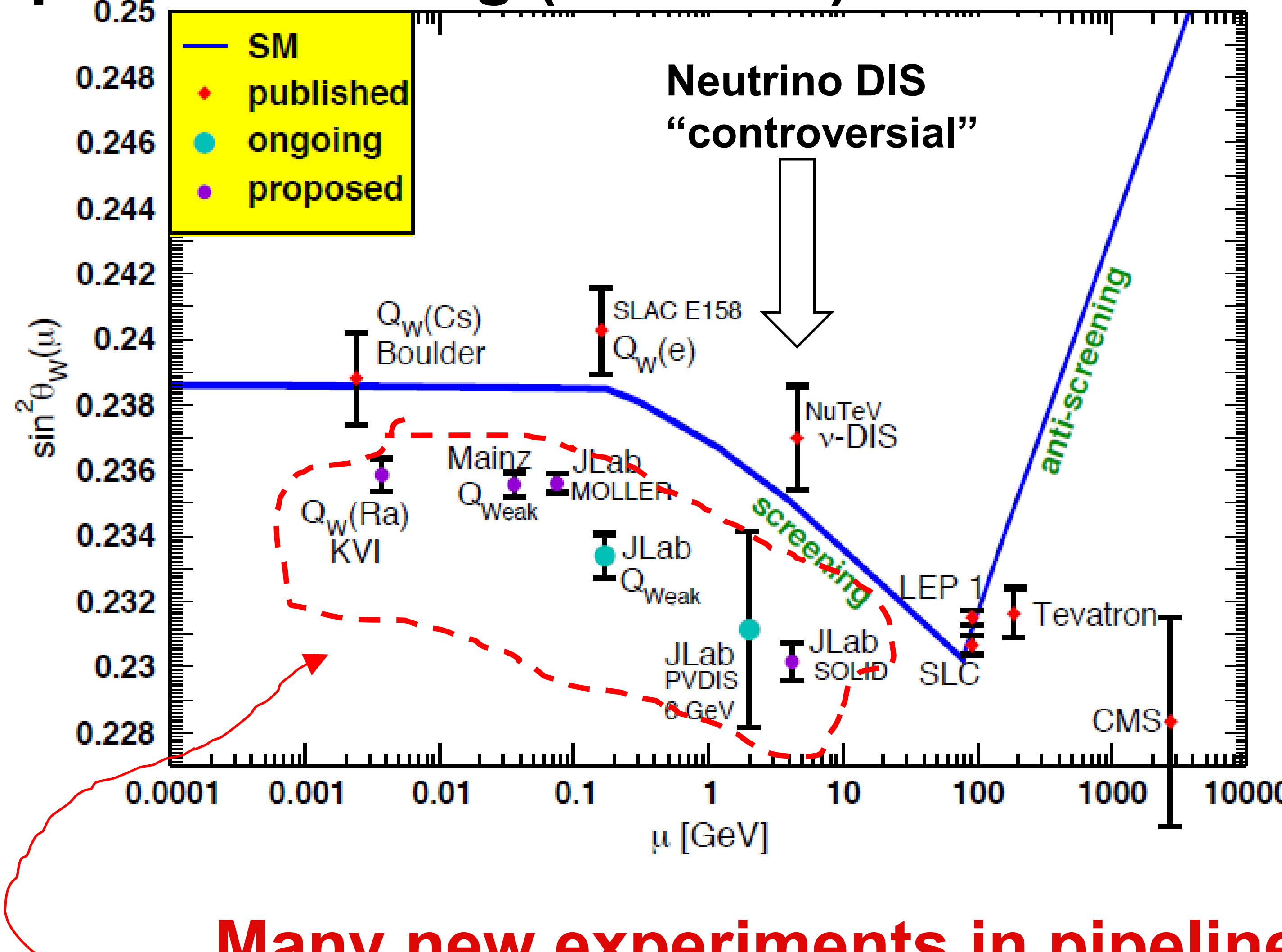
Weak Charge Phenomenology



	EM Charge	Weak Charge
q^{up}	$+2/3$	$1 - \frac{8}{3}\sin^2\theta_W \approx 1/3$
q^{down}	$-1/3$	$-1 + \frac{4}{3}\sin^2\theta_W \approx -2/3$
$Q^p = 2q^{up} + 1q^{down}$	$+1$	$1 - 4\sin^2\theta_W = .048$
$Q^n = 1q^{up} + 2q^{down}$	0	-1
Q^e	-1	$-(1 - 4\sin^2\theta_W) = -.048$

Roles of proton and neutron almost reversed
neutron weak charge dominant
proton weak charge nearly zero
electron weak charge nearly zero

The focus now is how precisely do things line up with expected running (blue line)

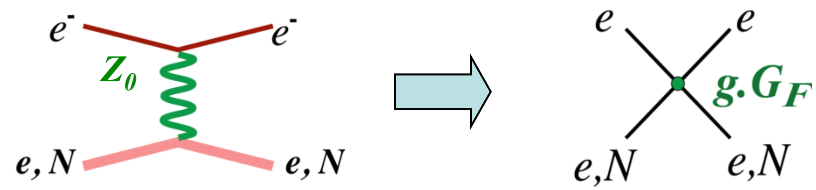


Many new experiments in pipeline

(the error bars are representative)

E.g., Next-Generation experiments sensitive to new, heavy, neutral current interactions?

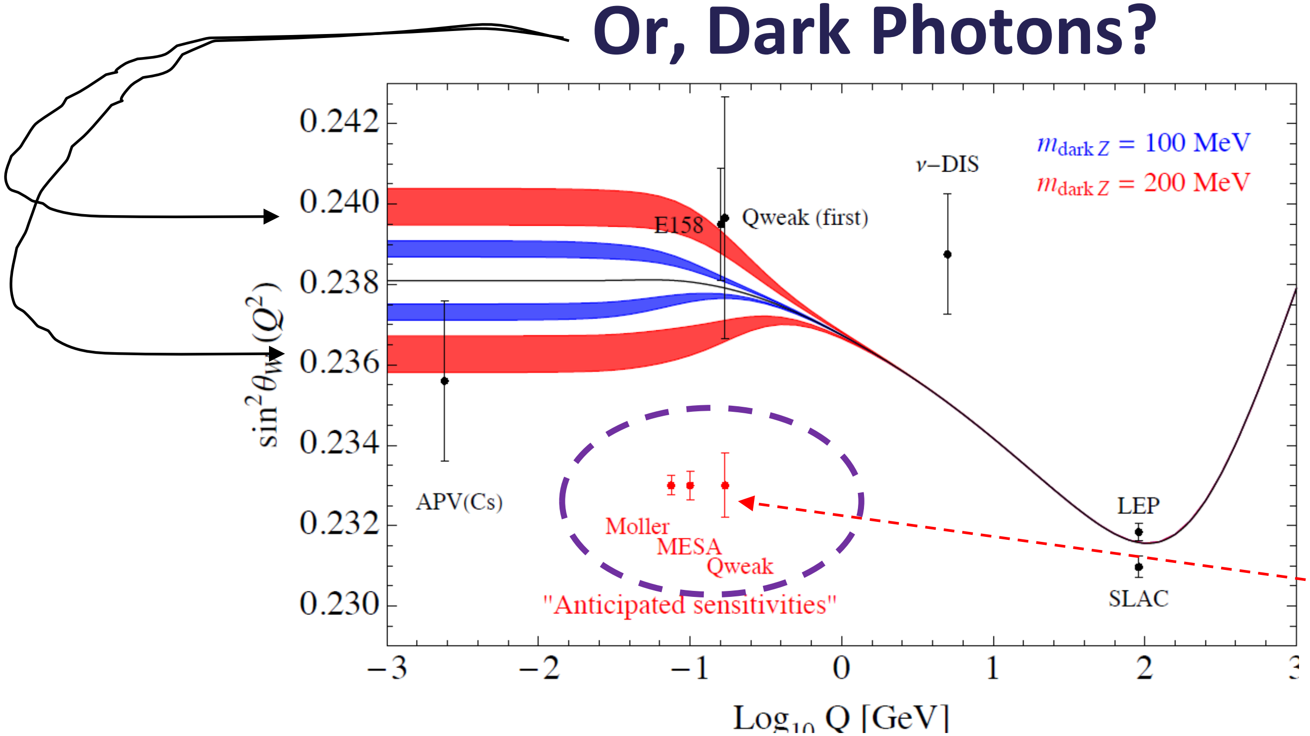
Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…



Sensitivity to TeV-scale contact interactions if:

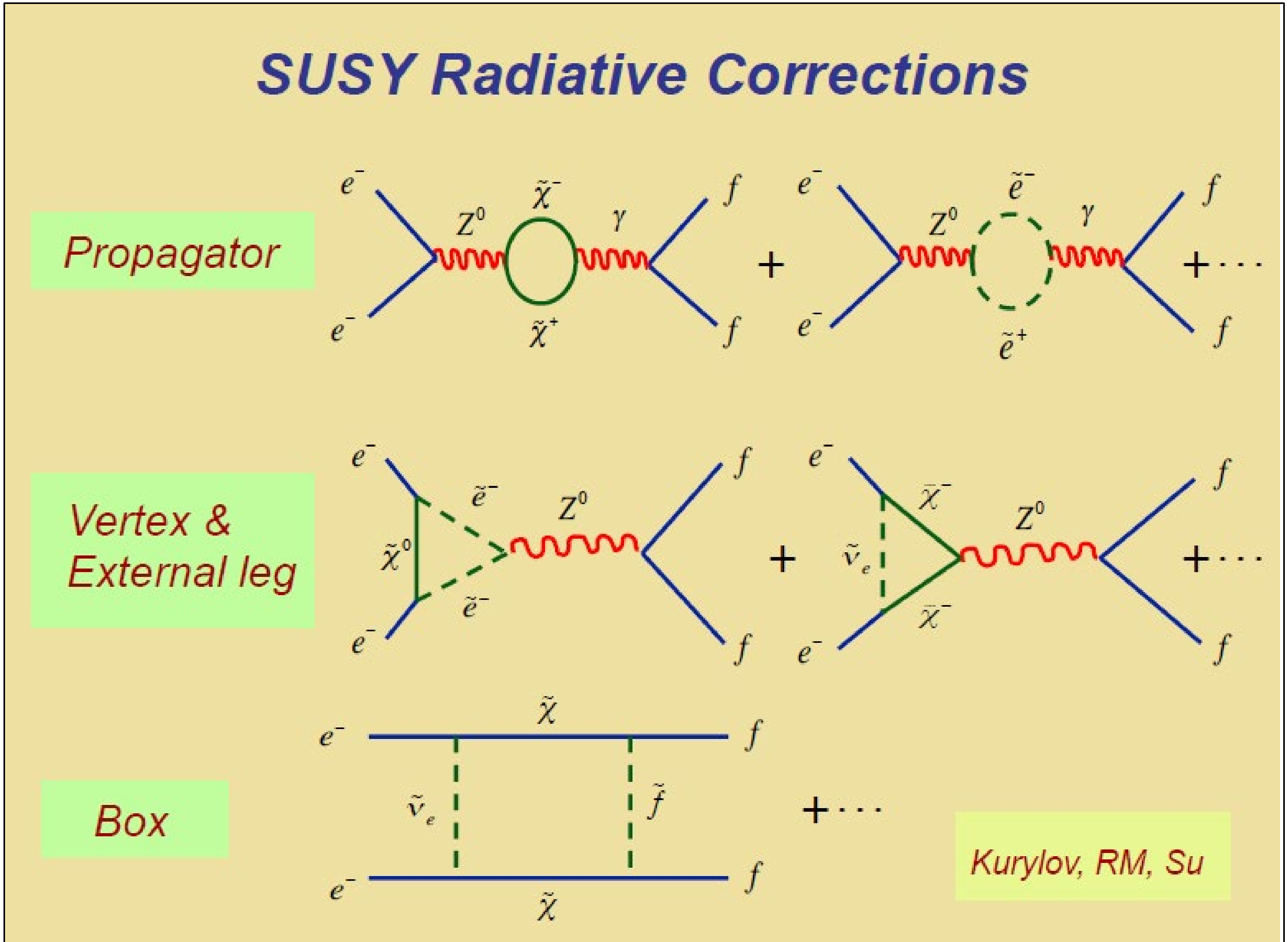
- $\delta(\sin^2\theta_W) \leq 0.5\%$
- away from the Z resonance

Or, Dark Photons?



Q_{weak} result will be announced this summer….

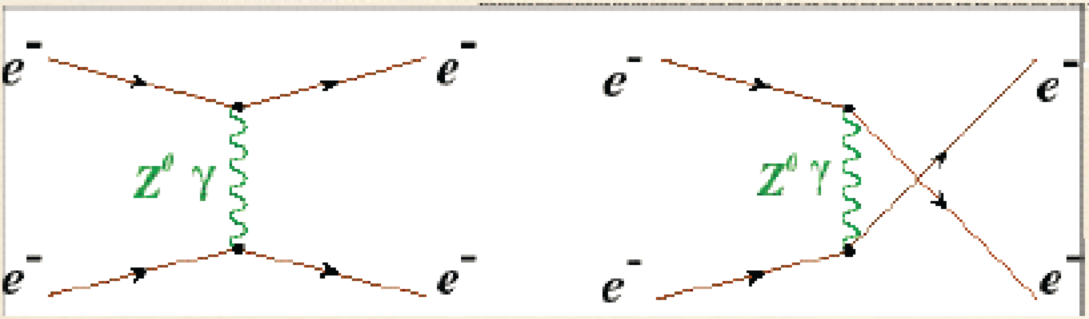
Or deviations from Supersymmetry

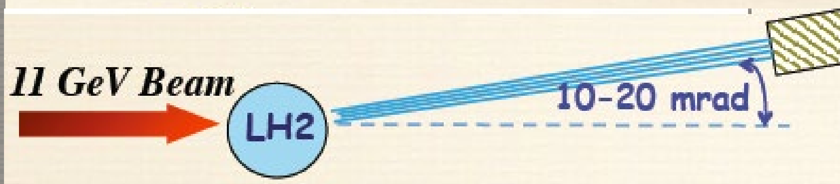


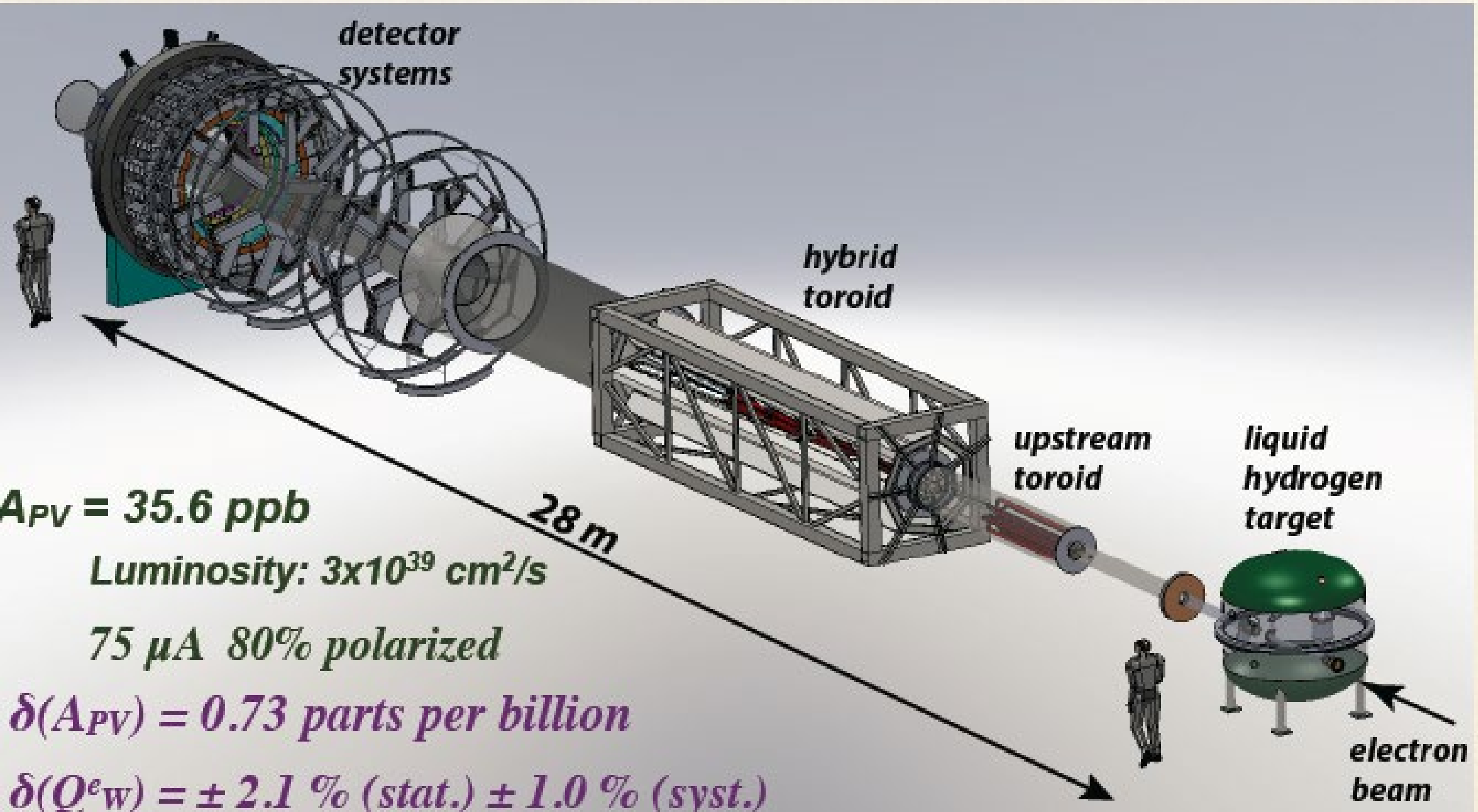
Most sensitive new test is:

MOLLER at JLab

Measurement Of Lepton Lepton Electroweak Reaction







A_{PV} = 35.6 ppb

Luminosity: 3x10^{39} cm^2/s

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm 2.1$ % (stat.) ± 1.0 % (syst.)

Kumar

.. This is a “stay tuned” moment …

- Qweak to announce
- Mainz program running
- MOLLER at JLAB
- SOLID at JLAB

- These things are ambitious … and will take time and $

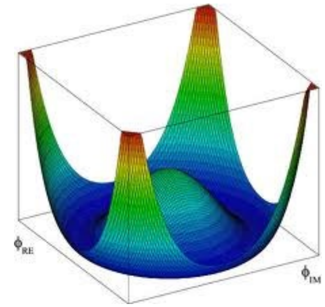
Topic 5

Can low-energy experiments discovery New Physics?

Particle Physicists ask few* questions:

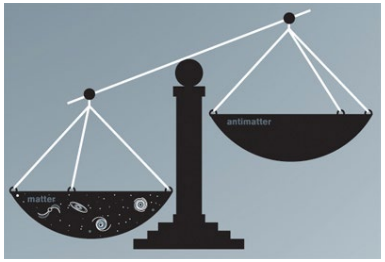
1. **Why mass?**

   Higgs field



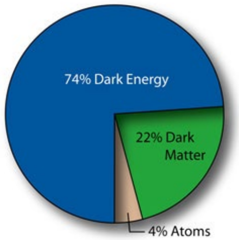
2. **Why matter?**

   New sources of CP Violation



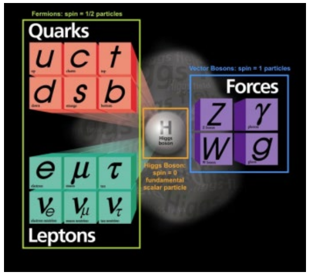
3. **Why Dark Matter**

   WIMP? Axion?



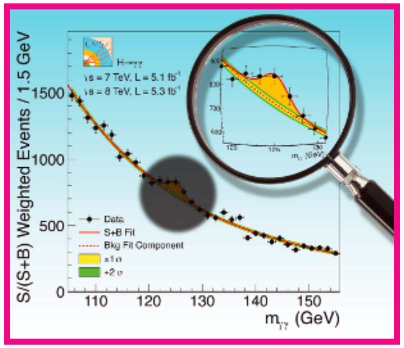
4. **Why this standard model?**

   SUSY, Dark Photons, UED, …



* But, very important !!

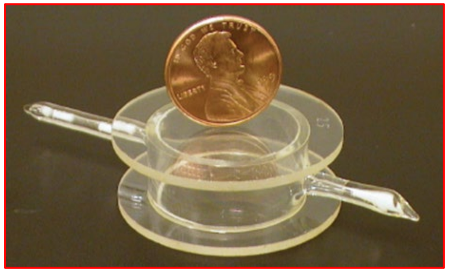
Often: Direct answers are found at the *Energy Frontiers*

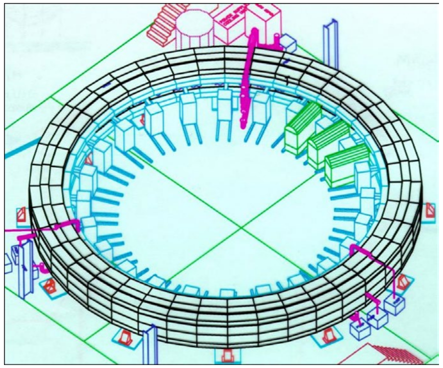


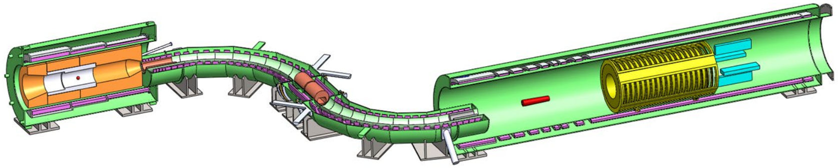
1. Higgs !!
2. But, sources of CP?
3. Hunt for Dark Matter?
4. And, so far data is almost behaving as expected …

And, if it was the case: How would we interpret some kind of BUMP at hundreds of GeV or at a TeV?

Let's discuss some very sensitive low-energy experiments that might help resolve these questions







1. Higgs
2. CP: no answer yet: *EDMs*, $0\nu\beta\beta$ See Kumar
3. Dark Matter: so far, null
4. New Physics? *cLFV or Muon g-2 ?*

Today: Some very sensitive experiments that might help resolve these questions

1. Higgs

2. CP: no answer yet: ***EDMs***, $0\nu\beta\beta$

3. Dark Matter: so far, null

4. New Physics? ***cLFV or Muon g-2 ?***

What does it take to explain the Baryon Asymmetry of the Universe ? (BAU)

- The dynamical generation of net baryon number during cosmic evolution requires the concurrence of three conditions:

Sakharov '67

1. B (baryon number) violation
    - To depart from initial (post inflation) B=0
2. C and CP violation $\boxed{\Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})}$
    - To distinguish baryon and anti-baryon production

3. Departure from thermal equilibrium
    - <B(t)>=<B(0)>=0 in equilibrium

Vincenzo Cirigliano

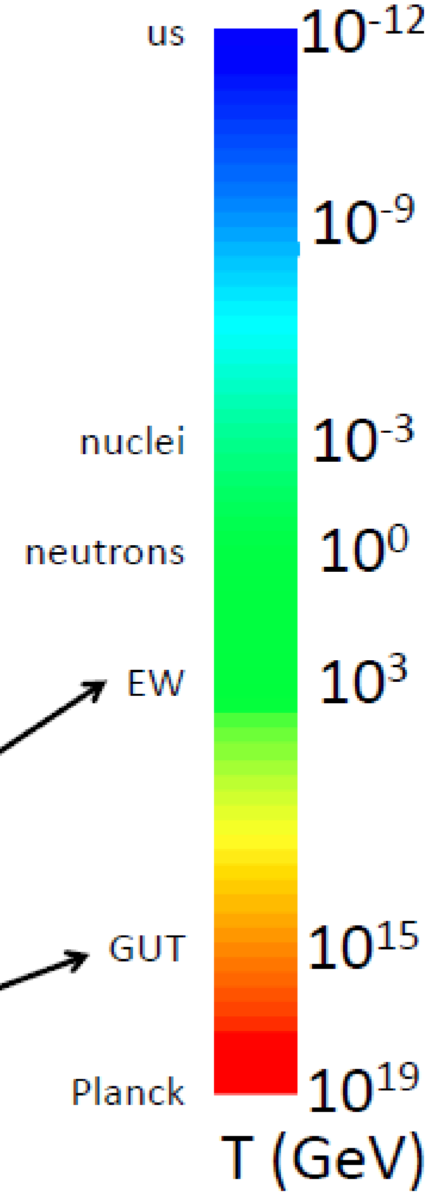
Baryon Asymmetry of the Universe

- Observation

$$\left.\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right)_{early\ universe} \equiv \frac{\Delta n_B}{n_B + n_{\bar{B}}} \sim \frac{n_{B,today}}{n_\gamma}$$

$$\sim few \times 10^{-10}$$

- Baryon asymmetry may come
  - during baryogenesis at electroweak symmetry breaking transition (EWB)
  - during leptogenesis at scale of heavy neutrino mass



Kumar lectures

Baryogenesis: At first, it was all about CPV in the CKM mass mixing matrix

- **1964: Observation of CPV in 2π decays of K^0 [1]**
  - Occurs ~ $2x10^{-3}$ times per normal decay
  - → INTERESTING!!! But, not enough for BAU
  - Lots of great work with kaons, direct CP, direct T violation, and so on, but … not enough

- **What about B mesons?**
  - "B Factories", experiments like BaBar and BELLE
  - CP discovered there too !
  - But, still not enough …

- **Now what do we do? We need "something" ?**
  - **EDMs of paramagnetic atoms and molecules, diamagnetic atoms, and the neutron … oh yeah, and maybe the muon**

[1] **Christenson, Cronin, Fitch, Turlay, PRL 13: 138 (1964)**

Topic 5

Time Reversal Invariance

CP Violation

→ Electric Dipole Moments

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Review

Electric dipole moments of nucleons, nuclei, and atoms: The Standard Model and beyond

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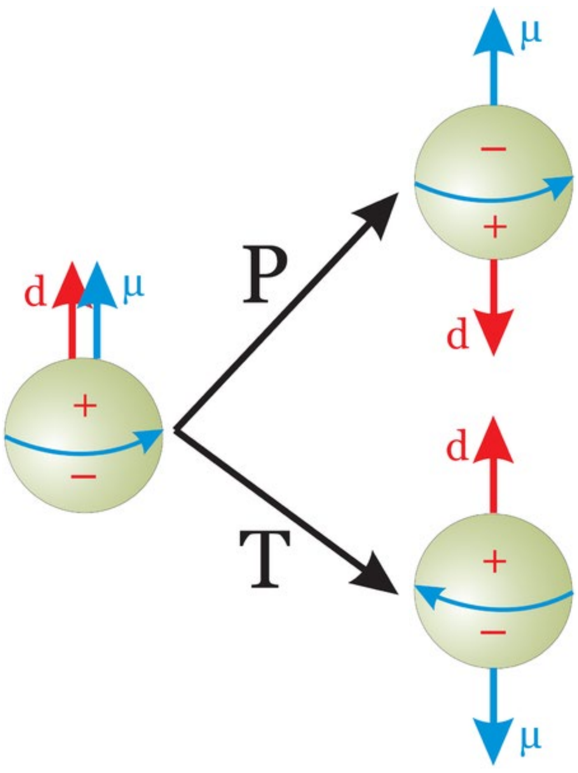
A Permanent Electric Dipole Moments violate P and T; thus a new source of CP Violation under assumption of CPT invariance.

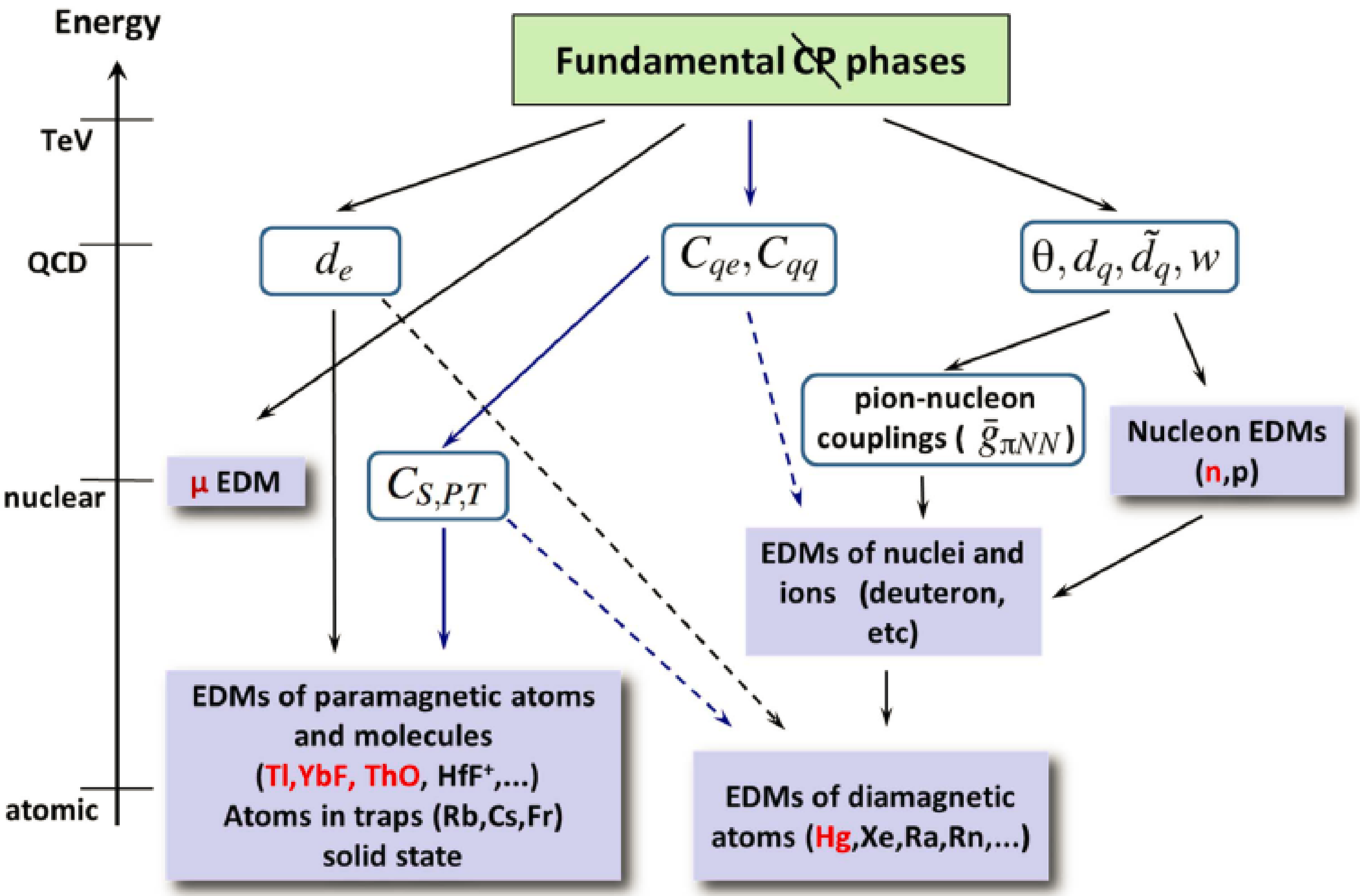


Current EDM Limits

Type	System	EDM Limit (e-cm)
Paramagnetic	YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$
Paramagnetic	ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$
Diamagnetic	^{199}Hg	$d_A = \cancel{(0.5 \pm 1.5) \times 10^{-29}}$ $(-2.20 \pm 2.75_{stat} \pm 1.48_{syst}) \times 10^{-30}$
Nucleon	Neutron	$d_n = (0.2 \pm 1.7) \times 10^{-26}$
Lepton	Muon	$d_\mu = (-0.1 \pm 0.9) \times 10^{-19}$

Many systems … mostly small

Graner et al, PRL 116, 161601 (2016)



Energy
TeV
QCD
nuclear
atomic
Fundamental $\cancel{CP}$ phases
d_e
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
pion-nucleon couplings ($\bar{g}_{\pi NN}$)
Nucleon EDMs (n,p)
μ EDM
$C_{S,P,T}$
EDMs of nuclei and ions (deuteron, etc)
EDMs of paramagnetic atoms and molecules (Tl,YbF, ThO, HfF⁺,...) Atoms in traps (Rb,Cs,Fr) solid state
EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn,...)

Experiments are largely the same

- **Spin is only Vector in system, so** $\vec{d} \uparrow\uparrow \vec{s}$ or $\vec{d} \uparrow\downarrow \vec{s}$
  - **EDM aligned with or against it**

- **Measure Larmor precession frequency in a B field with a *parallel* vs *anti-parallel* E field.**

$$\hbar\omega = 2\left(\mu_n B \pm d_n E\right)$$

- **Example then for a neutron:**

$$d_n = \frac{\hbar\left(\omega_+ - \omega_-\right)}{4E}$$

Partial List of EDM Experiments

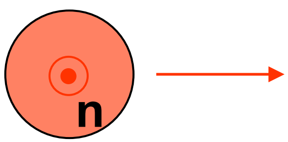
Leptonic EDMs		Hadronic EDMs	
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	U. Texas	n (UCN)	ILL-PNPI
Cs (fountain)	LBNL	n (UCN)	PSI
^{210}Fr (trapped)	Cyric	n (UCN)	KEK-Triumph
		n (UCN)	Munich
YbF (beam)	Imperial College	p (ring)	COSY, BNL
HfF+ (trapped)	JILA	d (ring)	COSY
ThO (beam)	Harvard-Yale		
PbF (trapped)	U. Oklahoma	^{129}Xe (liquid)	Princeton
WC (beam)	U. Michigan	^{129}Xe (cell)	GUMainz
		^{129}Xe (cell)	TUMunich
GGG (solid)	Indiana	^{129}Xe (cell)	Tokyo Inst. Tech.
		^{199}Hg (cell)	Seattle
muon (ring)	J-PARC	^{223}Rn (trapped)	TRIUMF
		^{225}Ra (trapped)	Argonne
		^{225}Ra (trapped)	KVI

So clever, it's worth 2 minutes: S. K. *Lamoreaux* and R. *Golub*,

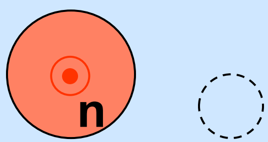
Cold polarized neutrons enter superfluid helium vessel, and get stopped & trapped

Incident neutrons have same energy *and* momentum as phonons in superfluid helium: they interact and stop

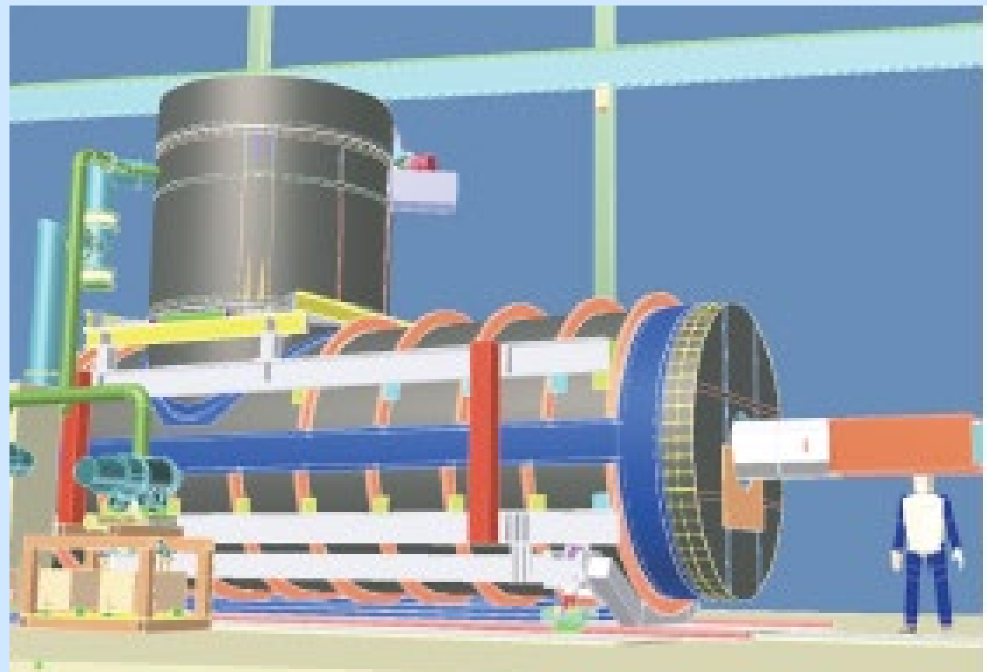
Spin out of page



polarized neutron
T = 1 meV



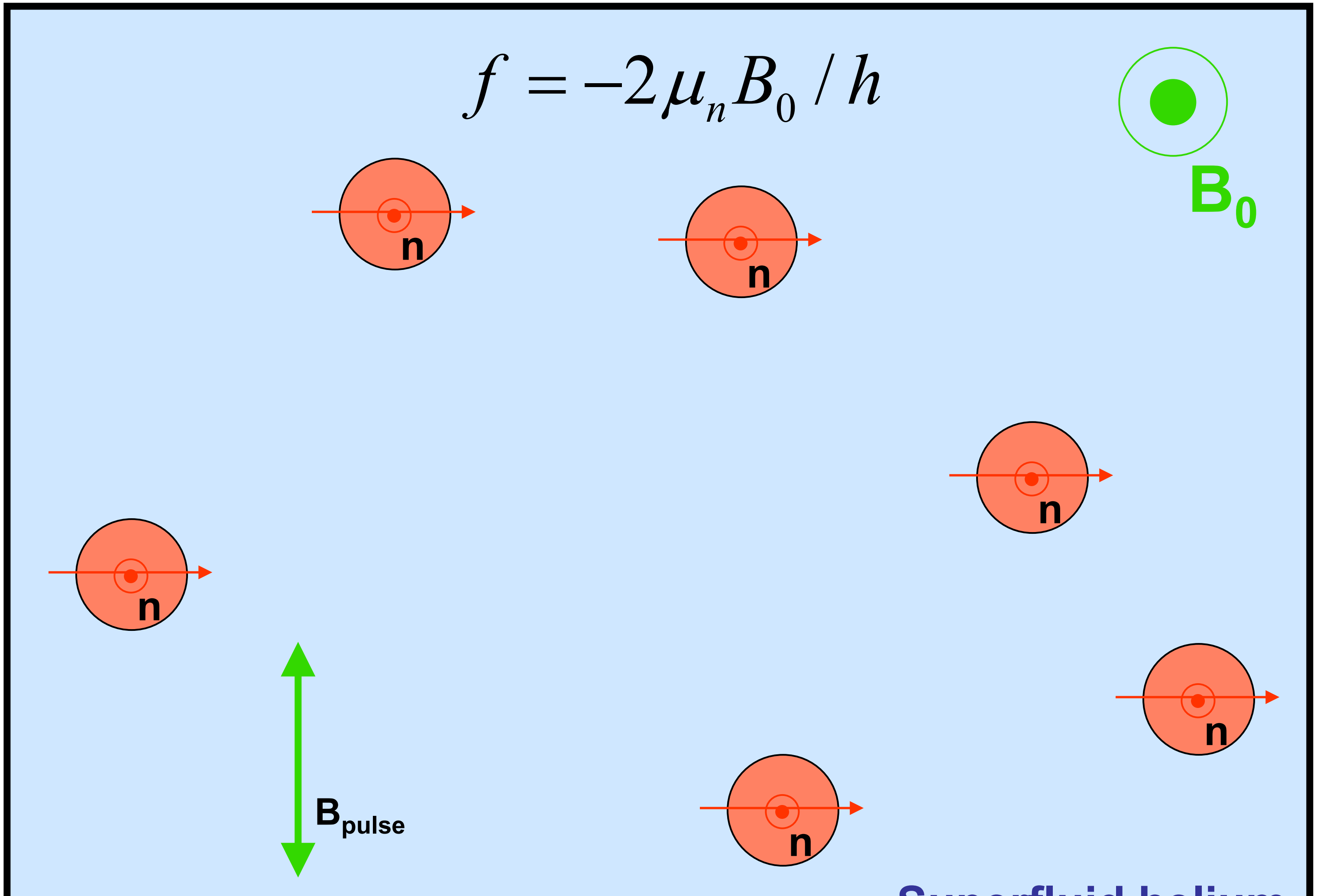
phonon



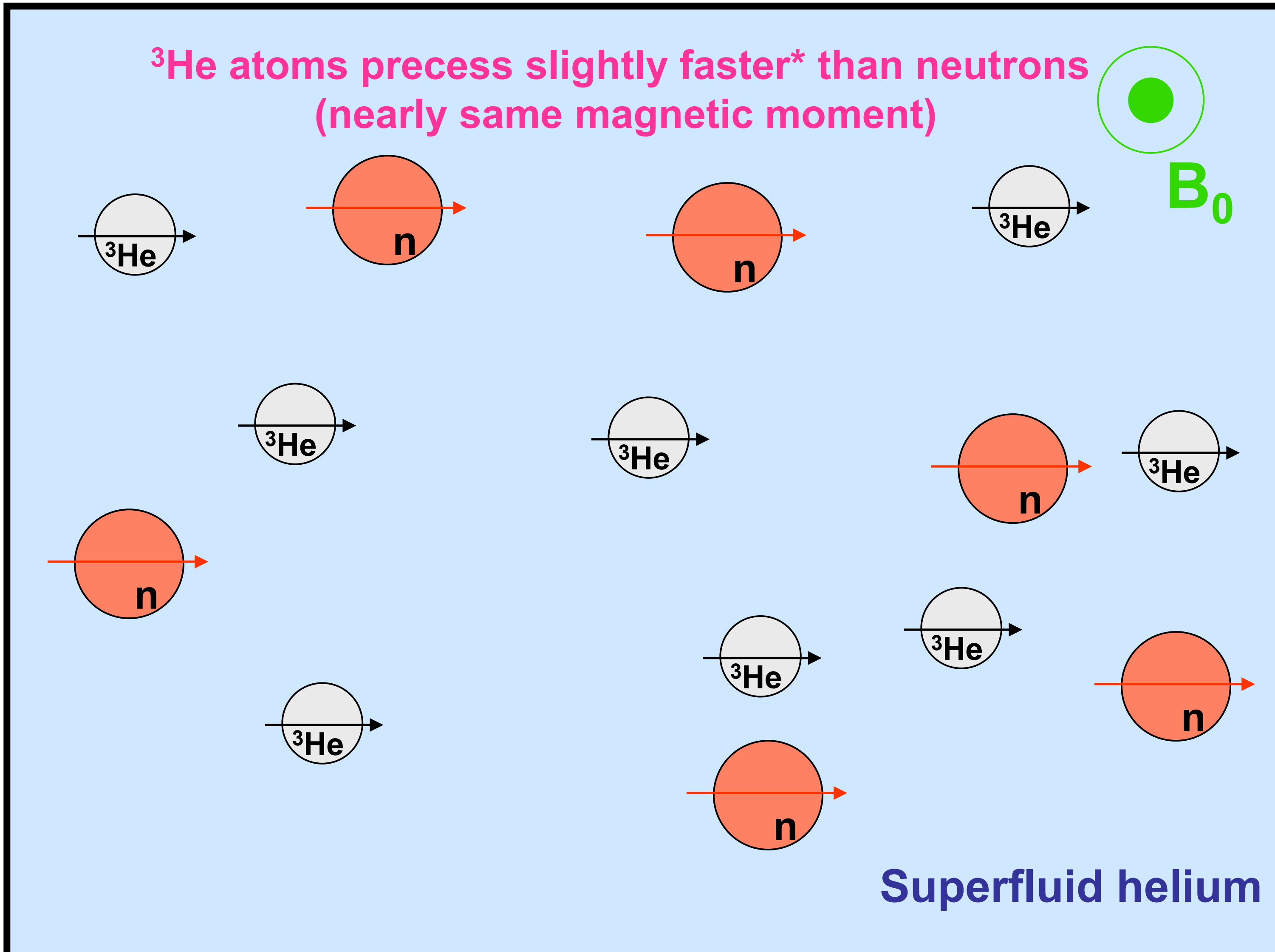
Aim: 2 orders of magnitude improvement to < 5 x 10^{-28} level

Superfluid helium

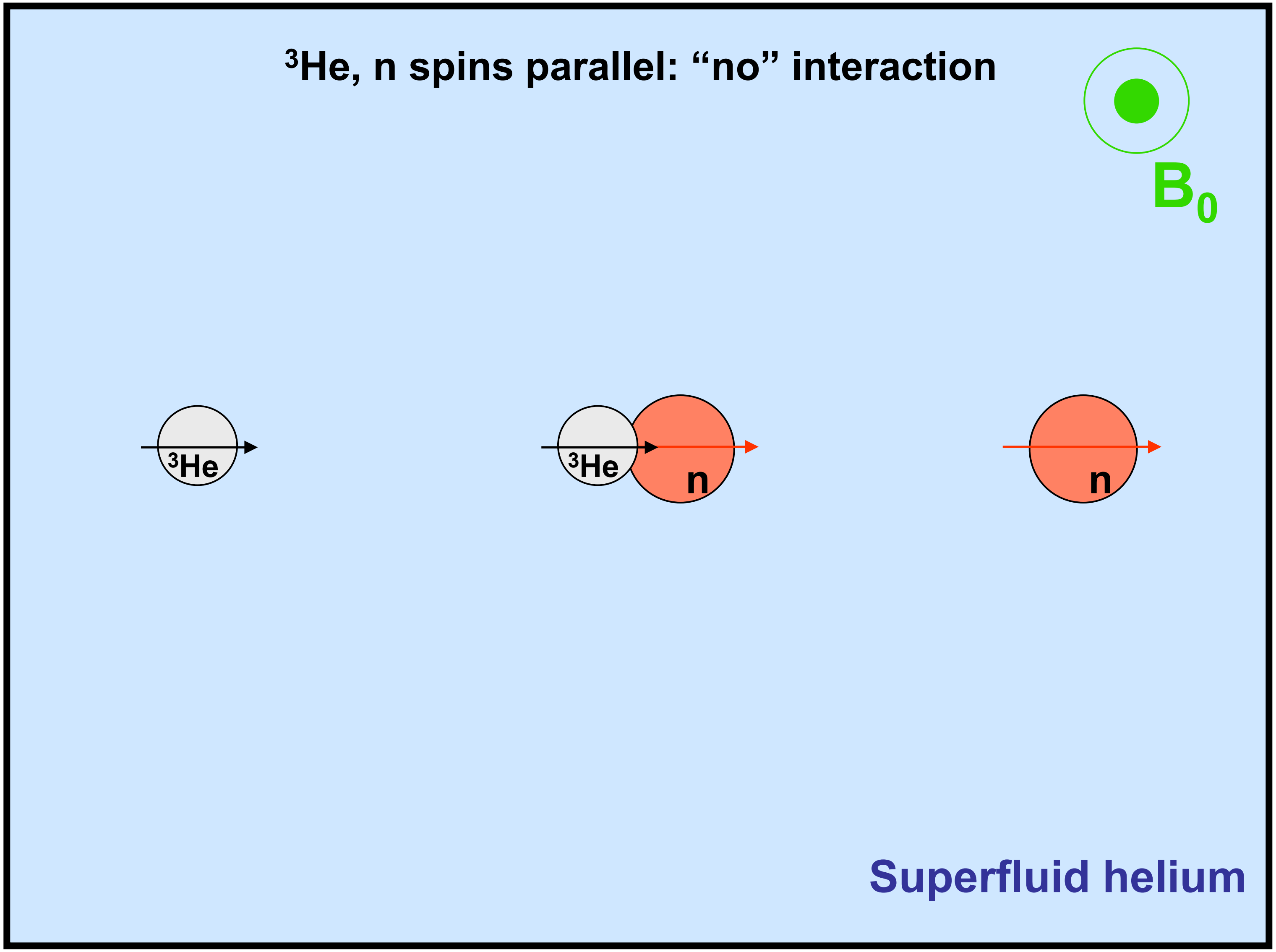
Neutron spins precess because of external magnetic field



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



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



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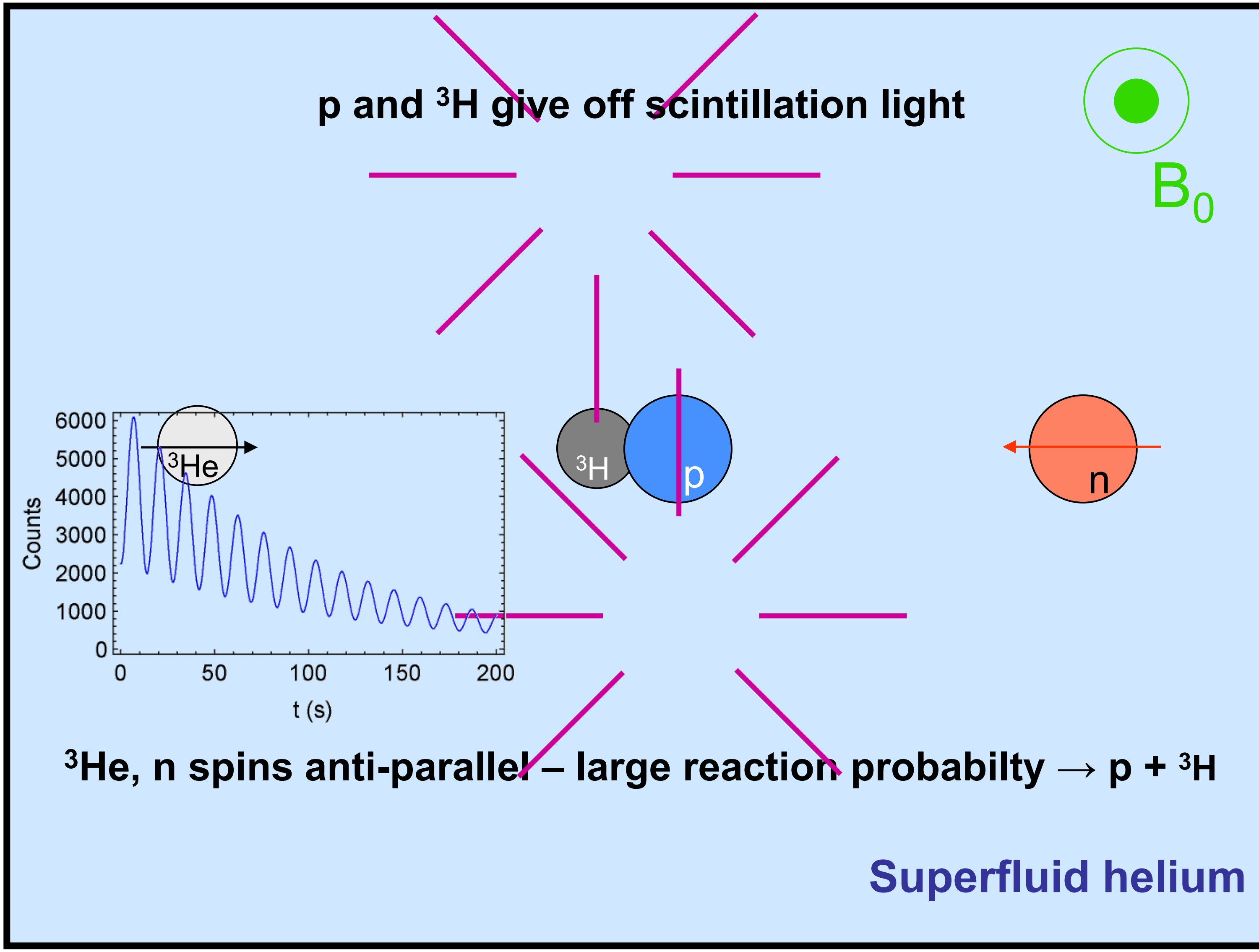
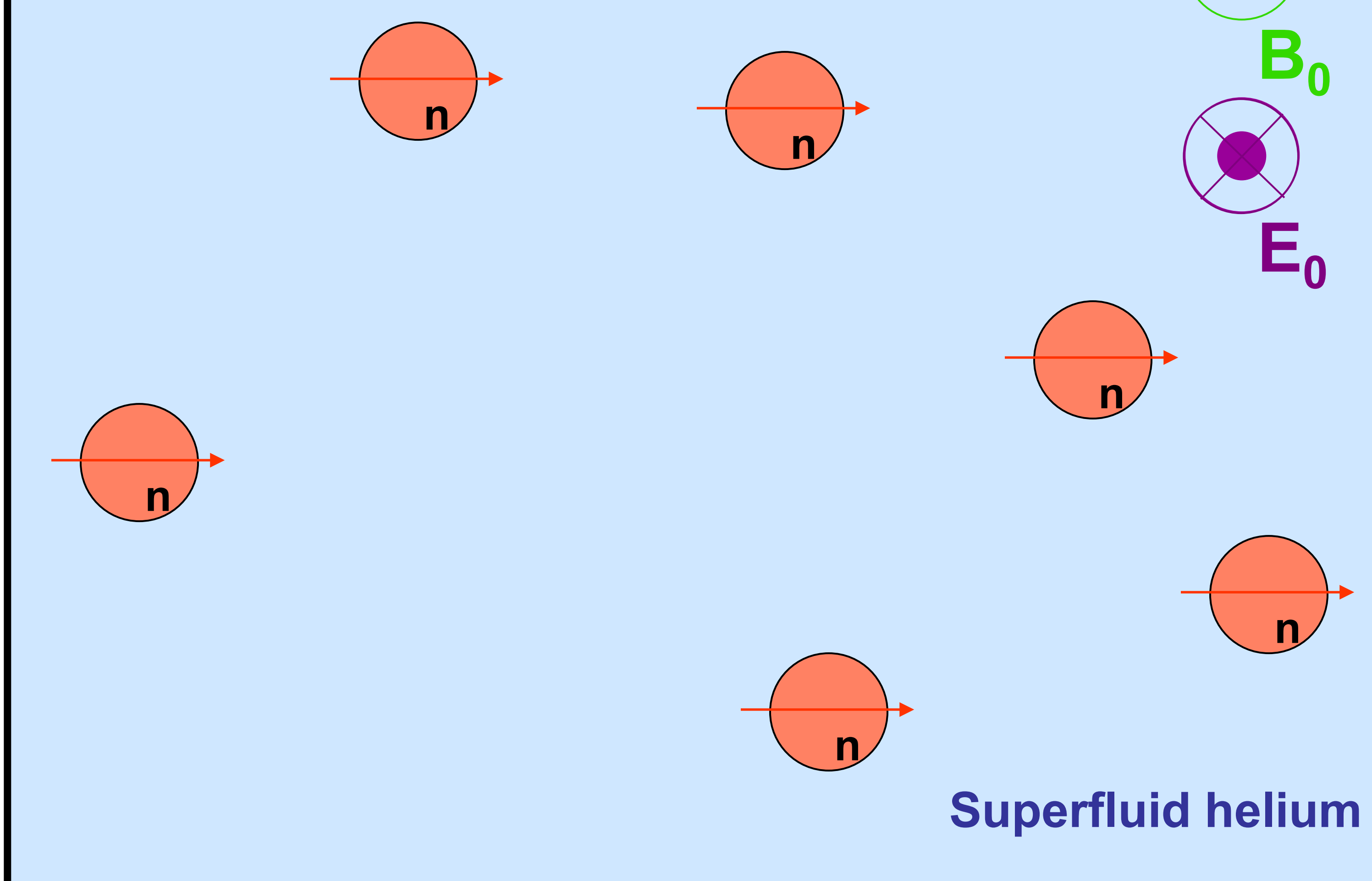


Now, add external electric field: spin rate of neutrons affected if EDM is non-zero

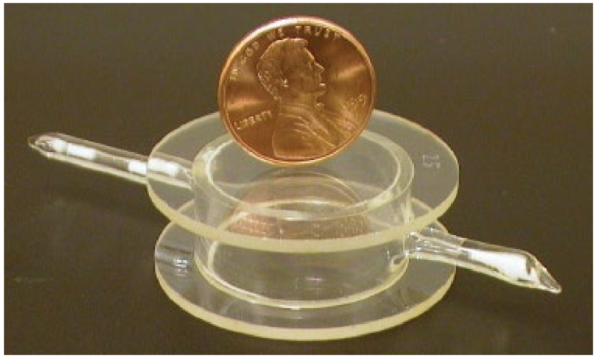
$$f = \left(-2\mu_n B_0 \boxed{\pm 2d_n E_0}\right)/h$$

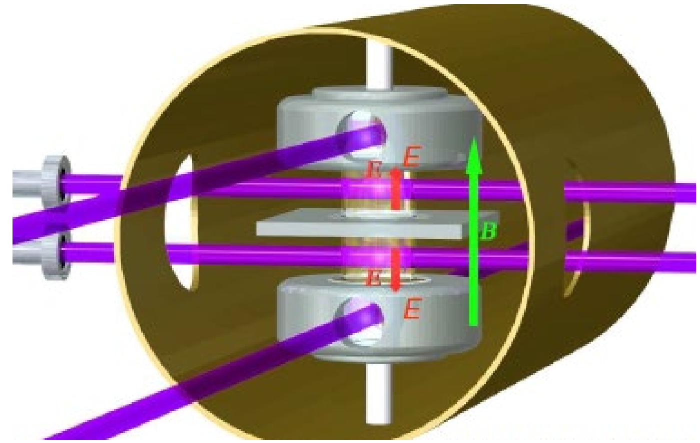


status

- Experiment is in a long phase of technical developments
- Perhaps starting in 202x, with x a small integer
- Several other nEDM experiments going on now
  - PSI
  - Others in planning

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



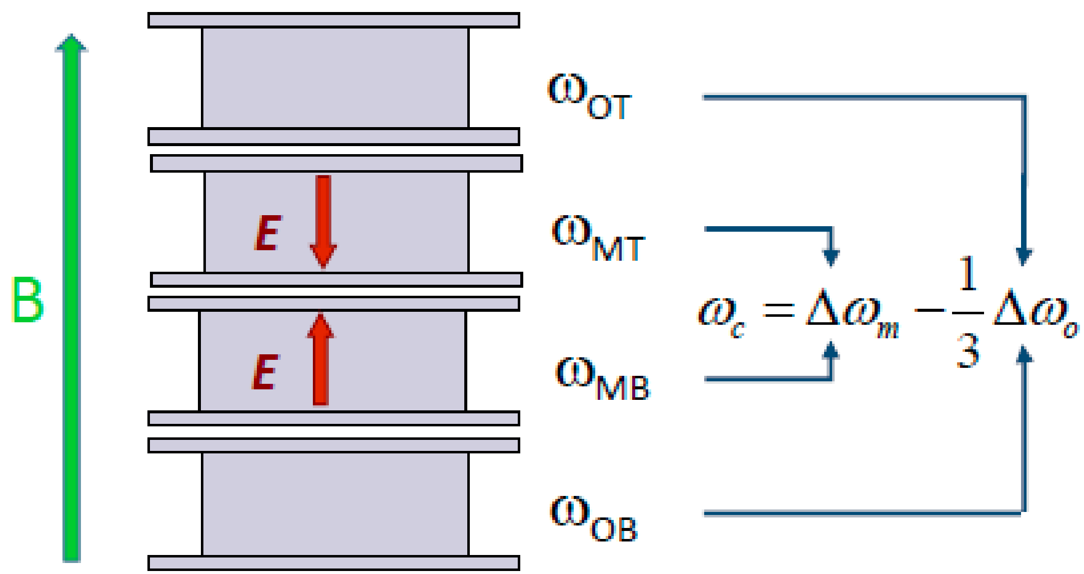


4 mercury vapor Cells:
2 with opposite E fields
2 for B field normalization

$$H = -(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E})$$

$$\omega_c = \frac{\mu}{\hbar}\left(-\frac{8}{3}\frac{\partial^3 B}{\partial z^3}\Delta z^3\right) + \frac{4dE}{\hbar}$$

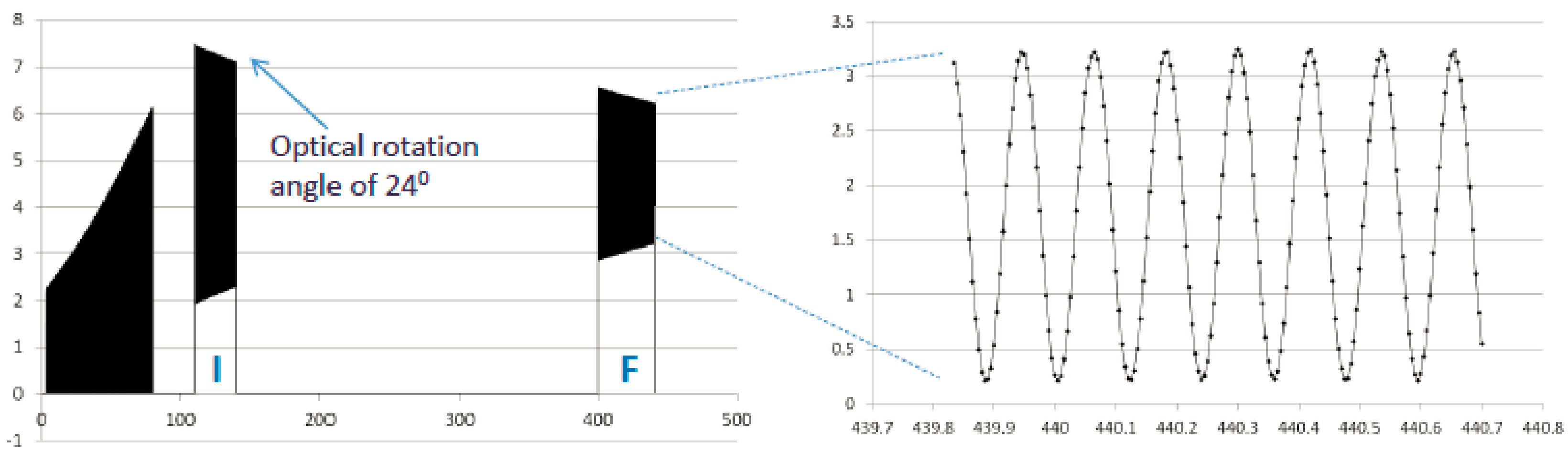
Cancels up to 2nd order gradient noise
Same EDM sensitivity as Middle Difference



Larmor precession “in the dark” to avoid influence of light

Optical pump with polarized laser, then

Measure ω_L via Optical Rotation



Photodiode signal (V) vs. time (seconds)

Extract precession phase f at the Start of the final period and the End of the initial period

$$\omega_{Dark} = (\varphi_F - \varphi_I)/T_{Dark}$$

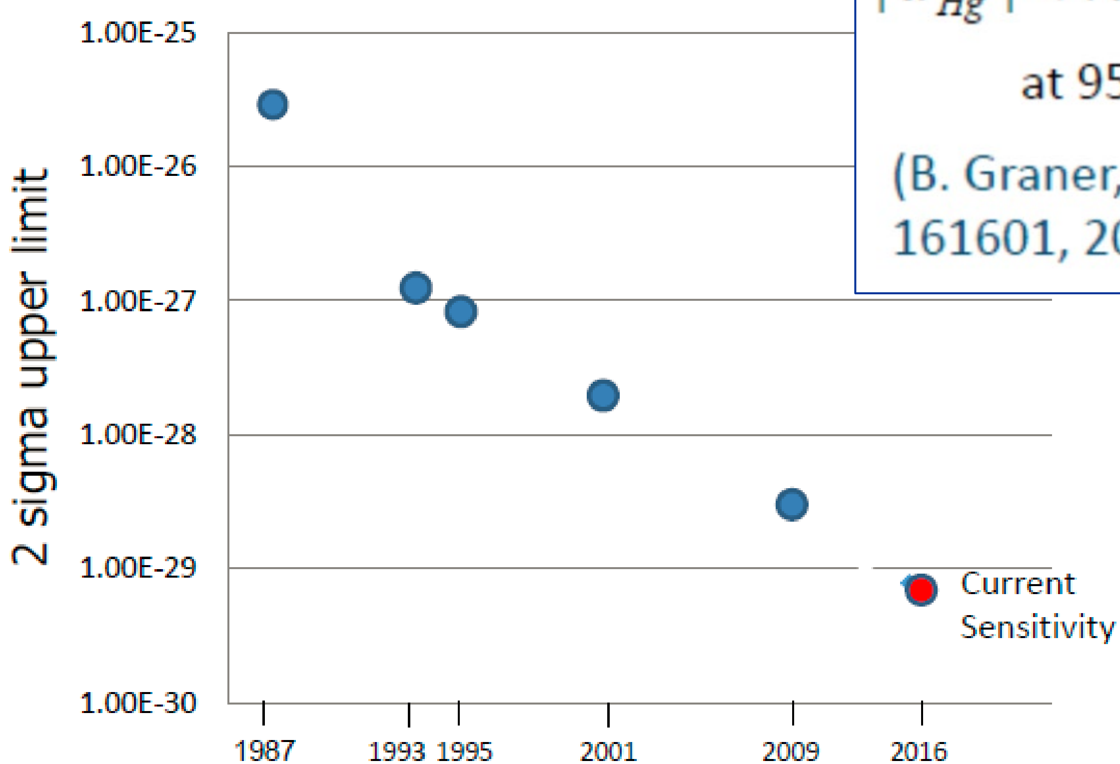
Latest result …

$$d_{Hg} = (2.20 \pm 2.75_{stat} \pm 1.59_{sys}) \times 10^{-30}\, e \cdot cm$$

$$|d_{Hg}| < 7.5 \times 10^{-30}\, e \cdot cm$$

at 95% C.L.

(B. Graner, et al, PRL 116, 161601, 2016)



History of Hg-199 Results

Stopping Point