T Violation Search at the EIC?

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The scientific motivation

The value of “null tests” of time reversal invariance

Searches for the electric dipole moments

Null tests in forward scattering

NSF PHY-1913789
NSF PHY-1806757
NSF PHY-1828512

Thx: V. Gudkov, H. Shimizu, P. Schmidt-Wellenburg, E. Stephenson, J. Chen, S. Degenkolb, V. Cirigliano …

Why Search for CP/T Violation in many different systems of first-generation particles (atoms/nucleons/nuclei)?

(1) Possible connection to the matter-antimatter asymmetry of the universe

(2) Search for new physics beyond the Standard Model.

CP/T odd effects from the CKM phase in the Standard Model are VERY small for first-generation particles. However one needs measurements in many different systems to search for the many possible CP/T violation channels at low-energy.

(3) Search for dark matter/dark sector physics (axions/ALPs)

Matter/Antimatter Asymmetry in Big Bang

n_B-$n_{\underline{B}}$ **starts from zero (otherwise inflation is destroyed, Dolgov)**

Today: $(n_B-n_{\underline{B}})/n_\gamma \sim 6 \times 10^{-10}$ (E. Komatsu et al, ApLS, 192 (2011))

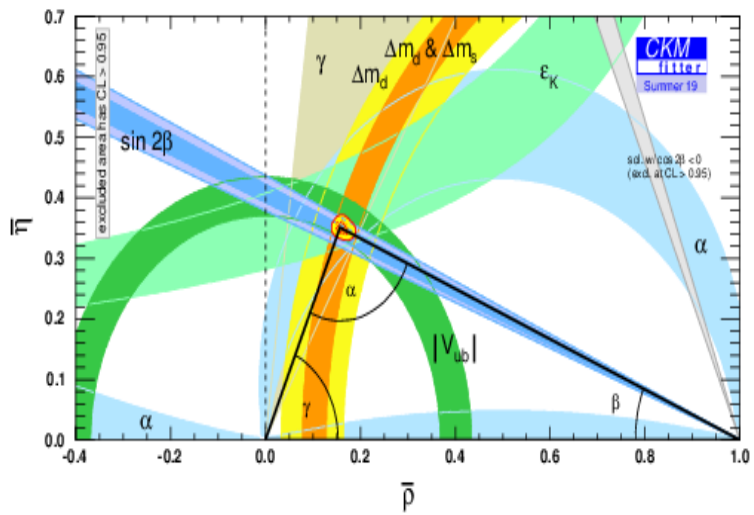
Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics (A.D. Sakharov, JETP Lett. 5, 24-27 (1967)**)**

(1) Baryon Number Violation (not yet seen)
(2) Departure from Thermal Equilibrium
(3) C and CP Violation (seen)
(1+2+3) far too small given the known Higgs mass

Sensitive Searches for T violation with nucleons:

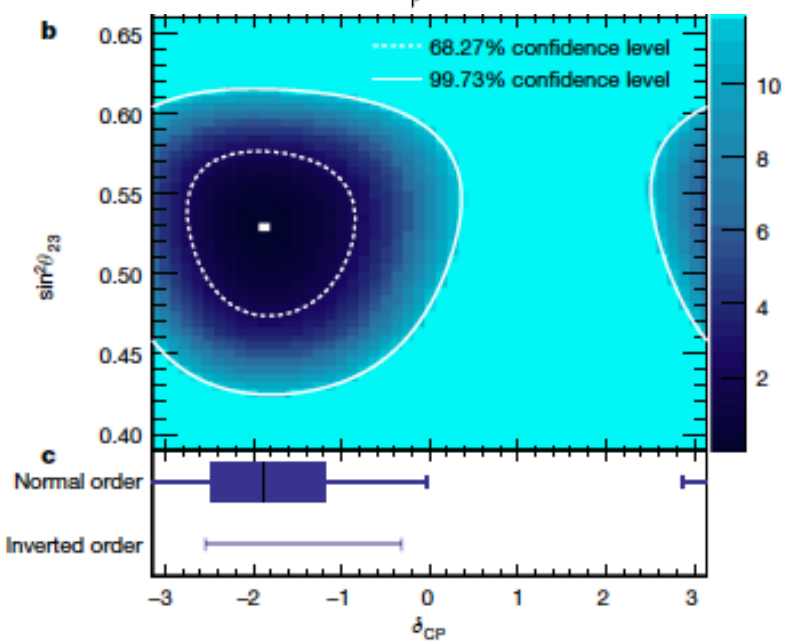
Electric Dipole Moment Searches
Axion-like Particle Searches
T-odd Polarized Neutron Optics

CP/T odd phases can/should be large



$$V_{\mathrm{CKM}} = \begin{bmatrix} V^{ud} & V^{us} & V^{ub} \\ V^{cd} & V^{cs} & V^{cb} \\ V^{td} & V^{ts} & V^{tb} \end{bmatrix}$$

CKM CP-odd phase is seen to be large



NMS CP-odd phase may be large
T2K now sees ~3σ effect
NOvA (in progress) and DUNE will look

Many (most?) BSM theories "should" possess new sources of CP/T violation

T2K collaboration, Nature **580,** 339 (2020).

Effective Field Theory Treatment for BSM CP/T Violation

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

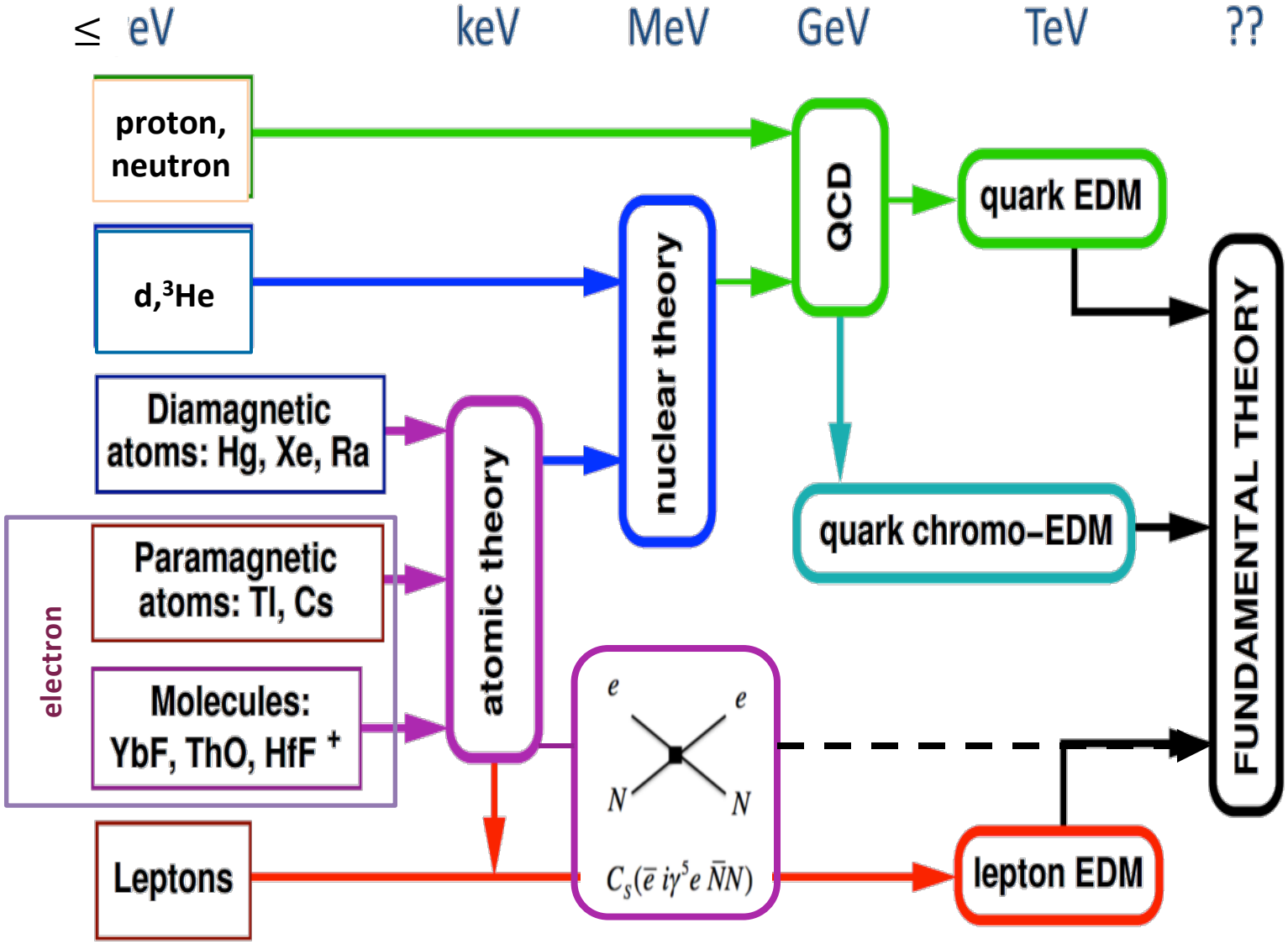
First nonzero BSM effects enter at dimension 6.
There are a lot of them.

$$\mathscr{L}_{\text{eff}}^{(6)} = -\frac{i}{2} \sum_{l,q} d_q \bar{q} \sigma_{\mu\nu} \gamma^5 F^{\mu\nu} q$$
$$- \frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma_{\mu\nu} \gamma^5 G^{\mu\nu} q$$
$$+ d_W \frac{g_s}{6} G \tilde{G} G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}, \mathrm{Im}\, C_{\ell eqd}$	Semi-leptonic (6)	3
δ_q	Quark EDM (6)	2
$\tilde{\delta}_q$	Quark chromo EDM (6)	2
$C_{\tilde{G}}$	Three-gluon (6)	1
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	Four-quark (6)	2
$\mathrm{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1
Total		13

J. Engel et al, Prog. Part. Nucl. Phys. **71**, 21 (2013)

CP/T violation searches in atomic/nuclear systems



QCD, nuclear, and atomic theory input also needed!

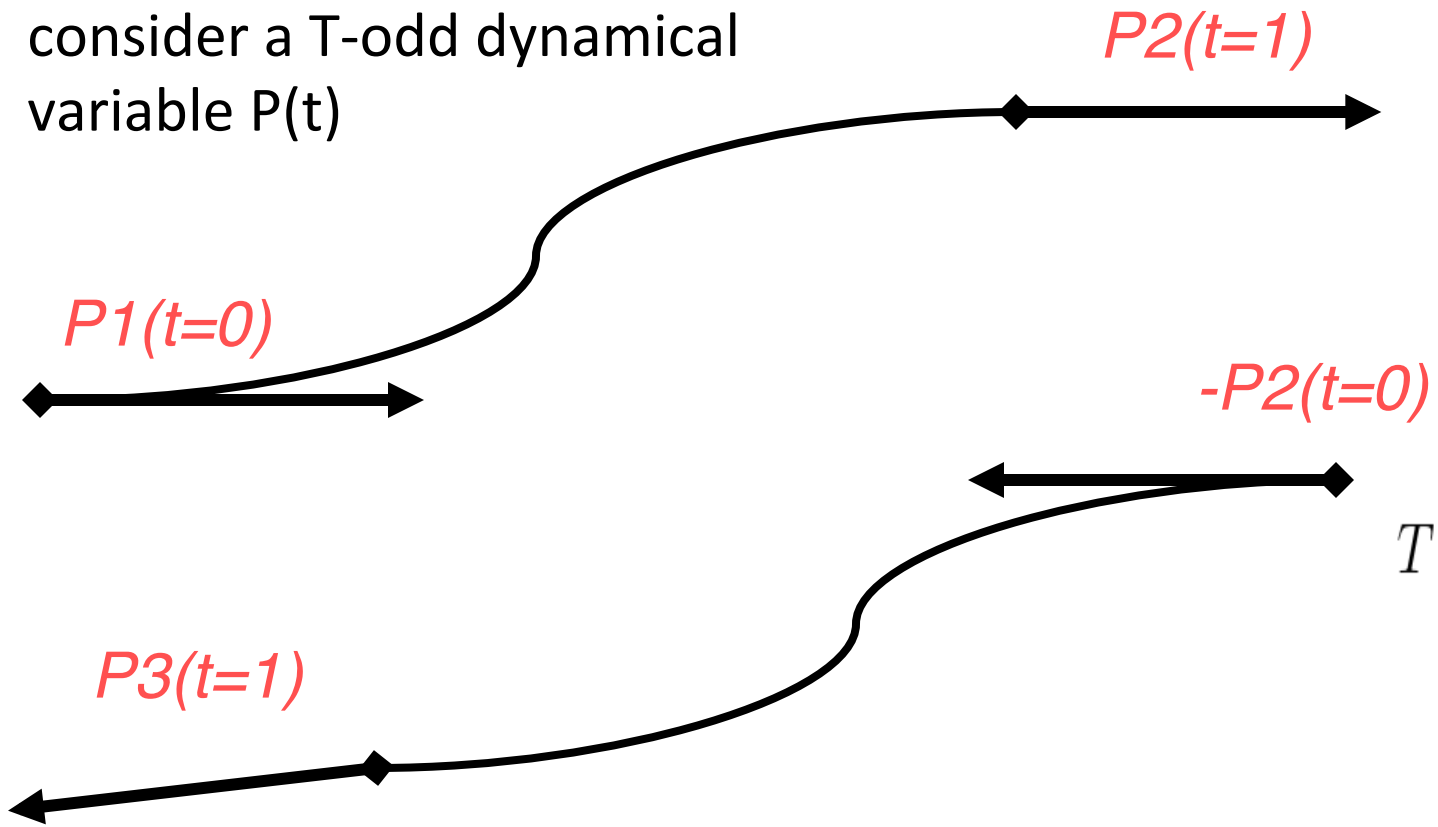
For EDMs see: T. Chupp et al, Rev. Mod. Phys. **91**, 015001 (2019)

P. Schmidt-Wellenburg

Scheme: adapted from Rob G. E. Timmermans

Time Reversal: “running the film backwards”

consider a T-odd dynamical variable P(t)



$$T\mathbf{r}T^{-1} = \mathbf{r}$$

$$T\mathbf{p}T^{-1} = -\mathbf{p}$$

$$T\boldsymbol{\sigma}T^{-1} = -\boldsymbol{\sigma}$$

$$T[\mathbf{r},\mathbf{p}]T^{-1} = -[\mathbf{r},\mathbf{p}]$$

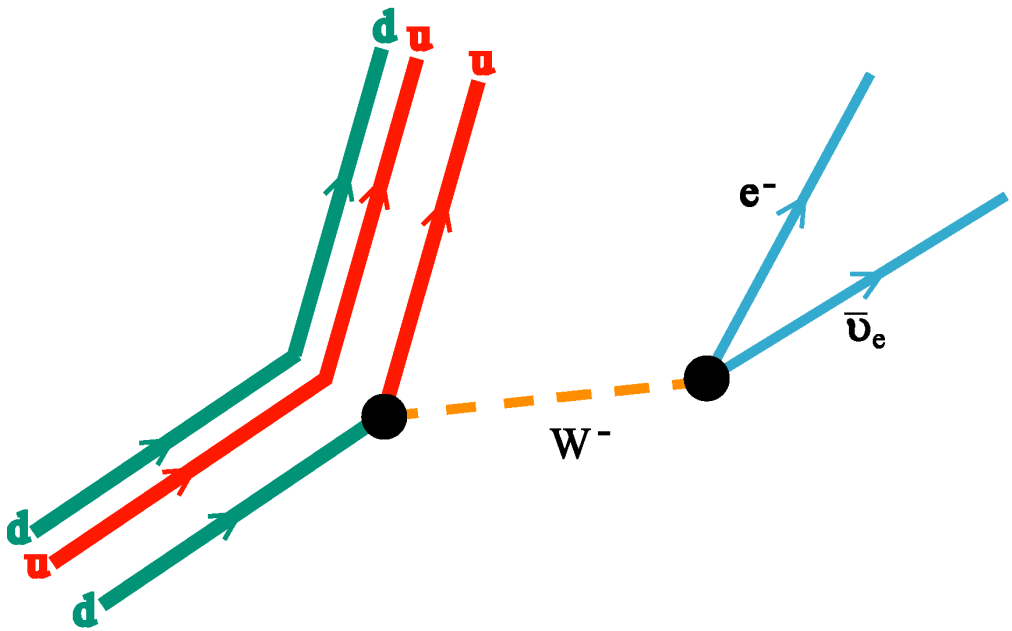
Etc.

Is the final state of the motion with time-reversed final conditions P3(t=1) the same as the time-reversed initial condition -P1(t=0)?

In QM: reversal of initial and final states:

$\langle a|O|b\rangle \rightarrow \langle b|O_T|a\rangle$ $\rightarrow TiT^{-1} = -i \quad T = UK,$ K=complex conjugation

Decay/nonforward scattering processes: can't "run the film backwards"



Can look for $\mathbf{S_n \bullet (P_p \times P_e)}$ angular correlation

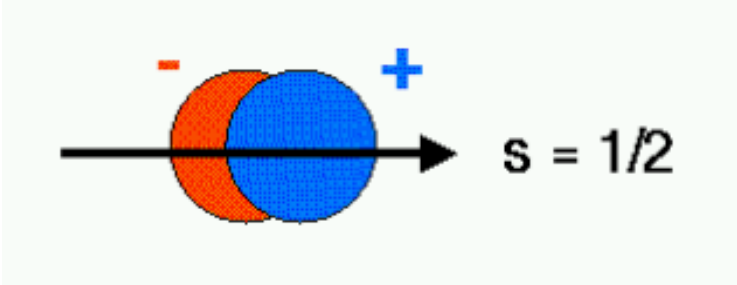
But: this can be caused by electromagnetic interaction of final state proton and electron

Reversing the electron, neutrino, and proton to get the neutron is impractical.

Still look for (formally) T-odd correlations of observables

But one must worry about "final state effects" giving T-odd correlation even if no real fundamental T violation is present

Electric Dipole Moments: P-odd/ T-odd Observable



$$\vec{d}_n = \int \vec{x}\rho(x)d^3x = d_n\hat{s}$$

Non-zero d_n violates both P and T

Under a parity operation:

$$\hat{s} \rightarrow \hat{s}, \quad \vec{E} \rightarrow -\vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

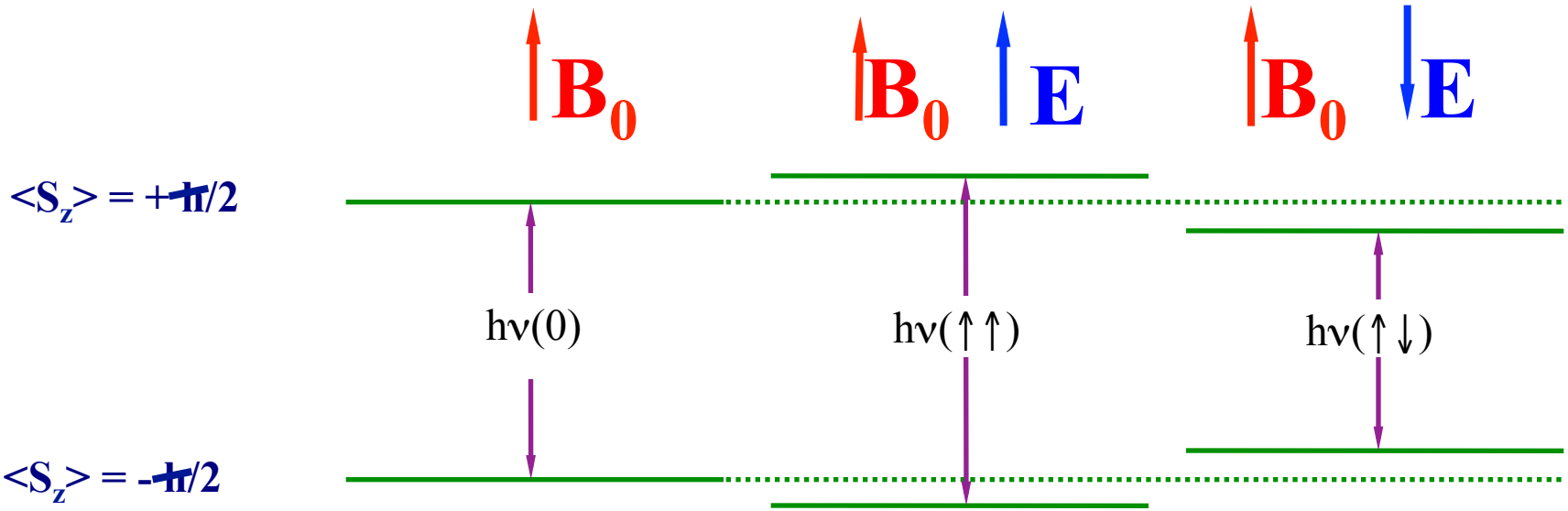
Under a time-reversal operation:

$$\hat{s} \rightarrow -\hat{s}, \quad \vec{E} \rightarrow \vec{E}$$

$$\vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E}$$

EDMs are “null tests” of time reversal invariance (no “final state effects” can fake an EDM) |i>=|f>

EDM Measurement Principle/Sensitivity



$$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/\,h$$

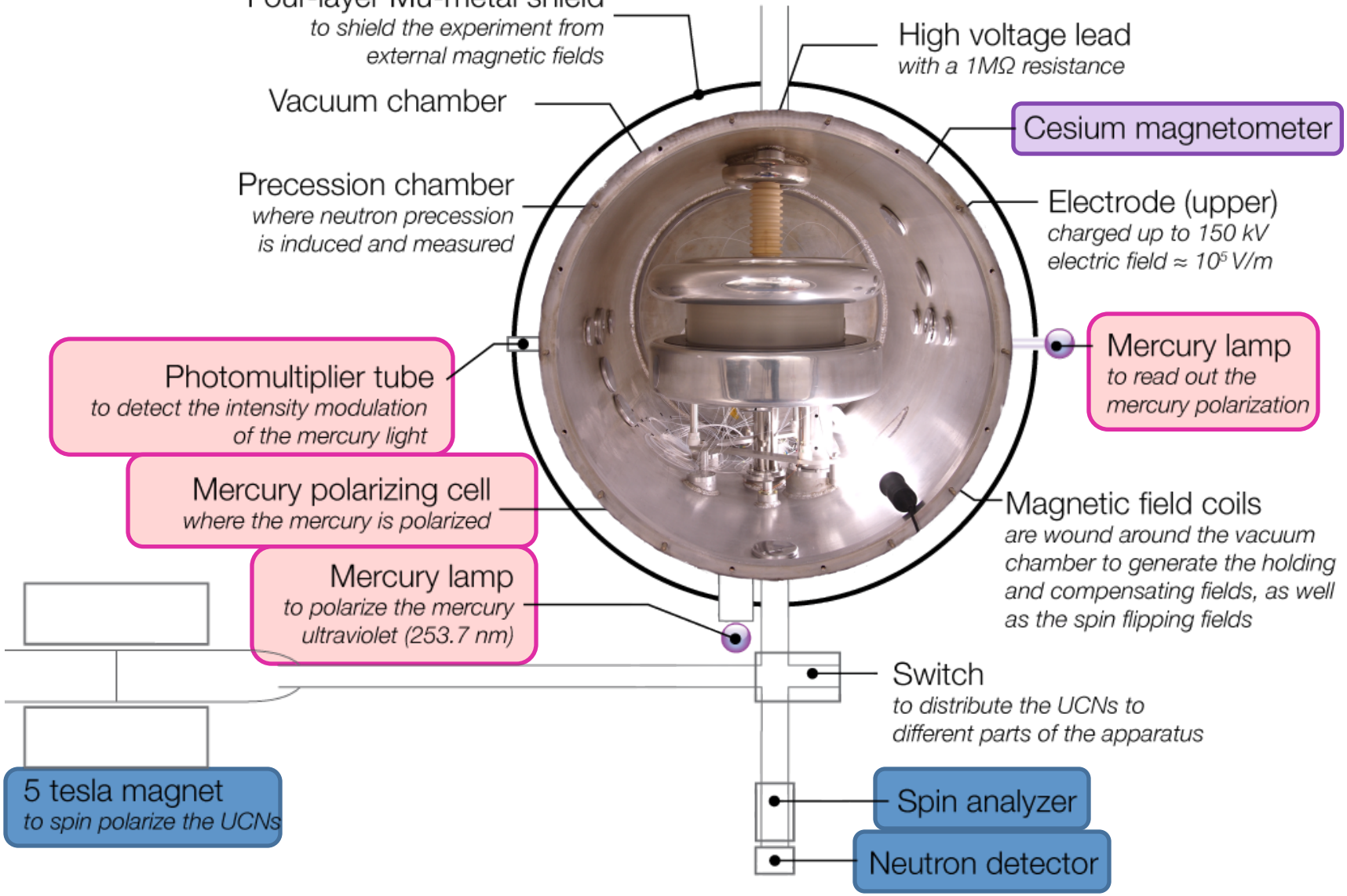
assuming **B** unchanged when **E** is reversed.

EDM limits -> ratio (P and T-odd amplitude/P-odd amplitude)~10^{-4}

T violation from CKM phases smaller by ~5 orders of magnitude here

EDM experiments should improve by >factor of 10 over next decade

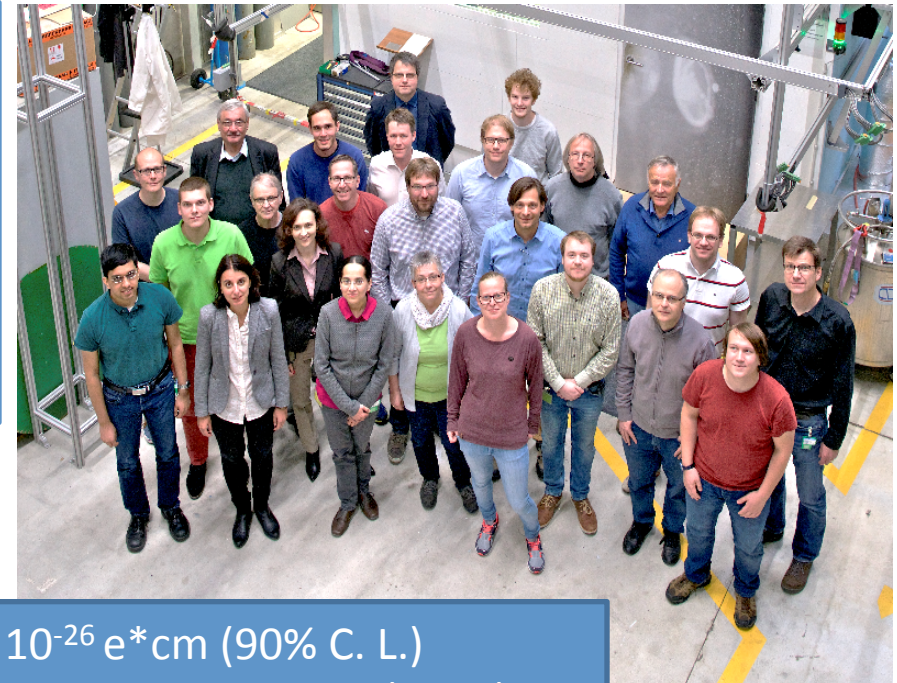
The nEDM spectrometer at PSI

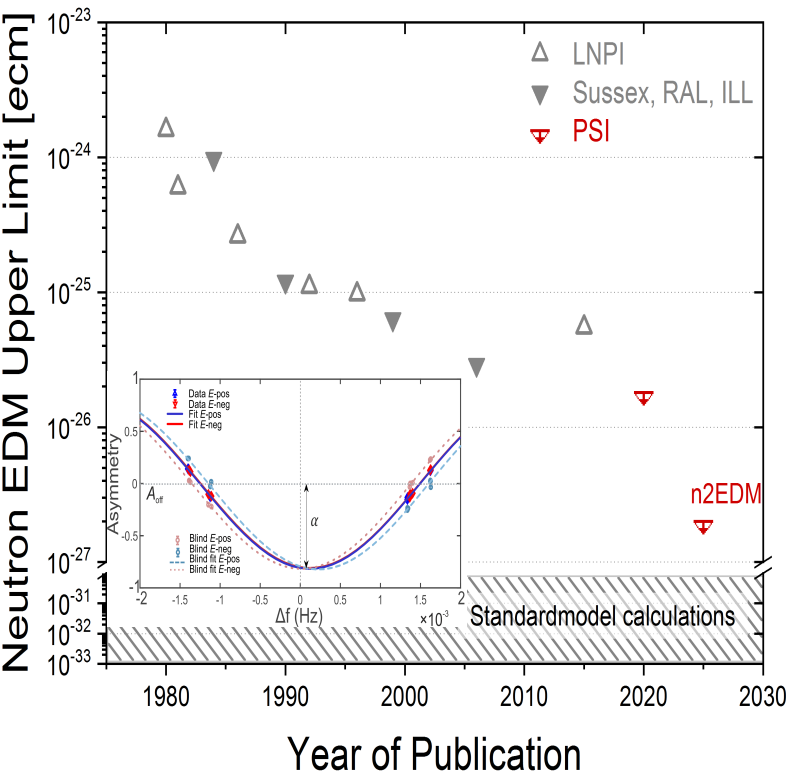


Most sensitive result on neutron electric dipole moment (EDM) measured at the PSI UCN source

EDMs unambiguously indicate charge parity violation (CPV)

- CPV natural in beyond standard model theories
- CPV required for matter / antimatter asymmetry
- Neutron EDM uniquely sensitive to strong CPV





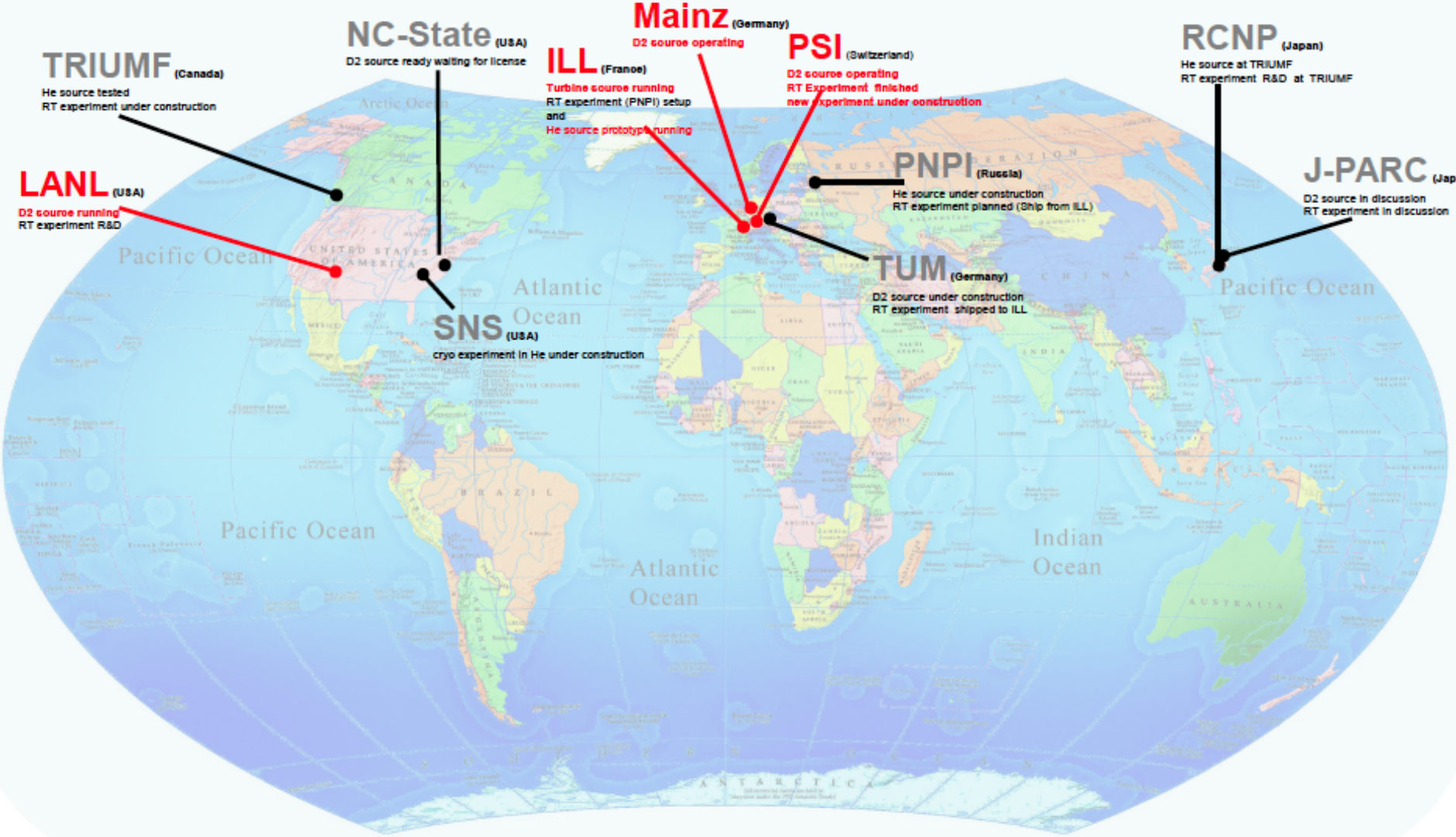
d_n <1.8 x 10^{-26} e*cm (90% C. L.)
Phys. Rev. Lett. 124, 081803 (2020)

Unique features of result published in **PRL**

- Limit improved by factor 1.7
- **Systematic errors reduced by factor five**
- Full comprehension of systematic effects from higher order magnetic field non-uniformity
- First fully blinded analysis in two distinct teams

P. Schmidt-Wellenburg

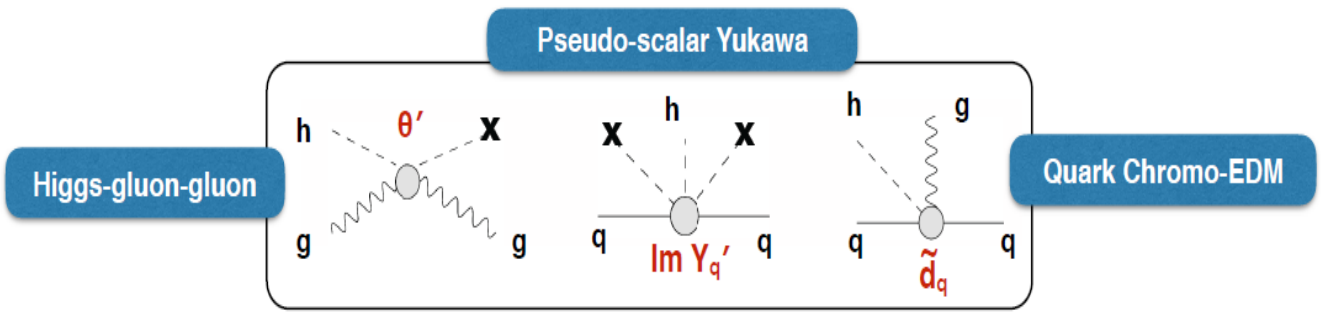
ULTRACOLD NEUTRON SOURCES AND NEDM EXPERIMENTS: THE WORLDVIEW



B. Lauss, AFCI workshop

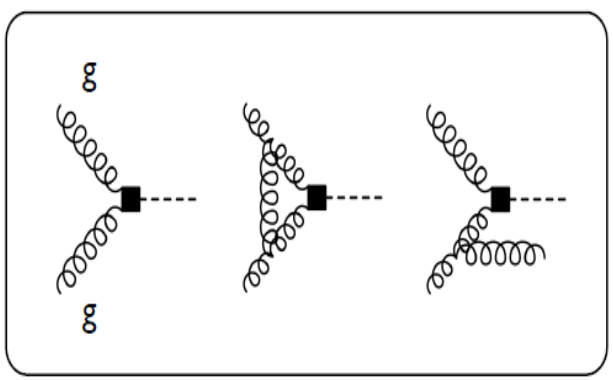
Connection to T-odd couplings

- Leading interactions with q,g strongly constrained by gauge invariance

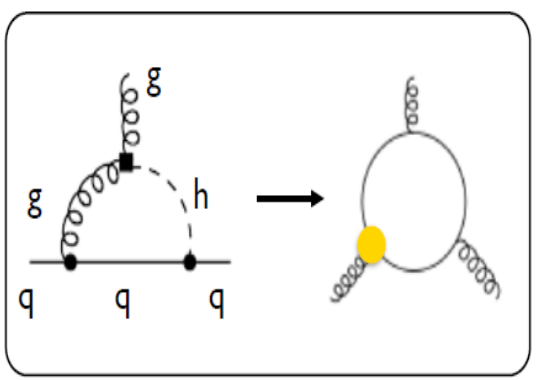


- Signatures of various operators: Higgs-gluon-gluon (θ′)

LHC: Higgs production via gluon fusion

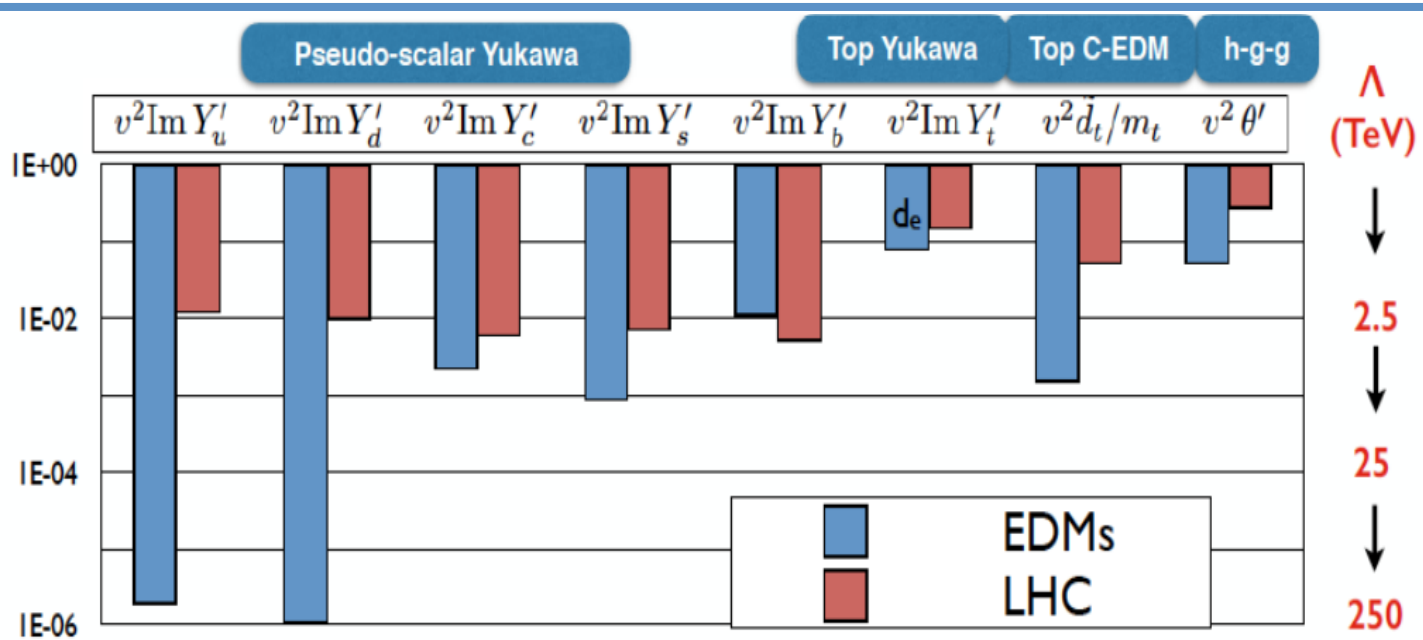


Low Energy: quark (C)EDM + Weinberg



V. Cirigliano
PPNS-2018

nEDM Scientific Reach



- Much stronger impact of nEDM with reduced uncertainties

$d_{n,p}[\tilde{d}_{u,d}]$ $d_{n,p}[d_s]$ $d_{n,p}[d_W]$

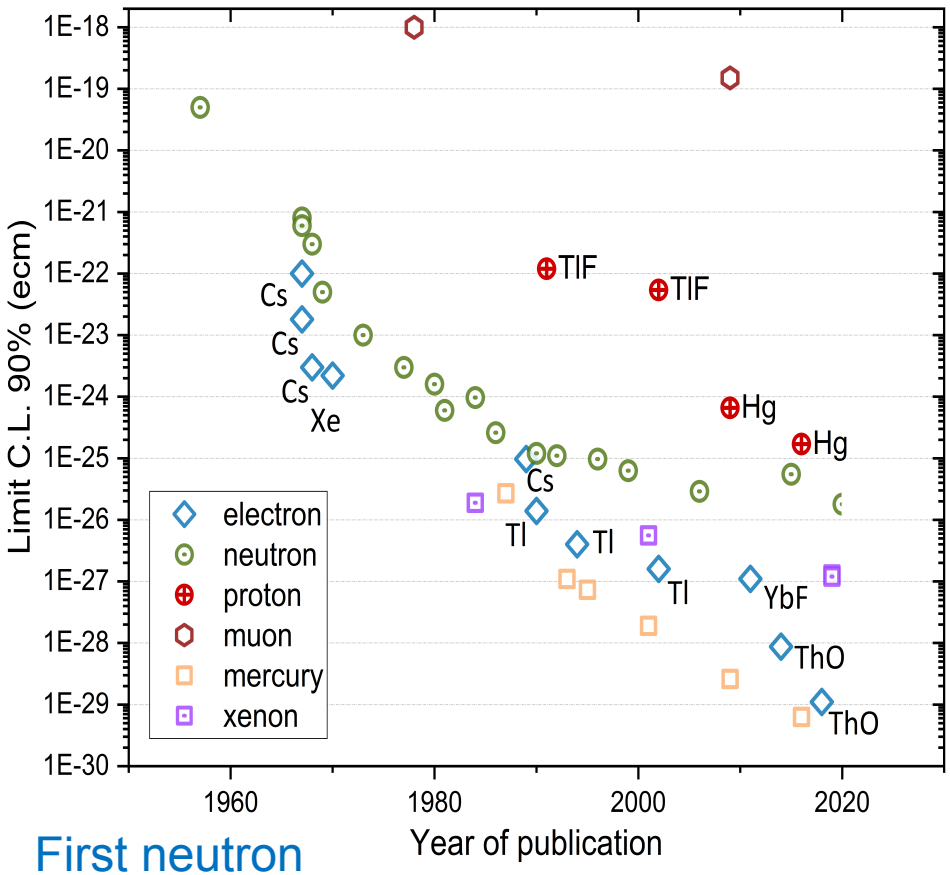
25% 50%

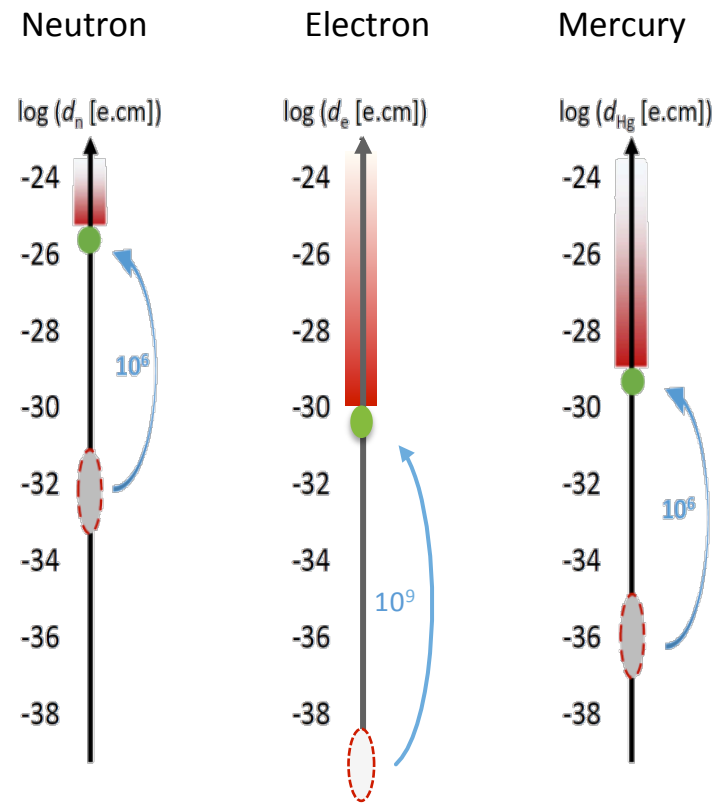
Target for Lattice QCD in the 5-year time scale

- Experiment at 5 x 10^{-27} e cm and improved matrix elements will make nEDM the strongest probe for all couplings

V. Cirigliano
PPNS-2018

A brief history of EDM searches





First neutron

Smith, Purcell, Ramsey

$d_n < 5 \times 10^{-20}$ e cm

PR 108 (1957) 120

~ 60 years

Previous

RAL-Sussex-ILL

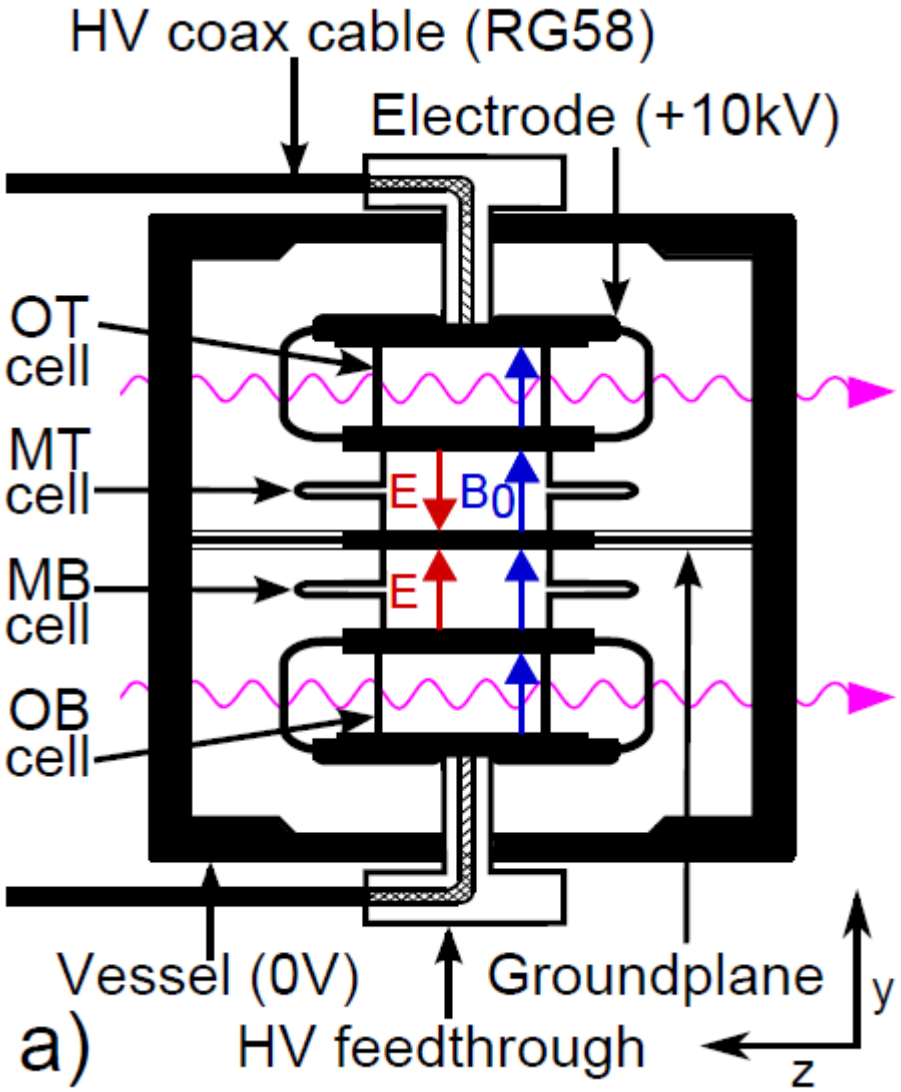
$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

J.M. Pendlebury et al., PRD 92 (2015) 092003

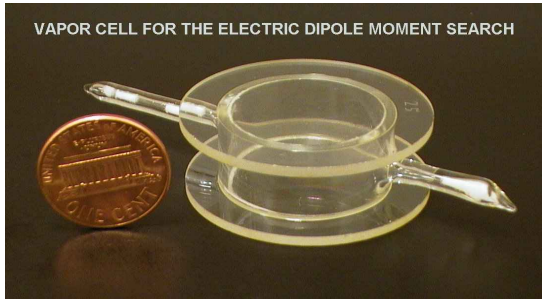
P. Schmidt-Wellenburg

^{199}Hg EDM Search



- Atoms are contained in a stack of 4 vapor cells in a common B field
- 2 conducting plastic electrodes at the same potential hold the 2 outer cells
- Opposite E field causes an EDM to shift the relative frequency of the 2 inner cells
- ^{199}Hg is pumped to align spins with laser beams
- Precession is observed by detecting Faraday rotation of weak, linear polarized light

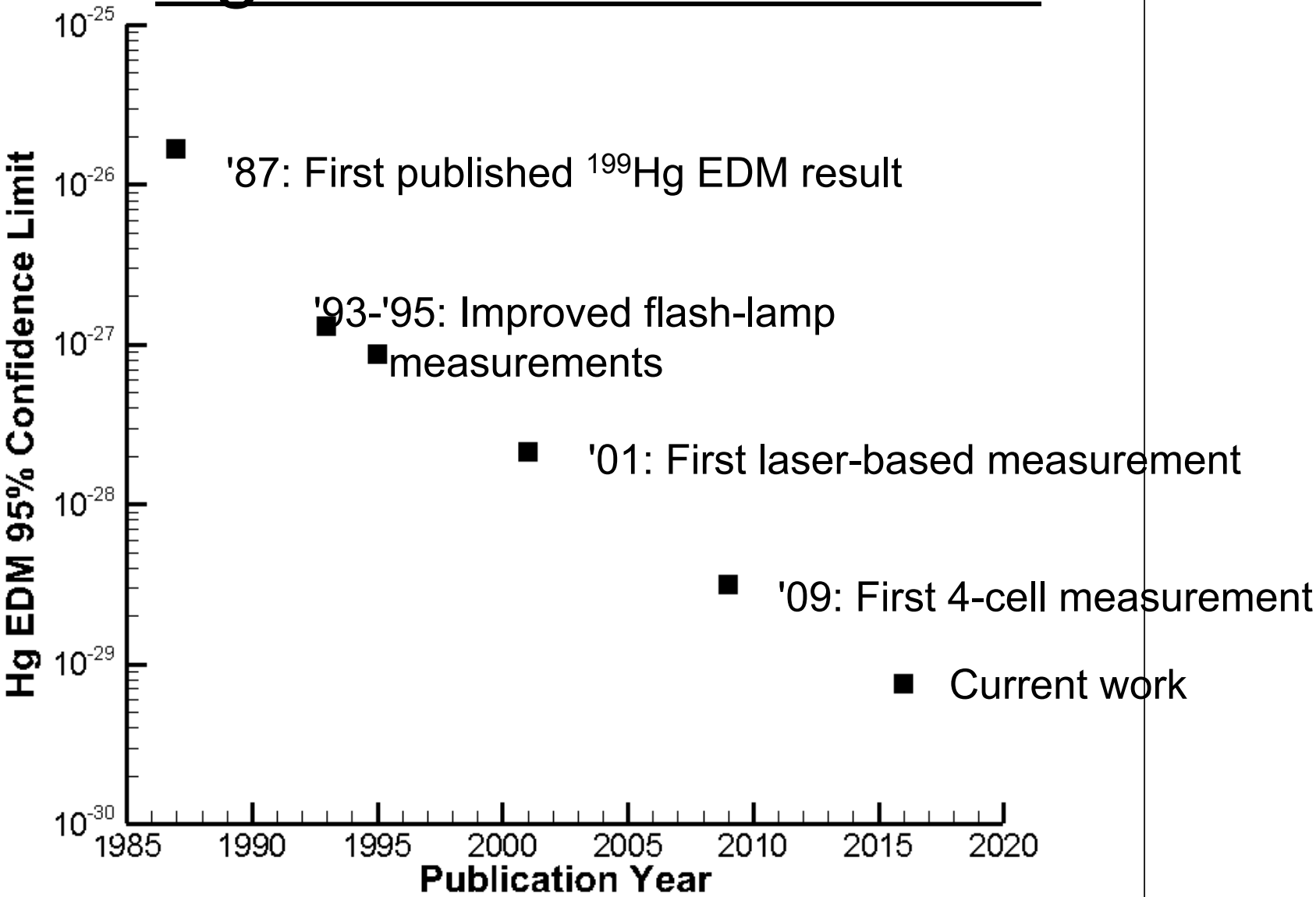
Hg-199 Vapor Cell



Team: J. Chen, B. Graner, E. Lindahl, B.R. Heckel

J. Chen

Hg EDM Limits vs. Time



$|d_{Hg}|<3.1 \times 10^{-29}$ e*cm B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel, PRL 116, 161601 (2016).

NOPTREX Collaboration

Nagoya U.: H.M. Shimizu, M. Kitaguchi, K. Hirota, T. Yamamoto, K. Ishizaki, S. Endoh, Y. Niinomi, I. Ide, H. Tada, T. Morishama, Y. Kiyanagi, J. Hisano, N. Wada, T. Matshshita

Kyushu U.: T. Yoshioka, S. Takada, J. Koga, S.Makise

JAEA: T. Okudaira, K. Sakai, A. Kimura, H. Harada

KEK: T. Ino, S. Ishimoto, K. Taketani, K. Mishima

U. British Columbia: T. Momose

Hiroshima U.: M. Iinuma

Tokyo Inst. Tech. : H. Fujioka, Y. Tani

Osaka U.: K. Ogata, H. Kohri, M. Yosoi, T. Shima, H. Yoshikawa

Yamagata U.: T. Iwata, Y. Miyachi

RIKEN: Y. Yamagata, T. Uesaka, K. Tateishi, H. Ikegami

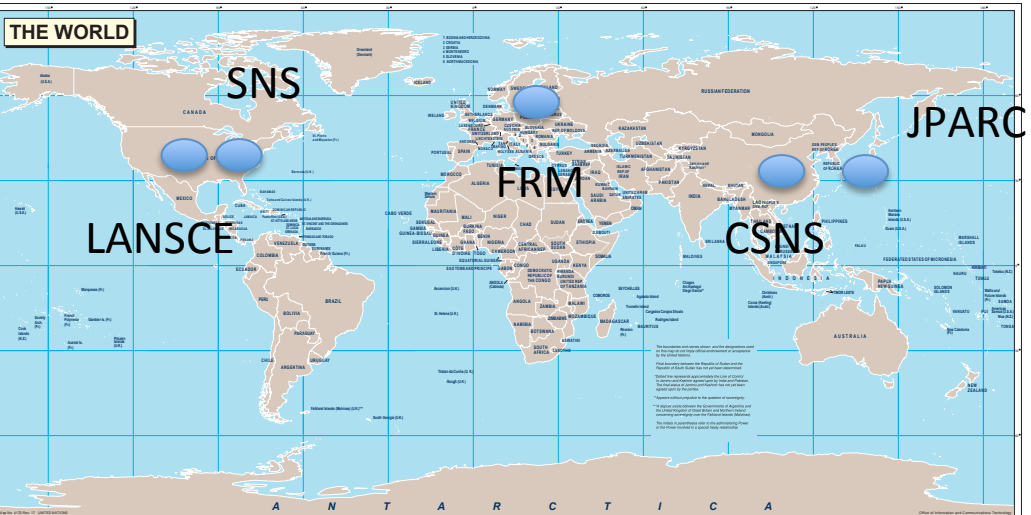
Kyoto U.: Y. I. Takahashi, M. Hino

Ashikaga U. D. Takahaski

Japan Women's U. R. Ishiguro

Kyungpook U.: G. N. Kim, S. W. Lee

CSNS: T. Tong



Indiana U: W. M. Snow, C. Auton,J. Carini, J. Curole, K. Dickerson, J. Doskow, H. Lu, G. Otero, K. Steffen, J. Vanderwerp, G. Visser

U. South Carolina: V. Gudkov

ORNL: J.D. Bowman, P. Jiang, S. Penttila

U. Kentucky: C. Crawford, B. Plaster, L. Cole, H. Dhahri

LANL: D. Schaper

NIST: C. Haddock

Southern Illinois U.: B.M. Goodson

Ohio U.: P. King

Middle Tennessee State U.: R. Maruhin

Eastern Kentucky U: J. Fry

Western Kentucky U: I. Novikov

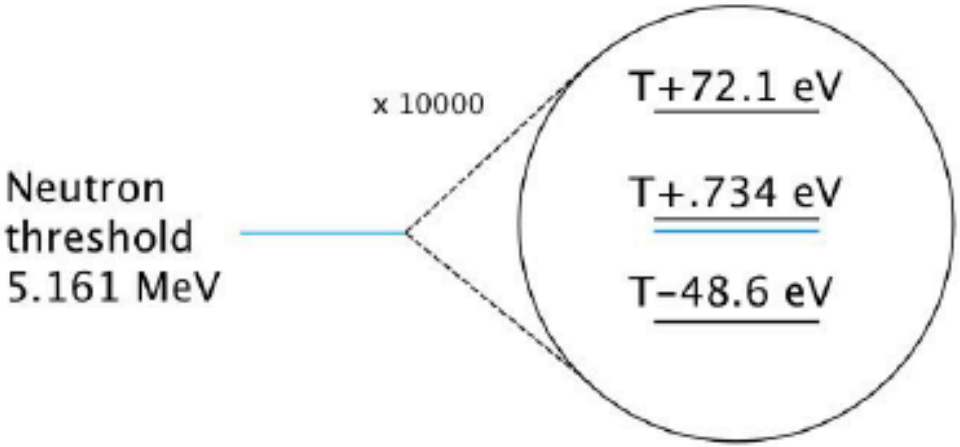
Berea College: M. Veillette, D. Olivera-Verlade

UNAM: L. Barron-Palos, A. Perez-Martin

PSI: P. Hautle

One experiment:
Five neutron sources

139La+n System



Compound-Nuclear States in ^{139}La+n system

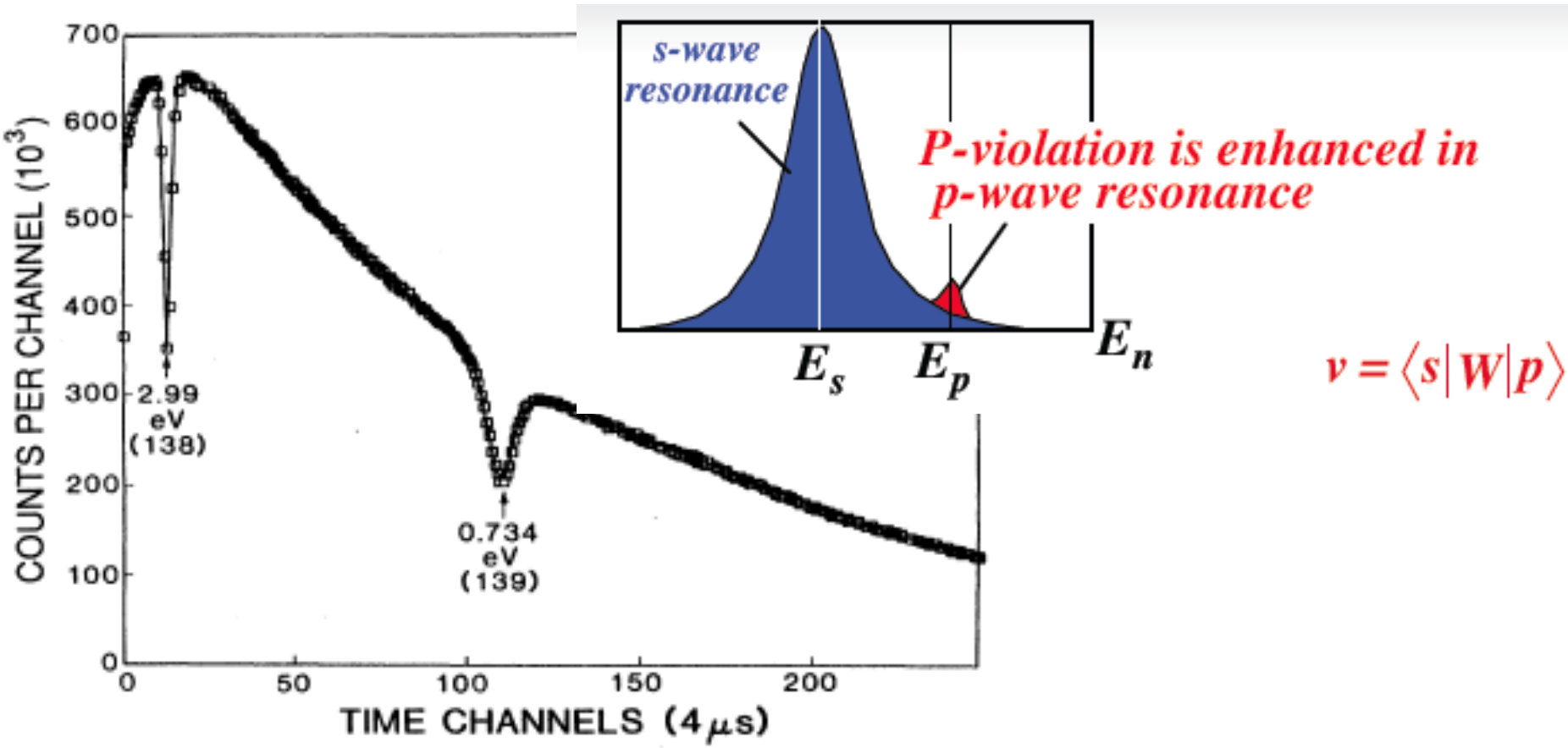
Low energy neutrons can access a dense forest of highly excited states in the compound nucleus.

Large amplification of discrete symmetry violation (P and T) is possible. Very large amplifications of P violation were observed long ago

140La G. S.

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma$ =0.097±.005.

10^6 amplification of P-odd weak amplitude on resonance

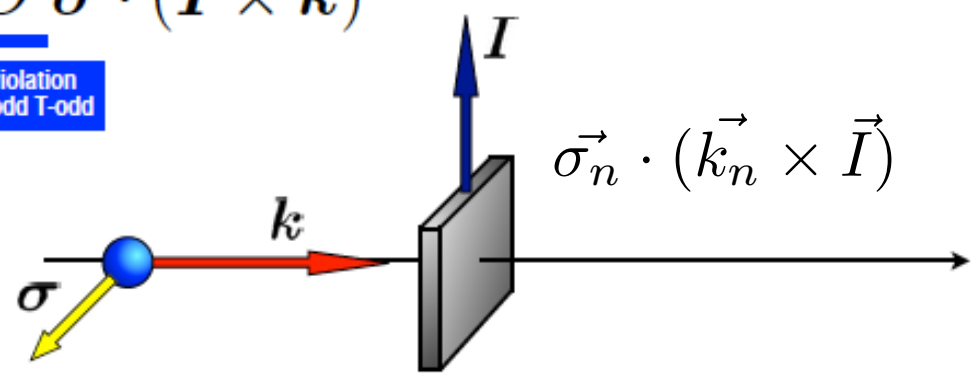


How? (1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000
(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000

Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

Forward Scattering Amplitude

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}}}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}} + \underbrace{C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}}}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}} + \underbrace{D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}$$



$\lvert s\rangle$	$\lvert p\rangle$	$\lvert p_{1/2}\rangle$	$\lvert p_{3/2}\rangle$	
$J_s\,E_s\,\Gamma_s\,\Gamma_s^n$	$J_p\,E_p\,\Gamma_p\,\Gamma_p^n$	$\Gamma_{p,1/2}^n$	$\Gamma_{p,3/2}^n$	$\langle W\rangle$

The enhancement of P-odd/T-odd amplitude on p-wave resonance ($\sigma.[K \times I]$) is (almost) the same as for P-odd amplitude ($\sigma.K$).

Experimental observable: ratio of P-odd/T-odd to P-odd amplitudes $\lambda_{PT} = \dfrac{\delta\sigma_{PT}}{\delta\sigma_P}$

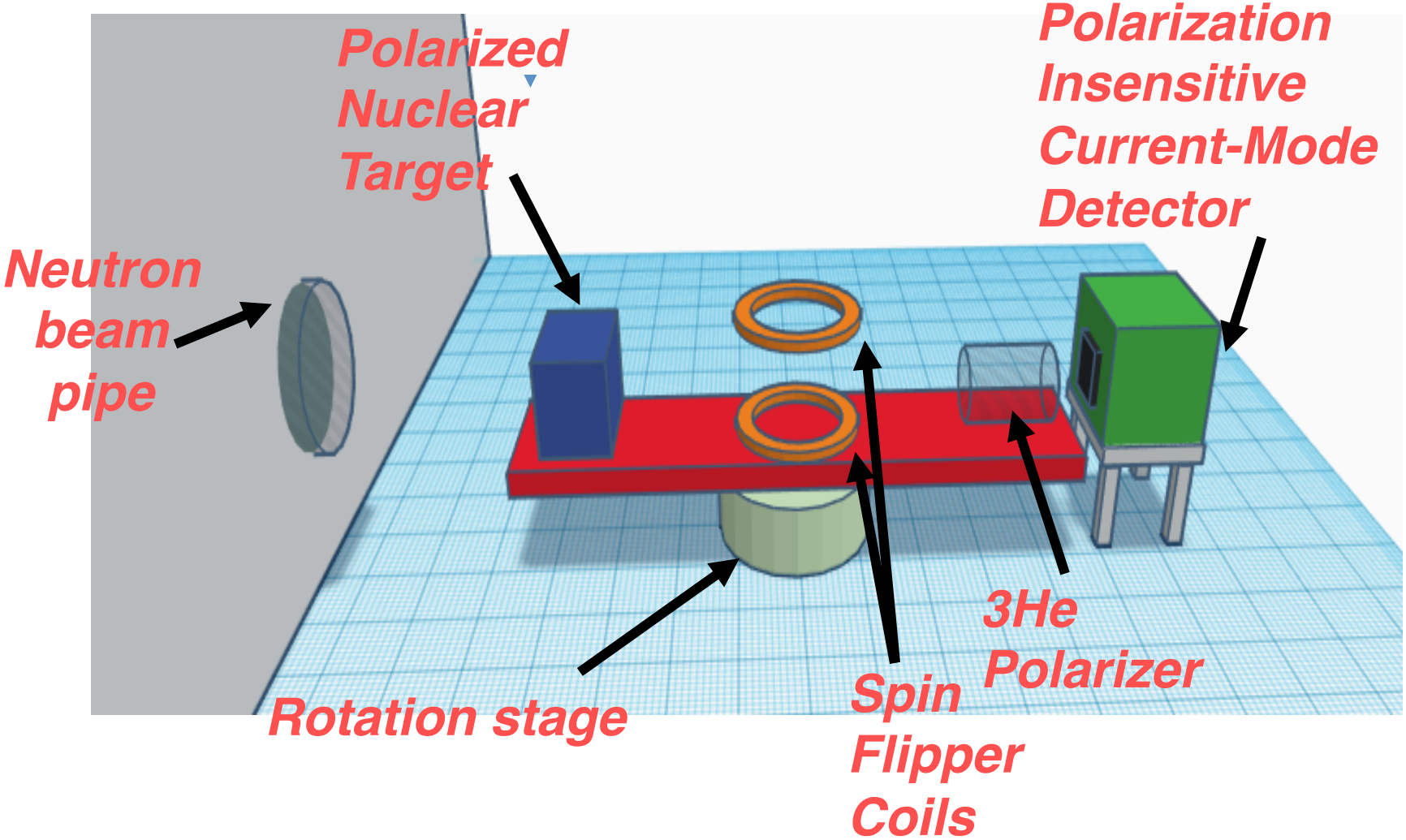
λ can be measured with a statistical uncertainty of ~10^{-5} in 10^7 sec at MW-class spallation neutron sources.

Ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-11}

Forward scattering neutron optics limit is null test for T (no final state effects)

Realization of Apparatus

One can experimentally reverse all of the vectors that are odd under the T transformation and reverse the initial and final states. Will be operated as a Ramsey separated oscillatory field measurement.



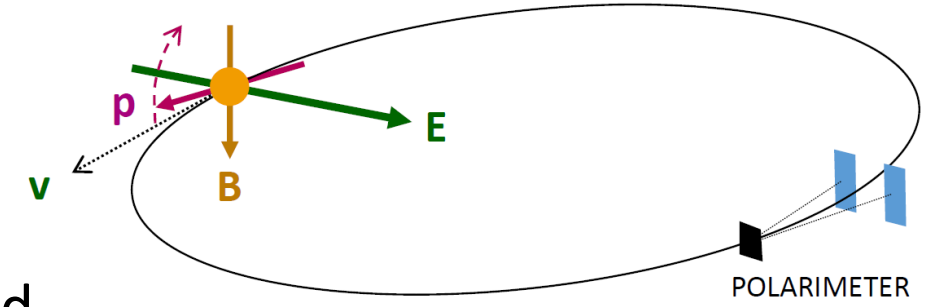
Storage Ring EDM Experiment: Experimental Concept and Main Features

Initially, *charged* particle spin is aligned along velocity.

In particle frame, magnetic field appears as radial electric field.

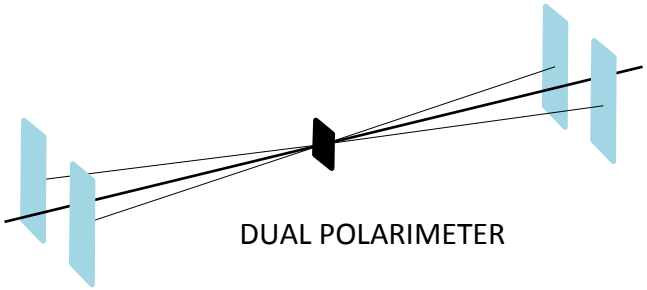
For EDM aligned with spin, torque rotates it vertically.

One can foresee the possibility of ~1×10^{-29} e*cm sensitivities for p, d, ^{3}He+. Would be nice complement to n.



Polarimeter detectors see rising left-right asymmetry as signal.

Comparing results with the time-reversed experiment allows systematic effects to be subtracted.



Both beam direction and all magnetic fields must reverse.

E. Stephenson

New approach to search for parity-even and parity-odd time-reversal violation beyond the Standard Model in a storage ring

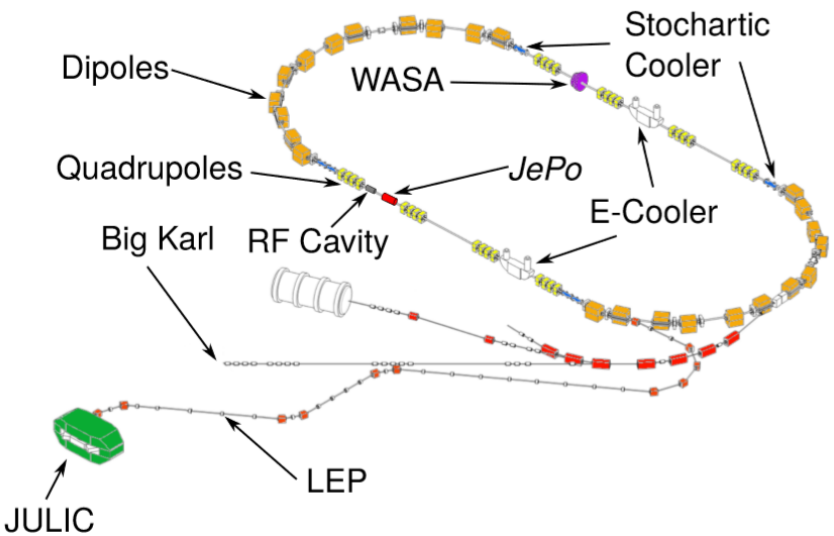
arXiv:2004.09943

N. N. Nikolaev,[1,2] F. Rathmann,[3] A. J. Silenko,[4,5,6] and Yu. Uzikov[7,8,9]

The spin-dependent total pd cross section is written as

$$\begin{aligned}\sigma_{\rm tot} = &\sigma_0 + \sigma_{\rm TT}\left[\left(\mathbf{P}^{\rm d}\cdot\mathbf{P}^{\rm p}\right) - \left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)\right] \\ &+ \sigma_{\rm LL}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right)\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma_{\rm T}T_{mn}k_m k_n \\ &+ \sigma^{\rm p}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right) + \sigma^{\rm d}_{\rm PV}\left(\mathbf{P}^{\rm d}\cdot\mathbf{k}\right) \\ &+ \sigma^{\rm T}_{\rm PV}\left(\mathbf{P}^{\rm p}\cdot\mathbf{k}\right)T_{mn}k_m k_n \\ &+ \sigma_{\rm TVPV}\left(\mathbf{k}\cdot\left[\mathbf{P}^{\rm d}\times\mathbf{P}^{\rm p}\right]\right) \\ &+ \sigma_{\rm TVPC}k_m T_{mn}\epsilon_{nlr}P^{\rm p}_l k_r\,. \end{aligned} \tag{1}$$

Here $\mathbf{P}^{\rm d}$ and $\mathbf{P}^{\rm p}$ are the vector polarizations of deuteron and proton, T_{mn} is the tensor polarization of the deuteron and $\mathbf{k}$ is the unit vector along the collision axis. We chose



Polarized and aligned deuteron beam transmission through polarized internal hydrogen target

At COSY one could reach stat. accuracy of 10^{-6} of strong NN amplitude for a P-even/T-odd interaction

Idea based on R&D conducted at COSY for storage ring EDM (N. Hemplemann et al, Phys. Rev. Lett. **119**, 014801 (2017).

Requires polarization components transverse to beam at interaction point

Summary

- Many excellent scientific motivations from particle physics/ cosmology to look for new sources of CP/T violation in first generation systems

- To compete with EDMs, need to be able to sense a P-odd/T-odd amplitude~10^{-4} - 10^{-5} of a P-odd amplitude

- Non-forward T-odd correlations can be sought but will suffer from (hard-to-calculate?) final state effects, not null tests

- P-odd/T-odd null test in forward transmission need polarization components transverse to beam, sensitive beam intensity monitor,…

- P-even/T-odd null test in forward transmission needs tensor alignment (deuterons). Such interactions are generally already constrained indirectly by EDM limits