$\hbar = c = 1$

Lorentz invariance on trial in β decay

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33rd Solvay Workshop on *Beta-Decay Weak Interaction Studies in the Era of the LHC*
ULB, Brussels, September 3-5, 2014

With Jacob Noordmans, Keri Vos & Hans Wilschut

university of groningen 2014 | 400 years

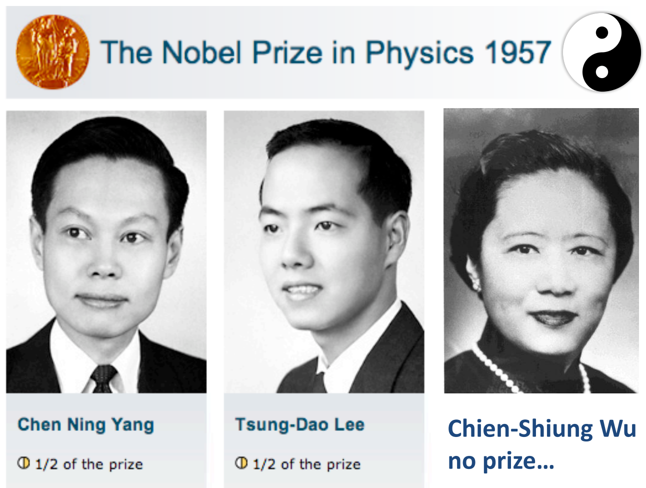
7th Solvay conference, Brussels, October 1933

- ✓ "Structure & properties of the atomic nucleus"
- ✓ 1930:
  - Neutrino
- ✓ 1932:
  - Neutron
  - Positron
- ✓ 1933/34
  - Fermi theory

- ✓ Beta decay finally starts to make sense…

Question of parity conservation in weak interactions

- ✓ Lessons from T.D. Lee & C.N. Yang, Phys. Rev. **104**, 254 (1956)
- ✓ Symmetries are not sacrosanct → experiment decides
  - "For the weak interactions parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence"
- ✓ Non-observable → symmetry → conservation law
  - "To decide unequivocally, one must perform an experiment to determine whether weak interactions differentiate the right from the left"
- ✓ Are other symmetries inviolate?
  - Baryon number OK
  - Electric charge OK
  - Energy & momentum OK
  - *Angular momentum?*
  - C, P & T?



Outline

1. Why test Lorentz & CPT invariance?
   – A window on the Planck scale

2. The need for effective field theory
   – Intermezzo: T violation in beta decay vs EDMs

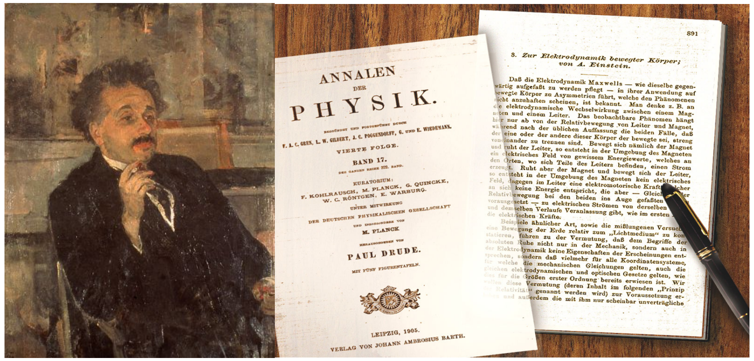
3. Allowed beta decay
   – Theoretical formalism
   – Proof-of-principle experiment @ KVI

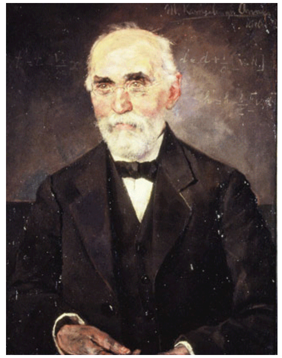
4. Revisiting forbidden beta decay

5. Conclusions
   – What is next?

1. Why bother?

Paintings by Menso &
Harm Kamerlingh Onnes





- ✓ Special relativity = laws of physics are Lorentz (Poincaré) invariant
  - Space-time translations, rotations, boosts

- ✓ SR + QM → QFT
  - Particles transform as irreps |m,s;p,λ> (Wigner, 1939)
- ✓ SM + GR → quantum gravity
  - Unification at the Planck scale $M_{\mathrm{Planck}} \approx 10^{19}$ GeV?

- ✓ Lorentz violation?
  - Viable mechanisms identified in string theories and other QG scenarios
  - Can be probed in ultraprecise low-energy experiments & astrophysics

The CPT theorem

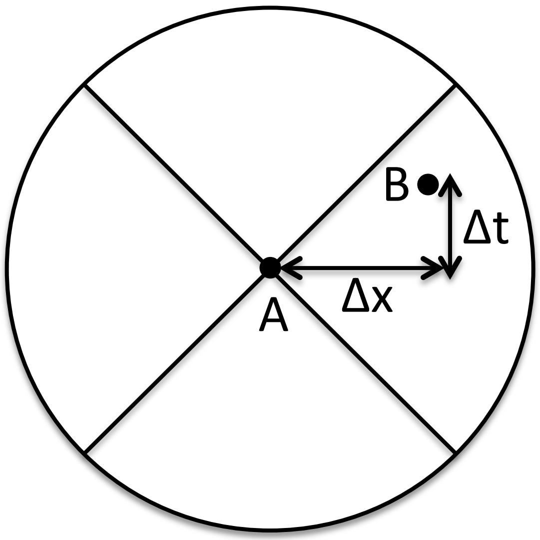
- ✓ Interchange left-right & past-future & particles-antiparticles, then

$$\langle b_1, b_2, \ldots | a_1, a_2, \ldots \rangle = \langle \overline{a}_1, \overline{a}_2, \ldots | \overline{b}_1, \overline{b}_2, \ldots \rangle^*$$

  - with all spins and momenta reversed (Pauli *et al.*, 1954/5)

- ✓ Lorentz invariant QFT $\rightarrow$ CPT invariance
  - Follows from relativistic, local QFT & spin-statistics
  - CPT violation $\rightarrow$ Lorentz violation

- ✓ CPT theorem breaks down at Planck scale (T.D. Lee)
  - Two points separated by $\Delta t < \Delta x < L_{\text{planck}} \approx 10^{-35}$ m
  - Heisenberg: $\Delta E \approx 1/\Delta t > 1/L_{\text{Planck}}$
  - ΔE creates a black hole of radius $R \approx G\,\Delta E > G/L_{\text{planck}}$
  - Since $G \approx L_{\text{Planck}}^2$ this implies $R > \Delta x$!



The program: Lorentz violation in weak decays

- ✓ Largely unexplored → systematic search within theoretical context

- ✓ Neutron decay & allowed + forbidden nuclear beta decay
  - J. P. Noordmans, H. W. Wilschut, RGET, Phys. Rev. C **87**, 055502 (2013)
  - J. P. Noordmans, H. W. Wilschut, RGET, Phys. Rev. Lett. **111**, 171601 (2013)

- ✓ Kaon, pion & muon decay
  - K. K. Vos, J. P. Noordmans, H. W. Wilschut, RGET, Phys. Lett. B **729**, 112 (2014)
  - J. P. Noordmans, K. K. Vos, Phys. Rev. D **89**, 101702(R) (2014)
  - J. P. Noordmans, C. J. G. Onderwater, H. W. Wilschut, RGET, submitted

- ✓ Experiment @ KVI Groningen:
  - H. W. Wilschut *et al.*, Ann. Phys. **525**, 653 (2013)
  - S. E. Müller *et al.*, Phys. Rev. D **88**, 071901(R) (2013)
  - A. Sytema *et al.*, in preparation

- ✓ Jacob Noordmans, PhD thesis University of Groningen, 2014

Effective field theory

- ✓ QED: $\mathcal{L}^{(4)}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \overline{\psi}(\gamma_\mu\partial^\mu + m)\psi + ie\overline{\psi}\gamma_\mu\psi A^\mu$
  - What about "non-renormalizable" terms (mass dimension > 4)?

$$\mathcal{L}^{(5,6)}_{\rm QED} = -\mu\,\overline{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu} - g\,\overline{\psi}\psi\,\overline{\psi}\psi$$

  - Integrating out heavy particles → local interactions at low energy
  - Couplings suppressed by scale of new physics $\mu = \mathcal{O}(1/\Lambda)\ ,\ g = \mathcal{O}(1/\Lambda^2)$
    - Electron magnetic moment → $\Lambda > O(1)$ TeV

- ✓ Standard Model = low-energy EFT

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{(4)}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots$$

  - Dim 5: neutrino masses; dim 6: lots of stuff (T viol, B viol, "non-*V*–*A*",…)
  - Weak interactions (*V*–*A*) at low energy

$$\mathcal{L}^{(4)}_{\rm SM} \to \mathcal{L}^{(4)}_{\rm QCD} + \mathcal{L}^{(4)}_{\rm QED} + \frac{1}{M_W^2}\mathcal{L}^{(6)}_{\rm Fermi}$$

A.V. Kostelecký , D. Colladay, PRD **55**, 6760 (1997), **58**, 116992 (1998);
S.R. Coleman, S. L. Glashow, PRD **59**, 116008 (1999)

EFT for Lorentz violation

- ✓ Effective field theory for Lorentz & CPT violation
  - Explicit Lorentz violation incompatible with GR
  - Spontaneous breaking → vacuum expectation value for tensor fields

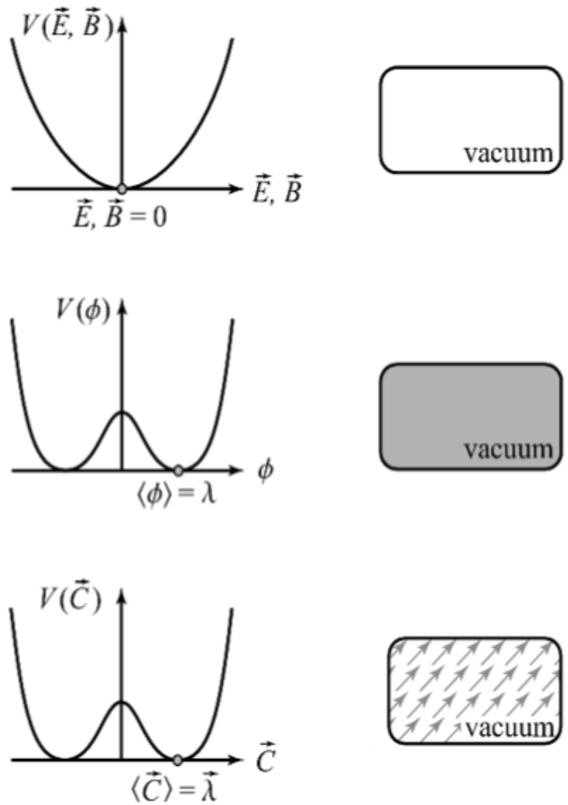
- ✓ Standard Model Extension (Kostelecký *et al.*)
  - Most general gauge-invariant Lagrangian
  - Field operators contracted with tensors
  - Many operators, about half are CPT-odd

- ✓ "Minimal SME": dim-3 and -4, *e.g.*

$$\mathcal{L}^{(3)} = -a_\mu \overline{\psi}\gamma^\mu\psi - b_\mu \overline{\psi}\gamma^\mu\gamma_5\psi$$

  - Scaling? $a_\mu, b_\mu \sim \Lambda_{\mathrm{IR}}^2/\Lambda_{\mathrm{UV}}$ or $\sim \Lambda_{\mathrm{UV}}$

- ✓ Extended SME: also dim-5 and higher
  - SUSY: no dim-3 & -4 operators



P. Herczeg, J. Res. NIST **110**, 453 (2005);
K.K. Vos, HW, RGET, in preparation

Intermezzo: Is beta decay "EDM-safe"?

✓ T-odd triple correlations in non-V−A searches

$$\mathrm{d}W = \mathrm{d}W^0 \left[1 + \ldots + D\,\langle \hat{I}\,\rangle \cdot \vec{\beta} \times \hat{q} + R\,\vec{\sigma}_e \cdot \langle \hat{I}\,\rangle \times \vec{\beta}\right]$$

- Interference of SM with new *V+A* (for *D*) or new *S* or *T* (for *R*) interactions
- Subtract T-violation FSI mimicry *e.g.* $D_{FSI}=O(10^{-5})$, $R_{FSI}=O(10^{-3})$ for neutron

✓ Competition

- P-even, T-odd *D*: *n* and atomic EDMs (^{199}Hg) due to P&T-odd *NN* forces
- P&T-odd *R*: atomic EDMs (^{205}Tl, YbF, ThO) due to P&T-odd *eN* forces

✓ Updated limits:

- 90% C.L.

	β decay		EDMs	
$\mathrm{Im}(a_{LR}/a_{LL})$	4×10^{-4}	*n*, ^{19}Ne	3×10^{-6}	*n*, ^{199}Hg
$\mathrm{Im}(a_{LS}/a_{LL})$	7×10^{-2}	*n*	10^{-5}	ThO
$\mathrm{Im}(a_{LT}/a_{LL})$	2×10^{-3}	^{8}Li	10^{-6}	^{199}Hg

J. de Vries *et al.*, Ann. Phys. **338**, 50 (2013)

A unique left-right four-quark operator

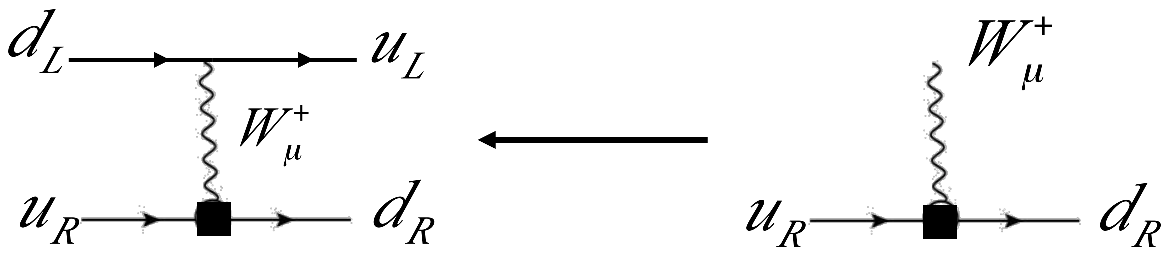
- ✓ Dim-6 quark-Higgs-Higgs interaction
  - Integrate out heavy new particles, break EW symmetry

- ✓ 1 TeV?

$$\Xi_1 \, (\overline{u}_R \gamma^\mu d_R) \, \tilde{\phi}^{*T} i D_\mu \phi + h.c. \qquad \Xi_1 \sim \frac{1}{\Lambda^2}$$

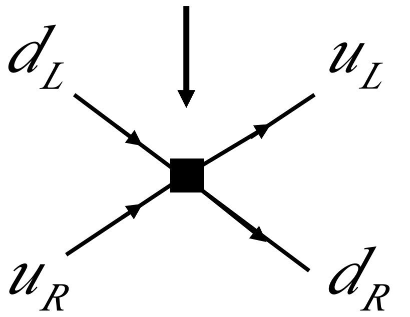
- ✓ 100 GeV

$$\longrightarrow \Xi_1 v^2 \, (\overline{u}_R \gamma^\mu d_R) \, W_\mu^+ + h.c.$$



Q

- ✓ 1 GeV

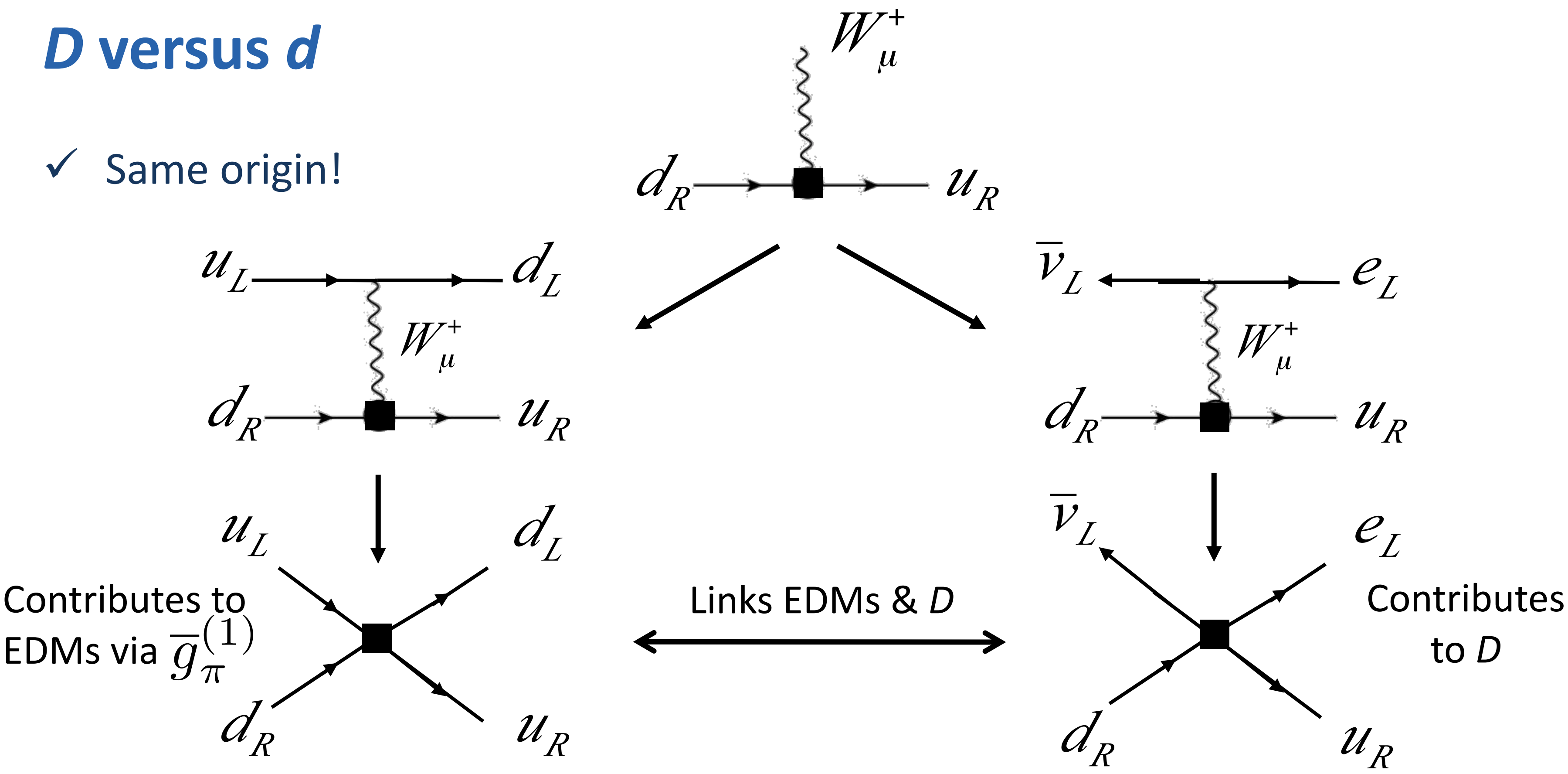


$\sim \frac{v^2}{M_W^2} \mathrm{Im}\Xi_1$ unsuppressed!

J. Ng, S. Tulin, PRD **85**, 033001 (2012)

D versus *d*

- ✓ Same origin!

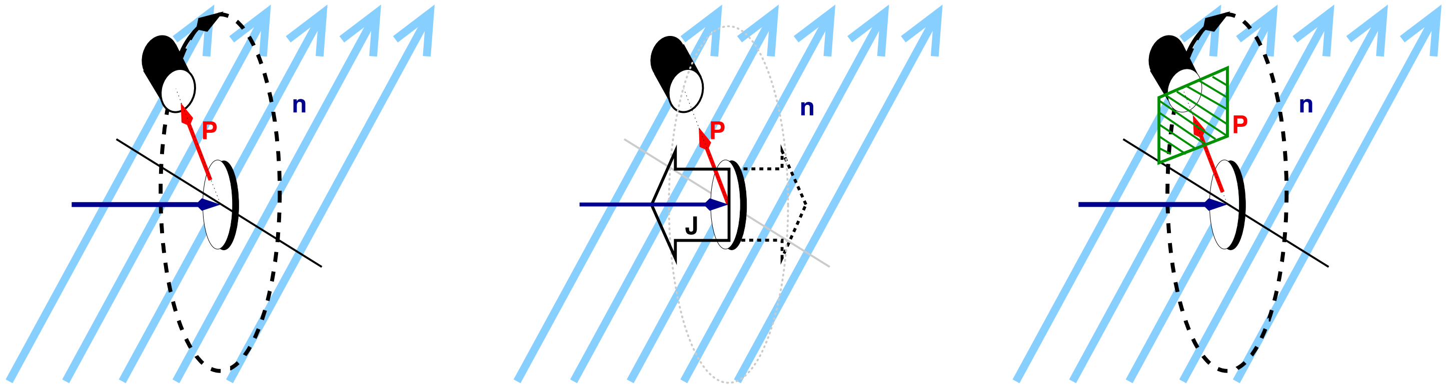


- ✓ Indirect limits from EDMs on *D* are *O*(10^2) × stronger than direct limit
  - Inescapable, beyond uncertainties & cancellations due to fine-tuning…
- ✓ Dim 8: Leptoquark models
  - Similar story…

$$\Xi_2 v^2 \overline{e}_L \gamma^\mu \nu_L \, \overline{u}_R \gamma_\mu d_R \ , \ \Xi_2 \sim \frac{1}{\Lambda^4}$$

3. Beta decay *redux*

- ✓ Decay rate, differential in energy & angle, for polarized nuclei
  - Frame dependence, with frame fixed at some cosmological scale
  - Signals: rotational, sidereal, and annual variations
- ✓ Some generic approaches



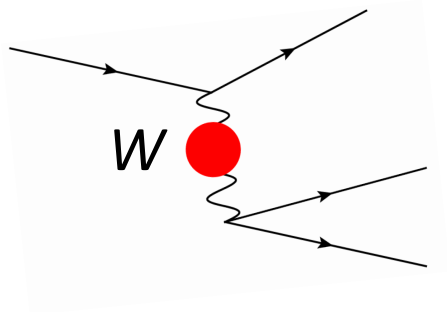
$$\mathrm{d}W \sim 1 + \vec{\beta} \cdot \left[A\,\hat{I} + \xi_1 \hat{n} \right] + \ldots$$
$$+\xi_2 \hat{I} \cdot \hat{n} + \xi_3 \vec{\sigma}_e \cdot \hat{n} + \xi_4 \beta_i \hat{I}_j \varrho^{ij} + \ldots$$

- ✓ *Ad hoc…* ⟶ need a theoretical framework to guide & interpret expt's

J.P. Noordmans *et al*., PRC **87** 055502 (2013);
PRL **111**, 171601 (2013)

Theoretical framework

- ✓ Testing the weak interaction → modified *W*-boson propagator
  - Broad class of Lorentz violation, also Lorentz-violating vertex



$$\langle W^{\mu+}(p) W^{\nu-}(-p) \rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2}$$

$$-i\Gamma^{\mu} = -ig\gamma_{\nu}(g^{\mu\nu} + \chi^{\mu\nu})$$

- ✓ Matching *e.g.* to the low-energy propagator in the minimal SME

$$\chi^{\mu\nu} = -k_{\phi\phi}^{\mu\nu} - \frac{i}{2g} k_{\phi W}^{\mu\nu} + \frac{2p_{\rho}p_{\sigma}}{M_W^2} k_W^{\rho\mu\sigma\nu}$$

  - *i.e.* Lorentz violation in Higgs & *W*-boson sector; *g* = SU(2) coupling
  - Neutrino sector in beta decay: J. S. Díaz *et al*., PRD **88**, 071902 (2013)

- ✓ Dim-5 contribution to $\chi_{\mu\nu}$ *e.g.* $\mathcal{L}^{(5)} \supset C^{\mu\nu\rho} \, \mathrm{tr}\, W_{\mu\lambda} D_{\nu} \widetilde{W}_{\rho}{}^{\lambda}$
  - In general, $\chi^{\mu\nu}$ can be momentum dependent & CPT-even or -odd

Differential decay rate for allowed transitions

- ✓ Generalized "JTW" formula
  - Standard QFT techniques to calculate observables (tricky…)
  - Assuming *V–A* ; including Coulomb corrections

$$
\begin{aligned}
\mathrm{d}W \;=\; \mathrm{d}W^0 \Bigg\{ & \left(1 \mp \frac{\vec{p}\cdot\vec{\sigma}_e}{E_e}\right) \left[\frac{1}{2}\left(1 + B\frac{\vec{q}\cdot\hat{I}}{E_\nu}\right) + t + \frac{\vec{w}_1\cdot\vec{q}}{E_\nu} + \vec{w}_2\cdot\hat{I} \right.\\
& \left. + T_1^{km}\hat{I}^k\hat{I}^m + \frac{T_2^{kj}\hat{I}^k q^j}{E_\nu} + \frac{S_1^{kmj}\hat{I}^k\hat{I}^m q^j}{E_\nu} \right]\\
& + \left[\left(1 \mp \frac{(E_e - \gamma m_e)(\vec{p}\cdot\vec{\sigma}_e)}{E_e^2 - m_e^2}\right)\frac{p^l}{E_e} \mp \frac{\gamma m_e}{E_e}\vec{\sigma}_e^l \mp \frac{m_e}{E_e}\sqrt{1-\gamma^2}(\vec{p}\times\vec{\sigma}_e)^l \right]\\
& \times \left[\frac{1}{2}\left(A - 3\frac{\vec{q}\cdot\hat{I}}{E_\nu}\right)\hat{I}^l + \frac{1}{2}(a+c)\frac{q^l}{E_\nu} + w_3^l + \frac{T_3^{lj}q^j}{E_\nu} \right.\\
& \left. + T_4^{lk}\hat{I}^k + S_2^{lmk}\hat{I}^m\hat{I}^k + \frac{S_3^{lmj}\hat{I}^m q^j}{E_\nu} + \frac{R^{lmkj}\hat{I}^m\hat{I}^k q^j}{E_\nu} \right] \Bigg\}
\end{aligned}
$$

- ✓ Parameters t, $w_{1,2,3}$, $T_{1,2,3,4}$, $S_{1,2,3}$, R all functions of $\chi^{\mu\nu}$
  - Sidereal time dependence: $\chi^{\mu\nu} \rightarrow X^{\mu\nu}$ in Sun-centered inertial frame

Fermi & Gamow-Teller transitions

- ✓ Fermi transitions
  - – Measure directional decay rate → access to χ_r^{0l}

$$\mathrm{d}W_{\mathrm{F}} = \mathrm{d}W^0 \left[1 + 2\chi_r^{00} + 2\chi_r^{0l}\frac{p^l}{E_e}\right]$$

$$\chi_r^{\mu\nu} = \mathrm{Re}(\chi^{\mu\nu})$$
$$\chi_i^{\mu\nu} = \mathrm{Im}(\chi^{\mu\nu})$$

- ✓ Gamow-Teller transitions
  - – Directional decay rate → disentangle χ_i^{mk}

$$\mathrm{d}W_{\mathrm{GT}} = \mathrm{d}W^0 \left[1 - \tfrac{2}{3}\chi_r^{00} + \tfrac{2}{3}(\chi_r^{l0} + \tilde{\chi}_i^l)\frac{p^l}{E_e}\right]$$

$$\tilde{\chi}^l = \epsilon^{lmk}\chi^{mk}$$
$$(\chi^{\mu\nu})^* = \chi^{\nu\mu}$$

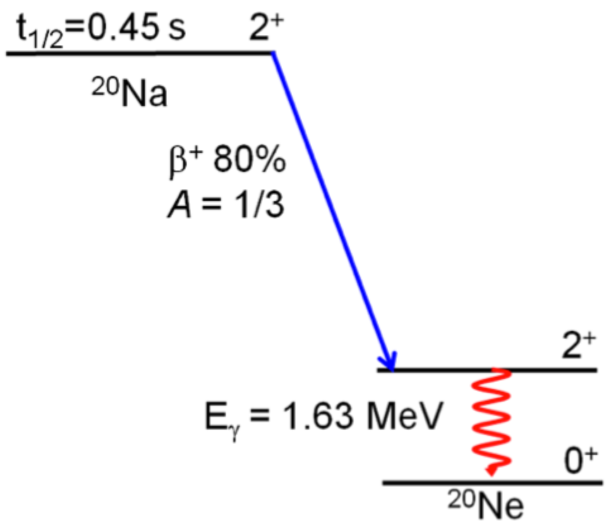
- ✓ Polarized nuclei

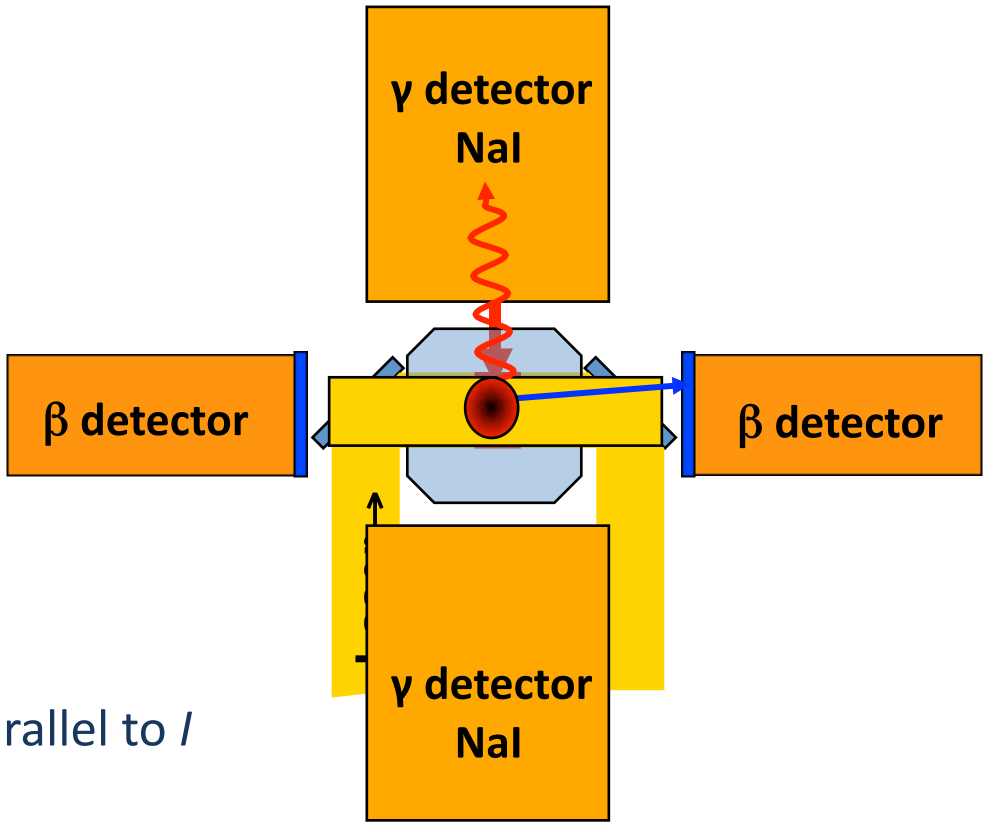
$$\begin{aligned}\mathrm{d}W_{\mathrm{GT}} = \; & \mathrm{d}W^0 \left[1 - \frac{2}{3}\chi_r^{00} + \frac{2}{3}(\chi_r^{l0} + \tilde{\chi}_i^l)\frac{p^l}{E_e}\right] \\ & \mp\Lambda^{(1)}\left[(1-\chi_r^{00})\frac{\vec{p}\cdot\hat{I}}{E_e} + \tilde{\chi}_i^l\hat{I}^l + \frac{\chi_r^{lk}p^l\hat{I}^k}{E_e} - \frac{\chi_i^{l0}(\vec{p}\times\hat{I})^l}{E_e}\right] \\ & +\Lambda^{(2)}\left[-\chi_r^{00} + (\chi_r^{l0} + \tilde{\chi}_i^l)\frac{p^l}{E_e} + 3\chi_r^{kl}\hat{I}^k\hat{I}^l - 3\chi_r^{l0}\hat{I}^l\frac{\vec{p}\cdot\hat{I}}{E_e} - 3\chi_i^{ml}\hat{I}^m\frac{(\vec{p}\times\hat{I})^l}{E_e}\right]\end{aligned}$$

S.E. Müller *et al.*, PRD **88**, 071901(R) (2013);
A. Sytema *et al.*, in preparation

A pioneering experiment @ KVI

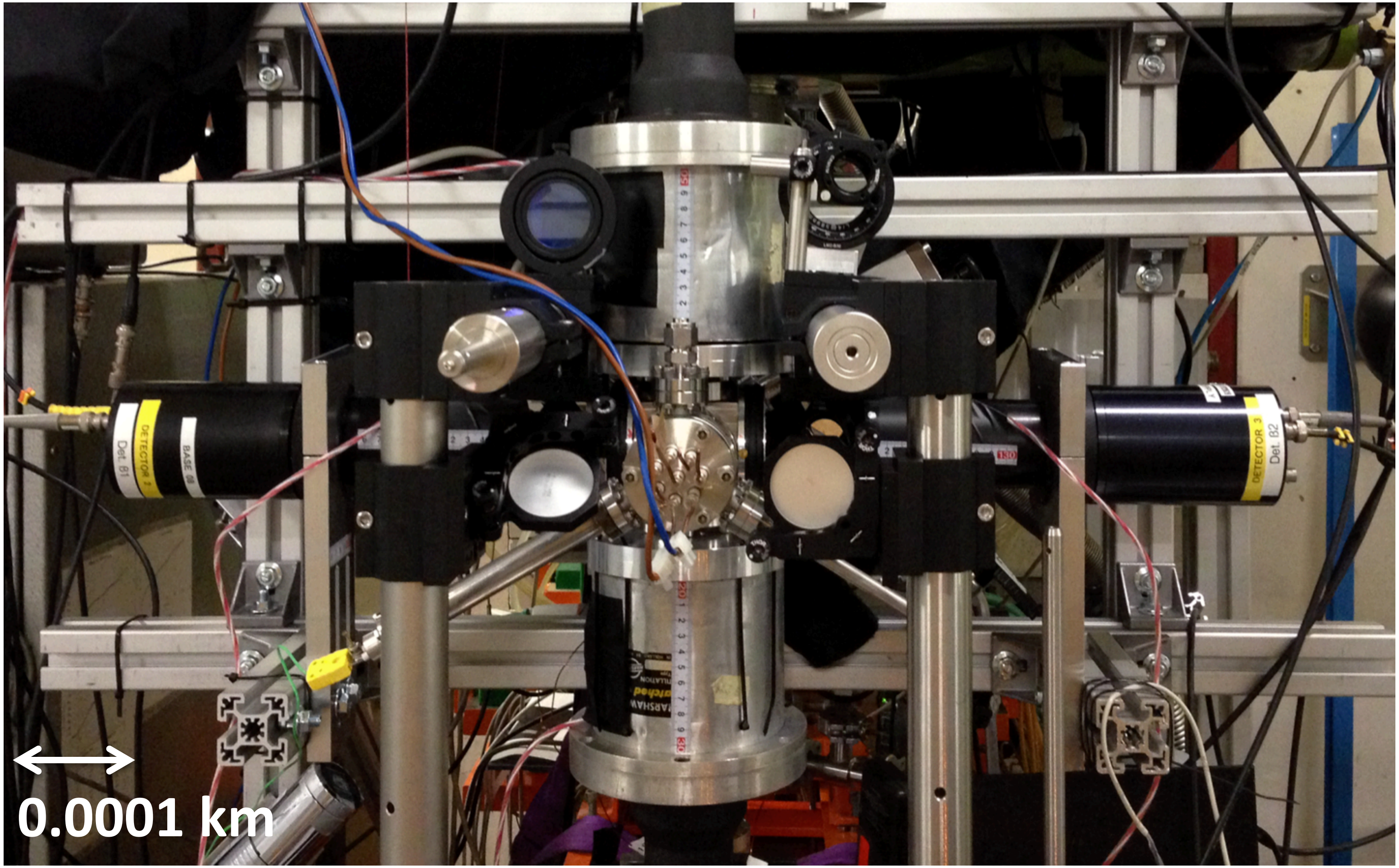
- ✓ 27 MeV/*A* beam of ^{20}Na from $p(^{20}\text{Ne},^{20}\text{Na})n$ stopped in Ne gas
  - Nuclear polarization via optical pumping



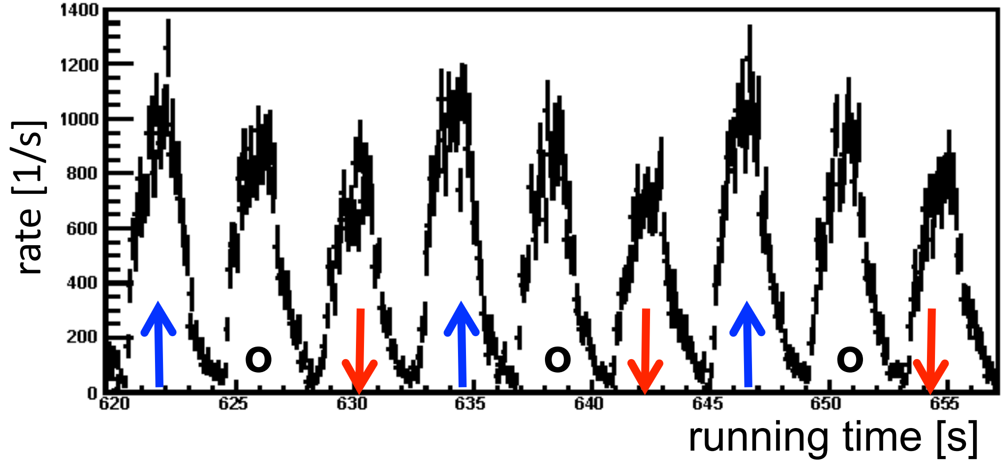


- ✓ Relativistic positrons detected parallel to *I*
  - Measures polarization *P*
- ✓ Gamma rate asymmetry due to Lorentz violation

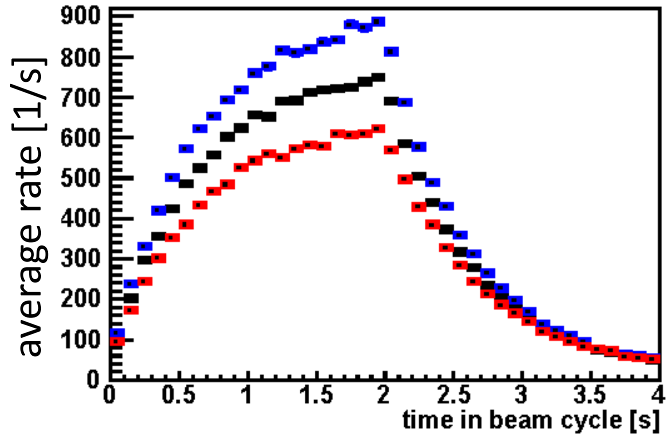
Setup

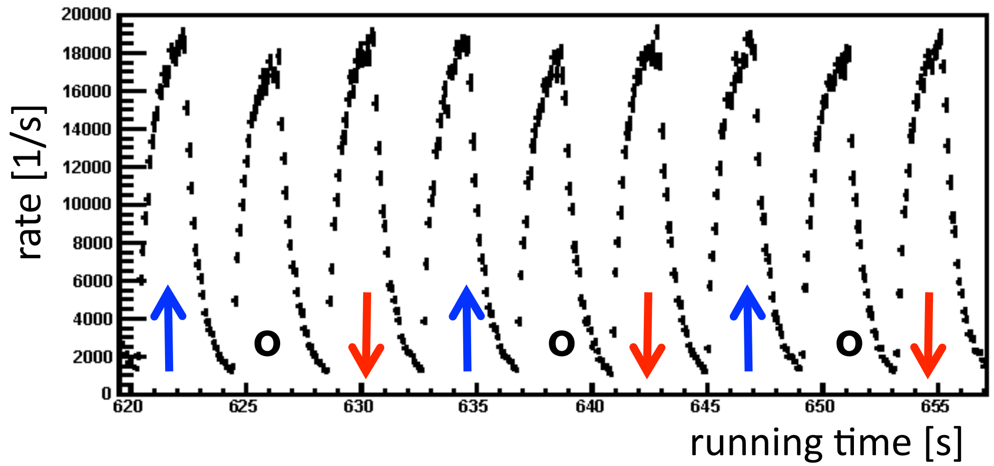


Beta and gamma asymmetry

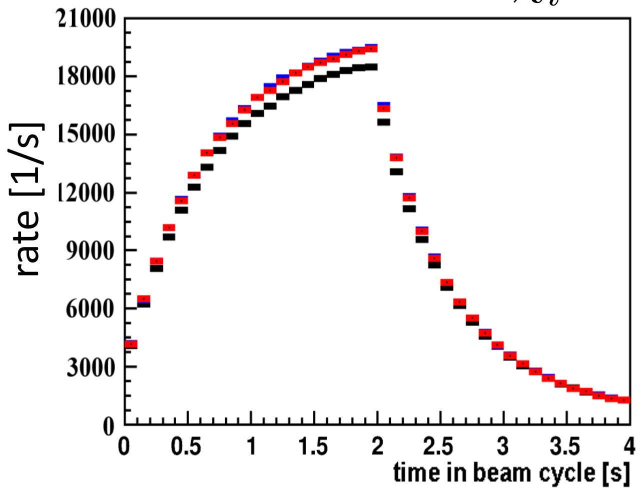


$$\mathrm{dW} \sim 1 + AP\,\vec{\beta}\cdot\hat{I}$$



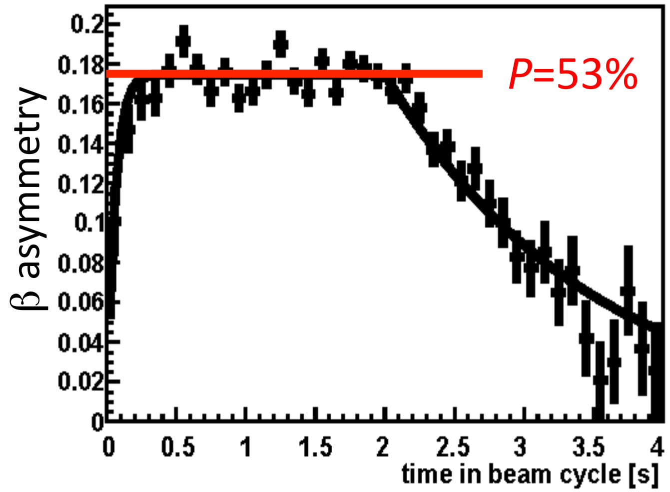


$$\mathrm{dW} \sim 1 + AP\,\tilde{\chi}_i^l\hat{I}^l$$



Limits on Lorentz violation

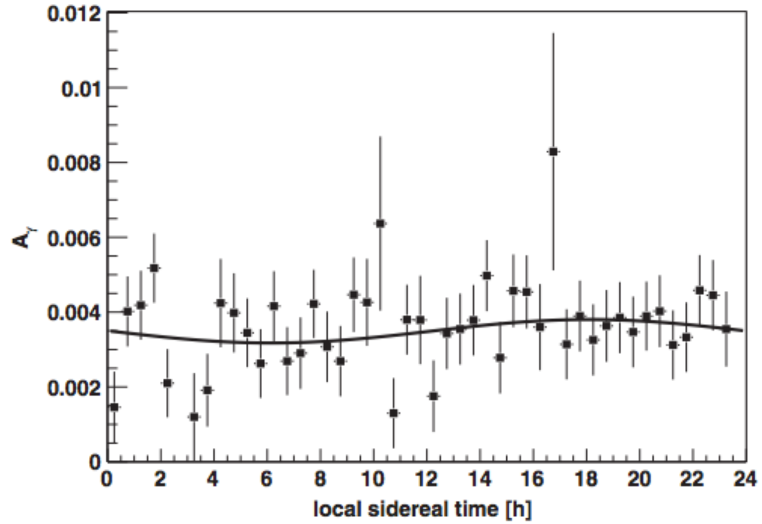
- ✓ Effective nuclear polarization (A=1/3)



- ✓ Signal for Lorentz violation
  - Gamma asymmetry / analyzing power

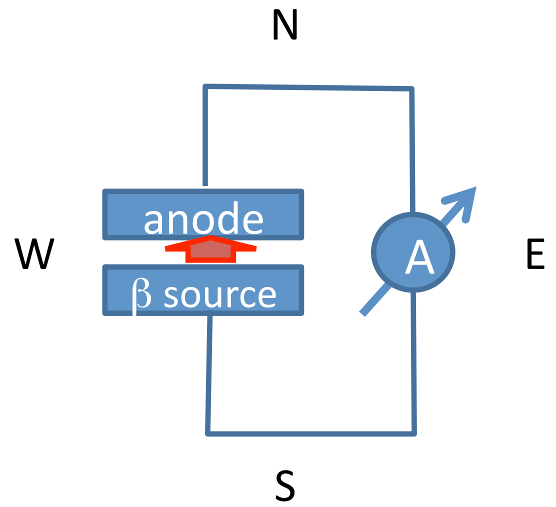
$$\tilde{\chi}_i^2 = \chi_i^{31} - \chi_i^{13}$$
$$= \left[\frac{\tau_\gamma^{\leftarrow} - \tau_\gamma^{\rightarrow}}{\tau_\gamma^{\leftarrow} + \tau_\gamma^{\rightarrow}}\right] / \left[\frac{N_\beta^{\rightarrow} - N_\beta^{\leftarrow}}{N_\beta^{\rightarrow} + N_\beta^{\leftarrow}}\right]$$

- ✓ Sidereal variation of gamma asymmetry
  - $|A_\gamma| < 4 \times 10^{-4}$ (95% C.L.)



- ✓ Order of magnitude improvement due
  - Blind analysis

4. *Eppur si muove*



- ✓ R. Newman & S. Wiesner, PRD **14**, 1 (1976)
  - Unique 1st-forbidden transition

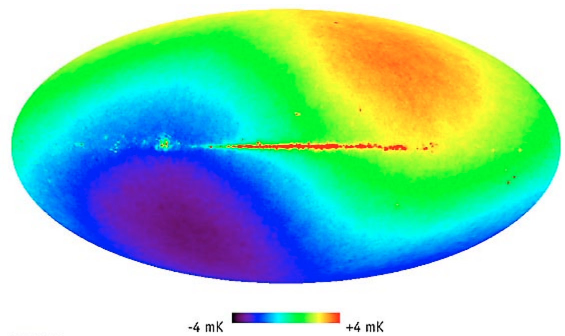
    $$^{90}\mathrm{Sr}(0^+, 28.8\,a) \to {}^{90}\mathrm{Y}(2^-, 64.1\,h) \to {}^{90}\mathrm{Zr}(0^+)$$

  - 10-Ci ^{90}Sr source, rotating apparatus 0.75 Hz

- ✓ J. D. Ullman, PRD **17**, 1750 (1978)
  - Unique 1st-forbidden, 2nd-forbidden transition

    $$^{137}\mathrm{Cs}(\tfrac{7}{2}^+, 30.2\,a) \to {}^{137m}\mathrm{Ba}(\tfrac{11}{2}^-) \quad {}^{99}\mathrm{Tc}(\tfrac{9}{2}^+, 2.1\times 10^5\,a) \to {}^{99}\mathrm{Ru}(\tfrac{5}{2}^+)$$

- ✓ Motivation:
  - Angular momentum conservation poorly tested
    - Enhancement in forbidden transitions?
  - Preferred frame defined by CMB dipole?
    - Measured by Smoot *et al*. on U2 plane (1977)



J.P. Noordmans *et al.*, PRL **111**, 171601 (2013)

Forbidden beta decay recycled

- ✓ 1970s experiments reinterpreted in our formalism
  - Extended to general forbidden beta decays
  - Violation $\Delta I \leq 1$, relative enhancement of Lorentz violation $\alpha Z/R \approx 10\,\chi$
  - Reconstructed the data analyses (contacted both emeriti)
  - Best limits from unique 1st-forbidden ^{90}Sr decay $\longrightarrow$ $\chi^{\mu\nu} \leq O(10^{-6}\text{-}10^{-8})$

- ✓ Dipole & quadrupole current asymmetries: *N–S*, *E–W*, (*N+S*)–(*E+W*)
  - Fitted as function of sidereal time (various corrections)

$$\delta = a_0 + a_1 \sin(\omega t + \phi_1) + a_2 \sin(2\omega t + \phi_2)$$

- ✓ Differential decay rate for unique 1st-forbidden transition

$$\mathrm{d}W \sim p^2 + q^2 + p^2\,\frac{\alpha Z}{pR} \times \left[\frac{3}{10}\frac{p}{E}\left(\chi_r^{ij}\hat{p}^i\hat{p}^j - \tfrac{1}{3}\chi_r^{00}\right) - \frac{1}{2}\tilde{\chi}_i^l\hat{p}^l + \chi_r^{l0}\hat{p}^l\right]$$

A.V. Kostelecký, N. Russell, RMP **83**, 11 (2011);
2014 version: arXiv:0801.0287v7 [hep-ph]

5. What is next?

✓ Limits from forbidden beta decay, assuming minimal cancellation:

$$-{}^{10}\log\left(|X^{\mu\nu}_{rs}|\right) > \begin{bmatrix} 6 & 7 & 7 & 8 \\ 7 & 6 & 6 & 6 \\ 7 & 6 & 6 & 6 \\ 8 & 6 & 6 & 6 \end{bmatrix} \; , \quad -{}^{10}\log\left(|X^{\mu\nu}_{ia}|\right) > \begin{bmatrix} \times & - & - & - \\ - & \times & 8 & 7 \\ - & 8 & \times & 7 \\ - & 7 & 7 & \times \end{bmatrix}$$

- Tough to beat… requires high-intensity sources

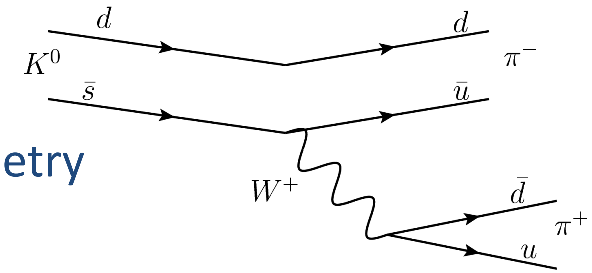
✓ Including pion decay and assuming maximal cancellation (fine-tuning):

$$-{}^{10}\log\left(|X^{\mu\nu}_{rs}|\right) > \begin{bmatrix} 3 & 5 & 4 & 3 \\ 5 & - & 6 & 6 \\ 4 & 6 & - & 6 \\ 3 & 6 & 6 & 3 \end{bmatrix} \; , \quad -{}^{10}\log\left(|X^{\mu\nu}_{ia}|\right) > \begin{bmatrix} \times & - & - & - \\ - & \times & 3 & 4 \\ - & 3 & \times & 4 \\ - & 4 & 4 & \times \end{bmatrix}$$

✓ Included in the 2014 SME Data Tables

K.K. Vos *et al.*, PLB **729**, 112 (2014)

Kaon decay explored



- ✓ KLOE collaboration, Eur. Phys. J. C **71**, 1604 (2011)
  - $K^0_s \rightarrow \pi^+ + \pi^-$ directional-dependent lifetime asymmetry
  - Parallel and antiparallel to motion of Earth in CMB

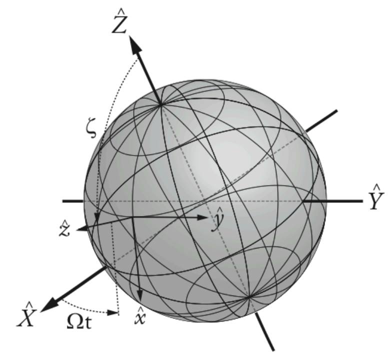
$$\mathcal{A}_{\hat{n}} = \frac{\tau^+ - \tau^-}{\tau^+ - \tau^-} = \frac{\frac{4}{3} + \frac{2}{3}\frac{m_\pi^2}{m_K^2}}{1 - \frac{m_\pi^2}{m_K^2}} \gamma_K^2 \left(\chi_r^{i0} + \chi_r^{0i}\right) \beta_K^i = 0.34\, \chi_S^{i0}\, \hat{\beta}_K^i$$

- ✓ Hard to compete with beta decay
  - Nonleptonic decay difficult
  - "Penguin diagram" insensitive to LV

	$\{l, b\}$	$10^3 \times A$
CMB	{264°, 48°}	−0.13±0.4
⊥ CMB	{174°, 0°}	0.2±1.0
⊥ CMB	{264°,−42°}	0.0±0.9

- ✓ However, asymmetry $A \approx \gamma^2 \rightarrow$ hadron factories?

Neutron beta decay



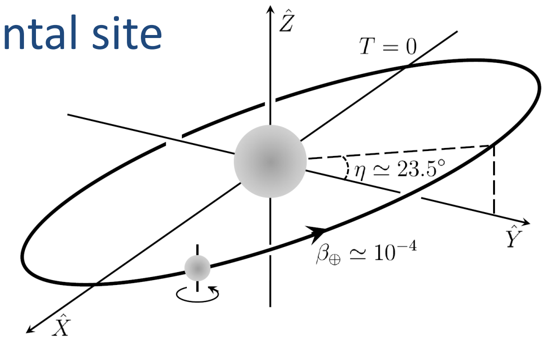
✓ Differential decay rate for polarized neutrons

$$\mathrm{d}W = \mathrm{d}W^0 \Big\{ 1 - 0.21\chi_r^{00} + (0.34\chi_r^{0l} + 0.55(\chi_r^{l0} + \tilde{\chi}_i^l))\frac{p^l}{E_e} + \frac{\langle m \rangle}{j}\hat{I}^k \Big[0.43(\chi_r^{k0} - \chi_r^{0k}) - 0.55\tilde{\chi}_i^k - (0.12 - 0.99\chi_r^{00})\frac{p^k}{E_e} - 0.99(\chi_r^{lk} - \chi_i^{s0}\epsilon^{ksl})\frac{p^l}{E_e} \Big] \Big\}$$

✓ Express in standard Sun-centered inertial frame $\chi^{\mu\nu} \rightarrow X^{\mu\nu}$

$$\mathrm{d}W = \mathrm{d}W^0 \big[1 - 0.12\mathcal{P}v\cos\theta - X_r^{TT}(0.21 - 0.99\mathcal{P}v\cos\theta) + Z_1 + Z_2\cos(\Omega t) + Z_3\sin(\Omega t) + Z_4\cos(2\Omega t) + Z_5\sin(2\Omega t) \big]$$

- $Z_{1,2,3,4,5}$ depend on $X^{\mu\nu}$ and colatitude ζ of experimental site
- Oscillation frequencies Ω = 2π/(23h56m) and 2Ω



✓ Should be explored!

Face the music

Watercolor by Marijke Kamerlingh Onnes

- ✓ Lorentz violation in allowed & forbidden beta decay
  - New twist to a long successful history
- ✓ Effective field theory framework
  - *D*, *R* : EDMs *O*(100) × better model independently
  - Open issues in Standard Model Extension
- ✓ Intensity frontier: need much higher statistics
  - 1 Ci events in 1 month = 10^{16} → accuracy of 10^{-8} → count rate > 10^{10}/s
  - Long-running experiments with high-intensity sources
  - Segmented counters, integrating detectors
  - Neutron activation: $^{32,33}P$, ^{35}S, ^{45}Ca, ^{63}Ni excellent options
- ✓ Decays at high velocity: boost gives enhanced sensitivity ≈ $O(\gamma^2)$
  - High-velocity beta beams *e.g.* ^{6}He 10^{18}/y @ γ=150
  - Semi-leptonic decays of hadrons at high-energy facilities
  - Next-generation muon "*g*−2" experiment