Muon-electron conversion from Lorentz- and CPT-violating operators

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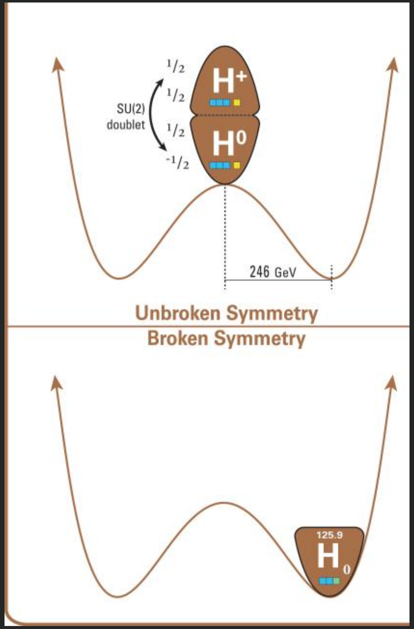
Work in collaboration with V. A. Kostelecký, E. Passemar, and N. Sherrill

Based on arXiv:2501.05986 (in review)

Why Violate Symmetries?

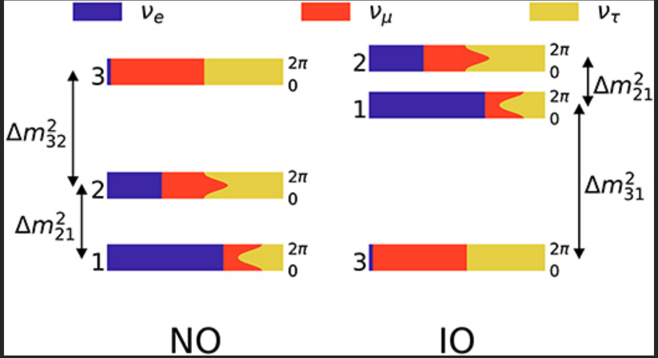
- Standard Model works well, but we know it's incomplete
- SM is based on symmetries, but symmetries have a habit of being broken (e.g., electroweak, chiral, CP)
    - Even small violations can have important consequences
    - Good place to look for new physics



Modified from Boyle (2014)

Lepton Flavor Violation

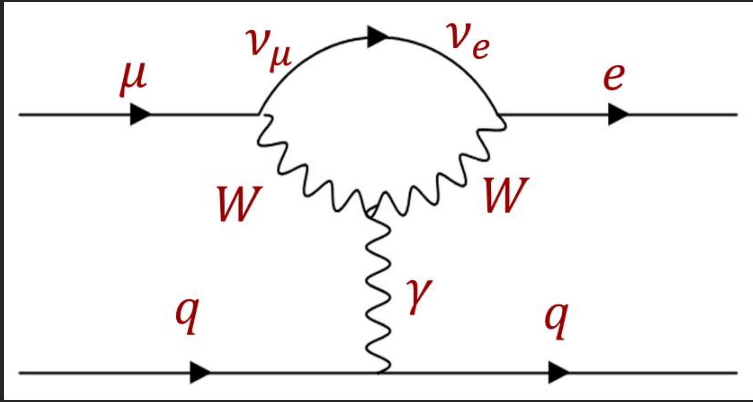
- Lepton flavor conservation is an *accidental* symmetry of SM
  - $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
- Lepton flavor conservation is *violated* by neutrino oscillations
  - Massive neutrinos give rise to PMNS mixing (analogous to CKM for quarks)



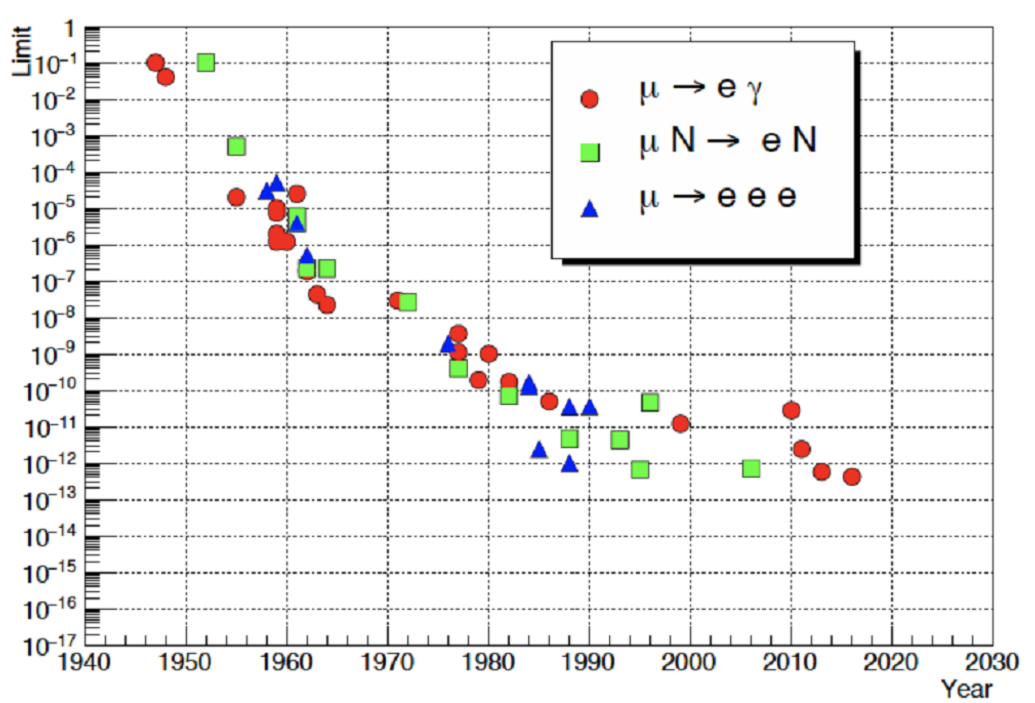
de Salas *et al.* (2018)

Charged Lepton Flavor Violation

- If LFV exists for neutrinos, then *charged* lepton flavor violation must also exist
- Process is highly suppressed in SM + neutrino oscillations: BR $\lesssim 10^{-54}$
  - Loop process
  - Smallness of neutrino masses
  - GIM mechanism



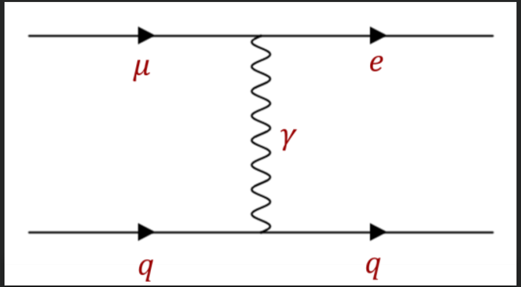
Experimental Progress in CLFV

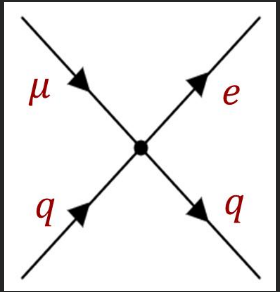


Calibbi & Signorelli (2017)

Nuclear $\mu - e$ Conversion Searches

- Basic idea: Collide muon beam with atomic target; some muonic atoms will be formed
- Primary background is decay $\mu \rightarrow e\,\nu_\mu \overline{\nu_e}$
  - Three-body decay spectrum
- *Hope* to observe clean, monoenergetic signal from rare $\mu \rightarrow e$ decay
  - $E_e^{conv} = m_\mu - E_{bind} - E_{recoil}$
    - $\approx 105\text{ MeV}$ for Al, $\approx 95.6\text{ MeV}$ for Au





Nuclear $\mu - e$ Conversion Searches

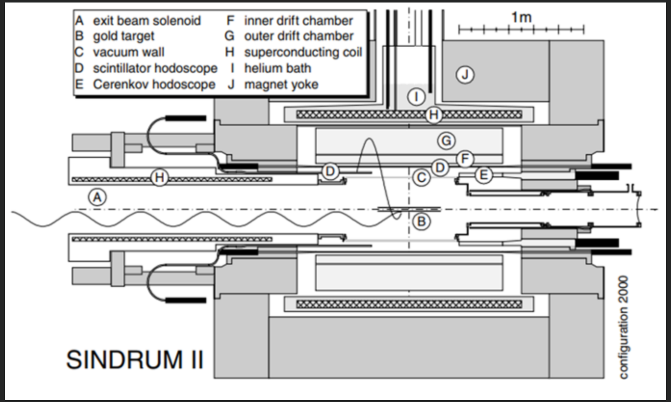
- Observable of interest is

$$R_{\mu e} = \frac{\omega_{conv}}{\omega_{capt}} = \frac{\Gamma\left[\mu + {}^{A}_{Z}N \rightarrow e + {}^{A}_{Z}N\right]}{\Gamma\left[\mu + {}^{A}_{Z}N \rightarrow \nu_\mu + {}^{A}_{Z-1}N\right]}$$

  - N.b.: We focus on coherent conversion; incoherent also possible (Haxton *et al.* 2024)

- Current best limit is from SINDRUM II (2006): $R_{\mu e} < 7 \times 10^{-13}$ on ${}^{197}_{79}\mathrm{Au}$ (90% C.L.)

- Near-future improvement expected by COMET Phase I ($R_{\mu e} < 7 \times 10^{-15}$) and Mu2e Run I ($R_{\mu e} < 6.2 \times 10^{-16}$), both on ${}^{27}_{13}\mathrm{Al}$

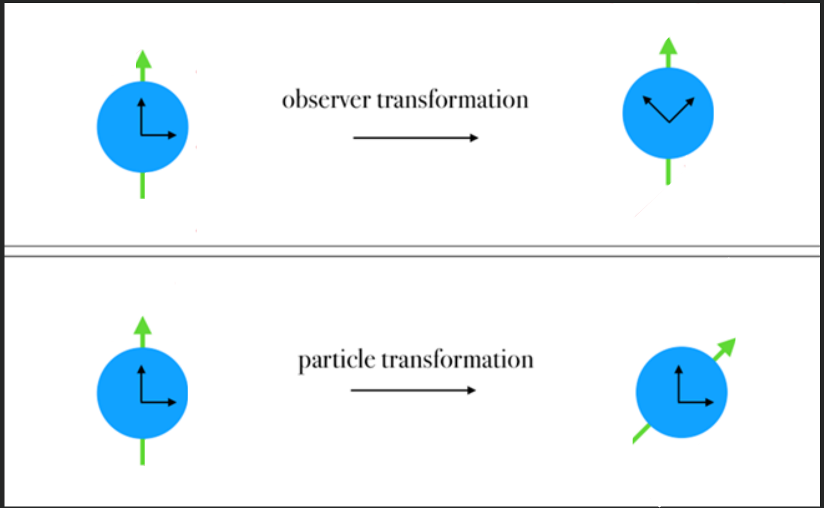


van der Schaaf (2003)

Lorentz Violation

- Lorentz symmetry is a *fundamental* symmetry of the SM
- Lorentz invariance is a statement of isotropy in spacetime (symmetry under rotations and boosts)
- Small violations of Lorentz invariance may exist and would be of enormous interest for moving beyond the SM
- Presence of such violations introduces meaningful distinction between *observer* and *particle* transformations

In a Lorentz-invariant theory…



Lorentz Violation

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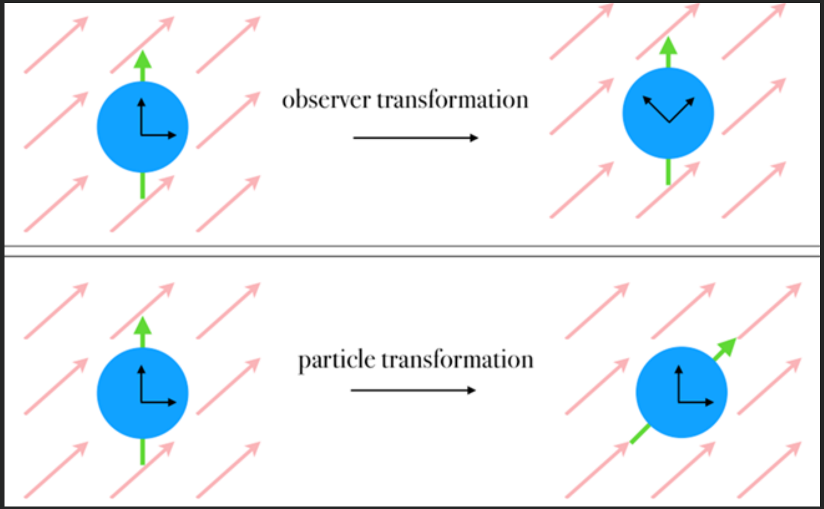
In a Lorentz-violating theory…



Standard Model Extension

- *Very* general effective field theory starting from SM+GR and built from known particles
- Allows for generic Lorentz- and CPT-violating interactions
    - CPTV ⇒ LV (Greenberg 2002), so CPTV automatically included
- LV can occur spontaneously or explicitly
- No assumptions about flavor structure, so possible CLFV interactions are also included
- Still requires *coordinate-independent* physics, so Lagrangian is observer Lorentz and general-coordinate scalar

Nuclear $\mu - e$ Conversion in the SME

- Most relevant for nuclear $\mu - e$ conversion are EM (mass dim. 5) and 4-point quark-lepton (mass dim. 6) operators
- Lagrangian ($Q \in \{u, d, s\}, q \in \{u, d\}$; red = CPT-odd) is given by

$$\mathcal{L} \supset -\frac{1}{2} F_{\alpha\beta} \overline{\psi_e} \left(\left(m_F^{(5)}\right)_{e\mu}^{\alpha\beta} + i \left(m_{5F}^{(5)}\right)_{e\mu}^{\alpha\beta} \gamma_5 + \left(a_F^{(5)}\right)_{e\mu}^{\mu\alpha\beta} \gamma_\mu + \left(b_F^{(5)}\right)_{e\mu}^{\mu\alpha\beta} \gamma_5 \gamma_\mu + \frac{1}{2} \left(H_F^{(5)}\right)_{e\mu}^{\mu\nu\alpha\beta} \sigma_{\mu\nu} \right) \psi_\mu$$
$$+ \overline{\psi_Q} \psi_Q \overline{\psi_e} \left(\left(k_{SV}^{(6)}\right)_{QQe\mu}^{\lambda} \gamma_\lambda + \left(k_{SA}^{(6)}\right)_{QQe\mu}^{\lambda} \gamma_5 \gamma_\lambda + \frac{1}{2} \left(k_{ST}^{(6)}\right)_{QQe\mu}^{\kappa\lambda} \sigma_{\kappa\lambda} \right) \psi_\mu$$
$$+ \overline{\psi_q} \gamma_0 \psi_q \overline{\psi_e} \left(\left(k_{VS}^{(6)}\right)_{qqe\mu}^{0} + i \left(k_{VP}^{(6)}\right)_{qqe\mu}^{0} \gamma_5 + \frac{1}{2} \left(k_{VV}^{(6)}\right)_{qqe\mu}^{0\lambda} \gamma_\lambda + \left(k_{VA}^{(6)}\right)_{qqe\mu}^{0\lambda} \gamma_5 \gamma_\lambda + \frac{1}{2} \left(k_{VT}^{(6)}\right)_{qqe\mu}^{0\kappa\lambda} \sigma_{\kappa\lambda} \right) \psi_\mu$$

Leptonic Wavefunctions

- The bound muon (1s, $\kappa = -1$) and the plane-wave electron wavefunctions are found by numerically solving the Dirac equation

$$\frac{d}{dr}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} -\kappa/r & W - V(r) + m \\ -(W - V(r) - m) & \kappa/r \end{pmatrix}\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

  - W is the energy; $\kappa = \mp(J + 1/2)$; $V(r)$ is the electric potential; $u_1(r)$ and $u_2(r)$ are related to the radial components of the wavefunction

- Spherically-symmetric models fitting experimental data exist for the nuclear charge distributions of various isotopes (e.g., de Vries *et al*. 1987)

Conversion Rates

- Conversion rates involve the square of the transition amplitude

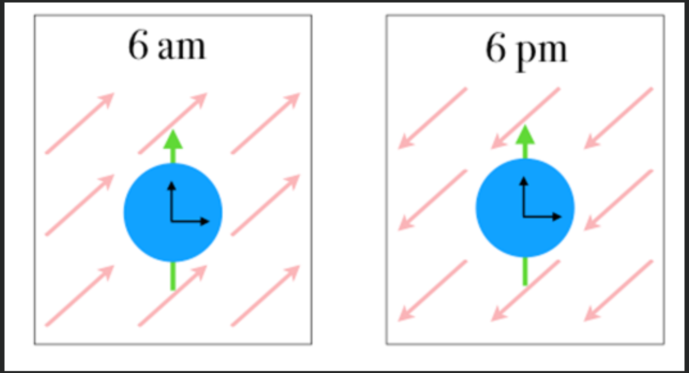
$$\omega_{\mathrm{conv}} = \frac{1}{2}\sum_{s=\pm\frac{1}{2}}\sum_{\kappa=\pm 1}\sum_{s'=\pm\frac{1}{2}}\left|\int d^3x F_{\alpha\beta}\overline{\psi}^{(e)}_{\kappa,s'}\mathcal{O}^{\alpha\beta}\psi^{(\mu)}_s\right|^2$$

$$\omega_{\mathrm{conv}} = \frac{1}{2}\sum_{s,s',\kappa}\left|\int d^3x\left(\alpha\overline{\psi}^{(e)}_{\kappa,s'}\mathcal{K}\psi^{(\mu)}_s + \beta\overline{\psi}^{(e)}_{\kappa,s'}\mathcal{K}_0\psi^{(\mu)}_s\right)\right|^2$$

- The nuclear matrix elements $\alpha = \langle N|\overline{q}q|N\rangle$ and $\beta = \langle N|\overline{q}\gamma_0 q|N\rangle$ contributing to coherent conversion have already been computed (e.g., Kosmas *et al*. 2001)

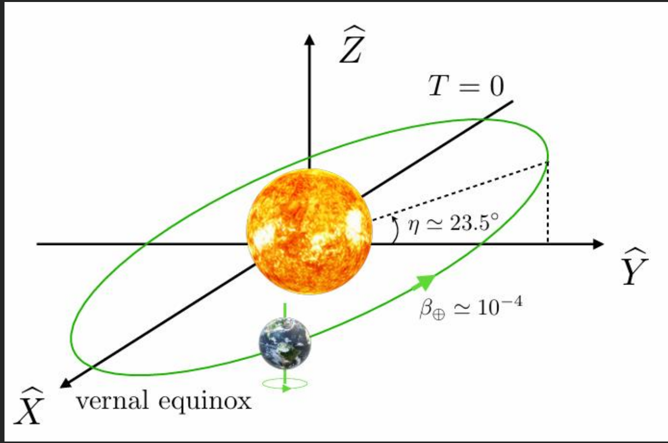
Consequences of Lorentz Violation

- Lorentz violation means location, time, and orientation of the experiment matter
    - Leading effect is rotation of Earth with respect to fixed SME background coefficients
- Conversion rates easiest to calculate in lab frame in spherical coordinates
- Bounds have to be translated to a standard reference frame to be meaningful



Sun-Centered Frame

- Standard reference frame for LV studies
  - Z-axis towards celestial north
  - X-axis from Earth to Sun at 2000 vernal equinox
- Rotation from SCF to lab-frame coefficients is time-dependent and relies on laboratory location and apparatus orientation



Obtaining Bounds

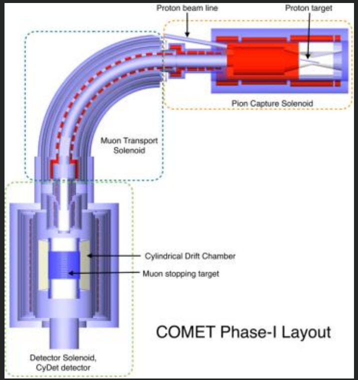
- Bounds are taken one-at-a-time on the various components of each relevant SME coefficient in the sun-centered frame
- The conversion frequency can be decomposed into a time-independent component and time-dependent harmonics in the sidereal frequency of the Earth
  - Our results are time-averaged, since we use only the time-integrated experimental limit on the rate
- Sidereal analysis of time-stamped data would provide greater sensitivity to some components of the coefficients
  - Sidereal oscillations in data could provide “smoking gun” signal of LV

Constraints and Projections

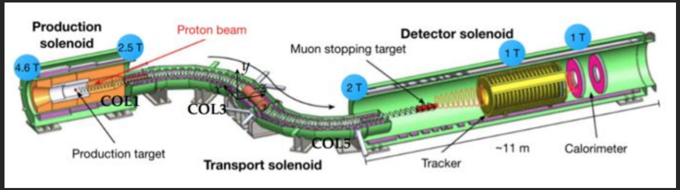
Coefficient Type	SINDRUM II Constraints (90% C.L.)	COMET Phase I (projected)	Mu2e Run I (projected)
Electromagnetic	$< 6 - 8 \text{ x } 10^{-12}\ \text{GeV}^{-1}$	$< 0.9 - 1 \text{ x } 10^{-12}\ \text{GeV}^{-1}$	$< 0.2 \text{ x } 10^{-12}\ \text{GeV}^{-1}$
Quark-Lepton, $\overline{\psi_{u,d}}\psi_{u,d}$	$< 6 - 7 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 1 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 0.2 \text{ x } 10^{-13}\ \text{GeV}^{-2}$
Quark-Lepton, $\overline{\psi_s}\psi_s$	$< 10 - 15 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 2 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 0.4 \text{ x } 10^{-13}\ \text{GeV}^{-2}$
Quark-Lepton, $\overline{\psi_{u,d}}\gamma_0\psi_{u,d}$	$< 20 - 30 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 4 \text{ x } 10^{-13}\ \text{GeV}^{-2}$	$< 0.7 \text{ x } 10^{-13}\ \text{GeV}^{-2}$

Outlook

- Better constraints on EM operators by about an order of magnitude already obtained from MEG (Kostelecký, Passemar, Sherrill 2022)
- MEG II will keep $\mu \to e\gamma$ competitive for the EM operators in the short term; final results from COMET and Mu2e could surpass those bounds
- Quark-lepton operators constrained uniquely in this channel (first bounds); nuclear conversion complementary to other channels
- With their full sensitivities, COMET and Mu2e should improve bounds about two orders beyond SINDRUM II



COMET Collaboration (2020)



Mu2e Collaboration (2023)

Thank you!

Backup

Current/Future $\mu \to e$ Conversion Limits

Channel	Current Limit: BR<	Future Sensitivity: BR<
$\mu \to e\gamma$	$4.2 \text{ x } 10^{-13}$ (MEG)	$6 \text{ x } 10^{-14}$ (MEG II)
$\mu \to 3e$	$1.0 \text{ x } 10^{-12}$ (SINDRUM)	10^{-16} (Mu3e)
$\mu N \to eN$	$7 \text{ x } 10^{-13}$ (SINDRUM II)	10^{-14} (DeeMe) $7 \text{ x } 10^{-15}$ / $7 \text{ x } 10^{-17}$ (COMET) $6.2 \text{ x } 10^{-16}$ / $8 \text{ x } 10^{-17}$ (Mu2e)

Coordinate Information

The transformation to the stationary SCF is accomplished, at lowest order, by applying the rotation

$$\mathcal{R}_{\text{tot.}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\chi\cos\omega_\oplus T_\oplus & \cos\chi\sin\omega_\oplus T_\oplus & -\sin\chi \\ -\sin\omega_\oplus T_\oplus & \cos\omega_\oplus T_\oplus & 0 \\ \sin\chi\cos\omega_\oplus T_\oplus & \sin\chi\sin\omega_\oplus T_\oplus & \cos\chi \end{pmatrix}.$$

to each spatial index. Here, χ is the colatitude, $\omega_\oplus$ is the rotational frequency of Earth, and $T_\oplus$ is local sidereal time, $T_\oplus \approx T - \frac{66.25^\circ - \lambda}{360^\circ}(23.934 \text{ hrs})$ for longitude λ. A final improper rotation sets the z-axis along the direction of the beamline; ψ is the angle of the laboratory z-axis, measured north of east.

Experiment	χ	λ	T_0	ψ	c
SINDRUM II	42.5°	8.2°	3.86 h	242°	0.44
COMET	53.6°	140.6°	−4.94 h	188°	0.34
Mu2e	48.2°	−88.2°	10.27 h	122°	0.50

Harmonic Dependences

$$
\begin{aligned}
\omega_{\text{conv}} \supset\ & (\zeta^{(0)}_{TJ} + \zeta^{(2c)}_{TJ} c_{2\omega_\oplus T_\oplus} + \zeta^{(2s)}_{TJ} s_{2\omega_\oplus T_\oplus}) \\
& \quad \times (|(m^{(5)}_F)^{TJ}_{\mu e}|^2 + |(m^{(5)}_{5F})^{TJ}_{\mu e}|^2) \\
& + (\zeta^{(0)}_{\alpha TJ} + \zeta^{(2c)}_{\alpha TJ} c_{2\omega_\oplus T_\oplus} + \zeta^{(2s)}_{\alpha TJ} s_{2\omega_\oplus T_\oplus} \\
& \quad + \zeta^{(4c)}_{\alpha TJ} c_{4\omega_\oplus T_\oplus} + \zeta^{(4s)}_{\alpha TJ} s_{4\omega_\oplus T_\oplus}) \\
& \quad \times (|(a^{(5)}_F)^{\alpha TJ}_{\mu e}|^2 + |(b^{(5)}_F)^{\alpha TJ}_{\mu e}|^2) \\
& + (\zeta^{(0)}_{\alpha\beta TJ} + \zeta^{(2c)}_{\alpha\beta TJ} c_{2\omega_\oplus T_\oplus} + \zeta^{(2s)}_{\alpha\beta TJ} s_{2\omega_\oplus T_\oplus} \\
& \quad + \zeta^{(4c)}_{\alpha\beta TJ} c_{4\omega_\oplus T_\oplus} + \zeta^{(4s)}_{\alpha\beta TJ} s_{4\omega_\oplus T_\oplus}) |(H^{(5)}_F)^{\alpha\beta TJ}_{\mu e}|^2
\end{aligned}
$$

$$
\begin{aligned}
\omega_{\text{conv}} \supset\ & ((\zeta_q)^{(0)}_\alpha + (\zeta_q)^{(2c)}_\alpha c_{2\omega_\oplus T_\oplus} + (\zeta_q)^{(2s)}_\alpha s_{2\omega_\oplus T_\oplus}) \\
& \quad \times (|(k^{(6)}_{SV})^{\alpha}_{qqe\mu}|^2 + |(k^{(6)}_{SA})^{\alpha}_{qqe\mu}|^2) \\
& + (\zeta^0_q)^{(0)}_T (|(k^{(6)}_{VS})^{T}_{qqe\mu}|^2 + |(k^{(6)}_{VP})^{T}_{qqe\mu}|^2) \\
& + \big[((\zeta_q)^{(0)}_{TJ} + (\zeta_q)^{(2c)}_{TJ} c_{2\omega_\oplus T_\oplus} + (\zeta_q)^{(2s)}_{TJ} s_{2\omega_\oplus T_\oplus}) \\
& \quad \times |(k^{(6)}_{ST})^{TJ}_{qqe\mu}|^2 + (TJ \to JZ)\big] \\
& + \big[(\zeta_q)^{(0)}_{TZ} |(k^{(6)}_{ST})^{TZ}_{qqe\mu}|^2 + (TZ \to JK)\big] \\
& + ((\zeta^0_q)^{(0)}_{T\alpha} + (\zeta^0_q)^{(2c)}_{T\alpha} c_{2\omega_\oplus T_\oplus} + (\zeta^0_q)^{(2s)}_{T\alpha} s_{2\omega_\oplus T_\oplus}) \\
& \quad \times (|(k^{(6)}_{VV})^{T\alpha}_{qqe\mu}|^2 + |(k^{(6)}_{VA})^{T\alpha}_{qqe\mu}|^2) \\
& + \big[((\zeta^0_q)^{(0)}_{TTJ} + (\zeta^0_q)^{(2c)}_{TTJ} c_{2\omega_\oplus T_\oplus} + (\zeta^0_q)^{(2s)}_{TTJ} s_{2\omega_\oplus T_\oplus}) \\
& \quad \times |(k^{(6)}_{VT})^{TTJ}_{qqe\mu}|^2 + (TTJ \to TJZ)\big] \\
& + \big[(\zeta^0_q)^{(0)}_{TTZ} |(k^{(6)}_{VT})^{TTZ}_{qqe\mu}|^2 + (TTZ \to TJK)\big]
\end{aligned}
$$

Constraints and Projections

Coefficients	SINDRUM II	COMET	Mu2e
$\lvert(m_F^{(5)})_{\mu e}^{TJ}\rvert, \lvert(m_{5F}^{(5)})_{\mu e}^{TJ}\rvert$	< 8	< 1	< 0.2
$\lvert(m_F^{(5)})_{\mu e}^{TZ}\rvert, \lvert(m_{5F}^{(5)})_{\mu e}^{TZ}\rvert$	< 8	< 0.9	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{TTJ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{TTJ}\rvert$	< 6	< 1	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{TTZ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{TTZ}\rvert$	< 6	< 0.9	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{JTJ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{JTJ}\rvert$	< 6	< 1	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{JTK}\rvert, \lvert(b_F^{(5)})_{\mu e}^{JTK}\rvert$	< 8	< 1	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{JTZ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{JTZ}\rvert$	< 8	< 0.9	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{ZTJ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{ZTJ}\rvert$	< 8	< 1	< 0.2
$\lvert(a_F^{(5)})_{\mu e}^{ZTZ}\rvert, \lvert(b_F^{(5)})_{\mu e}^{ZTZ}\rvert$	< 7	< 0.9	< 0.2
$\lvert(H_F^{(5)})_{\mu e}^{TJTJ}\rvert, \lvert(H_F^{(5)})_{\mu e}^{JZTK}\rvert$	< 7	< 1	< 0.2
$\lvert(H_F^{(5)})_{\mu e}^{TJTK}\rvert, \lvert(H_F^{(5)})_{\mu e}^{JZTJ}\rvert$	< 6	< 1	< 0.2
$\lvert(H_F^{(5)})_{\mu e}^{TJTZ}\rvert, \lvert(H_F^{(5)})_{\mu e}^{JZTZ}\rvert$	< 6	< 0.9	< 0.2
$\lvert(H_F^{(5)})_{\mu e}^{TZTJ}\rvert, \lvert(H_F^{(5)})_{\mu e}^{XYTJ}\rvert$	< 6	< 1	< 0.2
$\lvert(H_F^{(5)})_{\mu e}^{TZTZ}\rvert, \lvert(H_F^{(5)})_{\mu e}^{XYTZ}\rvert$	< 7	< 0.9	< 0.2

d=5 in units of $10^{-12}\mathrm{GeV}^{-1}$

d=6 in units of $10^{-13}\mathrm{GeV}^{-2}$

$J \in \{X, Y\}$

Coefficients	SINDRUM II	COMET	Mu2e
$\lvert(k_{SV}^{(6)})_{uue\mu}^{T}\rvert, \lvert(k_{SA}^{(6)})_{uue\mu}^{T}\rvert$	< 6	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{uue\mu}^{J}\rvert, \lvert(k_{SA}^{(6)})_{uue\mu}^{J}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{uue\mu}^{Z}\rvert, \lvert(k_{SA}^{(6)})_{uue\mu}^{Z}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{dde\mu}^{T}\rvert, \lvert(k_{SA}^{(6)})_{dde\mu}^{T}\rvert$	< 6	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{dde\mu}^{J}\rvert, \lvert(k_{SA}^{(6)})_{dde\mu}^{J}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{dde\mu}^{Z}\rvert, \lvert(k_{SA}^{(6)})_{dde\mu}^{Z}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{SV}^{(6)})_{sse\mu}^{T}\rvert, \lvert(k_{SA}^{(6)})_{sse\mu}^{T}\rvert$	< 10	< 2	< 0.4
$\lvert(k_{SV}^{(6)})_{sse\mu}^{J}\rvert, \lvert(k_{SA}^{(6)})_{sse\mu}^{J}\rvert$	< 15	< 2	< 0.4
$\lvert(k_{SV}^{(6)})_{sse\mu}^{Z}\rvert, \lvert(k_{SA}^{(6)})_{sse\mu}^{Z}\rvert$	< 15	< 2	< 0.4
$\lvert(k_{VS}^{(6)})_{uue\mu}^{T}\rvert, \lvert(k_{VP}^{(6)})_{uue\mu}^{T}\rvert$	< 30	< 4	< 0.8
$\lvert(k_{VS}^{(6)})_{dde\mu}^{T}\rvert, \lvert(k_{VP}^{(6)})_{dde\mu}^{T}\rvert$	< 30	< 4	< 0.7
$\lvert(k_{ST}^{(6)})_{uue\mu}^{TJ}\rvert, \lvert(k_{ST}^{(6)})_{uue\mu}^{JZ}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{ST}^{(6)})_{uue\mu}^{TZ}\rvert, \lvert(k_{ST}^{(6)})_{uue\mu}^{XY}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{ST}^{(6)})_{dde\mu}^{TJ}\rvert, \lvert(k_{ST}^{(6)})_{dde\mu}^{JZ}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{ST}^{(6)})_{dde\mu}^{TZ}\rvert, \lvert(k_{ST}^{(6)})_{dde\mu}^{XY}\rvert$	< 7	< 1	< 0.2
$\lvert(k_{ST}^{(6)})_{sse\mu}^{TJ}\rvert, \lvert(k_{ST}^{(6)})_{sse\mu}^{JZ}\rvert$	< 15	< 2	< 0.4
$\lvert(k_{ST}^{(6)})_{sse\mu}^{TZ}\rvert, \lvert(k_{ST}^{(6)})_{sse\mu}^{XY}\rvert$	< 15	< 2	< 0.4
$\lvert(k_{VV}^{(6)})_{uue\mu}^{TT}\rvert, \lvert(k_{VA}^{(6)})_{uue\mu}^{TT}\rvert$	< 20	< 4	< 0.7
$\lvert(k_{VV}^{(6)})_{uue\mu}^{TJ}\rvert, \lvert(k_{VA}^{(6)})_{uue\mu}^{TJ}\rvert$	< 25	< 4	< 0.7
$\lvert(k_{VV}^{(6)})_{uue\mu}^{TZ}\rvert, \lvert(k_{VA}^{(6)})_{uue\mu}^{TZ}\rvert$	< 25	< 4	< 0.7
$\lvert(k_{VV}^{(6)})_{dde\mu}^{TT}\rvert, \lvert(k_{VA}^{(6)})_{dde\mu}^{TT}\rvert$	< 20	< 4	< 0.7
$\lvert(k_{VV}^{(6)})_{dde\mu}^{TJ}\rvert, \lvert(k_{VA}^{(6)})_{dde\mu}^{TJ}\rvert$	< 20	< 4	< 0.7
$\lvert(k_{VV}^{(6)})_{dde\mu}^{TZ}\rvert, \lvert(k_{VA}^{(6)})_{dde\mu}^{TZ}\rvert$	< 20	< 4	< 0.7
$\lvert(k_{VT}^{(6)})_{uue\mu}^{TTJ}\rvert, \lvert(k_{VT}^{(6)})_{uue\mu}^{TJZ}\rvert$	< 25	< 4	< 0.7
$\lvert(k_{VT}^{(6)})_{uue\mu}^{TTZ}\rvert, \lvert(k_{VT}^{(6)})_{uue\mu}^{TXY}\rvert$	< 25	< 4	< 0.7
$\lvert(k_{VT}^{(6)})_{dde\mu}^{TTJ}\rvert, \lvert(k_{VT}^{(6)})_{dde\mu}^{TJZ}\rvert$	< 20	< 4	< 0.7
$\lvert(k_{VT}^{(6)})_{dde\mu}^{TTZ}\rvert, \lvert(k_{VT}^{(6)})_{dde\mu}^{TXY}\rvert$	< 20	< 4	< 0.7