CompEx – II
A pathway in search of BSM physics

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Lorentz Symmetry?

But what is Lorentz symmetry?

That all physical laws are same for inertial frames of reference.


Naturally gives rise to:

Rotational Symmetry: Conservation of Angular Momentum

Space Translational Symmetry: Conservation of Linear Momentum

Time Translational Symmetry: Conservation of Energy

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\( \mathbf{K} \) could break Lorentz symmetry.
- Breaks rotational symmetry

\[
E_\gamma = (1 - \mathbf{K} \cdot \hat{p}) p_\gamma + O(\kappa^2)
\]

The dispersion relation is no longer simply defined by the magnitude of the momentum.

Such a \( \mathbf{K} \) field can also cause modulations of a physical quantity arising from the interaction with this field.
2. Since the cross sections are proportional to actual $(P_e P_\gamma)$, measured asymmetry $(A)$ is proportional to actual $(P_e P_\gamma)$.

**Measurement Technique**

1. Calculate the physics asymmetry for completely polarized electron and photon beam.
2. Since the cross sections are proportional to $(P_e P_\gamma)$, measured asymmetry $(A)$ is proportional to actual $(P_e P_\gamma)$.
3. Helicity of the electron beam switched in order to measure the asymmetry.
Electron Detector
1. A diamond detector is used to measure the cross section of Compton scattering.
2. Each strip collects some number of electrons in a given time period.
3. Compton cross section drops at low energies and Qweak ran at a low energy of 1.165 GeV Luminosity enhanced by using Fabry-Perot cavity.
How do we measure speed of light?

\[
\frac{d\sigma}{d\rho} = 2\pi r_e^2 a \left[ \frac{\rho^2 (1-a)^2}{1-\rho(1-a)} + 1 + \left( \frac{1-\rho(1+a)}{1-\rho(1-a)} \right)^2 \right]
\]

\[
A_L(\rho) = \frac{2\pi r_e^2 a}{d\sigma/d\rho} (1-\rho(1+a)) \left[ 1 - \frac{1}{(1-\rho(1-a))^2} \right]
\]

• Compton Cross-Section is a well known number
• Longitudinal asymmetry could be calculated as function of scattered photon energy

• Modified (by \( \vec{k} \)) dispersion relation has sensitivity amplified by the squared of the boost.

\[
p'_\gamma = p_{\gamma}^{CE} \left[ 1 + \frac{2\gamma^2}{(1+4\gamma p_{\gamma}/m)^2} \vec{k} \cdot \hat{p} \right]
\]

Along with conservation of energy, the longitudinal asymmetry then becomes a function of:
\( \{ n, N_{CE}, P_e P_\gamma \} \)


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How do we measure speed of light?

Along with conservation of energy, the longitudinal asymmetry then becomes a function of:

\[ \{n, N_{CE}, P_e P_\gamma\} \]
$\rho(n) \sim \rho[1 + 2\gamma^2 f(x, \theta)\vec{k} \cdot \hat{p}]$

$n \sim [1 + \vec{k} \cdot \hat{p}]$

Fig. Value of ‘n-1’ plotted with data rolled into modulo sidereal day
The constraint on amplitude of sidereal modulation of (n-1) term gives (95% C.L.):

\[
\sqrt{\kappa_x^2 + \kappa_y^2} < 8.6 \times 10^{-10}
\]
3 Constrains on $(n-1)$

- Cherenkov Radiation
  $$|n - 1| < \frac{m^2_{p(e)}}{2E^2_{p(e)} - 2\omega\gamma E_{p(e)} - m^2_{p(e)}}$$

- Pair Production
  $$|n - 1| < \frac{2m^2_e}{\omega^2_{\gamma}}$$

- Gamma Ray Burst
  $$|n - 1| < \Delta tc/D$$
Constrains on $(n-1)$

- **HESS**: 100 TeV
- **HEGRA**: 22 TeV
- **OMG**: $p^+\rightarrow 10^{20}$ eV
Here asymmetry arises from flipping the polarization state of the laser instead of flipping the electron beam helicity.
JLab: Hall-A Compton Polarimeter


Error Source | Fractional Error (%)
--- | ---
Statistical | 2.1
Absolute Normalization of the Kinematic Factor | 0.5
Beam (second order) | 0.4
Beam polarization | 0.4
e + p(+)γ → e + X(+)γ | 0.4
Beam (position, angle, energy) | 0.4
Beam (intensity) | 0.3
e + p(+)γ → e + p(+)γ | 0.3
γ(+)p → (π, μ, K) + X | 0.3
Transverse polarization | 0.2
Neutral background (soft photons, neutrons) | 0.1
Total systematic | 1.1

Experiment (*actual) | physics asymmetry | stat. error | sys. error due to beam | limits on position differences | limits on angle differences | limits on diameter differences
--- | --- | --- | --- | --- | --- | ---
Qweak | -288 ppb | 5 ppb | ±1.4 ppb | < 2 nm | 30 mrad | < 7 x 10^-3
12 GeV Moller | 36 ppb | 0.6 ppb | ±0.05 ppb | ~ 0.5 mm | 0.05 mrad | < 10^-5

~2020: @x10 Energy, x2 the precision

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A constraint on \((n-1)\) can be translated to a lower limit on the scale of new physics, \(M_{QG}\).

1\(^{st}\) order LIV:

\[
\frac{\nu_\gamma}{c} \sim 1 + \frac{E_\gamma}{M_{QG}} + \sigma(E_\gamma^2)
\]

\((n - 1) \sim \frac{E_\gamma}{M_{QG}}\)

After rolling in the increase in {electron beam energy, precision (laser power), statistics}:
Compton Scattering with Un-polarized electrons

\[ n_L(\omega_m) - n_R(\omega_m) = \frac{(1 + x)^2}{\gamma^2} A \]

\[ A = \frac{\omega_m^L - \omega_m^R}{\omega_m^L + \omega_m^R} \]

\[ A = \frac{8\gamma^4 \omega_0 \sin^2 \left( \frac{\theta_0}{2} \right)}{(1 + x)^3} \frac{\zeta}{M_{QG}} \]

Phys. Rev. Lett. 109, 141103:
“for sufficiently high values of $\gamma$ the Planck-scale space birefringence generates a measurable asymmetry”
Here asymmetry arises from flipping the polarization state of the laser instead of flipping the electron beam helicity.
Perform the experiment using a light source unpolarised beam

In order to optimize the beam parameters, sensitivity depends upon:

- Electron Energy
- Beam Current
- Laser Power
- # events, Length of data collection
Perform the experiment using a light source unpolarised beam.

In order to optimize the beam parameters, sensitivity depends upon:

- Electron Energy (CERN secondaries)
- Beam Current **Given: No control over**
- Laser Power
- # events, Length of data collection

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Energy (GeV)</th>
<th>Circumf. (m)</th>
<th>Current (mA)</th>
<th>Emittance (nmrad)</th>
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<tr>
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<td>Japan</td>
<td>8</td>
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<td>200</td>
<td>3.8</td>
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<tr>
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<td>2304</td>
<td>100</td>
<td>1</td>
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<td>MAX-IV</td>
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<td>500</td>
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<td>3</td>
<td>518.1</td>
<td>500</td>
<td>1.6</td>
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<td>565.3</td>
<td>500</td>
<td>3.22</td>
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<td>ALBA</td>
<td>Spain</td>
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<td>268.8</td>
<td>200</td>
<td>4.33</td>
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<td>SSRF</td>
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<td>500</td>
<td>2.61</td>
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<tr>
<td>ASP</td>
<td>Australia</td>
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<td>216.28</td>
<td>500</td>
<td>7.12</td>
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<tr>
<td>SIRIUS</td>
<td>Brazil</td>
<td>3</td>
<td>518.4</td>
<td>500</td>
<td>0.25</td>
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<td>SOLEIL</td>
<td>France</td>
<td>2.75</td>
<td>354</td>
<td>500</td>
<td>3.68</td>
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</tbody>
</table>

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CompEx-2

![Graph showing energy shifts for different accelerators]

- **CERN**: 100 GeV
- **PETRA**: 6 GeV
- **APS**: 7 GeV
- **ILC**: 250 GeV
- **Spring-8**: 8 GeV

Log$_{10}(\zeta/m)$ vs Log$_{10}(A \times 1500$ MeV Energy Shift)
The increase in sensitivity comes from:

- Gain in electron beam energy
- Top-up mode of light sources: Increase in statistical precision of asymmetry arising from increased statistics coming from higher beam current.

CERN ≈ 1 pA

APS ≈ 0.1 A
Summary

CompEx-1a: Proof of Concept

CompEx-1b: Physics Result

CompEx-2: Quantum Gravity

More results in fundamental symmetry tests coming soon...

Ask me about: nEDM, Neutron Oscillation, NeX, Axions (Leptophilic $A'$, QCD – Gluon coupled Axion)...

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With significant inputs from D. Dutta...
Lorentz Symmetry is a commonality between all the field theories.

image courtesy of: http://www.exphy.uni-duesseldorf.de/ResearchInst/FundPhys.html

Lorentz Symmetry (Special Relativity)
But no known interaction or process has ever shown evidence of breaking Lorentz symmetry.
Any process that breaks Lorentz symmetry will belong to physics BSM.
C, P & T Symmetries

C: Charge Conjugation

P: Parity Inversion

T: Time Inversion

Courtesy: F. Tanedo, Quantum Diaries, 2005
CPT Symmetry


Some BSM Models violate CPT Symmetry

Quantum Gravity

Deformed Poincare Symmetry
Michelson – Morley Interferometry

- Was performed to test ether, the media in which light can propagate.
- No sidereal modulation was detected, which was interpreted as absence of ether.
- But also points towards a confirmation of LI.

www.mohanmurthy.com /teaching/ethznp
\[ \mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \mathcal{L}_{LV} + \cdots \]

Lorentz Conserving  Lorentz Violating
$\mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \mathcal{L}_{LV} + \cdots$

- LV interactions are constrained by a set of parameters.
- These constraints can be obtained from all the SM & GR sectors and uniquely for each particle in the SM.

Kostelecky & Russell RMP 83, 11 (2011)
Variations in Speed of Light

Einstein’s SR
Speed of light is constant in all inertial reference frames.

Deviations of speed of light w.r.t. spatial orientation provides one of the best test of LI.
Variations in Speed of Light

Einstein’s SR

*Speed of light is constant in all inertial reference frames.*

Deviations of speed of light w.r.t. spatial orientation provides one of the best test of LI.
Variations in Speed of Light

*Speed of light is a constant w.r.t the energy of the photon*

- Look for difference between the time of arrival of hard and soft photons in GRBs.
- Gives a measure of the scale of LV physics, $M_{LV} > \Delta E \cdot D / \Delta t$, \{with $(n-1)\sim E / M_{LV}\}$

arXiv:0910.2459
Compton Polarimeter

Q-Weak ($\sin^2\theta_W$) Experiment required sub % level precision on continuous electron polarimetry

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Contribution to $\Delta A_{\text{phys}}/A_{\text{phys}}$</th>
<th>Contribution to $\Delta Q^p_W / Q^p_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counting Statistics</td>
<td>2.1%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Hadronic structure</td>
<td>--</td>
<td>1.5%</td>
</tr>
<tr>
<td>Beam polarimetry</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Absolute $Q^2$</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.7%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Helicity-correlated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam properties</td>
<td>0.5%</td>
<td>0.8%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2.5%</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

$\delta A_{PV} \approx \pm 2.5\%$

$\Rightarrow \delta Q^p_W \approx \pm 4.2\%$

$\Rightarrow \delta (\sin^2\theta_W) \approx \pm 0.3\%$
Compton Polarimeter


\[ e(E) + \gamma (k) \rightarrow e'(E') + \gamma(k') \]


Prototype Testing
Longitudinal asymmetry could be calculated as a function of scattered photon energy. Compton Cross-Section is a well-known number. Longitudinal asymmetry could be calculated as a function of scattered photon energy. The parameter of relative scattered photon energy can be incorporated with ‘n’.

\[
\rho(n) = \frac{\omega(n)}{\omega_{\text{max}}(n)} = \rho \left[ 1 + \frac{2\gamma_0^2(n-1)(1+\gamma_0^2\theta^2)}{(1+x+\gamma_0^2\theta^2)^2} \right] \left[ 1 + \frac{2\gamma_0^2(n-1)}{(1+x)^2} \right]
\]

Along with conservation of energy, the longitudinal asymmetry then becomes a function of:

\{n, N_{CE}, P_eP_{\gamma}\}

How do we measure speed of light?

Along with conservation of energy, the longitudinal asymmetry then becomes a function of:

\[ \{n, N_{CE}, P_e P_\gamma\} \]
Here asymmetry arises from flipping the polarization state of the laser instead of flipping the electron beam helicity.
Applying the fit involving \( \{n, N_{CE}, P_e P_\gamma \} \) to JLab Hall-C data.
Proof of concept: MPLA 31 (2016) 38

Applying the fit involving \( \{n, N_{CE}, P_{e}P_{\gamma}\} \) to JLab Hall-C data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n-1 )</td>
<td>( &lt; 1.4 \times 10^{-8} )</td>
</tr>
<tr>
<td>( N_{CE} )</td>
<td>( 54.56 \pm 0.57 )</td>
</tr>
<tr>
<td>( P_{e} )</td>
<td>( 89.23 \pm 0.71 % )</td>
</tr>
</tbody>
</table>
Is the polarization extracted from the 3 parameter fit consistent?:
PRX 6 011013 (2016)

Consistent with $p_e = 89\%$, extracted from the 3 parameter fit.
CompEx-1a: Sidereal Modulation

\[ \rho(n) \sim \rho\left[1 + 2\gamma^2 f(x, \theta)\vec{k}.\hat{p}\right] \quad \text{and} \quad n \sim [1 + \vec{k}.\hat{p}] \]

Fig. Value of ‘n’ plotted for each run #
CompEx-1a: Sidereal Modulation

$$\rho(n) \sim \rho[1 + 2\gamma^2 f(x, \theta) \vec{k} \cdot \hat{p}] \quad n \sim [1 + \vec{k} \cdot \hat{p}]$$

Fig. Value of ‘n-1’ plotted with data rolled into modulo sidereal day

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$&lt; 1.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>B</td>
<td>$&lt; 0.38 \times 10^{-10}$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>1.24</td>
</tr>
</tbody>
</table>
But JLab Hall-C Compton measurement is not the most sensitive one, mostly owing to QWeak 1 GeV electron beam energy.

ESRF uses Compton backscattered photons from 6 GeV electrons.
But JLab Hall-C Compton measurement is not the most sensitive one, mostly owing to QWeak 1 GeV electron beam energy.

$$\sqrt{\kappa_x^2 + \kappa_y^2} < 1.6 \times 10^{-14}$$

ESRF uses Compton backscattered photons from 6 GeV electrons.
Putting it in perspective...

- Cherenkov Radiation
- Pair Production
- Gamma Ray Burst
String theory (and loop quantum gravity...) predicts dependence of speed of light w.r.t. the energy of the photon.

\[(n - 1) \sim \frac{E_Y}{M_{QG}} = \frac{\zeta k}{M_{QG}}\]
String theory (and loop quantum gravity…) predicts dependence of speed of light w.r.t. the energy of the photon.

\[
(n - 1) \sim \frac{E\gamma}{M_{\text{QG}}} = \frac{\zeta k}{M_{\text{QG}}}
\]

**Shift in Compton Edge**

\[
\omega_m(n) - \omega_m(1) = \frac{32\gamma^6 \omega_0 \sin^4 \left(\frac{\theta_0}{2}\right)}{(1 + x)^4} \frac{\zeta}{M_{\text{QG}}}
\]

The shift in Compton-edge scales as the 6th power of the boost factor of incident electrons (for low-x) → sufficient to compensate for \( M_{\text{QG}} \).
Birefringence

Compton Scattering with Un-polarized electrons

At the Compton-edge, the scattered photon polarization is completely defined by incident photon polarization.
In a birefringent vacuum the Compton edge energy is laser helicity dependent.

At the Compton-edge, the scattered photon polarization is completely defined by incident photon polarization.

\[ n_L(\omega_m) - n_R(\omega_m) = \frac{(1 + x)^2}{\gamma^2} A \]

Phys. Rev. Lett. 109, 141103:
“in a birefringent vacuum the Compton edge energy is laser helicity dependent”
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\[
\begin{align*}
  n_L(\omega_m) - n_R(\omega_m) &= \frac{(1 + x)^2}{\gamma^2} A \\
  A &= \frac{\omega_m^L - \omega_m^R}{\omega_m^L + \omega_m^R}
\end{align*}
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Phys. Rev. Lett. 109, 141103: “in a birefringent vacuum the Compton edge energy is laser helicity dependent”
Vetting of Analysis: SLD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-1</td>
<td>$(4.07 \pm 0.05) \times 10^{-13}$</td>
</tr>
<tr>
<td>$N_{CE}$</td>
<td>9.70 ± 0.37</td>
</tr>
<tr>
<td>$P_e P_\gamma$</td>
<td>0.628 ± 0.009</td>
</tr>
</tbody>
</table>

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Fig. Value of ‘n-1’ plotted with data rolled into modulo sidereal day

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$(0.16 \pm 0.02) \times 10^{-8}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$(0.03 \pm 0.20) \times 10^{-9}$</td>
</tr>
<tr>
<td>$\chi^2/\text{ndf}$</td>
<td>1.24 / 22</td>
</tr>
</tbody>
</table>
Holographic Principle: \[ [x, y] = 1 \]

make coordinates and measurements w.r.t. spatial coordinates non-commuting

\[ \sigma_x \propto \frac{1}{\sigma_y}, \text{where } \sigma_x \sim l_p \]

With a Planck length scale sensitivity, we can attempt:

\[
A = \frac{\omega_m^L - \omega_m^R}{\omega_m^L + \omega_m^R} \propto \zeta \\
A' = \frac{\omega_m^R - \omega_m^L}{\omega_m^L + \omega_m^R} \propto \zeta
\]

Both these term are in essence measuring a length scale and if the universe is a hologram, must follow holographic principle and \( \sigma_A \) must anti-correlate with \( \sigma_{A'} \)
\[ \sigma_x \propto \frac{1}{\sigma_y}, \text{ where } \sigma_x \sim \sqrt{10^{-34}} \text{ m @ 0.01 m} \]