What is QFT ?
Beyond Special Relativity

José Luis Cortés (Univ. de Zaragoza)

J. M. Carmona, J. Indurain, J. López-Sarrión, D. Mazón, F. Mercati

Lorentz invariance
as a low energy approximation
in Quantum Field Theory

1. INTRODUCTION

- What is QFT ? (for a particle physicist)
- Why ?
- Beyond this paradigme:

1) Perturbative non-renormalizability of gravitational interaction
2) Quantum space-time ⇒ Beyond Special Relativity
3) Fundamental symmetry tests
4) Deviations from Lorentz symmetry (LV)

⇓

Study the observable effects of and limits on LV

2. QUANTUM GRAVITY ⟹ BEYOND SPECIAL RELATIVITY

Three perspectives on Quantum Gravity:

- Particle physics: spontaneous symmetry breaking
- General relativity: discrete/non-commutative space-time
- Condensed matter: emergent (not fundamental) symmetry

Observations of BSR ⟶ Choice of perspective

3. QG / BSR phenomenology

Possible low energy signatures of QG in :

- Quantum decoherence and state colapse
- Initial cosmological perturbations
- Cosmological variations of couplings
- TeV Black Holes (↔ extra dimensions)
- Violation of discrete symmetries
- Violation of space-time symmetries

LV

3.1 BSR : Simple Models

- QG theory ? $\xrightarrow{?}$ Low energy limit

- Bottom – up approach : experiments ⇆ approaches to QG

- Two steps in the construction of simple models:

  - Kinematics : simplicity + inspiration from QG approaches
  - Dynamics: EFT (?)

    - CC problem
    - UV/IR mixing

BSR $\overset{?}{\rightarrow}$ BEFT

- Kinematic ingredients:

  - Modified dispersion relation :

$$E^2 = p^2 + m^2 + f(p, \mu, M)$$

  - Energy dependence of the velocity:

$$v = \partial E / \partial p \qquad ?$$

  - Modified energy-momentum conservation laws

    - $f = p^3/M$ universal
    - $v = \partial E / \partial p$
    - Standard conservation laws

- Simplest kinematical model:

- Second example : beyond a purely kinematic model

Assume validity of EFT

$\Downarrow$

Helicity dependent modified dispersion relation

Beyond universality but still the simplest choice for velocities and energy-momentum conservation laws

- Beyond simplest models :

  - More general non-universal modified dispersion relations
  - Alternatives for velocity (space-time)
  - Beyond standard conservation laws (non-commutativity)

- Results on and strategies to look for departures from SR

depend on details of the model

3.2 LV versus DSR

- Principle of relativity (RP)
- Isotropy and homogeneity
- Notion of causality

⇒ LORENTZ INVARIANCE

Preferred reference frame → RP lost → LV

Alternatives compatible with relativity principle:

- VSR : isotropy breakdown – new relativity group
- DSR : energy and velocity scale compatible with RP

Non-linear action of Lorentz group in momentum space

Formulation of DSR not complete: dynamics, space-time ?

Problems (ph-consistency, internal consistency) – debate

3.3 Relative Locality

Give up notions of:
- coincidence of events at large distances
- separation of space/momentum in phase space

Non-linear modification of energy-momentum conservation law

$\Updownarrow$

New implementation of translational symmetry

Consistent physical interpretation ?

Role of geometry of momentum space ?

3.4 Phenomenology

- Observations sensitive to possible departures from SR

$$M_{Pl} = \sqrt{\hbar c / G_N} \simeq 1.22 \times 10^{19} GeV/c^2$$

very small corrections → Observable effects

Amplification mechanisms :

- high precision
- accumulative effects
- symmetry tests

- Examples of observations sensitive to Planck scale LV effects :
  - Time of flight: γ-ray bursts (propagation/emission), neutrinos
  - Vacuum birefringence: polarized light/ γ-rays
  - Thresholds: $p\,\gamma \rightarrow p\,\pi$ / $\gamma\,\gamma \rightarrow e^+\,e^-$
  - Forbidden → viable reactions:

    $\gamma \rightarrow e^+\,e^-$ / $e^\pm \rightarrow e^\pm\,\gamma$ / $\nu \longrightarrow \nu\,\nu\,\bar{\nu}$
  - Synchrotron emission affected by LV: Crab nebula
  - Low energy signals: m_ν

    CPTV matter-antimatter asymmetry

    atomic interferometry

4. QFT $\longleftrightarrow$ BSR

- Is it possible to find a QFT including departures from SR and phenomenologically consistent ?

Several attempts to incorporate deviations from SR in QFT:

- Lagrangian with all possible terms violating LI

  with dimension $\leq$ 4 (perturbative renormalizability)

Phenomenogical consistency

FINE TUNING

Extremely small dimensionless coefficients

- perturbative renormalizability $\leftrightarrow$ low energy limit

EFT higher ($>$ 4) dimensional terms

natural suppression $(1/M_{Pl})^n$

- Tree level approximation with D=5,6 LV operators

  Consistent framework $\leftrightarrow$ constraints from observations

- Beyond tree level

  UV divergences $\rightarrow$ D=3,4 LV operators

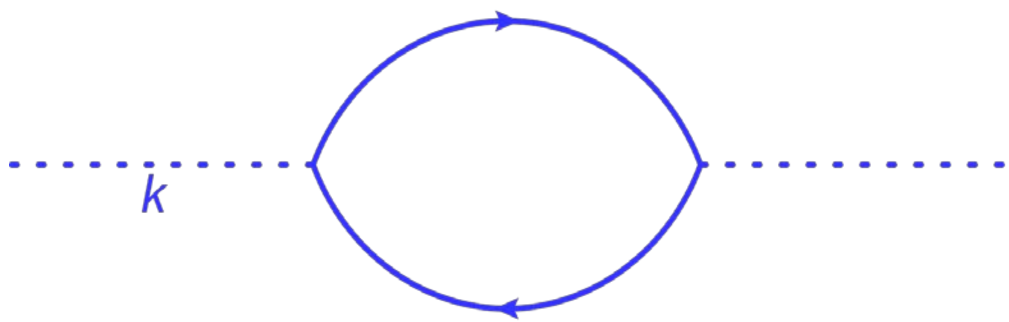
  unsuppressed

Fine tuning SUSY + CPT ?

- Sensitivity of low energy physics to the details (LV) of the high energy theory in a QFT framework

  - Simple illustrative calculation :

    One loop scalar self-energy in Yukawa model



LV of high energy theory modeled by

LV regularization factor $f(|\vec{k}|/\Lambda)$ in fermion propagator

$$\Pi(k) = A + B\,k^2 + \xi k_0^2 + \Pi^{(LI)}(k^2) + \mathcal{O}(1/\Lambda^2)$$

mass | wave function | unsuppressed | suppressed

LI renormalization | LV | LV

$$\xi = \frac{g^2}{6\pi^2}\left[1 + 2\int_0^\infty dx\,x\,f'(x)^2\right]$$

- EFT perspective : Lagrangian must contain all terms consistent with symmetries of high energy theory

- Add LI to the list of fine-tuning problems

- New guide in UV completion

- Physical regularization problem: Is it possible to define QFT as the limit of an ordinary quantum mechanical theory (regularized theory) in which LI is preserved naturally ?

  - In normal methods of regularization the regularized theory is not a normal quantum mechanical theory

LV as a regulator of QFT :

higher spatial derivatives

Physical regularization of QFT ?
LI fine tuning

extend the set of renormalizable QFT
(Horava-Lifshitz) GR fine tuning ?

➢ Non-locality as a way to evade the LI fine tuning problem ?

• Illustrative calculation: scalar self-energy

Regularized fermion propagator : $\vec{p} \to \vec{p}\, f(|\vec{p}|/\Lambda)$

$$\xi = -\frac{g^2}{2\pi^2} \int_0^\infty dx \frac{1}{x f^3(x)} \left[1 - f^2(x) - \frac{2}{3} x f(x) f'(x) - \frac{1}{3} x^2 f'^2(x)\right]$$

LI low energy limit → $\xi = 0$ → Condition on f

(Nonlocal LI fine tuning)

Fermion self-energy → Condition on g

Toy model for LI fine tuning as a guide for identification of high energy theory

order by order / gauge interactions ? / other fine tuning problems

- Non-perturbative formulation of QG free of LI fine tuning problem ?

claim based on two models:

- (Euclidean) lattice regularization with different time and space lattice steps
- LV version of Pauli-Villars regularization

LV suppressed

special features of models

LI fine tuning
argument based on Wilsonian non-perturbative formulation

- Other attempts of extensions of RQFT:

  - Non-commutativity:
    - canonical (LV, IR/UV mixing)
    - other cases of non-commutativity ?

  - QNCFT: free theory, dynamics ?

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