

What if? On the interplay between Serendipity, Intuition and Conjecture

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While the Standard Model is in good shape, there are many reasons to believe it is incomplete. There are high expectations that the LHC will shed light on some well studied possibilities, like technicolor and supersymmetry. Emboldened by this optimism, we consider some non-mainstream ideas that if established would change dramatically the way we view the world.

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1. Introduction: Now and Then

This may seem like an odd title for a talk at this conference, a Summary Talk no less! So before launching into it let me justify this. First, there seems little point in giving an actual summary. There were brilliant progress reports over four days of talks and several summary talks, including the excellent next-to-last talk by Hassan Jawahery. On the theory side, in addition to Vincenzo Cirigliano's status review of charged lepton flavor violation and Thomas Schwetz-Mangold's report on neutrino physics, we had two talks that completely encapsulated the output of flavor physics and CPV(iolation) (in the quark sector), namely, Enrico Lunghi's Lessons from CKM Studies and Zoltan Ligeti's talk on Physics Reach of Future Flavor Experiments. In turn, their reports and summaries rely on much other theory work reported here, *e.g.*, Jure Zupan on CKM angles, Guido Bell on theoretical issues in hadronic decays and Gilad Perez on D decays. Two of my favorite subjects (favorite since I surely owe my tenure job to them) were magnificently covered by old friends Mikolaj Misiak, on radiative B decays, and Thomas Mannel, on determination of V_{cb} and V_{ub} . The interpretation of experimental results is becoming clearer with ever improving Lattice studies, as reported by Jack Laiho and another old friend, Junko Shigemitsu.

Going back to the title... given all these talks, and particularly the comprehensive summaries, I hope you will agree with me that it is unnecessarily repetitious and exceedingly boring to present a grand final "Summary and Conclusions." So I thought it'd be better and more fun to talk about the big picture. And since the LHC is starting to collect data, the time is ripe for that. However, to paraphrase Frank Wilczek, *an unfortunate byproduct of the delays at the LHC and the slow pace of other experiments is that general talks about the grandeur of high energy physics are getting stale*.^[1] While previous installments of FPCP have had few, if any, such grand talks, surely most in the audience had heard some elsewhere. So I would like to take a different track. But before doing so, let me summarize Wilczek's Litany, just to make sure we all agree on the grandeur of our field and its exciting future. On the one hand the standard model of strong and electroweak interactions combined with the CKM framework is fantastically successful. Excellent agreement between theory and experiment severely constraints possible extensions of the model. On the other hand, there are many shortcomings of the model, among them, lack of understanding of the smallness and nature of neutrino masses, no accounting for dark matter and dark energy, no explanation of the smallness of the P and T violating θ parameter, and, of particular interest to FPCPers, no explanation for the triplication of families and a lack of fundamental principles to constrain the numerous masses and mixing angles.¹ But as I said, I want to discuss something else. I am interested in the possibility of paradigm shifting discoveries. I will give you my views on the possibility of such discoveries at the LHC towards the end of the talk. But for now let us recall that our field, both FP and CP in FPCP, resulted from such discoveries.

In 1935 Hideki Yukawa published his theory of mesons, which explained the interaction between protons and neutrons. Muons were discovered by Carl D. Anderson, and student Seth Neddermeyer, in 1936, while they studied cosmic radiation using a cloud chamber. Incidentally, on that same year Anderson received the Nobel prize for the discovery of the positron. In 1947, that's 11 years later, the name changed to mu-meson to differentiate it from the many other hadronic mesons

¹In my talk I let Jim Cronin present these last two shortcomings, by showing an excerpt from his video-recorded talk in [3].

being discovered. The mesotron was initially thought to be the pi-meson of Yukawa. I did not have the time to verify this, but I believe it is true, that Yukawa's work was an important motivation for Anderson's research. The discovery of the muon was a complete surprise. "Who ordered that?" quipped I.I. Rabi. Serendipity certainly played a role in the birth of flavor physics. The discovery was motivated by a theory which was irrelevant but was not quite incorrect.

This is what the title of the talk stands for: conjecture or speculation, right or wrong, can motivate a good experiment. Intuition is needed to follow the right path. Serendipity cannot hurt. As a theorist I find some solace in the possibility that a Theory of Nothing,² combined with Good Luck and a Good Experiment can lead to a Discovery. In the above example the theory was not really wrong, but was irrelevant to the discovery. Correct theoretical ideas can motivate an experiment, of course. Anderson's (1932) discovery of the positron was a direct response to Dirac's (1928) theory. What I am after is that sometimes a theory is just crazy enough that may push us to think about tests we have not carried out. And I am also saying that in some sense this is how our field of FPCP was born.

Serendipity played a role in the discovery of CP violation. That CP is not respected by nature was a surprise to the discoverers. There was no theory at the time, so there was no level of CP violation to aim for. For example, Sakharov's conditions for baryogenesis, which include T-reversal violation, were only published in 1967, four years later than Cronin, Fitch and Turlay submitted their proposal. The experiment was designed to measure better something (regeneration) for which there was a good knowledge base and in passing to improve limits on other impossibilities (like the branching fraction on $K_L \rightarrow \pi\pi$). I find remarkable Cronin's statement[3] that he does not know how they came about with the wrong estimate for sensitivity to CP violation in the proposal. This may be evidence that the experimenters did not take that aspect of the proposal as central. Testing for CP non-invariance was clearly worth doing, but not enough to put much effort into estimating the sensitivity *before* the project was approved. We can draw many other examples from history, not necessarily from FPCP. I will mention only one more. The proposal of Grand-Unified theories gave rise to a race to detect proton decay. As it turns out, as you all know, the theory is wrong. To be precise, the experiments were designed to test what we now call "minimal non-SUSY SH5." They managed to rule it out, well before electroweak precision experiments demonstrated that the couplings do not quite unify. But the experiments, it was soon discovered, make for wonderful neutrino telescopes, and made a number of remarkable discoveries, among them, the detection of neutrinos from supernova 1987a, and the oscillation of atmospheric neutrinos.

So I propose to you to take a sampling of non-mainstream, almost surely wrong, ideas. Some have well motivated theory. Some don't. The main criterion is that confirmation of any would result in a paradigm shift.³ Because of time limitations I just selected a few examples; this is not intended to be a comprehensive presentation. Also, I do not consider some of our favorite extensions of the SM to be paradigm shifting: in models like the MSSM, horizontal gauged symmetry, technicolor, unphysics, Little Higgs, etc, the basic tenets remain intact. Sure, these models require additional fields and interactions and it would be exciting and interesting to find out that nature is like any one of these. But the basic principles of modern particle physics, *e.g.*, that physics is described by

²By which I mean a model of nature that happens to be wrong because it does not describe reality; see also [2].

³From Wikipedia: "Paradigm shift . . . is the term first coined by Thomas Kuhn in his influential book *The Structure of Scientific Revolutions* (1962) to describe a change in basic assumptions within the ruling theory of science. "

a local relativistic quantum field theory which yields an analytic, causal, S -matrix, are unchanged. Extra-dimensions is, in my view, paradigm-shifting, and so is string theory. The examples I have chosen to discuss below are, however, less main-stream (or really “out there”).

2. Violation of CPT and/or QM

The CPT Theorem tells us that in a quantum mechanical model of local fields, with dynamics dictated by a hermitian Hamiltonian, one can define a discrete operation CPT that is a symmetry of the model, even when the individual operations C and P may not be well defined. Hence CPT is a symmetry of the SM. But observation of violation of CPT would not only clearly require to amend the SM, but would indicate a violent departure of our current paradigm that insists on describing the world on the basis of local Quantum Field Theory. String theory and loop Quantum Gravity (QG) are but two examples of such violent departures, formulated, in terms of non-local, non-field theories. Generally, theories of QG are expected to violate CPT. The argument is simple, that BHs cannot carry non-gauged conserved numbers, and there is no sense in which CPT can be thought of as a discrete gauge symmetry.

In fact Hawking has argued that Black Holes can introduce a more fundamental departure of the standard paradigm.[8] He proposed a generalization of quantum mechanics that allows pure states to evolve into mixed states. He did this to address problems, like the information paradox, that arise when trying to merge quantum mechanics and general relativity. Page showed that the proposal of Hawking leads to violation of CPT, and similarly for other generalizations of QM.[9] Since QM is very well established, in order to test it one must look for extremely small deviations from its predictions. It is very useful to have some idea of where to look, a testable extension of QM that properly reproduces all existing data to within present precision and accuracy. In 1989 Weinberg proposed a version of quantum mechanics where the algebra of observables, what we usually describe as matrices in Heisenberg’s quantum mechanics, as still forming an algebra but with a product that is no longer associative (and of course, just as in ordinary QM, non-commutative). I will not pursue this further, partly because Weinberg’s formulation is designed to incorporate Galilean invariance, rather than special relativity. There have been other attempts at this, one by Kibble trying to incorporate Lorentz invariance, and I refer you to Ref. [10] for further details and references.

This is an ongoing quest. I will turn to prospects shortly. But Already in 1976 an experiment was conducted to test the validity of QM. It was prompted by Eberhard’s 1972 phenomenological analysis of QM violation in the $K^0 - \bar{K}^0$ system.[11] Of course, no positive signal of violations of QM was reported.[12] This is perhaps an example of bad luck. Or bad intuition, perhaps. But since then the verification of the validity of the SM of electroweak and strong interactions, which is a local QFT, allows us to argue, in retrospect that, that the violations are expected to be characterized by parameters of order $m_K^2/m_{Planck} \sim 10^{-19}$ GeV, below the resolution of those experiments.

I do not intend to review the theory of violations to QM and CPT in general, or even in particular for the neutral K system. But I do want to flash/show a few equations so you get an impression of where modifications to the “normal” case arise, that is to the CPT conserving quantum mechanics.⁴

⁴For derivations and more complete discussion see Refs. [4, 6, 7]

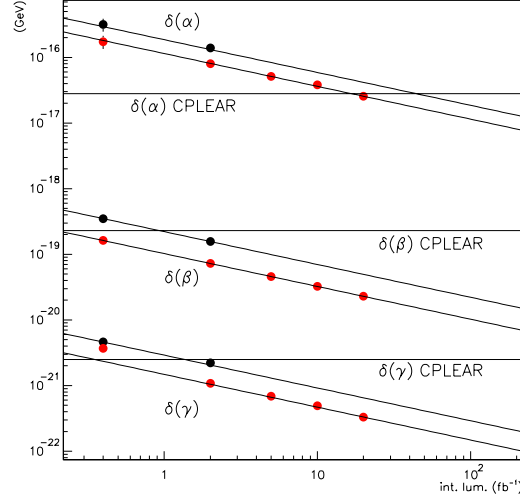


Figure 1: Limits obtained by CPLEAR[14] and the limits that KLOE may be able to obtain on the CPT/QM violating parameters α , β and γ as a function of luminosity. Two cases are shown. The black dots correspond to when using the present inner tracker which has a vertex resolution of 0.9 while the red dots correspond to what would obtain if the inner tracker had a resolution of 0.25. Figure taken from Ref. [13]

The short and long eigenstates are defined familiarly:

$$\begin{aligned} |K_S\rangle &\propto (1 + \varepsilon_S)|K^0\rangle + (1 - \varepsilon_S)|\bar{K}^0\rangle & \varepsilon_S &= \varepsilon + \Delta & m_S - \frac{i}{2}\Gamma_S &= \bar{m} - \frac{i}{2}\bar{\Gamma} - d \\ |K_L\rangle &\propto (1 + \varepsilon_L)|K^0\rangle + (1 - \varepsilon_L)|\bar{K}^0\rangle & \varepsilon_L &= \varepsilon - \Delta & m_L - \frac{i}{2}\Gamma_L &= \bar{m} - \frac{i}{2}\bar{\Gamma} + d \end{aligned} \quad d = \Delta m - \frac{i}{2}\Delta\Gamma$$

The parameter ε is CP odd, CPT even, while Δ is CP even but CPT odd. The masses and widths are given in terms of averages \bar{m} and $\bar{\Gamma}$ and a deviation d with positive real and imaginary parts. The time development in the exclusive charged mode decay

$$R_{+-}(\tau) = \frac{N(K(\tau) \rightarrow \pi^+\pi^-)}{N(K(\tau=0) \rightarrow \pi^+\pi^-)} \quad (2.1)$$

and in the semileptonic decay,

$$\delta(\tau) = \frac{N(K(\tau) \rightarrow \pi^-\ell^+\nu) - N(K(\tau) \rightarrow \pi^+\ell^-\bar{\nu})}{N(K(\tau) \rightarrow \pi^-\ell^+\nu) + N(K(\tau) \rightarrow \pi^+\ell^-\bar{\nu})}, \quad (2.2)$$

two extensively studied quantities that the FPCP audience know well, are given by:

$$\delta(\tau) = \frac{2\cos(\Delta m\tau)e^{-(\bar{\Gamma}+\alpha-\gamma)\tau} + 2\text{Re}\varepsilon_S^-e^{-\Gamma_S\tau} + 2\text{Re}\varepsilon_L^+e^{-\Gamma_L\tau}}{e^{-\Gamma_S\tau} + e^{-\Gamma_L\tau}} \quad (2.3)$$

$$R_{+-}(\tau) = e^{-\Gamma_S\tau} + R_L e^{-\Gamma_L\tau} + 2|\bar{\eta}_{+-}|\cos(\Delta m\tau + \phi_{+-})e^{-(\bar{\Gamma}+\alpha-\gamma)\tau} \quad (2.4)$$

For pure K_L beam,

$$\delta_L = 2\text{Re}\varepsilon_L^+ \quad \text{and} \quad R_L = |\varepsilon_L^-|^2 + \frac{\gamma}{\Delta\Gamma} + 4\frac{\beta}{\Delta\Gamma}\text{Im}\left(\frac{\varepsilon_L^-d}{d^*}\right), \quad (2.5)$$

where $\varepsilon_{L,S}^{\pm} = \varepsilon_{L,S} \pm \frac{\beta}{d}$. The formalism of Refs. [6, 7] has three parameters,⁵ α , β and γ , in addition to the ones in the standard, CPT conserving, normal-QM one. These equations display how they enter into these measurable quantities. Setting these new parameters to zero reduce these expressions to the standard ones. Note that they have units of mass. As mentioned above, if the violations to QM or CPT arise from QG their natural size is 10^{-19} GeV.

Is it crazy to go after this? The plot in Fig. 1, taken from [13], shows the limits obtained by CPLEAR[14] and the limits that KLOE may be able to obtain as a function of luminosity. As you can see KLOE cannot improve on the CPLEAR bound on α , which is more than two orders of magnitude above where effects may be expected to show up. However, KLOE can improve the bounds on β and γ . Note that the bound on γ is already quite stringent. But it may be worth pushing it: one can easily imagine that the order of magnitude estimate of 10^{-19} GeV should be modified by a small coupling constant; after all, the GUT fine structure constant is about $1/40$.

3. Violations to Lorentz Invariance

Establishing the validity of Lorentz invariance (LI) has a long history, going back to the famous Michelson-Morely experiment and many others by their contemporaries. As in the case of departures from Quantum Mechanics one starts by inventing a framework which parametrizes the deviations by a small parameter that one can then bound experimentally (for a review see [15]). But as opposed to the QM case, it is very easy to invent a framework to parametrize deviations from LI: simply take the SM and add terms to the Lagrangian constructed of the same fields but that are not Lorentz invariant. This is conveniently done by introducing would-be tensors and writing Lorentz invariant terms that include these tensors, only we take the tensors to be (coupling) constants, [16] *e.g.*,

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}(k_F)_{\mu\nu\lambda\sigma}F^{\mu\nu}F^{\lambda\sigma}. \quad (3.1)$$

The theory in (3.1) is equivalent to propagation in anisotropic media: the relation between electric displacement, magnetic intensity and electric-magnetic fields differs from that of in-vacuum:

$$\begin{pmatrix} \vec{D} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} 1 + \kappa_{DE} & \kappa_{DB} \\ \kappa_{HE} & 1 + \kappa_{HB} \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix} \quad \text{where} \quad \begin{aligned} \kappa_{DE}^{jk} &= -2k_F^{0j0k}, \\ \kappa_{HB}^{jk} &= \frac{1}{2}\varepsilon^{jpq}\varepsilon^{krs}k_F^{pqrs}, \\ \kappa_{DB}^{jk} &= -\kappa_{HE}^{kj} = \varepsilon^{kpq}k_F^{0j pq}. \end{aligned} \quad (3.2)$$

It is convenient to define combinations of these κ 's that have definite parity and that are either boost invariant or first order in the frame velocity. Here are two of them, the only two that do not produce birefringence: the parity even, boost independent $\tilde{\kappa}_{e-} = \frac{1}{2}(\kappa_{DE} - \kappa_{HB}) - \frac{1}{3}\text{Tr}\kappa_{DE}$, and the parity odd, boost dependent, $\tilde{\kappa}_{o+} = \frac{1}{2}(\kappa_{DB} + \kappa_{HE})$. Astrophysical measurements set bounds on the coefficients I have not written here, through absence of birefringence, at some ridiculously low level, 10^{-32} or so. The rest can be bound in laboratory experiments. The table on next page shows, in units of 10^{-17} , the results of an experiment published earlier this year by a group from Berlin and Bremen.[17] The frequencies of two lasers, each stabilized to one of two orthogonal cavities, are compared during active rotation of their setup. The factor β_{\oplus} , defined to be 10^{-4} , accounts for

⁵Not to be confused with $\phi_{1,2,3}$ of the unitarity triangle!

	Ref. [17]	Ref. [18]
κ_{e-}^{XY}	-0.31 ± 0.73	29 ± 23
κ_{e-}^{XZ}	0.54 ± 0.70	-69 ± 22
κ_{e-}^{YZ}	-0.97 ± 0.74	21 ± 21
$\kappa_{e-}^{XX} - \kappa_{e-}^{YY}$	0.80 ± 1.27	-50 ± 47
κ_{e-}^{ZZ}	-0.04 ± 1.73	1430 ± 1790
$\beta_{\oplus} \kappa_{o+}^{XY}$	-0.14 ± 0.78	-9 ± 26
$\beta_{\oplus} \kappa_{o+}^{XZ}$	-0.45 ± 0.62	-44 ± 25
$\beta_{\oplus} \kappa_{o+}^{YZ}$	-0.34 ± 0.61	-32 ± 23

the Earth's orbital boost. A four year old result by Stanwix *et al* [18] is displayed side by side with this result, of earlier this year, to highlight the pace of progress in the field (also, a comparable result by yet another group was published last year[19]).

The question arises as to what is the expected level of violation? And why would some of the coefficients, the ones that can produce birefringence, automatically vanish or are much suppressed (else one would expect a priori equal order of magnitude and the search should aim at improving the 10^{-32} bound that already exists for the small kappas). These questions cannot be addressed by SME which is not a theory, not even a model, but at best only a parametrization.

3.1 Scale of Lorentz violation? (Origin of Lorentz Violation?)

It is natural to point to quantum gravity as responsible for violations of Lorentz invariance. This is what proponents of doubly special relativity (DSP) suggest. At least one of the proposals of DSP argues that loop quantum gravity will result in an invariant energy. As far as I know there is no complete argument that demonstrates this. This is not going to deter us, given that we decided at the outset to look at non-mainstream ideas. But I should point out that some independent proposals of the same idea have made no attempt to connect this to loop QG. Non-commutative spacetimes have also been studied extensively. These, I think, are on a stronger footing than DSP since for them one can consistently formulate a theory of fields. There is no reason why the length scale should be taken as the Planck Length, but since the theory originated from work in string theory and there the fundamental scale is almost always taken to be Planck's, the prejudice made it into non-commutative spacetime. And there are many others (Rainbow (energy dependent) metric, κ -Minkowski, Hopf-algebras, spacetime foam, etc), which I have no time to review (and besides, I know next to nothing about them). But they all have one thing in common, they modify the dispersion relation of special relativity. They do not agree, however, on what the modification ought to be. In fact, in most cases the precise form of the modification is not known. Take DSP. There is an infinite class of dispersion relations that work. To see this construct a non-linear realization of the Lorentz group as follows. Take $F : P \rightarrow \mathcal{P}$ to be an invertible function from the space of physical 4-momentum P to a fictitious space \mathcal{P} of four vectors on which the Lorentz group acts linearly. Then Lorentz transformations on P are given by mapping to the unphysical space, Lorentz transforming and then mapping back. Now, since a Lorentz transformation leaves $\pi = 0$ or $\pi = \infty$ invariant, we can choose a function that maps some particular value of p^0 to either $\pi = 0$ or $\pi = \infty$.

As you can see this is very general. Since we want to probe for a small effect we take any one of these proposals and expand in powers of energy divided by M_{Planck} . This is good enough for phenomenological studies and is as much as we can expect from the state of theory. Note also that we are only dealing here with modification to the dispersion relation. This is as much as DSP can give you now. Full fledged theories, like Non-commutative space time can also give you modifications to the SM Lagrangian, and more. We content ourselves with this for now and see where we get.

For ultra-relativistic particles a parametrization of Ref. [20] is as follows:

$$E \approx p + \frac{m^2}{p} - \frac{E}{\kappa} \quad (3.3)$$

There is a lot of slop here. You can construct a non-linear representation so that the correction only comes in at some higher power of E . The sign and magnitude of the coefficient of the correction are not fixed either. But this is a good starting point for phenomenological tests. A non-linear dispersion relation, applied to massless particles, say, photons, gives an energy dependent speed of light. This gives an immediate avenue for testing these ideas, looking for energy dependent variations in time of travel over a fixed distance, $\Delta t \approx (\Delta E / \kappa)L$. A source of photons that is both very distant and has a wide (energy) spectrum is required. Gamma Ray Bursts fit the bill. We do not understand these sources well enough to argue that photons leave simultaneously. But we can be conservative and use the observed time delay as an upper bound of the time delay produced by DSR and hence a lower bound $\kappa > 1.3 \times 10^{18} GeV \approx 0.10 M_{Planck}$, [20] which, remarkably, is close to the Planck scale.

There are severe difficulties in constructing a quantum theory of fields that respects invariance of a fundamental speed and of a fundamental length. I do not wish to go into these difficulties. For one thing I don't really understand the issues. Coraddu and Mignemi suggest one can get glimpses of what such theory may be like by considering a sort of first quantized version, a Schrodinger like equation based on a modified dispersion relation.[21] This is just like the Klein-Gordon theory but for a more complicated energy-momentum dispersion relation. They take a particular version of double-special relativity, get the following dispersion relation

$$E = \frac{-\frac{m^2 c^4}{\kappa} \pm \sqrt{\left(1 - \frac{m^2 c^4}{\kappa^2}\right) c^2 \vec{p}^2 + m^2 c^4}}{1 - \frac{m^2 c^4}{\kappa^2}} \quad (3.4)$$

and then solve the Klein-Gordon-like equation. From the non-relativistic limit they find that the inertial mass is not the same as the invariant mass parameter,

$$m^\pm = \pm \frac{m}{1 \pm \frac{mc^2}{\kappa}}. \quad (3.5)$$

The minus sign is for a solution that is interpreted as a hole, so $-m^-$ is the actual mass of the antiparticle. While I do not understand any of this would-be-formalism, I can certainly plug in numbers. The limit on the $K^0 - \bar{K}^0$ mass difference is very good[22] so we can obtain

$$\kappa > \frac{2mc^2}{(\Delta m/m)_{\max, \exp}} \approx 1.1 \times 10^{18} GeV \quad (3.6)$$

The result is tantalizingly close to (but better than) the bound obtained from time delays in GRBs, and suggests another experimental direction in which to push.

4. Acausality and Nonlocality

We have to be very careful when discussing violations to causality. First of all, we must not mean that things can happen without having a cause. Metaphysically we want to insist that every effect has a cause, else we can replace religion for science. Contemporary physics's view of causality has taken shape by incorporating two additional principles: Lorentz covariance and locality. The causal-light-cone construction is based on this. That a point can only influence another point if it is in its future light-cone assumes that information from the point propagated no faster than the speed of light and it acted on the second point at its location. Suppose we drop the assumption of locality and allow a mild departure, whereby an interaction can be non-local but only at small, microscopic range (this can be phrased in a Lorentz invariant fashion). Then we can send a signal that in the future influences an object outside our light-cone. Now, as we learn in elementary courses on special relativity, superluminal communication may lead to paradoxes. For example, the grandfather paradox says that if you can shoot a bullet that travels faster than the speed of light then there is a frame where it travels back in time; you can shoot your grandfather before your mom was conceived. One is tempted to conclude that non-local interactions, even if Lorentz invariant, are ruled out by consistency (that is, by requiring no grandfather paradoxes). I believe that would be rushing to conclusions. It is not trivial to connect even in principle a sequence of non-local interactions to produce effectively superluminal information propagation. Furthermore, one has to incorporate quantum mechanics into the picture.

Schrodinger's equation is perfectly causal: given an initial wavefunction it gives a method for computing evolution of the wavefunction into a later time. Of course, we want to incorporate into this Lorentz covariance, so we are really talking about QFT. And while we do in principle have a Schrodinger equation for the field functional in QFT, the issue of causality is a murky one. If you open a textbook on QFT you may or may not find a discussion of causality, other than the common requirement that commutators vanish outside the light-cone. But it is easy to find acausal theories with such commutators. So this is not a sufficient condition. There are also conditions on analyticity of amplitudes in the upper half of the complex energy plane. But these conditions are too strong. It seems that Schrodinger evolution plus Lorentz covariance should be a recipe for causal QFT, but this must fail if we have non-locality on arbitrarily long distances.

So as confusion reigns the one thing limited minds like mine can turn to is explicit examples. It is straightforward to invent such a theory. Just add to any normal looking theory (say the SM of EW interactions) some additional terms with higher derivatives. The new theory is still renormalizable, Lorentz invariant and has controlled non-locality, the distance scale of the non-locality being fixed by the dimensional parameter ℓ that accompanies the higher derivatives. But this is tough business: there are many publications on theories that are hopelessly sick because non-localities can introduce ghosts (states with negative metric) or bad instabilities or both. As far as I know the Lee-Wick procedure is the best shot at a consistent quantization with indefinite metric.[23]

In theories of this sort you have some unstable states, resonances, that behave weirdly. They are very heavy, their mass of order of the inverse of the scale of non-locality. They may or may

not be narrow. It is amusing to consider the case of a narrow resonance of this type, which I will call a “Lee-Wick” particle. To understand better let me remind you of the behavior of a resonance produced in a fixed target experiment. A particle beam impinging on a fixed target produces a signal consisting of, *e.g.*, pair production behind the target. The location of the production of the pair is determined from extrapolation back from the detectors, and the rate of production of these pairs decays exponentially away from the target. This is interpreted as a resonance being produced followed by its decay in flight. The number of produced pairs falls off exponentially with distance from the target, which is related to the life-time (or inverse width) of the resonance times its velocity.

Now for the Lee-Wick case:[24] The signal would be exactly the same except that the pair is produced ahead of the target, as if the resonance decays before the interaction takes place, so it appears it travels backwards in time. The number of pairs produced again decreases exponentially with distance from the target. You can imagine trying to construct a grandfather’s-like paradox in this situation: to a particle detector connect a mechanism that quickly removes the target, so that one detects the collision products but there is no target for the collision to take place. But this does not happen, if you remove the target the collision does not occur. If the distance scale ℓ is microscopic, say a TeV^{-1} or smaller, this effect is tremendously difficult to observe (and may explain why this sort of acausality has not been seen). A TeV is the relevant scale if the higher derivatives are the cure of the hierarchy problem.[25]

However there may be better ways to test for these effects. It is still not easy, but probably doable. The idea is to study this resonance’s phase shift. While the shape of the LW resonance itself is very normal, the phase shift quickly *decreases* across the resonance (it rotates *clockwise* in the Argand diagram)! To measure a phase shift one needs to study exclusive processes. So I do not think this is LHC physics. Instead, once the LW resonances are discovered at the LHC we will need the ILC to verify their unusual clockwise phase shifts. But don’t hold your breath waiting for a time machine out of this!

5. Final Remarks

As I remarked earlier, particle physicists have done a remarkable job of establishing the validity of the SM at a great level of precision. I also reminded us why we believe it is incomplete: I do believe exciting discoveries are about to occur at the LHC. We need an explanation for the hierarchy problem, for neutrino masses, for baryogenesis, for dark matter and energy. We would really like to have an answer to “who order that!” and to be able to calculate all masses and mixing angles in quark and lepton sectors. And is there anything to the apparent unification in the MSSM? Some answers to these are bound to reveal themselves and the process of discovery will be fun and exciting. But things can be even wilder. And we have to be open to those possibilities if we are to find out. I argued that it was along these lines that FP and CP were born. So it makes sense to imagine “what if.” Now, not a single idea I presented is solid. Worse, much of the theory I presented is flimsy, or not well motivated, or both. Some of it may not even be mathematically or metaphysically consistent. But it may give us the lamppost with the light to look under. Perhaps in some years the FPCP in the title of the conference will refer to something else. To something we

ought to continue doing, looking for departures from the standard paradigm which may look very different from our current SM. Something like “Future and Pseudo-Causal Physics...”

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