NON-STANDARD DIMENSIONS AND THE LHC

Q: MORE Dimensions?

Q: FEWER Dimensions?

A: One example of each.

Means

(1) CERTAIN NEW PARTICLES (e.g., Gauge Singlets)

TRAVEL BACKWARDS IN TIME

or,

(2) AN ANISOTROPIC LATTICE, a “CHRYSTAL WORLD”,

with hierarchical spacing $\Lambda_3^{-1} > \Lambda_2^{-1} > \Lambda_1^{-1}$.

"Causality-Violating Higgs Singlets at the LHC"

by Chiu Man Ho and T.J. Weiler

ABSTRACT: We construct a simple class of compactified five-dimensional metrics which admits closed timelike curves (CTCs), and derive the resulting CTCs as analytic solutions to the geodesic equations of motion. The associated Einstein tensor satisfies the null, weak, strong and dominant energy conditions; in particular, no negative-energy "tachyonic" matter is required. From our brane point of view, some particles would appear to travel backward in time. We give a simple model in which such time-traveling Higgs singlets can be produced by the LHC, either from decay of the Standard Model Higgses or through mixing with the SM Higgses. The signature of these time-traveling singlets is a secondary decay vertex pre-appearing before the primary vertex which produced them. The two vertices are correlated by momentum conservation.

Builds upon earlier paper:

"Closed Timelike Curves in Asymmetric Brane Universe"

by H. Päs, S. Pakvasa, J. Dent, T.J. Weiler

PRD (2009) and arXiv.

Time travel is an ambitious dream of science fiction. And from the early days of general relativity onward, theoretical physicists have realized that closed timelike curves (CTCs) are allowed solutions of general relativity, and hence time travel is theoretically possible.
Proposals include van Stockum's rotating cylinder
(extended much later by Tipler),
Gödel's rotating universe,
Wheeler's spacetime foam,
Kerr and Kerr-Newman's black hole event horizon (interior),
Morris, Throne and Yurtsever's traversable wormholes,
Gott's pair of spinning cosmic strings,
Alcubierre's warp drive,
and Ori's vacuum torus.
More additions to the possibilities continue to unfold.

Common pathologies associated with these candidate CTCs are
- that the required matter distributions are often unphysical,
- tachyonic,
- unstable under the back-reaction of the metric,
- or violate one or more of the desirable null, weak, strong and dominant energy conditions.

The visceral arguments against the relevance of the Gödel and TvS metrics are that:

they are not asymptotically flat, and so presumably can neither occur within, nor be, our Universe.

And the initial conditions from which they can evolve are either non-existent (Gödel) or sick (TvS).

Furthermore, the TvS metric assumes an infinitely-long cylinder of matter, which is unphysical.

On the positive side, the Einstein equation endows

$\rho = T^0_{\ 0} = (R^0_{\ 0} - \frac{1}{2}R)/8\pi\, G_N$

(the geometric RHS is determined by the metric) with a positive value everywhere; there is no need for "exotic" $\rho < 0$ matter.

A further positive feature is the simplicity of finding the CTC by travel along the periodic variable, ϕ for (Gödel) and (TvS).

These common pathologies have led Hawking to formulate his "chronology protection conjecture".

The logical basis for the conjecture is that we do not know how to make sense of a non-causal Universe – time travel leads to many paradoxes.

However, after almost two decades of intensive research on this subject, Hawking's conjecture remains a hope that is not mathematically compelling. Chronology protection probably will not be settled until we have a much better understanding of gravity itself, whether quantizable or emergent.

Popular for the previous decade is a low-scale gravity idea of Arkani-Hamed–Dimopoulos–Dvali (ADD). In the ADD scenario, all particles with gauge charge, which includes all of the standard model (SM) particles, are open strings with charged endpoints confined to the brane (our 4D spacetime). Gauge singlets, which include the graviton, are closed strings which may freely propagate throughout the brane and bulk (the extra dimensions). After all, wherever there is spacetime, whether brane or bulk, there is Einstein's gravity. Speculative gauge singlets other than the graviton include sterile neutrinos and scalar singlets. Due to mixing with gauge non-singlet particles, e.g. active neutrinos or SM Higgs doublets, respectively, sterile neutrinos or scalar singlets can "appear" when they cross the brane. We will show that in a calculable class of metric, these particles can PRE-appear.

Superluminal travel through extra-dimensional "shortcuts" generally doesn't guarantee a CTC. To obtain a CTC, one needs the light cone in a t-versus-r diagram to tip below the horizontal r axis for part of the path. For this part of the path, travel along our brane progresses along negative time. When the positive time part of the path is added, one has a CTC if the net travel time is negative.

The Periodic 5 (or more) D Model

First of all, we seek a class of CTCs embedded in a single compactified extra dimension; We require the CTCs to be geodesic paths, so that physical particles will become negative-time travelers.

Secondly, we ensure that this class of CTCs is free of undesirable pathologies.

Thirdly, we ask whether particles traversing these CTC geodesics may reveal unique signatures at the LHC. A phenomenologically interesting number is a compactification scale $L \lesssim 10$ TeV since this opens the possibility of new effects at the LHC.

We found a class of 5D metrics which generates solvable geodesic equations whose solutions are in fact CTCs. We adopt an ADD framework where only gauge singlet particles (gravitons, sterile neutrinos, and Higgs singlets) may leave our 4D brane and traverse the CTC embedded in the extra dimension. The signature of negative-time travel is the appearance of a secondary decay or scattering vertex *earlier in time* than the occurrence of the primary vertex which produces the time-traveling particle. The two vertices are associated by overall momentum conservation.

The Class of Metrics Admitting Closed Timelike Curves is given by the time-independent – "stationary" metric (like Gödel's, Kerr's, etc.).

$$d\tau^2 = \eta_{ij} dx^i dx^j + dt^2 + 2\, g(u)\, dt\, du - h(u)\, du^2 \,, \qquad (0.1)$$

where i, $j = 1$, 2, 3;

η_{ij} is the spatial part of the Minkowskian metric,

and u is the coordinate of a spatial extra dimension.

The induced metric on the brane is trivially Minkowskian; so coordinate t is laboratory time.

And it is worth mentioning that our 5D metric is easily embeddable in further extra dimensions.

The determinant of the metric is

$$\mathrm{Det} \equiv \mathrm{Det}[\mathrm{g}_{\mu\nu}] = \mathrm{g}^2 + \mathrm{h}\,. \tag{0.2}$$

We normalize the determinant by requiring the standard Minkowskian metric on the brane, i.e., $\mathrm{Det}(\mathrm{u} = 0) = \mathrm{g}^2(0) + \mathrm{h}(0) = +1$. In fact, for added simplicity, we take $g^2(u) + h(u) = +1, \quad \forall\, u$.

The elements of the metric tensor must reflect the symmetry of the compactified dimension, i.e., they must be periodic functions of u with period L. Expanded in Fourier modes, the general metric function $g(u)$ is

$$Fg(u) = g_0 + A - \sum_{n=1}^{\infty} \left\{ a_n \cos\left(\frac{2\pi\, n\, u}{L}\right) + b_n \sin\left(\frac{2\pi\, n\, u}{L}\right)\right\}\,, \tag{0.3}$$

where $g(0) = g_0$ and $A \equiv \sum_{n=1}^{\infty} a_n$ are constants.

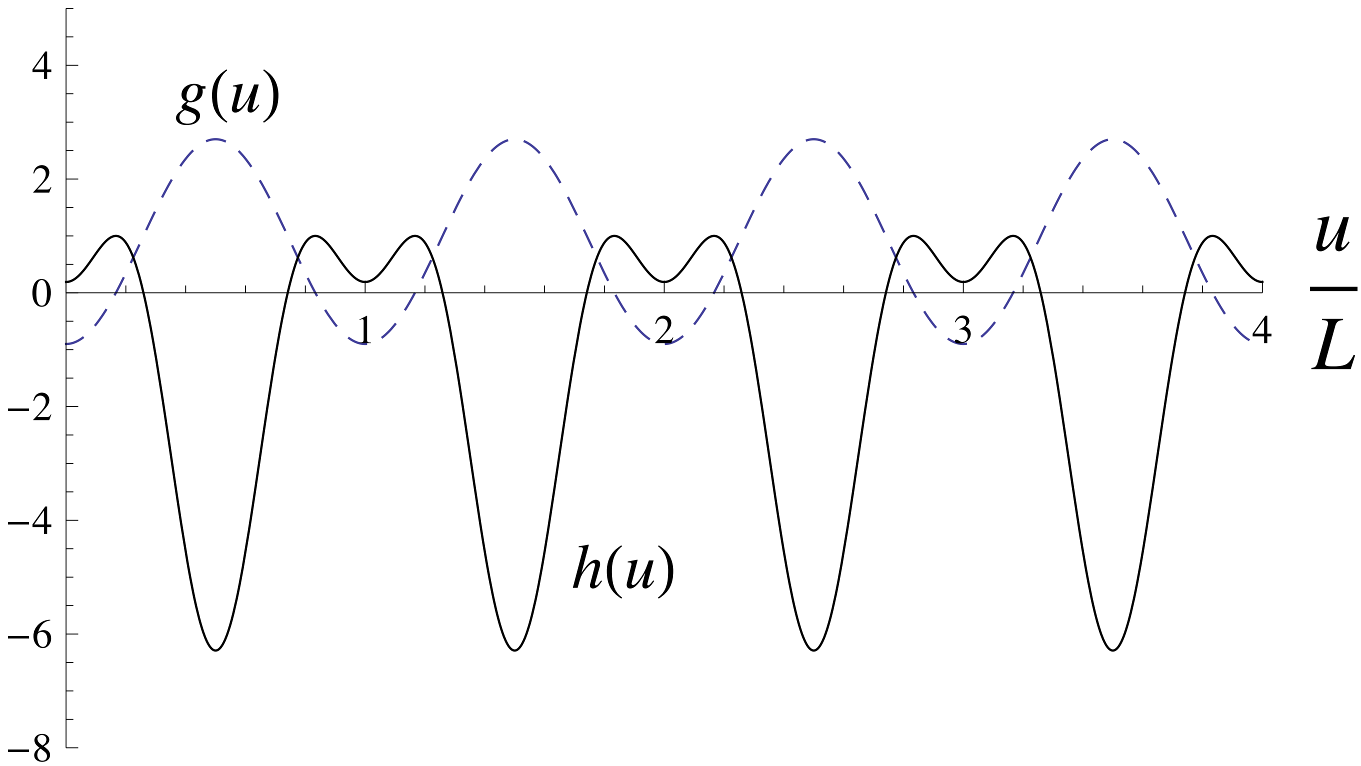

FIG. 1. $g(u)$ (dashed) and $h(u) = 1 - g^2(u)$ (solid) versus u/L, for parameter choices $g_0 = -0.9$, $a_1 = A = 1.8$, and $a_{n\neq1} = b_n = 0$.

On the brane, the metric (0.1) is completely Minkowskian. Accordingly, $\ddot{\vec{r}} = 0$. Thus,

$$\dot{\vec{r}} = \dot{\vec{r}}_0 \,, \quad \text{or} \quad \vec{r} = \vec{r}_0\, \tau \,. \tag{0.4}$$

Since the metric is time-independent ("stationary"), there is a time-like Killing vector with an associated conserved quantity:

$$\dot{t} + g(u)\, \dot{u} = \gamma_0 + g_0\, \dot{u}_0 \,, \tag{0.5}$$

From this conserved quantity, we may already deduce that time will run backwards, equivalently, that $\dot{t} < 0$,

if $g(u)\, \dot{u} > \gamma_0 + \dot{u}_0\, g_0$ is allowed by the remaining geodesic equation (It Is !).

One readily obtains the eom $\ddot{u} = 0$, which implies

$$\dot{u}(\tau) = \dot{u}_0 \,, \quad \text{and} \tag{0.6}$$

$$u(\tau) = \dot{u}_0\, \tau \,, \qquad (\bmod L\,) \,. \tag{0.7}$$

In analogy to the historical CTCs arising from metrics containing rotation, we will call the geodesic solutions with positive $\dot{u}_0$ "co-rotating", and solutions with negative $\dot{u}_0$ "counter-rotating".

From Eqs. (0.5) and (0.6), we have

$$\dot{t} = \gamma_0 - (g(u) - g_0)\, \dot{u}_0 \,, \tag{0.8}$$

and its value averaged over the period path of length L

$$\bar{\dot{t}} = \frac{1}{L}\int_0^L du\, \dot{t} = \gamma_0 - (\bar{g} - g_0)\, \dot{u}_0\,. \tag{0.9}$$

Apparently, existence of the CTC will depend on the relation between the mean metric element $\bar{g}$ and the value of the element on the brane g_0, and on the relation between the velocities of the particle along the brane and along the bulk (γ_0 and $\dot{u}_0$, respectively).

By definition, a CTC is a geodesic that returns a particle to the same space coordinates from which it left, with an arrival time before it left. The "closed" condition of the CTC can be satisfied easily in our metric due to the S^1 topology of the extra dimension. The other condition for a CTC, the "timelike" condition, is that the time elapsed during the particle's return path as measured by an observer sitting at the initial space coordinates is negative. To ascertain the other condition for the CTC, negative time of travel, we proceed to solve for $t(u)$. As indicated by (0.8), to do so we need to return to $g(u)$, given by (0.3).

Defining the symbol

$$\beta_0 = \frac{\dot{u}_0}{\gamma_0} = \left(\frac{du}{dt}\right)_0 , \tag{0.10}$$

for the initial velocity of the particle in u-direction as would be measured by a stationary observer on the brane ($\beta_0 > 0$ for the co-rotating particle, and $\beta_0 < 0$ for the counter-rotating particle), and pushing the eom's, we arrive at

$$t(u) = \left(\frac{1}{\beta_0} - A\right) u + \left(\frac{L}{2\pi}\right) \sum_{n=1}^{\infty} \left(\frac{1}{n}\right) \left\{ \begin{array}{c} a_n \, \sin\left(\frac{2\pi\, n\, u}{L}\right) \\ +b_n \, \left[1 - \cos\left(\frac{2\pi\, n\, u}{L}\right)\right] \end{array} \right\}, \tag{0.11}$$

pictured in Fig. (2).

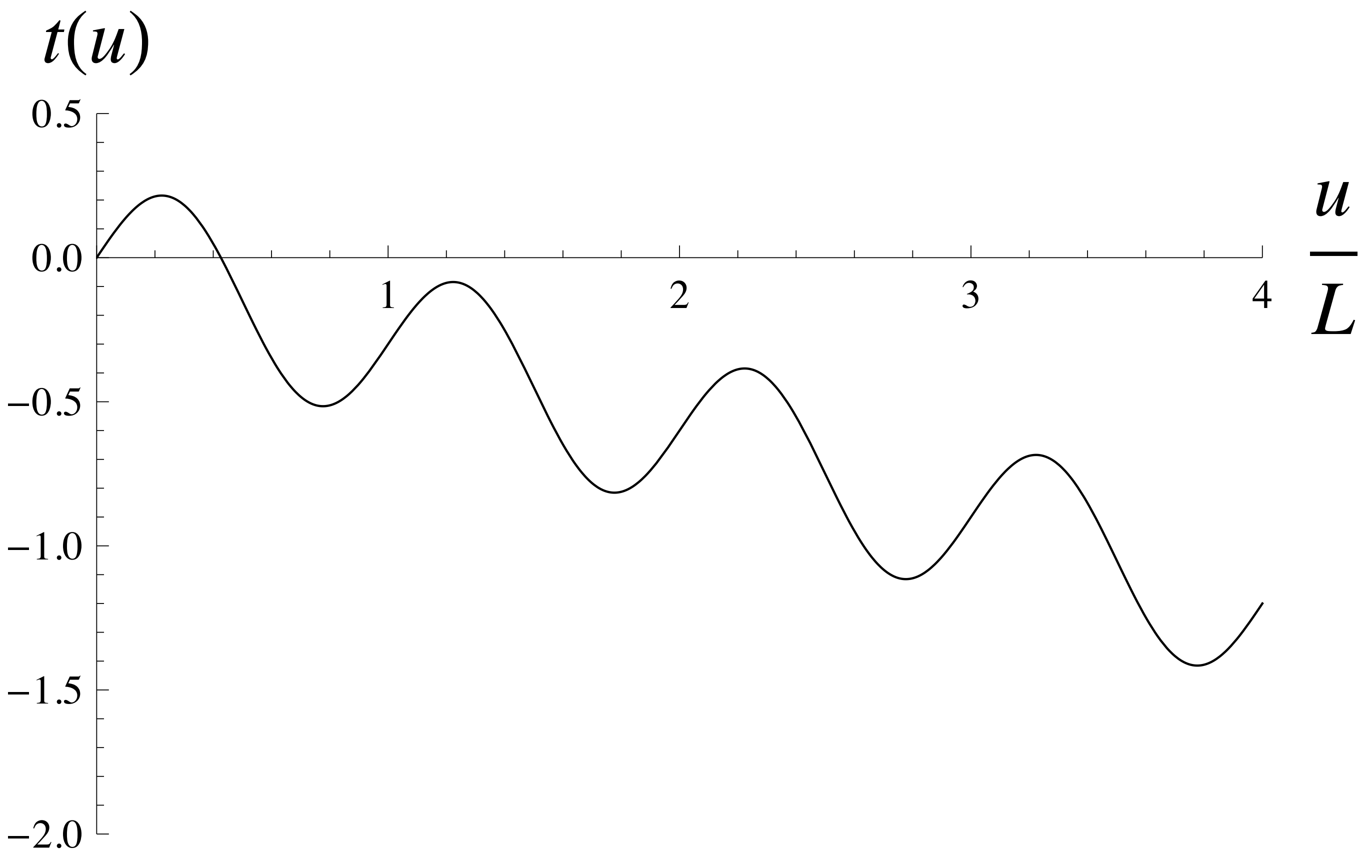

FIG. 2. $t(u)$ versus u/L, for the same parameter choices as in Fig. 1, and with $\beta_0 = 2/3$.

Due to the S^1 topology of the compactified extra dimension, the particle returns to the brane at $u = \pm NL$, for integer $N > 0$. Physically, N counts the number of times that the particle has traversed the compactified extra dimension. When the particle crosses the brane for the N^{th} time, the time as measured by a stationary clock on the brane is

$$t_N \equiv t(u = \pm NL) = \pm \left(\frac{1}{\beta_0} - A \right) NL \,. \tag{0.12}$$

This crossing time depends on the Fourier modes only through $A = \sum_{n=1} a_n$, and is independent of the b_n.

For a co-rotating particle ($\beta_0 > 0$ and positive signature), a viable CTC requires the conditions

$$A > \frac{1}{\beta_0} > 1 \,, \tag{0.13}$$

while a counter-rotating particle ($\beta_0 < 0$ and negative signature), requires

$$A,\ \beta_0 < 0 \quad \text{and} \quad |A| > \left| \frac{1}{\beta_0} \right| > 1 \,. \tag{0.14}$$

Nature chooses the constant A with a definite sign, and so the CTC conditions for co-rotating and counter-rotating particles are incompatible. For definiteness we assume that it is the co-rotating particles which may traverse the CTC, while the counter-rotating particles move forward in time.

The negative time of the CTC scales linearly with the number of times N that the particle traverses the compact u-dimension. The temporal period of this march backwards in time is $\left|\frac{1}{\beta_0} - A\right| L$, with the natural time-scale being L/c multiplied by large N (see below) if the interaction/mixing with the SM Higgs is small.

Stroboscopic World-lines for Higgs Singlets

We are interested in possible discovery of negative time travel at the LHC, sometimes advertised as a "Higgs factory". The time-traveling Higgs singlets can be produced either from the decay of SM Higgs or through mixing with the SM Higgs. The physical paths of the Higgs singlets are the geodesics which we calculated in previous sections, solutions to $\ddot{\vec{r}}$ and $\ddot{u} = 0$. Thus, the projection of the particles position onto the brane coordinates is

$$\vec{r}\,(\tau) = \dot{\vec{r}}_0\,\tau + \vec{r}_0 = \dot{\vec{r}}_0\,\frac{u}{\dot{u}_0} + \vec{r}_0 = \frac{v_0}{\beta_0}\,u\,\hat{p}_0 + \vec{r}_0\,. \tag{0.15}$$

Here, $\hat{p}_0$ is the particle's three-momentum direction as seen by a brane observer, $v_0 = |d\vec{r}/dt_0|$ is the initial speed of the particle along the brane direction, and $\vec{r}_0$ is the point of origin for the Higgs singlet particle, i.e., the primary vertex of the LHC collision.

Inserting $u = \pm NL$ into (0.15) demonstrates that the particle crosses the brane stroboscopically; the trajectory lies along a straight line on the brane, but piercing the brane at regular spatial intervals given by

$$\vec{r}_N = \frac{v_0}{|\beta_0|}\,NL\,\hat{p}_0 + \vec{r}_0\,. \tag{0.16}$$

The discrete spatial intervals are likely too small to be discerned.

However, the Higgs singlet is only observed when it scatters or decays to produce a final state of high-momenta SM particles. We expect the decay or scattering rate to be small, so that many bulk orbits are traversed before the Higgs singlet reveals itself.

The coordinate times of the reappearances of the particle on the brane are given by Eq. (0.12) as

$$t_N = \pm \left(\frac{1}{\beta_0} - A \right) NL\,. \tag{0.17}$$

The time intervals for PRE-appearances of co-rotating particles are

$$t_N(\text{co}-\text{rotating}) = -\left(A - \frac{1}{\beta_0} \right) NL < 0\,. \tag{0.18}$$

The counter-rotating particles reappear on the brane but do not pre-appear.

Dividing the particle's apparent travel distance along the brane, $\vec{r}_N(t) - \vec{r}_0$ (0.16), by the apparent travel time t_N (0.17) yields the the velocity which an observer on the brane, e.g. an LHC experimenter, would infer. For the co-rotating particles

$$\vec{v}\,(\text{co}-\text{rotating}) = -\,\frac{v_0}{\beta_0\,A - 1}\,\hat{p}_0\,, \tag{0.19}$$

negative for $\beta_0 A > 1$ because the particles are traveling backwards in time.

We note that the apparent speeds of co-rotating particles can be superluminal in either forward time ($\beta_0\, A < 1$) or backwards time ($\beta_0\, A > 1$). We display the velocities in Fig. (3) with a plot of v/v_0 versus the parameter combination $\beta_0 A$. The particle speed diverges at $\beta_0 A = 1$; the value $\beta_0\, A = 1$ corresponds to the slope of the light-cone passing through zero, a necessary condition for CTC geodesics. The region $\beta_0 A > 1$ is the CTC region, of interest for this article.

In Fig. (4) we show schematically the world lines on our brane for co-rotating particles with negative transit times, and for counter-rotating particles with positive ($\beta_0\, A < 1$) and negative ($\beta_0\, A > 1$) transit times.

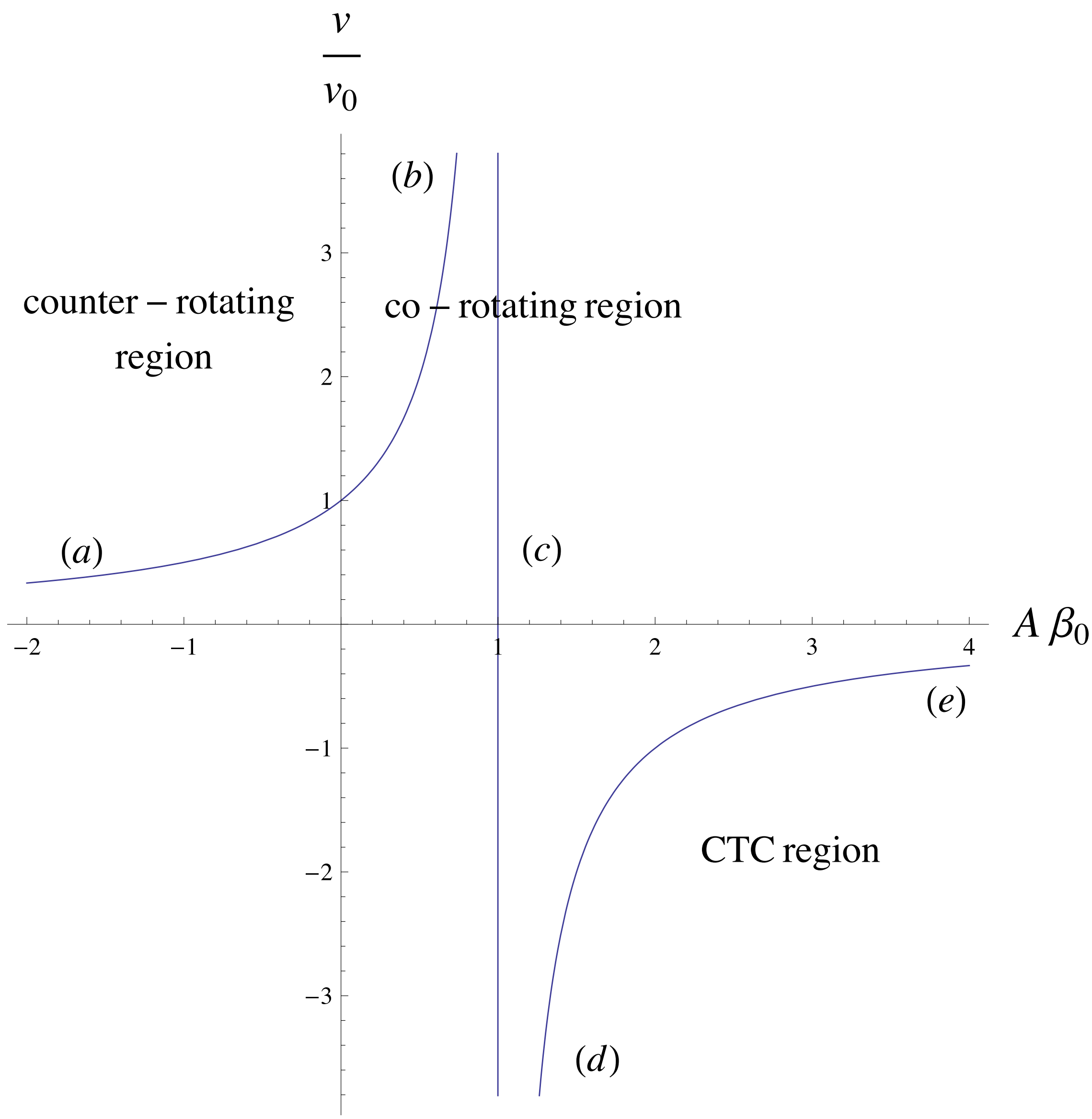

FIG. 3. Apparent brane velocity v as fraction of initial brane velocity v_0 versus $\beta_0 A$. The counter-rotating particle always moves subluminally forward in time, but the co-rotating particle may move superluminally in either time direction. Brane velocities are divergent at $\beta_0 A = 1$, which occurs as the lightcone crosses the horizontal axis of the spacetime diagram. For $\beta_0 A > 1$, the co-rotating geodesic is a CTC. The regions delineated by (a), (b), (c), (d), (e) map into the world lines of Fig. 4 with the same labels.

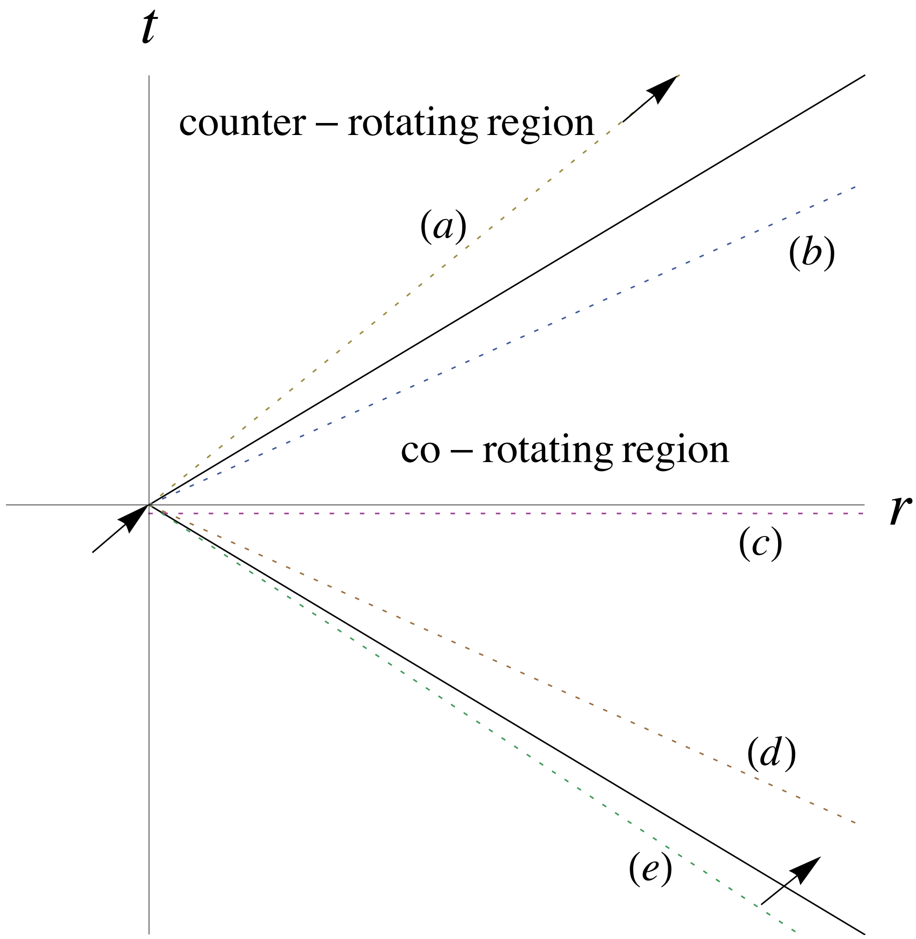

FIG. 4. Shown are stroboscopic piercings (dots) of our brane by a returning Higgs singlet. World lines delineated by (a), (b), (c), (d), (e) correspond to regions of Fig. 3 with the same labels. In (a), the counter-rotating particle travels forward in brane/coordinate time, within the forward light-cone. The co-rotating particle travels outside the brane's forward light-cone. In (b), the world line is superluminal but moving forward in brane time t. In (c), the world line is horizontal; the particle "moves" instantaneously in brane time. In (d) and (e), the particle travels superluminally and subluminally, respectively, backwards in brane time (signifying a CTC).

At some point along the world line, during one of the brane piercings, the Higgs singlet decays or interacts to produce a secondary vertex. The pre-appearance of the secondary vertex with respect to the primary vertex reveals the acausal nature of the Higgs singlet.

During each brane piercing, the particle's three-momentum is just that missing from the primary vertex, i.e., three-momentum on the brane is conserved. The arrows in Fig. (4) are meant to denote the three-momentum missing from the primary vertex at the origin, and re-appearing or pre-appearing in a displaced secondary vertex.

It is this momentum completion – exactly the three-momentum missing from the primary vertex pre-appears in the secondary vertex – that provides the identification of the secondary vertex with a *later* primary vertex rather than with an *earlier* vertex.

5D Lagrangian for the Coupled Higgs System A simple and economical model involves the Higgs singlet ϕ coupling/mixing only with the SM Higgs doublet H.

$\mathcal{L}^{(5D)} = \mathcal{L}_0 + \mathcal{L}_I$:

$$\mathcal{L}_0 = \frac{G^{AB}}{2}\, \partial_A \phi\, \partial_B \phi - \frac{m^2}{2}\, \phi^2 \,, \tag{0.20}$$
$$\mathcal{L}_I = -\frac{\lambda_1}{\sqrt{L}}\, \phi - \sqrt{L}\, \lambda_3\, \phi\, H^\dagger\, H\, \delta(u) - L\, \lambda_4\, \phi^2\, H^\dagger\, H\, \delta(u) \,,$$

where $A, B = \{\mu, 5\}$ and G^{AB} is the 5D inverse metric tensor with nonzero entries

$$G^{00} = h(u) \;\; ; \;\; G^{05} = G^{50} = g(u) \;\; ; \;\; G^{55} = G^{ii} = -1 \,,$$

From the 5D kinetic term, one gets the mass dimension of ϕ as 3/2. Therefore, the operator ϕ^4 is not renormalizable in 5D.

The operator ϕ^3 is 5D-renormalizable, but inadmissably leads to a Hamiltonian unbounded from below.

The appearance of the delta function $\delta(u)$ in $\mathcal{L}^{(5D)}$ restricts the interactions with SM particles to the brane ($u = 0$).

The limited set of operators allowed in $\mathcal{L}^{(5D)}$ implies that in the bulk where H vanishes, ϕ is a free field.

The **energy dispersion relation** for the ϕ particle modes is easily be obtained from the equation of motion for the free ϕ field:

$$G^{AB}\,\partial_A\,\partial_B\,\phi + m^2\,\phi = 0\,. \quad \text{(5D Klein} - \text{Gordon equation)} \tag{0.21}$$

In fact, an inspection of (0.21) (and the earlier definition of $\tilde{t}$) suggests the form for the general solution

$$\phi_n^{(\mathrm{KG})} = e^{-i\,E_n\,[\,t+\int_0^u\, g(u)\,du\,]}\; e^{i\,\vec{p}\cdot\vec{x}}\; e^{i\,\xi\,u}\,, \tag{0.22}$$

The compact boundary condition $\phi_n(u+L) = \phi_n(u)$ in turn requires that

$$\xi = \bar{g}\,E_n + \frac{2\pi\,n}{L} \qquad \text{with} \qquad n = 0,\, \pm 1,\, \pm 2,\, \ldots \tag{0.23}$$

where

$$\bar{g} = \frac{1}{L}\int_0^L\; g(u)\;du = g_0 + A\,. \tag{0.24}$$

Thus, the solution to the KG equation is given by

$$\phi_n^{(\mathrm{KG})} = e^{-i\,E_n\,t}\; e^{i\,\vec{p}\cdot\vec{x}}\; e^{-i\,E_n\,\int_0^u\,(g-\bar{g})du}\; e^{i\,n\,u/R}\,, \tag{0.25}$$

where we have defined an extra-dimensional "radius" $R \equiv L/2\pi$.

Plugging (0.25) into the 5D KG equation, we then solve for E_n.

$$E_n = \frac{\bar{g}\,\frac{n}{R} + \sqrt{(1-\bar{g}^2)\,(\vec{p}^{\;2}+m^2) + \frac{n^2}{R^2}}}{1-\bar{g}^2}\,. \tag{0.26}$$

With the restriction $|\bar{g}| = |g_0 + A| < 1$, E_n is always real.

The ultimate conditions on the metric which guarantee CTC solutions are simple, and shown in Fig. (5).

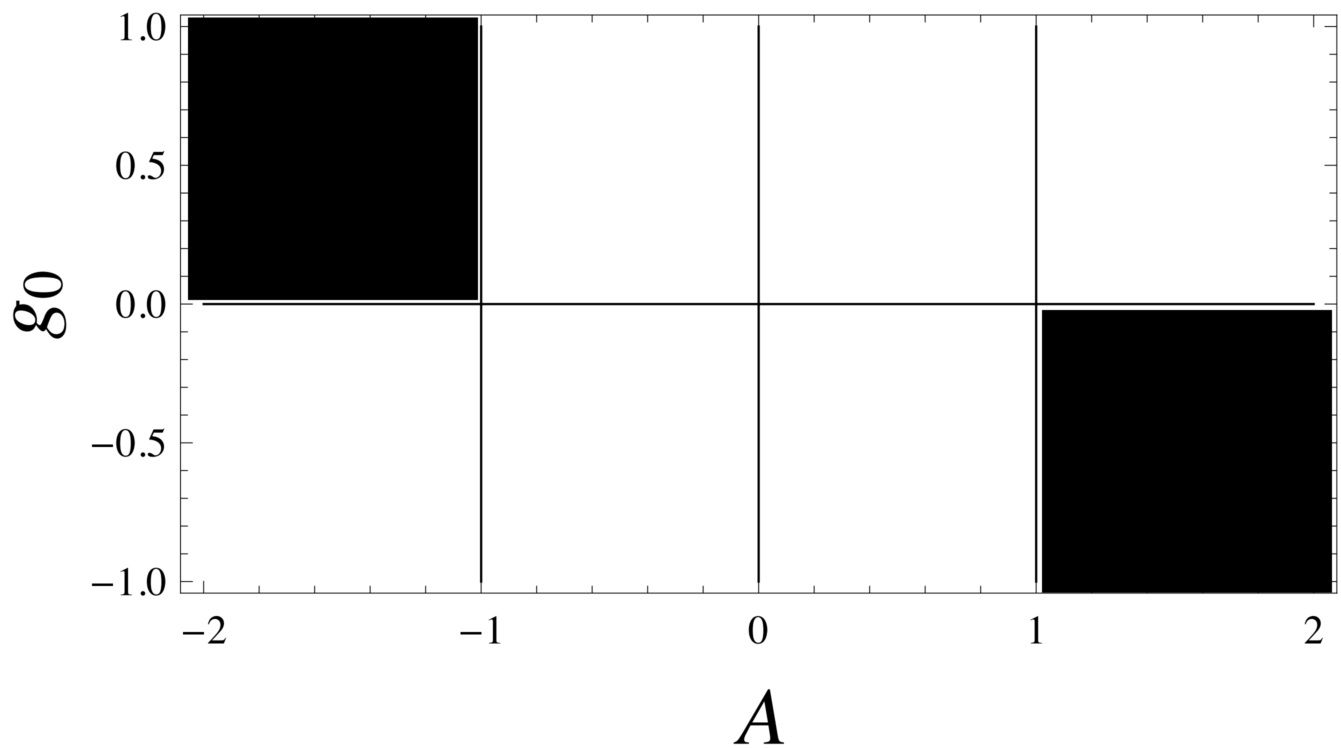

FIG. 5. The two regions in the g_0–A plane for which CTCs are possible.

For the LHC energy scale to probe the extra dimension, we must assume that the size of the extra dimensions L is $\gtrsim 1/\sqrt{s_{\mathrm{LHC}}} \sim 1/\mathrm{TeV} \gtrsim 10^{-19}$ m. The strongest constraint on the ADD scenario comes from limits on excess cooling of supernova due to KK graviton emission. One extra dimension is ruled out. For two extra dimensions, the lower bound on the fundamental Planck scale is comfortably and interestingly at 10 TeV.

The reduction of the 5D theory to an effective 4D Lagrangian density is accomplished by the integration

$$\mathcal{L}^{(4D)} = \int_0^L du \;\left(\mathcal{L}_0 + \mathcal{L}_I \right) \; . \tag{0.27}$$

Electroweak symmetry breaking (EWSB) in $\mathcal{L}^{(4D)}$ is effected by the replacement $H^\dagger H \to \frac{1}{2}(h+v)^2$, where $v \sim 246$ GeV is the SM Higgs vev. The result is

$$\mathcal{L}^{(4D)} = \int_0^L du \; \mathcal{L}_0 - \frac{\lambda_3}{2}\left(2\, v\, h + h^2 \right) \sum_n \bar{\phi}_n - \frac{\lambda_4}{2}\left(v^2 + 2\, v\, h + h^2 \right) \sum_{n_1, n_2} \bar{\phi}_{n_1} \bar{\phi}_{n_2} \, . \tag{0.28}$$

From this we obtain the explicit Higgs doublet-singlet mixing and decay terms and construct rates.

For example, the ratio of decay widths of Higgs doublet to $\bar{\phi}_n$ pairs and to τ-lepton pairs is

$$\frac{\Gamma_{h\to\bar{\phi}_n\,\bar{\phi}_{\pm n}}}{\Gamma_{h\to\tau^+\tau^-}} \sim \frac{\lambda_4^2\,v^4}{M_h^2\,m_\tau^2}\,\beta_{n,\pm n}\,. \tag{0.29}$$

This ratio can be much greater than unity, even for perturbatively small λ_4. Thus, it appears likely that

(i) $\bar{\phi}_n$ particles will be copiously produced by SM Higgs decay if kinematically allowed,

(ii) that they will explore extra dimensions if the latter exist,

(iii) and finally, that the KK modes will traverse the geodesic CTCs, if nature chooses an appropriately warped metric.

Note:

$(10^{-2})^3 = 10^{-6}$, and $(10^{-3})^3 = 10^{-9}$, etc.

How would one know that the Higgs singlets are crossing and re-crossing our brane, again and again?

The essential correlation is via momentum. Exactly the missing three-momentum from the primary vertex is present in the secondary vertex.

And roughly equal in numbers, the secondary vertices of counter-rotating particles will appear later than the primary vertices which produced them, comprising a standard "displaced vertex" event.

Without a Z_2 symmetry, the singlet-doublet mass-mixing term $\lambda_3\, v\, h\, \sum_n \bar{\phi}_n$ arises. But only occur when the singlet particle $\bar{\phi}_n$ is traversing the brane, as the field H is confined to the brane. The electroweak interaction which produces the Higgs doublet now also produces the singlet $\bar{\phi}_n$, with probability

$$P_{\mathrm{P}_n} \equiv \frac{1}{2} \sin^2(2\theta_{h\bar{\phi}_n}) \overset{\theta_{h\bar{\phi}_n} \ll 1}{\longrightarrow} \sim 2\theta^2_{h\bar{\phi}_n}\,. \tag{0.30}$$

Each produced singlet $\bar{\phi}_n$ exits the brane and propagates into the bulk, traverses the geodesic CTCs, and returns to cross the brane at stroboscopic times t_N (0.17). Upon returning to the brane, these pure $\bar{\phi}_n$ states mix again and hence split into h_2 and h_1 states. The total probability per returning $\bar{\phi}_n$ particle per brane crossing to decay or interact as a SM Higgs h is again $P_{\mathrm{I}_n} \equiv \frac{1}{2}\sin^2(2\theta_{h\bar{\phi}_n}) = P_{\mathrm{P}_n}$.

$P_{\mathrm{I}_n} \sim 2\theta^2_{h\bar{\phi}_n}$ is a very small number. A fiducial value might be 10^{-4} or 10^{-6}.

Conversely, the probability per returning $\bar{\phi}_n$ particle to *not* interact on each brane-crossing is $1-P_{\mathrm{I}_n}$. Therefore, per initial Higgs doublet production, the probability for the Higgs singlet, once produced with probability P_{I_n}, to survive N traversals of the extra-dimension and "then" decay or scatter acausally on the $(N+1)^{th}$ traversal is

$$P(N+1) = P_{\mathrm{I}_n}\,(1-P_{\mathrm{I}_n})^N \sim P_{\mathrm{I}_n}\,e^{-NP_{\mathrm{I}_n}}\,. \tag{0.31}$$

For this Poissonian probability, we have some standard results: the mean number of traversals is $\langle N\rangle = 1/P_{\mathrm{I}_n}$ (very large), and the rms deviation, $\sqrt{\langle N^2\rangle - \langle N\rangle^2}$, is again $1/P_{\mathrm{I}_n}$ (very wide). Thus, the typical negative time between the occurrence of the primary vertex and the pre-appearance of the secondary vertex is of order

$$t_{\langle N\rangle} = \langle N\rangle\, t_1 = \frac{L/c}{P_{\mathrm{I}_n}} = 3\left(\frac{L}{10^{-7}m}\right)\left(\frac{10^{-4}}{P_{\mathrm{I}_n}}\right)\text{picosec}\,. \tag{0.32}$$

So the acausal pre-appearance of the secondary vertex for the co-rotating singlet may be observable.

The correlation relating the pre-appearing secondary vertex and the post-appearing primary vertex is the conserved momentum. As with familiar causal pairs of vertices, the total momentum is zero only for the sum of momenta in both vertices.

One may wonder whether an acausal theory could be compatible with quantum field theory (QFT). After all, in the canonical picture, QFT is built upon time-ordered products of operators, and the path integral picture is built upon a time-ordered path. What does “time-ordering” mean in an acausal theory? And might the wave packet of a particle traversing a CTC interfere with itself upon its simultaneous emission and arrival? We note that each of these two questions has been discussed before, the first one long ago in Feynman-Wheeler, and the second one more recently in Greenberger. For the present, we have the LHC available to explore whether acausality at the TeV scale is realized in Nature.

Many believe that a true theory of quantum gravity should be somehow background independent, with spacetime being a derived concept and hence emergent. If spacetime is emergent, then the idea of CTCs or time travel is meaningless at the scale of quantum gravity, since there is no spacetime at all; and the discussion of chronology protection and time travel then become intimately related with the dynamics of how spacetime emerges.

AND NOW FOR SOMETHING
NOT–QUITE COMPLETELY DIFFERENT:

“Searching for the Layered Structure of Space at the LHC”

by L.A. Anchordoqui, D.C. Dai, H. Goldberg, G, Landsberg, G. Shaughnessy, D. Stojkovic and T.J. Weiler

ABSTRACT: Alignment of cosmic ray particles in a target plane has been observed by experiment in the Pamir mountains. The fraction of events with alignment is statistically significant for families with very high energies and large numbers of hadrons. This can be interpreted as evidence for coplanar hard-scattering of secondary hadrons produced in the early stages of the atmospheric cascade development, and can be described within the recently proposed context of latticized and anisotropic spatial dimensions (the “crystal world”) . Planar events are expected to dominate particle collisions at a hard-scattering energy exceeding the scale Λ_3 at which space transitions from 3D $\rightleftharpoons$ 2D.

We present two specific collider signatures that will test this hypothesis:

(1) the energy-spectrum of Drell-Yan scattering is significantly modified in this framework.

(2) At the LHC, while two and three jet events are necessarily planar, FOUR JET events can test the hypothesis. For the ideal scenario

in which all $pp \to 4$ jet scattering processes become coplanar above Λ_3, we show that with an integrated luminosity of 10(100) fb^{-1} the LHC experiments have the potential to discover four jet coplanaritiy correlations at 5σ if $\Lambda_3 \lesssim 1.25(1.6)$ TeV.

Paper preceded by

"Vanishing Dimensions and Planar Events at the LHC",
by Luis A. Anchordoqui, De Chang Dai, Malcolm Fairbairn,
Greg Landsberg and Dejan Stojkovic.

An intriguing alignment of high-energy gamma-hadron families (i.e., the secondary particles from a single collision in the atmosphere) along a straight line in a target (transverse) plane has been observed with (lead and carbon) X-ray emulsion chambers in the Pamir mountains. This allows determination of the total energy in gamma-rays and the total energy of hadrons released to gamma-rays. All families in the experiment are classified by the value of the total energy observed in gamma-rays, $\sum E_\gamma$. Recall that most of the hadrons in the family are pions and the average fraction of energy transferred by pions to the electromagnetic component is $\simeq 1/3$. The criterion for alignment is given by the asymmetry parameter

$$\lambda_N = \frac{1}{N(N-1)(N-2)} \sum_{i \neq j \neq k} \cos 2\varphi_{ij}^k \,, \qquad (0.33)$$

where N is the number of subcores and φ_{ij}^k is the angle between vectors issuing from the k-th subcore to the i-th and j-th subcores [**?**]. The parameter λ_N decreases from 1 for complete planar alignment to $-1/(N-1)$ for a random, isotropic case. Events are referred to as aligned if the N most energetic subcores satisfy $\lambda_N \geq \lambda_N^{\rm cut}$. A common choice is $N = 4$ jets and $\lambda_N^{\rm cut} = 0.8$.

The data have been collected at an altitude of 4400 m a.s.l., *i.e.*, at an atmospheric slant depth of 594 g/cm^2. For "low energy" showers $E_\gamma \lesssim 200$ TeV, the fraction of aligned events coincides with background expectations. However, for “high energy” events $\sum E_\gamma > 700$ TeV, a statistically significant alignment appears: the fraction (f) of aligned events is $f(\lambda_4 \geq 0.8) = 0.43 \pm 0.17$ (6 out of 14) in the Pb–catalogue, and $f(\lambda_4 \geq 0.8) = 0.22 \pm 0.05$ (13 out of 59) in the C–catalogue. The predominant part of the gamma-hadron families is produced by hadronic interactions with a center-of-mass energy $\sqrt{s} \gtrsim 4$ TeV. Production of most aligned groups occurs low above the detector. Thus, it is perhaps not surprising that the KASCADE Collaboration operating at sea level (1000 g/cm^2) has no evidence for this phenomenon.

In seeming corroboration, the fraction of aligned events in Fe at Mt. Kanbala (in China) is unexpectedly large. At $\sum E_\gamma \geq 500$ TeV, $f(\lambda_3 \geq 0.8) = 0.5 \pm 0.3$ (3 out of 6). In addition, two events with $\sum E_\gamma \geq 1000$ TeV, both highly aligned, have been observed in stratospheric experiments.

(i) the so-called STRANA superfamily, detected in emulsion on a Russian balloon, has $\lambda_4 = 0.99$;

(ii) the JF2af2 superfamily, detected with emulsion on board the supersonic aircraft Concord, has $\lambda_4 = 0.998$.

It is worth noting that stratospheric experiments record the unadulterated alignment of secondary particles.

The LHC can do the same.

Here we describe a general search for planar scattering at the LHC. Firstly, we generate Standard Model (SM) four–jet QCD events, with or without b-quark jets, using a MC pgm.

The event sample is divided according to a standard aplanarity parameter, or the ratio of non("bi")-planar to planar events (N_b/N_p), with uncertainty based on Poisson statistics for a given luminosity L.

Finally, we calculate the required luminosity to obtain 5σ, 3σ, and 95% C.L. measures of coplanarity.

Aplanarity is defined in terms of the jet–momenta (in CoM frame) two–tensor

$$M_{ab} = \frac{\sum_i k_{ia} k_{ib}}{\sum_i k_i^2} \tag{0.34}$$

where $i = 1, \ldots, 4$, as

$$A_p = \frac{3}{2} Q_1 \, ; \tag{0.35}$$

Q_1 is the smallest normalized eigenvalue of the momentum tensor. Planar or collinear events possess $A_p \sim 0$ values, while more 3D events approach the maximum $A_p = \frac{1}{2}$.

Sensitivity of the LHC to 4 planar-jet events

The $2 \to 4$ scattering processes involve multiple virtual particles. We assume that when the momentum transfer Q ($Q^2 = -\hat{t}$) in each of the hard propagators is comparable with Λ_3, a growing fraction of the jets are coplanar, drastically different from the usual acoplanar topology of QCD scattering in 4D.

While a fraction of the simulated events is planar, the entire sample is generally bi-planar. Given the lack of control over the parton momentum fractions at a hadron collider, the probe of truly planar events is statistics limited. Some technical cuts on jet p_T, pseudo-rapidity and its differences, azimuthal angle differences, and jet–jet invariant masses are employed, to enrich the coplanar sample. Detector resolutions are included.

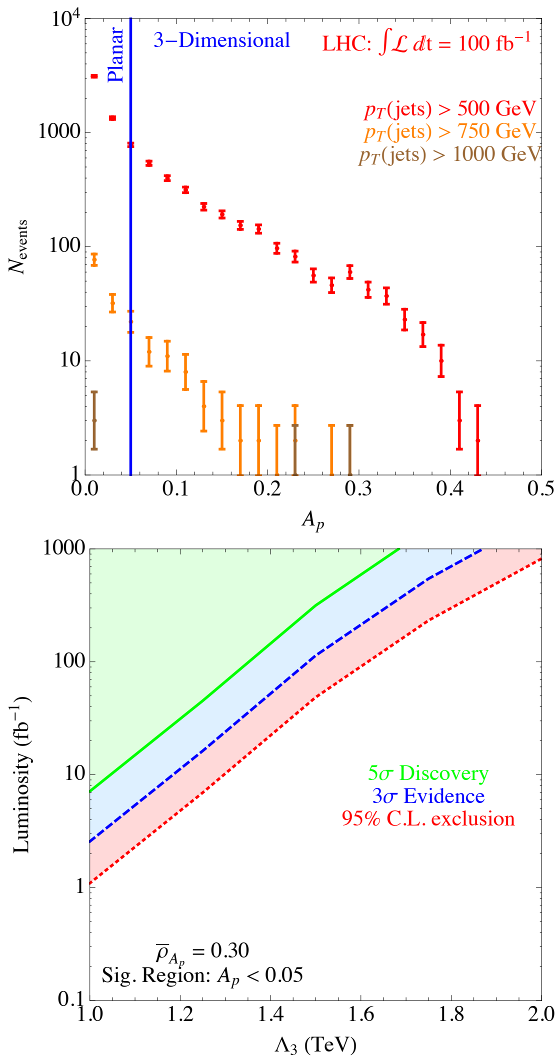

FIG. 6. *(a)* Aplanarity of SM QCD 4-jet events for 100 fb^{-1} and jet p_T acceptance cuts (from above) of 500, 750 and 1000 GeV. We take events with $A_p < 0.05$ as being planar. *(b)* Reach of Λ_3 at the LHC based on the aplanarity event shape variable. The 5σ discovery is indicated by a solid line, the 3σ evidence by a dashed line, and the 95% CL exclusion by a dotted line.

The crystal world

Motivated by condensed matter systems, Anchordoqui et al. recently proposed that space as an anisotropic lattice structure at very small distances. This idea that spatial dimensions effectively reduce with increasing energy directly contrasts with field/string theories in continuous spacetime dimensions, where dimensionality increases with a rise in energy.

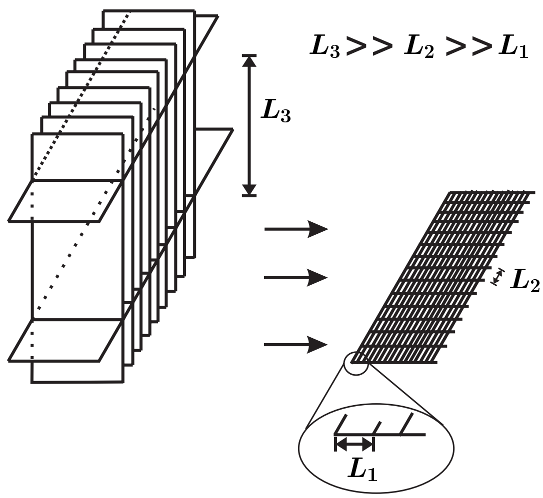

FIG. 7. Ordered lattice. The fundamental quantization scale of space is indicated by L_1. Space structure is $1D$ on scales much shorter than L_2, while it appears effectively $2D$ on scales much larger than L_2 but much shorter than L_3. At scales much larger than L_3, the structure appears effectively $3D$.

Layered strongly correlated metals have an insulating character in the direction perpendicular to the layers at high temperatures, but metal-like at low temperatures; transport parallel to the layers remains metallic over the whole temperature range. The analogy is to replace the temperature variable in materials with short-distance "virtuality" in the parton–scattering processes.

Must further assume that the lattice orientation is randomized on a scale sufficiently small to avoid a preferred direction on the macro scale.

On the small scale, the the local lattice orientation provides a preferred direction . Therefore, hard scattering processes resolve the lattice spacings, while macro objects like beam protons see the average, a spacetime continuum.

We are not aware of any data that would rule out this conjecture of dimensional reduction at higher energies. With the reduction in spatial dimension, phase space is reduced, the cross-sections are reduced, and multi-jet final states are necessarily coplanar (for $3D \to 2D$). In contrast, with an increase in spatial dimension, phase space is increased, cross-sections increase, and multi-jet final states fill the three spatial dimensions but also lose energy and multiplicity into the extra dimensions.

Besides the striking coplanar-jet signals at the LHC if $\Lambda_3 \sim 1/L_3 \sim 1$ TeV, many related aspects of beyond the SM field theory will occur at high-energy, including:

(1) the transition of the renormalizable SM to a super-renormalizable field theory,

(2) modification in the evolution properties of parton distribution functions,

(3) running coupling constants, running anomalous dimensions of operators, and so on.

If the LHC provides indications for the correctness of the conjecture, then it becomes imperative to embed the new physics in a field theory.

Drell-Yan meets the Crystal World

The effect on Drell-Yan cross sections at colliders,due to coplanar scattering of partons above the energy $\sim \Lambda_3 \sim 1$ TeV is somewhat subtle. The standard definition of cross section as transition rate divided by the flux is

$$d\sigma_D = \frac{1}{(2\pi)^{D-2}} \frac{1}{16\hat{s}} \frac{p_f^*}{p_i^*} \left|\mathcal{M}_D\right|^2 \, d\Omega^*_{D-1} |\vec{p}_f^*|^{D-4} \,. \tag{0.36}$$

Thus

$$\sigma_4 \propto \mathcal{M}_4^2/\hat{s} \tag{0.37}$$

whereas for $D = 3$

$$\sigma_3 \propto \frac{\mathcal{M}_3^2}{\hat{s}^{3/2}} \propto \sigma_4 \left(\frac{\Lambda_3}{\sqrt{s}}\right) . \tag{0.38}$$

Thus signature is a faster fall of the DY cross-section (“extra” power) with CoM energy.

A dimensional reduction at $\Lambda_3 = 1$ TeV is consistent with Tevatron data at 1σ. Interestingly, the $\Lambda_3 \sim 1$ TeV region will be tested early by the LHC.

"Chrystal World" Conclusions:

• model independent study of LHC reach for planar 4 jet events; the only free parameter is the characteristic energy scale for coplanarity onset, Λ_3. For the extreme scenario in which all $pp \to 4$ jet scattering is coplanar above Λ_3, an integrated luminosity of 10 fb^{-1} at the LHC reaches to $\Lambda_3 \lesssim 1.25$ TeV, and (100) fb^{-1} to 1.6 TeV

• the anisotropic crystal world yields planar events when the energies of hard scatterings exceed the 3D $\rightleftharpoons$ 2D scale. Four jet events at the LHC from parton-parton scattering with $Q \gtrsim \Lambda_3$ should show striking planar alignment. Jets with this strong azimuthal anisotropy may have been already observed by the Pamir Collaboration (phenomenon inexplainable by conventional physics.

• predicted energy spectrum of Drell-Yan scattering is significantly modified (downward) at $\sqrt{\hat{s}} \gtrsim \Lambda_3$