UNPARTICLE PHYSICS

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Detecting the Unexpected
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OVERVIEW

- New physics weakly coupled to SM through heavy mediators
- Many papers [hep-un]
- Many basic, outstanding questions
- Goal: provide groundwork for discussion, LHC phenomenology
CONFORMAL INVARIANCE

• Conformal invariance implies scale invariance, theory “looks the same on all scales”

• Scale transformations: \( x \rightarrow e^{-\alpha} x, \phi \rightarrow e^{d\alpha} \phi \)

• Classical field theories are conformal if they have no dimensionful parameters: \( d_\phi = 1, d_\psi = 3/2 \)

• SM is not conformal even as a classical field theory – Higgs mass breaks conformal symmetry
CONFORMAL INVARIANCE

- At the quantum level, dimensionless couplings depend on scale: renormalization group evolution

- QED, QCD are not conformal
CONFORMAL FIELD THEORIES

• Banks-Zaks (1982)
  \( \beta \)-function for SU(3) with \( N_F \) flavors

  \[
  \beta(g) = -\left( \beta_0 \frac{g^3}{16\pi^2} + \beta_1 \frac{g^5}{(16\pi^2)^2} + \beta_2 \frac{g^7}{(16\pi^2)^3} \right),
  \]

  \[
  \beta_0 = 11 - \frac{3}{2} T(R) N_F,
  \]

  \[
  \beta_1 = 102 - (20 + 4C_2(R)) T(R) N_F,
  \]

  \[
  \beta_2 = \left( \frac{2887}{2} - \frac{5033}{18} N_F + \frac{325}{32} N_F^2 \right), \quad (R = \text{fundamental}).
  \]

  For a range of \( N_F \), flows to a perturbative infrared stable fixed point

• \( N=1 \) SUSY SU\( (N_C) \) with \( N_F \) flavors

  For a range of \( N_F \), flows to a strongly coupled infrared stable fixed point

  Intriligator, Seiberg (1996)
UNPARTICLES

- Hidden sector (unparticles) coupled to SM through non-renormalizable couplings at $M$

- Assume unparticle sector becomes conformal at $\Lambda_U$, couplings to SM preserve conformality in the IR

- Operator $O_{UV}$, dimension $d_{UV} = 1, 2, \ldots \rightarrow$ operator $O$, dimension $d$

- BZ $\rightarrow d \approx d_{UV}$, but strong coupling $\rightarrow d \neq d_{UV}$.
  Unitary CFT $\rightarrow d \geq 1$ for scalar $O$, $d \geq 3$ for vector $O$. 
  [Loopholes: unparticle sector is scale invariant but not conformally invariant, $O$ is not gauge-invariant.]
UNPARTICLE INTERACTIONS

- Interactions depend on the dimension of the unparticle operator and whether it is scalar, vector, tensor, …

- There may also be super-renormalizable couplings: $\lambda \Lambda^{2-d} H^2 O_U$

This is important – see below.
UNPARTICLE PHASE SPACE

• The density of unparticle final states is the spectral density $\rho$, where

$$\langle 0 | O_\mathcal{U}(x)O_\mathcal{U}^\dagger(0) | 0 \rangle = \int \frac{d^4 P}{(2\pi)^4} e^{-i P \cdot x} \rho_\mathcal{U}(P^2)$$

• Scale invariance $\Rightarrow \rho_\mathcal{U}(P^2) = A_{d_\mathcal{U}} \theta(P^0) \theta(P^2) (P^2)^{d_\mathcal{U}-2}$

• This is similar to the phase space for $n$ massless particles:

$$(2\pi)^4 \delta^4 \left( P - \sum_{j=1}^{n} p_j \right) \prod_{j=1}^{n} \delta(p_j^2) \theta(p_j^0) \frac{d^4 p_j}{(2\pi)^3} = A_n \theta(P^0) \theta(P^2) (P^2)^{n-2}$$

$$A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1) \Gamma(2n)}$$

• So identify $n \rightarrow d_\mathcal{U}$. Unparticle with $d_\mathcal{U} = 1$ is a massless particle. Unparticles with some other dimension $d_\mathcal{U}$ looks like a non-integral number $d_\mathcal{U}$ of massless particles

Georgi (2007)
UNPARTICLE DECONSTRUCTION

Stephanov (2007)

- An alternative (more palatable?) interpretation in terms of “standard” particles

- The spectral density for unparticles is

\[ \rho_U(P^2) = A_{d_U} \theta(P^0) \theta(P^2) (P^2)^{d_U/2} \]

\[ A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n + 1/2)}{\Gamma(n - 1) \Gamma(2n)} \]

- For \( d_U \to 1 \), spectral function piles up at \( P^2 = 0 \), becomes a \( \delta \)-function at \( m = 0 \). Recall: \( \delta \)-functions in \( \rho \) are normal particle states, so unparticle is a massless particle.

- For other values of \( d_U \), \( \rho \) spreads out to higher \( P^2 \). Decompose this into un-normalized delta functions. Unparticle is a collection of un-normalized particles with continuum of masses. This collection couples significantly, but individual particles couple infinitesimally, don’t decay.
TOP DECAY

• Consider $t \rightarrow u U$ decay through

$$i \frac{\lambda}{\Lambda^{d_U}} \bar{u} \gamma_\mu (1 - \gamma_5) t \partial^\mu O_U + \text{h.c.}$$

• For $d_U \rightarrow 1$, recover 2-body decay kinematics, monoenergetic $u$ jet.

• For $d_U > 1$, however, get continuum of energies; unparticle does not have a definite mass.

Georgi (2007)
Unparticle propagators are also determined by scaling invariance. E.g., the scalar unparticle propagator is

\[ \frac{i}{(q^2)^{2-d}} B_d, \quad B_d \equiv A_d \frac{(e^{-i\pi})^{d-2}}{2 \sin d\pi}, \quad A_d \equiv \frac{16\pi^{5/2} \Gamma(d + \frac{1}{2})}{(2\pi)^{2d} \Gamma(d - 1) \Gamma(2d)} \]

- Propagator has no mass gap and a strange phase
- Becomes infinite at \(d = 2, 3, \ldots\) Most studies confined to \(1 < d < 2\)
SIGNALS

COLLIDERS
• Real unparticle production
  – Monophotons at LEP: $e^+e^- \rightarrow g\,U$
  – Monojets at Tevatron, LHC: $g\,g \rightarrow g\,U$
• Virtual unparticle exchange
  – Scalar unparticles: $f\,f \rightarrow U \rightarrow \mu^+\mu^-, \gamma\gamma, ZZ, \ldots$
    [No interference with SM; no resonance: $U$ is massless]
  – Vector unparticles: $e^+e^- \rightarrow U^\mu \rightarrow \mu^+\mu^-, \, qq, \ldots$
    [Induce contact interactions; Eichten, Lane, Peskin (1983)]

LOW ENERGY PROBES
• Anomalous magnetic moments
• CP violation in B mesons
• 5th force experiments

ASTROPHYSICS
• Supernova cooling
• BBN

Many Authors (2007)
CONSTRANTS COMPARED

High Energy (LEP)

Low Energy (SN)

FIG. 6: Bounds from $e^+e^- \rightarrow \mu^+\mu^-$ on the fundamental parameter space ($\Lambda_{\mu}, M$) for a vector unparticle operator with $d_{UV} = 3$, and $d = 1.1$ (solid), 1.5 (dashed), and 1.9 (dotted). The regions below the contours are excluded. The shaded region is excluded by the requirement $M > \Lambda_{\mu}$.

Bander, Feng, Shirman, Rajaraman (2007)

FIG. 1: Constraints on vector unparticle operators from SN bremsstrahlung emission, assuming $d_{UV} = 3$, for $d = 1$, 3/2, and 2 as indicated. The regions below the contours are excluded.

Hannestad, Raffelt, Wong (2007)
CONFORMAL BREAKING

- EWSB $\rightarrow$ conformal symmetry breaking through the super-renormalizable operator
  \[ c_2 \Lambda_2^{2-d} O H^2 \]

- This breaks conformal symmetry at
  \[ \Lambda_{\not\!d} = \left( c_2 \Lambda_2^{2-d} v^2 \right)^{\frac{1}{4-d}} \]

- Unparticle physics is only possible in the conformal window

Fox, Shirman, Rajaraman (2007)

16 Nov 07

Feng 14
CONFORMAL WINDOW

The window is narrow

Many Implications

- Low energy constraints are applicable only in fine-tuned models
- Mass Gap

\[ |\langle 0|O_{\mu}|P\rangle|^2 \rho(P^2) = A_{d_{\mu}} \theta(P^0) \theta(P^2 - \mu^2)(P^2 - \mu^2)^{d_{\mu} - 2} \] (2007)

- Colored Unparticles

  Cacciapaglia, Marandella, Terning (2007)

- Higgs Physics

  Delgado, Espinoza, Quiros (2007)

- Unresonances

  Rizzo (2007)

FIG. 2: Energy scales in the minimal unparticle model as functions of \( d \), assuming \( \Lambda_{u} = v \simeq 246 \text{ GeV} \), \( M = 2v \), and \( d_{UV} = 3 \). The two lines for \( \Lambda_{u} \) are for \( c_2 = 1 \) (upper) and \( c_2 = 0.01 \) (lower).
UNRESONANCES

Figure 3: (Top) Same as the previous figure but now with $\Lambda = 1$ TeV and $\mu = 600$ GeV for $a = 1, 1.3, 1.5, 1.7, 1.9$ corresponding to the red (green, blue, magenta) histograms, respectively. (Bottom) In this case $\Lambda = 1$ and $a = 1.5$ with $\mu = 200, 300, 400, 500$ or 600 GeV. The SM prediction is the (almost invisible) black histogram in both panels.
MULTI-UNPARTICLE PRODUCTION

Feng, Rajaraman, Tu (2007)

- Strongly interacting conformal sector → multiple unparticle vertices don’t cost much

- LHC Signals

- Cross section is suppressed mainly by the conversion back to visible particles
3 POINT COUPLINGS

- 3-point coupling is determined, up to a constant, by conformal invariance:

\[
\langle 0 | O(x)O(y)O^\dagger(0) | 0 \rangle \propto \frac{1}{|x-y|^d} \frac{1}{|x|^d} \frac{1}{|y|^d}
\]

\[
\langle 0 | O(p_1)O(p_2)O^\dagger(p_1+p_2) | 0 \rangle \propto \int \frac{d^4 q}{(2\pi)^4} \left[ -q^2 - i\epsilon \right]^{d-2} \left[ -(p_1-q)^2 - i\epsilon \right]^{d-2} \left[ -(p_2-q)^2 - i\epsilon \right]^{d-2}
\]

- E.g.: \( gg \rightarrow O \rightarrow O O \rightarrow \gamma\gamma\gamma\gamma

- Rate controlled by value of the (strong) coupling, constrained only by experiment

- Kinematic distributions are predicted

- Many possibilities: \( \gamma\gamma ZZ, \gamma\gamma ee, \gamma\gamma\mu\mu, \ldots \)
SUMMARY

• Unparticles: conformal window implies high energy colliders are the most robust probes

• Virtual unparticle production $\rightarrow$ rare processes

• Real unparticle production $\rightarrow$ missing energy

• Multi-unparticle production $\rightarrow$ spectacular signals

• Distinguishable from other physics through bizarre kinematic properties