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

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

\[
\beta_0 = 11 - \frac{3}{2} T(R)N_F, \\
\beta_1 = 102 - (20 + 4 C_2(R)) T(R) N_F, \\
\beta_2 = \left( \frac{2837}{2} - \frac{5033}{18} N_F + \frac{325 N_F^2}{3} \right), \quad (R = \text{fundamental}).
\]

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 $O$. Mack (1977)

[Loopholes: unparticle sector is scale invariant but not conformally invariant, $O$ is not gauge-invariant.]
UNPARTICLE INTERACTIONS

Spin – 0 \[ \lambda_0 \frac{1}{\Lambda_{ul}^{d_{ul}-1}} \tilde{f} f O_{ul} \] \[ \lambda_0 \frac{1}{\Lambda_{ul}^{d_{ul}-1}} \tilde{f} i\gamma^5 f O_{ul} \]

Spin – 1 \[ \lambda_1 \frac{1}{\Lambda_{ul}^{d_{ul}-1}} \tilde{f} \gamma_{\mu} f O_{ul}^\mu \] \[ \lambda_1 \frac{1}{\Lambda_{ul}^{d_{ul}-1}} \tilde{f} \gamma_\mu \gamma_5 f O_{ul}^\mu \]

Spin – 2 \[ -\frac{1}{4} \lambda_2 \frac{1}{\Lambda_{ul}^{d_{ul}}} \tilde{\psi} i \left( \gamma_{\mu} \overrightarrow{D_{\nu}} + \gamma_{\nu} \overrightarrow{D_{\mu}} \right) \psi O_{ul}^{\mu\nu} \] \[ \lambda_2 \frac{1}{\Lambda_{ul}^{d_{ul}}} G_{\mu\alpha} G_{\nu\beta} O_{ul}^{\mu\nu} \]

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

- There may also be super-renormalizable couplings: This is important – see below.

\[ \lambda \Lambda^{2-d} H^2 O_{ul} \]
UNPARTICLE PHASE SPACE

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

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

• 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:

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

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

• 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

\[ i \frac{\lambda}{\Lambda_{dU}} \overline{u} \gamma_\mu (1 - \gamma_5) t \partial^{\mu} O_\mu + \text{h.c.} \]

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

• For $d_\mu > 1$, 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

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

- 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: $f\ f \rightarrow U \rightarrow \mu^+\mu^- , \gamma\gamma , ZZ ,...$
    [No interference with SM; no resonance: $U$ is massless]
  – Vector unparticles: $e^+e^- \rightarrow U^{\mu} \rightarrow \mu^+\mu^- , qq ,...$
    [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
CONSTRAINTS COMPARED

High Energy (LEP)

Low Energy (SN)

FIG. 6: Bounds from $e^+e^- \rightarrow \mu^+\mu^-$ on the fundamental parameter space ($\Lambda_{ul}, M$) 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 $M > \Lambda_{ul}$.

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

\[ \Lambda_{\mathcal{U}} = \left( c_2 \Lambda_2^{2-d} v^2 \right)^{1 \over 4-d} \]

• Unparticle physics is only possible in the conformal window

Fox, Shirman, Rajaraman (2007)
CONFORMAL WINDOW

The window is narrow

Many Implications

- Low energy constraints are applicable only in fine-tuned models
- Mass Gap
  \[ |\langle 0 | O_{\ell t} | P \rangle|^2 \rho(P^2) = A_{\ell t} \theta(P^0) \theta(P^2 - \mu^2)(P^2 - \mu^2)^{d_{\ell t} - 2} \] (2007)
- Colored Unparticles
  \[ \text{Cacciapaglia, Marandella, Terning (2007)} \]
- Higgs Physics
  \[ \text{Delgado, Espinoza, Quiros (2007)} \]
- Unresonances
  \[ \text{Rizzo (2007)} \]

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

Figure 3: (Top) Same as the previous figure but now with $A = 1$ TeV and $\mu = 600$ GeV for $\alpha = 1.3(1.5, 1.7, 1.9)$ corresponding to the red(green,blue,magenta) histograms, respectively. (Bottom) In this case $A = 1$ and $\alpha = 1.5$ 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 $\rightarrow$ 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:

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

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

- 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: \( \gamma\gamma ZZ \), \( \gamma\gamma ee \), \( \gamma\gamma\mu\mu \),...

Photon \( p_T \)
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