UNPARTICLE PHYSICS

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Detecting the Unexpected
UC Davis
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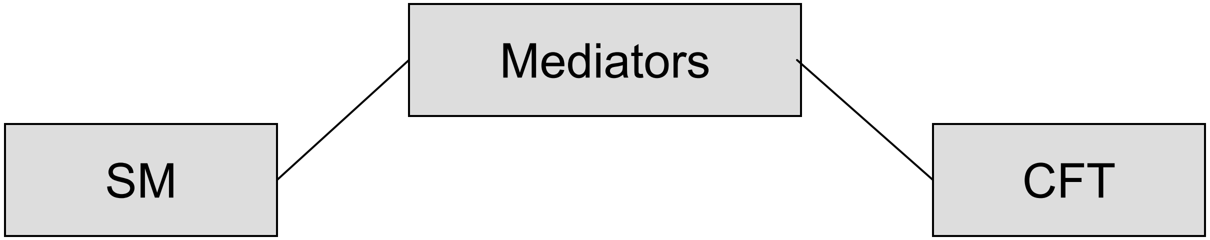
OVERVIEW

- New physics weakly coupled to SM through heavy mediators



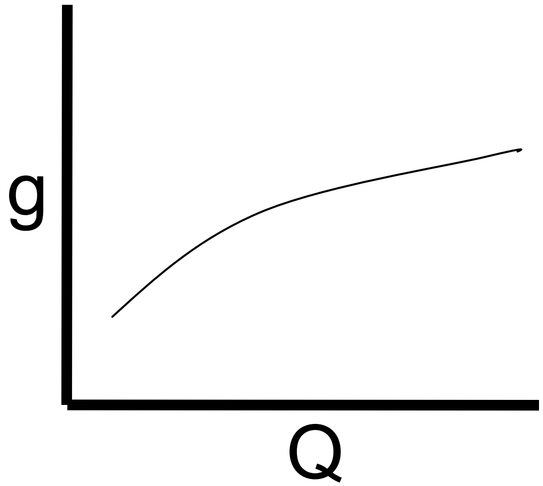
- Many papers [hep-un]
- Many basic, outstanding questions
- Goal: provide groundwork for discussion, LHC phenomenology

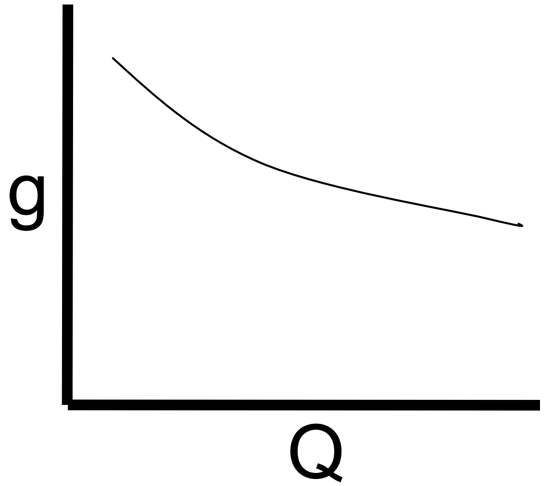
CONFORMAL INVARIANCE

- 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)

  β-function for SU(3) with N_F flavors

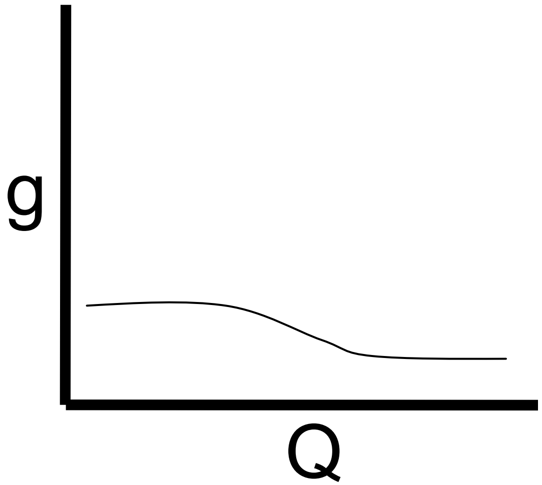
$$\beta(g) = -\left(\beta_0 \frac{g^3}{16\pi^2} + \beta_1 \frac{g^5}{(16\pi^2)^2} + \beta_2 \frac{g^7}{(16\pi^2)^3}\right),$$

$$\beta_0 = 11 - \tfrac{4}{3} T(\mathrm{R}) N_F,$$

$$\beta_1 = 102 - (20 + 4C_2(\mathrm{R})) T(\mathrm{R}) N_F,$$

$$\beta_2 = \left(\tfrac{2857}{2} - \tfrac{5033}{18} N_F + \tfrac{325}{54} N_F^2\right), \qquad (\mathrm{R} = \text{fundamental}).$$

  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

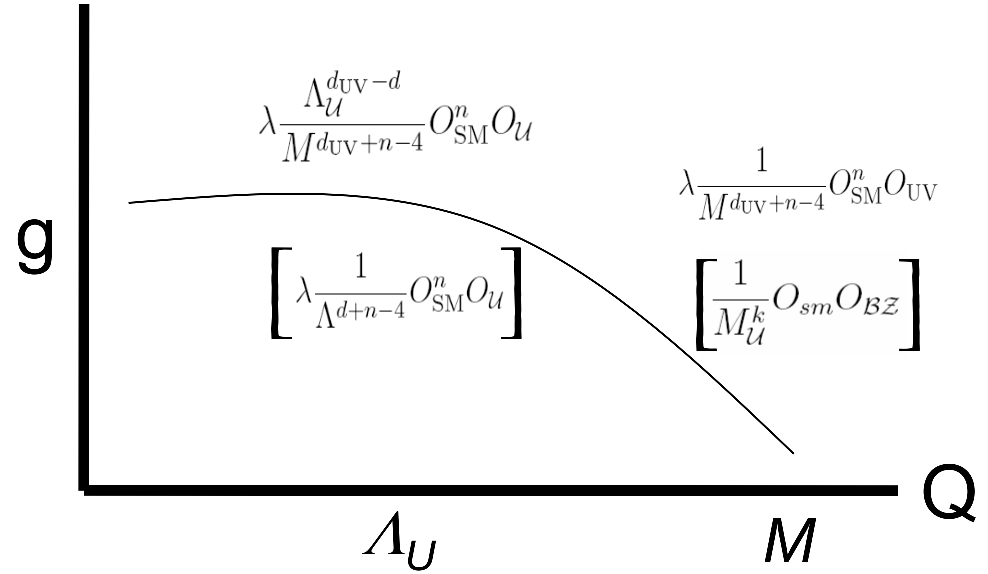
Intriligator, Seiberg (1996)

UNPARTICLES

Georgi (2007)

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

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



- Operator O_{UV}, dimension d_{UV} = 1, 2,… → operator O, dimension d

- BZ → d ≈ d_{UV}, but strong coupling → d ≠ d_{UV}.
  Unitary CFT → d ≥ 1 for scalar O, d ≥ 3 for vector O. Mack (1977)
  [Loopholes: unparticle sector is scale invariant but not conformally invariant, O is not gauge-invariant.]

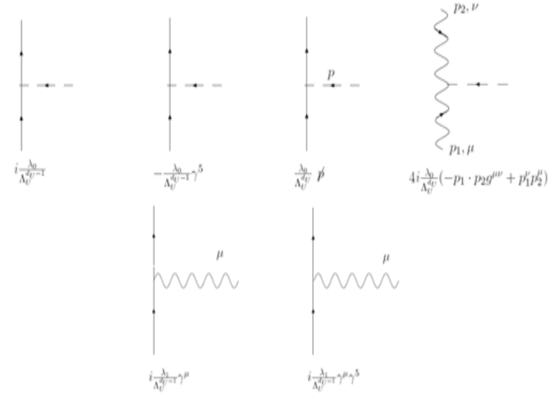
UNPARTICLE INTERACTIONS

Spin − 0 $\quad \lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} f O_{\mathcal{U}}\,, \quad \lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} i \gamma^5 f O_{\mathcal{U}}\,,$

$\lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{f} \gamma^\mu f (\partial_\mu O_{\mathcal{U}})\,, \lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\alpha\beta} G^{\alpha\beta} O_{\mathcal{U}}\,,$

Spin − 1 $\quad \lambda_1 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} \gamma_\mu f\, O_{\mathcal{U}}^\mu\,, \quad \lambda_1 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} \gamma_\mu \gamma_5 f\, O_{\mathcal{U}}^\mu\,,$

Spin − 2 $\quad -\frac{1}{4} \lambda_2 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{\psi}\, i \left(\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu \right) \psi\, O_{\mathcal{U}}^{\mu\nu}\,, \lambda_2 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\mu\alpha} G_\nu^{\ \alpha} O_{\mathcal{U}}^{\mu\nu}$



Cheung, Unparticle Workshop (2007)

- 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.

$$\lambda \Lambda^{2-d} H^2 O_{\mathcal{U}}$$

UNPARTICLE PHASE SPACE

- The density of unparticle final states is the spectral density ρ, where

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

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

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

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

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

- So identify n → d_U. Unparticle with d_U = 1 is a massless particle. Unparticles with some other dimension d_U looks like a non-integral number d_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

$$\rho_{\mathcal{U}}(P^2) = A_{d_{\mathcal{U}}}\, \theta(P^0)\, \theta(P^2)\, (P^2)^{d_{\mathcal{U}}-2}$$

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

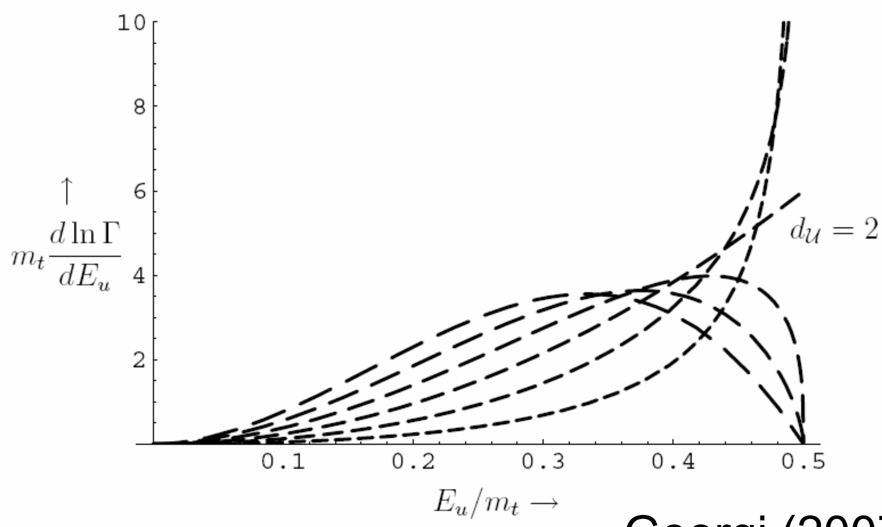
- For $d_U \to 1$, spectral function piles up at $P^2 = 0$, becomes a δ-function at m = 0. Recall: δ-functions in ρ are normal particle states, so unparticle is a massless particle.

- For other values of d_U, ρ 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 → u U decay through

$$i\,\frac{\lambda}{\Lambda^{d_{\mathcal{U}}}}\,\overline{u}\,\gamma_\mu(1-\gamma_5)\,t\,\partial^\mu O_{\mathcal{U}} + \mathrm{h.c.}$$



Georgi (2007)

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

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

UNPARTICLE PROPAGATOR

Georgi (2007), Cheung, Keung, Yuan (2007)

- Unparticle propagators are also determined by scaling invariance. E.g., the scalar unparticle propagator is

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

- Propagator has no mass gap and a strange phase

- Becomes infinite at d = 2, 3, …. 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
- 5^{th} force experiments

ASTROPHYSICS

- Supernova cooling
- BBN

Many Authors (2007)

CONSTRAINTS COMPARED

High Energy (LEP)

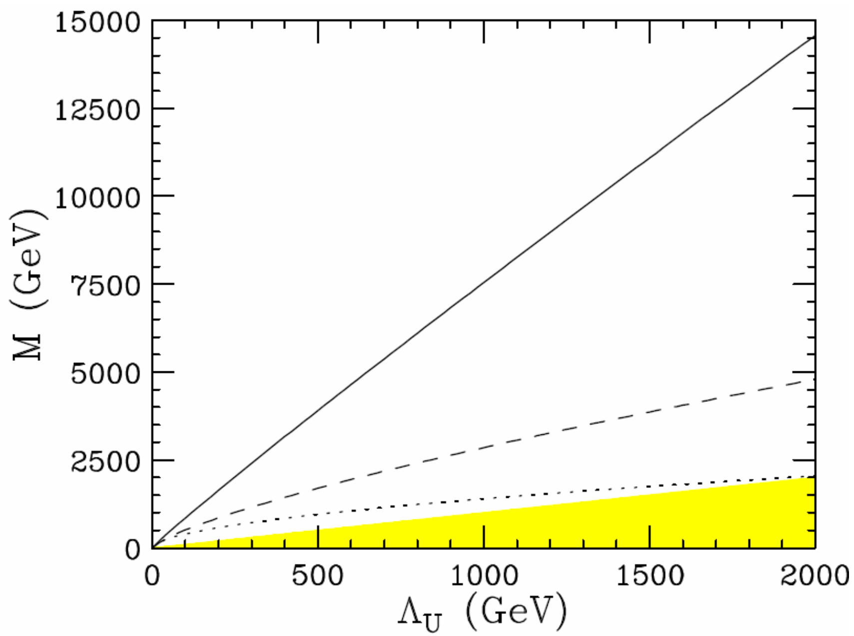


FIG. 6: Bounds from $e^+e^- \to \mu^+\mu^-$ on the fundamental parameter space $(\Lambda_{\mathcal{U}}, M)$ for a vector unparticle operator with $d_{\rm UV} = 3$, and $d = 1.1$ (solid), 1.5 (dashed), and 1.9 (dotted). The regions below the contours are excluded. The shaded region is excluded by the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

Bander, Feng, Shirman, Rajaraman (2007)

Low Energy (SN)

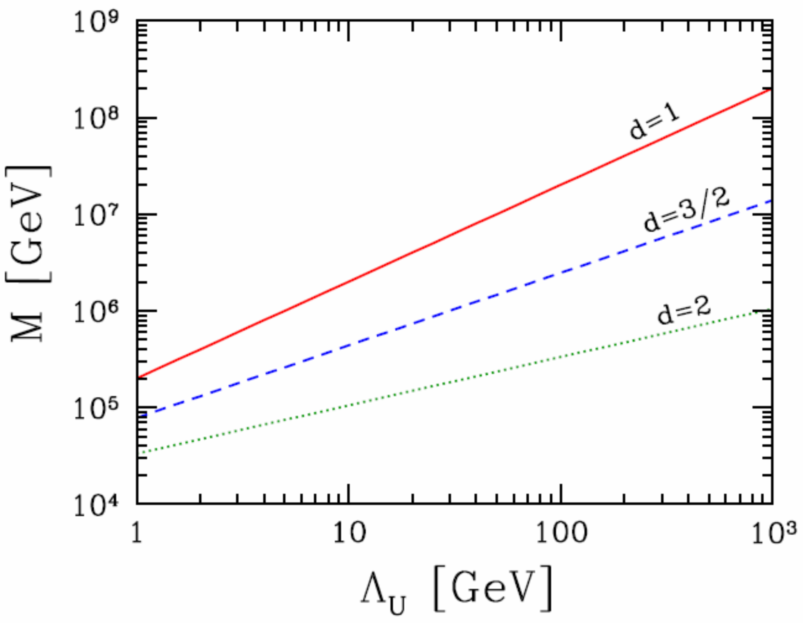


FIG. 1: Constraints on vector unparticle operators from SN bremsstrahlung emission, assuming $d_{\rm UV} = 3$, for $d = 1$, 3/2, and 2 as indicated. The regions below the contours are excluded.

Hannestad, Raffelt, Wong (2007)

CONFORMAL BREAKING

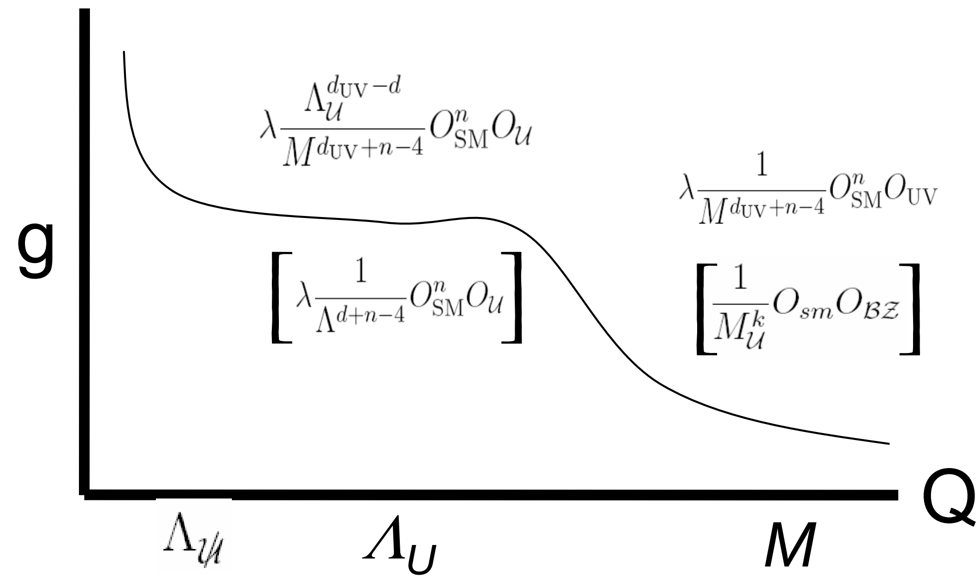
Fox, Shirman, Rajaraman (2007)

- EWSB → conformal symmetry breaking through the super-renormalizable operator

$$c_2 \Lambda_2^{2-d} O H^2$$

- This breaks conformal symmetry at

$$\Lambda_{\not{\mathcal{U}}} = \left(c_2 \Lambda_2^{2-d} v^2 \right)^{\frac{1}{4-d}}$$



- Unparticle physics is only possible in the conformal window

CONFORMAL WINDOW

The window is narrow

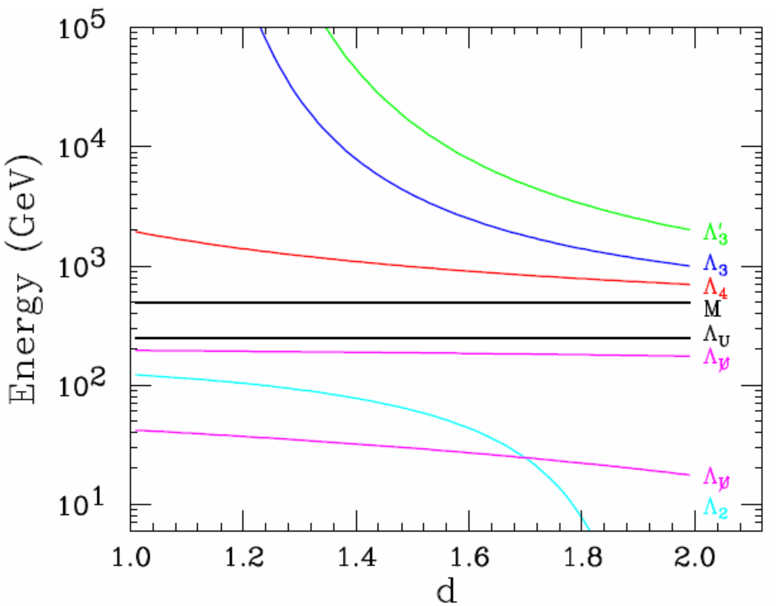


FIG. 2: Energy scales in the minimal unparticle model as functions of d, assuming $\Lambda_{\mathcal{U}} = v \simeq 246$ GeV, $M = 2v$, and $d_{\rm UV} = 3$. The two lines for $\Lambda_{\not{\mathcal{U}}}$ are for $c_2 = 1$ (upper) and $c_2 = 0.01$ (lower).

Bander, Feng, Shirman, Rajaraman (2007)

Many Implications

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

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

- Colored Unparticles

Cacciapaglia, Marandella, Terning (2007)

- Higgs Physics

Delgado, Espinoza, Quiros (2007)

- Unresonances

Rizzo (2007)

UNRESONANCES

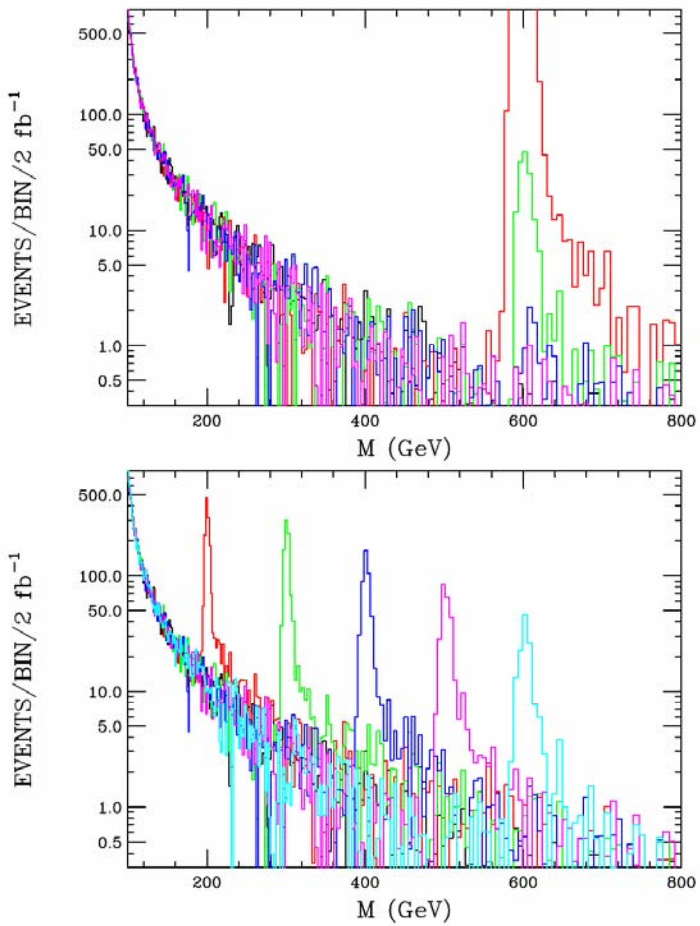


Figure 3: (Top) Same as the previous figure but now with $\Lambda = 1$ TeV and $\mu = 600$ GeV for d=1.3(1.5,1.7,1.9) corresponding to the red(green,blue,magenta) histograms, respectively. (Bottom) In this case $\Lambda = 1$ and $d = 1.5$ with $\mu = 200, 300, 400, 500$ or 600 GeV. The SM prediction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

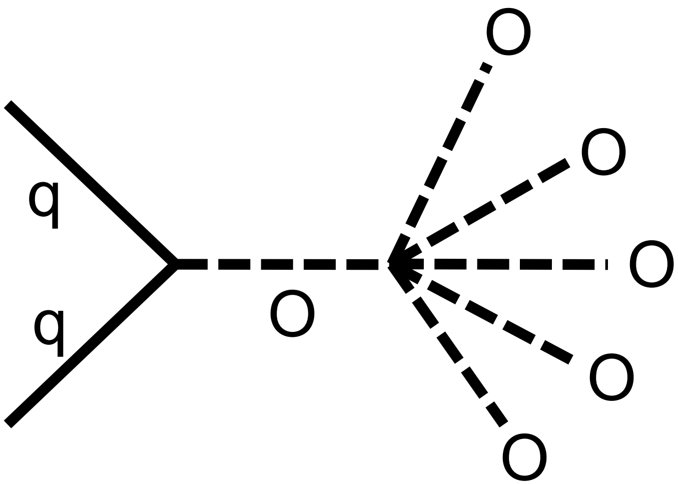
Rizzo (2007)

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

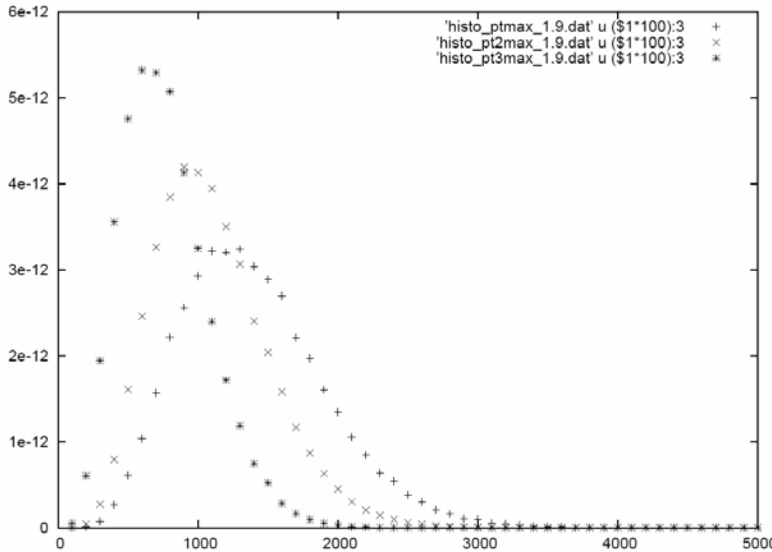
3 POINT COUPLINGS

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

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

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

- E.g.: gg → O → O O → γγγγ
- Rate controlled by value of the (strong) coupling, constrained only by experiment
- Kinematic distributions are predicted
- Many possibilities: γγZZ, γγee, γγμμ, …



Photon p_T

SUMMARY

- Unparticles: conformal window implies high energy colliders are the most robust probes
- Virtual unparticle production → rare processes
- Real unparticle production → missing energy
- Multi-unparticle production → spectacular signals
- Distinguishable from other physics through bizarre kinematic properties