Unparticles: Theoretical Aspects

Arvind Rajaraman

University of California, Irvine

Santa Fe 2008

Introduction and Motivation

Introduction

The Standard Model is believed to be incomplete (hierarchy problem, flavor problems etc.)

We expect there to be a new physics sector coupled to the Standard Model.

The new physics can be of several basic forms:

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Weakly coupled: e.g. supersymmetry

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Strongly coupled: e.g. technicolor

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The new physics can be of several basic forms:

Conformal: unparticles

Introduction

Unparticles introduced by Howard Georgi
Phys Rev Lett. 98, (2007) 221601.

Builds on previous work in CFT, extra dimensions

Most relevant is Randall-Sundrum (RS2):
extra dimensional version of CFT coupled to Standard Model.

Unparticles are a simplified version of these models.

Why unparticles?

- Unlike SUSY, extra dimensions, technicolor, unparticles do not solve any problem like the hierarchy problem, CP problem, flavor problem.

- Unparticles are somewhat theoretically unmotivated.

- No reason for unparticles to be associated with the TeV scale.

Why unparticles?

- Should explore all possibilities

- LHC coming online; perhaps time to not worry about theoretical motivations so much, but rather worry about whether some interesting signals may be missed.

- Many interesting theoretical and experimental issues with unparticles.

The Unparticle Theory

The Conformal Field Theory

To discuss the signals of unparticles, we need

a. Description of the hidden sector (the CFT)

b. A form for the interactions between the CFT and the SM.

The Conformal Field Theory

Many possible examples.

Simple model for conformal sector: focus on a few operators of the theory rather than the full complexity.

We will assume that the only coupling to the conformal sector is through a single operator O_{CFT} .

All interactions will be of the form $O_{SM}\ O_{CFT}$.

The Conformal Field Theory

Operator O_{CFT} can be scalar O, vector O_μ , fermion O_α etc.

Propagator then fixed by conformal invariance e.g.

$$<0|\, T\, (O(x)\, O(0)\,)\, |0> \;=\; \frac{B_d}{x^{2d}}$$

with similar expressions for vectors, fermions.

The Conformal Field Theory

The momentum space propagator can be written as a dispersion integral

$$\int d^3x\, e^{ipx}\, T\,(O(x)\, O(0)\,) = \frac{A_d}{2\pi} \int dM^2 \frac{\rho(M^2)}{p^2 - M^2 + i\varepsilon}$$

with $\rho(M^2) = (M^2)^{d-2}$.

Georgi, Stephanov

This shows that the propagator can be understood as a sum over resonances where the resonance masses are continuously distributed. No mass gap.

The Conformal Field Theory

The dimension is constrained by the unitarity of the conformal algebra.

Mack

Scalar operators:	$d \geq 1$
Fermion operators:	$d \geq 3/2$
Vector operators:	$d \geq 3$

The Conformal Field Theory

The dimension is constrained by the unitarity of the conformal algebra. Mack

Scalar operators: $d \geq 1$

Fermion operators: $d \geq 3/2$

Vector operators: $d \geq 3$

These limits can be avoided if the theory is scale-invariant, but not conformal.

The Conformal Field Theory

Since $\rho(M^2) = (M^2)^{d-2}$, we also see that for $d>2$, the theory is UV sensitive; small changes at high energies radically alter the propagator.

We find singular behavior in many situations with $d>2$ e.g. energy density at finite temperature and some cross-sections are proportional to $(2-d)$.

Terning et al.

Restrict to $d < 2$ ($d < 5/2$ for fermions).

Vector, higher spin operators problematic; focus on scalars.

Unparticle Interactions

with the

Standard Model

Standard Model Interactions

The unparticle is coupled to the Standard Model by terms of the form $O_{SM}\ O_{CFT}$.

Only constraint: dimensional analysis.

Huge number of possible couplings.

Standard Model Interactions

$L_{int} = \Lambda^{2-d}\, O\, H^2$	Higgs couplings
$+\ c_\Psi\, \Lambda^{1-d}\, O\, \bar{\Psi}\, \Psi$	Fermion couplings
$+\ c_F\, \Lambda^{-d}\, O\, F^2$	Gauge boson couplings

For every quark pair, lepton pair and gauge field, we have an independent coupling.

Couplings unconstrained by theory.

Standard Model Interactions

We now turn to the experimental signals of unparticles.

Unparticles can be probed through their effects on low energy precision experiments, as well as in collider experiments.

To analyze these signals, we must first understand how the interactions affect the hidden sector.

Standard Model Interactions

The experimental signals are strongly dependent on the fact that the conformal sector is itself affected by the interactions.

We shall discuss two such important effects

- The introduction of a mass gap
- Unparticle decays to Standard Model particles

The Unparticle Mass Gap

The Unparticle Mass Gap

Scale invariance precludes a mass gap for unparticles.

Unparticles would thus mediate long range forces.

They would also contribute to precision experiments like $(g\text{-}2)_{\mu}$ through loop effects. Since they are effectively massless, this can be a big effect unless the couplings are extremely suppressed.

These effects strongly constrain unparticle interactions.

Cheung, Keung, Yuan; Luo, Zhou; Liao …..

The Unparticle Mass Gap

We now argue that in fact interactions induce a mass gap for unparticles.

This removes all these low energy constraints.

This happens due to the Higgs couplings

$$L_{int} = \Lambda^{2-d}\, O\, H^2$$

Relevant operator: important at low energies.

The Unparticle Mass Gap

Once the Higgs field gets a vev $\langle H \rangle = v$, we get

$$L_{int} = \Lambda^{2-d}\, O\, H^2 \sim \Lambda^{2-d}\, (O\, v^2)$$

Introduces scale μ with $\mu^{4-d} = \Lambda^{2-d} v^2$; breaks scale invariance in hidden sector.

Modifies $\rho(M^2)$; the modification is model dependent.

The Unparticle Mass Gap

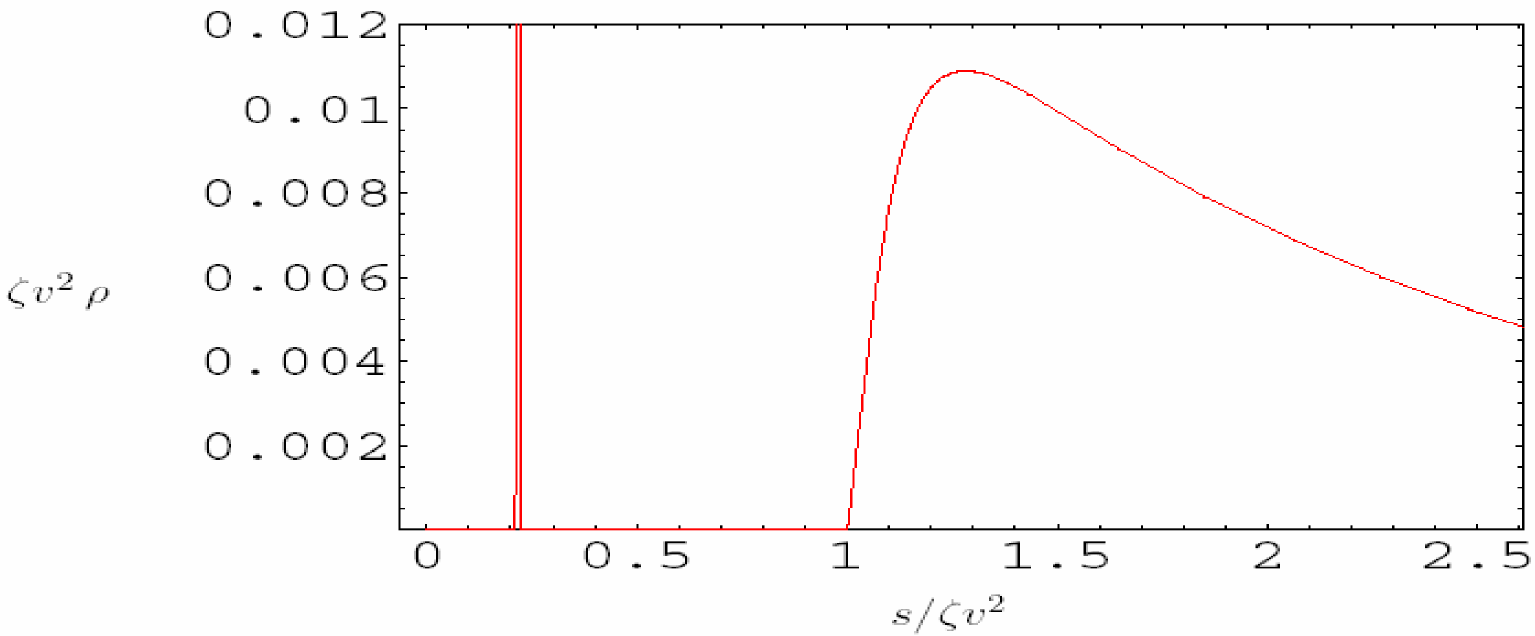
Generically, we find that a mass gap is introduced:

$$\rho(M^2)=0 \quad \text{for} \quad M^2 << \mu^2$$

Fox, AR, Shirman;
Delgado, Espinosa, Quiros

Also, for high energies, the density is unchanged:

$$\rho(M^2)= (M^2)^{d-2} \quad \text{for } M^2 >> \mu^2$$



The Unparticle Mass Gap

$\mu^{4-d} = \Lambda^{2-d} v^2$; $\Lambda \geq v \sim 100$ GeV

In the absence of fine tuning, the mass gap is at least of order few GeV.

• No long range forces from unparticle exchange.

• Precision constraints (say from $(g-2)_\mu$) essentially disappear.

• Unparticles are best probed at colliders.

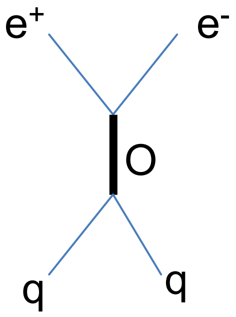
Collider Signals of Unparticles

Collider Signals

We turn to collider signals of unparticles.

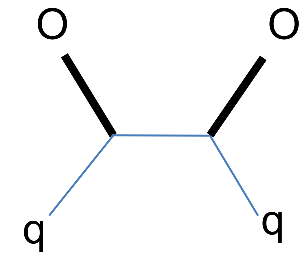
These are of two types:

a. Virtual unparticle exchanges



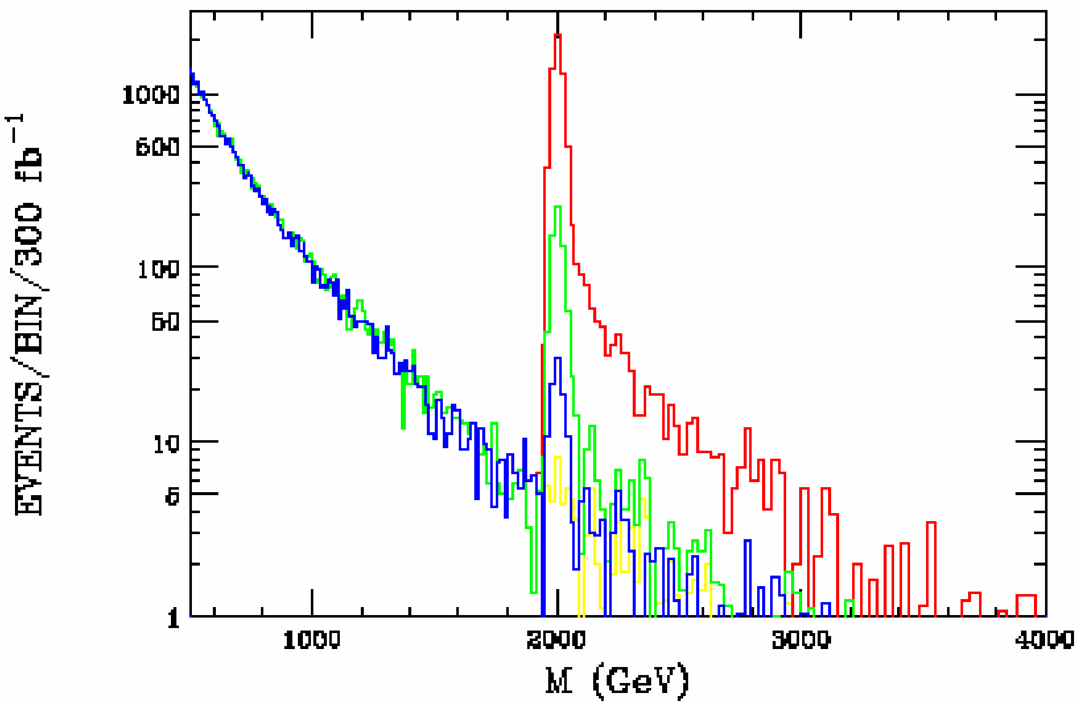
and

b. Real production of unparticles.



Collider Signals

Virtual unparticle exchange is very similar to Drell-Yan processes. Main difference: no resonant pole. Instead “half a resonance”.



Rizzo

Figure 5: High resolution scan of the Drell-Yan dilepton mass distribution at the LHC assuming a large integrated luminosity taking $d = 1.5$, $\mu = 2$ TeV with $\Lambda = 3(10, 25)$ TeV corresponding to the

Unparticle Self-Interactions

Feng, AR, Tu

More interesting: unparticle self-interactions.

3-point interactions of operators are fixed up to a constant by conformal invariance

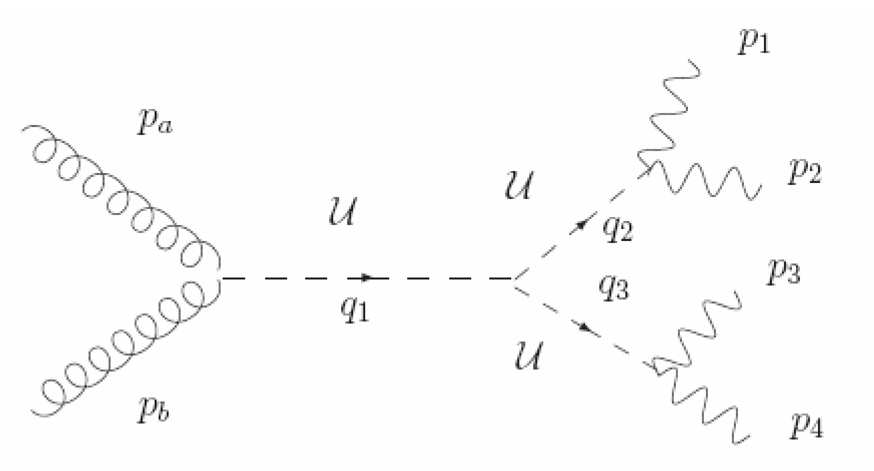
$$T\,(O(x)\,O(y)\,O(z)) = \frac{C}{(x-y)^d\,(y-z)^d\,(z-x)^d}$$

Unparticle Self-Interactions

Assume again that the unparticle couples to gluons and photons

$$L_{int} = \Lambda^{-d} O F^2 + \Lambda^{-d} O G^2$$

At the LHC we can now have four-photon processes



Unparticle Self-Interactions

Rate set by constant C in three point-function.

This constant is not constrained by theory.

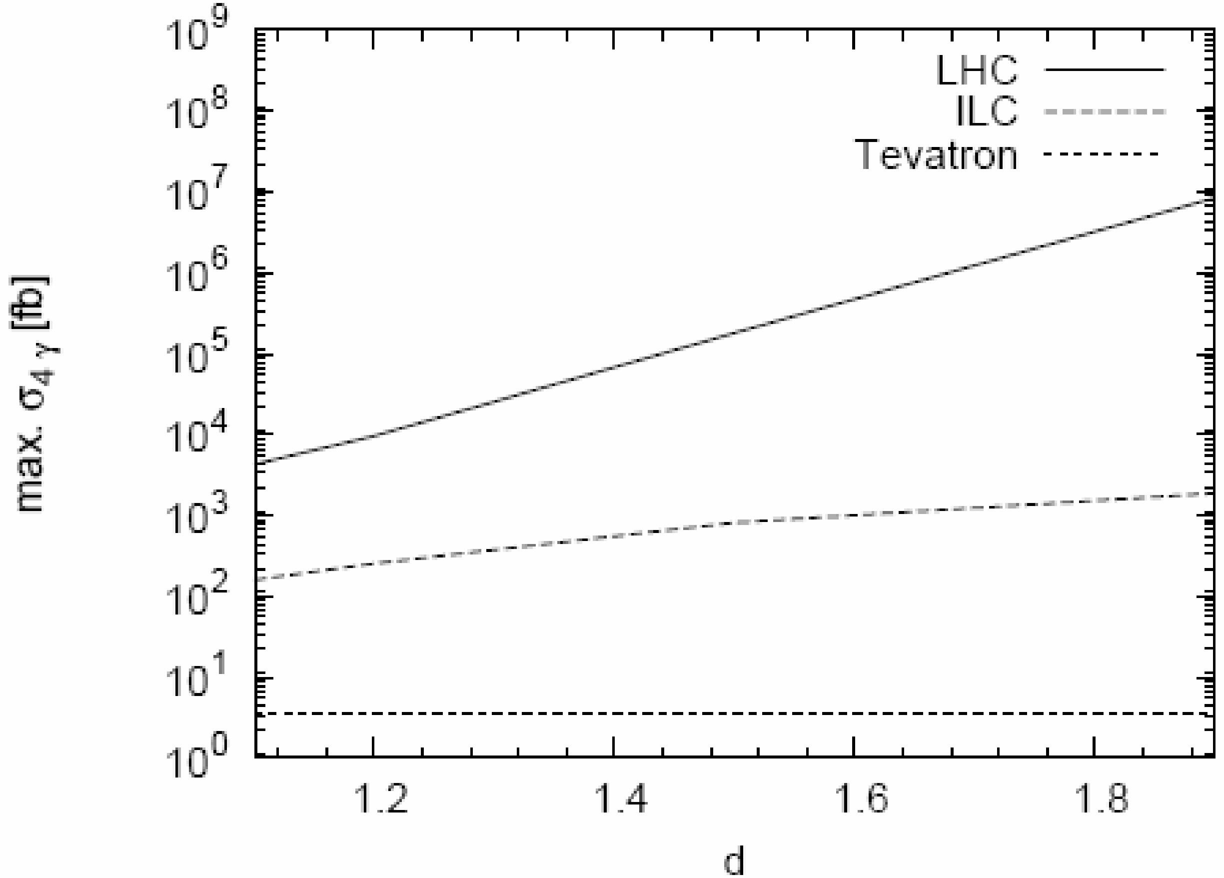
From experiments (Tevatron) we find that

$$\frac{C}{(\Lambda/\mathrm{TeV})^{3d}} < \begin{cases} 1.3 \times 10^{4} & \text{for } d=1.1 \\ 4.8 \times 10^{5} & \text{for } d=1.9 \end{cases}$$

Unparticle Self-Interactions

Feng, AR, Tu

With these bounds, huge signals at LHC, ILC.



Almost background free!

Collider Signals of Unparticles:

Effects from Unparticle Decays

Unparticle Decays

Unparticles can be produced at hadron colliders through processes like $gg \rightarrow gO$.

If the unparticle does not decay we get monojets. More generally, we would get missing energy signals.

Unparticle Decays

Unparticles can be produced at hadron colliders through processes like gg $\rightarrow$ gO.

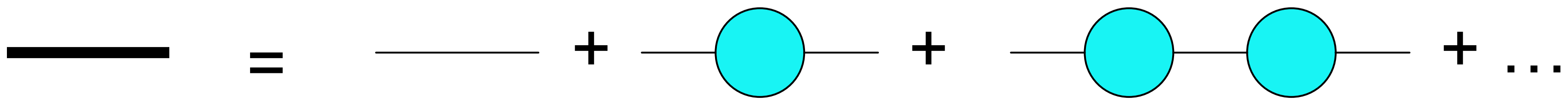
If the unparticle does not decay we get monojets. More generally, we would get missing energy signals.

We will now argue that in fact unparticles can decay to SM particles. Rajaraman

This will severely modify this set of signals. We do not get missing energy signals in general.

Unparticle Decays

To see this, sum corrections from loop diagrams



$$iB_d D(p^2) \;=\; iB_d D_0(p^2) + iB_d D_0(p^2)\,(-i\,\Sigma)\,iB_d D_0(p^2) + \ldots$$

$$= \frac{iB_d}{(D_0(p^2))^{-1} - B_d \Sigma}$$

Unparticle Decays

$$\text{Propagator} = \frac{iB_d}{(D_0(p^2))^{-1} - B_d\Sigma}$$

If Σ is imaginary, appears like a width.

In deconstructed form:

$$\text{Propagator} = \frac{A_d}{2\pi} \int dM^2 \frac{\rho(M^2)}{p^2 - M^2 + iM\Gamma + i\varepsilon}$$

where the width is proportional to the imaginary part of Σ .

Unparticle Decays

Rajaraman

For example, if $(D_0(p^2)\,)^{-1} = (p^2 - \mu^2)^{2-d}$

then we find

$$M\Gamma = \frac{A_d \cot(\pi d)\,(M^2 - \mu^2)^{d-1}}{2(2-d)}\ \mathrm{Im}\,\Sigma$$

except for $(M^2 - \mu^2)^{2-d} < \mathrm{Im}\,\Sigma$ where

$$M\Gamma = B_d\,(M^2 - \mu^2)^{d-1}\,\mathrm{Im}\,\Sigma$$

Unparticle Decays

If unparticles are produced at colliders, they can themselves decay back to Standard Model particles.

Depending on the lifetime, we have different signals:

Short lifetime:	prompt decay
Very long lifetime:	monojets
Intermediate situation:	delayed events, displaced vertices

Unparticle Decays

Example: suppose the unparticle has the couplings

$$L_{int} = \Lambda^{-d}\, O\, F^2 + \Lambda^{-d}\, O\, G^2$$

Unparticles can be produced at hadron colliders through the process $gg \to gO$.

These unparticles can then decay to photons and gluons with prompt decays, monojets, or delayed events.

Unparticle Decays

We calculate the number of each type of event, with 10 fb^{-1} of LHC data. We take $d=1.1$, $\Lambda = 10$ TeV.

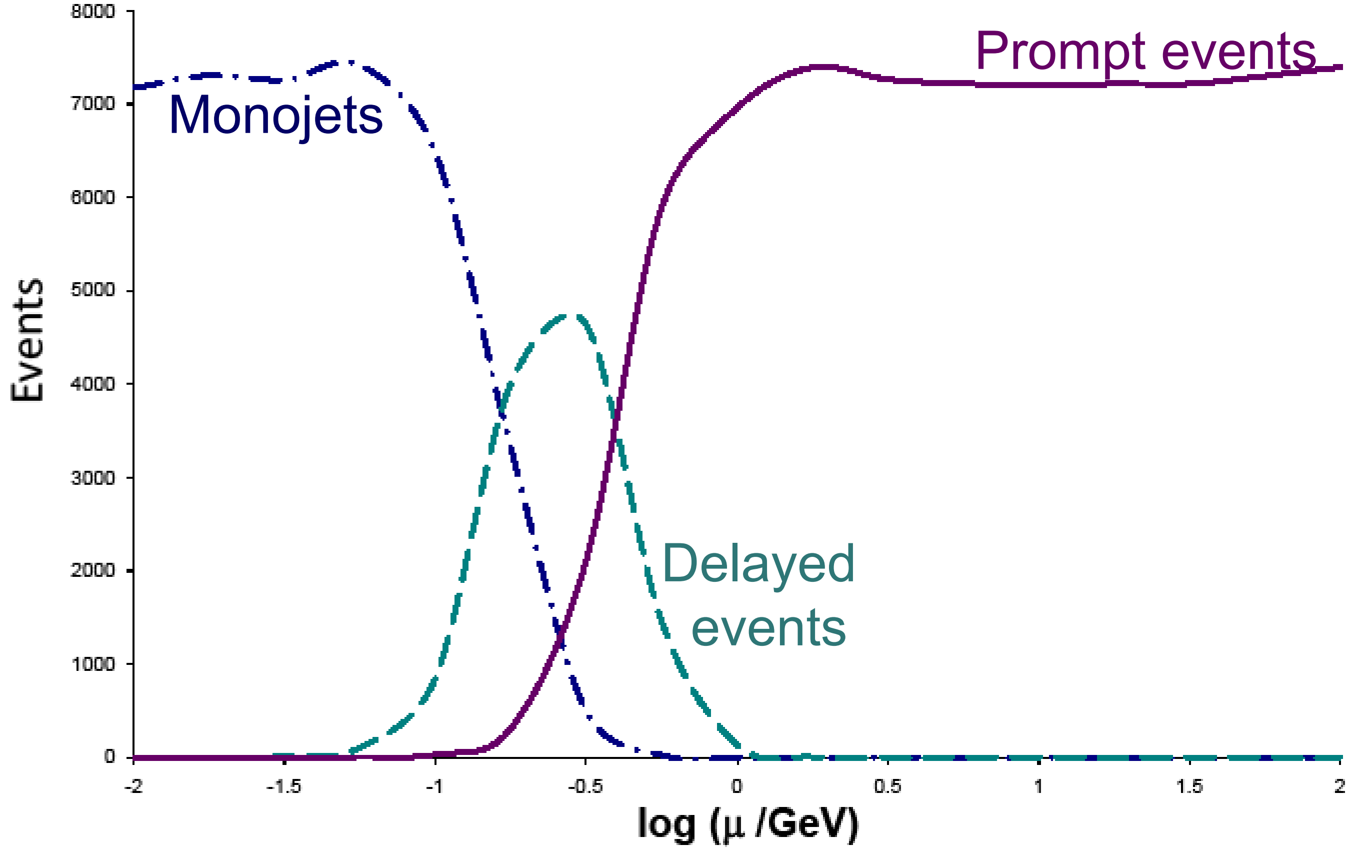
We require that the gluon jet has energy > 100 GeV.

We shall assume that

a. the detector is ~ 1m in size
b. delays of 100ps can be measured.

Unparticle Decays

Events as a function of the mass gap μ.



Unparticle Decays

For μ > 10 GeV, only prompt events.

Significant number of monojets only if μ < 100 MeV.

Intermediate range (μ ~ 1 GeV): large number of delayed events.

Conclusions

Unparticles are an interesting alternative model for the hidden sector.

Considering the modification of the unparticle sector (mass gap, decays) due to interactions is crucial for doing phenomenology.

Many unique and striking signals at colliders.

Delayed events
Displaced vertices
Multiphoton processes

Conclusions

There is still much work to do in unparticles…