Novel Signatures for Unparticle Physics

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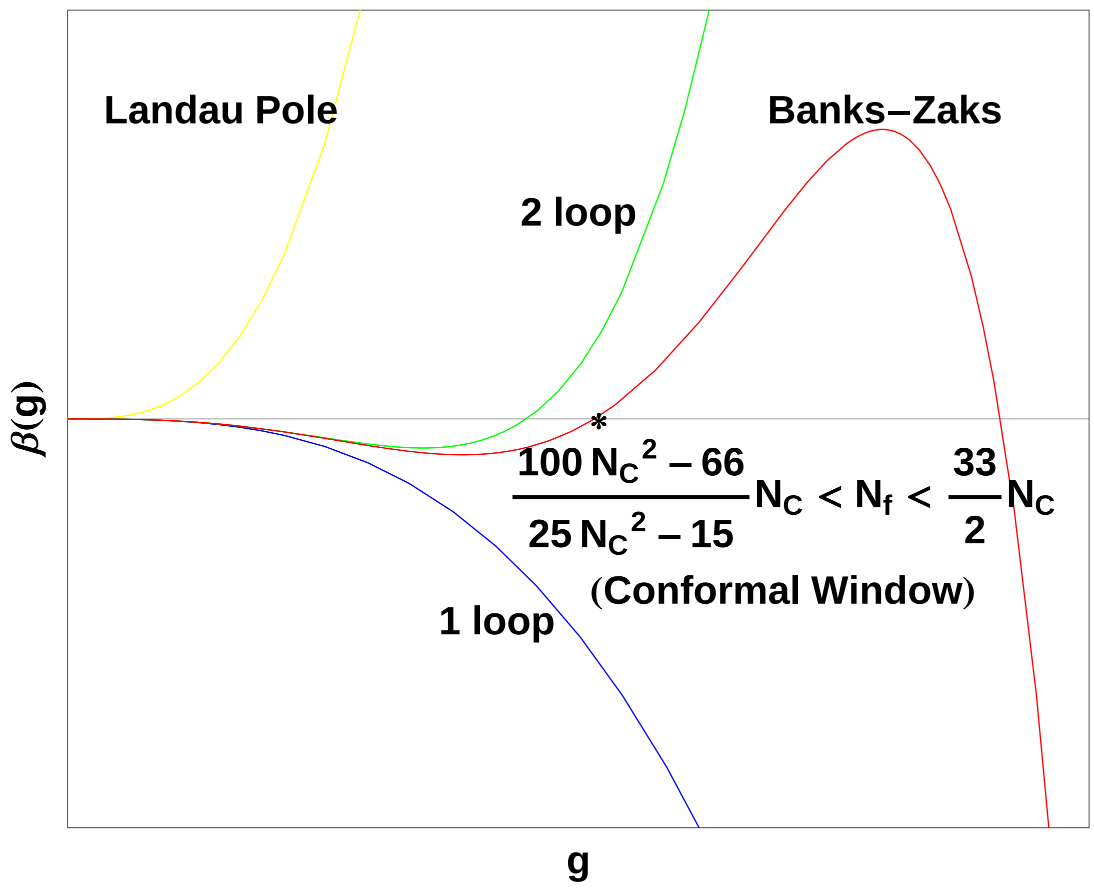
Motivation:

- Banks-Zaks Theory – IR fixed point (Perturbative)



- Imagine there exists a scale invariant sector at a high scale $M_{\mathcal{U}}$. (Banks-Zaks is an example). Below $M_{\mathcal{U}}$,

$$\frac{\mathcal{O}_{\rm SM}\,\mathcal{O}_{\mathcal{BZ}}}{M_{\mathcal{U}}^k} \qquad (k>0)$$

Dimensional Transmutation $\rightsquigarrow \Lambda$

$$\frac{C_{\mathcal{O}_{\mathcal{U}}}\Lambda^{d_{\mathcal{BZ}}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^k}\,\mathcal{O}_{\rm SM}\,\mathcal{O}_{\mathcal{U}}$$

- $d_{\mathcal{BZ},\mathcal{U}}$ is the engineering dimension of $\mathcal{O}_{\mathcal{BZ},\mathcal{U}}$
- $\mathcal{O}_{\mathcal{U}} = O_{\mathcal{U}}, O_{\mathcal{U}}^{\mu}, O_{\mathcal{U}}^{\mu\nu}, \cdots$

Unparticle Scalar Operator:

- Two-point function

$$
\begin{aligned}
\langle 0|O_{\mathcal{U}}(x)O^{\dagger}_{\mathcal{U}}(0)|0\rangle &= \langle 0|e^{iP\cdot x}O_{\mathcal{U}}(0)e^{-iP\cdot x}O^{\dagger}_{\mathcal{U}}(0)|0\rangle \\
&= \int \frac{d^4P}{(2\pi)^4}\, e^{-iP\cdot x}\, |\langle 0|O_{\mathcal{U}}(0)|P\rangle|^2 \rho(P^2) \\
\rho(P^2) &= Spectral\ density
\end{aligned}
$$

- Inverse Fourier transformation

$$
\begin{aligned}
|\langle 0|O_{\mathcal{U}}(0)|P^2\rangle|^2 \rho(P^2) &= \int d^4x e^{iP\cdot x}\langle 0|O_{\mathcal{U}}(x)O^{\dagger}_{\mathcal{U}}(0)|0\rangle \\
&= A_{d_{\mathcal{U}}}\ \theta(P^0)\ \theta(P^2)\ (P^2)^{\alpha} \\
\alpha &= Scaling\ exponent\ to\ be\ fixed
\end{aligned}
$$

- Scale Transformation:

$$\begin{aligned} x &\rightarrow sx \\ O_{\mathcal{U}}(sx) &\rightarrow s^{-d_{\mathcal{U}}} O_{\mathcal{U}}(x) \\ d_{\mathcal{U}} &= \mathit{Scale\ Dimension\ of\ } O_{\mathcal{U}} \end{aligned}$$

- Under scale transformation

$$\begin{aligned} A_{d_{\mathcal{U}}}\,(P^2)^{\alpha}\theta(P^0)\,\theta(P^2) &= \int d^4x s^4 e^{isP\cdot x}\langle 0|s^{-2d}O_{\mathcal{U}}(x)O^{\dagger}_{\mathcal{U}}(0)|0\rangle \\ &= s^{-2(d_{\mathcal{U}}-2)}A_{d_{\mathcal{U}}}\,(s^2P^2)^{\alpha}\theta(P^0)\,\theta(P^2) \end{aligned}$$

- Scale invariance implies

$$\begin{aligned} \alpha &= d_{\mathcal{U}} - 2 \\ |\langle 0|O_{\mathcal{U}}(0)|P\rangle|^2\rho(P^2) &= A_{d_{\mathcal{U}}}\,\theta(P^0)\,\theta(P^2)\,(P^2)^{d_{\mathcal{U}}-2} \end{aligned}$$

- N massless particle phase space: $(p_1 + p_2 + \cdots + p_n)^2 = s^2$

$$dLIPS_n \quad = \quad A_n s^{n-2} \;, \quad A_n = \frac{16\pi^2\sqrt{\pi}}{(2\pi)^{2n}} \frac{\Gamma(n+\frac{1}{2})}{\Gamma(n-1)\Gamma(2n)}$$

- Georgi (arXiv:hep-ph/0703260, PRL 98, 221601 (2007)) introduces unparticle

$$d_{\mathcal{U}} \to n \quad ; \qquad A_{d_{\mathcal{U}}} \to A_n$$

- Unparticle of scale dimension $d_{\mathcal{U}}$ behaves like a collection of $d_{\mathcal{U}}$ massless invisible particles. A priori, $d_{\mathcal{U}}$ can be any real or even complex number. First special feature of unparticle.
- Unparticle phase space (No fixed mass!)

$$\int A_{d_{\mathcal{U}}}\, \theta(P^0_{\mathcal{U}})\, \theta(P^2_{\mathcal{U}})\, \left(P^2_{\mathcal{U}}\right)^{d_{\mathcal{U}}-2} \frac{d^4 P_{\mathcal{U}}}{(2\pi)^4}$$

- As $d_{\mathcal{U}} \to 1$, unparticle $\to$ 1 massless particle.

Low Energy Phenomenology:

- Effective Operators

$$\lambda_0 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\alpha\beta} G^{\alpha\beta} O_{\mathcal{U}} \;, \lambda_0' \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} f O_{\mathcal{U}} \;, \quad \lambda_0'' \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{f} \gamma^5 f O_{\mathcal{U}} \;,$$

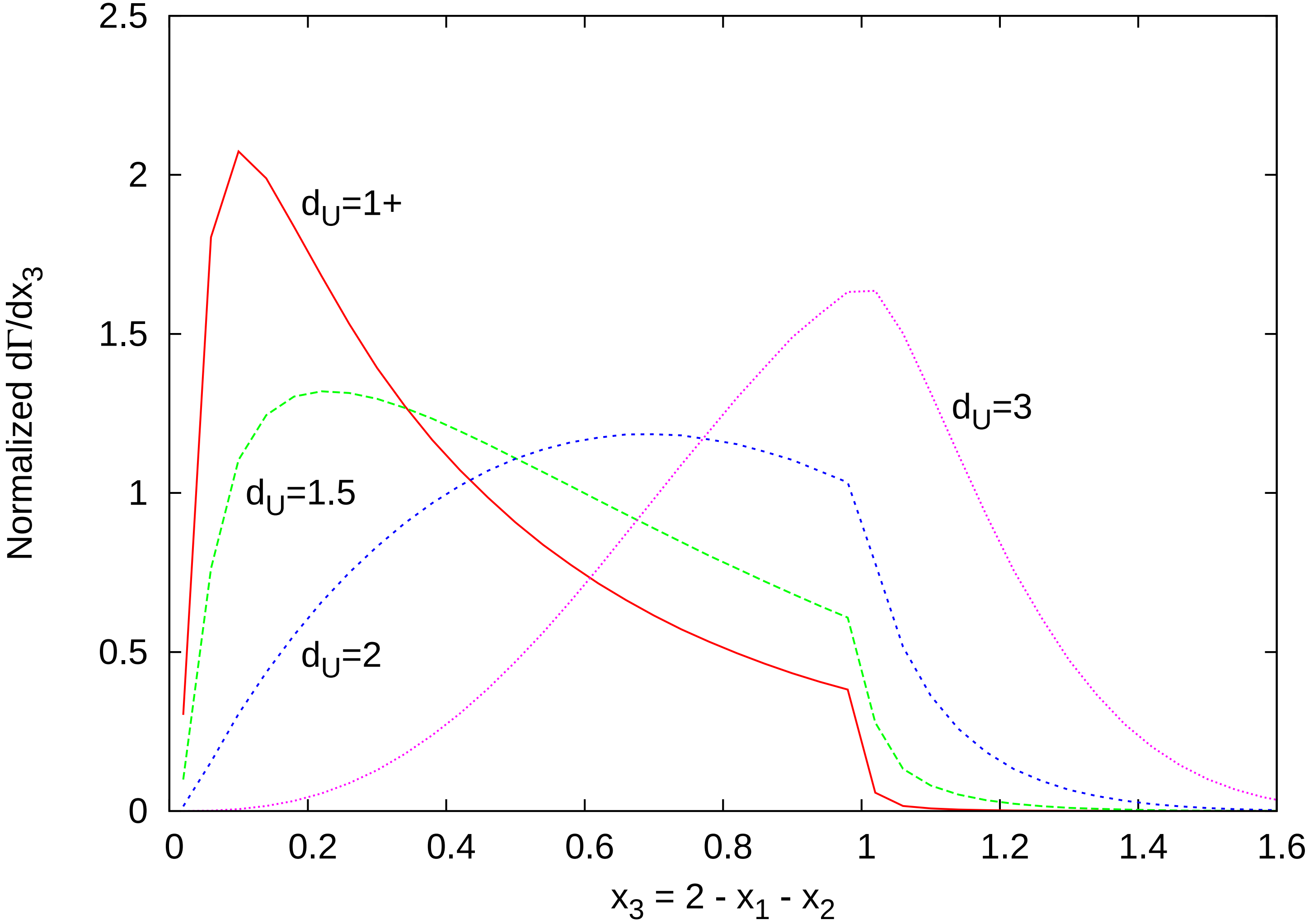
$$\lambda_0''' \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{f} \gamma^\mu f (\partial_\mu O_{\mathcal{U}}) \;,$$

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

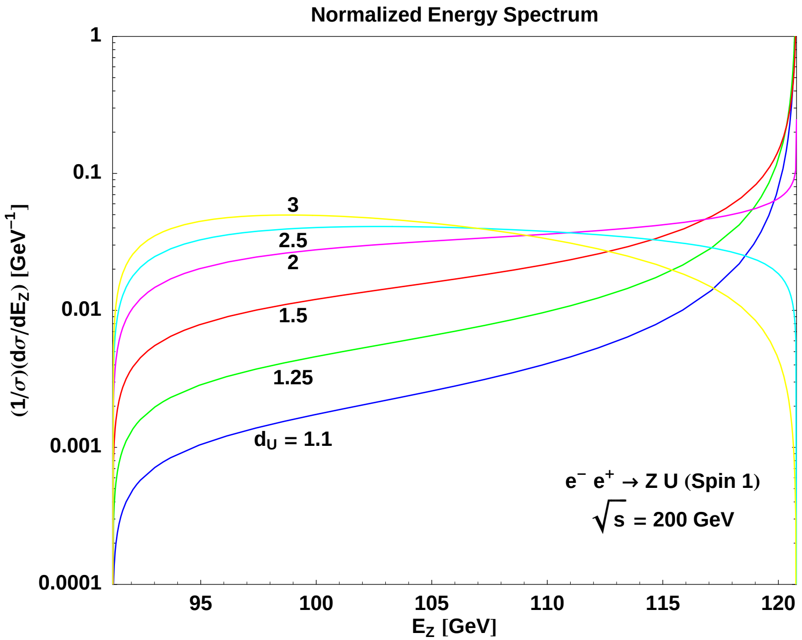
$$\lambda_2 \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} G_{\mu\alpha} G_\nu^{\;\alpha} O_{\mathcal{U}}^{\mu\nu} \;, \quad -\frac{1}{4} \lambda_2' \frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{\psi} \, i \left(\gamma_\mu \overset{\leftrightarrow}{D}_\nu + \gamma_\nu \overset{\leftrightarrow}{D}_\mu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

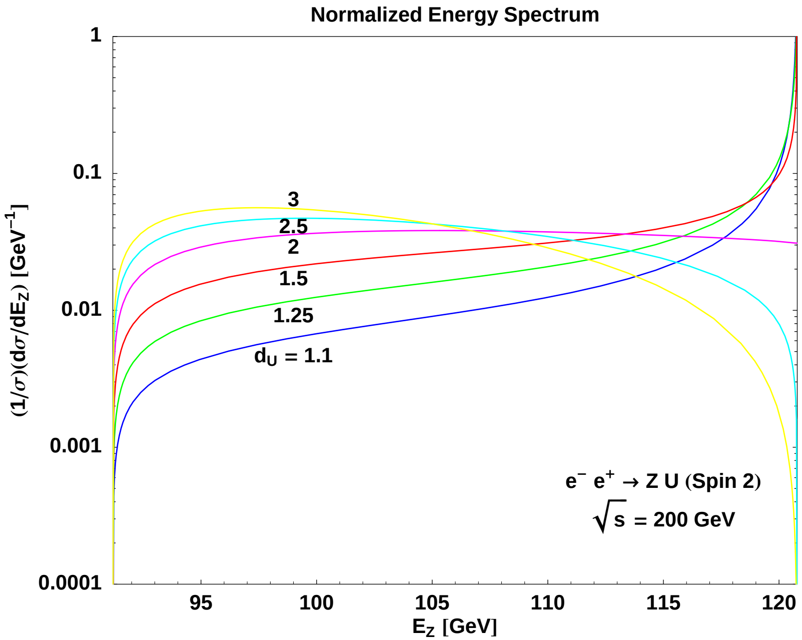
$$\cdots\cdots (\mathrm{Chen\,and\,He,\;arXiv:0705.3946\,[hep-ph]})$$

- $Z \to f\bar{f}\mathcal{U}$ (Spin 1)

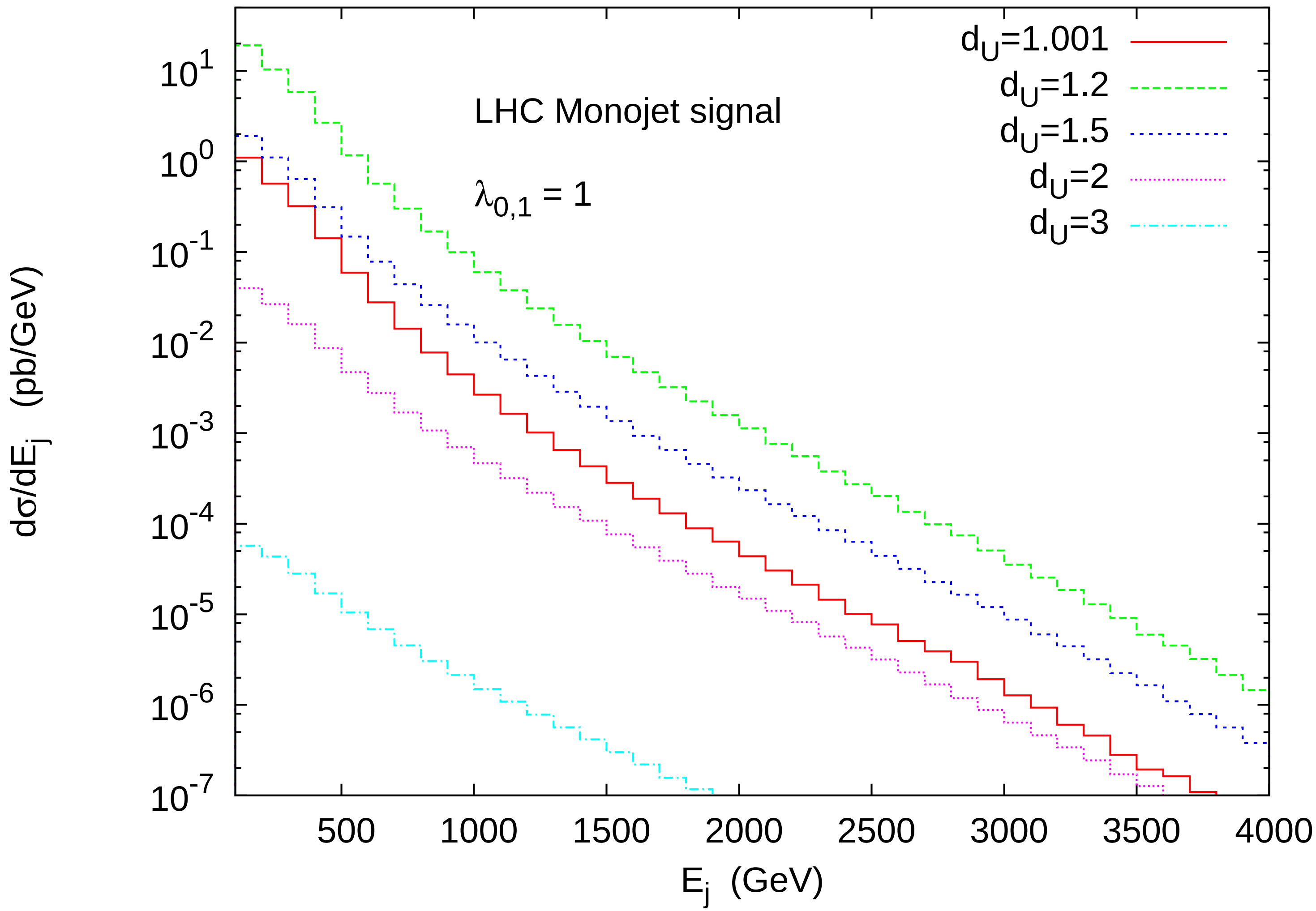


- $e^- e^+ \to Z\mathcal{U}$ at LEP2 (Spin 1 and 2 unparticle)

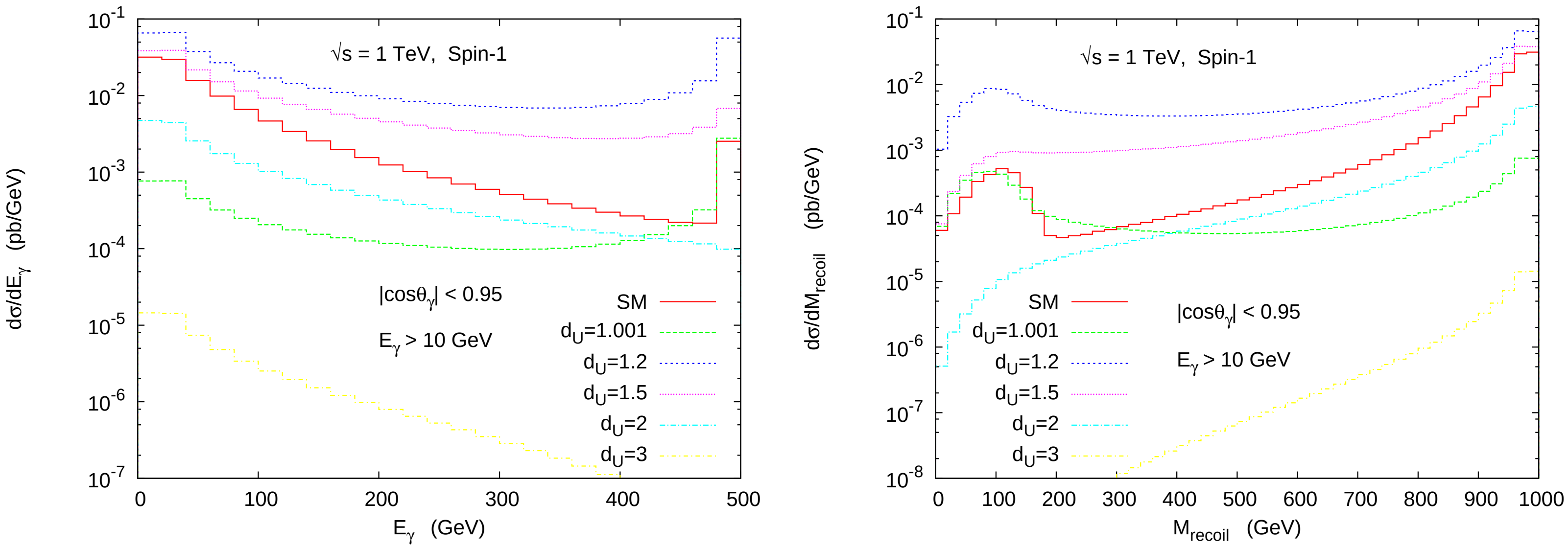




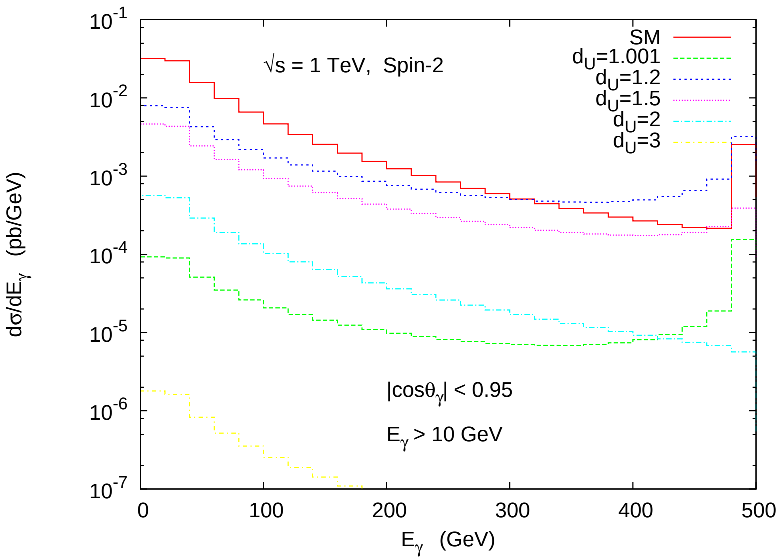
- Monojet + $\mathcal{U}$ production at LHC

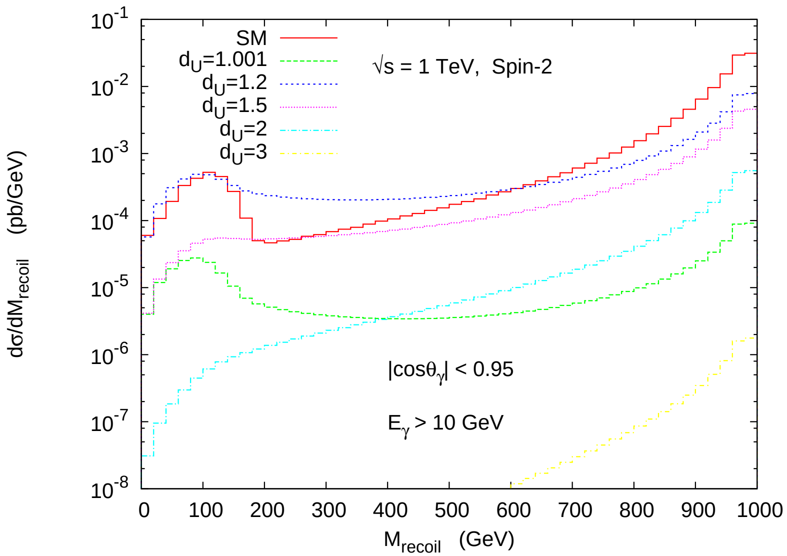


- $e^- e^+ \to \gamma\mathcal{U}$ (Spin 1)



- $e^- e^+ \to \gamma \mathcal{U}$ (Spin 2)





Unparticle Propagator:

- Källén-Lehmann Spectral Representation Formula

$$\begin{aligned}\Delta_{\mathcal{U}}(P^2) &= \frac{1}{2\pi}\int_0^\infty \frac{\rho(M^2)dM^2}{P^2 - M^2 + i\epsilon} \\ &= \frac{1}{2\pi}\,(\text{p.v.})\int_0^\infty \frac{\rho(M^2)dM^2}{P^2 - M^2} - i\frac{1}{2}\,\rho(P^2)\theta(P^2)\end{aligned}$$

- Georgi – arXiv:0704.2457 [hep-ph];
  Cheung, Keung and TCY – arXiv:0704.2588 [hep-ph].

$$\Delta_{\mathcal{U}}(P^2) = \frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}(-P^2 - i\epsilon)^{d_{\mathcal{U}}-2}$$

- For time-like $P^2 > 0$, $\Delta_{\mathcal{U}}(P^2)$ has a phase due to the branch cut for non-integral $d_{\mathcal{U}}$. Second special feature of unparticle.

- 4-fermion interaction with spin 1 and 2 unparticle exchange

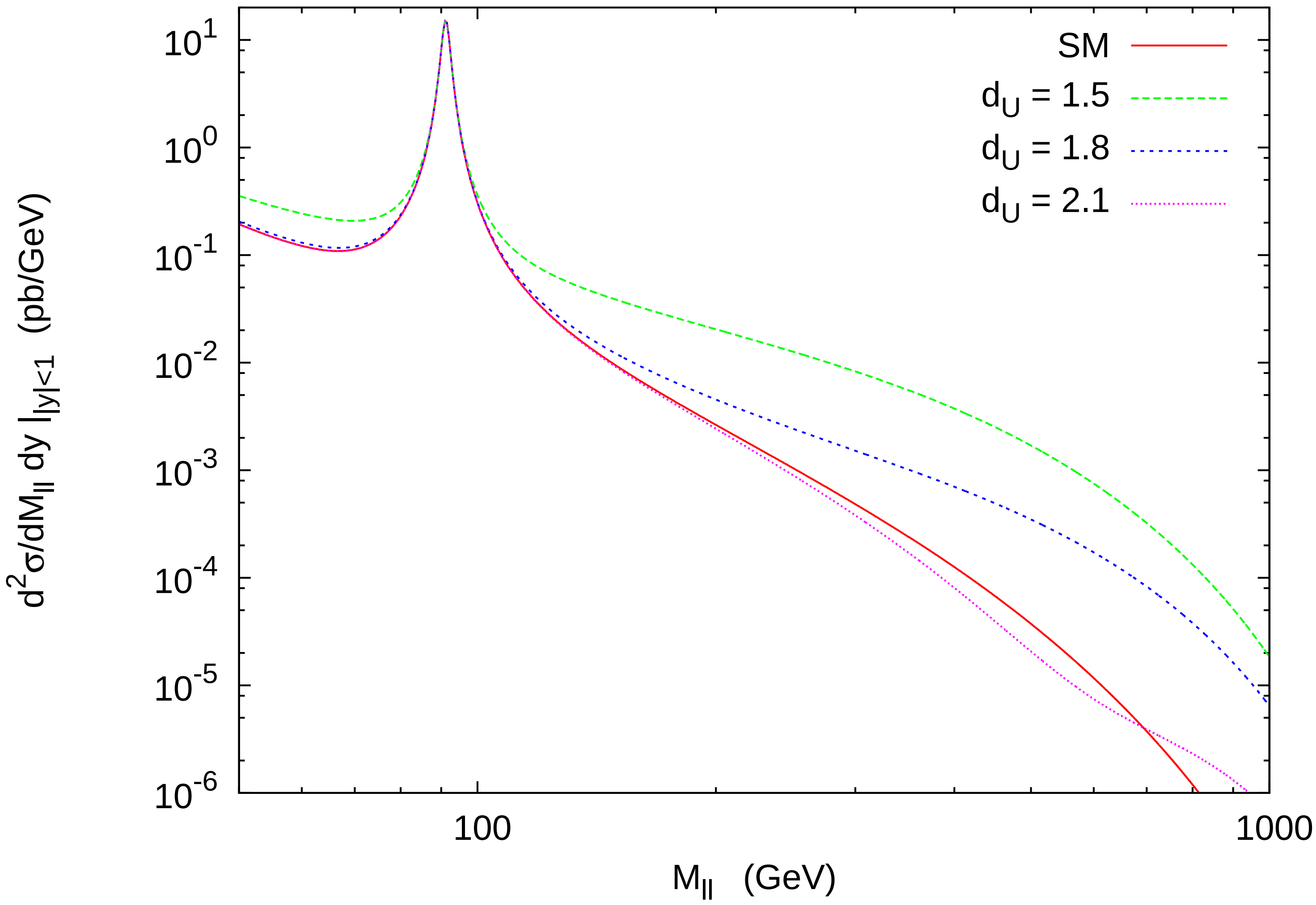
$$\mathcal{M}_1^{4f} = \lambda_1^2 \, Z_{d_\mathcal{U}} \, \frac{1}{\Lambda_\mathcal{U}^2} \left(-\frac{P_\mathcal{U}^2}{\Lambda_\mathcal{U}^2} \right)^{d_\mathcal{U}-2} \, (\bar{f}_2 \gamma_\mu f_1) \, (\bar{f}_4 \gamma^\mu f_3)$$

$$\begin{aligned} \mathcal{M}_2^{4f} &= \lambda_2'^2 \, Z_{d_\mathcal{U}} \, \frac{1}{\Lambda_\mathcal{U}^4} \left(-\frac{(p_1 - p_2)^2}{\Lambda_\mathcal{U}^2} \right)^{d_\mathcal{U}-2} \, \left(\bar{f}_2 \gamma^\mu f_1\right) \, \left(\bar{f}_4 \gamma^\nu f_3\right) \\ &\times \frac{1}{4} \left[(p_1 + p_2) \cdot (p_3 + p_4) g_{\mu\nu} + (p_1 + p_2)_\nu (p_3 + p_4)_\mu \right] \end{aligned}$$

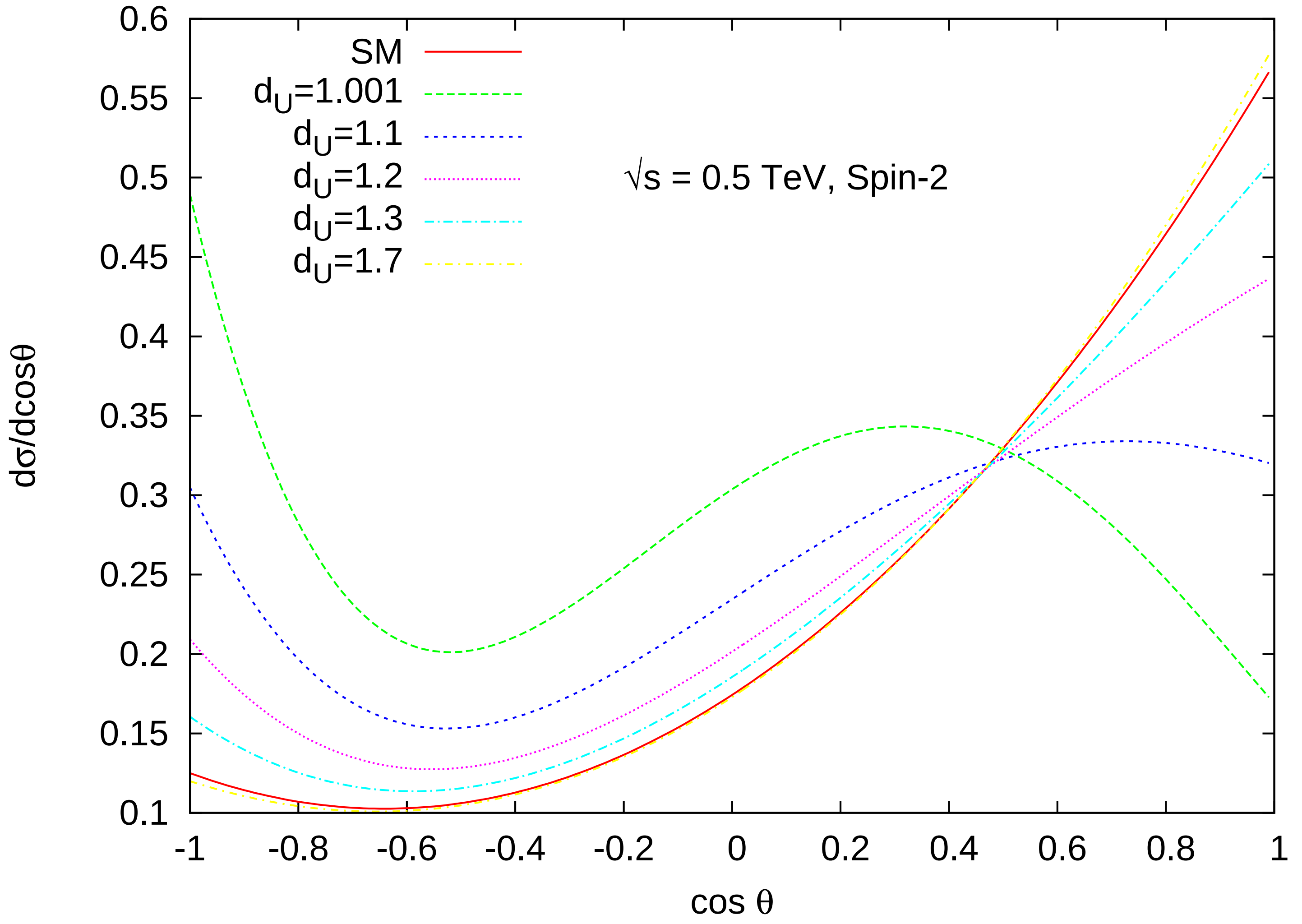
with

$$Z_{d_\mathcal{U}} = \frac{A_{d_\mathcal{U}}}{2 \sin(d_\mathcal{U} \pi)}$$

- Drell-Yan at Tevatron: SM + Spin 1 Unparticle Interference

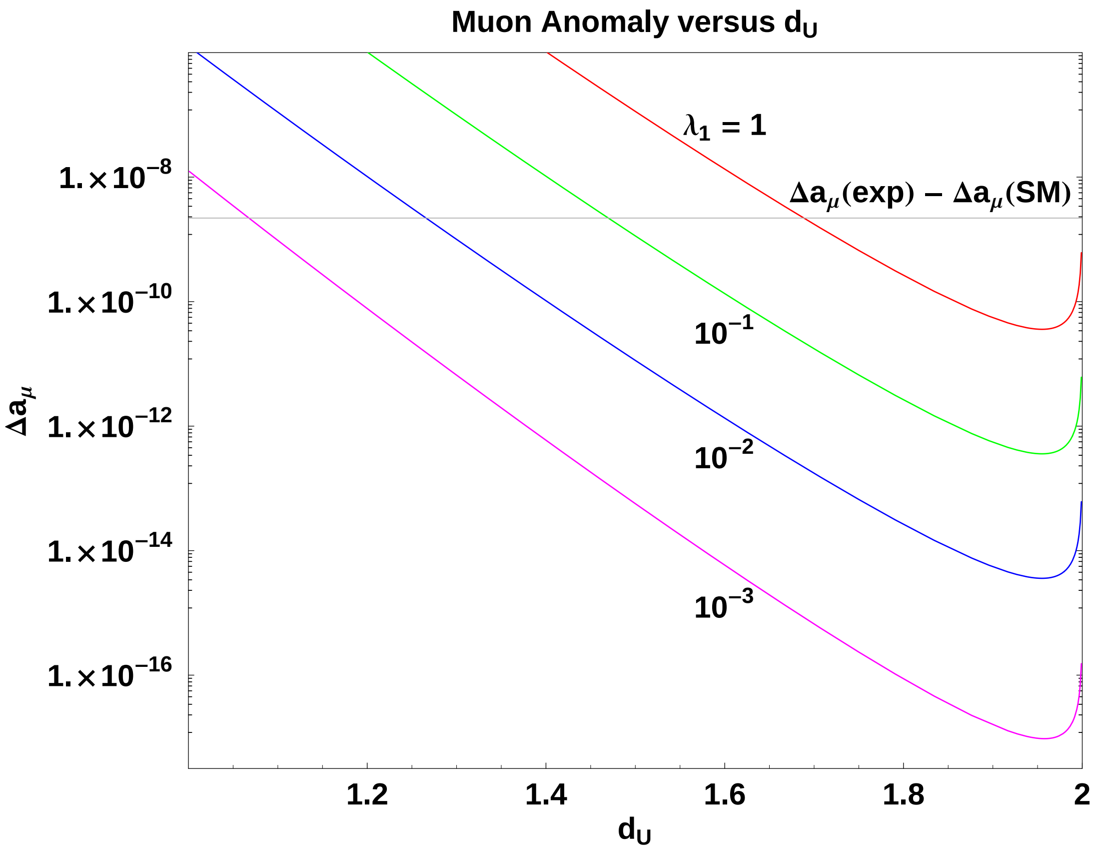


- $e^-e^+ \to f\bar{f}$ at ILC: SM + Spin 2 Unparticle Interference



- Muon Anomalous Magnetic Moment

$$\Delta a_l = -\frac{\lambda_1^2}{8\pi^2}\frac{A_{d_{\mathcal{U}}}}{\sin(d_{\mathcal{U}}\pi)}\left(\frac{m_l^2}{\Lambda_{\mathcal{U}}^2}\right)^{d_{\mathcal{U}}-1} \mathrm{B}(3-d_{\mathcal{U}}, 2d_{\mathcal{U}}-1)$$



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Summary:

- Rich Phenomenology!
- But, What is UNPARTICLE?
- Corresponds to Higher Dimension Theory?
- " ... To my mind, this would be a much more striking discovery than the more talked about possibilities of supersymmetry (SUSY) or extra dimensions. SUSY is more new particles. From our four-dimensional point of view until we see black holes or otherwise manipulate gravity, finite extra dimensions are just a metaphor (infinite extra dimensions, however, can have unparticle behaviors – see [9]). Again, what we see is just more new particles. We would be overjoyed and fascinated to see these new particles and eventually patterns might emerge that show the beautiful theoretical structures they portend. But I will argue that unparticle stuff with nontrivial scaling would astonish us immediately." – H. Georgi