Collider phenomenology of the unparticle physics

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Plan

- Introduction
- Processes with real unparticle emissions
- Processes with virtual unparticle exchange
- Summary
- H. Georgi, PRL98, 221601 (2007);PLB650, 275 (2007), K. Cheung etal., PRL99, 051803 (2007); PRD76,055003 (2007), D. Choudhury, PLB658, 148 (2008); arXiv:0707.2074[hep-ph], accepted for publication in IJMPA, K. Huitu etal. PRD77,035015 (2008).

Scale Invariant Sector

- Scale invariance forbids mass terms in the theory.
- A free massless particle is a simple example of scale invariant theory.
- There could be a exactly scale invariant sector at a high scale above TeV that could be probed at the LHC or ILC.
- Scuh a sector might be strongly interacting and highly non-trivial, but can weakly interacting with the rest of the SM.
- One expects that such a sector decouples effectively from the low energy and can use the technique of effective field theory to describe its low energy effects.

Scale Invariant Sector

- Imagine that at a very high energy scale there exists an exact scale-invariant sector with non-trivial IR fixed point. Let us call the fields of the scale-invariant sector as BZ fields.

- The interactions between the SM sector and the BZ sector is introduced just in an effective field theory way, by exchanging heavy messenger particles (of mass scale $M_{\mathcal{U}}$) leading to non-renormalizable interaction below the scale $M_{\mathcal{U}}$

$$\mathcal{L}_{eff} = \frac{1}{M_{\mathcal{U}}^{d_{\rm BZ}+d_{\rm SM}-4}} \mathcal{O}_{\rm BZ} \mathcal{O}_{\rm SM}$$

- As in massless non-Abelian gauge theories, renormalizaton effects the scale invariant BZ sector induce dimensional transmutation at an energy scale $\Lambda_{\mathcal{U}}$.

Scale Invariant Sector

- In the effective theory below the scale $\Lambda_{\mathcal{U}}$, the BZ operators must match onto new (unparticle) operators which have the following form of the interaction:

$$\mathcal{L}_{eff} = c_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{\rm BZ} - d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{\rm BZ} + d_{\rm SM} - 4}} \mathcal{O}_{\rm SM} \mathcal{O}_{\mathcal{U}}$$

- $d_{\mathcal{U}}$ is the scale dimension of the unparticle operator $\mathcal{O}_{\mathcal{U}}$ and $c_{\mathcal{U}}$ is a coefficient fixed by the matching.

- Three unparticle operators with different Lorentz structure were addressed by Georgi : $\mathcal{O}_{\mathcal{U}}, \mathcal{O}_{\mathcal{U}}^{\mu}, \mathcal{O}_{\mathcal{U}}^{\mu\nu}$ which correspond to scalar, vector and tensor operators respectively.

- We assume that these operators are SM singlet.

Scale Invariant Sector

- If one assumes the scale invariant BZ theory at $\Lambda_{\mathcal{U}}$ to be strongly coupled, the BZ particles will be confined into a composite states.
- Therefor a natural interpretation of the unparticles is that they are composite states made of confined BZ particles.
- The strongly interacting sector is scale invariant $\Longrightarrow$ no distinct mass or length scale associated with these states.
- The unparticles will correspond normal particles with states of continuous mass.
- This continuous mass states leads to a very unconventional phenomenology.

Phase space for real emission of unparticle

- Consider a two -point function for a scalar unparticle operator $\mathcal{O}_{\mathcal{U}}$:

$$
\begin{aligned}
\langle 0|\mathcal{O}_{\mathcal{U}}(x)\mathcal{O}^{\dagger}_{\mathcal{U}}(0)|0\rangle &= \langle 0|e^{i\hat{P}\cdot x}\mathcal{O}_{\mathcal{U}}(0)e^{-i\hat{P}\cdot x}\mathcal{O}^{\dagger}_{\mathcal{U}}(0)|0\rangle \\
&= \int d\beta \int d\beta' \langle 0|\mathcal{O}_{\mathcal{U}}(0)|\beta'\rangle\langle\beta'|e^{-i\hat{P}\cdot x}|\beta\rangle\langle\beta|\mathcal{O}^{\dagger}_{\mathcal{U}}(0)|0\rangle \\
&= \int \frac{d^4P}{(2\pi)^4}\, e^{-iP\cdot x}\, \rho_{\mathcal{U}}(P^2)
\end{aligned}
$$

- $\rho_{\mathcal{U}}(P^2)$ is the spectral density and is formally given by :

$$
\rho_{\mathcal{U}}(P^2) = (2\pi)^4 \int d\beta\, \delta^4(P - p_\beta)|\langle 0|\mathcal{O}_{\mathcal{U}}(0)|\lambda\rangle|^2.
$$

- The function $\rho_{\mathcal{U}}(P^2)$ is real valued, positive definite, and Lorentz invariant. It depends on the scalar variable P^2.

Phase space for real emission of unparticle

- Scale invariance $\Longrightarrow$:

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

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

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

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

- Identify $n \Rightarrow d_{\mathcal{U}}$. Unparticles of scale dimension $d_{\mathcal{U}}$ behaves like a collection of $d_{\mathcal{U}}$ of massless particles.

- $d_{\mathcal{U}} = 1 \Rightarrow$ unparticle $=$ one massless particle which couples weakly to the SM particles.

Scalar unparticle propagator

- Let us first calculate the scalar unparticle propagator :
- From Wightman 2-point correlation function we have after imposing scale invariance:

$$\int d^4x e^{iPx} \langle 0 | \mathcal{T}[\mathcal{O}_{\mathcal{U}}(x) \mathcal{O}^{\dagger}_{\mathcal{U}}(0)] | 0 \rangle = \frac{A_{d_{\mathcal{U}}}}{(2\pi)} \int_0^{\infty} \frac{dM^2 (M^2)^{d_{\mathcal{U}}-2} i}{(P^2 - M^2 + i\epsilon)}$$

- Integration of the R.H.S. gives

$$\frac{A_{d_{\mathcal{U}}}}{2} \frac{i(-P^2 - i\epsilon)^{d_{\mathcal{U}}-2}}{\sin(\pi d_{\mathcal{U}})}, \qquad A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n+1/2)}{\Gamma(n-1)\,\Gamma(2n)}$$

- $(-P^2 - i\epsilon)^{d_{\mathcal{U}}-2} = \mid P^2 \mid^{d_{\mathcal{U}}-2} \exp(-i d_{\mathcal{U}} \pi)$ for $P^2 > 0 \Longrightarrow$ Complex phase
- $(-P^2 - i\epsilon)^{d_{\mathcal{U}}-2} = \mid P^2 \mid^{d_{\mathcal{U}}-2}$ for $P^2 < 0 \Longrightarrow$ No Complex phase

Vector unparticle propagator

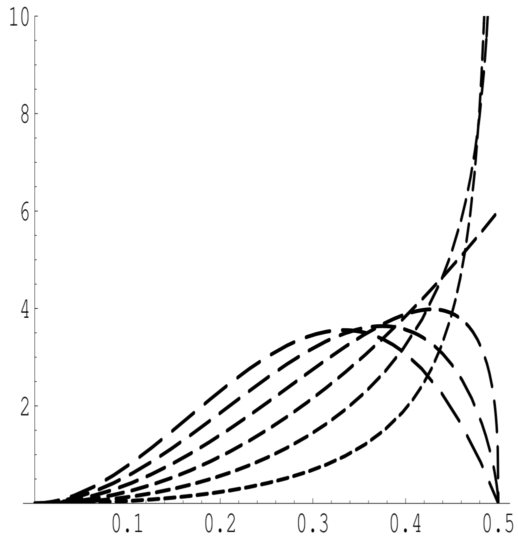
- spin-1 transverse $(\partial_\mu \mathcal{O}^\mu_\mathcal{U} = 0)$ unparticle propagator :
- In this case the 2-point correlation function is :

$$\begin{aligned}\Pi^{\mu\nu}(q) &= \int d^4x e^{iqx} \langle 0|\mathcal{O}^\mu_\mathcal{U}(x)\mathcal{O}^{\nu\dagger}_\mathcal{U}(0)|0\rangle \\ &= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) \frac{A_{d_\mathcal{U}}}{(2\pi)} \int_0^\infty \frac{dM^2 (M^2)^{d_\mathcal{U}-2} i}{(q^2 - M^2 + i\epsilon)} \\ &= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) i\Delta_\mathcal{U}\end{aligned}$$

- Where, $\Delta_\mathcal{U} = \frac{A_{d_\mathcal{U}}}{2\sin(\pi d_\mathcal{U})} \left(-q^2 - i\epsilon\right)^{d_\mathcal{U}-2}$.
- Propagator has a singularity at integral values of $d_\mathcal{U} = 2, 3..$, these integer values of $d_\mathcal{U}$ describes multi particle cuts.
- Compare with Z propagator : $\pi^Z_{\mu\nu}(q) = \frac{i\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)}{q^2 - M_Z^2 + iM_Z\Gamma_Z}$

Real Unparticle emission

$t \to u + \mathcal{U}$ [Georgi, PRL 98, 221601 (2007)]



- Unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a non-integral number $d_{\mathcal{U}}$ of invisible particles.

- Consider $t \to u + \mathcal{U}$ through scalar Unparticle operator: $i\frac{\lambda}{\Lambda_{\mathcal{U}}^{d}}\bar{u}\gamma_\mu(1-\gamma_5)t\partial^\mu \mathcal{O}_U + h.c.$

- The energy spectrum of the u is given by :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_u} = 4d_{\mathcal{U}}(d_{\mathcal{U}}^2 - 1)(1 - 2E_u/m_t)^{d_{\mathcal{U}}-2}E_u^2/m_t^2$$

- Figure shows $dln\Gamma/dE_u$ versus E_u in units of m_t with $d_{\mathcal{U}} = j/3$ for $j = 4 - 9$. The dashes get longer as j increases.

- As $d_{\mathcal{U}} \to 1^+$, $dln(\Gamma)/dE_u$ becomes more peaked at $E_u = m_t/2$ matching smoothly unto the kinematics of a 2-particle decay in the limit.

Single γ production at e^+e^- Machine [K. Cheung etal. PRD76,055003 (2007)]

- The differential cross-section for $e^+(p)e^-(p') \to \gamma(k)\mathcal{U}(P_\mathcal{U})$ (Vector Unparticle) is :

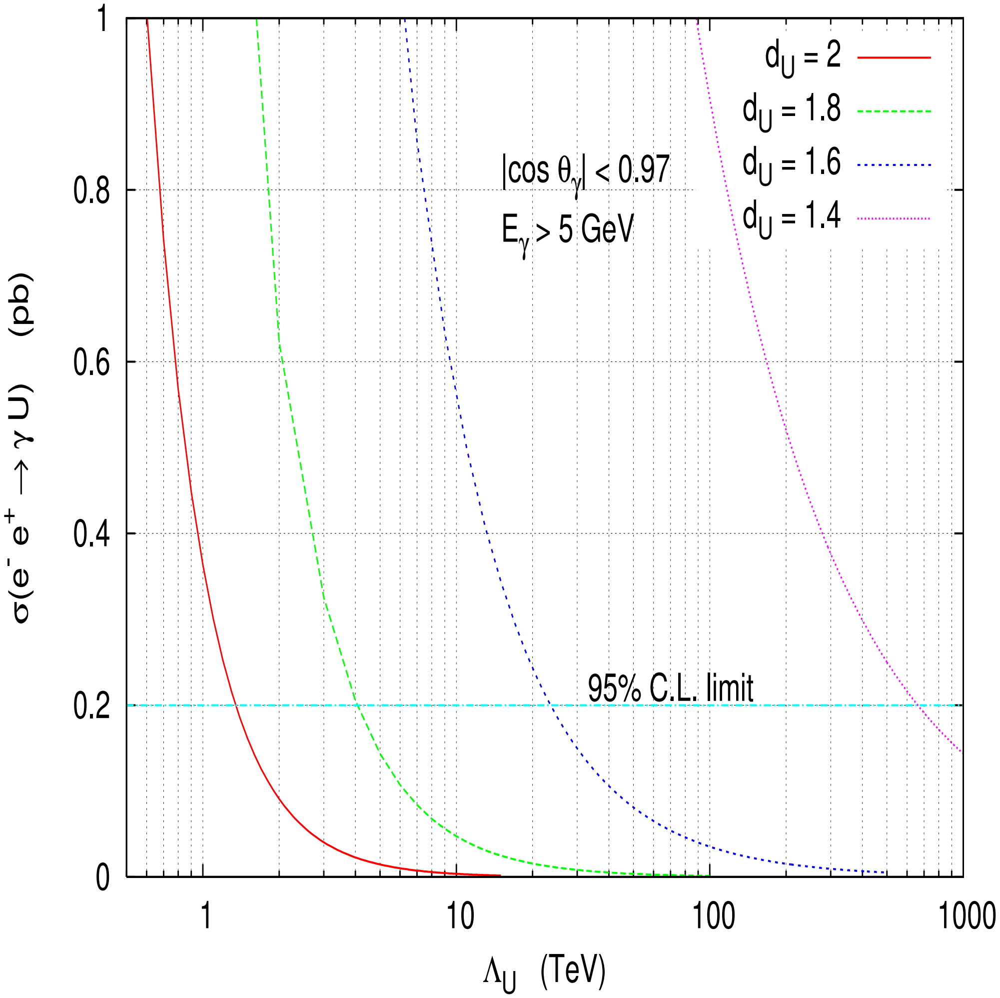
$$\begin{aligned} d\sigma &= \frac{1}{2s} \mid \overline{\mathcal{M}} \mid^2 \frac{E_\gamma^2 A_{d_\mathcal{U}}}{16\pi^3 \Lambda_\mathcal{U}^2} \left(\frac{P_\mathcal{U}^2}{\Lambda_\mathcal{U}^2} \right)^{d_\mathcal{U}-2} dE_\gamma d\Omega \\ P_\mathcal{U}^2 &= s - 2\sqrt{s}E_\gamma \\ \mid \overline{\mathcal{M}} \mid^2 &= 2\lambda_1^2 e^2 \frac{u^2 + t^2 + 2sP_\mathcal{U}^2}{ut} \end{aligned}$$

- LEP Collaborations had measured single photon plus missing energy in the context of different BSM scenarios.

- Strongest bound comes from L3: 95% C.L. upper limit on $\sigma(e^+e^- \to \gamma + X) \simeq 0.2$ pb, under the cuts $E_\gamma > 5$ GeV and $\mid \cos\theta_\gamma \mid < 0.97$ at $\sqrt{s} = 207$ GeV.

- Limits on $\Lambda_\mathcal{U} > 600(1.35)$ (TeV) for $d_\mathcal{U} = 1.4(2.0)$ for fixed $\lambda_1 = 1$.

Single γ production at e^+e^- Machine [K. Cheung etal. PRD76,055003 (2007)]



$\mu \to e + \mathcal{U}$ (Scalar unparticle operator)

- In the SM $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ is allowed.
- This mode can be faked by $\mu^- \to e^- + \mathcal{U}$ decay in the Uparticle model.
- The simplest term in the effective Lagrangian which can lead to the above decay involves a scalar unparticle:

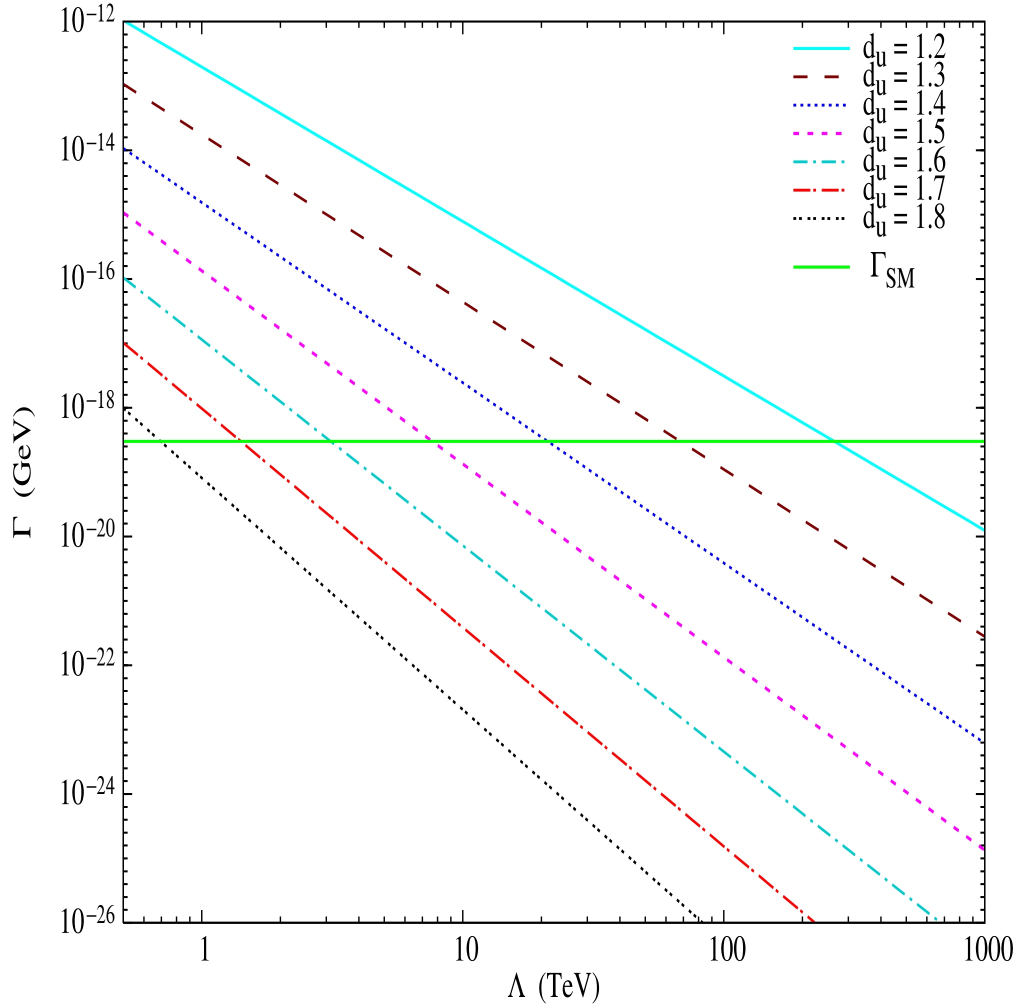
$$\mathcal{L}_1 = \Lambda^{-d_u}\, \bar{e}\,\gamma_\eta\,(c_1 + c_2\,\gamma_5)\mu\,\partial^\eta \mathcal{O}_\mathcal{U}$$

- The decay profile is given by :

$$\begin{aligned} \frac{d\Gamma_S}{dE_e}(\mu \to e + \mathcal{U}) &= \frac{A_{d_u}}{4\,\pi^2}\,(c_1^2 + c_2^2)\; m_\mu^2\; E_e^2\;\left(m_\mu^2 - 2\,m_\mu\,E_e\right)^{d_u - 2}\Lambda^{-2\,d_u}\;\Theta(m_\mu - 2\,E_e) \\ \Gamma_S(\mu \to e + \mathcal{U}) &= \frac{A_{d_u}}{16\,\pi^2}\,\frac{c_1^2 + c_2^2}{d_u^3 - d_u}\; m_\mu\;\left(\frac{m_\mu}{\Lambda}\right)^{2\,d_u} \end{aligned}$$

where the mass of the electron has been neglected and the second equality follows only for $d_u > 1$.

$\mu \to e + \mathcal{U}$(Scalar unparticle operator)



$\mu \rightarrow e + \mathcal{U}$ (Vector Unparticle operator)

- Now consider a different possible couplings of the unparticles to the muon-electron current, namely a vector one:

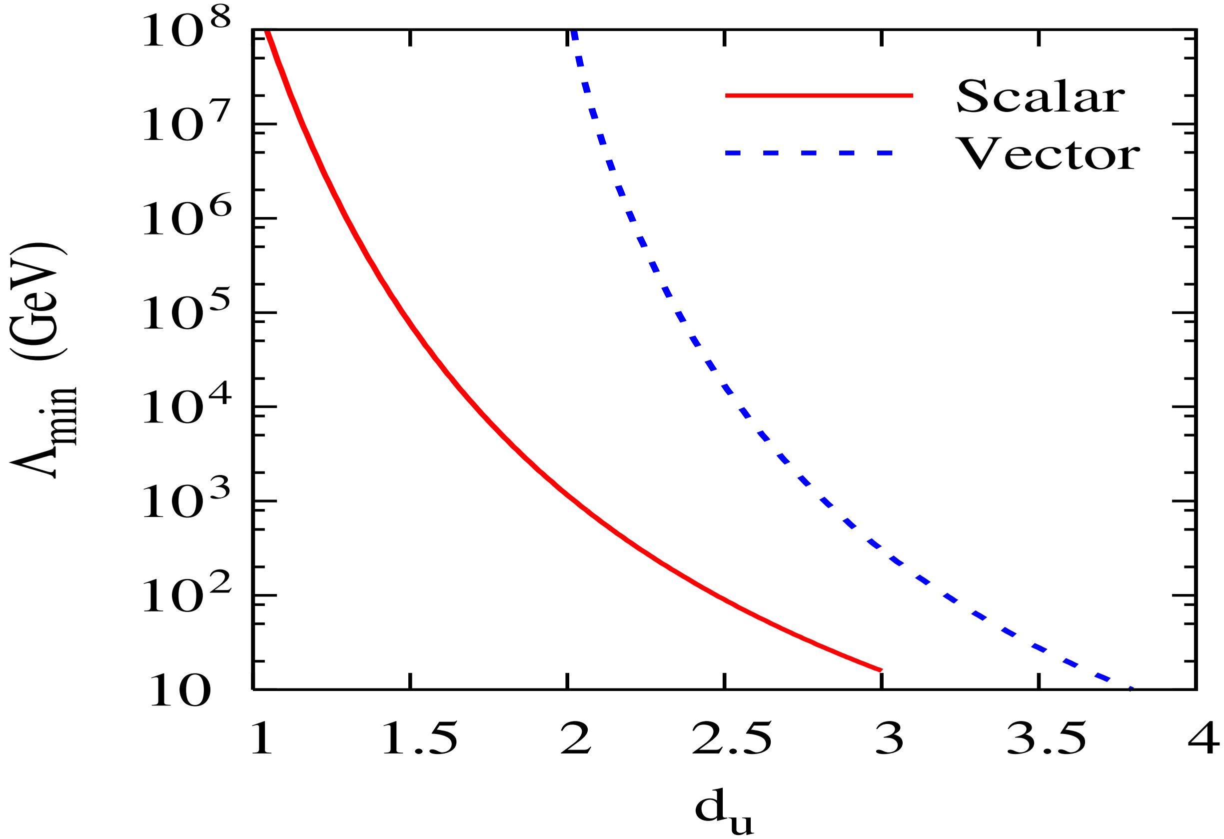
$$\mathcal{L}_2 = \Lambda^{1-d_u}\, \bar{e}\, \gamma_\eta\, (c_3 + c_4\, \gamma_5) \mu\, {\mathcal{O}_{\mathcal{U}}}^\eta$$

- The decay profile is given by :

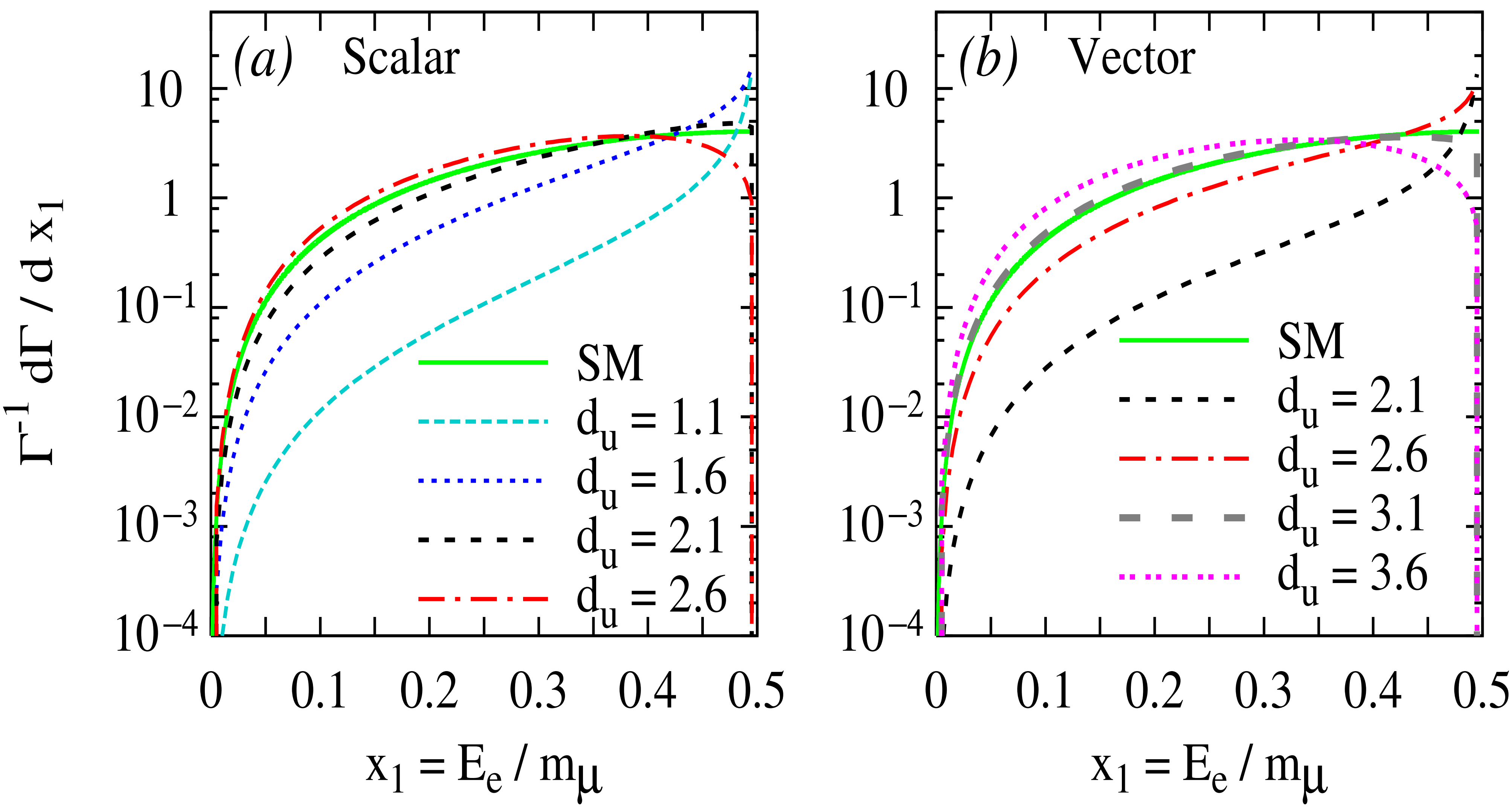
$$\begin{aligned}
\frac{d\Gamma_V}{dE_e}(\mu \rightarrow e + \mathcal{U}) &= \frac{A_{d_u}}{4\,\pi^2}\,(c_3^2 + c_4^2)\, m_\mu\, E_e^2\, \left(m_\mu^2 - 2\, m_\mu\, E_e\right)^{d_u - 3} \Lambda^{2-2\,d_u} \\
&\quad (3m_\mu - 4E_e)\, \Theta(m_\mu - 2\, E_e) \\
\Gamma_V(\mu \rightarrow e + \mathcal{U}) &= \frac{3\, A_{d_u}}{16\,\pi^2}\, \frac{c_3^2 + c_4^2}{d_u^3 - d_u^2 - 2\, d_u}\, m_\mu\, \left(\frac{m_\mu}{\Lambda}\right)^{2\, d_u - 2}
\end{aligned}$$

where the mass of the electron has been neglected and the second equality holds for $d_u > 2$.

$\mu \to e + \mathcal{U}$(**Bound on** Λ)



$\mu^- \to e^- + \mathcal{U}$



$\mu^- \rightarrow e^- + \mathcal{U}$

- Can MEG distinguish between the possible unparticle operators if there is an discrepancy in $\mu^- \rightarrow e^- +$ nothing in the forthcoming experiment.

- For small $d_{\mathcal{U}}$, the distributions are naturally peaked at $E_e = m_\mu/2$ as is expected for a decay into two massless particles.

- For vector case, the peaking persists to much larger values of $d_{\mathcal{U}}$ is the reflection of the differing powers of P^2 in the two cases ($d_{\mathcal{U}} - 3$ for vector vs. $d_{\mathcal{U}} - 2$ for scalar).

- $d_{\mathcal{U}} \rightarrow 1^+$ for scalar correspond to the two body decay in the case of the vector, it is the limit $d_{\mathcal{U}} \rightarrow 2^+$ that corresponds to the same.

- The limit $d_{\mathcal{U}} \rightarrow 2^+$ in the scalar case corresponds to a 3 body decay (close to SM curve in Fig a).

- For vector case, this feature is exhibited in the limit $d_{\mathcal{U}} \rightarrow 3$.

Virtual Unparticle exchange

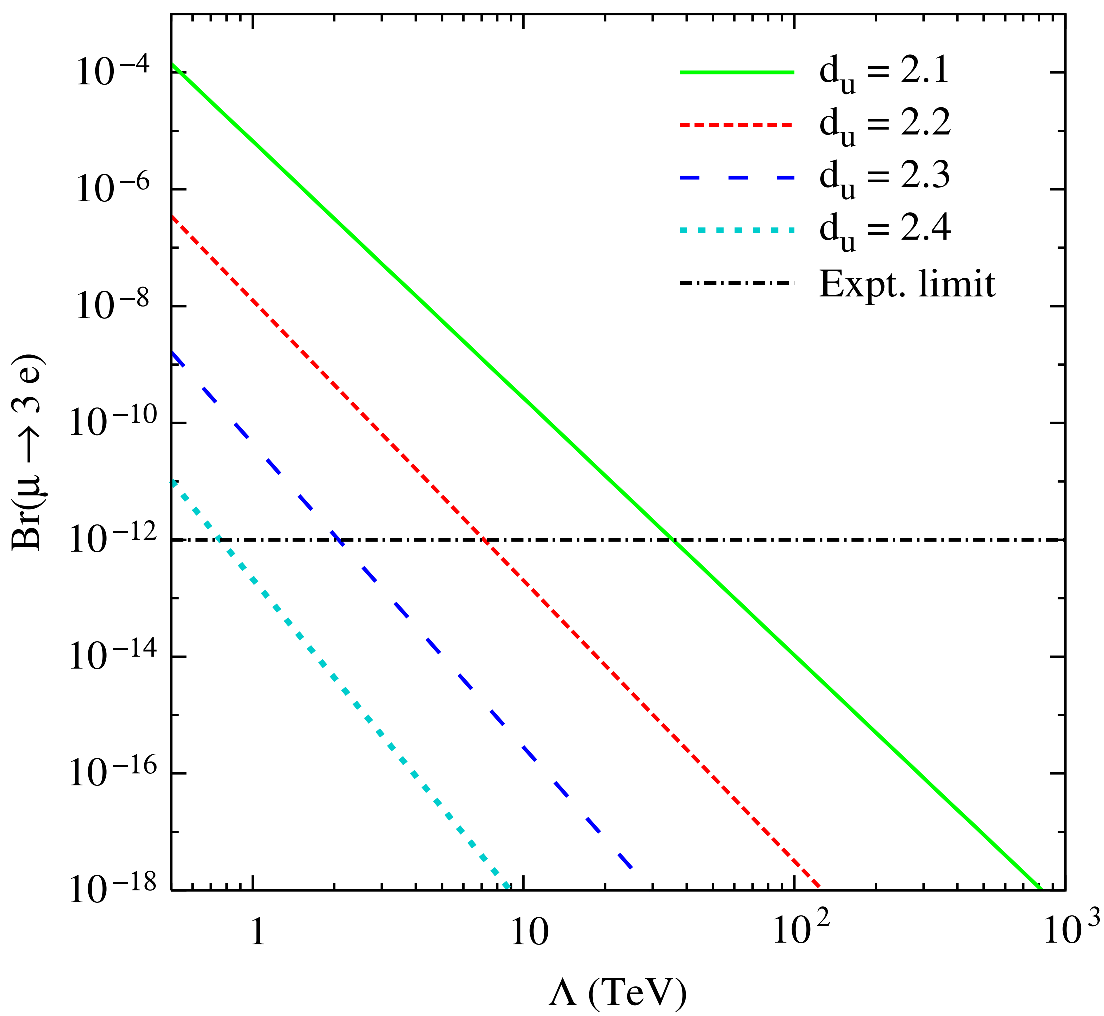
$\mu^- \to 3e$

- Unparticle sector can also couple to lepton flavour conserving currents
- Restricting ourselves to the vector operator, an additional term relevant for μ decay :

$$\mathcal{L}_3 = \Lambda^{1-d_{\mathcal{U}}} \bar{e}\gamma_\alpha \left(c_5 + c_6\gamma_5\right) e {\mathcal{O}_{\mathcal{U}}}^\alpha \tag{1}$$

- Simultaneous presence of both sets of operators $\mathcal{L}_2$ and $\mathcal{L}_3$ would lead to unparticle mediated $\mu \to 3e$ decay.
- We concentrate on $d_{\mathcal{U}} > 2$.
- The experimental limit on $Br(\mu \to 3e) < 10^{-12}$ PDG (2006).
- We set $c_3 = c_4 = c_5 = c_6 = \frac{1}{\sqrt{2}}$
- The branching ratio is very sensitive to the scaling dimension $d_{\mathcal{U}}$.

$\mu \to 3e$



10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
1
10
10^2
10^3
Λ (TeV)
$Br(\mu \to 3e)$
$d_u = 2.1$
$d_u = 2.2$
$d_u = 2.3$
$d_u = 2.4$
Expt. limit

Drell-Yan process [K. Cheung etal. PRL99,051803 (2007)]

- The virtual exchange of vector unparticle between two fermionic current can be expressed as 4-fermion interactions (assuming massless fermions):

$$\mathcal{A} = \lambda^2 \frac{A_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)\Lambda_\mathcal{U}^2}\left(-\frac{Q_\mathcal{U}^2}{\Lambda_\mathcal{U}^2}\right)^{d_\mathcal{U}-2} (\bar{f}_2\gamma_\alpha P_\mu f_1)(\bar{f}_4\gamma^\alpha P_\nu f_3)$$

- $Q_\mathcal{U}^2 > 0 \Longrightarrow$ phase factor $\exp(-i\pi d_\mathcal{U})$.

- No such phase factor for $Q_\mathcal{U}^2 < 0$

Drell-Yan process [K. Cheung etal. PRL99,051803 (2007)]

- The differential cross-section for DY process (through Vector Unparticle) is :

$$\frac{d^2\sigma}{dM_{\ell\ell}\,dy} = K\frac{M_{\ell\ell}^3}{72\pi s}\sum_q f_q(x_1)f_{\bar{q}}(x_2)\times\left(|M_{LL}|^2+|M_{LR}|^2+|M_{RL}|^2+|M_{RR}|^2\right)$$

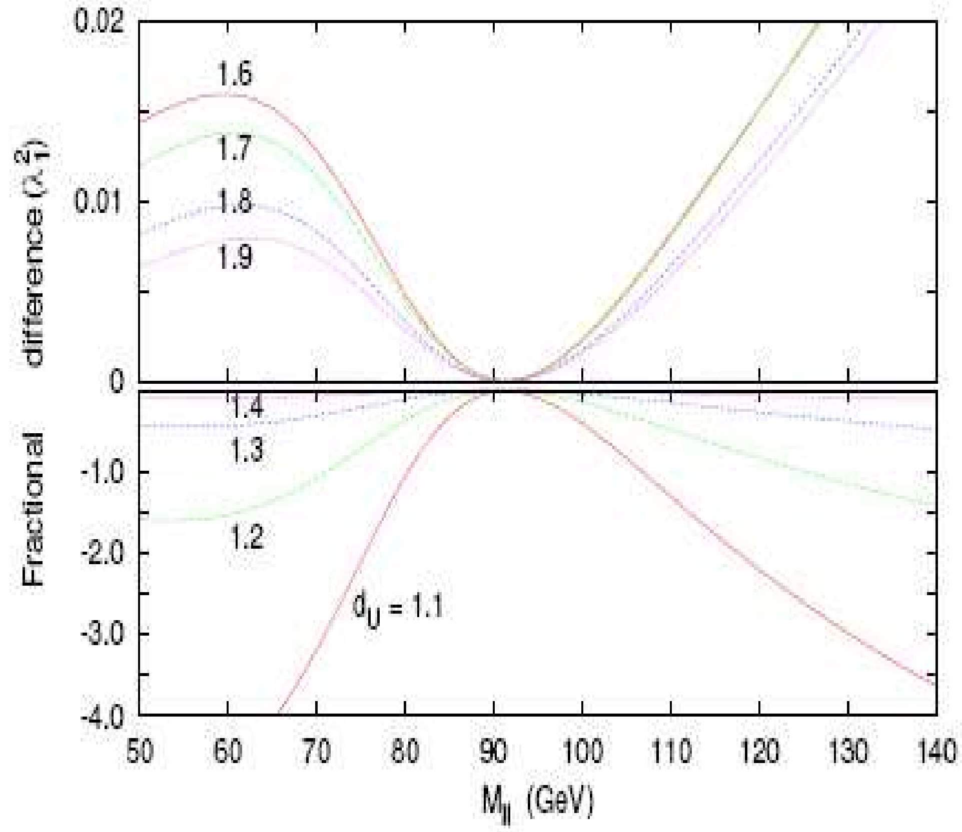
where,

$$M_{\alpha\beta} = \frac{\lambda^2 A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{1}{\Lambda_{\mathcal{U}}^2}\left(-\frac{\hat{s}}{\Lambda_{\mathcal{U}}^2}\right)^{d_{\mathcal{U}}-2} + \frac{e^2 Q_\ell Q_q}{\hat{s}} + \frac{e^2 g_\alpha^\ell g_\beta^q}{\sin^2\theta_{\rm w}\cos^2\theta_{\rm w}}\frac{1}{\hat{s}-M_Z^2+iM_Z\Gamma_Z}$$

- where $\hat{s} = M_{\ell\ell}^2$ and $K = 1 + \frac{4\alpha_s}{6\pi}(1+\frac{4\pi^2}{3})$.

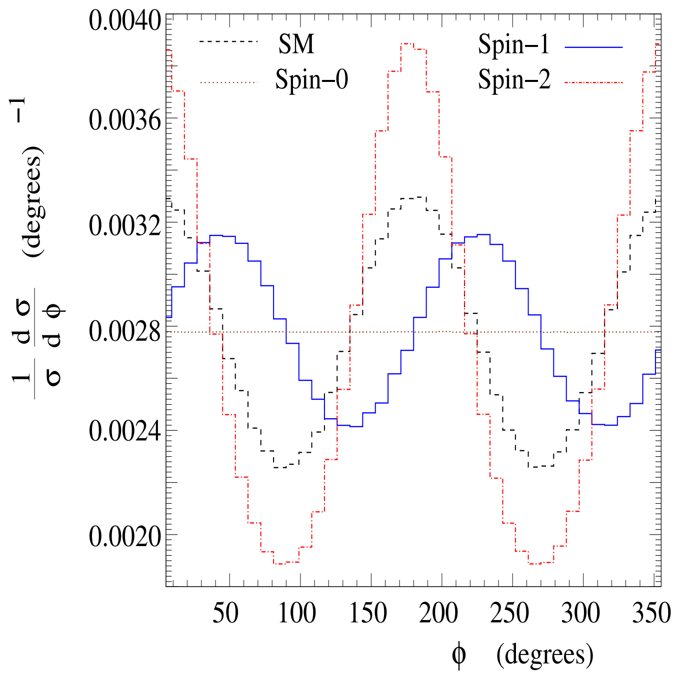
- $\hat{s} > 0$, the phase of the Unparticle propagator $\exp(-i\pi d_{\mathcal{U}})$ will interfere with both the real γ propagator and also the real and imaginary parts of the Z propagator in a non-trivial way.

DY process [K. Cheung etal. PRL99,051803 (2007)]



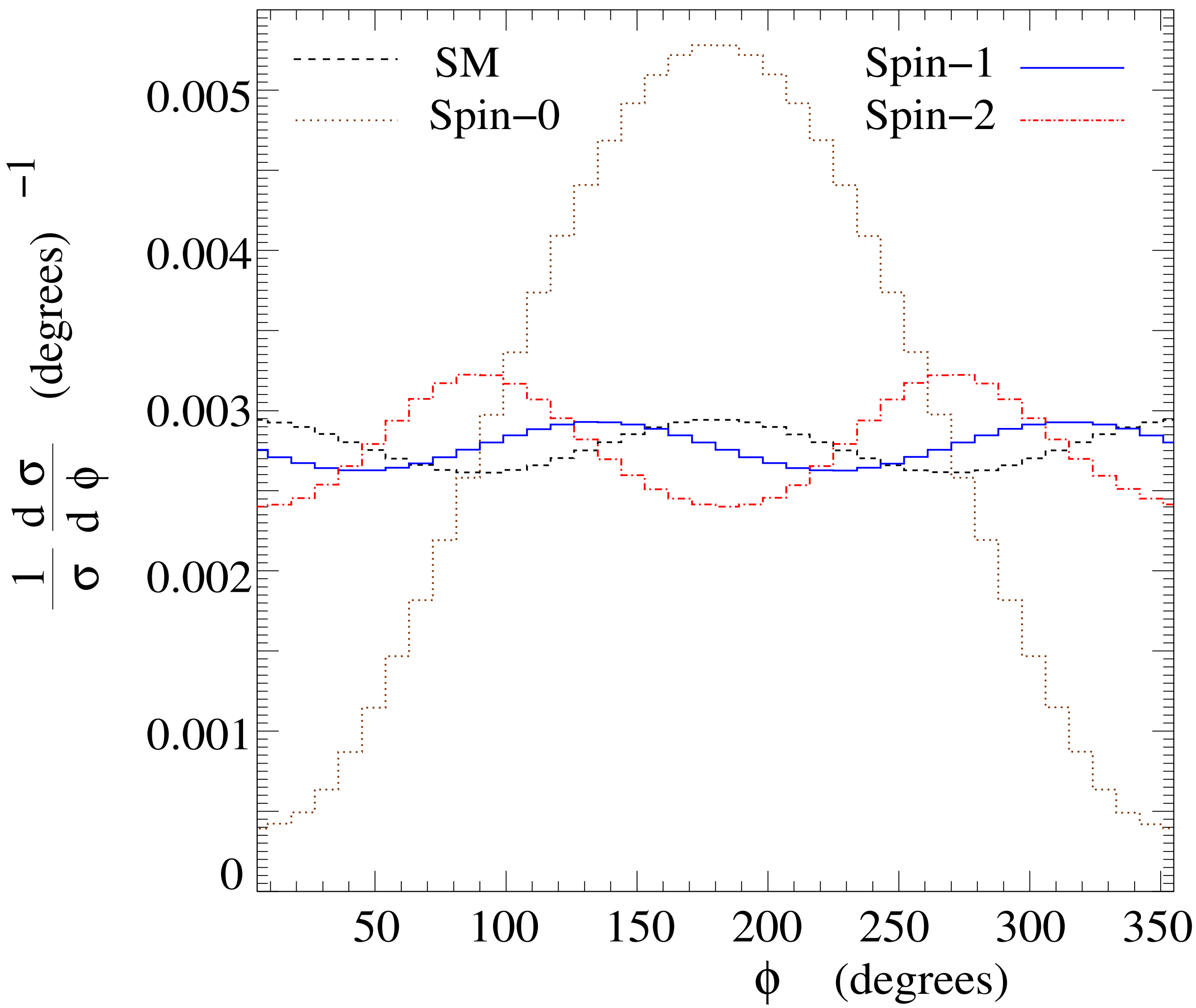
Interference of $\mathcal{U}$ with γ, Z propagators

Disentangling the unparticles with polarized beams at e^+e^- Machine [K. Huitu and S. Rai, PRD77, 035015 (2008)]



- The effect of complex phase in the virtual Unparticle propagator can be probed by studying the azimuthal distribution of the final state particles using the transverse beam polarizations.
- The azimuthal angle is defined by the directions of the $e^{\pm}$ transverse polarization and the plane of the momenta of the outgoing fermions in the $e^+e^- \longrightarrow f\bar{f}$ process.
- Here the azimuthal angle distribution for the μ final state is shown.
- $\Lambda_{\mathcal{U}} = 10$ TeV, $d_{\mathcal{U}} = 1.5$(spin-0 and spin-1).
- $\Lambda_{\mathcal{U}} = 1$ TeV, $d_{\mathcal{U}} = 1.3$(spin-2).

Disentangling the unparticles with polarized beams....



Relevant Unparticle operators for $t\bar{t}$ process

- The relevant operators in the effective Lagrangian are given by :

$$\mathcal{L}_{scalar} = \Lambda^{-d_{\mathcal{U}}} \left[\bar{t}\gamma_\mu (a + b\gamma_5) t \partial^\mu \mathcal{O}_S + G_{\mu\nu}\left(\tilde{c}_1 G^{\mu\nu} + \tilde{c}_2 \widetilde{G}^{\mu\nu} \right) \mathcal{O}_S \right] \quad (2)$$

$$\mathcal{L}_{vector} = \Lambda^{1-d_{\mathcal{U}}} \sum_q \bar{q}\gamma_\mu (\tilde{v}^q + \tilde{a}^q \gamma_5) q \mathcal{O}_V^\mu \quad (3)$$

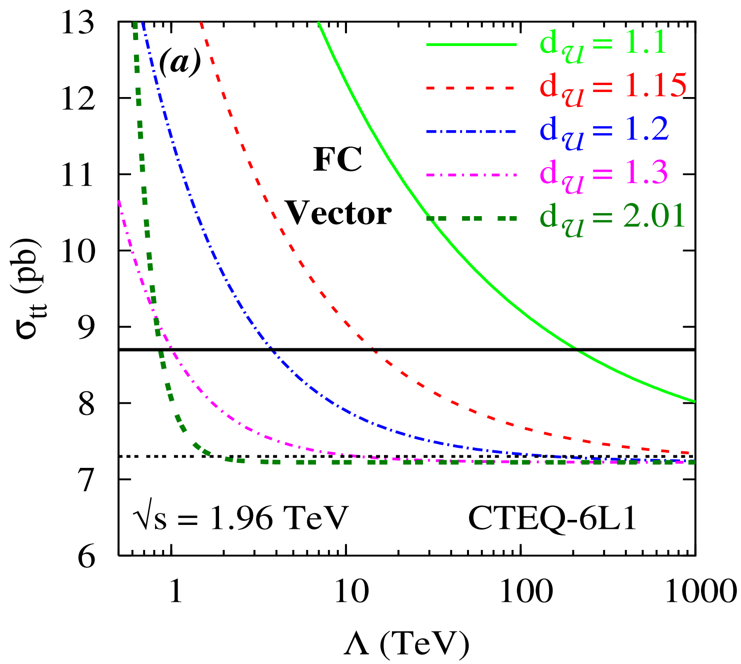
$$\mathcal{L}^1_{tensor} = \Lambda^{-d_{\mathcal{U}}} \mathcal{O}_T^{\mu\nu} \left[\sum_q \bar{q} \left(\gamma_\mu \overleftrightarrow{\partial}_\nu + \gamma_\nu \overleftrightarrow{\partial}_\mu \right) \left(a_q^T + b_q^T \gamma_5 \right) q \right] \quad (4)$$

$$\mathcal{L}^2_{tensor} = \Lambda^{-d_{\mathcal{U}}} \mathcal{O}_T^{\mu\nu} \left[G_\nu^\alpha \left(a_g \, G_{\mu\alpha} + b_g \, \widetilde{G}_{\mu\alpha} \right) \right] \quad (5)$$

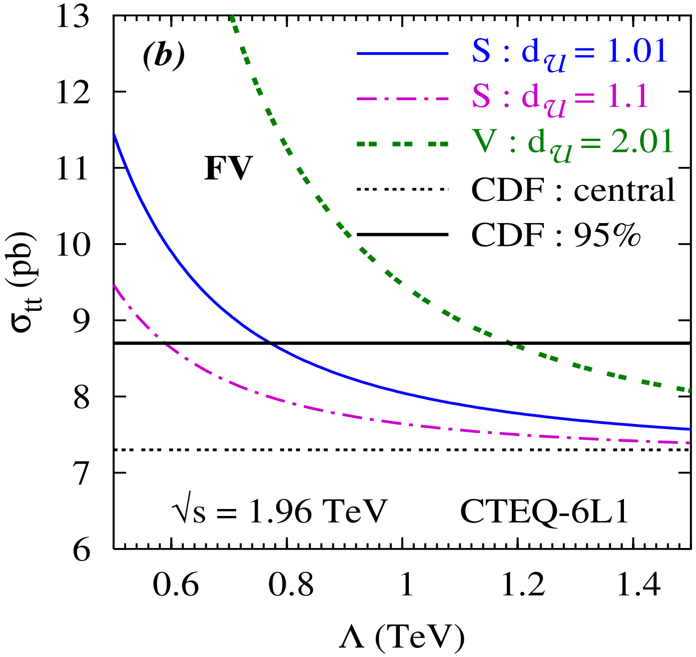
- We shall consider the coefficients to be order unity.

- The coupling of $\mathcal{O}_S$ to light fermions are negligible.

$t\bar{t}$ pair cross-section at Tevatron Run II



- Variation of the total $\sigma_{t\bar{t}}$ at the Tevatron Run II with Λ in the presence of a vector unparticle operator.
- New physics contribution : through s-channel, No interference with the (dominant) QCD amplitude.
- Thus unparticle effect can become appreciable only when the amplitude becomes comparable to the QCD one.
- EW contribution is small $\longrightarrow$ the phase factor $exp(-i\pi d_{\mathcal{U}})$ in the unparticle propagator is of little consequence.
- $\sigma(t\bar{t}) = 7.3 \pm 0.5(stat) \pm 0.6(syst) + \pm 0.4(lum)$ pb, (CDF Run II results averaged over all channels)



- Variation of the total $\sigma_{t\bar{t}}$ at the Tevatron Run II with Λ in the presence of either scalar or vector flavour violating unparticle operator.

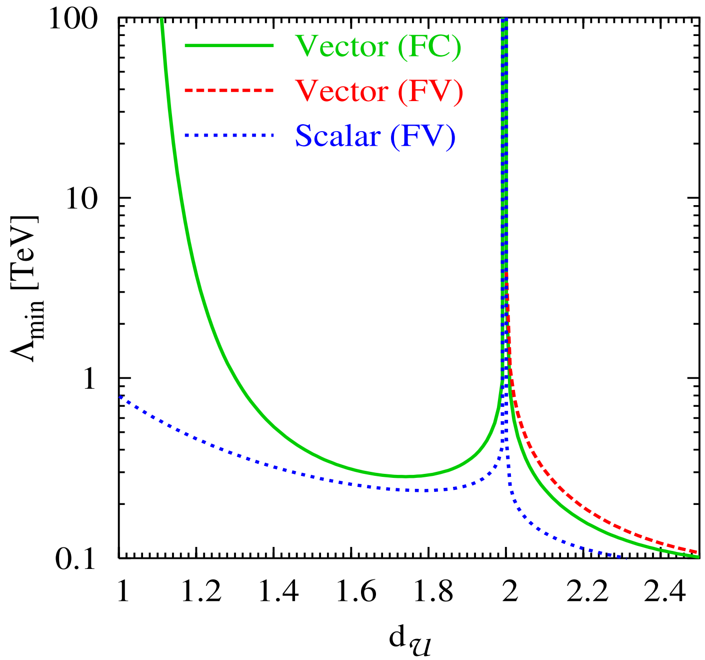
- This being only an effective theory, flavour-violating (FV) unparticle couplings are also possible. For example, the vector coupling can be generalized to :

$$\mathcal{L}_{FV} \supset \Lambda^{1-d_{\mathcal{U}}}\, \bar{q}\,\gamma_\eta\,(\tilde{v}^{qq'} + \tilde{a}^{qq'}\,\gamma_5)\,q'\,\mathcal{O}_V^\eta$$

- Similarly for the scalar and tensor operators.

- These operators result in a t-channel diagram for $u\bar{u} \longrightarrow t\bar{t}$, which interferes with the QCD amplitude.

Bound on Λ from $\sigma_{t\bar{t}}$ at Tevatron Run II



- Using the $\sigma(t\bar{t})^{\rm exp}$ (with errors added in quadrature), one may impose bounds on the unparticle parameter space for a given choice of operators.

- Here we show the 95% C.L. bounds assuming that only one of the operators, whether FC or FV contributes.

- The constraint is strongly dependent on the structure of the operator involved as well as on the scale dimension $d_{\mathcal{U}}$.

- The sharp rise of the limit at $d_{\mathcal{U}} = 2$ is but a manifestation of the presence of physical poles in the unparticle propagators at all integral values of $d_{\mathcal{U}} > 1$.

summary

- Unparticle is a hidden scale invariant sector which couples to the SM particles only through higher dimensional operators.
- An EFT can be used to explore the unparticle physics.
- It can lead to a very interesting phenomenological consequences due to non-integral value of the scale dimension.
- Production of real unparticle at the colliders give rise to missing energy.
- The unpaticle propagator in the time like region contains an additional phase.
- In our study of unparticle physics in the LFV $\mu \to e + \mathcal{U}$, we obtained strong limit on the unparticle parameter space.
- We have also shown that the LFV decay width $\mu^- \to e^+ e^- e^-$ is highly sensitive to the virtual unparticle effects.

summary

- The current Tevatron measurements on top pair production cross-section can be used to impose significant constraints on the unparticle physics

- The bounds are strongly dependent on the Lorentz structure of the relevant unparticle operator as well as its mass dimension $d_{\mathcal{U}}$.