Unparticle Phenomenology

Tzu-Chiang Yuan 阮自強
(NCTS, Hsinchu)

- Introduction
- Indirect interference effects
- Direct production of unparticle stuff (Tevatron, LHC, ILC)
- Existing constraints
- Summary

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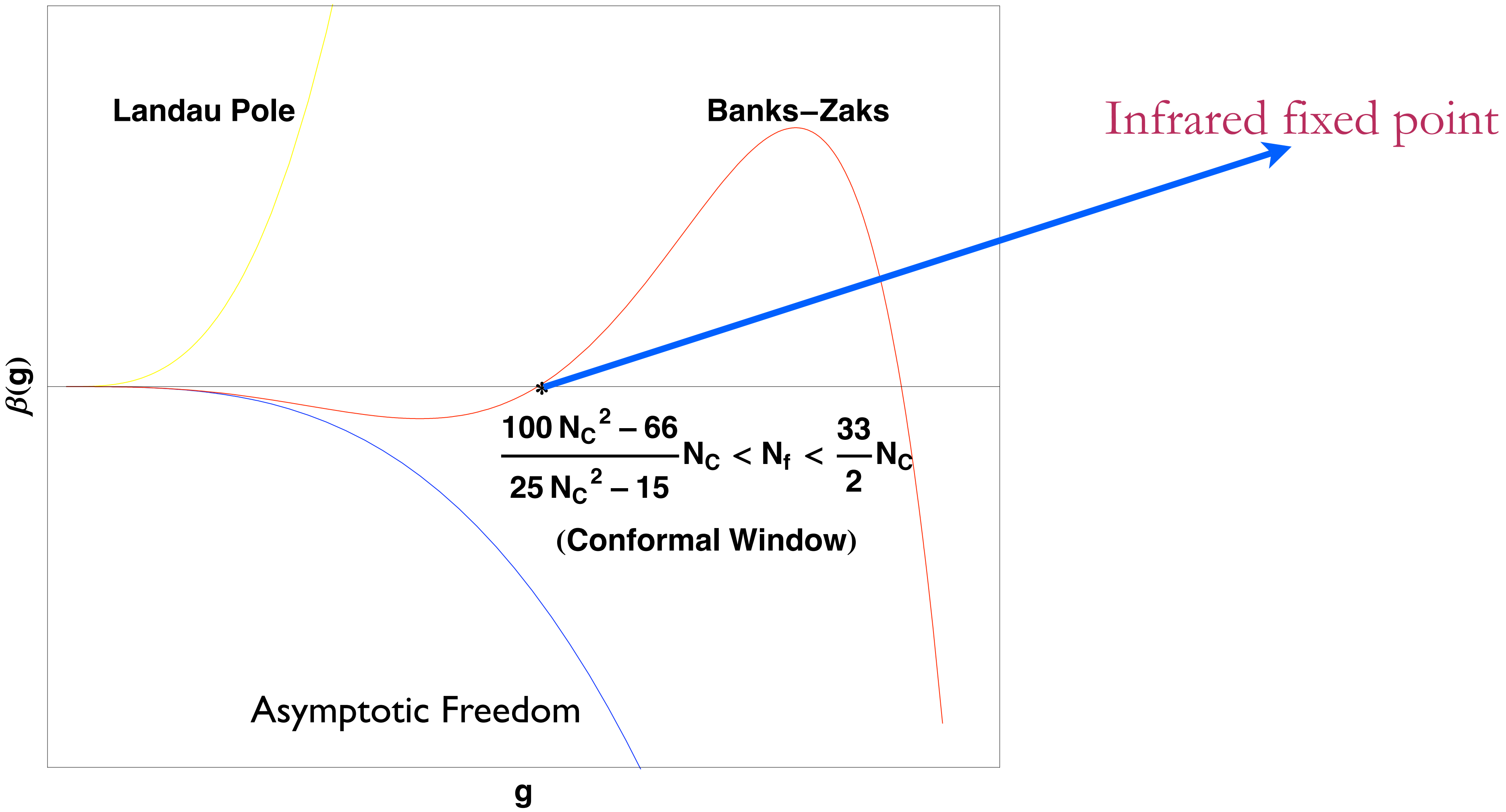
Introduction

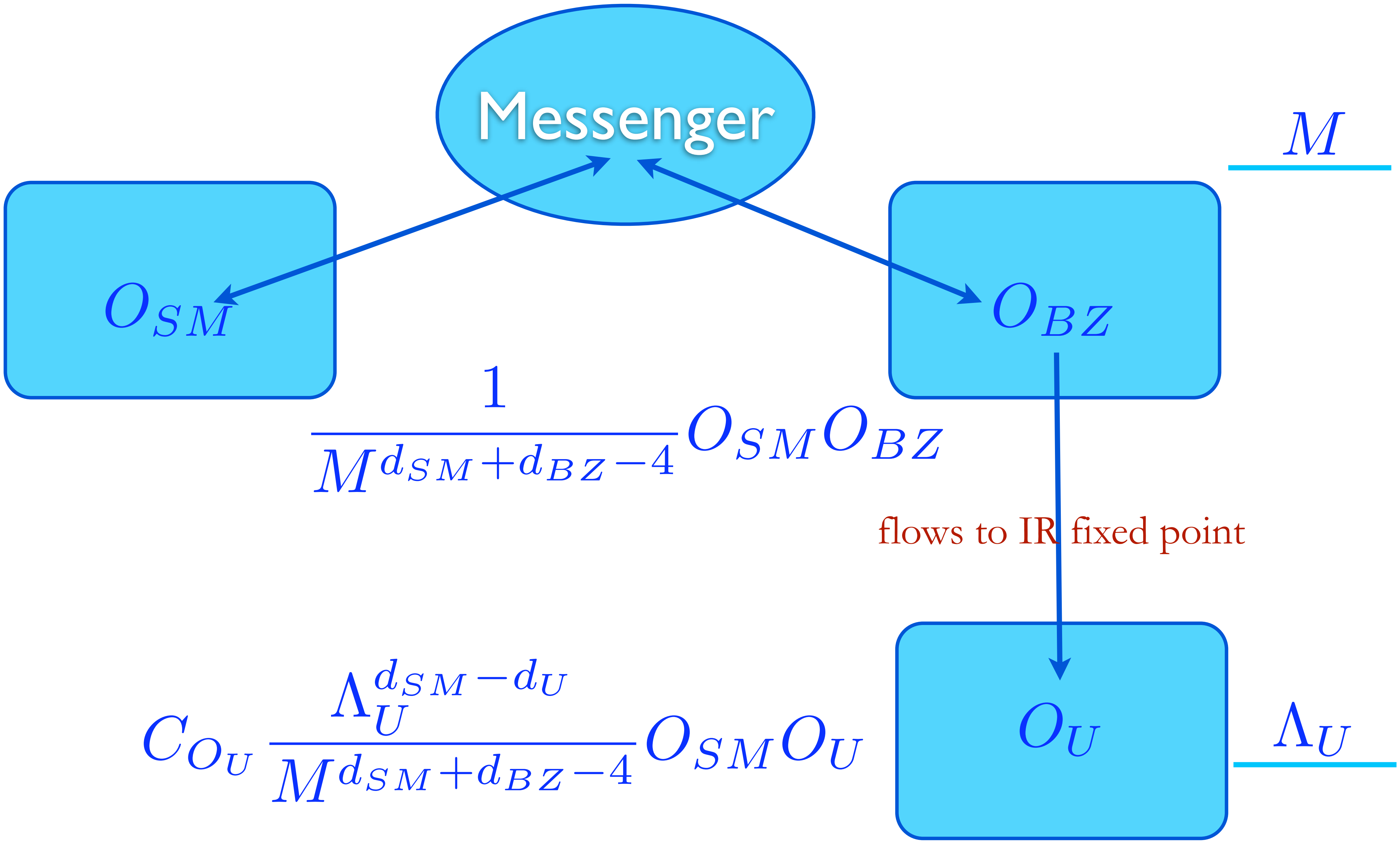
Georgi's notion of unparticle stuff (PRL, 98 (2007) 221601) is based on

(1) Existence of a hidden sector (e.g. Banks-Zaks theory) at a high energy scale M but flows to an infrared fixed point at a low energy scale Λ_U through dimensional transmutation ----

Unparticle stuff emerges below Λ_U



(2) Effective field theories to describe SM particles couplings with unparticle stuff



$$\frac{1}{M^{d_{SM}+d_{BZ}-4}} O_{SM} O_{BZ}$$

$$C_{O_U} \frac{\Lambda_U^{d_{SM}-d_U}}{M^{d_{SM}+d_{BZ}-4}} O_{SM} O_U$$

Unparticle operator O_U emerges that scales with non-integral scaling dimension d_U

$$x \to \lambda x \;\; ; \;\; O_U(\lambda x) \to \lambda^{-d_U} O_U(x)$$

Unparticle Phase Space (Georgi, PRL, 98 (2007) 221601)

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

$$d\mathrm{LIPS}_n = A_n s^{n-2}, \quad A_n = \frac{16\pi^{5/2}}{(2\pi)^{2n}} \frac{\Gamma(n+\frac{1}{2})}{\Gamma(n-1)\Gamma(2n)}$$

- By scale invariance

$$\Phi(P_U^2) = A_d \theta(P_U^0)\theta(P_U^2)(P_U^2)^{d-2}$$

- Identifies $d \to n$; $A_d \to A_n$
- Unparticle resembles a collection of d (non-integral) massless particles
- Unparticle stuff has continuous mass distribution – Infraparticles in QFT (Schroer, 1963, 2008)

Unparticle propagator

[Georgi, PLB650, 275 (2007); Cheung, Keung and TCY, PRL 99, 051803 (2007).]

- Spin 0:

$$\Delta_U(P) = \frac{A_d}{\sin(d\pi)} \frac{1}{(-P^2 - i0^+)^{2-d}}$$

- Spin 1:

$$\Delta_U^{\mu\nu}(P) = \Pi^{\mu\nu}(P)\Delta_U(P) \quad ; \quad \Pi^{\mu\nu}(P) = -g^{\mu\nu} + \frac{P^\mu P^\nu}{P^2} \quad \text{(Transverse)}$$

- Spin 2:

$$\Delta^{\mu\nu\rho\sigma}(P) = \frac{1}{2}\left[\Pi^{\mu\rho}(P)\Pi^{\nu\sigma}(P) + \Pi^{\mu\sigma}(P)\Pi^{\nu\rho}(P) - \frac{2}{3}\Pi^{\mu\nu}(P)\Pi^{\rho\sigma}(P)\right]\Delta_U(P)$$

- For non-integral d and time-like P^2, there is a CP-conserving phase $\exp(-id\pi)$ in the propagator.

Fermionic unparticle propagator:
See Luo and Zhu, PLB659, 341 (2008); Liao, 0804.0752;
Basu, Choudhury and Mani, 0803.4110]

$$S_U(P) = \frac{F(d)}{2\sin(d\pi)}\left[(-P^2 - i0^+)^{(d-2)} - \tan(d\pi)(-P^2 - i0^+)^{(d-\frac{5}{2})}\not{p}\right] \quad ; \quad F(d) = \frac{16\pi^{5/2}}{(2\pi)^{2d-1}} \frac{\Gamma(d)}{\Gamma(d-\frac{3}{2})\Gamma(2d-1)}$$

Conformal unparticle propagators

[Grinstein, Intriligator and Rothstein, PLB 662 (2008) 367]

- spin 1 :

$$\Pi^{\mu\nu}(P) = -g^{\mu\nu} + 2\left(\frac{d-2}{d-1}\right)\frac{P^\mu P^\nu}{P^2}$$

- spin 2 :

$$c_1 = \frac{4-d(d+1)}{2d(d-1)} \quad ; \quad c_2 = -2\frac{(d-2)}{d}$$

$$c_3 = 4\frac{(d-2)}{d(d-1)} \quad ; \quad c_4 = 8\frac{(d-2)(d-3)}{d(d-1)}$$

$$\begin{aligned}\Pi^{\mu\nu,\rho\sigma}(P) = \frac{1}{2}\Bigg\{ & g^{\mu\rho}g^{\nu\sigma} + g^{\nu\rho}g^{\mu\sigma} + c_1 g^{\mu\nu}g^{\rho\sigma} \\ & + c_2\left(g^{\mu\rho}\frac{P^\nu P^\sigma}{P^2} + g^{\mu\sigma}\frac{P^\nu P^\rho}{P^2} + g^{\nu\rho}\frac{P^\mu P^\sigma}{P^2} + g^{\nu\sigma}\frac{P^\mu P^\rho}{P^2}\right) \\ & + c_3\left(g^{\mu\nu}\frac{P^\rho P^\sigma}{P^2} + g^{\rho\sigma}\frac{P^\mu P^\nu}{P^2}\right) + c_4\frac{P^\mu P^\nu P^\rho P^\sigma}{(P^2)^2}\Bigg\}\end{aligned}$$

- $\Pi^{\mu\nu}, \Pi^{\mu\nu\rho\sigma}$ no longer transverse!
- Unitarity constraints [Nakayama, PRD 76 (2007) 105009; Mack, CMP55 (1977) 1]:

  $d \geq 3$ (spin 1)

  $d \geq 4$ (spin 2)

$$d \geq 2 + j_1 + j_2 \text{ for } j_1 \neq 0 \text{ and } j_2 \neq 0$$

- However, they produce same results in $\gamma\gamma \to \gamma\gamma$, $gg \to gg$, $q_1 q_2 \to q_3 q_4$.

Effective Field Theory according to Georgi's scheme

• (Non-)Renormalizable operators

$$\text{Spin 0}: \quad \lambda_0 \frac{1}{\Lambda^d} G_{\alpha\beta} G^{\alpha\beta} O \, , \lambda_0' \frac{1}{\Lambda^{d-1}} \bar{f} f O \, , \quad \lambda_0'' \frac{1}{\Lambda^{d-1}} \bar{f} i \gamma^5 f O \, ,$$
$$\lambda_0''' \frac{1}{\Lambda^d} \bar{f} \gamma^\mu f (\partial_\mu O) \, ,$$
$$\text{Spin 1}: \quad \lambda_1 \frac{1}{\Lambda^{d-1}} \bar{f} \gamma_\mu f \, O^\mu \, , \quad \lambda_1' \frac{1}{\Lambda^{d-1}} \bar{f} \gamma_\mu \gamma_5 f \, O^\mu \, ,$$
$$\text{Spin 2}: \quad \lambda_2 \frac{1}{\Lambda^d} G_{\mu\alpha} G_\nu^{\ \alpha} O^{\mu\nu} \, , \quad -\frac{1}{4} \lambda_2' \frac{1}{\Lambda^d} \bar{\psi} \, i \left(\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu \right) \psi \, O^{\mu\nu} \, ,$$
$$\ldots\ldots$$

• Super-renormalizable operator [Fox, Rajaraman and Shirman, PRD76 (2007) 075004]

$$\text{Spin 0}: \quad \lambda_H \frac{1}{\Lambda^{d-2}} H^\dagger H O$$

breaks scale invariant when Higgs gets VEV.

• Ungravity [Goldberg and Nath, PRL 100, 031803 (2008)]

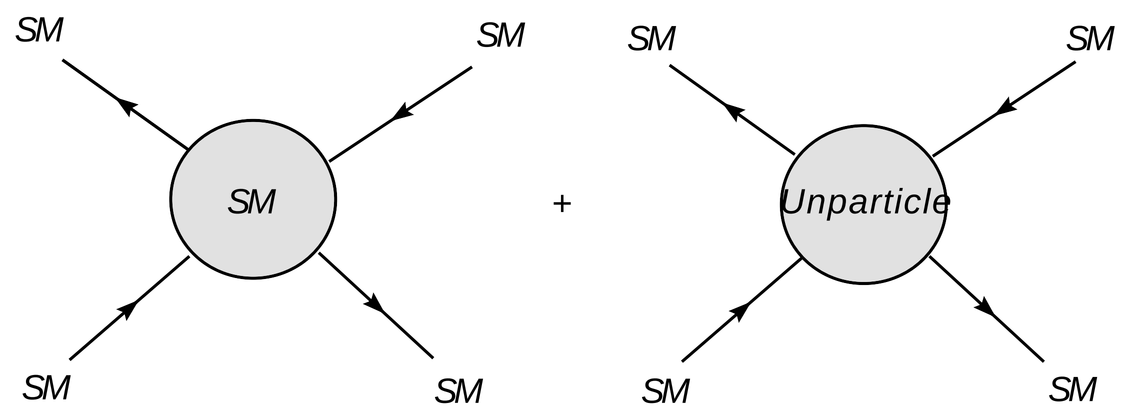
$$\text{Spin 2}: \quad \kappa_* \frac{1}{\Lambda_U^{d-1}} \sqrt{g} T^{\mu\nu} O_{\mu\nu}$$

Scale invariant power law correction to Newton's law at submillimeter - $(R_G/r)^{2d-1}$

Indirect Interference Effects

Virtual Unphysics – Indirect search of unparticle

- Interference effects - SM amplitudes versus unparticle's



- Hadron Colliders:
  Drell-Yan process, diphoton production, $t\bar{t}$ production, WW scatterings, dijets production, etc

- Linear Colliders:

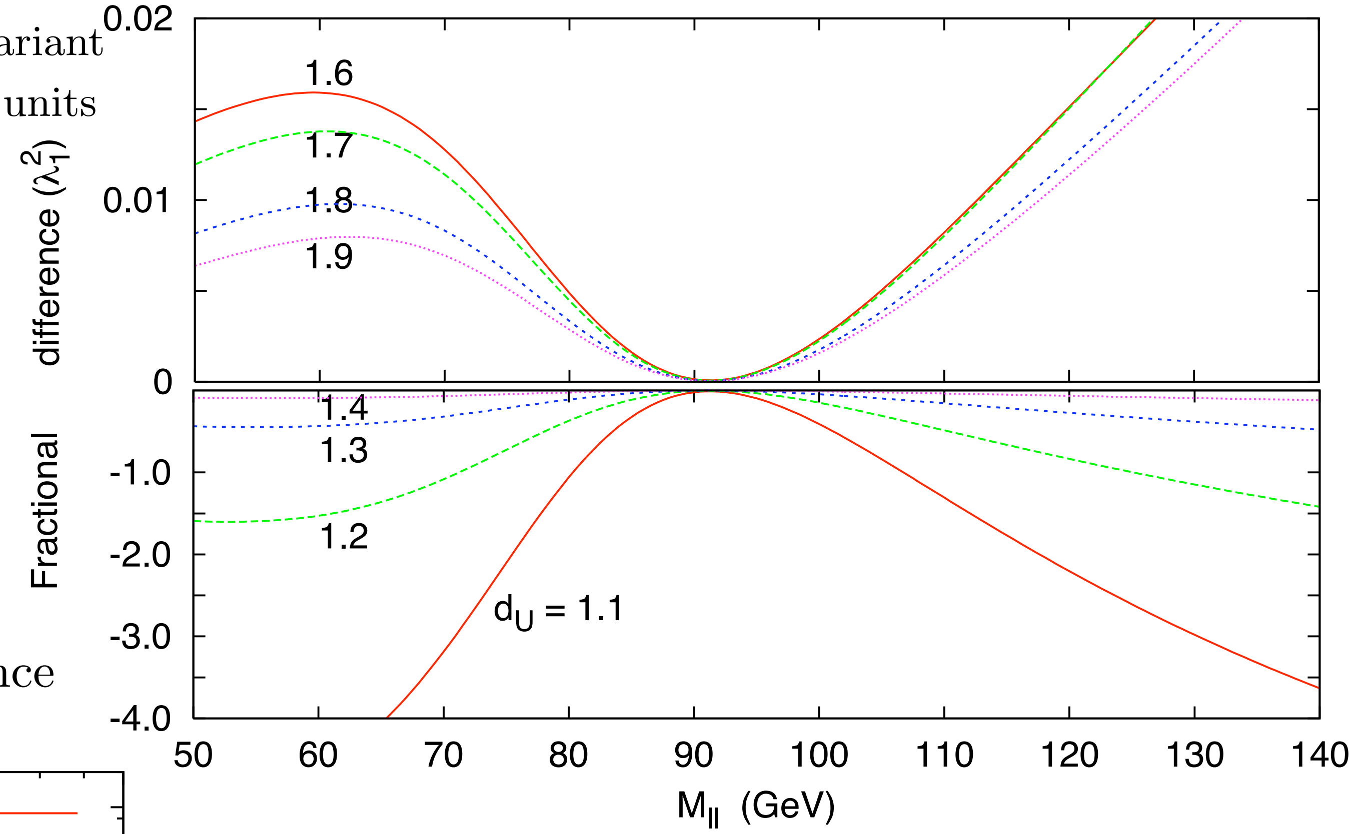
$$
\begin{aligned}
e^- e^+ &\rightarrow \mu^- \mu^+, t\bar{t}, \ldots \\
e^- e^+ &\rightarrow \gamma\gamma, \gamma Z, W^- W^+, ZZ, \ldots \\
\gamma\gamma &\rightarrow \gamma\gamma
\end{aligned}
$$

etc

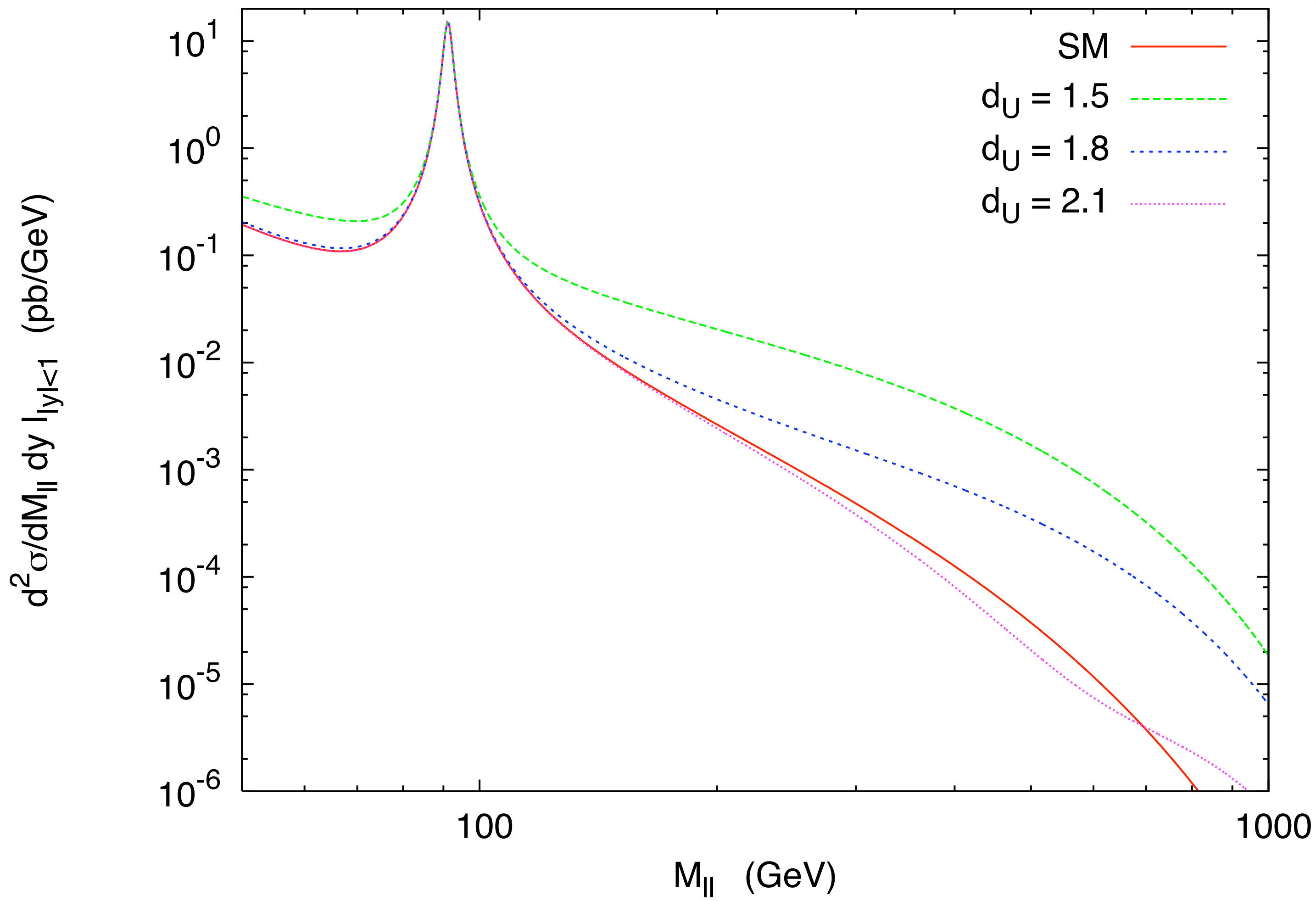
Drell-Yan at Tevatron

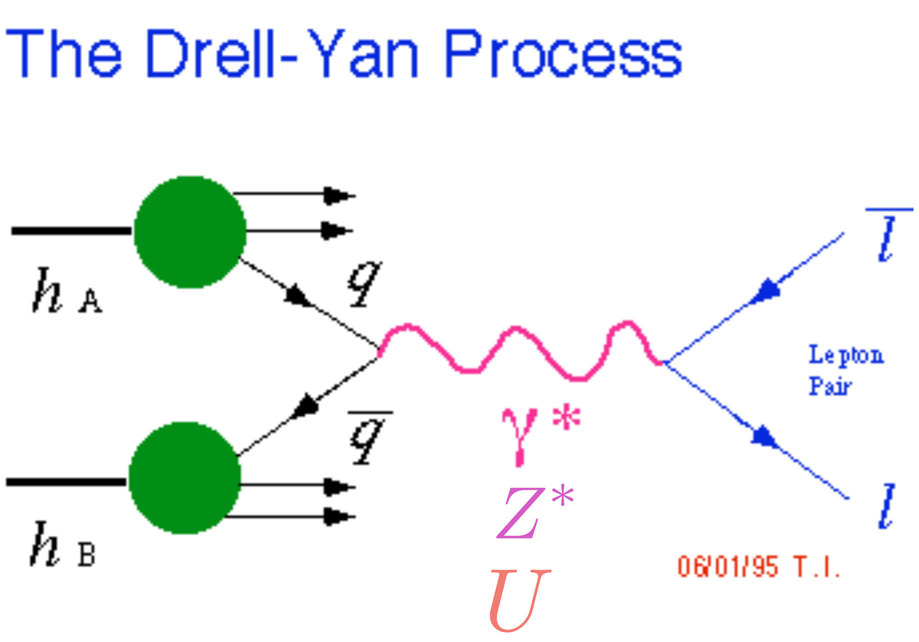
- Fractional difference from the SM prediction of the Drell-Yan invariant mass spectrum near the Z pole for various $d_{\mathcal{U}}$ at the Tevatron in units of λ_1^2. We have chosen $\Lambda_{\mathcal{U}} = 1$ TeV.
- Interference between $\mathcal{U}$ and γ and Z progagators

Sensitive dependence on d via the phase factor!



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

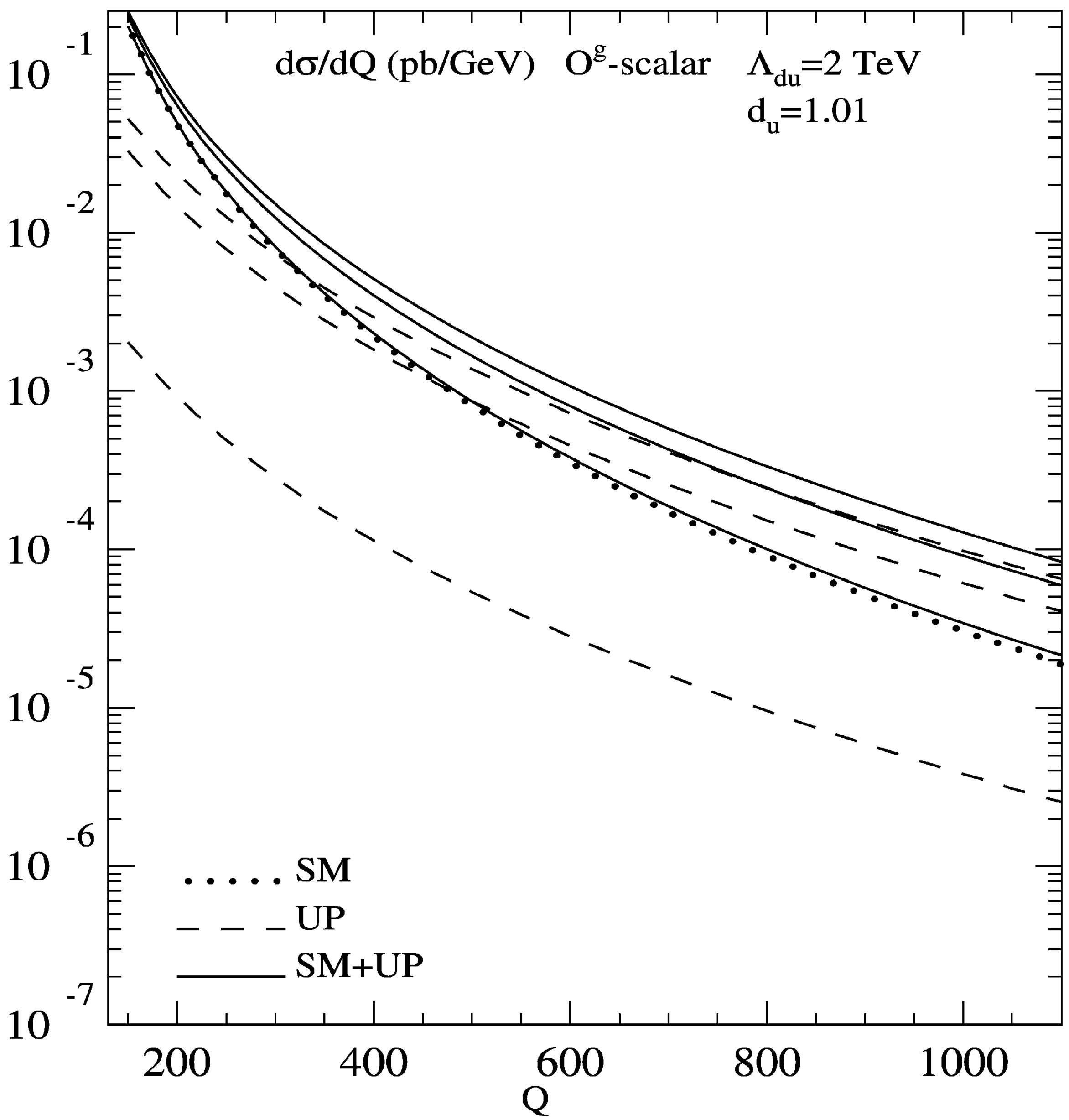


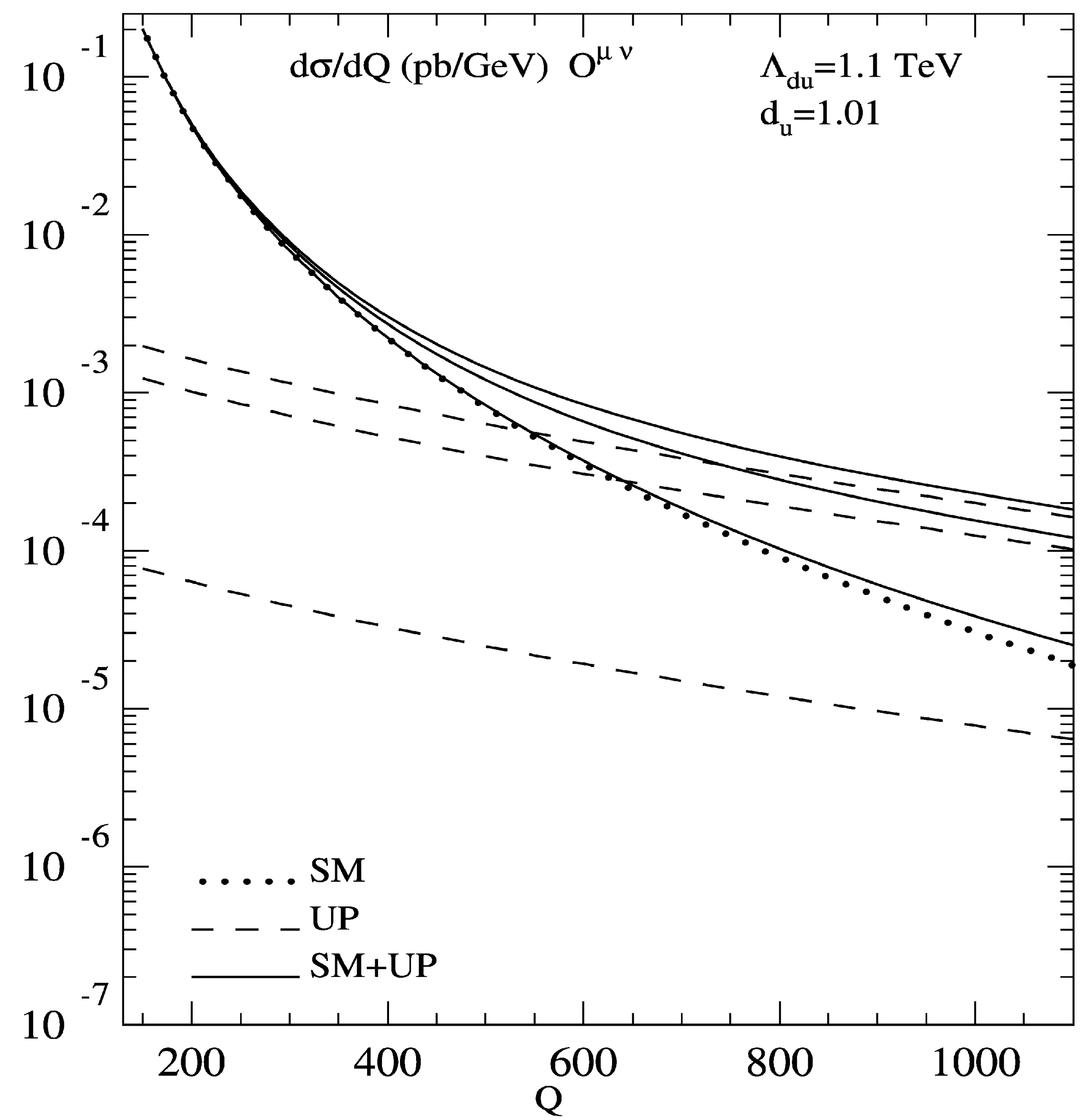


[Cheung et al, PRL99, 051803 (2007)]

Drell-Yan at LHC

[Mathews and Ravindran, PLB657, 198 (2007)]





$\lambda_S = 0.4, 0.8, 0.9$ (Scalar unparticle-Glue) $\lambda_T = 0.4, 0.8, 0.9$ (Tensor unparticle-Quarks/Glue)

Diphoton production at LHC

[Kumar, Mathews, Ravindran and Tripathi, PRD77, 055013 (2008)]

$$P_1(p_1) + P_2(p_2) \to \gamma(p_3) + \gamma(p_4) + X(p_X),$$

$$\lambda_\kappa = C^\kappa_{\mathcal{U}} \left(\frac{\Lambda_{\mathcal{U}}}{M_{\mathcal{U}}}\right)^{d_{\mathcal{B}Z}} \frac{1}{M_{\mathcal{U}}^{d_{\rm SM}-4}}.$$

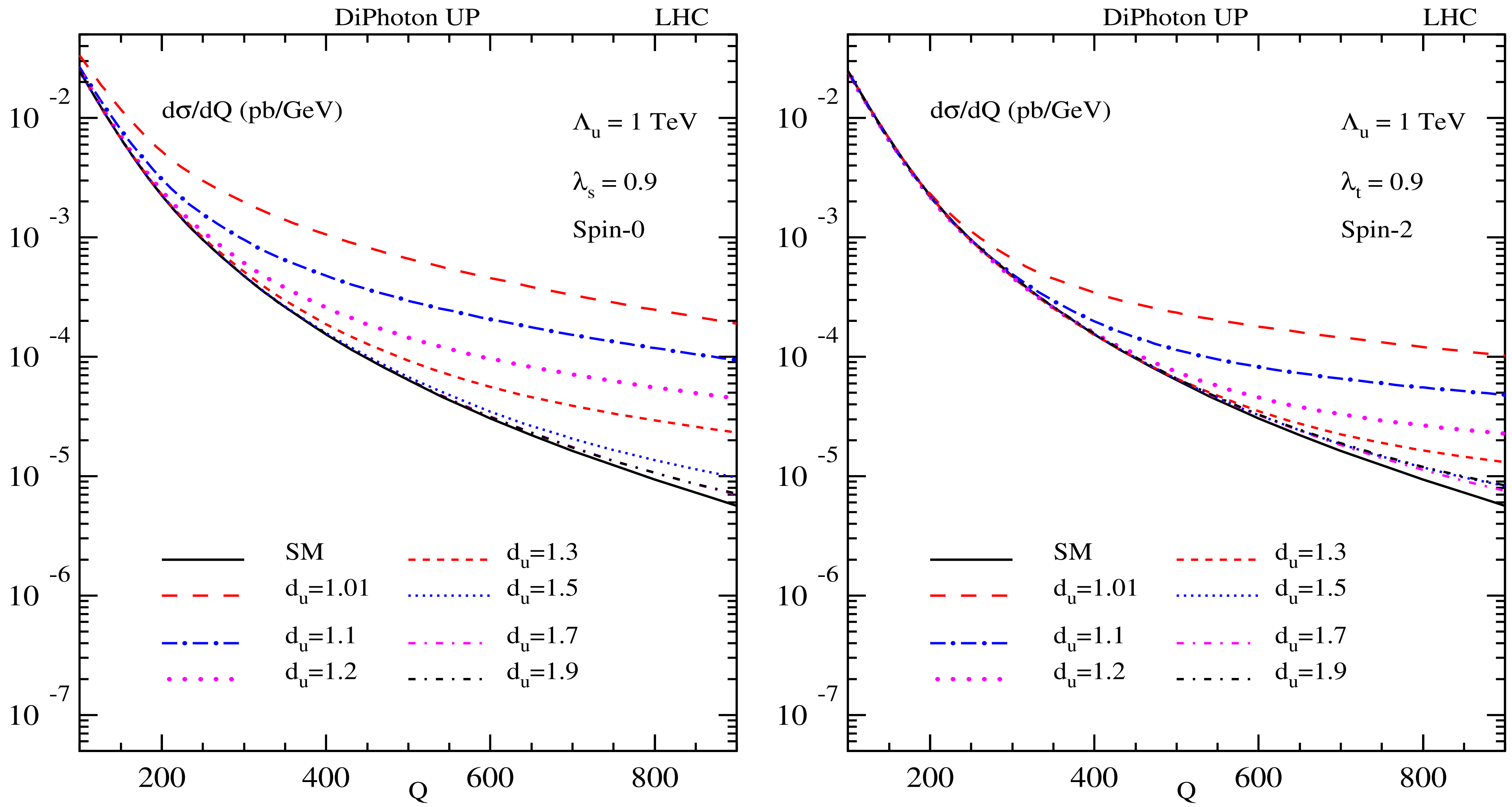
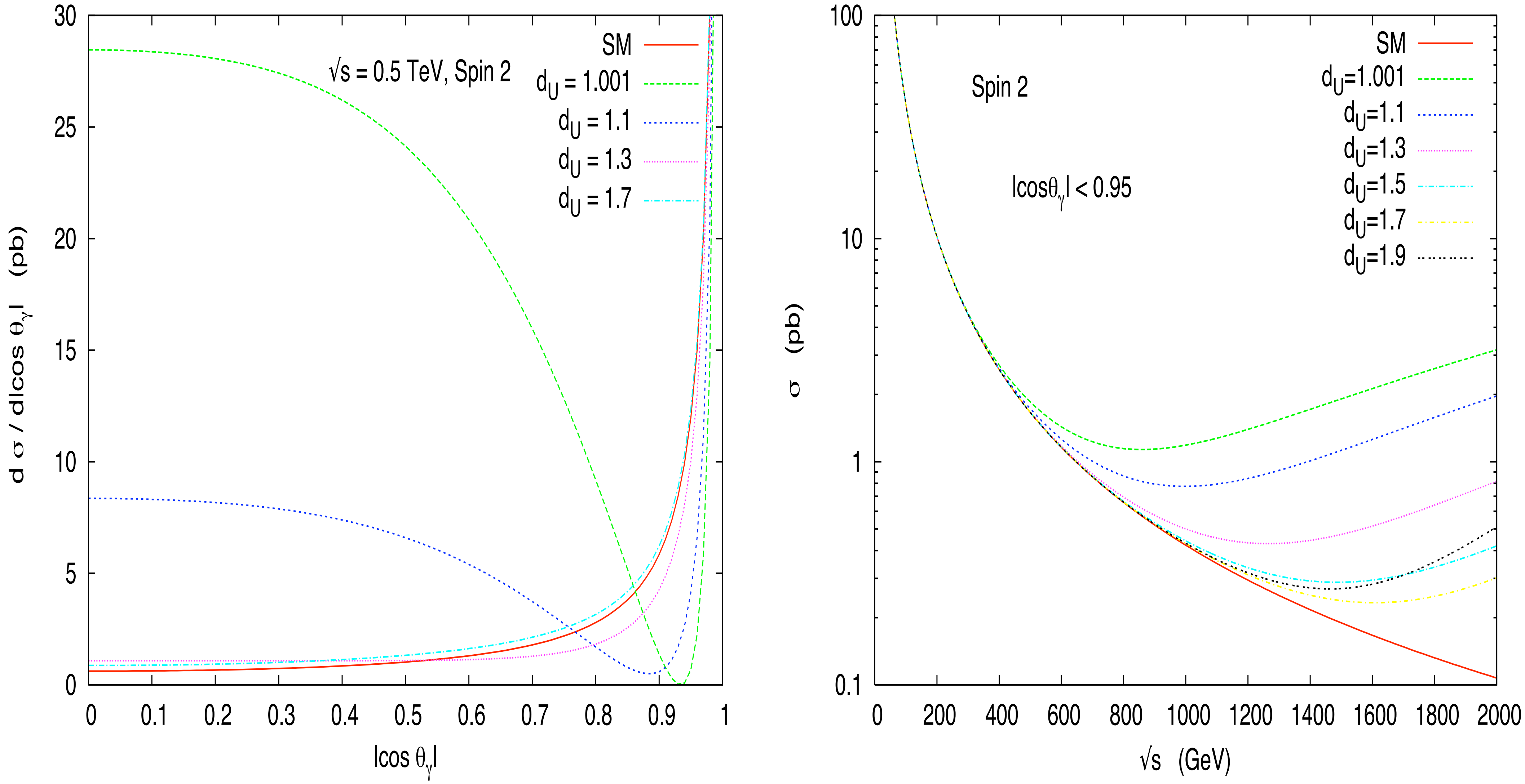


FIG. 3 (color online). Invariant mass distribution plotted for different values of $d_{\mathcal{U}}$ for spin-0 (left) and spin-2 (right) with $\Lambda_{\mathcal{U}} =$ 1 TeV and λ_s, $\lambda_t = 0.9$, with an angular cut on the photons $|\cos\theta_\gamma| < 0.8$.

Diphoton production at ILC [Cheung et al, (2007)]

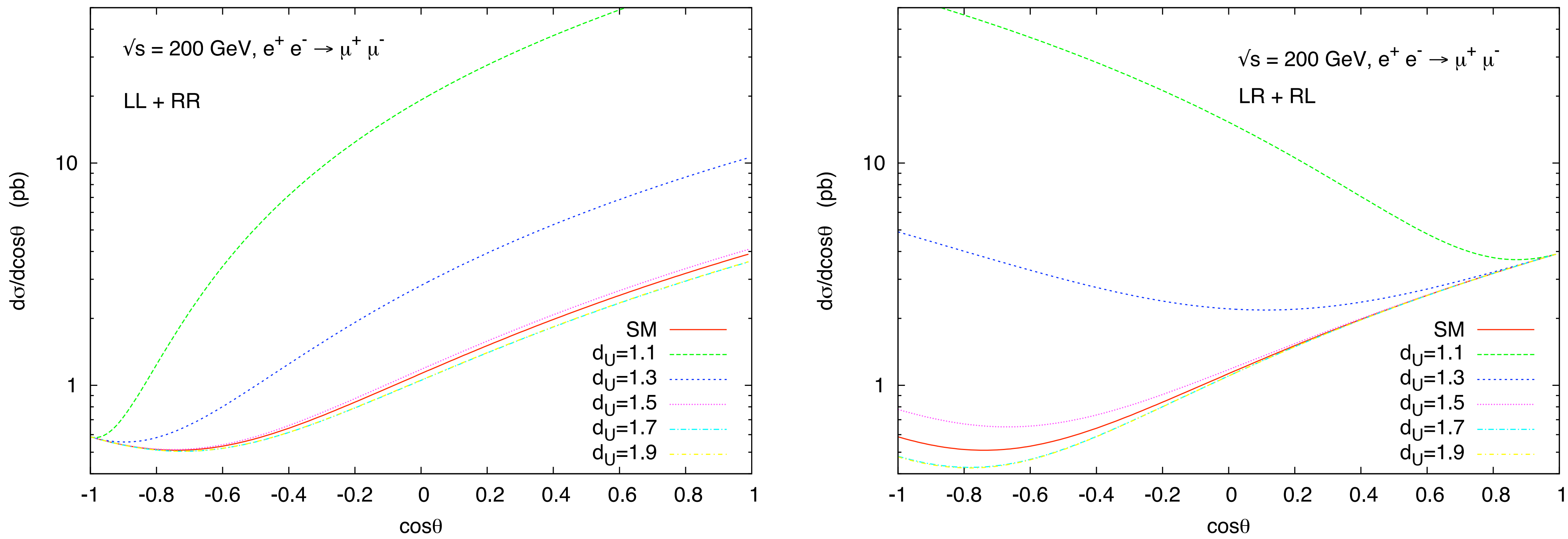
- $e^- e^+ \to \gamma\gamma$: SM + Spin 2 Unparticle Interference



- Spin 2 unparticle effects look like KK gravitons in LED
- Sensitive dependence on scaling dimension $d_{\mathcal{U}}$

Dilepton production at LEP2 [Cheung et al, (2007)]

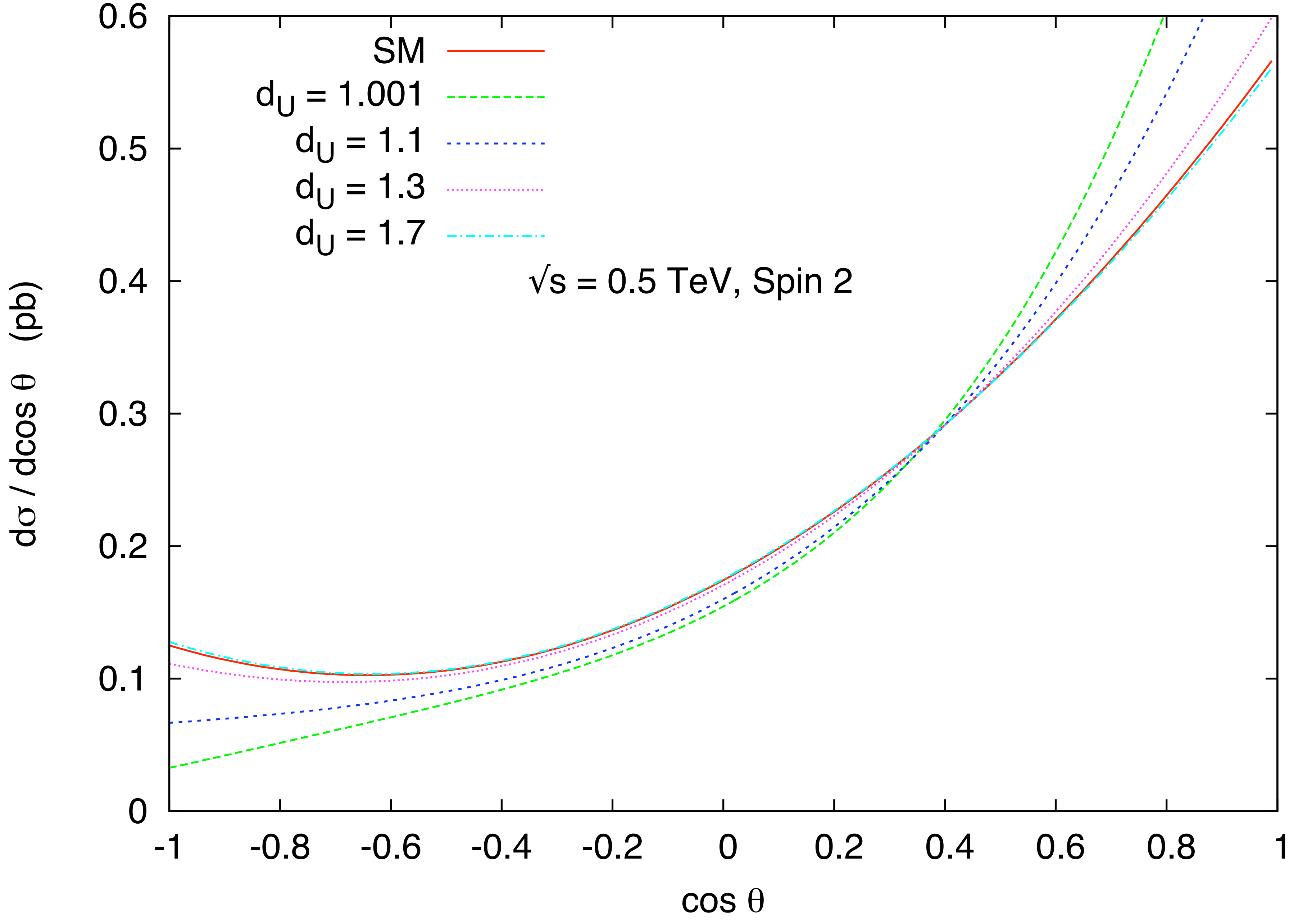
- Angular distribution of $e^- e^+ \to \mu^- \mu^+$ at LEP2 (Spin 1)



- Left Panel = LL + RR; Right Panel = LR + RL; $\Lambda_{\mathcal{U}} = 1$ TeV
- Virtual unphysics is discernible in angular distribution!

Dilepton production at ILC [Cheung et al, (2007)]

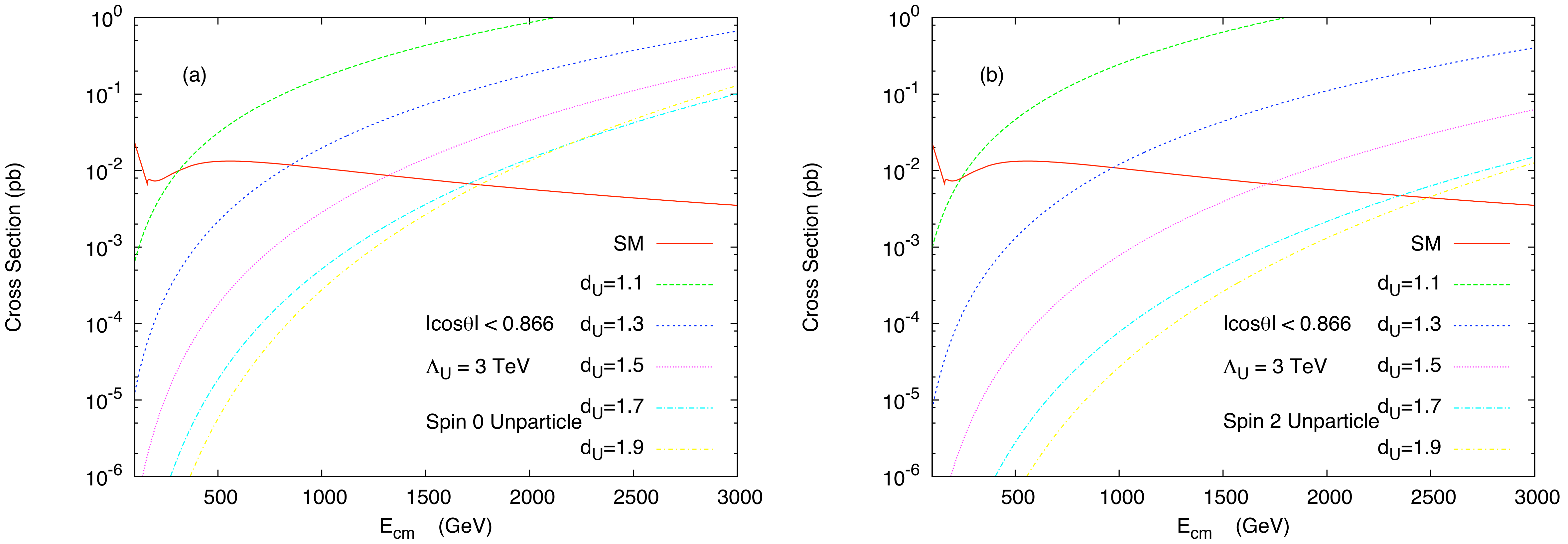
- $e^- e^+ \to \mu^- \mu^+$ at ILC: SM + Spin 2 Unparticle Interference



Unparticle physics at photon collider

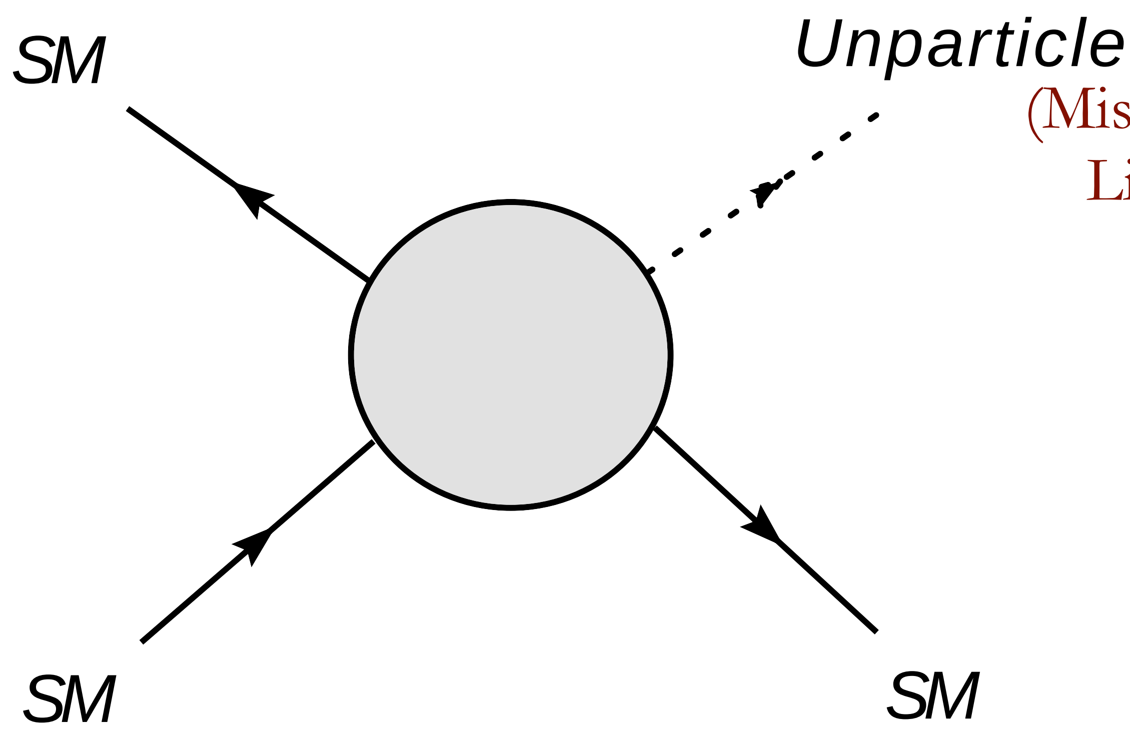
[Cakir and Ozansoy, 0712.3812;
Kikuchi, Okada and Takeuchi, PRD77, 094012 (2008);
Chang, Cheung, and TCY, 0801.2843, to appear PLB]

- $\gamma\gamma \to \gamma\gamma$ using laser back-scattering or bremsstrahlung at ILC
- SM (box) versus tree level spin 0 or 2 unparticle exchange



Direct production of unparticle stuff

Phenomenology -- Real emission of unparticle in SM processes.
Signature -- Missing energy/momentum carried away by unparticle. Search strategies is therefore very much like KK modes in LED. No fixed mass, no rest frame, just a funny phase space associated with continuous mass distribution.



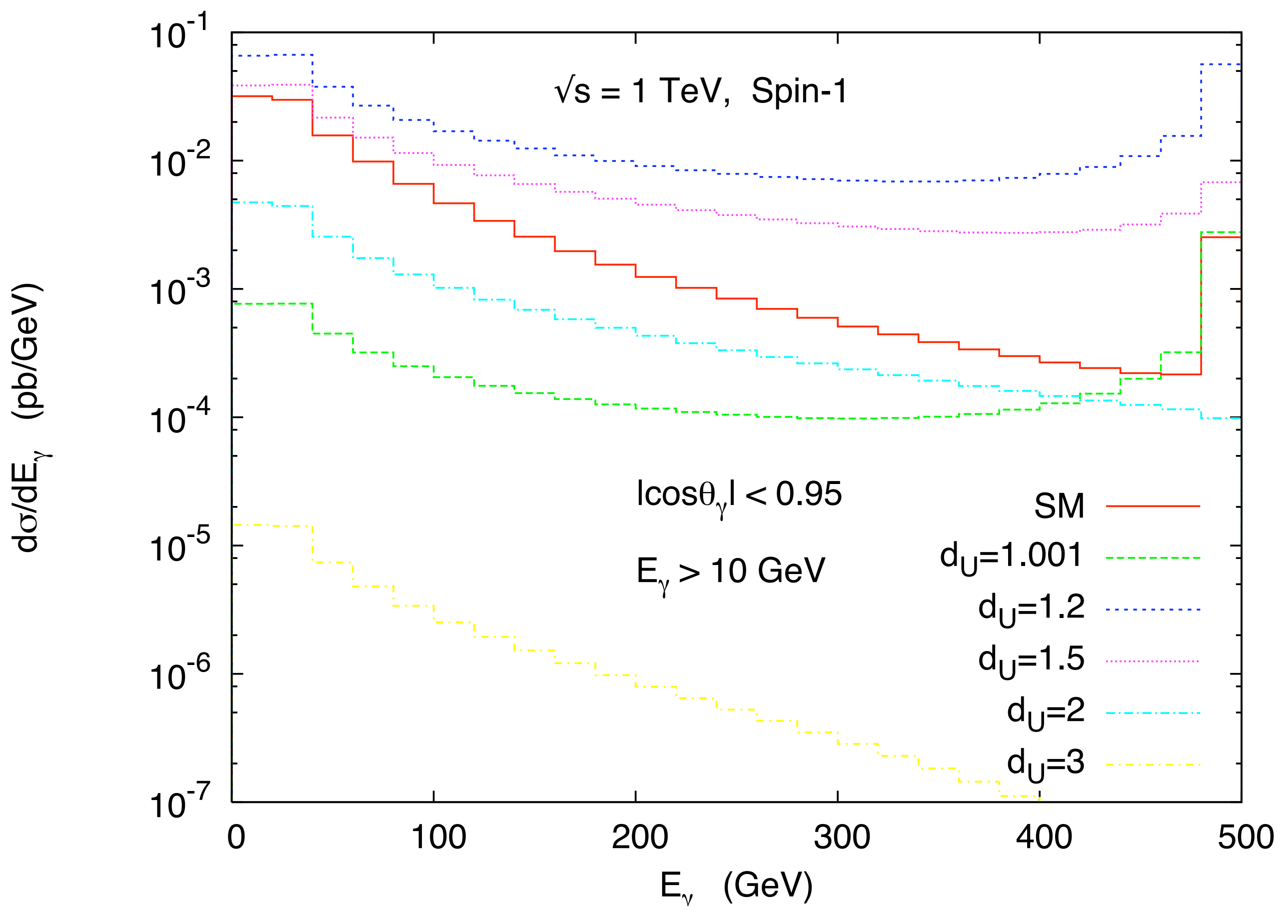
(Missing energy/momentum)
Like KK modes in LED

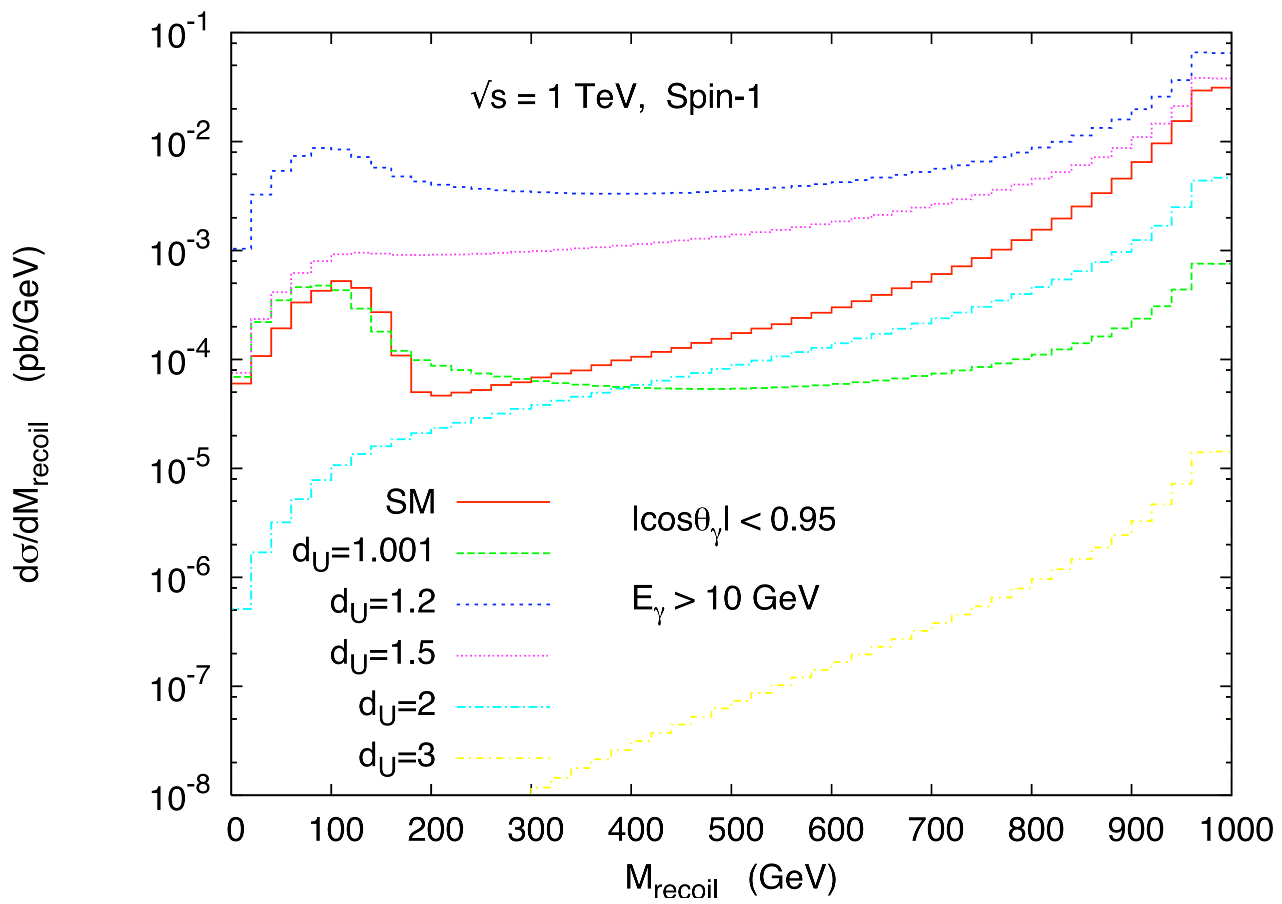
- $Z \to f\bar{f}U$
- Single photon: Quarkonia $\to \gamma U$; $H \to \gamma U$; $Z \to \gamma U$; $e^- e^+ \to \gamma U, ZU$; etc
- Monojet: $q\bar{q} \to gU$, $gg \to gU$, $qg \to qU$, $\bar{q}g \to \bar{q}U$
- etc

Single photon plus vector unparticle at ILC ($\sqrt{s} = 1$ TeV)

- $e^- e^+ \to \gamma U$
- $M^2_{recoil} = s - 2E_\gamma \sqrt{s}$
- SM background: $e^- e^+ \to \gamma Z^* \to \gamma \nu \bar{\nu}$ (Red)
- Sensitive dependence on d_U is easily discerned!

Cheung, Keung and TCY, PRD76 (2007) 055003;
Chen and He, PRD76 (2007) 091702(R).



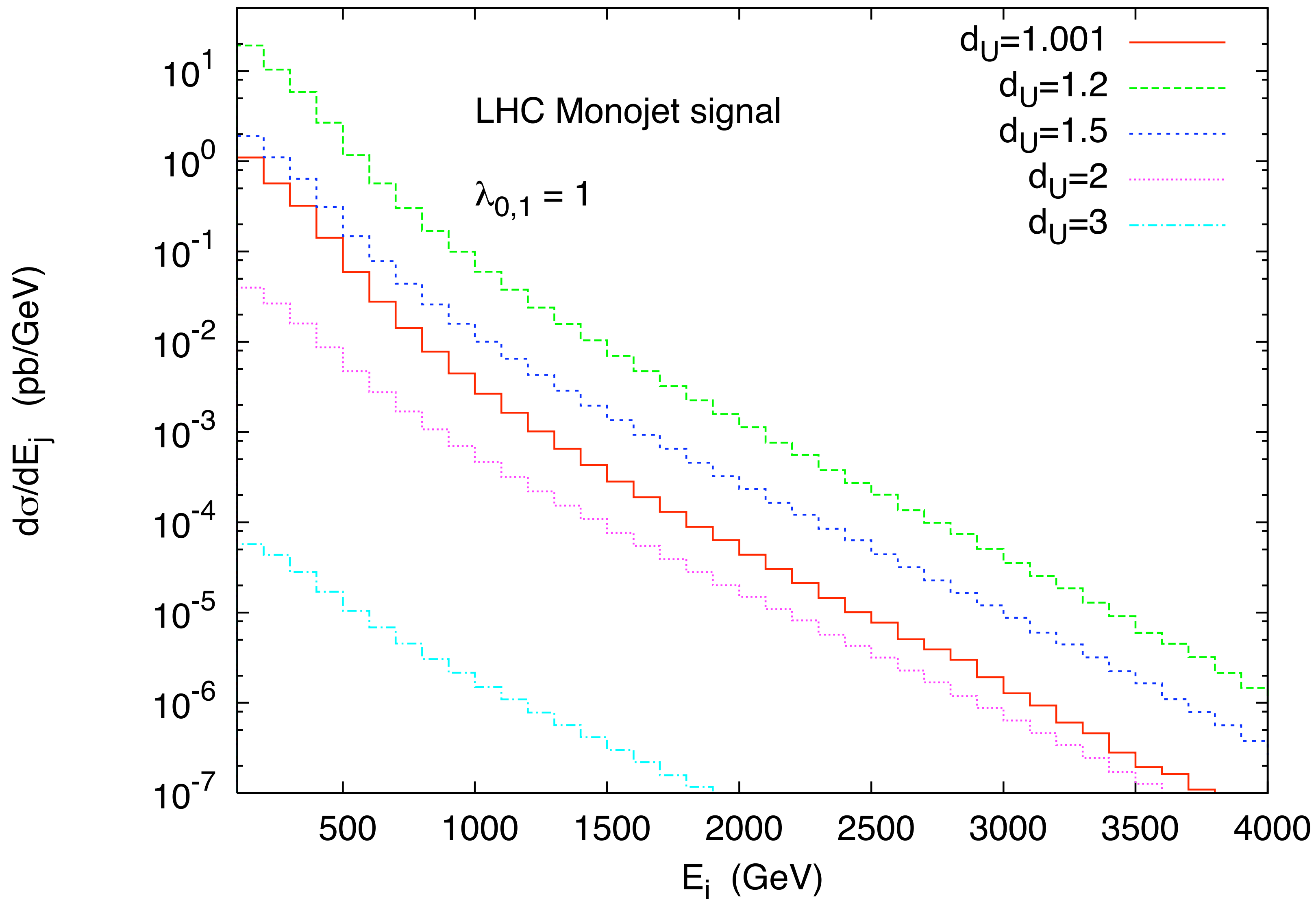


Similar effects found for spin 2 unparticle and in Z+U!

Monojet + (Scalar/Vector) Unparticle Production at LHC

(Cheung, Keung and TCY, PRL 99 (2007) 051803)

$$gg \to gU, qg \to qU, \bar{q}g \to \bar{q}U, q\bar{q} \to gU$$



Peculiar dependence on d_U has been washed out by parton smearing

Identification of origin of monojet at LHC
Using the shape and Et distribution
(Rizzo, 0805.0281 [hep-ph])

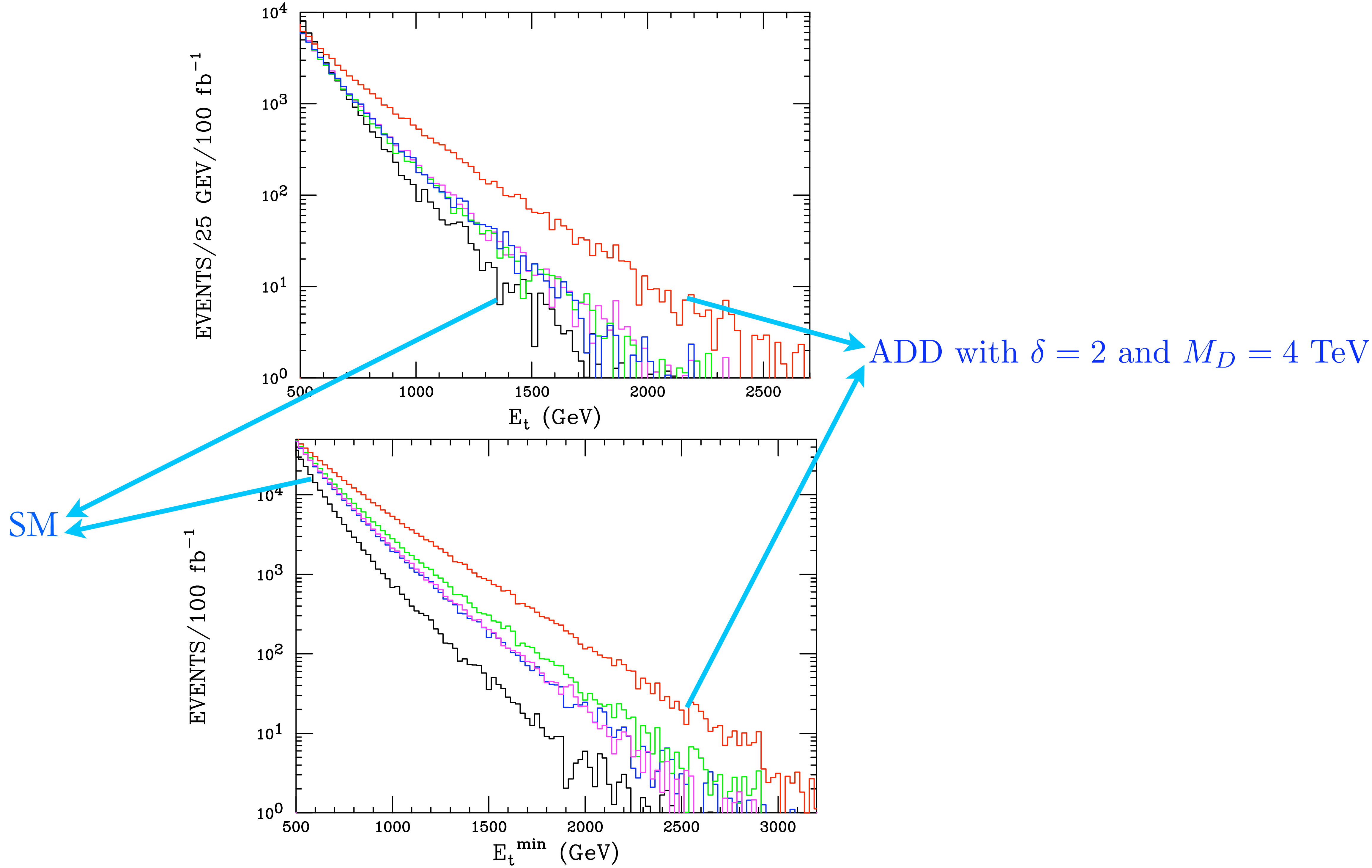
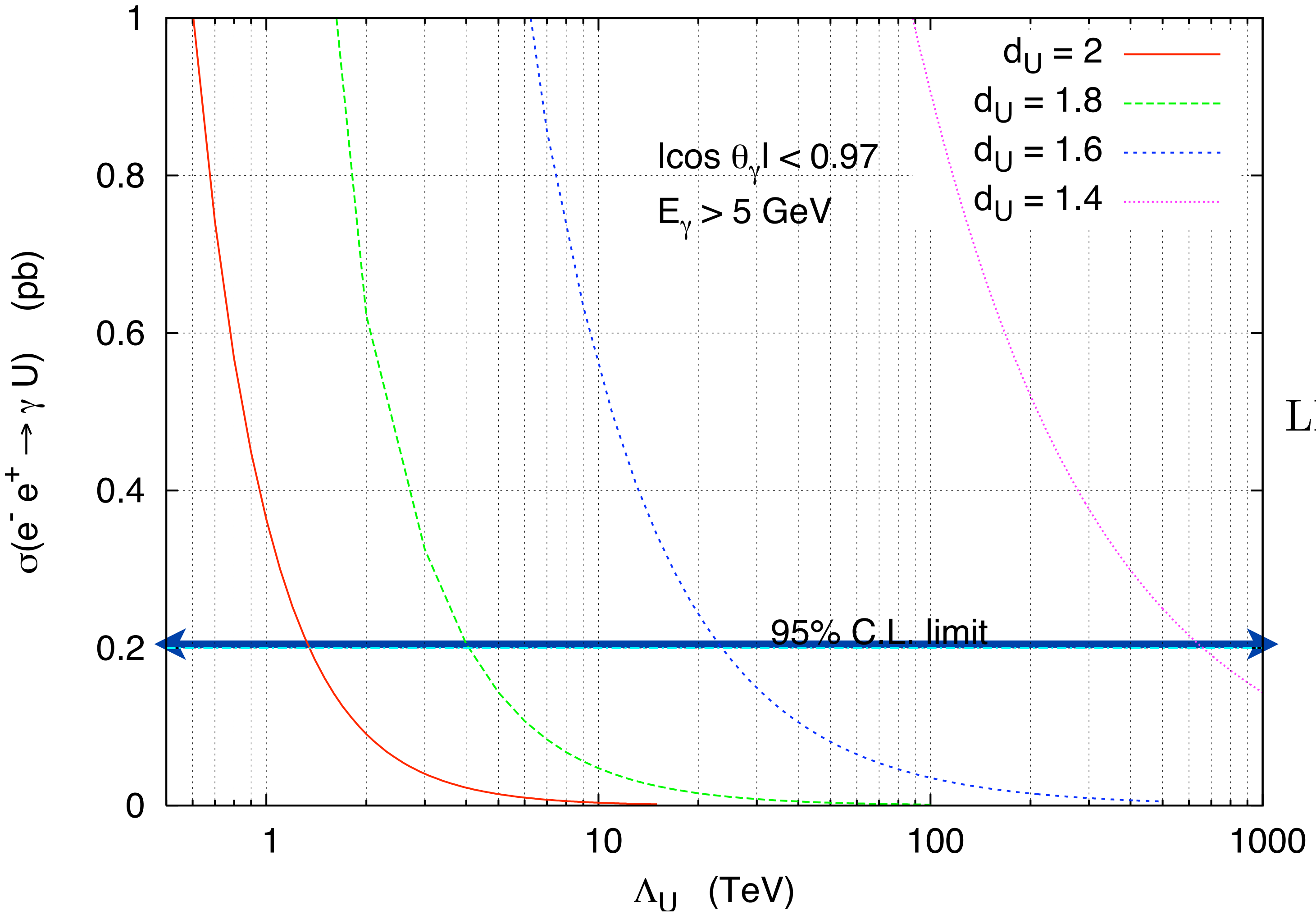


Figure 6: Sample comparison of the predictions for the monojet E_T and E_T^{cut} distributions in the ADD model with $M_D = 4$ TeV and $\delta = 2$ (upper red histogram) with the case of vector Blue histogram) and scalar unparticles (with either $r = 0, 1$ in the green and magenta histograms, respectively) assuming $d = 1.8$, corresponding to the. Also shown is the SM background (black histogram).

Existing Constraints

(1) Monophoton emission at LEP2 [Cheung et al, (2007)]



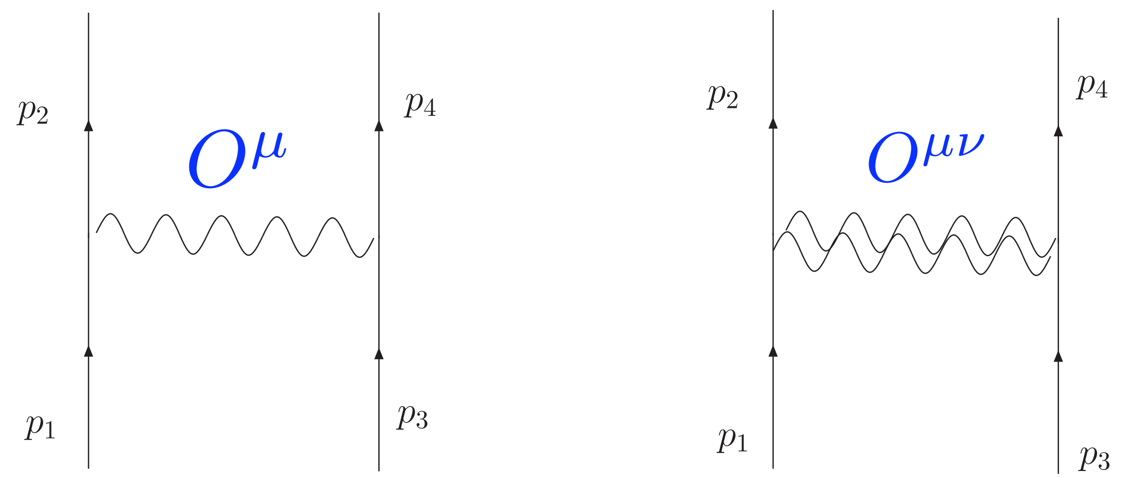
LEP2 constraints on $\Lambda_{\mathcal{U}}$ from single photon production:

$d_{\mathcal{U}}$	$\Lambda_{\mathcal{U}}$ (TeV)
2.0	1.35
1.8	4
1.6	23
1.4	660

Strongest limit from L3 at $\sqrt{s} = 207$ GeV

$$\sigma^{95} \approx 0.2 \text{ pb with } E_\gamma > 5 \text{ GeV and } |\cos\theta_\gamma| < 0.97$$

(II) From global fits of *eeqq* contact interactions at LEP2



(a) (b)

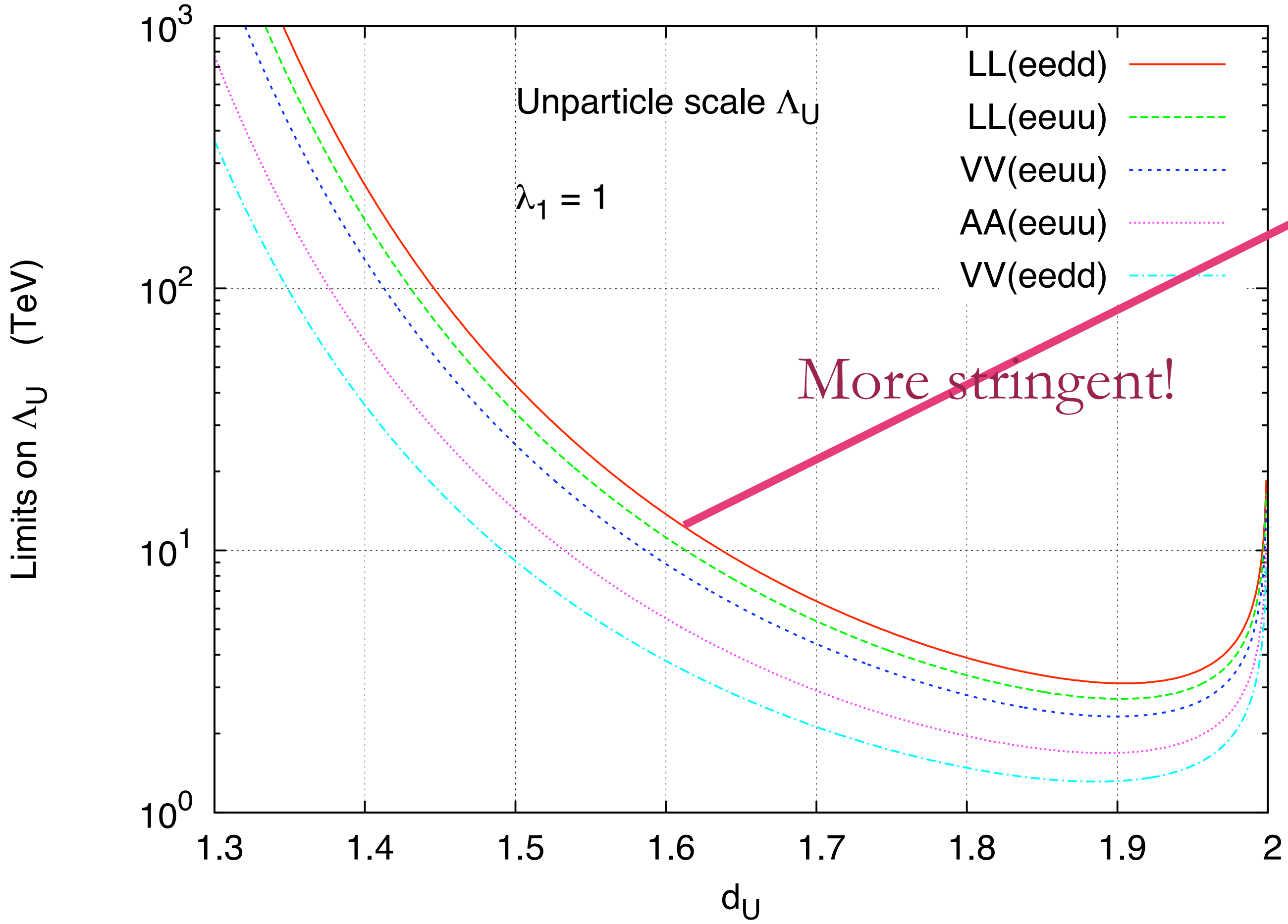
- New 4-fermion contact interaction with spin 1 and 2 unparticle exchange

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

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

- Conformal propagators gives the same results! [Chang, Cheung, TCY (unpublished)

LEP2 constraint on unparticle scale $\Lambda_{\mathcal{U}}$ (contact interaction)



LEP2 data: (95% C.L.)

$\Lambda^{95}_{LL}(eeuu) \approx 23$ TeV

$\Lambda^{95}_{LL}(eedd) \approx 26$ TeV

$\Lambda^{95}_{VV}(eeuu) \approx 20$ TeV

$\Lambda^{95}_{VV}(eedd) \approx 12$ TeV

$\Lambda^{95}_{AA}(eeuu) \approx 15$ TeV

$\Lambda^{95}_{AA}(eedd) \approx 15$ TeV

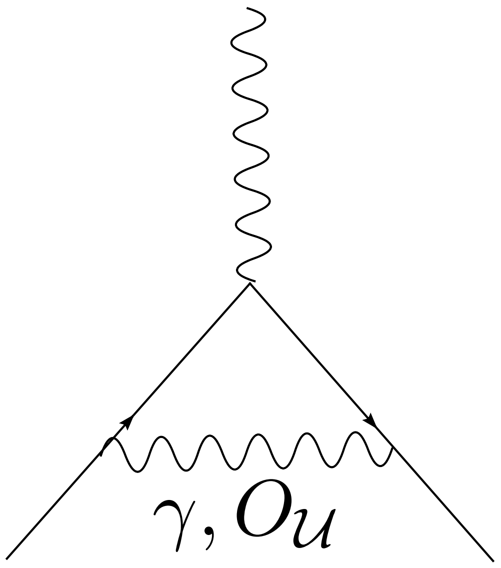
$$\lambda_1^2 \, Z_{d_{\mathcal{U}}} \, \frac{1}{\Lambda_{\mathcal{U}}^2} \left(-\frac{P_{\mathcal{U}}^2}{\Lambda_{\mathcal{U}}^2} \right)^{d_{\mathcal{U}}-2} \approx \frac{4\pi}{(\Lambda^{95})^2} \quad \text{with} \quad P_{\mathcal{U}}^2 = (0.2 \text{ TeV})^2$$

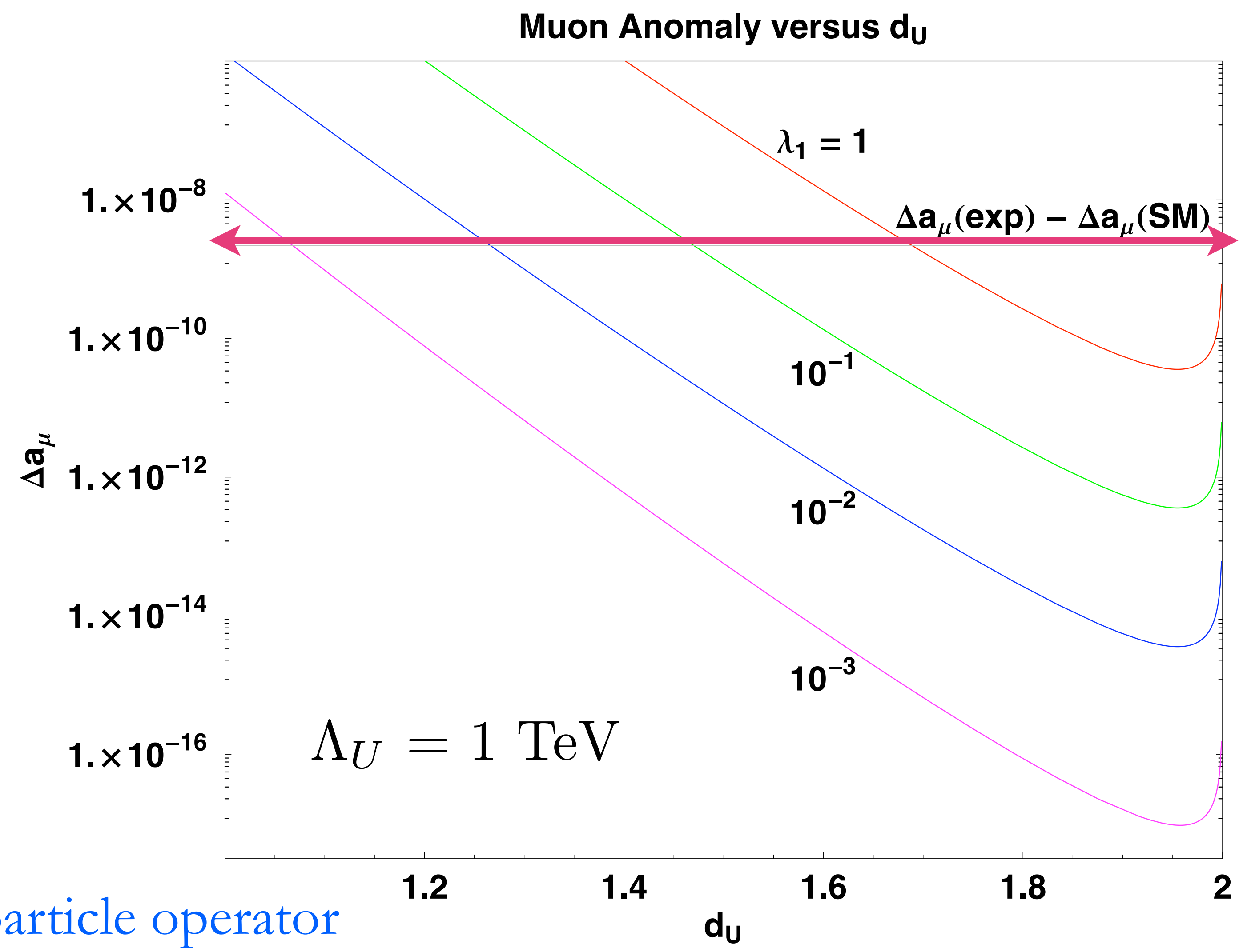
(III) Muon Anomalous Magnetic Moment (g-2)

$$\Delta a_\mu \equiv \left(\frac{g-2}{2}\right)_\mu = \frac{\alpha}{\pi} \quad \text{(QED)}$$

$$= -\frac{\lambda_1^2}{8\pi^2}\frac{A_d}{\sin(d\pi)}\left(\frac{m_\mu^2}{\Lambda_U^2}\right)^{d-1} B(3-d, 2d-1) \quad \text{(unparticle)}$$

Cheung et al (2007)



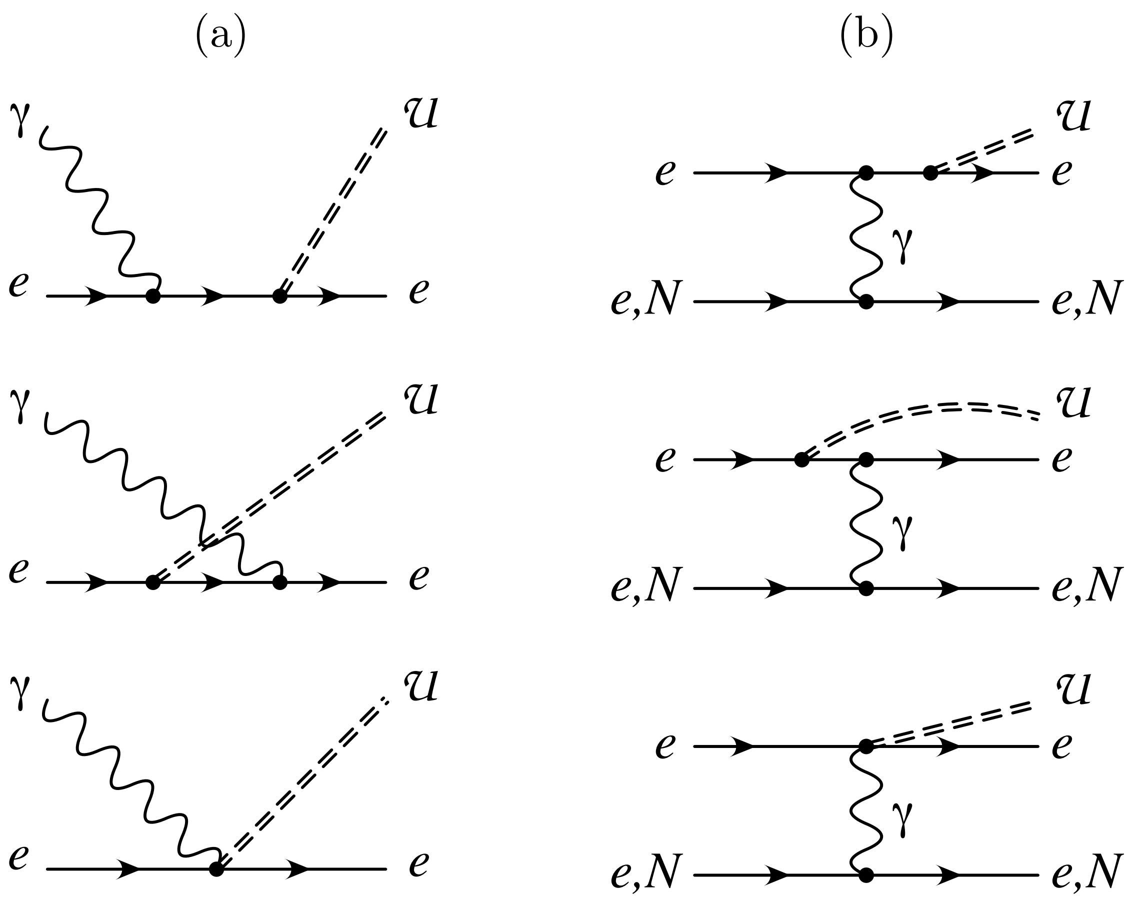


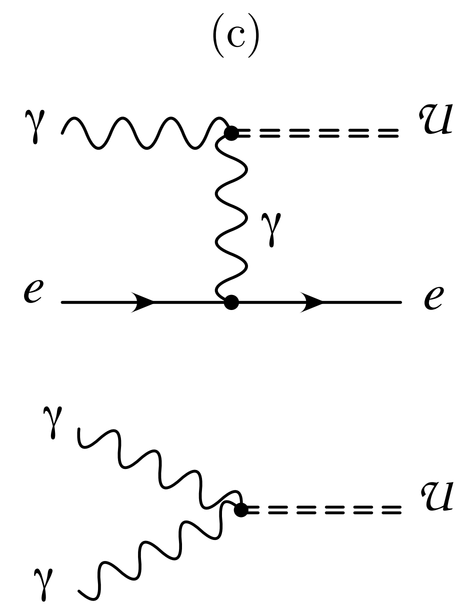
For anti-symmetric rank 2 tensor unparticle operator contribution to (g-2), see Hur, Ko and Wu, PRD76, 096008 (2007)

(IV) Astrophysical and cosmology constraints (5th force, Stellar Cooling, SN1877A, BBN, relic density, ...)

[Davoudiasl, PRL 99 (2007), 141301; Freitas and Wyler, JHEP 12 (2007) 033;
Hannestad, Raffelt and Wong, PRD76, 121701 (2007);
Goldberg and Nath, PRL 100, 031803 (2008);
Deshpande, Hsu and Jiang, PLB659 (2008) 888;
McDonald, 0709.2350, 0805.1888; Lewis, 0710.4147; Das, PRD76, 123012 (2007);
Hur and Ko, unpublished; Cheung et al, unpublished.]

Star Cooling Mechanism



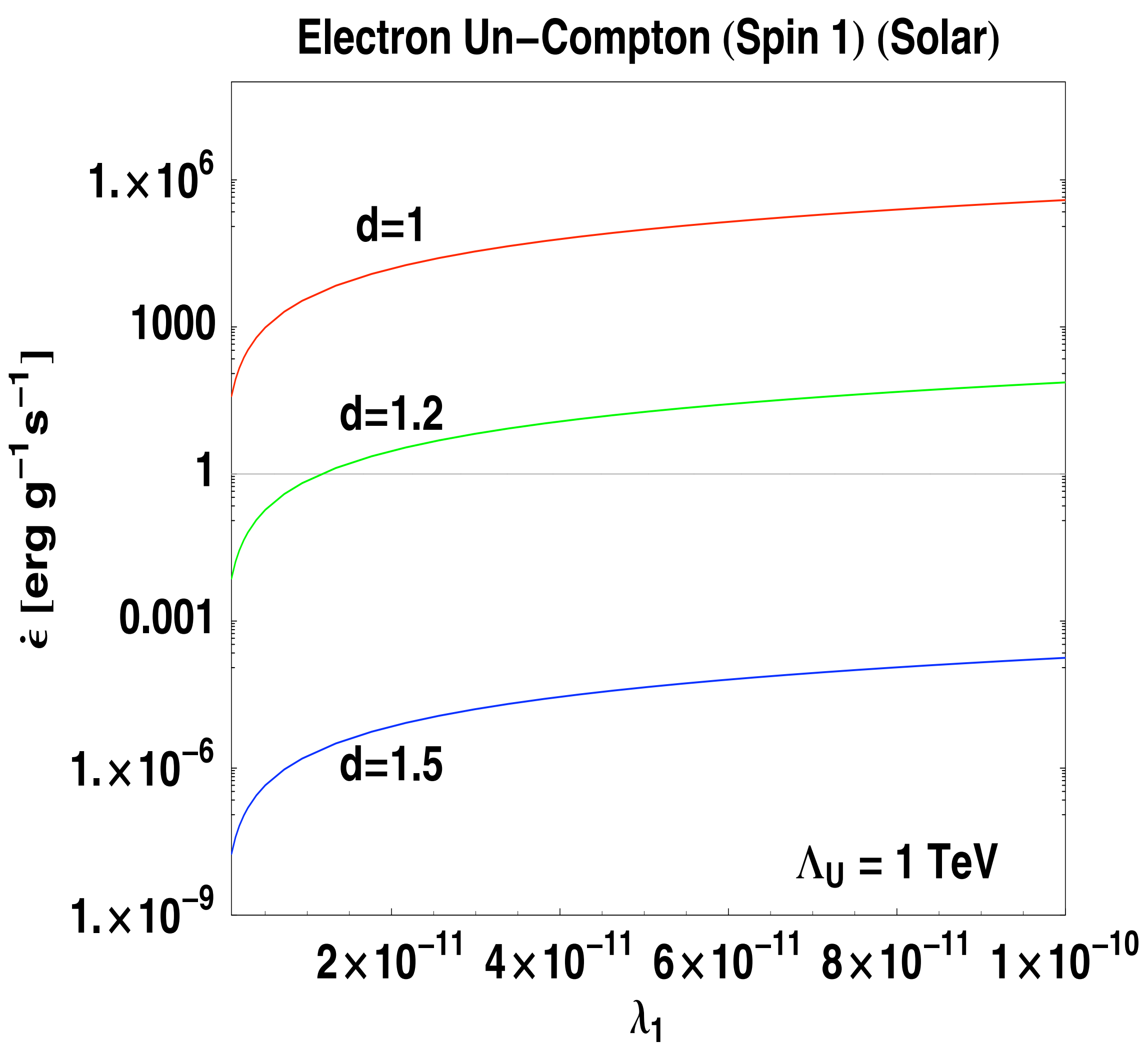


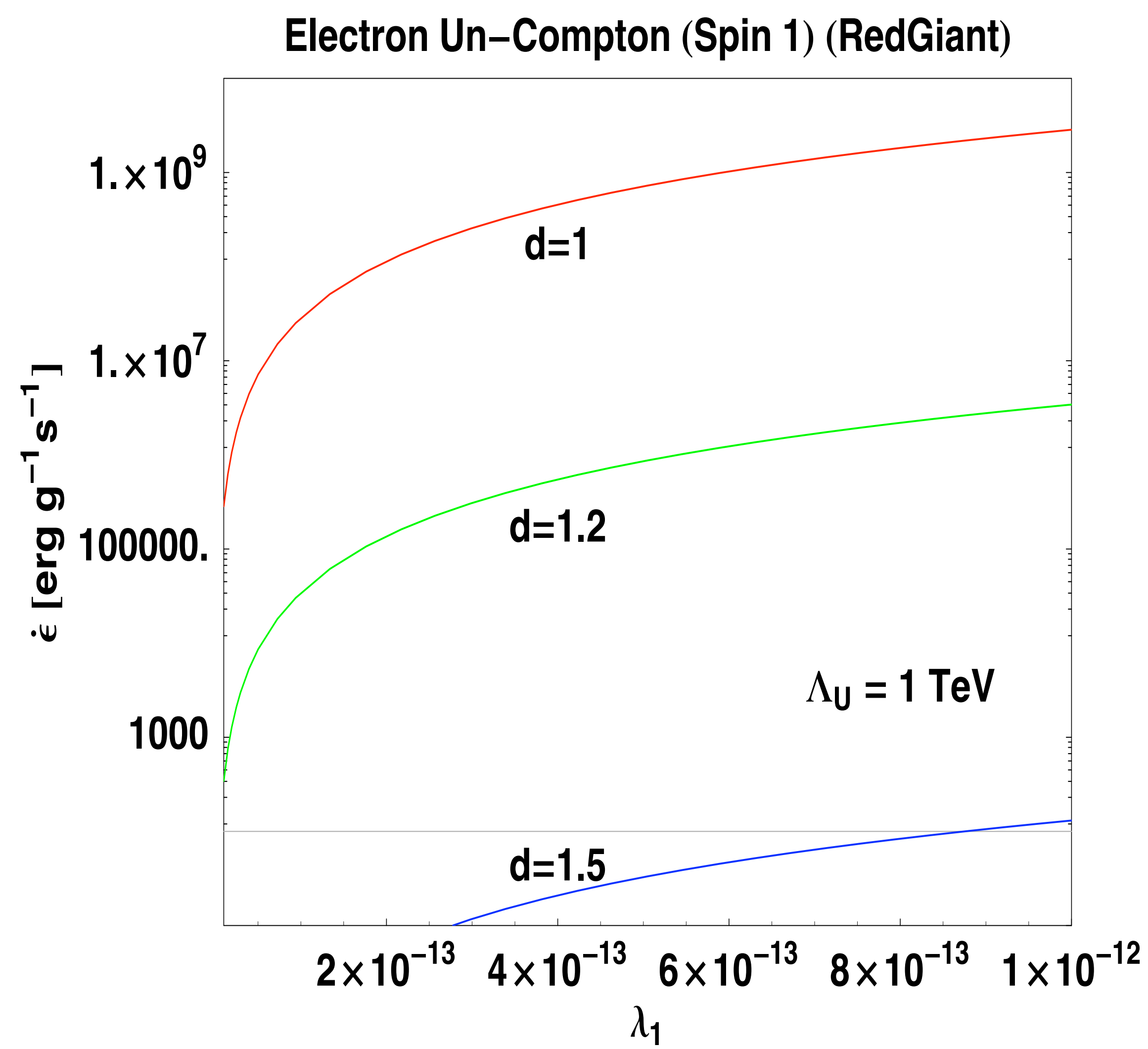
Energy loss rate

$$
\begin{aligned}
\dot{\varepsilon}_{\odot} &\simeq 1\ \mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{s}^{-1} \\
\dot{\varepsilon}_{\text{Red Giant}} &\simeq 100\ \mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{s}^{-1} \\
\dot{\varepsilon}_{\text{SN1987A}} &\simeq 10^{19}\ \mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{s}^{-1}
\end{aligned}
$$

Figure 2: Feynman diagrams for unparticle emission in (a) Compton-like processes, (b) bremsstrahlung-like processes and (c) processes with unparticle-photon couplings.

Constraints from energy loss rate from the Sun and Red Giant





- Constraints from Red Giant are stronger than the Sun

[Cheung et al, unpublished]

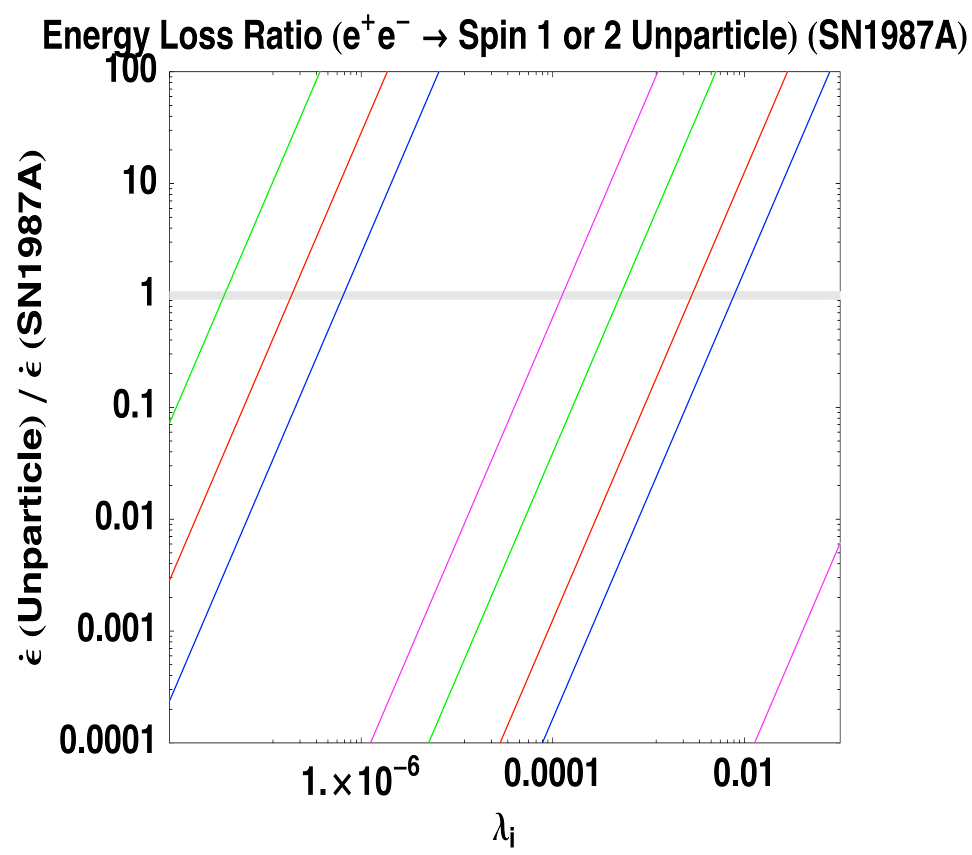
$$\mathcal{L}_{\mathcal{U}ff} = \frac{c_V}{M_Z^{d_U-1}}\bar{f}\gamma_\mu f O^\mu + \frac{c_A}{M_Z^{d_U-1}}\bar{f}\gamma_\mu\gamma_5 f O^\mu + \frac{c_{S1}}{M_Z^{d_U}}\bar{f}\not{D} f O + \frac{c_{P1}}{M_Z^{d_U}}\bar{f}\not{D}\gamma_5 f O + \frac{c_{S2}}{M_Z^{d_U}}\bar{f}\gamma_\mu f \partial^\mu O + \frac{c_{P2}}{M_Z^{d_U}}\bar{f}\gamma_\mu\gamma_5 f\partial^\mu O$$

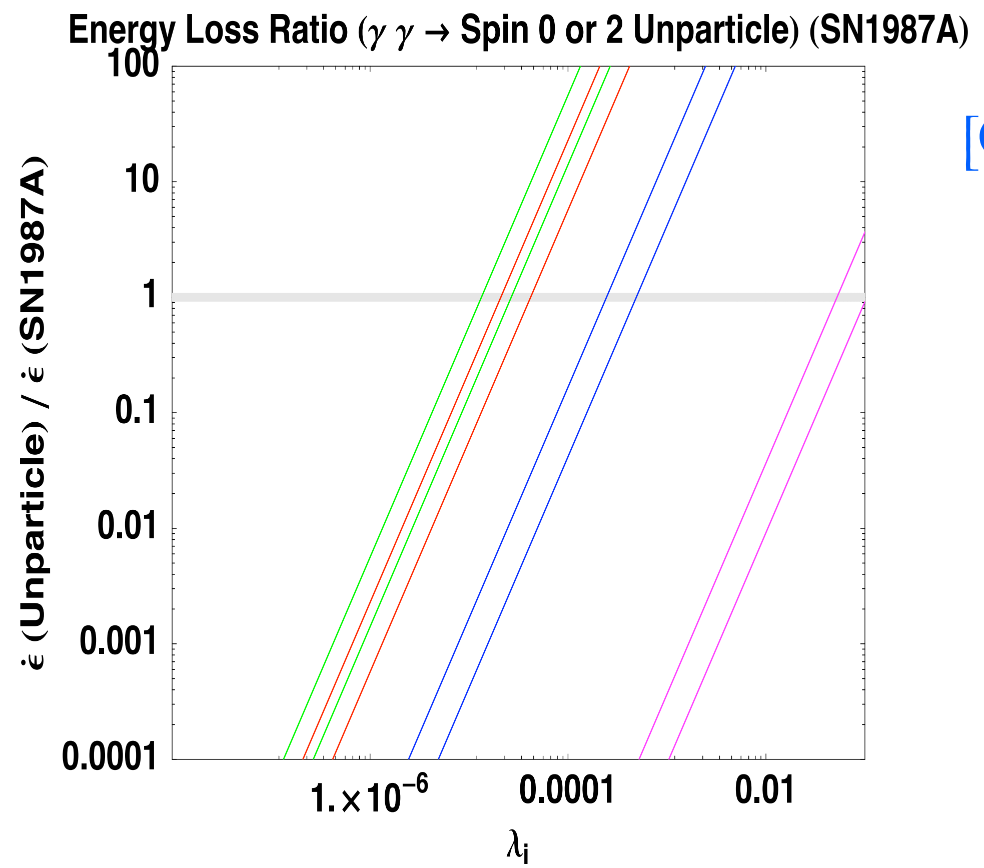
Coupling	c_{V}				c_{A}			
$d_{\mathcal{U}}$	1	4/3	5/3	2	1	4/3	5/3	2
5th force ("Eötvös")	$7\cdot10^{-24}$	$1.4\cdot10^{-15}$	$1.8\cdot10^{-10}$	$2\cdot10^{-5}$	$4\cdot10^{-24}$	$8\cdot10^{-16}$	$1\cdot10^{-10}$	$1.1\cdot10^{-5}$
Energy loss from stars	$5\cdot10^{-15}$	$2.5\cdot10^{-12}$	$1\cdot10^{-9}$	$3.5\cdot10^{-7}$	$6.3\cdot10^{-15}$	$2\cdot10^{-12}$	$7.3\cdot10^{-10}$	$3\cdot10^{-7}$
SN 1987A	$1\cdot10^{-9}$	$3.5\cdot10^{-8}$	$1\cdot10^{-6}$	$3\cdot10^{-5}$	$2\cdot10^{-11}$	$5.5\cdot10^{-10}$	$1.5\cdot10^{-8}$	$4.1\cdot10^{-7}$
LEP	0.005	0.045	0.04	0.01	0.1	0.045	0.04	0.008
Tevatron		0.4	0.05					
ILC	$1.6\cdot10^{-4}$	$1.4\cdot10^{-3}$	$1.3\cdot10^{-3}$	$3.2\cdot10^{-4}$	$3.2\cdot10^{-3}$	$1.4\cdot10^{-3}$	$1.3\cdot10^{-3}$	$2.5\cdot10^{-4}$
LHC		0.25	0.02					
Electroweak precision	1	0.2	0.025		1	0.15	0.01	
Quarkonia		0.01	0.1	0.45				
Positronium		0.25				$2\cdot10^{-13}$	$2\cdot10^{-8}$	0.03

[Freitas and Wyler, JHEP 12 (2007) 033]

Coupling	c_{S1}				$c_{\mathrm{P1}},\ 2c_{\mathrm{P2}}$			
$d_{\mathcal{U}}$	1	4/3	5/3	2	1	4/3	5/3	2
5th force ("Eötvös")	$6.5\cdot10^{-22}$	$1.2\cdot10^{-13}$	$1.6\cdot10^{-8}$	$1.7\cdot10^{-3}$	—	—	—	—
Energy loss from stars	$1.3\cdot10^{-9}$	$7\cdot10^{-7}$	$3\cdot10^{-4}$	0.13	$4\cdot10^{-8}$	$1.1\cdot10^{-5}$	$3.3\cdot10^{-3}$	1
SN 1987A	$8\cdot10^{-8}$	$2.4\cdot10^{-6}$	$6.6\cdot10^{-5}$	$2\cdot10^{-3}$	$5.5\cdot10^{-8}$	$1.3\cdot10^{-6}$	$3.5\cdot10^{-5}$	$9\cdot10^{-4}$
LEP	>1	>1	>1	>1	>1	>1	>1	>1
ILC	>1	>1	>1	>1	>1	>1	>1	>1

Constraints from energy loss rate from SN1987A ($\Lambda_{\mathcal{U}} = 1$ TeV)





[Cheung et al, unpublished]

- Constraints on $e^+e^- \to \mathcal{U}$ are more severe than $\gamma\gamma \to \mathcal{U}$.

$$\mathcal{L}_{\mathcal{U}\gamma\gamma} = -\frac{c_{\gamma\gamma}}{4M_Z^d} F_{\mu\nu}F^{\mu\nu}O - \frac{c_{\tilde\gamma\tilde\gamma}}{4M_Z^d}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}O$$

[Freitas and Wyler, JHEP 12 (2007) 033]

Coupling	$c_{\gamma\gamma}, c_{\tilde\gamma\tilde\gamma}$			
$d_{\mathcal{U}}$	1	4/3	5/3	2
Energy loss from stars	$5.5\cdot10^{-14}$	$1.7\cdot10^{-11}$	$5.3\cdot10^{-9}$	$1.7\cdot10^{-6}$
SN 1987A	$9\cdot10^{-7}$	$4\cdot10^{-6}$	$4\cdot10^{-5}$	$8\cdot10^{-4}$

(V) Effects of broken scale invariance

[Fox, Rajaraman, Shirman, PRD76 (2007) 075004;
Bander, Feng, Rajaraman, Shirman, PRD76 (2007) 115002]

Model broken scale invariance -- put in by hand a mass gap in the unparticle spectral density

$$\rho(M^2) = A_d \theta(M^2 - \mu^2)(M^2 - \mu^2)^{d-2}$$

Unparticle propagator is modified as

$$\Delta_F(P^2) = \frac{A_d}{2\sin(d\pi)} \left[- \left(P^2 - \mu^2 \right) \right]^{d-2}$$

This leads to μ-like resonance phenomena (un-resonance)!
[Rizzo, JHEP 0710 (2007) 044]

Moreover, many stringent constraints on the unparticle sector can be relaxed.

$e^+e^- \to \mu^+\mu^-$: $A_{\rm FB}(s;\mu)$ and $R_{\mathcal{U}}(s;\mu)$

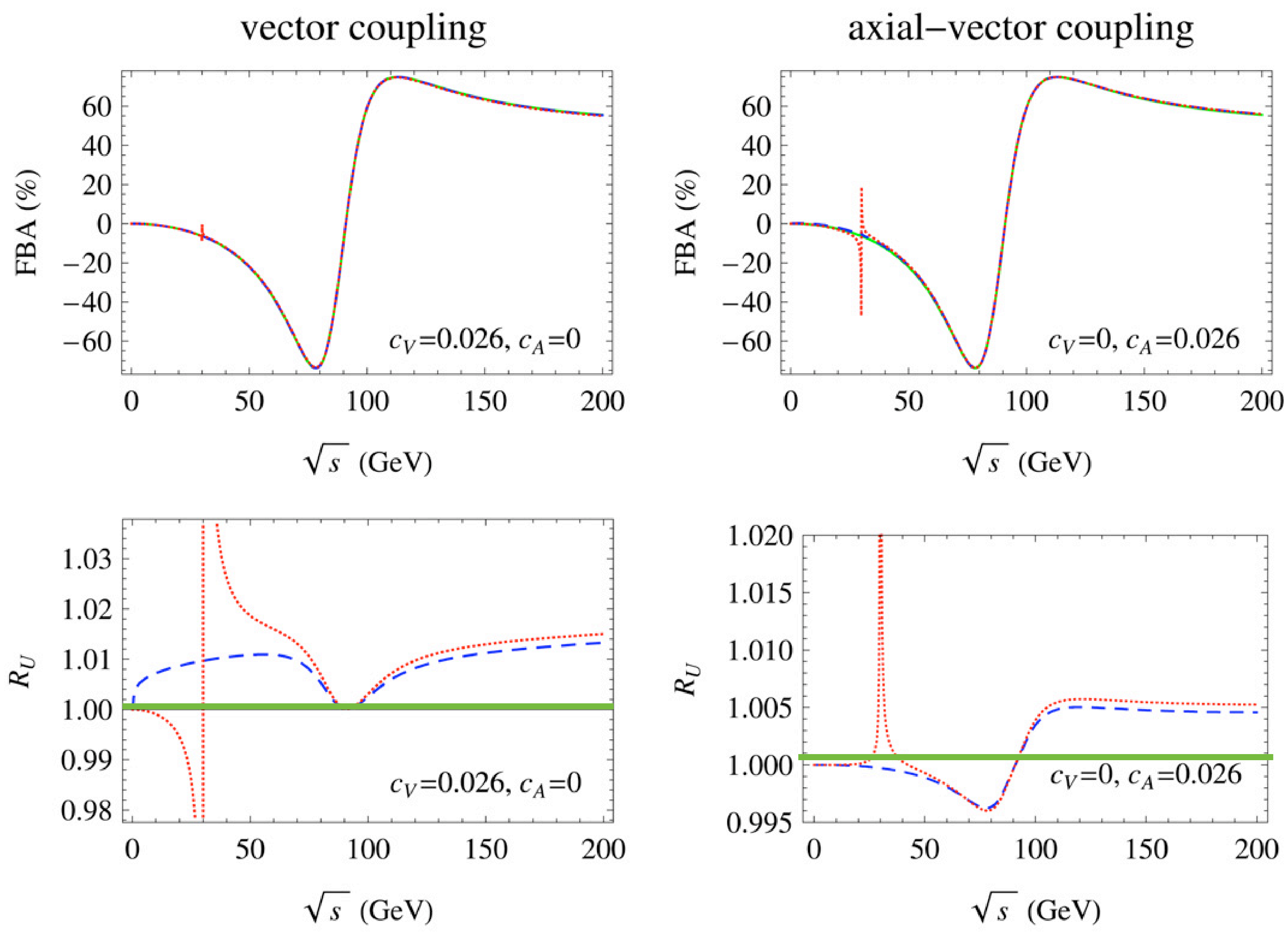


Fig. 4. FBA and R_U for $e^+e^- \to \mu^+\mu^-$ with $d = 1.1$. Solid green curves: SM; dashed blue curves: unparticles with $\mu = 0$, dotted red curves: unparticles with $\mu = 30$ GeV. ($c_{V,A} = 0.026$ correspond to the mono-photon bound of Section 2.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

SM (——)
$\mu = 0$ GeV (- - - - -)
$\mu = 30$ GeV (.........)

[Barger, Gao, Keung, Marfatia, Senoguz, PLB661 (2008) 276]

Summary

(1) Unparticle phenomenology at colliders are quite peculiar and rich due to the non-integral scaling dimensions of the scalar, vector, tensor (symmetric and antisymmetric), spinor unparticle operators.
(2) Due to parton smearing, these peculiar effects are more challenging to detect at hadron colliders.
(3) Assuming exact scale invariance at very low energy, constraints for the effective couplings of the unparticle sector are more stringent from astrophysics than from colliders, especially for small scaling dimension close to unity.
(4) However, if scale invariance is broken at a lower scale, say below Z mass, many existing constraints can be evaded or relaxed, and un-resonance might occurs.
(5) Many theoretical questions regarding the hidden unparticle sector remain open.


Thank you!
감사합니다!

Unparticles with SM quantum numbers?

[Cacciapaglia, Marandella and Terning, JHEP 0801:070,2008;
Litch, 0801.0892, 0801.1148,0802.4310,0805.3849;
Galloway, Martin and Stancato, 0802.0313; Liao, 0804.4033.]

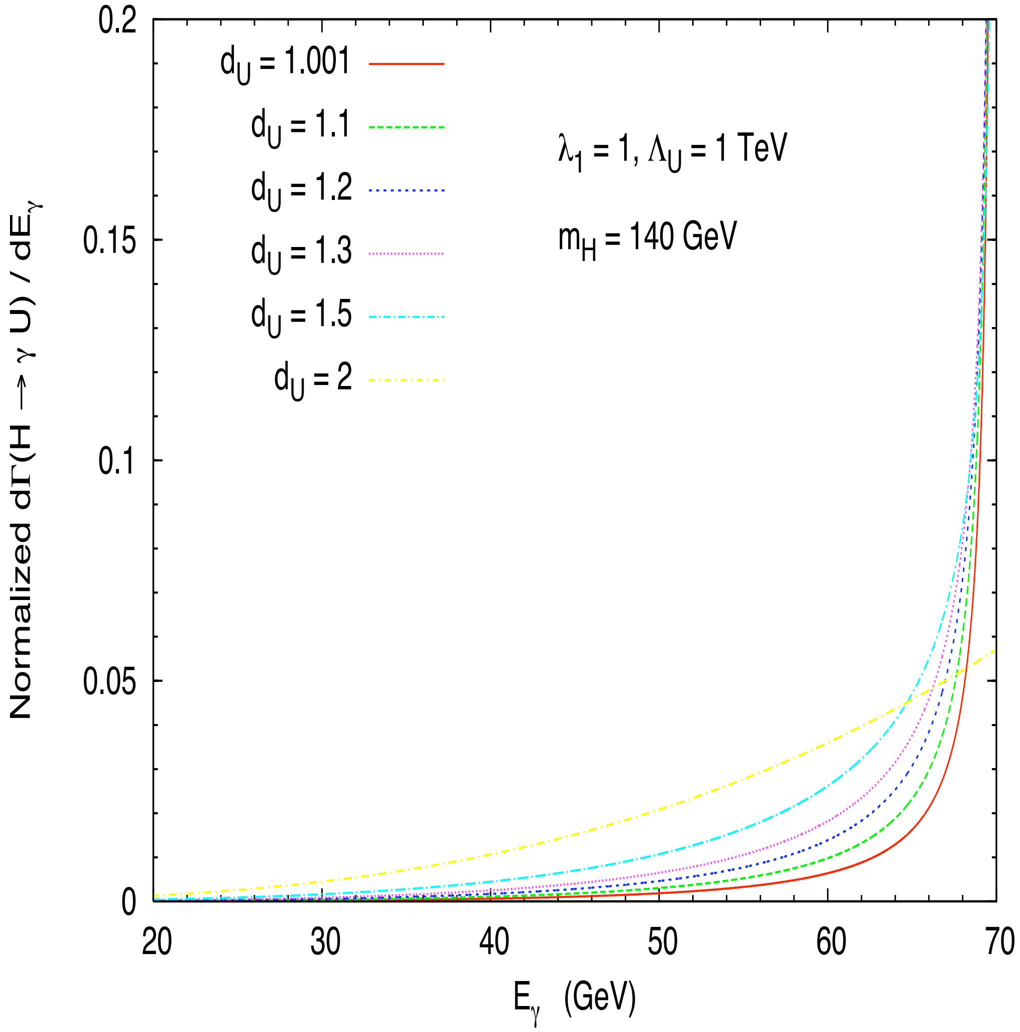
$O(x)$: A multiplet of scalar unparticles

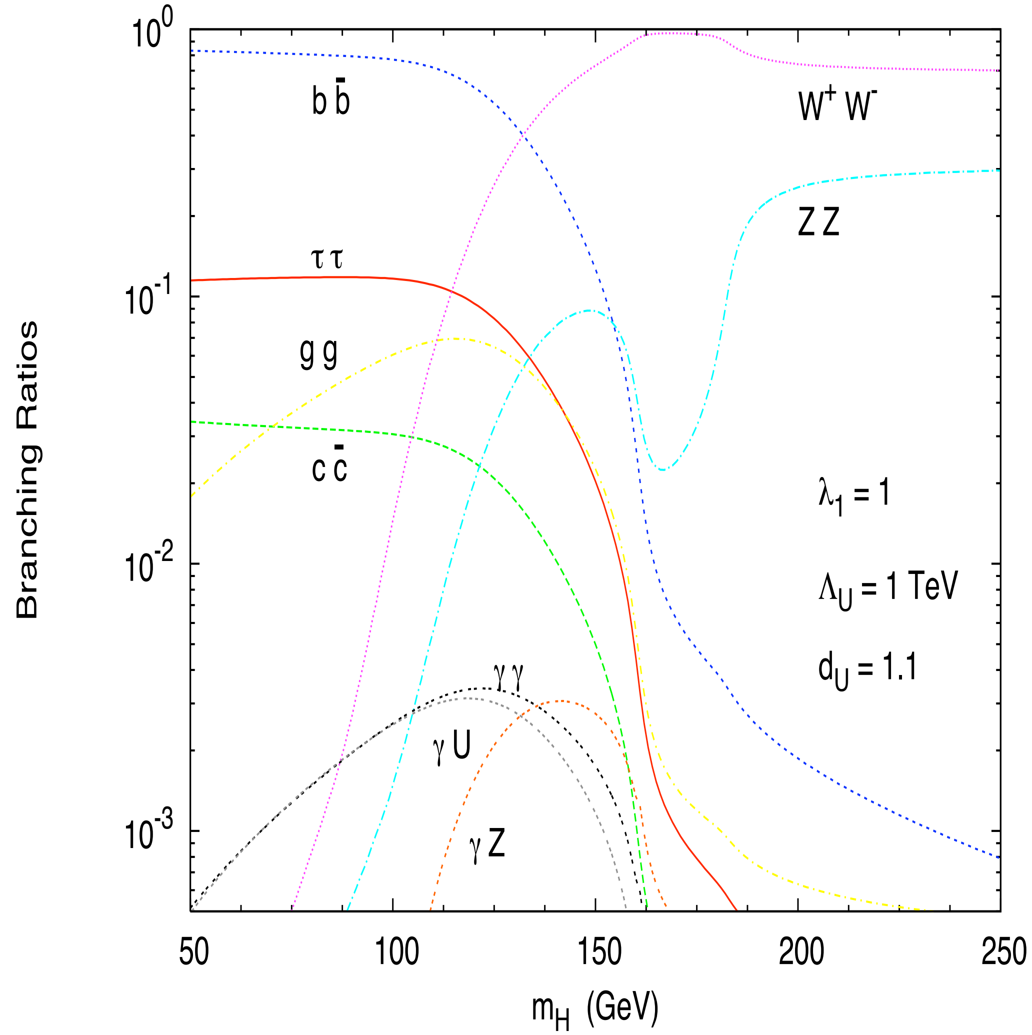
$$
\begin{aligned}
S &= \int d^4x d^4y O^\dagger(x) \Delta_O(x-y) W(x,y) \\
W(x,y) &= P \exp\left[-igT^a \int_x^y A^a_\mu(z) dz^\mu\right] O(y)
\end{aligned}
$$

- Non-local action
- Infinite numbers of vertices and complicated Feynman rules
- Path-dependence!

Rare decay mode of intermediate mass Higgs:

$H \to \gamma + \text{spin } 1\ \mathcal{U}$ [K. Cheung, C.S. Li and TCY, PRD 77, 097701 (2008)]





- Emitted photon has continuous energy spectrum!
  Unlike in the discovery mode $H \to \gamma\gamma$, $E_\gamma = m_H/2$.

Volume emissivity Q [Energy loss per unit volume]

$$
\begin{aligned}
Q &= \prod_{j=1}^{N} \int \frac{d^3\mathbf{p}_j}{2E_j(2\pi)^3} f_j(E_j) \prod_{i=1}^{N'} \int \frac{d^3\mathbf{p}'_i}{2E'_i(2\pi)^3} \left[1 \pm f'_i(E'_i)\right] \\
&\times \int d\Phi_U^{\rm Georgi}(P_U^2)\; E_U \;\left[1 \pm f_U(E_U)\right] \\
&\times \frac{1}{N_{\rm id}!} \frac{1}{N'_{\rm id}!} \sum_{\rm spins} |\mathcal{M}|^2 (2\pi)^4 \delta^4 \left(\sum_{j=1}^{N} p_j - \sum_{i=1}^{N'} p_i - P_U \right)
\end{aligned}
$$

$$
\boxed{\text{Energy Loss Rate } \dot{\varepsilon} = \frac{\text{Volume emissivity}}{\text{Mass density}}}
$$

- un-Compton

$$
\begin{aligned}
Q^{\rm spin-1}_{\gamma e^- \to U e^-} &\approx n_e \frac{\alpha \lambda_1^2}{3\pi^3} A_{d_U} \left(\frac{T}{m_e}\right)^{2(d_U+1)} \left(\frac{m_e^2}{\Lambda_U^2}\right)^{d_U-1} m_e^2 \\
&\times \Gamma\left(2d_U+2\right) \zeta\left(2d_U+2\right) \left[B\left(\frac{3}{2}, d_U - 1\right) + \frac{1}{2} B\left(\frac{3}{2}, d_U\right) \right]
\end{aligned}
$$

- un-bremsstrahlung

$$
\langle Q^{\rm spin-1}_{e(Ze) \to e(Ze)U} \rangle \approx \frac{2^{2(2-d_U)} d_U}{(1-2d_U)^2(1+2d_U)} \left(\frac{m_e}{\pi \Lambda_{d_U}}\right)^{2(d_U-1)} \left(\frac{T}{m_e}\right)^{2(d_U-1)}
$$

$$
\times \sum_j \frac{Z_j^2 \alpha^2 \lambda_1^2 n_e n_{Z_j}}{\pi m_e}
$$