$B \to K(K^*)$ + missing energy in UnParticle Physics

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T. M.Aliev, A.S.Cornell & N. Gaur, JHEP 0707, 072 (2007) arXiv:0705.4542 [hep-ph]

Motivation

Georgi's view :

- Scale Invariance is very powerful concept and has found wide applications in many disciplines.
- Scale Invariance at low energies is broken by masses of particles
- What if we have a scale invariant sector in our theory?
- The interacting scale invariant theory will be described by Unparticles.

Unparticles : interacting quantum fields that do not excite particles.

add conformal/scale-invariant sector with IR fixed point to SM

Introduction

Scale Invariance is a feature due to which objects/laws do not change if length/energy scales are multiplied by a common factor.

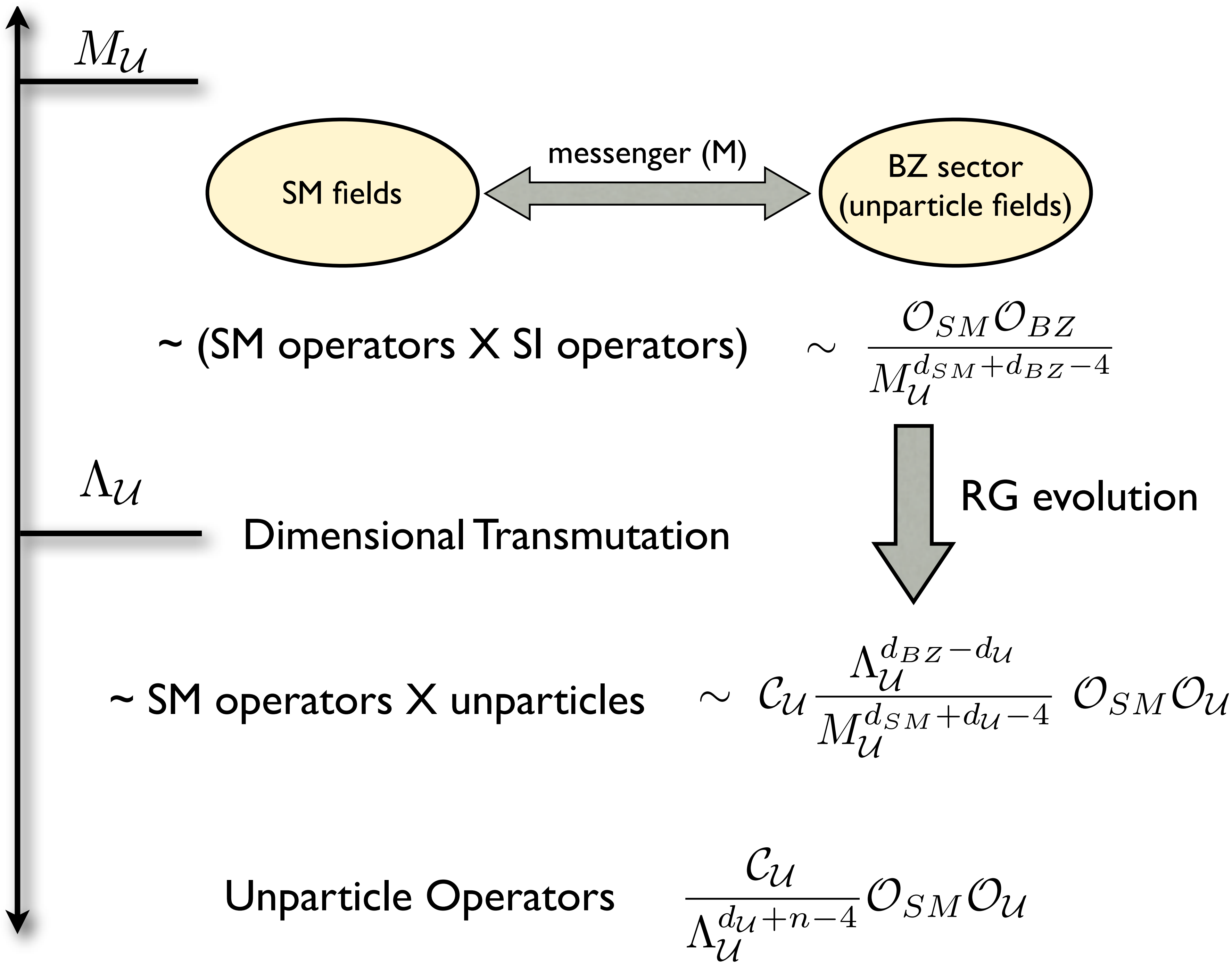
- Statistical Mechanics, this is the feature of phase transitions. Near a phase transition/critical point, the fluctuations occur at all length scales
- In QFT, scale invariance means that particle interactions do not depend upon the energy scales involved

An Effective theory is a approximate theory that contains the approximate degrees of freedom to describe the physical phenomena at a chosen length scale, but ignores the substructure and degrees of freedom at shorter length scales.

At energy scale E << M the theory can be described by effective interaction

$$\mathcal{H} \sim \frac{1}{M} \, \mathcal{C} \, \mathcal{O}$$

short distance ($\mathcal{C}$) long distance ($\mathcal{O}$)


$M_{\mathcal{U}}$
SM fields
messenger (M)
BZ sector
(unparticle fields)
~ (SM operators X SI operators)
$\sim \frac{\mathcal{O}_{SM}\mathcal{O}_{BZ}}{M_{\mathcal{U}}^{d_{SM}+d_{BZ}-4}}$
$\Lambda_{\mathcal{U}}$
RG evolution
Dimensional Transmutation
~ SM operators X unparticles
$\sim \mathcal{C}_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{BZ}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{SM}+d_{\mathcal{U}}-4}} \mathcal{O}_{SM}\mathcal{O}_{\mathcal{U}}$
Unparticle Operators
$\frac{\mathcal{C}_{\mathcal{U}}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}+n-4}} \mathcal{O}_{SM}\mathcal{O}_{\mathcal{U}}$

Phase space for real unparticle emission

(use scale invariance)

Two point function (Kallen-Lehmann representation)

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

spectral density

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

to be fixed

scale transformation : $x \to sx,\ O_{\mathcal{U}}(sx) \to s^{-d_{\mathcal{U}}} O_{\mathcal{U}}(x)$

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

scale invariance gives : $\alpha = d_{\mathcal{U}} - 2$

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

Scale Invariance & QFT

Particle formulation

All particles are either massless or have continuous distribution of mass

Field formulation

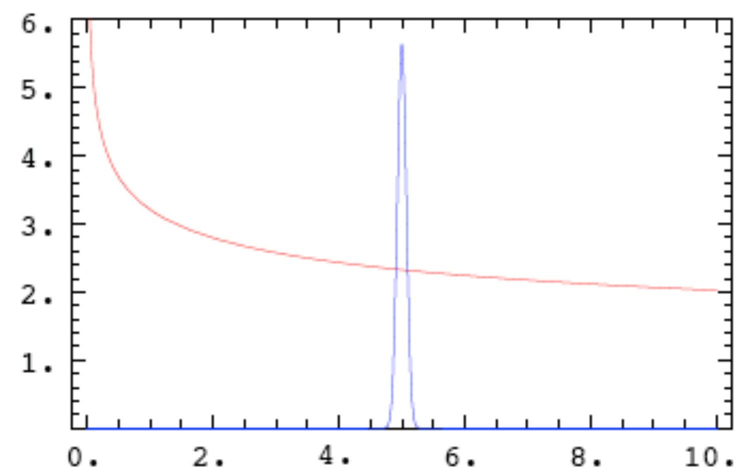
Scale invariant fields have no particle like excitations with definite mass. The field response to the energy is not creation of particles but the generation of non-localised waves in full momentum region, this effectively means dissipation of energy

Particles : Fields with massive particle excitations

$$\rho(p^2) \propto \delta(p^2 - m^2)$$

Un-Particles : conformal fields, injected energy gets dissipated instead of creating lumps of matter

$$\rho(p^2) \propto (p^2)^{d_{\mathcal{U}}-2}$$



Phase space of mass-less n-particles

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

$$(p_1 + p_2 + \cdots + p_n)^2 = s^2$$

Unparticles are introduced by making identification

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

Unparticle Phase space then is

$$d\Phi \quad = \rho_{\mathcal{U}}(P_{\mathcal{U}}^2)\frac{d^4 P_{\mathcal{U}}}{(2\pi)^4} = A_{d_{\mathcal{U}}}\,\theta(P_{\mathcal{U}}^0)\,\theta(P_{\mathcal{U}}^2)\ (P_{\mathcal{U}}^2)^{d_{\mathcal{U}}-2}\ \frac{d^4 P_{\mathcal{U}}}{(2\pi)^4}$$

In the limit , $d_{\mathcal{U}} \to 1$ $\qquad d\Phi \to \theta(P_{\mathcal{U}}^0)\,\frac{d^3 \vec{P}_{\mathcal{U}}}{2P_{\mathcal{U}}^0(2\pi)^3}$

behaviour like a single mass-less particle

Differential cross-section for $ij \to \mathcal{U} + \text{particles}$

$$d\sigma(p_1, p_2 \to P_{\mathcal{U}}, k_1, k_2, \ldots) = \frac{1}{2s} \, |\overline{\mathcal{M}}|^2 \, d\Phi$$

$$d\Phi = (2\pi)^4 \, \delta^{(4)} \left(p_1 + p_2 - P_{\mathcal{U}} - k_1 - k_2 - \cdots\right) \prod_i \left[2\pi \, \theta(k_i^0) \, \delta(k_i^2) \, \frac{d^4 k_i}{(2\pi)^4} \right] \times \; A_{d_\mathcal{U}} \, \theta(P_\mathcal{U}^0) \, \theta(P_\mathcal{U}^2) \, \left(P_\mathcal{U}^2\right)^{d_\mathcal{U}-2} \, \frac{d^4 P_\mathcal{U}}{(2\pi)^4}$$

Effective Operators

(as tabulated by Cheung et.al.)

scalar : $\lambda_0 \frac{1}{\Lambda_\mathcal{U}^{d_\mathcal{U}-1}} \bar{f} f O_\mathcal{U} \, , \; \lambda_0 \frac{1}{\Lambda_\mathcal{U}^{d_\mathcal{U}-1}} \bar{f} i \gamma^5 f O_\mathcal{U} \, , \; \lambda_0 \frac{1}{\Lambda_\mathcal{U}^{d_\mathcal{U}}} \bar{f} \gamma^\mu f (\partial_\mu O_\mathcal{U}) \, , \lambda_0 \frac{1}{\Lambda_\mathcal{U}^{d_\mathcal{U}}} G_{\alpha\beta} G^{\alpha\beta} O_\mathcal{U} \, ,$

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

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

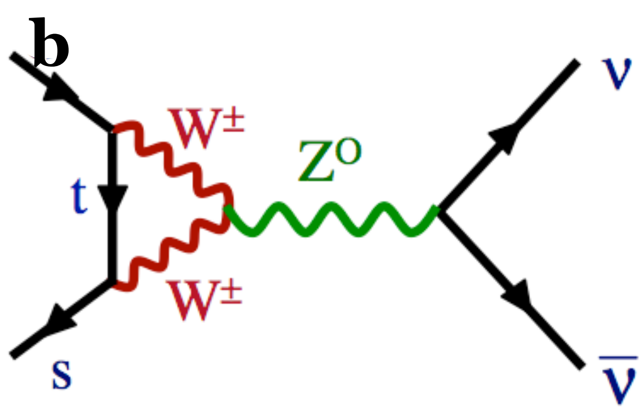
K.Cheung, W. Keung & T.Yuan, arXiv:0706.3155 [hep-ph]

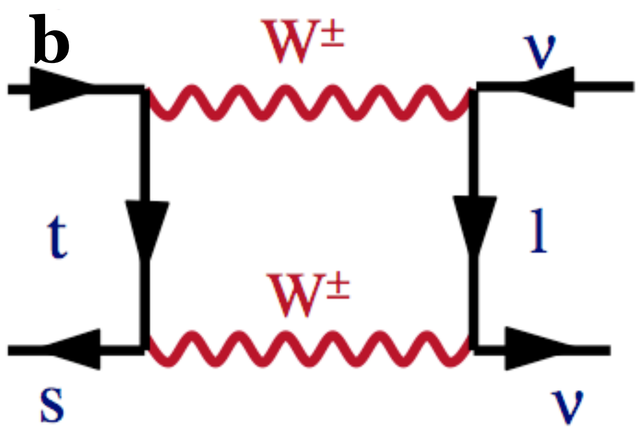
$\mathbf{B \to K(K^*)}$ + missing energy

In this work we have restricted ourselves to unparticles which are SM singlets.

Standard Model

- ✦ Theoretically very clean, no long distance contributions
- ✦ Proceeds through electro-weak penguins & box diagrams
- ✦ Sensitive to new physics (say non-universal Z' models)
- ✦ Sensitive to light dark matter [Bird, PRL 93, 201803 (2004)]





Effective Hamiltonian (in SM) :

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi} V_{tb} V_{ts}^* C_{10} \; \bar{s}\gamma_\mu (1-\gamma_5) b \; \bar{\nu}\gamma_\mu (1-\gamma_5) \nu$$

Differential decay rate :

$$\frac{d\Gamma^{SM}}{dE_K} = \frac{G_F^2 \alpha^2}{2^7 \pi^5 m_B^2} \; |V_{ts} V_{tb}^*|^2 \; |C_{10}|^2 f_+^2(q^2) \; \lambda^{3/2}(m_B^2, m_K^2, q^2)$$

$$\frac{d\Gamma^{SM}}{dE_{K^*}} = \frac{G_F^2 \alpha^2}{2^9 \pi^5 m_B^2} |V_{ts} V_{tb}^*|^2 \lambda^{1/2} |C_{10}|^2 \Bigg(8\lambda q^2 \frac{V^2}{(m_B + m_{K^*})^2} + \frac{1}{m_{K^*}^2} \Big[\lambda^2 \frac{A_2^2}{(m_B + m_{K^*})^2} + (m_B + m_{K^*})^2 (\lambda + 12 m_{K^*}^2 q^2) A_1^2 - 2\lambda (m_B^2 - m_{K^*}^2 - q^2) Re(A_1^* A_2) \Big] \Bigg) \; ,$$

Unparticle effects

$$\Gamma = \Gamma^{SM} + \Gamma^{\mathcal{U}}$$

Scalar Operators

$$\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{s}\gamma_\mu \left(\mathcal{C}_S + \mathcal{C}_P\gamma_5\right) b\, \partial^\mu O_{\mathcal{U}}$$

$$\frac{d\Gamma^{S\mathcal{U}}}{dE_K} = \frac{1}{8\pi^2 m_B}\frac{A_{d_\mathcal{U}}}{\Lambda_{\mathcal{U}}^{2d_\mathcal{U}}}|\mathcal{C}_S|^2\sqrt{E_K^2 - m_K^2}\left(m_B^2 + m_K^2 - 2m_B E_K\right)^{d_\mathcal{U}-2} \times\left[f_+(m_B^2 - m_K^2) + f_-(m_B^2 + 2m_K^2 - 2m_B E_K)\right]^2$$

$$\frac{d\Gamma^{S\mathcal{U}}}{dE_{K^*}} = \frac{m_B}{2\pi^2}\frac{A_{d_\mathcal{U}}}{\Lambda_{\mathcal{U}}^{2d_\mathcal{U}}}|\mathcal{C}_P|^2 A_0^2\left(E_{K^*}^2 - m_{K^*}^2\right)^{3/2}\left(m_B^2 + m_{K^*}^2 - 2m_B E_{K^*}\right)^{d_\mathcal{U}-2}$$

Vector Operators

$$\frac{1}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{s}\gamma_\mu \left(\mathcal{C}_V + \mathcal{C}_A\gamma_5\right) b\, O_{\mathcal{U}}^\mu$$

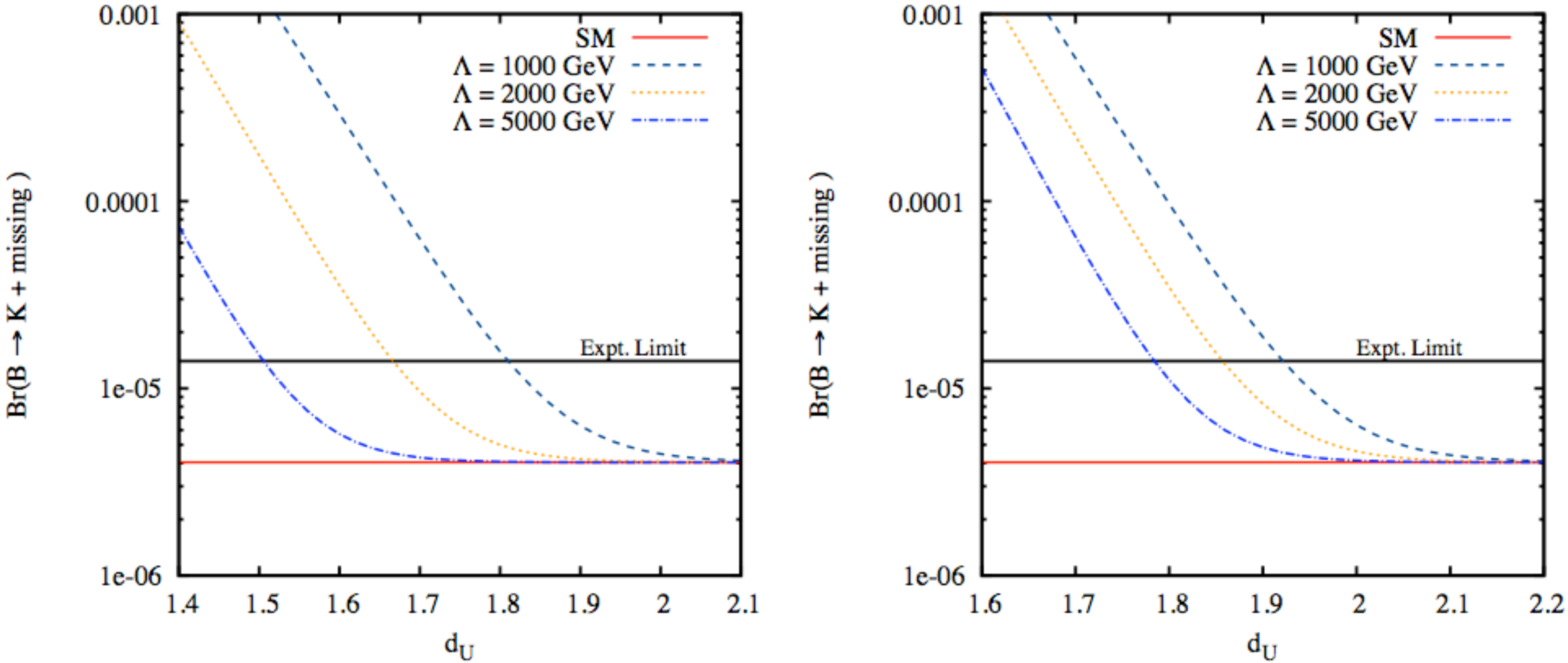
$$\frac{d\Gamma^{V\mathcal{U}}}{dE_K} = \frac{1}{8\pi^2 m_B}\frac{A_{d_\mathcal{U}}}{\Lambda_{\mathcal{U}}^{2d_\mathcal{U}-2}}|\mathcal{C}_V|^2|f_+|^2\left(m_B^2 + m_K^2 - 2m_B E_K\right)^{d_\mathcal{U}-2}\sqrt{E_K^2 - m_K^2} \times\left\{-(m_B^2 + m_K^2 + 2m_B E_K) + \frac{(m_B^2 - m_K)^2}{(m_B^2 + m_K^2 - 2m_B E_K)}\right\}$$

$$\frac{d\Gamma^{V\mathcal{U}}}{dE_{K^*}} = \frac{1}{8\pi^2 m_B}(q^2)^{d_\mathcal{U}-2}\sqrt{E_{K^*}^2 - m_{K^*}^2}\frac{A_{d_\mathcal{U}}}{\left(\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}\right)^2}\left\{8|C_V|^2 m_B^2\left(E_{K^*}^2 - m_{K^*}^2\right)\frac{V^2}{(m_B + m_{K^*})^2}\right.$$
$$+|C_A|^2\frac{1}{m_{K^*}^2(m_B + m_{K^*})^2 q^2}\Big[(m_B + m_{K^*})^4(3m_{K^*}^4 + 2m_B^2 m_{K^*}^2 - 6m_B m_{K^*}^2 E_{K^*} + m_B^2 E_{K^*}^2)A_1^2$$
$$\left.+4m_B^4(E_{K^*}^2 - m_{K^*}^2)^2 A_2^2 + 4(m_B + m_{K^*})^2(m_B E_{K^*} - m_{K^*}^2)(m_{K^*}^2 - E_{K^*}^2)m_B^2 A_1 A_2\Big]\right\}.$$

BELLE results (FPCP 07)

$$Br(B \to K\nu\bar{\nu}) < 1.4 \times 10^{-5}$$

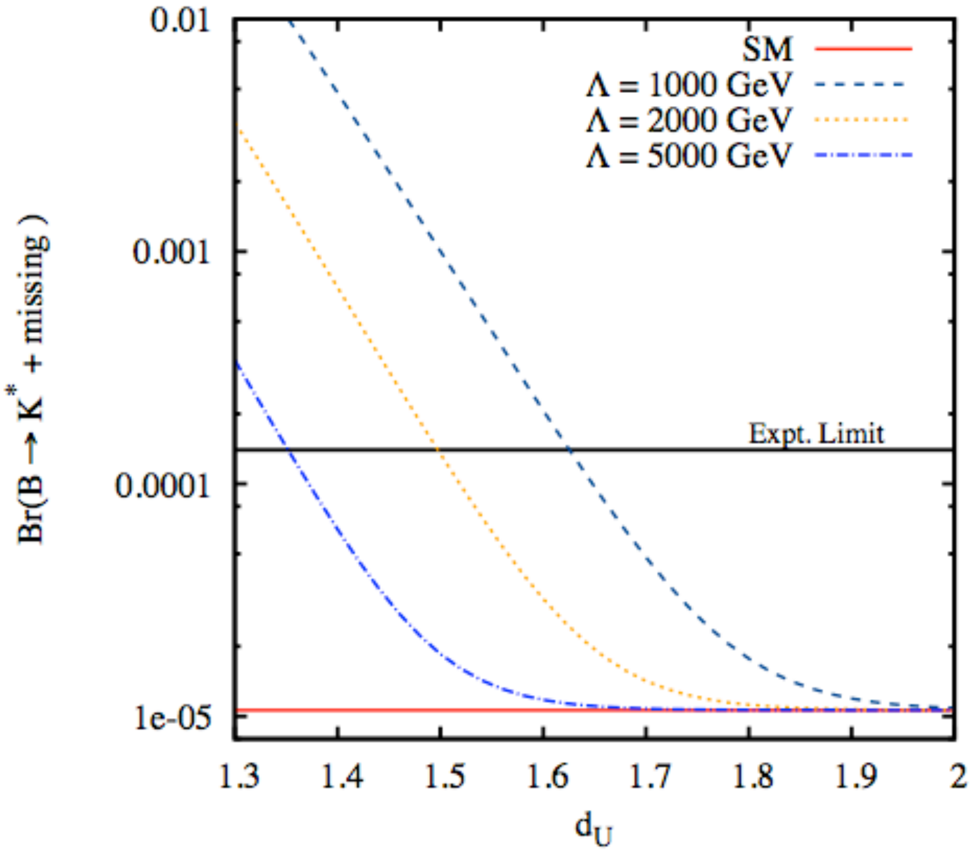
$$Br(B \to K^*\nu\bar{\nu}) < 1.4 \times 10^{-4}$$

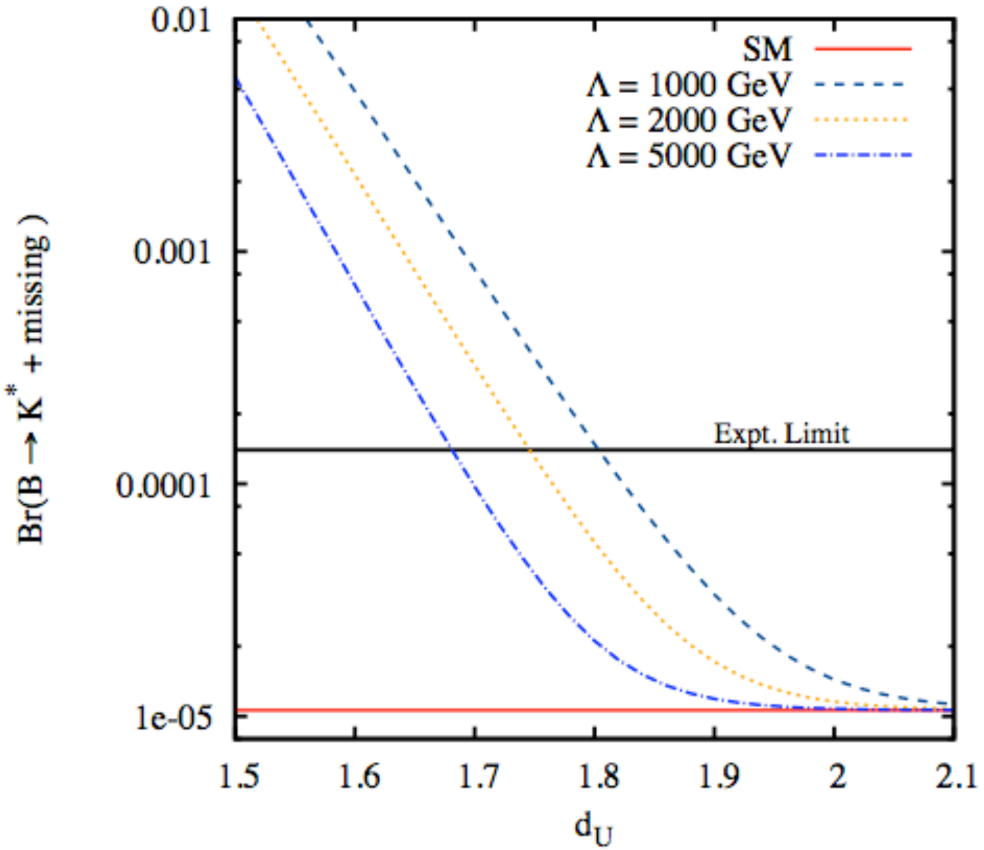


scalar operator

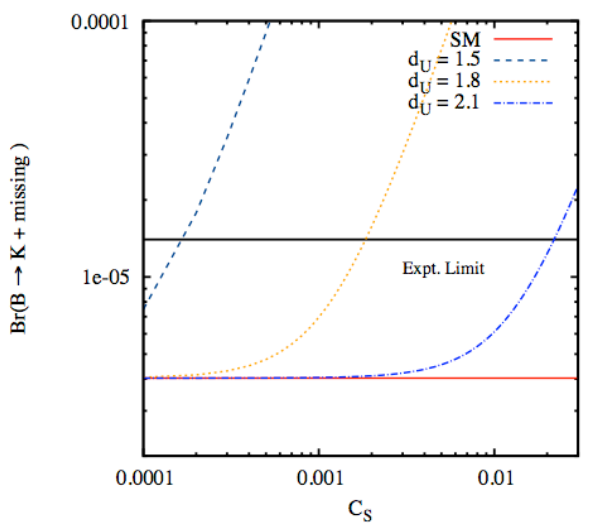
vector operator

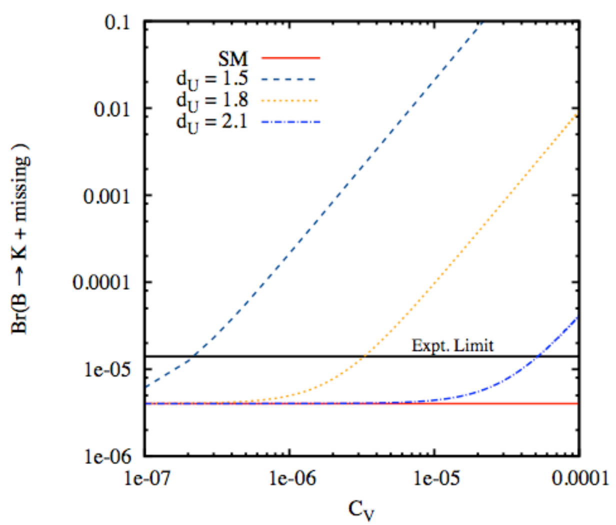
$$C_S = 2 \times 10^{-3} \ and \ C_V = 10^{-5}$$



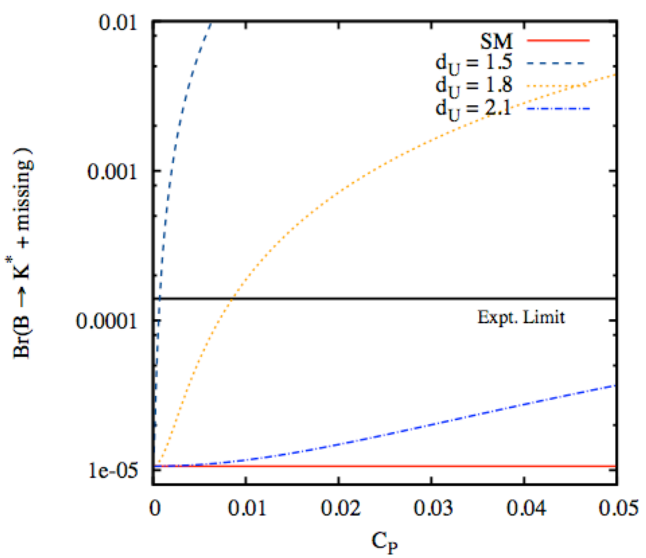


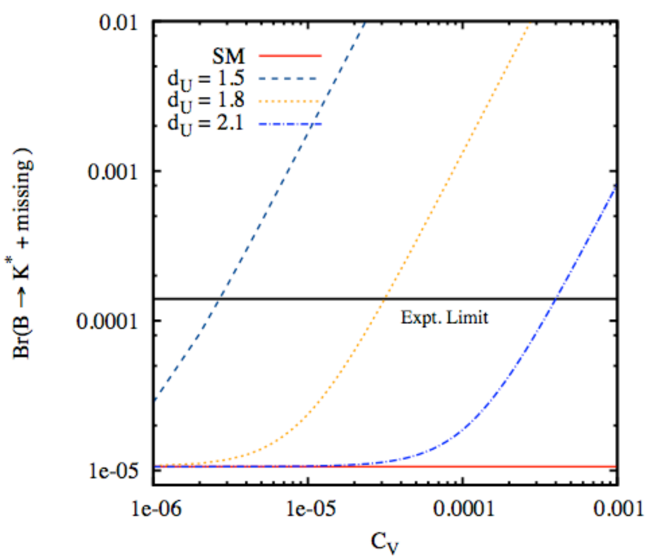
$$\mathcal{C}_P = 2 \times 10^{-3} \ and \ \mathcal{C}_V = \mathcal{C}_A = 10^{-5}$$

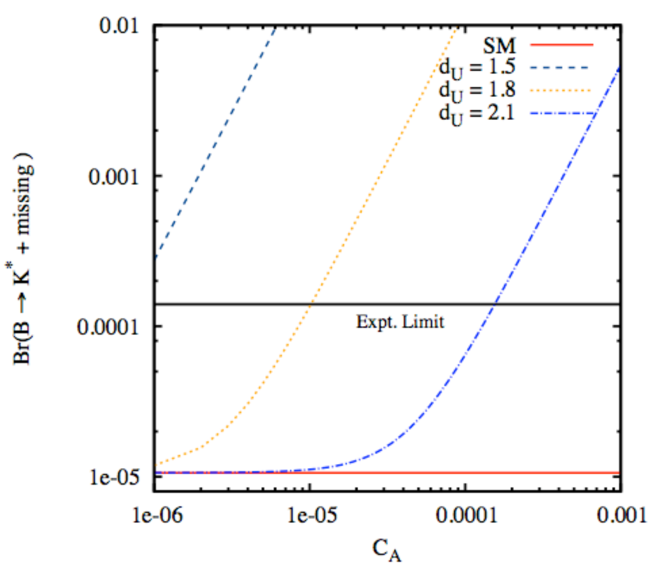


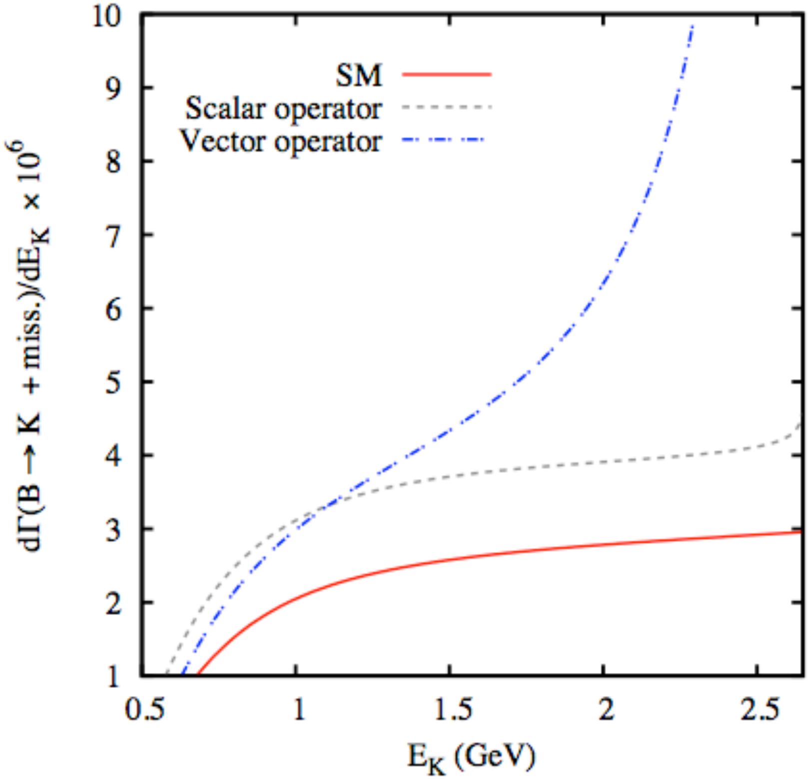


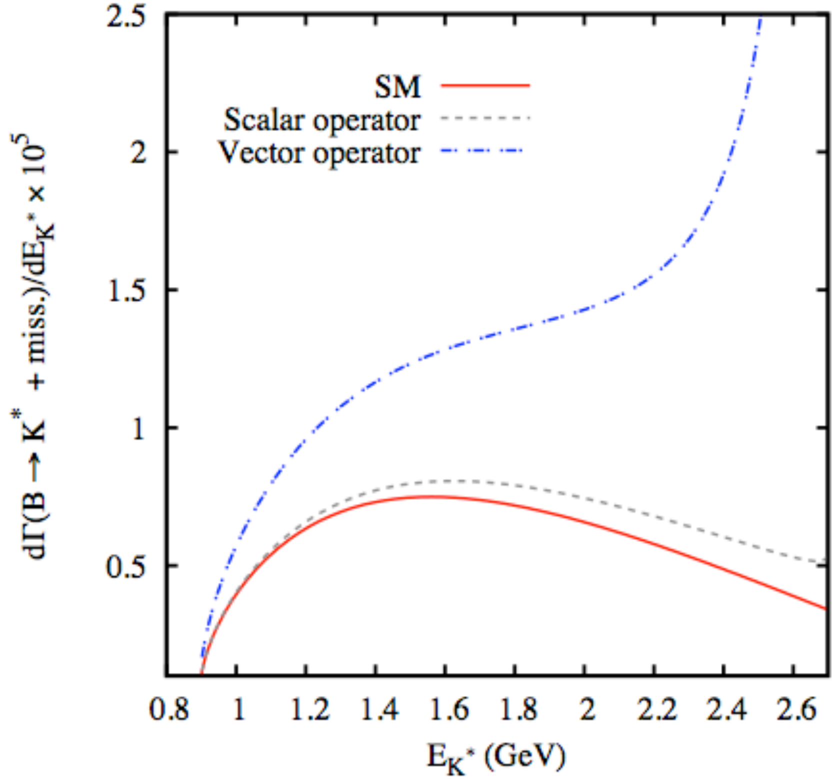
$$\Lambda_{\mathcal{U}} = 1000\,GeV$$











$$d_{\mathcal{U}} = 1.9,\ \Lambda_{\mathcal{U}} = 1000\,GeV,\ \mathcal{C}_P = \mathcal{C}_S = 2 \times 10^{-3}\ and\ \mathcal{C}_V = \mathcal{C}_A = 10^{-5}$$

Some other possibilities (not much discussed in literature) :

- Charged unparticles (Wu & Huang arXiv:0707.1268, Zwicky arXiv:0707.0677)
- Fermionic unparticles (Luo & Zhu arXiv:0704.3532)
- SUSY unparticles (N.G. Despande, Xiao-Gang He, J. Jiang arXiv:0707.2959)

- Very rich phenomenology which can be explored !!
- Analogy with higher dimensional models !!

> the LHC. To my mind, this would be a much more striking discovery than the more talked about possibilities of SUSY or extra dimensions. SUSY is more new particles. From our 4-dimensional point of view until we see black holes or otherwise manipulate gravity, finite extra dimensions are just a metaphor.[6] 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.
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> : H. Georgi