Unparticles

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Georgi, 2007

- Assume the existence of a sector with a non-trivial conformal fixed point e.g. SQCD, Banks-Zaks, ...
- Couple it in the UV to the SM through exchange of a heavy state

$$\boxed{\text{SM}} \xrightarrow{\quad Z' \quad} \boxed{\begin{array}{c}\text{Hidden}\\ \text{Sector}\end{array}} \quad \rightarrow \frac{1}{M^{l+d_{UV}-4}} \mathcal{O}_{SM} \mathcal{O}_{UV}$$

- Evolve down to low energies

$$C \frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{\mathcal{U}}}}{M^{l+d_{UV}-4}} \mathcal{O}_{SM} \mathcal{O}_{IR}$$

UPS Two point function

Entirely determined by scale invariance:

$$\int d^4 x e^{iPx} \langle 0 | T \mathcal{O}_{IR}(x) \mathcal{O}_{IR}(0) | 0 \rangle = \int \frac{dM^2}{2\pi} \rho(M^2) \frac{i}{P^2 - M^2 + i\epsilon}$$

with $\rho(M^2) = \int_\lambda 2\pi\, \delta(M^2 - M_\lambda^2) |\langle 0 | \mathcal{O}_{IR}(0) | \lambda \rangle|^2$

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

$$A_{d_\mathcal{U}} = \frac{4\pi^{5/2}}{(2\pi)^{2d_\mathcal{U}}} \frac{\Gamma(d_\mathcal{U} + 1/2)}{\Gamma(d_\mathcal{U} - 1)\Gamma(2d_\mathcal{U})}$$

$$\boxed{\Delta(P^2) = \frac{A_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)} (-P^2)^{d_\mathcal{U} - 2}}$$

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Phase Space

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

This is the phase space for $d_{\mathcal{U}}$ (non-integer) number of particles

Now we are free to calculate...

Assume $\mathcal{O}_{d_\mathcal{U}}$ is SM and UPS singlet (cf Cacciapaglia, Marandella and Terning)

- Scalar unparticles

$$\frac{\mathcal{O} H^2}{\Lambda^{d-2}} , \frac{\mathcal{O} H \bar{f}_L f_R}{\Lambda^d} , \frac{\mathcal{O} F_{\mu\nu} F^{\mu\nu}}{\Lambda^d} \text{, etc}$$

- Vector unparticles

$$\frac{\mathcal{O}^\mu \bar{f} \gamma_\mu f}{\Lambda^{d-1}} , \frac{\mathcal{O}^\mu H^\dagger D_\mu H}{\Lambda^{d-1}} \text{, etc}$$

- Tensor unparticles

$$\frac{\mathcal{O}^{\mu\nu} H \bar{f}_L \sigma_{\mu\nu} f_R}{\Lambda^d} , \frac{\mathcal{O}^{\mu\nu} H^\dagger D_\mu D_\nu H}{\Lambda^d} \text{, etc}$$

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G Mack, 1977

(see also Grinstein et al, 2008)

CFT implies lower bounds on gauge invariant operators

Operator in (j,k) representation of Lorentz group:

$$d \gtrsim \begin{cases} j+k+2 & j,k \neq 0 \\ j+1 & k=0 \end{cases}$$

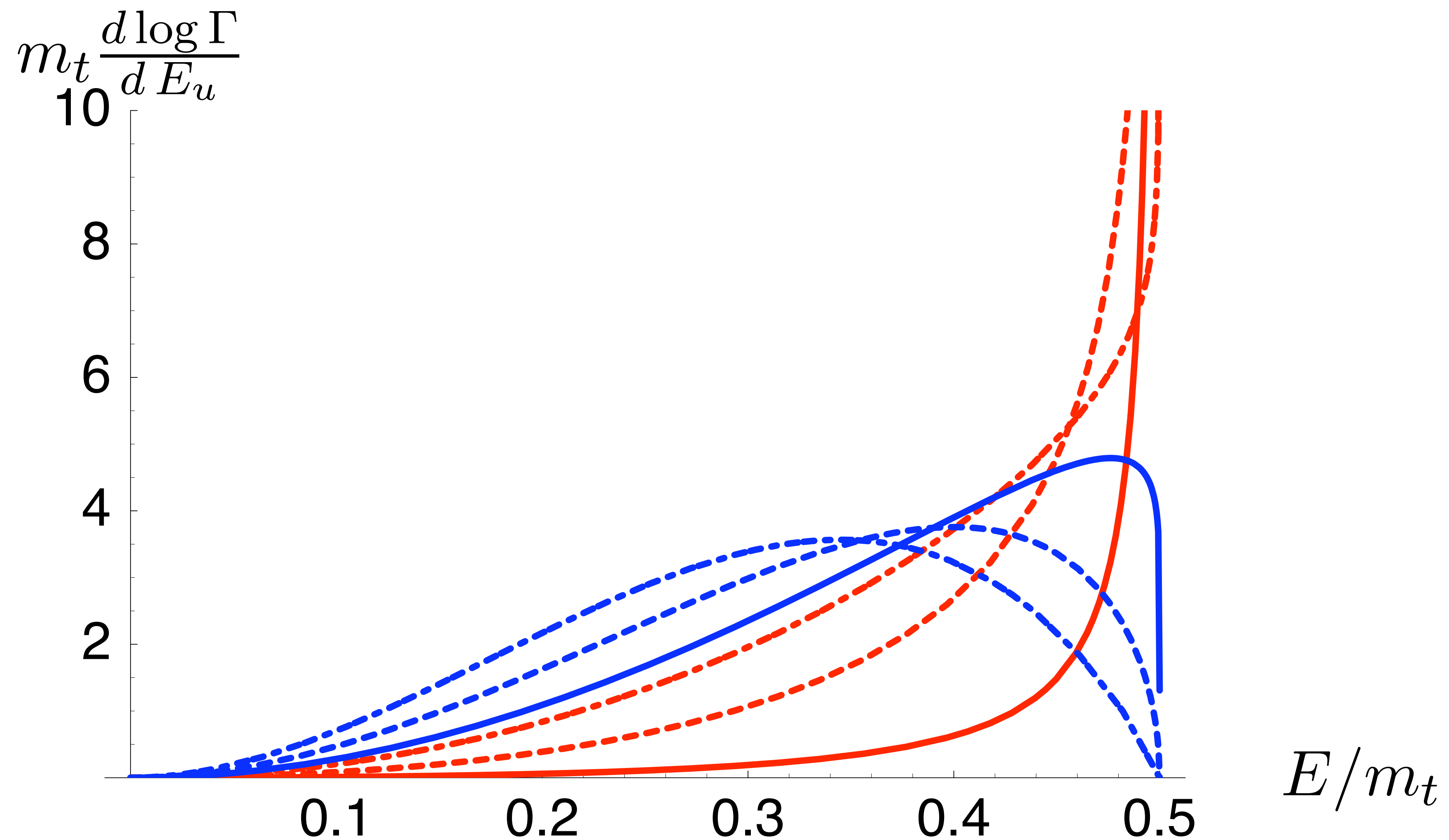
$$d_S \geq 1 \qquad d_{T_A} \geq 2$$

$$d_V \geq 3 \qquad d_{T_S} \geq 4$$

Scalar unparticles

$$\frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{IR}}}{M^{d_{UV}}}\partial^\mu \mathcal{O}_{IR}\bar{f}\gamma_\mu f$$

e.g. $t \to u + \mathcal{U}$ Georgi



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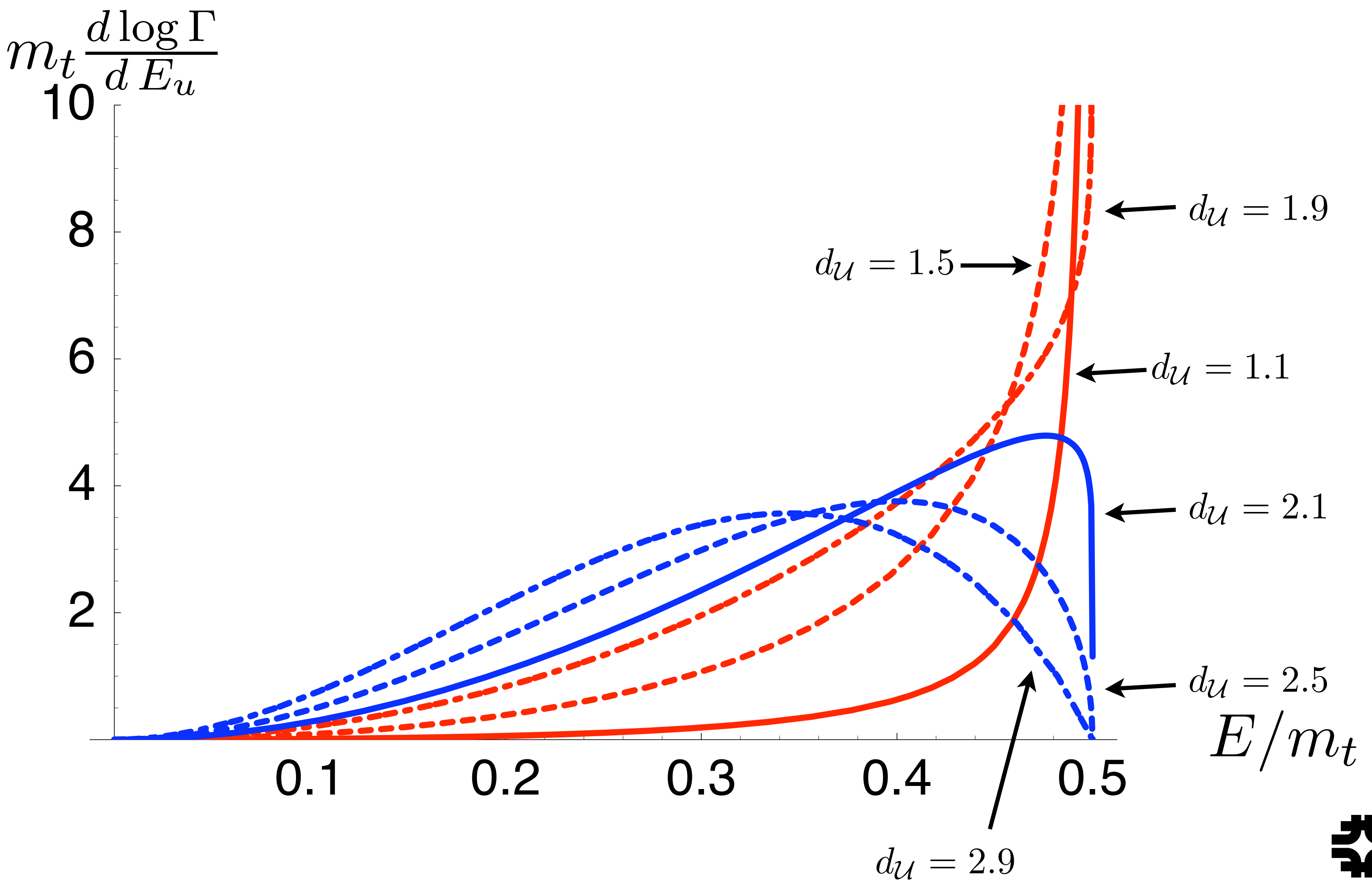
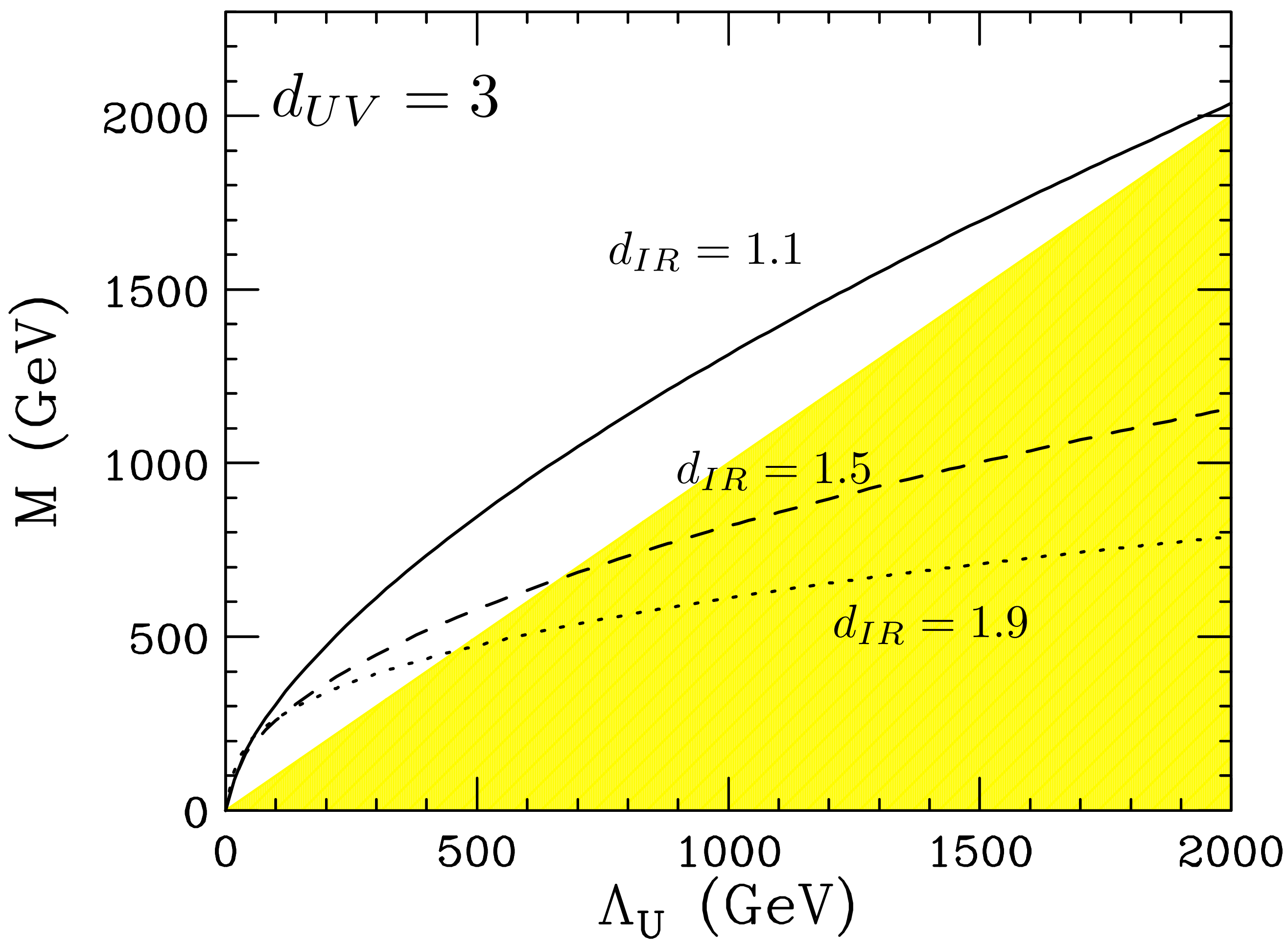


Scalar unparticles

$$\frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{IR}}}{M^{d_{UV}}}\partial^\mu \mathcal{O}_{IR}\bar{f}\gamma_\mu f$$

e.g. $e^+e^- \to \mu^+\mu^-$ Bander, Feng, Rajaraman and Shirman



Unparticles and the Higgs

PJF, Rajaraman and Shirman

So far $l \geq 3$, irrelevant operators

Consider,

$$\frac{1}{M_{\mathcal{U}}^{d_{UV}-2}}|H|^2\mathcal{O}_{UV} \longrightarrow C_{\mathcal{U}}\frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{UV}-2}}|H|^2\mathcal{O}_{IR}$$

No symmetry can forbid this operator

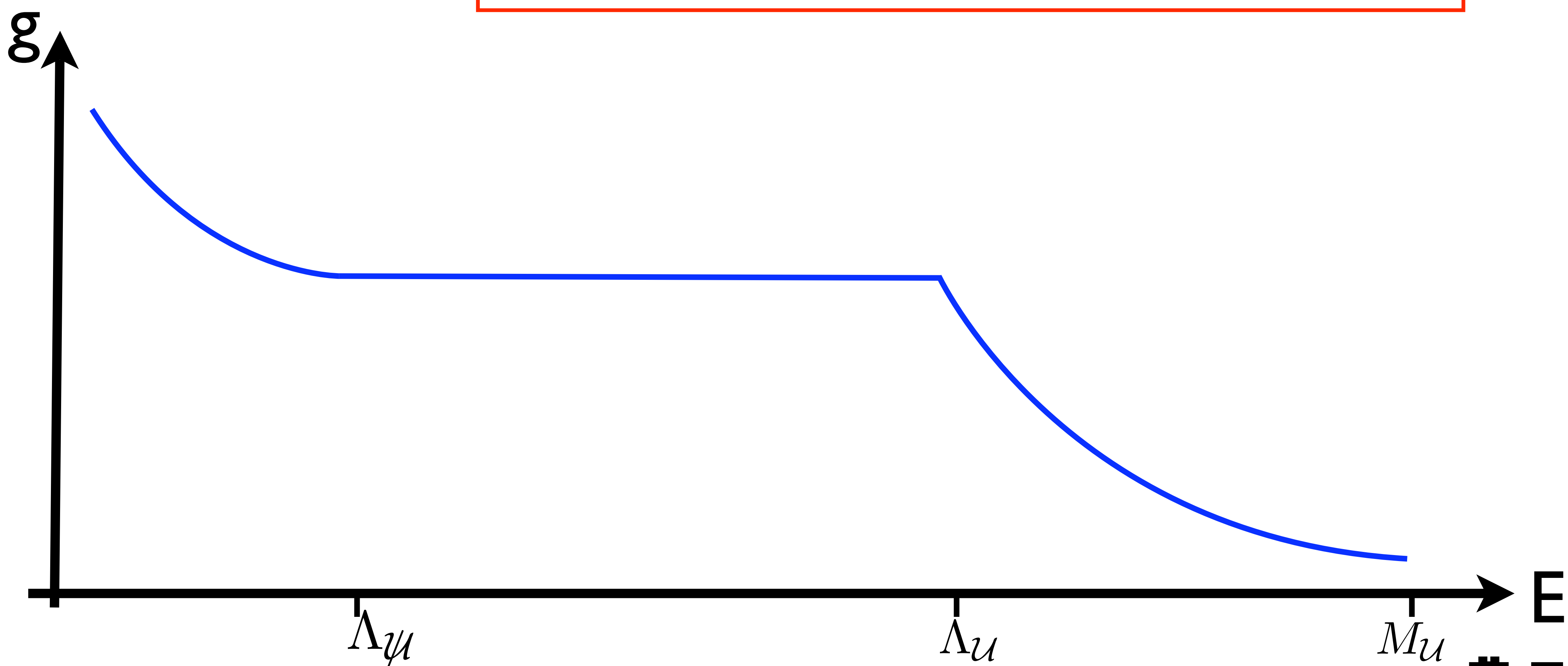
Mass gap

$$C_{\mathcal{U}}\frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{UV}-2}}|H|^2\mathcal{O}_{IR} \longrightarrow$$

Unparticles flow away from fixed point

Scale of breaking:

$$\boxed{\Lambda_{\not{\mathcal{U}}}^{4-d_{\mathcal{U}}} = \left(\frac{\Lambda_{\mathcal{U}}}{M_{\mathcal{U}}}\right)^{d_{UV}-d_{\mathcal{U}}} M_{\mathcal{U}}^{2-d_{\mathcal{U}}} v^2}$$



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Mass gap

$$C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{UV}-2}} |H|^2 \mathcal{O}_{IR}$$ $\longrightarrow$ Unparticles flow away from fixed point

Scale of breaking:

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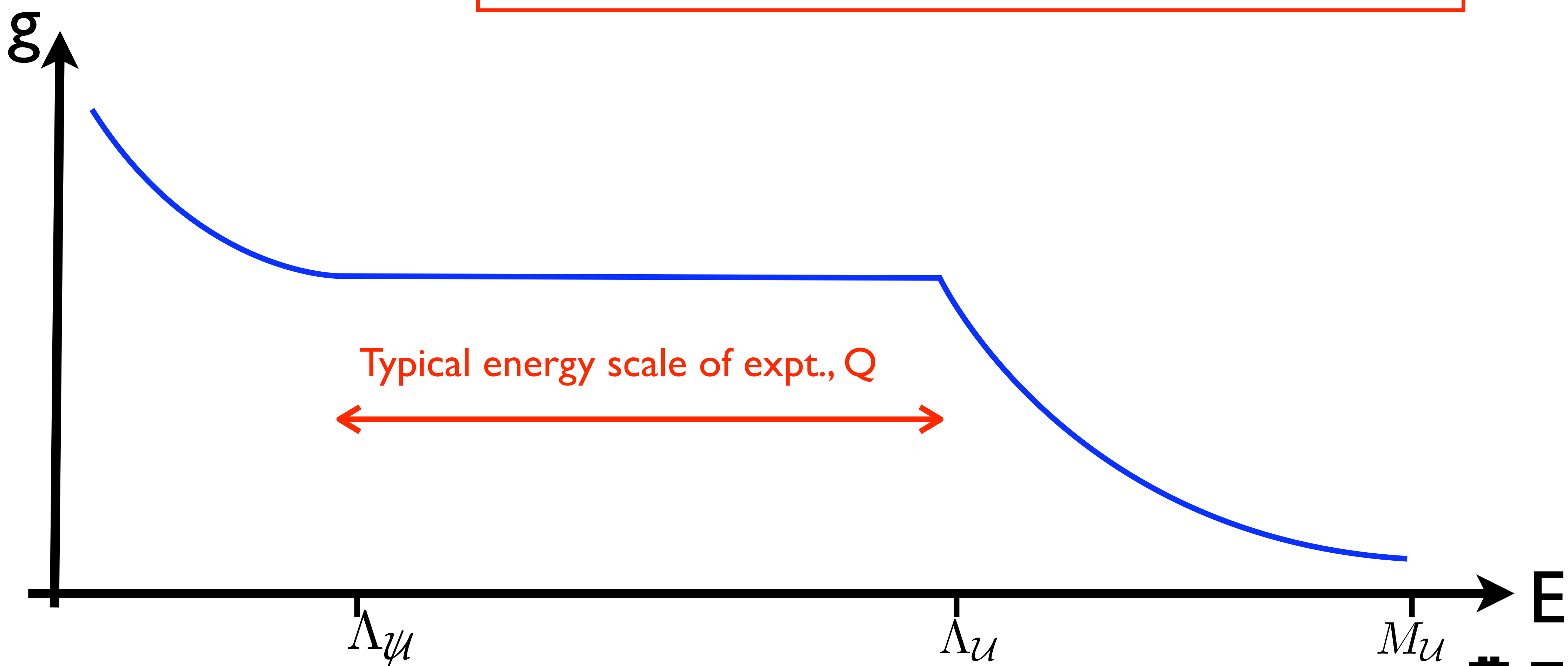

To see unparticle physics in expt of typical energy scale Q

$$Q^{4-d_{IR}} > \left(\frac{\Lambda_{\mathcal{U}}}{M_{\mathcal{U}}}\right)^{d_{UV}-d_{IR}} M_{\mathcal{U}}^{2-d_{IR}} v^2$$

Observable effects of the operator $\frac{\Lambda_{\mathcal{U}}^{d_{UV}-d_{IR}}}{M_{\mathcal{U}}^{l+d_{UV}-4}} \mathcal{O}_{SM} \mathcal{O}_{IR}$

$$\epsilon = \left(\frac{\Lambda_{\mathcal{U}}}{M_{\mathcal{U}}}\right)^{2(d_{UV}-d_{IR})} \left(\frac{Q}{M_{\mathcal{U}}}\right)^{2(d_{IR}+l-4)}$$

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Observable effects bounded

$$\epsilon < \left(\frac{Q}{M_{\mathcal{U}}}\right)^{2l}\left(\frac{M_{\mathcal{U}}}{v}\right)^{4}$$

Independent of d_{UV} and d_{IR}

e.g. (g-2) of the electron

$$\mathcal{O}_{SM} = \bar{e}e \qquad Q \sim m_e \qquad \epsilon_{expt} < 10^{-11}$$

$$\Rightarrow \epsilon < \frac{m_e^6}{M_{\mathcal{U}}^2\, v^4} \xrightarrow{M_{\mathcal{U}} \gtrsim 100\,\mathrm{Gev}} \epsilon < 10^{-28}$$

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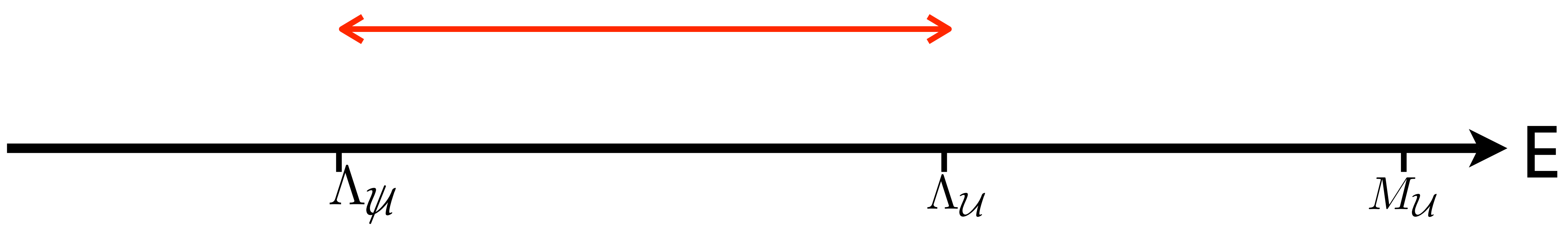
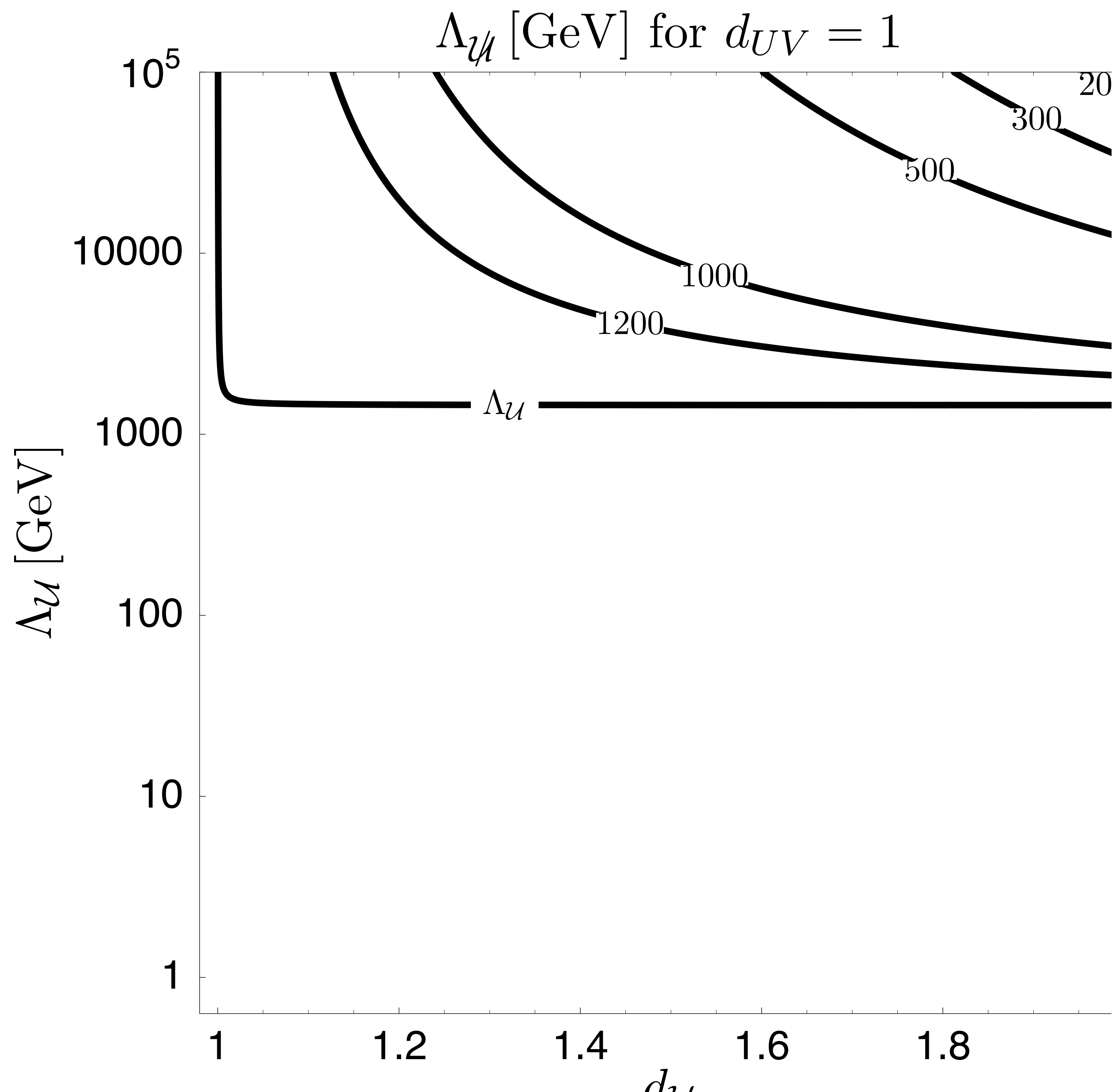
High scale tests: LHC

(l=3) $$\epsilon < \frac{Q^6}{M_{\mathcal{U}}^2 v^4}$$ favours high energy experiments

For a 1% deviation at the LHC need $M_{\mathcal{U}} \lesssim 10^5\,\mathrm{GeV}$



$$\Lambda_{\not{\mathcal{U}}}^{4-d_{\mathcal{U}}} = \left(\frac{\Lambda_{\mathcal{U}}}{M_{\mathcal{U}}}\right)^{d_{UV}-d_{\mathcal{U}}} M_{\mathcal{U}}^{2-d_{\mathcal{U}}} v^2$$



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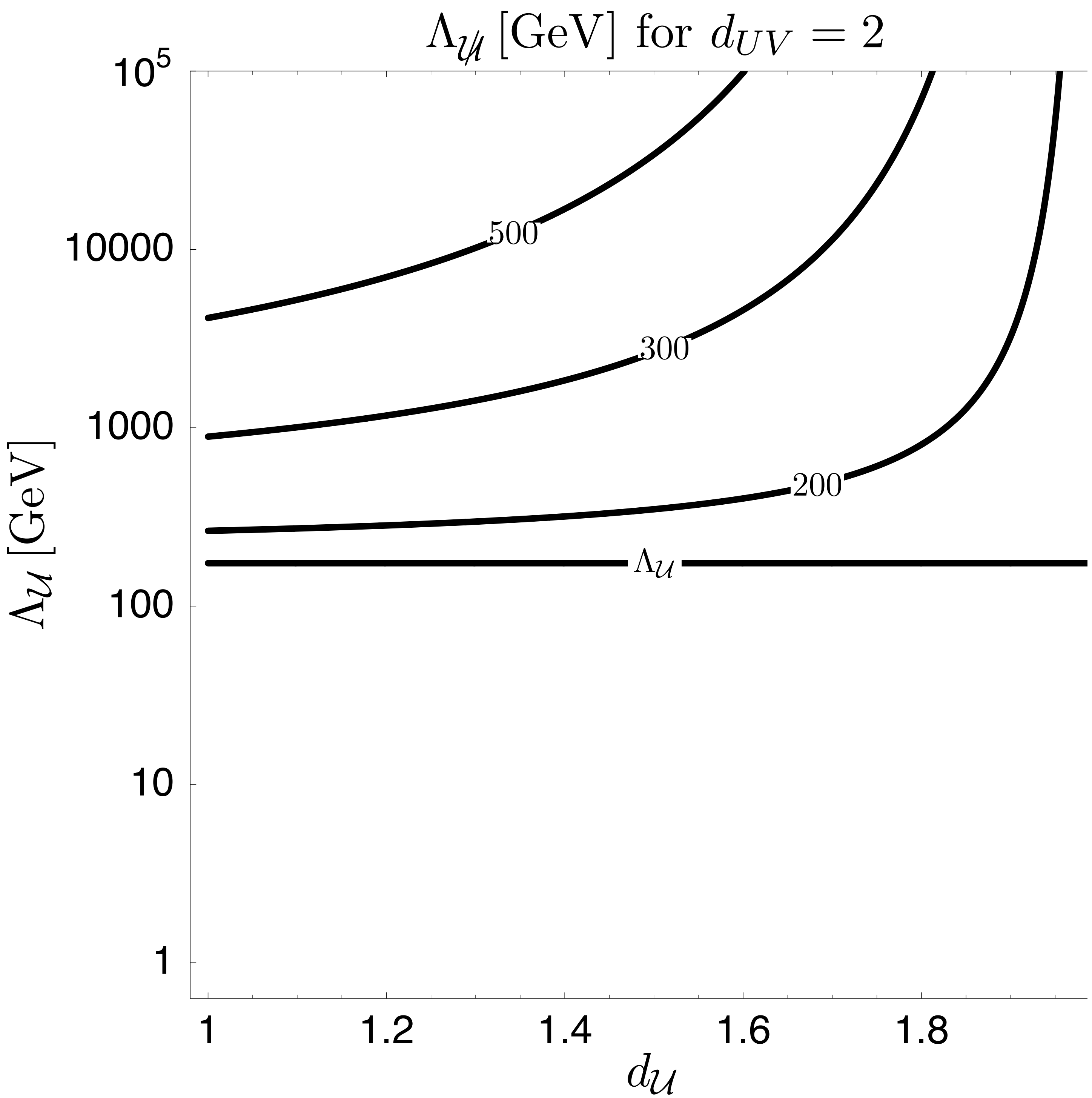
Independent of $M_{\mathcal{U}}$ for $d_{UV} = 2$



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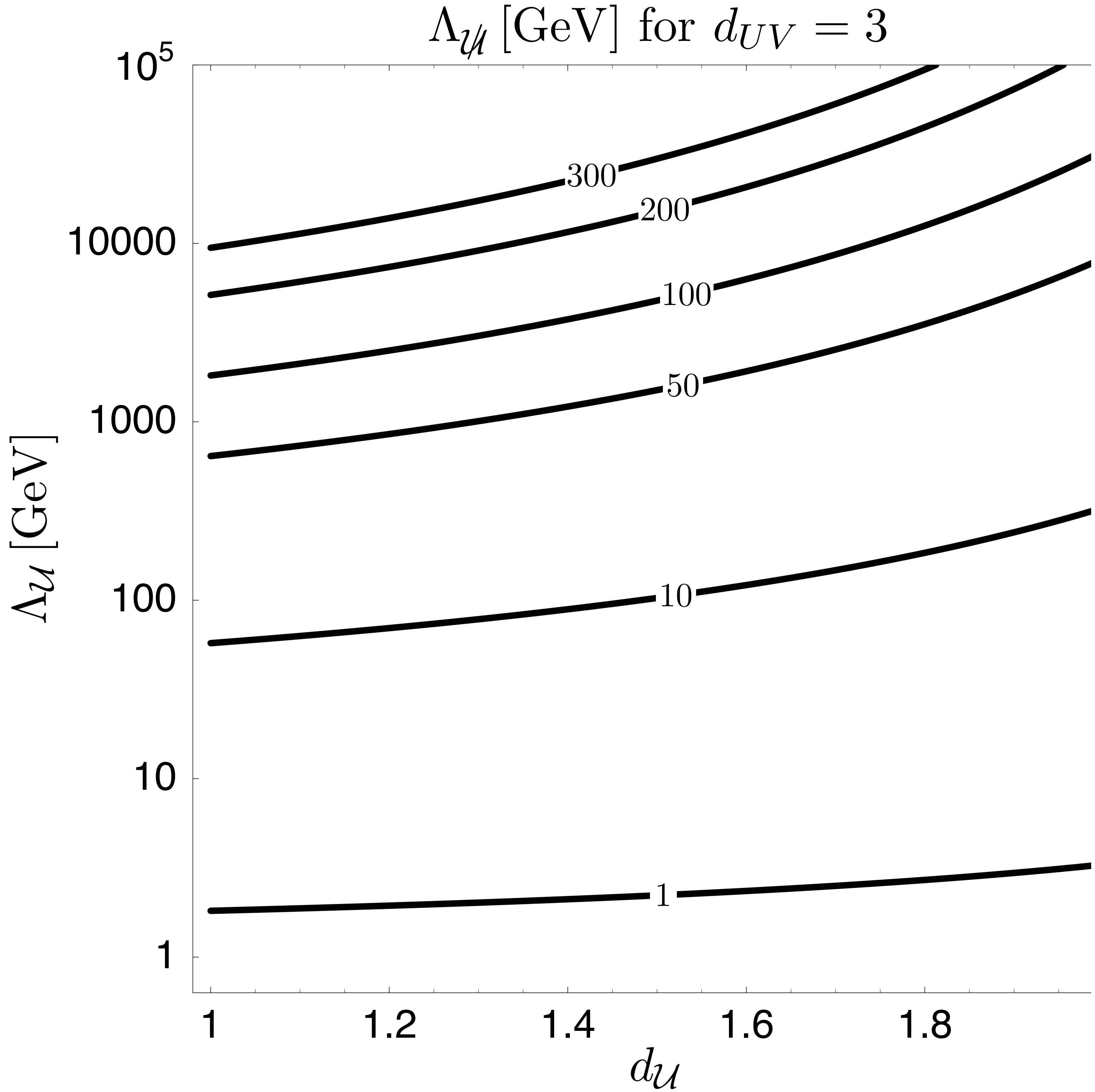

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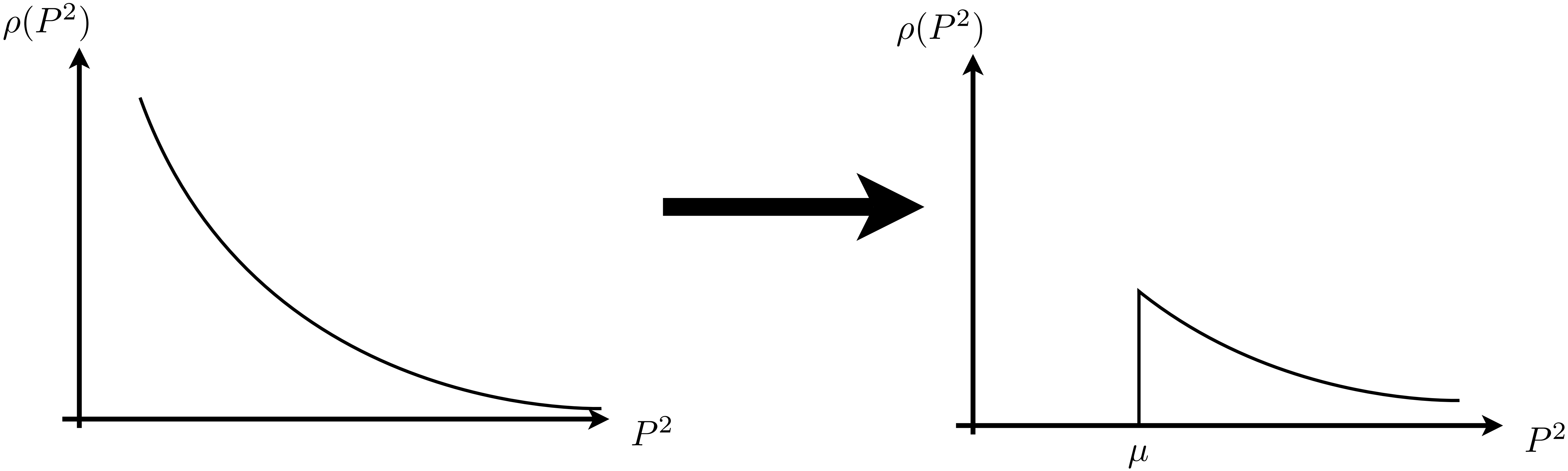
Non-unparticles

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

Scale invariance broken at scale $\mu \; (= \Lambda_{\not{\mathcal{U}}})$

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



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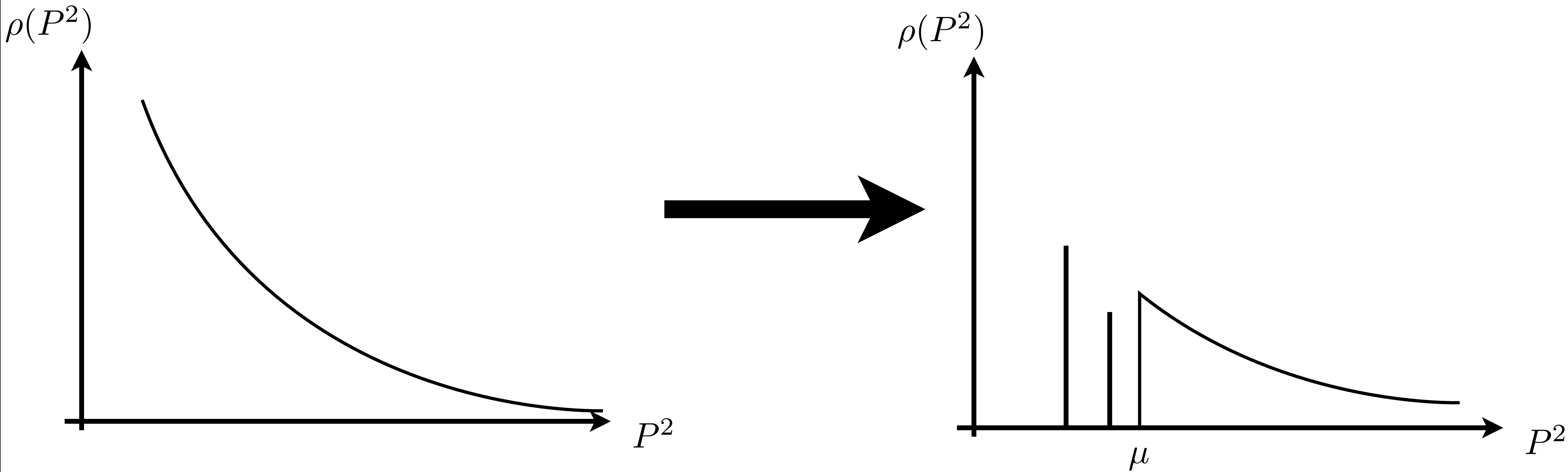
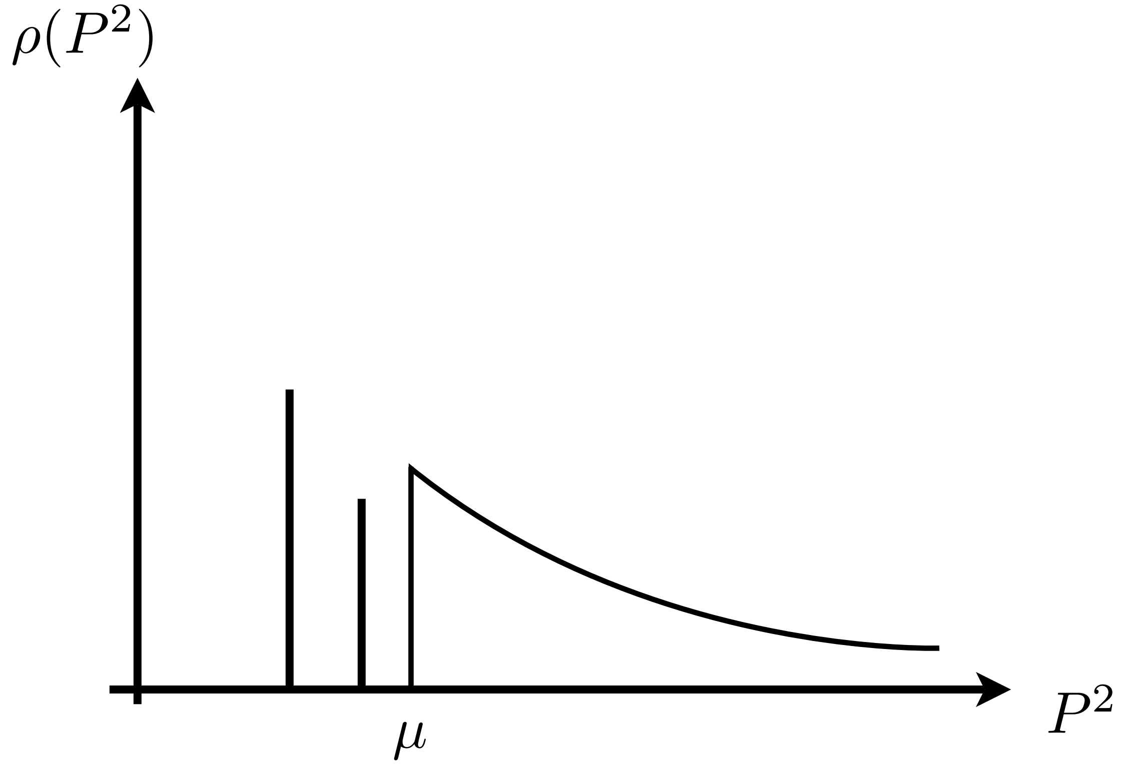


Observable effects of non-unparticles

With the mass gap the unparticles can decay back to SM states. No longer invisible Strassler; Feng, Rajaraman and Tu



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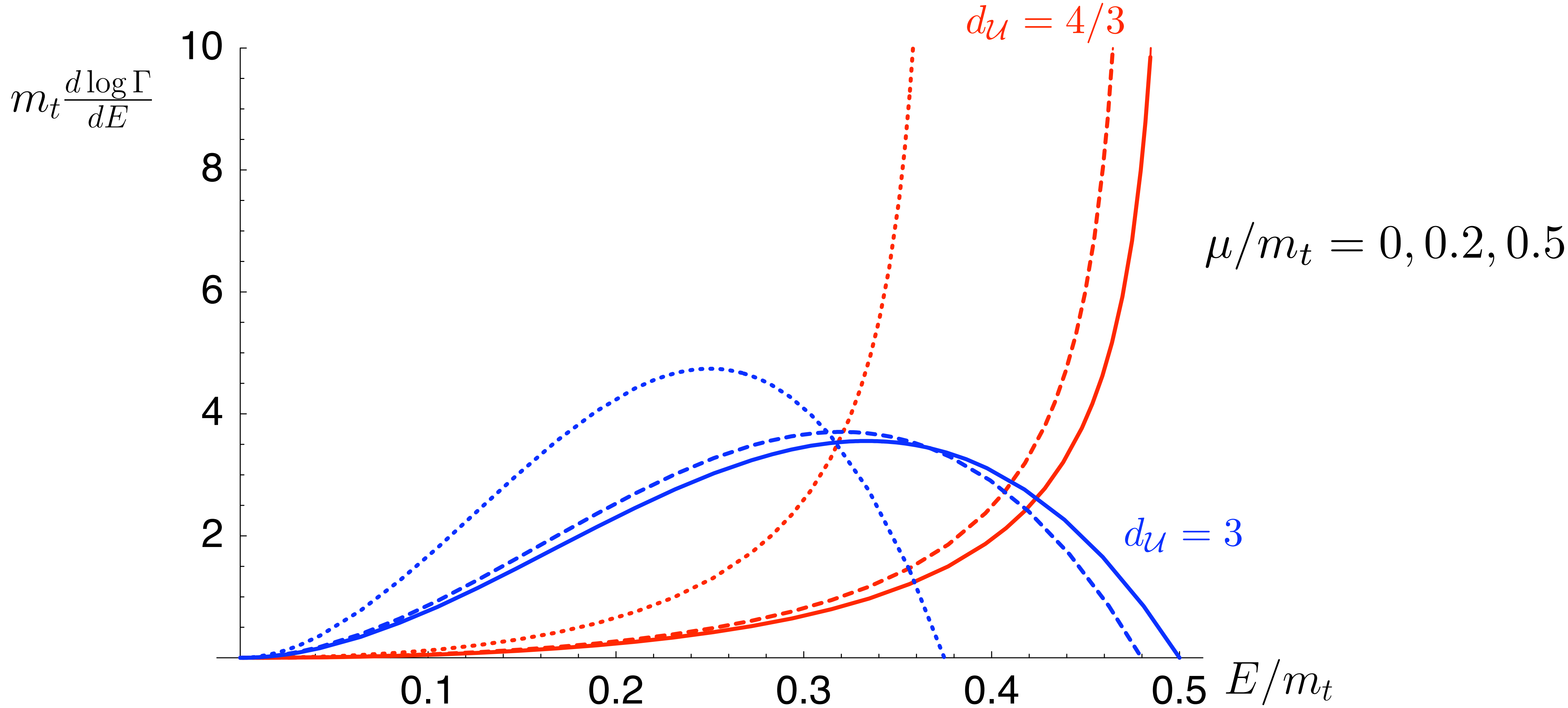
Observable effects of non-unparticles

$$t \to u + \mathcal{U}$$

$$m_t \frac{d \log \Gamma}{dE_u} = 4 d_{\mathcal{U}} (d_{\mathcal{U}}^2 - 1) \left(\frac{m_t}{M}\right)^6 \left(\frac{E_u}{m_t}\right)^2 \left(1 - 2\left(\frac{m_t}{M}\right)^2 \frac{E_u}{m_t}\right)^{d_{\mathcal{U}}-2}$$



Conclusions

- Unparticles look like a non-integral number of invisible particles
- Scalar unparticles most interesting
- New signatures at colliders, not low scale experiments
- Coupling to Higgs creates a mass gap: non-unparticles
- Changes distributions, makes unparticles visible

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