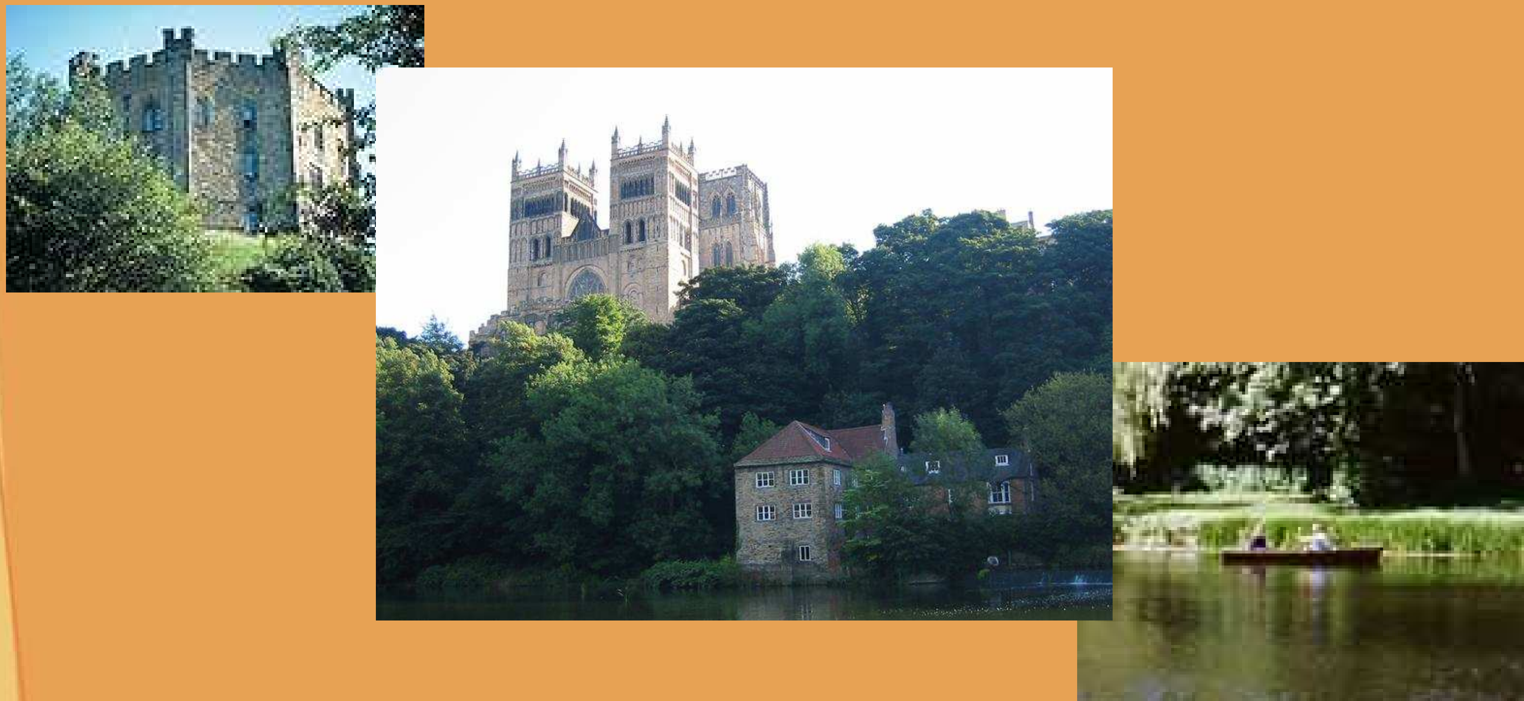
“Unparticles” and CP-violation



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EPS (Manchester) 19 July 2007

Overview

A. Big picture - scenario - propagator - phase

B. Phenomenology (assuming $\mathcal{L}^{\text{eff}}$)

C. CP-violation $B^+ \to \tau^+ \nu$

D. Theoretical constraints from CPT

E. End of scale invariance

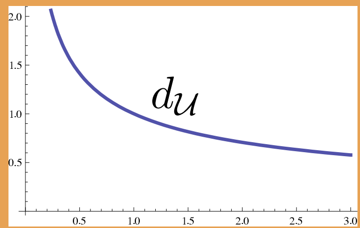
- RZ arXiv:0707.0677 C.,D.(E.)
- many other applications in literature

Broad Picture

- "Unparticles": scale invariant sector weakly coupled to SM

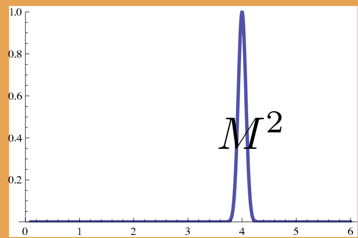
$$\mathcal{L}^{\text{eff}} \sim O_{\text{SM}} O_{\mathcal{U}}$$

- spectrum



P^2

unparticle

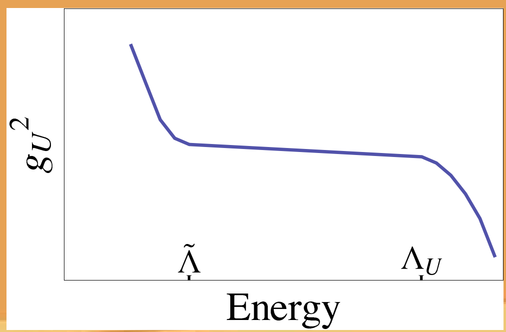


P^2

particle

- There is symmetry but **no** worked out model

  possible realization: theories "walking" technicolor



scale invariant window:

- powerlike running $O(\mu) = \left(\frac{\mu}{\mu_0}\right)^{\gamma} O(\mu_0)$
- unlike QCD asymptotic freedom log-running

Scenario (by Georgi PRL98)

$M_{\mathcal{U}} \gg 1\,\text{TeV}$

SM $\quad \frac{1}{M_{\mathcal{U}}} \quad$ UV sector self-interacting

$$\mathcal{L}^{\text{eff}} \sim \frac{1}{M_{\mathcal{U}}^{d_{\text{UV}}+(d_{\text{SM}}-4)}} O_{\text{SM}} O_{\text{UV}}$$

$\Lambda_{\mathcal{U}} \sim 1\,\text{TeV}$

non-trivial IR fixpoint

Dimensional Transmuation

$$\mathcal{L}^{\text{eff}} \sim \frac{\lambda}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}+(d_{\text{SM}}-4)}} O_{\text{SM}} O_{\mathcal{U}}$$

$$\lambda = C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{\text{UV}}}}{M_{\mathcal{U}}^{d_{\text{UV}}}}$$

$C_{\mathcal{U}}$ matching coefficient Wilson coefficient

$O_{\mathcal{U}} \equiv O_{\text{IR}}$

How far can we go with symmetry?

Define **propagator** from dispersion representation (assume $P^2 \geq 0$ $P_0 > 0$)

$$\Delta_{\mathcal{U}}(P^2) \equiv i\int_0^\infty d^4x e^{ip\cdot x}\langle 0|TO_{\mathcal{U}}(x)O_{\mathcal{U}}^\dagger(0)|0\rangle = \int_0^\infty \frac{ds}{\pi}\frac{\text{Im}[\Delta_{\mathcal{U}}(s)]}{s-P^2-i0} + \text{s.t.}$$

By scale invarince ($d_{\mathcal{U}} = 1+\gamma$ scaling dimension)

$$2\text{Im}[\Delta_{\mathcal{U}}(P^2)] = |\langle 0|O_{\mathcal{U}}(0)|P\rangle|^2 P^{-2} = A_{d_{\mathcal{U}}}(P^2)^{d_{\mathcal{U}}-2}$$

$1 < d_{\mathcal{U}} < 2$ convergence

Integral elementary ...

$$\Delta_{\mathcal{U}}(P^2) = \frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{1}{(-P^2-i0)^{2-d_{\mathcal{U}}}} \overset{P^2>0}{\longrightarrow} \frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{e^{-id_{\mathcal{U}}\pi}}{(P^2)^{2-d_{\mathcal{U}}}}$$

1. Phase i0 prescription ⇨ CP even (strong) phase !?!

Normalization $A_{d_{\mathcal{U}}}$?

$(P^2)^{d_{\mathcal{U}}-2} \sim$ phase space $d_{\mathcal{U}}$ massless particles

$$\Rightarrow A_{d_{\mathcal{U}}} = 16\pi^{5/2} \frac{\Gamma(d_{\mathcal{U}} + 1/2)}{\Gamma(d_{\mathcal{U}} - 1)\Gamma(2d_{\mathcal{U}})}$$

Sensible normalisation-limit:

$$\lim_{d_{\mathcal{U}} \to 1} \Delta_{\mathcal{U}}(P^2) = \frac{1}{P^2}$$

Many other possible choices consistent with limit above.

Unparticles in the final states e.g. $t \to u + \mathcal{U}$

2. Unparticles FS like (non-integral) $d\mathcal{U}$ invisible particles

Chronology

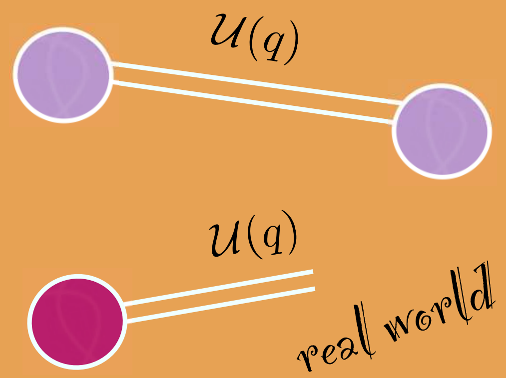
Observation 2 Georgi PRL98(2007)

Observation 1 Georgi 0704.2457 [hep-ph]
Cheung et al PRLxx(2007)

Phenomenology I

- virtual propagation with momentum flow q^2
  assumes scale invariance extends q^2

- real propagation integrates over all q^2 ?!
  $(P^2)^{d_\mathcal{U}-2}\Theta(P^2) \overset{\text{Model lit.}}{\rightarrow} (P^2-\tilde{\Lambda}^2)^{d_\mathcal{U}-2}\Theta(P^2-\tilde{\Lambda}^2)$



1. virtual propagation more transparent
2. (relatively) high momentum flow q^2 preferable (breaking scale invariance)
3. The nature of (real) unparticles can only be clarified in specific models

Phenomenology II

- **no** model assume $\mathcal{L}^{\rm eff}$ (unsatisfactory)
- strong phase allows characteristic phenomena (worthwhile)

  e.g. CP-violation in flavour physics

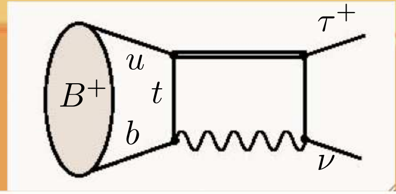
- Two examples:

$$\mathcal{L}^{\rm eff}_W = \frac{\lambda_S{}^{UD}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}(\bar{U}D)\,O_{\mathcal{U}} + \frac{\lambda_S{}^{\nu l}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}(\bar{\nu}l)\,O_{\mathcal{U}} + \{P \leftrightarrow S\} + h.c.$$

$$\mathcal{L}^{\rm eff}_{FCNC} = \frac{\lambda^{ut}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\bar{u}\gamma_\mu(1\pm\gamma_5)tO^\mu_{\mathcal{U}} + h.c. + (leptons)$$

- interference $\mathcal{A}^{SM}$ and $\mathcal{A}^{\mathcal{U}}$ leads to CP-violation (weak phase difference)
  - looked at $B \to D^+D^-$ (Belle high $C_{D^+D^-} = -0.91(23)(6)$ SM 5%)
  - move to semileptonic: $B \to \tau\nu$

$B^+ \Rightarrow \tau^+ \nu$

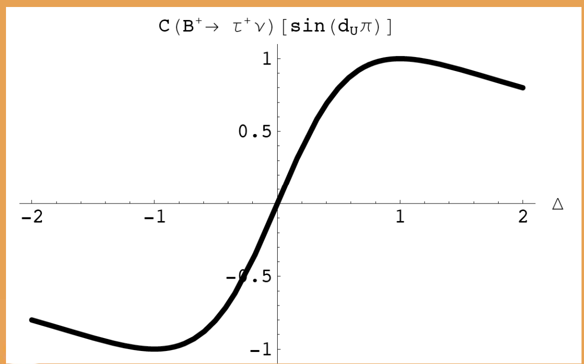


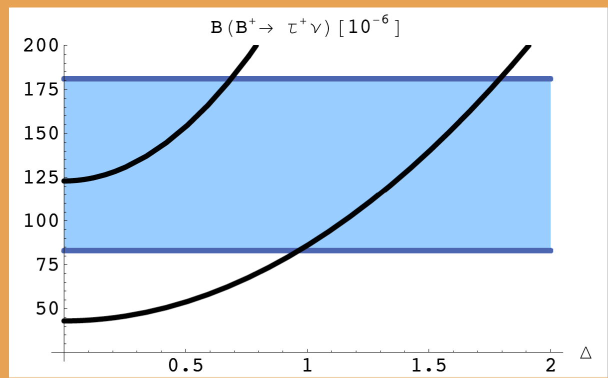
$\mathcal{L}_{FCNC}$

$\mathcal{L}_W$

$$\mathcal{A}_{\rm CP} = \frac{2\Delta \sin(-d_{\mathcal{U}}\pi)\sin(\delta\phi_{weak})}{1 + 2\Delta\cos(d_{\mathcal{U}}\pi)\cos(\delta\phi_{weak}) + \Delta^2} \qquad \Delta = \frac{|\mathcal{A}^{\mathcal{U}}|}{|\mathcal{A}^{\rm SM}|}$$

- How large can CP-asymmetry be? and consistent with branching fraction

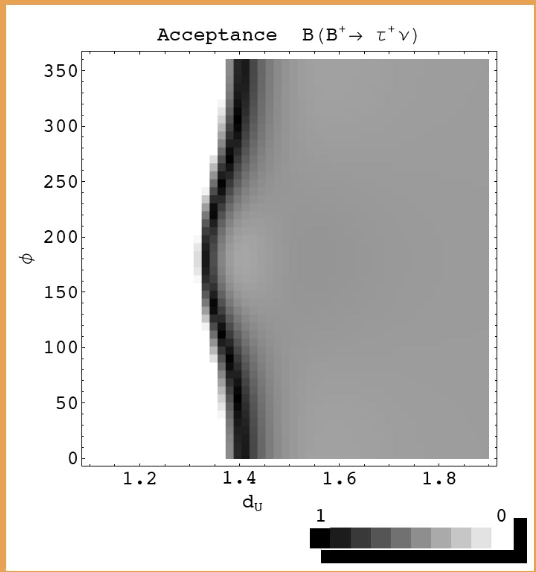


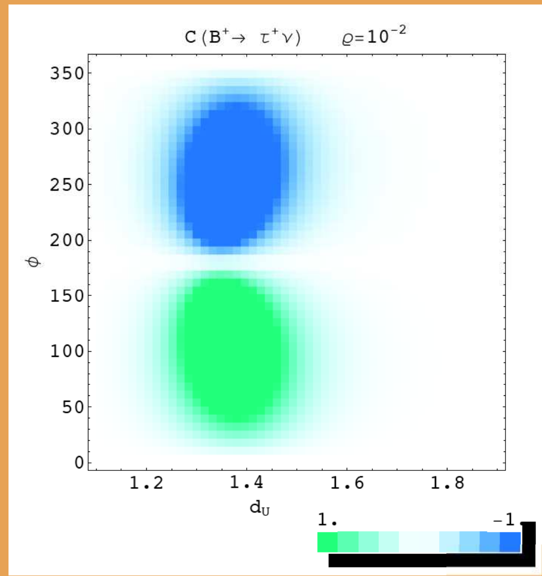


Ex: $\mathcal{L}_W$

Not constrained for $\delta\phi_{weak} = 90°$ (max CP violation)

- the generic case parameters $(\phi, d_{\mathcal{U}})$





- Experimentally not searched for !? (reason CPT? ..later)
  "Charge-conjugate modes are implied throughout this paper."
- In principle no problem, groups interest updates
- Babar & Belle 30 events
- LHCb no go - It is one SuperB modes

Experiment

Constraints from CPT

- well-known CPT $\Rightarrow \Gamma(B) = \Gamma(\bar{B}) \quad M(B) = M(\bar{B})$
- practice stronger constraint:

  Equality holds: sum partial rates of final states rescattering into each other

  From antiunitarity of CPT

  $$\Gamma(B) = \cdots = \sum_f \langle f, in|H_{\rm decay}|\bar{B}\rangle|^2 = \sum_f |\langle f, out|H_{\rm decay}|\bar{B}\rangle|^2 = \Gamma(\bar{B})$$

-
  $$\sum_{i\in I} \Delta\Gamma(B \to f_i) = 0\,, \qquad \langle f_i, in|1|f_j, out\rangle \neq 0 \quad i,j \in I\,,$$

  $$\text{SM Examples :} \qquad \begin{array}{l} \Delta\Gamma(K^0 \to \pi^0\pi^0) + \Delta\Gamma(K^0 \to \pi^+\pi^-) = 0 \\ \Delta\Gamma(K^+ \to \pi^0 l^+\nu) = 0 \end{array}$$

Puzzling ....

- What is the CPT compensating mode for $\mathcal{A}_{\rm CP} \sim \Delta\Gamma(B^+ \to \tau^+\nu)$??
- No candidate within SM (final state)
- $\Delta\Gamma(B^+ \to \tau^+\tau^-\mathcal{U}^+)$ fails counting coupling const. (already)
- Is the phase real ? Found example in the literature

  Thirring model (2D V-V interaction scale invariant)

$$\langle 0|T\Psi(x)\bar{\Psi}(0)|0\rangle = \frac{i}{2\pi}\frac{\gamma_\mu x^\mu}{(-x^2+i0)^{1+\gamma}}$$

$d_{\mathcal{U}} = 1/2 + \gamma$, $\gamma = \Lambda^2(1-\Lambda^2)^{-1}$ Johnson'61,Wilson'70

- Problems CPT? Causality major ingredient CPT is ok:

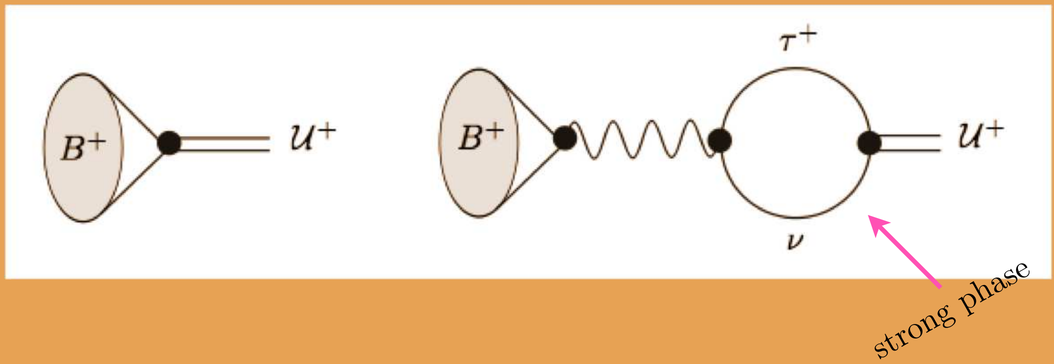
$$\langle 0|[O_{\mathcal{U}}(x), O_{\mathcal{U}}(0)]|0\rangle = -i\,{\rm sign}(x_0)\theta(x^2)(x^2)^{-d_{\mathcal{U}}} f(d_{\mathcal{U}})$$

There was a paradox causality in the mid 70' ... resolved

Solution

1. count coupling constants carefully $\Delta\Gamma = (weak^2, unparticle^2)$
2. remember unparticle has continuous spectrum

$B^+ \to \mathcal{U}^+$ is compensating mode (for $\mathcal{L}_W^{\text{eff}}$)



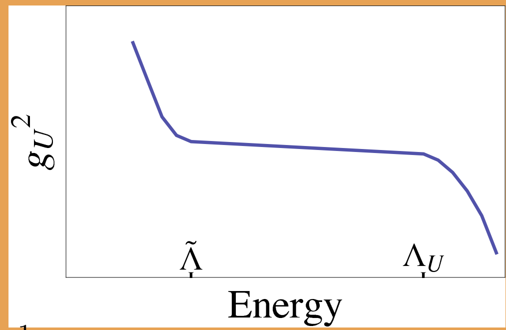
$$\Delta\Gamma(B^+ \to \tau^+\nu) + \Delta\Gamma(B^+ \to \mathcal{U}^+)_{\tau\nu-\text{loop}} = 0 \qquad \text{exactly verified}$$

- detail: graph no $e^{id_{\mathcal{U}}\pi}$, $\mathcal{A}_{\text{CP}} \sim \sin(d_{\mathcal{U}}\pi)\Delta$
  $\Delta \sim 1/\sin(d_{\mathcal{U}}\pi)$ from propagator (useful counting guidance)

End of scale invariance

- SM is not scale invariant, particular EW scale†

$$\mathcal{L}^{\text{eff}} = \frac{\lambda_H}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}_0}-2}} |H|^2 O_{\mathcal{U}_0}$$



- Dim analysis ⇒ breaking scale: $\tilde{\Lambda} = \Lambda_{\mathcal{U}} (\lambda_H \frac{v^2}{\Lambda_{\mathcal{U}}^2})^{\frac{1}{4-d_{\mathcal{U}_0}}}$

- Requiring $\mu_{\text{HF}} > \tilde{\Lambda}$, ⇒ bound: $\Delta < \frac{c_{\mathcal{U}}^S}{c_{\mathcal{U}}^H} \left(\frac{\mu_{\text{HF}}}{M_{\mathcal{U}}}\right)^{d_{\text{SM}}-2} \left(\frac{\mu_{\text{HF}}^2}{v^2}\right) \left(\frac{G_F^{-1}}{\mu_{\text{HF}}^2}\right) \left(\frac{\mu_{\text{HF}}}{\Lambda_{\mathcal{U}}}\right)^{d_{\mathcal{U}}-d_{\mathcal{U}_0}}$

  (rel. operators, size VEV, weak enhancement $G_F^{-1}/\mu_{\text{HF}}^2$, $d_{\mathcal{U}0} \neq d_{\mathcal{U}}$)

  - Is it possible to have $\tilde{\Lambda} \leq \mu_{\text{HF}}$ **and** sizable Δ-effects for $c_{\mathcal{U}}^H = O(1)$?
    Depends on anomalous dim. $d_{\mathcal{U}}, d_{\mathcal{U}0}$, .., model dep. ⇒ need models
    (e.g. $O_{\mathcal{U}_0} = O_{\mathcal{U}} O_{\mathcal{U}}^\dagger$, $0 \leq d_{\mathcal{U}0} \leq 2d_{\mathcal{U}}$)

† Adapted from Fox et al for weak sector

Epilogue-Conclusions

- Unparticles new(old?)[†] idea
  Striking feature: strong phase! Not been seen before?
- Based on symmetry; situation $\mathcal{L}^{\text{eff}}$ unsatisfactory
  Look striking phenomena and inconsistences
- Model desirable regardless of whether phenomenologically relevant
  Study nature of (real) "unparticles", (resummed effective d.o.f.?)
- Large CP viol. $B \to \tau\nu$ consistent constraints in that channel
- Formalism satisfies theoretical constraints from CPT
  $\Rightarrow$ Framework looks theoretically consistent
  - Weak sector enhanced $G_F^{-1}/\mu_{\text{HF}}^2$, other features model dep.

[†] "Heidi and the unparticle" (van der Bij & Dilcher)

merci de votre attention

Deconstruction (Stephanov)

- Can we recast the setup in particle language ?

- suppose spectrum ∞-sum of massive particles

$$\mathrm{Im}[\Delta_{\mathcal{U}}(P^2)] = A_{d_{\mathcal{U}}}(P^2)^{d_{\mathcal{U}}-2} \to \pi \sum_n \delta(P^2 - M_n^2) f_n^2$$

  mass $M_n^2 = \epsilon n^2$, meson decay constants $f_n = \frac{A_{d_{\mathcal{U}}}}{2\pi} \epsilon^2 (M_n^2)^{d_{\mathcal{U}}-2}$
  reproduces prop. and calculations in limit $\epsilon \to 0$

- Imaginary part ?
  $\lim_{\epsilon \to 0} f_n = 0$ unparticle does not decay ?
  Finite imaginary part does not mean finite lifetime ?

  - anomalous dimension ? ... is input, no insight