

“Unparticles” and CP-violation



*Roman Zwicky (Durham IPPP)
EPS (Manchester) 19 July 2007*



Overview



- A. Big picture - scenario - propagator - phase
- B. Phenomenology (assuming \mathcal{L}^{eff})
- C. CP-violation $B^+ \rightarrow \tau^+ \nu$
- D. Theoretical constraints from CPT
- E. End of scale invariance

- RZ arXiv:0707.0677 C.,D.(E.)

- many other applications in literature



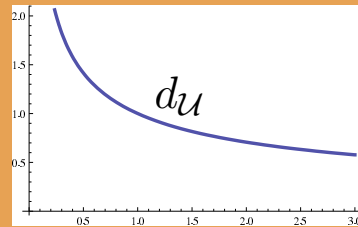
Broad Picture



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

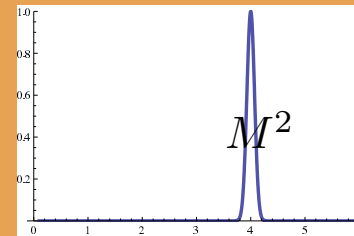
$$\mathcal{L}^{\text{eff}} \sim O_{\text{SM}} O_u$$

- spectrum



unparticle

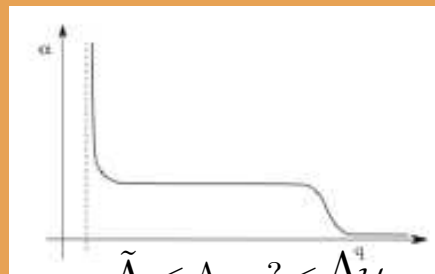
P^2



particle

P^2

- There is **symmetry** but **no** worked out model
possible realization: theories "walking" technicolor



$\tilde{\Lambda} < \Lambda_{\text{EW}}? < \Lambda_U$

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 PRL 98)



$$M_u \gg 1 \text{ TeV}$$

SM

$$\frac{1}{M_u}$$

UV sector
self-interacting

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

$$\Lambda_u \sim 1 \text{ TeV}$$

non-trivial IR fixpoint

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

**Dimensional
Transmutation**

$$\lambda = C_u \frac{\Lambda_u^{d_{\text{UV}}}}{M_u^{d_{\text{UV}}}}$$

C_u matching coefficient Wilson coefficient

$$O_u \equiv O_{\text{IR}}$$



How far can we go with symmetry?



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

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

By **scale invariance** ($d_U + 1 + \gamma$ scaling dimension)

$$\text{Im}[\Delta_U(P^2)] = |\langle 0 | O_U(0) | P \rangle|^2 = A_{d_U} (P^2)^{d_U - 2}$$

$1 < d_U < 2$
convergence

Integral elementary ...

$$\Delta_U(P^2) = \frac{A_{d_U}}{2 \sin(d_U \pi)} \frac{1}{(-P^2 - i0)^{2-d_U}} \xrightarrow{P^2 > 0} \frac{A_{d_U}}{2 \sin(d_U \pi)} \frac{e^{-id_U \pi}}{(P^2)^{2-d_U}}$$



1. Phase $i0$ prescription \Leftrightarrow \mathcal{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:

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

Many other possible choices

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

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 II

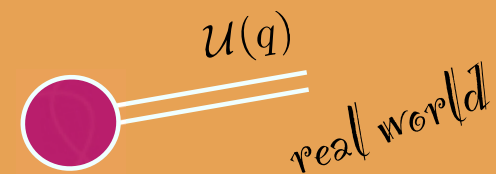
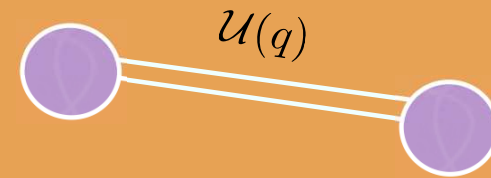
- **virtual propagation** with mom. flow q
assumes scale invariance extends q^2

- **real propagation** integrates over all q^2 ?!

$$(P^2)^{d_U-2} \Theta(P^2) \xrightarrow{\text{Model lit.}} (P^2 - \tilde{\Lambda}^2)^{d_U-2} \Theta(P^2 - \tilde{\Lambda}^2)$$

- \Rightarrow virtual propagation more transparent

The nature of (real) unparticles can only be clarified in specific models



Phenomenology II



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

e.g. CP-violation in flavour physics

- Two examples:

$$\mathcal{L}_W^{\text{eff}} = \frac{\lambda_S^{UD}}{\Lambda_U^{d_U-1}} (\bar{U}D) O_U + \frac{\lambda_S^{\nu l}}{\Lambda_U^{d_U-1}} (\bar{\nu}l) O_U + \{P \leftrightarrow S\} + h.c.$$

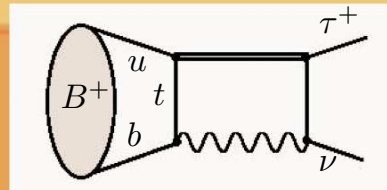
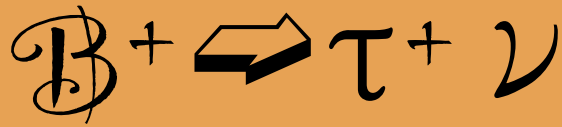
$$\mathcal{L}_{FCNC}^{\text{eff}} = \frac{\lambda^{ut}}{\Lambda_U^{d_U-1}} \bar{u} \gamma_\mu (1 - \gamma_5) t O_U^\mu + h.c.$$

- interference \mathcal{A}^{SM} and \mathcal{A}^U leads CP-violation (weak phase difference)

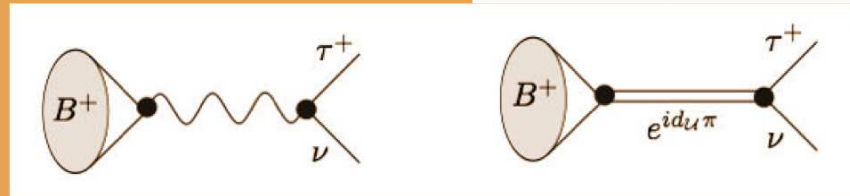
– looked at $B \rightarrow D^+ D^-$ (Belle high $C_{D^+ D^-} = -0.91(23)(6)$ SM 5%)

– move to **semileptonic**: $B \rightarrow \tau \nu$





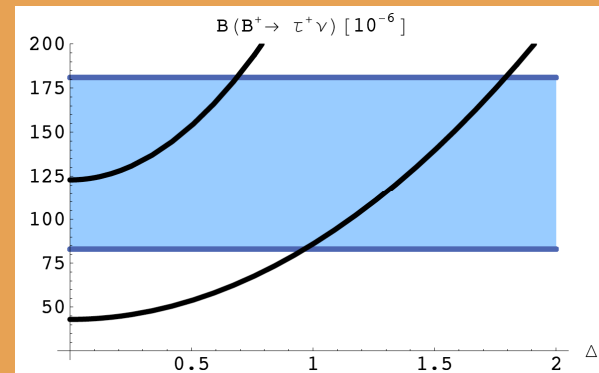
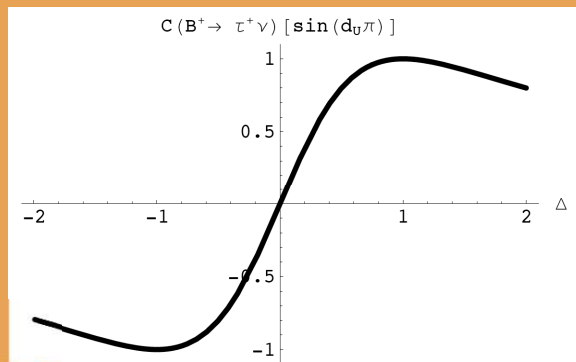
\mathcal{L}_{FCNC}



\mathcal{L}_W

$$A_{CP} = \frac{2\Delta \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{1 + 2\Delta \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2) + \Delta^2} \quad \Delta = \frac{|\mathcal{A}^U|}{|\mathcal{A}^{SM}|}$$

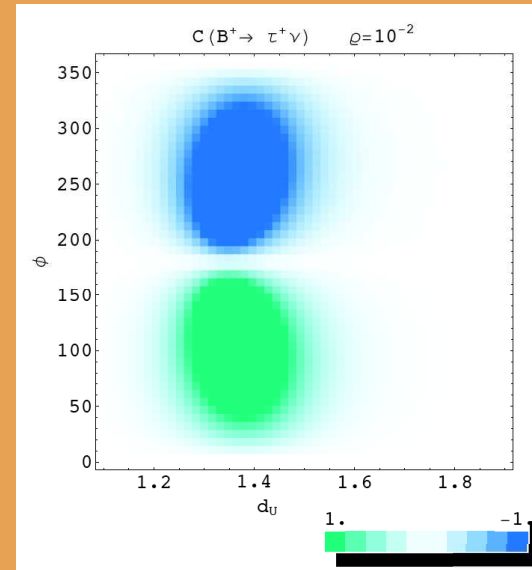
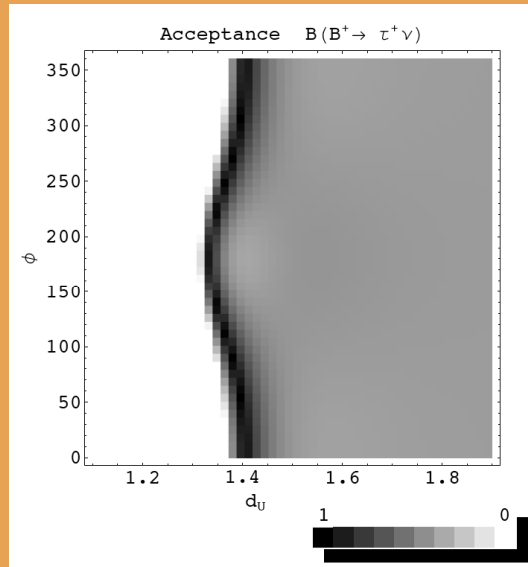
- Size CP asymmetry, consistent branching fraction?



Ex: \mathcal{L}_W

Ex: \mathcal{L}_W

- the generic case parameters (ϕ, d_U)



- Experimentally not searched for !? (reason .. 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 partial sum rates final states rescattering into each other

From antiunitarity of CPT

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

•

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

SM Examples :

$$\Delta\Gamma(K^0 \rightarrow \pi^0 \pi^0) + \Delta\Gamma(K^0 \rightarrow \pi^+ \pi^-) = 0$$
$$\Delta\Gamma(K^+ \rightarrow \pi^0 l^+ \nu) = 0$$

Puzzling



- What is the CPT compensating mode for $\mathcal{A}_{\text{CP}} \sim \Delta\Gamma(B^+ \rightarrow \tau^+\nu)$??
- No candidate within SM (final state)
- $\Delta\Gamma(B^+ \rightarrow \tau^+\tau^-\mathcal{U}^+)$ fails counting coupling const. (already)
- Is the **phase real** ? Found example in the literature
Thirring model (2D V-V interaction scale invariant)

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

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

- Problems CPT? Causality major ingredient CPT is ok:

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

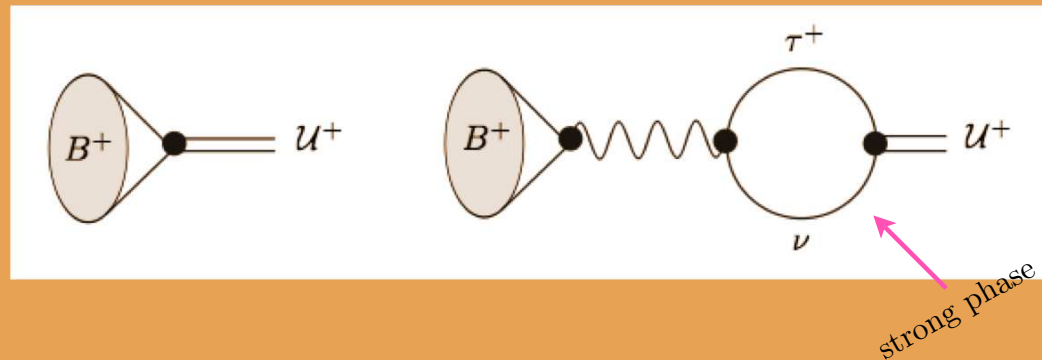
There was a paradox causality in the mid 70' ... resolved



Solution

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

$B^+ \rightarrow U^+$ is compensating mode



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

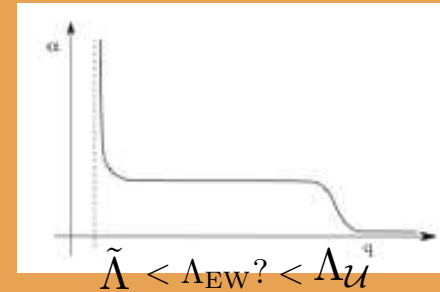
- detail: graph no $e^{idu\pi}$, $\mathcal{A}_{CP} \sim \sin(d_U\pi)\Delta$
 $\Delta \sim 1/\sin(d_U\pi)$ from propagator (useful counting guidance)

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: $\tilde{\Lambda} = \Lambda_{\mathcal{U}} \left(\lambda_H \frac{v^2}{\Lambda_{\mathcal{U}}^2} \right)^{\frac{1}{4-d_{\mathcal{U}_0}}}$
- 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. $d_{\mathcal{U}}, d_{\mathcal{U}_0}, \dots$, model dep. \Rightarrow need models
 (e.g. $O_{\mathcal{U}_0} = O_{\mathcal{U}} O_{\mathcal{U}}^\dagger$, $0 < d_{\mathcal{U}_0} < 2d_{\mathcal{U}}$)



[†] 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}^{eff} unsatisfactory
Look striking phenomena and inconsistencies
- Model desirable regardless of whether phenomenologically relevant
Study nature of (real) "unparticles", (resummed effective d.o.f.?)
- Large CP viol. $B \rightarrow \tau\nu$ 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

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

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 $\epsilon \rightarrow 0$

- **Imaginary part ?**

$\lim_{\epsilon \rightarrow 0} f_n = 0$ unparticle does not decay ?

Finite imaginary part does not mean finite lifetime ?

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

