NonRelativistic UnParticles

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Q. What is an elementary particle?

A. Irreducible representation
of the Poincare group

particle is characterized by mass *m* and spin *s*

Poincare group

includes 4 spacetime translations
3 rotations
3 Lorentz boosts

10 dimensions

Standard Model of Particle Physics:
SU(3)xSU(2)xU(1) gauge theory

17 elementary particles

s = 0: Higgs boson

s = 1/2: 6 quarks, 6 leptons

s = 1: photon, gluon, $W^{\pm}$, Z^0

Beyond the Standard Model ??

more elementary particles ?

new interactions ?

Hidden Sector ??

with no Standard Model interactions

"Unparticle Physics"

Howard Georgi hep-ph/0703260

Hidden sector could be scale invariant theory
with conformal symmetry
consists of "unparticles"

Q. What is an unparticle?

A. Irreducible representation
of the conformal group

unparticle is characterized by scaling dimension Δ

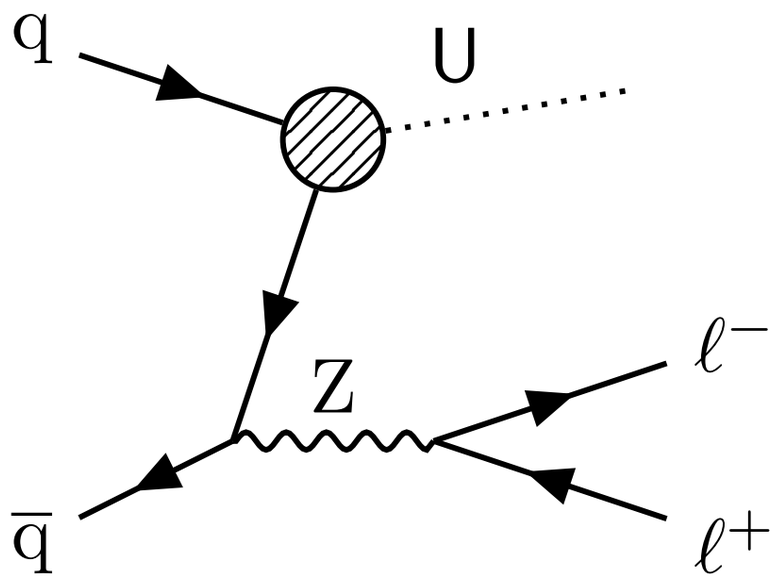
Conformal group includes 4 spacetime translations
3 rotations
3 Lorentz boosts
1 scale transformation
4 spacetime inversions

4 15 dimensions

Searches for Unparticles at the LHC

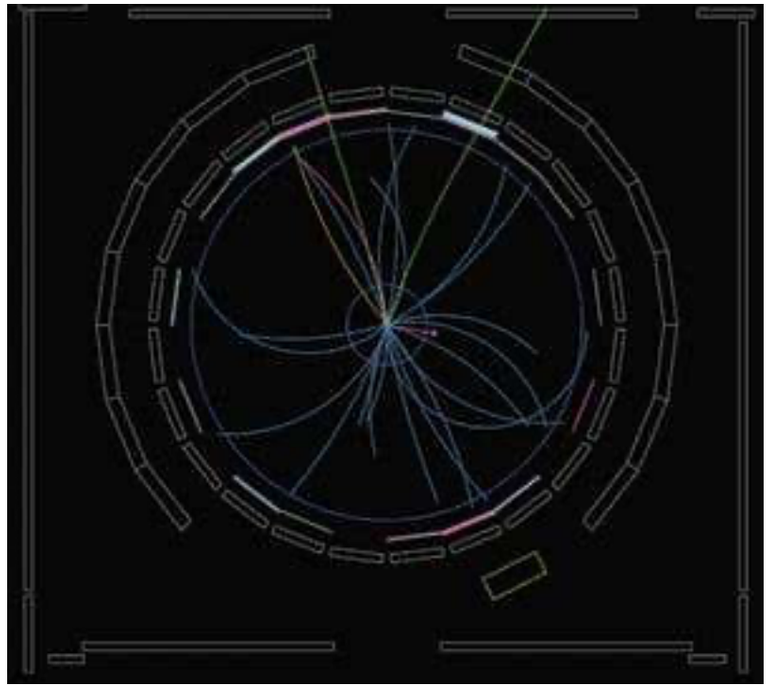
CMS collaboration arXiv:1408.3583, 1511.09375, 1701.02402

production of unparticle
in association with Z^0



Unparticle invariant mass distribution

$$\frac{d\hat{\sigma}}{dP_u^2} \sim (P_u^2)^{\Delta-2}$$



CMS: "95% confidence limits
are obtained on the effective cutoff scale
as a function of the scaling dimension"

NonRelativistic Effective Field Theories

NREFT can have Galilean symmetry

if mass is conserved in every reaction

Galilean group includes 4 spacetime translations

3 rotations

3 Galilean boosts

1 phase transformation

11 dimensions

phase symmetry guarantees mass conservation

Q. What is a Galilean particle?

A. Irreducible representation of the Galilean group characterized by mass M and spin s

"UnNuclear Physics"

Hammer & Son arXiv:2103.12610

Unparticles can rise in nonrelativistic effective field theories

Q. What is a nonrelativistic unparticle?

A. Irreducible representation
of the Schroedinger group
(nonrelativistic conformal group)

unparticle is characterized by mass *M* and scaling dimension *Δ*

Schroedinger group includes 4 spacetime translations
3 rotations
3 Galilean boosts
1 phase transformation
1 scale transformation
1 time inversion

13 dimensions

"UnNuclear Physics"

Hammer & Son arXiv:2103.12610

Low-energy neutrons are unparticles !

Neutrons (*n* = *udd*, spin 1/2)
can be described by nonrelativistic conformal EFT
(same EFT as ultracold fermionic atoms tuned to Feshbach resonance that makes scattering length infinite)

	mass	scaling dimension
1 neutron:	m_n	$\Delta_1 = 3/2$
2 neutrons:	$2m_n$	$\Delta_2 = 2$
3 neutrons:	$3m_n$	$\Delta_3 = 4.27272$
4 neutrons:	$4m_n$	$\Delta_4 \approx 5.1$

“UnNuclear Physics”

Hammer & Son arXiv:2103.12610

Low-energy neutrons with opposite spins

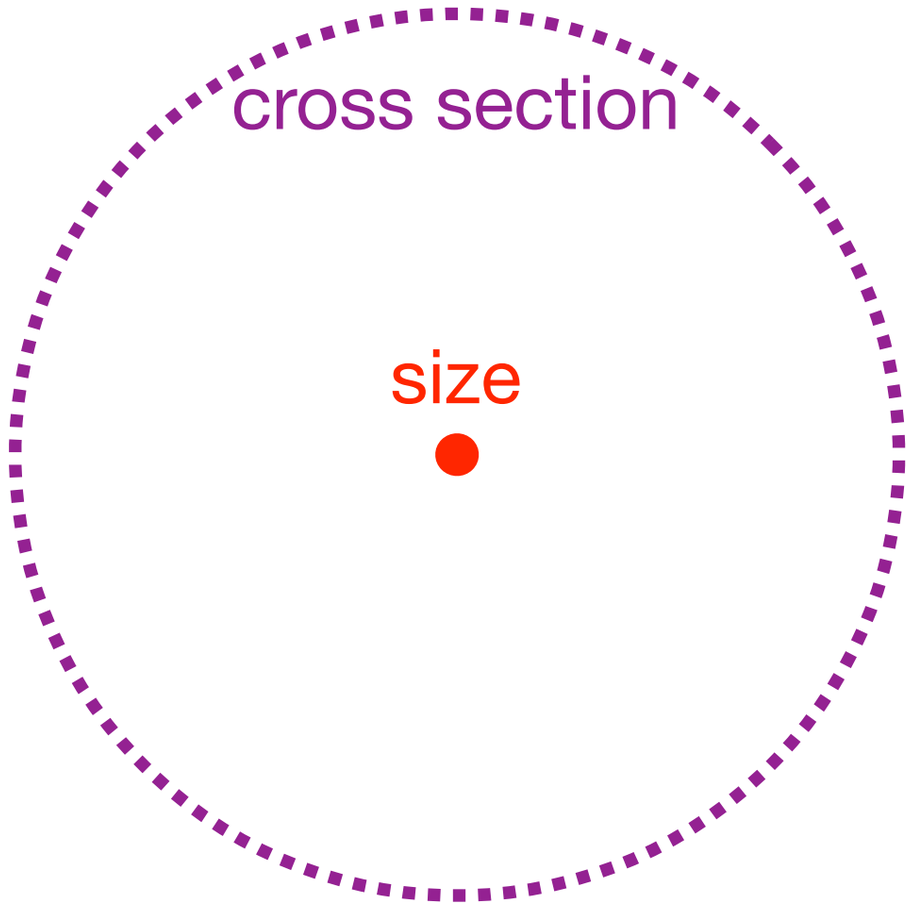
have large scattering length a = -19 fm

and enormous cross section

(accidental fine tuning of QCD makes dineutron almost bound)

radius of neutron: 0.8 fm

radius of cross section: 20 fm



Interactions between low-energy neutrons

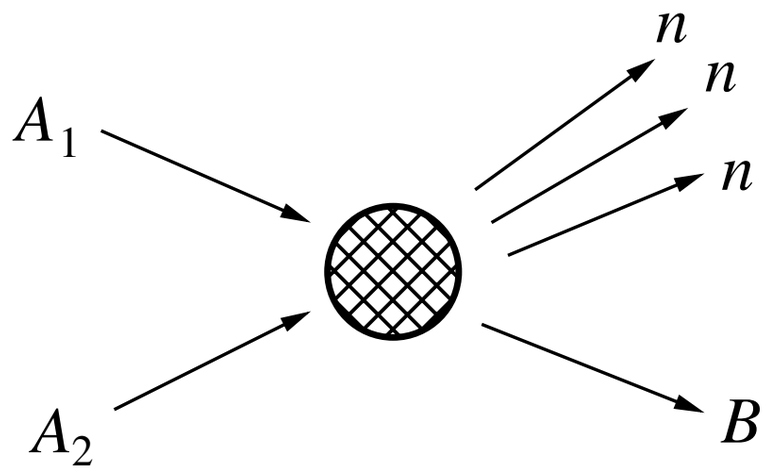
are approximately scale invariant !

"UnNuclear Physics"

Hammer & Son arXiv:2103.12610

Nuclear reaction $A_1\ A_2 \rightarrow B + (N\ n)$

creates N neutrons with invariant mass $N\ m_n + E$ near threshold



Invariant mass distribution of neutrons
can be determined using
recoil momentum of nucleus B

$$\frac{d\sigma}{dE} \sim E^{\Delta_N - 5/2}$$

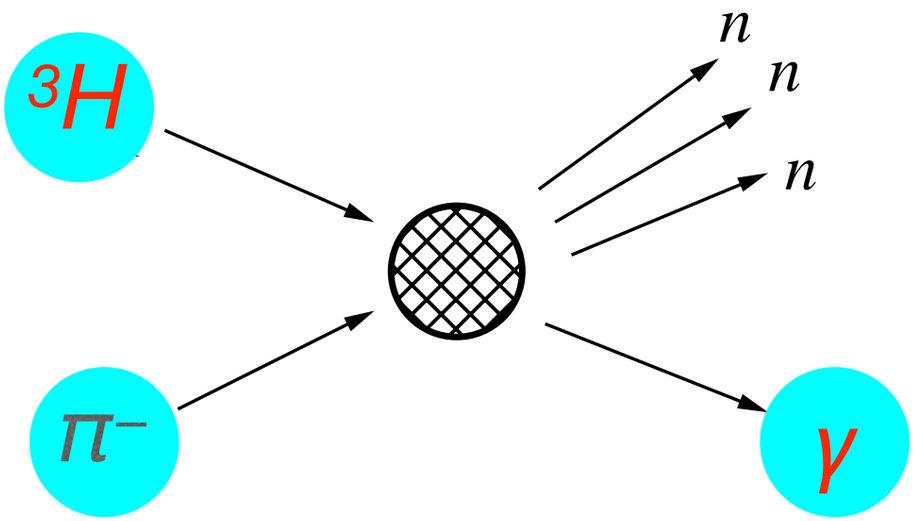
Power law behavior with exponent Δ_N - 5/2: signature for unparticle

"UnNuclear Physics"

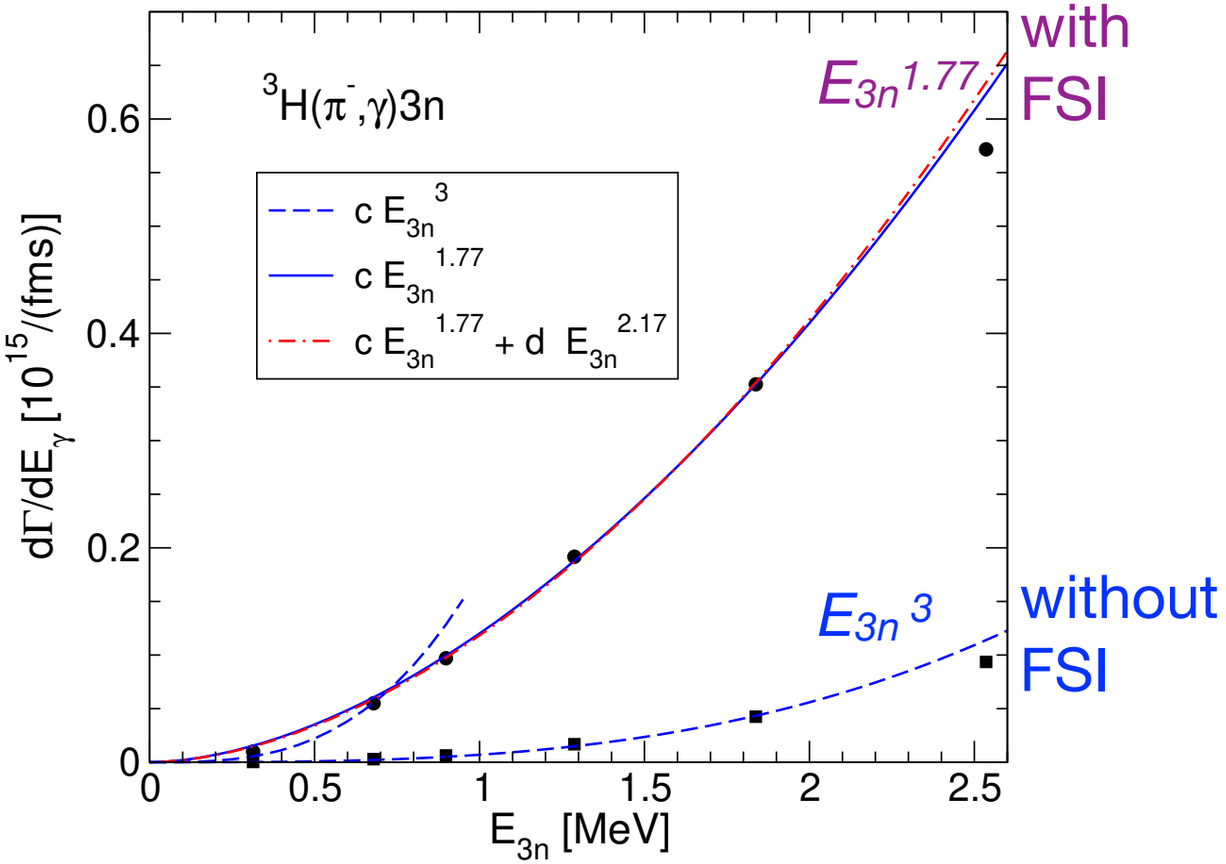
Hammer & Son arXiv:2103.12610

Nuclear reaction $\pi^- \, {}^3H \rightarrow \gamma + (3\,n)$

creates *3* neutrons with invariant mass $3\,m_n + E$ near threshold



$$\frac{d\sigma}{dE} \sim E^{1.77272}$$



Power law behavior with exponent $\Delta_3 - 5/2$: signature for unparticle

Low-energy neutral charm mesons are Unparticles ! (with H.-W. Hammer)

Neutral charm mesons

spin 0: $D^0 = u\bar{d}$, $\bar{D}^0 = d\bar{u}$ mass: 1865 MeV

spin 1: $D^{*0} = u\bar{d}$, $\bar{D}^{*0} = \bar{d}u$ mass: 2007 MeV

X(3872) resonance
implies that neutral charm mesons
can be described by nonrelativistic conformal effective field theory

	scaling dimension
D^0, $\bar{D}^0$, D^{*0}, $\bar{D}^{*0}$:	$\Delta_1 = 3/2$
$X = D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$:	$\Delta_2 = 2$
$D^{*0}\bar{D}^0 - D^0\bar{D}^{*0}$:	3
XD^0, $X\bar{D}^0$:	$\Delta_3 = 3.1012$
XD^{*0}, $X\bar{D}^{*0}$:	$\Delta_{3*} = 3.0870$

$X(3872) \equiv \chi_{c1}(3872)$

discovered at e^+e^- collider Belle 2003

$B^\pm \to K^\pm X, \quad X \to J/\psi\, \pi^+\pi^-$

- quantum numbers $J^{PC} = 1^{++}$ LHCb 2013

- mass LHCb 2020

  extremely close to $D^{*0}\bar{D}^0$ threshold

  $E_X \equiv M_X - (M_{D^{*o}} + M_{D^o}) = (-0.07 \pm 0.12)$ MeV

  $|E_X| < 0.22$ MeV at 90% CL

- width LHCb 2020

  $\Gamma_X = (1.19 \pm 0.19)$ MeV (Breit-Wigner line shape)

- 7 observed decay modes

  $J/\psi\, \pi^+\pi^-$, $J/\psi\, \pi^+\pi^-\pi^0$, $J/\psi\, \gamma$, $\psi(2S)\, \gamma$, $\chi_{c1}\, \pi^0$, $D^0\bar{D}^0\gamma$, $D^0\bar{D}^0\pi^0$

What is the *X(3872)*?

given: $J^{PC} = 1^{++}$, $|E_X| < 0.22$ MeV

resonant interactions with neutral charm mesons
transform *X* into loosely bound molecule !!

$$X(3872) = (D^{*0}\bar{D}^0 + D^0\bar{D}^{*0})/\sqrt{2}$$

<u>small additional components</u>

at long distances: $D^0\bar{D}^0\pi^0$

at short distances:

charged charm mesons $D^{*+}D^- + D^+D^{*-}$

P-wave charmonium $\chi_{c1}(2P)$??

compact tetraquark $[cq][\bar{c}\bar{q}]$??

Low-energy neutral charm mesons are Unparticles ! (with H.-W. Hammer)

X(3872) is bound state of neutral charm mesons
(accidental fine tuning of QCD makes *X* just barely bound)

$$X(3872) = (D^{*0}\bar{D}^{0} + D^{0}\bar{D}^{*0})/\sqrt{2}$$

X unparticle

operator with scaling dimension $\Delta_2 = 2$
creates $D^{*0}+\bar{D}^{0}$, $D^{0}+\bar{D}^{*0}$, *and* $X(3872)$

XD unparticle

operator with scaling dimension $\Delta_3 = 3.1012$
creates $D^{*0}+\bar{D}^{0}+D^{0}$, $D^{0}+\bar{D}^{*0}+D^{0}$, *and* $X(3872)+D^{0}$

*XD** unparticle

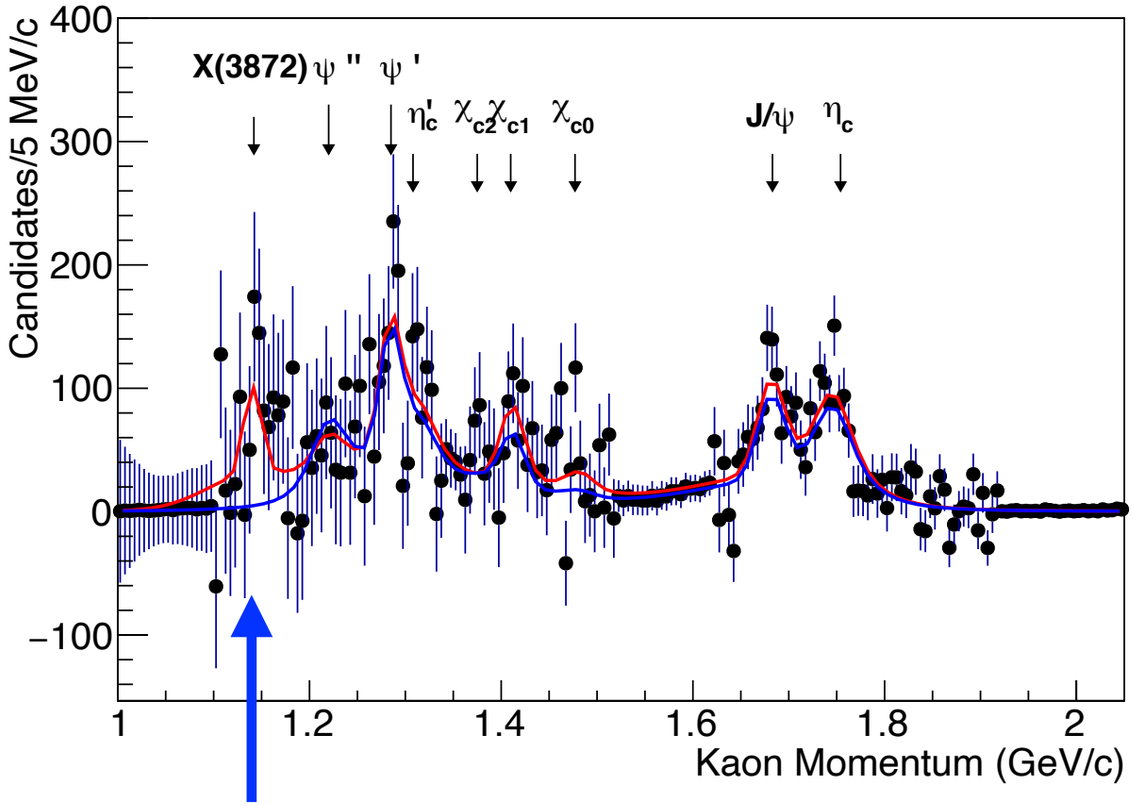
operator with scaling dimension $\Delta_3 = 3.0870$
creates $D^{*0}+\bar{D}^{0}+D^{*0}$, $D^{0}+\bar{D}^{*0}+D^{*0}$, *and* $X(3872)+D^{*0}$

X Unparticle

Babar collaboration arXiv:1911.11740

inclusive decays $B^{\pm} \rightarrow K^{\pm}$ + (anything)

measure momentum distribution of $K^{\pm}$



X unparticle

may have been observed as peak near p_{max} = 1141 MeV

could be confirmed by observing scaling region near p_{max} with power-law determined by $\Delta_2 = 2$ $\frac{d\Gamma}{dp} \sim (p_{\max} - p)^{-1/2}$

can it be confirmed by Belle II collaboration ?

XD and *XD** Unparticles

production of *XD* or *XD** unparticles
requires creation of two $c\bar{c}$ pairs
sufficient rate only for prompt production at Large Hadron Collider

no trigger for events with 3 charm mesons
need *X(3872)* → $J/\psi\ \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$ to provide trigger

XD unparticle

observe through *X(3872)* + D^0 component
scaling region with energy dependence $E^{-0.1012}$

*XD** unparticle

observe through *X(3872)* + D^{*0} component
scaling region with energy dependence $E^{-0.0870}$

can they be observed by LHCb collaboration ?

Summary

Nonrelativistic Unparticle

excitation created by an operator with definite scaling dimension
in a Nonrelativistic Effective Field Theory

Low-energy neutrons are Unparticles !

because the dineutron is almost bound

Hammer & Son arXiv:2103.06290

Low-energy neutral charm mesons are Unparticles !

because of the existence of the *X(3872)* resonance

Braaten & Hammer arXiv:2106.nnnnn

X unparticle: observed in inclusive decays $B^{\pm} \to K^{\pm}$ + (anything) ?

XD and *XD** unparticles: observable in prompt production at LHC ?

Can Unparticles be observed using ultracold atoms ?