Neutral Charm Mesons
are
UnParticles!

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research support from U.S. Department of Energy

UnParticles

Relativistic Unparticles

Georgi

Phys. Rev. Lett. 98, 221601 (2007) [hep-ph/0703260]

NonRelativistic Unparticles

Hammer & Son

Proc.Nat.Acad.Sci. 118 (2021)
[arXiv:2103.12610]

Neutrons are Unparticles !

Neutral charm mesons are Unparticles !

Braaten & Hammer

Phys. Rev. Lett. 128, 032002 (2022) [arXiv:2107.03821]

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
excitations are "unparticles"

Q. What is an unparticle?

A. Irreducible representation
of the conformal group

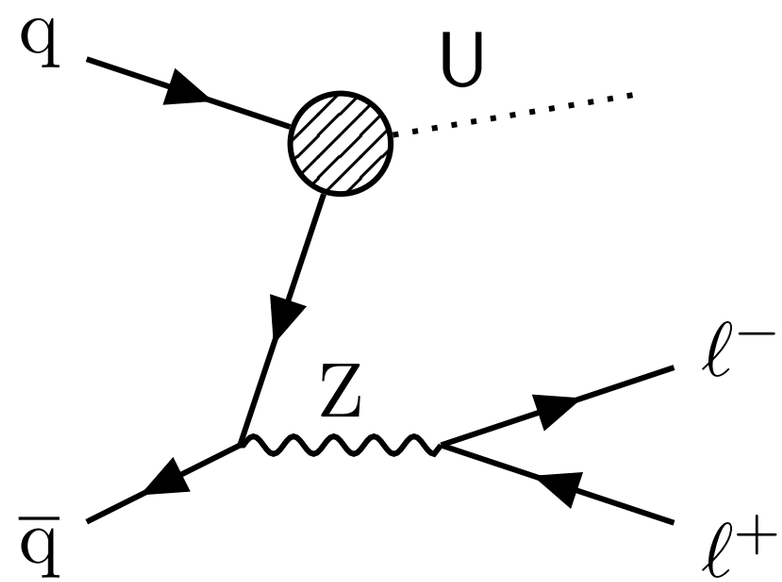
unparticle is characterized by scaling dimension Δ

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

15 dimensions

Observation of Unparticles

Unparticle in a hidden sector cannot be observed directly
However it can be observed indirectly
if it is produced in association with a Standard Model particle
(such as Z^0)



Invariant mass distribution P_U^2 of Unparticle
can be measured using recoil momentum of Standard Model particle

$$d\sigma/dP_U^2 \sim (P_U^2)^{\Delta-2}$$

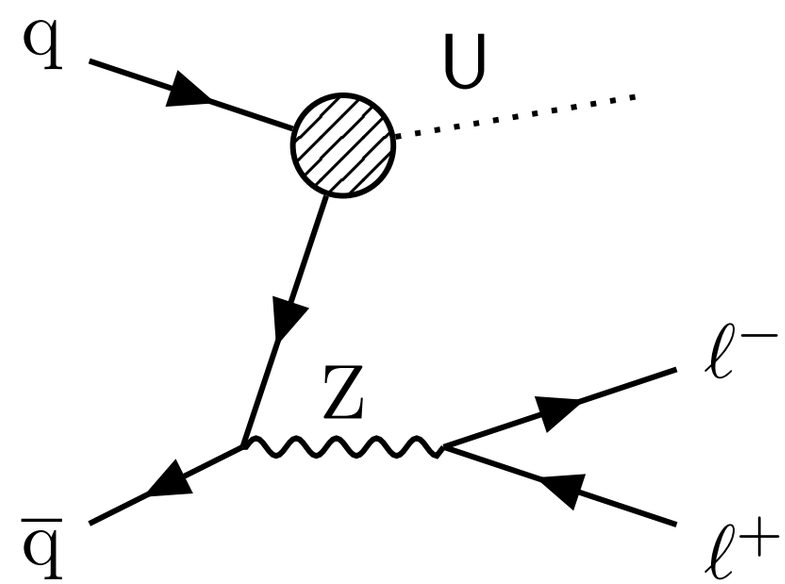
Unparticle signature: power-law dependence on P_U^2
exponent Δ determined by conformal symmetry

For N massless particles, $\Delta = N$.
For Unparticle, Δ can be noninteger

Searches for Unparticles at the LHC

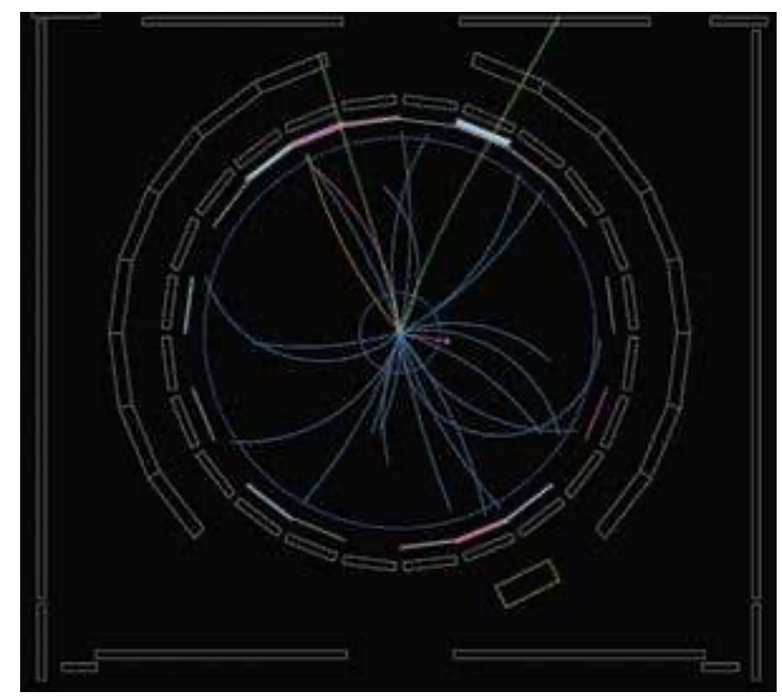
CMS collaboration arXiv:1408.3583, 1511.09375, 1701.02402

production of Unparticle
in association with Z^0, …



Unparticle invariant mass distribution

$$d\sigma/dP_U^2 \sim (P_U^2)^{\Delta-2}$$



CMS: limits on effective cutoff scale
as function of scaling dimension

NonRelativistic Effective Field Theories

NREFT can have Galilean symmetry
if kinetic 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 kinetic mass conservation

Q. What is a Galilean particle?

A. Irreducible representation
of the Galilean group
characterized by kinetic mass M, 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 nonrelativistic conformal group

unparticle is characterized by kinetic mass M, scaling dimension Δ

nonrelativistic conformal (Schroedinger) group

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

13 dimensions

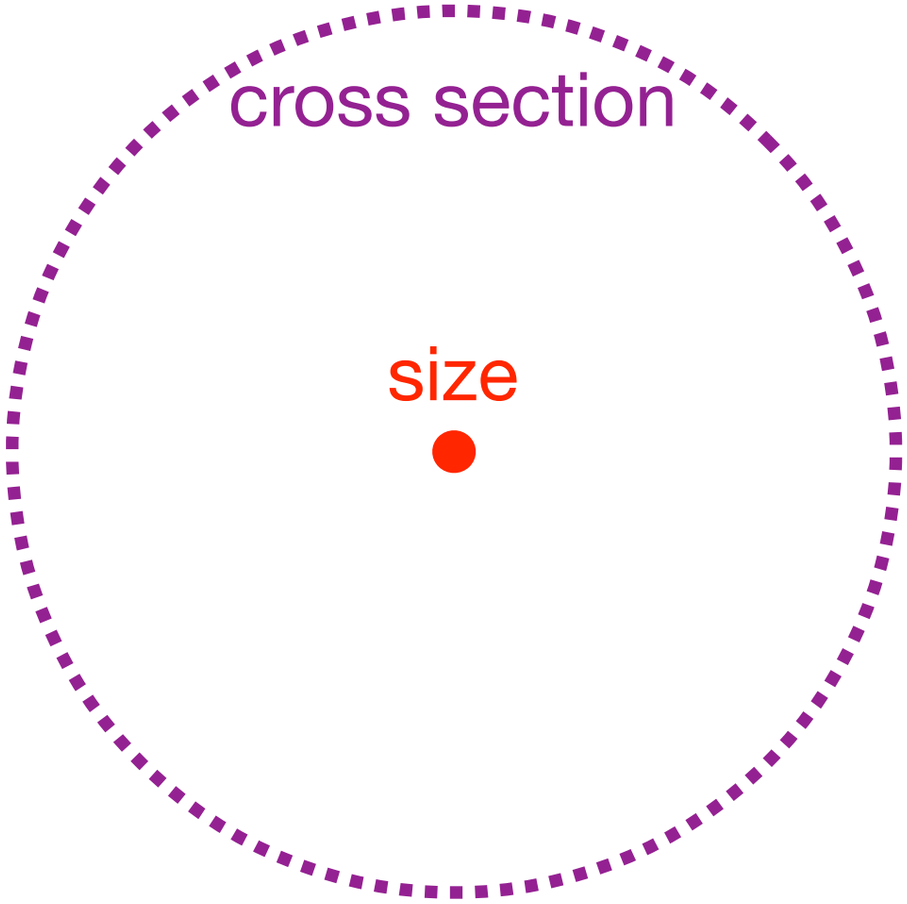
"UnNuclear Physics"

Hammer & Son arXiv:2103.12610

Neutrons with opposite spins
have large scattering length $a = -19$ fm
and enormous cross section at low energy
(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

Low-energy neutrons can be described by nonrelativistic conformal field theory

Neutrons are Unparticles !

For N weakly interacting nonrelativistic particles, $\Delta = (3/2)N$.
For Unparticle, Δ can be non-half-integer

	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:	$4m_n$	$\Delta_4 \approx 5.1$

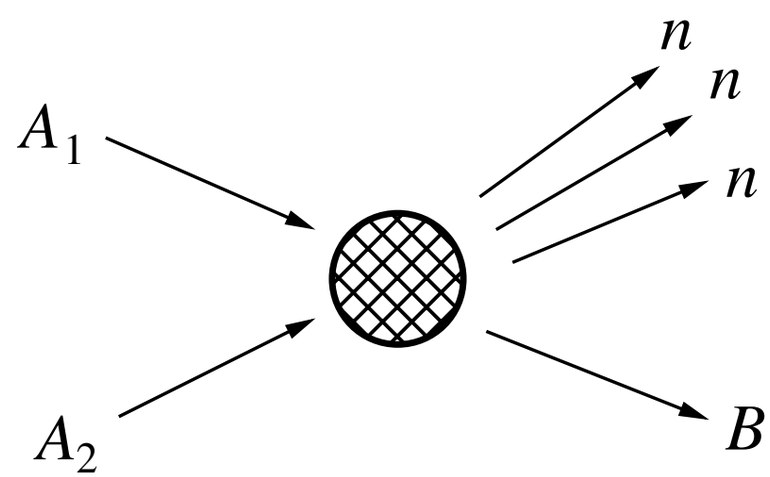
"UnNuclear Physics"

Hammer & Son arXiv:2103.12610

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

creates N neutrons recoiling against nucleus B

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



Energy distribution of neutrons can be measured using recoil momentum of nucleus B

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

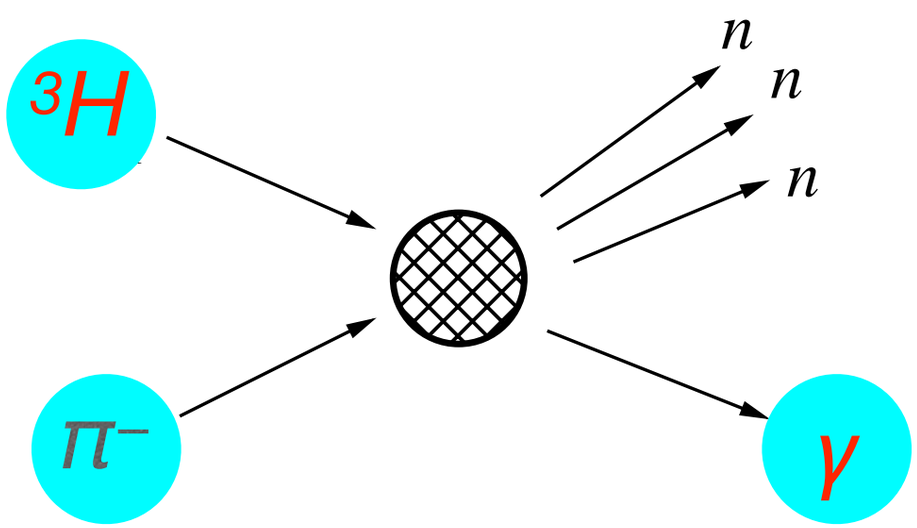
Unparticle signature:
power-law behavior at low energy
exponent Δ_N is determined by conformal symmetry

"UnNuclear Physics"

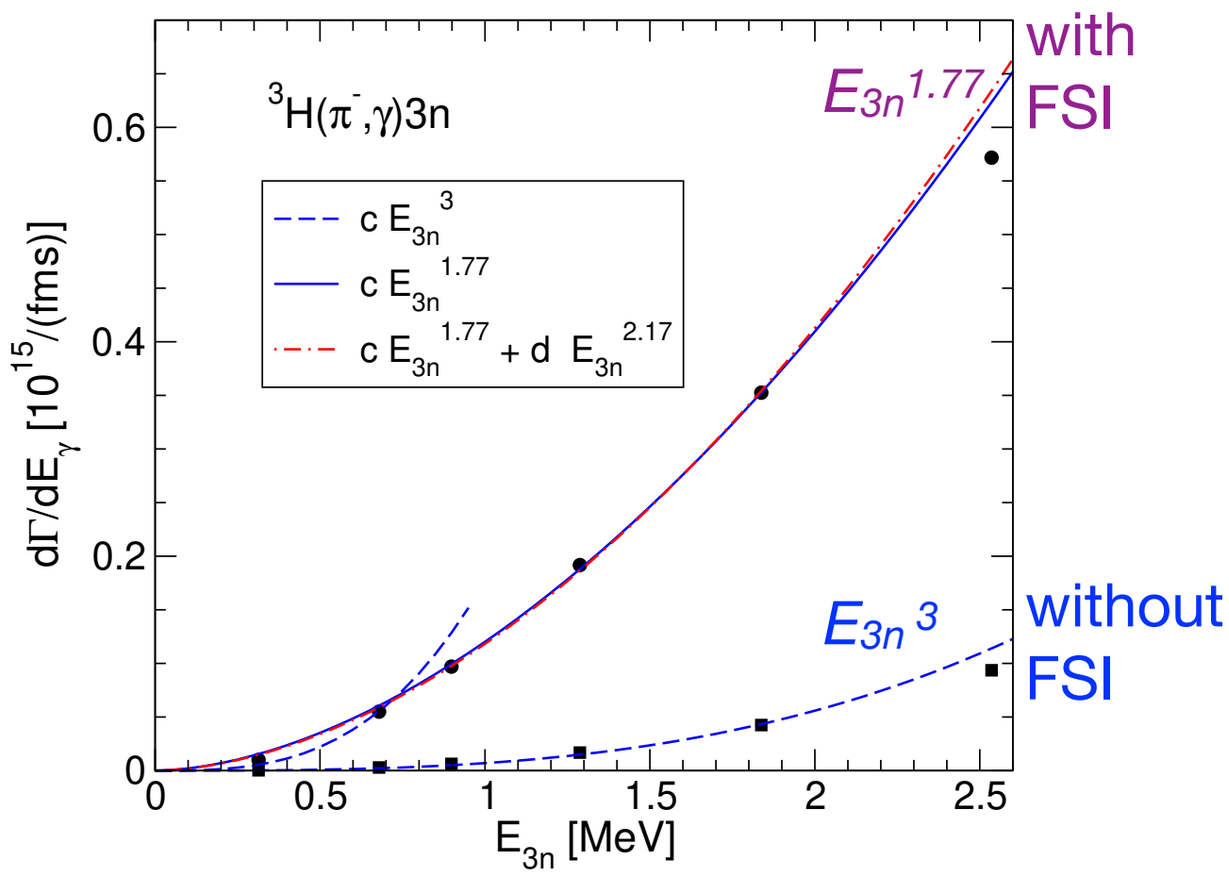
Hammer & Son arXiv:2103.12610

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

creates 3 neutrons with invariant mass $3\,m_n + E$ with $E \ll m_\pi^2/2M_n$



$$\frac{d\sigma}{dE_{3n}} \sim (E_{3n})^{1.77272}$$



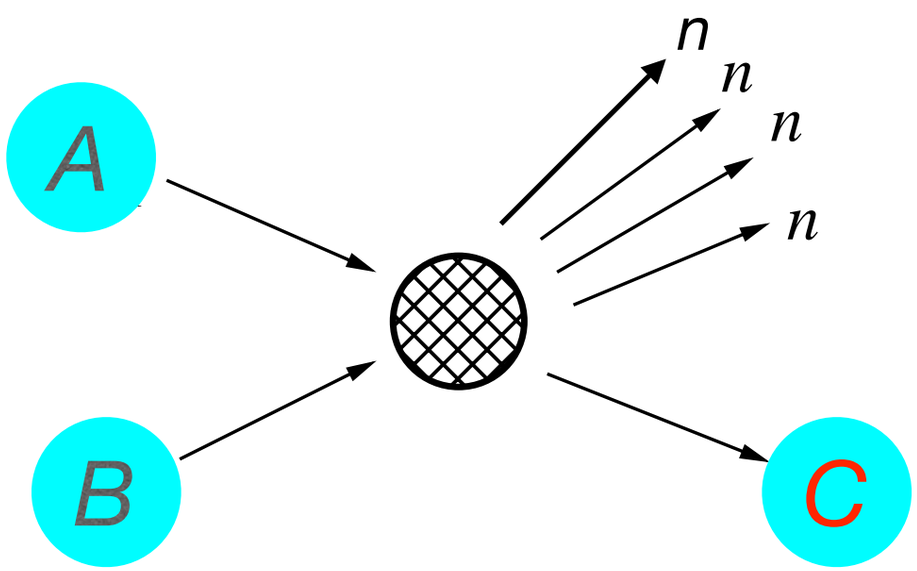
Signature for 3-neutron unparticle: power-law behavior with exponent 1.77272 (naive exponent is 3.0)

"UnNuclear Physics"

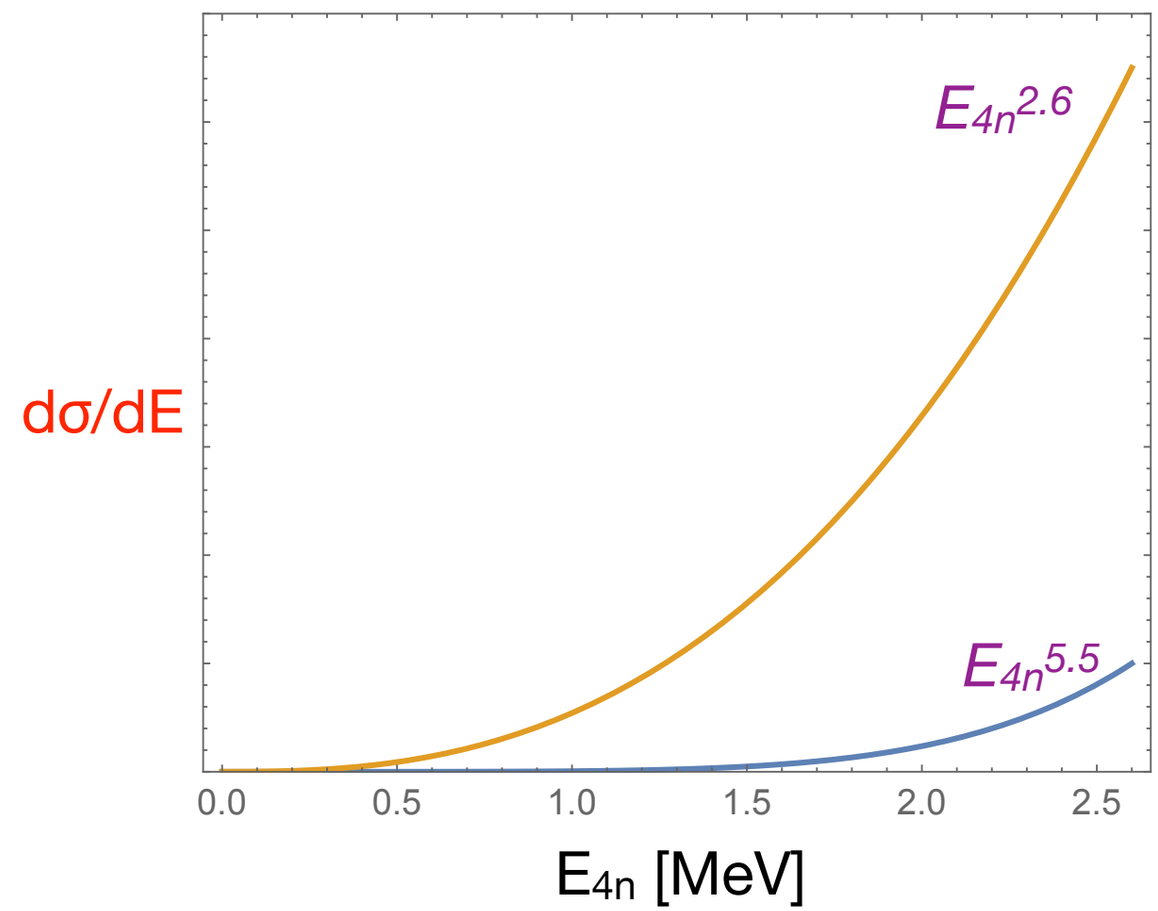
Nuclear reaction $A\ B \rightarrow C + (4\ n)$

creates *4* neutrons with small invariant mass $4\ m_n + E$ with $E \ll m_\pi^2/2M_n$

and large recoil momentum



$$\frac{d\sigma}{dE_{4n}} \sim (E_{4n})^{2.6}$$



Signature for 4-neutron unparticle: power-law behavior

with exponent 2.6

(naive exponent is 5.5)

Nonrelativistic Unparticles

Nonrelativistic particles with

- reactions that conserve kinetic mass
- bound state very close to threshold
- scale invariance in limit as binding energy goes to 0
  (not discrete scale invariance, which gives Efimov effect)

low-energy behavior: Unparticles!

- reaction rates with power-law dependence on energy
- exponents determined by conformal symmetry

Low-energy neutral charm mesons are Unparticles !

arXiv:2107.03821
with H.-W. Hammer

Neutral charm mesons

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

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

$X(3872)$ resonance in $D^{*0}\bar{D}^0 + \bar{D}^0 D^{*0}$ $J^{PC} = 1^{++}$ channel

$\Longrightarrow$ S-wave bound state very close to threshold: $|E_X| < 0.22$ MeV

$\Longrightarrow$ scale invariance in limit $|E_X| \to 0$

(because resonant channel is superposition)

reaction rates with power-law behavior

exponents determined by conformal symmetry !!

- for multiple charm mesons (different scaling dimensions for bosons)
- for $X(3872)$ + charm mesons (new reactions involving bound state)

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

discovered at e^+e^- collider Belle 2003

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

- <u>quantum numbers</u> $J^{PC} = 1^{++}$ LHCb 2013

- <u>mass</u> is 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 LHCb 2020

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

- <u>width</u> is extremely narrow

  $\Gamma_X = (0.22 \pm 0.14)$ MeV LHCb 2020

- 7 observed decay modes

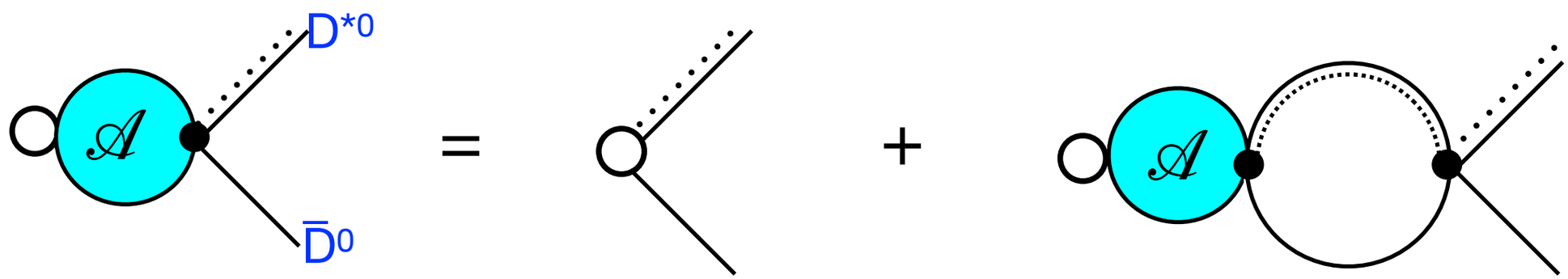
  $J/\psi\, \pi^+\pi^-$, $J/\psi\, \pi^+\pi^-\pi^0$, $J/\psi\, \gamma$, $\psi(2S)\, \gamma$, $\chi_{c1}\, \pi^0$, $D^0\bar{D}^0\gamma$, $D^0\bar{D}^0\pi^0$

first of dozens of exotic heavy hadrons

that have been discovered since 2003 !

Point Production of $D^{*0}\bar{D}^0$

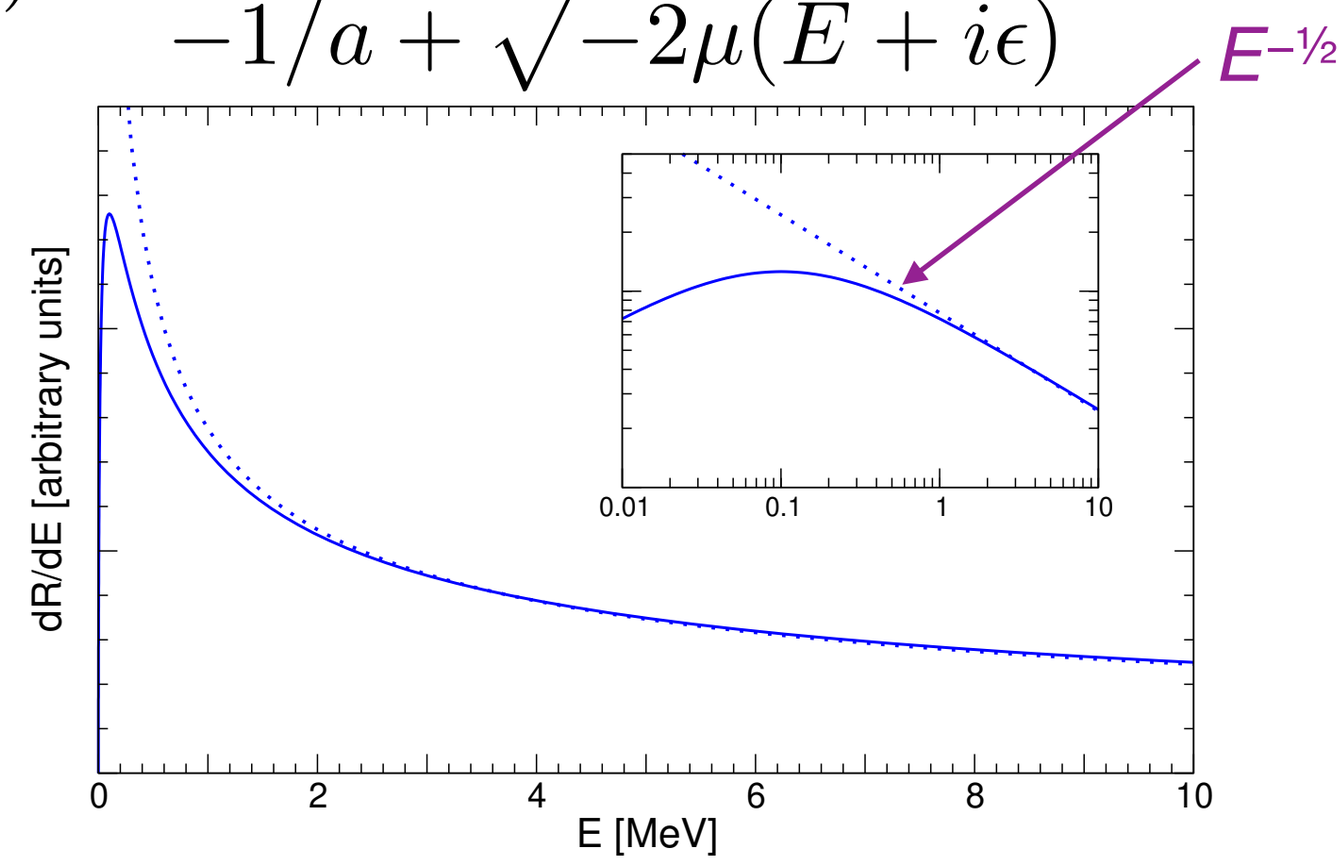
integral equation for production amplitude for $D^{*0}D^0$
from creation of charm mesons at a point



solve algebraically:

$$\mathcal{A}(E) = \frac{1}{-1/a + \sqrt{-2\mu(E + i\epsilon)}}$$

Production rate
as function of the energy E:
$dR/dE \sim |\mathscr{A}(E)|^2 \sqrt{E}$

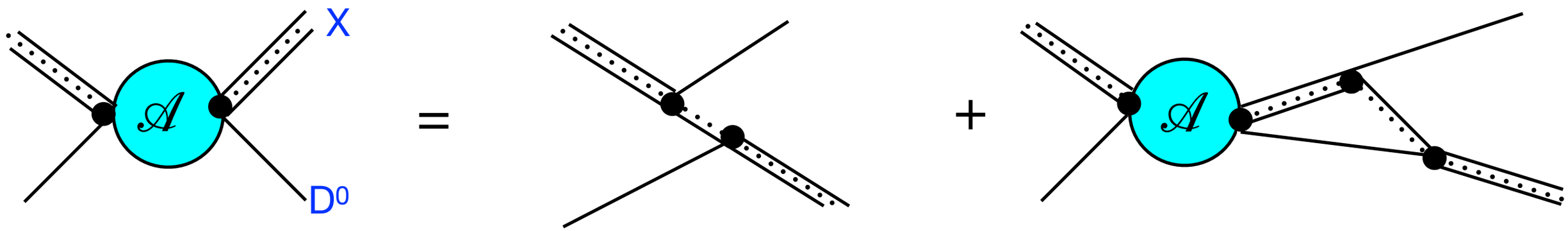


high energy scaling behavior: $dR/dE \sim E^{-1/2}$

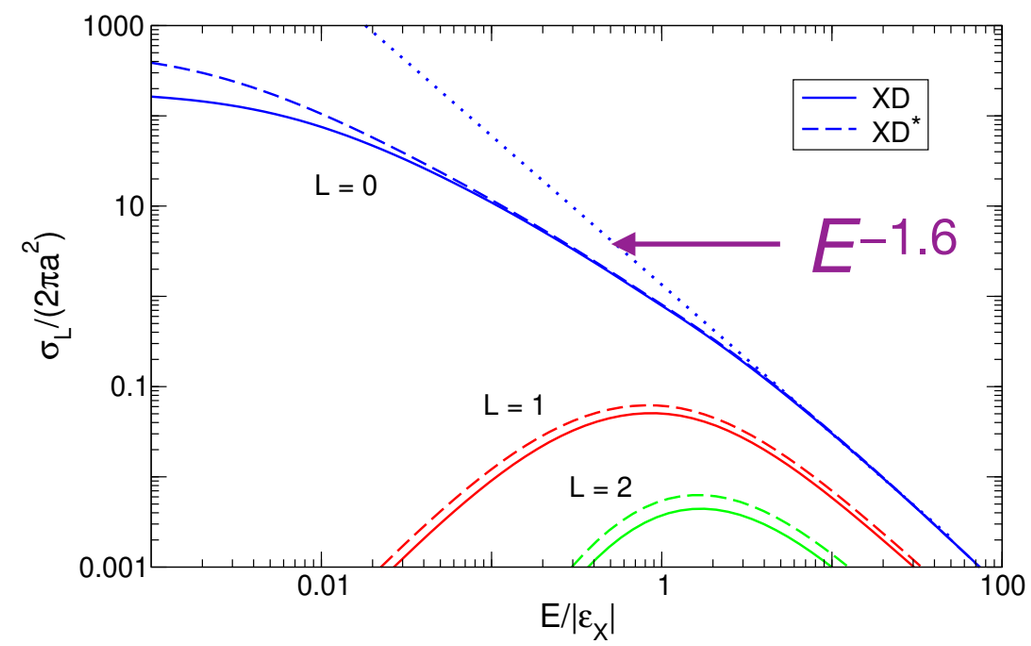
Scattering of *X(3872)* and Charm Meson

Canham, Hammer & Springer arXiv:0906.1263

numerical solution of STM integral equation for $X\,D \to X\,D$ ($D = D^0$ or D^{*0})



cross sections
as functions of energy E

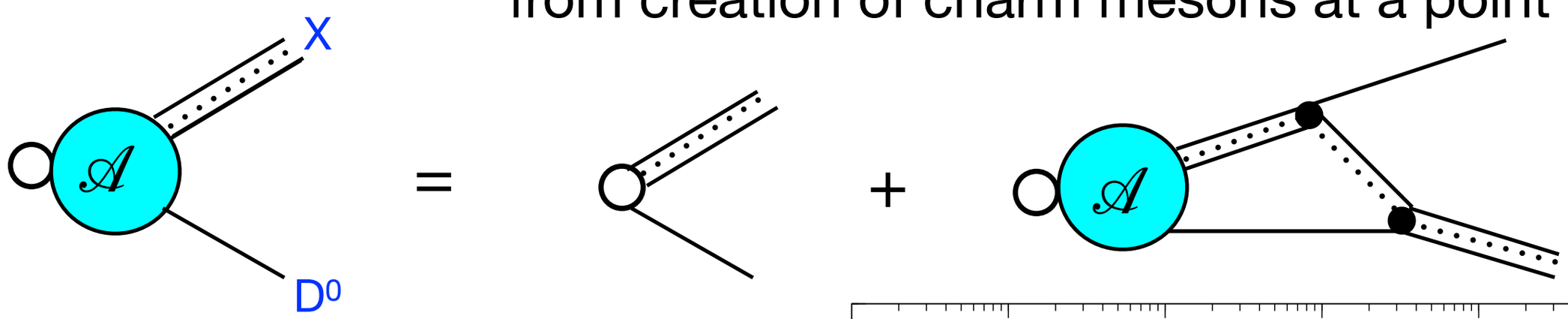


<u>high energy scaling behavior</u>: $\sigma(E) \sim E^{-1.6}$

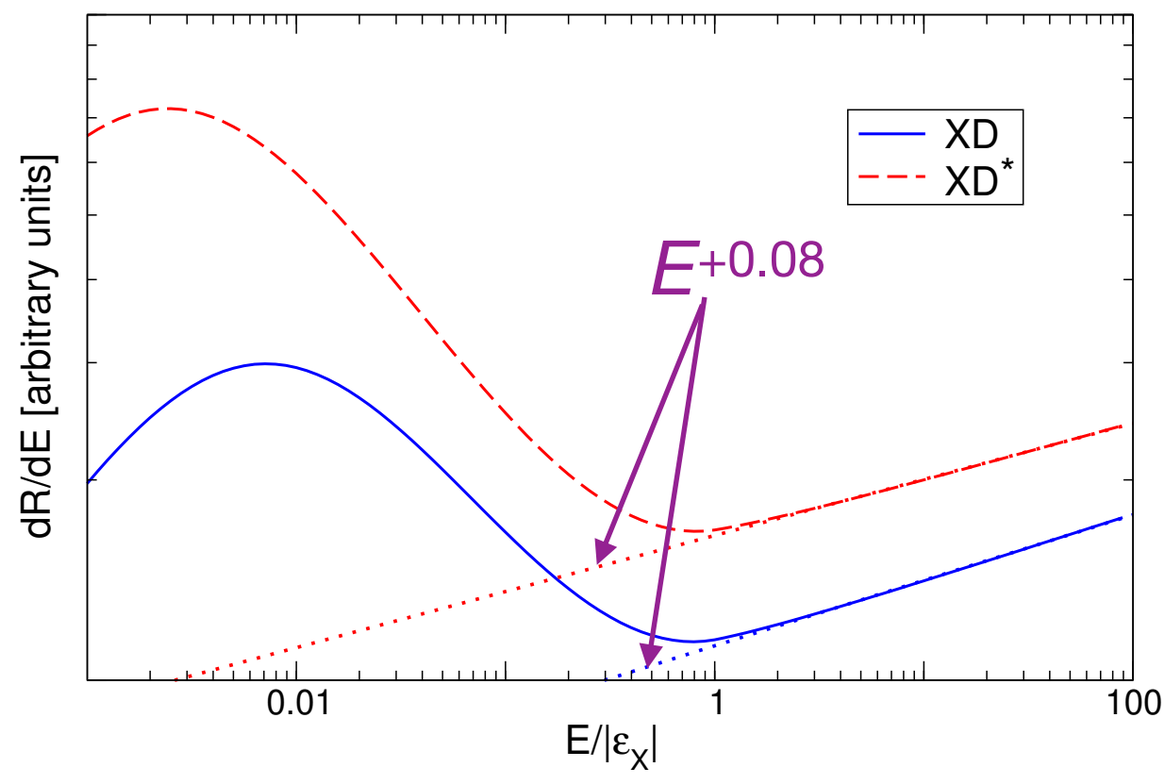
power-law with approximately same exponent for $X\,D^0$, $X\,D^{*0}$

Point Production of *X(3872)* + Charm Meson

STM integral equation for production of *X D* (*D* = D^0 *or* D^{*0})
from creation of charm mesons at a point



production rates *dR/dE*
as function of energy *E*



<u>high energy scaling behavior</u>: $dR/dE \sim E^{+0.08}$
power-law with approximately same exponent for XD^0, XD^{*0}

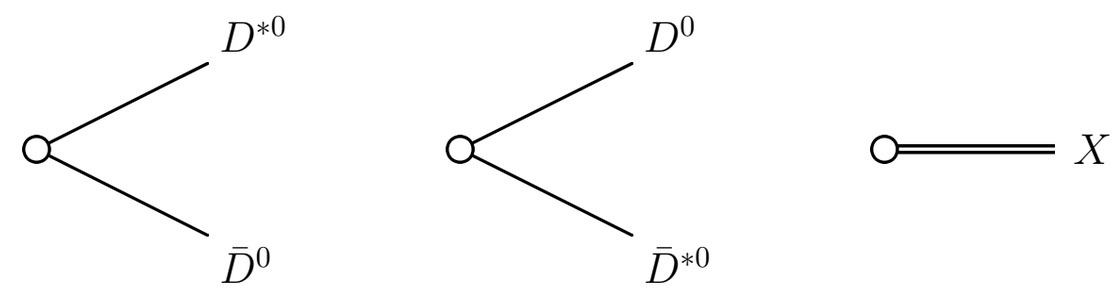
Low-energy neutral charm mesons are Unparticles !

arXiv:2107.03821
with H.-W. Hammer

in the limit $\varepsilon_X \to 0$
Effective Field Theory for neutral charm mesons is scale invariant
$\Rightarrow$ Nonrelativistic Conformal Field Theory !

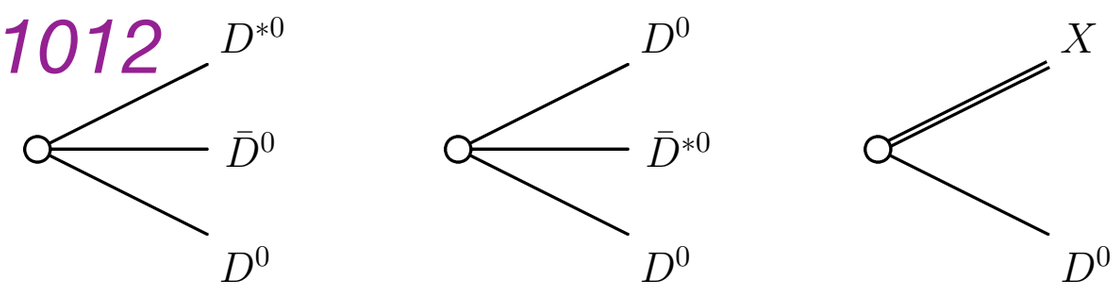
X unparticle

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 $X(3872)+D^0$

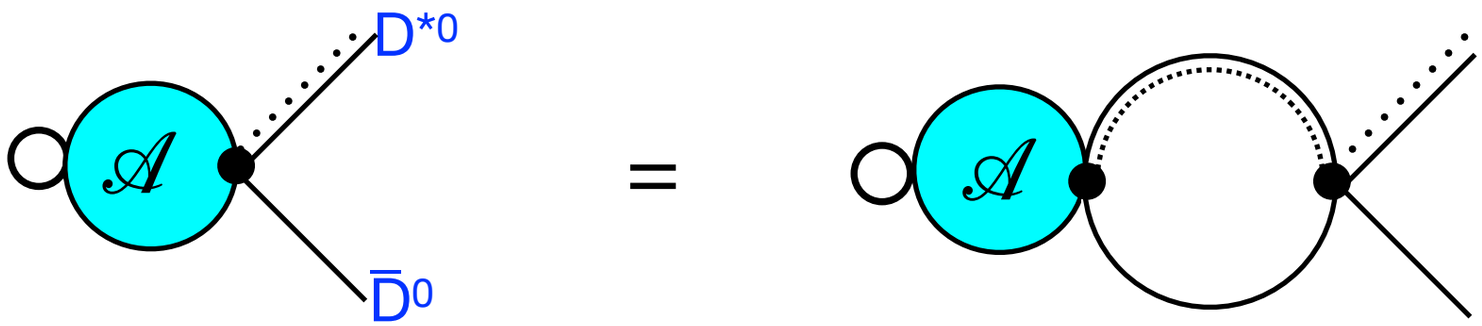


*XD** unparticle

operator with scaling dimension $\Delta_{3*} = 3.0870$
creates $D^{*0}+\bar{D}^0+D^{*0}$, $D^0+\bar{D}^{*0}+D^{*0}$, *and* $X(3872)+D^{*0}$

Scaling Dimension: *X* Unparticle

homogeneous integral equation for production of $D^{*0}\bar{D}^0$
from creation of charm mesons at a point



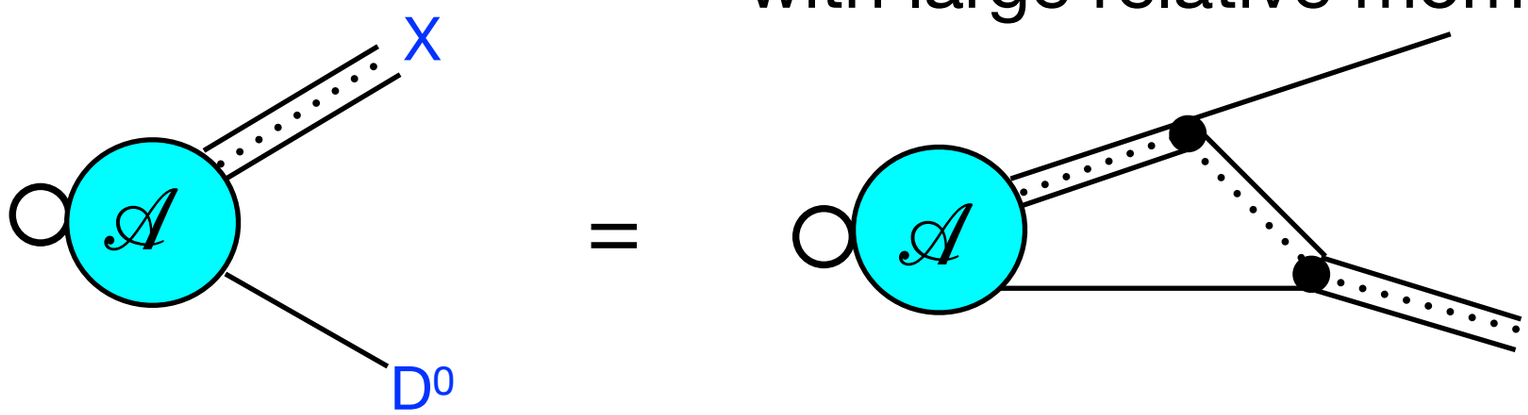
solve algebraically for large *E*: $\mathcal{A}(E) = E^{-1/2}$

$\mathscr{A}(E) \sim |E|^{\Delta - 5/2} \quad \Rightarrow \quad \Delta = 2$

X Unparticle has scaling dimension $\Delta_2 = 2$

Scaling Dimensions: *XD, XD** Unparticles

homogeneous STM integral equation for production of *XD* (*D* = D^0 or D^{*0})
with large relative momentum $p \gg \sqrt{2\mu E}$



$$\mathcal{A}(p) = \frac{1}{4\pi r\sqrt{1-r^2}\,p}\int_0^\infty dq\mathcal{A}(q)\log\frac{p^2+q^2+2rpq}{p^2+q^2-2rpq} \qquad r = M_D/M_X$$

look for power-law solution: $\mathscr{A}(p) = p^{s-1}$

$$1 = \frac{\sin\left(s\arcsin(r)\right)}{2r\sqrt{1-r^2}\,s\cos(s\pi/2)}$$

smallest positive solution: $s = 0.60119$ if $D = D^0$
$s = 0.51834$ if $D = D^{*0}$

operator dimension: $\Delta = 5/2+s$

XD Unparticle has scaling dimension $\Delta_3 = 3.10119$
*XD** Unparticle has scaling dimension $\Delta_{3*} = 3.08697$

Propagators for Unparticles

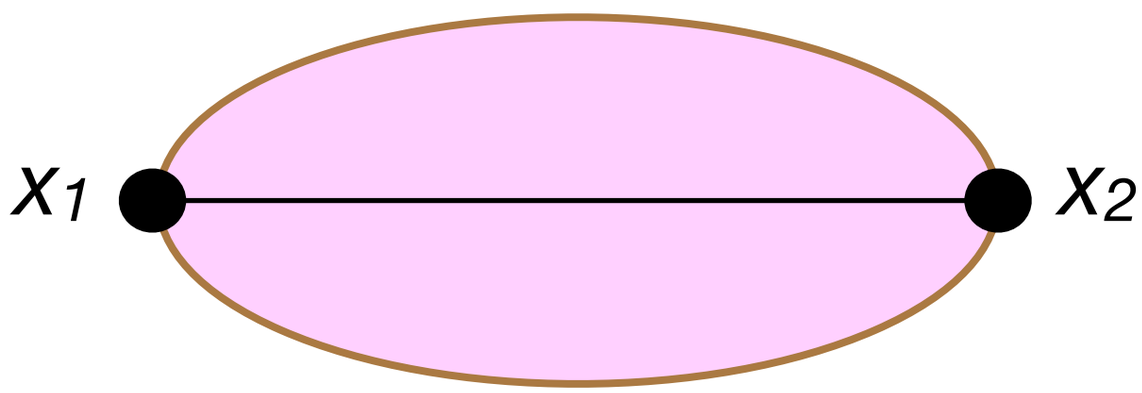
primary operator $\phi_n(x)$: scaling dimension Δ_n, mass M_n

propagator is determined by conformal symmetry

spacetime propagator: $\langle \phi_n(x_1)\phi_n^\dagger(x_2)\rangle = C_n\,\theta(t_{12})\,(t_{12})^{-\Delta_n}\,\exp(iM_n r_{12}^2/2t_{12})$

Fourier transform has branch cut: $D_n(E,p) = C_n'\left(\frac{p^2}{2M_n} - E - i\epsilon\right)^{\Delta_n - 5/2}$

AdS/CFT correspondence: spacetime is boundary of anti-deSitter space



Unparticle propagator: free-field propagator in AdS space

Correlator for Three Operators

primary operators $\phi_1(x)$, $\phi_2(x)$, $\phi_3(x)$: scaling dimensions Δ_1, Δ_2, Δ_3
masses M_1, M_2, $M_3 = M_1+M_2$

3-point function is determined by conformal symmetry!

Henkel and Unterberger 1993
Fuertes and Morozov 2009
Volovich and Wen 2009

$$\langle \phi_1(x_1)\phi_2(x_2)\phi_3^\dagger(x_3)\rangle = C_{12,3}\,\theta(t_{13})\,(t_{13})^{-\Delta_{13,2}/2}\,\exp(iM_n r_{13}^2/2t_{13})$$
$$\times\,\theta(t_{23})\,(t_{23})^{-\Delta_{23,1}/2}\,\exp(iM_n r_{23}^2/2t_{23})$$
$$\times\,(t_{12})^{-\Delta_{13,2}/2}\,\Phi(w)$$

$$\Delta_{ij,k} = \Delta_i + \Delta_j - \Delta_k$$

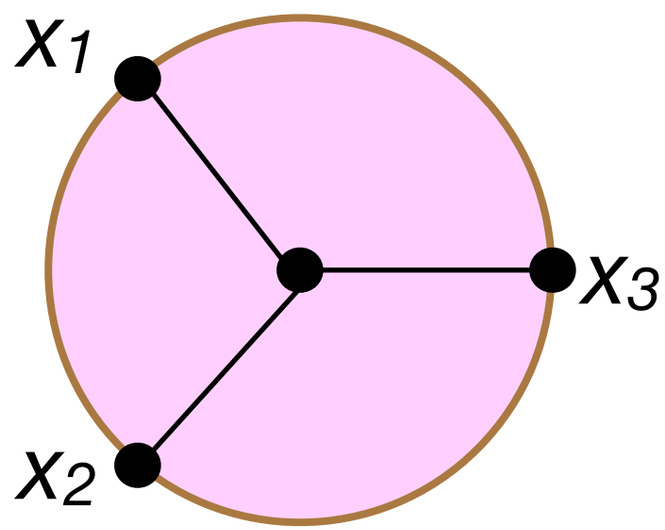
$\Phi(\omega)$ is function of single scaling variable $w = \dfrac{r_{12}^2}{2t_{12}} - \dfrac{r_{13}^2}{2t_{13}} + \dfrac{r_{23}^2}{2t_{23}}$
2-dimensional integral representation

$$\Phi(w) = \int_{-\infty}^{+\infty} du(u+i\epsilon)^{-\Delta_{13,2}/2} e^{-iM_1 u}$$
$$\times \int_{-\infty}^{+\infty} dv(v+i\epsilon)^{-\Delta_{23,1}/2} e^{-iM_2 v}\left[u - v + (1+i\epsilon)w\right]^{-\Delta_{12,3}/2}$$

Correlator for Three Operators

$\left\langle \phi_1(x_1)\phi_2(x_2)\phi_3^\dagger(x_3)\right\rangle$ is determined by conformal symmetry!

Henkel and Unterberger 1993
Fuertes and Morozov 2009
Volovich and Wen 2009



- Fourier transform in time
- Fourier transform in space
- isolate pole from particle propagator $D_1(E_1,p_1) = i/(E_1 - p_1^2/2M_1)$
- isolate branch cut from 2-Unparticle propagator

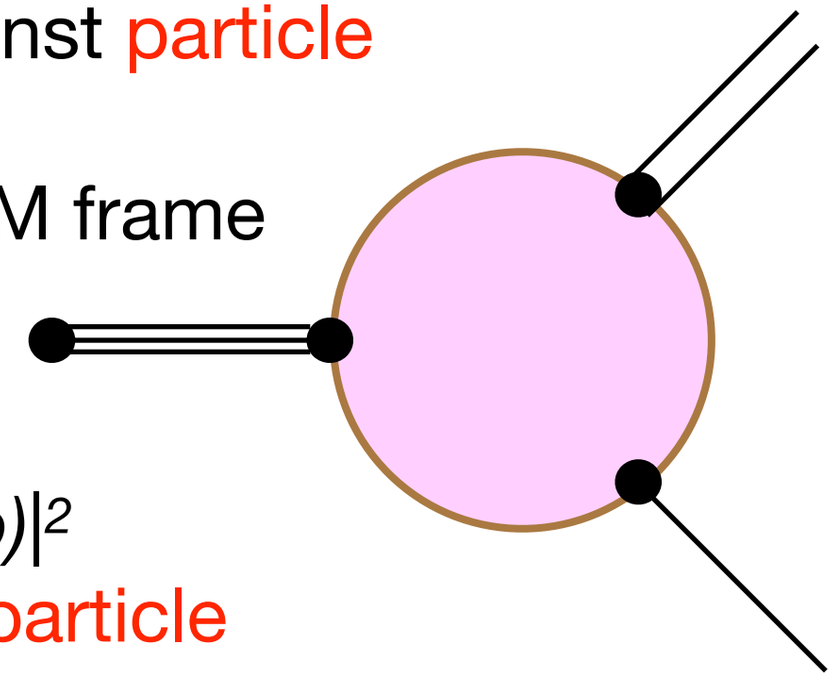
$$D_2(E_2,p_2) = C_2\left(\frac{p_2^2}{2M_2} - E_2 - i\epsilon\right)^{\Delta_2 - 5/2}$$

amputated 3-point function with particle on shell: $E_1 = p_1^2/2M_1$

$$G(E_1,p_1;E_2,p_2) = D_1(E_1,p_1)\,D_2(E_2,p_2)\,G_{\rm amp}(p_1;E_2,p_2)$$

Point Production of Unparticle

production rate of 2-Unparticle recoiling against particle
from the creation of a 3-Unparticle at a point
with energy E_3 in its CM frame



amputated 3-point function $G_{amp}(E_2,p)$

- multiply by complex conjugate: $|G_{amp}(E_2,p)|^2$
- multiply by discontinuity in propagator of particle

$$D_1(E_1+i\epsilon,p)-D_1(E_1-i\epsilon,p)=2\pi\delta\left(E_2-p^2/2M_2\right)$$

- multiply by discontinuity in propagator of 2-Unparticle

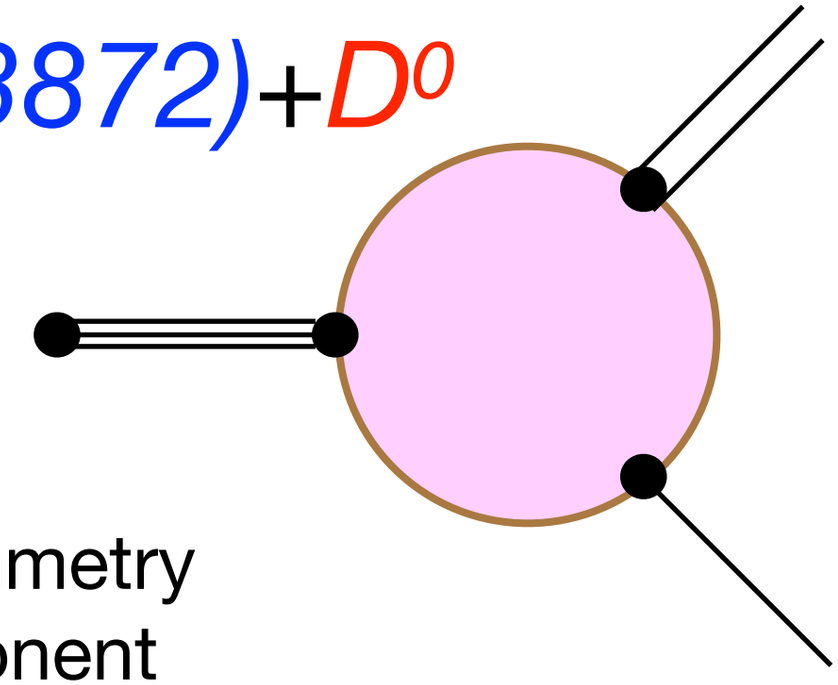
$$D_2(E_2+i\epsilon,p)-D_2(E_2-i\epsilon,p)=\frac{1}{\sqrt{E_2-p^2/2M_2}}\theta\left(E_2-\frac{p^2}{2M_2}\right)$$

- integrate over phase space: $\int dE_1 d^3p/(2\pi)^4$

behavior near the threshold $E_3 > p^2/2M_{12}$

$$dR \longrightarrow C\left(E_3-\frac{p^2}{2M_{12}}\right)^{\Delta_2-5/2}\left(\frac{p^2}{2M_{12}}\right)^{\Delta_3-\Delta_1-\Delta_2}\frac{d^3p}{(2\pi)^3}$$

Point Production of *X(3872)*+*D⁰*



finite binding energy ε_X breaks conformal symmetry

- 2-Unparticle develops bound state component
- 3-Unparticle develops bound state + particle component

discontinuity in 2-Unparticle propagator

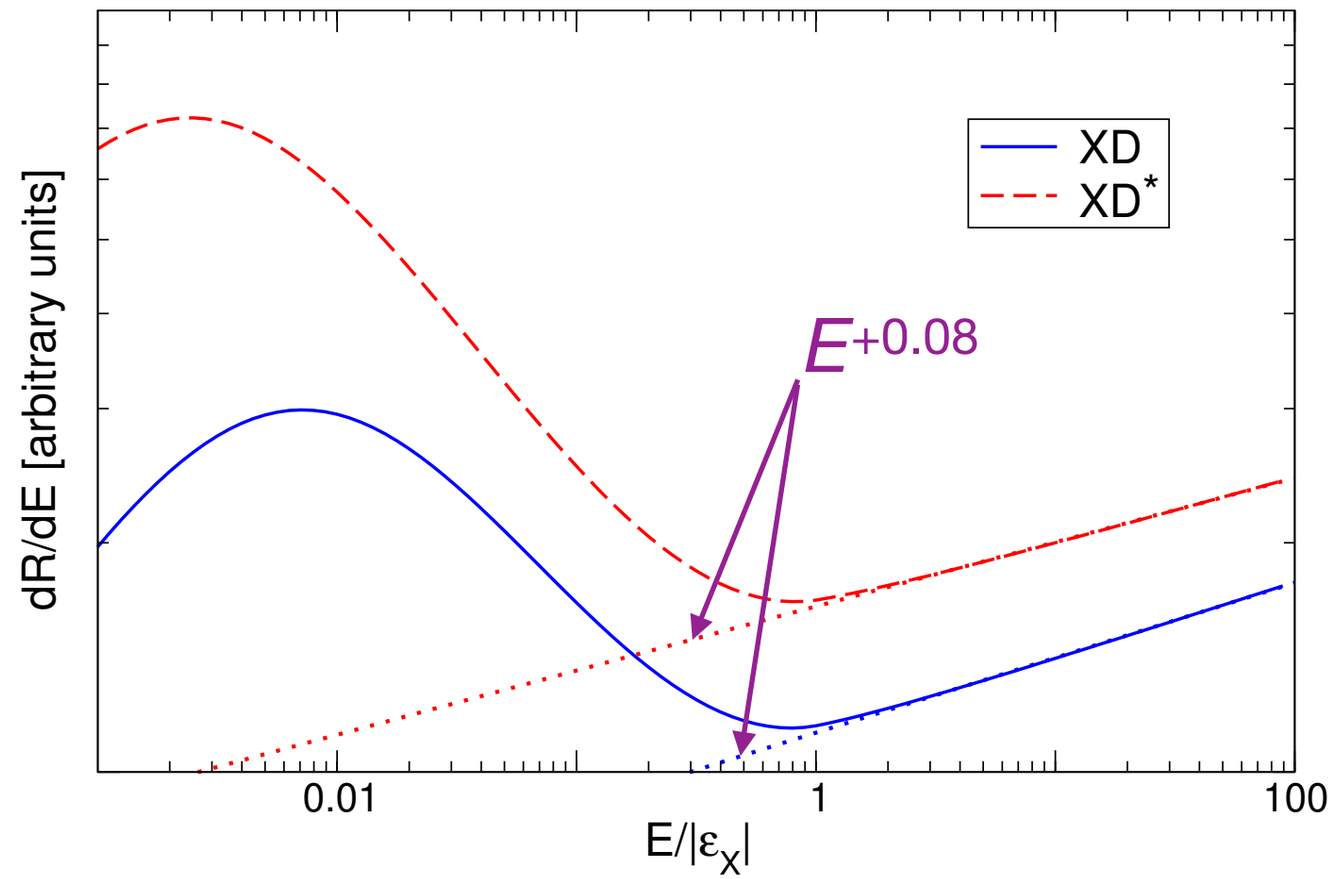
$$D_2(E_2+i\epsilon,p)-D_2(E_2-i\epsilon,p)=\frac{\sqrt{E_2-p^2/2M_2}}{E_2-p^2/2M_2+|\varepsilon_X|}\theta\left(E_2-\frac{p^2}{2M_2}\right)$$
$$+2\pi\sqrt{|\varepsilon_X|}\delta\left(E_2-\frac{p^2}{2M_2}+|\varepsilon_X|\right)$$

rate for producing bound state + particle: keep δ-function term

$$dR\longrightarrow(\text{constant})\sqrt{|\varepsilon_X|}\,E_3^{\Delta_3-\Delta_2-\Delta_1+1/2}dE_3$$

Point Production of Bound State + Particle

production rate *dR/dE*
as function of energy *E*



dR/dE has power-law behavior at high energy

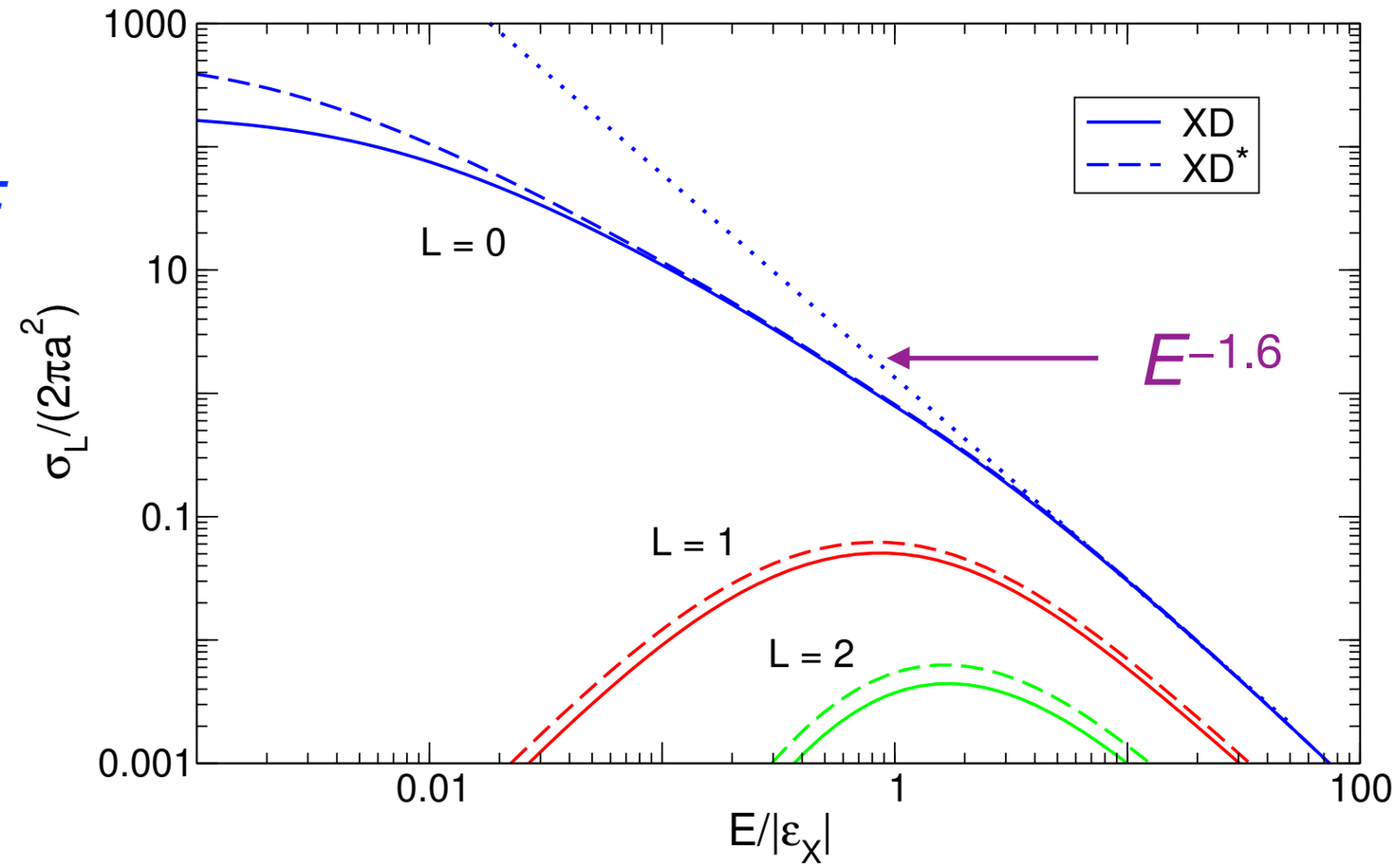
exponent is determined by conformal symmetry !!

$\Delta_3 - \Delta_2 - \Delta_1 + ½ = +0.1012$ for XD^0

$\Delta_{3*} - \Delta_2 - \Delta_1 + ½ = +0.0870$ for XD^{*0}

Scattering of *X(3872)* and Charm Meson

cross sections
as functions of energy *E*



σ(E) has power-law behavior at high energy

challenge: postdict the exponent

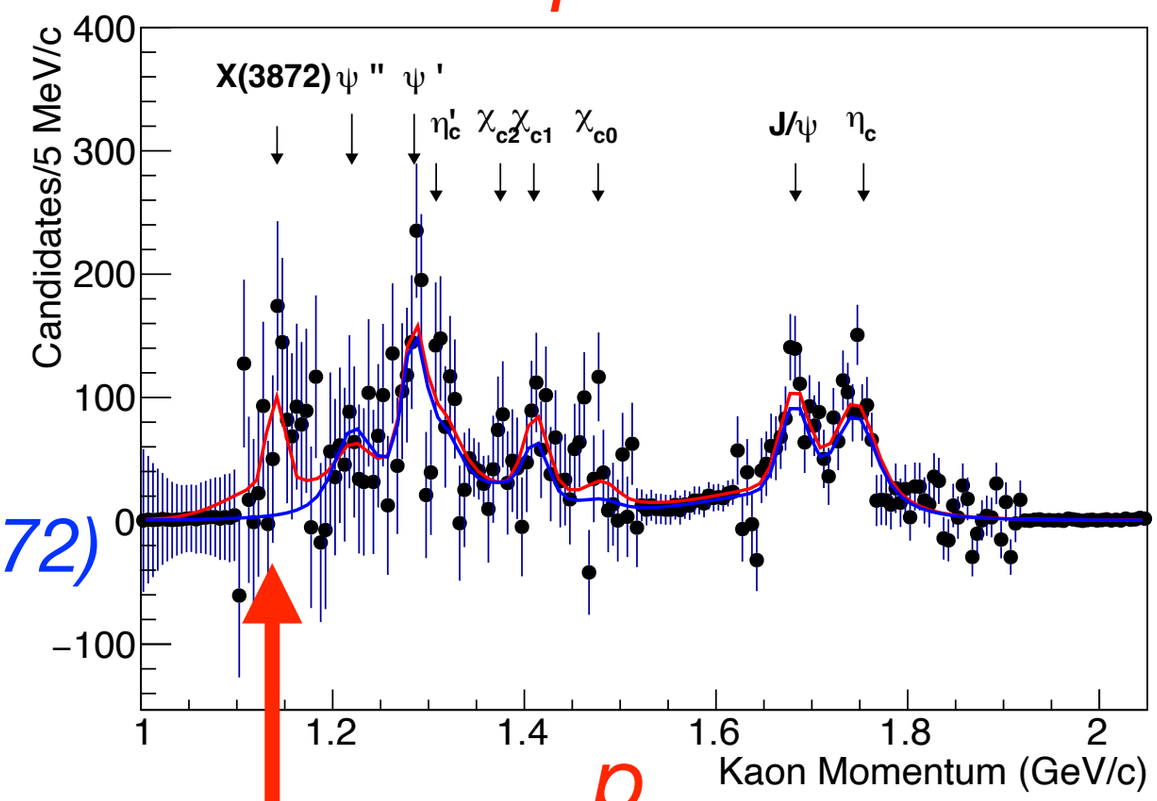
is exponent determined by conformal symmetry?

X Unparticle

Babar collaboration arXiv:1911.11740

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

measure distribution of K recoil momentum p



p

transition $B^{\pm} \rightarrow K^{\pm}$

creates X unparticle

produces $D^{*0}+D^{0}$, $D^{0}+D^{*0}$, *and* $X(3872)$

peak from $X(3872)$

above p_{max} = 1141 MeV

peak from $D^{*0}+D^{0}$, $D^{0}+D^{*0}$ below p_{max} = 1141 MeV

power-law behavior determined by $\Delta_2 = 2$ $d\Gamma/dp \sim (p_{\max} - p)^{-1/2}$

can it be resolved by Belle II collaboration ?

will collect larger data set by factor of 40

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 $X(3872) \to J/\psi\, \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$ to provide trigger

XD unparticle

observe through $X(3872)+D^0$ component with decay $D^0 \to K^-\pi^+$
production rate with energy dependence $E^{+0.1012}$

can it be observed by LHCb collaboration ?

Summary

Nonrelativistic Unparticle

excitation created by an operator with definite scaling dimension
in a Nonrelativistic Conformal Field Theory
can explain power-law dependence of reaction rates
with exponents determined by conformal symmetry

Low-energy neutrons are Unparticles !

because dineutron is almost bound Hammer & Son arXiv:2103.06290

Low-energy neutral charm mesons are Unparticles !

because of *X(3872)* resonance Braaten & Hammer arXiv:2107.03821