## Hadron Spectroscopy

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To get ground state energies of states in BCD, we calculate a correlation tunction C: (n = (0/6: (n) 6; (0/0) = (0: (n) 6; (d)) with by and bis operators that act on quark tields, producing a state at time to and annihilating it at a later time t.

Inserting a complete point of states, we get city SKA, WIN (MI) of Ein, with a real exponential since we are in Euclidean time. For it this is positive definite and converge more topically tran above

At large Earlidean times or this goes to (1/(1+0) = Ze For. This we can get an effective mass by taking amost = log ( C(1)).

A typical plot of such a quartity look like this. Early on we see that farmer The function has to settle into the ground) state. Then, we have a splateaul a region

ct convergence which we take to be the desired value.

For some calculations, we see that the signal-to-noise ratio plummets atter a certain time has passed. This is a manifestation of the sign problem. The time at which your signal vanisher depends on the calculation, and in principle it may happen before your correlator has had time to converge, rendering the calculation uspless. This is why people want to have control over the sign problem.

tor excited and unstable states this method is not going to make it easy to extract ENTO.

One nether people have come up with for accessing excited states is called the variational method. I won't get into much detail about this, but I just want	
to show that there is in principle a better method for getting excited state energies.	
16 Hall Well O IN DIRECTLE of Selling Walled	
In this method, we take (1/4) to be an element of some motile of correlation	
tunctions (19) defined by a basis of operators \$1.	
Then me solve a generalized eigenvalue problem cont = x (1) (1) (1) it can be shown that	\ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \
the eigenvalues are related to the state energles in the limit that the two to be gradually et	1, + 6(6411)
This contines a method the getting the energy spectra of states in QQ, some groups have sent	
reversed this in order to measure the quark mass by measuring a set of quantities for a variety of choices of quark masses and seeing which issults have the boot agreement with	and an anti-money depth anniverse respect for an investment of the COLD STATE
experiment, the results of these simulations desperally than that the physical quark masses do ind	
have the best connection to experiment.	
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	AND CONTRACTOR CONTRAC
Hadron Strusture: Deep Inclustic scattering of some of Educ	
My = 7 \( \text{Cb(2" \( \text{X}(\text{X}) \( \text{Lb} \) \( \text{Lagrange} \) \( \te	In Sid + sliv gil
MIT	

## An Unexpected Break from YPT

point replaced with a new behavior.

One interesting result come from calculations of the pion mass dependence of the nucleon. In Chiral penturbation theory the 2-flavor Lagrangian is given by (with mumama) 2=N(x-m)N+ gymyN(z+st)N+vnTr(z+st)+", for z=eitern This form is constrained by chiral symmetry and how it is broken by the condensals. An expansion in the given fields gives &+&+ 2 - 72. From the last term, we get a constant term which does not affect physics and a quadratic term in The given by - 20 mg The This looks like a mass term for the film - {miti with min = to ma = time The nucleon mass to order my can be obtained from the other two terms to get MN=M-tan my + B(M); the remaining pieces coming from loops Lattice BCD calculations have been done for many values of Mu 1.2 W= 800 Wer + WA the firm mass above the physical [GeV] ... 1.6 point, and they all have been found 10 to match strikingly well to a linear 0,5 4.0 1.0 tit of MN=80 MN+MA. 15/ 15 M At first plance this seems incompatible with chiral perturbation theory, but we must recall that the XPT is an expansion about MIND. It is known to be valid for Ma ranging from a to the physical value, but it is not known any further. There results would indicate that XPT breaks down just begood the physical

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	gad galaxie politik i silikis vidik oʻzmonoti oʻda e tiringa iza aasaan mada dinitik aala amayo ga qoʻr a ci
Note that this new behavior is above the threshold of XPT but below that	
of perturbative Q(D. This is also inaccessible to experiment he my is lixed in nate	
This means that this feature of QO is currently Only accessible to lattice with	
and acting else, illustrating that lattice &co is not only a too that can replie	I - E
experiments but also people new insight into nonperturbative theories.	tandaria menerala men
The model with the beautiful was the world to the sail with	and a make filled an og a fill solvhorga Eth Etha (1955) vil Zivid od und vinney europrovo gjern þeigið gendegarða græ
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	Experience of the Contract of
	ette funktion ( men vitaren til se skatan i 2000 frå til station vita de de derbekende mennen grenne grant (2000 til 2000
	Budger eller som er

## Lüscher's Formula in QM

	One aspect of latticizing a theory that harn't really been touched on a whole let
	is the effects of putting the theory in a finite box of length L.
THE STATE STATE OF THE STATE OF	Use periodic bundary conditions so that all quantities follow A(x) = A(x+xt).
	For low energy processes (infrared), this can be more important than the lattice spacing
	- In momentum space, the finite box size has the effect of discretizing the momentum so that
TTTN PARAN SETTEMBLE IN MELLING SETTEMBLE PARAMETER (FILM PARAMETER AND CONTROL CONTROL CONTROL CONTROL CONTROL	p= 2th for some integer vector is
Provide distribution of the first of the state of the sta	
	Let's consider QM scattering in such a box to illustrate
	Scattering off of a central potential is phrased around
	having an incoming plane wown piking hitting a central limited
	range spherically symmetric potential and eminating specieally outward to infinity.
nontrologica estado altrologica estado e	Outside the range of the potential, the wavefunction is tree again, and the wavefunction is known to behave like 4.(1)=11 = 1 (corsejulus) + sinson (kr)) for s-wave scattering.
	Is known to behave like 4. (1) = N = N (cor & ) (les) + 5 in So no (kg)) tot 5 - wave scattering.
999 (1998 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1995 - 1	where So is the s-wave phase shift determined by the form of the potential.
BBB 000 TBB 400 TBB 40	
	In a finite volume with periodic boundary conditions, this doesn't
	work so well. One way to imagine this box is to think of
and the second s	it as infinite space but with an infinite good of scattering
	potentials (hall of mirrors). There is no notion of taking the dans wave to asymptotically for
	away from the center, since you will always be within a certain distance from the potential.
n til men sette til skall til till men sesset til skall skall til skall	
TT TOWNS AND STORM TO THE STORM OF THE STORM	Lischer devised a way of solving for this wavefunction, arraning that the potential
ZONOSIMO COLUMBRIO POR PORTE ACOSTO CON A MESA O ASSESSA MESA COLUMBRIA NO SEGUIDA DE PRESENTA D	terminator before hitting the box. It this is the case, then there is a spherical
	shall where the particle is tree, as in here the wavefunction is that News johns with the particle is tree, as in here the wavefunction is that News johns with the single particle is tree.
The control of the co	The Mt, E = contex many energy

This solution accounts for the physics of the certial potential, but door not include the extra boundary condition from the box, that P(x) = \(\frac{2}{2}\) = \(\frac{1}{2}\) (0,0) = \(\frac{1}{2}\) (x +x 1). Lingher noted that it sinds to then this partial wavefunction Your has a pale at the origin In other words, we have (2+4) note) = 2 Str). This resembles a Green's function equation (52+12) G(x-17-8(x-y)), the Green's function for the free schriptinger equation is given by G(x)=\frac{1}{2}\frac{2}{12 This Green's function obeys the periodic boundary conditions, but does not know about the contral potential. We also know that a function Yolv satisfying the Schrödinger equally and both boundary conditions must be a unique solution. Thus if we try to motel the rostflights of the poles together, then the solution in terms of the spherical bessel function must by the same as those of the Green's Eunction. Matching the coefficients from sins, and G duss in Mischess friunds to cot soll) = II ( 2 1/2 - 1/2) - 1/4) On the left hand side, we have the continuum chase shift. On the right hand side we have an artifact of the periodic poundary conditions from the box. This fells us that the only allowed energies are the CM momenta that satisfy this equation. Axtracting the spectrum from a lattice simulation and patting it into the RHZ will glave he the LHS - the scattering phase shift.

## Cirkher's formula in QFT.

The abestion remains it we can generalize this to tield theories.
- Liseher showed that you can, up to exponential corrections for large L.

In fact, we can replicate Lascher's formula using a pronless EFT for nacleons  $d = N^t(\partial_e + \frac{d^2}{2n})N - (oN^tN)^t$ .

Fixite Volume: In = 1 2 M (2 1 (12) - 4 M) ( = 4 M ) ( = 4 M ) ( = 4 M ) ( = 4 M )

We can introduce more contact operators such as (2(N'(ō-ō)2N)(N'N) to the Lagrangian. Doing this calculation again with them gives the same result but with (0 > \frac{1}{2}(5, p^2) = \frac{1}{10} \fra

The poles of the scattering amplitude give you bound state energies, which implies that the energy lovels are located at k s.t. The cot SCH = til S((LL)), which is lisseher's formula.

The benefit of seconting this as a field theory is that we can more early incorporate gions into the theory, which will increase the range of its producting power part the pion production threshold.

The finite volume corrections introduced by this will be exponentially sufpressed, justified by the following argument: Pien effects will arise due to a propagator of the form of the effects there is no go term since in our peopletivistic power counting and, so its effects are lower order. The fourier transferm for this interpolation space is emain.

	in Chambard (Colon Consider the American Colon C
If we go back to this picture of the central potential in a !!!	83-818 W W W W W W W W W W W W W W W W W W
box we see that the copies of the potential are separated from	and the difference from the construction of the land of the construction and the construction of the const
the NN system by a length of order t, so the potential is of order Empl.	
	AN BOOKEE TO THE WAS TENED TO SEE THE WAS TO SEE THE WAS THE W
Thus as long as L>> 1 - Lüschers formula can still be used.	
	The control of the co
It has been shown that the perturbative expansion for this EFT converges slowly	
at NNLO for the So channel and door not converge at NNLO in the I, channel which	Polymetrianic transfer and supplementary and provide a transfer and polymetric supplementary consists.
is where the deuteren liver. A lattice calculation wring this method could be performed	
using L'uscher's tormala in the regime where perturbation theory struggles, so long as you	nchall holista fissu dem ham en
comain nourslativistic (polea Mh).	blommhel Olassausaumammenemissen ausemällö miniskan noch villemiskh
In conclusion, we've seen how through the calculation of matrix elements on a lattice	Betättliche Verleiten webstanderererendererering segungs
we can find a wide variety of quantitles in GCD, and even some features of the	indiadalaren arrennen erren erren de den der 1864 erreländische 1868 (1865) (240)
theory that would not otherwise be visible to us. Note that we have restricted currelyes	
to RCD; there are efforts that use the lattice outside of this to calculate wedle	Carrente Tradition for the state of the second
descays of quarks and even probe BSM physics such as SUSY theories.	eneren hangi Olem And Laneren enerek (dala in 1220 dilikoleh (dala in 1220 dilikoleh (dala in 1220 en
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