Strings and QCD

Or the rise, fall, and rebirth of string models of the strong interactions

J. Harvey, 2 May, 2012
Fermilab

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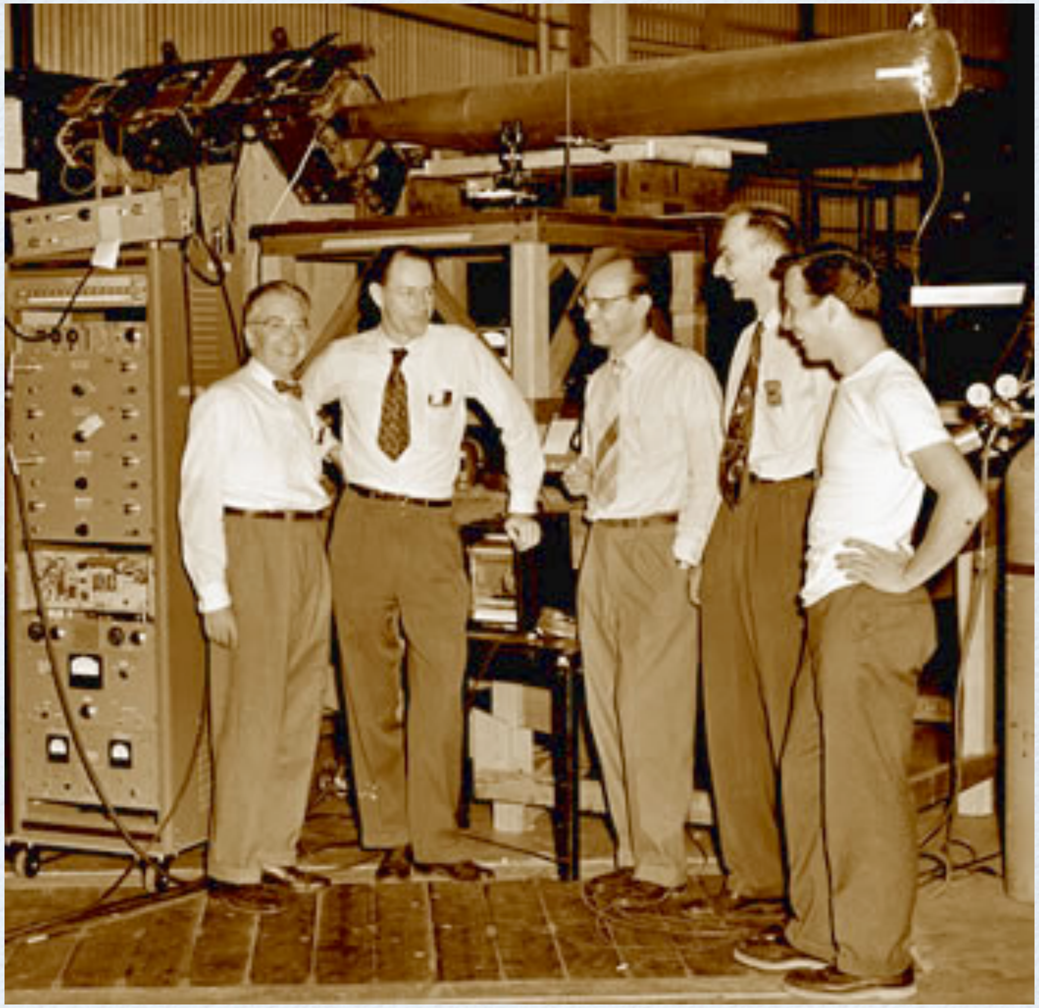

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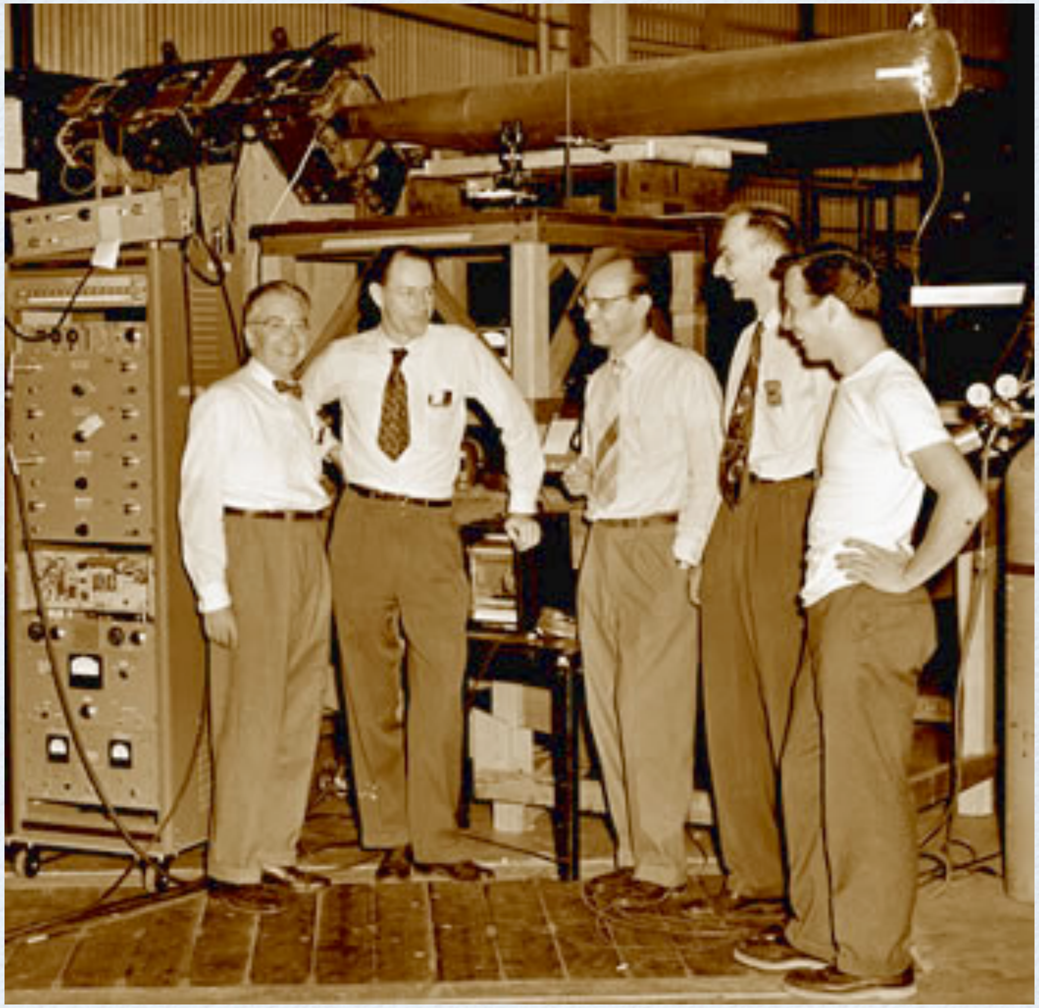

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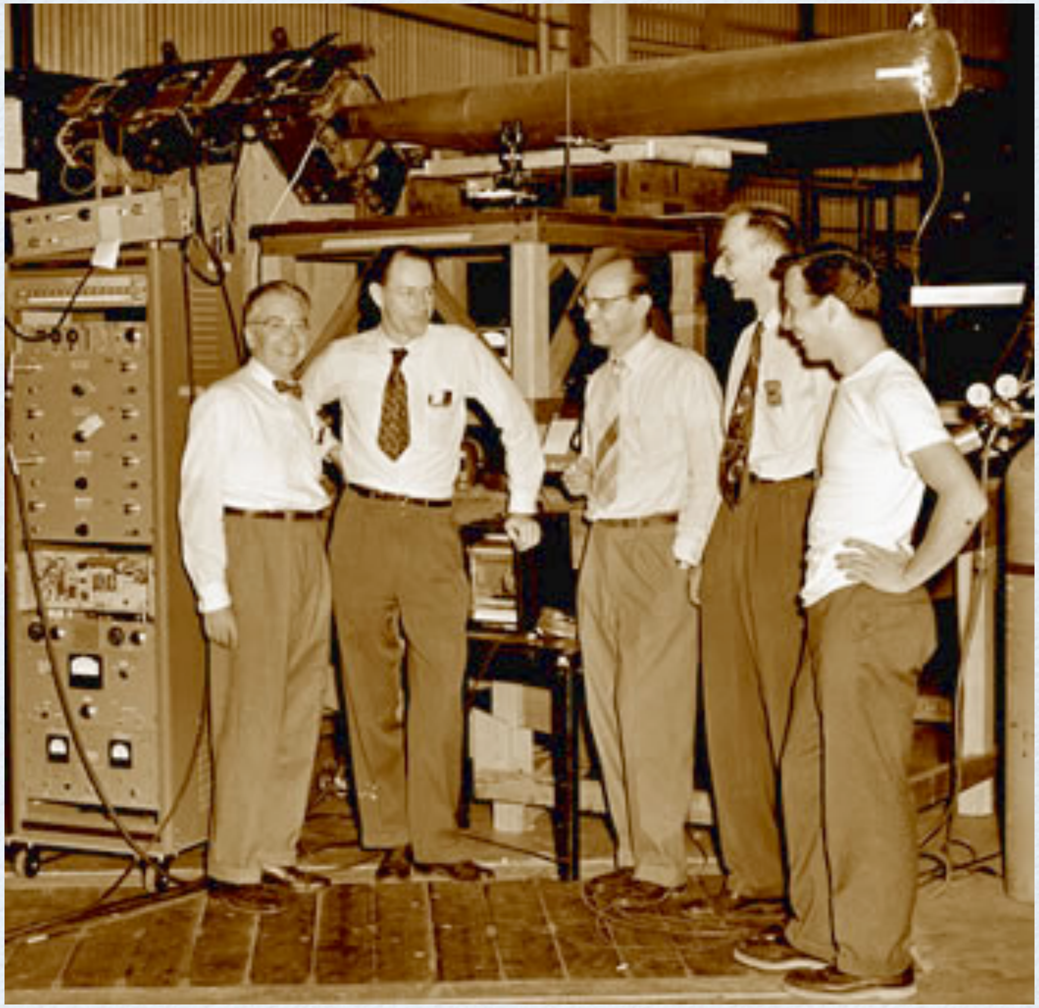

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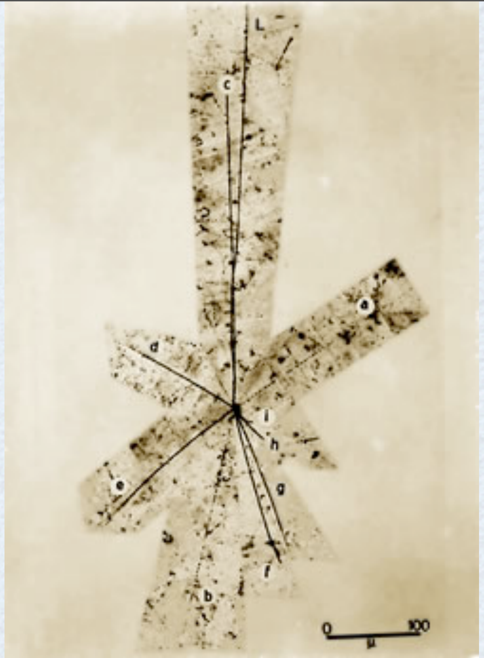
The particle is the antiproton.

They used magnetic quadrupole lenses to filter the momentum, scintillation counters and Cerenkov detectors to measure the velocity, and an emulsion stack for final confirmation of antiproton annihilation with protons.



They eventually produced 60 antiprotons during a 7 hour run and were awarded the Nobel Prize in 1959 for their discovery. The public reaction was mixed. After being told that the new particles would “blow up” a person they came in contact with, a reporter from the Berkeley Gazette wrote

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``Grim New Find at UC"

On the theoretical front: Yang and Mills (1954)

Demand that the isospin invariance of nuclear forces, rotating (n,p) into each other, be promoted to a local symmetry, analogous to the gauge symmetry of electromagnetism.

→ New spin 1, isospin 1 meson

Such a meson, the $\rho(770)$ was discovered a few years later, and the fact that its couplings to other particles obeyed a kind of universality led to the idea (Sakurai (1960) that the Yang-Mills gauge principle could be used as the basis for a theory of the strong interactions. The symmetry group is what we now call flavor symmetry.

This was the start of the era when particle accelerators took over from cosmic rays as the primary method for discovering new particles. It led to a flood of new particles and discoveries. Today the Particle Data Group lists hundreds of strongly interacting particles. Just the mesons include

$f_4(2050)$ ρ $a_1(1260)$

$\pi^{\pm}$ Υ f_0 D^0 B_s^*

$b_1(1235)$ $a_4(2040)$

$f_0(980)$ ω $f_1(1285)$

$f_2(2340)$ η

$K^{\pm}$ $\pi_2(1880)$

$a_0(980)$ η' $h_1(1170)$

J/ψ

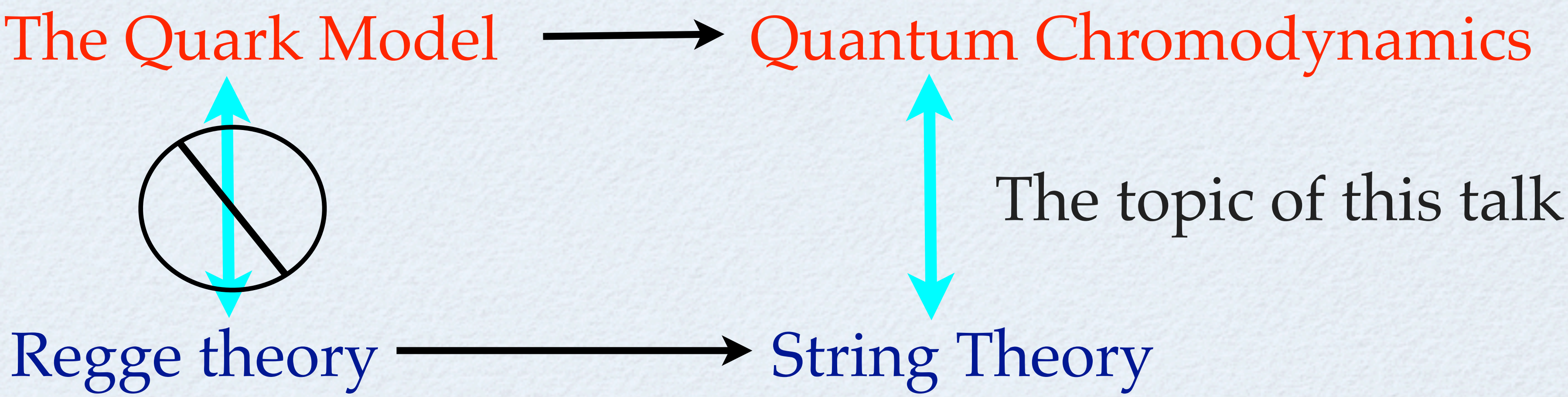
$f_2(2010)$ π^0 $f_2(1270)$ $f_2(2300)$

$f_2(1950)$

The simplicity of the gauge principle had to be abandoned. It couldn't account for the zoo of particles, and to the degree the theory was understood, it seemed to predict massless spin one particles like the photon, not massive particles like the rho.

Two ideas which seemed mutually inconsistent helped to organize the wealth of data:

{fundamental particles}

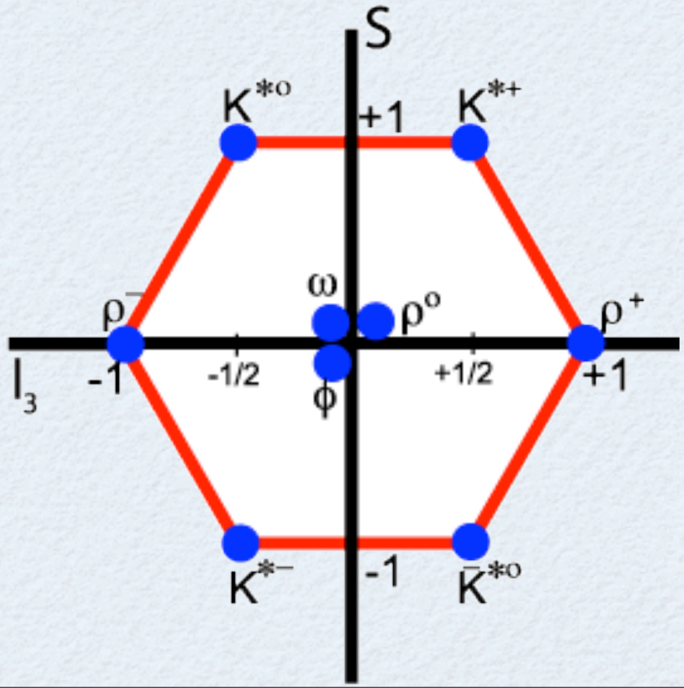


{an infinite number of particles, none fundamental}

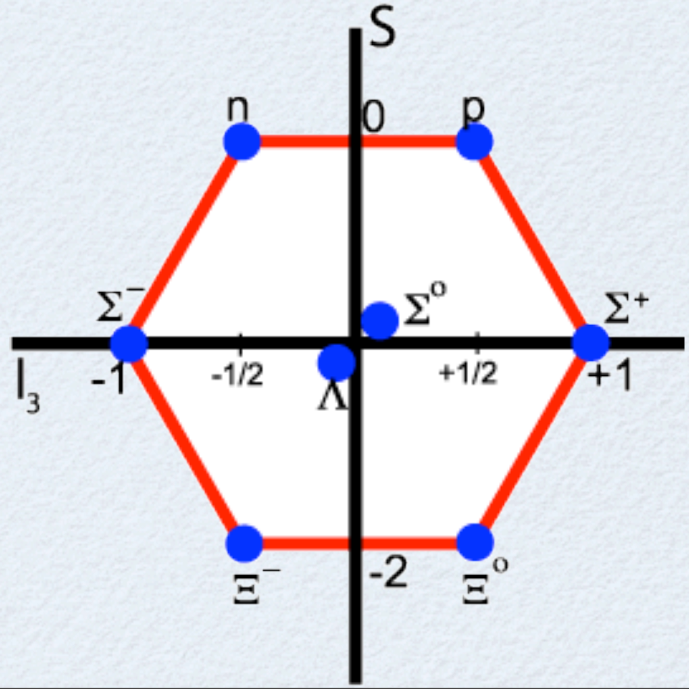
The Quark Model

Mesons ($\bar{q}q$) and baryons (qqq) are bound states of fractionally charged objects called quarks which come in 3 flavors (u,d,s) with an approximate $SU(3)$ flavor symmetry "rotating" the u,d,s, quarks into each other.

$J^P = 1^-$ mesons



Spin 1/2 baryons

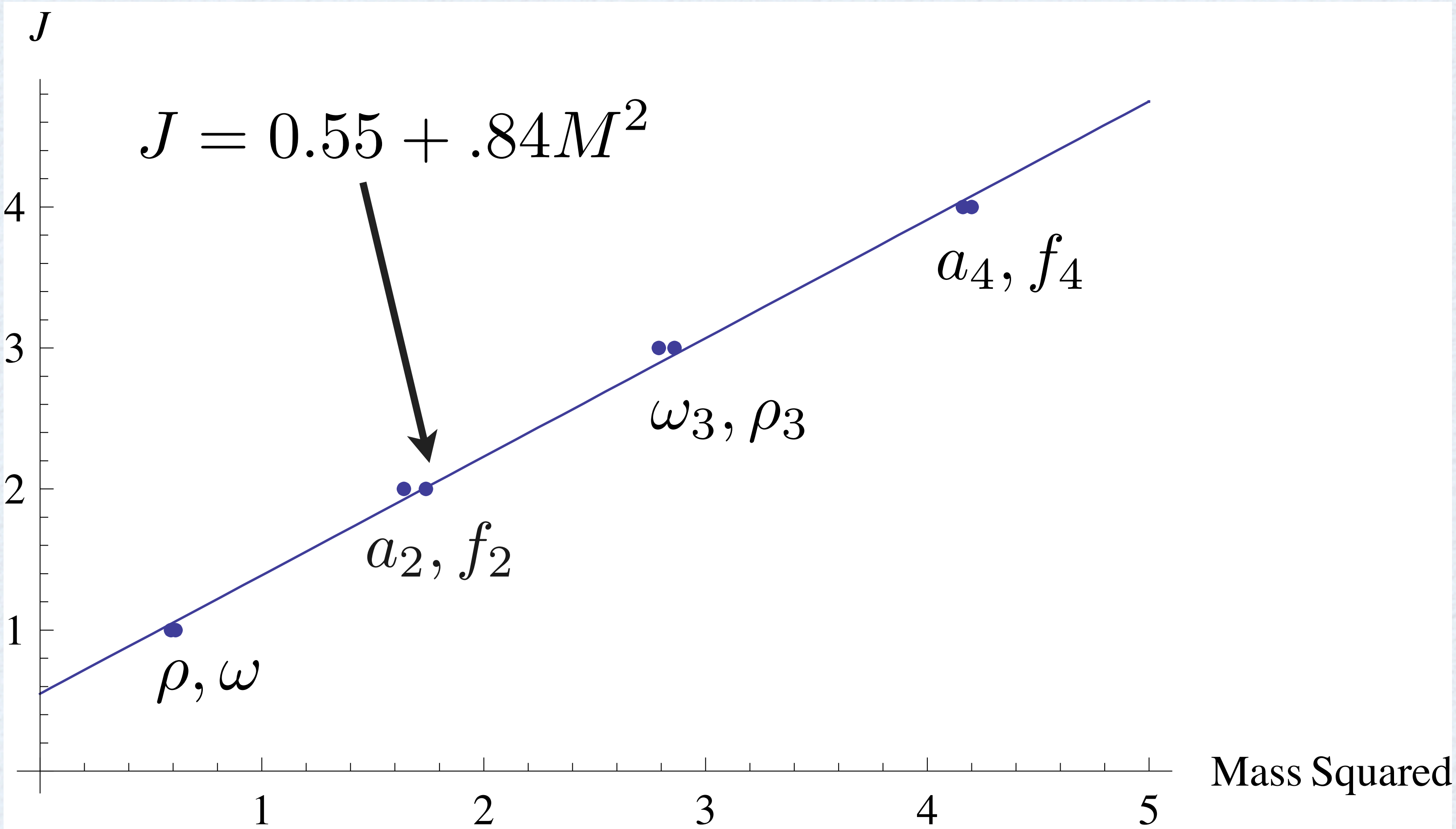


Today we understand the approximate SU(2) (SU(3)) flavor symmetry as an "accident" due to the fact that the u,d (s) quarks are light compared to the natural energy scale of the strong interactions $\Lambda_{QCD} \simeq 220\ \mathrm{MeV}$.

The gauge principle was reinstated by using it to described the color force binding quarks into mesons and baryons.

In the SU(3)xSU(2)xU(1) Standard Model the gauge principle also accounts for the weak and electromagnetic interactions. The spin 1 electroweak gauge fields acquire mass by the Higgs mechanism and we are now searching for the Higgs boson predicted over 30 years ago by accelerating protons to unprecedented energies. 55 years after Yang&Mills we are still learning fundamentally new things about gauge theory.

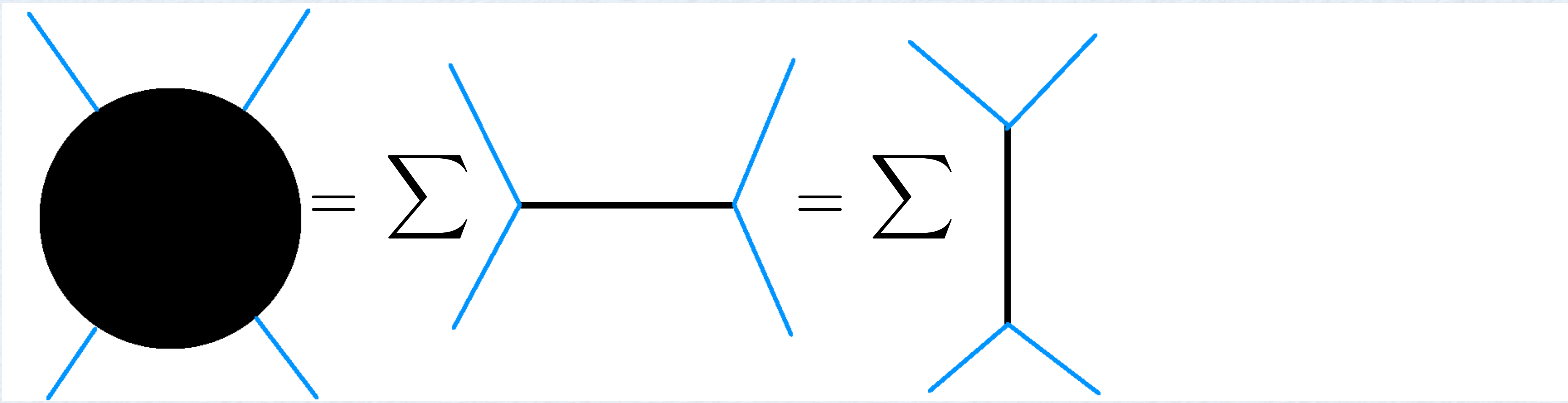
Chew-Frautschi Plot and Regge Theory



Mesons with fixed quantum numbers lie on straight lines in a plot of angular momentum vs. mass squared.

Dual Resonance Models

What if there are an infinite number of resonances/particles and all are created equal?



Time

t s

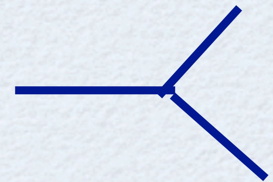
``s-t channel duality"

This is possible only if the sum is infinite so that polynomials can be turned into poles.

This was realized mathematically in the Venenziano amplitude

$$T_{\pi\pi\to\pi\omega} \simeq \frac{\Gamma(1-\alpha_s)\Gamma(1-\alpha_t)}{\Gamma(2-\alpha_s-\alpha_t)}$$

s~energy
t~scattering angle

Nambu (1970): Find states and couplings 

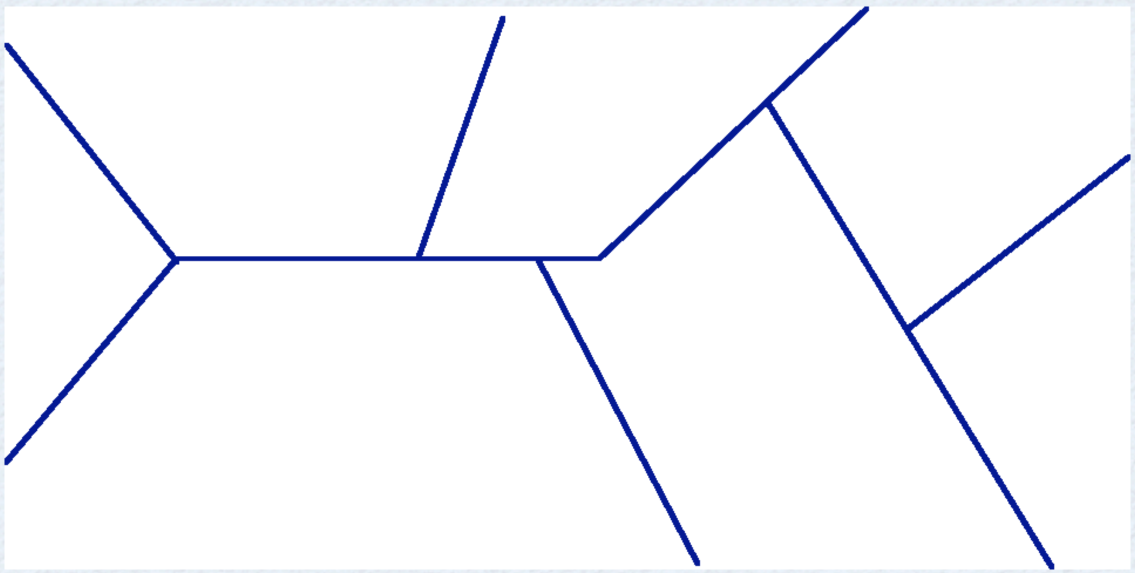


exhibit generalize s-t duality

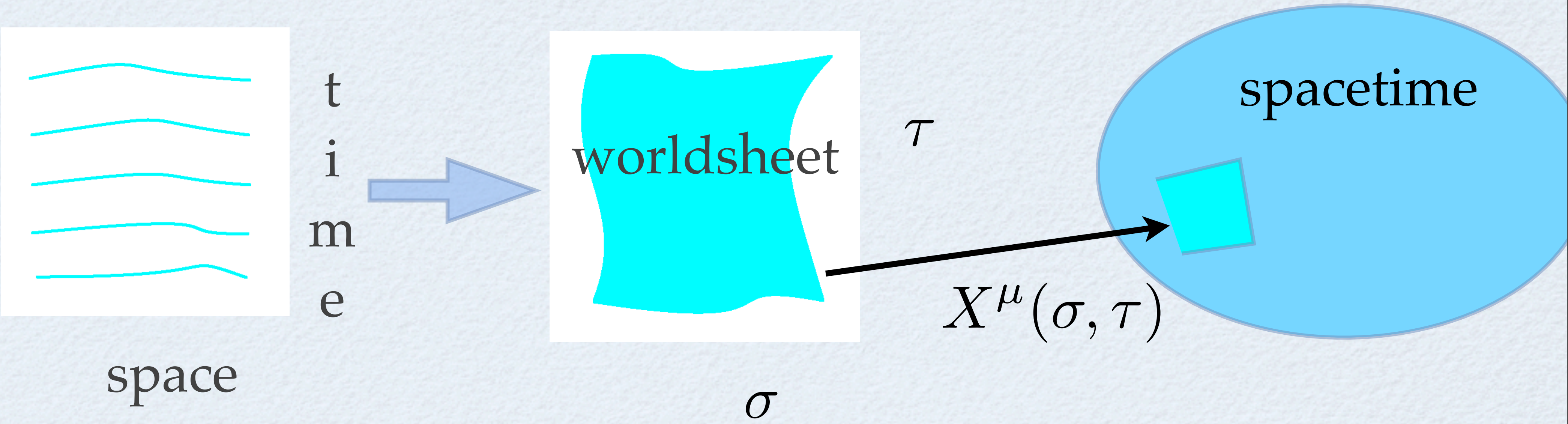
In doing so he found an expression for the energy of a resonance

$$N = -\frac{1}{\pi}\int_0^{2\pi} \partial_\xi \phi \partial_\xi \phi + \pi(\xi) \cdot \pi(\xi) d\xi \qquad (17)$$

``Eq. 17 suggests that the internal energy of a meson is analogous to that of a quantized string of finite length"

Similar suggestions were made soon thereafter by Nielsen and by Susskind. String theory was born and the idea of an infinite number of particles of Regge theory and dual resonance models was realized with the infinite number of particles corresponding to the excited modes of a relativistic string.

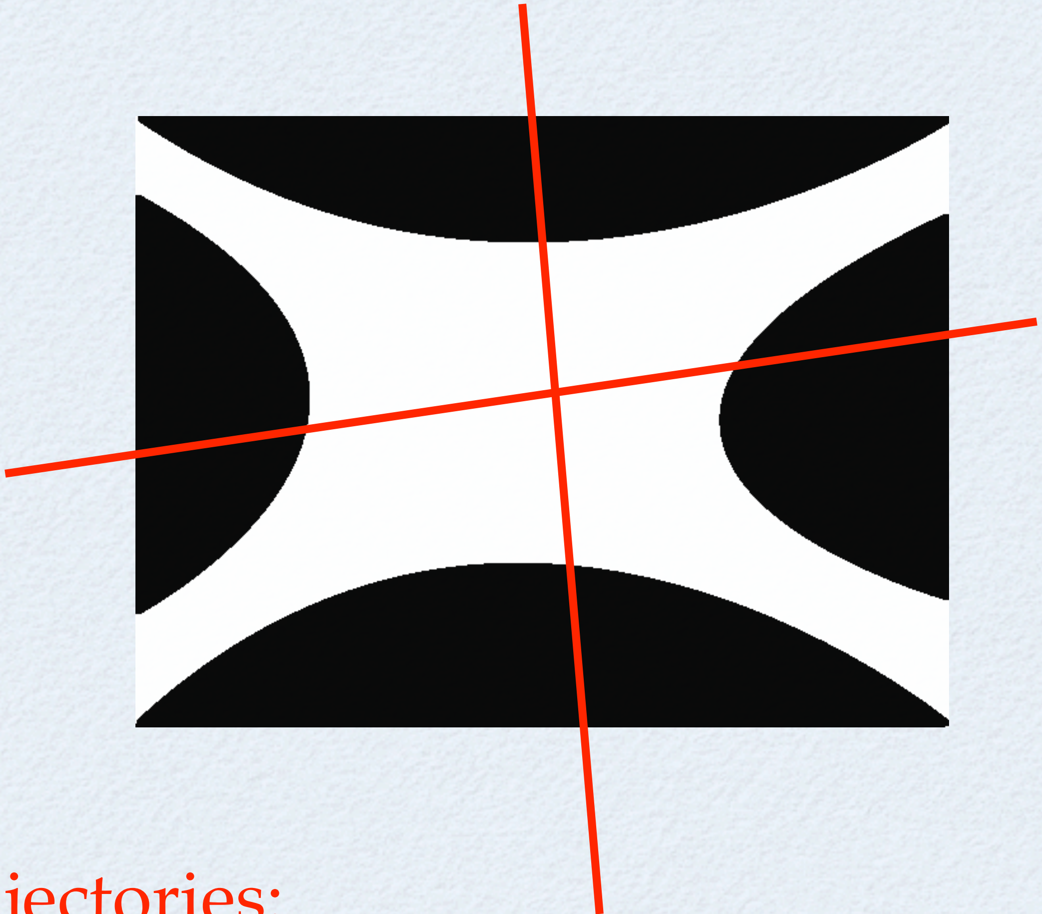
This analogy was turned into a geometrical picture and an action was proposed (Nambu-Goto):



The action S is ~ the Area of the String World Sheet

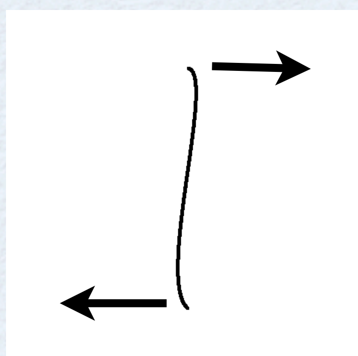
This string picture with its geometrical foundation soon replaced and explained much of the earlier formalism

Duality:



There is just one string diagram, s, t channels are just different ways to slice the string.

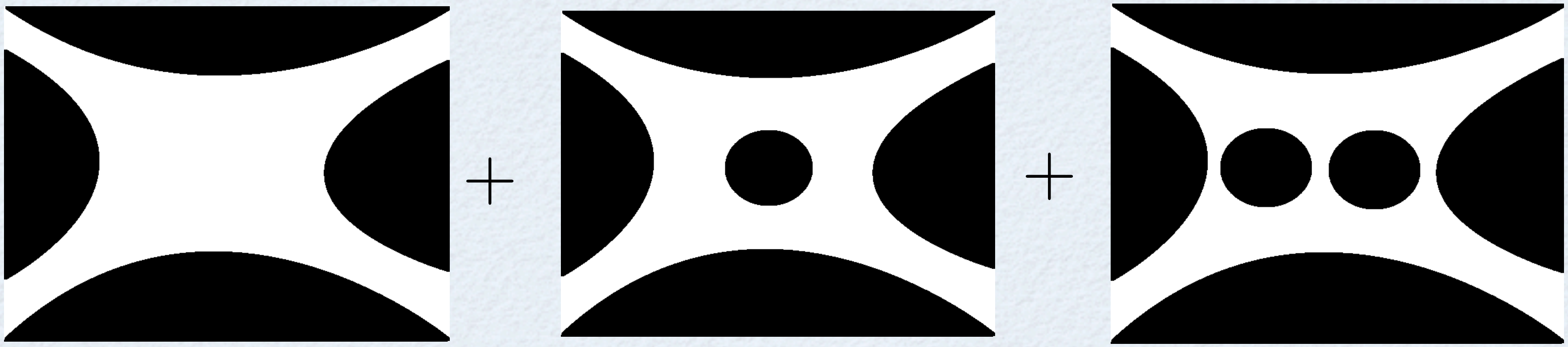
Regge trajectories:



Rotating strings with

$\mathrm{mass}^2 \propto J_{max}$

String (meson) scattering computed by expanding in the number of times the string splits and rejoins --coupling is related to the topology of the string world-sheet.



These developments led to a clear understanding of the quantum mechanics of relativistic string, culminating in the 1973 paper of Goddard, Goldstone, Rebbi and Thorn. Consistency required D=26 (bosonic string) or D=10 (superstring).

This, other phenomenological problems, and the discovery of asymptotic freedom by Gross, Wilczek and Politzer, also in 1973, led to the resurgence of field theory, and the abandonment of this approach to hadronic physics.

String theory was later reborn as a theory of quantum gravity (Scherk, Schwarz, Yoneya) and of unification of the forces of the Standard Model with gravity.

Sudarshan:``Don't you think that the goal of physics is to find general principles?"
Nambu:``Right now I am more interested in substance than principle."

String theory has made great progress on some problems of principle:

- Quantum gravity with perturbative expansion.
- Understanding of black hole entropy.
- Weak-strong coupling dualities.

The AdS/CFT correspondence, aka string/gauge duality, promises to add some substance to the accomplishments of string theory.

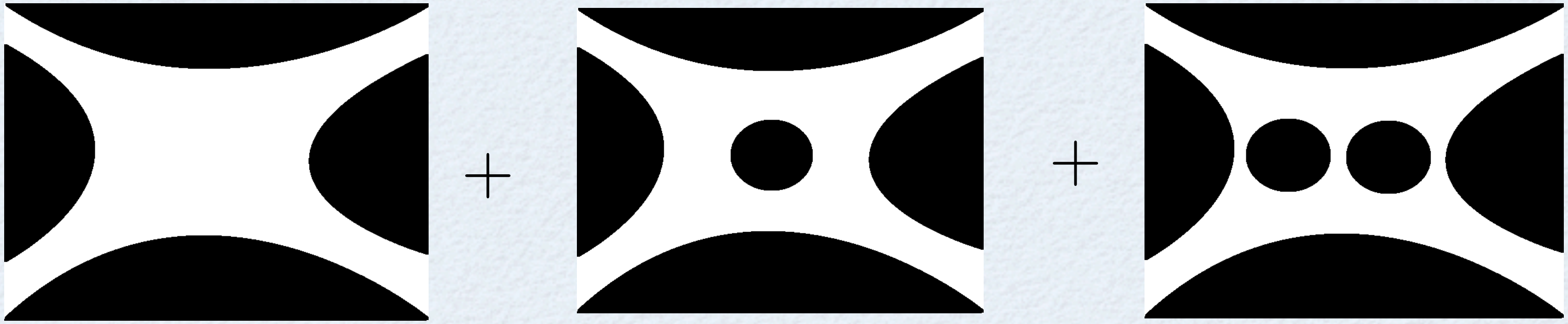
There were early glimmerings of a stringy duality, but the start of a precise connection between string theory and QCD is due to 't Hooft who connected the topological expansion in string theory to the $1/N_c$ expansion in QCD.

The basic idea is simple and brilliant.

QED $\alpha = e^2/4\pi \simeq 1/137$

QCD Let quarks have N_c colors, expand in $1/N_c$.
Keep $g_{YM}^2 N_c$ fixed.

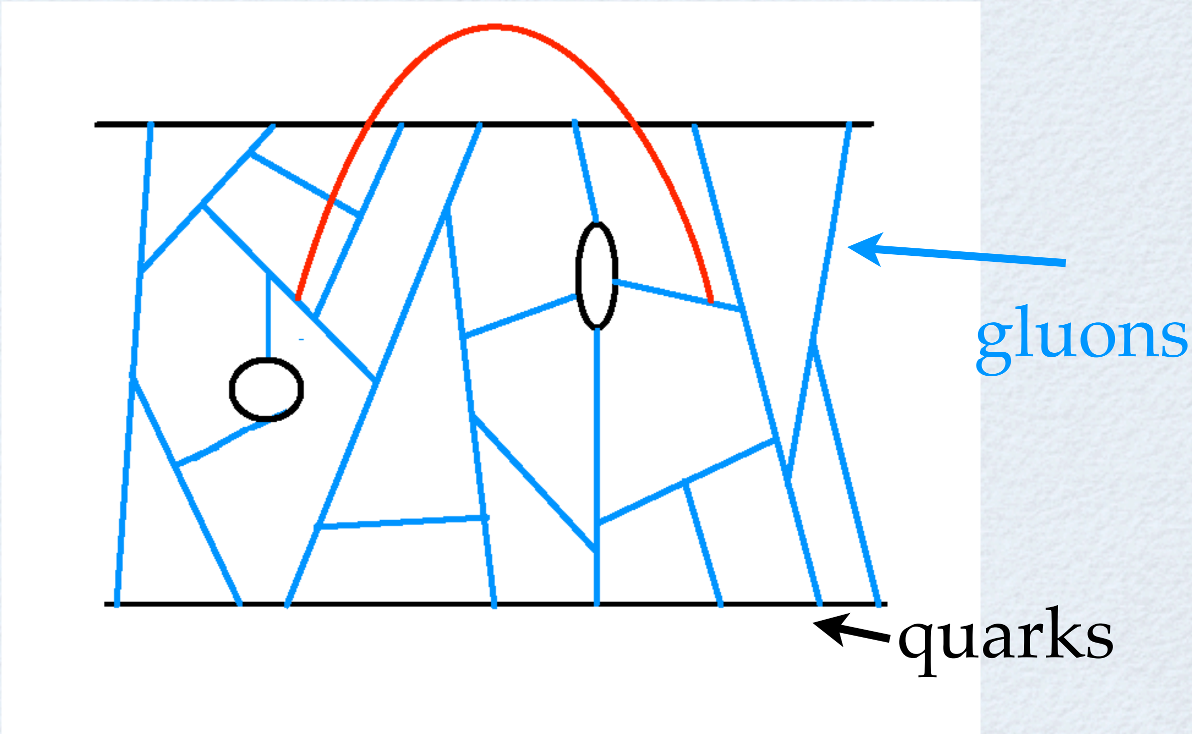
The topological expansion in string theory



is related to the expansion in QCD in the number of quark colors $1/N_c$

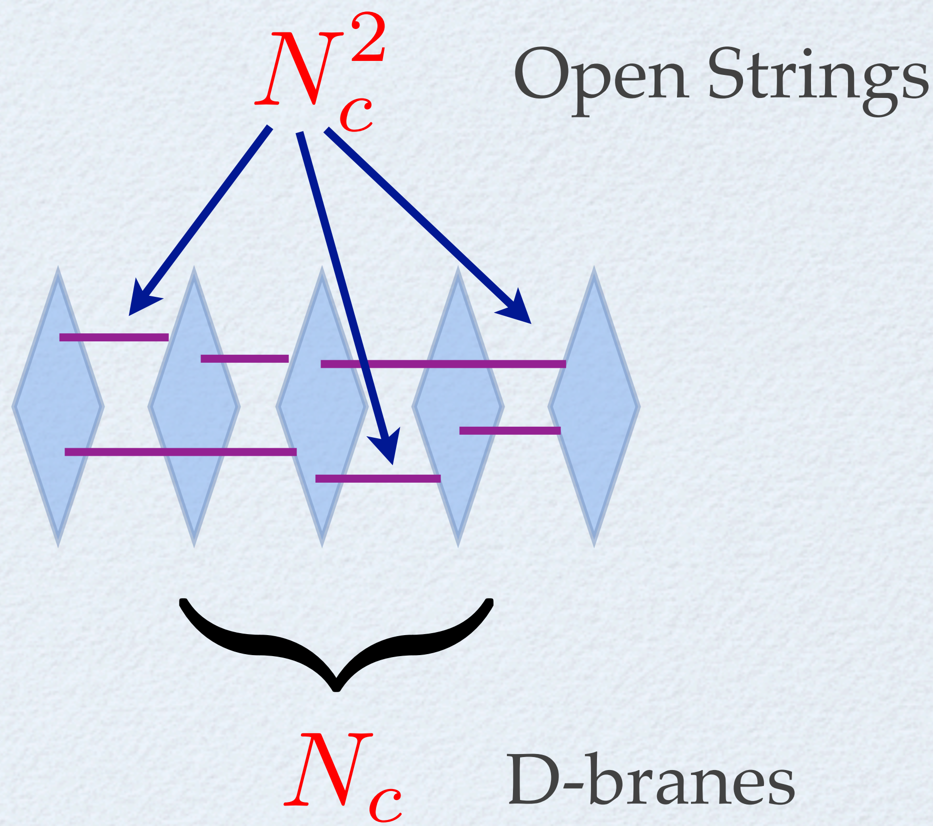
Open strings: HOLES

Closed strings: HANDLES



These connections were made much more concrete following the discovery of D-branes in string theory. Objects on which open strings can end, and whose dynamics are described by $SU(N_c)$ Yang-Mills theory.

At large N_c one finds a decoupled set of states near coincident D-branes with two different descriptions.



$SU(N_c)$ Yang-Mills with N=4 SUSY

IIB string theory on $AdS_5 \times S^5$

$$\frac{R^2}{\ell_s^2} \sim \sqrt{g_{YM}^2 N_c}$$

This AdS/CFT correspondence was proposed by Maldacena and extended by Gubser, Klebanov,Polyakov and Witten into a well defined scheme for computing quantities in strong coupling, large N_c Super Yang-Mills theory in terms of classical computations in a dual, gravitational theory (the low-energy limit of string theory).

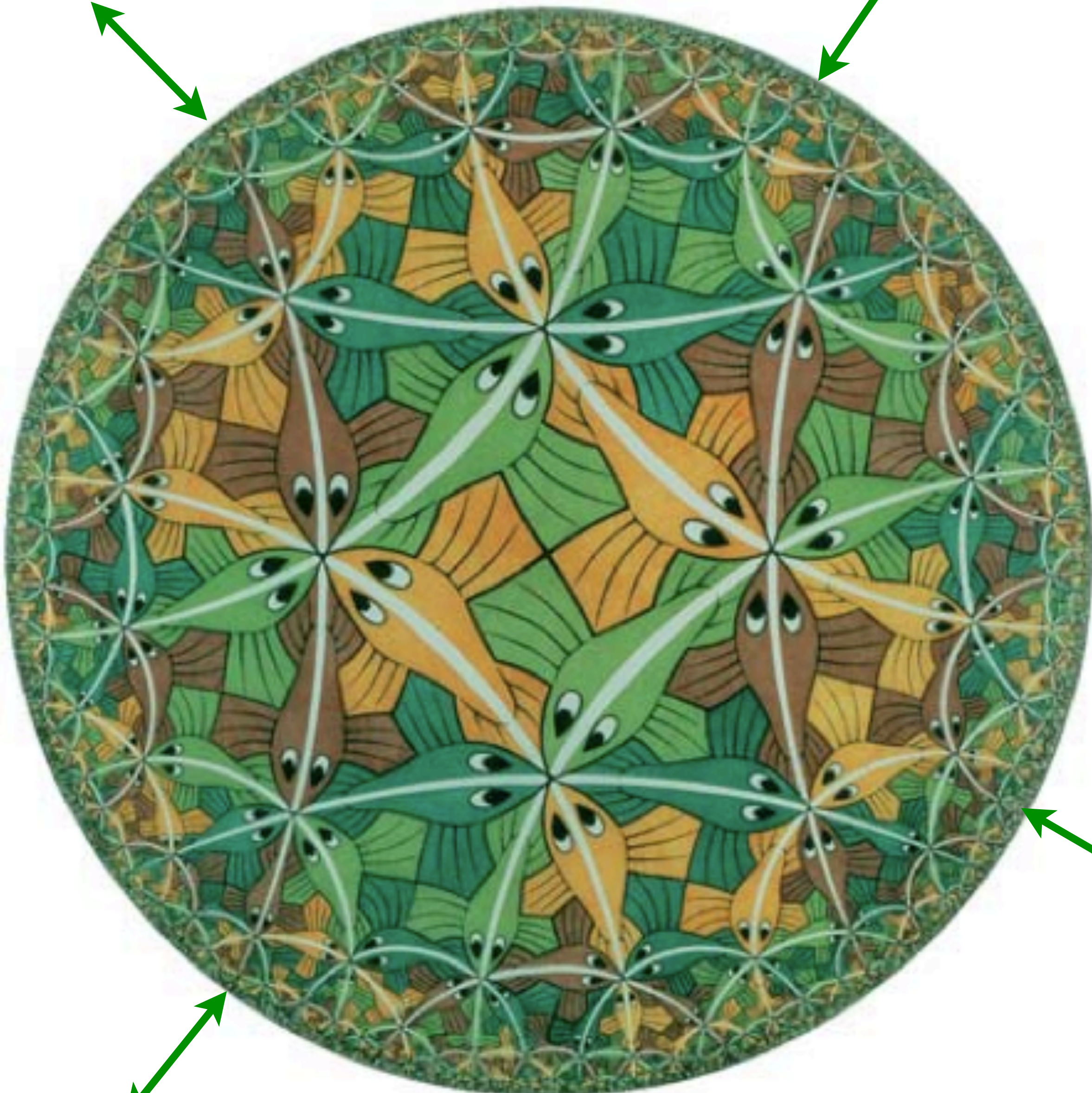
How is this possible?

- The large N_c limit IS a classical limit in which correlation functions factorize: $\langle AB \rangle = \langle A \rangle \langle B \rangle + O(1/N_c)$
- Gravitational theories in asymptotically AdS spaces are not well defined without a specification of boundary conditions.
- Black Hole entropy ~ Area suggests gravitational theories have fewer degrees of freedom than field theories.
- The fifth direction is dual to the energy scale

Euclidean AdS_2

$\phi(x_1)$

$\phi(x_2)$



$\phi(x_3)$

$\phi(x_n)$

$\cdots\;\cdots$

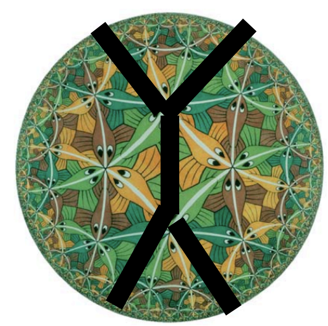
$O(x) \in N = 4$ SYM

$\langle O(x_1) O(x_2) \cdots O(x_n) \rangle$

$O(x) \longrightarrow \phi(z, x)$

$\phi(x, z_{\mathrm{bndy}}) = \phi^0(x)$

$S_{\mathrm{grav}}(\phi^0)$

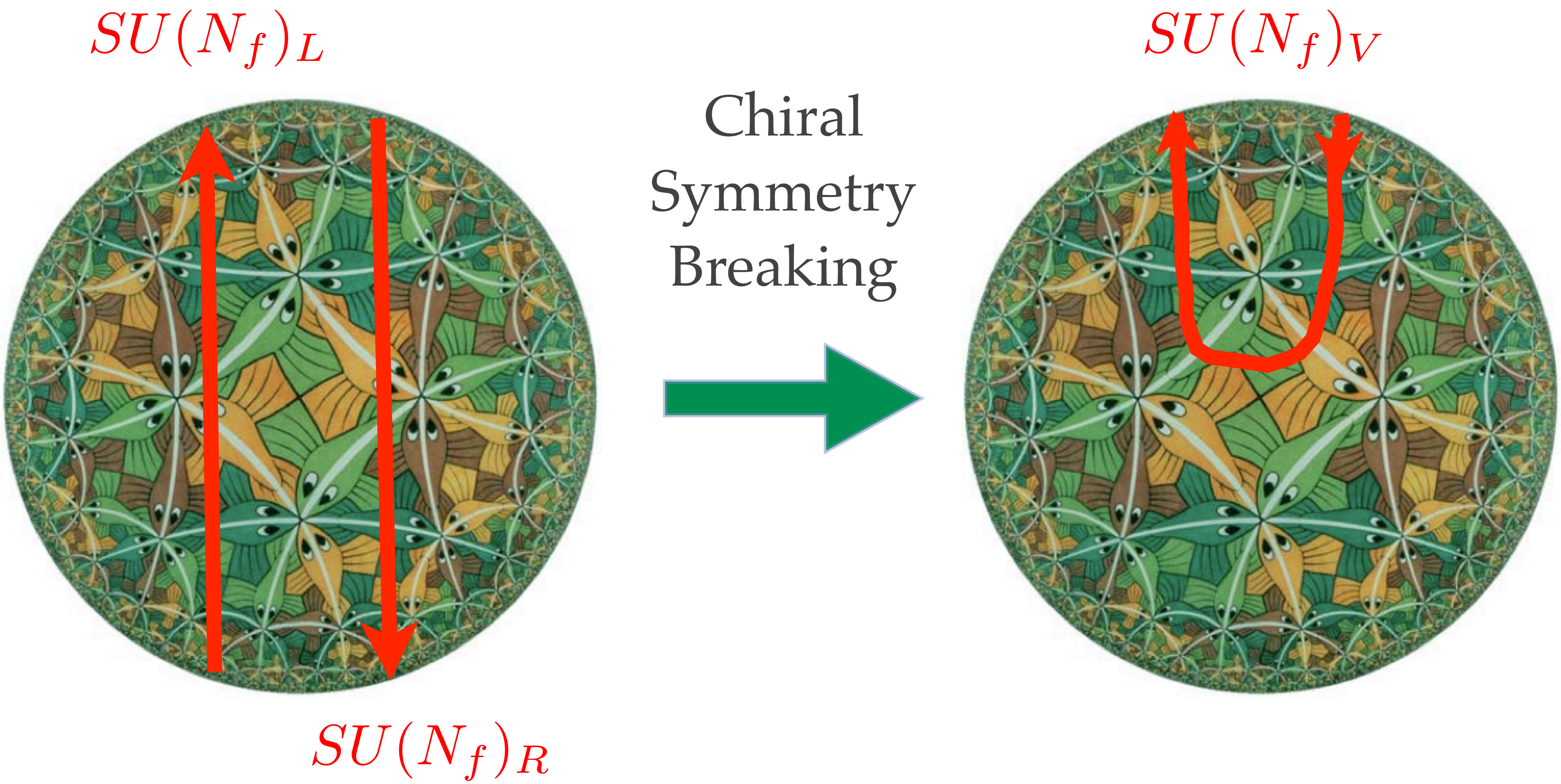


In the original, highly supersymmetric setting there have now been many non-trivial tests of this correspondence, and there are hopes that the large N_c limit may eventually be solved exactly.

What about QCD? What new ingredients are needed? What can we do with it? Isn't lattice gauge theory good enough?

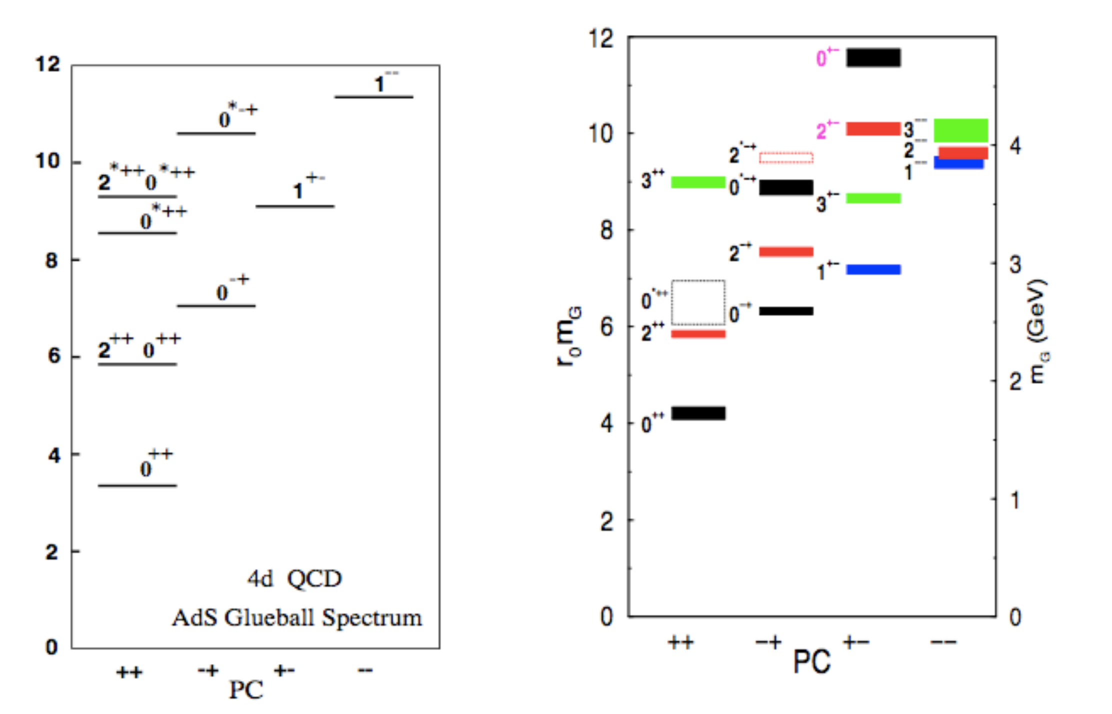
- D-branes and a modified metric.
- Study QCD in new ways and in exotic environments.
- Not for some problems, and analytic understanding is always good.

To add quarks: add D-branes to AdS



The old idea of flavor symmetry as a gauge symmetry is revived, but in a higher-dimensional space!

QCD has glueballs → Closed strings



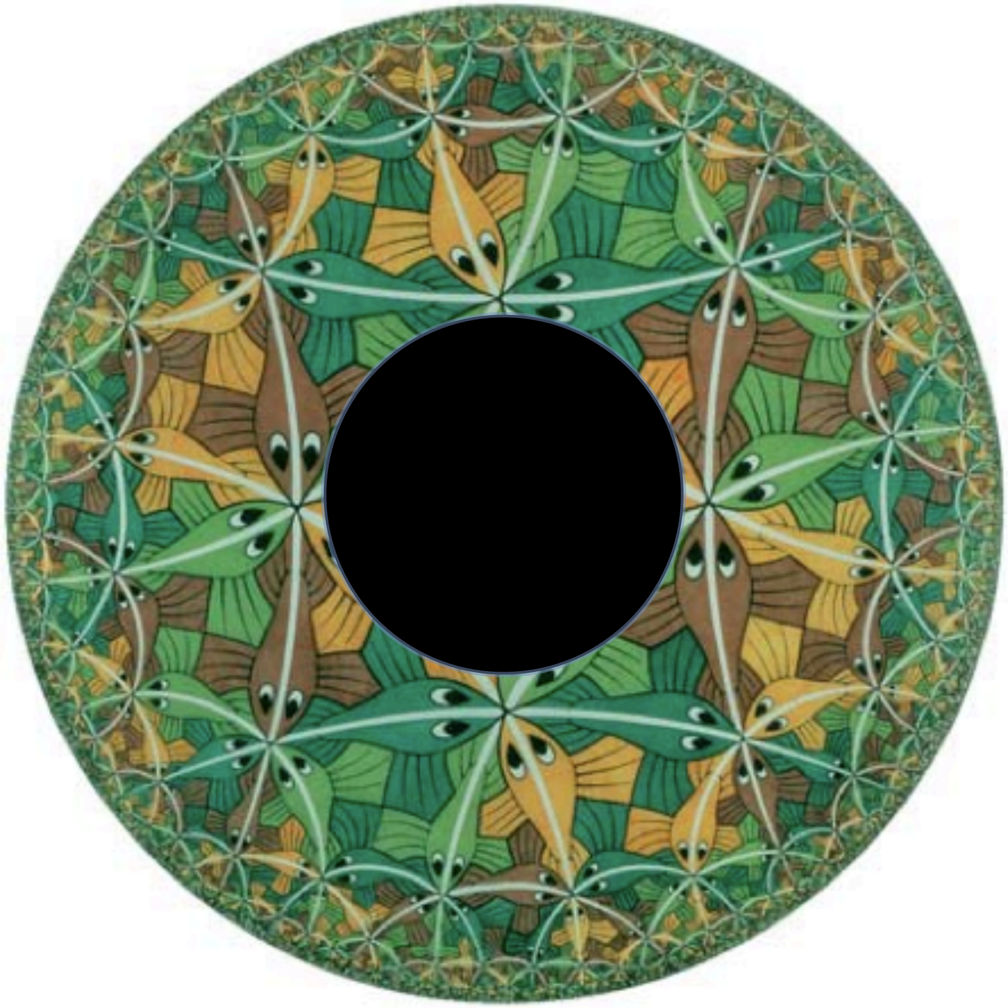
Brower, Mathur&Tan AdS and
Morningstar&Pearson Lattice QCD

mesons → Open strings

Meson spectrum and couplings in hard wall AdS/QCD model.

Observable	Measured (MeV)	Model A (MeV)	Model B (MeV)
m_π	139.6±0.0004 [8]	139.6*	141
m_ρ	775.8±0.5 [8]	775.8*	832
m_{a_1}	1230±40 [8]	1363	1220
f_π	92.4±0.35 [8]	92.4*	84.0
$F_\rho^{1/2}$	345±8 [15]	329	353
$F_{a_1}^{1/2}$	433±13 [6, 16]	486	440
$g_{\rho\pi\pi}$	6.03±0.07 [8]	4.48	5.29

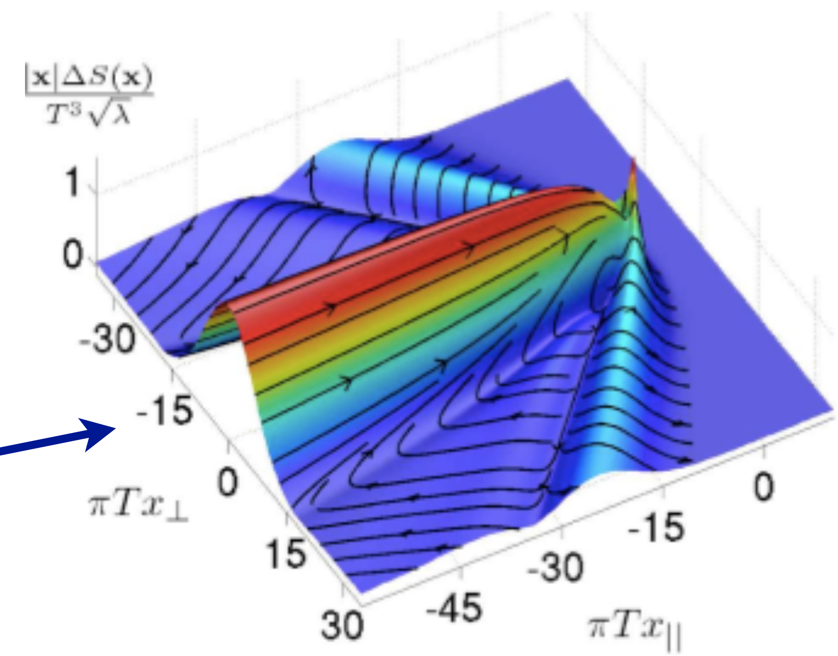
To study QCD at finite temperature add a Black Hole to AdS. The temperature is the Hawking temperature!



RHIC Physics:

Viscosity/entropy of quark-gluon plasma

Drag/energy loss



Energy flux of a quark moving through the quark/gluon plasma (Chesler&Yaffe)

These ideas have also developed into a useful tool for exploring the phase structure of QCD that complements lattice QCD and experimental efforts. There have been new insights into the transitions to deconfinement and restoration of chiral symmetry and into the behavior in dense matter (e.g. in neutron stars).

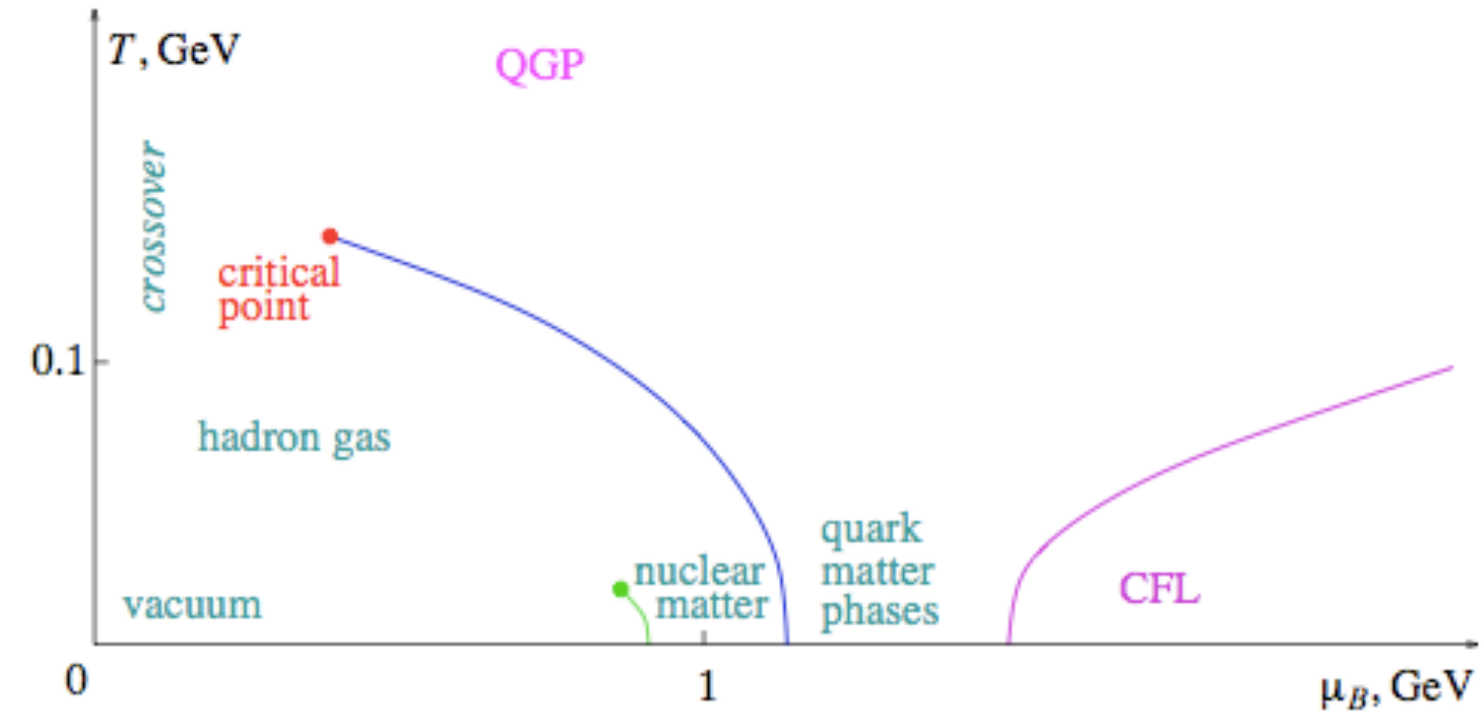


Figure 3: The contemporary view of the QCD phase diagram – a semiquantitative sketch.

(from M. Stephanov)

It is even possible to say something about LHC physics, although not what most people are interested in (Higgs, SUSY, Dark Matter etc.).

What sets the scale of the total cross section for p-p scattering at 7 TeV?

First, this is not a question that can be answered by perturbative QCD. It is a "soft" observeable as evidenced by the optical theorem.

There are two main approaches. One is a phenomenological approach incorporating the Froissart bound and using general properties like analyticity.

$$\sigma_{tot} \sim B(\log(s/s_0))^2, \quad B \sim .31\ mb$$

Another approach, more in line with AdS/QCD, assumes Pomeron exchange dominates and to fit the slope and intercept of the Pomeron Regge trajectory. In current language the Pomeron is the Regge trajectory that starts with the lightest spin two glueball state of QCD. This leads to

$$\sigma_{tot} \sim c\pi\lambda_P^2 \left(\frac{\alpha_c' s}{2}\right)^{\alpha_c(0)-1}$$

Fit to Data: $\lambda_P = 8.28 \ \mathrm{GeV}^{-1}$

5D AdS calculation $\lambda_P = 6.38 \ \mathrm{GeV}^{-1}$ S. Domokos, JH, N. Mann

(It is not possible to do this calculation exactly with current technology since we do not know how to solve string theory in the appropriate curved backgrounds)

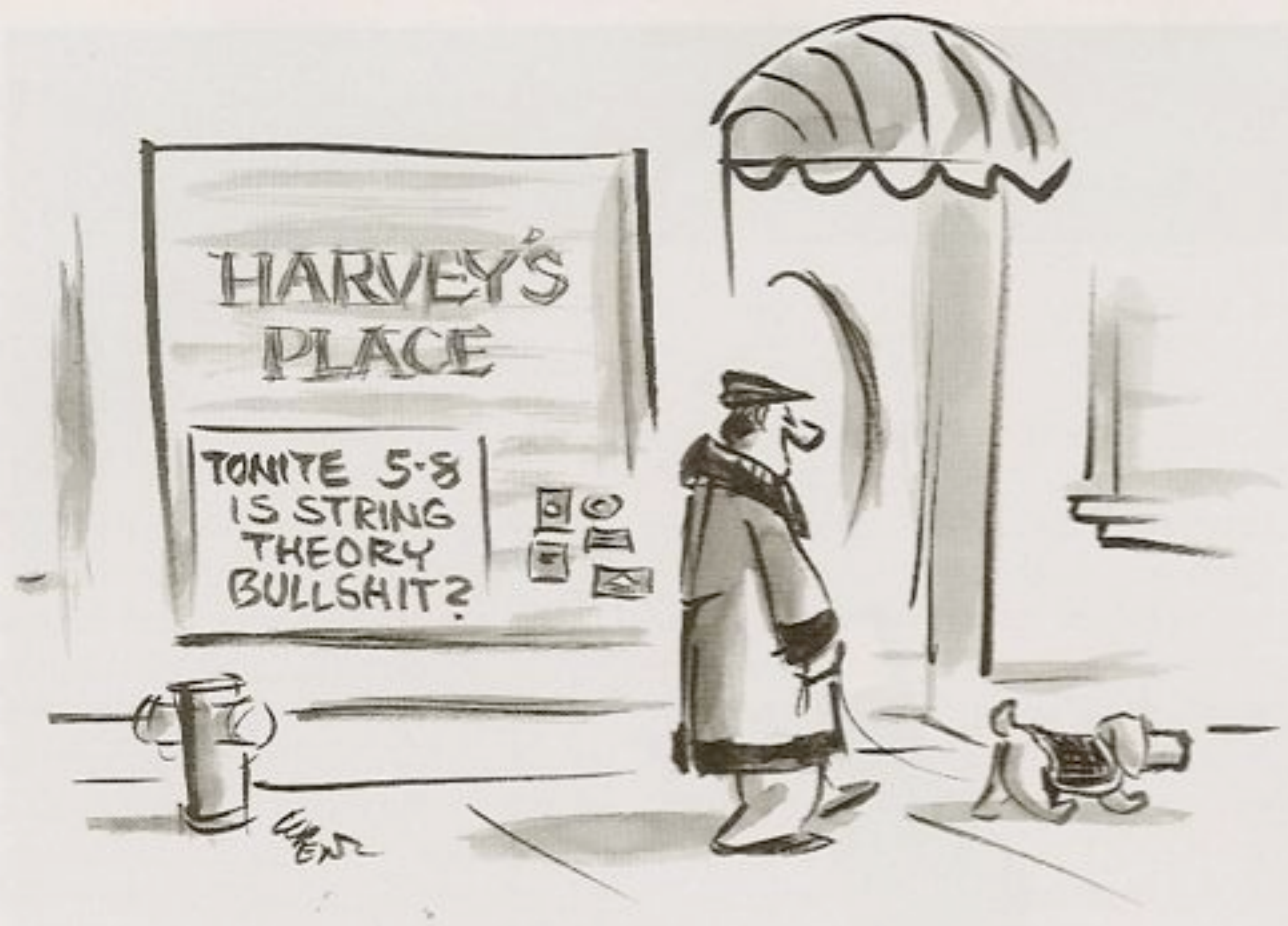
Outlook/Caveats/Conclusions

The principles behind gauge/string duality are clearly very general, but we do not know how general, in part because we don't know how to derive or prove even the best tested version. It does not seem to require supersymmetry, Lorentz invariance, or even conformal symmetry except asymptotically.

In applying these ideas to QCD or other systems most computations are done in the gravity approximation to string theory, but we know from data that there is often no separation of energy scales that justifies this approximation. It will be interesting to see if progress in string theory leads to improved string models of QCD and gives a firmer foundation for the phenomenological applications of Regge theory.

Some old ideas have had reemerged in a surprising new way. For example, the idea that the vector mesons of QCD should be thought of as (massive) gauge fields is true in AdS/QCD since they arise as modes of a 5D gauge field.

There are fascinating new ideas for applying these techniques and ideas to other physical systems including hydrodynamics and strongly coupled condensed matter systems, and there are even hints of applications to pure mathematics.


HARVEY'S
PLACE
TONITE 5-8
IS STRING
THEORY
BULLSHIT?