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From the hadronic string to quantum gravity…and back

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Dedicated to Sergio Fubini and Miguel Virasoro

Strong interactions in the mid sixties

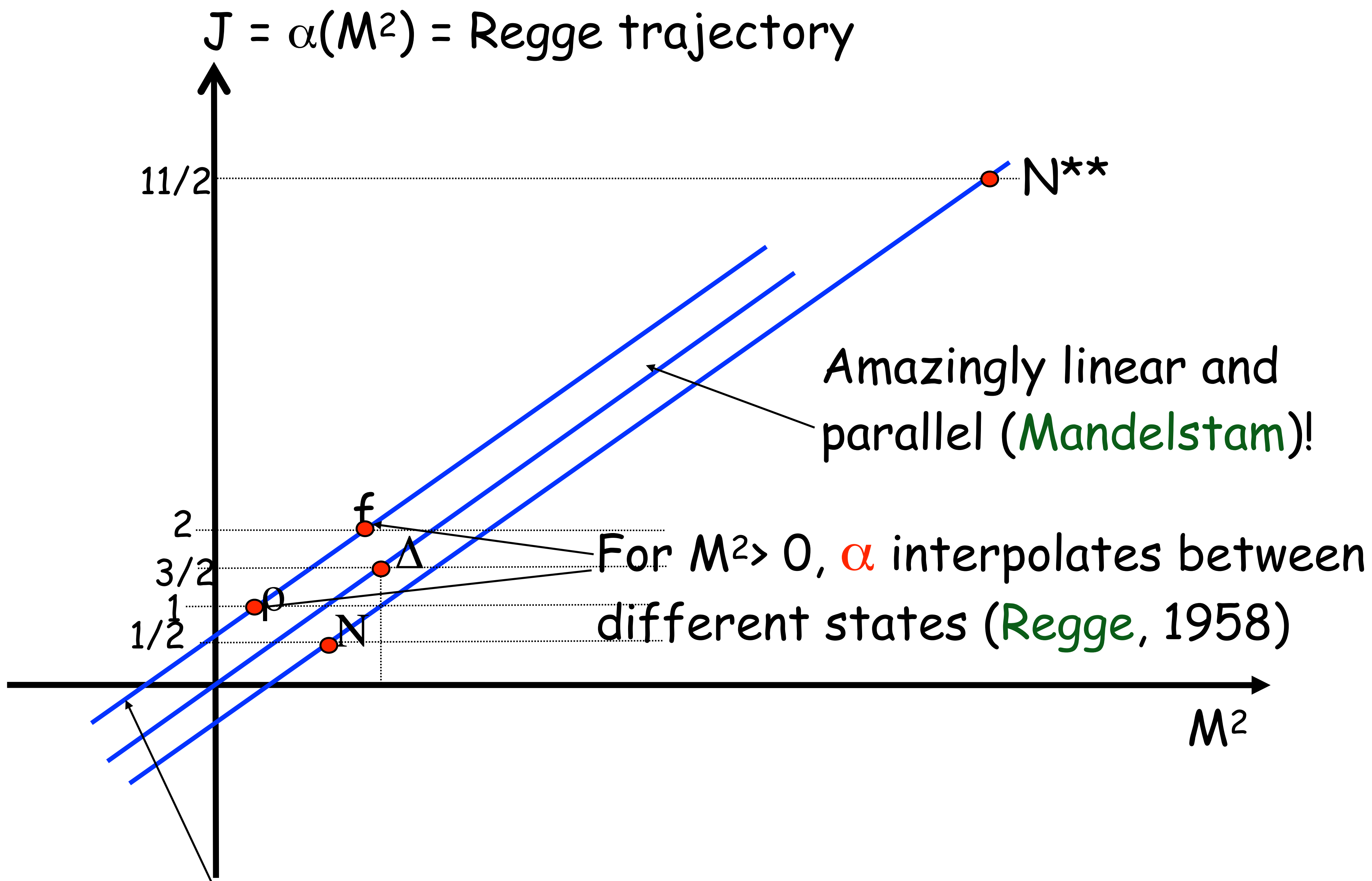
(I got my laurea with Raoul Gatto in 1965)

- Lots of data, lack of a decent theory
- QED's successes looked hard to duplicate for the hadronic "zoo"
- An S-Matrix approach looked much more promising

Chew's "expensive" bootstrap...

Add to the general constraints of symmetry, causality, unitarity of the S-matrix that of Nuclear Democracy:

"All hadrons lie on Regge trajectories @ $M^2>0$;
All asymptotics fixed by <u>the same</u> trajectories @ $M^2<0$"



For $M^2 < 0$, α controls high-energy scattering at momentum transfer ~ $|M|$ (Gribov-Chew-Mandelstam, early sixties)

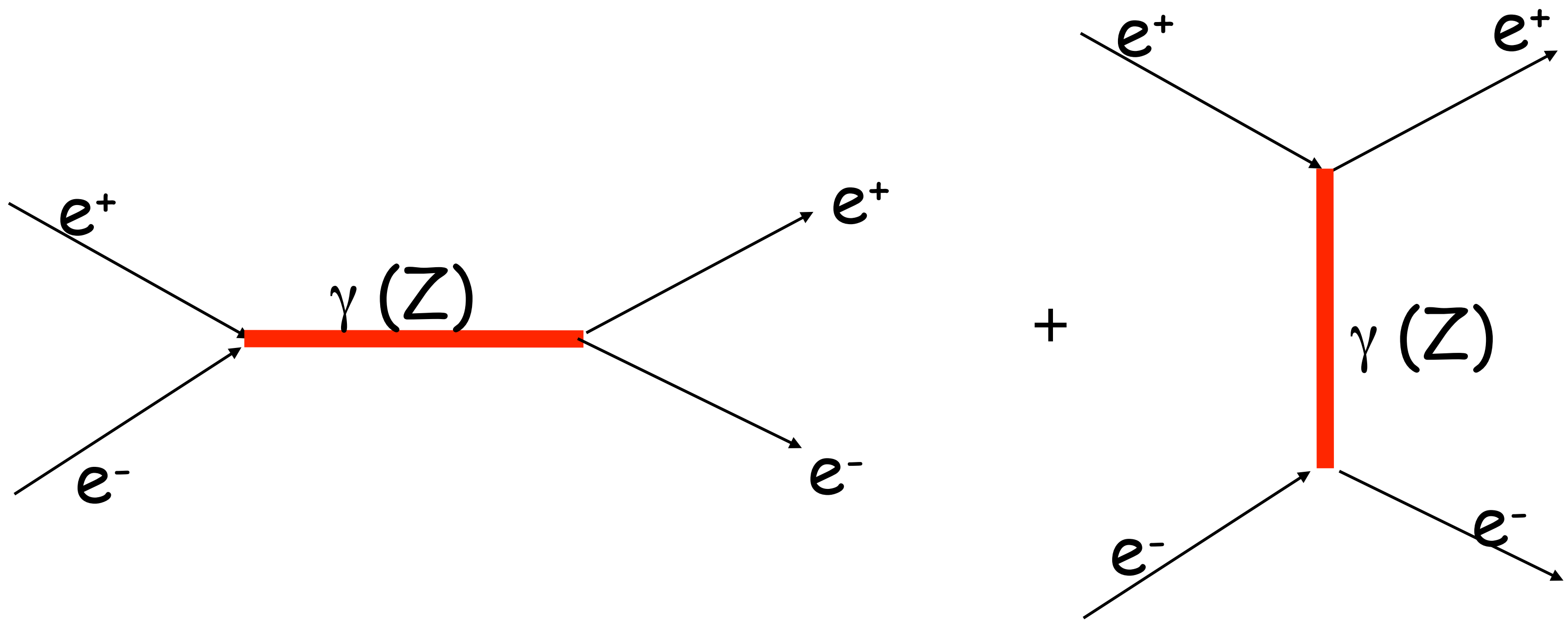
Prominent role of Unitarity: a non-linear constraint

Will this give a unique S-matrix?

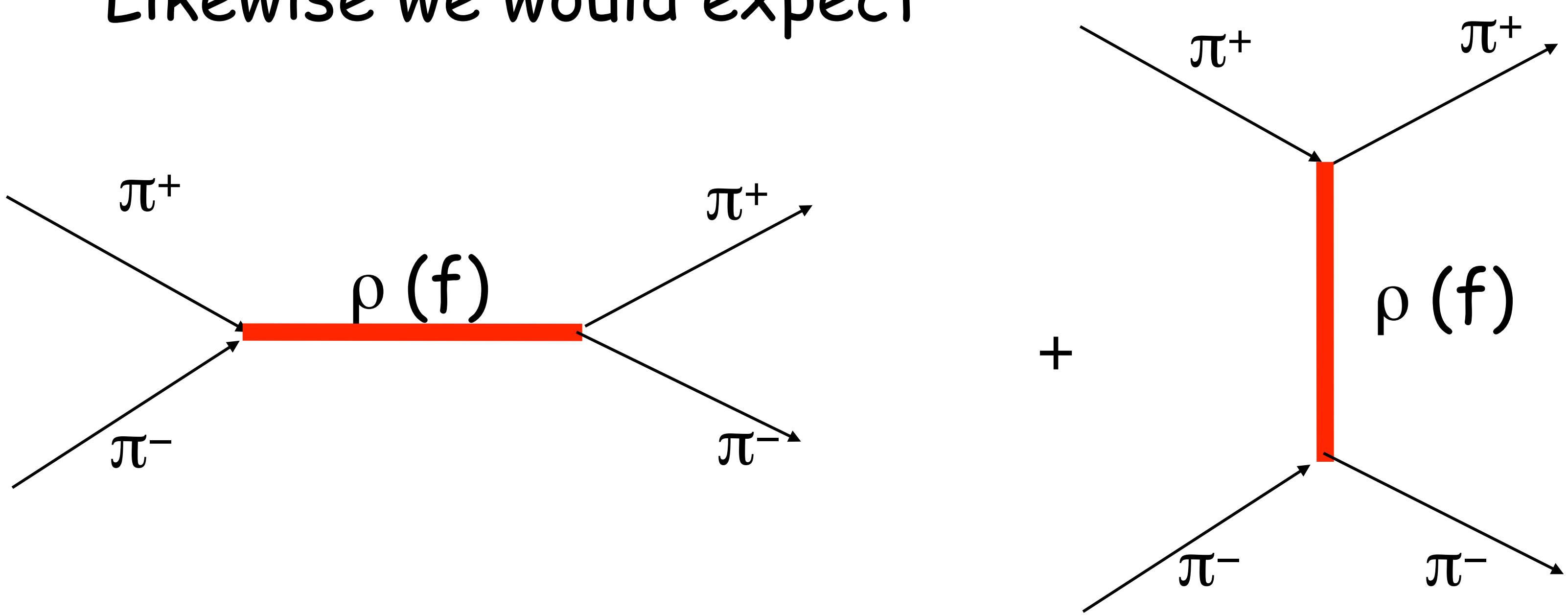
The S-matrix knew about both uses of Regge Theory:

$$S = S_{s\text{-channel}} + S_{t\text{-channel}}$$

Like in QED: $e^+ e^- \dashrightarrow e^+ e^-$ is given (to lowest order) by the coherent sum of two Feynman diagrams



Likewise we would expect



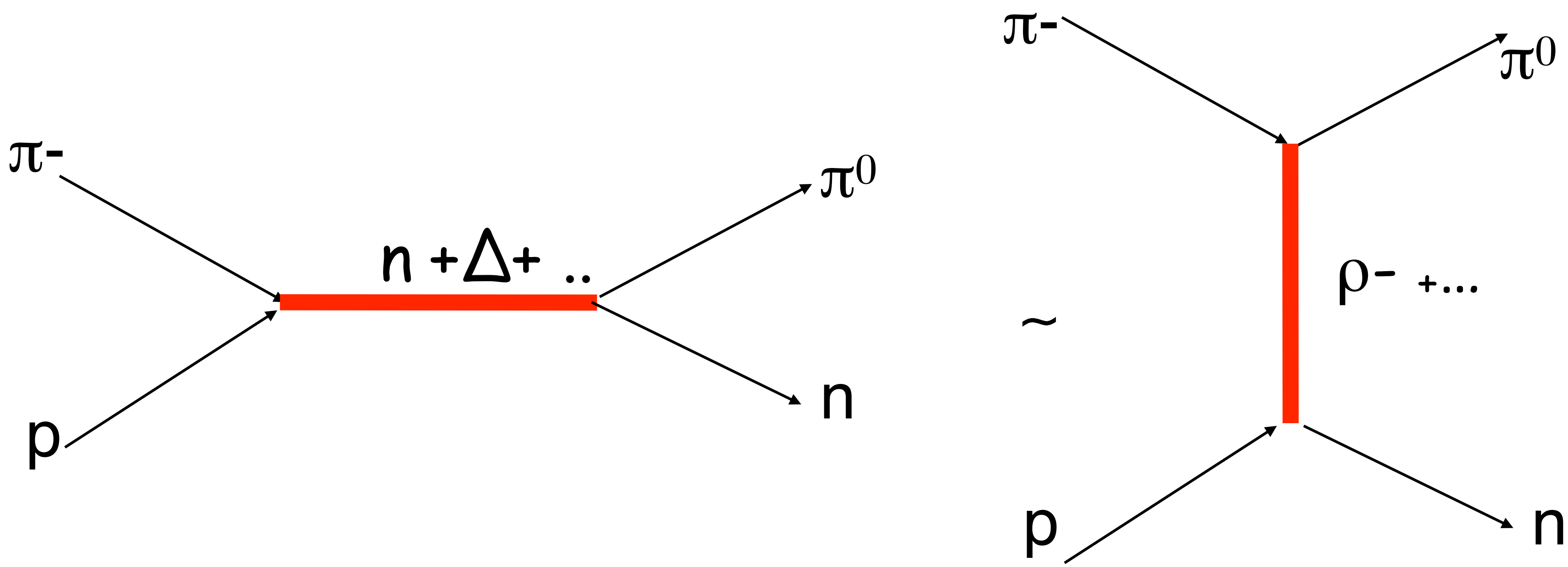
A cheaper bootstrap?

Erice summer 1967

M. Gell Mann brings news from Caltech

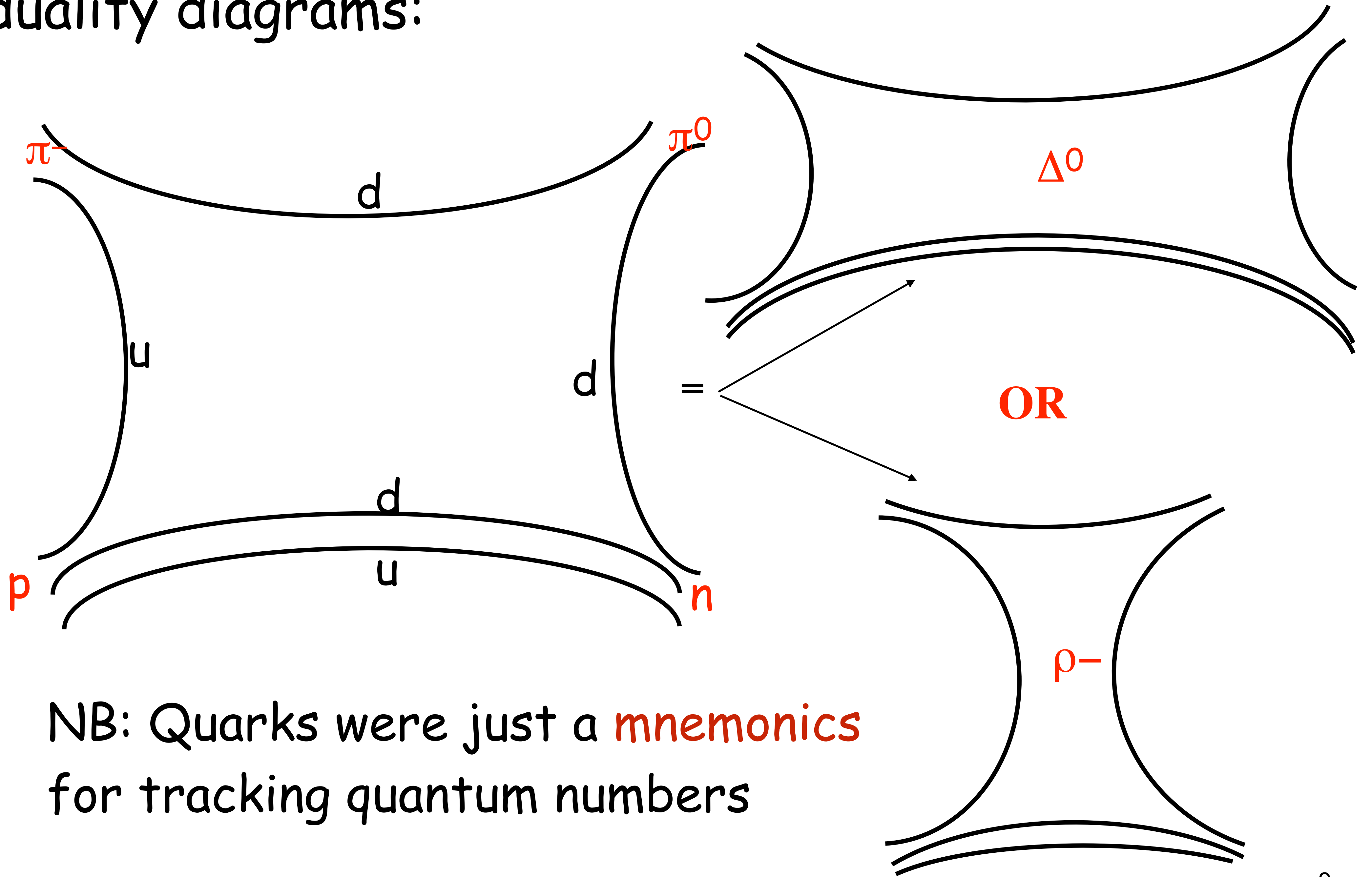
Dolen-Horn-Schmit (DHS) duality:

In $\pi^- p \to \pi^0 n$ s and t-channel descriptions are roughly (i.e. on average) equivalent, complementary, DUAL



A non-trivial yet LINEAR, "CHEAPER" bootstrap...

DHS duality prompted Harari & Rosner to introduce duality diagrams:



NB: Quarks were just a mnemonics for tracking quantum numbers

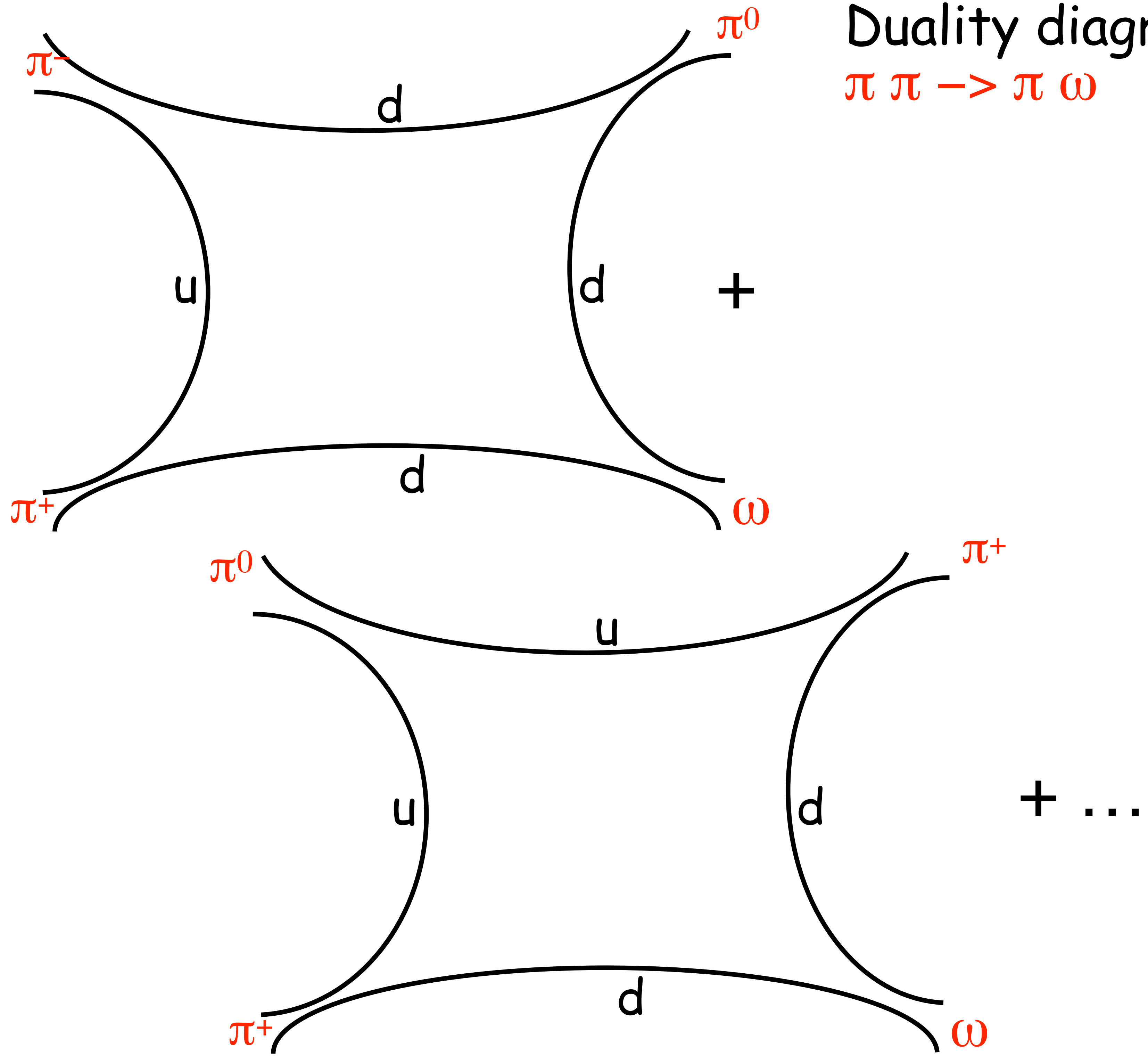
Can we associate a precise mathematical expression to those diagrams (like with Feynman's)?

$\pi\,\pi \rightarrow \pi\,\omega$ was the first reaction to be considered.

It is described, pictorially, by three duality diagrams.

Duality diagrams for

$\pi\ \pi \rightarrow \pi\ \omega$



An educated guess came in 1968: A = A(s,t) + A(s,u) + A(t,u)
where

$$\boxed{A(s,t) = \beta \frac{\Gamma(1-\alpha(s))\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)-\alpha(t))} = \beta\, B(1-\alpha(s), 1-\alpha(t))}$$

with: $$\alpha(x) = \alpha_0 + \alpha' x$$

NB: linear!

Nicely tested in $\omega \to 3\pi$ (Odorico)

Also successfully extended to $\pi\,\pi \to \pi\,\pi$ scattering by Lovelace and Shapiro

Its generalization to more than 4 external legs led to the so-called Dual Resonance Model (DRM).

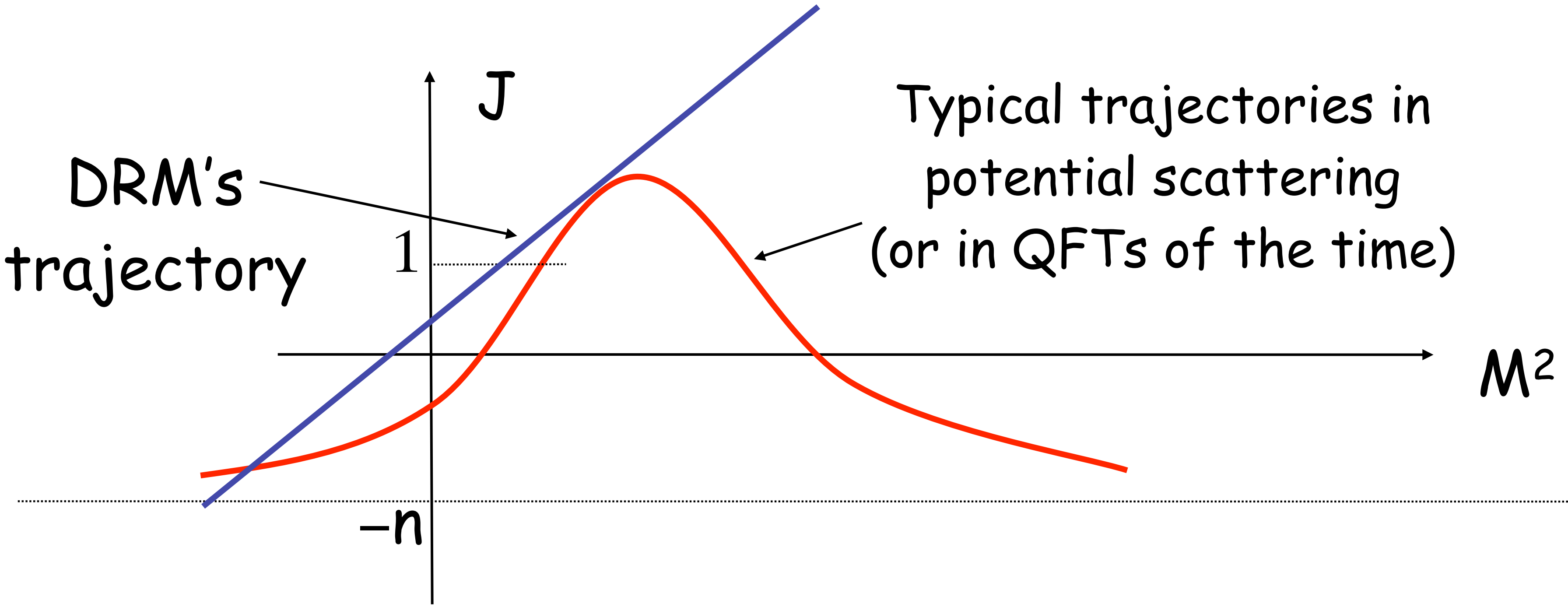
DRM = Strings Theory: from hints to proof

(see also Paolo Di Vecchia's talk)

Hints of a string?

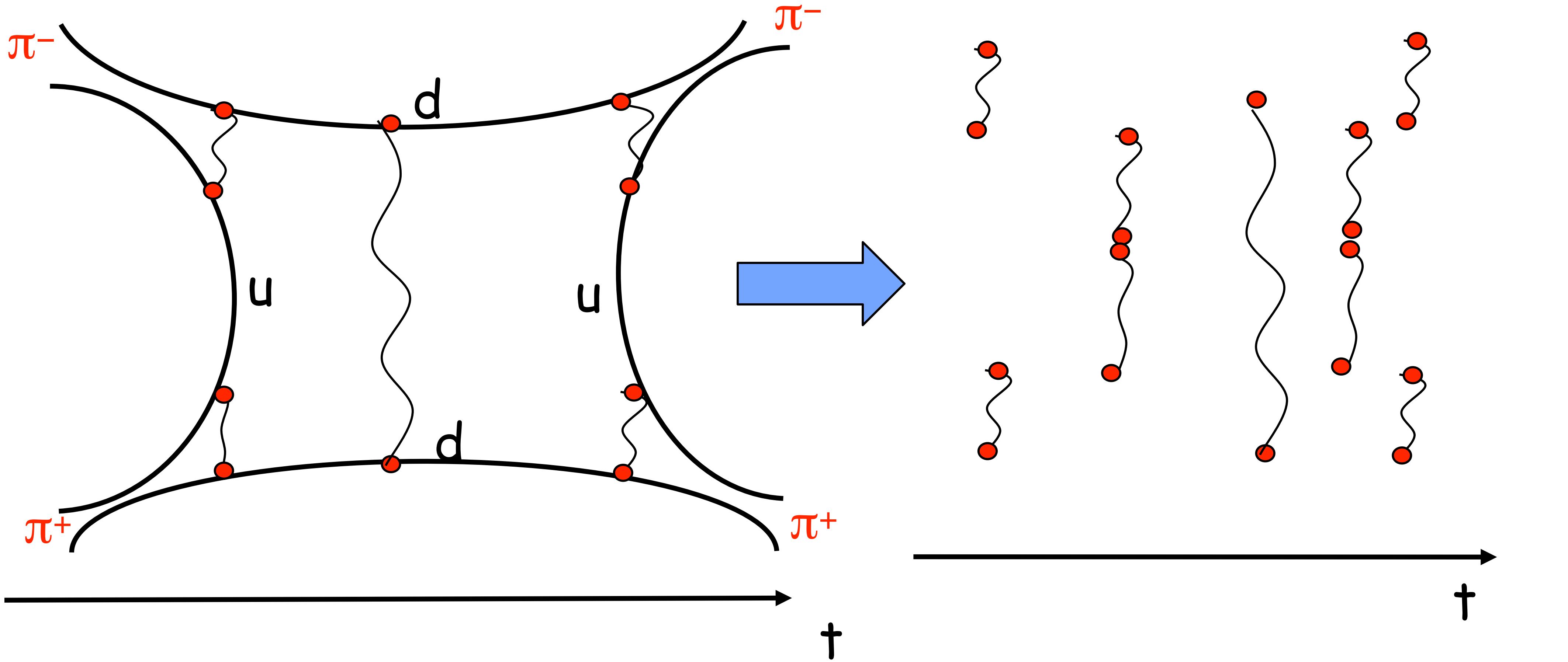
1. From linear Regge trajectories
2. From duality and duality diagrams
3. From the harmonic oscillators needed to describe the DRM spectrum (Fubini-Gordon-GV, Nambu)
4. From an underlying 2-d field theory (Fubini-GV)
5. From the Virasoro operators, algebra
6. …

A first missed hint?



$\alpha' = dJ/dM^2 \sim 10^{-13}$ cm/GeV. Meaning of this new constant?
Its inverse, T, has dimensions of a string tension (E/L)!

A second missed hint?



joining and splitting of strings ?

- The remaining hints were not missed, but the connection with strings remained qualitative for sometime
- Eventually it was established on solid grounds through a precise formulation of the classical relativistic string (Nambu & Goto, 1970) and its first correct (light-cone) quantization (Goddard, Goldstone, Rebbi &Thorn, 1972) .
- See P. Di Vecchia's talk for more details

Not the right theory!

Paradoxically, now that the DRM had been raised to the level of a respectable Theory, it became apparent that it was not the right one for strong interactions!

Good and bad news (see also Paolo's talk)

1. The good (theoretical) news:

   Neveu-Scherk-Ramond extensions, Gliozzi-Scherk Olive projection, supersymmetry discovery (in the west)

   => Fully consistent superstrings (no ghosts, no tachyons)

2. The bad (phenomenological) news:

   a. Unwanted $m = 0$ states => problems @ large distance

   b. Softness => problems @ short distance

   c. Need for extra dimensions ($D = 9+1$),

   whereas:

   HE limit of $R = \sigma(e^+ e^- \rightarrow \text{hadrons})/\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$, Bj scaling in DIS, large p_t events @ the ISR, were all evidences for point-like structures in hadrons

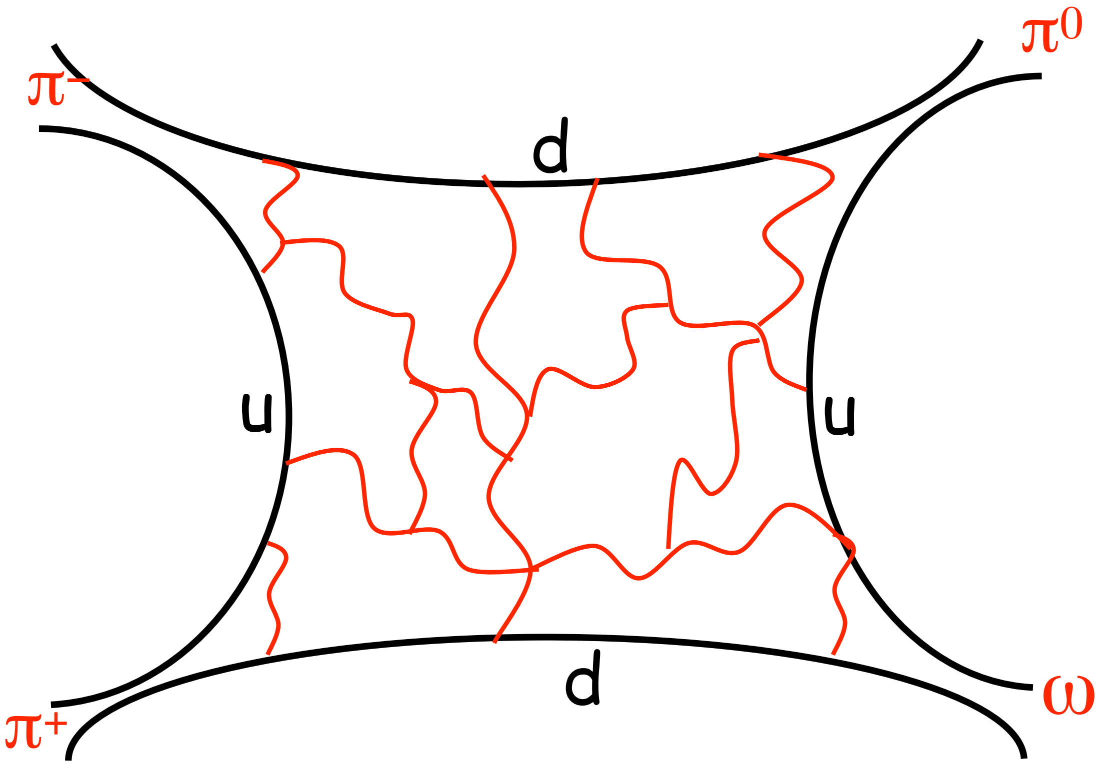
QCD takes over

with its

1. Proven ultraviolet (asymptotic) freedom
2. Conjectured (a later proved, see Guido's talk) infrared slavery (confinement) leading to string-like excitations via chromo-electric flux tubes.
3. A reinterpretation of the duality diagrams (and their higher topologies) in terms of large-N expansions…. ('t Hooft 1974, GV 1976)

In large-N_c QCD duality diagrams take up a precise meaning: they are the sum of planar Feynman diagrams bounded by quark propagators & filled with gluons.

In this approximation resonances have zero width, the scattering amplitude is meromorphic, has DHS duality, generates a scale ($\Lambda^{-2} \sim \alpha'$) via dim.^{al} transmutation



explaining why, from a bottom-up approach, we landed on a string theory of hadrons although:

Not on the right one!

(latter is still unknown)

Turning a defeat into a victory (?)

(Scherk and Schwarz 1974, Green and Schwarz 1984)

1. Massless particles w/ J= 1, 2 are needed for gauge theories and gravity
2. Softness cures the long-standing problem of QFT's UV divergences, making quantum string gravity well defined (at least perturbatively).
3. Extra dimensions, if compact, can be used to generate new gauge interactions through (a stringy version of) the Kaluza-Klein idea.

The (TOE) dream

Upon a rescaling of the string tension by some 20 orders of magnitude string theory can be reinterpreted as a (<u>candidate</u>) theory of all truly elementary particles: not hadrons, but quarks, leptons, gauge bosons, and the graviton.

A finite quantum theory of all interactions, including gravity.

Stringy symmetries

The stringy version of Kaluza-Klein leads to new kinds of symmetries, known as T (target space)-dualities: large and small compactification radii (wrt α') are equivalent for closed strings (upon momentum <-> winding) implying a minimal R_c.

At the self-dual radius, $R_c^2 = \alpha'$, compactification gives non-abelian gauge groups with R_c playing the role of the Higgs field.

A cosmological variant of T-duality is also at the basis of new (big bounce) cosmologies (M. Gasperini and GV, 1991)

The D-brane revolution

(J. Polchinski 1994, ...)

- T-duality looked only possible for closed strings since open strings can carry momentum but, apparently, no winding.
- T-duality is deeply rooted in the canonical transformation P <-> X' (the latter being related to winding)
- For open strings such a transformation relates open strings with Neumann b.c. (free ends) to open strings with Dirichlet b.c. (fixed ends).
- D-strings carry winding but no momentum.
- T-duality connects open N- and D-strings while it relates closed strings to themselves.
- D (Dirichlet)-branes are sub-manifolds of 9-d space on which the ends of D-strings are stuck.

The brane revolution led to many important results e.g.

- The first example of black-holes whose Bekenstein-Hawking entropy can be given a stat. mech. interpretation by counting their micro-states (Strominger-Vafa, 1995);
- Apparently unrelated string theories are actually connected to each other through a web of dualities so that, eventually, they all appear to descend from different limits of a common ancestor, a mysterious M-theory in 11 d (Witten, 1995) with the 11th dim. related to the string coupling.
- The most recent (and amazing) use of D-branes came however in 1997.

Gauge-gravity duality
(J. Maldacena 1997)

A stack of N D3-branes has a U(N) gauge theory living on their 4-d space-time.

Take the large-N limit, keeping $\lambda = g^2N$ fixed ('t-Hooft limit)

In the ambient 10d space-time the branes source a geometry which approaches asymptotically AdS_5xS_5 with radius fixed by λ.

In 1997 J. Maldacena conjectured an equivalence (made precise by E. Witten) between a maximally supersymmetric gauge theory in 4d and a 10d supergravity theory in AdS_5xS_5

The large-λ limit of the gauge theory gets related to the large-R_{AdS} limit of the gravity theory.

Difficult non-perturbative phenomena on the gauge-theory side get mapped into an "easy" small curvature regime on the gravity side.

Example: a lower bound on shear viscosity ($\eta/\sigma > 1/2\pi$) was predicted and is apparently saturated by the quark-gluon plasma produced at Brookhaven-LHC.

There is by now overwhelming evidence for the validity Maldacena's conjecture.

Back to square one?

Maldacena' conjecture has been generalized to other gauge-gravity pairs.

Attempts have been made, with some success, to extend the correspondence to less supersymmetric theories and even to (large-N_c) QCD.

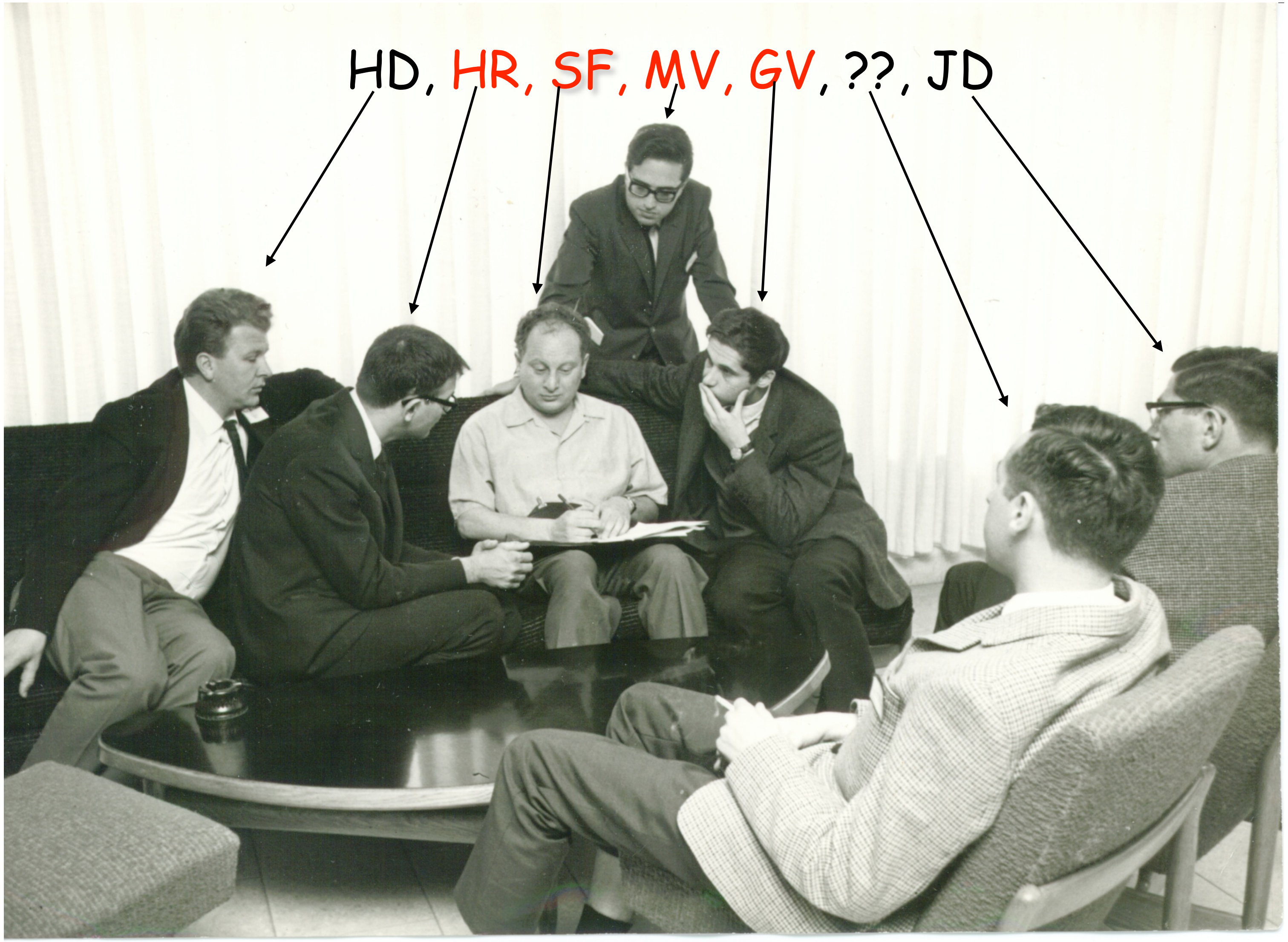
We seem to be back to the problem we mentioned earlier:

Can we find out, at least at large N_c, how to describe the true string lurking behind the hadronic world?

Perhaps a simple gravity problem can shed light on a hard gauge theory problem...

That would close
a 50 years old circle!

Thank You!



Weizmann Institute, 1967