LECCE 21-25 May 2004

KIRITSIS

STRING PHYSICS
at
LHC (?)

Reading

EK : hep-th/0310001
CC : hep-~~ph~~/0404096
GG : hep-ph/0308112
GG : hep-ph/0311344

<u>Units</u>: $\hbar = c = 1$, $M \sim \frac{1}{L}$

Introduction

Why do we believe there is anything more at LHC (except Higgs)?

- (Esthetics): "Explain" the parameters of the SM

- (Practical): $U(1)_Y$ is UV strong $\longrightarrow$ new physics

AND somewhere gravity must "fall in".

CRASH COURSE IN HISTORY

$\Rrightarrow$ GUTs $\longrightarrow$ One gauge group
no gravity

$\Rightarrow$ $M_U \sim 10^{16}\,\text{GeV}$

DOWNSIDE: HIERARCHY PROBLEM

HIERARCHY → SUSY (global)

~~SUSY~~ (global) → SUSY (local) $\equiv$ SUGRA

Gravity + strings. (UV completion

What do we expect at TeV scale experiments ?

IT SEEMS THAT:

- SUSY at ~TeV
  and/or
- New physics at TeV
  and/or
- None of the above!

WHAT I will tell you is what some guesses about new physics are.

Rough plan

- Extra spacetime dimensions
- Gravity and strings
- Models and obsen
bles
    - string states
    - BHs
    - Z's (anomalous U(1)'s

- Experimentalists need to know what theorists tell them to look for.

- Most need to understand the "rough" theoretical ideas (in order to appreciate their weight)

↳ this helps to make them excited about the physics : Without excitement they will never become top physicists.

- Once in a while be different : search for something nobody told you to!!!

Extra dimensions

Why?

- Esthetic: (unifications of gauge and gravitational forces (at the expence of renormalizability)
- String theory imposes them (UV completenes at hand)

Why extra dimension are not visible today?

A popular option **(klein)**: Extra dimensions are compact and small (other options later)

Consider 5 dimensions
$M_4 \times S^1$ with radius R.
and a single massless scalar
in 5D.

$M = 0,1,2,3,4$

$$\mathcal{L} = -\frac{1}{2} \partial_M \Phi \partial^M \Phi$$

$$\Phi(t,\vec{x},y) \equiv \Phi(x^\mu, y)$$

Periodicity: $\Phi(x^\mu; y + 2\pi R) = \Phi(x^\mu, y)$

$$\Rightarrow \Phi(x,y) = \sum_{n \in \mathbb{Z}} \phi_n(x) e^{in\frac{y}{R}}$$

$$\phi_n^* = \phi_{-n}$$

A 5D field $\Phi(x,y)$ is equivalut to an infinite collection of 4D fields $\underline{\phi_n(x), \ n \in \mathbb{Z}}$

$$S = \int d^4x \int_0^{2\pi R} dy \, \mathcal{L} = -\pi R \int d^4x \sum_{n=-\infty}^{+\infty} \Big(\partial_\mu \phi_n \partial^\mu \phi_n^*$$
$$+ \frac{n^2}{R^2} \phi_n \phi_n^* \Big)$$

The infinite collection of fields ⑦
ϕ_n are 4d, free and have
4d masses $m_n^2 = \frac{n^2}{R^2}$ $\Big\}$ kaluza-klein modes

$\rightsquigarrow$ $m_0^2 = 0$

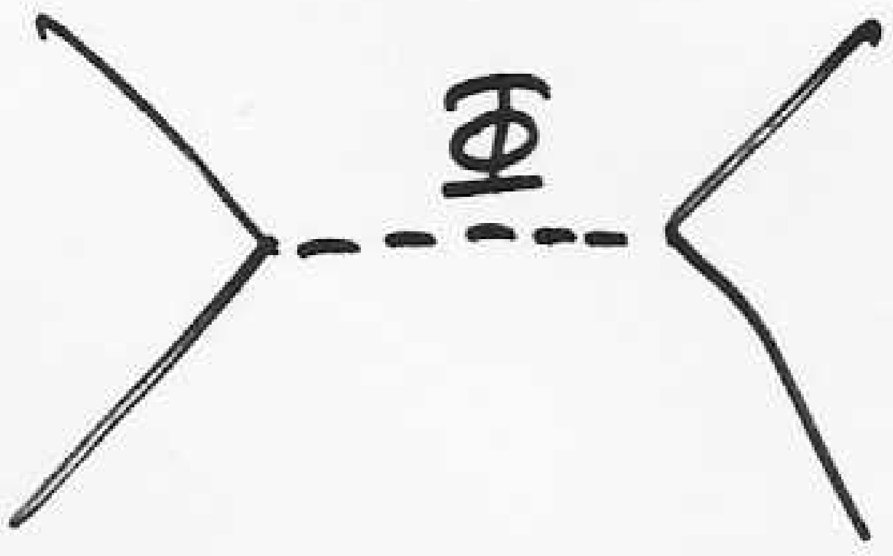
If the available energy $E \ll \frac{1}{R}$, the massive fields cannot be produced

Only $\phi_0(x)$ is observable

$\Longrightarrow$ 5th-d is <u>unobservable</u>

if we can have $E \gg \frac{1}{R}$
we can observe the KK states and have a glimpse in the 5-th Dimension.

Consider the force mediated by this 5D scalar:



For distances $r \gg R$

$\Rightarrow$ 4d behavior

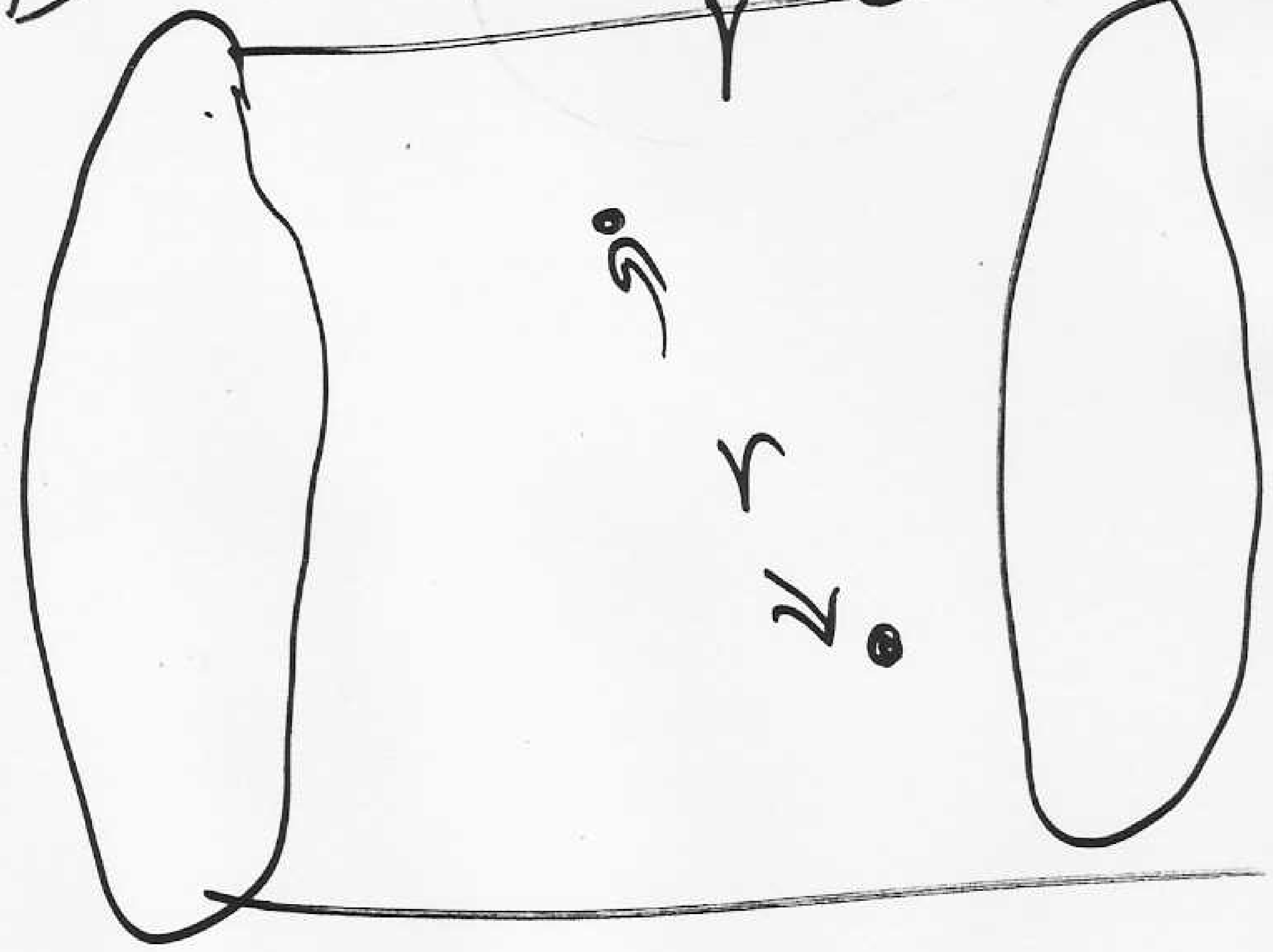
$\phi_0 \sim$ Force: $\frac{1}{r^2}$ → 4d

$\phi_n \sim \frac{1}{r^2} e^{-m_n \cdot r} = \frac{1}{r^2} e^{-\frac{nr}{R}}$

$r \gg R \Rightarrow \phi_n$ force irrelevant

But for $r \ll R$ all ϕ_n contribute $\Rightarrow$ like in 5D

$\Rightarrow$ Force is 5D $\sim \frac{1}{r^3}$



5D gravity

Consider now a graviton g_{MN} in 5D

$$\begin{array}{c|c} & \begin{array}{cc} \phantom{g_{\mu\nu}} & 5 \end{array} \\ \begin{array}{c} 4\times4 \\ 5 \end{array} & \left(\begin{array}{c|c} g_{\mu\nu} & A_\mu \\ \hline A_\mu & \phi \end{array}\right) \end{array}$$

We expect to have (at zero mode lev
a graviton, a U(1) gauge field and a scalar in 4D.

$$S_5 = \frac{1}{2} M^3 \int d^4x\, dy \sqrt{\det G}\; R_{(5)}$$

$$\Downarrow$$

KALUZA

$$M_p^2 \longleftarrow$$

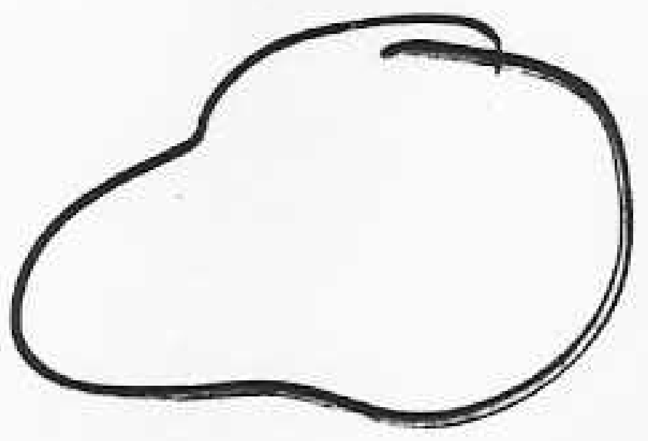
$$= \pi \boxed{M^3 R} \int d^4x \left\{ R_4(g) - \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{4} e^{-\sqrt{3}\,\phi} F_{\mu\nu}^2 \right\} + \text{KK states}$$

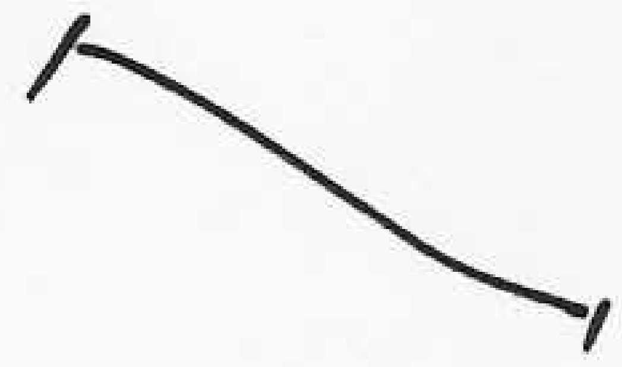
Higher dimensional QFT has more "phase space" but looses control in the UV

Enter : String theory

- UV finiteness including gravity { From the closed string sector
- Seems to contain all SM ingredients (gravitn, gauge theories, Yukawa interactions, chiralitn)
- Existence of fermions ⟹ high energy supersymmetry (born first in ST G.N.)

Main ingredient : fundamental entities are not "point-like" particles but strings

A closed string  with tension T

An open string 

Classical strings under tension T
→ collapse to points

In the quantum theory they do-
not (due to Heisenberg)
their minimum legth (string legth)

$$l_s \sim \frac{1}{\sqrt{T}} \qquad T \equiv \frac{\text{energy}}{\text{legth}}$$

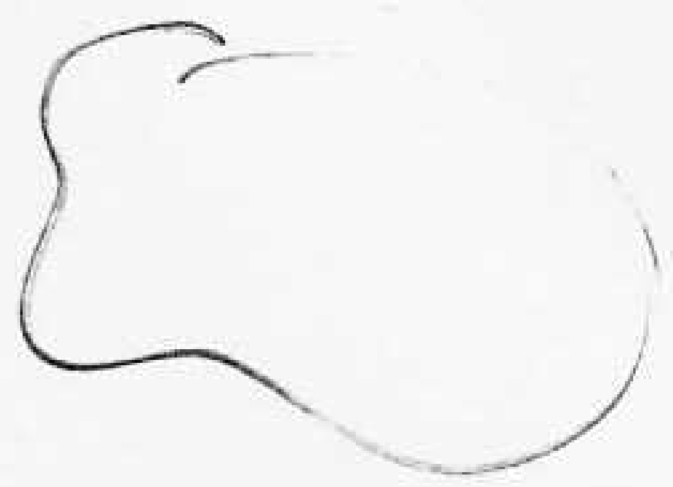
(Excercize)

What is the difference between a  and

a 

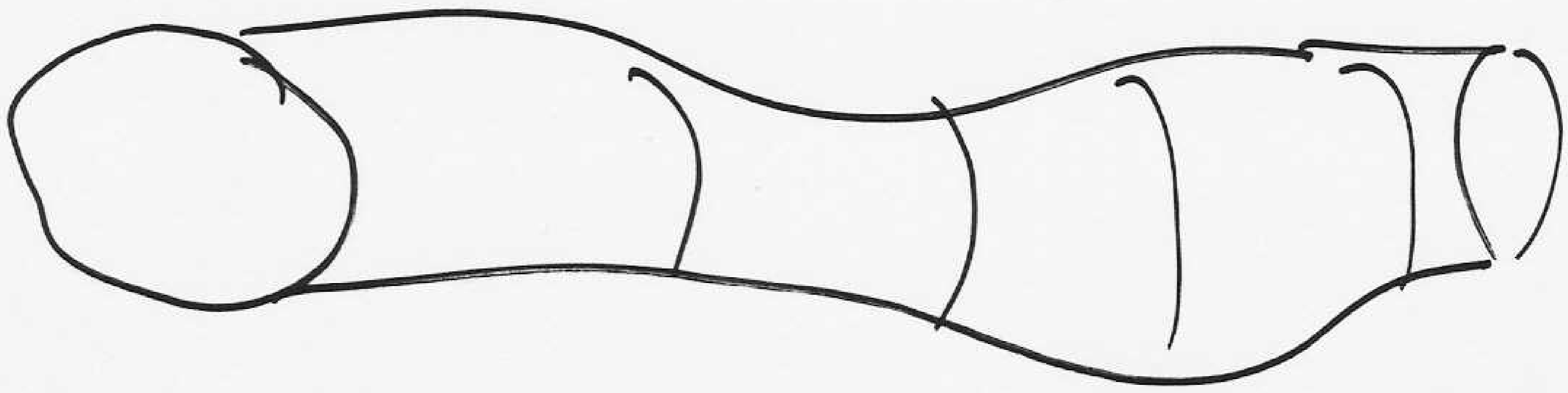
A • gives rise to a quantu field (particel)

A



has many more degrees of freedom:

it can move like a particle (CM motion)



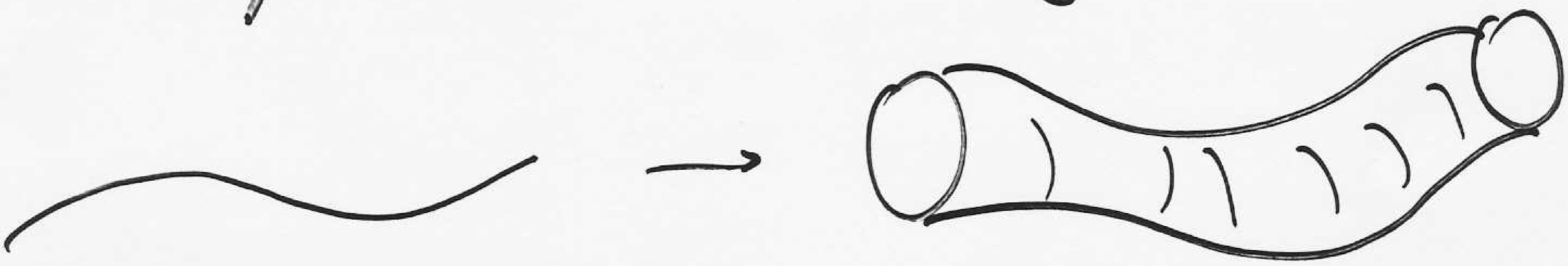
But it can also vibrate in an ∞ # of modes (harmonics)

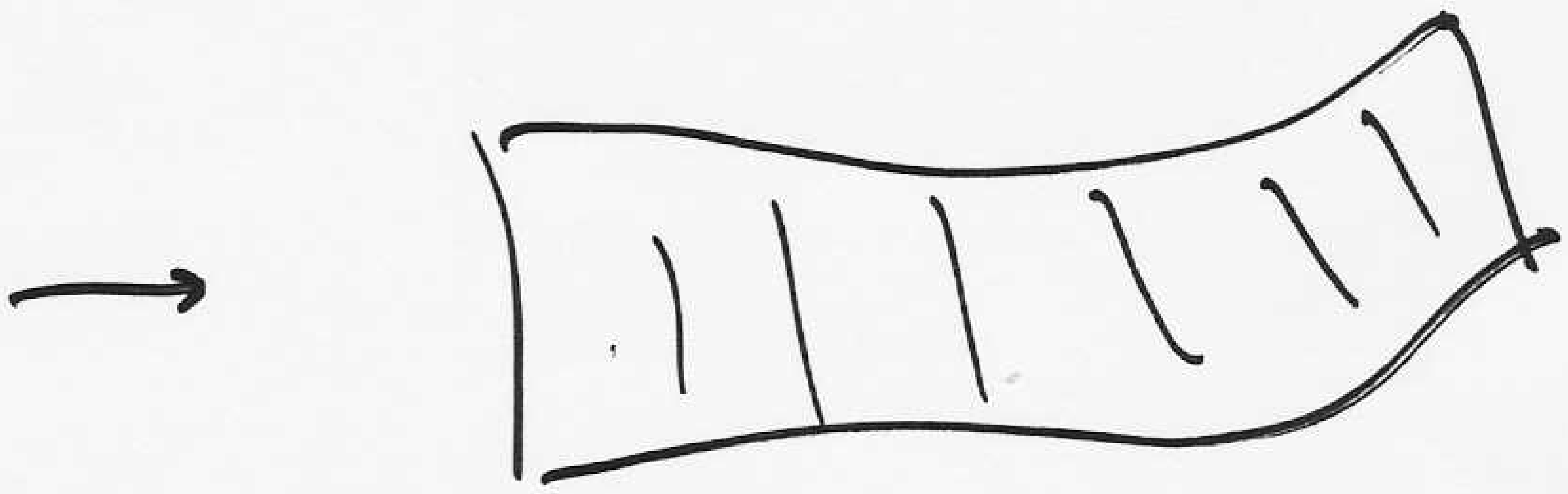
A string vibrating in a given harmonic is equivalent to a different type of particle

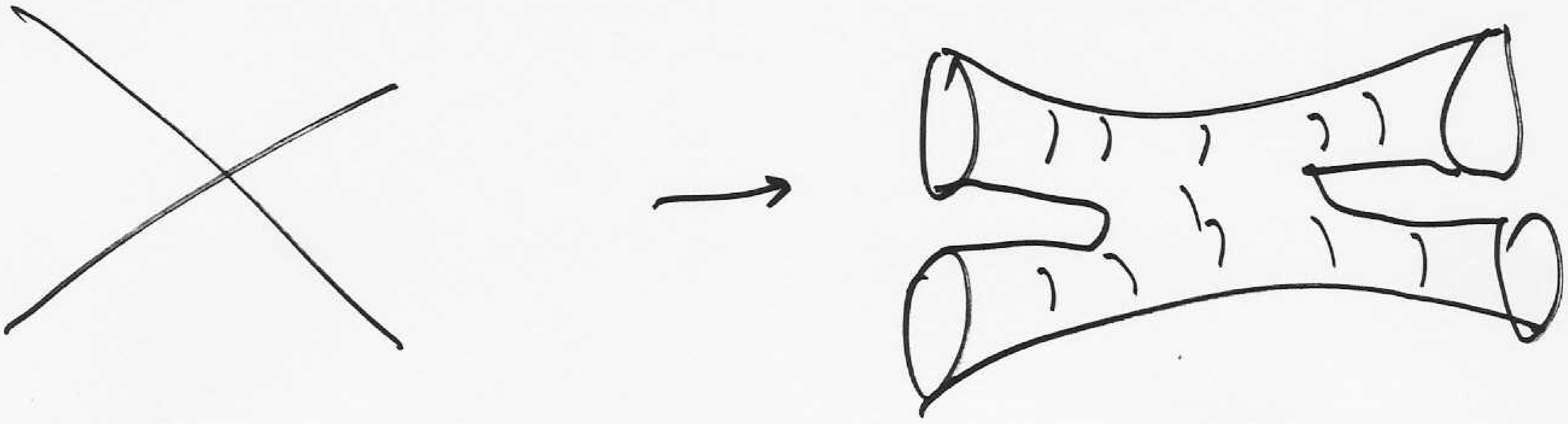
The frequencies are $n \cdot \sqrt{T}$
The masses of the vibrating modes are:

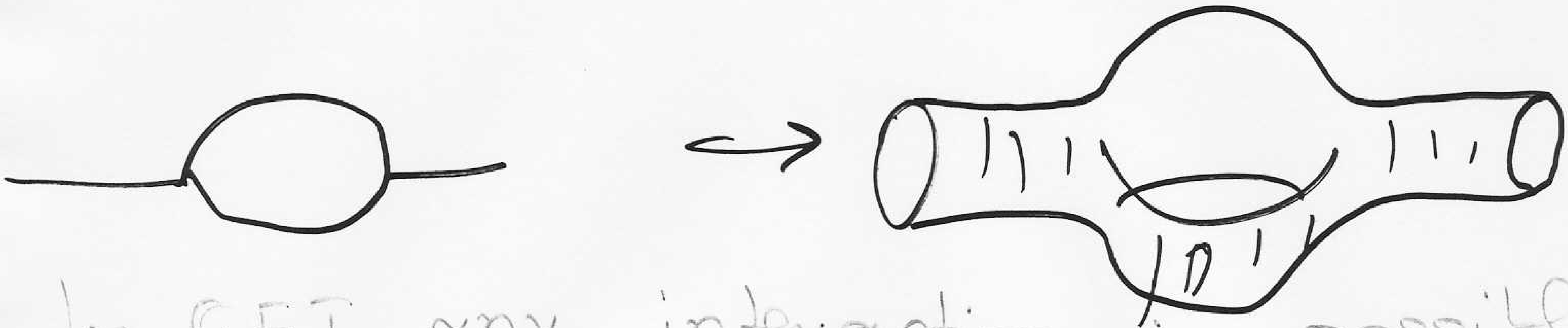
$$m_n^2 = n \cdot T$$

Feynman diagrams



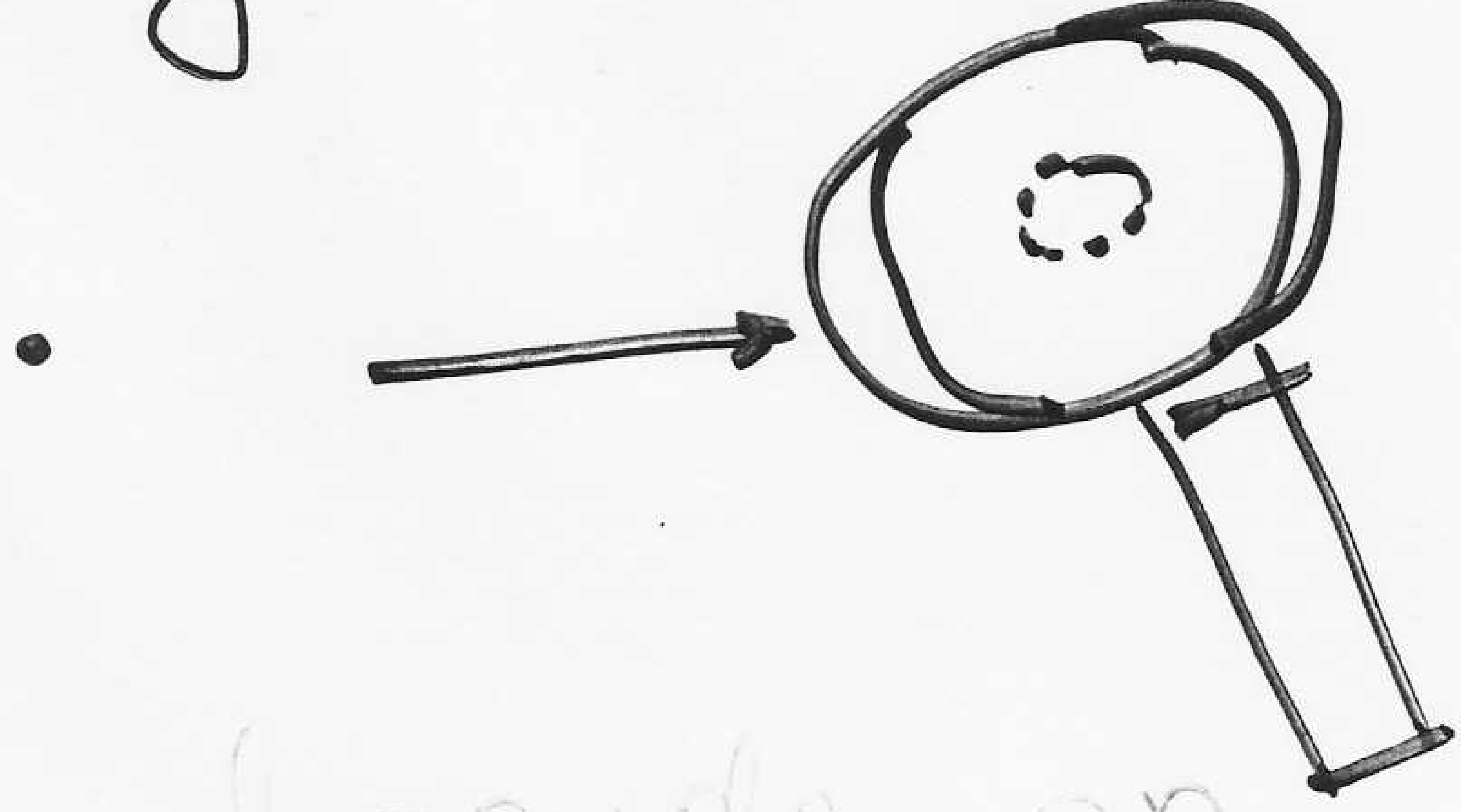






In QFT any interaction is possible
NOT IN S. T.

If elementary particles are strings how did we miss it?



it depends on our probe.

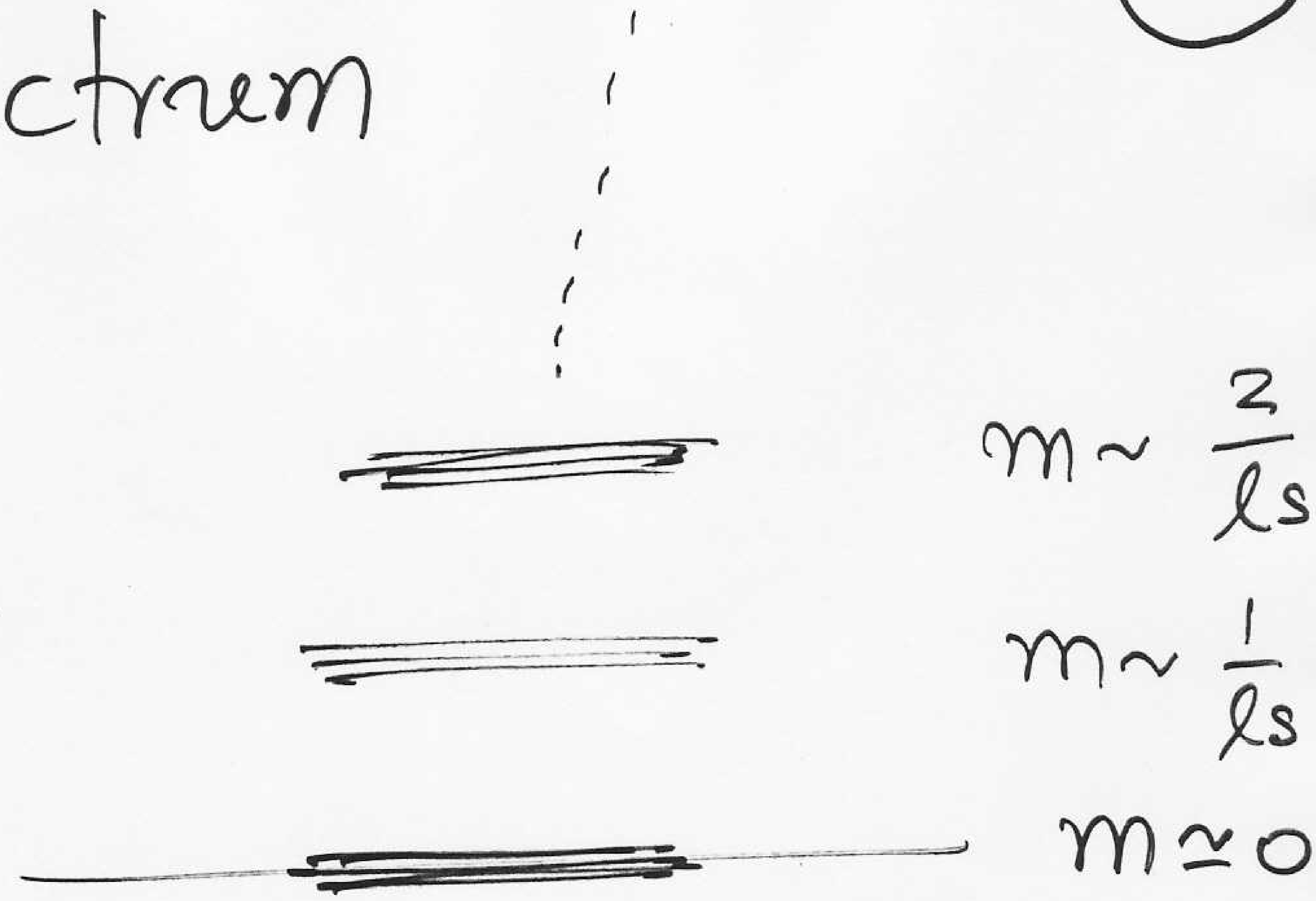
if the string length is
<< our present magnifying glass (CLEP) then they are visible as points.

String T

QFT | string physics.

$\ell' << \ell_s << \ell$

String spectrum



iff experimentally available energies are $\leq \frac{1}{l_s} \equiv M_s$ string excitations cannot be produced $\Rightarrow$ **strings behave as stiff** $\Rightarrow$ cannot tell the difference from point particles.

So: what values can M_s take?

It depends: it can take anywhere from 1 TeV to 10^{16} TeV (Planck scale)

- if $M_s \sim 10^{16}$ TeV

  there is no chance to see strings at LHC (compare with gluons at 10^{-5} eV

- if $M_s \gtrsim 1$ TeV

  there is a reasonable chance to detect string physics.

Strings (for consistency)
live in 10D spacetime

Where are the extra 6D.

Probably hidden à la KK

They are compact → M_6
with Volume ~ R^6

Again if $\frac{1}{R} \sim$ TeV
we may see them at LHC
if $\frac{1}{R} \sim 10^{16}$ TeV

⟹ <u>no chance!</u>

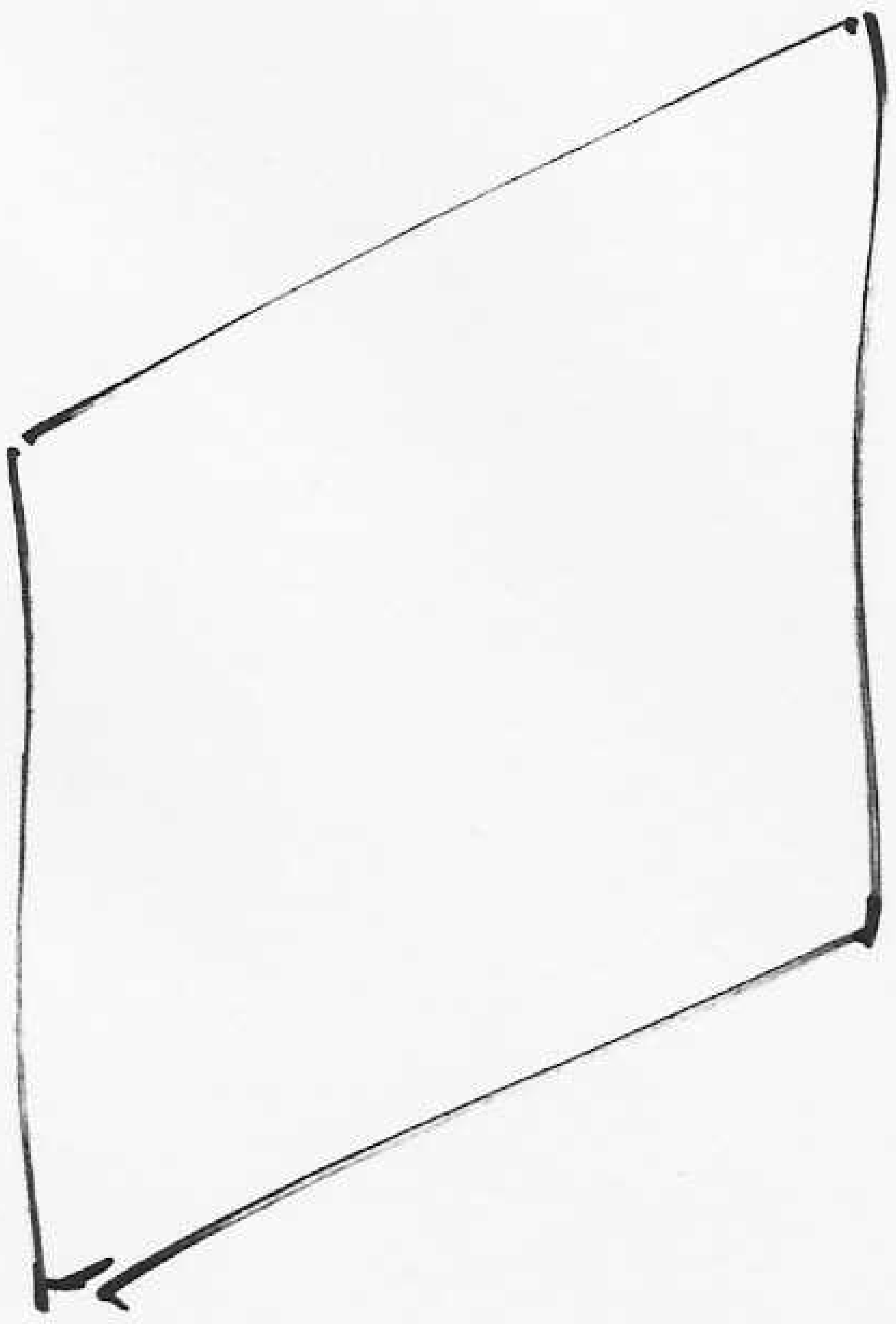
More strange stuff:
(Mem)- branes

Why just strings and not membranes?
(fundamental membrane theories are too difficult to handle)

But....
"soliton-like" branes are possible,
(and in string theory
mandatory)

They imply lots of interesting new physics.

D_p - BRANES



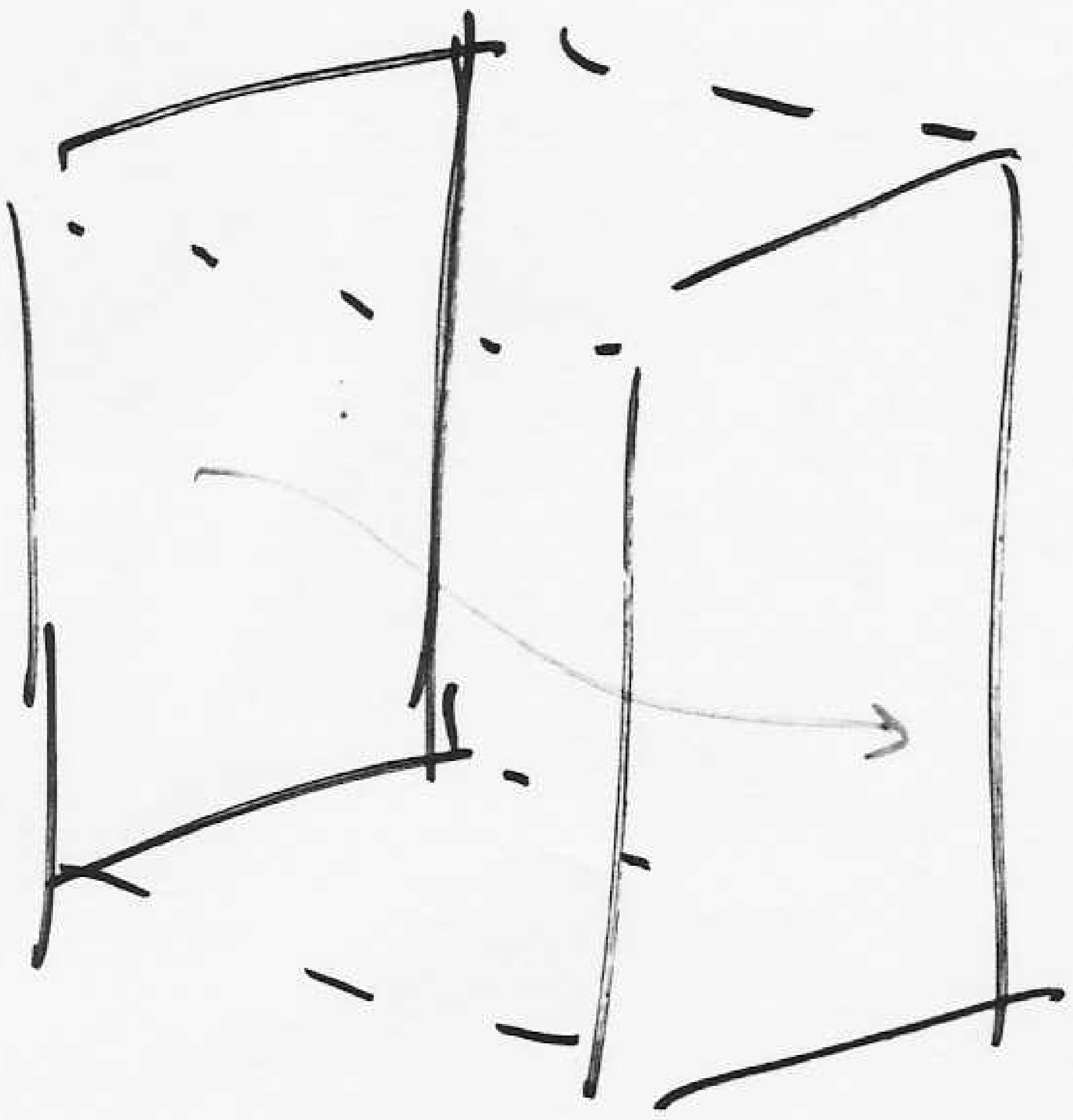
p-dimensional hyper-plane

$p=0 \Rightarrow$ particle

$p=1 \Rightarrow$ string

$p=2 \Rightarrow$ membrane

etc.

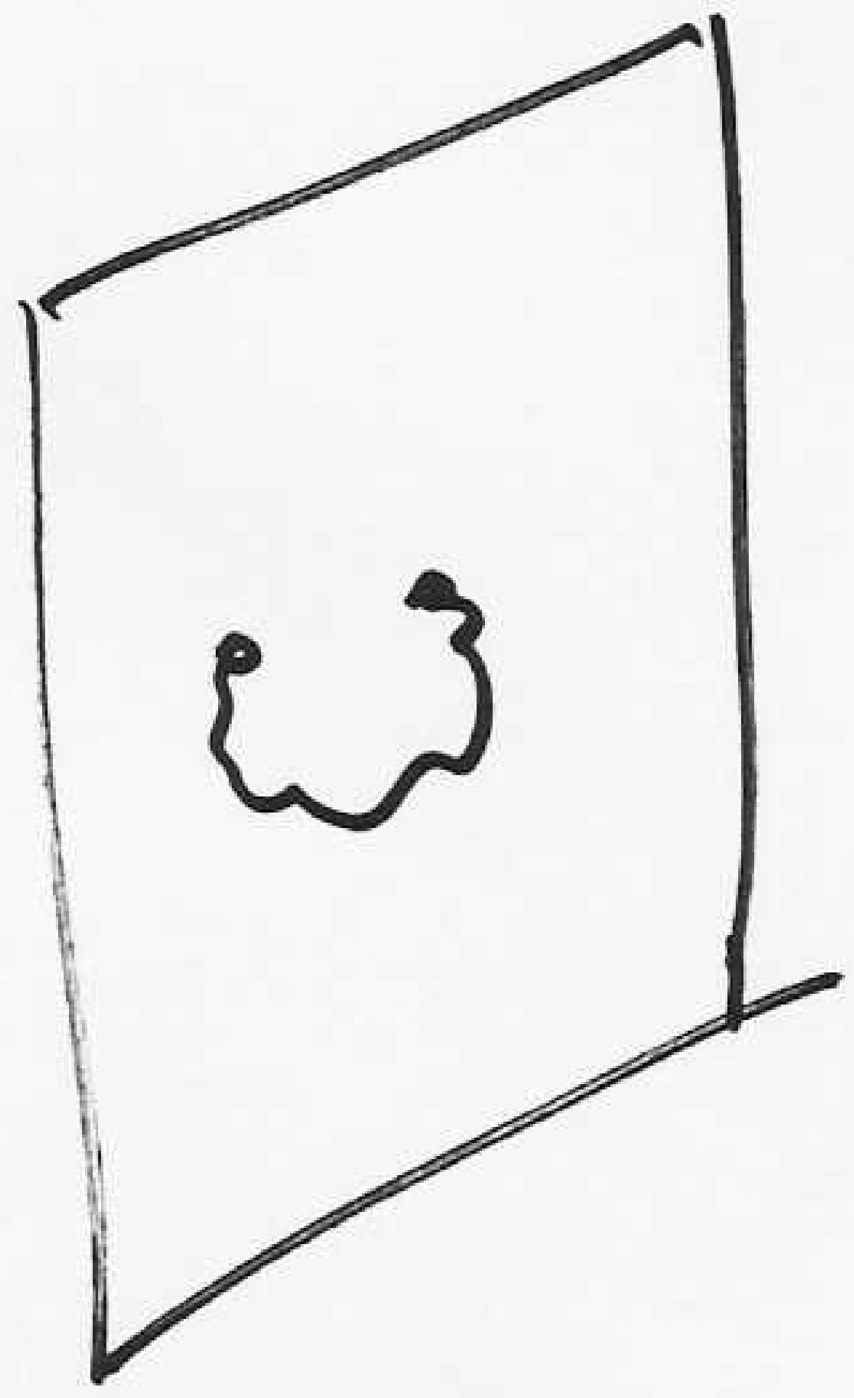


→ $(p+1)$ - dim world volume.

IT IS DYNAMICAL (can fluctuate)

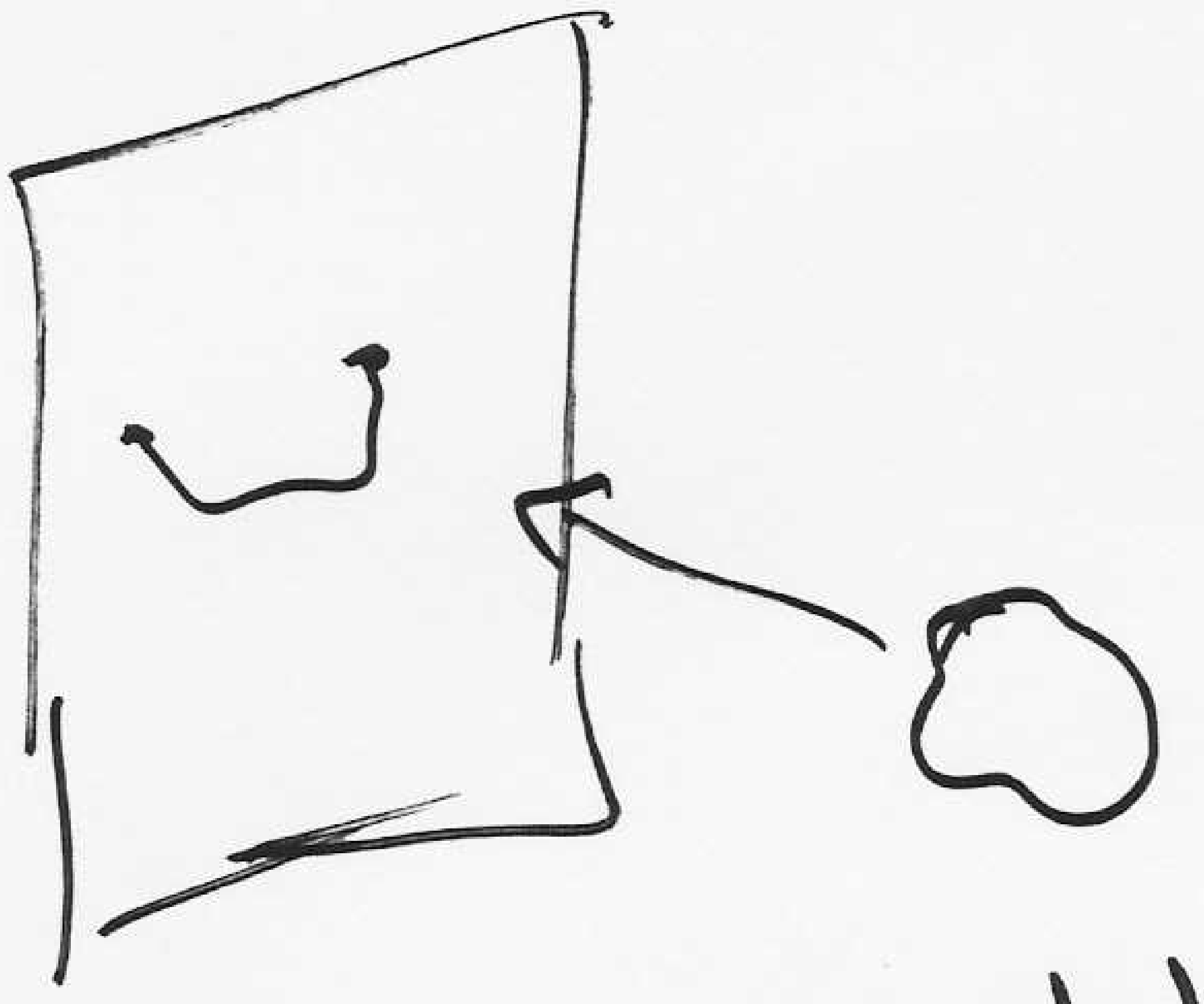
⇒ There are degrees of freedom (waves) living on the W.V.

The fields living on the D-branes are vectors, fermi and scalars



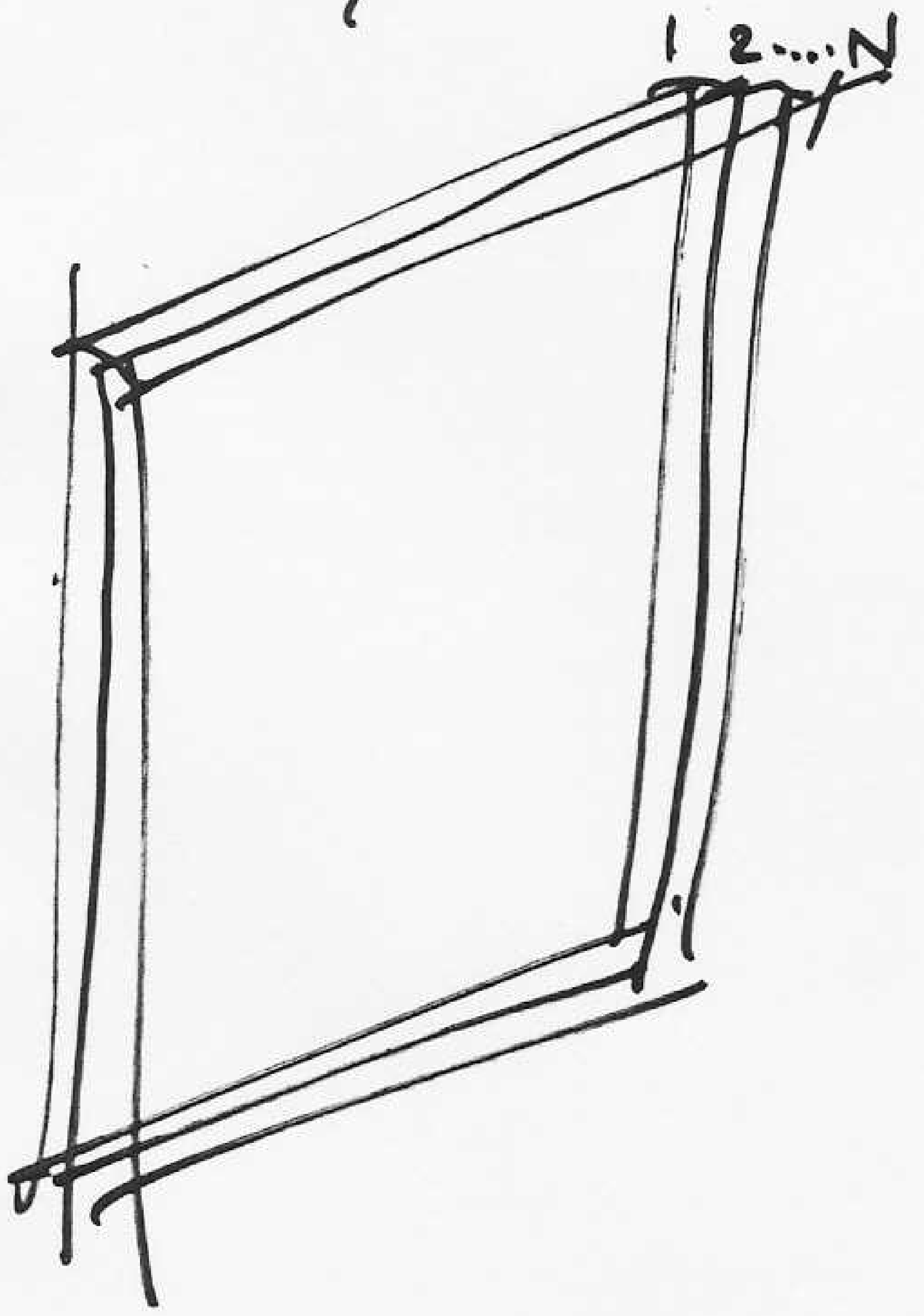
They are described by open strings with end points ending on the brane.

Their vibrational modes are the particles localised on the branes.

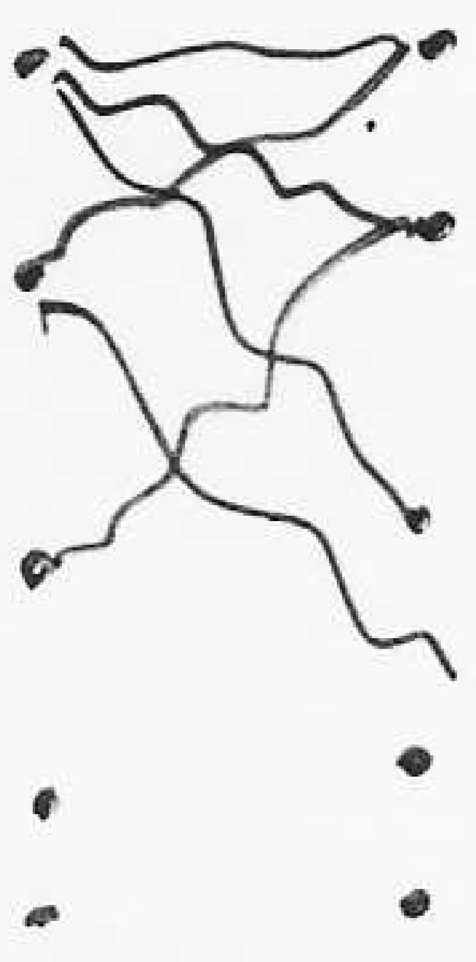


There are also the closed strings in the bulk that interact with the brane.

many branes (at the same place)



Many open strings.



$N \times N = N^2$

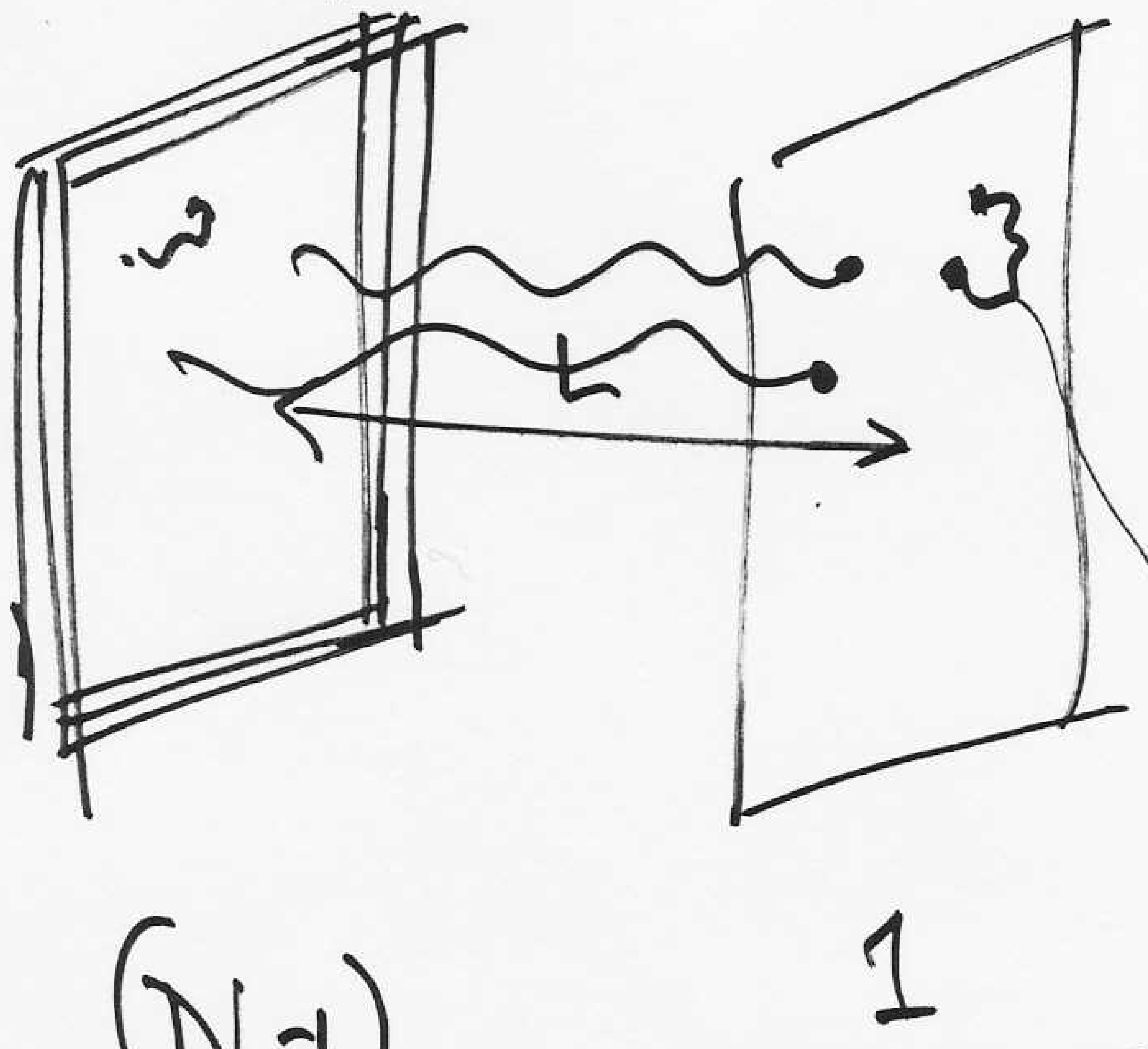
Each gives a vector boson

$\Longrightarrow$ the full theory on the brane U(N) Yang-Mills

$\Rightarrow$ # of branes $\equiv$ # of "colors"
(geometrical) (gauge theoretical)

Because all the strings have length $=0$ $\Rightarrow$ gauge bosons are massless.

take one of the branes appart:



N-1 branes as before:
$\longrightarrow$ U(N-1)

$\longrightarrow$ U(1)

But: 2(N-1) strings are streched

$\Rightarrow$ vectors are massive

$$m^2 \sim L^2$$

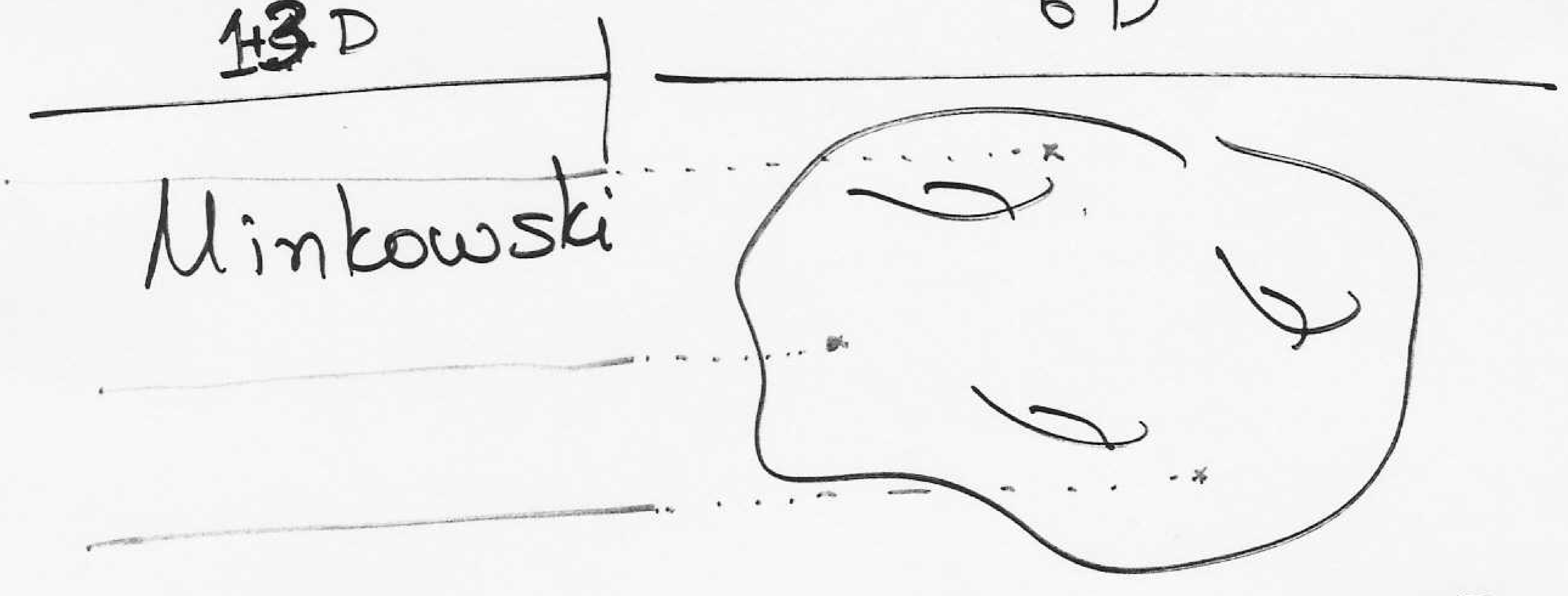
$\Rightarrow$ U(N-1) × U(1) and 2(N-1) massive gaug bosons.

$\rightarrow$ Higgs effect (geometrical)

$$U(N) \longrightarrow U(N-1) \times U(1)$$

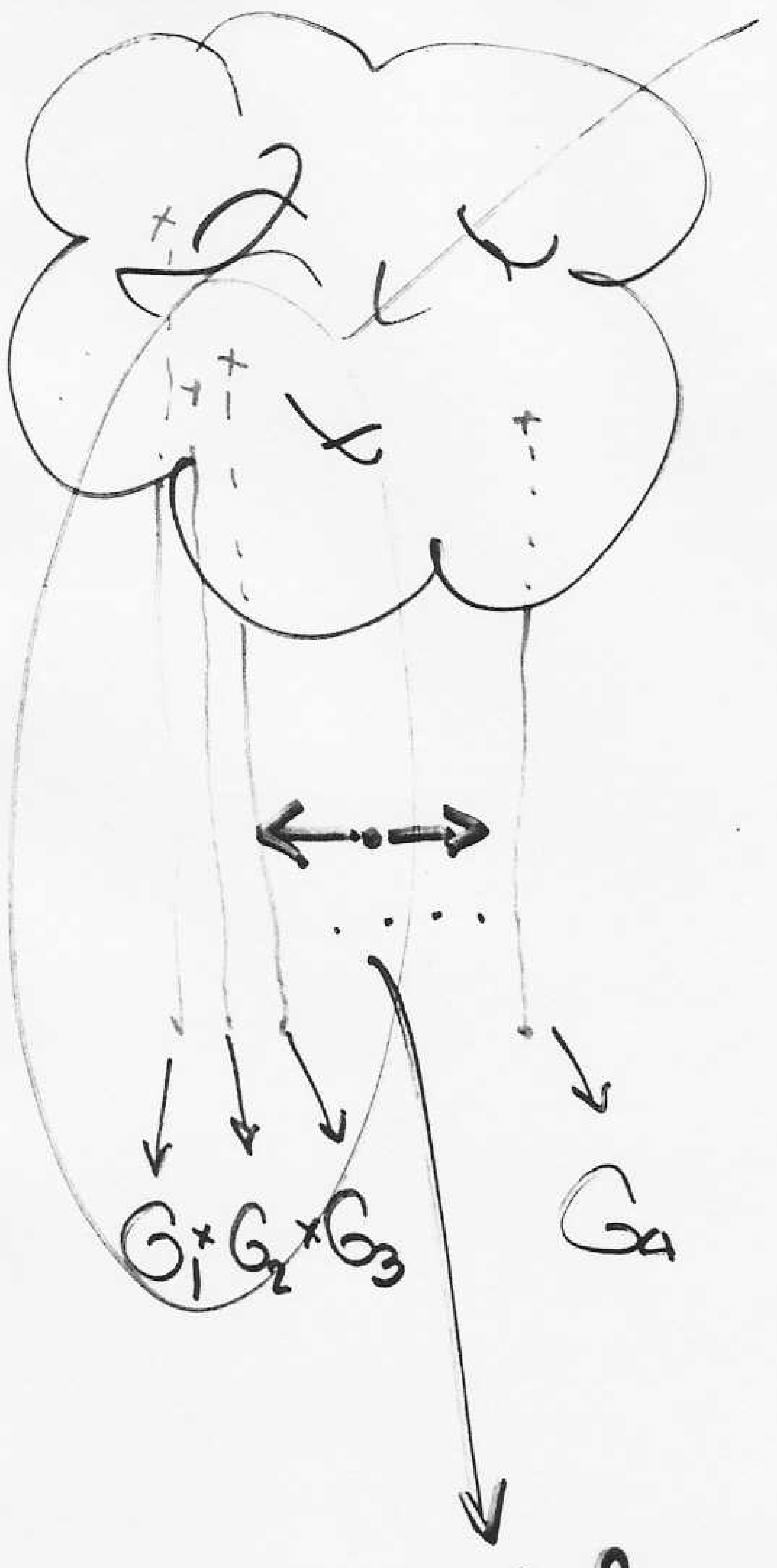
D-branes geometrize gauge theory dynamics.

What does, a generic string ground state (with $M_s \sim$ TeV look like?



compact 6D manifold. M_6

+ D3 branes (or higher) inserted at various points in M_6



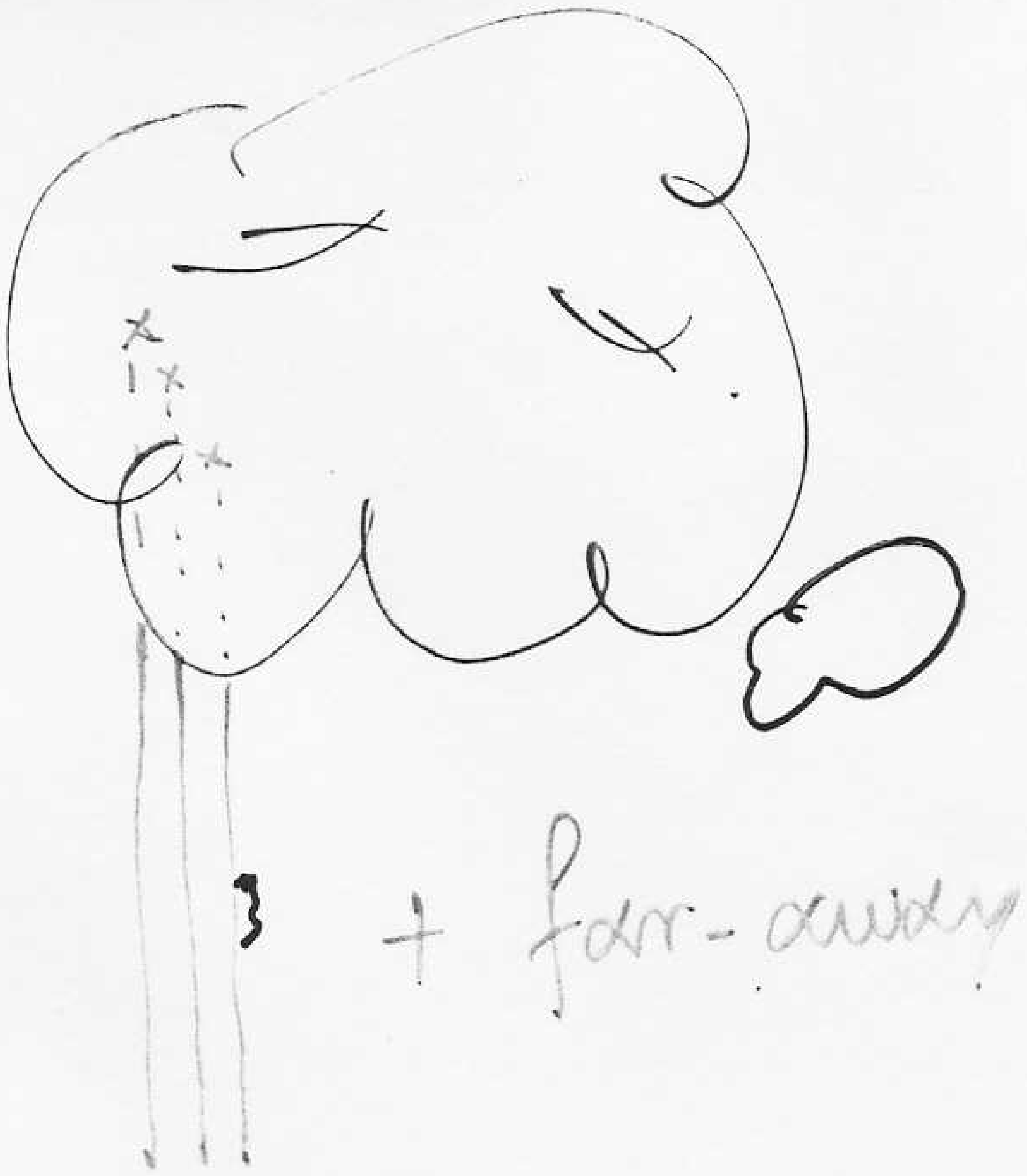
Low energy gauge group:

$G_1 \times G_2 \times \ldots$

from branes.

if this distance is $\geq (\text{TeV})^{-1}$ other branes are invisible (today)

So we can focus on the local brane collection.



Particles?

- on branes : gauge theory +
  standard model
  matter
  + stringy vibratio
  (masses ~ M_s)
  ~ $\frac{1}{l_s}$

- in the " bulk "
  gravity and other
  universal interact

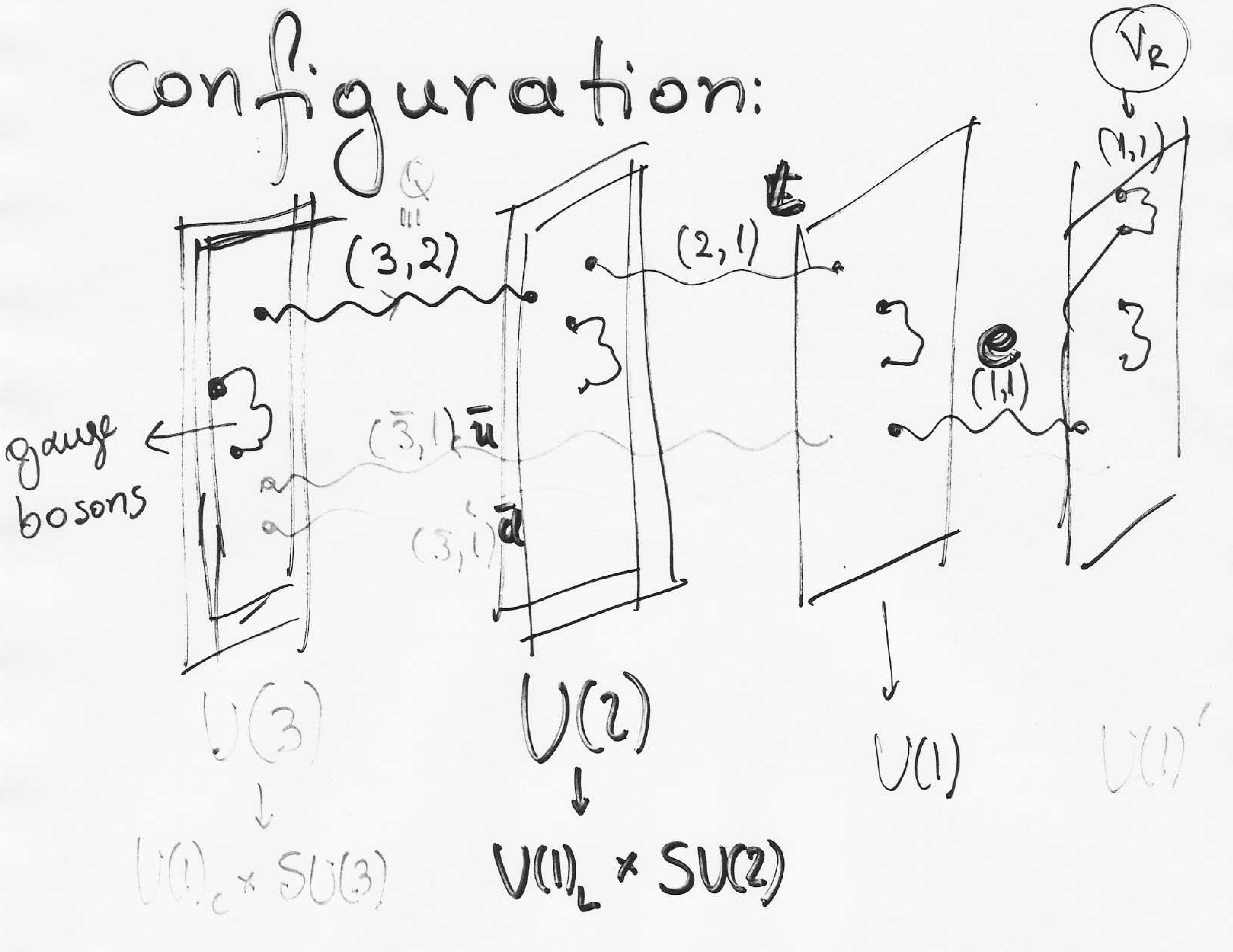
+ KK states from M_6
(masses ~ $\frac{1}{R}$) $V_6 \simeq R^6$

+ stringy vibrations (masses ~ M_s

We will now look closer to each class of new(?) particles.

Particles from the branes

The minimal brane configuration:



There seems to be something wrong!!

$$G_S = SU(3)_c \times SU(2)_L \times U(1)_c \times U(1)_L \times U(1) \times U(1)'$$

Too many photons !!

BUT: . . . . . beware of anomalies

Out of the 4 U(1)'s, 1 is anomaly free ⟶ Hyperchang
the others are "anomalous"

Anomaly = a classical (gauge) symmetry is violated because of quantum effects

result in string theory " the gauge symmetry "breaks

(27)

The breaking is almost like the spontaneous symmetry breaking.

The masses of the "anomalous" U(1) gauge bosons can be calculated from string theory.

Typically: $m \sim M_s$

sometimes much smaller.

$\Rightarrow$ at the string scale: 3 U(1)'s break

at the EW scale $SU(2) \times U(1)_Y \xrightarrow{\text{break}} U(1)_{EM}$

Generic feature: at least 3 massive ($U(1)$) gauge bosons with masses of M_s or smaller.

(they are calle usually Z's

* * *

For anything to be observable in LHC

$$M_s \sim 1 - 10 \text{ TeV}$$

(maybe a bit more!)

Of all (suspected) signals
(Z', string states, BH, KK states), Z's are
the most generic + easiest. (mass ~ $\frac{1}{10}(M_s)$

What are their couplings

⟶ mixing with Z
(because of Higgs effect)

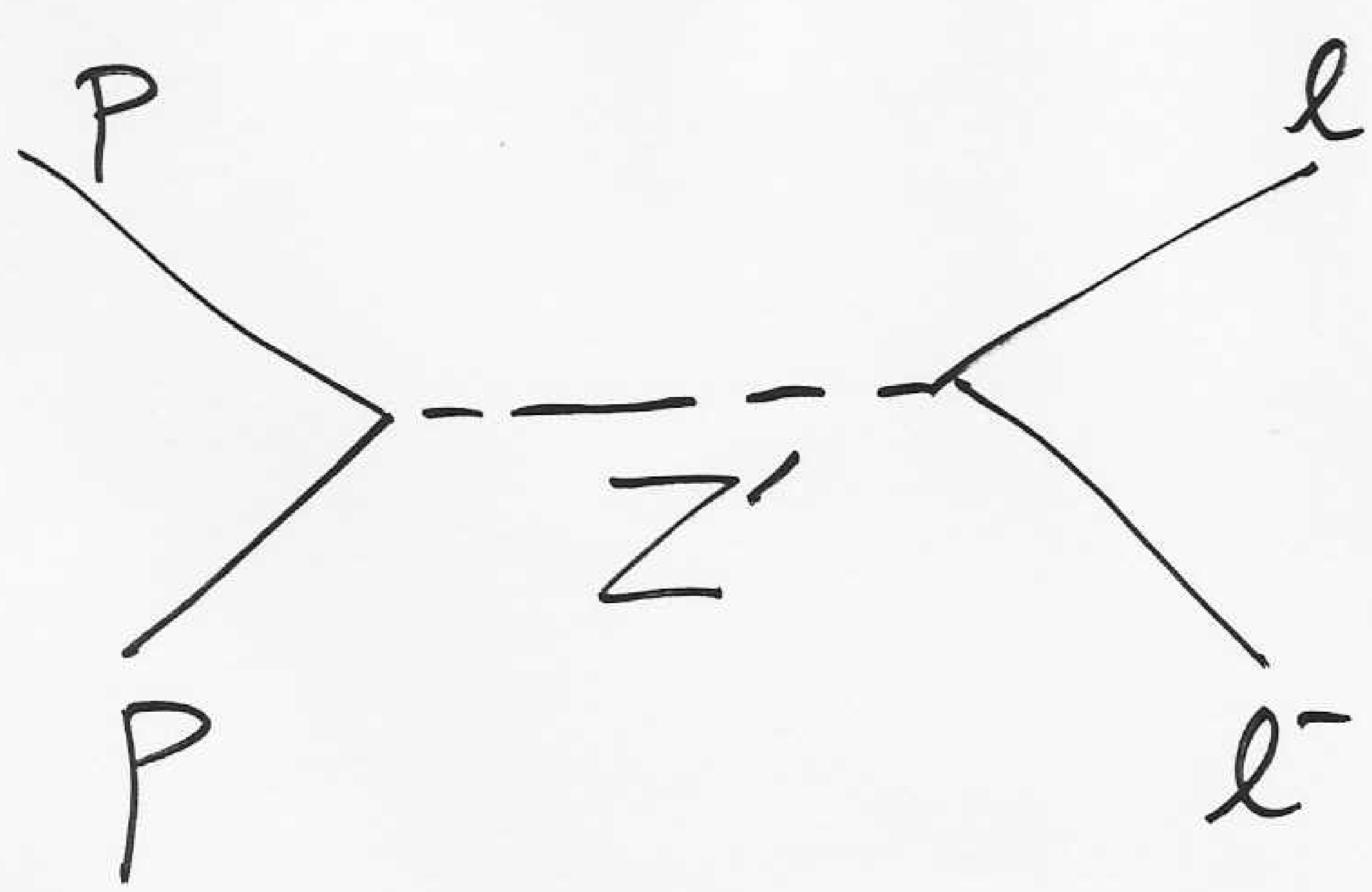
Constraints on their masses (from L.E.P.)

⟶ Couple to quarks and leptons

new: couple to scalars (+ axions)

Well known methods of search

see: hep-ph/0307020



at LHC

Discovery potential: up to $M \sim 5$ TeV (100 fb^{-1}).

Measuring couplings: must sit on Z' resonance.

(mass, total width, cross section)

+ FB assymetry on and off the resonance.

Total decay width: Fit the invariant mass distribution of the dilepton to:

$$\frac{a_0}{\left(M_{ee}^2 - M_{Z'}^2\right)^2 + a_1 \sim \Gamma_{Z'}^2 M_{Z'}^2}$$

Z′ cross section × (leptonic branching ratio)

From # of reconstructed events around the peak.

Leptonic FB asymmetry:

$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}\left(1+\cos^2\theta\right) + A_{FB}^{\ell}\cos$$

($\theta \sim$ angle between initial quark to ℓ in Z′ rest-frame)

(Can be cleaned up by rapidity cuts

Z′ rapidity distribution

STRINGY VIBRATIONS

Masses $\sim M_s$

Quantum # : spin $s = 0, 1/2, 1, 3/2, 2 \ldots$

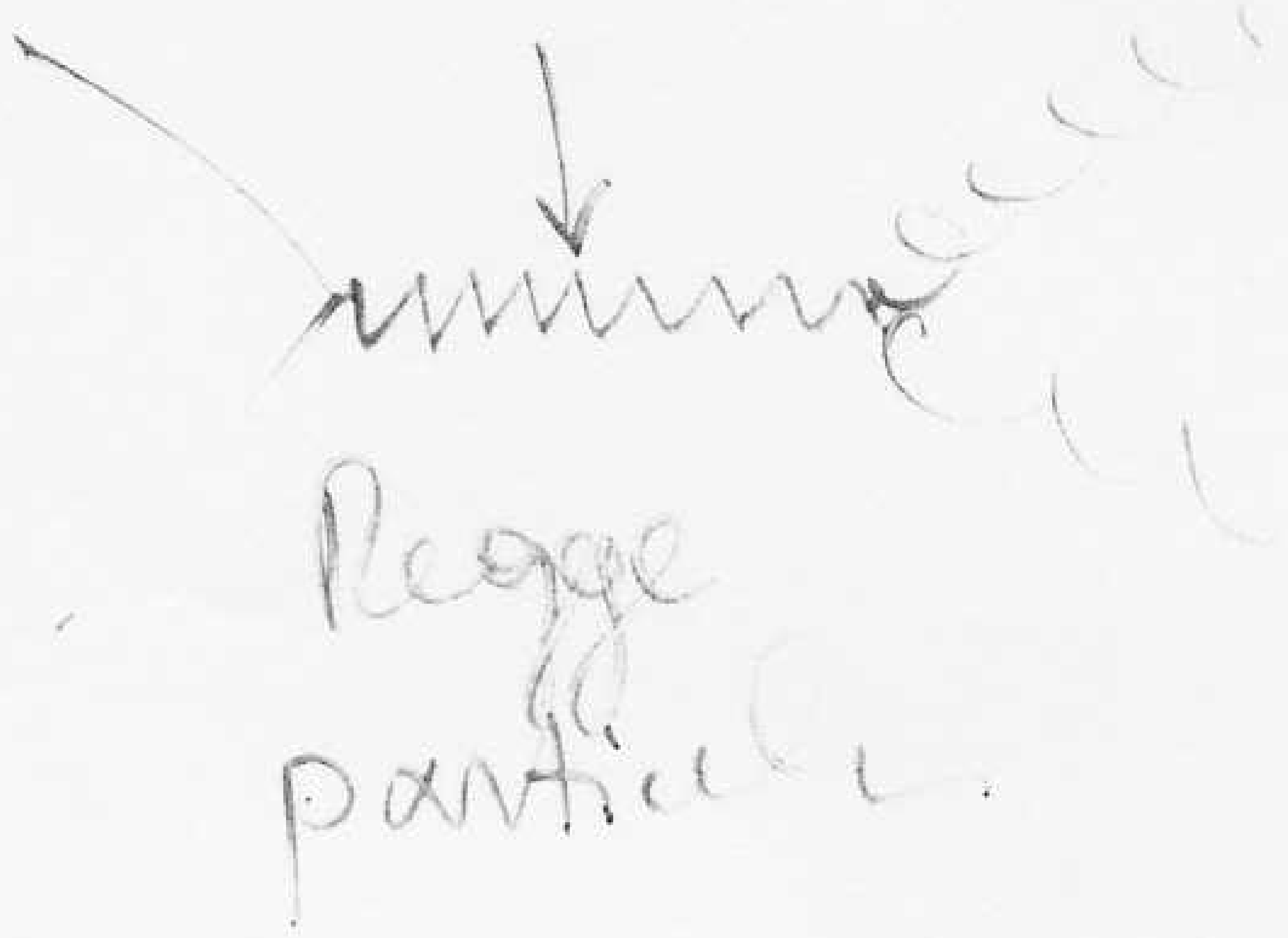
gauge quantum # : as the zero modes

(adjoints, fundamentals etc)

Example: $q\bar{q} \to gg$

leading effect

Stringy contributions



$$A_{lead} \sim \sqrt{\frac{u}{t}}$$

$$A_{full} \sim \sqrt{\frac{u}{t}} \; \frac{\Gamma\left(1 - \frac{s}{M_s^2}\right)\Gamma\left(1 - \frac{t}{M_s^2}\right)}{\Gamma\left(1 - \frac{s+t}{M_s^2}\right)}$$

Such corrections become important at resonance

$\rightarrow$ poles of $\Gamma\left(1-\frac{s}{M_s^2}\right)\Gamma\left(1-\frac{t}{M_s^2}\right)$

All tree level processes behave similarly.

Another diference: (not important for LHC)

stringy scattering at $E \gg M_s$ is exponentially supresed

(Unlike QFT)

Particles from the "bulk"

In 10D $\rightarrow M_{PP}^8 = \frac{M_s^8}{g_s^2}$

$$M_{PP}^8 \int d^{10}x \sqrt{g} \cdot R_{(10)}$$

Upon $\big\downarrow$ compactification:

$$\underbrace{M_P^8 V_6} \int d^4x \, R_{(4)}$$

$$M_P^2 = \frac{M_s^2}{g_s^2} \left[M_s^6 V_6\right] \rightarrow$$ dimensionle (volume in string units

gauge coupling on D3 branes:

$$\frac{1}{g_{YM}^2} \sim \frac{1}{g_s} \sim O(1) \text{ numbe}$$

$V_6 \sim R^6$

$$\Rightarrow \quad M_p^2 = \frac{M_s^2}{g_s^2} (M_s R)^6$$

$M_s \sim 1\,\text{TeV} \quad \Rightarrow \quad M_s^6 V_6 \sim 10^{32}$

$M_p \sim 10^{16}\,\text{TeV} \quad \Rightarrow \quad \frac{V_6}{l_s^6} \sim 10^{32}$

One large dimension $V_6 = R_1 \dots\dots R_6$

$R_2 \sim R_3 \dots R_6 \sim 1$

$R_1 \sim 10^{32}\, l_s \sim 10^{12}\, m$ } excluded

Two large dimensions $R_1 = R_2$

$R_1 = R_2 \sim 10^{16}\, l_s \sim 10^{-4} m \sim 10^{-5} m$

Can we see it?

(Not easy):

Signals ?

the gravitational interactions changes at distances below the $10^{-4}, 10^{-5}$ m range

from $\frac{1}{r^2} \rightarrow \frac{1}{r^4}$

Table-top experiments have given a limit $\sim 10^{-4}$ m.

KK states of the graviton

$$m_n \sim \frac{n}{R} \sim n \times 10^{-4} \text{ eV}$$

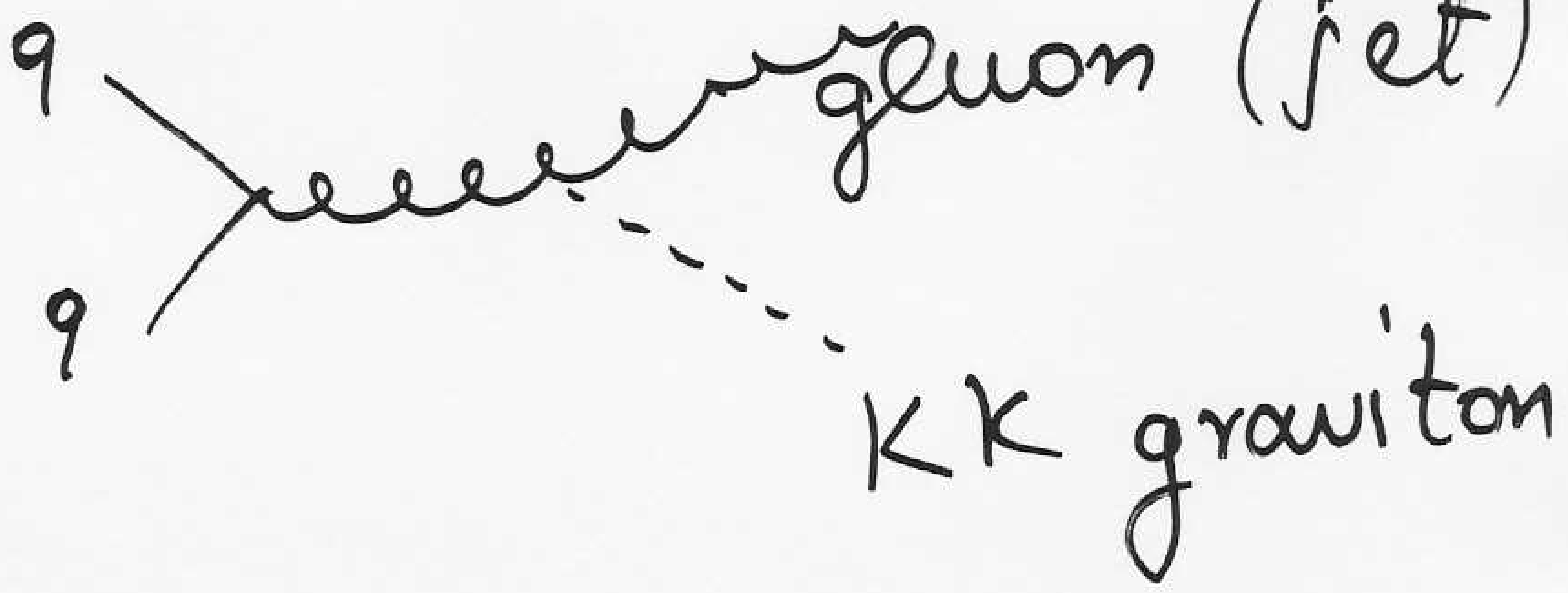
How come we did not see them?

Because they have gravitational couplings. (supressed

$$\sim \frac{1}{M_p^2}$$

But they are many of them:

Example:



if we have energy E, we can produce at most up to $\frac{n}{R} \sim E \Rightarrow n = E \cdot R$ KK states.

for 2 large dimension $N \sim (E \cdot R)^2$

Total amplitude:

$$\sim (E \cdot R)^2 \cdot \frac{1}{M_P^2} = g_s^2 \frac{E^2 \cdot \cancel{R^2}}{M_s^4 \cancel{R^2}}$$

$$\sim \frac{1}{M_s^2} \left(\frac{E}{M_s} \right)^2$$

Becomes important at $E \sim M_s$

At LHC:

- KK graviton production

$$pp \to \text{jet} + \not{E}_T$$

$qg \to qG \to$

$q\bar{q} \to gG \to$

(background from →Z → neutrinos)
can be subtracted by a suffici-
ently high cut in E_T^{jet}.

also $pp \to \gamma + \not{E}_T$

$$q\bar{q} \to G\gamma$$

(background : $\bar{q}q \to Z\gamma$)

- Processes with a tree-level exchange of KK gravitons.

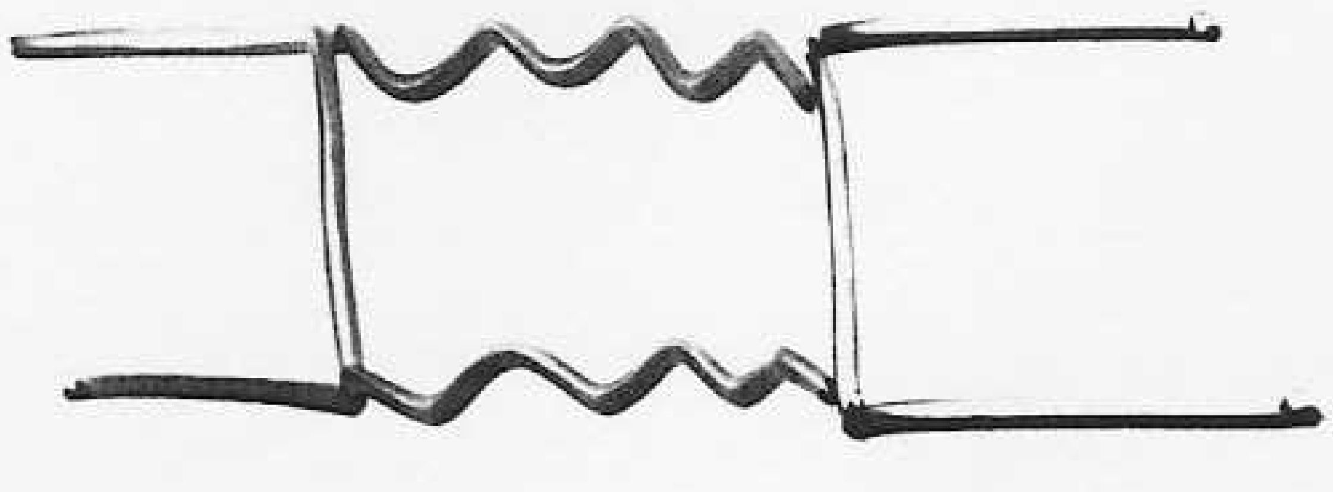
$\sim h^{(n)}_{\mu\nu}\, T^{\mu\nu}$ → dimension-4 operatos

→ dimension-8 induced operator

$\frac{1}{M_s^4} T_{\mu\nu} T^{\mu\nu}$ → important suppression

- One-loop exchang can give dimension-6 operators (more important)

$\partial^\mu h_{\mu\nu}^{(n)}\, O_3$ → $\bar{f}\, \gamma^\mu \gamma^5 f$



$\sim \frac{1}{M_s^2}\, O_3 O_3$ $\Big\{$ dimensio six

Bulk particles (gravitons and others)

also have stringy excitations.

Although the masses are in the TeV range the couplings are gravitational (too-small!)

BH at LHC?

When we have 2 large dimensions → gravity becomes 6-d with a Planck scale:

$$M_*^4 = M_P^2 \cdot R^2$$

$$\Rightarrow \quad M_* \sim 1\text{–}10 \text{ TeV}$$

For energies in the TeV region gravity becomes strong.

When $E \gg M_*$ BH may be formed.

Much more speculative than the rest.

Conclusion

There is a lot of new physics that may be accessible at LHC.

The potential is enormous and the outcome depends on

YOU!