Spacetime, Quantum Mechanics and the L.H.C

Triumph of 20th Century

Relativity + Quantum Mechanics

↓

Universe is Inevitable

Central Dramas of 21st Century

End of Space-time [Gravity]

Limitations of QM [Cosmology]

Why is the Universe BIG, with BIG THINGS in it?

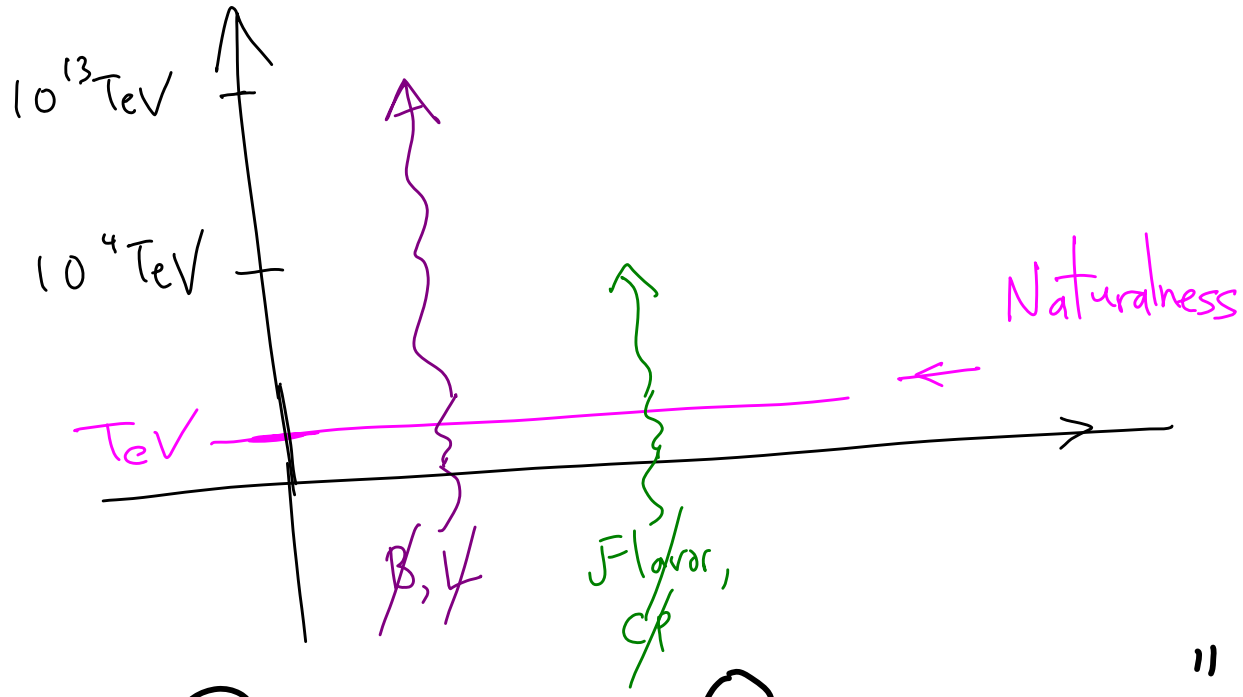
Grappling with L.H.C physics is giving us startling insights into both these mysteries!

Naturalness

||

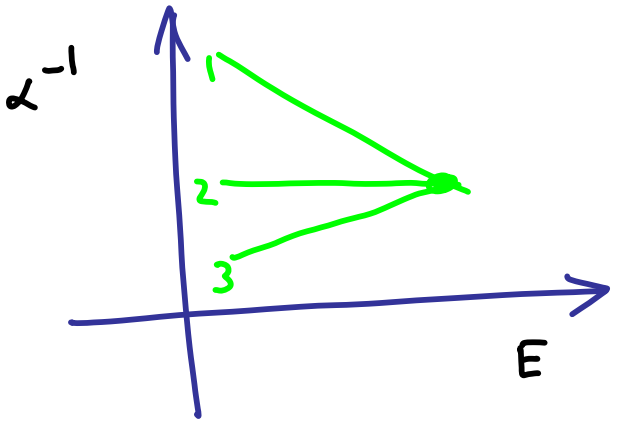
Why is there a Macroscopic Universe?

Tension Driving BSM Physics For 30 yrs



"Not Problems – Opportunities"

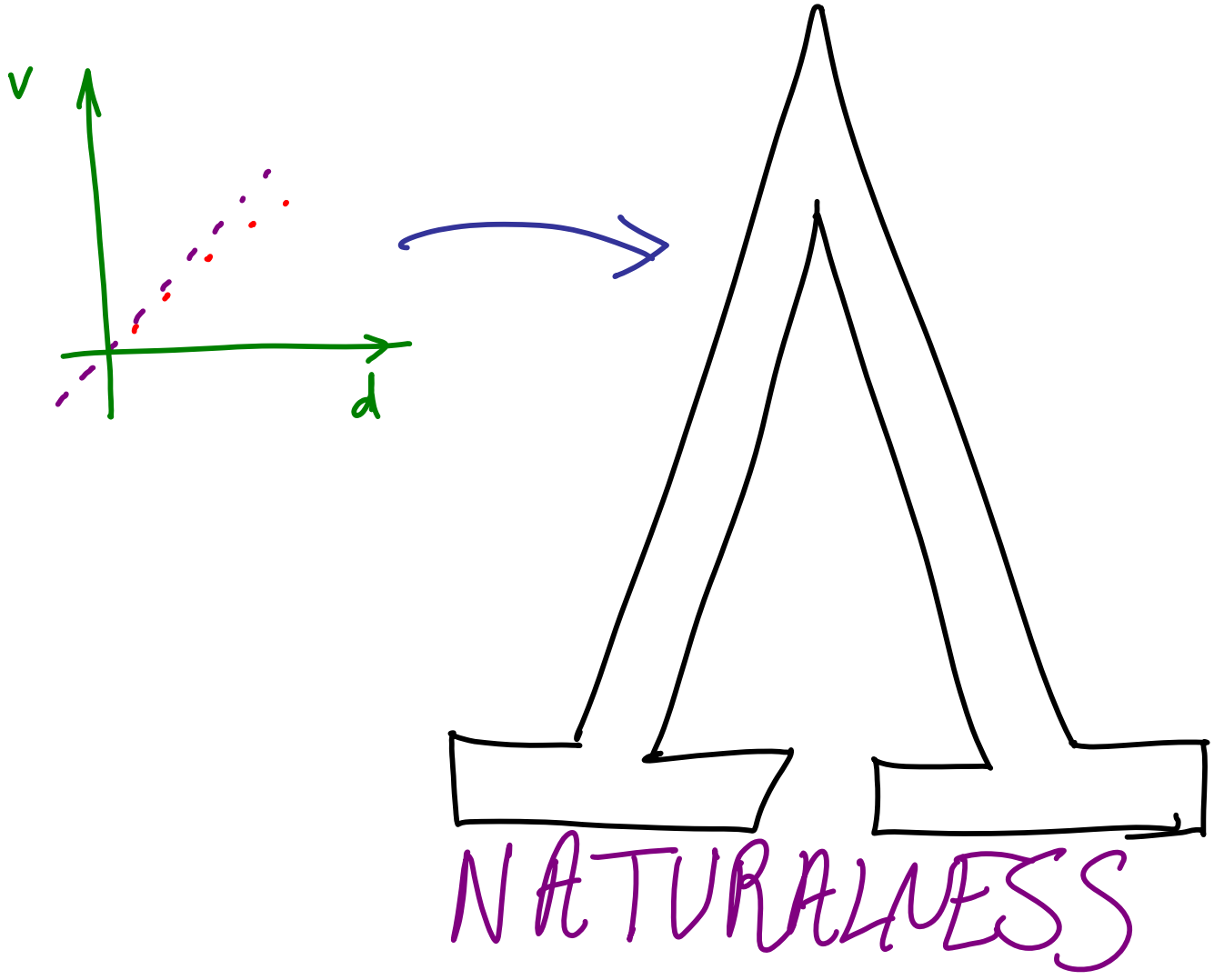
SUSY circa 1990

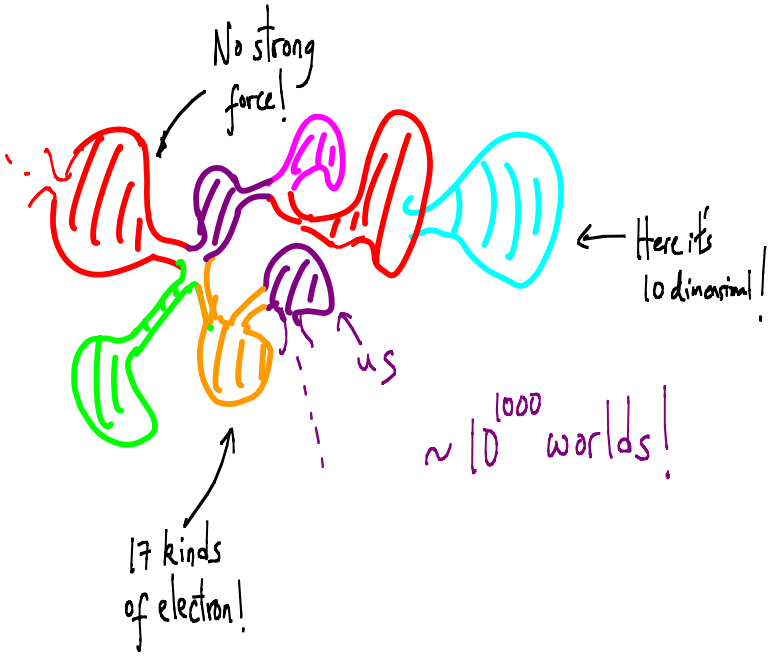


+ D.M.

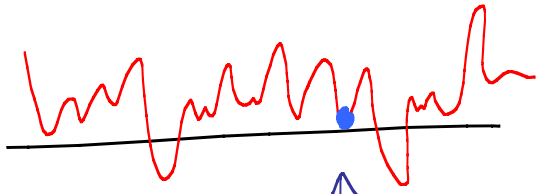
SPECTACULAR

BUT WHERE IS EVERYBODY?


v
d
NATURALNESS



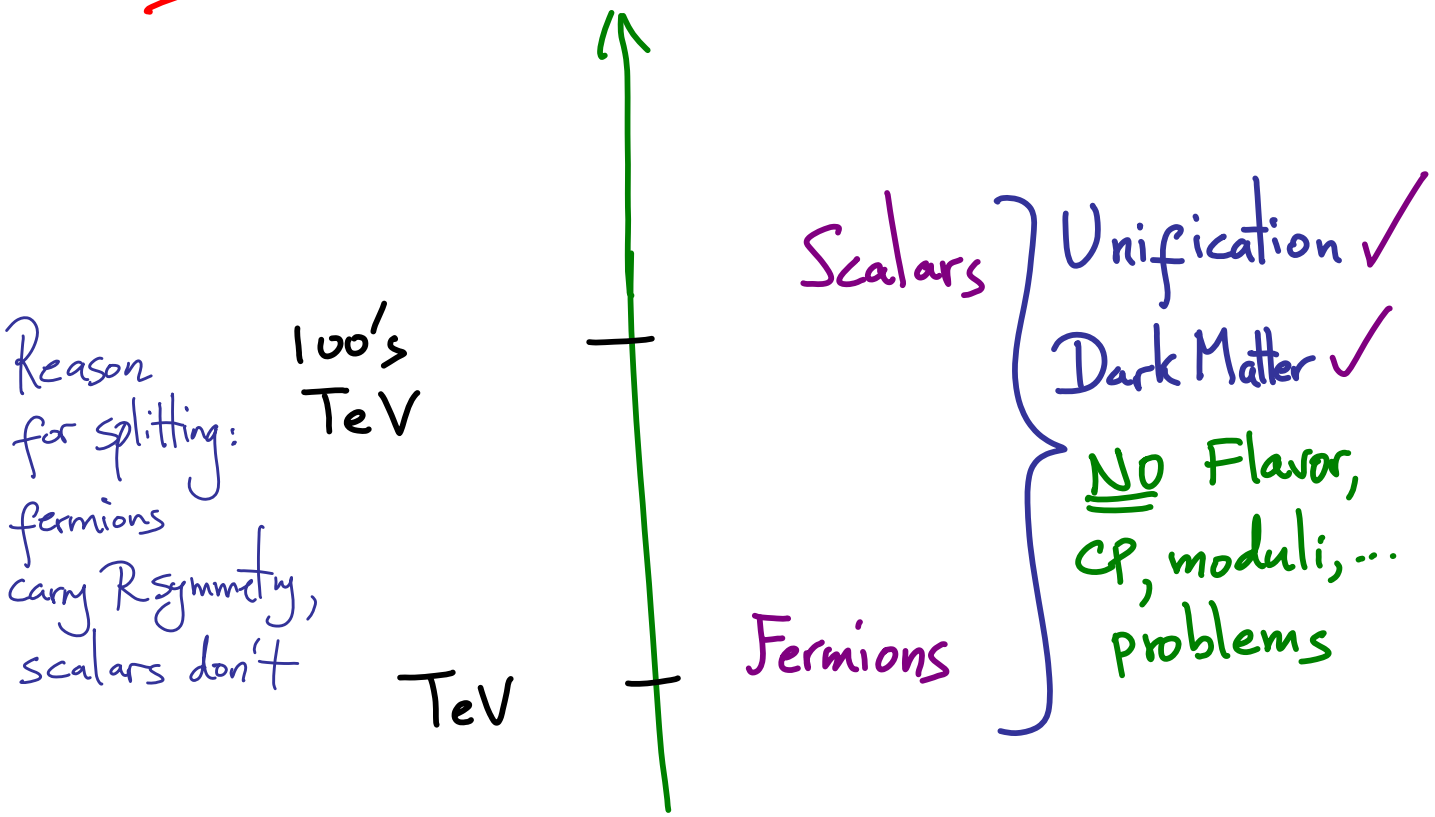
$\sim 10^{1000}$ worlds!



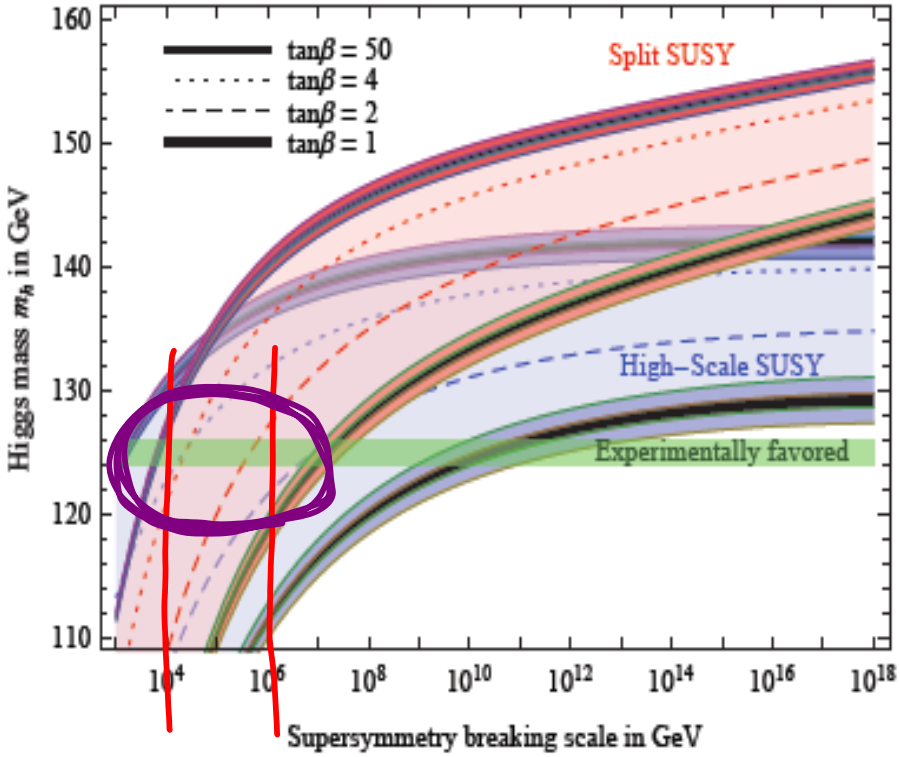
Everywhere Lethal + Empty except ...

Here, accidentally, Universe not empty

Minimal Split SUSY

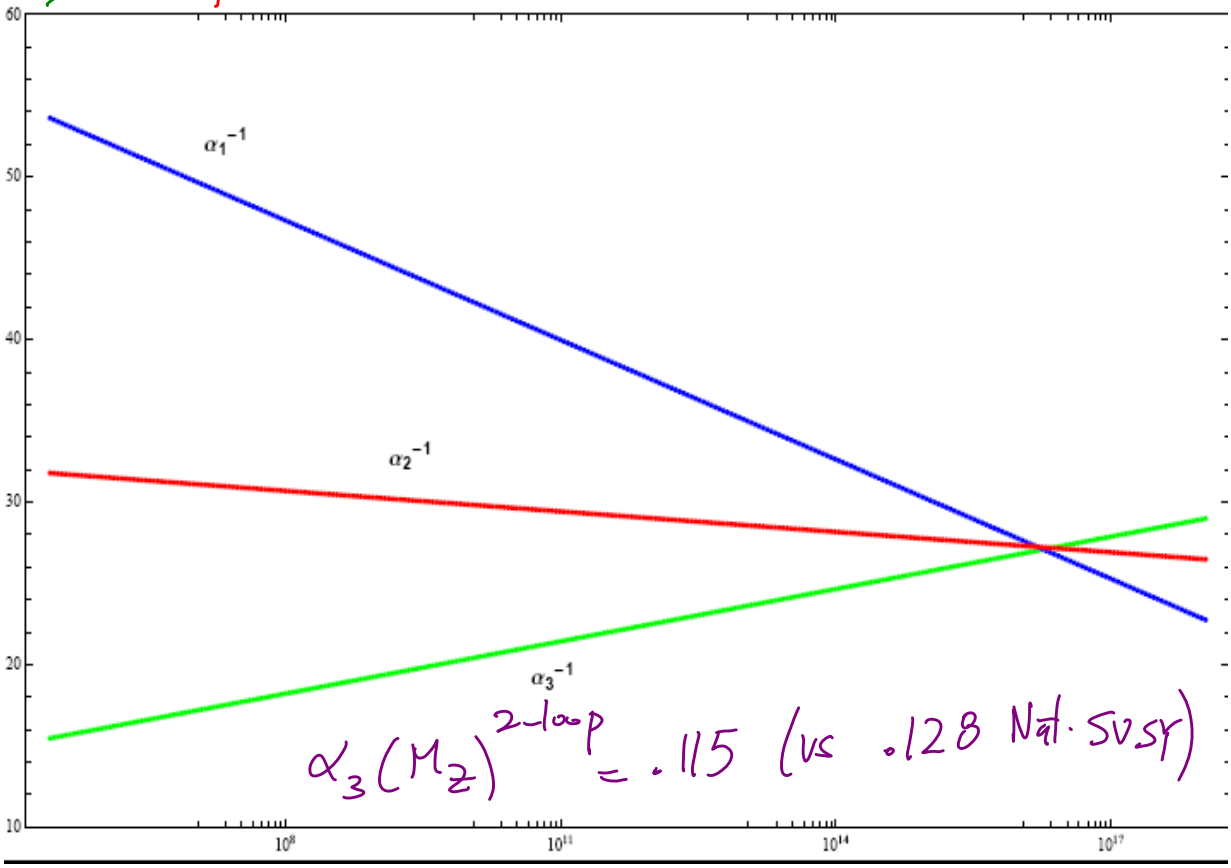


Predicted range for the Higgs mass

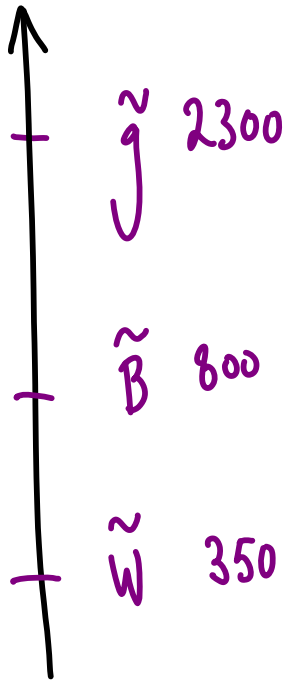


120 GeV $\lesssim m_{Higgs} \lesssim$ 135 GeV

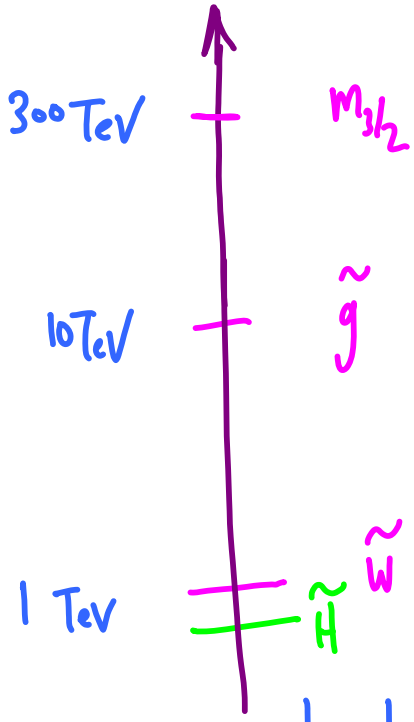
Unification a Bit Better than Natural SUSY

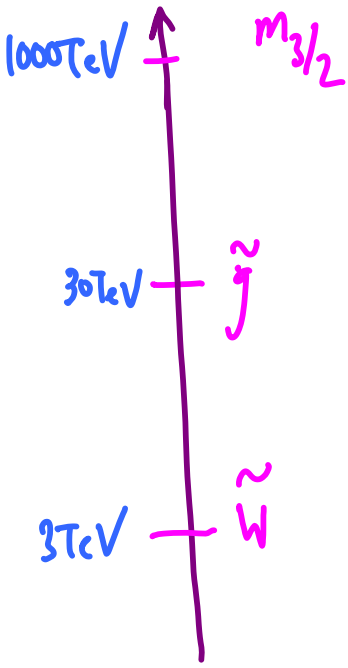


$\alpha_3(M_Z)^{2\text{-loop}} = .115$ (vs .128 Nat. SUSY)

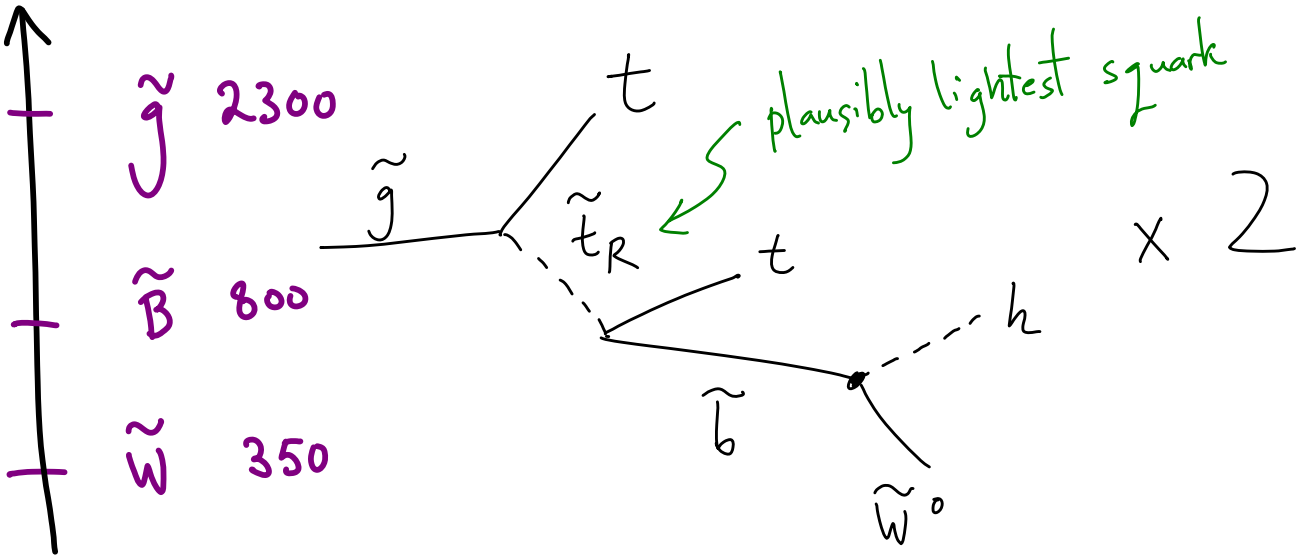


LHC Accessible





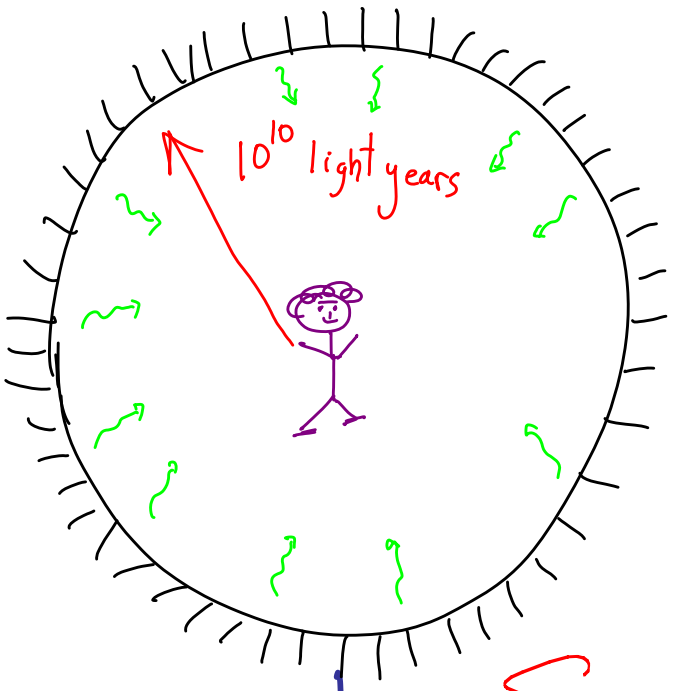
LHC Inaccessible



8 b's, 4 W's [+ perhaps displacement]
in every event!

Are we tiny part of a Vast Multiverse?

Conceptual Problem – how can we "see" other universes – how can we know that they're there?



What are the correct observables??

Emergent Space-Time

Extension of Quantum Mechanics?

Explaining Parameters vs Understanding Dynamics

"Why are planetary distances what they are"

vs

"What is Motion?"

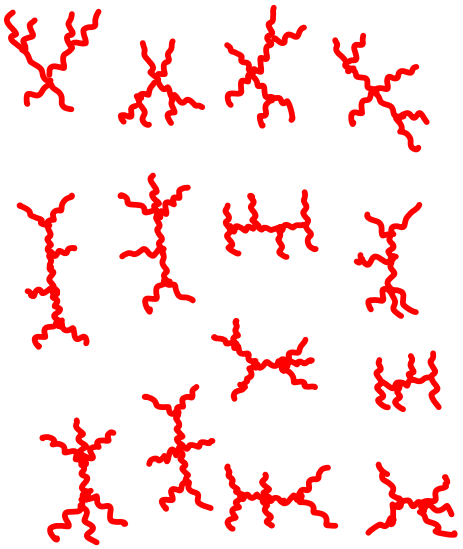
"What is QFT?"

{+ Note: NOT EUCLIDEAN QFT! Look at Questions where TIME ⇝ COSMOLOGY are crucial}

Is there a deeper structure underlying Space-Time + Quantum Mechanics?

If so: Must involve deep new Physical and Mathematical ideas

Feynman Follies



+ ...

220 Diagrams

10's of thousands of terms ...

Result of a brute force calculation:

$$k_1 \cdot k_4 \varepsilon_2 \cdot k_1 \varepsilon_1 \cdot \varepsilon_3 \varepsilon_4 \cdot \varepsilon_5$$

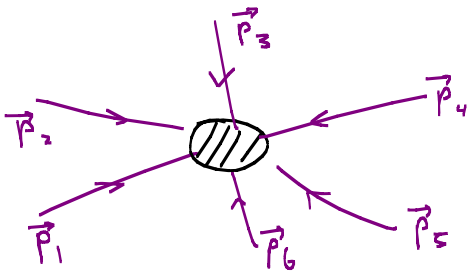
+ ~ 100 more pages....

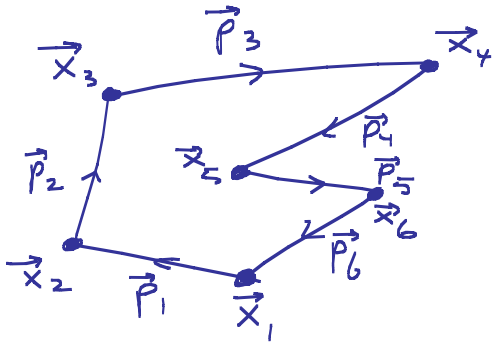
$$(1^-2^+3^-4^+5^+6^+)$$

$$\frac{\langle 13\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 56\rangle\langle 61\rangle} \quad (!)$$

Feynman's way of doing physics makes usual rules of spacetime + QM manifest — but is obviously hiding some extraordinary new structures!

Amazing Hidden Symmetry





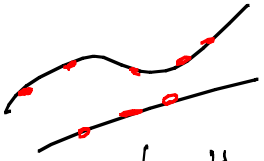
Same if we replace $\vec{x} \to \frac{\vec{x}}{x^2}$!

{ Contains + Generalizes Ancient Runge-Lenz Symmetry
Explaining why Planetary Orbits are Ellipses! }

Sitting Under Our Noses for 60 years!

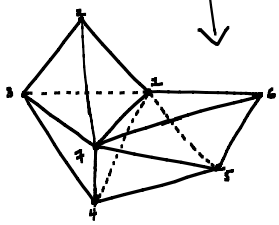
String Theory

Spin Chains



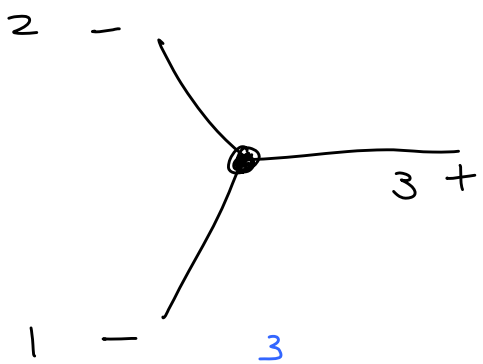
Twistor theory

New Formulation of Standard Physics emergent ST + QM

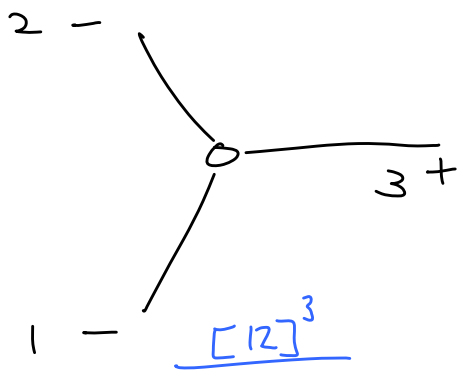


New Structures in in Algebraic Geometry + Combinatorics

Basic Building Blocks For Gluon Amps



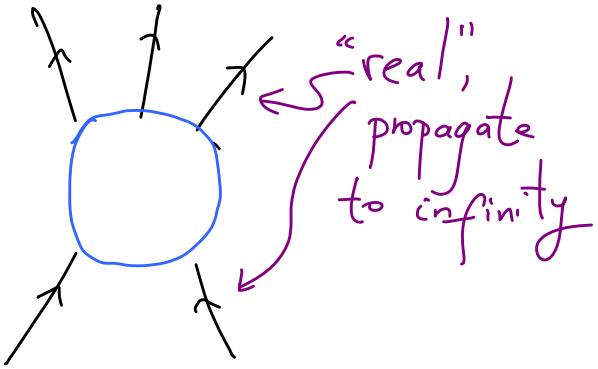
$$\frac{\langle 12\rangle^3}{\langle 13\rangle\langle 23\rangle}$$

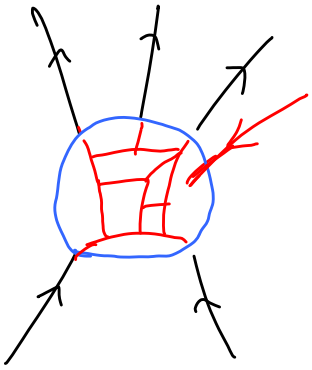


$$\frac{[12]^3}{[13][23]}$$

Very Simple

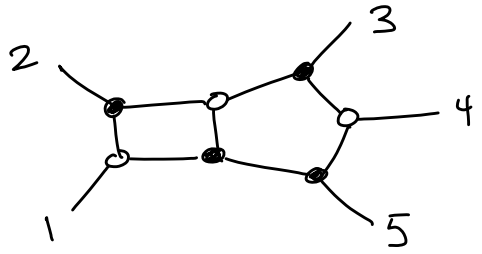
"Real" versus "Virtual" Particles



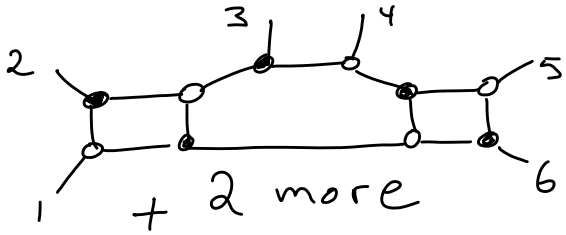


ORIGIN OF HORRIBE COMPLEXITY

Physical Idea: Eliminate "Virtual Particles"!



= instead of 30 pages of

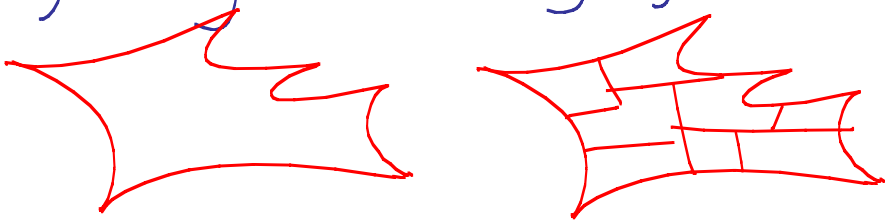


= instead of 100 pages of

* "Physical only" processes not individually local in space-time, nor individually quantum-compatible!
* Huge array of different ways of expressing answer in this form — what new world do these objects come from?

Goal

Find a new picture for scatt. amps where space-time + quantum mechanics are not primary — but emerge from more primitive ideas



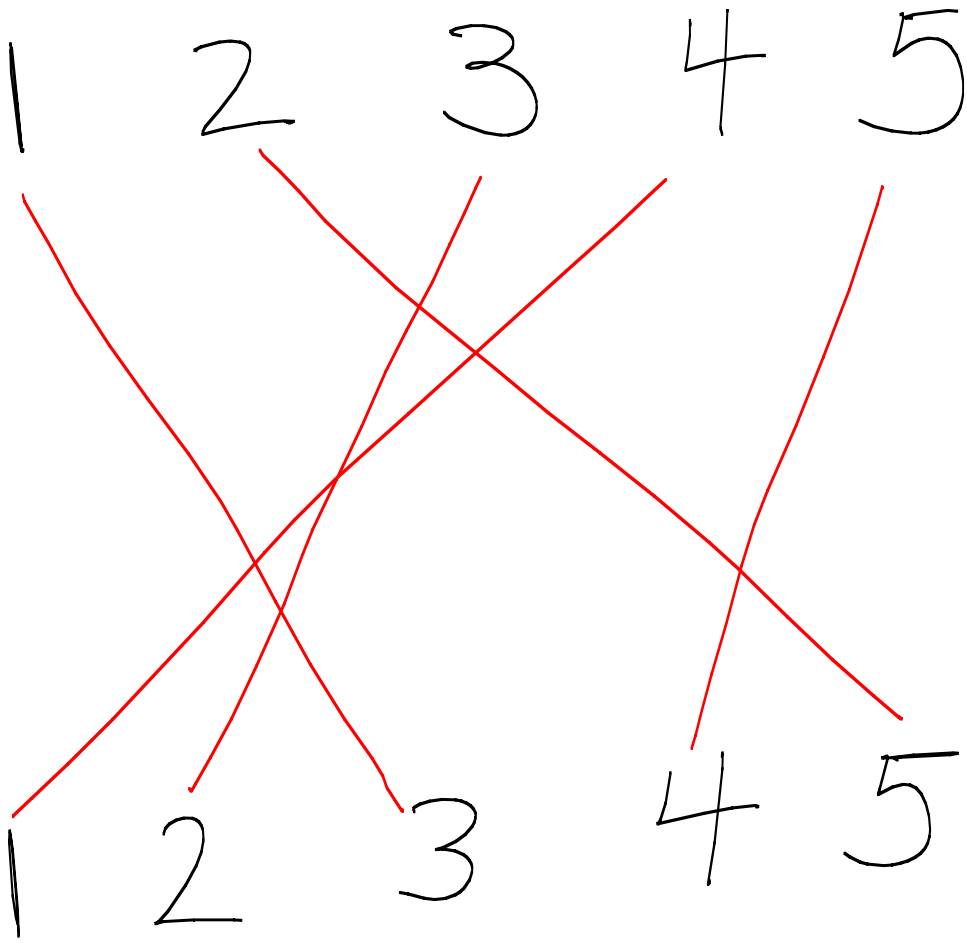
"The Volume" of "Some Region" in "Some Space"

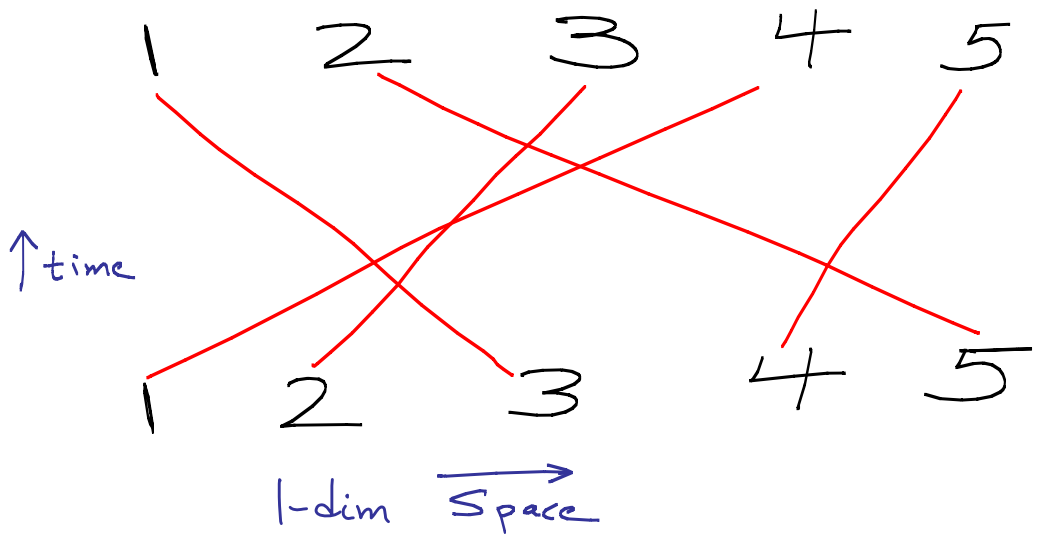
{Expose all Hidden Symmetries}

Amplitude = "Volume" of "Amplituhedron"

{Planar $\mathcal{N}=4$ SYM}

12345 → 35214

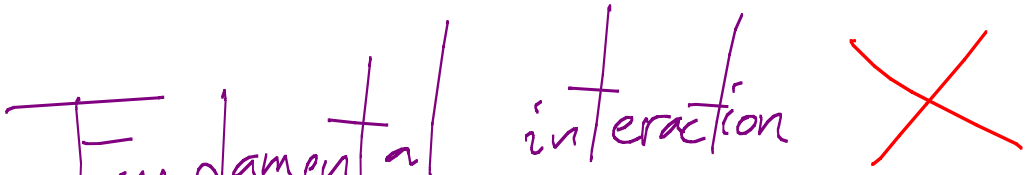

1 2 3 4 5
1 2 3 4 5

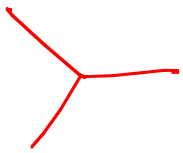


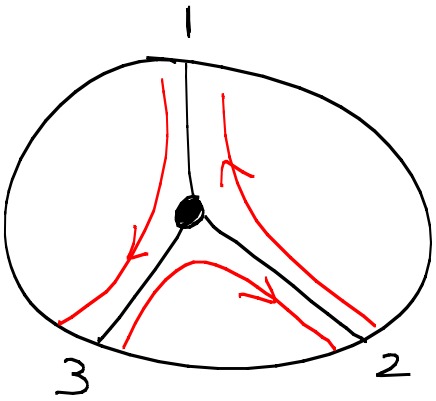
Breaking up permutation into product of adjacent transpositions [non-unique]

3 5 2 1 4
3 2 5 1 4
3 2 1 5 4
3 1 2 5 4
1 3 2 5 4
1 2 3 5 4
1 2 3 4 5

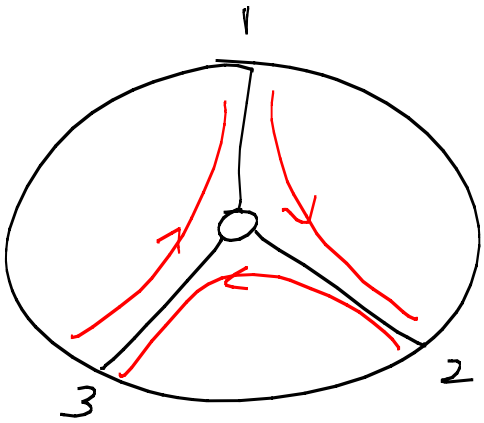
Can't Apply to Real World!

- No particle creation/destruction
- Fundamental interaction  ,

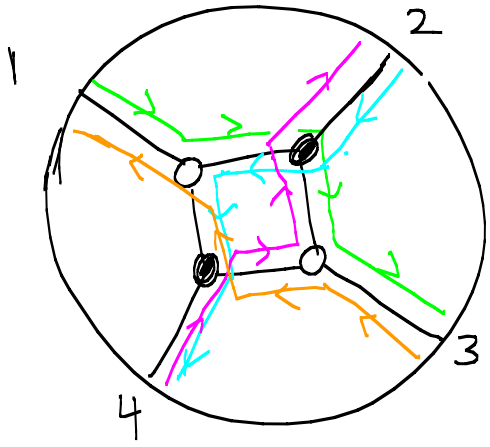
not 



$1 \to 3$
$2 \to 1$
$3 \to 2$



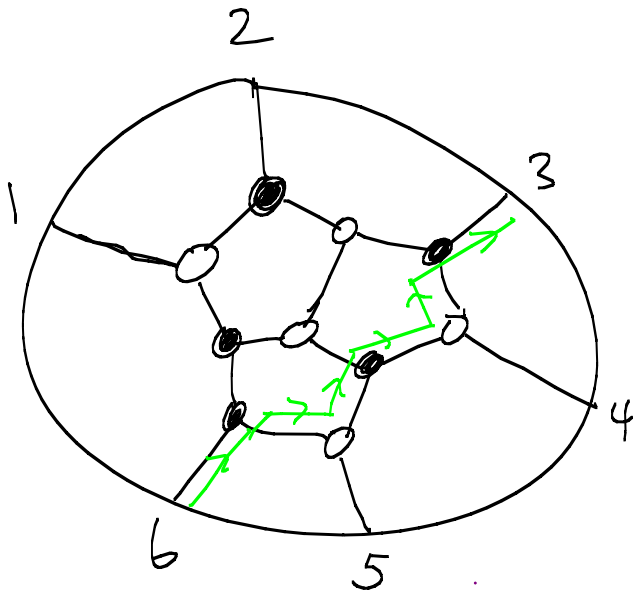
$1 \to 2$
$2 \to 3$
$3 \to 1$



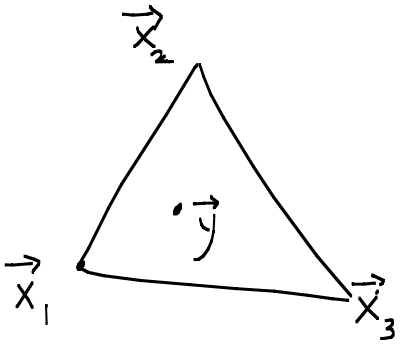
$1 \to 3$
$2 \to 4$
$3 \to 1$
$4 \to 2$

Every perm. can be represented like this

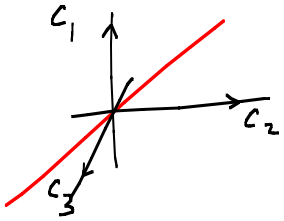
$1 \to 4$
$2 \to 6$
$3 \to 5$
$4 \to 1$
$5 \to 2$
$6 \to 3$



Generalizing Triangles

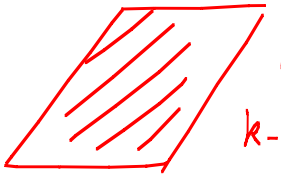


$$\vec{y} = c_1\vec{x}_1 + c_2\vec{x}_2 + c_3\vec{x}_3$$



(c_1, c_2, c_3)

$c's > 0$



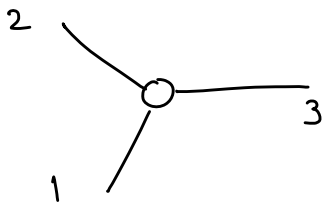
"Grassmannian"

k-plane in n-dim

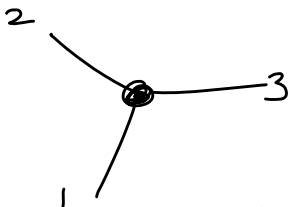
$$\begin{pmatrix} 1 & 2 & 0 & -5 \\ 0 & 3 & 1 & 7 \end{pmatrix}$$

"Positive Grassmannian"

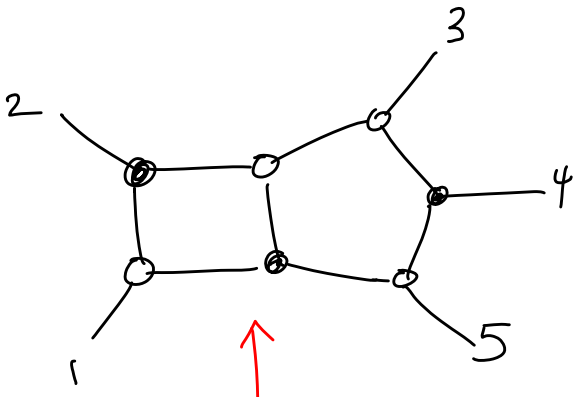
All determinants Positive!



$$\begin{pmatrix} 1 & x & y \end{pmatrix}$$

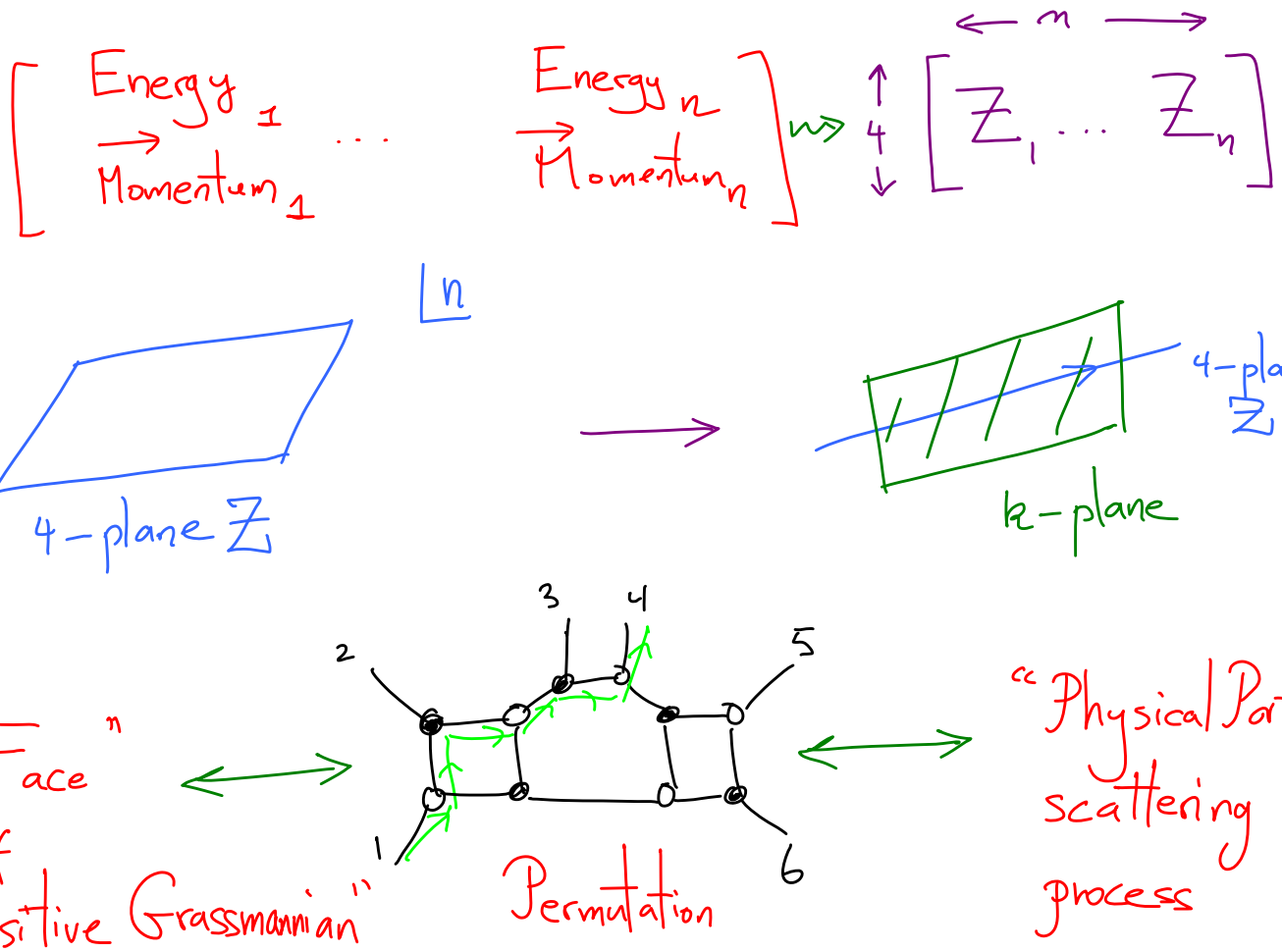


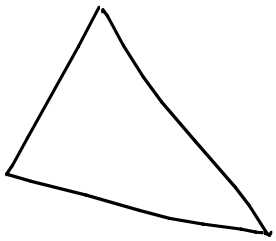
$$\begin{pmatrix} 1 & a & 0 \\ 0 & b & 1 \end{pmatrix}$$



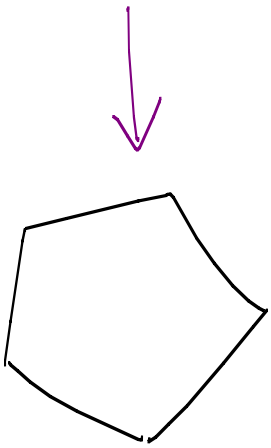
$$\begin{pmatrix} 1 & a & c & e & 0 \\ 0 & ab & c(b+d) & e(b+d+f) & 1 \end{pmatrix}$$

Build Big Positive Matrices from Gluing Together Little Ones!


Energy 1
Momentum 1
Energy n
Momentum n
n
4
Z1 ... Zn
n
4-plane Z
4-plane
Z
k-plane
"Face"
of
"Positive Grassmannian"
1
2
3
4
5
6
Permutation
"Physical Particle"
scattering
process



"Positive Grassmannian"

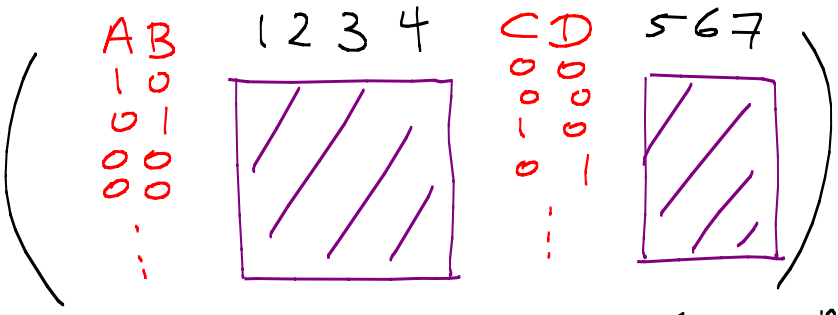


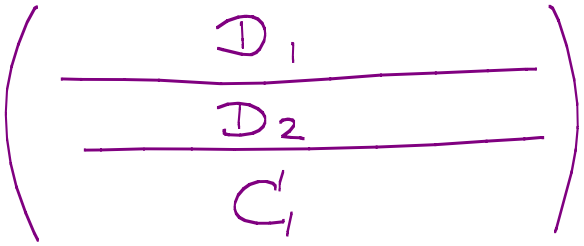
"Tree Amplituhedron"

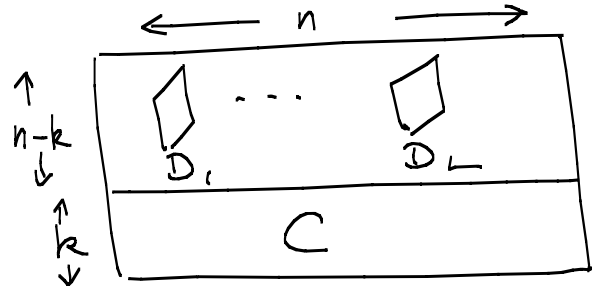
Hide ↓ Particles

"Amplituhedron"

Hiding Particles

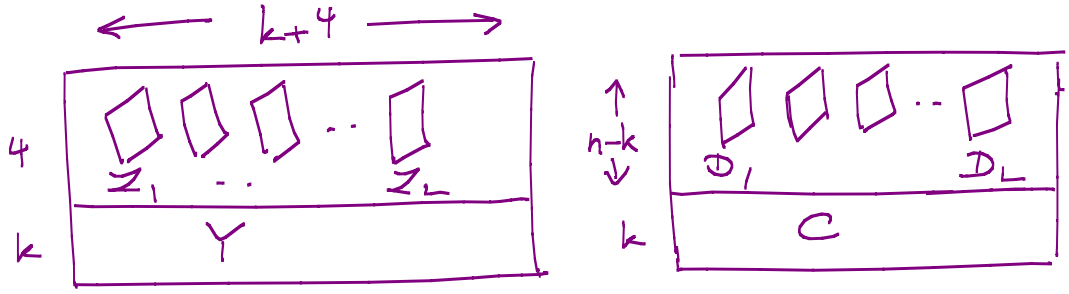




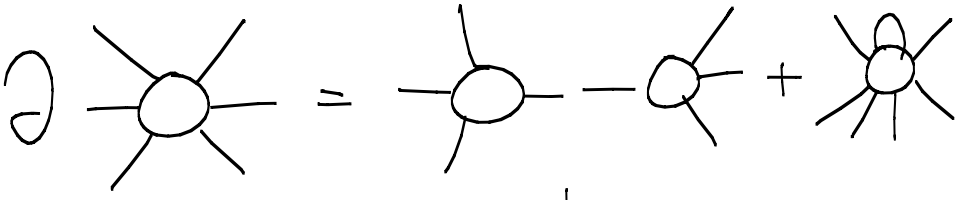


$$[C + \text{any } D\text{'s}] > 0$$

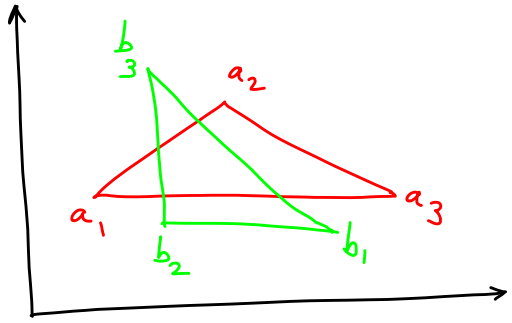
The Amplituhedron $A_{n,k,L}[Z]$

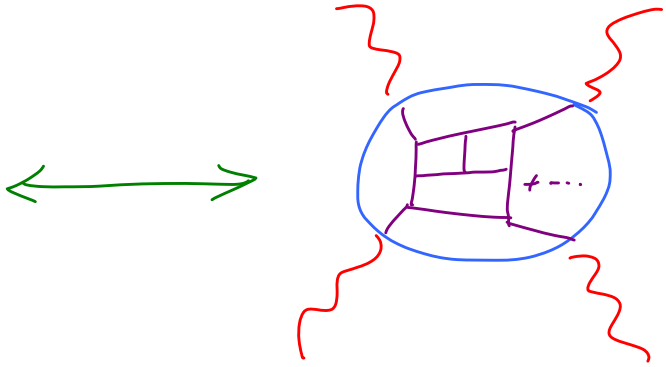


$$\mathcal{Y} = C^{+} \cdot Z^{+}$$

Boundaries → ∂ 

Positive Diffs → Yangian Symmetry



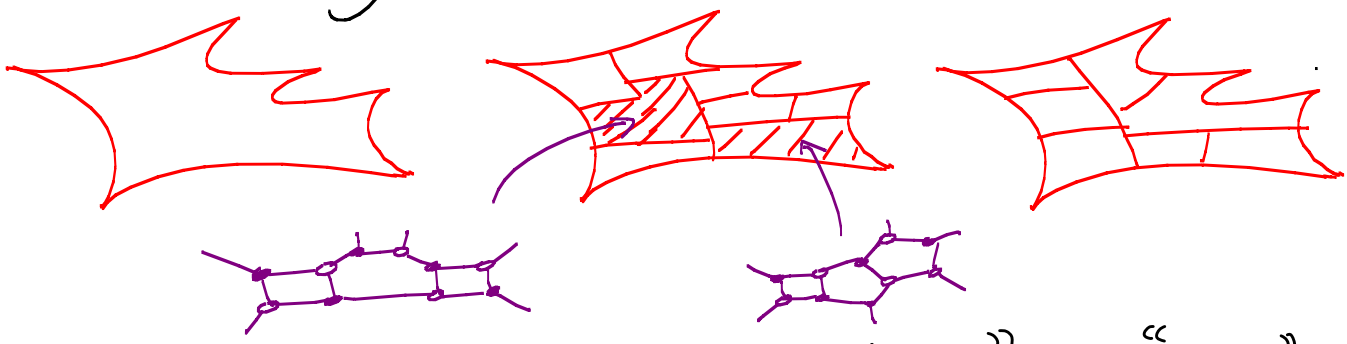


L points $\vec{a}_i, \vec{b}_i$ in positive quadrant with $(\vec{a}_i - \vec{a}_j) \cdot (\vec{b}_i - \vec{b}_j) < 0$

L-loops

High school Geometry $\longleftrightarrow$ Quantum Field Theory

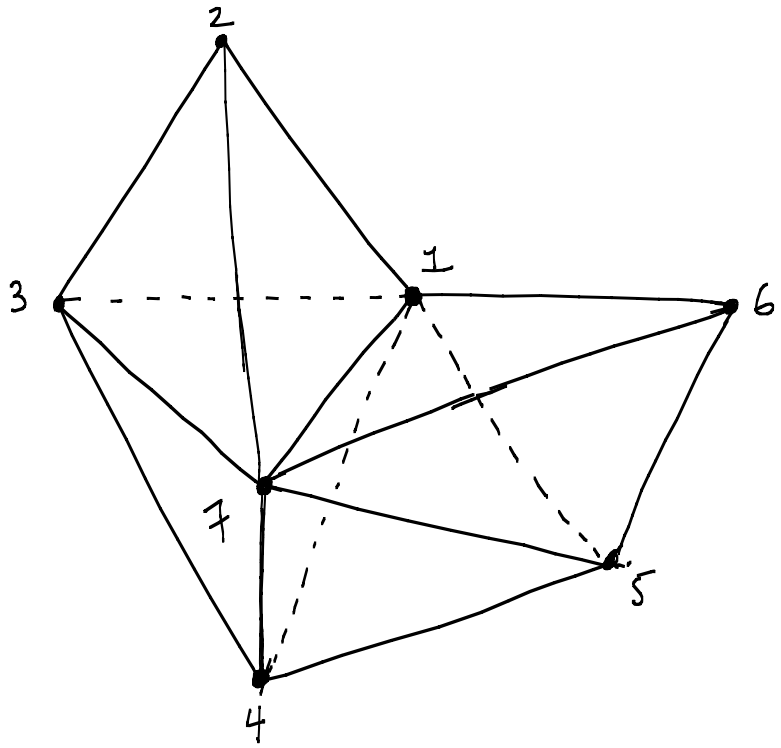
So: $Amp = Vol[Ampl.]$



Pieces don't have "spacetime" or "QM" interpretation — full volume does. The rules of Spacetime + QM emerge as derivative notions.

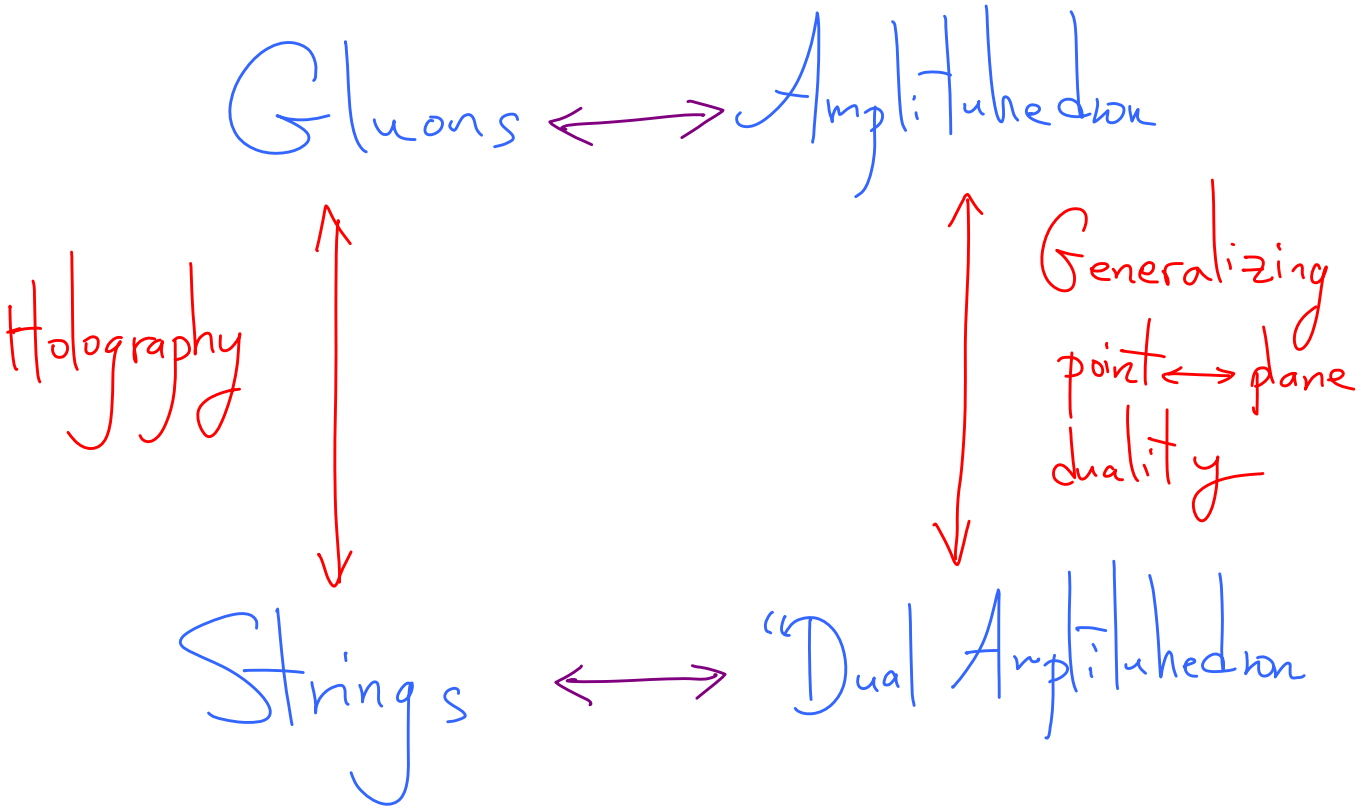
Obvious Symmetry: transformations keeping shape of Amplituhedron fixed $\Rightarrow$ hidden infinite symmetry!

A 3D "Face"

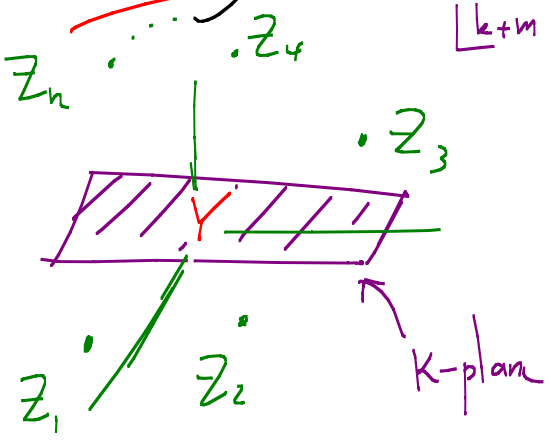


Tree Amplitude for $[\bar{1}\,2^{+}3^{+}4^{+}5^{-}6^{+}7^{-}\,8^{-}]$ @LHC!

{ Hundreds of Pages of Feynman Diagrams }


Gluons ⟷ Amplituhedron
Holography
Generalizing
point ⟷ plane
duality
Strings ⟷ "Dual Amplituhedron

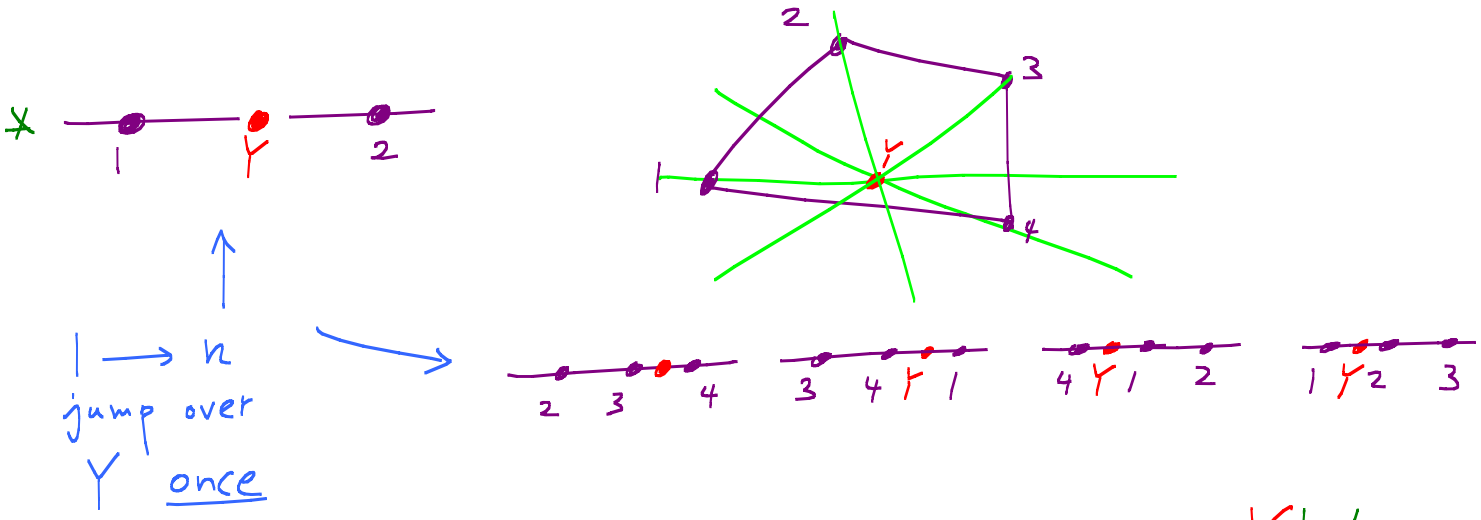
Amplituhedron is Binary Code



When is Y in the amplituhedron?

Project through Y → m dim. picture. What does this picture look like?

l



* $m = 1$ amplituhedron:

, jump over Y k times

$\equiv \{\langle Y1\rangle, \ldots, \langle Yn\rangle\} = \{++--++--\}$

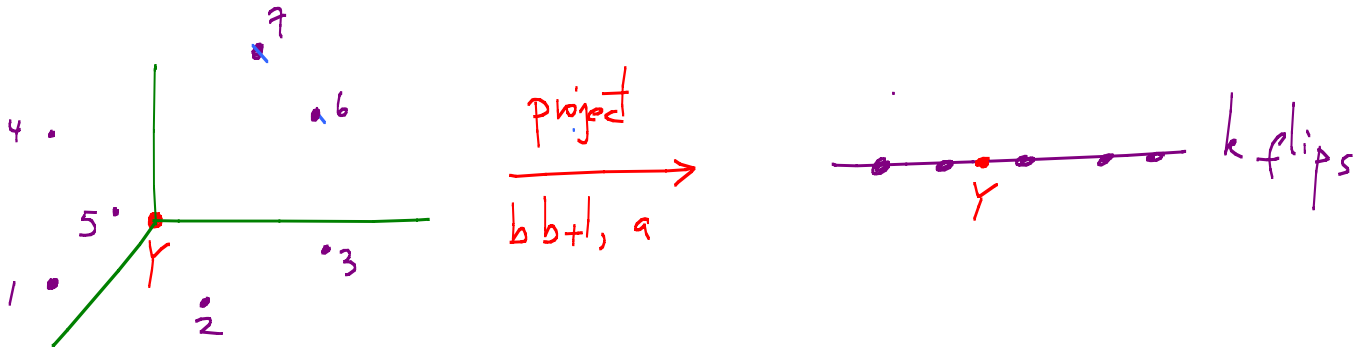
k sign flips!

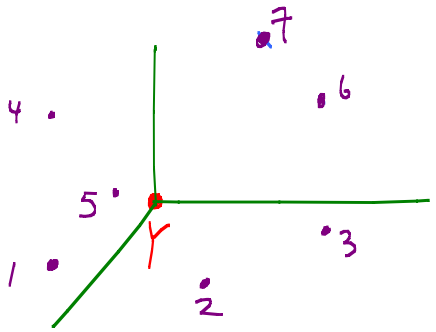
* General m : $Y \in$ Ampl. $\Longleftrightarrow$ projecting through $\begin{cases} Z_a Z_{a+1}\ Z_b Z_{b+1} \cdots & m \text{ odd} \\ \| \qquad\qquad + Z_c & m \text{ even} \end{cases}$

We are in $m = 1$ Amplituhedron!

e.g. $m = 2$ $\{\langle Y 12\rangle, \cdots, \langle Y 1n\rangle\}$ k sign flips

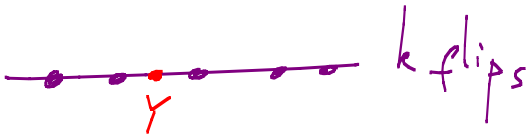
$m = 4$ $\{\langle Y 1234\rangle, \cdots, \langle Y 123n\rangle\}$

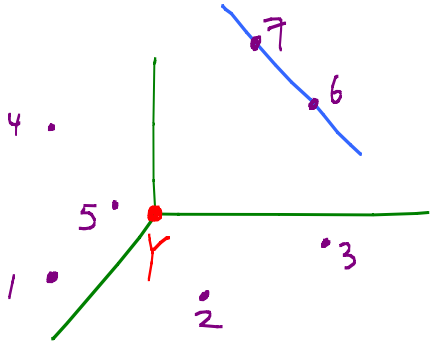

7
6
4
5
Y
3
1
2
project
b b+1, a
Y
k flips

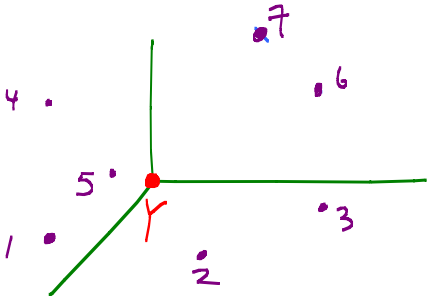


project

$b\ b+1,\ a$

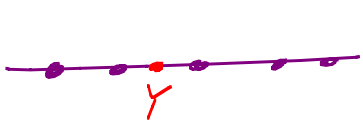




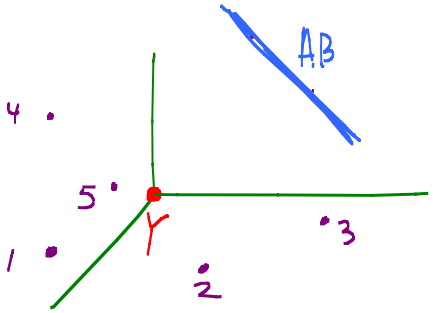


project

b b+1, a

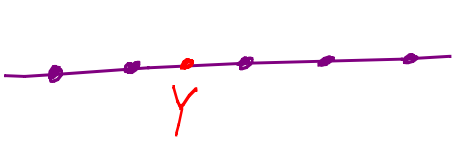


k flips



project

AB, a



k+2 flips

Loops = Hiding Particles

Amplituhedron Code

* $\llcorner$ $(k+2)$ planes $(YAB)_i$ intersecting on k-plane Y

* $\{\langle Y\underset{a}{1}\underset{b}{2}\underset{b+1}{3}4\rangle, \ldots, \langle Y123n\rangle\}$ has k sign flips

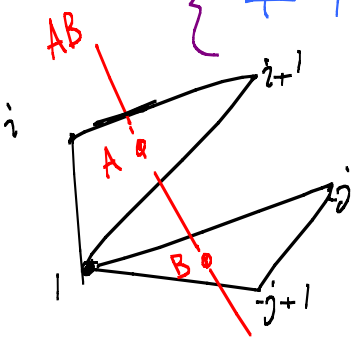
* $\{\langle YAB_i\underset{a}{1}2\rangle, \ldots, \langle YAB_i 1n\rangle\}$ has $(k+2)$ sign flips

* Scattering form fixed by log singularities on ∂

Example: 1-loop MHV

* $\{\langle AB|2\rangle, \dots, \langle AB|n\rangle\}$ has $k+2=2$ sgn flips

$$\{ + + \cdots \overset{i}{+} \overset{i+1}{-} \cdots \overset{j}{-} \overset{j+1}{+} \cdots + \}$$



$$A = Z_1 + \alpha_i Z_i + \alpha_{i+1} Z_{i+1} \qquad \alpha_{i,i+1,j,j+1} > 0$$

$$B = -Z_1 + \alpha_j Z_j + \alpha_{j+1} Z_{j+1}$$

$$\Rightarrow \Omega = \sum_{i,j} d\log\alpha_i \, d\log\alpha_{i+1} \, d\log\alpha_j \, d\log\alpha_{j+1}$$

$$= \sum_{i,j} d\log\frac{\langle AB|i\rangle}{\langle AB\,i\,i+1\rangle} \, d\log\frac{\langle AB|i+1\rangle}{\langle AB\,i\,i+1\rangle} \, d\log\frac{\langle AB|j\rangle}{\langle AB\,j\,j+1\rangle} \, d\log\frac{\langle AB|j+1\rangle}{\langle AB\,j\,j+1\rangle}$$

At least for planar $\mathcal{N}=4$ SYM, we have a concrete example where we see locality + unitarity as derived notions, joined at the hip, arising from ultimately algebraic-geometric — combinatorial origins, counting +'s and −'s.

Can we see something like this for Cosmological Correlators in dS/Inflation?

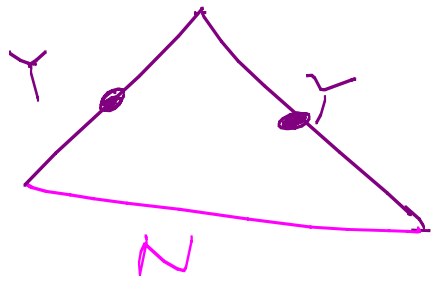
(I) How is consistent "unitary time evolution physics" encoded in late-time correlators? {Dinosaurs in Fossil Record}

(II) Is there an autonomous object that satisfies these rules without bulk time evolution?

{Practical Cosmological Hologram} {Fossil Record without Dinosaurs}

Cosmological Polytopes

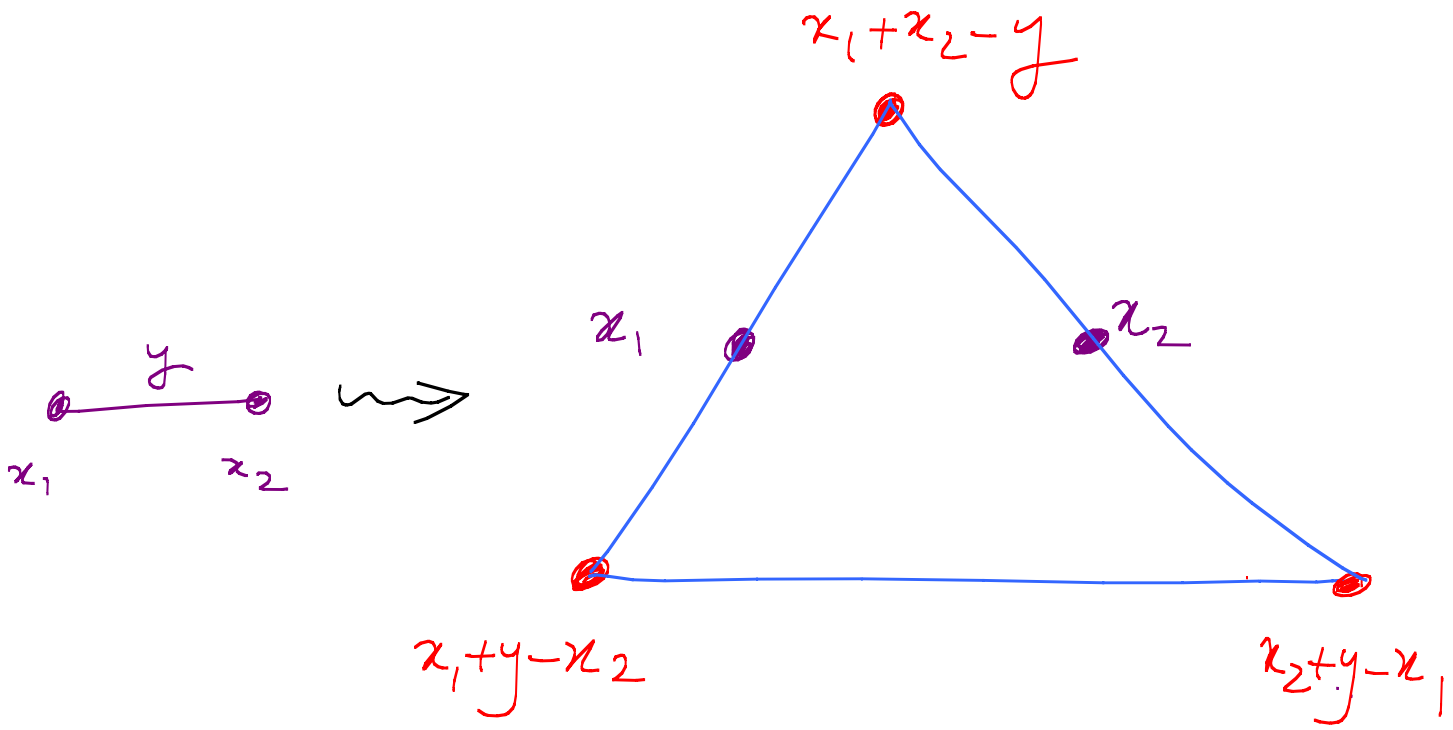
* Collection of triangles (a_i, b_i, c_i)
* Allowed to intersect on 2 of 3 midpoints

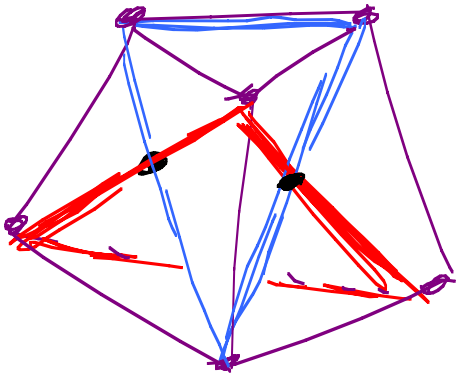


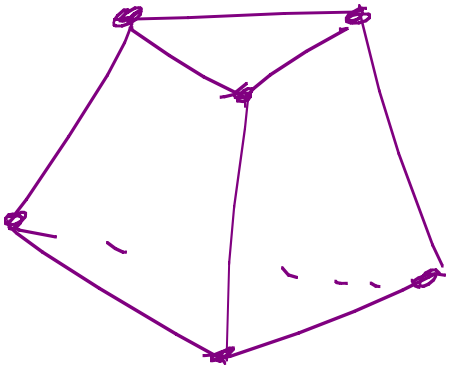
= Relations of form

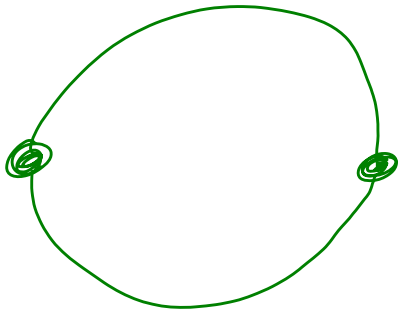
$$a_i + b_i = a_j + b_j$$
$$a_i + c_i = a_j + c_j$$

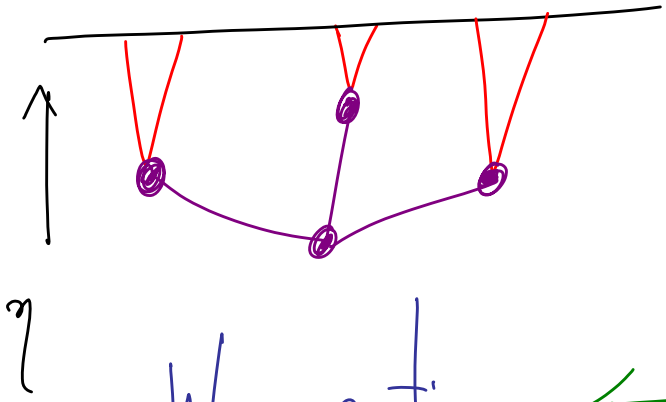
$\Longrightarrow$ Associated w/ graph G


y
x_1
x_2
x_1+x_2-y
x_1
x_2
x_1+y-x_2
x_2+y-x_1



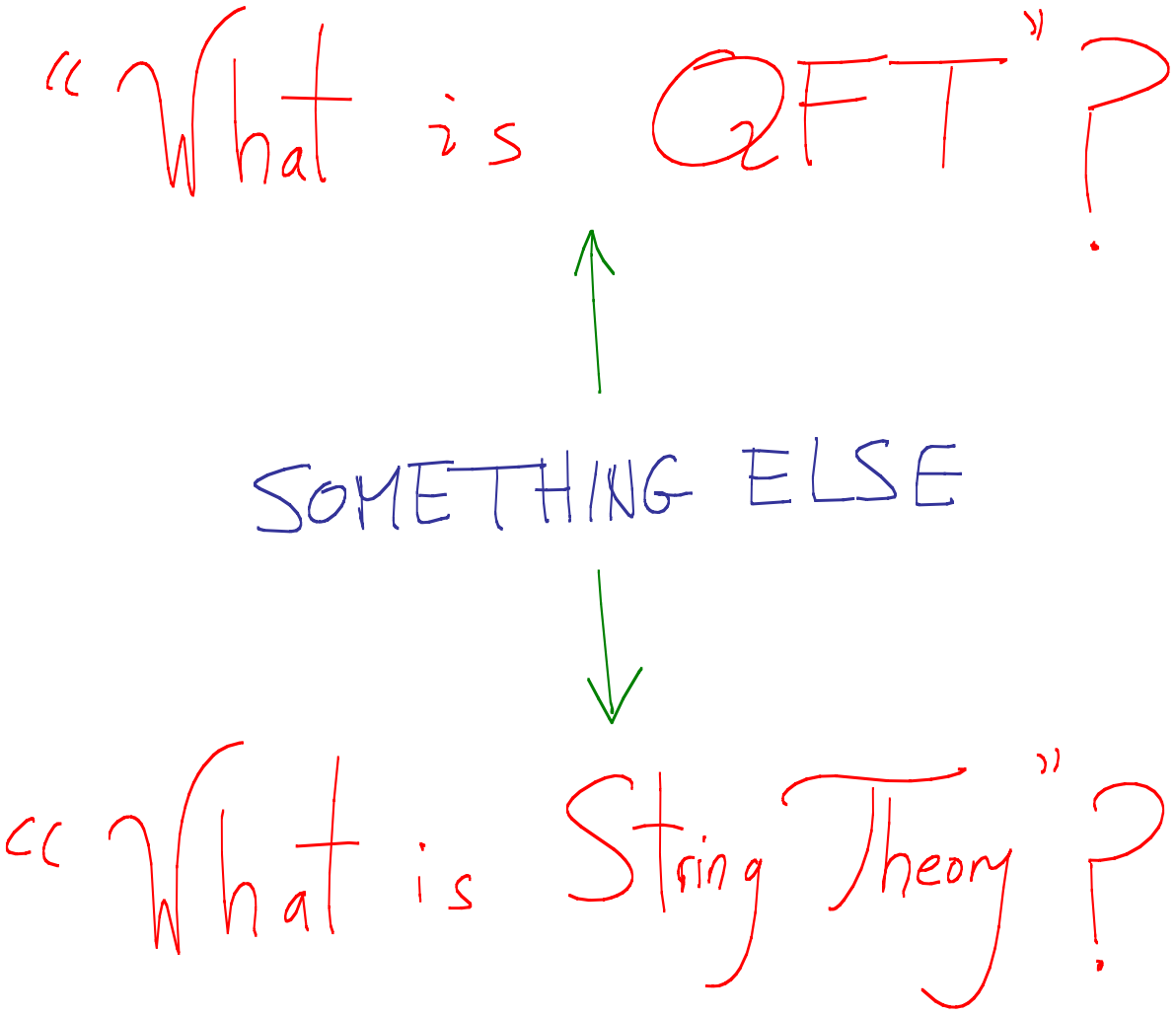






Wave-function From Cosmological TIME evolution

Volume of Cosmological Polytope of Associated Graph


"What is QFT"?
SOMETHING ELSE
"What is String Theory"?

Emergent

Space-Time + QM

(Hand in Hand)

Emergent Spacetime?

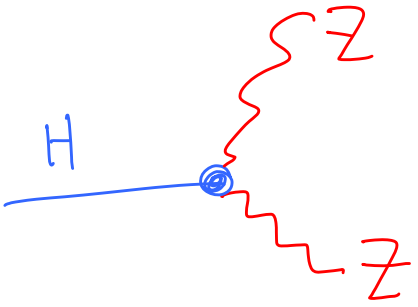
We are clearly missing something HUGE about Quantum Mechanics of our Relativistic Vacuum!

Macroscopic Universe?

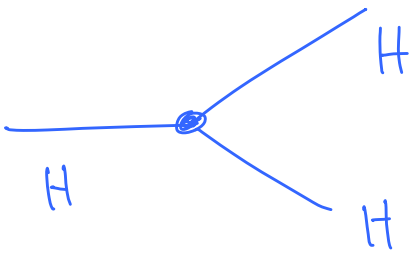
The Higgs is the most important particle/character in this mystery

* We've never an elementary particle like it
* Must put it under more powerful microscope!

Clear Motivation for Future Colliders



Higgs factory: does it look more pointlike than pion?



100 TeV Collider: does it look pointlike to itself?

Extremely Weakly Interacting Frontiers

* Gravity Waves (!!)
* Cosmic neutrino background
* Dipole moments
* Axions
* "Dark" photons
* Dark matter

Many New Ideas Exploit Advances in Quantum-Coherent Atomic Physics!

This is a singular time in the development of Fundamental Physics

The questions on the Table are the deepest ones — underpinnings of space + time, origins + fate of our large Universe

Nature is teaching us deep, surprising, (disquieting to some!) lessons via the L·H·C

We are being forced to rethink + reformulate the foundations

And we await and need more input from experiment: from LHC of course, cosmological observations + the new frontier of small-scale experiments

Exhilirating Time To Be Doing Physics

"Next Steps" needed will likely be Revolutionary

IDEAL TIME TO BE 25!