

From Collider Physics

to

A Common Origin for QM + Spacetime

(I) Future of Experimental Particle Physics

(II) Towards emergent  $\{\text{Space-time} + \text{QM}\}$

Experimental / Future



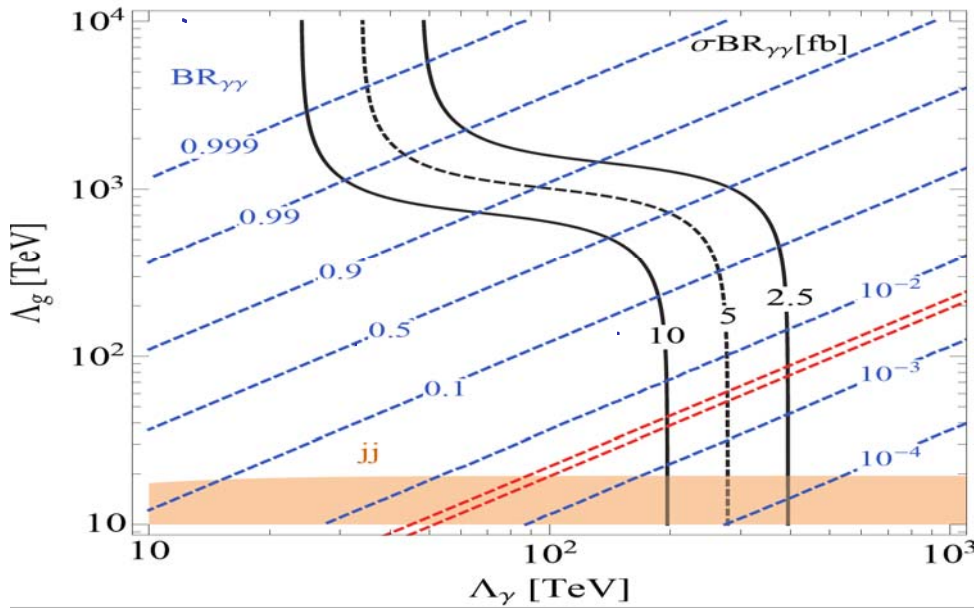
IS NOW!

\* 2016 is most crucial year  
of all for LHC — maximum  
discovery potential.

# S(750)?

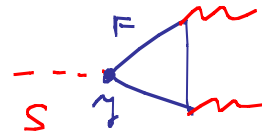
- \* Definitely most interesting + likely LHC anomaly - Exciting!
- [\* Run 1 vs Run 2 tension, "other channels look elsewhere", width issue; also big coincidence that S/B ~ few with 900 events (but just where syst/background fluct. hurt!)]
- \* I give it a ~15% chance of being real (= betting odds)

$$\frac{\phi}{\Lambda_g} G_{\mu\nu,a} G^{\mu\nu,a} + \frac{\phi}{\Lambda_\gamma} F_{\mu\nu} F^{\mu\nu}$$



\* Very weak coupling to SM!

\* Trivial to UV complete

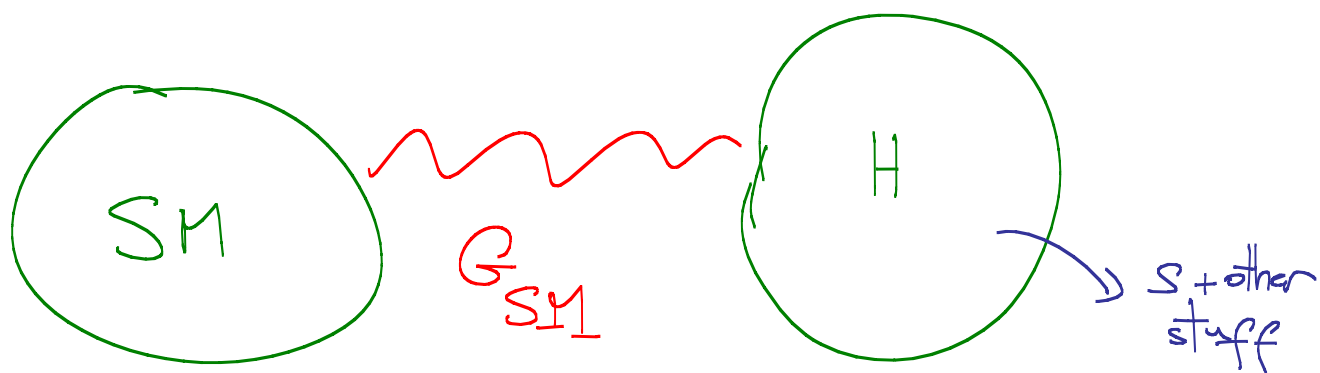


$$\frac{1}{\Lambda} \sim \frac{\alpha}{4\pi} \frac{g}{M_F}$$

If reasonably weakly coupled,  
 $M_F \lesssim \text{TeV}$  + must produce F

$M_F$  from 100s GeV  
 $\rightarrow 10 \text{ TeV OK}$

# "Horizontal" New Physics



(dom couplings  $\rightarrow 0$  as  $g_{SM} \rightarrow 0$ )

\* SUSY unification above  $\sim 100 \text{ TeV}$   
[i.e. MSSM, or mini-split SUSY...]

Matter in complete  $SU(5)$  multiplets  $\eta_F + 3\eta_T, 5^4$

\* Non-abelian gauge grps:  $SU(2)$ ,  $SU(2) \times SU(2)$ ,  
 $SU(3)$ ,  $SU(4)$ ,  $Sp(4)$

Automatically in conformal  
window

# The 44-fold Way

\* Simplest thry: Add 2  $5(10)10'_S = 2(5+\bar{5})'_S \begin{pmatrix} D^c \\ L \end{pmatrix} \dots \begin{pmatrix} D^c \\ L \end{pmatrix}_x + \text{gauge } SU(2)$   
 to (split) MSSM  $\Rightarrow SU(2)$  with 10 doublets near top of conf window! (10  $D^c + 10 L^c$ )  
 Decouple squarks, gauginos of  $SU(2)$  @ 10-100 TeV  $\rightarrow SU(2)$  w/ 10 ferm. doublets

\* Symmetry breaking  $SU(10) \rightarrow Sp(10) = 44 \text{ goldstones } [\Lambda \sim \text{few TeV}]$   
 $(44) \rightarrow (\frac{1}{3} D^c D - \frac{1}{2} L^c L)_S, L^c L, D^c D, \underbrace{(L^c D^c), (L^c D), (LL), (D^c D^c)}_{\text{Collider stable, or e.g.}}$   
 $\downarrow \quad \downarrow$   
 $WW \quad gg$

Rich spectrum of states with  
 large production rates + striking  
 decay patterns

$(D^c D^c) \rightarrow d_i^c d_j^c \quad i \neq j$   
 $(LL) \rightarrow e_i \nu_j \quad i \neq j$   
 $(L D^c) \rightarrow \ell_i d_j^c$   
 $(L D) \rightarrow \bar{\ell} \bar{d}^c (LL) \rightarrow e_i \nu_j$

[Safe!] flavor violation

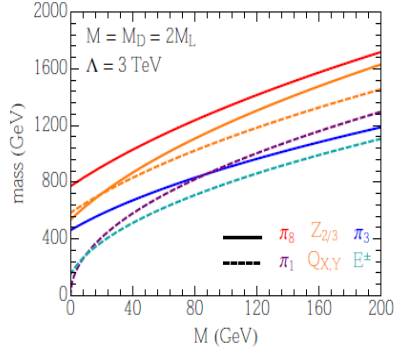


Figure 1: Masses of pions in the 24 and in the 44.

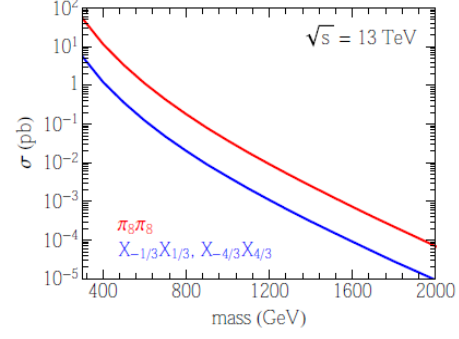
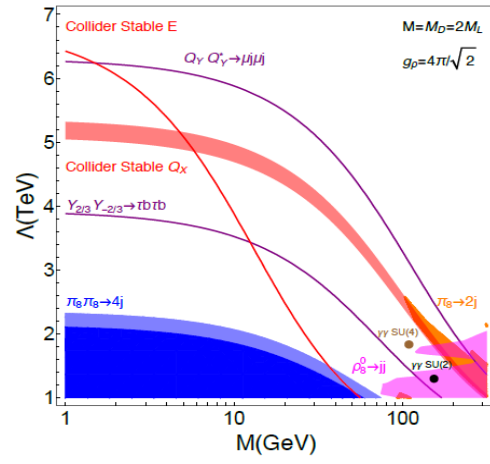
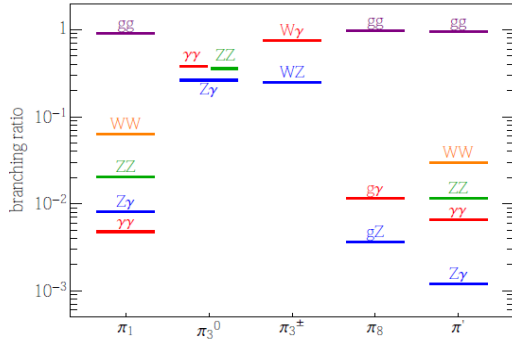
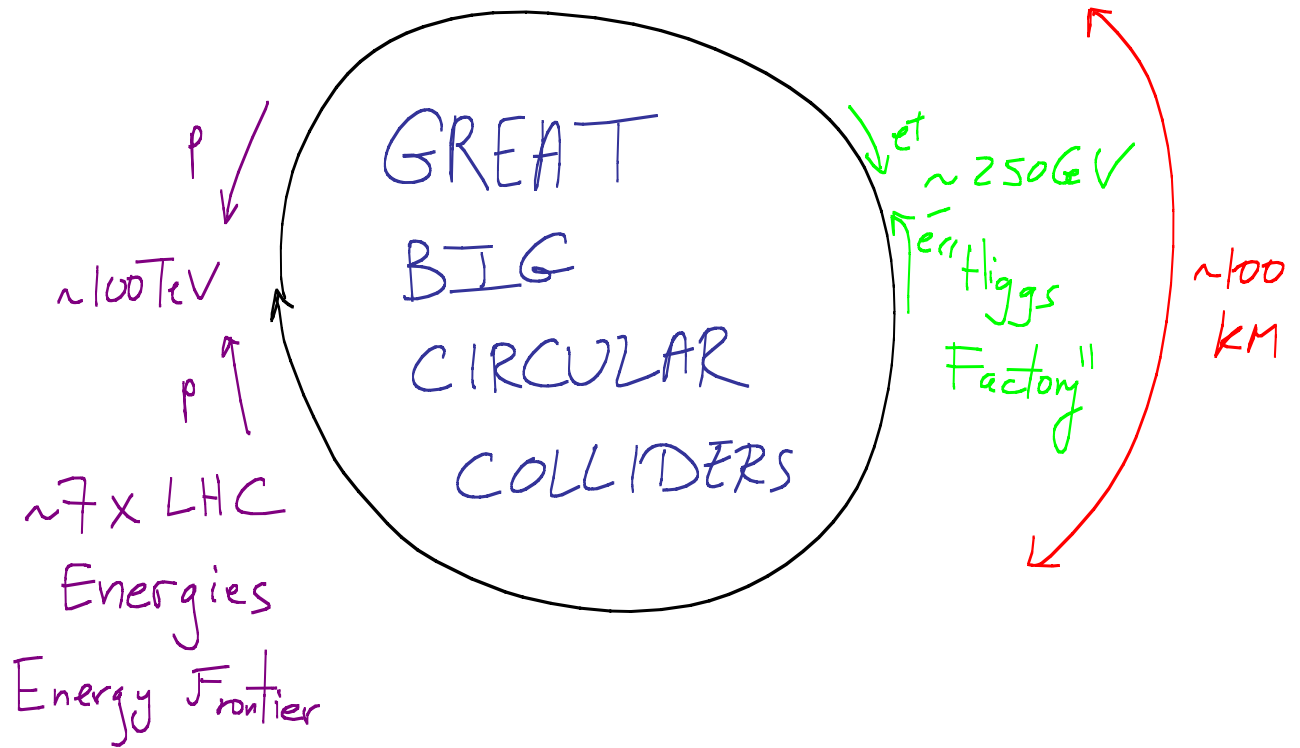


Figure 2: Cross section of colored pions in the 24.



# Motivations For



# Particle Physics

|| ?

Study of Building Blocks of Matter

# Particle Physics

// [At least not merely]

Study of Building Blocks of Matter

# Particle Physics

||

Study of Fundamental Laws of Nature,  
governed by still-mysterious union of  
Space-Time + Quantum Mechanics

New Physics  $\stackrel{?}{=}$  New Particles

New Physics  $\neq$  New Particles

New Physics = New Phenomena

New Physics = New Principles

$$\left(\frac{E}{V}\right) = \int d^3k \frac{1}{2} \sqrt{k^2 + m_B^2} - \frac{1}{2} \sqrt{k^2 + m_F^2}$$

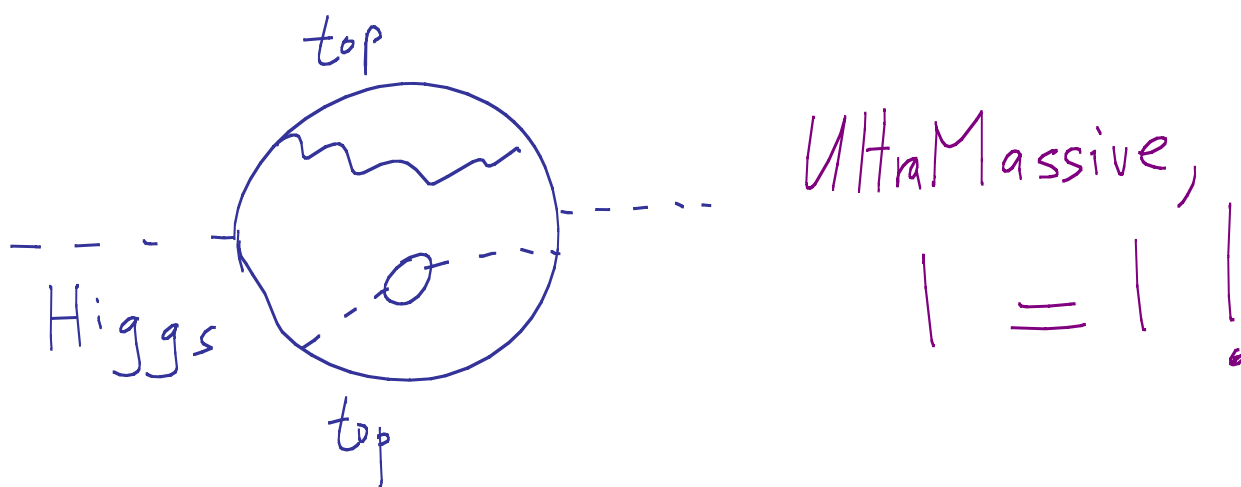
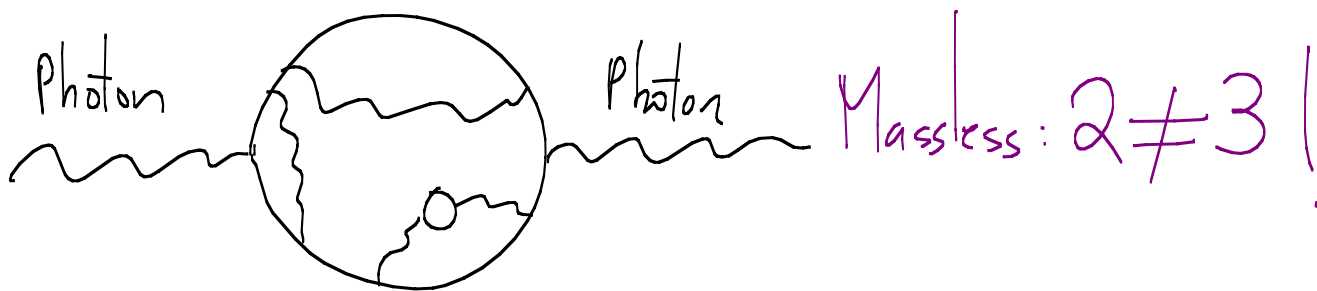
$\downarrow$   $g^2|h|^2$                        $\downarrow$   $\lambda^2|h|^2$

$$= \Lambda_{UV}^4 + (g^2 - \lambda^2) \Lambda_{UV}^2 |h|^2 + \dots$$

↑  
Cosmological  
Constant Problem

↑  
Hierarchy Problem

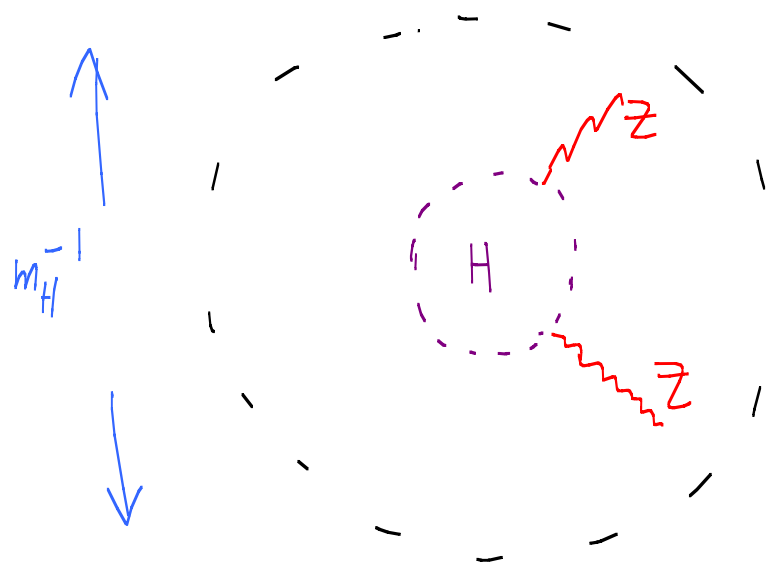
WHY IS THERE A MACROSCOPIC UNIVERSE?



Higgs is Really New Physics!

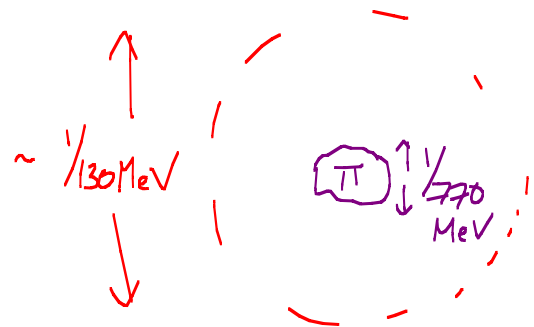
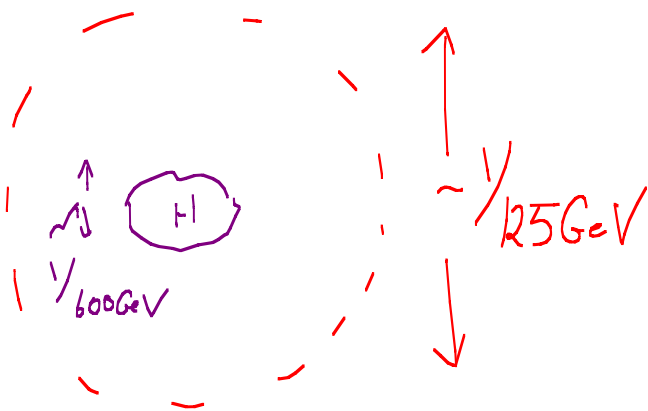
- \* We've never seen anything like it
- \* Harbinger of profound New Principles  
at work in quantum vacuum
- \* MUST Look AT IT CLOSELY!

Never Seen Point-Like Scalar

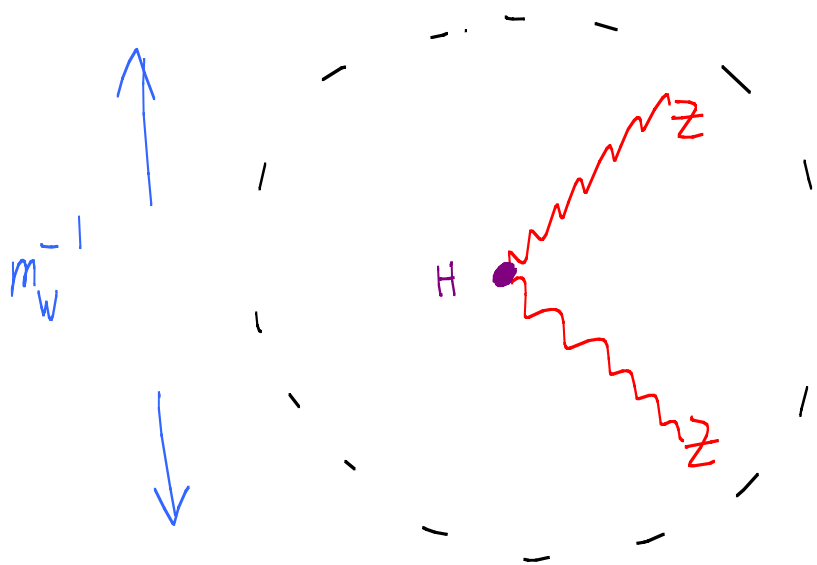


So, how  
pointlike is  
it?

But with LHC resolution,  
Higgs could be about as elementary  
as a "pion":



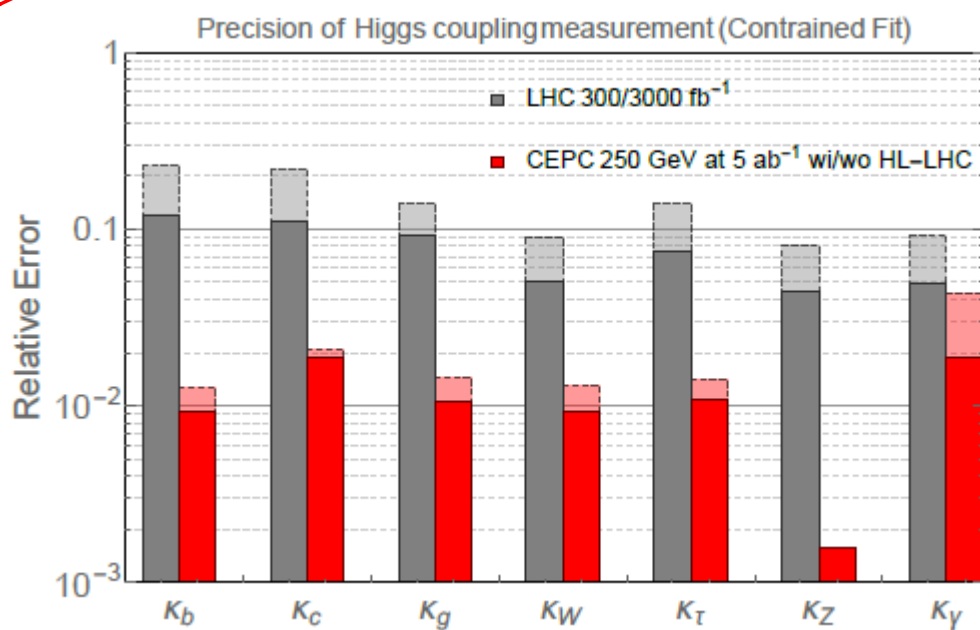
Never Seen Pion-Like Scalar



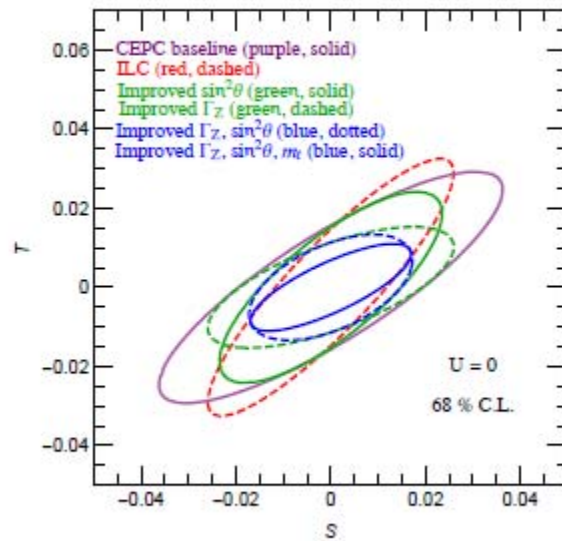
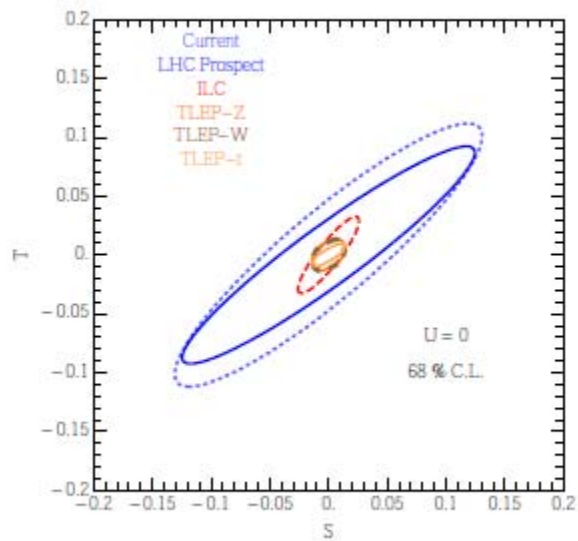
Higgs Factory

+  
We will know  
FOR SURE  
if it is  
"a pion"

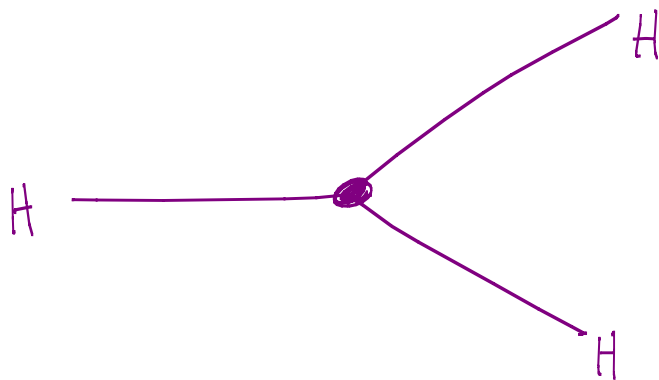
# Higgs / Z factory Leap in Precision



# Higgs / Z factory Leap in Precision



Never Seen Self-Interacting Fundamental Particles

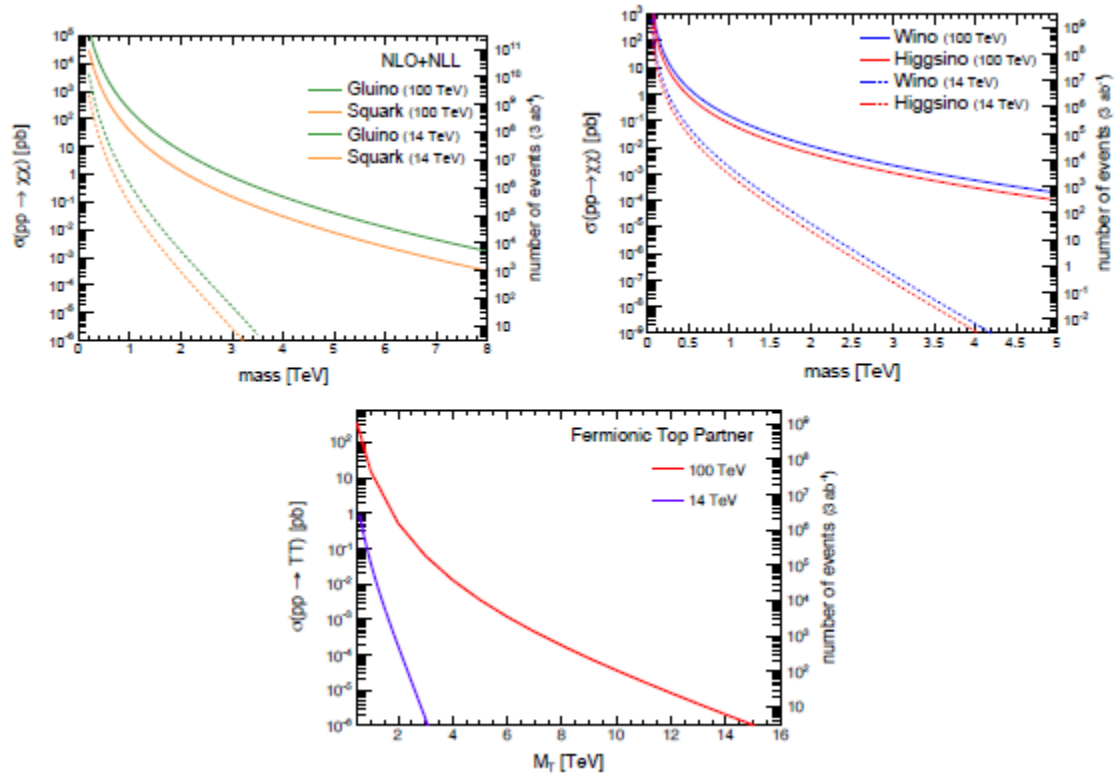


100 TeV  
Collider

Measured to  $\sim 5-10\%$   
level!

Also, 100 TeV collider  
blasts into the high energy  
frontier. New particles  $\sim 10 \times \text{LHC reach}$ .  
Probes vacuum quantum fluctuations  
with power  $100 \times \text{LHC}$

# 100 TeV Leap



Phase Transition

"No Lose"

DM

See or Rule out  
Simplest possibilities

Naturalness

NO LOSE

What is Shape of Potential?

$$V(h) \rightarrow m^2 h^\dagger h + \lambda (h^\dagger h)^2 \quad \text{Landau-Ginzburg...}$$

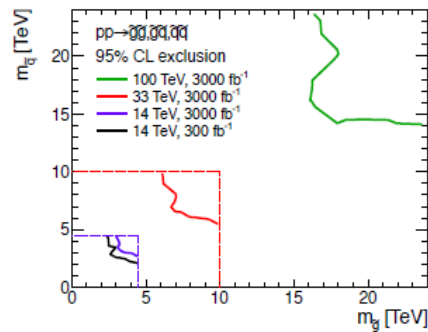
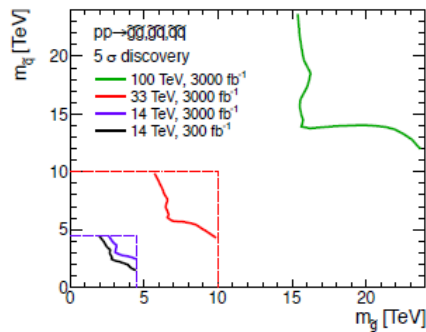
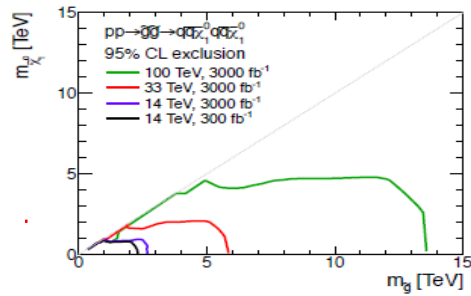
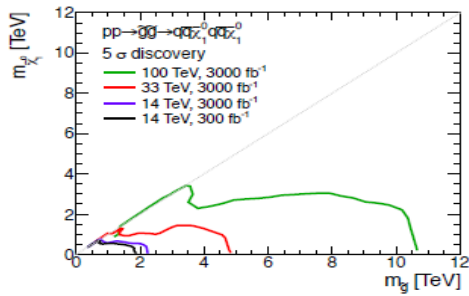
NOT INNOCUOUS!

$$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 + \frac{1}{\Lambda^2} (h^\dagger h)^3$$
$$V(h) \xrightarrow{?} \lambda (h^\dagger h)^2 \log \frac{h^\dagger h}{\Lambda^2}$$

} LHC won't tell us!

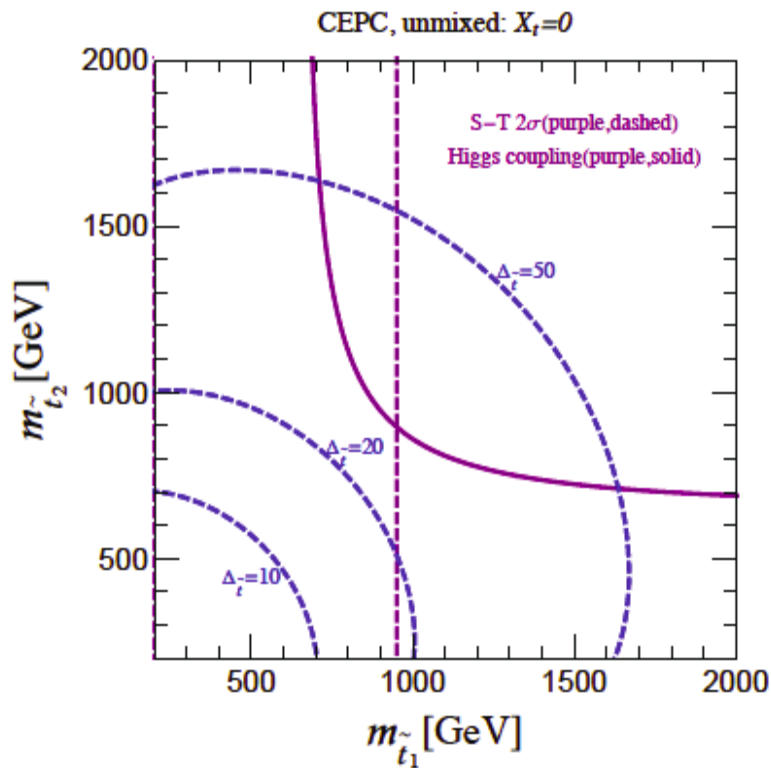
(O(1) Deviations in  $HHH$  coupling)

# 100 TeV Collider Reach For e.g. SUSY



But "Hadronic Muck Gaps" possible...

Stops have nowhere to Hide!

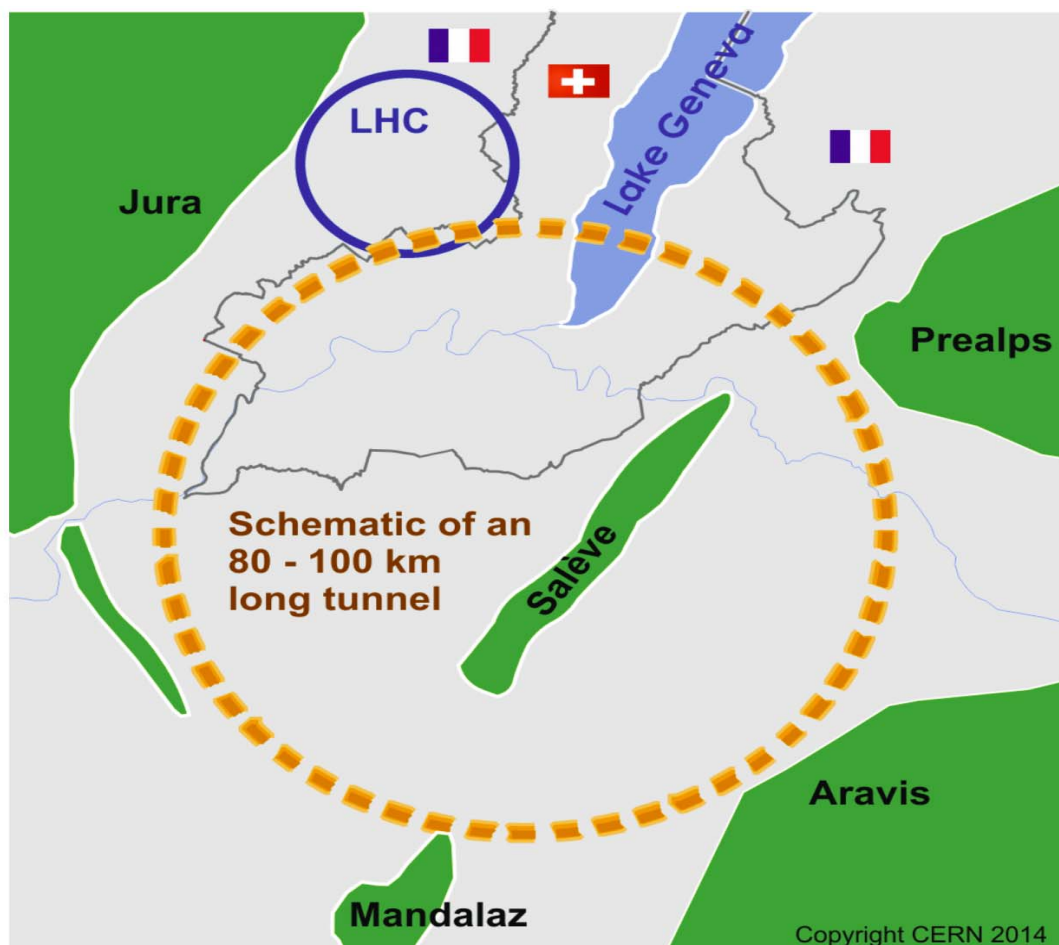


higgs/Z  
coupling  
shifts,  
Can't  
be hidden  
in hadronic  
muck

We're entering most exciting phase of LHC!

But **NOMATTER** WHAT we see from LHC, case for proceeding to circular coll. is rock-solid.

- \* Nothing but Higgs?  $\Rightarrow$  Study Higgs, only fuzzy from LHC
- \* See new particles e.g. "stops" — not high enough rate @ LHC to know what it is! Higgsfact. confirms coupling to higgs(!), 100 TeV for the "factory"



# Site

- Preliminary selected: Qinhuangdao (秦皇岛)
- Strong support by the local government



The questions raised by the accelerating universe, and the higgs discovery, both go to the heart of our understanding of the nature of spacetime, quantum mechanics + the vacuum.

The scale of our vision  
+ ambition must be  
commensurate with what  
the science demands: **BE  
MORE, NOT LESS AGGRESSIVE  
IN PURSUING IT!**

Towards a Common Origin of



Space-time + Quantum Mechanics



QM



Emergent  
Space

vs.

?

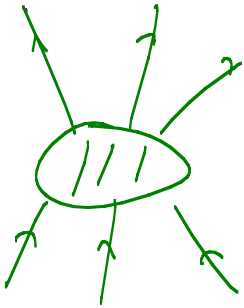


|                |                       |
|----------------|-----------------------|
| Emergent<br>QM | Emergent<br>Spacetime |
|----------------|-----------------------|

Emerge together,  
joined inexorably

# Big Reasons to Expect It

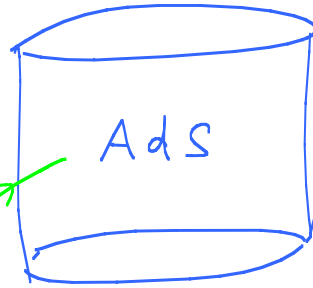
- \* We eventually run out of precise quantum observables  
[infalling observers into Bth, accelerating cosmologies]
- \* TENSION between two revolutions of 90's!



Unique (flat space)  
theory! Many solns  
of same theory

vs.

Is  
some QG



Any  
chappy  
QM system

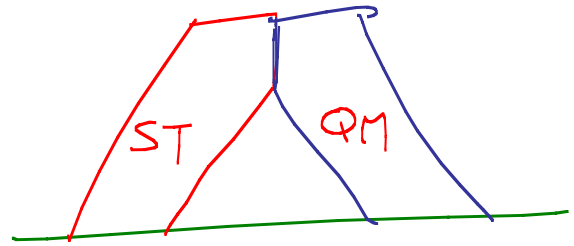
# Other Circumstantial Clues

QFT  
in  $(3+1)$  dim

$(4+0)$  more natural

$(2+2)$  more natural

"Causal" + "Probabilistic"  
intimately tied together



They Buttress Each  
Other, making each other  
more rigid + robust

Locality + Unitarity

Result of a brute force calculation:

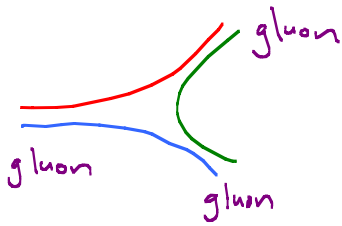
[illegible][illegible][illegible][illegible][illegible]
$$\begin{aligned} \text{a) } \{x\} &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, x_{26}, x_{27}, x_{28}, x_{29}, x_{30}, x_{31}, x_{32}, x_{33}, x_{34}, x_{35}, x_{36}, x_{37}, x_{38}, x_{39}, x_{40}, x_{41}, x_{42}, x_{43}, x_{44}, x_{45}, x_{46}, x_{47}, x_{48}, x_{49}, x_{50}, x_{51}, x_{52}, x_{53}, x_{54}, x_{55}, x_{56}, x_{57}, x_{58}, x_{59}, x_{60}, x_{61}, x_{62}, x_{63}, x_{64}, x_{65}, x_{66}, x_{67}, x_{68}, x_{69}, x_{70}, x_{71}, x_{72}, x_{73}, x_{74}, x_{75}, x_{76}, x_{77}, x_{78}, x_{79}, x_{80}, x_{81}, x_{82}, x_{83}, x_{84}, x_{85}, x_{86}, x_{87}, x_{88}, x_{89}, x_{90}, x_{91}, x_{92}, x_{93}, x_{94}, x_{95}, x_{96}, x_{97}, x_{98}, x_{99}, x_{100}\} \\ \text{b) } \{x\} &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, x_{26}, x_{27}, x_{28}, x_{29}, x_{30}, x_{31}, x_{32}, x_{33}, x_{34}, x_{35}, x_{36}, x_{37}, x_{38}, x_{39}, x_{40}, x_{41}, x_{42}, x_{43}, x_{44}, x_{45}, x_{46}, x_{47}, x_{48}, x_{49}, x_{50}, x_{51}, x_{52}, x_{53}, x_{54}, x_{55}, x_{56}, x_{57}, x_{58}, x_{59}, x_{60}, x_{61}, x_{62}, x_{63}, x_{64}, x_{65}, x_{66}, x_{67}, x_{68}, x_{69}, x_{70}, x_{71}, x_{72}, x_{73}, x_{74}, x_{75}, x_{76}, x_{77}, x_{78}, x_{79}, x_{80}, x_{81}, x_{82}, x_{83}, x_{84}, x_{85}, x_{86}, x_{87}, x_{88}, x_{89}, x_{90}, x_{91}, x_{92}, x_{93}, x_{94}, x_{95}, x_{96}, x_{97}, x_{98}, x_{99}, x_{100}\} \\ \text{c) } \{x\} &= \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, x_{26}, x_{27}, x_{28}, x_{29}, x_{30}, x_{31}, x_{32}, x_{33}, x_{34}, x_{35}, x_{36}, x_{37}, x_{38}, x_{39}, x_{40}, x_{41}, x_{42}, x_{43}, x_{44}, x_{45}, x_{46}, x_{47}, x_{48}, x_{49}, x_{50}, x_{51}, x_{52}, x_{53}, x_{54}, x_{55}, x_{56}, x_{57}, x_{58}, x_{59}, x_{60}, x_{61}, x_{62}, x_{63}, x_{64}, x_{65}, x_{66}, x_{67}, x_{68}, x_{69}, x_{70}, x_{71}, x_{72}, x_{73}, x_{74}, x_{75}, x_{76}, x_{77}, x_{78}, x_{79}, x_{80}, x_{81}, x_{82}, x_{83}, x_{84}, x_{85}, x_{86}, x_{87}, x_{88}, x_{89}, x_{90}, x_{91}, x_{92}, x_{93}, x_{94}, x_{95}, x_{96}, x_{97}, x_{98}, x_{99}, x_{100}\} \end{aligned}$$

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

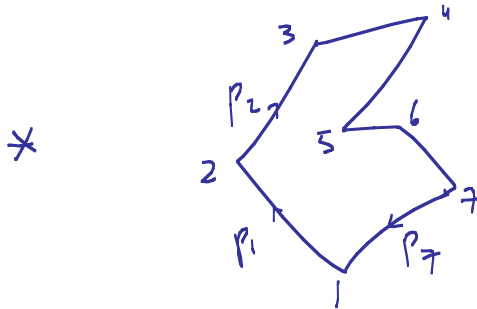
$+ 25 \text{ pages} \dots = \frac{\langle 13 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle}$

# "Hydrogen Atom" of 21<sup>st</sup> Century

\* Maximally supersymmetric theory of gluons



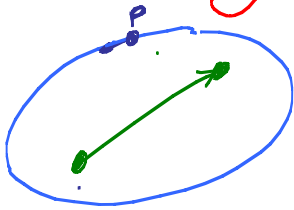
$$\underbrace{\text{[Feynman diagrams]} + \dots}_{\mathcal{M}_n[p_a, h_a]}$$



Hidden Dual Conformal symmetry (any  $D$ )  
 + Conformal in  $4D \Rightarrow$  Hidden  
 Infinite Yangian symmetry

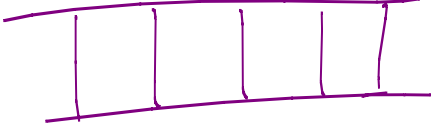
The Yangian contains [+ vastly generalizes]

"Runge-Lenz" symmetry  $\rightarrow$  Elliptic Keplerian Orbits!



$$\vec{A} = \vec{p} \times \vec{J} - G_N m \hat{r} \quad \text{conserved}$$

[Hidden  $SO(4)$  symmetry]

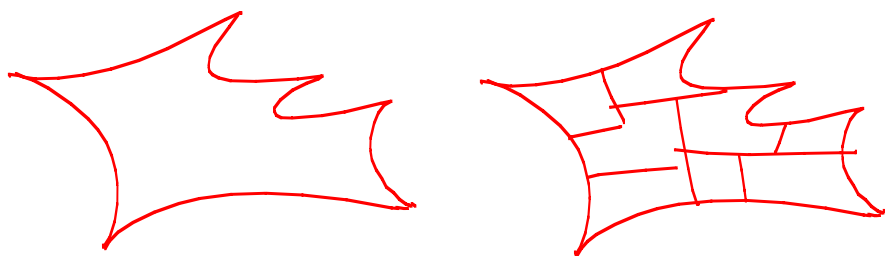
{ Dual conformal symmetry of  first observed by Wick + Cutkosky in 50's }

# Strategy

- \* Reformulate QFT — eviscerating Locality + Unitarity. See them as derived, not primary concepts (NOT merely exploit L+U to fix result — OPPOSITE philosophy to S-matrix program)
- \* Start with Planar  $N=4$  SYM!

# Goal

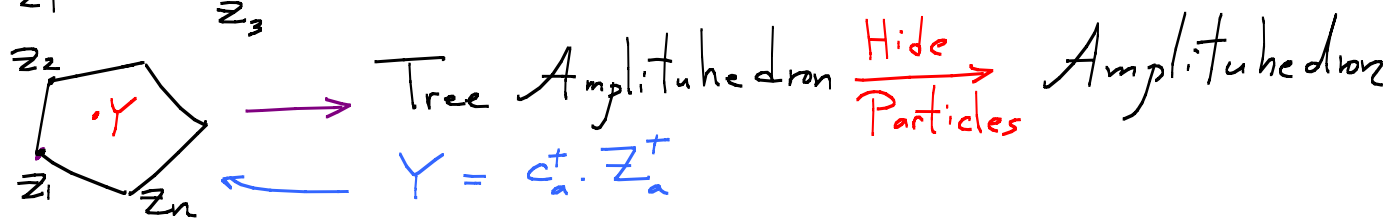
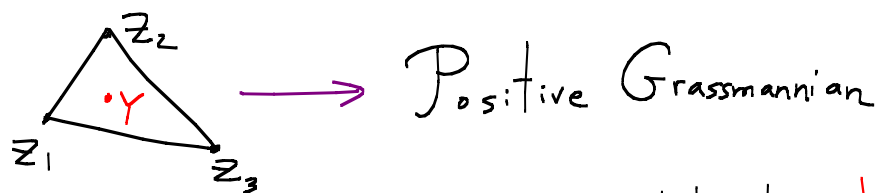
Find a new picture for scatt. amps  
with no space-time, Hilbert space, no  
 $\mathcal{L}, \mathcal{H}$ , no  $\int \mathcal{D}\varphi e^{iS}$ , no Gauge Redundancy....



"The Volume" of "Some Region" in "Some Space"  
Symmetries Manifest; Loc+Un. Derived

$$\mathcal{M}_{n,k,L}[Z] = "V_0|" [A_{n,k,L}[Z]]$$

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



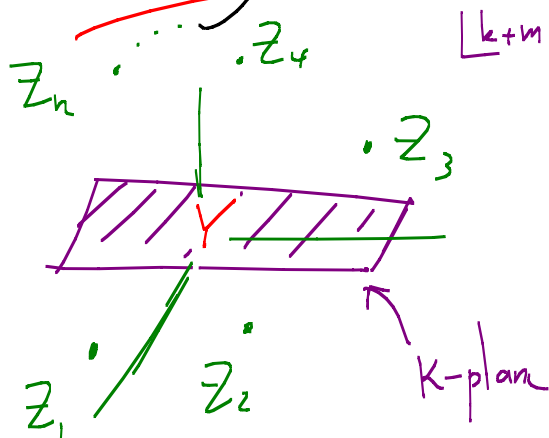
$$Y = C^+ \cdot Z^+$$

\* Scattering Form: Form with log sing. on  $\partial$  Amplituhedron.

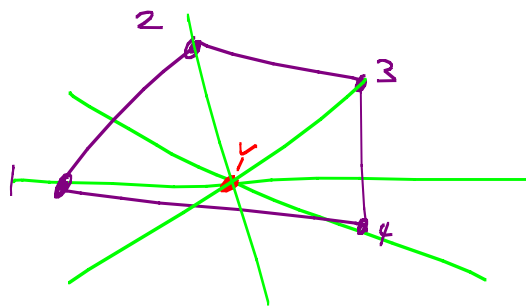
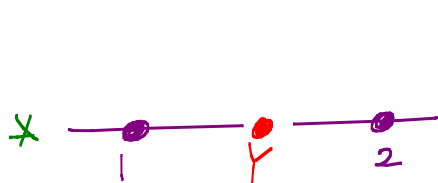
\* Boundaries  $\rightarrow \partial$  = - +

\* Yangian manifest: positive diffeomorphisms

# Amplituhedron is Binary Code



When is  $Y$  in the amplituhedron?  
Project through  $Y \rightarrow m$  dim.  
picture. What does this picture  
look like?



↑  
1 → n  
jump over  
Y once



\*  $m = 1$  amplification: , jump over Y  $k$  times

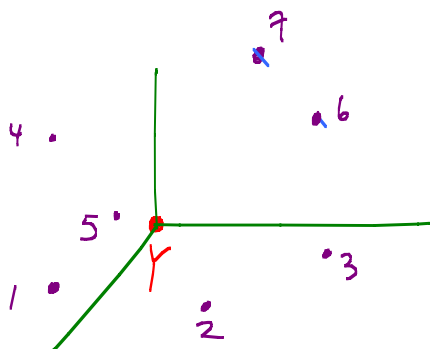
$$\equiv \{ \langle Y_1 \rangle, \dots, \langle Y_n \rangle \} = \{ ++--++-- \}$$

$k$  sign flips!

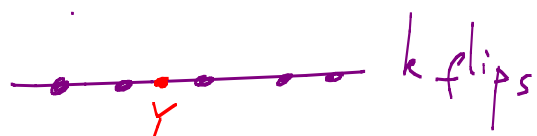
\* General  $m : Y \in \text{Ampl.} \iff$  projecting through  $\begin{cases} Z_a Z_{a+1} & Z_b Z_{b+1} & \dots & m \text{ odd} \\ " & + Z_c & & m \text{ even} \end{cases}$

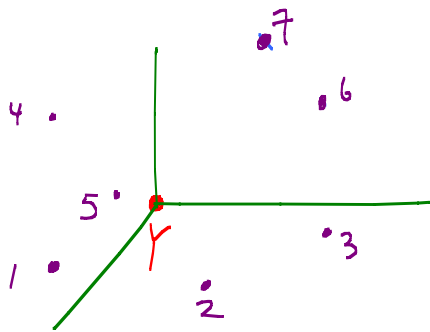
We are in  $m=1$  Amplitude down!

e.g.  $m = 2$   $\{ \langle \tau_{12} \rangle, \dots, \langle \tau_{1n} \rangle \}$   $k$  sign-flips  
 $m = 4$   $\{ \langle \tau_{1234} \rangle, \dots, \langle \tau_{123n} \rangle \}$

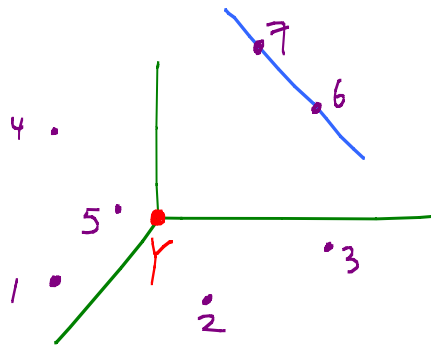
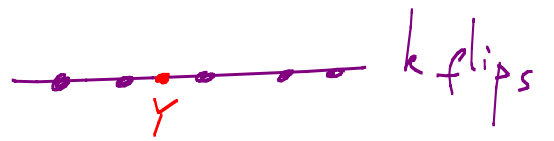


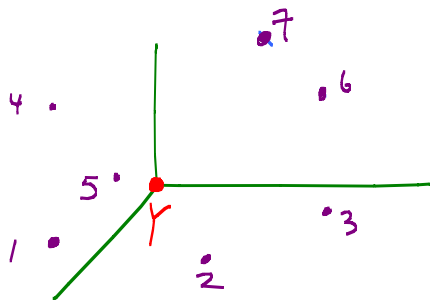
project  
 $\xrightarrow{\quad}$   
 $b, b+1, a$



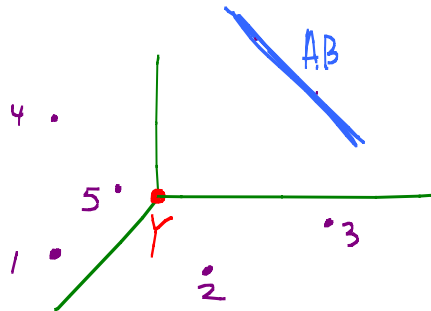


project  
 $\xrightarrow{bb+1, a}$

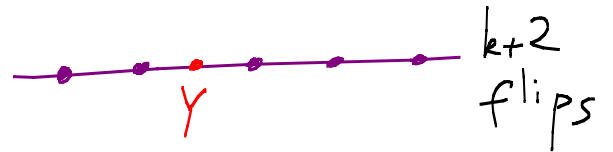




project  
 $\xrightarrow{bb+1, a}$



project  
 $\xrightarrow{AB, a}$



$\mathcal{L}_{\text{ops}} = \text{Hiding Particles}$

# Amplituhedron Code

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

\*  $\{ \langle Y_{\substack{a \ b \ b+1}}{1234}} \rangle, \dots, \langle Y_{123n} \rangle \}$  has  $k$  sign flips

\*  $\{ \langle Y_{AB_i \substack{a}}{12}} \rangle, \dots, \langle Y_{AB_i 1n} \rangle \}$  has  $(k+2)$  sign flips

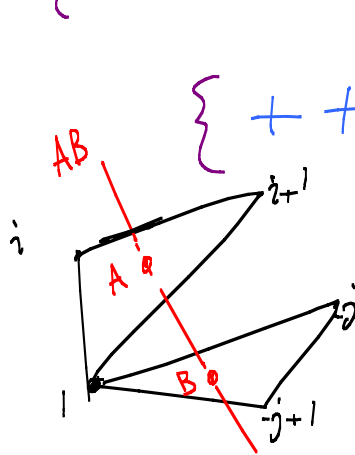
\* Scattering form fixed by log singularities on  $\partial$

# Amplituhedron Code

- \*  $L$   $(k+2)$  planes  $(YAB)_i$  intersecting on  $k$ -plane  $Y$
- \*  $\langle Y Z_a Z_{a+1} Z_b Z_{b+1} \rangle, \langle Y A B_i Z_a Z_{a+1} \rangle, \langle Y A B_i A B_j \rangle > 0$
- \*  $\{\langle Y 1234 \rangle, \dots, \langle Y 123n \rangle\}$  has  $k$  sign flips
- \*  $\{\langle Y A B_i 12 \rangle, \dots, \langle Y A B_i 1n \rangle\}$  has  $(k+2)$  sign flips
- \* Scattering form fixed by log singularities on  $\partial$

Example: 1-loop MH V

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



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

$$A = z_1 + \alpha_i z_i + \alpha_{i+1} z_{i+1} \quad \alpha_{i,i+1,j,j+1} > 0$$

$$B = -z_1 + \alpha_j z_j + \alpha_{j+1} z_{j+1}$$

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

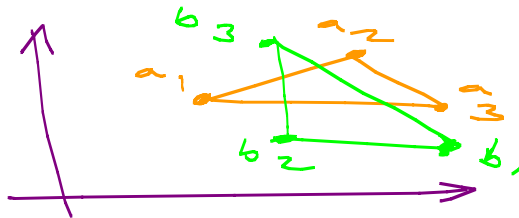
$$= \sum_{i,j} d \log \frac{\langle AB|i \rangle}{\langle AB|i+1 \rangle} d \log \frac{\langle AB|i+1 \rangle}{\langle AB|i+1 \rangle} d \log \frac{\langle AB|j \rangle}{\langle AB|j+1 \rangle} d \log \frac{\langle AB|j+1 \rangle}{\langle AB|j+1 \rangle}$$

# 4 Particles to All Loops

$$(AB)_i, \quad A_i = 1 + x_i^2 - z_i^4, \quad B_i = 3 + y_i^2 + w_i^4$$

$$\vec{a}_i = \begin{pmatrix} x_i^+ \\ y_i^+ \end{pmatrix}, \quad \vec{b}_i = \begin{pmatrix} w_i^+ \\ z_i^+ \end{pmatrix}, \quad (\vec{a}_i - \vec{a}_j) \cdot (\vec{b}_i - \vec{b}_j) < 0$$

↑  
"Triangulate"  
= 4-pt to all  
loop order!



A  
highschool  
geometry  
problem

Textbook Unitarity  
follows from geometry

$$\text{Diagram with 4 external lines (1, 2, 3, 4) and a loop L} = \sum_{L_1, L_2} \text{Diagram with 4 external lines (1, 2, 3, 4) and loops L1, L2}$$

At least for planar  $N=4$  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*.

\* Still need to connect to amazing integrability techniques that are heading to exact solution to all amps!

\* I believe the connection will involve finding a "dual" amplituhedron, generalizing point-plane duality from projective geometry

\* The singularity structure of amplitudes is universal — so we should look for similar structures in more general theories

Ex: "dlog" representation highly non-trivial + associated with positive geometry. The "dlog" forms have now been seen in non-planar  $\mathcal{N}=4$  amps, + in  $\mathcal{N}=8$  SUGRA, through 3 loops.

# Is String Theory Unique Weakly Coupled UV Completion of Grav?

$$\mathcal{M}(s, t, u) = \frac{\delta'^6(Q)}{stu} \times F(s, t, u) \equiv \delta'^6(Q) A(s, t, u)$$

- \* Only poles as sing. [weak coupling]
  - \*  $A(s, t, u) \rightarrow \frac{1}{stu} \quad s, t, u \ll 1$  [math low-E]
  - \*  $A < \text{const}$  at high en. - fixed angle. [good UV]
  - \*  $A(s, \text{fixed}) < s^{\mathcal{D}(E)}$  for large  $s$  [Causality]
  - \* As  $s \rightarrow m^2$   $A \rightarrow \frac{1}{s-m^2} \times \mathcal{P}[\cos\theta]$  [Unitarity]
- $$\mathcal{P}[\cos\theta] = \sum_s \underbrace{c_s}_{\neq 0} G_{s, \alpha}[\cos\theta]$$

"Only game in town" = sharp conjecture:

$$F(s, t, u) = \sum_{\alpha'} c_{\alpha'} \frac{\Gamma(1-\alpha's)}{\Gamma(1+\alpha's)} \frac{\Gamma(1-\alpha't)}{\Gamma(1+\alpha't)} \frac{\Gamma(1-\alpha'u)}{\Gamma(1+\alpha'u)}$$

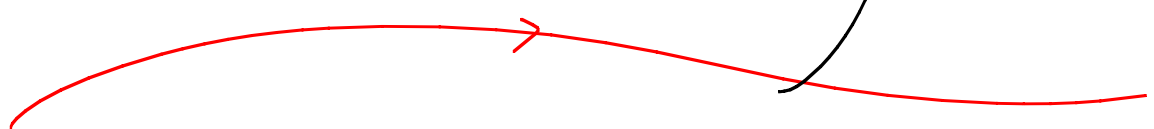
# Positivity of residues HUGELY non-trivial

$$\prod_{i=1}^{n-1} \left( \cos^2 \theta - \left( \frac{2i-1}{2n-1} \right)^2 \right) = \sum_s c_s \cos s\theta = \sum_s c_s^{(n)} G_{d,s}[\cos \theta]$$

for  $d \leq 9$

- \* Only known proof: worldsheet + no-ghost theorem!
- \* But we have observed many other properties of these polynomials that do not have a worldsheet interpretation.
- \* They are "barely" positive  $Q(x) P_n(x)$  will fail positivity unless  $Q(x) = 1$
- \* They are "prime"
- \* Higher spin symmetry non-trivially in action?
- \* Strings without the worldsheet?

Back To Experiment



\* We are approaching the end of an amazing 30 yr program of experiments in fundamental Physics

\* Crucial time to think new thoughts about program for next 30 yrs

# Extremely Weakly Interacting Frontiers

- \* Gravity Waves (!!!!)
- \* Cosmic neutrino background
- \* Dipole moments
- \* Axions
- \*  $P$  decay
- \* "Dark" photons
- \* Dark matter

Many new  
ideas connecting  
to table-top  
physics

Theorists can + should play a big role  
in thinking of new ideas,  
new probes of fundamental physics

