Title: The Higgs confronts 3 universes at the LHC

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Abstract: The recent discovery
of the Higgs boson is a fundamental advance in particle physics. This talk gives a theorist's perspective of the significance of this discovery. The Higgs boson was proposed in the 1960s, but it is best understood in the context of the quest to understand the weak interactions, which began with Fermi's theory of weak interactions almost 80 years ago. This has led to three very different paradigms for the structure of fundamental interactions at the TeV scale: supersymmetry, compositeness/extra dimensions, and anthropic selection. The Large Hadron Collider is the experimentum crucis for deciding between these different possible universes, and the discovery of the Higgs is a crucial clue. This talk will describe these paradigms, the implications of the Higgs discovery for them, and the outlook for further discoveries that would decide between them.

The Higgs Confronts Three Universes at the LHC

Markus Luty
UC Davis

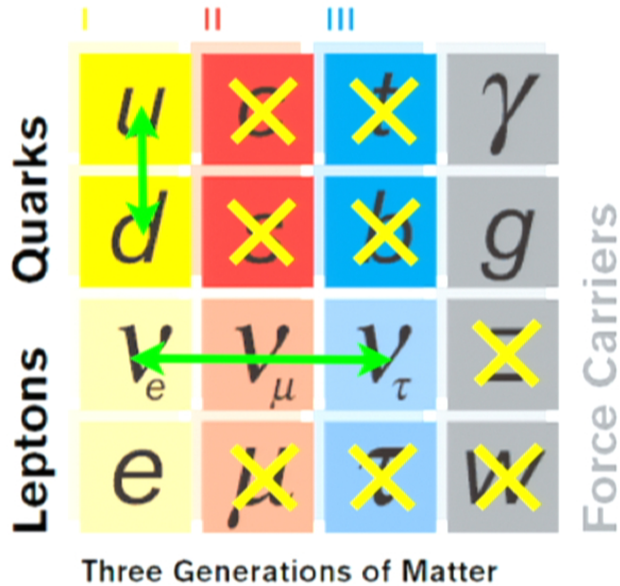
Outline

- The story of the weak interactions
  from Fermi theory to the Higgs discovery
- Puzzles lead to three possible universes
- The LHC is the experiment to decide between them
- What we learn from the Higgs

Weak Interactions

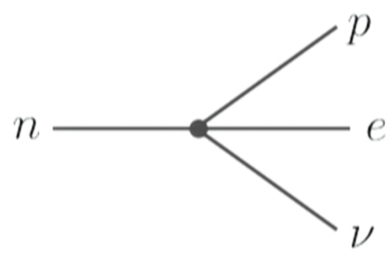
Only interaction that can change particle type

Responsible for the decay of most known elementary particles...



...and nuclear β decays and mixing of neutrinos

Fermi Theory (1934)



$$\mathcal{L}_{\text{eff}} = G_F (\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$$

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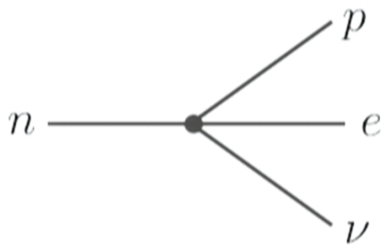

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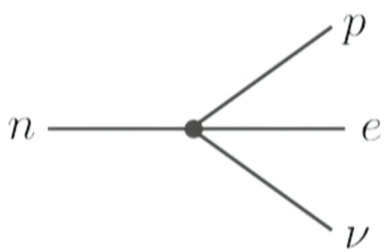

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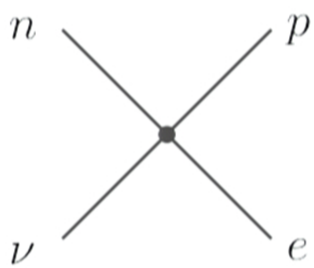

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⇒ breaks down at

$$E \sim 4\pi G_F^{-1/2} \sim \text{TeV}$$

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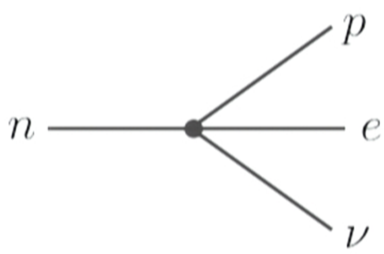

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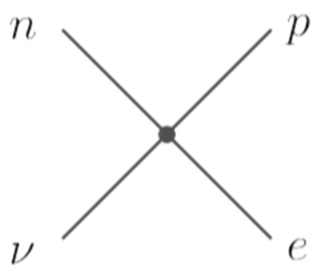

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$\Rightarrow$ breaks down at

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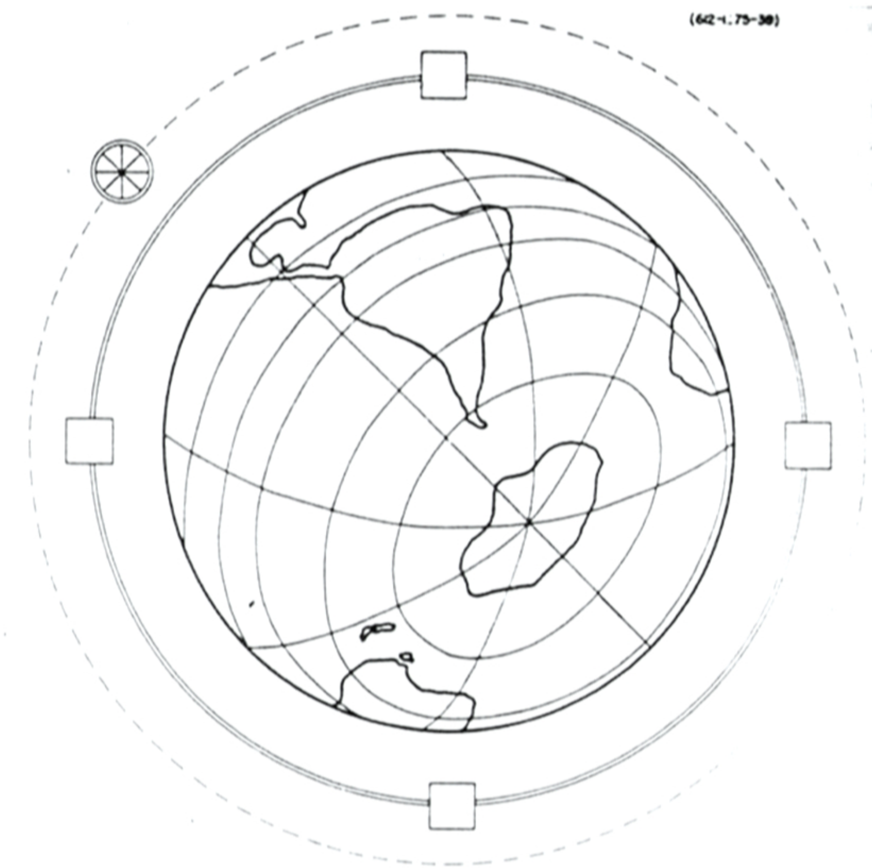
Motivates a TeV collider!

“Globatron”

E. Fermi, 1954



$$R \sim 6000 \text{ km}$$
$$B \sim 1 \text{ T}$$
$$E_{\text{beam}} \sim 10^3 \text{ TeV}$$
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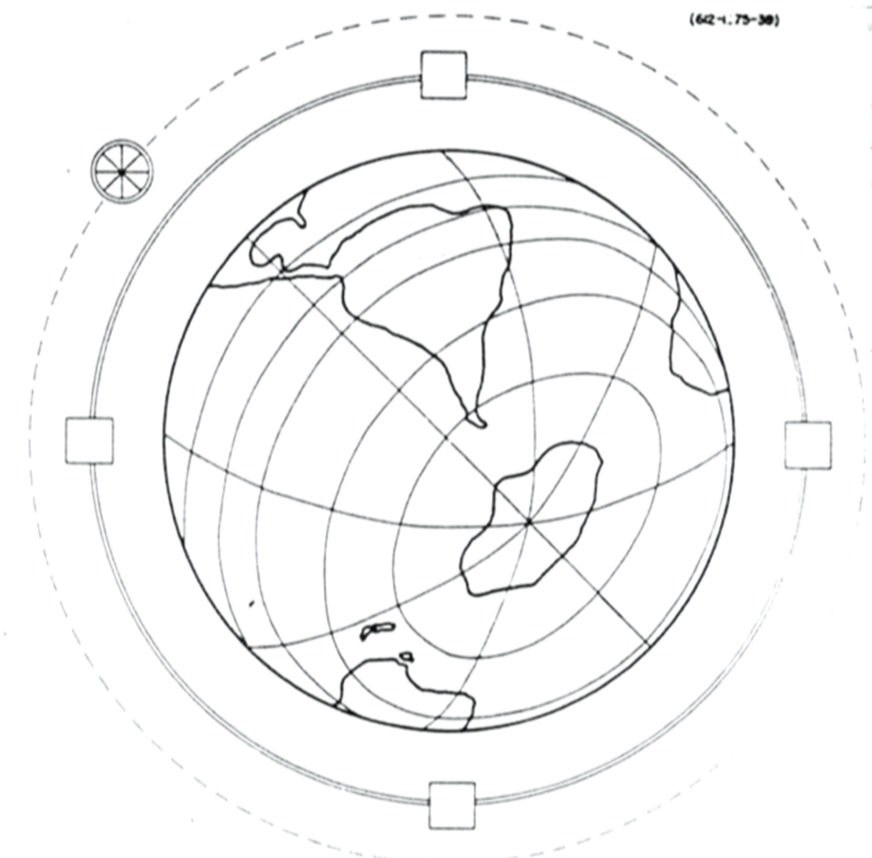

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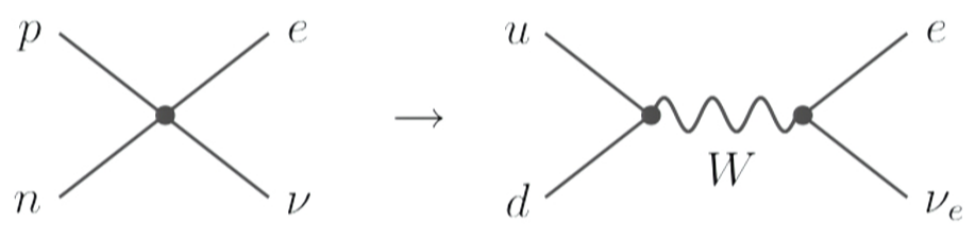

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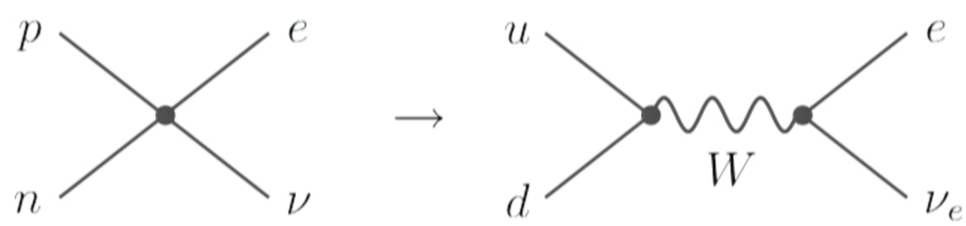

- Electroweak unification
- Prediction and discovery of W, Z

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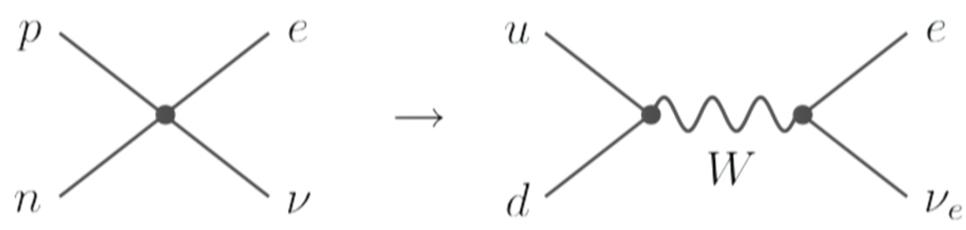
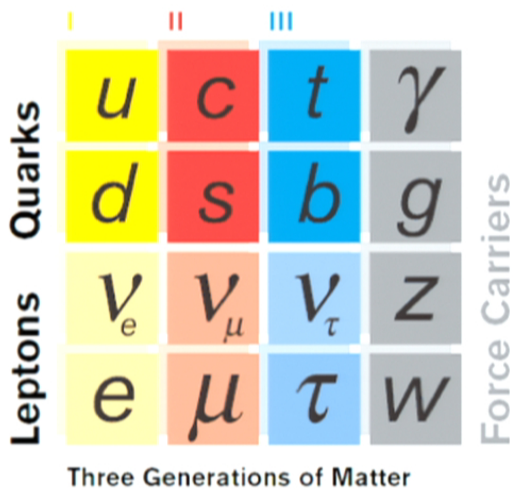
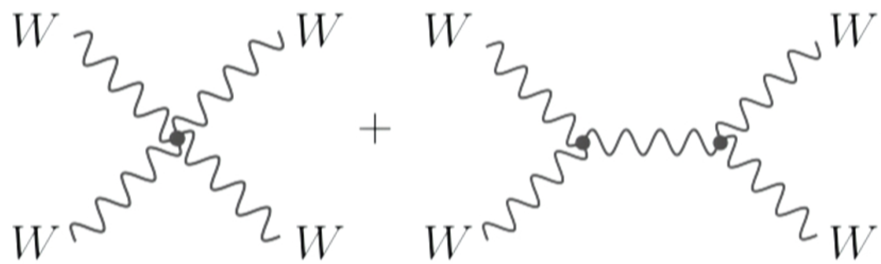


- Electroweak unification
- Prediction and discovery of W, Z
- "Periodic table" of elementary particles



Incompleteness



$$\sim \frac{g^2 E^2}{m_W^2}$$

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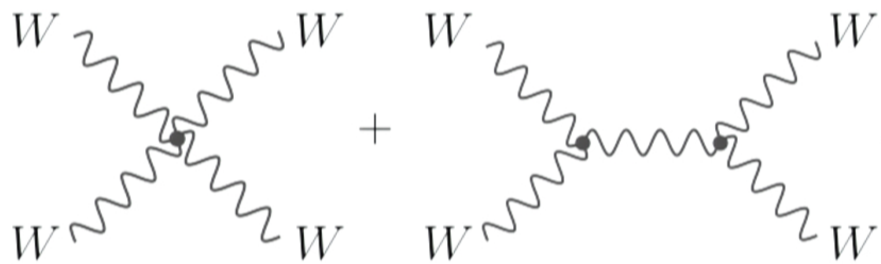

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LHC

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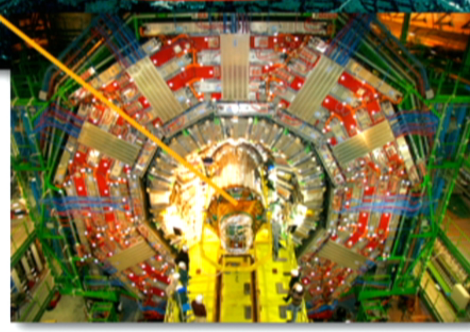
$$B = 8 \text{ T}$$

$$E_{\text{cm}} = E_{\text{beam}}$$
$$= 8 \text{ TeV}$$
$$\to 14 \text{ TeV}$$



ATLAS

The Standard Model Higgs

Simplest completion of electroweak theory

1 new particle: spin 0 Higgs boson

1 new parameter: Higgs mass

$H =$ fundamental scalar field

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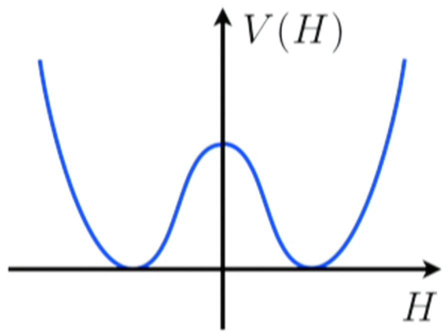
$H \neq 0$ in vacuum (ground state)



Masses of elementary particles arise from interactions with the Higgs field

Just Add Mass?

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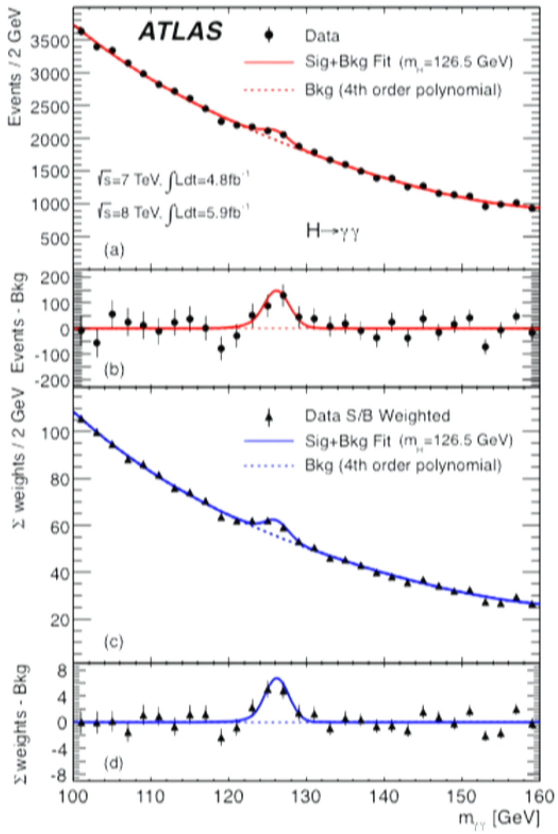
Fermions: $m = 0$ 4 polarizations: fermion + antifermion

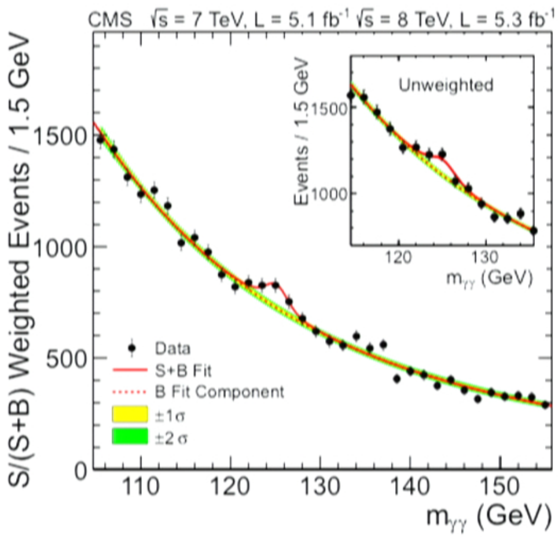
$m \neq 0$ requires fermion $\leftrightarrow$ antifermion mixing
no antifermion with same charges

Fermion $\leftrightarrow$ antifermion mixing from interactions
with Higgs field

Higgs Boson Discovery!



New York Times, 7/4/12



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$\Rightarrow$ neutrino masses and mixing

Naturalness

One term at $\mathcal{O}(M^2)$:

$$\mathcal{L}_{\rm SM} = \underbrace{m_H^2 |H|^2}_{\text{"relevant"}} + \mathcal{O}(M^0) \qquad m_H^2 \sim M^2$$

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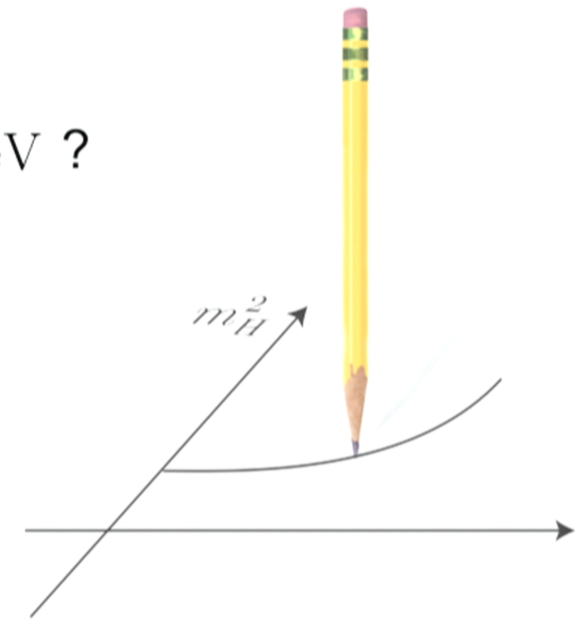

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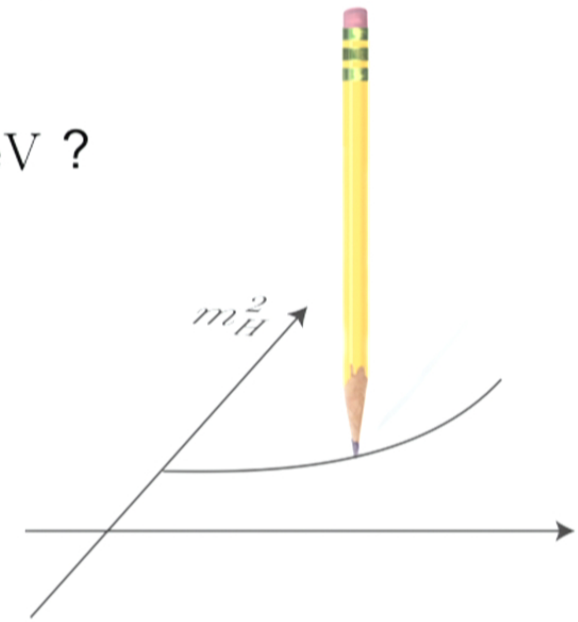

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Motivates new physics beyond the standard model

Three Universes

Three completely different paradigms
for addressing naturalness problem

- Supersymmetry "Logos"
- Compositeness/extra dimensions "Stratus"
- Multiverse "Chaos"

Supersymmetry

Eliminate UV sensitivity with new spacetime symmetry

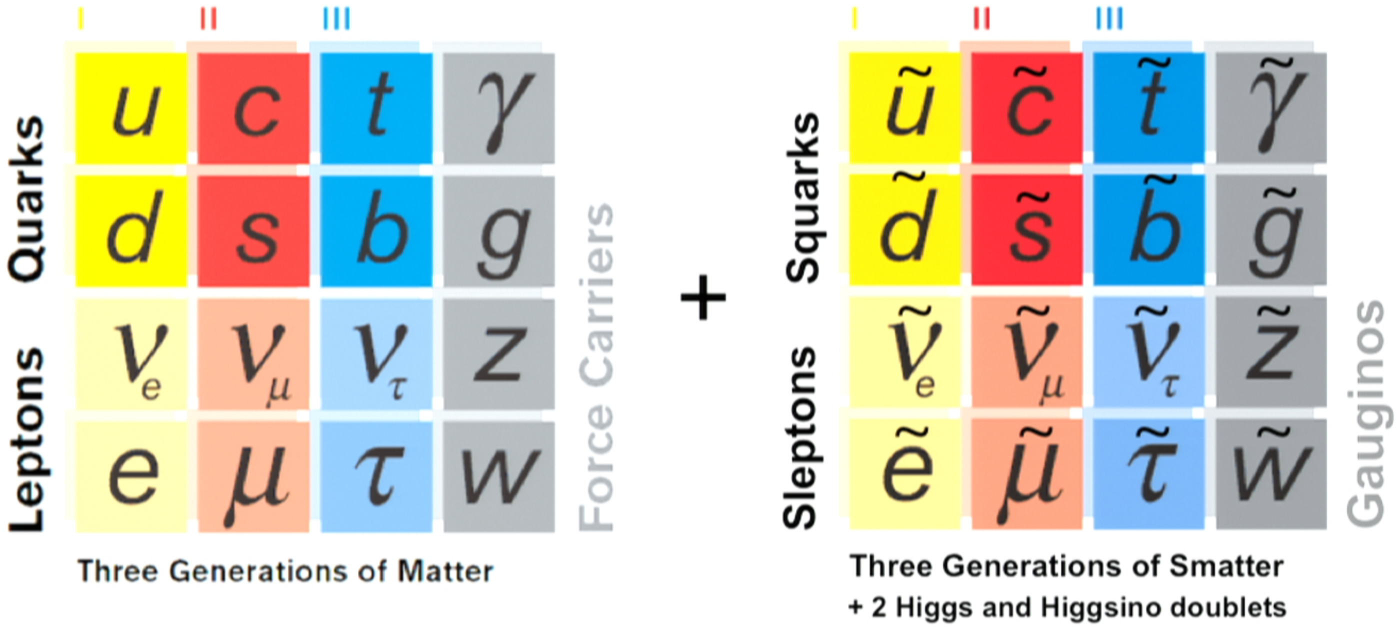
$$[Q, H] = 0$$

$$\left.\begin{array}{l} Q|\text{boson}\rangle = |\text{fermion}\rangle \\ Q|\text{fermion}\rangle = |\text{boson}\rangle \end{array}\right\} \Rightarrow m_{\text{boson}} = m_{\text{fermion}}$$

$m_{\text{fermion}} \to 0 \;\Rightarrow$ extra “chiral” symmetry

$\Rightarrow\; m_H^2 \ll M^2$ natural

Minimal SUSY



SUSY broken ⇒ superpartners heavy

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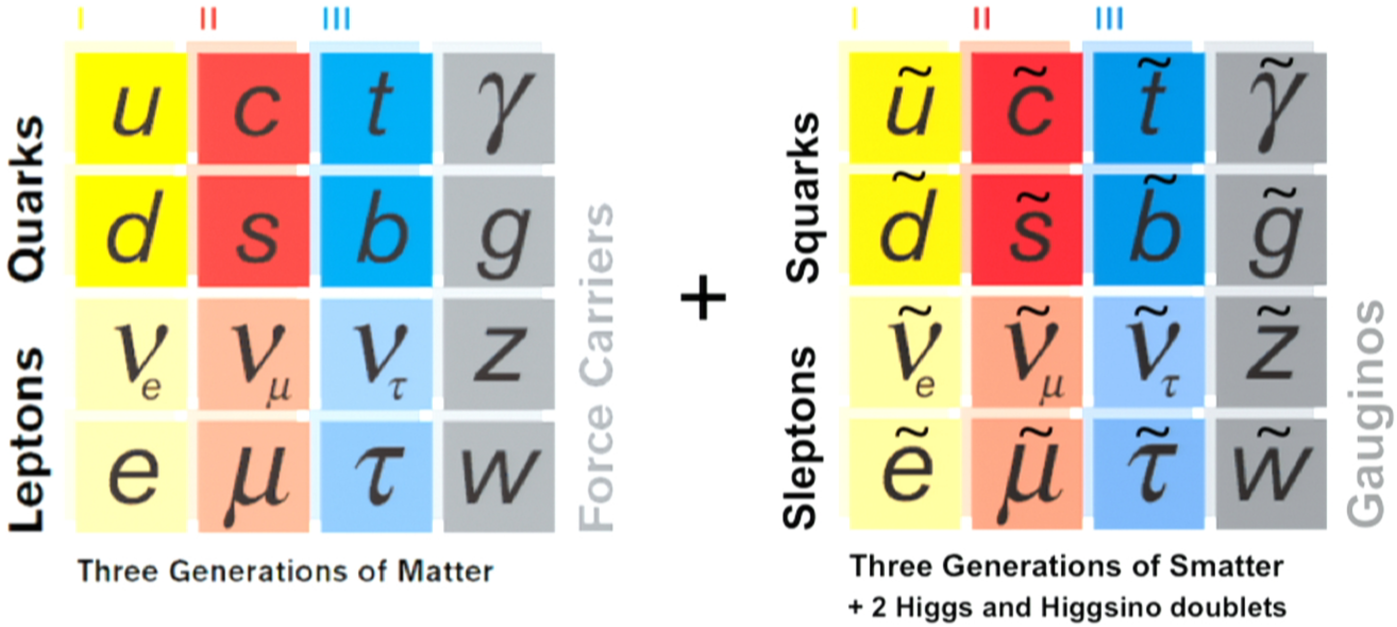

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Naturalness problem cured if superpartners at TeV scale

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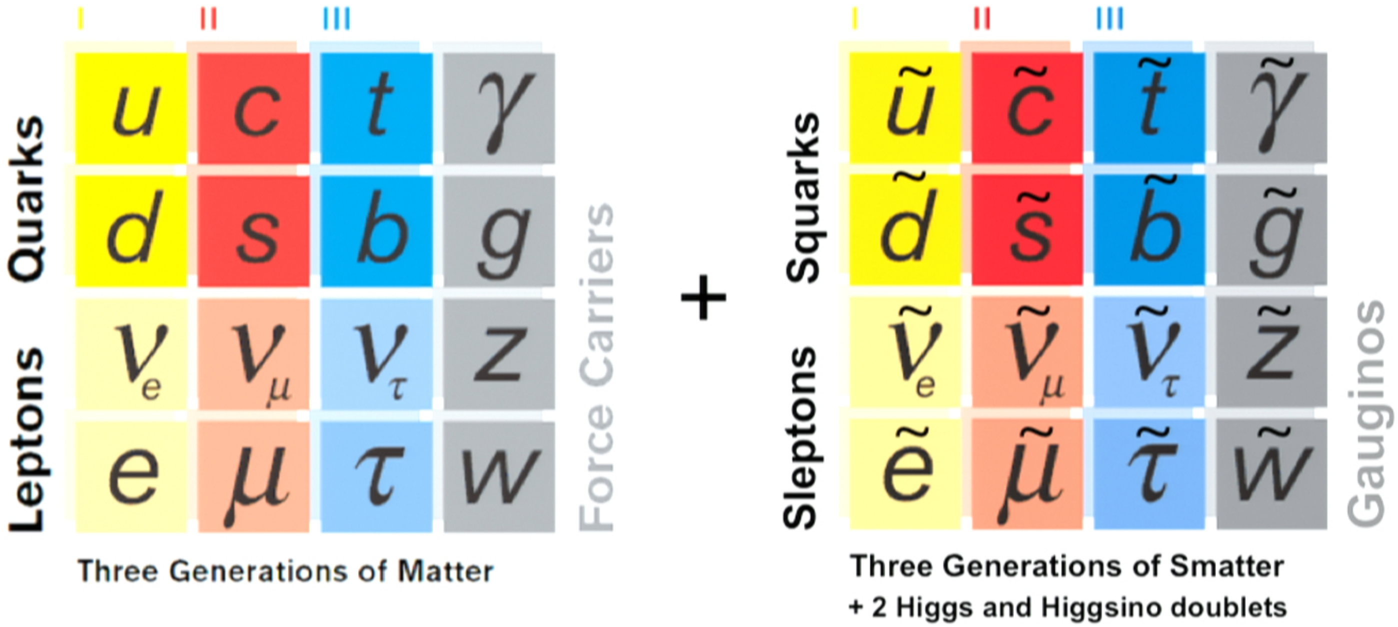

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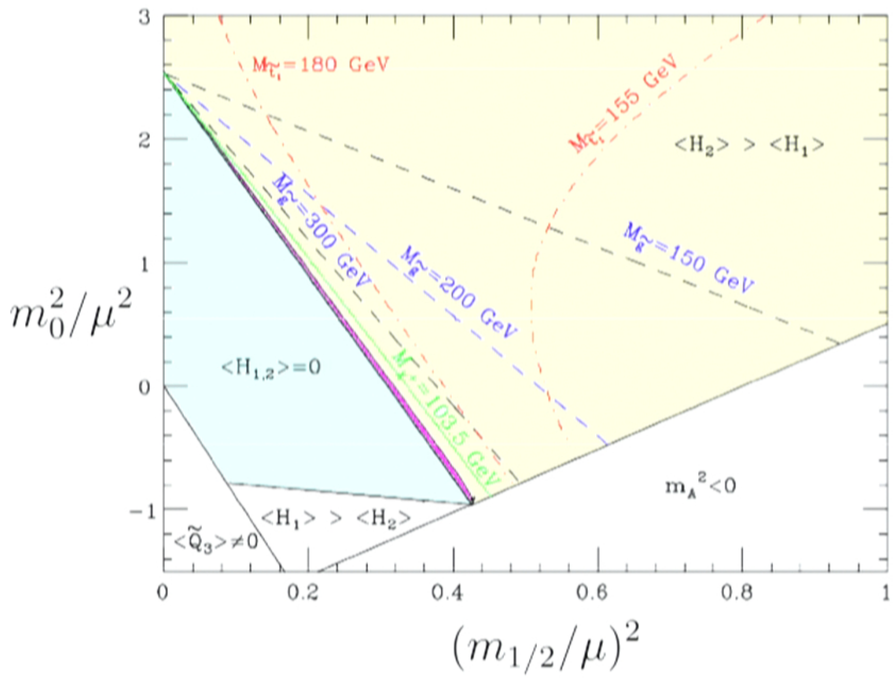
Lightest supersymmetric particle is naturally a stable dark matter candidate

SUSY Naturalness

Minimal model (MSSM) is unnatural after LEP 2 (2000)



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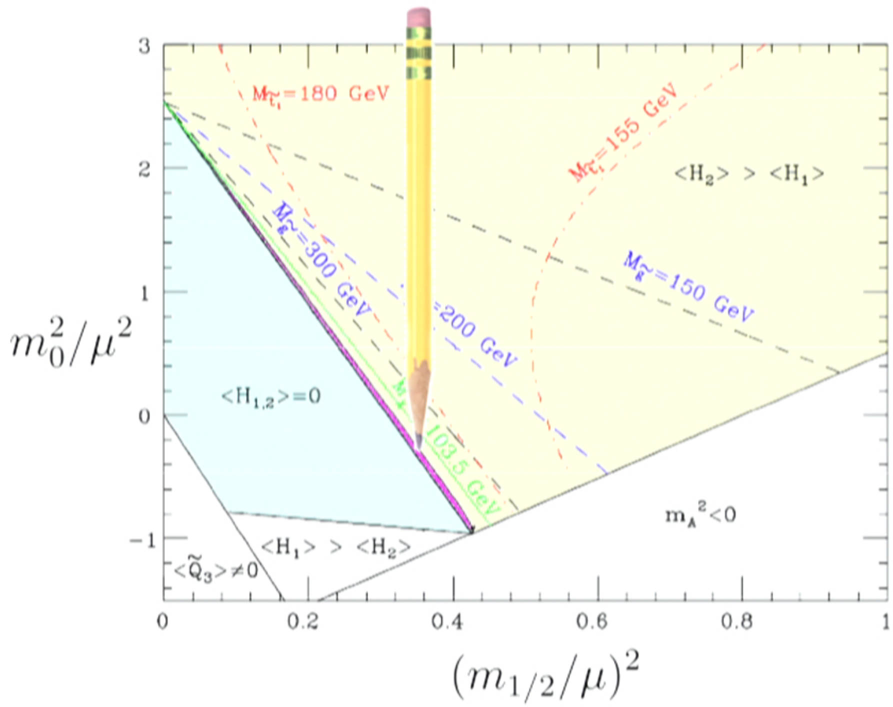
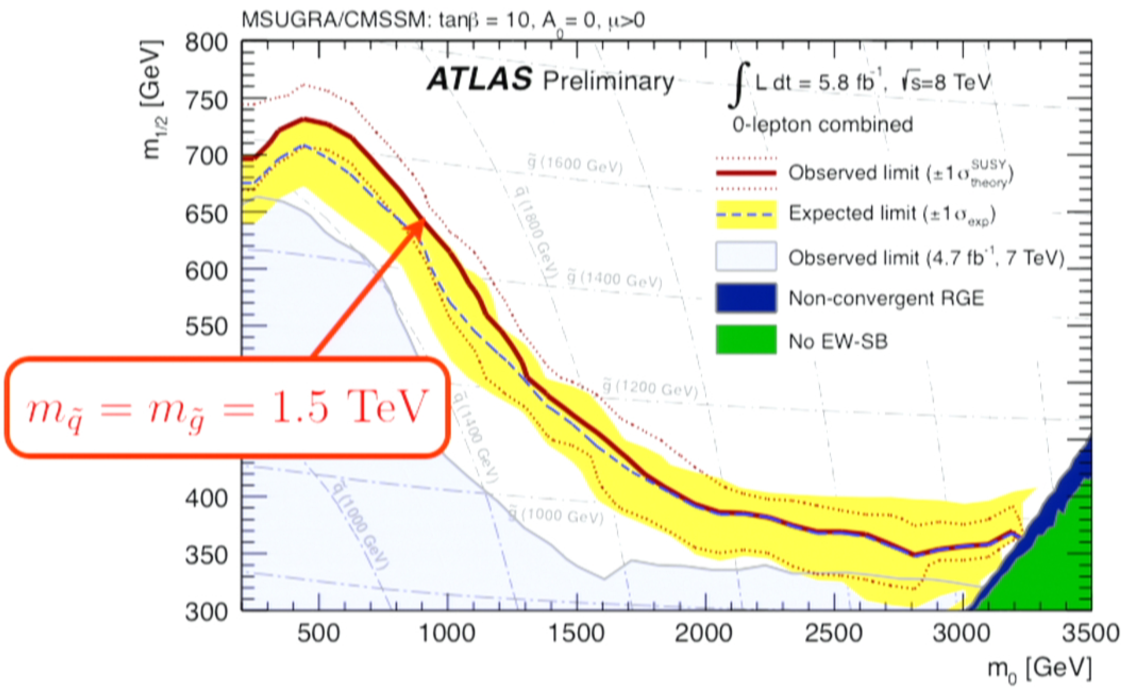


$$\Delta m_H^2 \sim \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2$$ ⇒ ~1% tuning

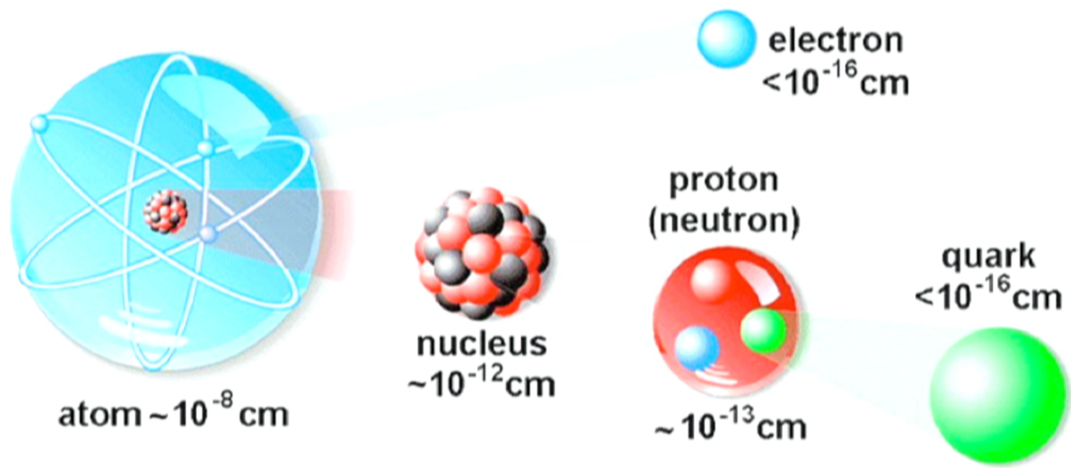
LHC Searches

Search for pair creation of gluino and squarks decaying to standard model particles + LSP



Compositeness

"Big things are made of littler things"



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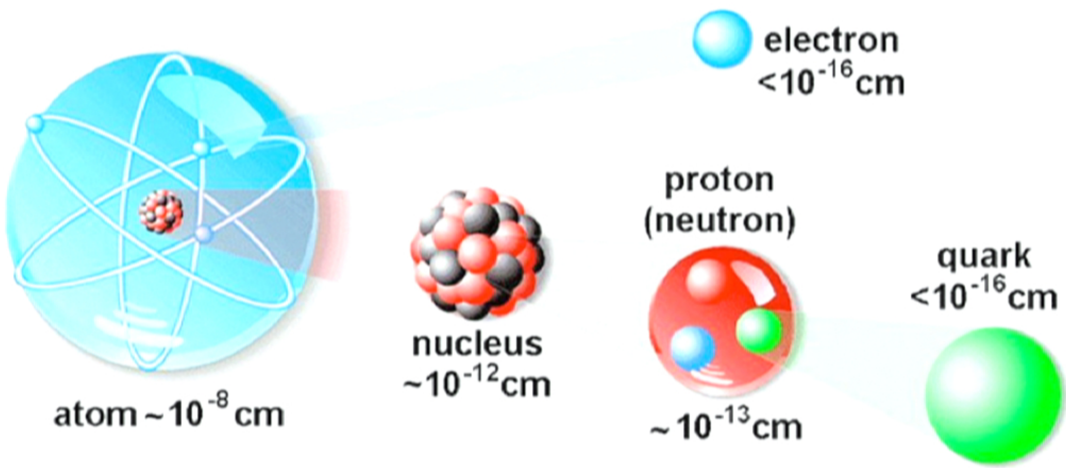
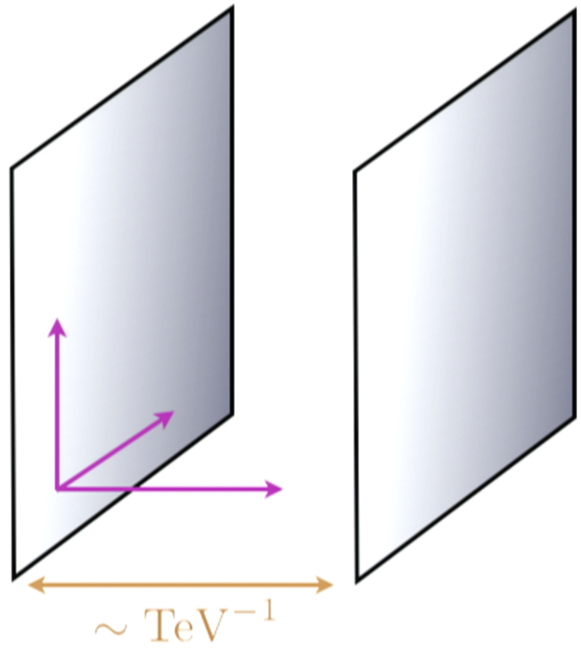


TeV scale could be associated with new substructure

Suggests TeV resonances (QCD...)

Extra Dimensions



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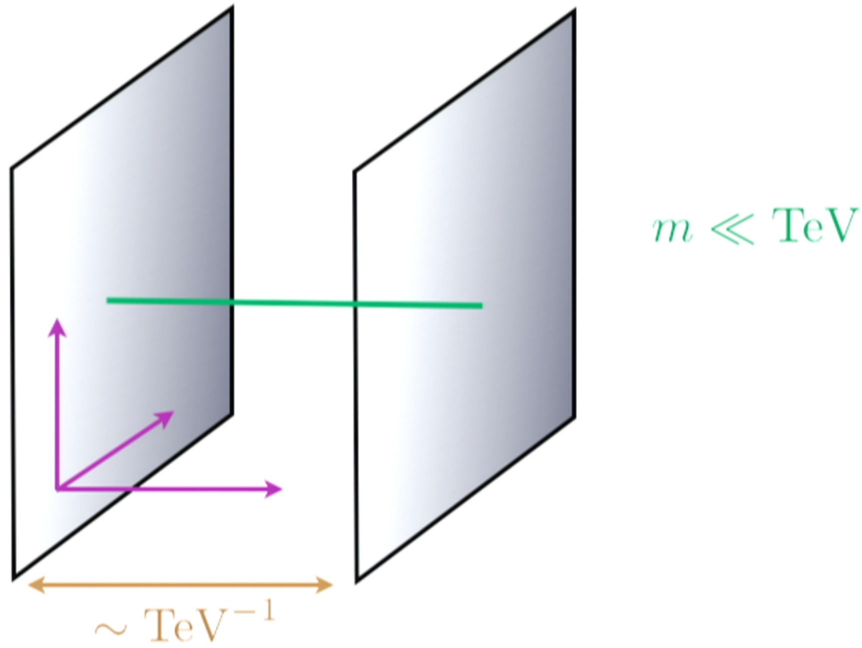

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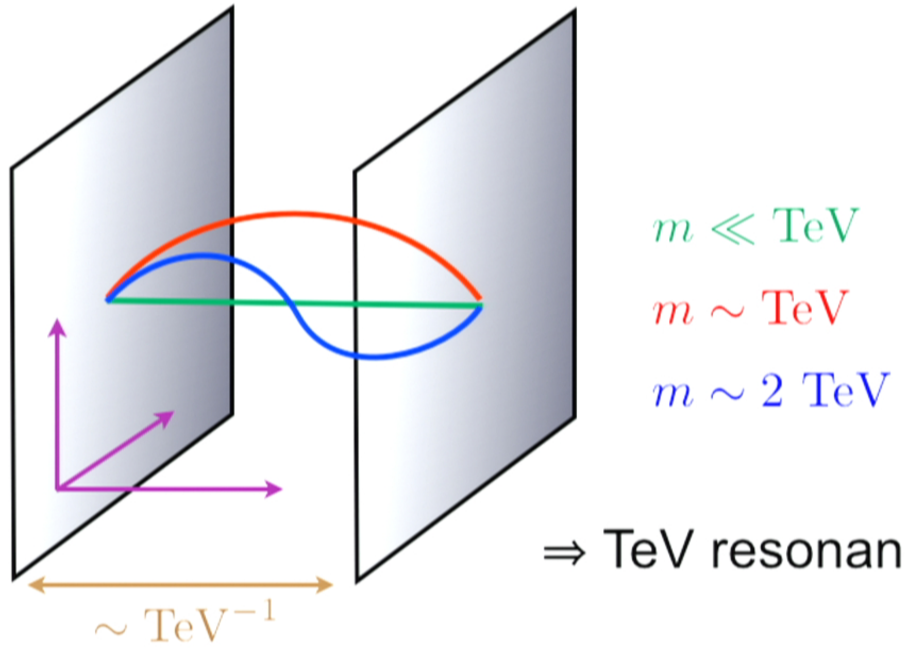
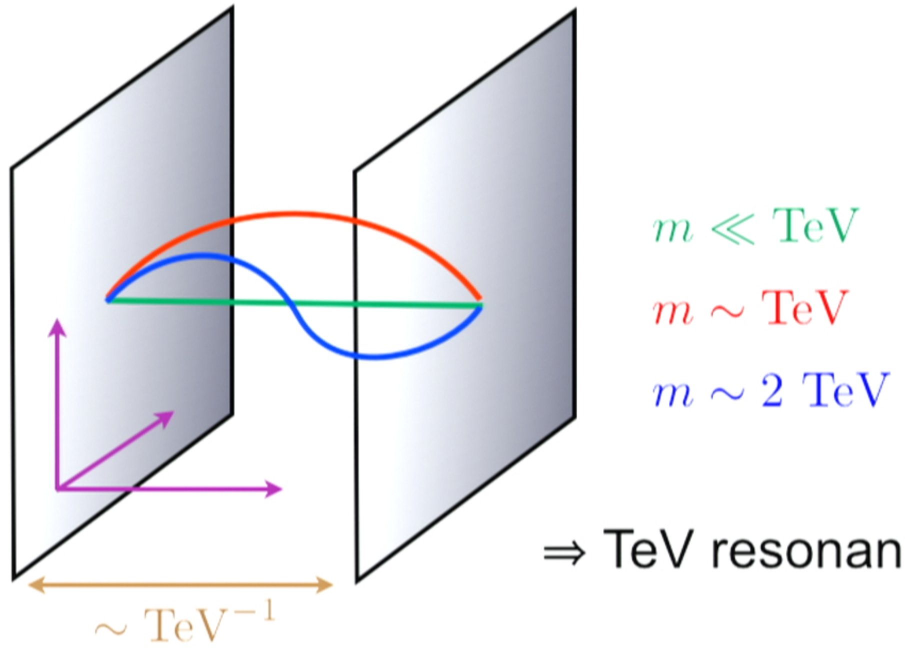


$\Rightarrow$ TeV resonances!

Deep connections between
compositeness and extra dimensions
(AdS/CFT...)

Extra Dimensions



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Deep connections between compositeness and extra dimensions

(AdS/CFT...)

Stratus

From the Latin: a cover or spread; low-lying clouds

Technicolor

Originally based on QCD, many variants

No light Higgs boson

© Nima Arkani-Hamed

Composite Higgs

Light Higgs can arise as approximate Nambu-Goldstone boson

Models and Signals

"Composite Higgs"

$v \simeq 3f$ ⇒ 10% tuning

⇒ strong resonances at $\sim 3\ \mathrm{TeV}$
decaying to Higgs bosons

"Little Higgs"

Additional particles ⇒ bottom-up naturalness

⇒ top partners

"Only" Higgs found so far...

Cosmological Constant

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$\mathcal{O}(M^4)$ term in standard model

$$\mathcal{L}_{\text{eff}} = \lambda\sqrt{g} + \mathcal{O}(M^2) \qquad \lambda \sim M^4$$

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$\mathcal{O}(M^4)$ term in standard model

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Existence of the universe ⇒ $\lambda \lesssim (10^{-12}\ \text{GeV})^4$

Can't be forbidden by any symmetry

No known solution of this naturalness problem!

Radical Conservatism?

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String theory predicts "landscape" of $\sim 10^{500}$ vacua with different ground state energies, Higgs mass,...

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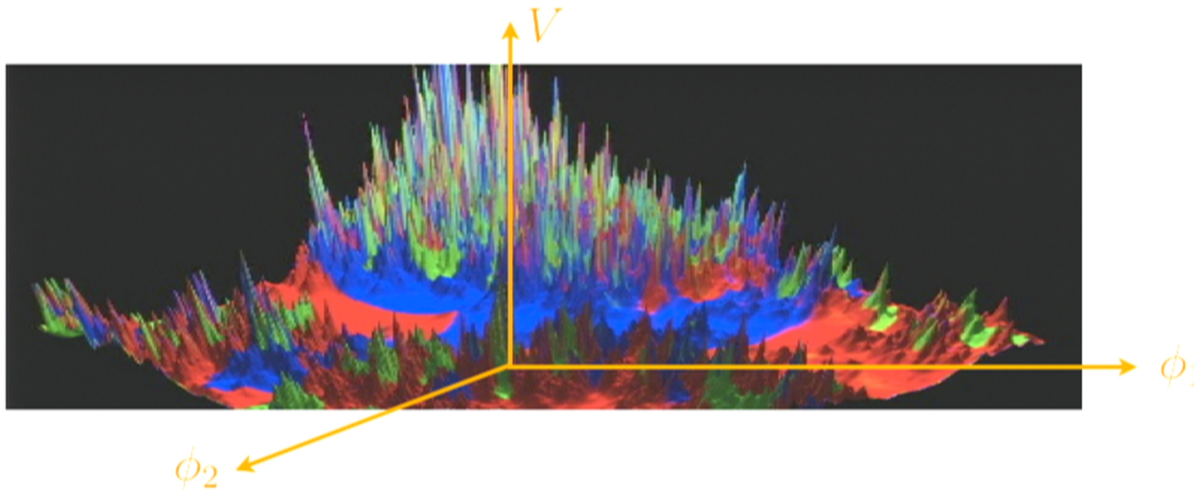

Prediction

S. Weinberg, 1987

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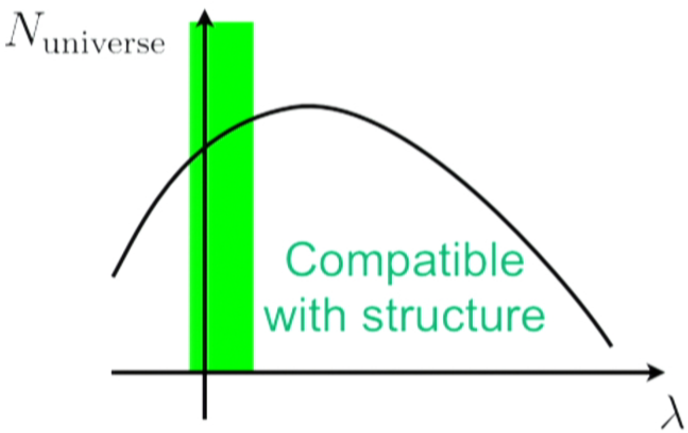
Universes with large λ do not have galaxies



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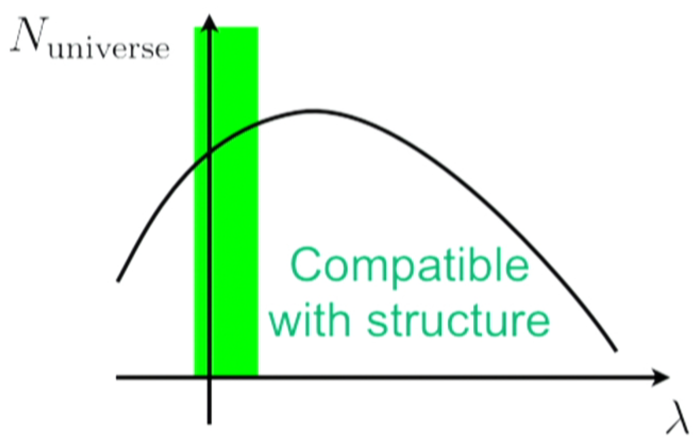

$\Rightarrow \lambda \sim (10^{-12}\ \text{GeV})^4$

Nonzero cosmological constant observed in 1998

Anthropic Bound on the Cosmological Constant

Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 5 August 1987)

In recent cosmological models, there is an "anthropic" upper bound on the cosmological constant Λ. It is argued here that in universes that do not recollapse, the only such bound on Λ is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

Multiverse Higgs

Only universes with $m_H^2 \lesssim (100\ \mathrm{GeV})^2$ have complex nuclei

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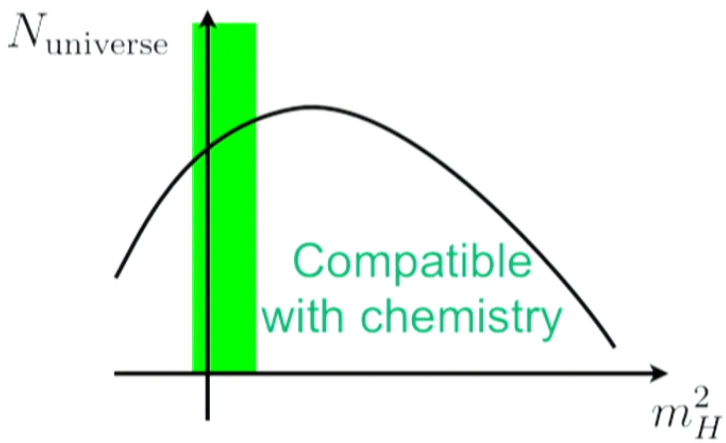
Only universes with $m_H^2 \lesssim (100\ \mathrm{GeV})^2$ have complex nuclei

$$v \gg 246\ \mathrm{GeV} \Rightarrow m_d \gg m_u$$

$$\Rightarrow n \to pe\nu$$ even in nuclei



"Predicts" $m_H^2 \sim 100\ \mathrm{GeV}$

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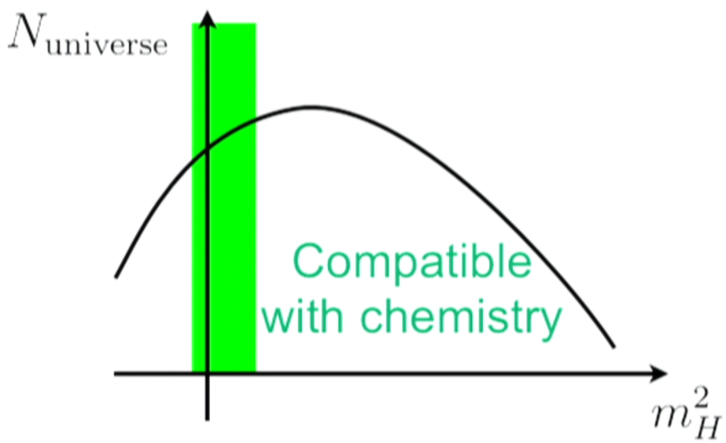
$$v \gg 246\ \mathrm{GeV} \ \Rightarrow\ m_d \gg m_u$$

$$\Rightarrow\ n \to pe\nu \quad \text{even in nuclei}$$



"Predicts" $m_H^2 \sim 100\ \mathrm{GeV}$

⇒ no physics beyond standard model?

Problems

Problems

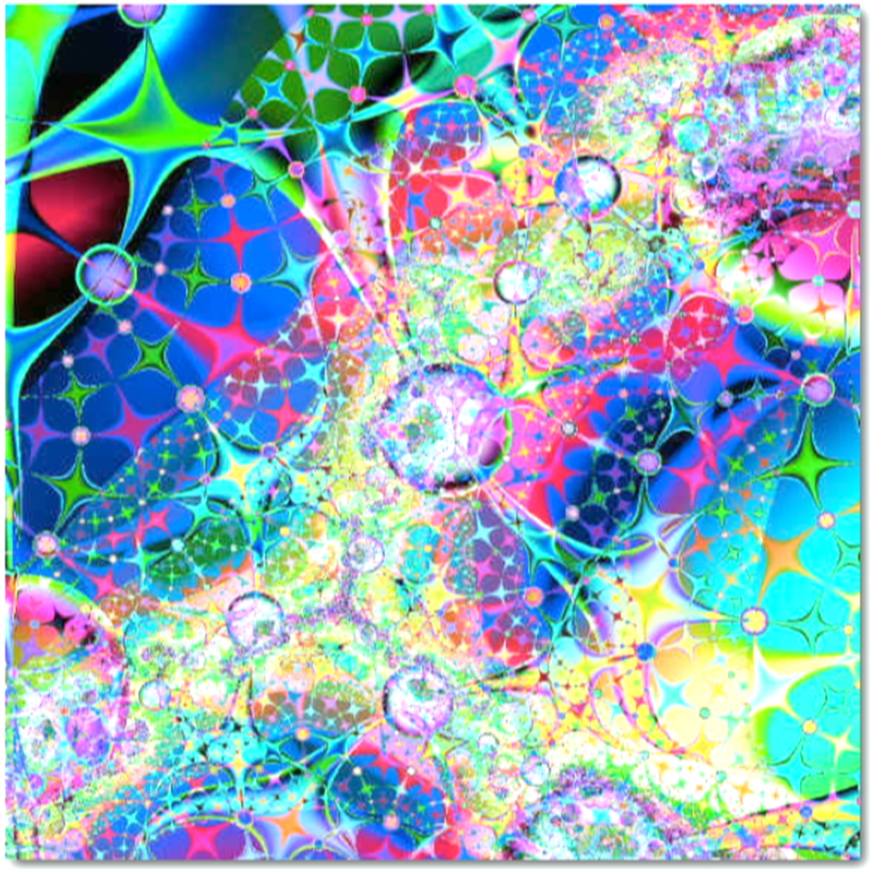
What parameters are "scanned?"

If Yukawa couplings are allowed to vary, we can have complex nuclei even for $m_H^2 \to M_{\rm Planck}^2$

Can we verify/falsify this picture?

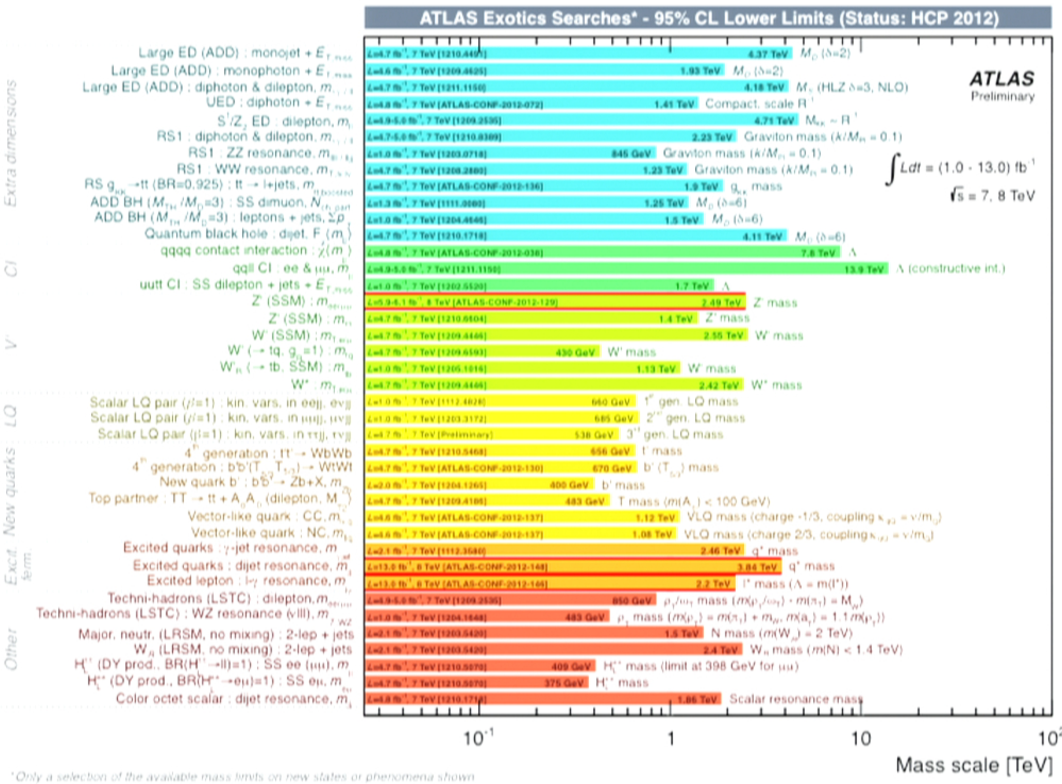
Chaos

From the Greek: formlessness, confusion



What Does LHC Say?

No new physics beyond the Higgs...



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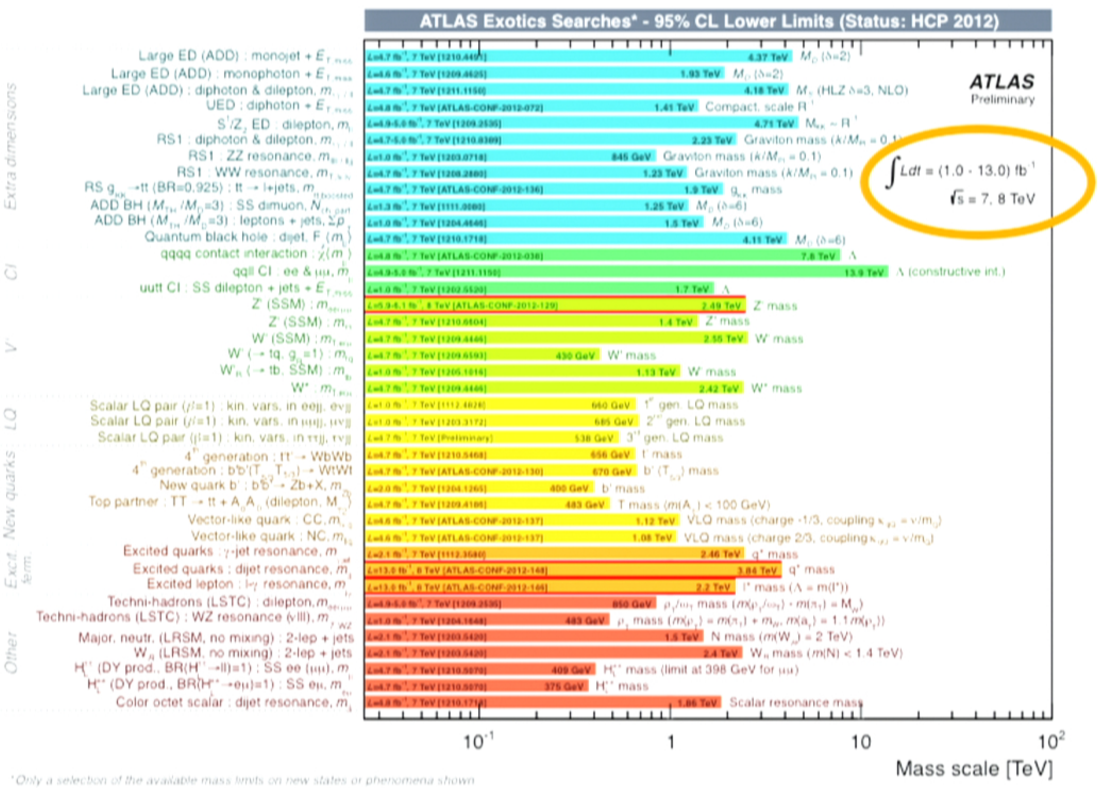

...but still room for natural physics to be seen

LHC Higgs Discovery

Higgs physics different in three universes

Mulitverse/tuning	standard model Higgs
SUSY	additional Higgs bosons

LHC Higgs Discovery

Higgs physics different in three universes

Mulitverse/tuning	standard model Higgs
SUSY	additional Higgs bosons $\Rightarrow$ modified Higgs couplings from mixing
Composite Higgs	$\Rightarrow$ modified Higgs couplings from compositeness

LHC Higgs Discovery

Higgs physics different in three universes

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SUSY	additional Higgs bosons ⇒ modified Higgs couplings from mixing
Composite Higgs	⇒ modified Higgs couplings from compositeness

Higgs production, decay sensitive to couplings

$$h\bar{t}t,\ \ h\bar{b}b,\ \ hWW,\ \ hZZ$$

Higgs Couplings

$$c_t = \frac{g_{htt}}{g_{htt}(\mathrm{SM})} \qquad c_b = \frac{g_{hbb}}{g_{hbb}(\mathrm{SM})} \qquad c_g = \frac{g_{hWW}}{g_{hWW}(\mathrm{SM})}$$

Higgs Couplings

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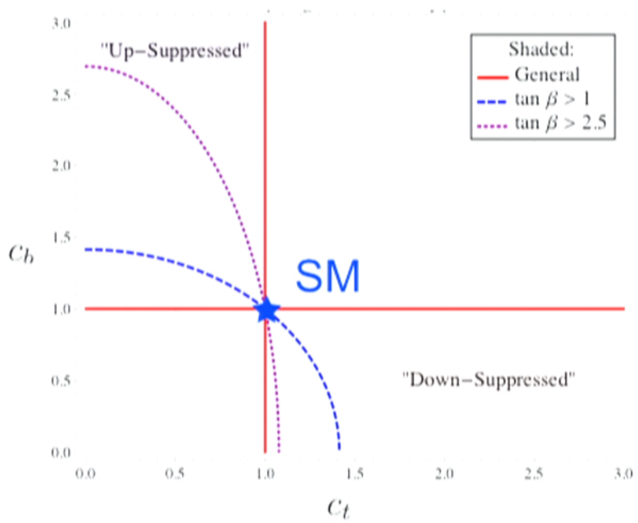

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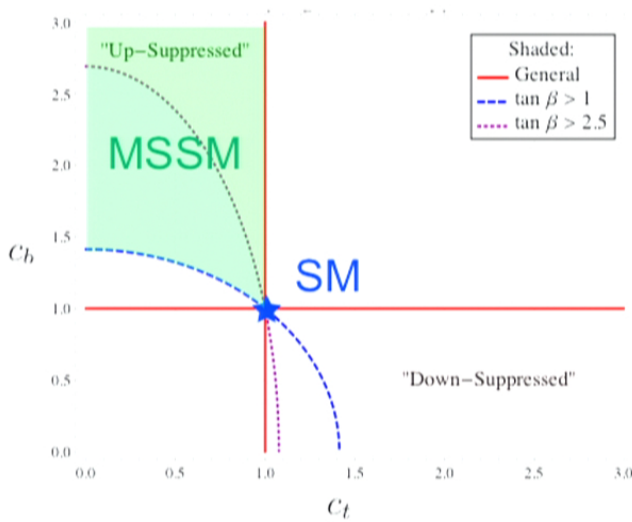

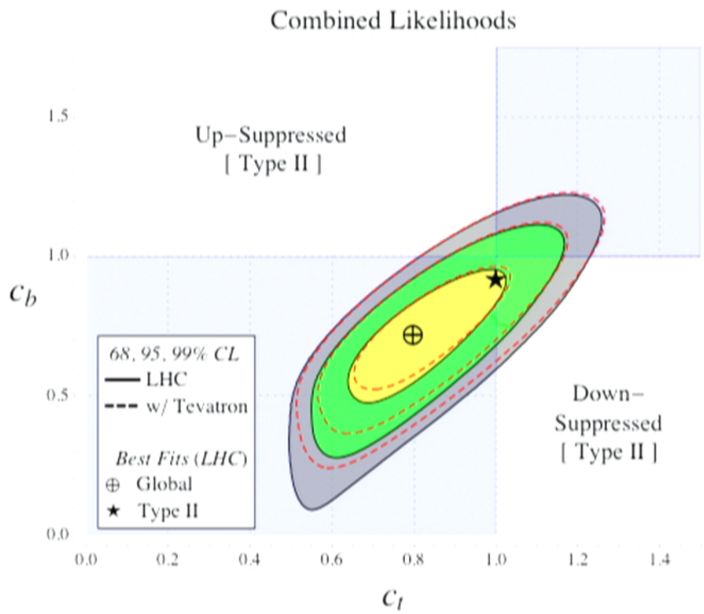

Azatov, Galloway

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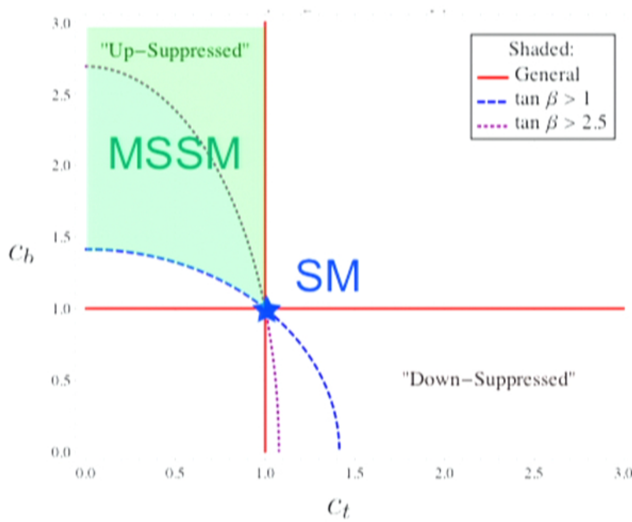
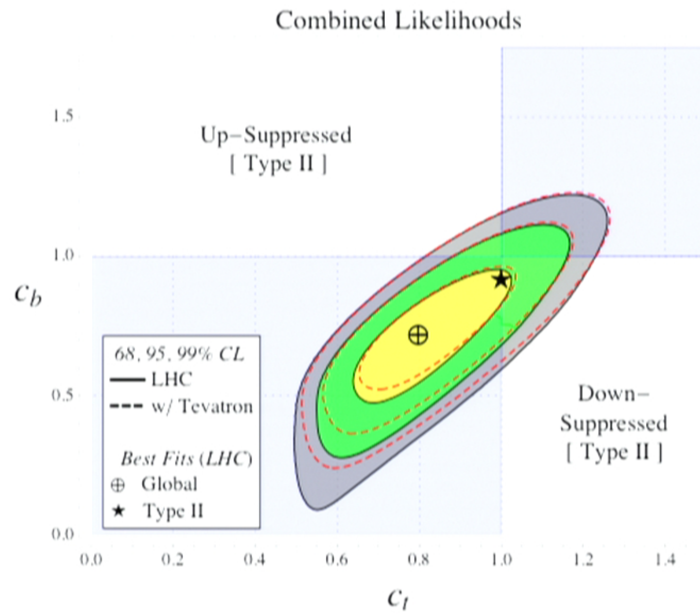
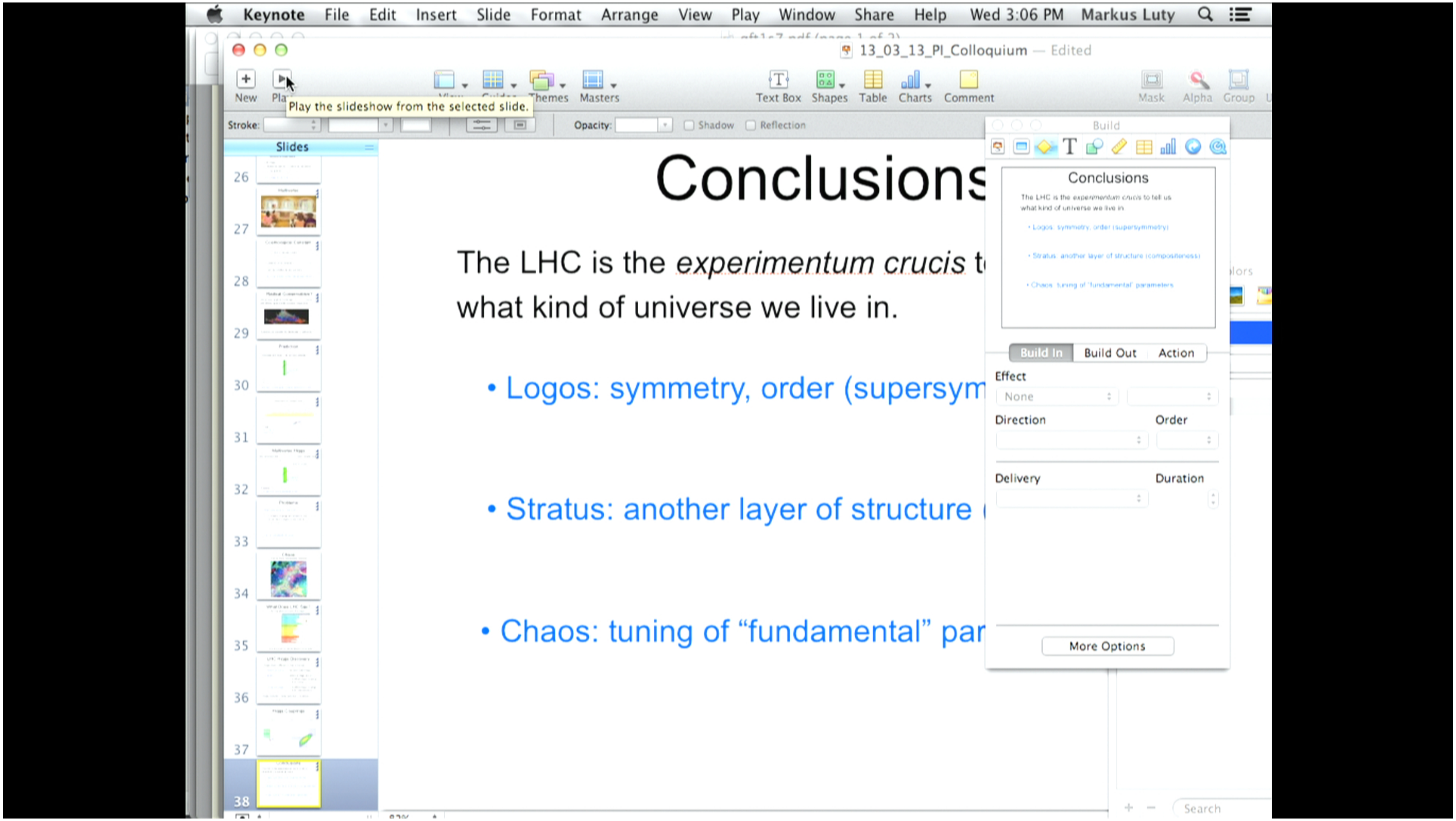




Azatov, Galloway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• Stratus: another layer of structure (
• Chaos: tuning of “fundamental” par
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Build Out
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None
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