Theoretical Particle Physics
and the hunt for the next standard model

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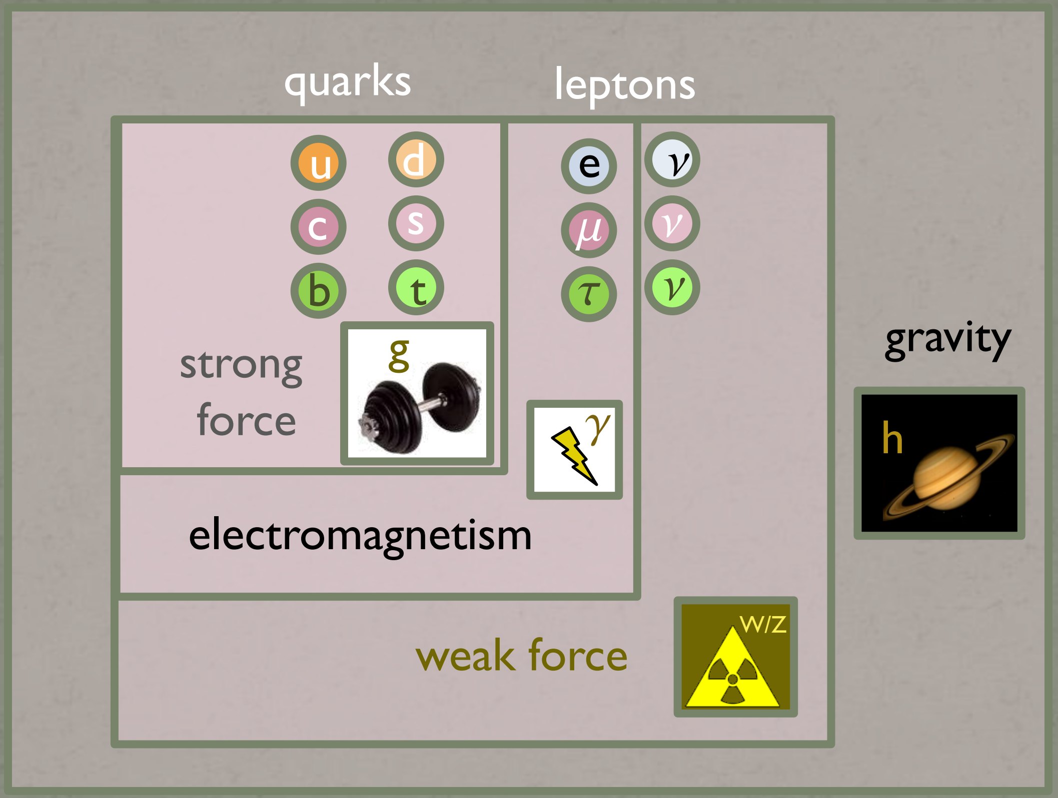
Harvard University

The Standard Model

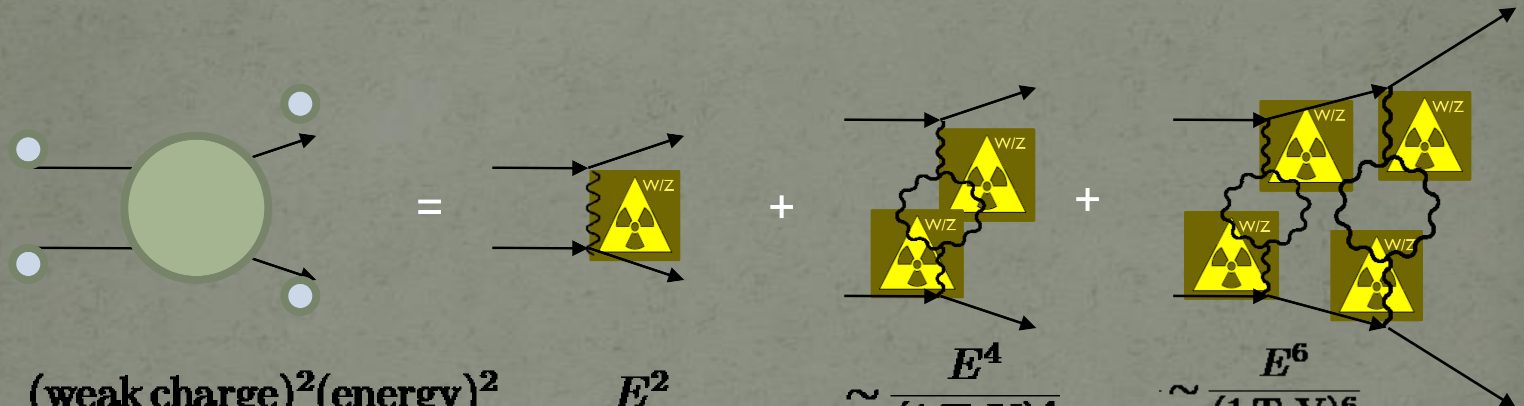


That's it!

What's the problem?

Perturbation theory fails for the weak force

Quantum Corrections



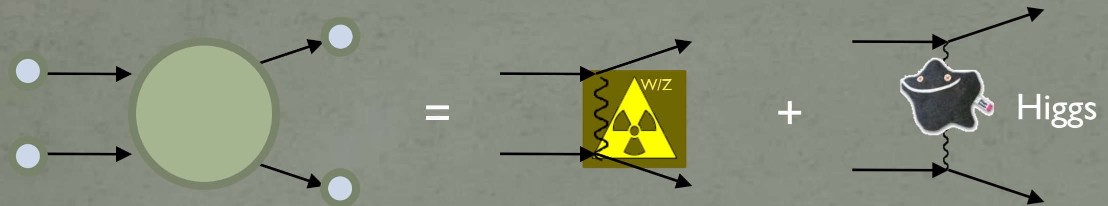
$$\propto \frac{(\text{weak charge})^2(\text{energy})^2}{(\text{mass of } Z)^2} \sim \frac{E^2}{(1\,\text{TeV})^2} \qquad \sim \frac{E^4}{(1\,\text{TeV})^4} \qquad \sim \frac{E^6}{(1\,\text{TeV})^6}$$

Tiny correction at atomic energies $E \sim 10^{-6}$ TeV …

…but as big as leading order a LHC energies E~1 TeV

The Higgs boson

Perturbation theory is restored if there is a Higgs



$$\sim \frac{E^4}{(1\,\mathrm{TeV})^4} \quad \sim \frac{-\,E^4}{(1\,\mathrm{TeV})^4}$$

~ 0.01

Large correction cancels

The Higgs Boson restores our ability to calculate

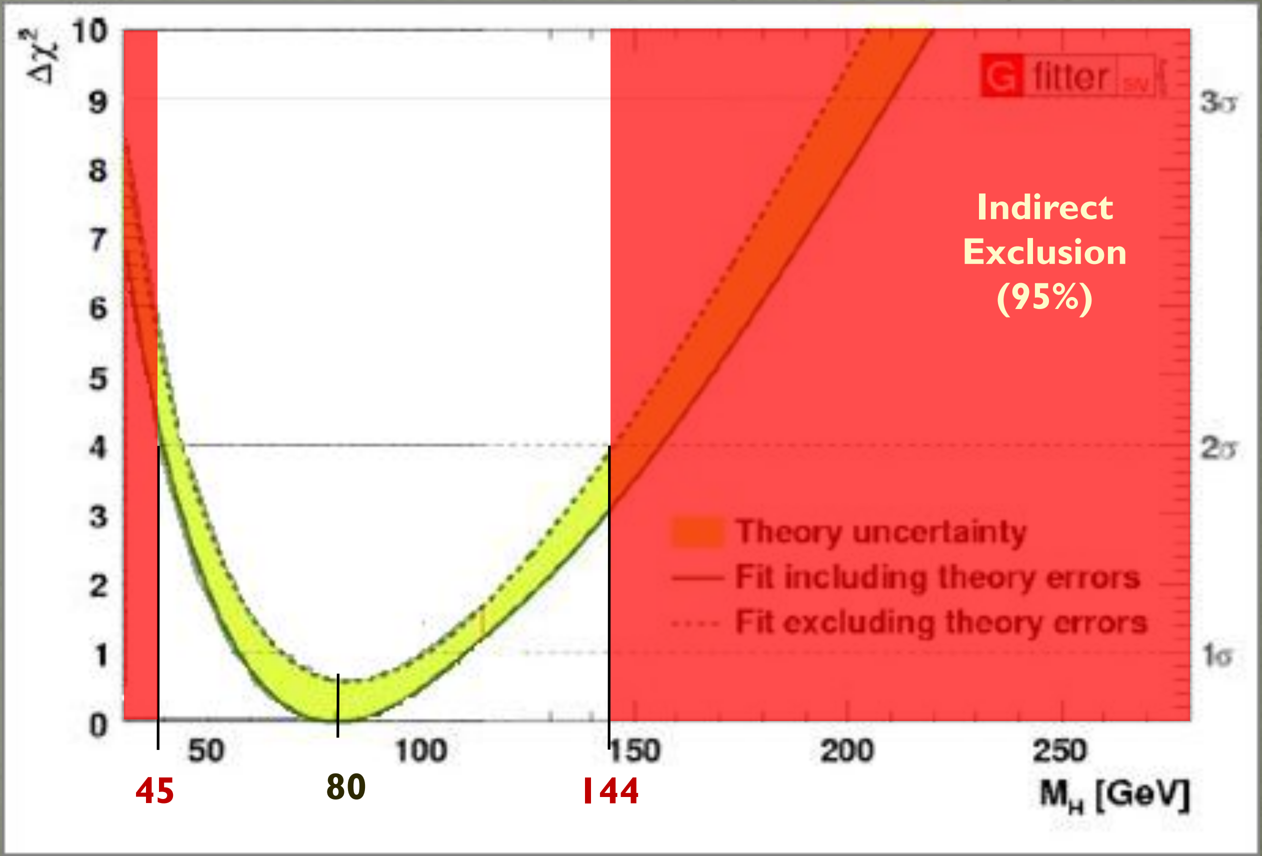
Must there be a Higgs? No.

- But then quantum field theory fails above 1 TeV
- We would need a new framework for particle physics
- Very exciting possibility!

Where is the Higgs?

Parameter	Input value
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\sin^2\theta^\ell_{\text{eff}}(Q_{\text{FB}})$	0.2324 ± 0.0012

Combine many observables to constrain Higgs mass



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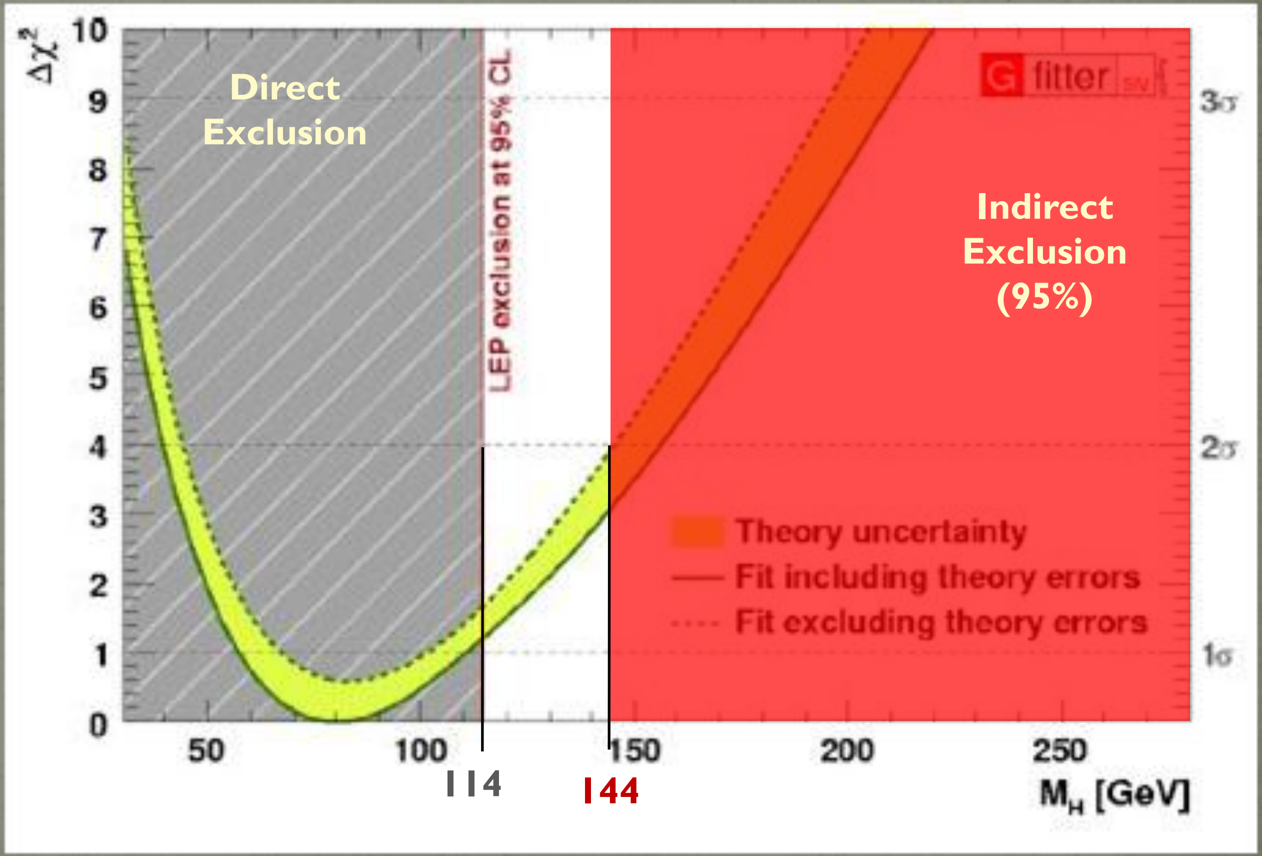

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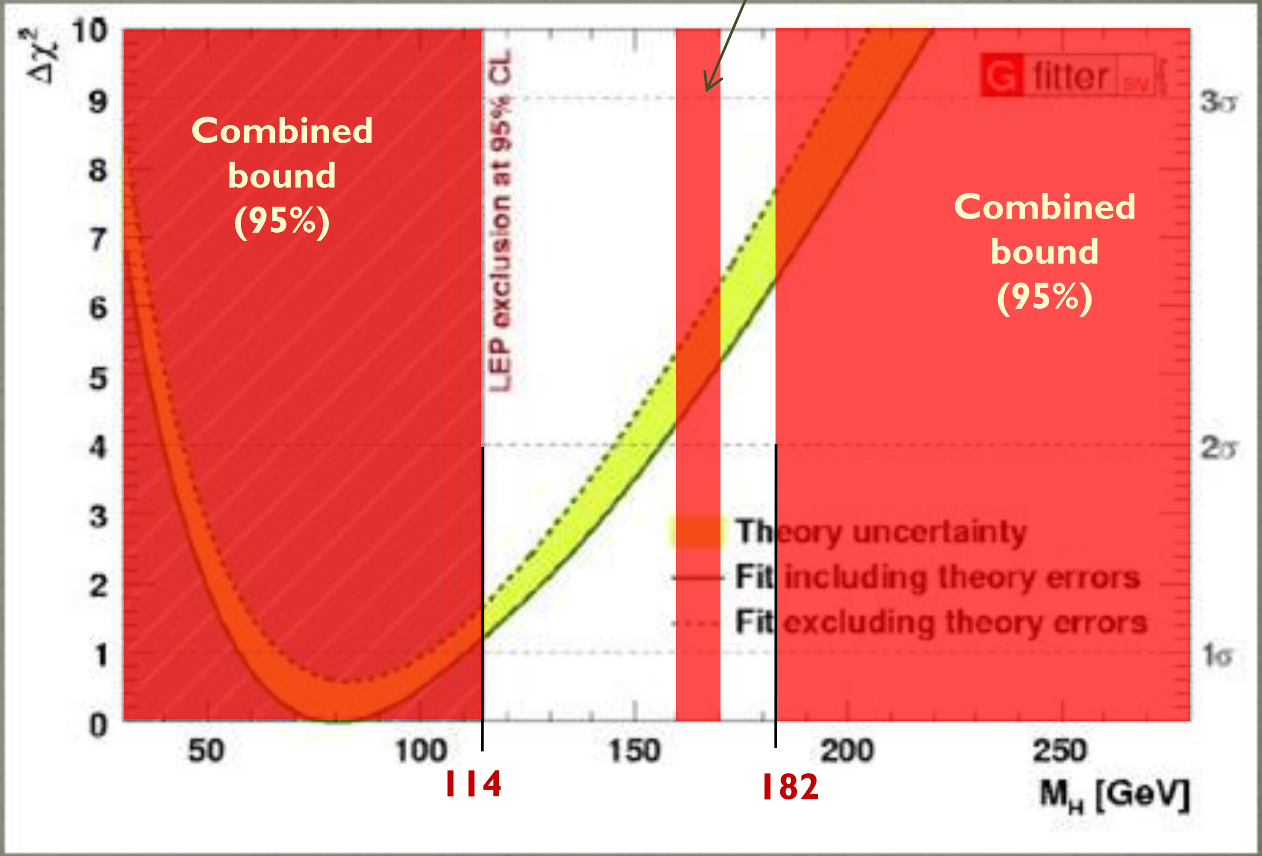
Combine many observables to constrain Higgs mass

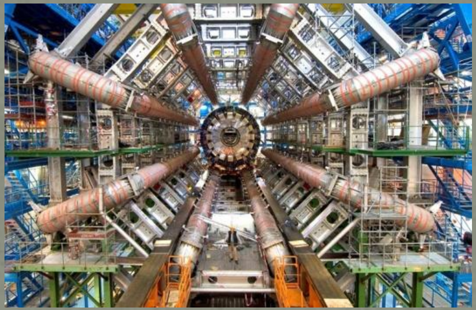
Recent Tevatron exclusion (160-170 GeV)



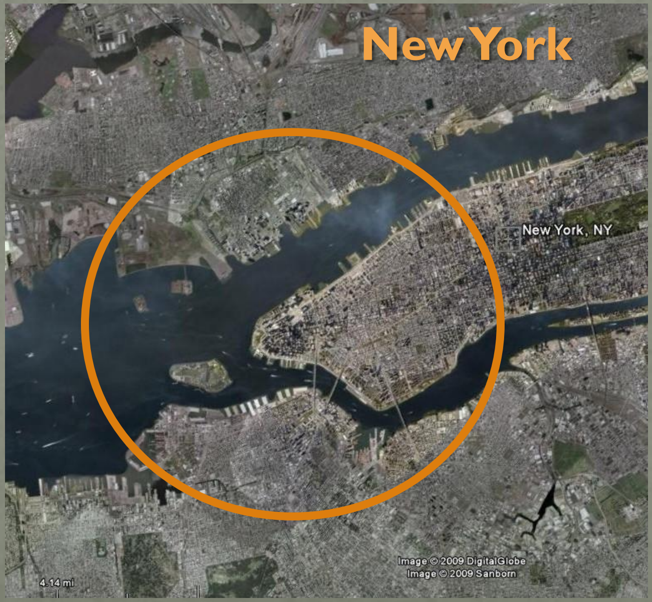
Large Hadron Collider

Two experiments can find the Higgs

ATLAS



CMS



25 kilometers in diameter

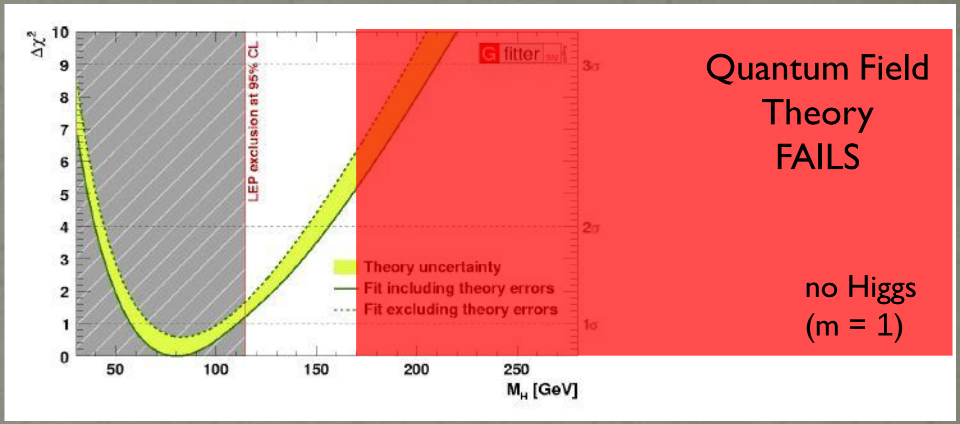
Higgs Summary

The LHC is being built to find the Higgs

If there is no Higgs

The LHC will find something better

- supersymmetry
- technicolor
- extra-dimensions
- …



most exciting possibility!

The LHC is a win-win situation

Can there be *just* a Higgs?

Yes.

But we hope not.

Clues to new physics

1. Dark Matter
2. Unification
3. The Higgs is weird
4. Quantum Gravity

Can there be *just* a Higgs?

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Clues to new physics

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Unification

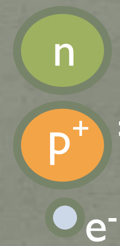
When two seemingly different things turn out to be the same

Electromagnetism

 = 

=  =

Electroweak unification



=

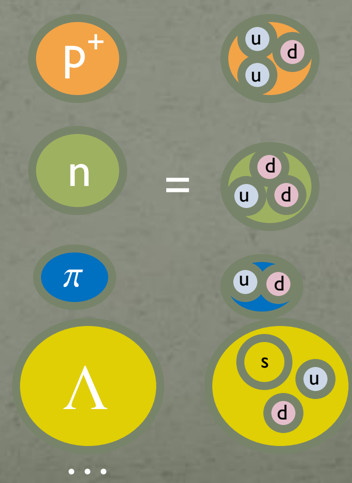
Chemistry

=

=

Gravity

Quark model



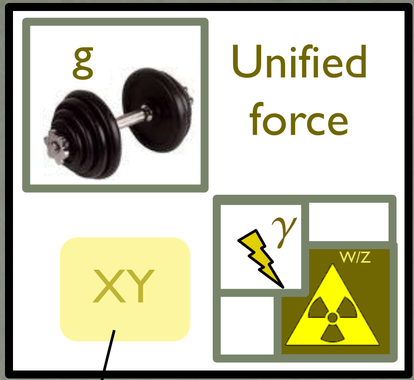
Grand Unification

H. Georgi and S. Glashow

strong force

electromagnetism

weak force



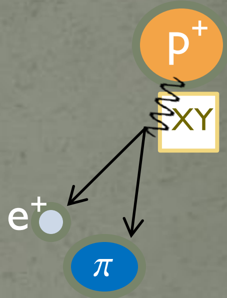
electroweak force

- Explains why proton and electron have the same charge
- Coupling constants should be the same
  - α_{strong} = 0.15
  - α_e = 0.04
  - α_{weak} = 0.02

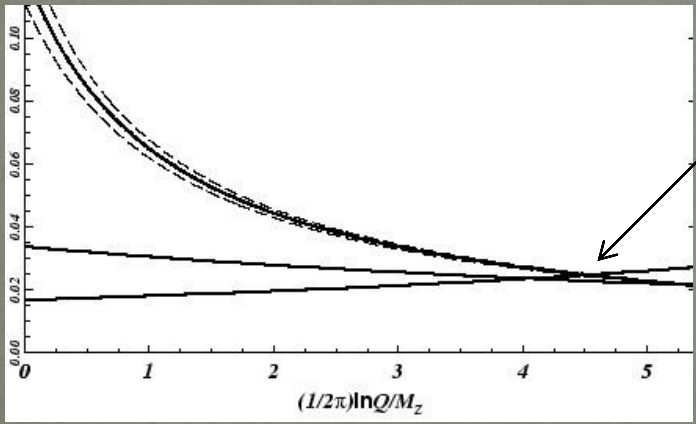
hmm…

New force!
New effects!

proton decay



unification at 10^{15} GeV



but they are energy dependent!

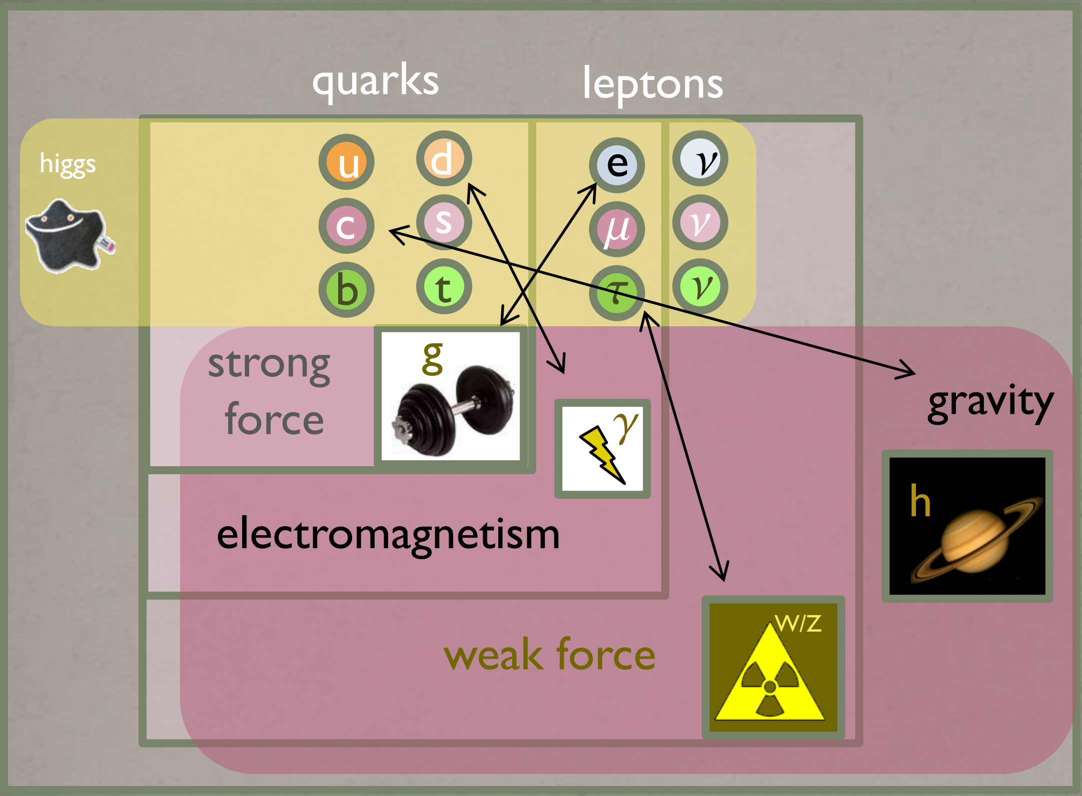
predicts:
proton lifetime = 10^{31} years

limit (1974) ~ 10^{29} years

limit (2009) ~ 5×10^{33} years

hmm…

Supersymmetry



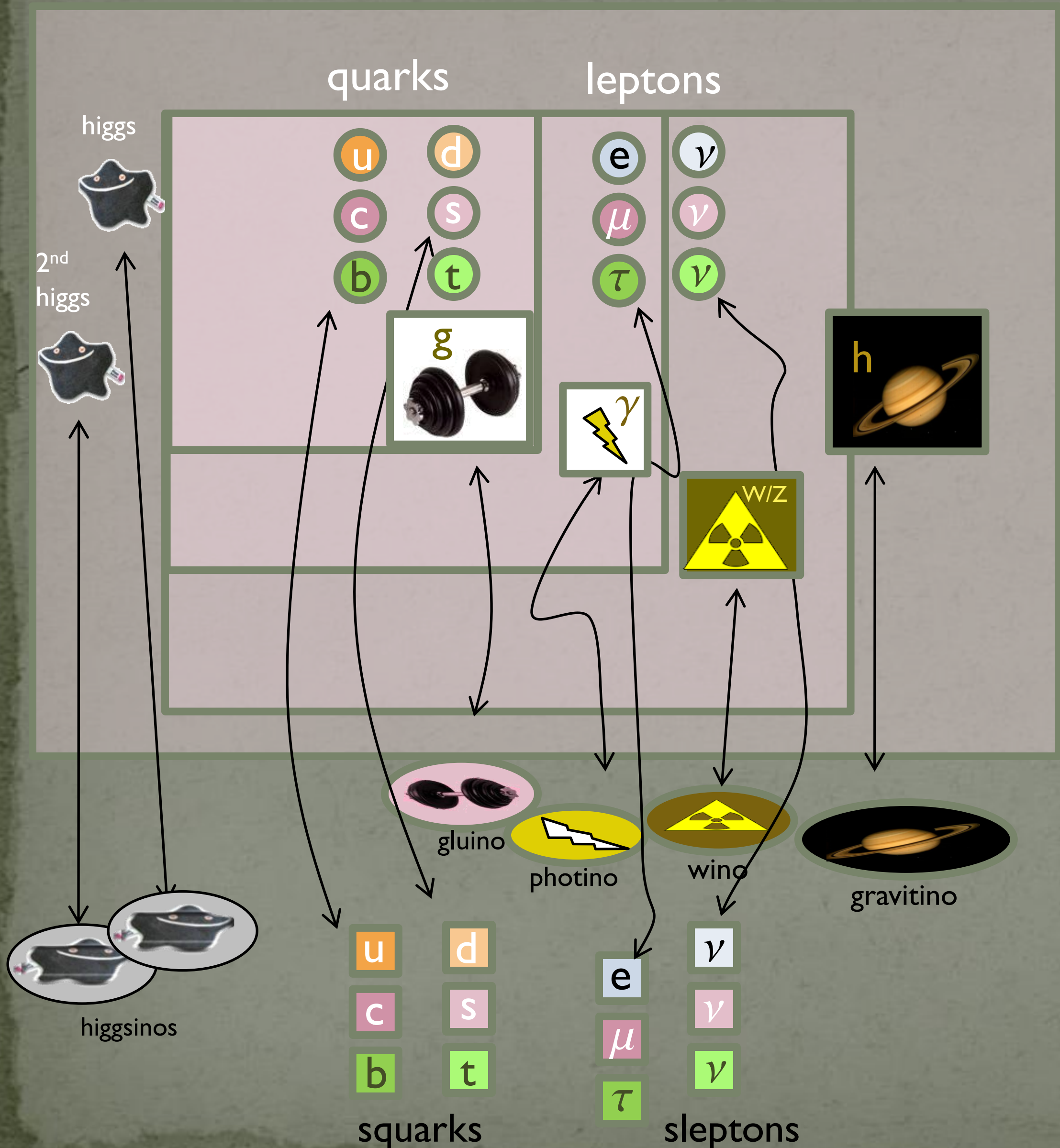
Particles and Forces

- What if every matter particle is unified with a force particle?
- Matter and force particles must have the same charges!
- No pairings work…

hmm…

Supersymmetry

H. Georgi and S. Dimopoulos



Particles and Forces

- What if every matter particle is unified with a force particle?
- Matter and force particles must have the same charges!
- No pairings work…

  hmm…

- Invent new particles!
- Superpartners must have the same mass!

  hmm…

- Supersymmetry must be broken!

Broken Supersymmetry

Standard Model:
18 particles, 30 parameters

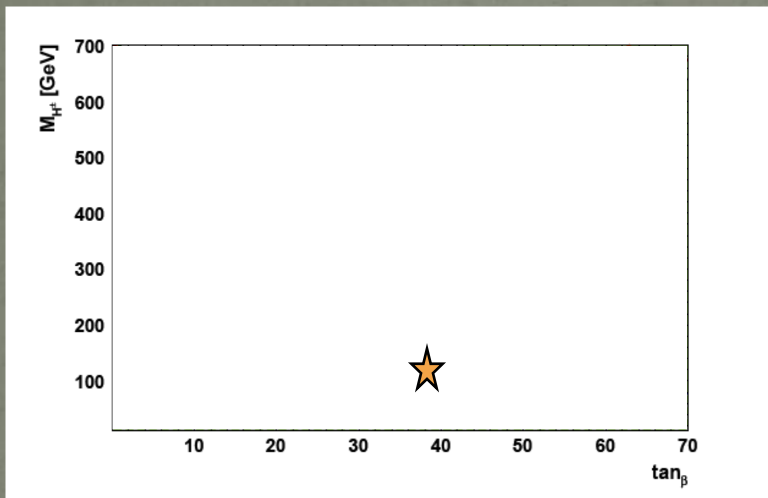
Minimal Supersymmetry Standard Model:
40 particles, 140 parameters

"With 4 parameters I can fit an elephant, with 5 parameters I can make him wiggle his trunk"

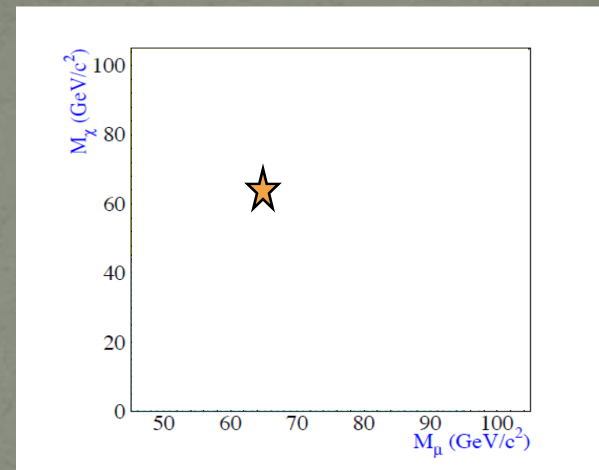
-- Carl Friedrich Gauss

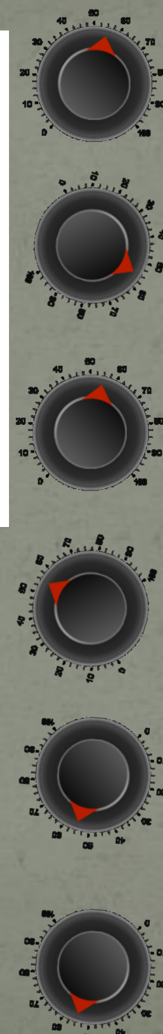
Constraints

Tanβ and charged Higgs mass

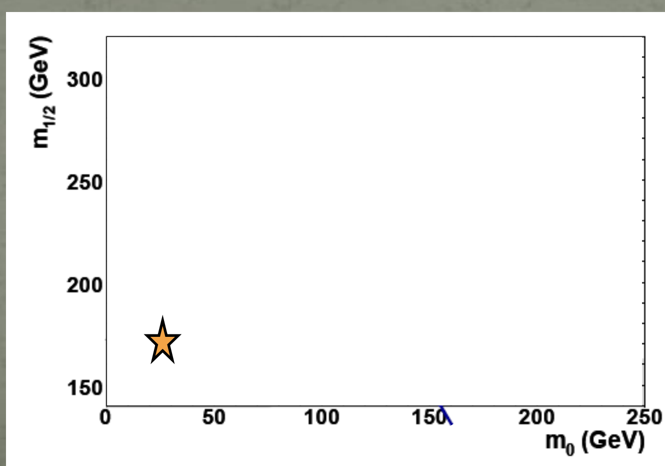


smuon and neutralino mass

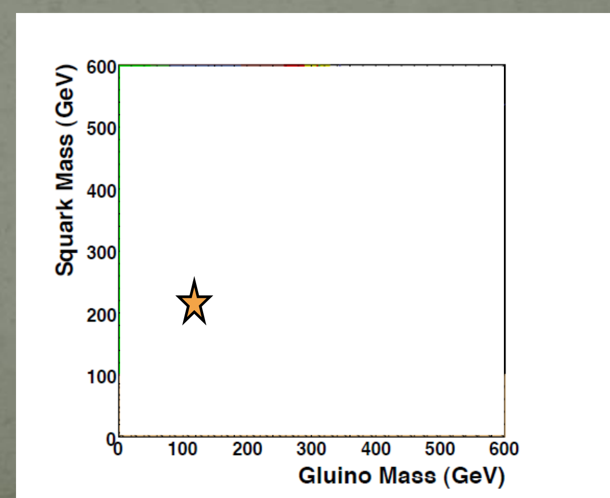




mSUGRA parameterers



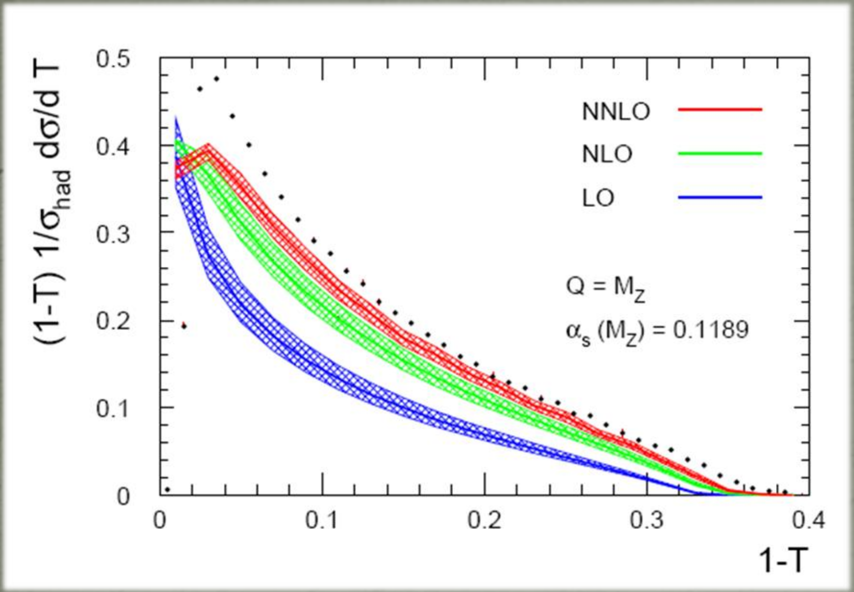
gluino and squark masses



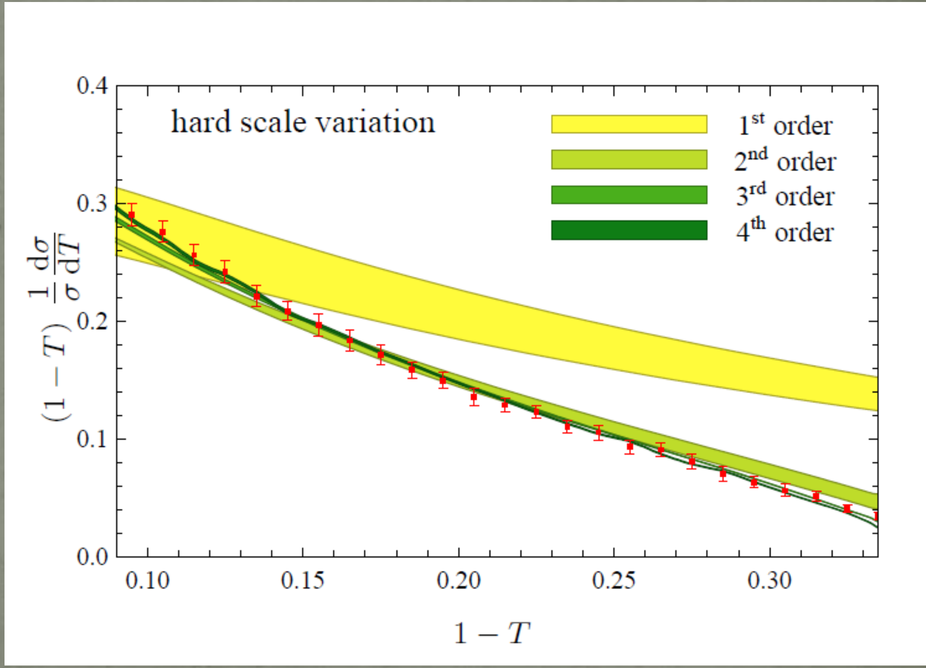
Need better tests

Jets at LEP

Old Way (Brute Force)



New Way (Effective Field Theory)



MDS, T. Becher,: JHEP: 0807.2477 (2008)

Need better tests

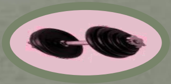
World's best measurement of strong coupling constant:

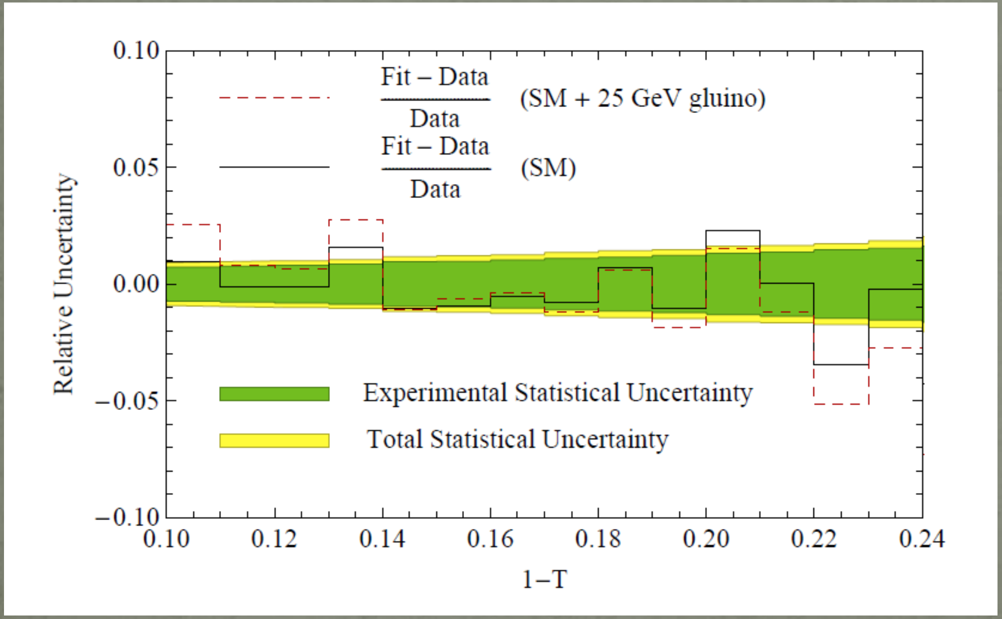
$\alpha_s(m_Z) = 0.1134 \pm 0.0013$

Old value from LEP

$$\alpha_s(M_Z) = 0.1202 \pm 0.0003\,(\mathrm{stat}) \pm 0.0049\,(\mathrm{syst})$$

New model-independent bound on the **gluino**





Old value: $m_g > 5$ GeV

New value: $m_g > 50$ GeV

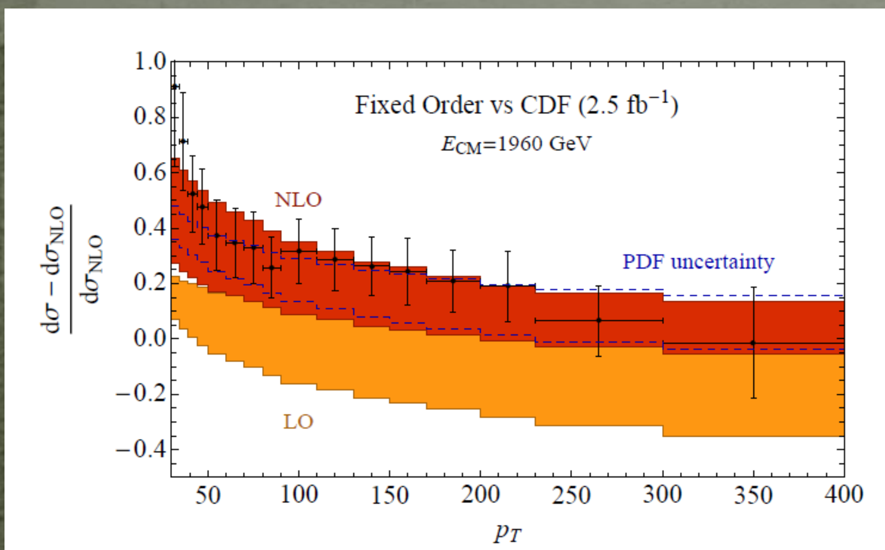
Factor of 10 improvement!

MDS, D. Kaplan PRL 101.022002 (2008)

Need better tests

Photons at the LHC

Old Way (Brute Force)



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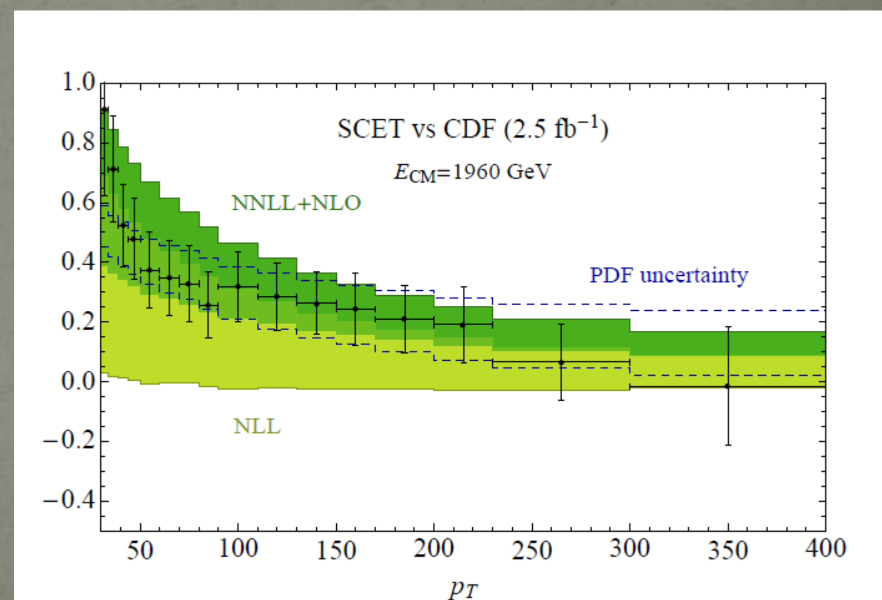


MDS and T. Becher, appears at 8pm

SUSY is *highly constrained*

Predictions

- detectable dark matter
- proton decay
- calculable Higgs mass
- B meson decays and mixings
- new sources of CP violation
- muon anomalous magnetic moment (g-2)
- flavor changing neutral currents
- collider signatures

Problems

- where are the sparticles?
- μ problem
- SUSY flavor problem
- Little hierarchy problem
- Proton decay
- CP problems
- Moduli problems
- …

Solutions

- Gauge/Gravity/Anomaly/Gaugino mediation
- R-parity
- Hidden sectors
- NMSSM
- A terms, D terms
- …

1000s of models!

If supersymmetry is relevant to TeV scale physics,

Why is it hiding?

Can there be *just* a Higgs?

Yes.

But we hope not.

Clues to new physics

1. Dark Matter
2. Unification
3. The Higgs is weird
4. Quantum Gravity

The Higgs is Weird

The Higgs boson is a spinless particle.

It naturally wants to clump together.

(bad)

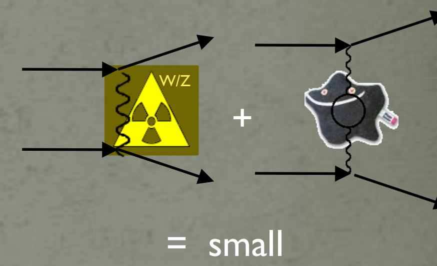
It also clumps around fermions to give them mass

(good)

This makes it very heavy (10^{19} GeV)

Scale of gravity

but it has to be light to cancel strong W/Z scattering



This is known as the hierarchy problem:

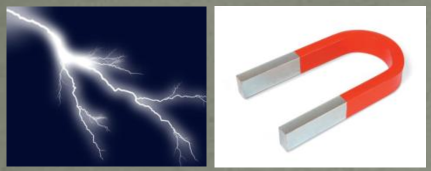
- •Why is the weak scale (100 GeV) so much smaller than the Planck scale (10^{19} GeV)?
- •Why is the Higgs so light?

supersymmetry:

fermions don't clump

The Higgs is Weird

Electromagnetism



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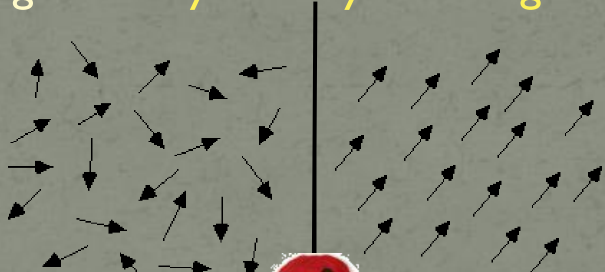
Weak force

The Higgs is just an order parameter for electroweak symmetry breaking

Magnetization is an order parameter for spin-alignment symmetry breaking



Not magnetized

magnetized

Does a "magentization particle" exist?

No. There are electrons with spins.

What are the "electrons" for electroweak symmetry breaking?

Technicolor

What if the order parameter is a fermion condensate?

$$h = \langle \bar{\psi}\psi \rangle$$

Solves the Hierarchy Problem: fermions don't clump!

Weak scale (100 GeV) can be much smaller than Planck scale (10^{19} GeV)

Weak scale is generated by pairs of virtual techniquarks and technigluons

(We already know that the strong scale is generated
by pairs of virtual quarks and gluons)

Technicolor

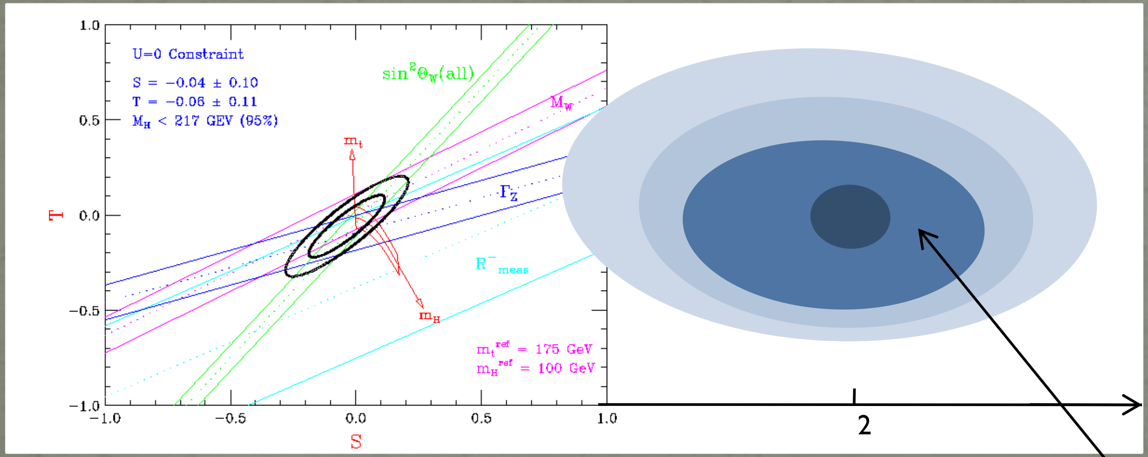
Beautiful idea.

•But it cannot explain fermion masses.

??

•Huge problem with flavor-changing neutral currents

•Ruled out by precision measurements



Theories like technicolor with strong dyanmics are very hard to study

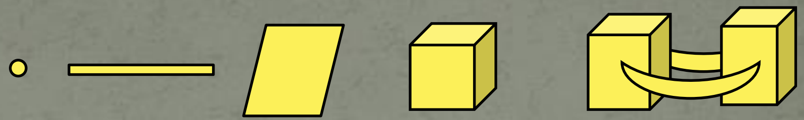
Many more types that we don't understand

Typical technicolor prediction

Other ideas

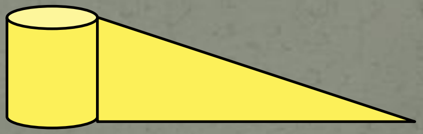
Extra dimensions

- Why not?
- Must be tiny and curled up
- Fun to think about, but not particularly well-motivated

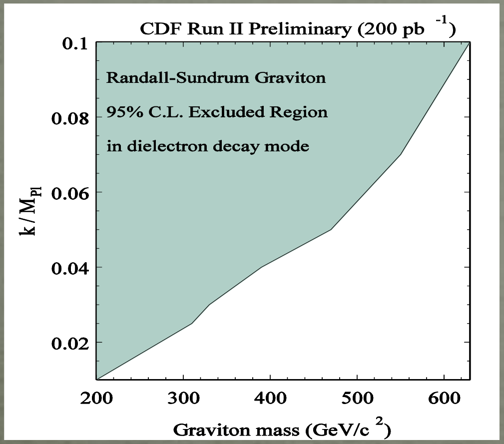


Warped Extra dimensions

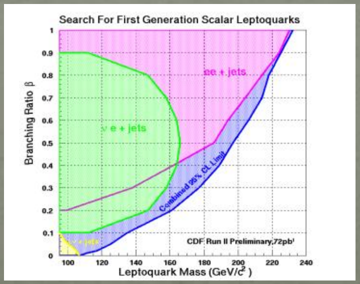
- Randall-Sundrum models
- Related to technicolor by duality
- Thousands of parameters
- Current bounds are strong
    - hard to see at the LHC



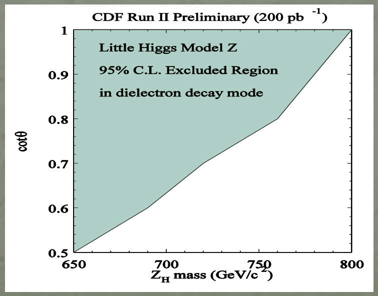
AdS/CFT correspondence



Leptoquarks



Little Higgs models



Can there be *just* a Higgs?

Yes.

But we hope not.

Clues to new physics

1. Dark Matter
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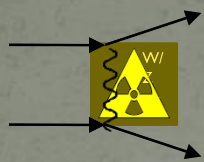
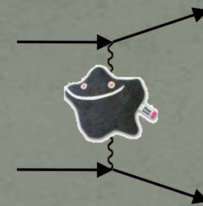
Quantum Gravity

Recall weak boson scattering grows with energy



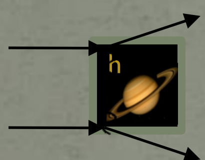
$$\sim \frac{E^4}{(1\,\mathrm{TeV})^4}$$

growth canceled by Higgs



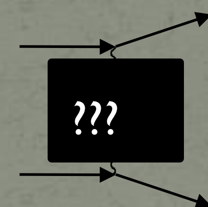
$$\sim \frac{-\,E^4}{(1\,\mathrm{TeV})^4}$$

Graviton scattering grows with energy too



$$\sim \frac{E^4}{(10^{19}\,\mathrm{GeV})^4}$$

what cancels the growth?



strings?

maybe.

Sadly, there is little chance that the LHC will tell us anything about quantum gravity…

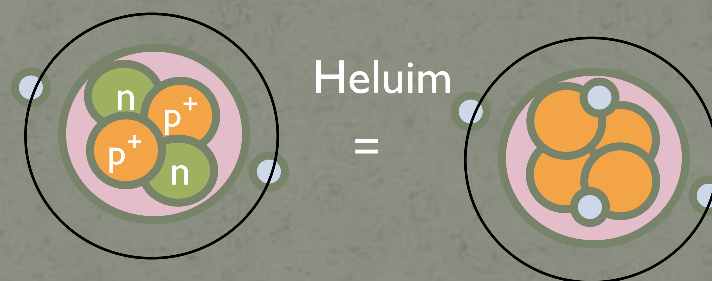
…but who knows?

Particle physics in 1930

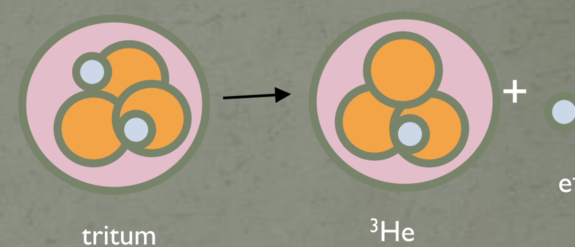
Three particles:

Two forces:

Nuclei are made up of protons and electrons



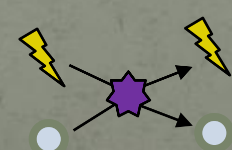
Simple explanation of β decay (Occam's razor)



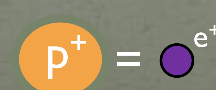
Dirac equation (1928)

$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k \, c\right) \psi(\mathbf{x},t) = i\hbar \frac{\partial \psi(\mathbf{x},t)}{\partial t}$$

- explains spin
- predicts positron



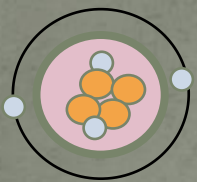
- Klein-Nishina formula
  - explains details of Compton scattering (γ e $\rightarrow$ γ e)
  - requires virtual positrons
- Dirac (1930): Maybe proton is the positron!



1930

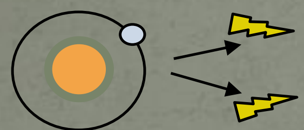
Three problems

1. Nuclear spins and magnetic moments made no sense



$$\mu_B = \frac{e}{2m}$$

2. If $p^+ = e^+$, nuclei can implode



3. β decay spectrum continuous

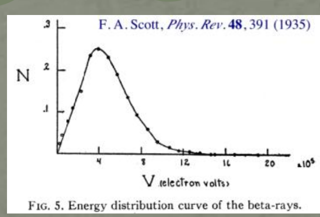
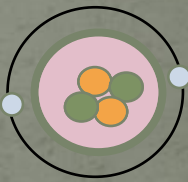


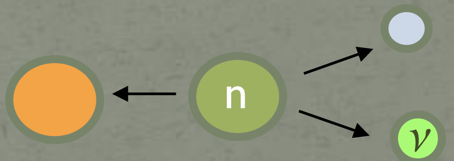
Fig. 5. Energy distribution curve of the beta-rays.

Bohr (1930)
Perhaps energy only conserved *on average*

neutron discovered (1932)



positron discovered (1932)



neutrino (theory 1930) (discovery 1956)

Three separate solutions

Needed EXPERIMENTS to find out

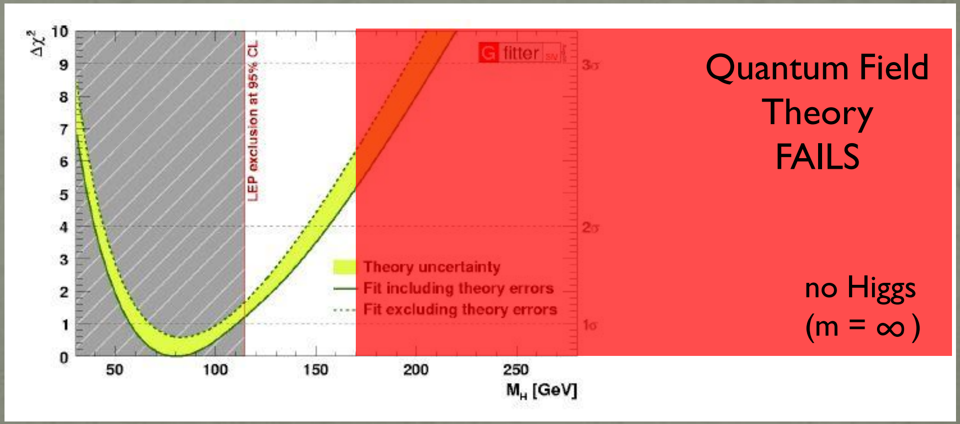
There is a lot we don't understand today

1. Dark Matter
2. Unification
3. The Higgs 
4. Quantum Gravity

What will the LHC find?

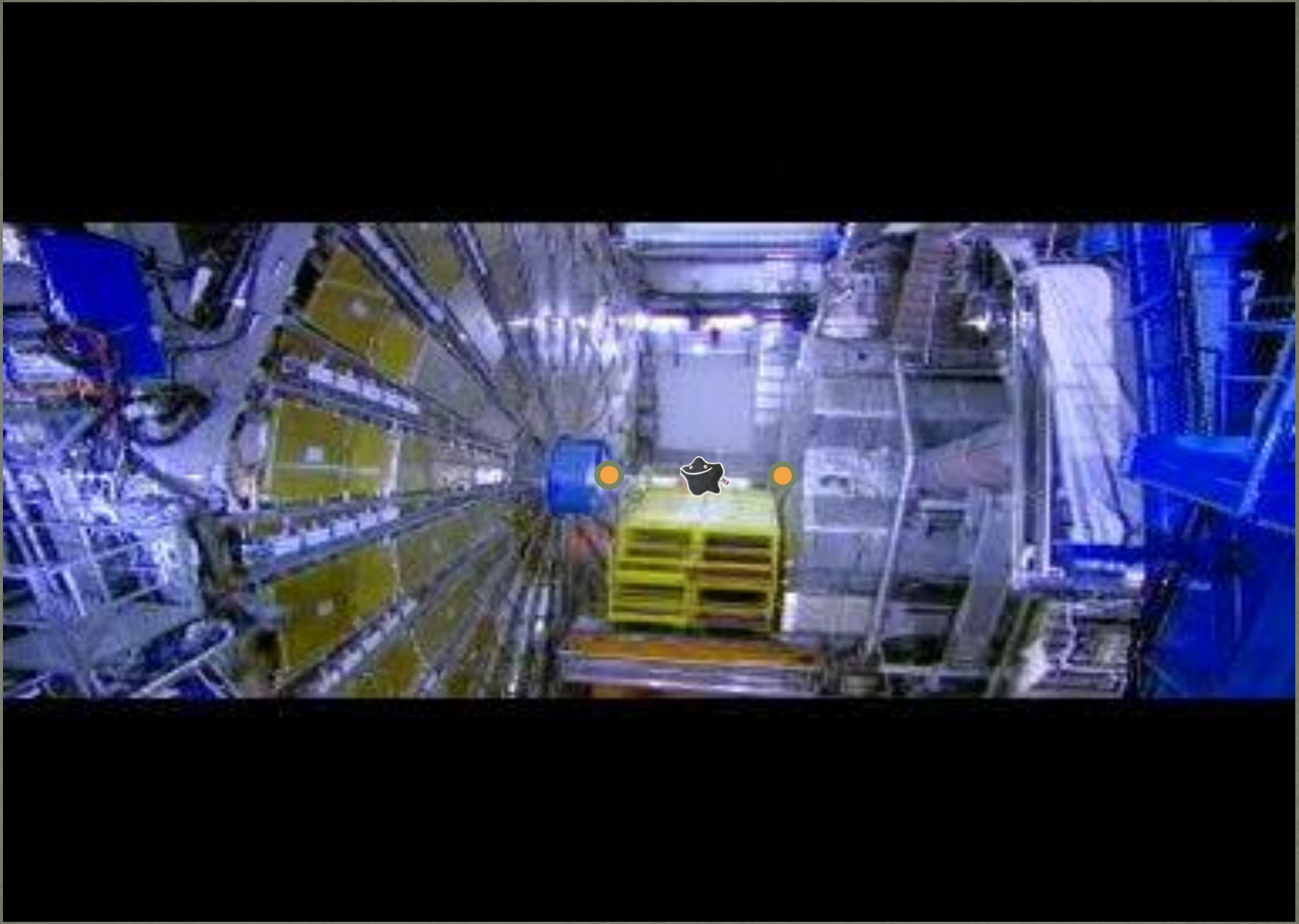
- supersymmetry
- technicolor
- extra-dimensions
- …

Will we need a new principle?



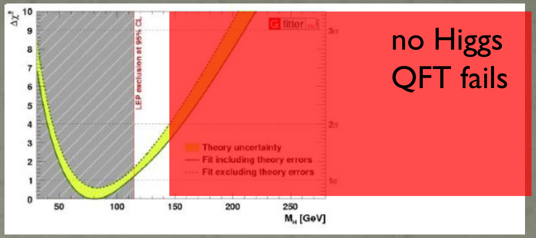
ATLAS

ATLAS



From A&E's "The Next Big Bang"

Conclusions

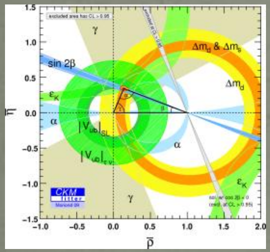


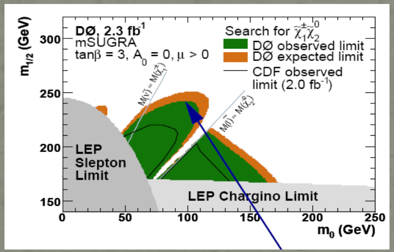
- The Higgs is missing

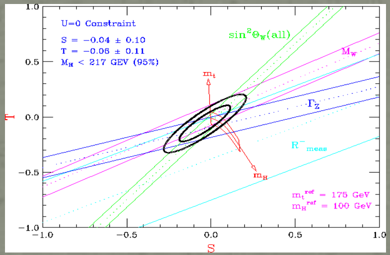
- Quantum field theory fails without a Higgs.
- The Higgs is weird

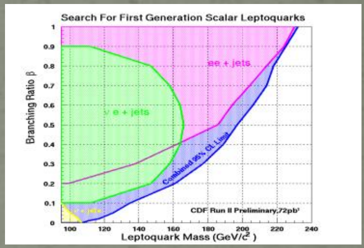
Higgs clumping
(Hierarchy problem)

- None of our "better" ideas seem to work









- The LHC must either find the Higgs, find something else, or disprove quantum field theory

> **"There are more things in Heaven and in Earth than are dreamt of in our philosophy"**
>
> -- Ernest Rutherford, 1914, from Hamlet