Expectations for the LHC:
Perpectives on the state of particle physics

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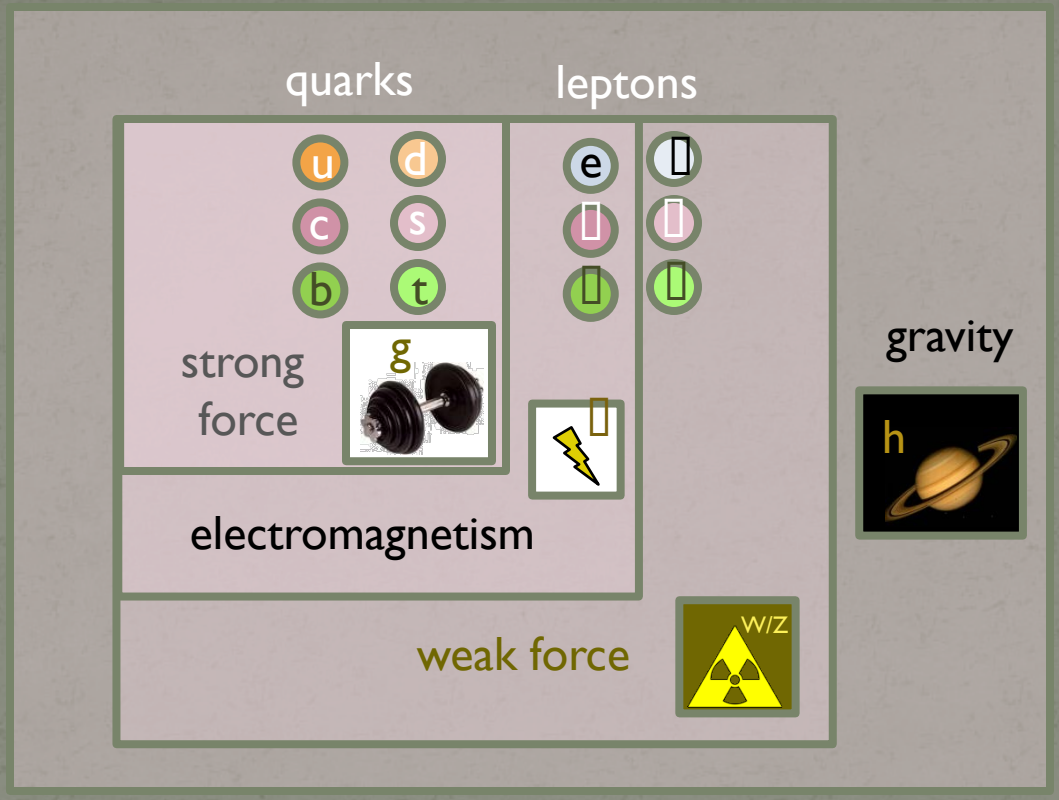
Harvard University

The Standard Model

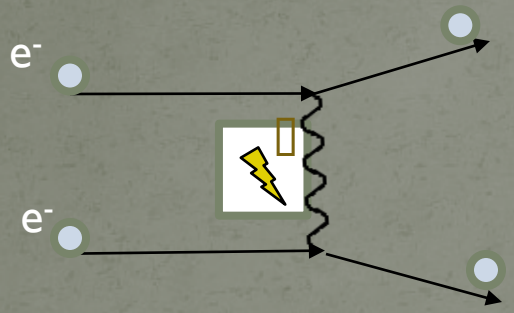


That's it!

What's the problem?

The standard model is a perturbative quantum field theory

Perturbation theory works great in Quantum Electrodynamics:

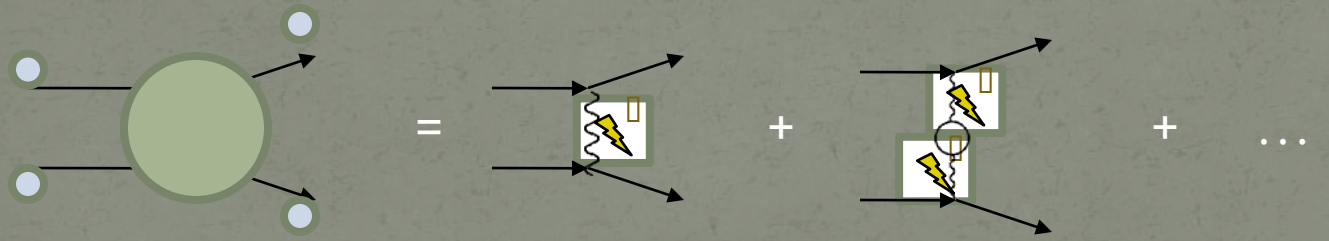


fine structure constant

$$\propto (\text{electric charge})^2 \sim \alpha_e \sim \frac{1}{137} = 0.007 \ll 1$$

(Coulomb's law $F = \frac{\alpha_e}{r^2}$)

Quantum corrections are small

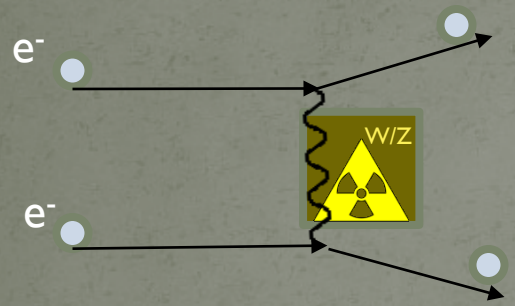


$$\propto (\text{electric charge})^4 \sim \alpha_e^2 \sim 0.00005$$

(observable 1% correction to Coulomb's law)

What's the problem?

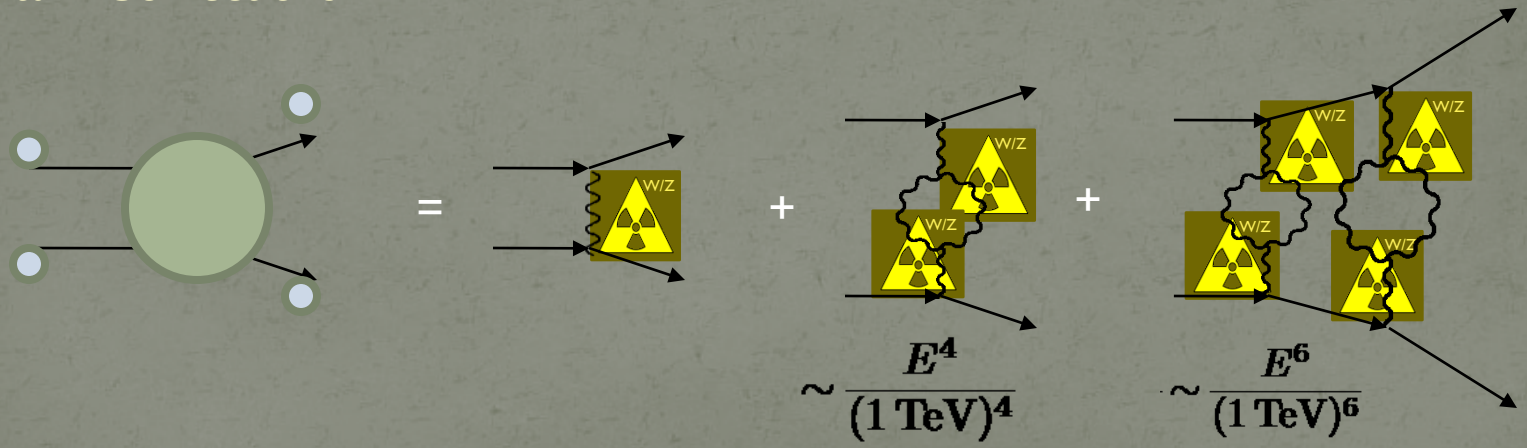
Perturbation theory fails for the weak force



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

- Radioactive decay at atomic energies E ~10^{-6} TeV is very rare

Quantum Corrections



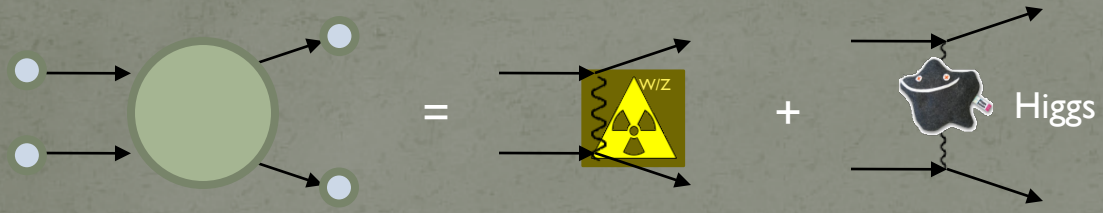
$$\sim \frac{E^4}{(1\,\text{TeV})^4} \qquad \sim \frac{E^6}{(1\,\text{TeV})^6}$$

Tiny correction at atomic energies E ~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?

How do we know where to look?

W boson

- mass predicted from indirect precision experiments 82 ± 2.4 GeV
- Discovered at CERN in 1983 at 81 ± 5GeV

Z boson

- mass predicted from indirect precision experiments 94 ± 2.5 GeV
- Discovered at CERN in 1983 at 95.2 ± 2.5GeV

Top quark

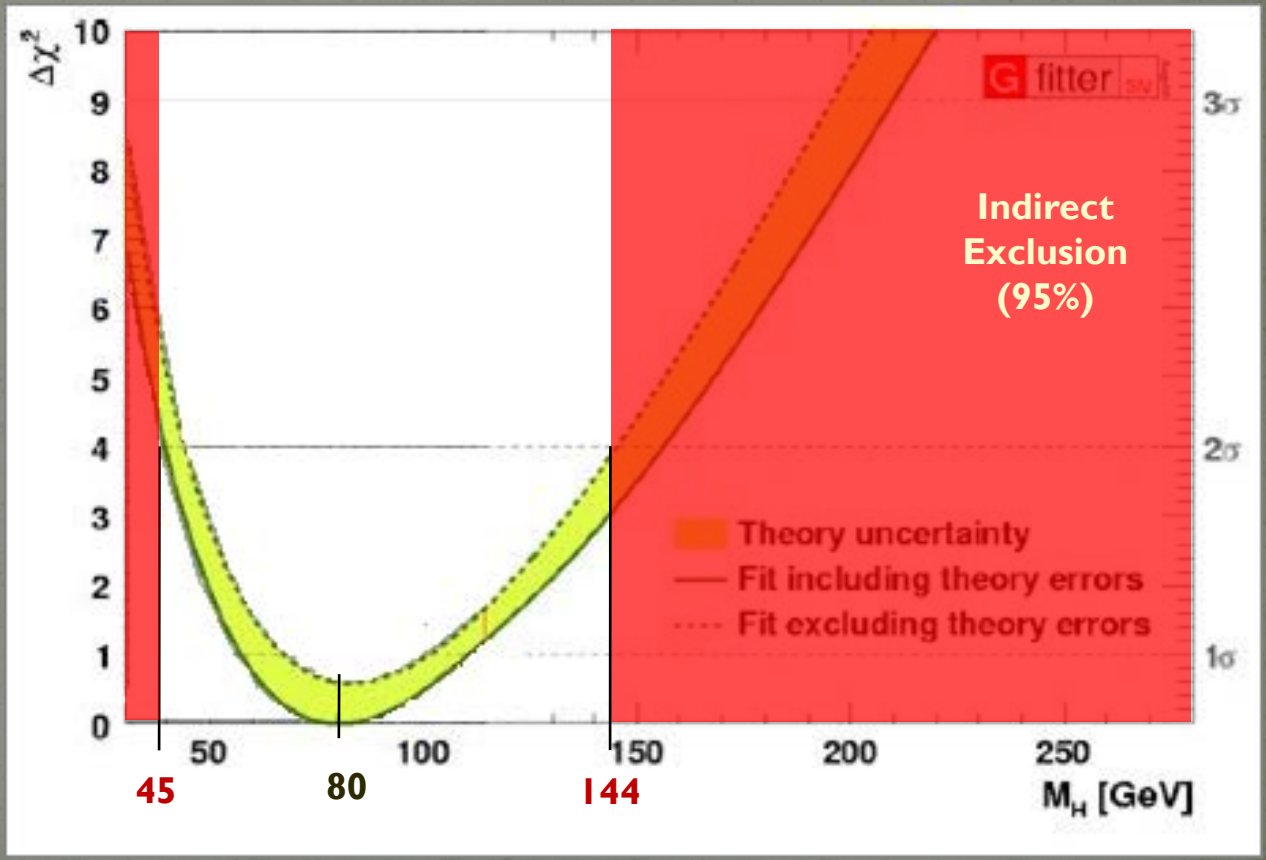
- first discovered (3) at CERN at m_t = 40 ± 10 GeV (1984)
- underestimated backgrounds!
- mass predicted from indirect precision experiments m_t = 179 ± 20 GeV
- Discovered at Fermilab in 1994 at m_t= 174 ± 20 GeV

Agreement between theory and measurements strong test of Quantum Field Theory

Where is the Higgs?

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

Combine many observables to constrain Higgs mass



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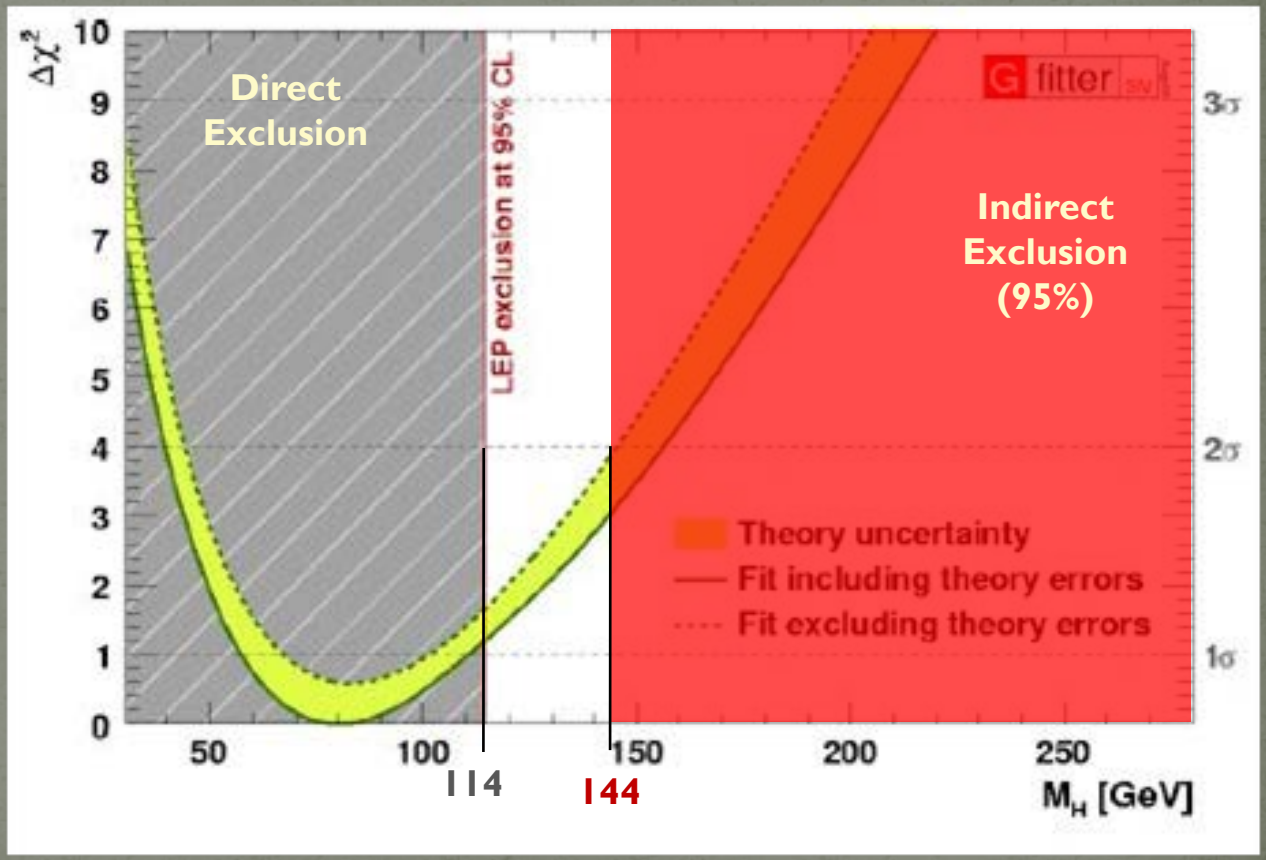

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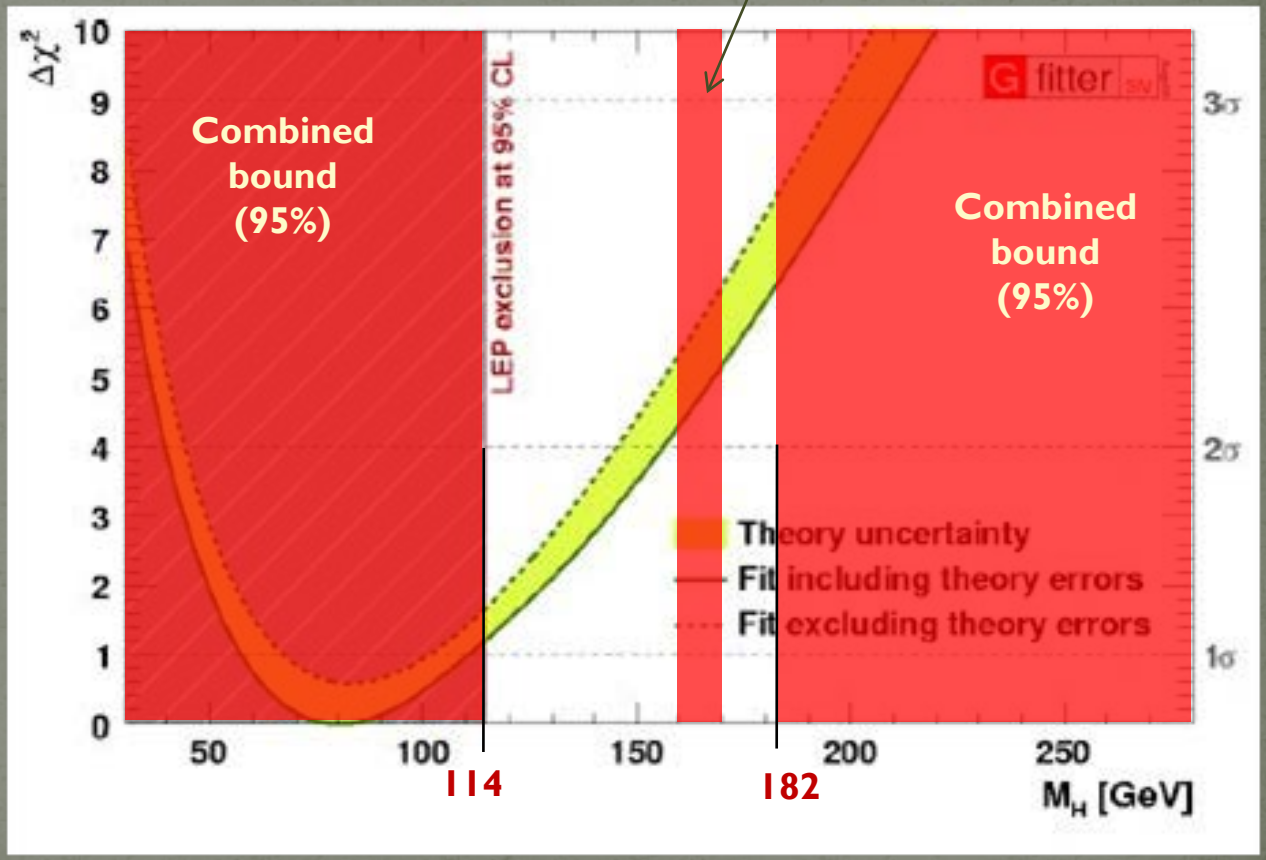
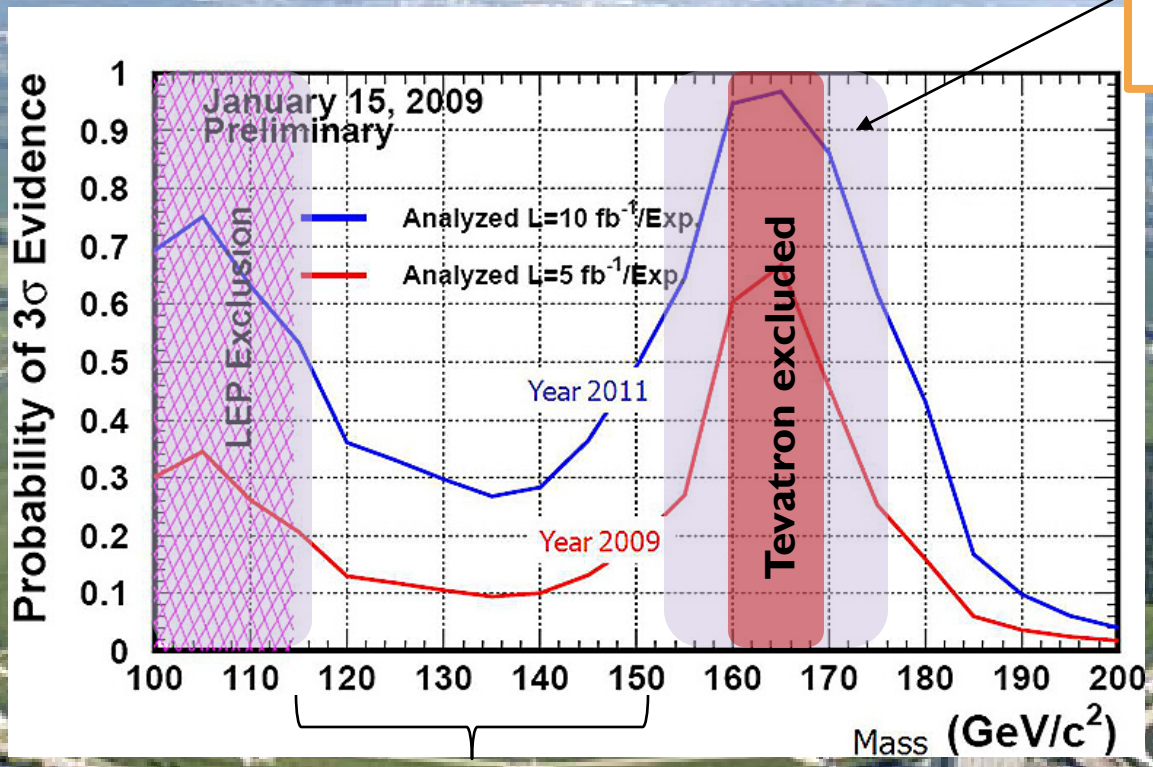
Combine many observables to constrain Higgs mass

Recent Tevatron exclusion (160-170 GeV)



Tevatron Higgs search

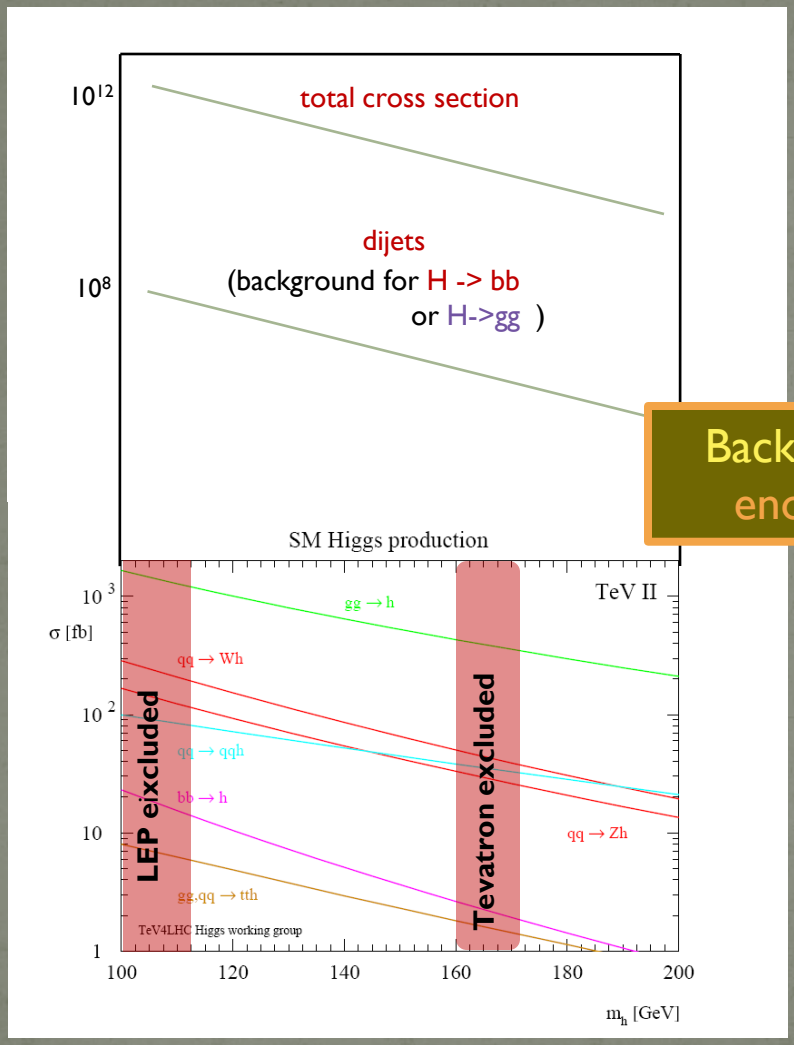


May exclude by 2011

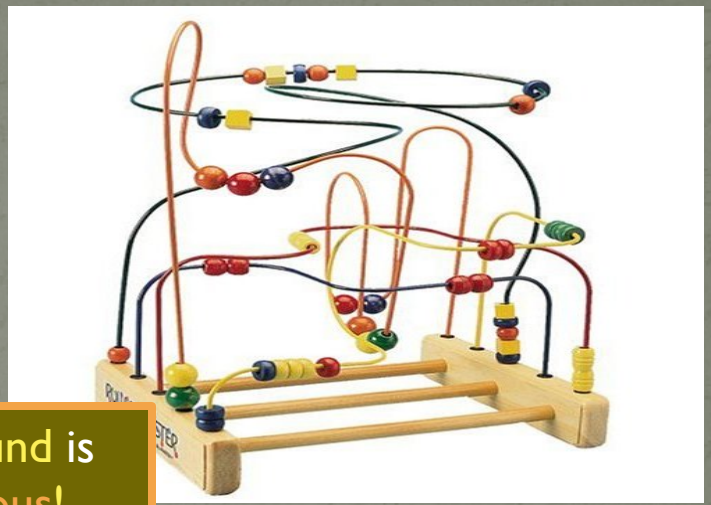
Tevatron can't do much in the most likely region

Sadly, it **CANNOT** find the Higgs (5)

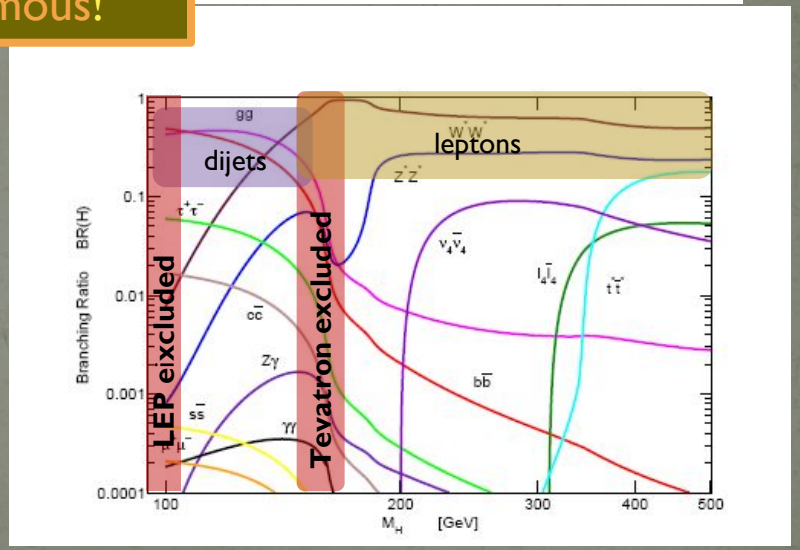
Why is it so difficult to find the Higgs?



Production



Background is enormous!

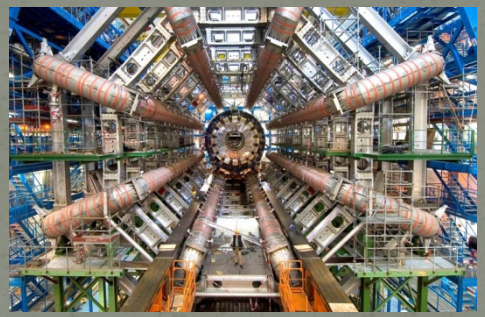


Decay

Large Hadron Collider

Two experiments can find the Higgs

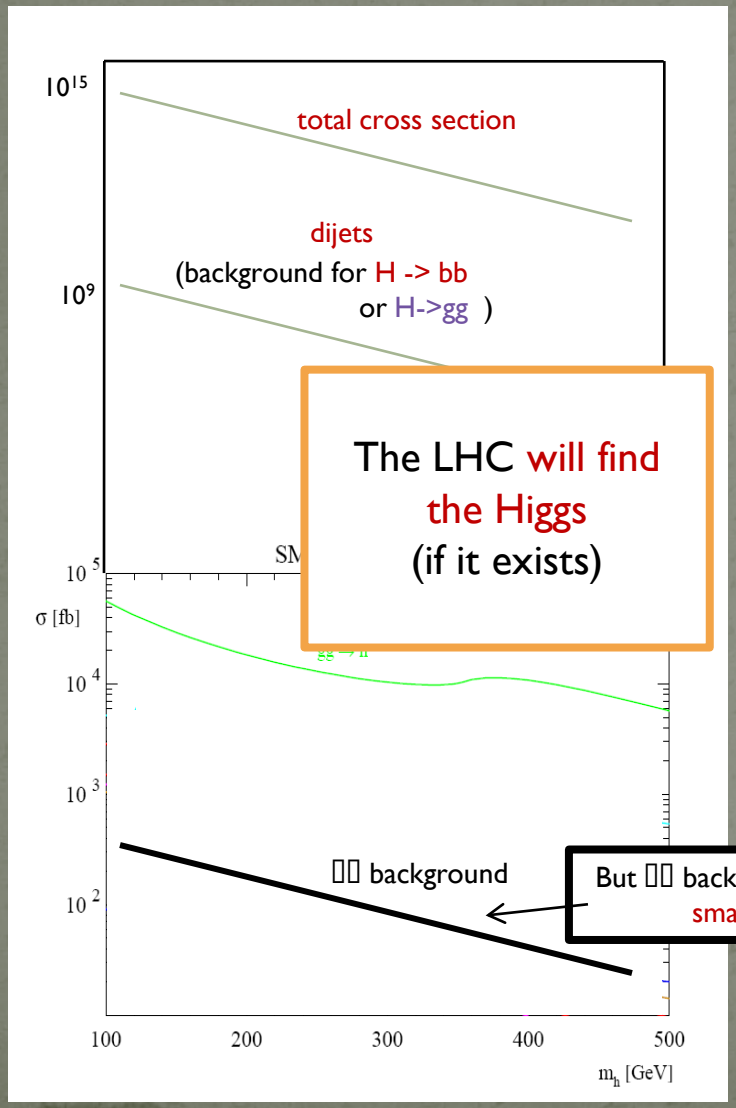
ATLAS



CMS

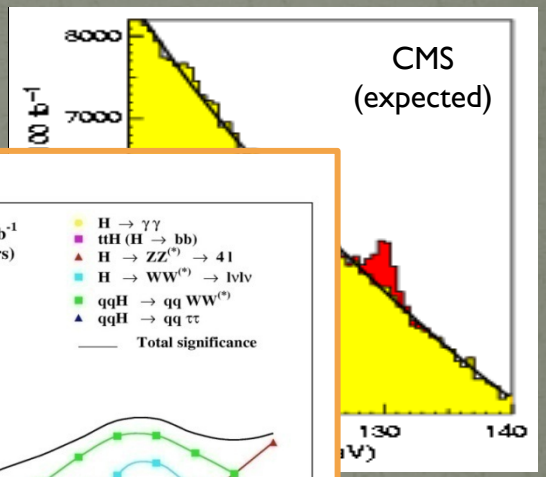
25 kilometers in diameter

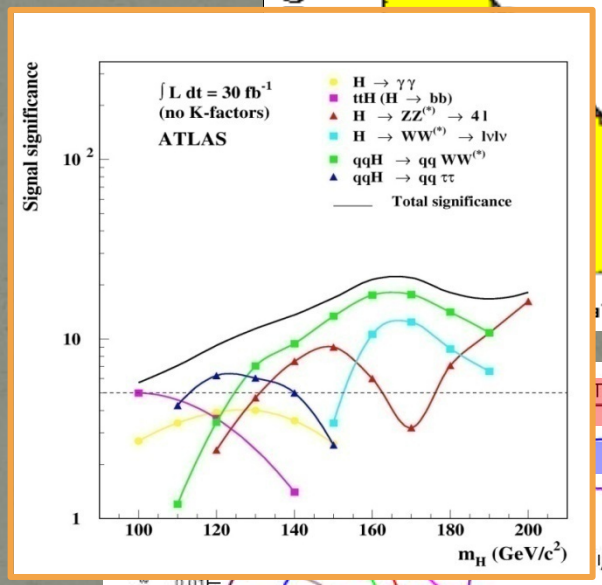
LHC can see rare Higgs decays

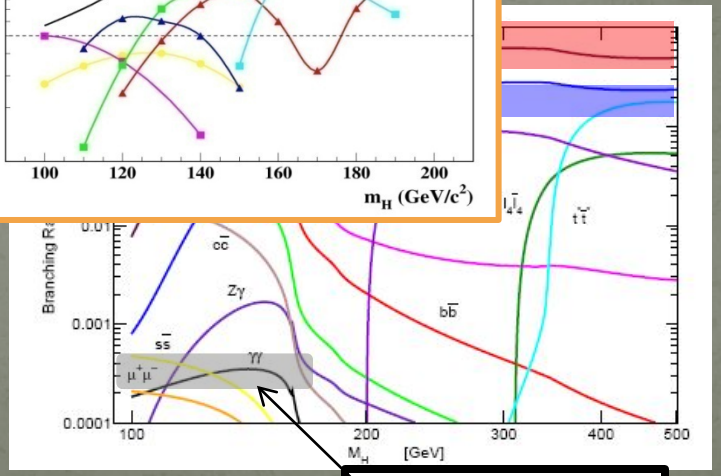


The LHC will find the Higgs
(if it exists)

so we can see it!







1 in 1000
Higgses decays to

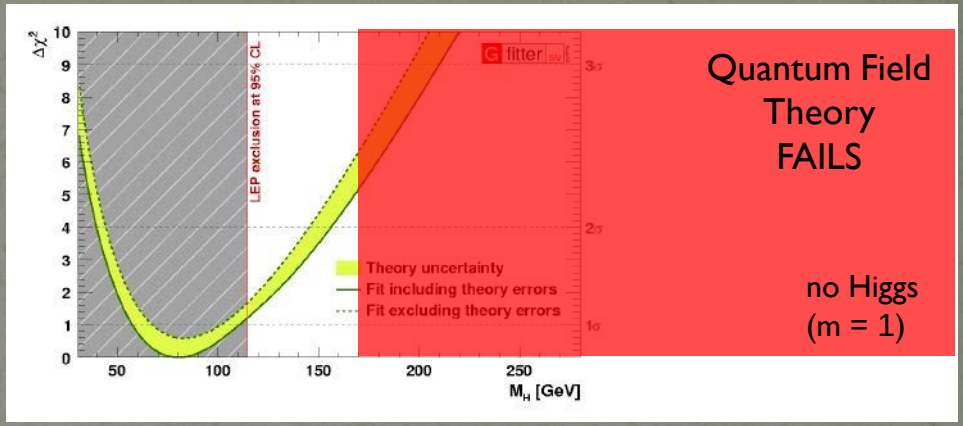
Higgs Summary

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.

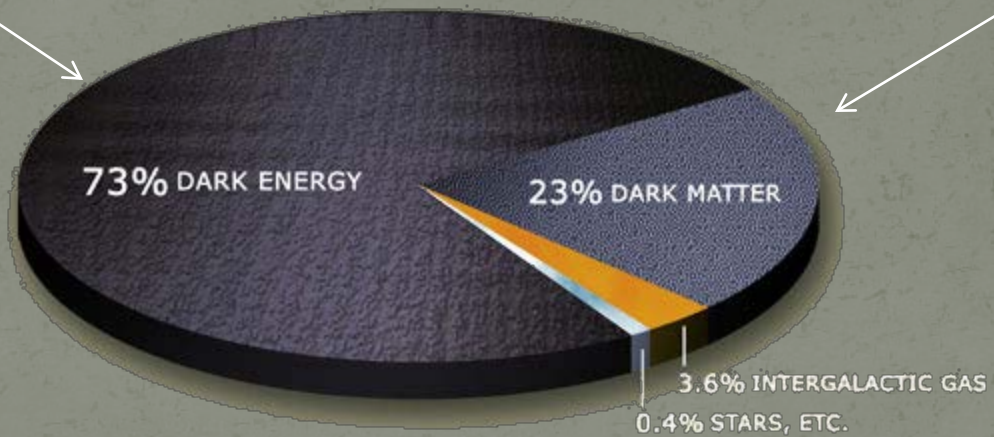
Clues to new physics

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

Dark Matter

Cosmological Constant?

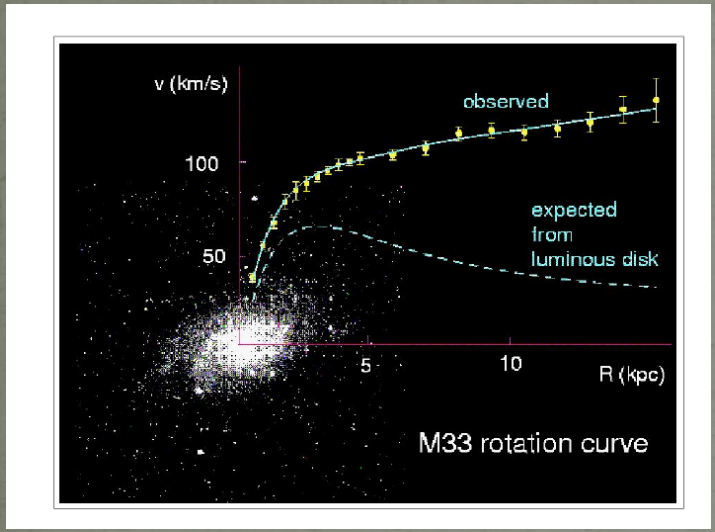
Beyond the Standard Model physics



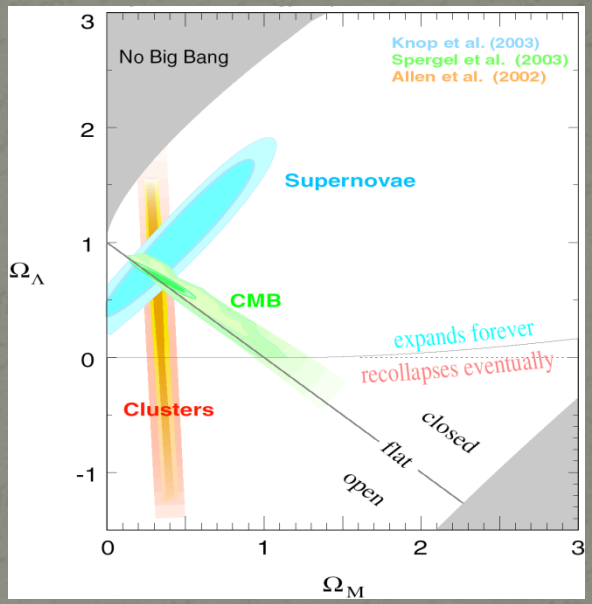
Stuff we understand

Plenty of evidence

- Galaxy rotation curves



- Cosmic microwave background, Supernova, Galactic clusters



- Simulations:

  With only visible matter, structure doesn't form

Dark Matter

What do we know?

- Must be stable

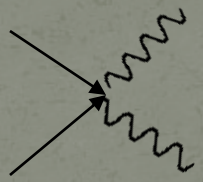
Not dark

- Must be dark

- Must clump

Doesn't clump

- Must equilibrate with matter



$$\sigma_{\rm ann} \approx \frac{\alpha^2_{\rm dark\ matter}}{(\rm mass)^2}$$

mass ~ TeV
coupling ~ weak
Weakly Interacting Massive Particle (WIMP)

We can compute the density left over from big bang:

$$\Omega_M = \text{const} \times \frac{1}{M_P^3 H_0^2 \sigma_{\rm ann}} \approx \frac{1}{\sigma_{\rm ann}} \frac{\alpha^2_{\rm weak}}{(\rm TeV)^2} \approx 1$$

calculable numbers

Planck's constant (10^{19} GeV)

Age of the universe (10^{10} years)

observed amount

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

Unification

When two seemingly different things turn out to be the same

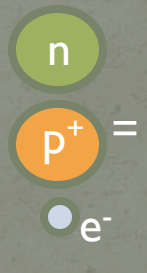
Electromagnetism

=

=

Electroweak unification

Chemistry



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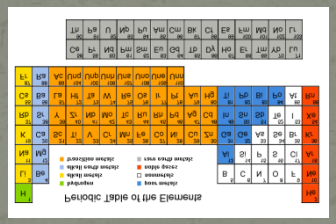

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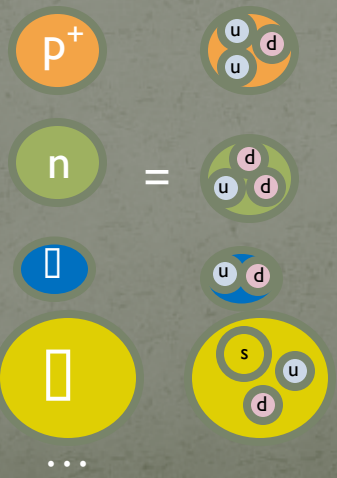
Gravity

=

Quark model

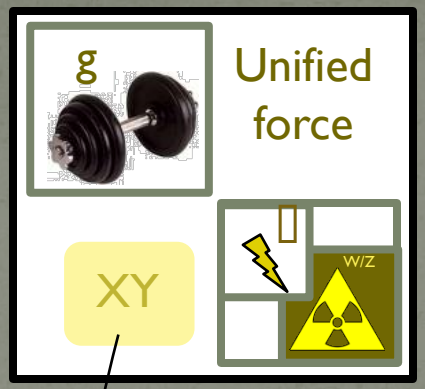


Grand Unification

strong force 

electromagnetism 

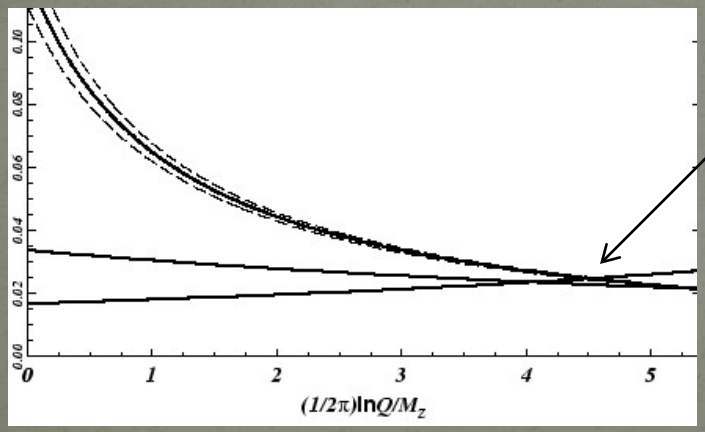
weak force 



electroweak force

- Explains why proton and electron have the same charge
- Coupling constants should be the same
  - $\alpha_{strong} = 0.15$
  - $\alpha_{e} = 0.04$
  - $\alpha_{weak} = 0.02$

hmm…

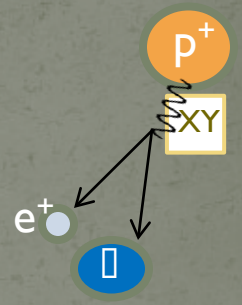


unification at 10^{15} GeV

but they are energy dependent!

New force!
New effects!

proton decay



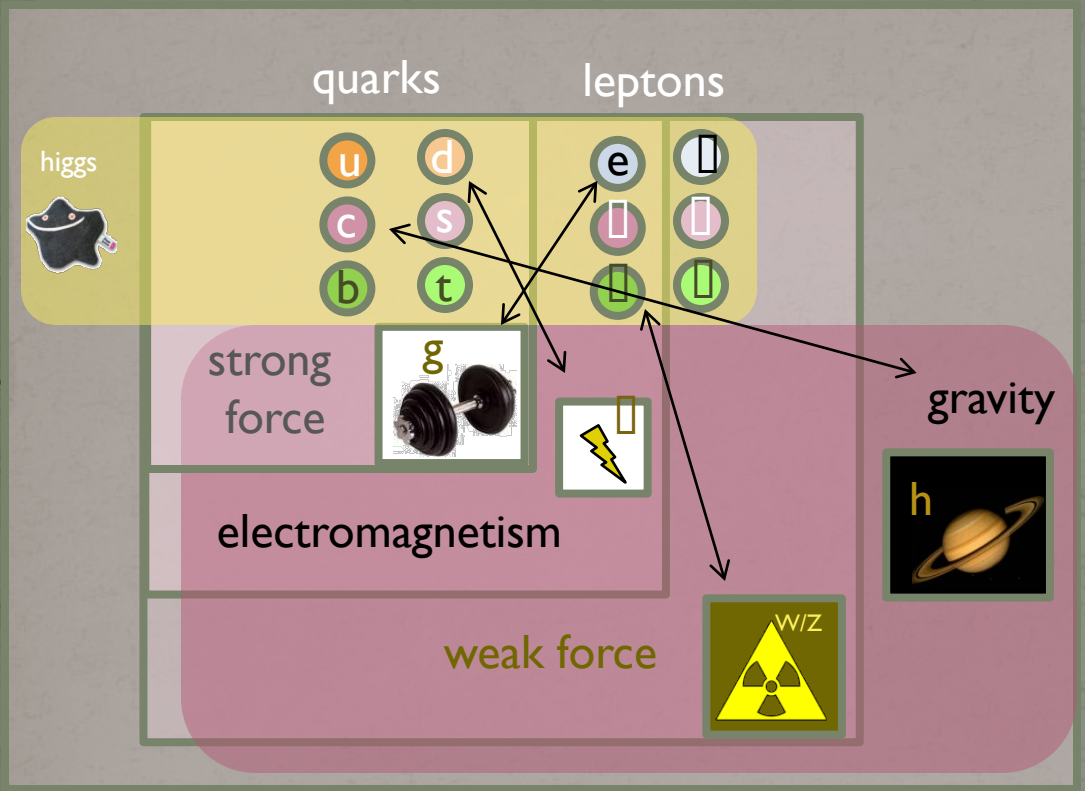
predicts:
proton lifetime = 10^{31} years

limit (1974) ~ 10^{29} years

limit (2009) ~ 5×10^{33} years

hmm…

Supersymmetry

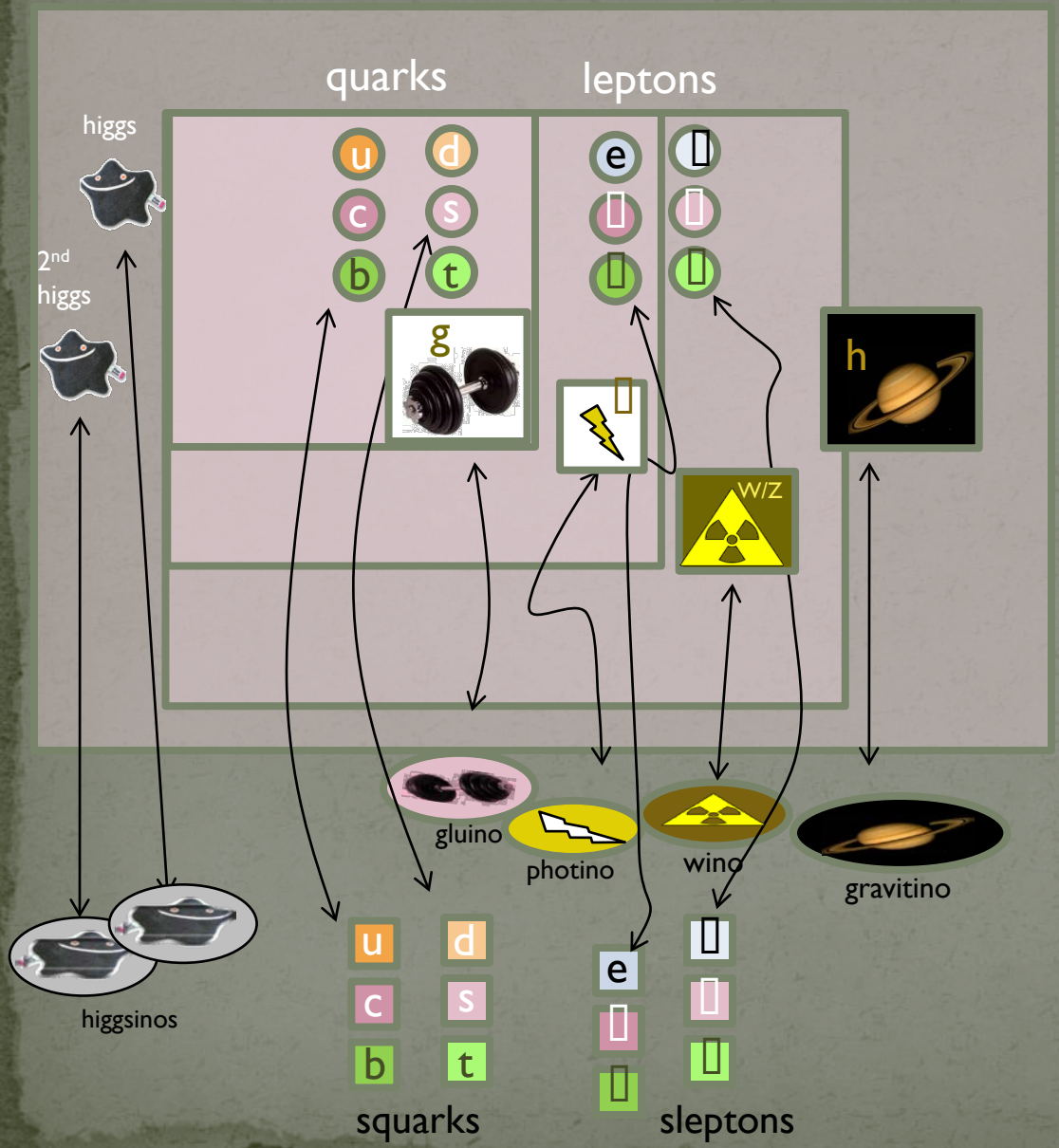


Particles and Forces

- 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



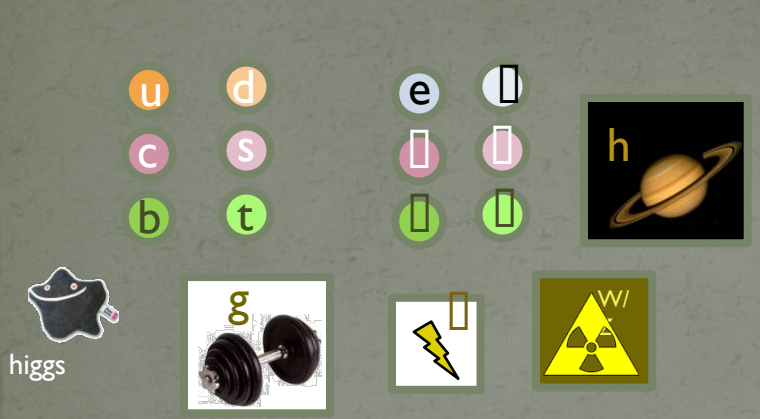
Particles and Forces

- 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

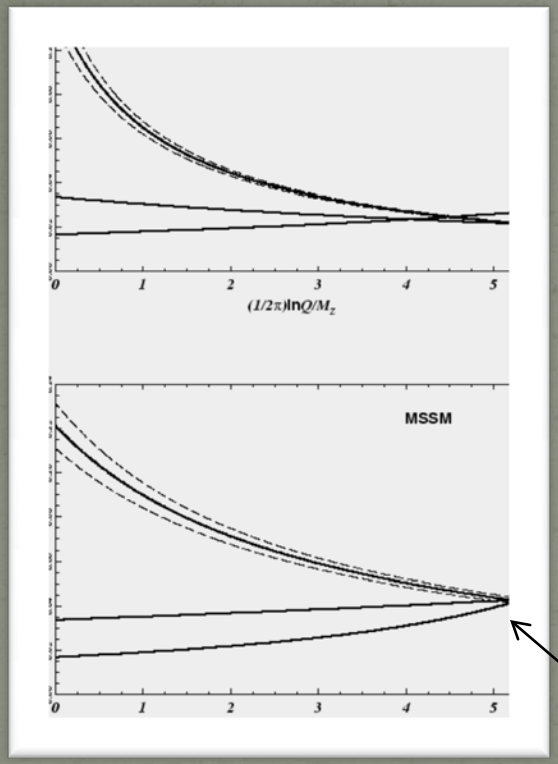
"With 4 parameters I can fit an elephant, with 5 parameters I can make him wiggle his trunk"

-- Carl Friedrich Gauss

Broken Supersymmetry

Benefits
- Dark matter candidates!
- Unification improved!

Bino
Higgsino
Gravitino



Predictive!

- dark matter detectable
- proton decay around current limits
- predicts Higgs mass
- new sources of CP violation
- B meson decays and mixings
- muon anomalous magnetic moment (g-2)
- flavor changing neutral currents
- collider signatures – jets, leptons, missing energy

Higher scale

Proton lifetime ~ 10^{32} years

limit (2009) ~ 5×10^{33} years

Higgs mass

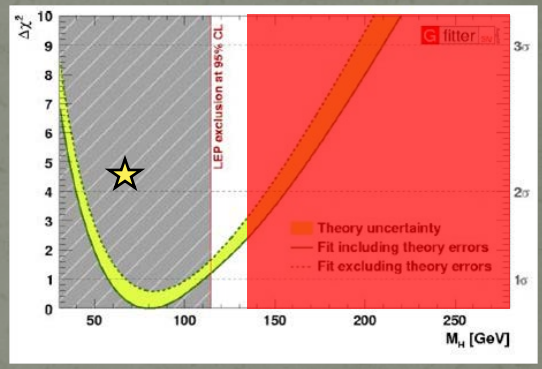
In the Minimal Supersymmetric Standard Model, the Higgs mass is calculable

$$m_{h^0} < m_Z |\cos(2\beta)| < 90 \text{ GeV}$$

Free parameter

MSSM predicted that the Higgs would be seen by UA1, the Tevatron or LEP!

LEP bound: $m_{h^0} > 114$ GeV



Can increase mass with parameters

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha\ y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right).$$

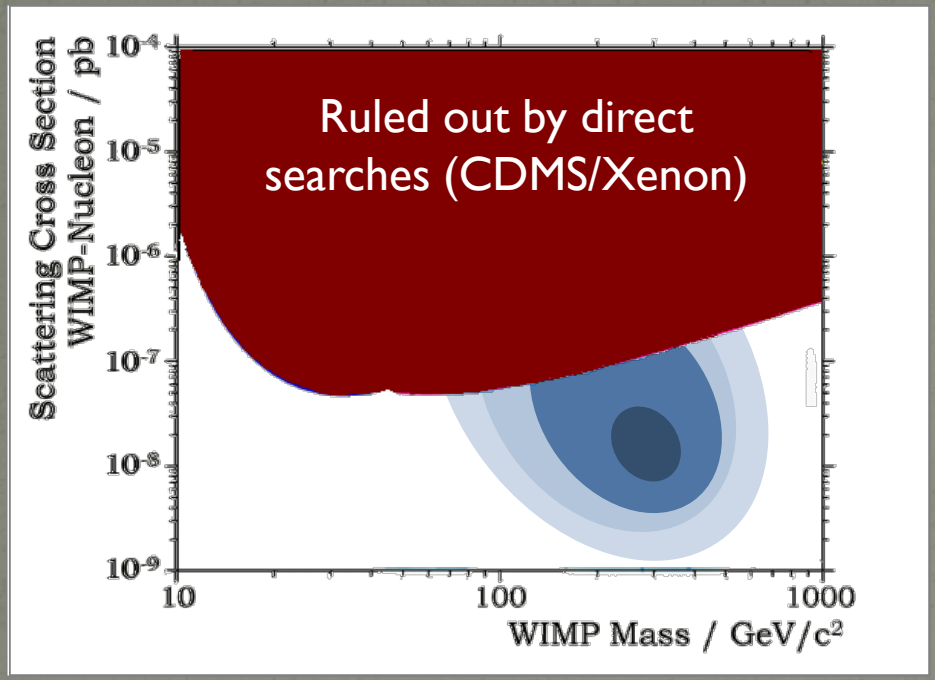
Free parameters

SUSY "requires"

$$m_{h^0} \lesssim 135 \text{ GeV}$$

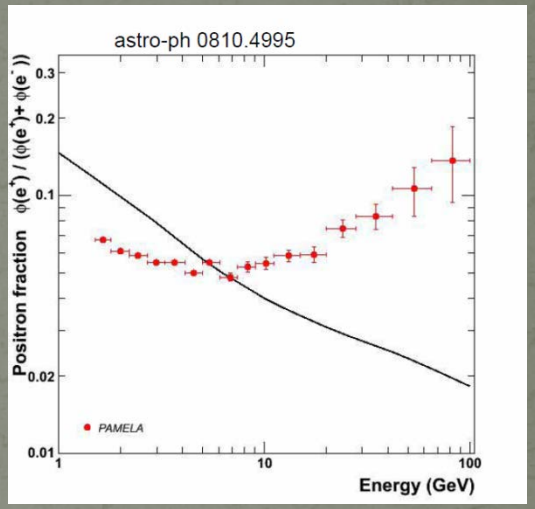
Remaining SUSY window 114 < m_h<135 will be probed by the LHC

SUSY Dark matter

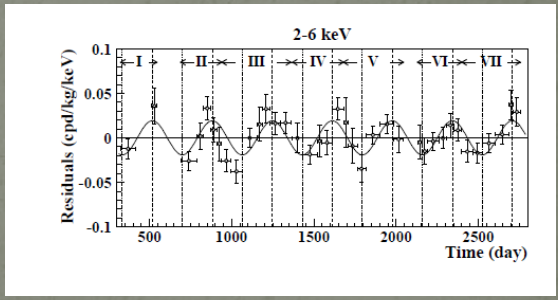


Typical SUSY WIMPs

Intriguing excesses at PAMELA

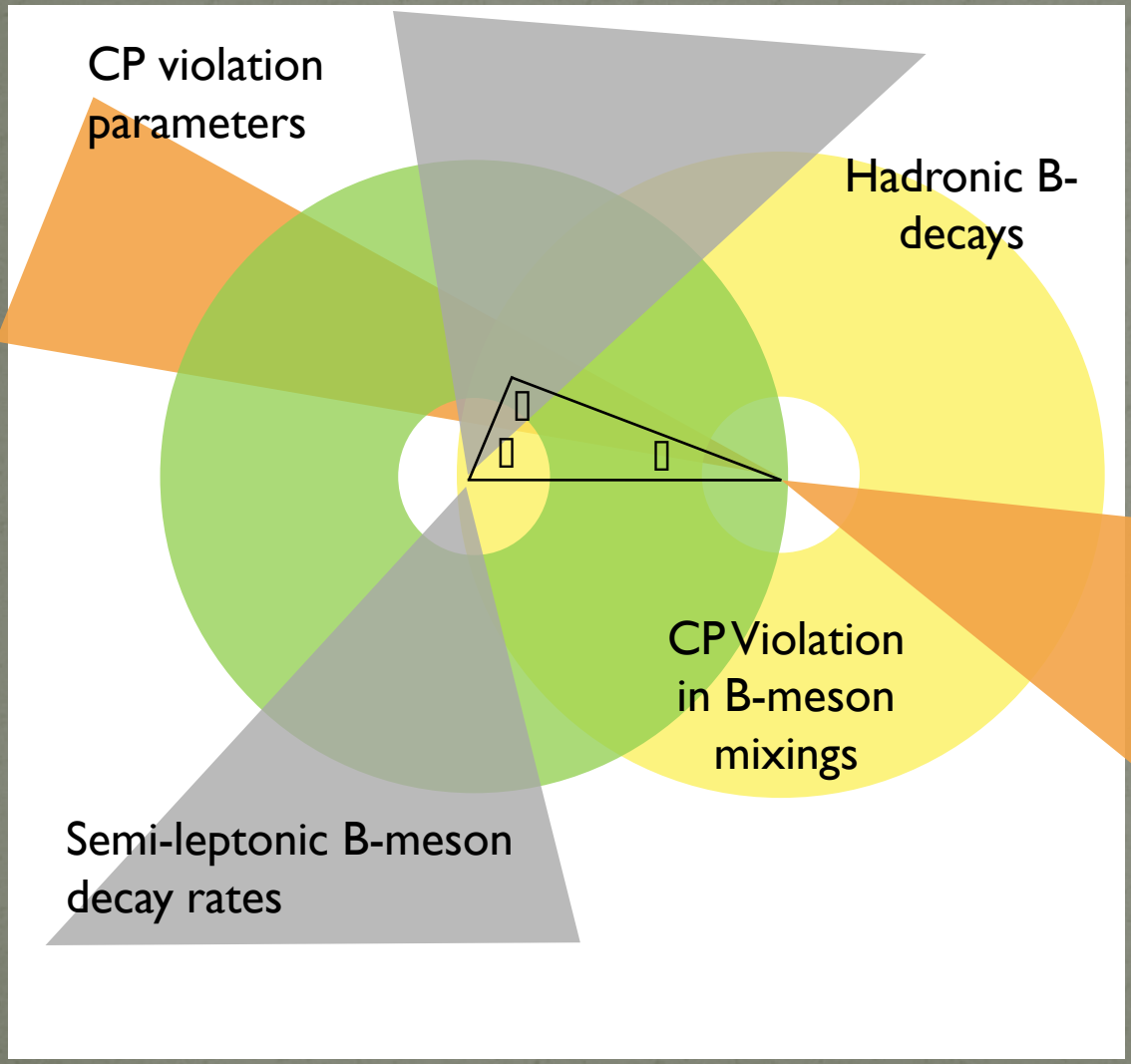


and DAMA



Not really consistent with typical WIMPS…

Indirect Constraints



Flavor parameters in the SM can be parameterized by

□ + □ + □ = 180°

Represent with a triangle:

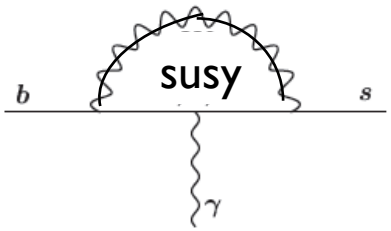
The Unitarity Triangle

If the triangle doesn't close, there must be physics beyond the SM

supersymmetry predicts many deviations

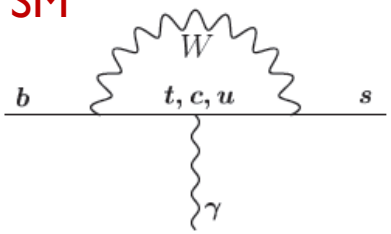
B-factories

$b \to s\gamma$

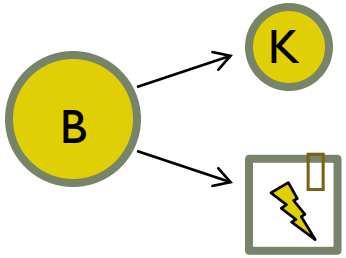


~10^{-3}

SM



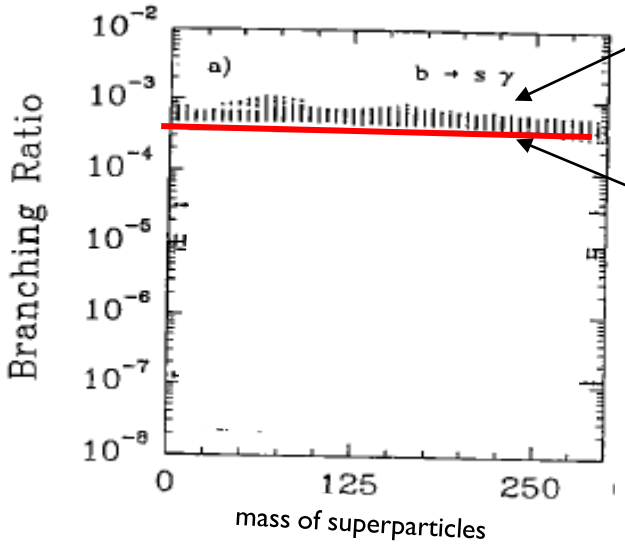
~10^{-4}



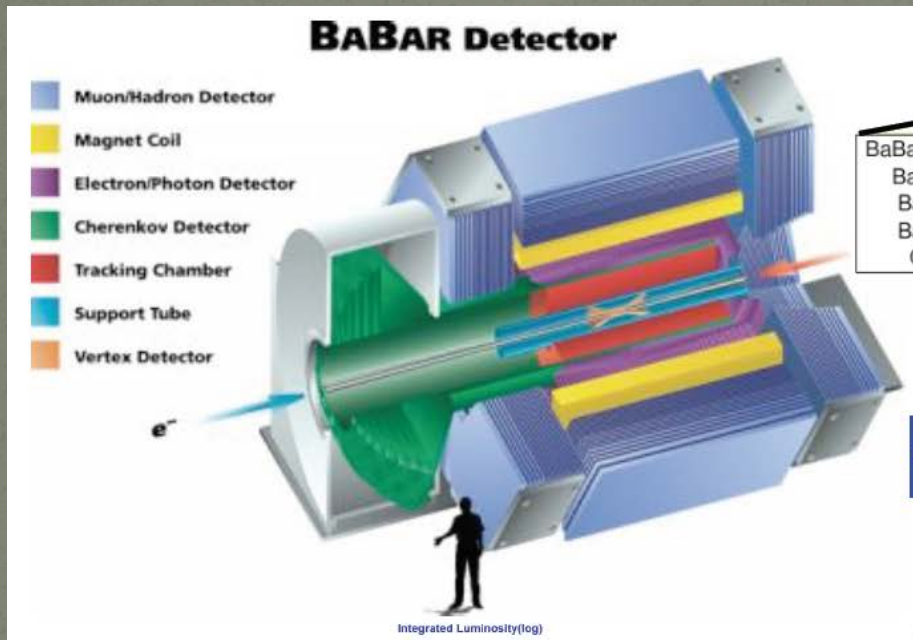
(1991)

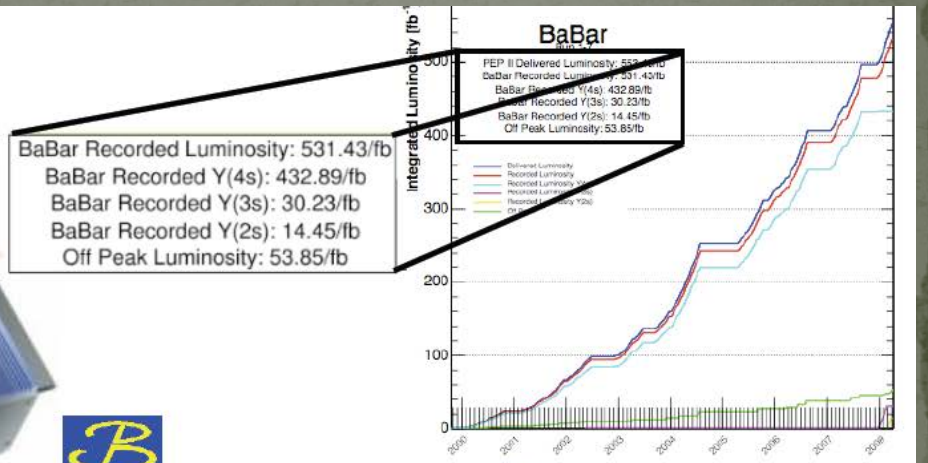
SUSY prediction

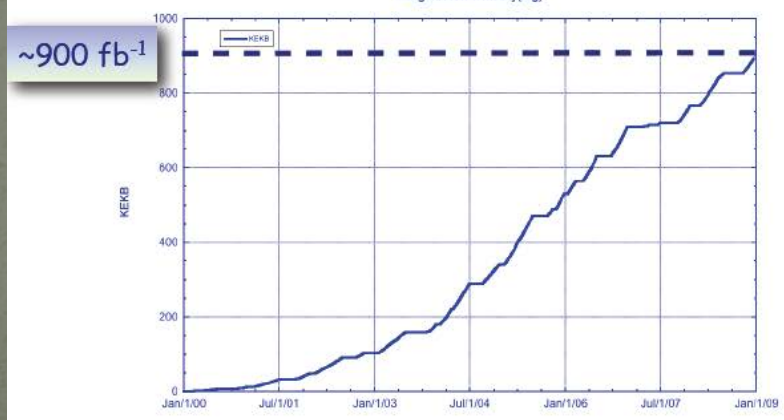
SM prediction

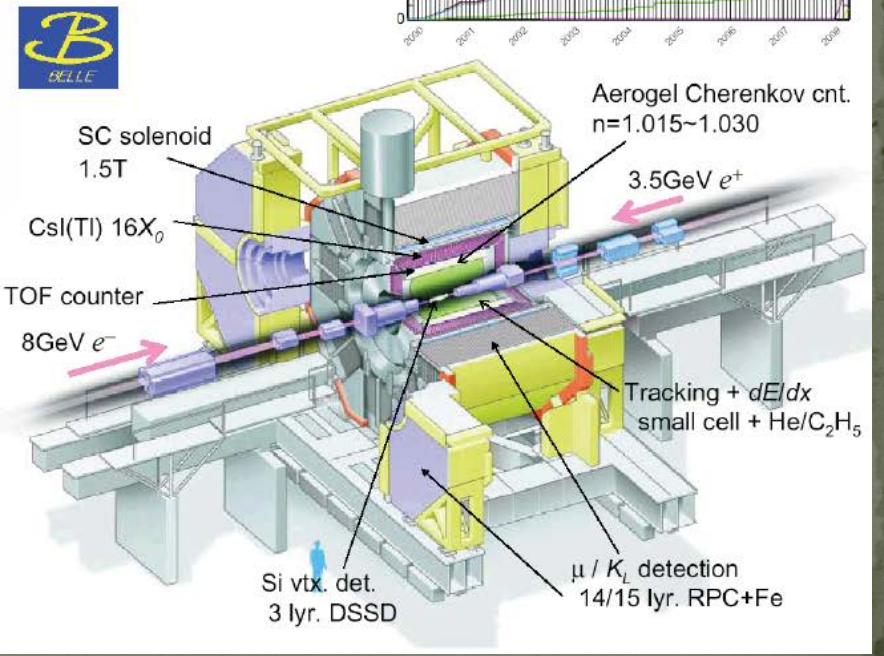


B-factories

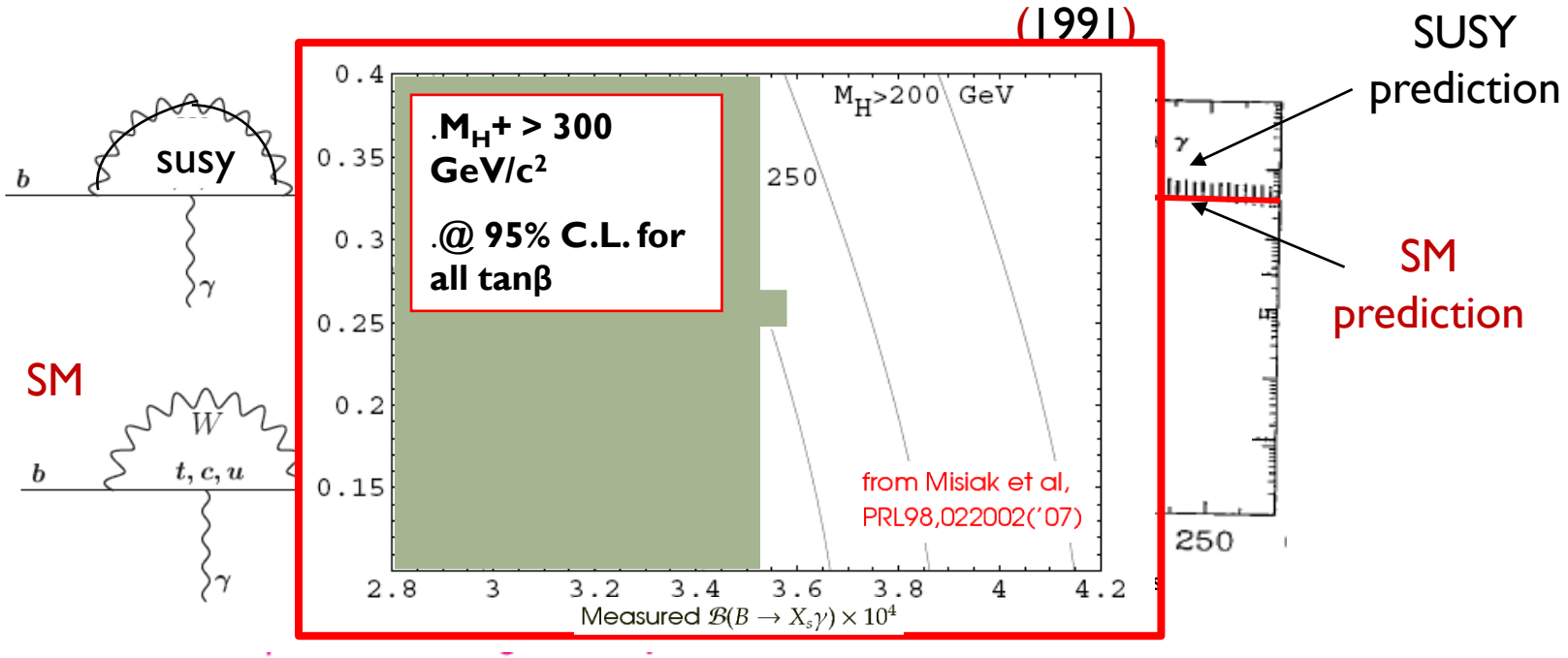

BABAR Detector
Muon/Hadron Detector
Magnet Coil
Electron/Photon Detector
Cherenkov Detector
Tracking Chamber
Support Tube
Vertex Detector
e⁻


BaBar Recorded Luminosity: 531.43/fb
BaBar Recorded Y(4s): 432.89/fb
BaBar Recorded Y(3s): 30.23/fb
BaBar Recorded Y(2s): 14.45/fb
Off Peak Luminosity: 53.85/fb
BaBar
Integrated Luminosity [fb⁻¹]
PEP II Delivered Luminosity: 553.10/fb
BaBar Recorded Luminosity: 531.43/fb
BaBar Recorded Y(4s): 432.89/fb
BaBar Recorded Y(3s): 30.23/fb
BaBar Recorded Y(2s): 14.45/fb
Off Peak Luminosity: 53.85/fb
0
100
200
300
400
2000
2001
2002
2003
2004
2005
2006
2007
2008


~900 fb⁻¹
Integrated Luminosity(log)
KEKB
0
200
400
600
800
1000
Jan/1/00
Jul/1/01
Jan/1/03
Jul/1/04
Jan/1/06
Jul/1/07
Jan/1/09


BELLE
Aerogel Cherenkov cnt.
n=1.015~1.030
SC solenoid
1.5T
3.5GeV e⁺
CsI(Tl) 16X₀
TOF counter
8GeV e⁻
Tracking + dE/dx
small cell + He/C₂H₅
Si vtx. det.
3 lyr. DSSD
μ / K_L detection
14/15 lyr. RPC+Fe

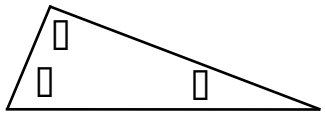
$b \to s\gamma$



$$\mathcal{B}(B \to X_s\gamma)\big|_{E_\gamma > 1.6\mathrm{GeV}}$$

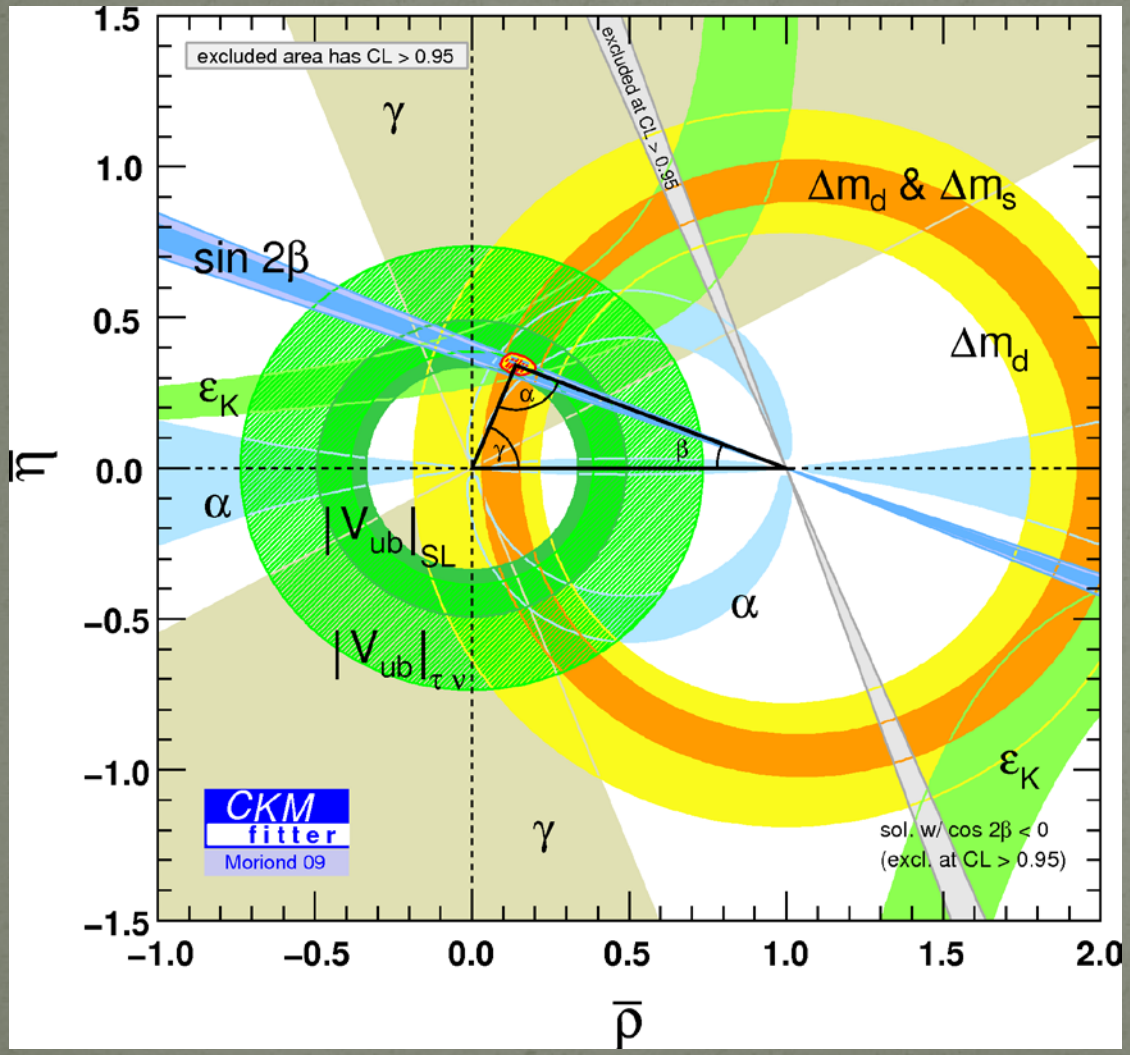
measurement: $(3.52 \pm 0.25) \times 10^{-4}$

Indirect Constraints



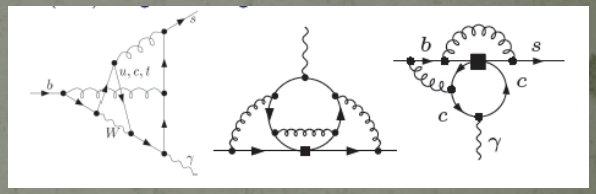
The Unitarity Triangle

Indirect Constraints



Everything agrees!

Impressive SM calculations:

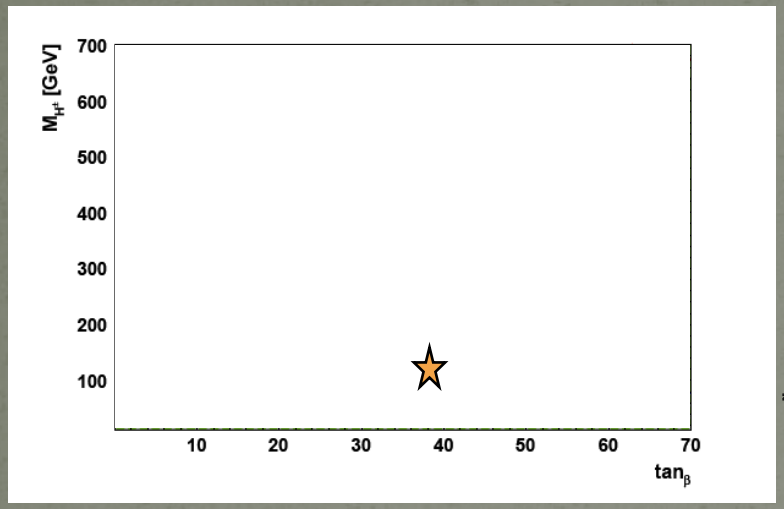


Awkward for supersymmetry

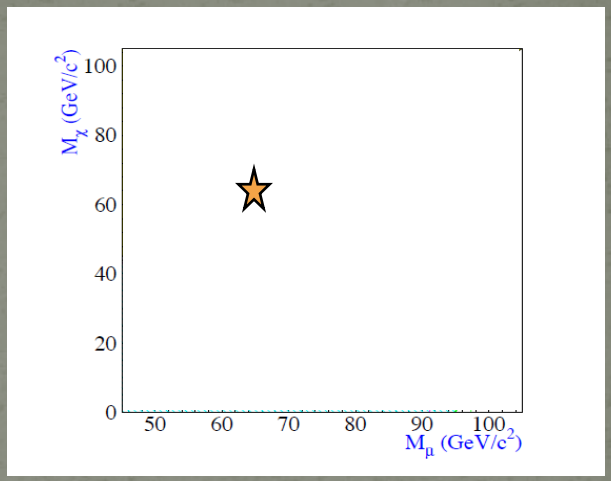
- Can avoid constraints with fancy models

Direct Constraints

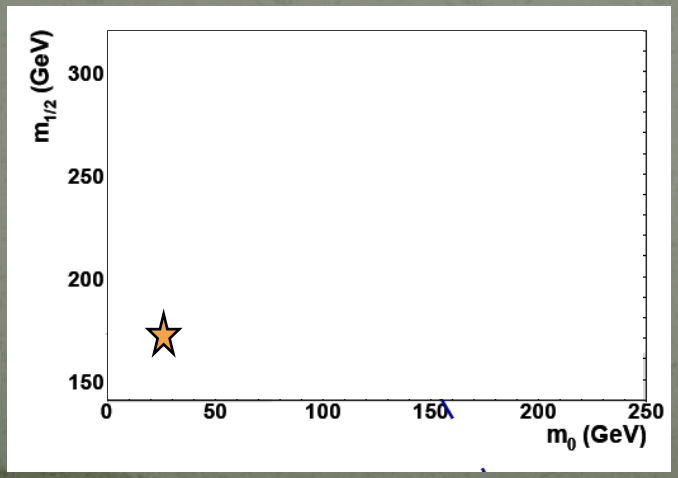
Tanβ and charged Higgs mass



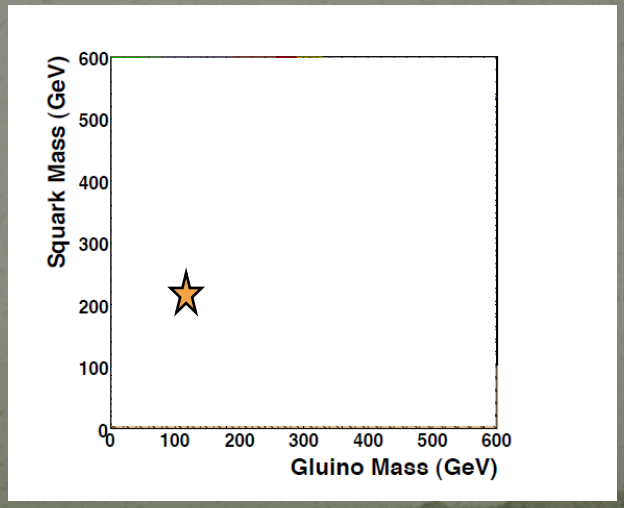
smuon and neutralino mass



mSUGRA parameterers



gluino and squark masses



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?
- □ 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. It also clumps around fermions to give them mass

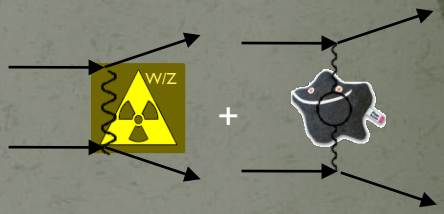
(bad)

(good)

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

Scale of gravity

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



= small

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:

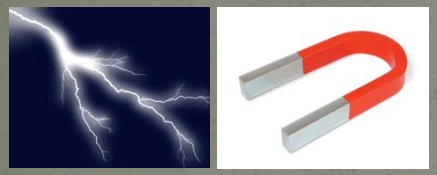
=

higgsino

fermions don't clump

The Higgs is Weird

Electromagnetism

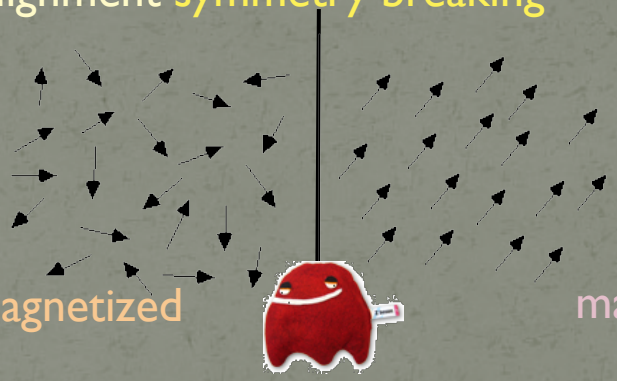


=

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)

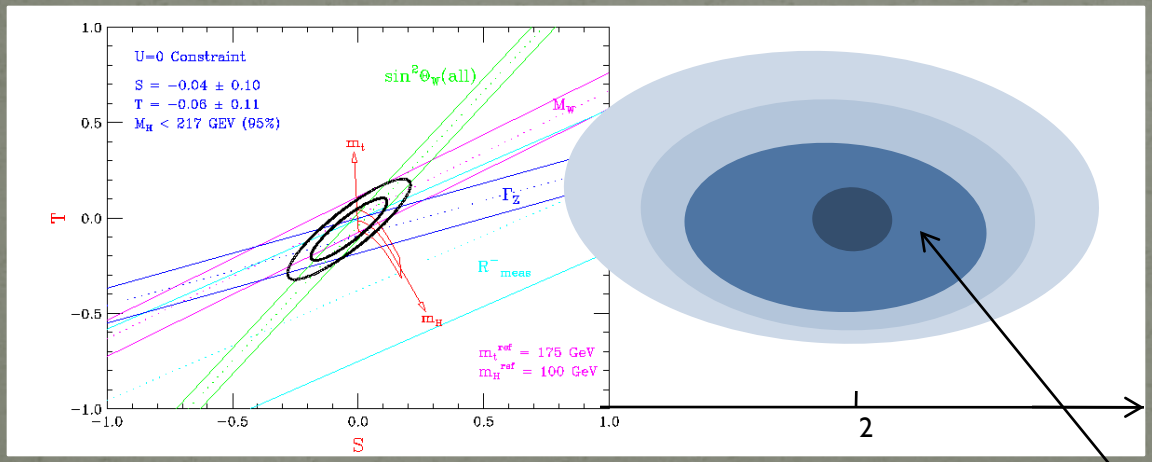
Technicolor

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

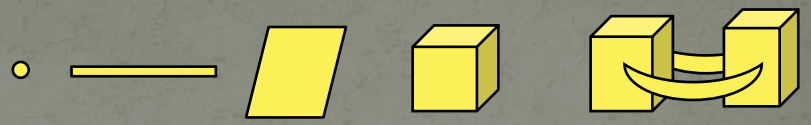
Many more types that we don't understand

Typical technicolor prediction

Other ideas

Extra dimensions

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

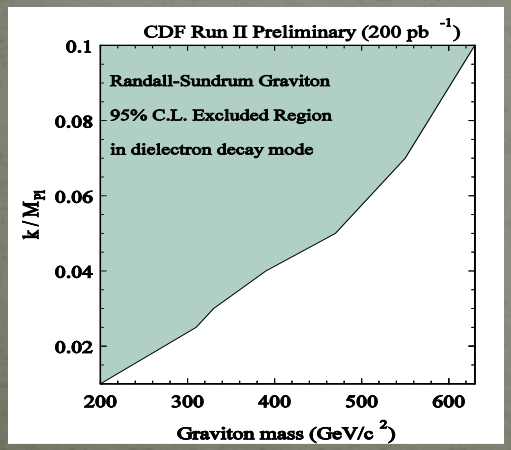


hard to visualize

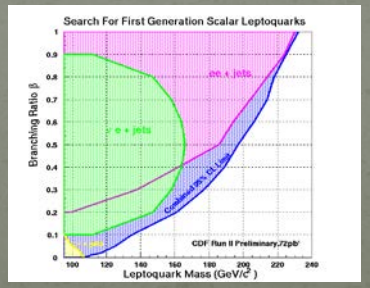
Warped Extra dimensions

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

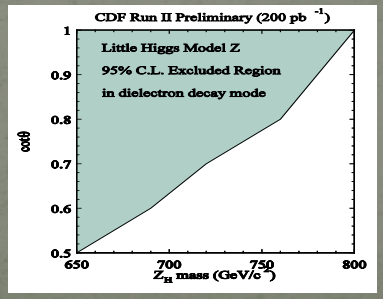
AdS/CFT correspondence



Leptoquarks



Little Higgs models



Can there be *just* a Higgs?

Yes.

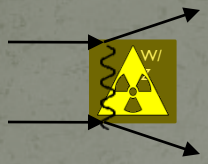
But we hope not.

Clues to new physics

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

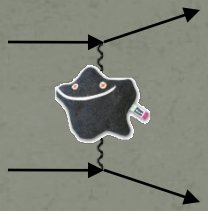
Quantum Gravity

Recall weak boson scattering grows with energy



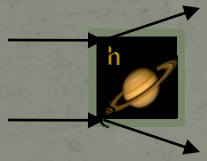
$$\sim \frac{E^4}{(1\,\mathrm{TeV})^4}$$

growth canceled by Higgs



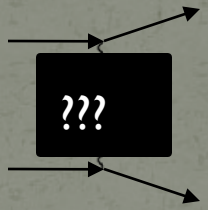
$$\sim \frac{-E^4}{(1\,\mathrm{TeV})^4}$$

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?

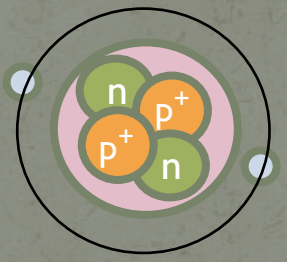
Particle physics in 1930

Three particles: proton p^+, electron e^-, photon

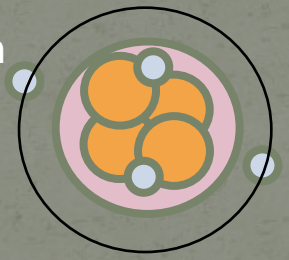
Two forces: Electromagnetism, gravity

Nuclei are made up of protons and electrons

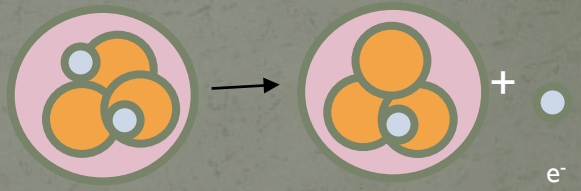
n = neutron



Heluim =



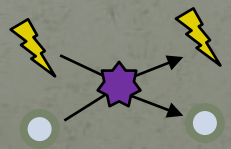
Simple explanation of β decay (Occam's razor)



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 e^+



- Klein-Nishina formula
  - explains details of Compton scattering (γe → γ e)
  - requires virtual positrons

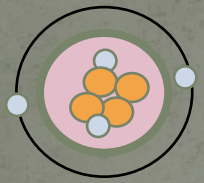
- Dirac (1930): Maybe proton is the positron!

$p^+ = e^+$

1930

Three problems

1. Nuclear spins and magnetic moments made no sense

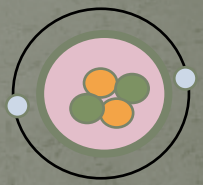


$$\mu_B = \frac{e}{2m}$$

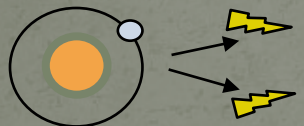
Bohr (1930)
Perhaps energy only conserved *on average*

n

neutron discovered (1932)



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



e^+

positron discovered (1932)

3. β decay spectrum continuous

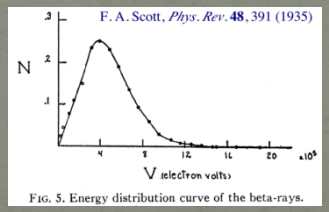
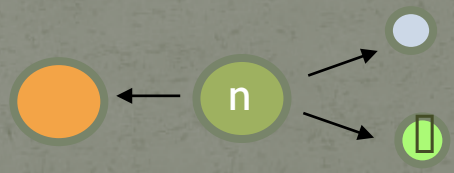


FIG. 5. Energy distribution curve of the beta-rays.



neutrino (theory 1930) (discovery 1956)

Three separate solutions

Needed EXPERIMENTS to find out

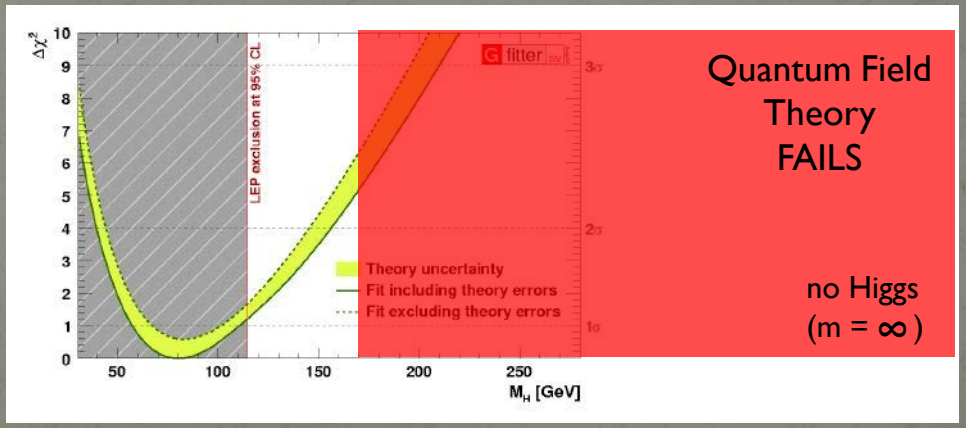
There is a lot we don't understand today

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

What will the LHC find?

- supersymmetry
- technicolor
- extra-dimensions
- …

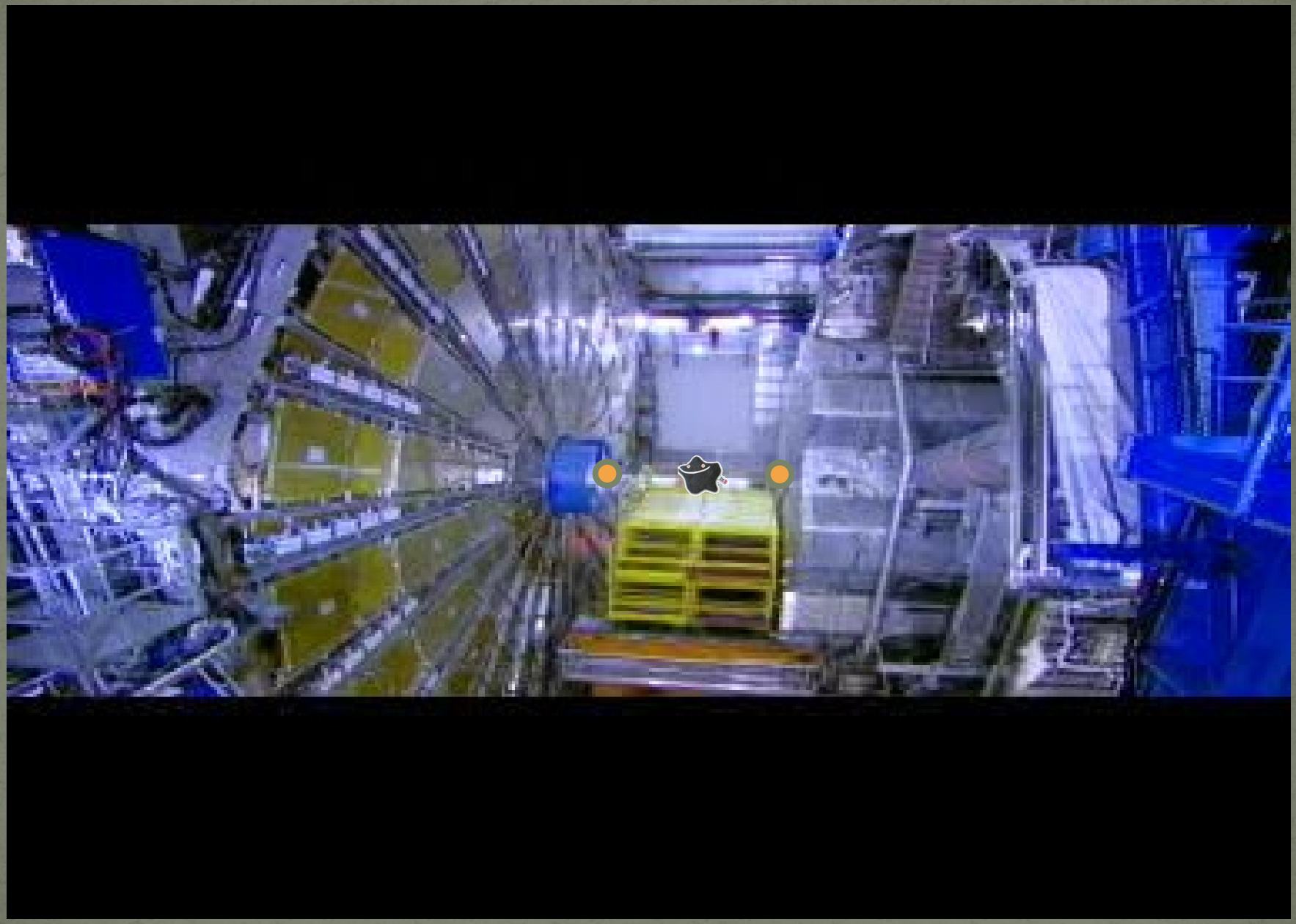
Will we need a new principle?



ATLAS

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

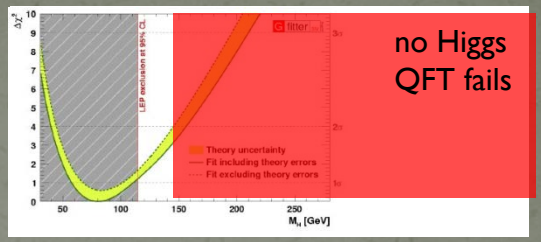
ATLAS



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

Conclusions

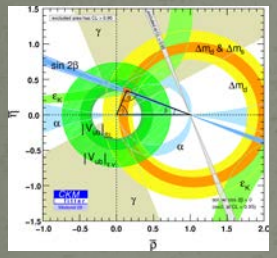
- The Higgs is missing

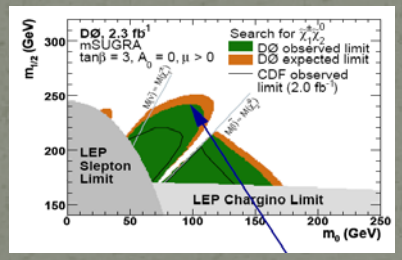


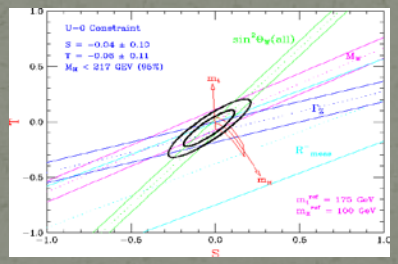
- Quantum field theory fails without a Higgs.
- The Higgs is weird

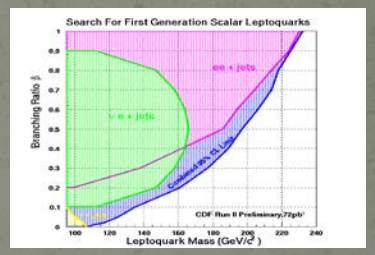
Higgs clumping
(Hierarchy problem)

- 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

Backup Slides

Origin of mass?

Why do people say the Higgs explains the origin of mass?

		mass	mass without Higgs
proton		938.3 MeV	800 MeV
neutron		938.3 MeV	800 MeV
electron		0.5 MeV	0.0 MeV

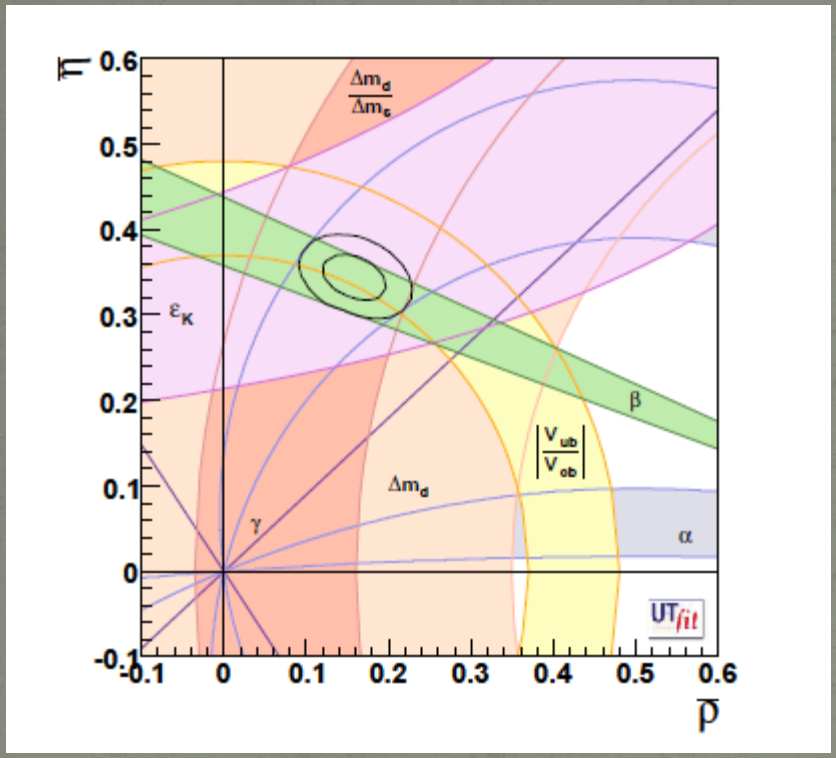
The Higgs is very important for mass, but it is not the *origin* of mass

God particle?

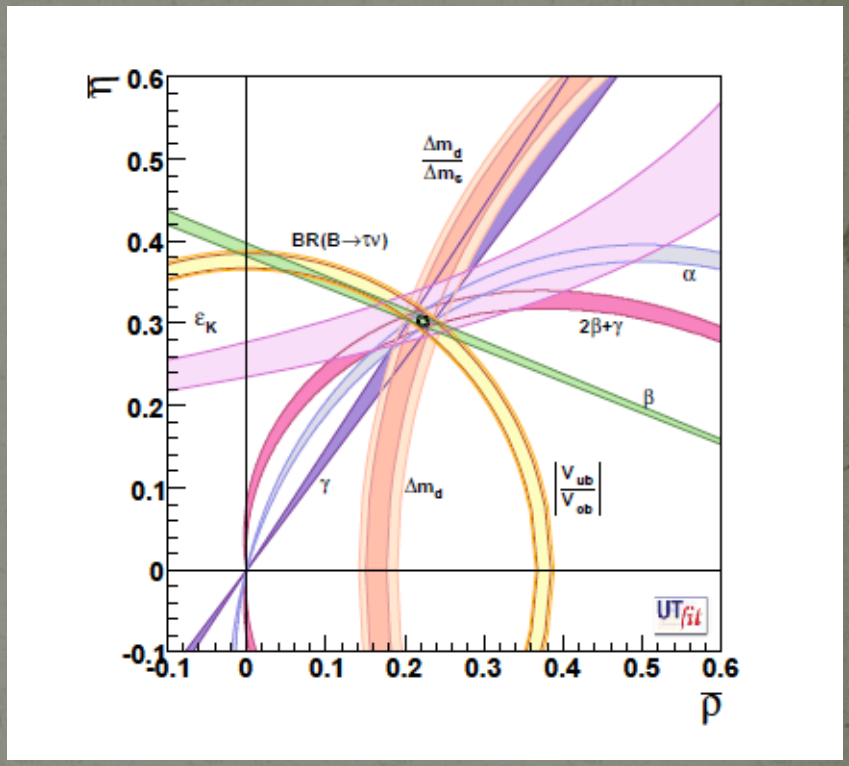
Give me a break!

Indirect Constraints

Current Constraints



Super B-factory potential
(under study)



Super B-factories will give very precise indirect measurements of new flavor physics – if there is any!

ATLAS

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