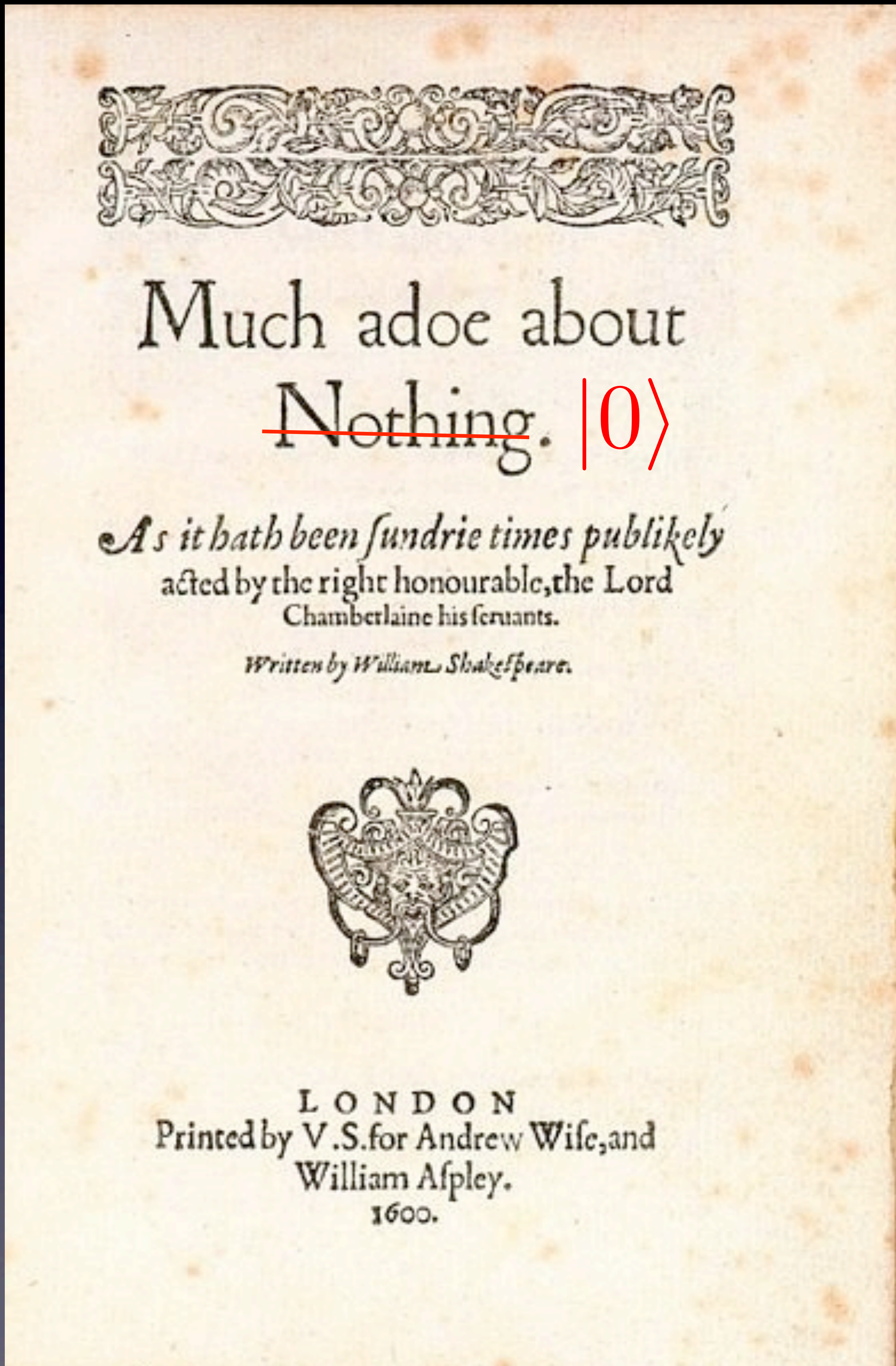

Much adoe about
~~Nothing~~. $|0\rangle$

As it hath been ſundrie times publikely
acted by the right honourable, the Lord
Chamberlaine his ſeruants.

Written by William Shakeſpeare.

LONDON
Printed by V.S. for Andrew Wiſe, and
William Aſpley.
1600.

A State of the Vacuum Address

S.U. Physics Colloquium

Jay Hubisz

10/4/2012

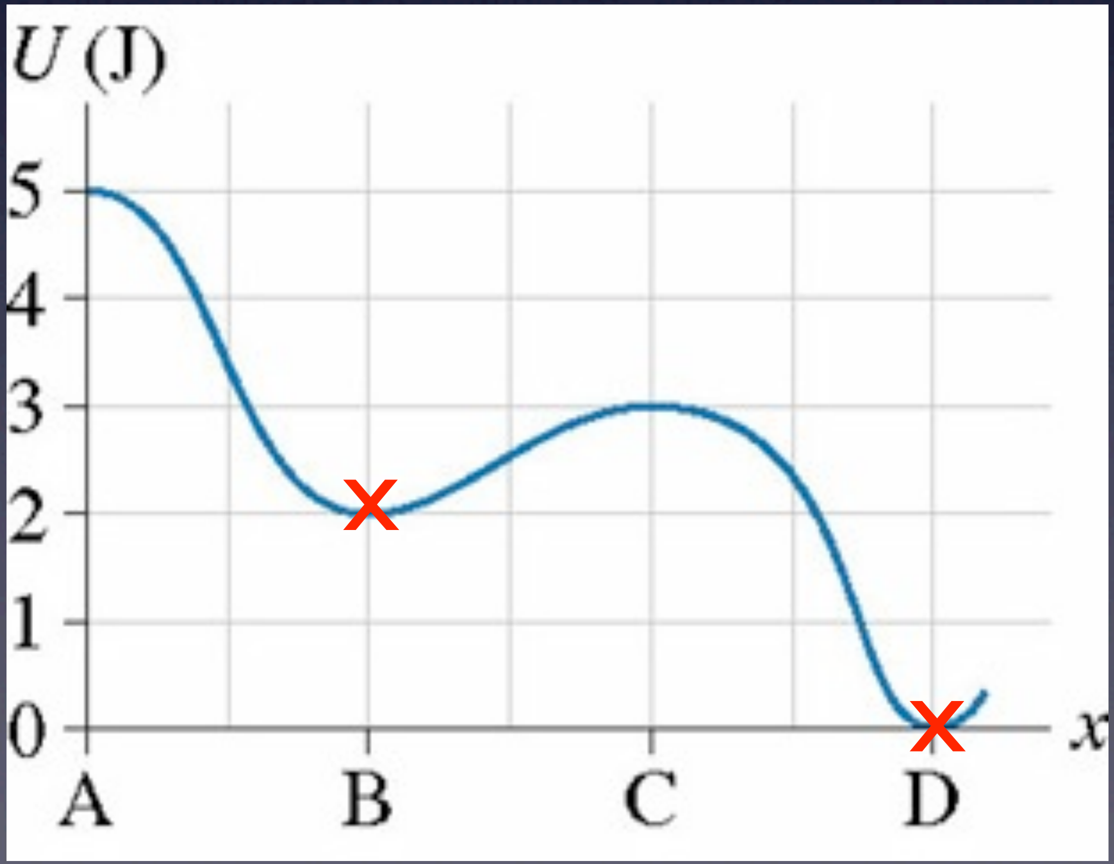
What is the vacuum?

SHO's

A system with a potential energy has a set of stationary points

Extrema of the potential

Near the minima, nearly all systems are simple harmonic oscillators
(which we know how to quantize)



SHO's

Generalizes to systems with many degrees of freedom

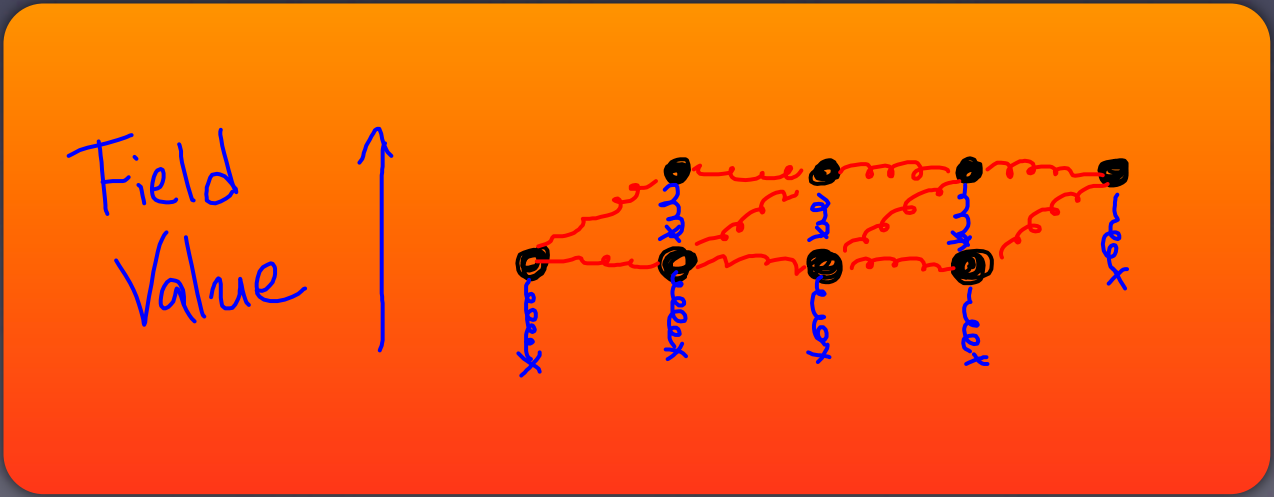
(string, gas, ...) infinite set of nearest neighbor coupled SHO's

Linear equations of motion for small perturbations

Particle physics is very well described by relativistic quantum field theory

Quantum field - an infinite set of coupled quantum SHO's

one for each point in space-time



Blue springs - global potential

Red springs - NN coupling

The Vacuum

There are many different quantum fields in the Standard Model

Many oscillators at each coordinate

The vacuum is the state in which every oscillator, at every spacetime point, is in its own ground state

(zero particle state - no wiggles of the fields)

We characterize this vacuum state by the field content and with a description of the equilibrium position of the fields

The Standard Model

Building a Field Theory

We start with the symmetries of space-time (Poincaré Invariance)

We only add fields that have well-defined behavior under these transformations

Simplest ones are:

Scalar fields → spin-0 particles ϕ

Spinor fields → spin-1/2 particles ψ^{α} α=1,2

massless LH and RH

- can join them to make 1 massive

Vector fields → spin-1 particles A^{μ} μ=0,4

We construct a Lagrangian that is invariant under Poincaré transformations

Quadratic in fields - linear equations of motion (SHO's)

The Standard Model Fermions

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

Their masses span an enormous range! ~12 OOM

Standard Model Bosons

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

These three are massive!
Their mass sets the distance at which the weak interaction 'turns off'

These are all spin-1 (vector fields)

(I'll get to the Higgs later)

Gauge Invariance & Mass

gauge invariance is a crucial ingredient

$$\langle A^\mu | A^\nu \rangle \propto g^{\mu\nu} = \mathrm{diag}(-1,1,1,1)$$

A^0 has negative norm!!

That's Bad!

$F^{\mu\nu} \sim \partial^\mu A^\nu - \partial^\nu A^\mu \rightarrow$ gauge invariant

(no time derivative on A^t)

no dynamics so not quantized!

That's Good!

Action *must* be gauge invariant quantity

conserved charges

Mass term: $m_A^2 A^\mu A_\mu$

Not gauge invariant - neg norm states creep in and wreck the theory

That's Bad!

Interactions

Our discussion pre-supposes that anharmonicities are small

In the lagrangian - terms that are cubic or higher in the fields

Euler-Lagrange equations become non-linear

If these are small, we can treat them with perturbation theory

electromagnetism: $eA_\mu \bar{\Psi}\gamma^\mu \Psi$

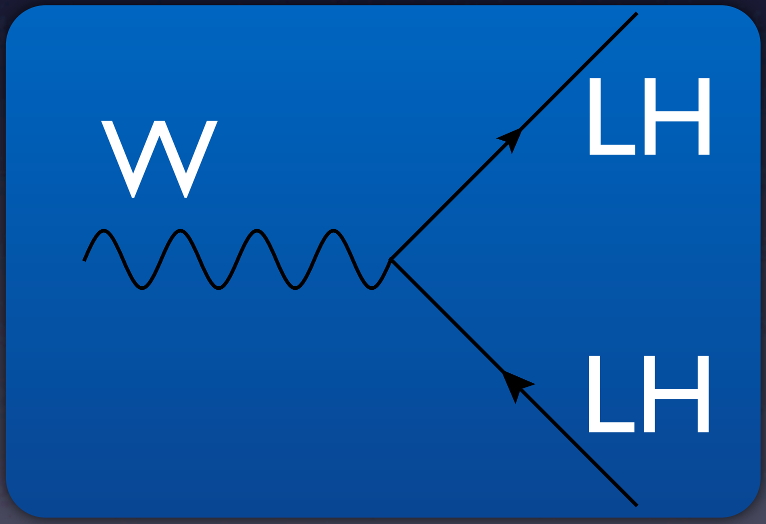
Gauge invariant - if fermion carries electric charge

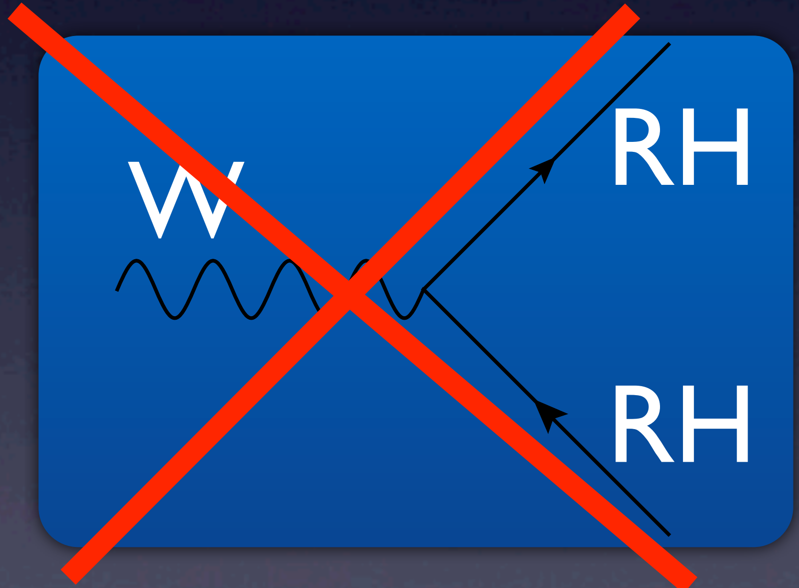
Charges

There are conserved charges for the weak and strong forces

some fermions carry these, some don't

As Lee and Yang postulated, and Wu showed to be the case experimentally, the weak interactions badly violate parity



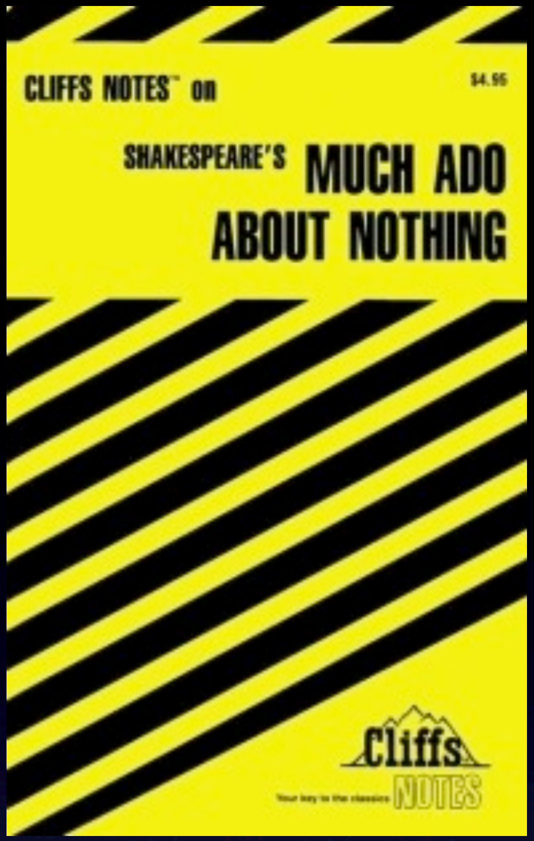


In SM - All LH spinor fields carry weak charge, RH fields do not

$q_L \neq 0$

fermion mass term: $m_f \psi_L \psi_R$ mass term violates charge conservation/G.I.

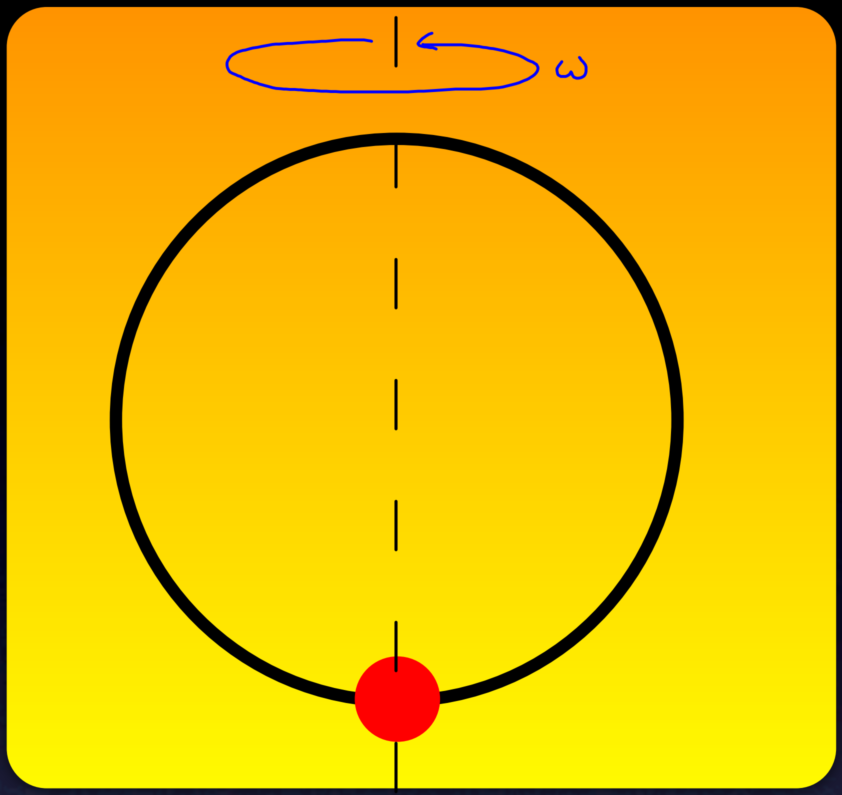
$q_R = 0$



Cliff's Notes

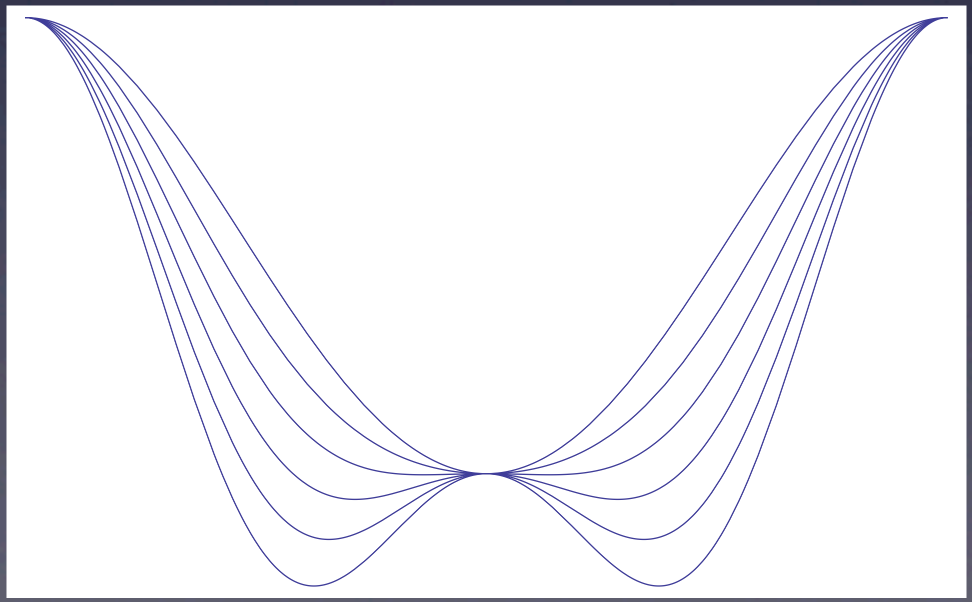
- Quantum field theory - infinite collection of QSHO's
- Vacuum - state in which all SHO's are in ground state
  - characterized by field content, stationary points in potential
- standard model fields spin-1 and spin-1/2
- gauge invariance required for successful quantization
  - forbids any mass terms!

James Watt's Governor



$$\ddot{\theta} = -\omega^2 \sin\theta \left(\frac{g}{\omega^2 R} - \cos\theta \right)$$ Sufficiently non-linear

As omega grows, one stable stationary point passes criticality - bifurcates into one unstable, two stable stationary points



"BROKEN" L-R SYMMETRY

The Higgs Field

In the SM, without a Higgs field, there are
NO MASS TERMS

Such mass terms violate the conservation laws for the charges associated with the electromagnetic and weak forces - gauge invariance broken

Scalar fields are different! - H can have charge AND mass

$$m^2 H^\dagger H \to m^2 H^\dagger e^{-i\alpha(x)} e^{i\alpha(x)} H = m^2 H^\dagger H$$

The Higgs *just has* a mass
it does not come from somewhere else
(at least not in the Standard Model)

The Higgs Potential

In fact, it has more than just a mass - it has a full potential

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

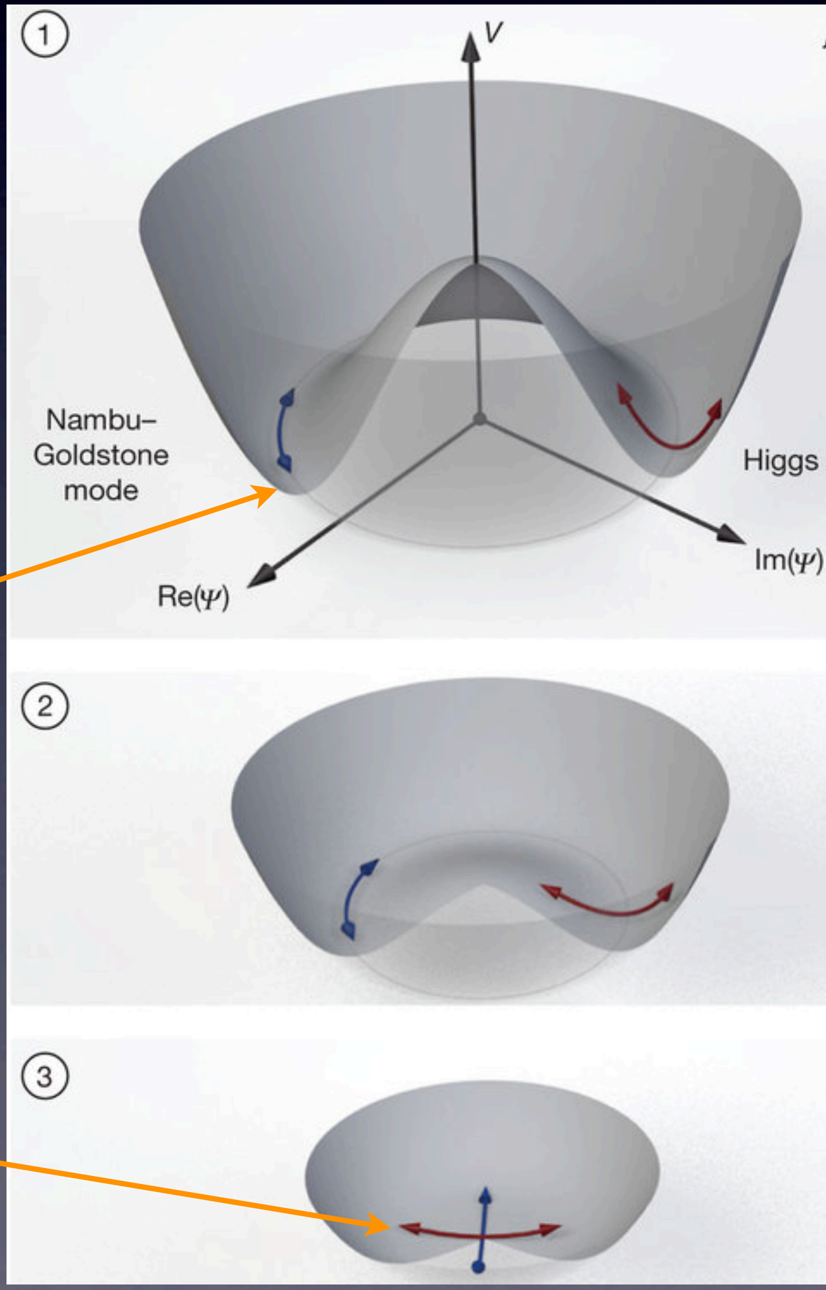
As you vary μ, you get very different behavior!

$\mu^2 > 0$, minimum away from H=0

$$|H|^2_{\mathrm{min}} = \frac{\mu^2}{2\lambda}$$

"vacuum expectation value"

$\mu^2 < 0$, minimum at H=0



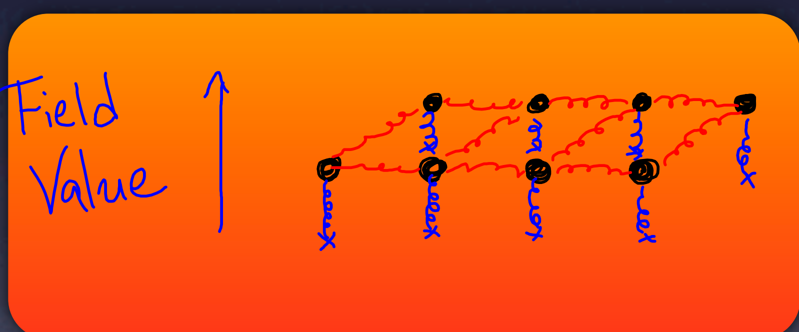
Degrees of freedom

H is a complex field - 2 fields inside it

(actually 4 in SM)

Good coordinates:

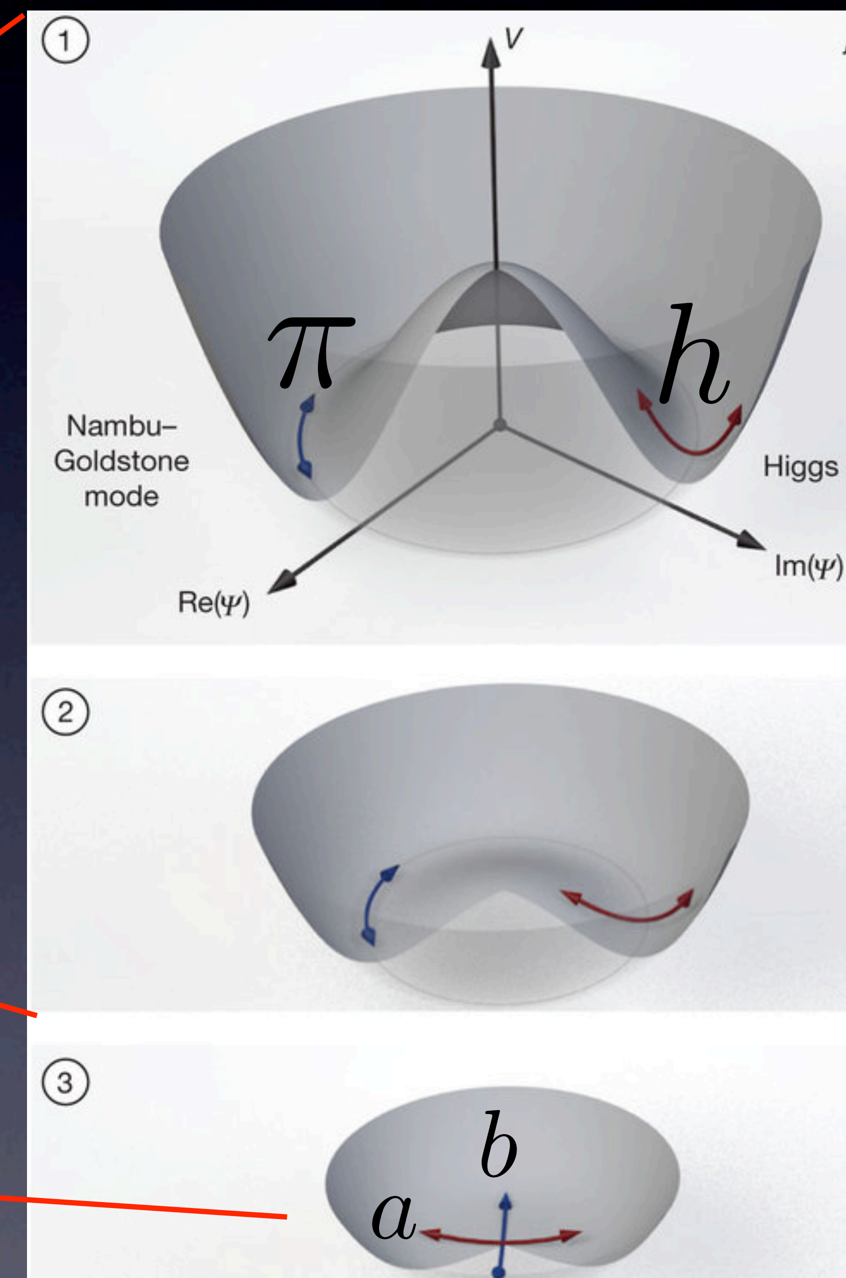
$$H = (v + h)e^{i\pi}$$



h has mass

π is massless

(3 of these in SM)



$$H = a + ib$$

a and b both massive - degenerate

Higgs interactions

Can add gauge invariant anharmonic terms with H

$$\lambda H \psi_L \psi_R \qquad q_H = -q_L; \quad q_R = 0$$

$$e^2 |H|^2 A_\mu A^\mu$$

When H finds its minimum, and everything is SHO's again:

$$\underbrace{\boxed{\lambda v \psi_L \psi_R}}_{\text{mass!}} + \lambda h \psi_L \psi_R + \pi \text{ stuff}$$

$$\underbrace{\boxed{e^2 v^2 A_\mu A^\mu}}_{\text{mass!}} + 2e^2 v h A_\mu A^\mu + e^2 h^2 A_\mu A^\mu + \pi \text{ stuff}$$

The gauge invariance is still there, manifest in the shift symmetry of π - this dof accounts for 3rd polarization

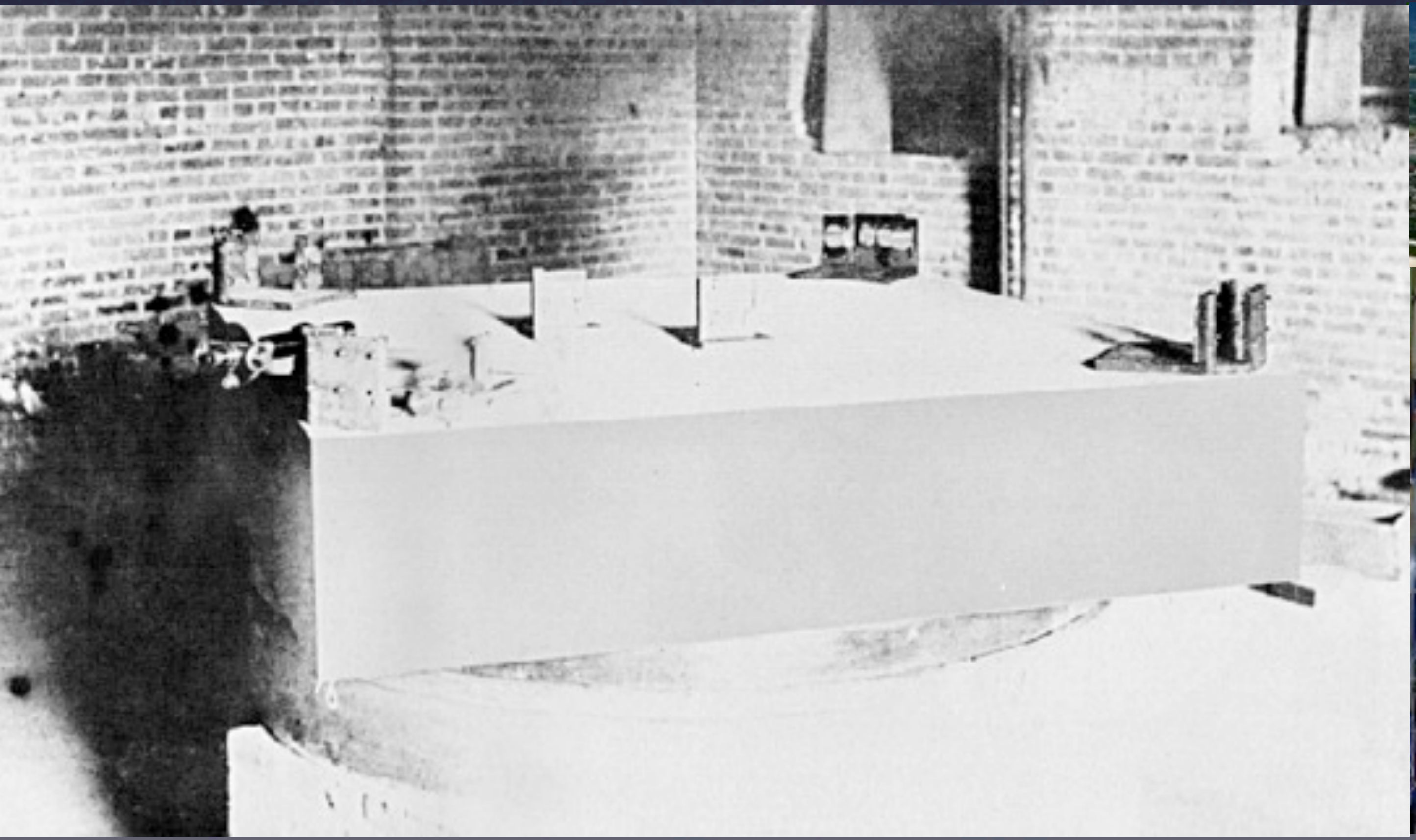
Ether 2.0

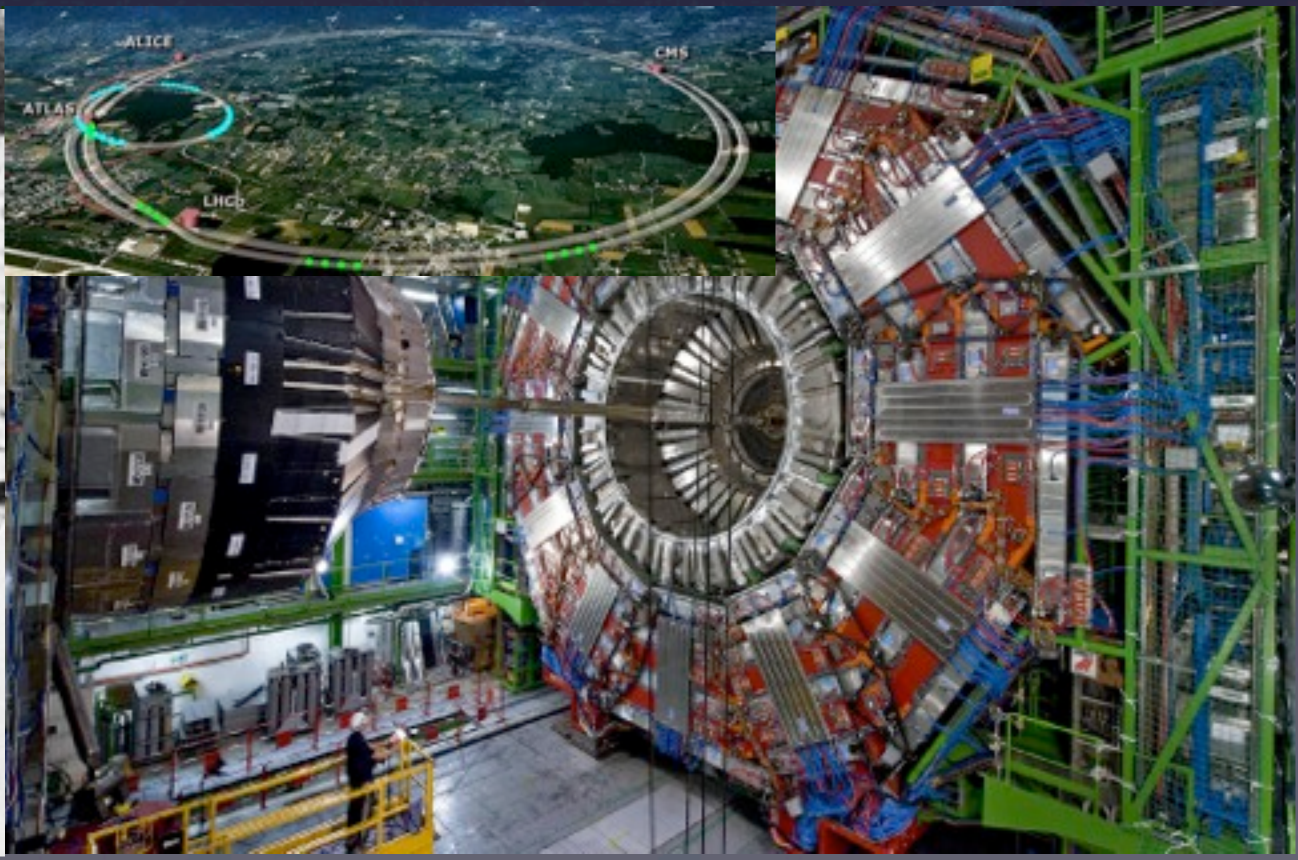
The stationary point for H is away from 0
the charge of the vacuum is non-vanishing!

Empty space-time is filled with charge
a form of *Poincaré invariant* ‘ether’

h constitutes wiggles of this ether

The LHC is in part a (massively) upgraded ether inspector





Higgs Low Energy Theorems

A Higgs field configuration with 0 momentum is constant in space and time

Just Like the Vacuum Expectation Value!

Everywhere you see a vacuum expectation value, there's an h

$$H = v\left(1+\frac{h}{v}\right)e^{i\pi}$$

For every particle mass, there is a v

$$m \to m\left(1+\frac{h}{v}\right)$$

The Higgs Interactions and Decays

Higgs to taus

$$m_\tau \bar{\tau}\tau \implies \frac{m_\tau}{v} h\bar{\tau}\tau \implies h \to \bar{\tau}\tau$$

Higgs to b's

$$m_b \bar{b}b \implies \frac{m_b}{v} h\bar{b}b \implies h \to \bar{b}b$$

Higgs to Z's

$$m_Z^2 Z_\mu Z^\mu \implies 2\frac{m_Z^2}{v} hZ_\mu Z^\mu \implies h \to Z^* Z \to 2l^+ 2l^-$$

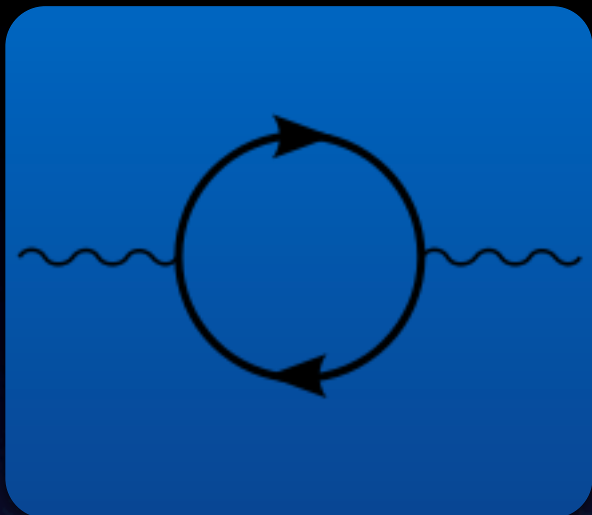
Higgs to W's

$$m_W^2 W_\mu^+ W^{-\mu} \implies 2\frac{m_W^2}{v} hW_\mu^+ W^{-\mu} \implies h \to W^+ W^- \to l^+ \nu l^- \nu$$

The last 2, run in reverse, are important for Higgs production

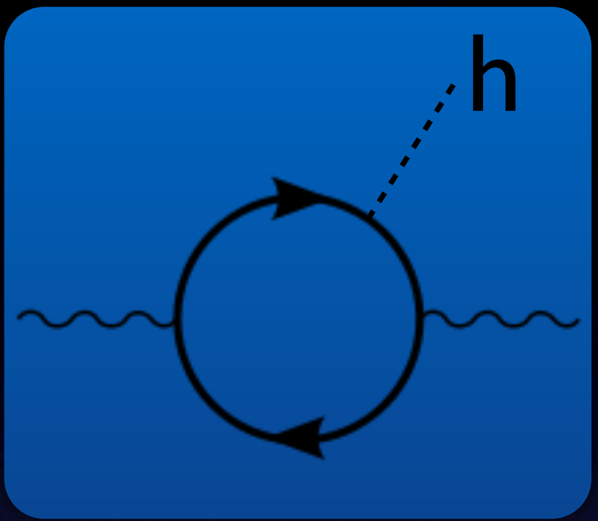
2 Other crucial ones

As you probably have heard, coupling constants 'run' with energy



$$\alpha^{-1}(\mu = 0) \approx 137$$

$$\alpha^{-1}(\mu = M_Z) \approx 128$$



Here's the equation:

$$\alpha^{-1}(\mu) = \alpha^{-1}(\Lambda) + \sum_{\text{heavy}} \frac{b_{\text{heavy}}}{8\pi} \log \frac{\Lambda}{m_i} + \sum_{\text{light}} \frac{b_{\text{light}}}{8\pi} \log \frac{\Lambda}{\mu}$$

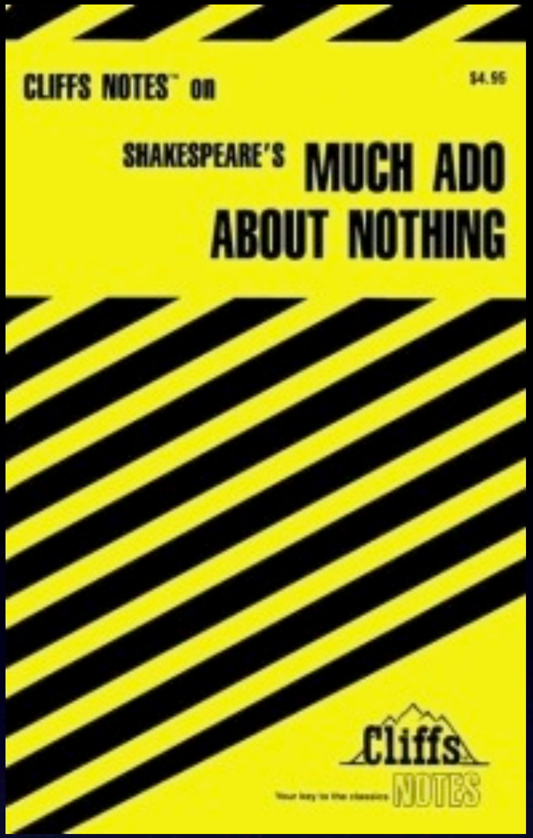
very high scale

There are v's here!

$$(4\pi\alpha)^{-1} F_{\mu\nu}F^{\mu\nu} \implies \frac{\sum b_{\text{heavy}}}{8\pi} \frac{h}{v} F_{\mu\nu}F^{\mu\nu} \implies h \to \gamma\gamma$$

$$(4\pi\alpha_s)^{-1} G_{\mu\nu}G^{\mu\nu} \implies \frac{\sum b_{\text{heavy}}}{8\pi} \frac{h}{v} G_{\mu\nu}G^{\mu\nu} \implies gg \to h$$

Last is crucial for h production

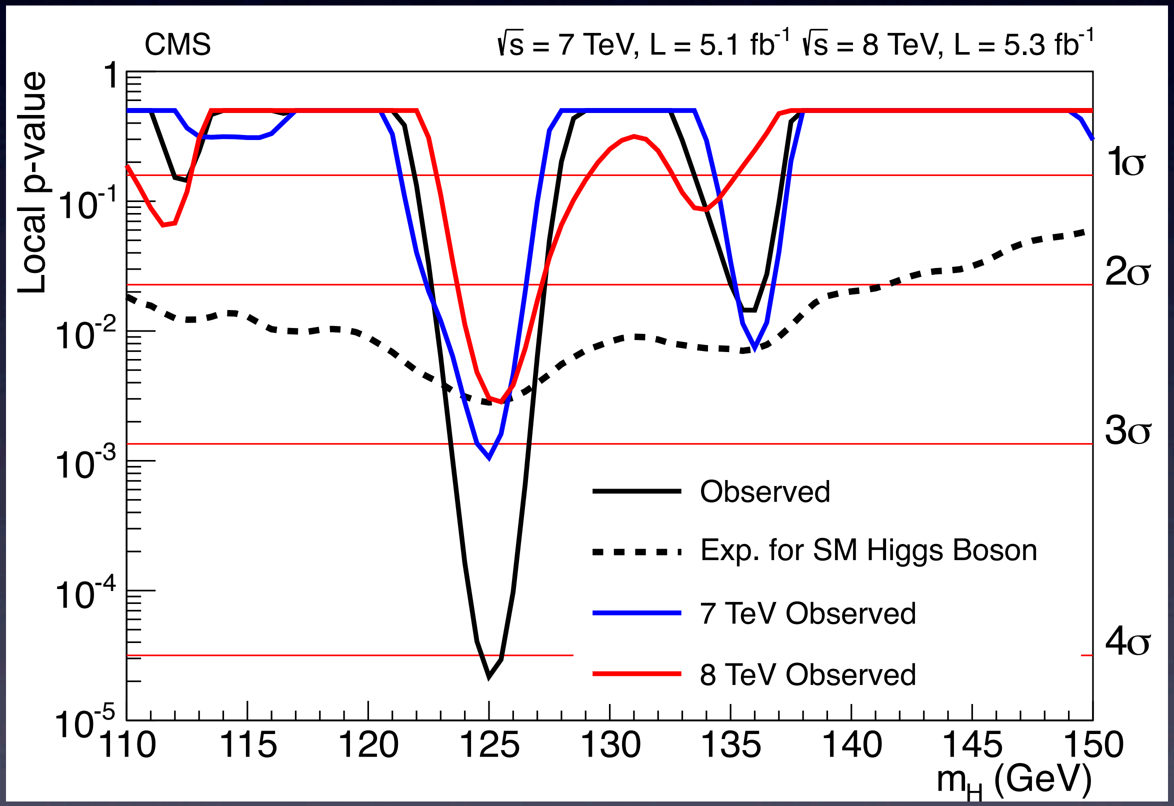


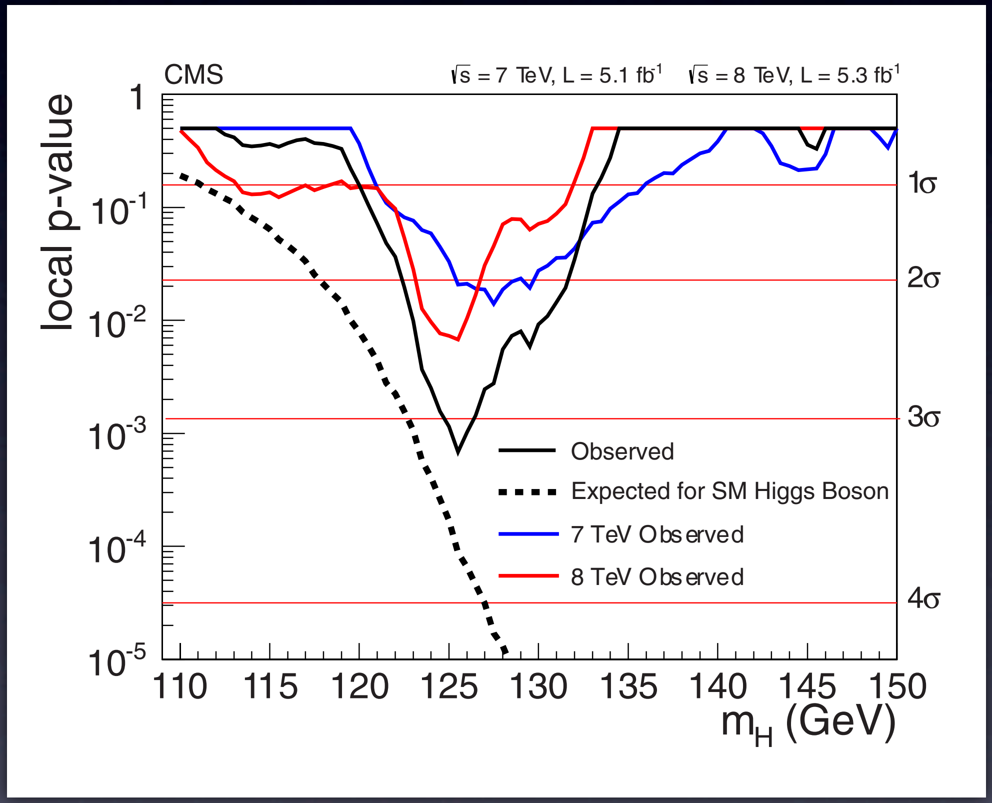
Cliff’s Notes

- The Higgs mechanism is a gauge invariant method of generating masses for standard model fields
- It predicts a Higgs particle - wiggles in the ether
- It is extremely predictive, once you measure the masses

One More Boson!

CMS Higgs Discovery at ~125 GeV



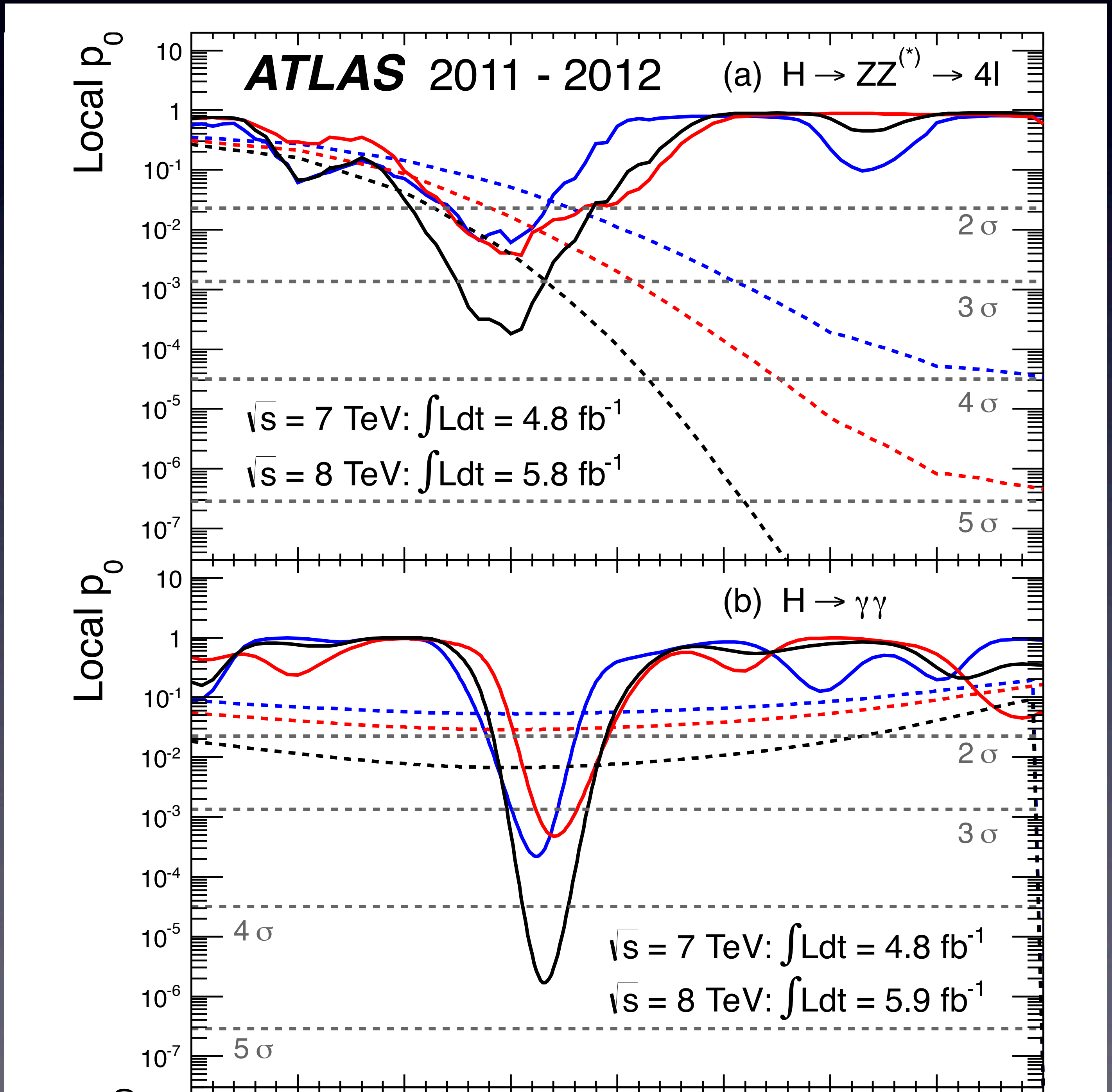


$h \to \gamma\gamma$ $\quad$ $h \to ZZ^* \to 2l^+2l^-$

These are high resolution channels - low resolution push it beyond 5 sigma

One More Boson!

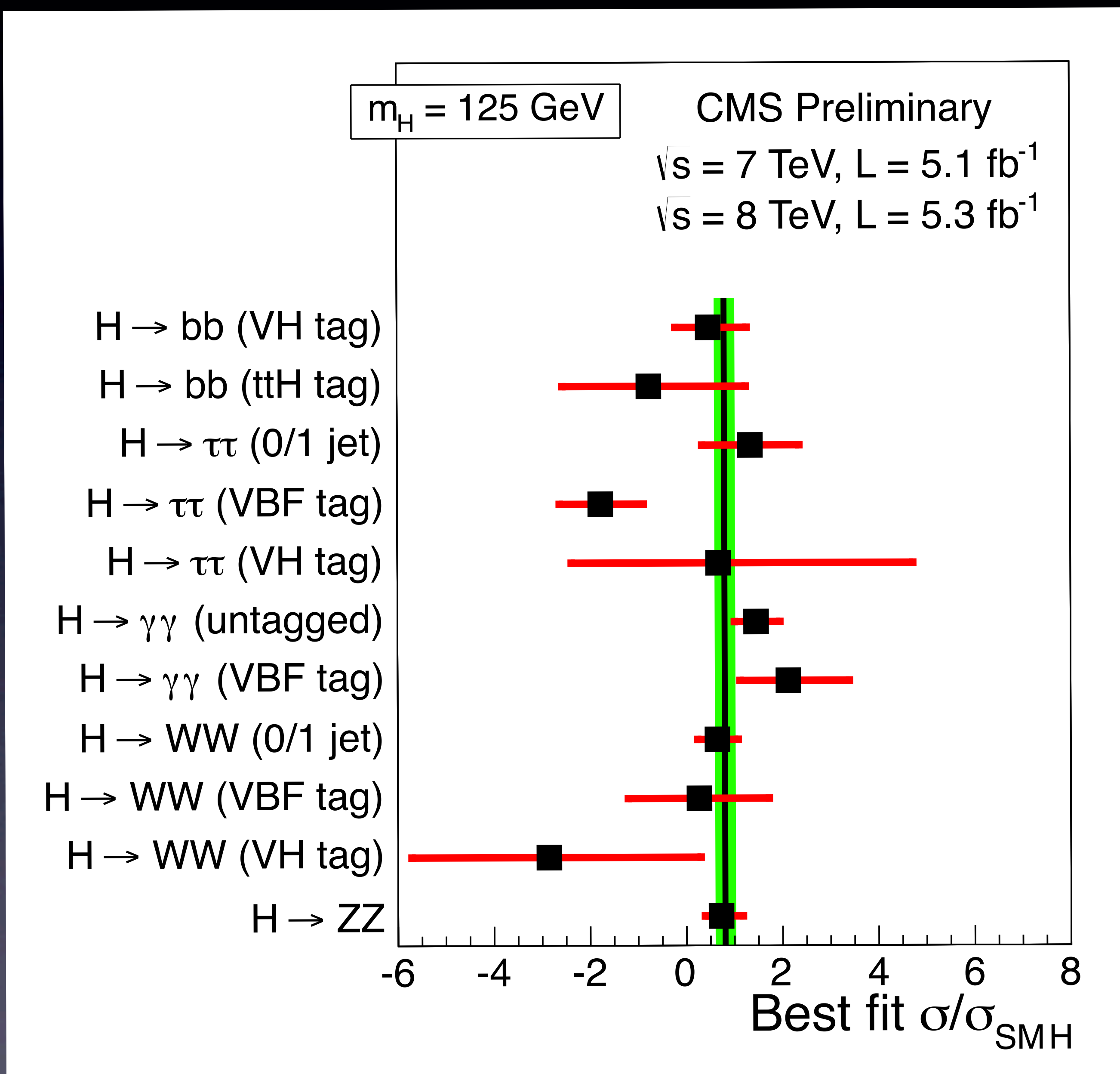
ATLAS Higgs Discovery

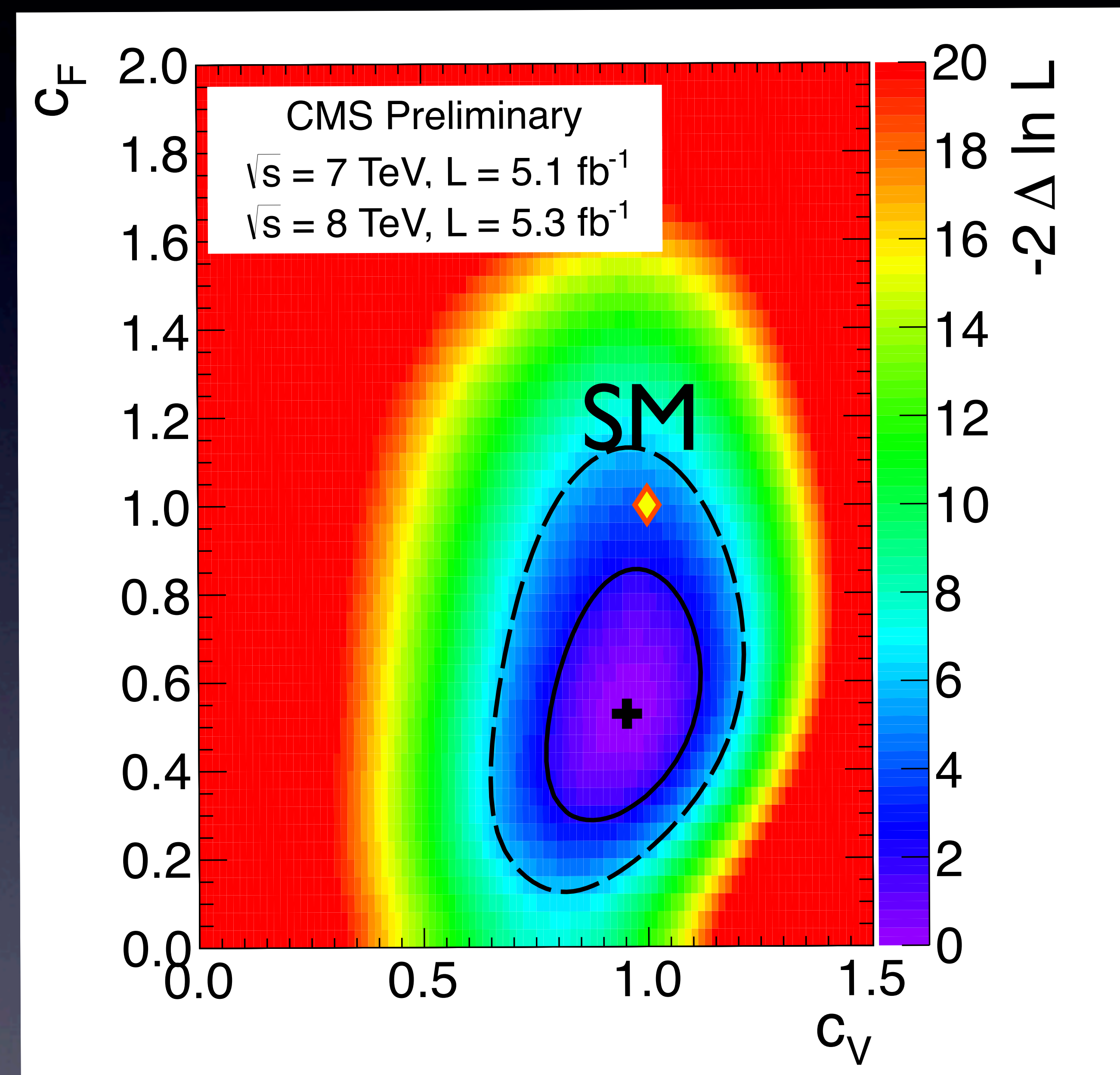


$$h \to ZZ^* \to 2l^+2l^-$$

$$h \to \gamma\gamma$$

Higgs fit - CMS

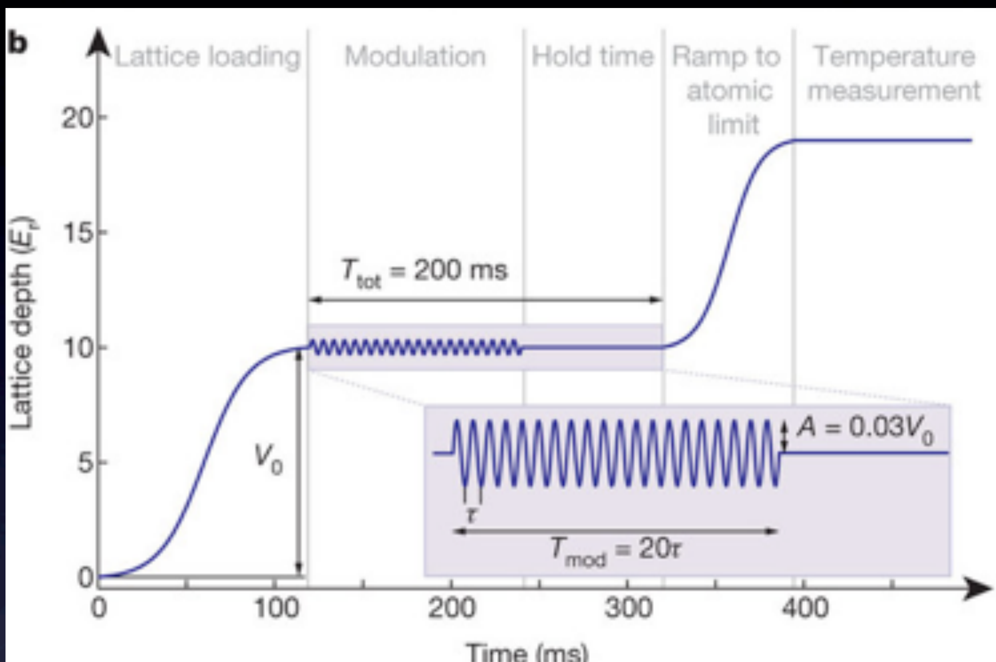


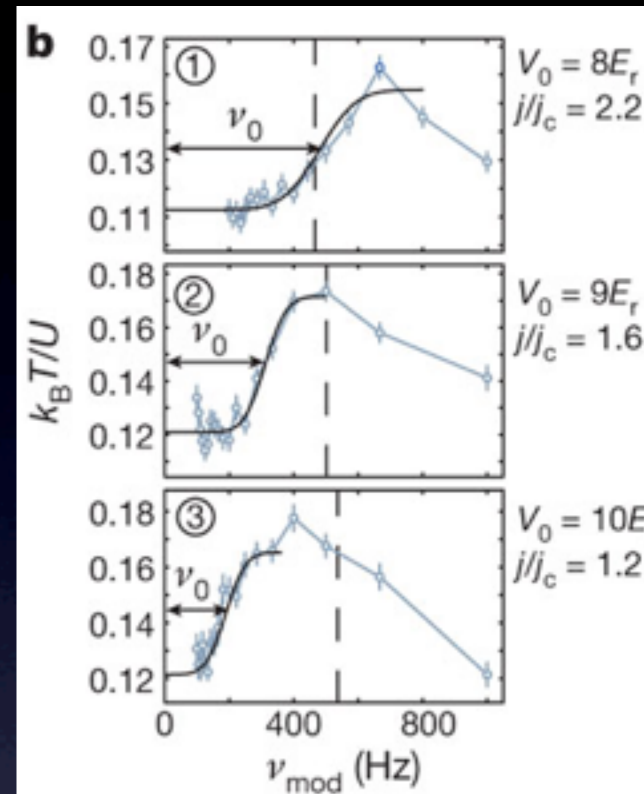


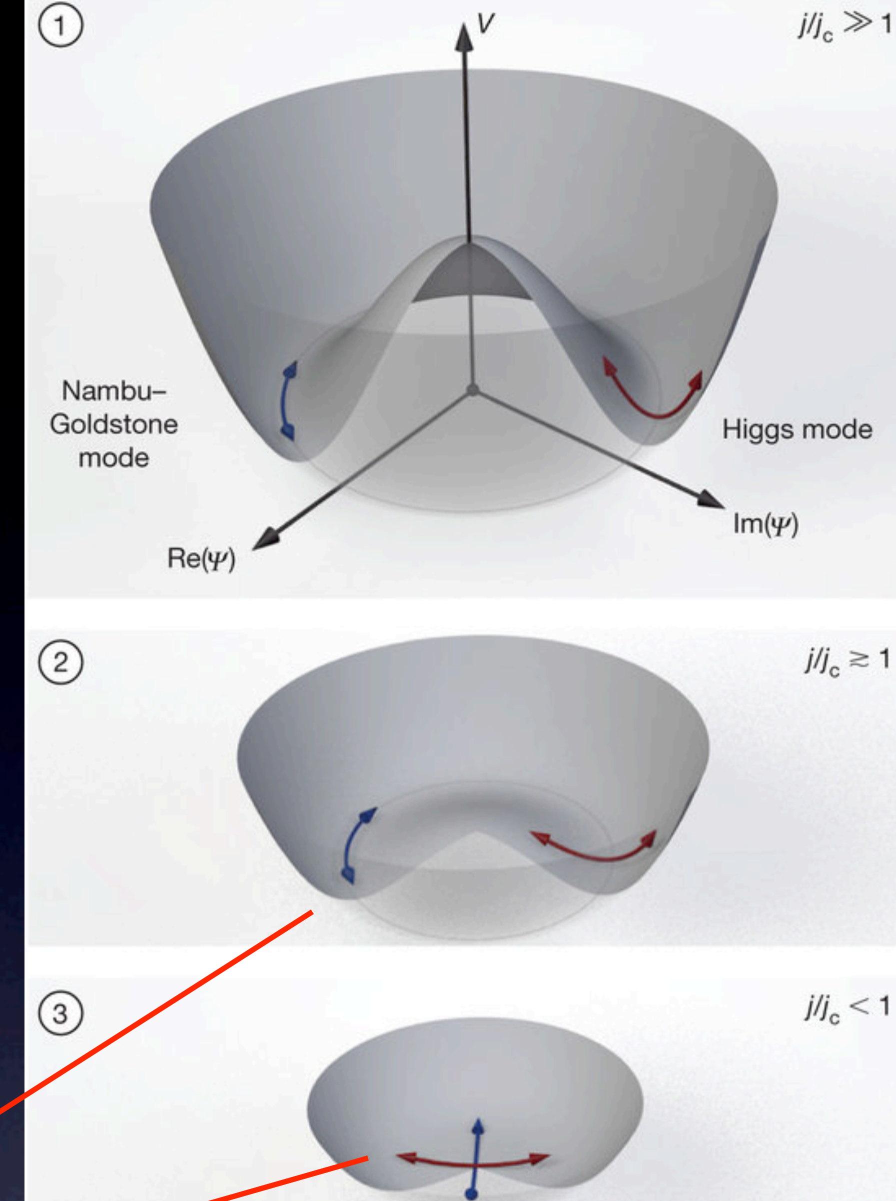
The Particle you love to hate

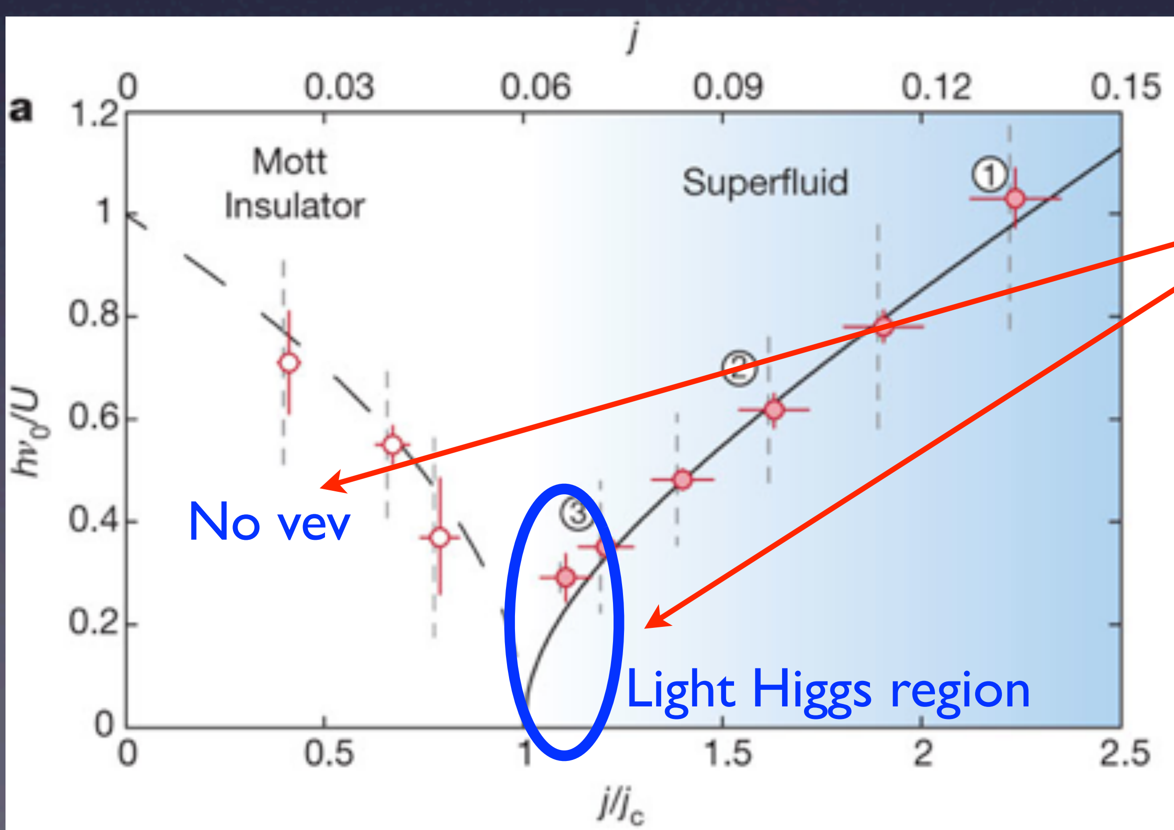
Fine Tuning

In Condensed matter, you get to play "God":









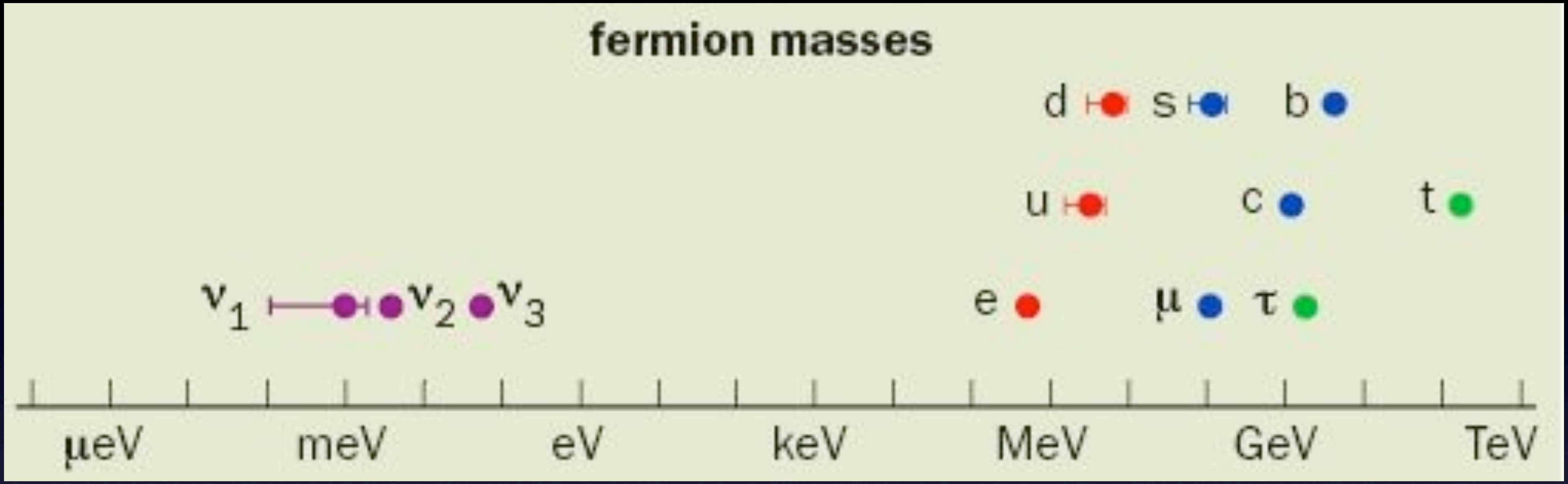
In particle physics:

$$\frac{j}{j_c} - 1 \sim 10^{-32} \sim \left(\frac{M_{\rm weak}}{M_{\rm planck}}\right)^2$$

Masses would generically be of order $M_{\rm Planck}$ or $M_{\rm GUT}$

Nature **487**, 454–458 (26 July 2012)

Fermion masses



These come from the Higgs

$$\sum \lambda_{ij} H \psi_L^i \psi_R^j$$

When you diagonalize this matrix to get nice uncoupled SHO's again, you get vast spectrum of eigenvalues

Neutrinos are special

$$\sum \frac{1}{\Lambda} \lambda_{ij} \nu_i^T H i\tau 2 H \nu_j$$

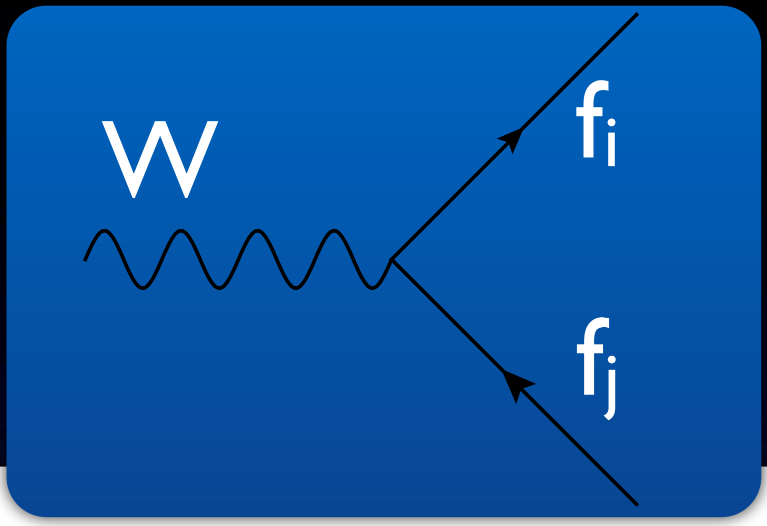
very small #'s

or

very high scale

Flavor

When you diagonalize the masses, you undiagonalize the interactions



e.g. top-bottom, top-strange, top-down

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347^{+0.00016}_{-0.00012} \\ 0.2252 \pm 0.0007 & 0.97345^{+0.00015}_{-0.00016} & 0.0410^{+0.0011}_{-0.0007} \\ 0.00862^{+0.00026}_{-0.00020} & 0.0403^{+0.0011}_{-0.0007} & 0.999152^{+0.000030}_{-0.000045} \end{pmatrix}$$

$J = (2.91^{+0.19}_{-0.11}) \times 10^{-5}$ - weak CP violation

This is close to the identity, and very hierarchical

off-diagonals quantify amount of flavor changing in weak interactions

weak charge and masses almost simultaneously diagonalizable...why?

Strong CP Problem

QCD generically violates CP

neutron electric dipole moment - sensitive to both strong and weak CP violating phases

$$\mathcal{L}_{\rm CP} = \theta G \cdot \tilde{G}$$

$\bar{\theta} = \theta - \arg\det M_q$ This part is from the Higgs!

must be < 10^{-11}!

The 'best' solution so far - Peccei Quinn Axion

$V_{\rm axion}$ minimized when strong CP violation vanishes

only QCD can contribute...another tuning!

Cosmological Constant

$\Lambda_{cc} \simeq (10^{-12}\ \text{GeV})^4$

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

$$\langle H \rangle^2 = \frac{\mu^2}{2\lambda}$$ from minimization

$$V(\langle H \rangle) = V_0 - \frac{\mu^4}{4\lambda} \simeq (10^2\ \text{GeV})^4$$

55 orders of magnitude!!??

There are also a bunch of quantum contributions that seem to greatly exacerbate the problem

also other contributions of similar style

What does the Higgs not do?

- It doesn't give masses of order M_{Planck}
  - It should
- It doesn't give huge contribution to E_{vacuum}
  - It should
- It doesn't give huge contribution to strong CP violation
  - It should
- It doesn't give generically large flavor changing couplings
  - It should

It's getting to be a bit much

I can hold up the cup
And the milk and the cake!
I can hold up these books! And the fish on a rake!
I can hold the toy ship! And a little toy man!
And look! With my tail I can hold a red fan!
I can fan with the fan As I hop on the ball!
But that is not all. Oh, no. That is not all....

Add to this:

- It doesn't explain dark matter
- More ingredients are necessary for neutrino masses
- Not enough CP violation for baryon assymetry

Is it *THE* Higgs?

Don Pedro: ... I think this is your daughter.
Leonato: Her mother hath many times told me so.
Benedick: Were you in doubt, sir, that you ask'd her?

What is the 'parentage' of the Higgs particle?

Have we tested all the ways that the ether wiggles?

Supersymmetry

Higgs comes with opposite spin partners

Composite Higgs

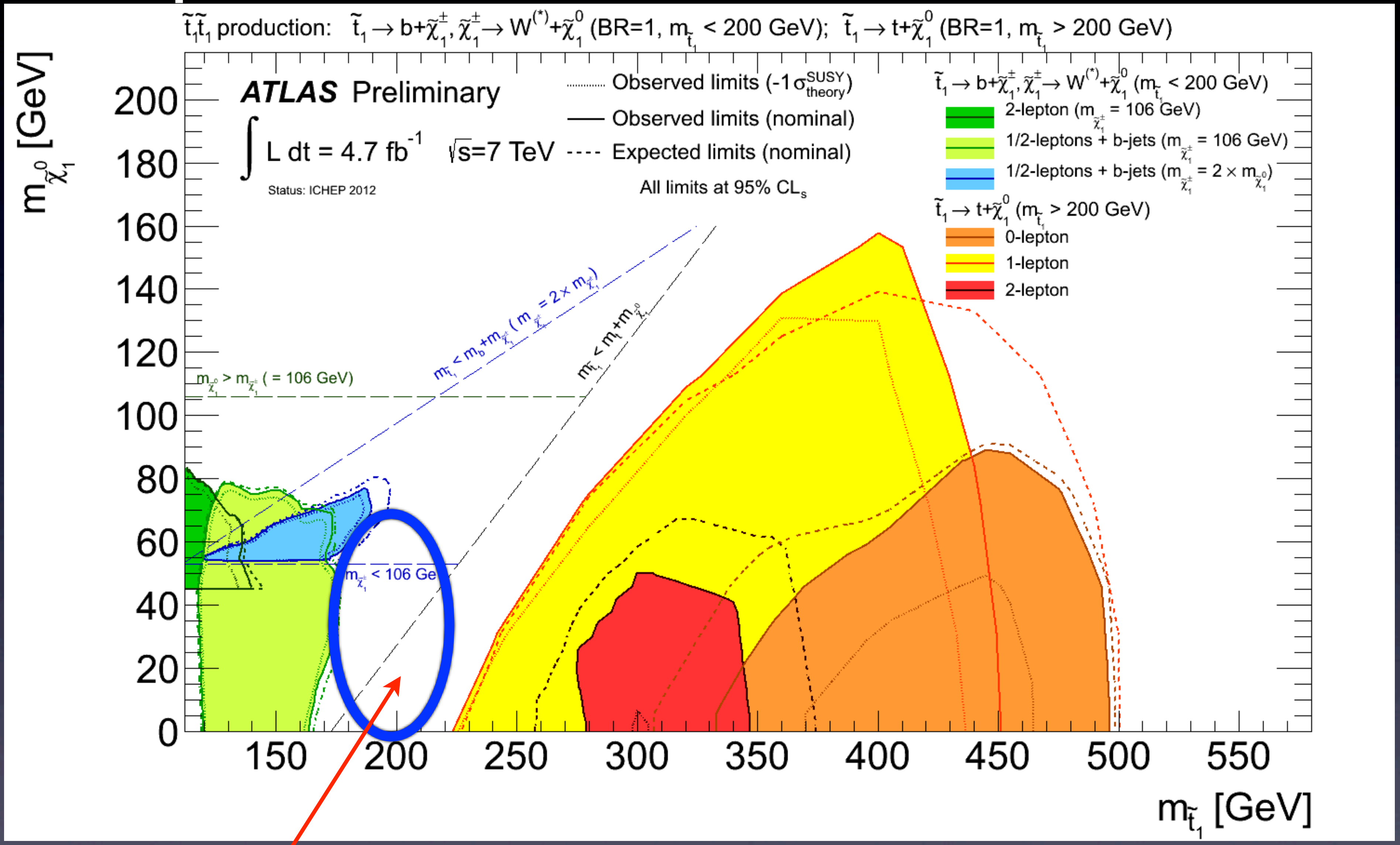
Higgs is a collective excitation dissolves near 1-10 TeV

Combination of both?

Status of SUSY

Supersymmetry softens quantum corrections to Higgs

Stops are crucial for SUSY naturalness

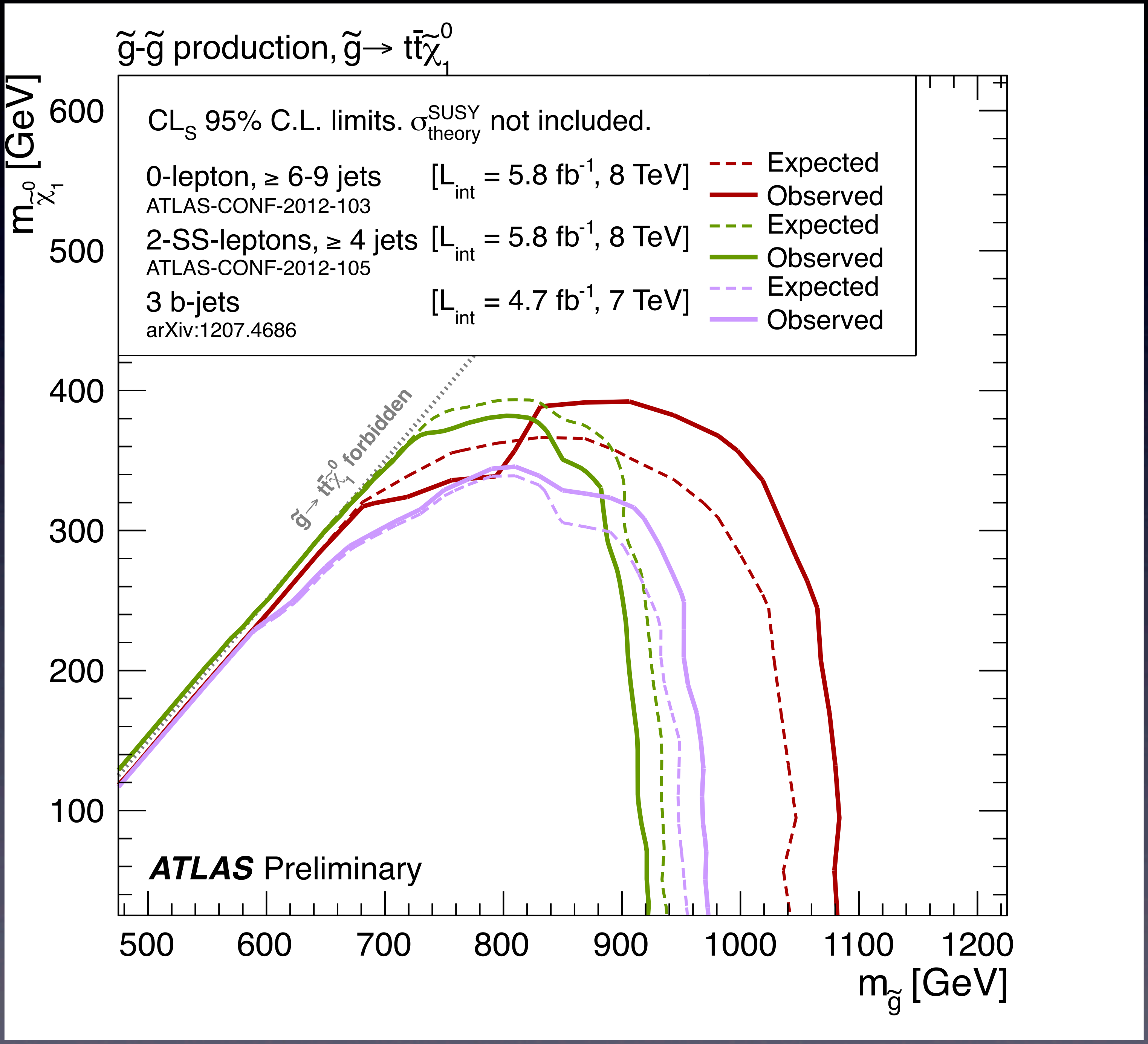


This allowed region is great for naturalness: stop quasi-degenerate with top "stealthy stop"

Is there a mechanism of getting this automatically?

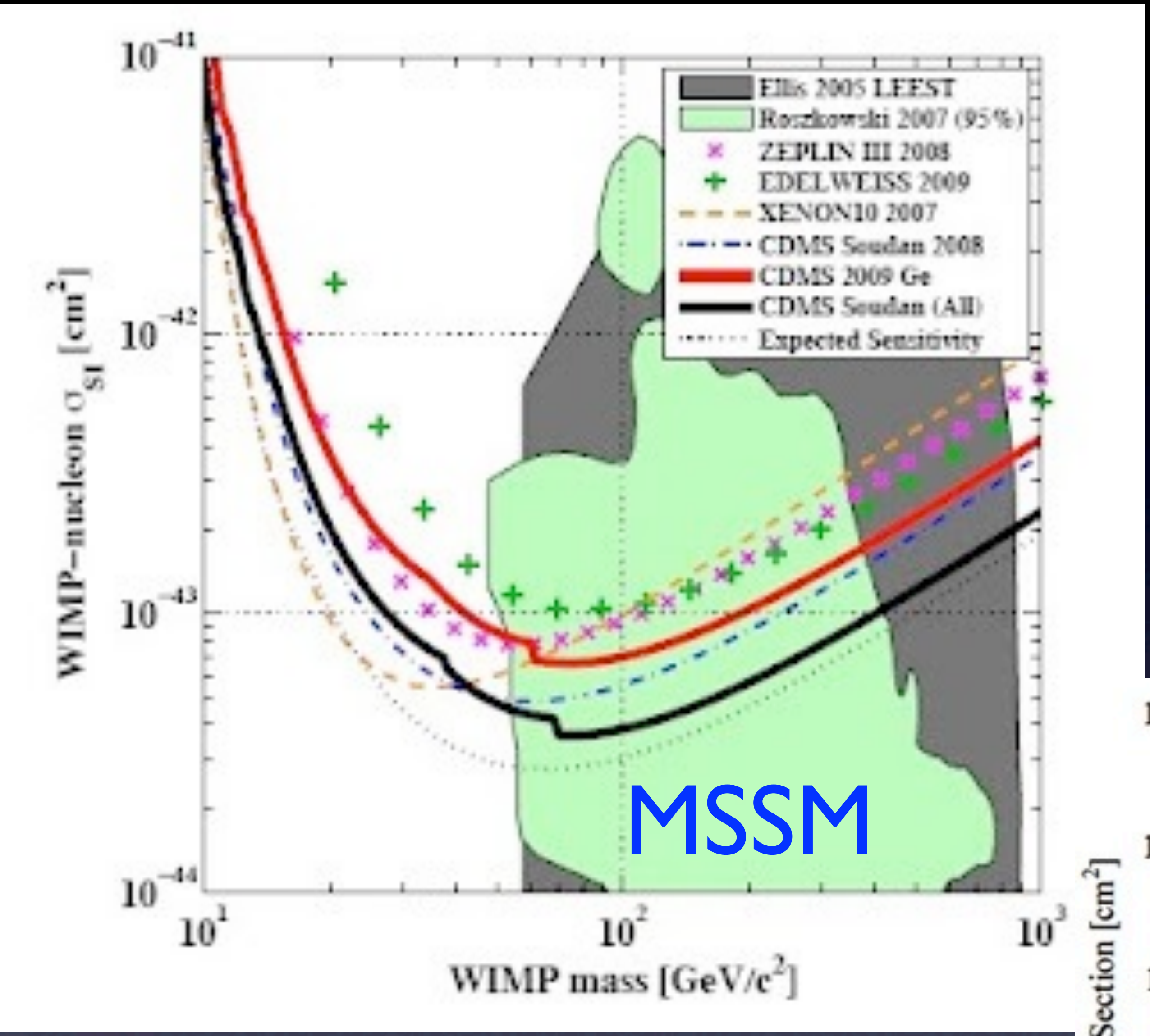
Status of SUSY

Even the gluino can't be too heavy (~2-3 TeV)



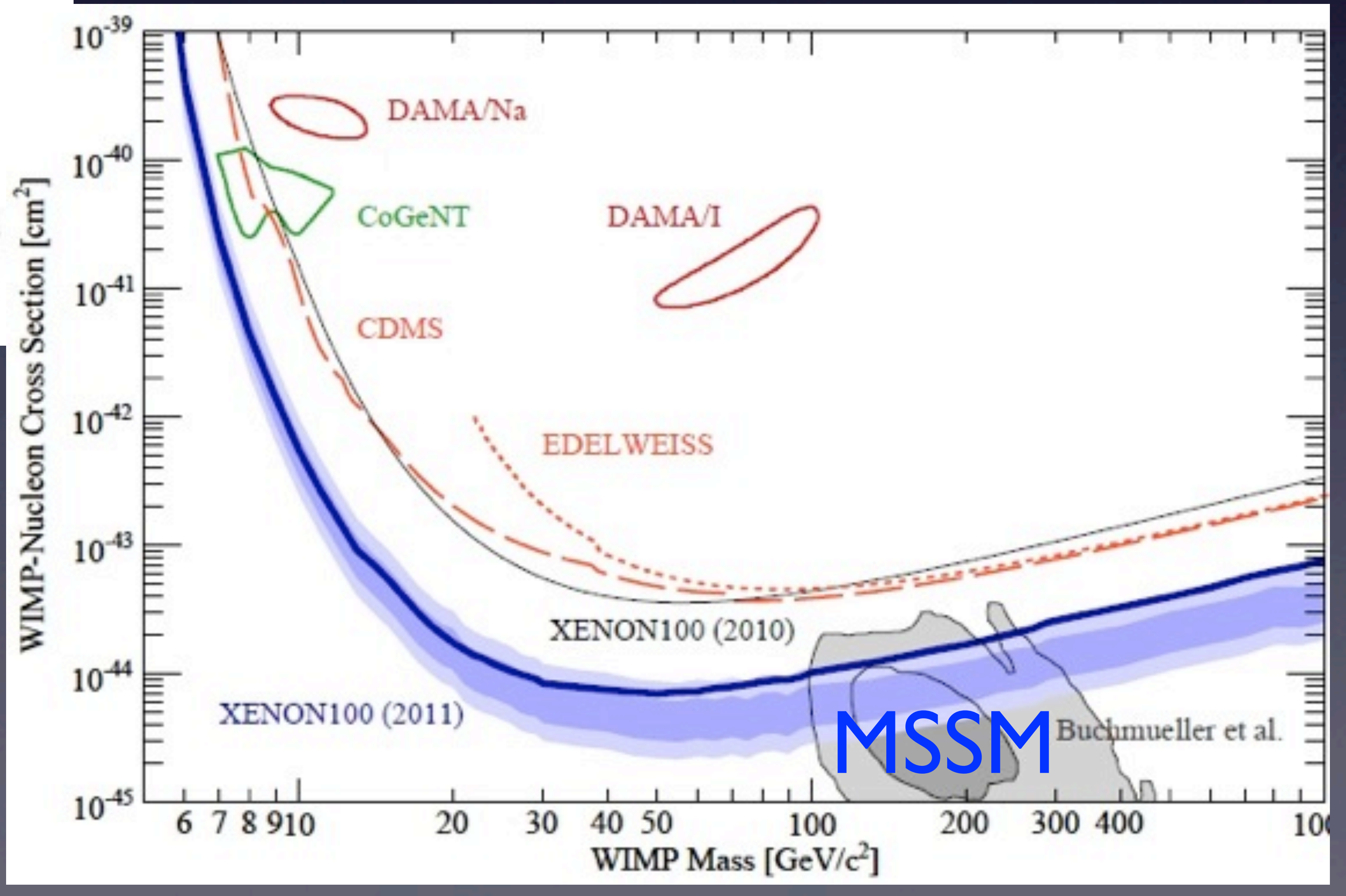
Tuning from high order quantum corrections

Status of SUSY Dark Matter



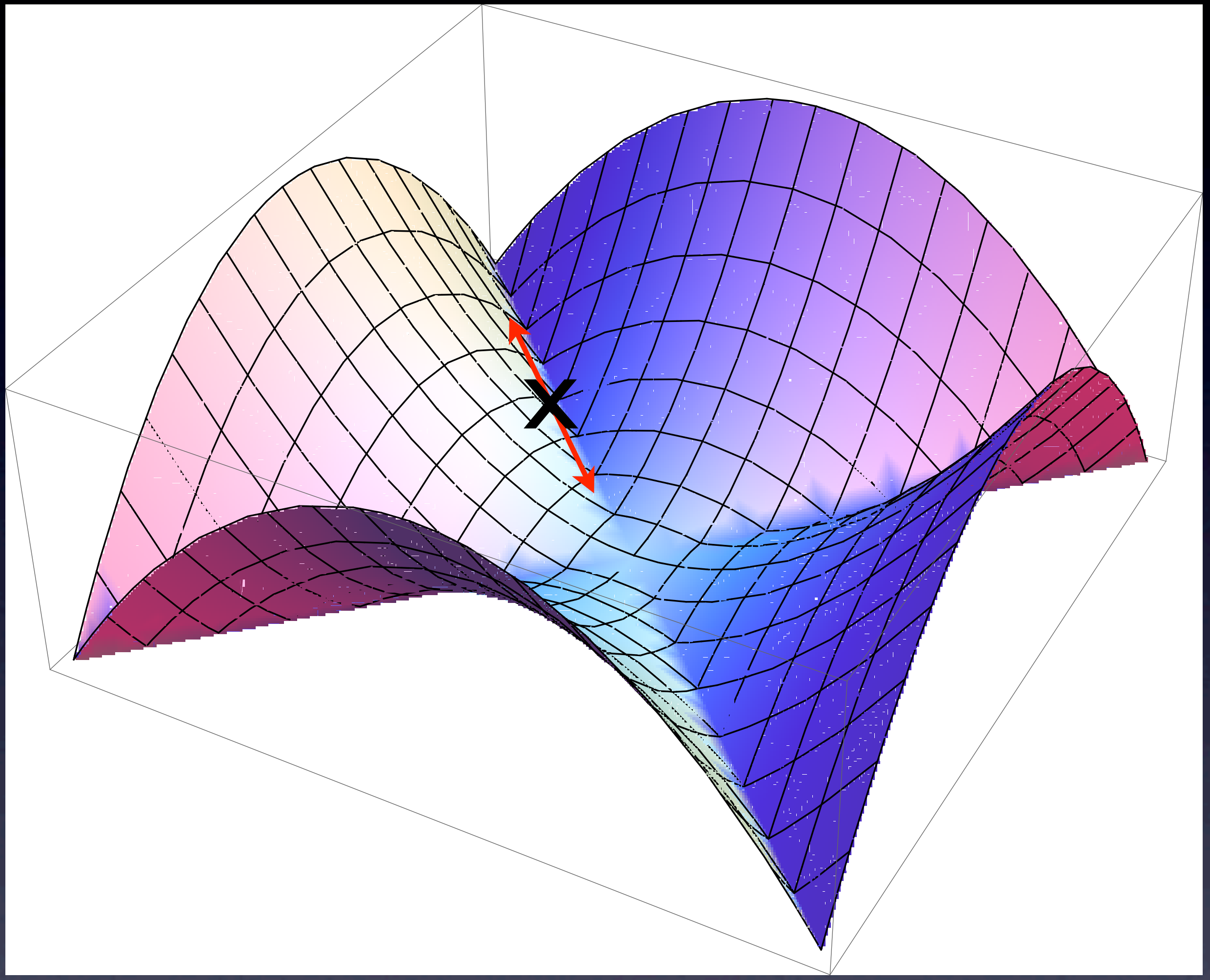
Note the everchanging SUSY blob

Tuning required to evade direct detection



Another kind of potential

Beside solving the hierarchy problem, SUSY also provides some other very interesting features



Directions in field space along which V = 0

No dynamics to set the vevs, could be anywhere

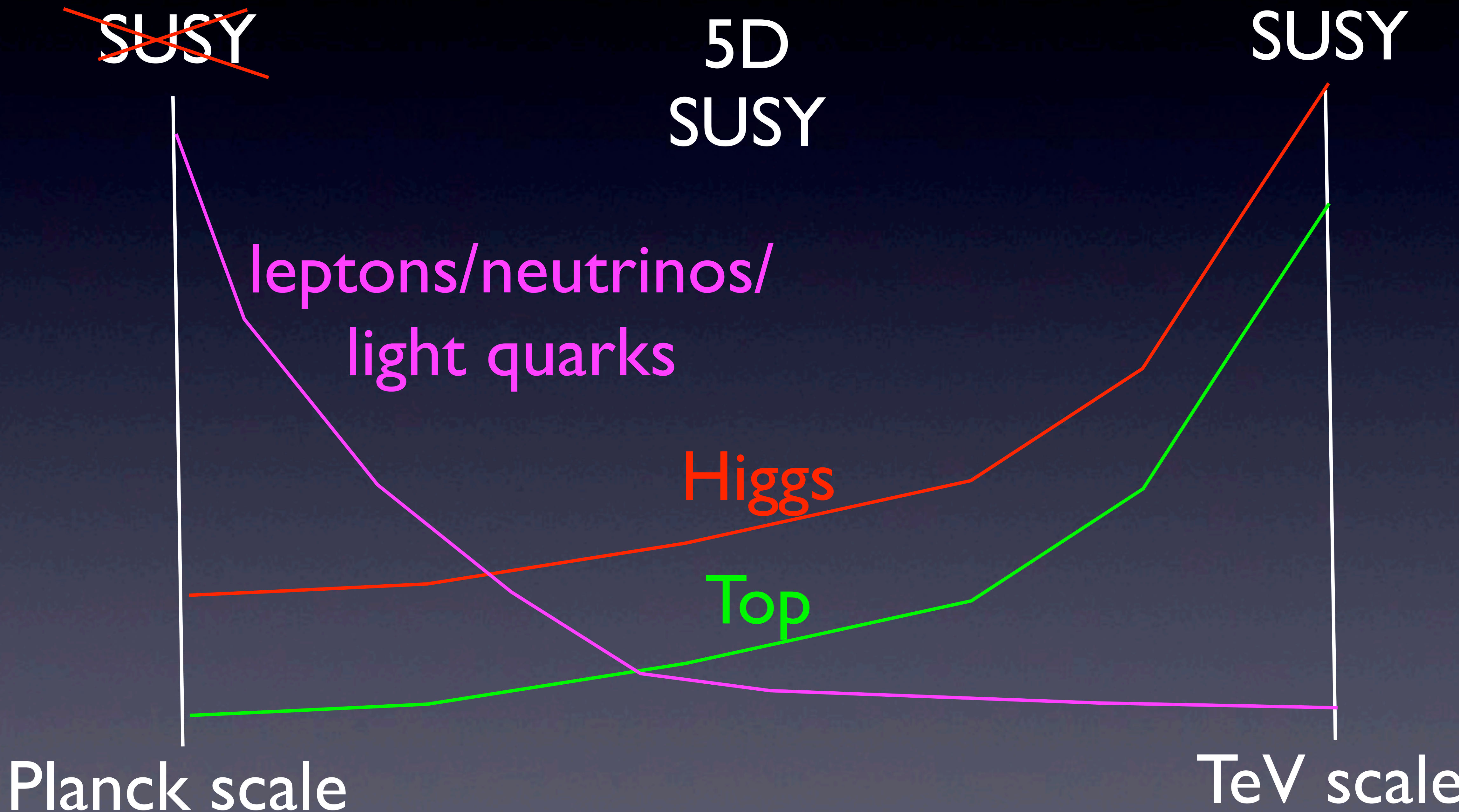
No cosmological constant!

Massless quantum field along radial direction - light Higgs?

Usually destroyed along with SUSY breaking

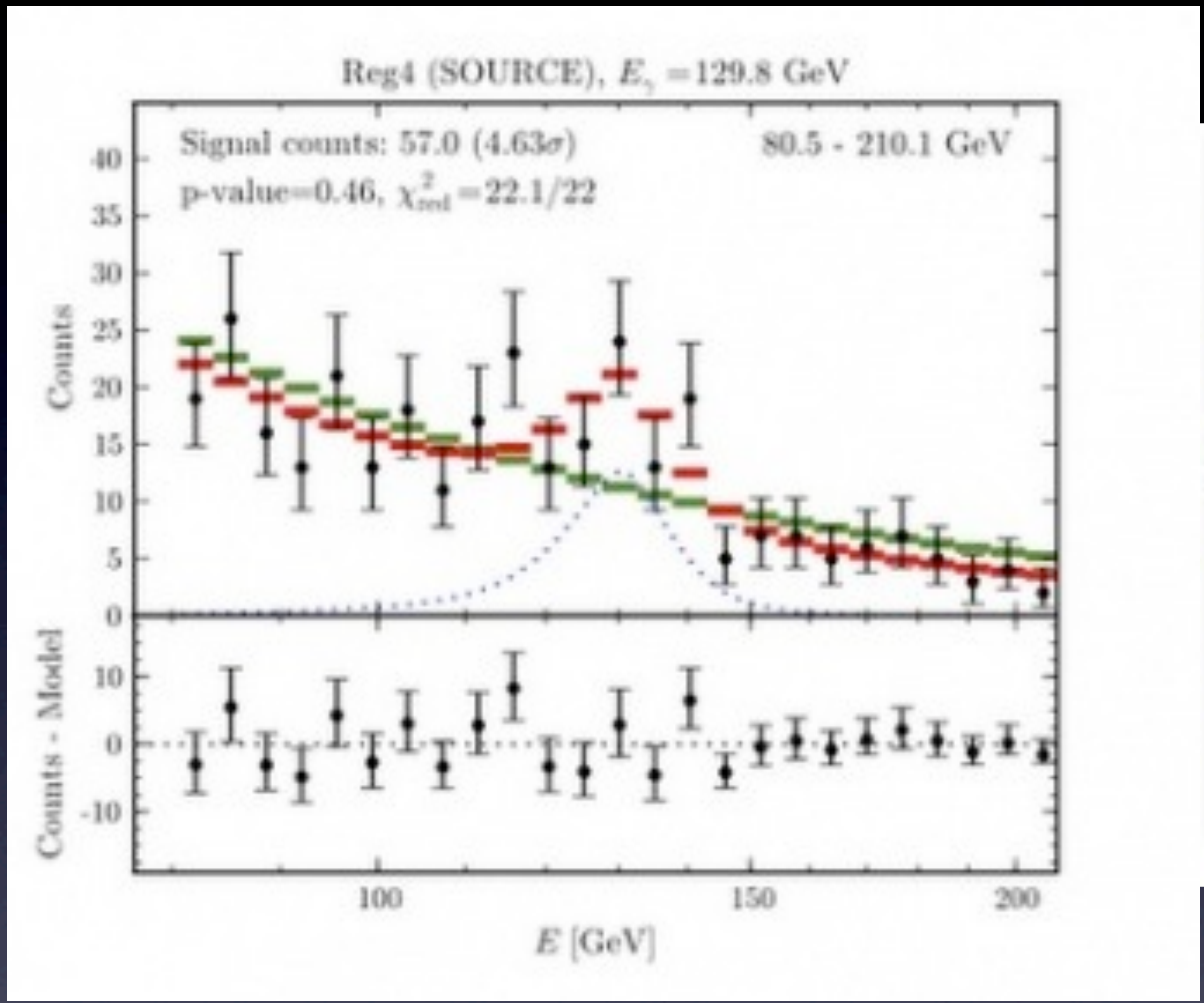
“Accidental SUSY”

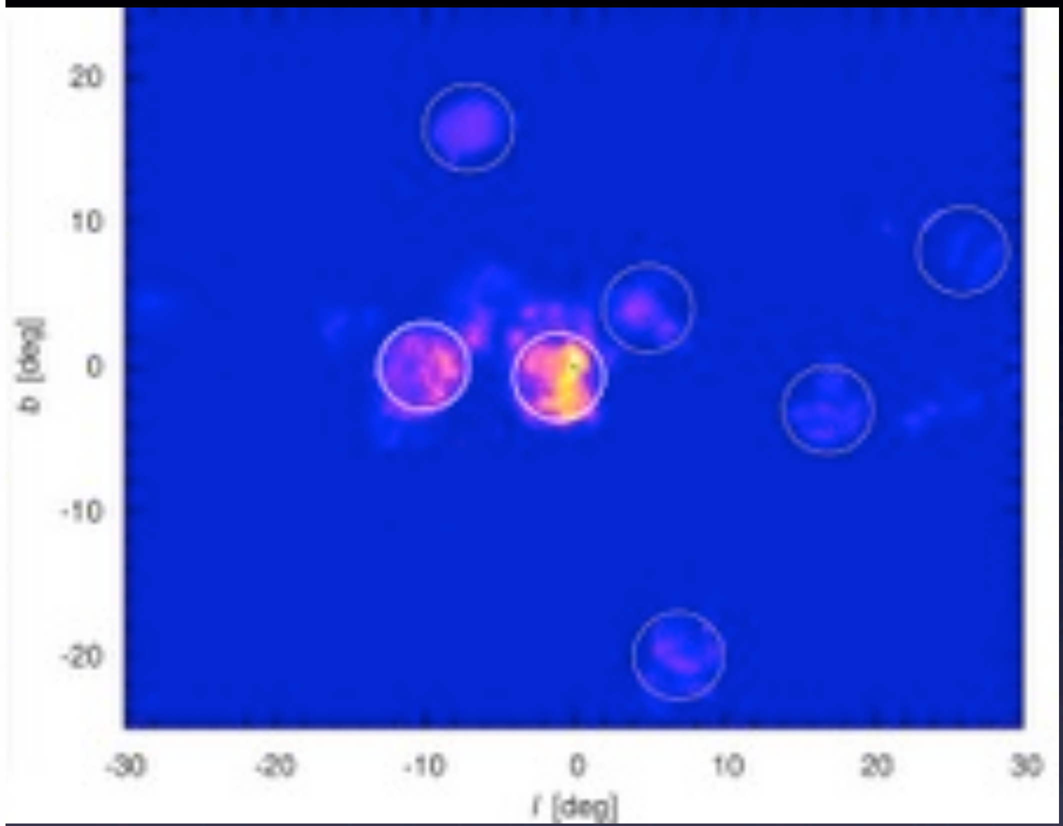
Hero: And when I liv’d I was your other wife;
And when you lov’d, you were my other husband



Higgs/Higgsino top/stop nearly degenerate (don’t feel SUSY breaking!)

Weniger Line





Looks for annihilation of DM into photons in galactic center

130 GeV - Close to 125...

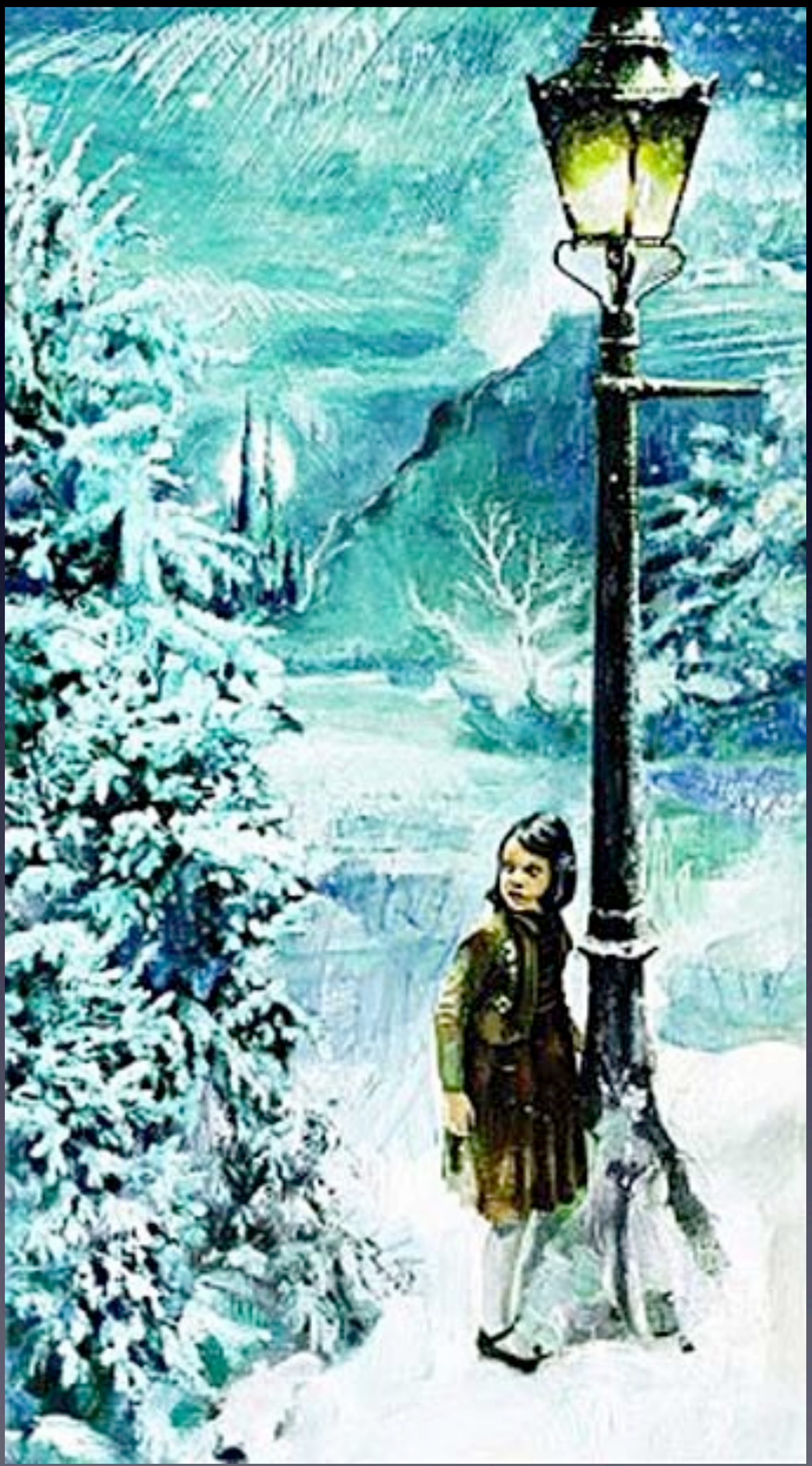
FERMI-LAT data analysis by external theorist

Accidental SUSY

- Natural stop spectrum - “stealthy”
- what happens to the flat directions?
  - if they remain, they may be crucial in obtaining a light higgs, or even an axion
- Fermion mass hierarchy natural! Light fermions hide from the Higgs, top overlaps with it.

The Lamp Post “problem”

Beatrice: I have a good eye, uncle; I can see a church by daylight.



We’re great at seeing the things that are easy to see...

Perturbation theory has been our guide

small anharmonicities

In some instances, we have been able to brighten the lamp...

rephrase strongly coupled theory in terms of weakly coupled one

Beyond standard model lattice studies vitally important!

Conclusions

- We've likely found some ripples in an electroweak ether
  - have we found all of them?
- Many serious issues of the SM remain unsolved
  - the ether likely needs another upgrade
- strongly coupled scale invariance (5D models)
  - to get light Higgs likely need supersymmetry

"He that hath a beard is more than a youth, and he that hath no beard is less than a man."

Thanks!