

Mass

Chris Quigg

Fermi National Accelerator Laboratory



YITP@40 · Stony Brook · 4 May 2007

I. Newton (1687)

Mass: *the quantity of matter ...
arising from its density and bulk conjointly*

$$\mathbf{F} = m\mathbf{a}$$

+

Universal Gravitation

Measure of Inertia
Gravitational Source

Mass is conserved.

Mass of an object: summed masses of parts

Law of Conservation of Mass
Lavoisier, Lomonosov, ... Dalton

↳ Atomic Theory

Classically, mass does not arise, it simply is.

ca. 1900 · M.Abraham & H.A. Lorentz:
electron mass as EM self-energy?

1905 · A. Einstein:

Does the inertia of a body depend on its energy content?

The mass of a body is a measure of its energy content;

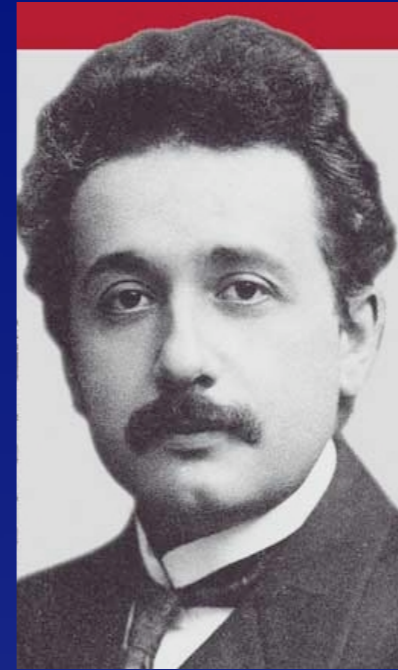
Mass is rest energy

$$m = E_0/c^2; \quad m = (1/c^2) \sqrt{E^2 - p^2 c^2}$$

Invitation to consider the origins of mass



sum of parts



rest energy

Atoms & molecules: nuclear masses, electron mass,
binding energy (QED) H atom: $BE \approx 10^{-8}$ Mass



fossil-fuel economy feeds on such tiny deviations



sum of parts



rest energy

Nuclei: nucleon masses + nuclear forces

Mass defect of ${}^4\text{He}$: $\frac{3}{4}\%$

proxy for a prodigious store of energy



sum of parts



rest energy

Nucleon mass: exemplar of $m = E_0/c^2$

up and down quarks contribute 1%

$$3 \frac{m_u + m_d}{2} = 10 \pm 2 \text{ MeV}$$

Lattice QCD: quark confinement origin of nucleon mass
has explained nearly all visible mass in the Universe

up and down quark masses are crucial

$$M_n - M_p = 1.29 \text{ MeV}$$

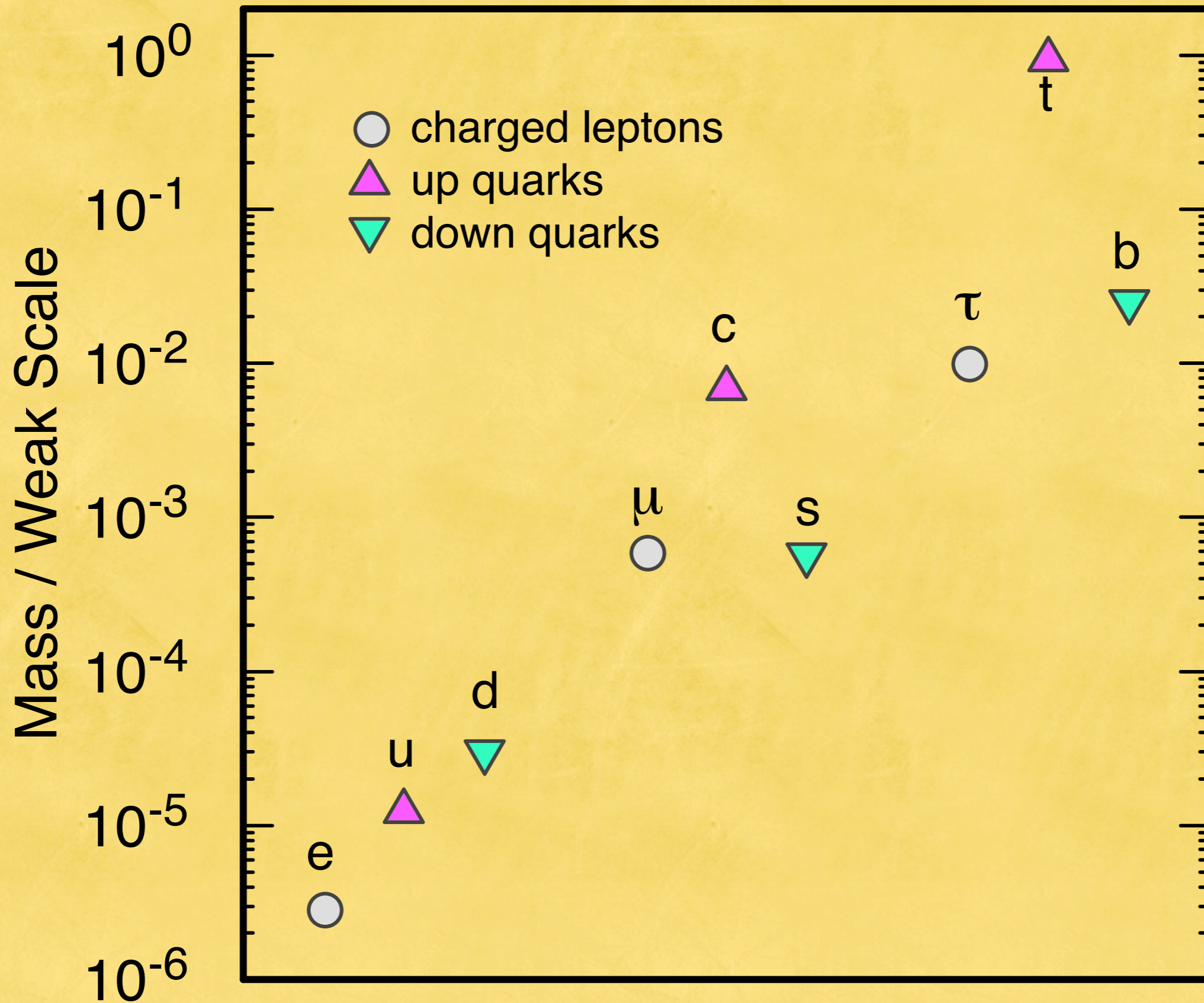
$m_d > m_u$ overcomes electrostatic energy,
so proton is lightest nucleus

$$p = uud, n = udd$$

The Higgs boson is *not*
the source of all mass
in the Universe

The Higgs boson & EWSB are of capital importance:

- Masses of weak force particles:
gauge couplings $\times v_{ev}$
- Quark & lepton masses?
Yukawa couplings $\times v_{ev}$



The Higgs boson is *not*
the source of all mass
in the Universe

The Higgs boson & EWSB are of capital importance:

- Masses of weak force particles:
gauge couplings $\times v_{\text{ev}}$
- Quark & lepton masses?
Yukawa couplings $\times v_{\text{ev}}$
- Shaping the everyday world
Why atoms? chemical bonds? stable structures?

Imagine a world without a Higgs mechanism

If electroweak symmetry were not hidden ...

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- *Nucleon mass little changed*
- QCD breaks EW symmetry, gives tiny W, Z masses; weak-isospin force doesn't confine
- *p outweighs n*: rapid β -decay
⇒ lightest nucleus is *n* ... *no hydrogen atom*
- Some light elements from BBN, but ∞ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, ...

*... character of the physical world
would be profoundly changed*

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

New Physics on the Fermi Scale

Thought experiment (1977): WW scattering

Electroweak theory makes sense if

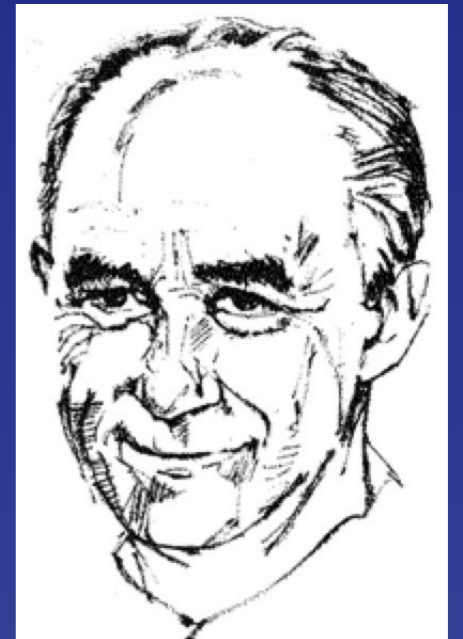
something happens

at energies around 1 TeV

Either the Higgs boson

Or strong WW scattering

Tipping point: $M_{\text{Higgs}} < \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2}$

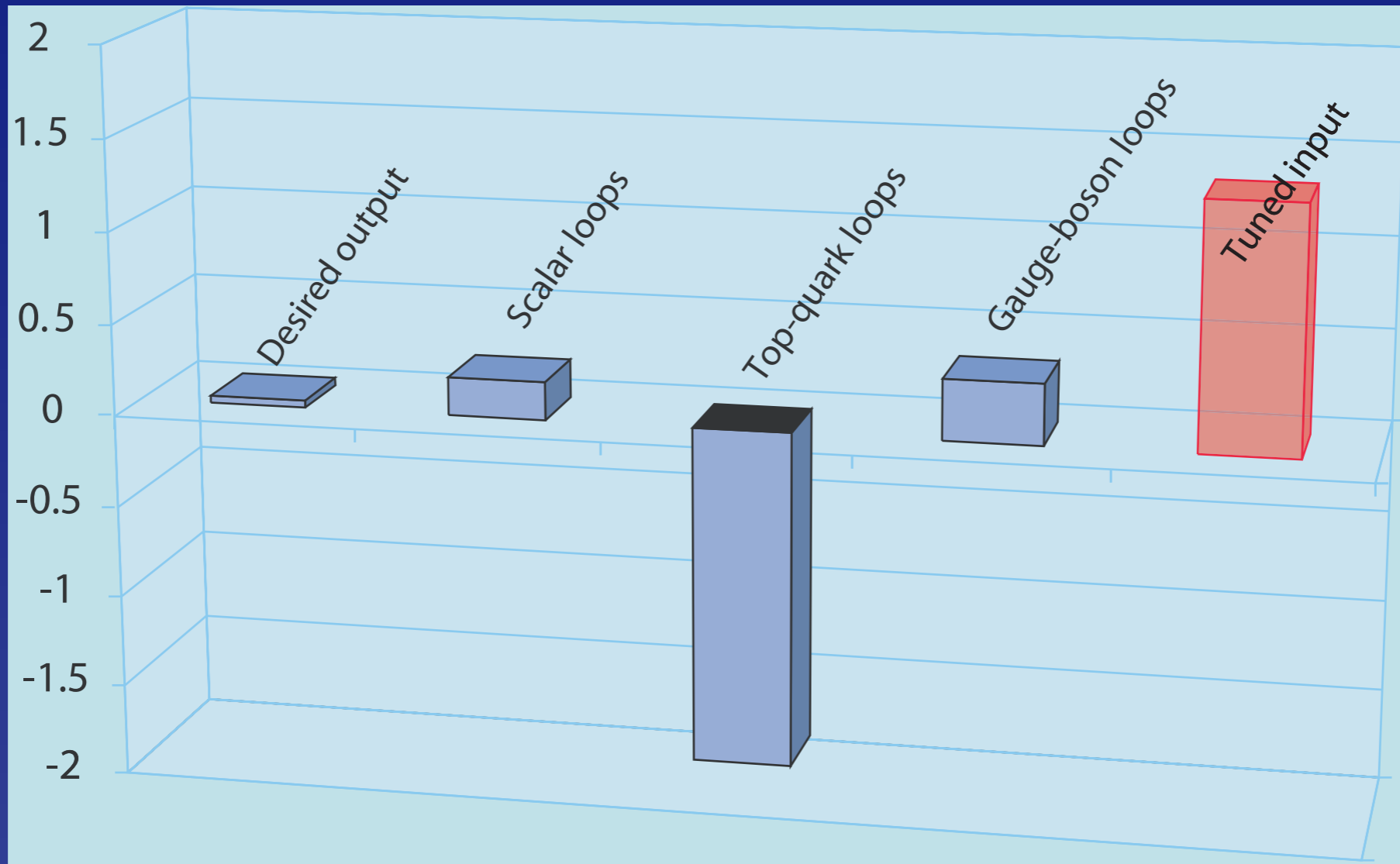


More

New Physics on the Fermi Scale?

Does $M_H < 1 \text{ TeV}$ make sense?

The peril of quantum corrections – hierarchy problem



5 TeV

More

New Physics on the Fermi Scale?

Does $M_H < 1 \text{ TeV}$ make sense?

The peril of quantum corrections – hierarchy problem

Responses: extend electroweak theory

Supersymmetry

Technicolor

Extra spacetime dimensions

“Little Higgs” models

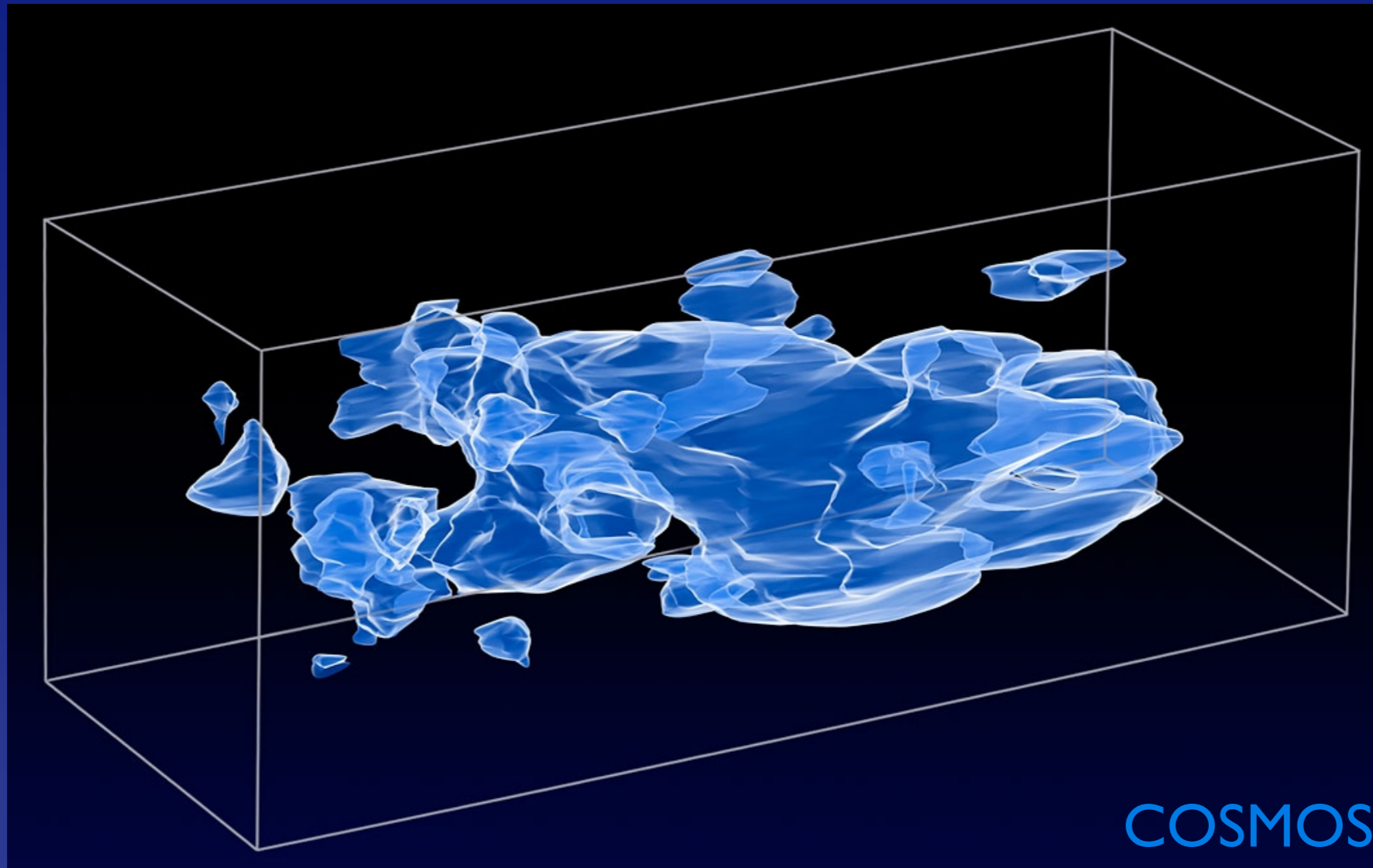
Bring new physics down to 1 TeV

Opinion: Fermi scale holds Higgs boson + other new physics

More

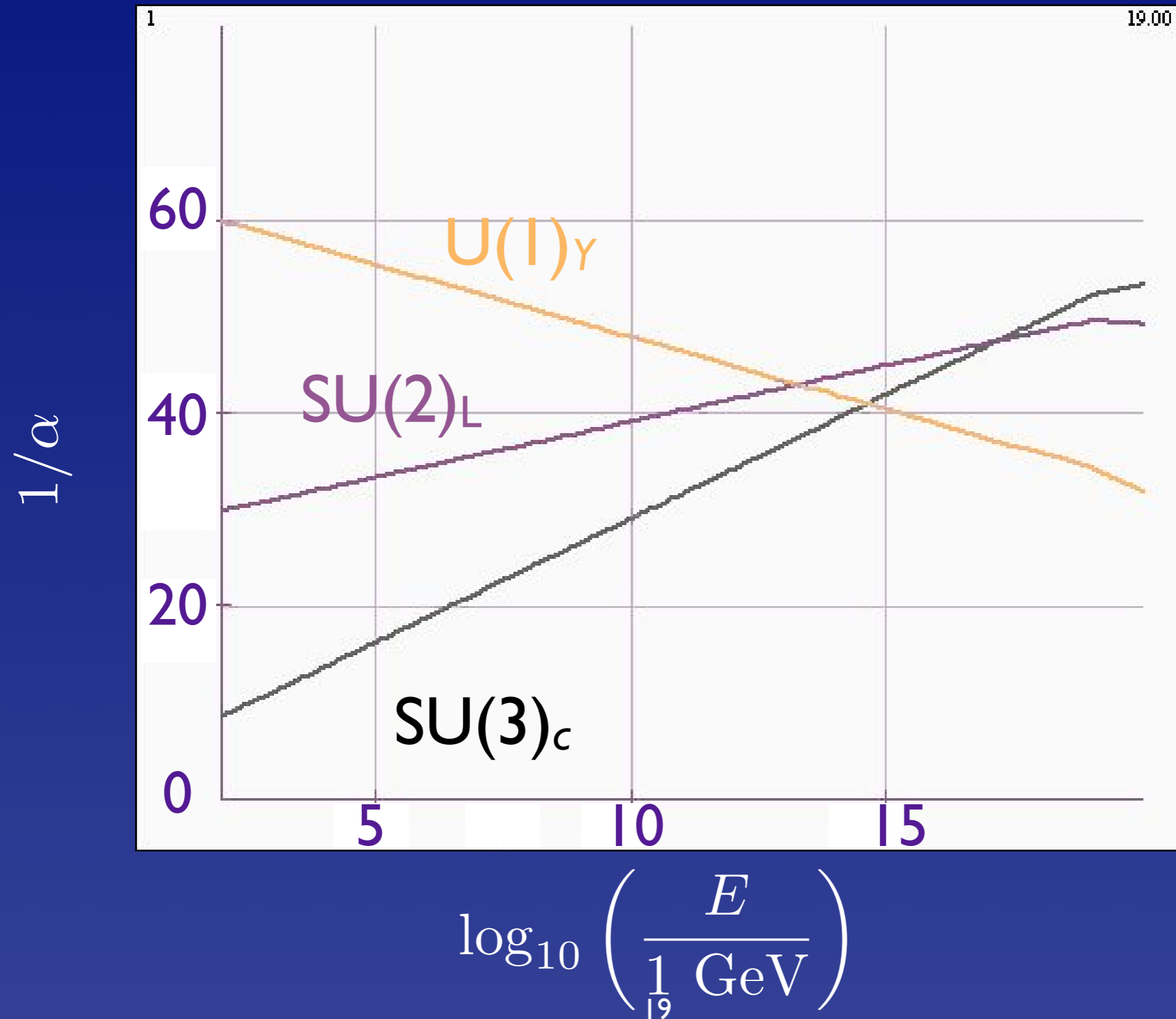
New Physics on the Fermi Scale?

If dark matter interacts weakly ...

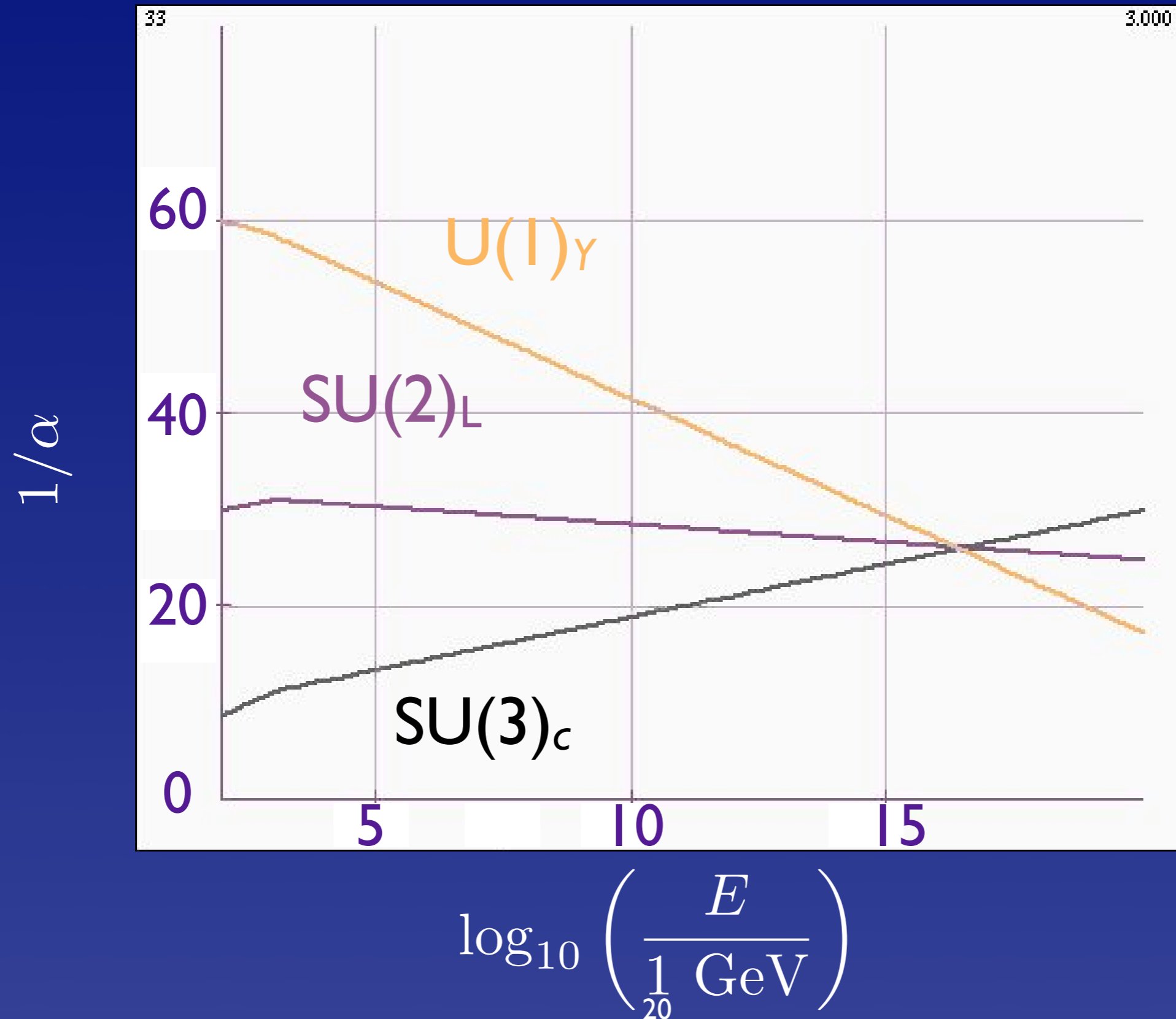


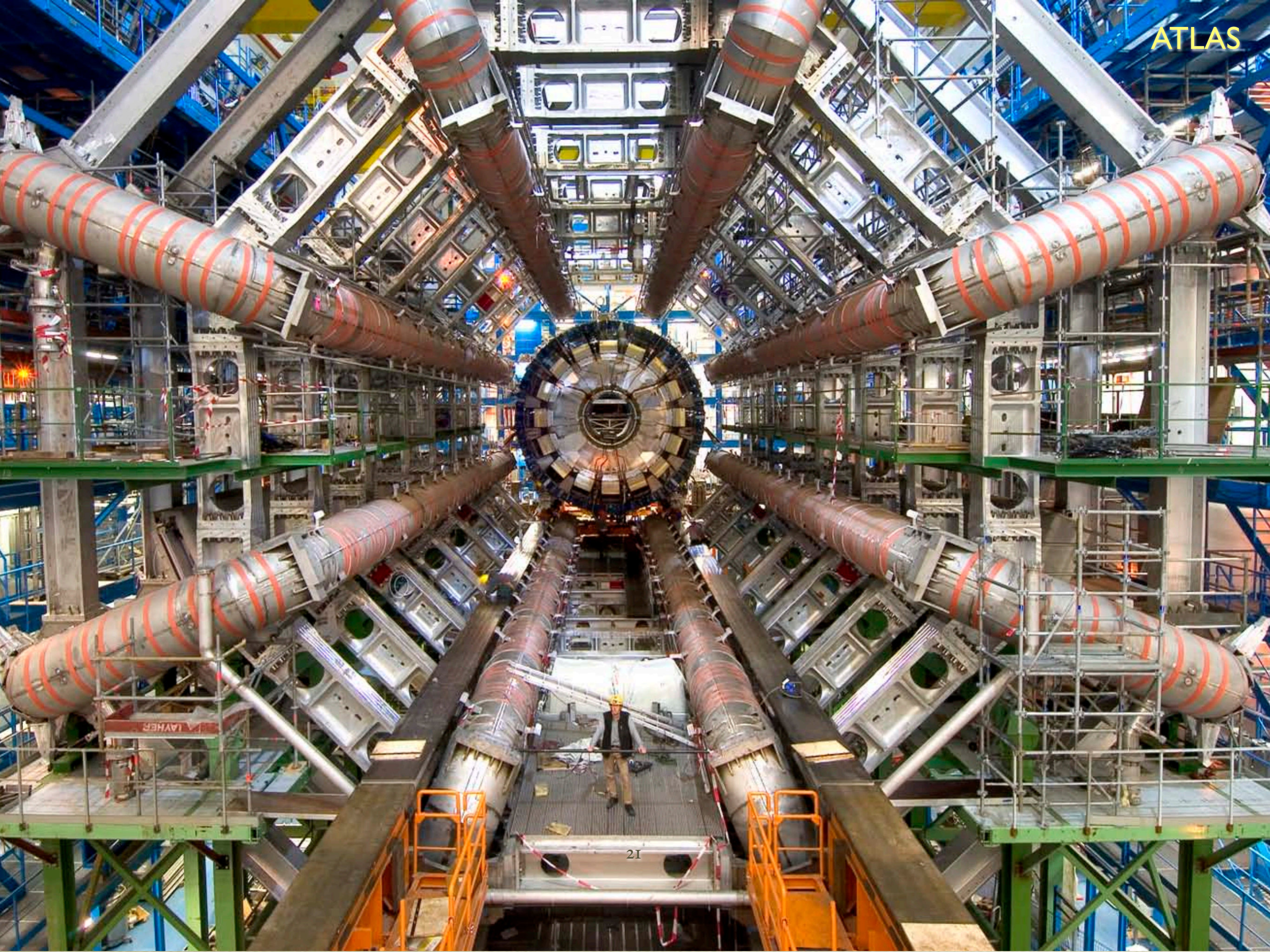
... its likely mass is 0.1 to 1 TeV: *Fermi scale*

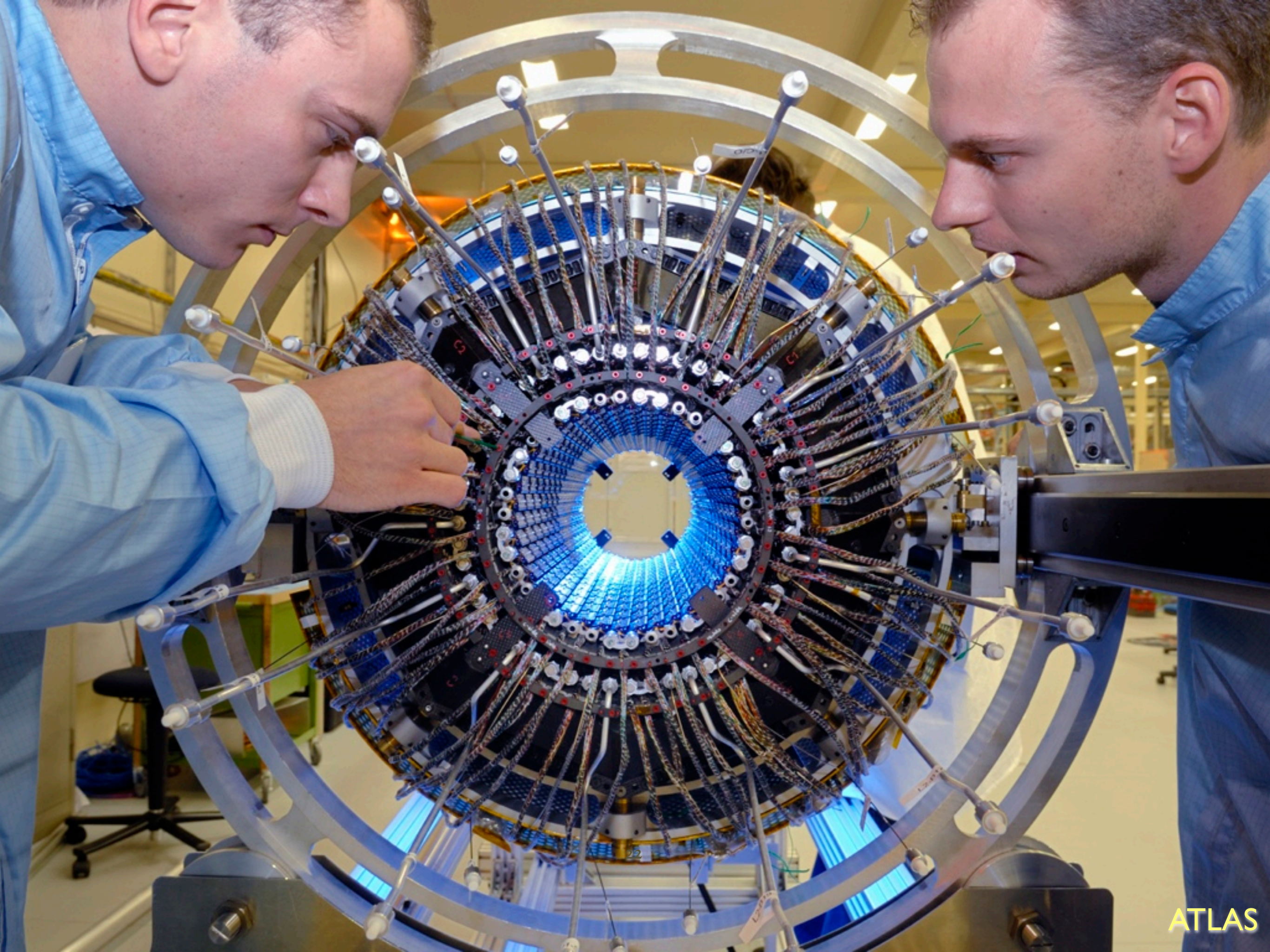
Fermi scale + supersymmetry : unification?

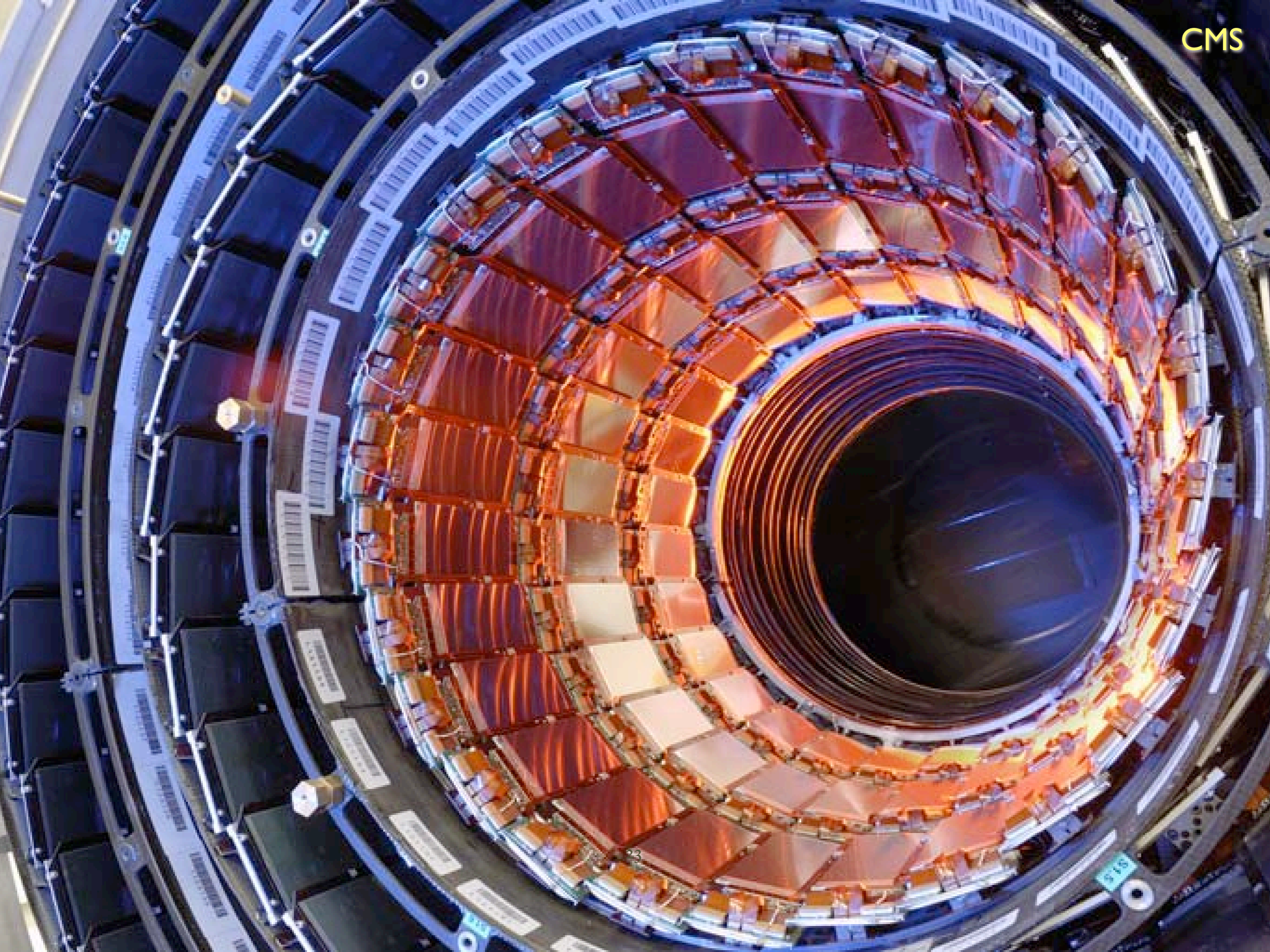


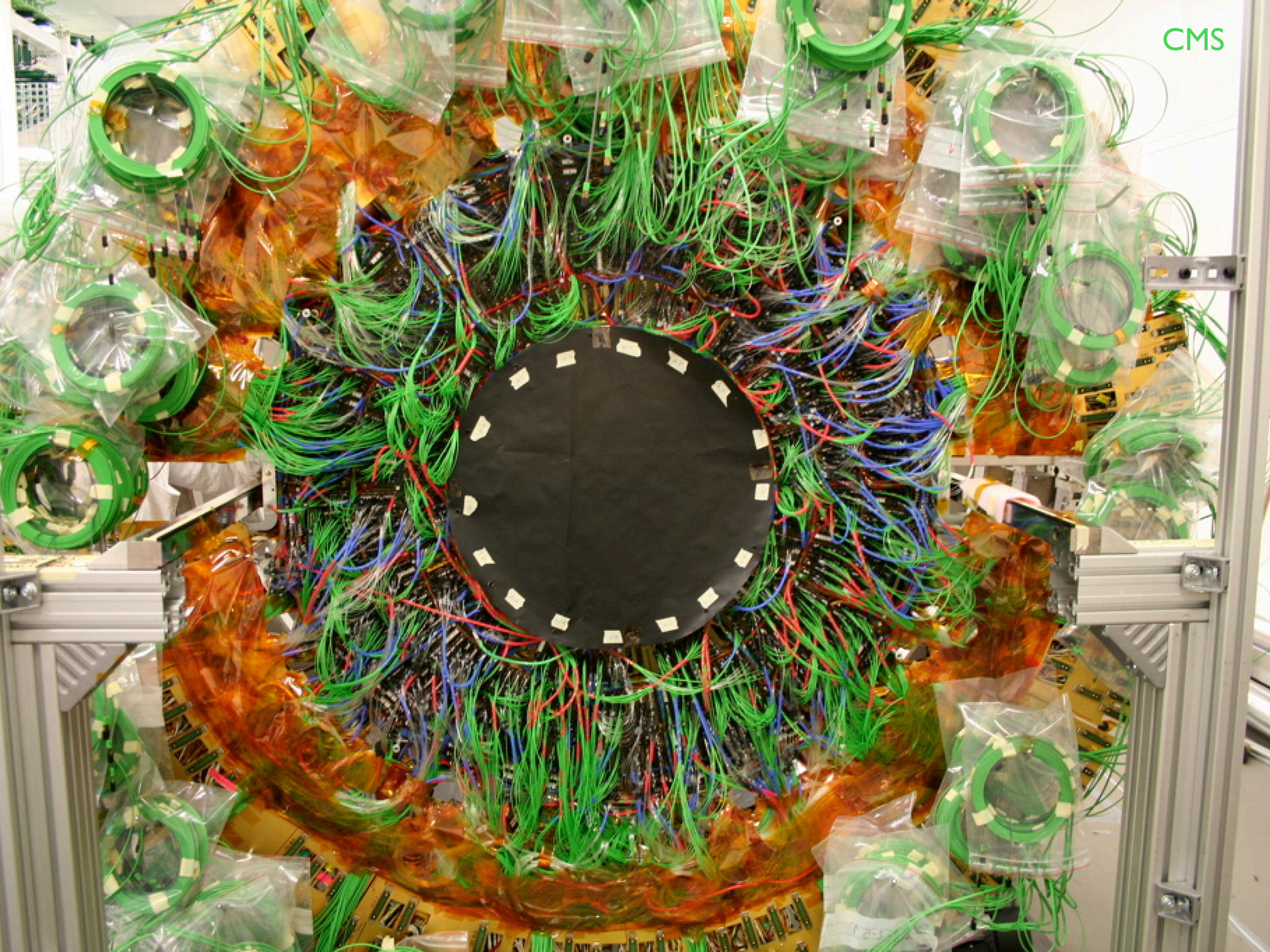
Fermi scale + supersymmetry : unification?











What hides electroweak symmetry?

Is there a Higgs boson? Several?

Does H give mass to fermions, or only to W, Z ?

How does H interact with itself?

Do we live in a metastable vacuum?

Is H elementary or composite?

New physics in H decays? New kinds of matter?

What stabilizes $M_H < 1 \text{ TeV}$?

Is nature supersymmetric?

New strong dynamics? Extra dimensions?

What resolves vacuum energy problem?

What lessons for unified theories?

for inflationary U ? for dark energy?



arXiv:0704.2232

