The Coming Revolutions in Particle Physics

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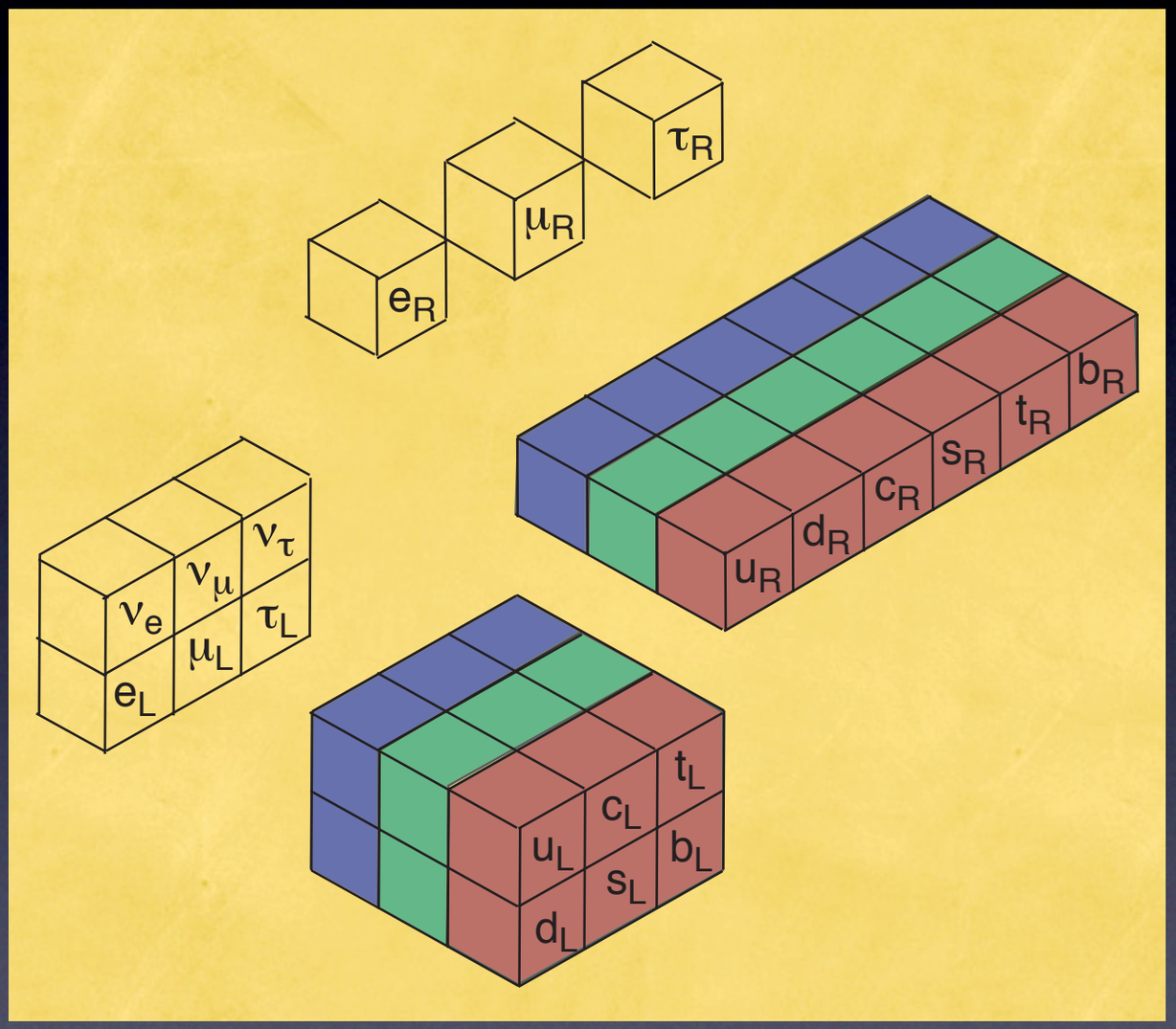
A Decade of Discovery Past

- ▷ Electroweak theory $\longrightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \longrightarrow \nu_\tau$, $\nu_e \longrightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \longrightarrow \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \longrightarrow B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons



Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

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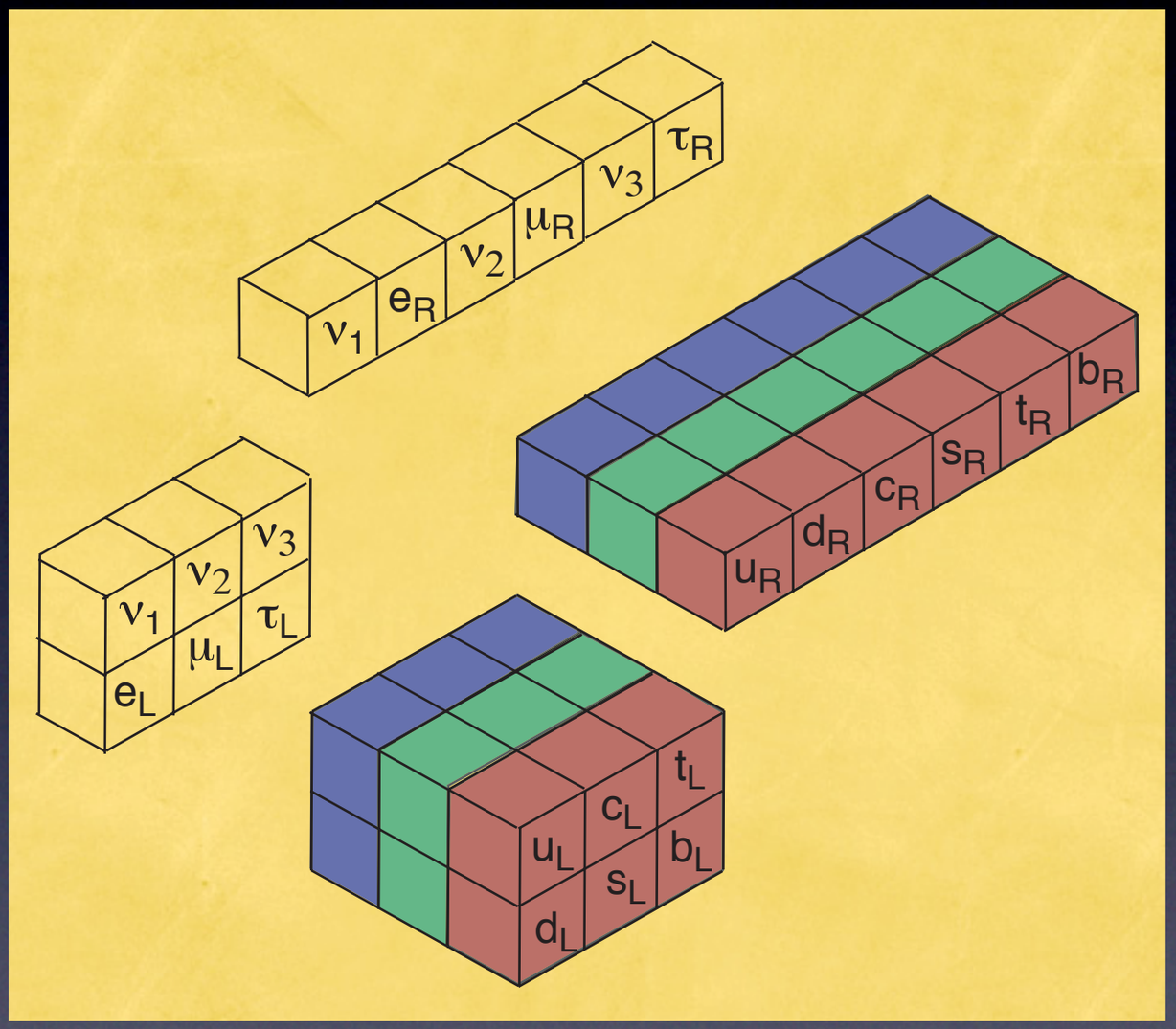


Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

The World's Most Powerful Microscopes

nanonanophysics

Fermilab's Tevatron Collider & Detectors

900-GeV protons: $c - 586$ km/h

980-GeV protons: $c - 495$ km/h

Improvement: 91 km/h!

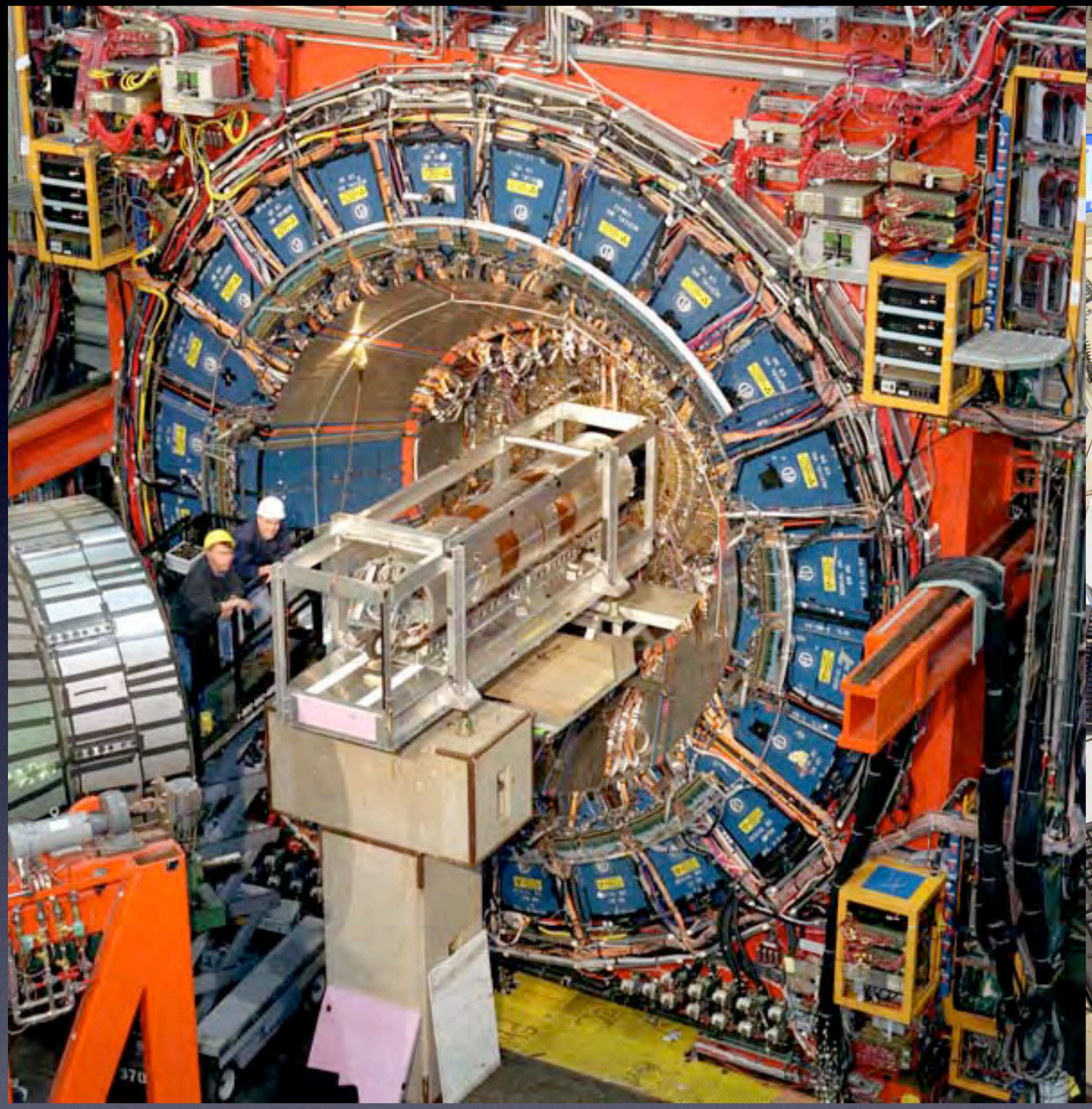
Protons, antiprotons pass my window 45 000 times / second

achieved

. . . working toward $20 \times$ increase in luminosity

$\Rightarrow 10^7$ collisions / second

CERN's Large Hadron Collider, 7-TeV protons: $c - 10$ km/h



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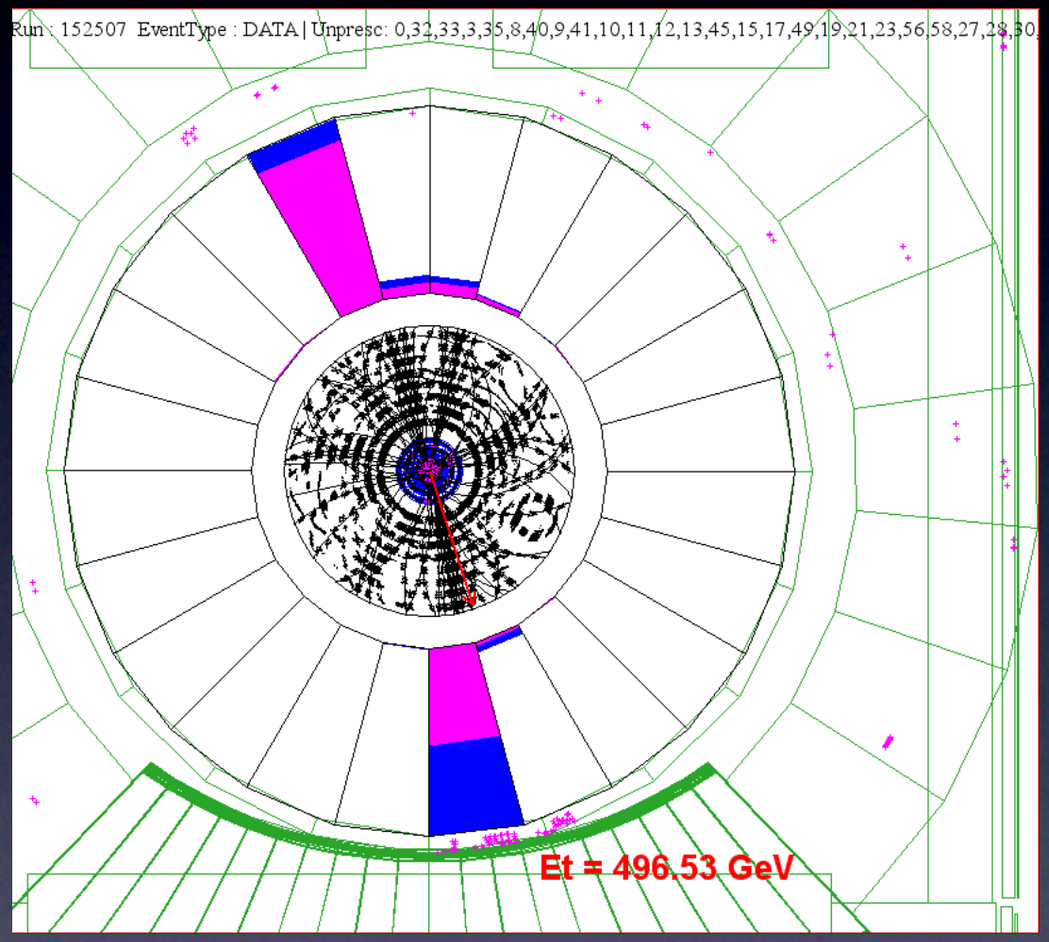
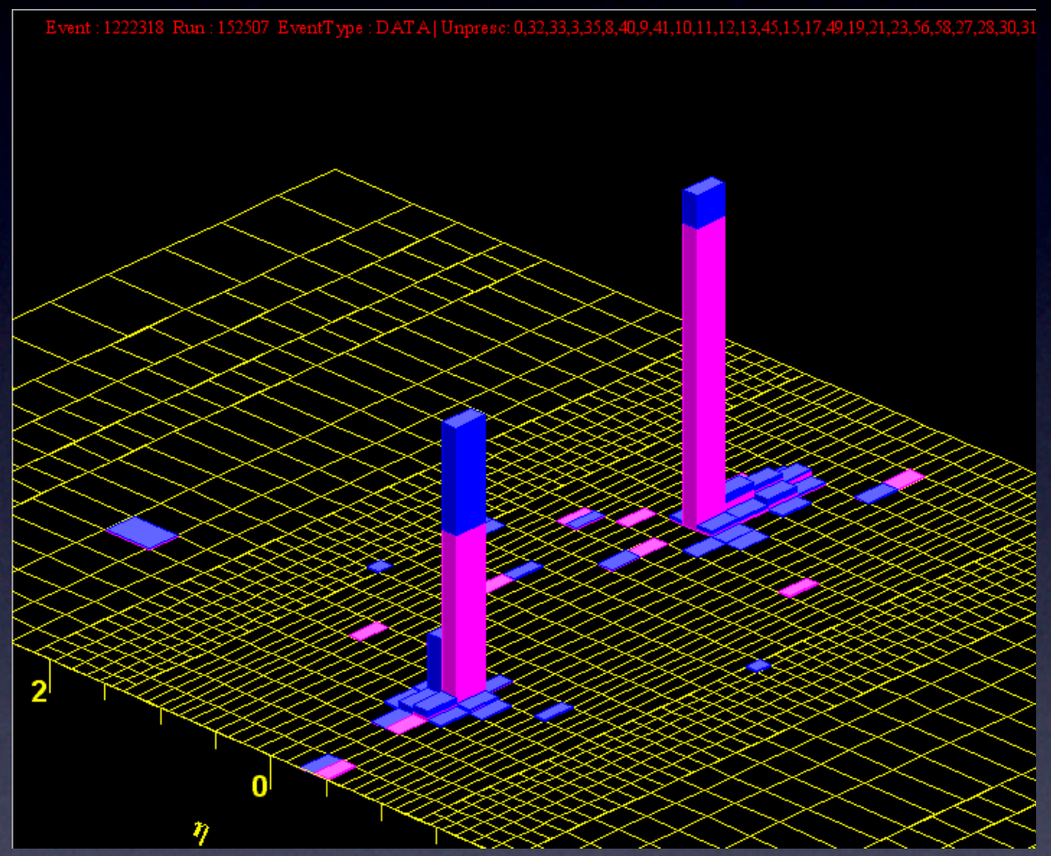
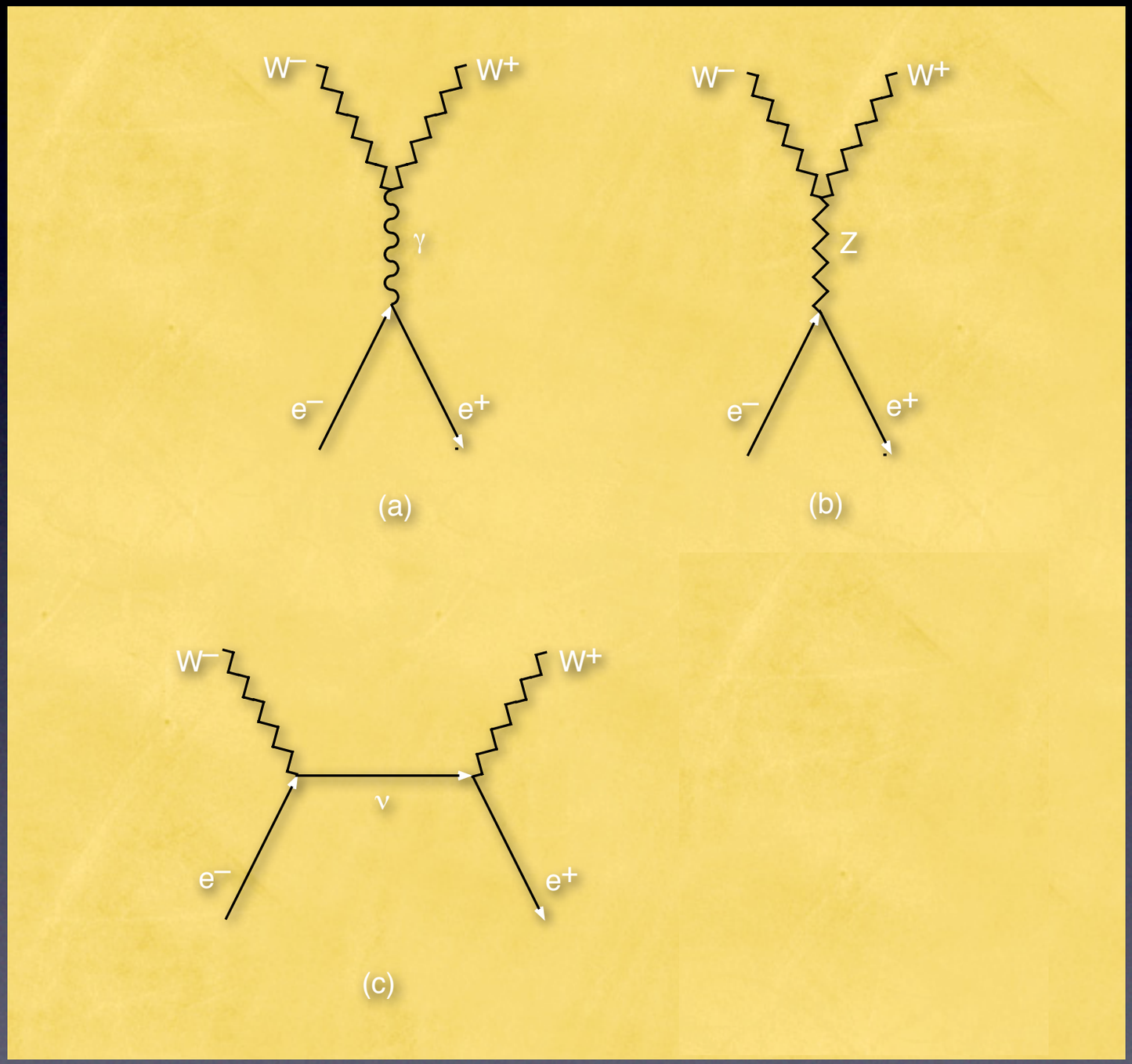




CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



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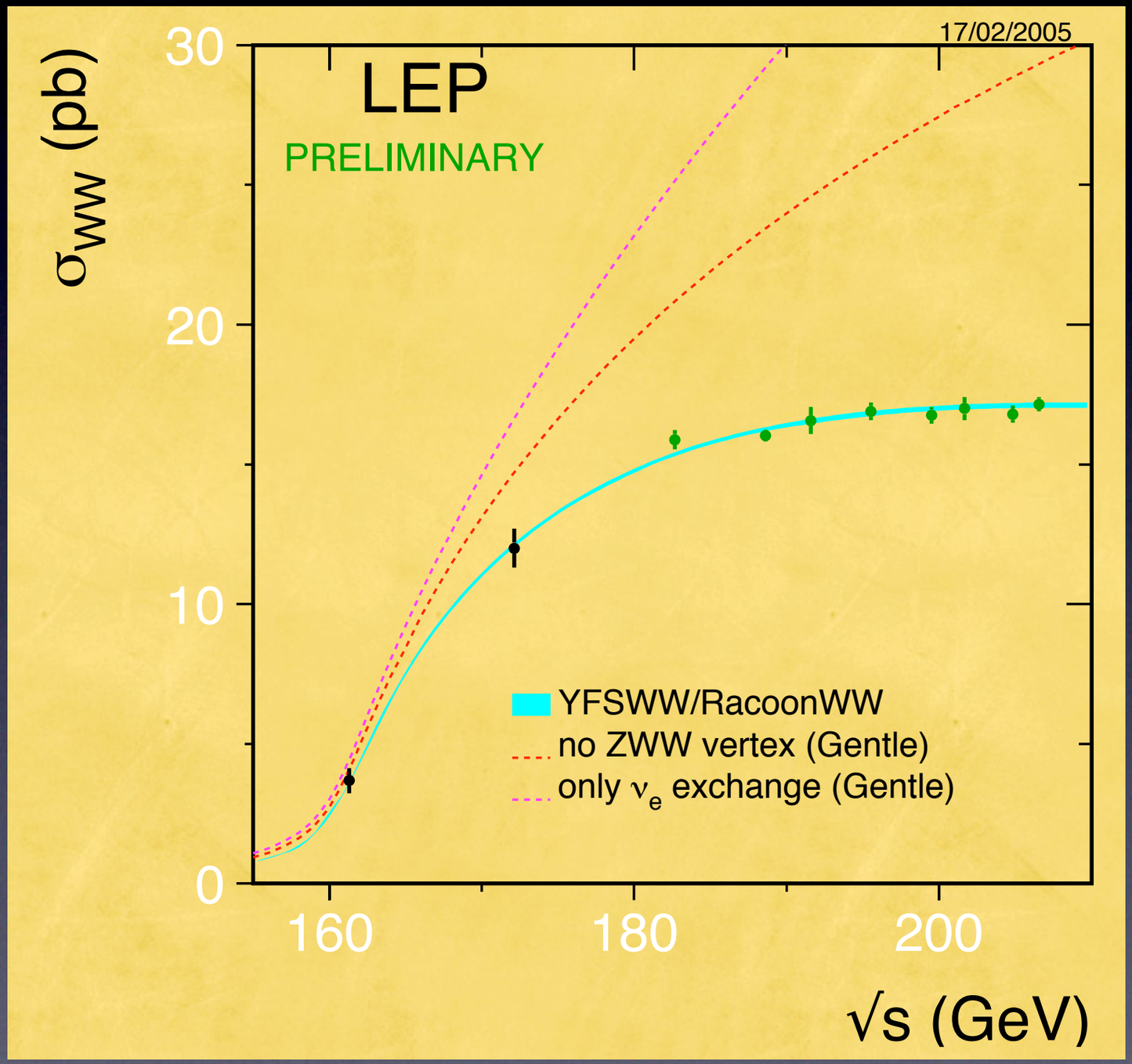

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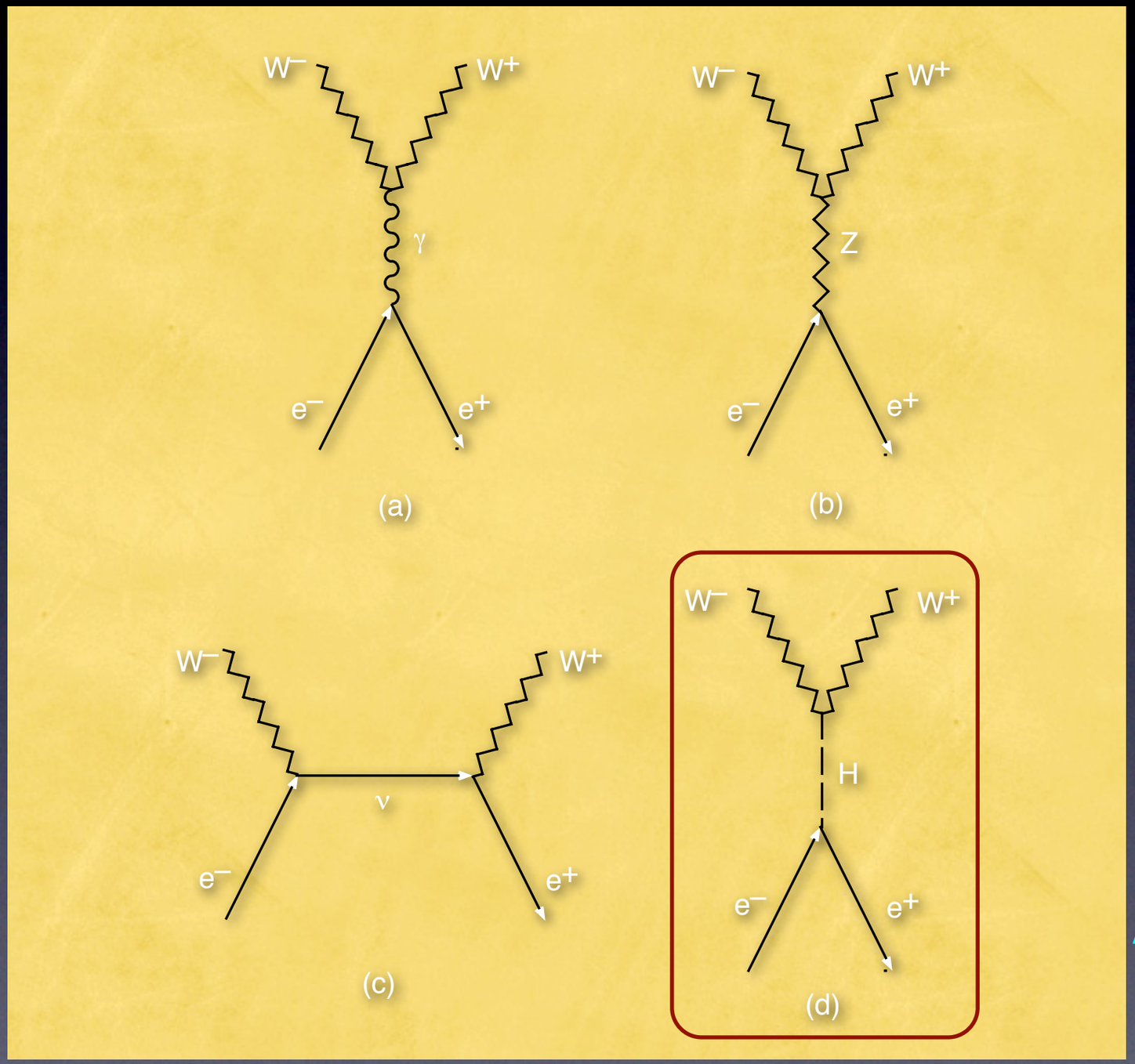


Massive weak bosons: Higgs boson

Meissner effect

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

$W_L^+W_L^-, Z_L^0Z_L^0, HH, HZ_L^0$ satisfy *s*-wave unitarity,

provided $\boxed{M_H \leq \left(8\pi\sqrt{2}/3G_F\right)^{1/2} = 1 \text{ TeV}}$

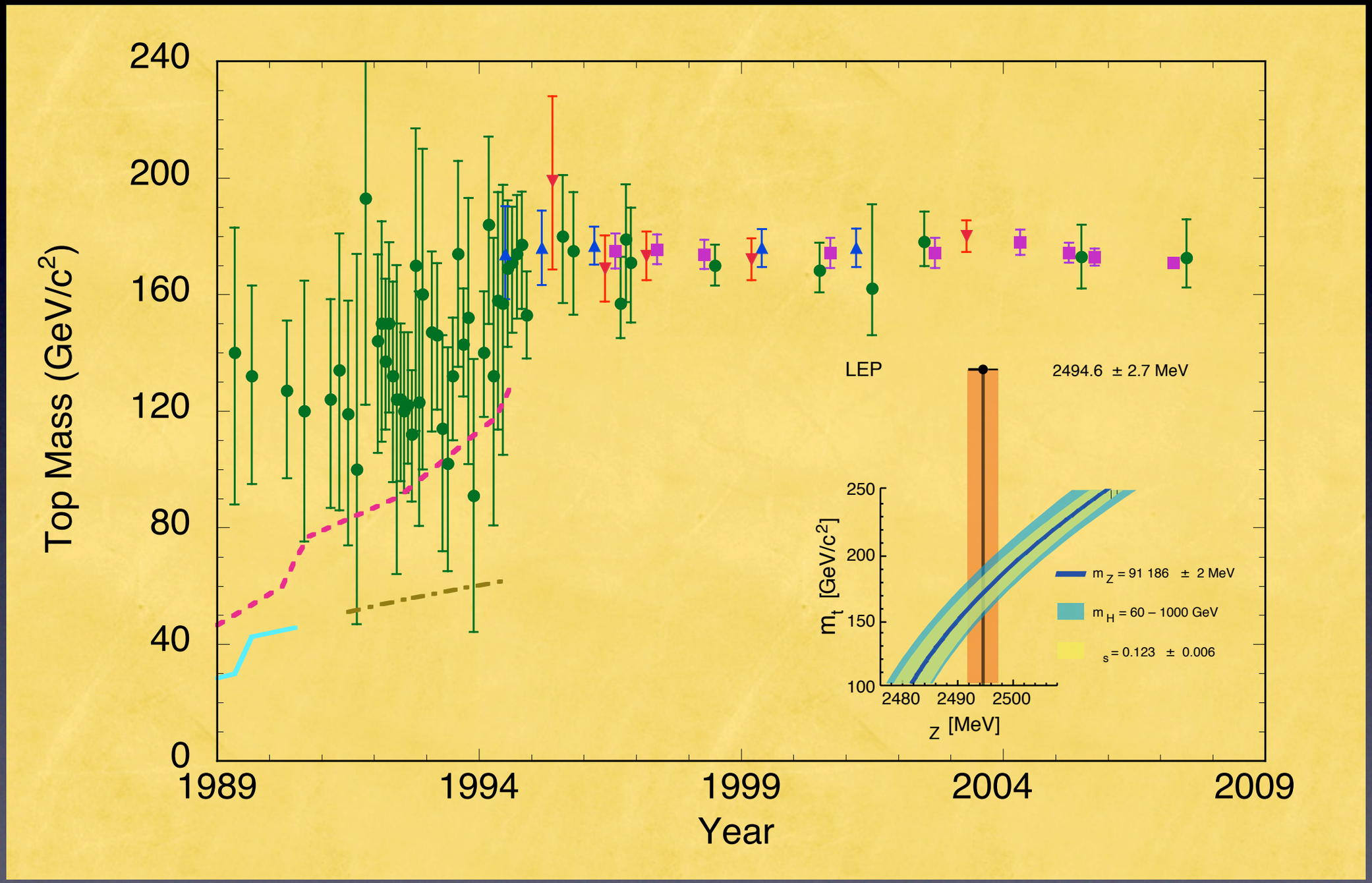
- If bound is respected, perturbation theory is everywhere reliable
- If not, weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Precision Measurements Test the Theory …

LEP EWWG

… and determine unknown parameters



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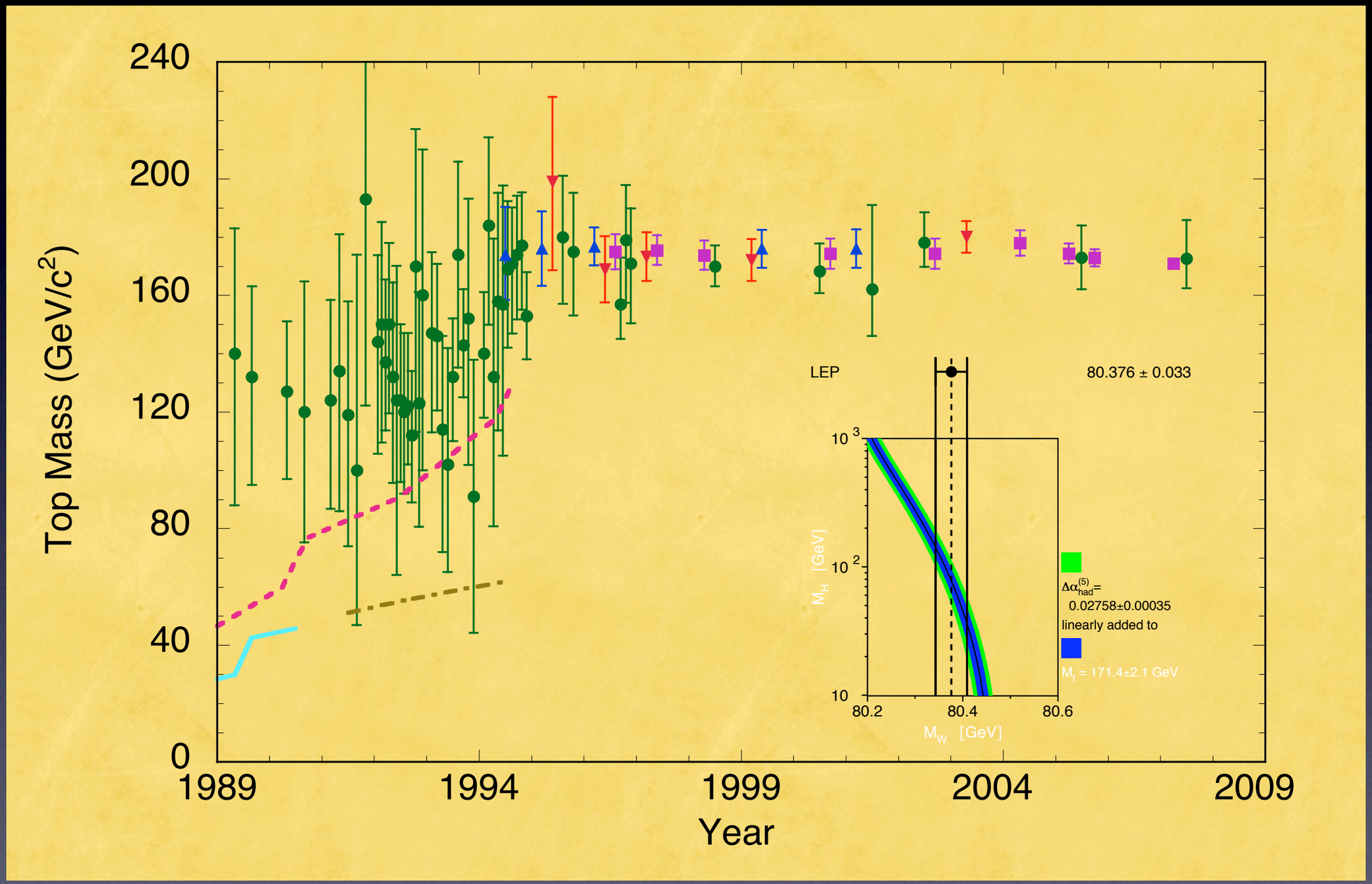


Revolution:

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why 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

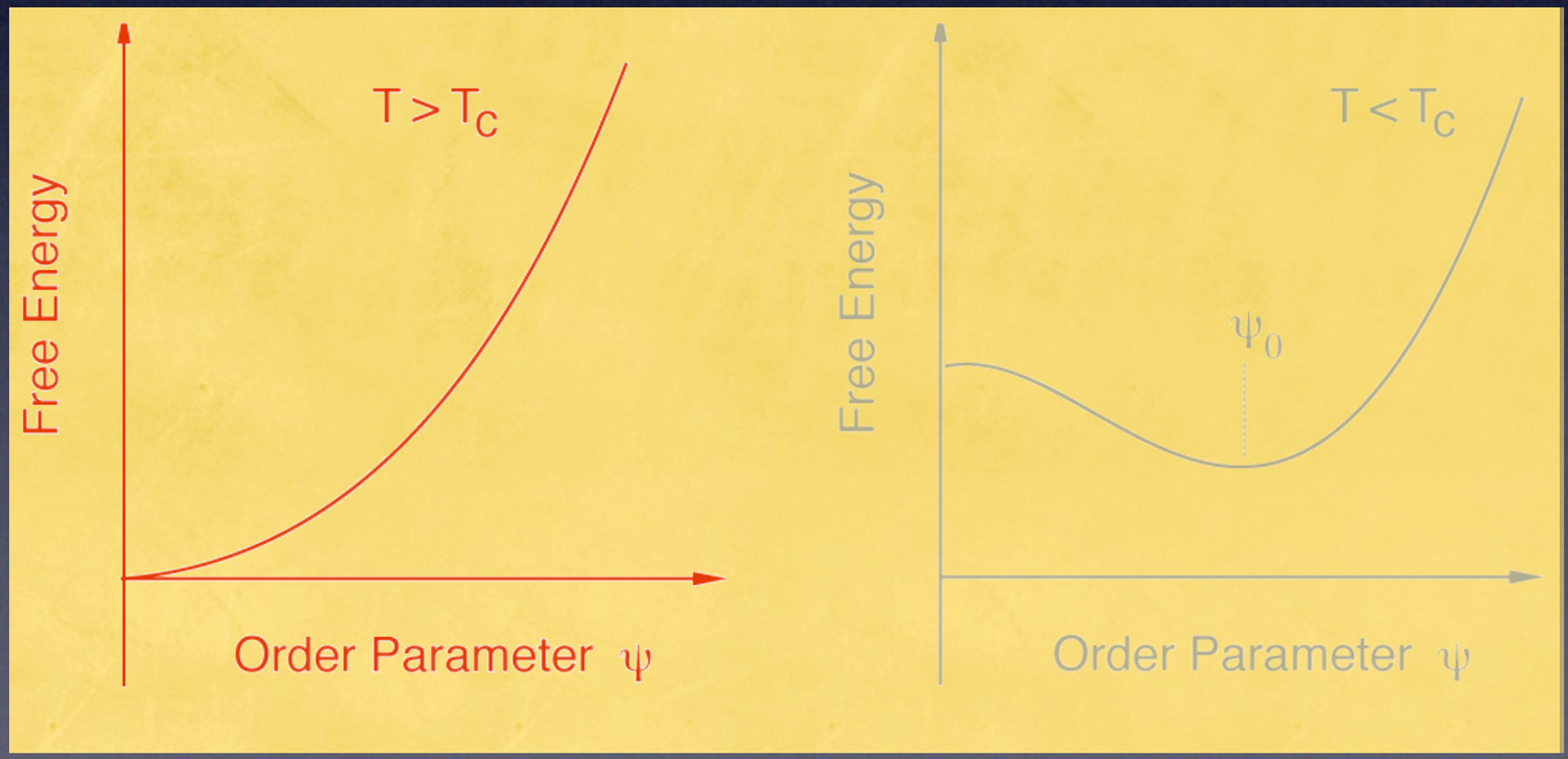
why the world is the way it is.

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

it is coming within the reach of particle physics.

The agent of electroweak symmetry breaking
represents a novel fundamental interaction
at an energy of a few hundred GeV …

We do not know the nature of the new force.



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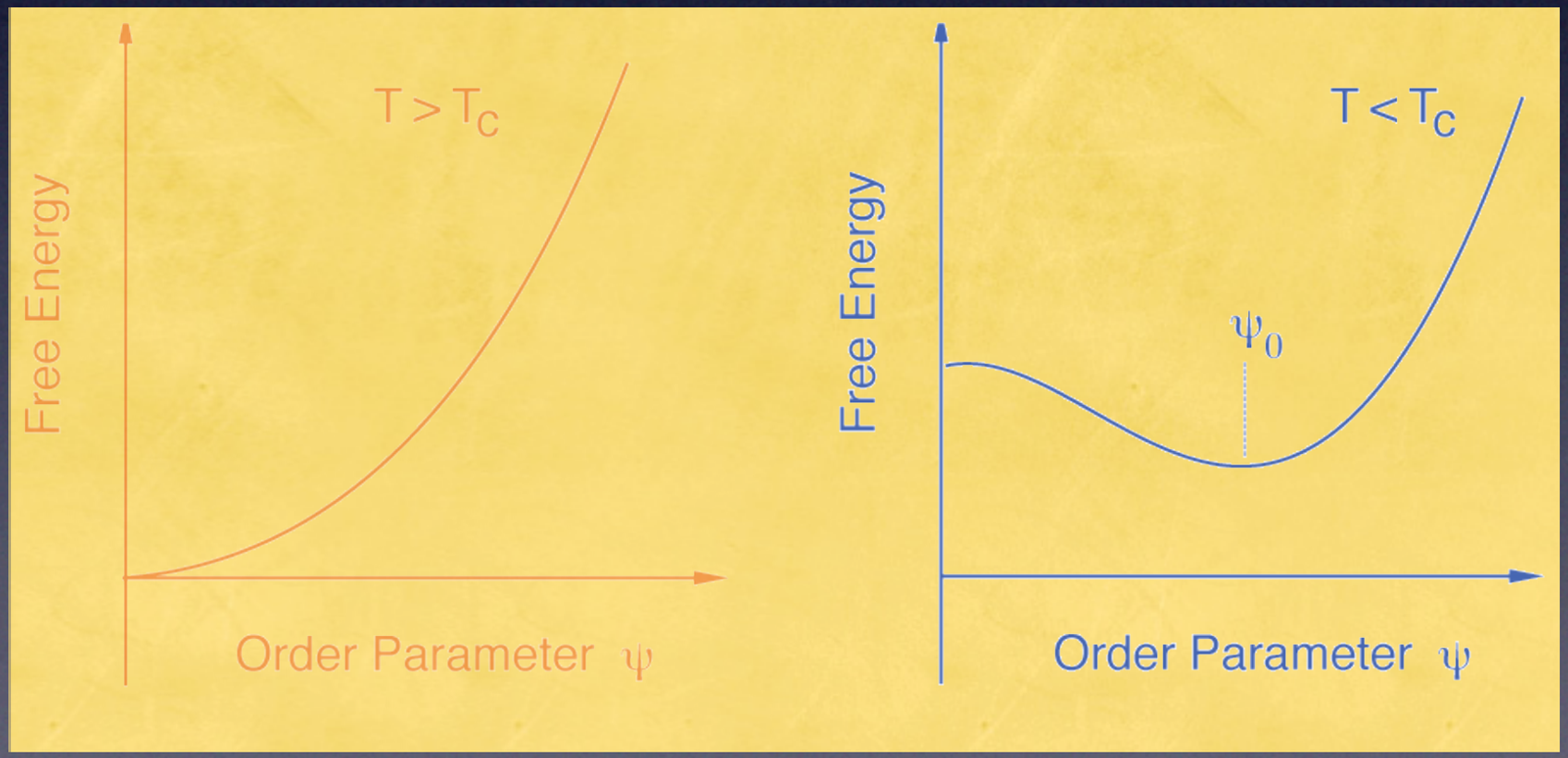


What is the nature of the mysterious new force that hides electroweak symmetry?

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

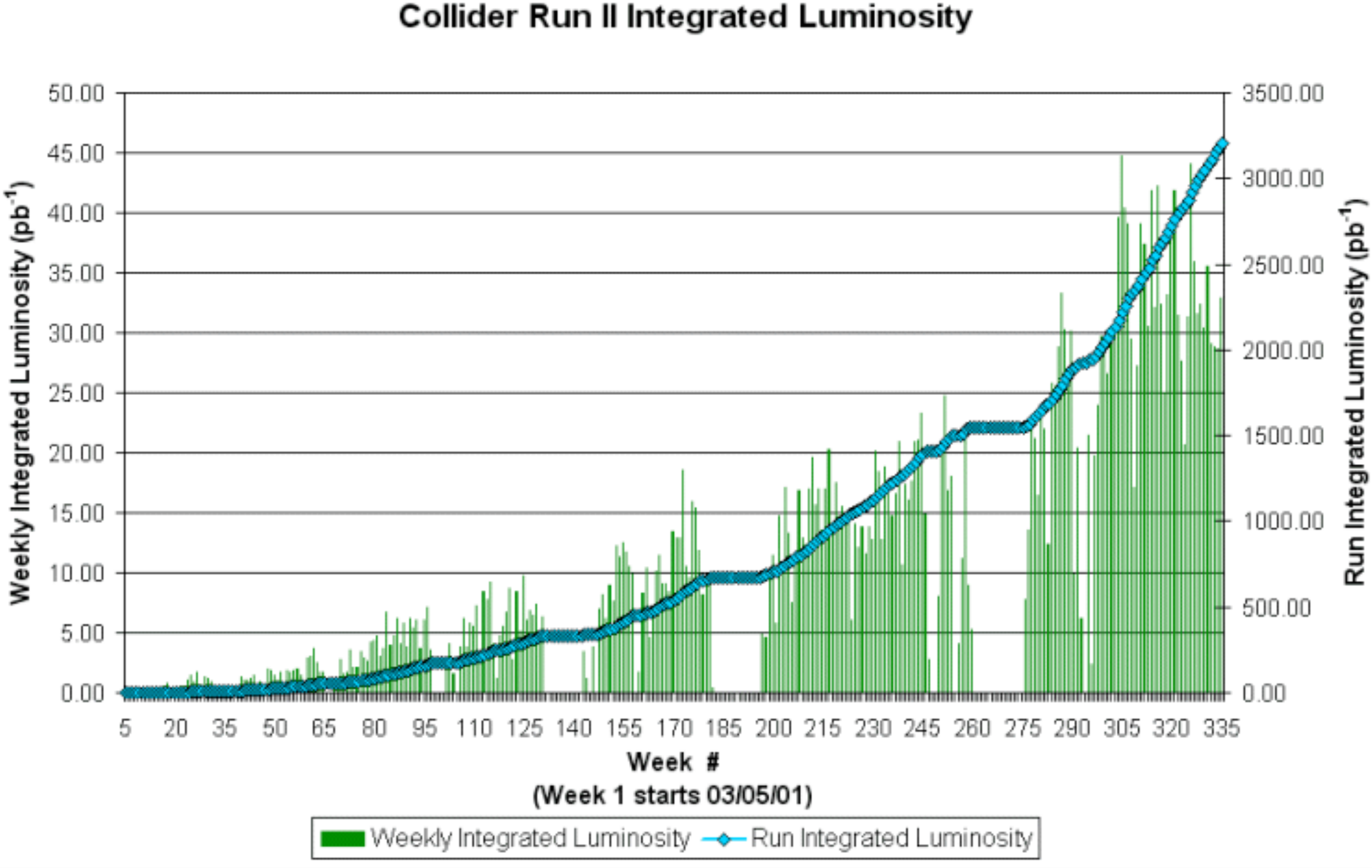
Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

- ✳ Is it there? How many?
- ✳ Verify quantum numbers (spin, parity, …)
- ✳ Does *H* generate mass for gauge bosons and for fermions?
- ✳ How does *H* interact with itself?

Finding the Higgs boson starts a new adventure!

Tevatron


Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
50.00
45.00
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35.00
30.00
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3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
5 20 35 50 65 80 95 110 125 140 155 170 185 200 215 230 245 260 275 290 305 320 335
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

GENEVE

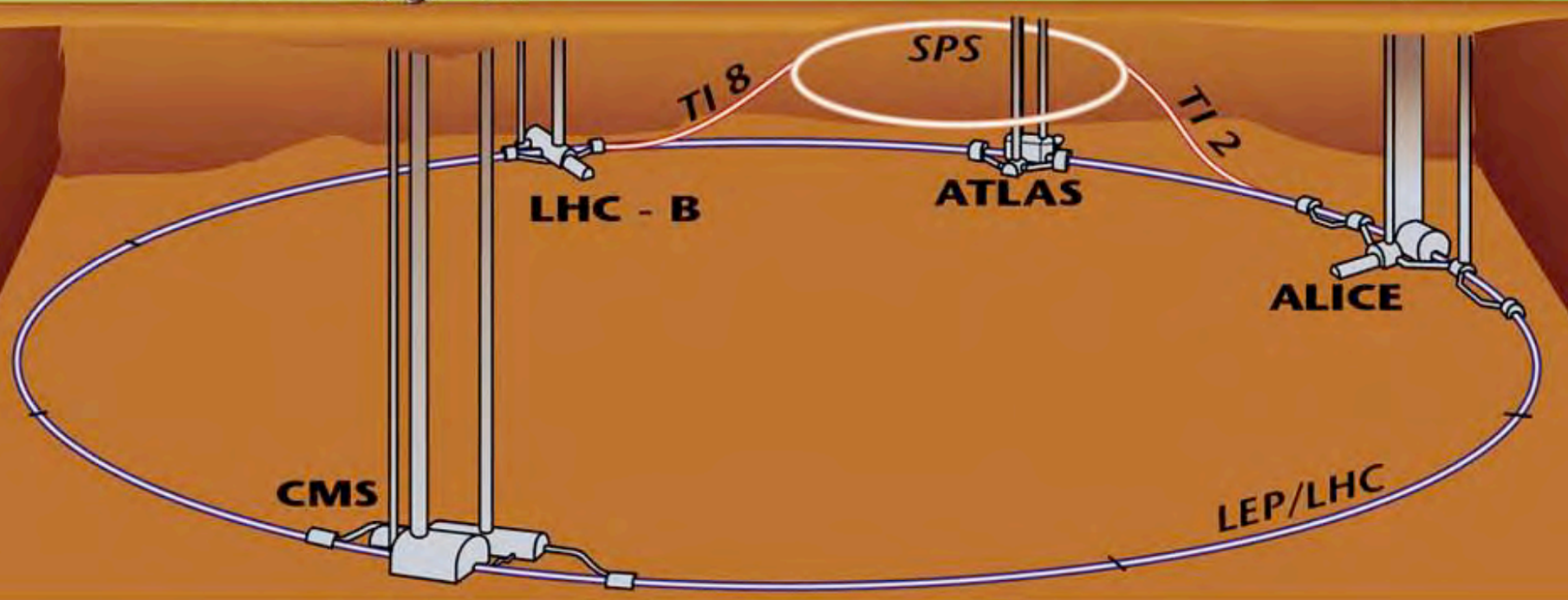
LHC - B
Point 8

CERN

ATLAS
Point 1

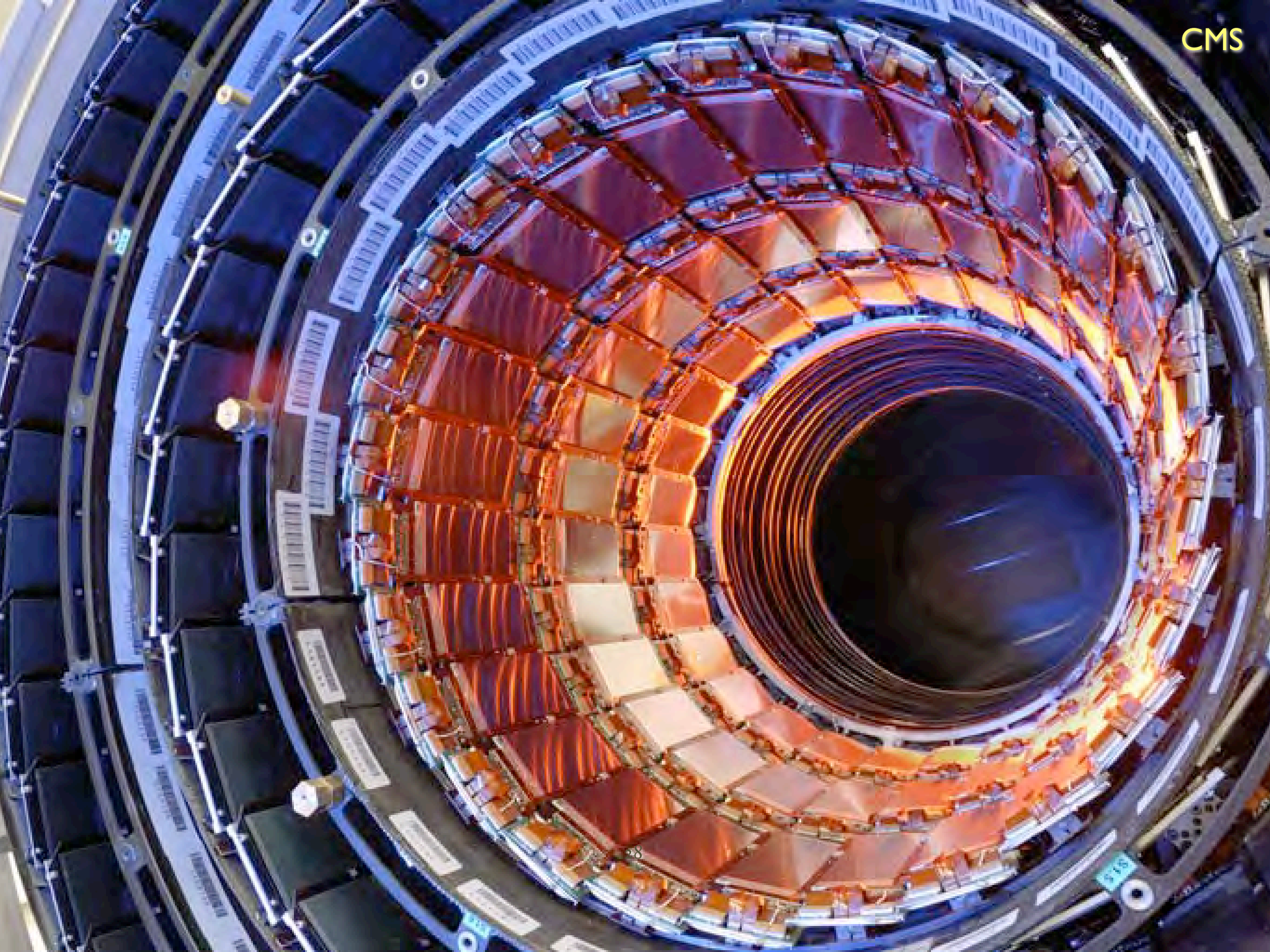
ALICE
Point 2

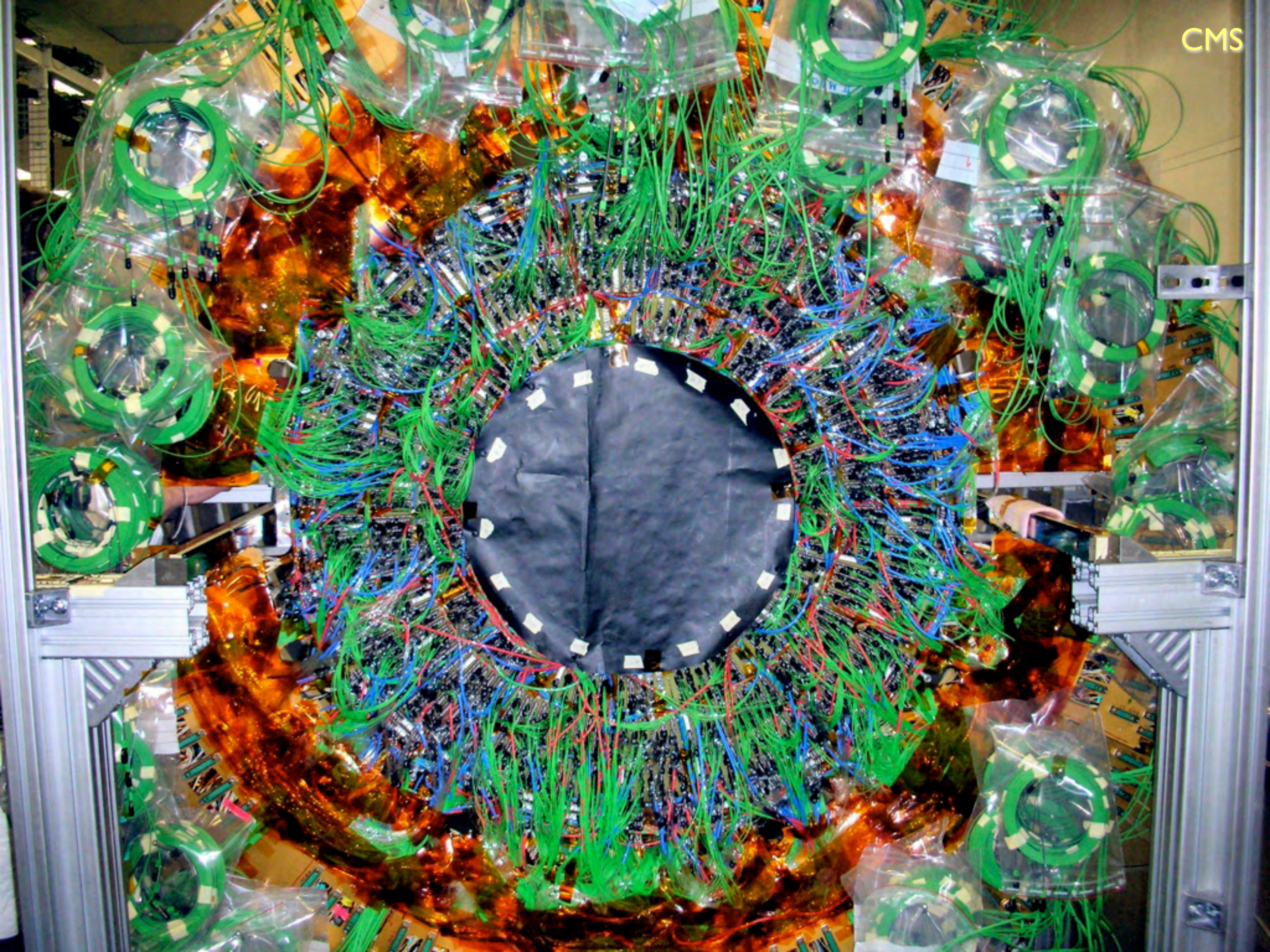
CMS
Point 5



E540 - V10/09/97

CMS


CMS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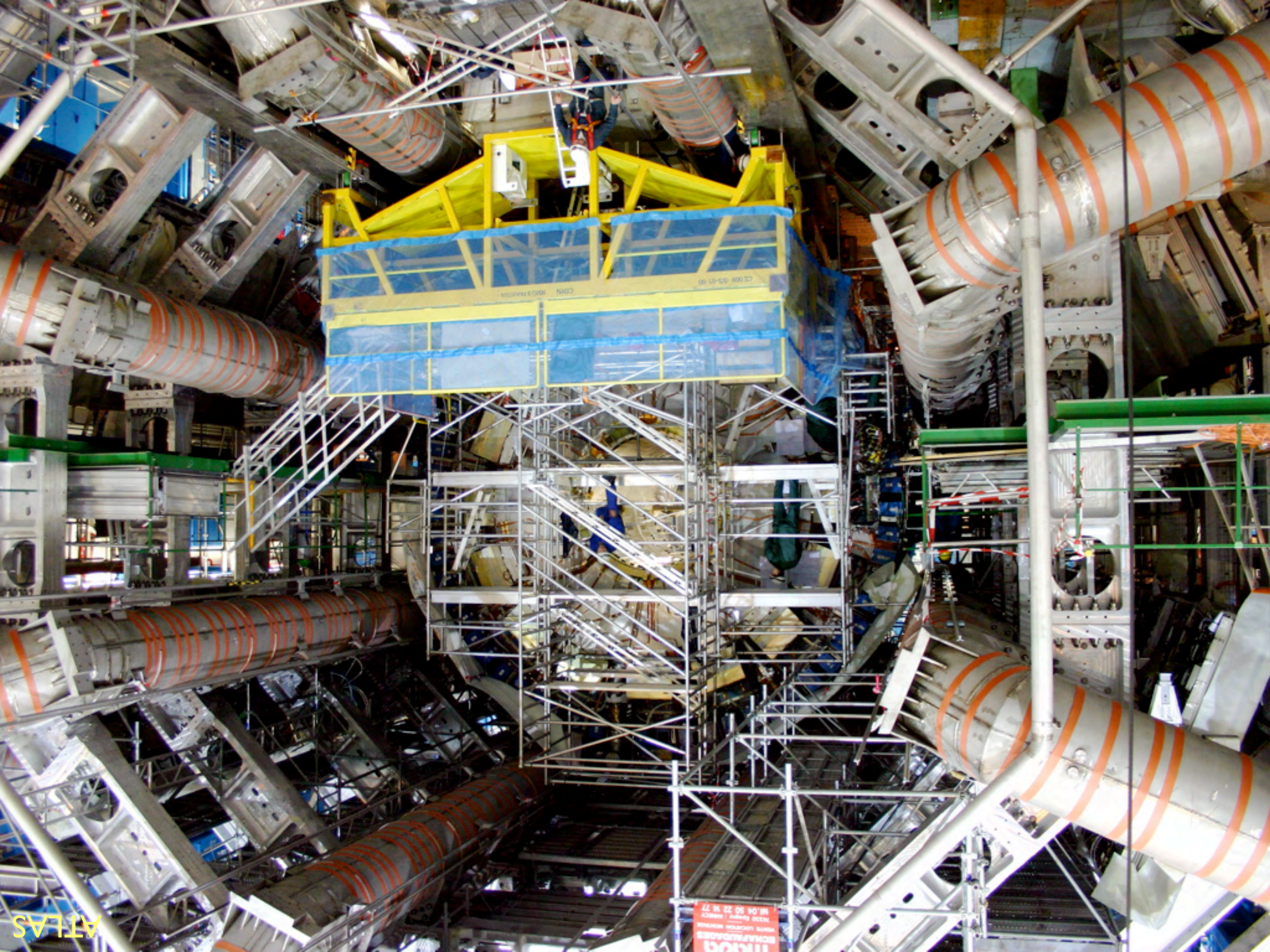

ATLAS

ATLAS

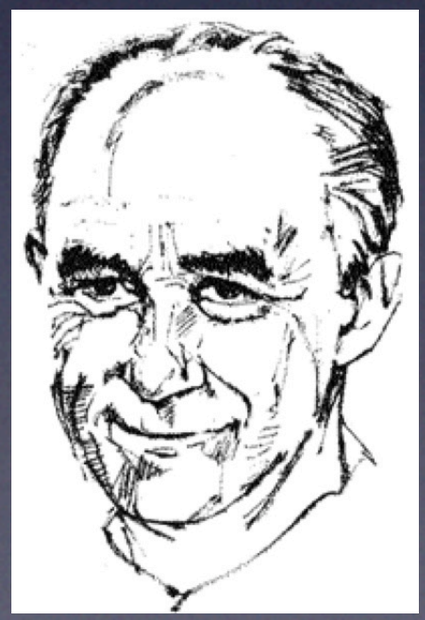
ALICE
ATLAS
max
AREA
B

What the LHC is *not* really for …

1. Find the Higgs boson,
 the Holy Grail of particle physics,
 the source of all mass in the Universe.
2. Celebrate.
3. Then particle physics will be over.

We are not ticking off items on a shopping list …

We are exploring a vast new terrain
… and reaching the Fermi scale



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Revolution:

The Meaning of Identity

Varieties of matter

- ▷ What sets masses and mixings of quarks and leptons?
- ▷ What is $\mathcal{CP}$ violation trying to tell us?
- ▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the Universe.

All fermion masses and mixings mean new physics

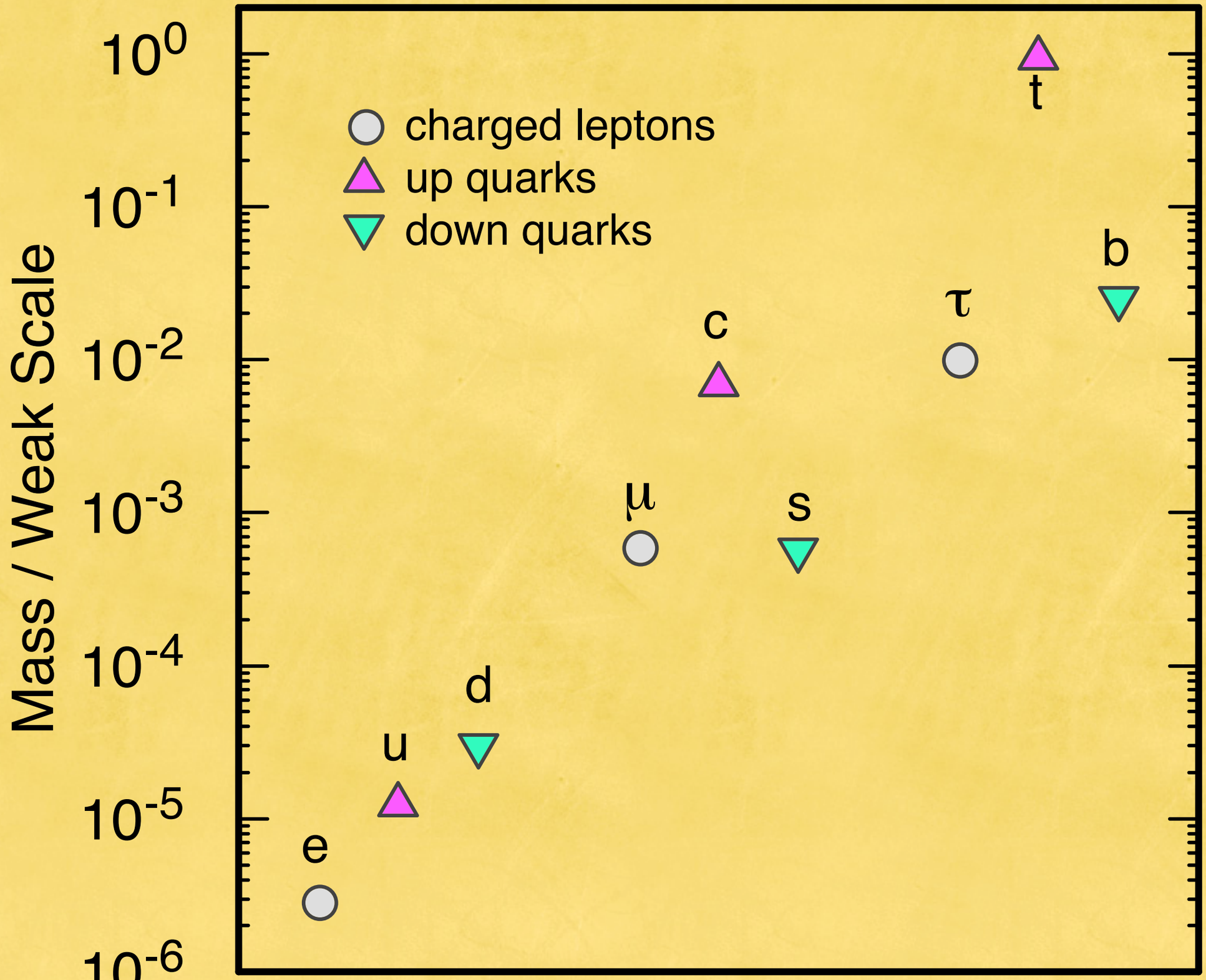
- ▷ Will new kinds of matter help us to see the pattern?

What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

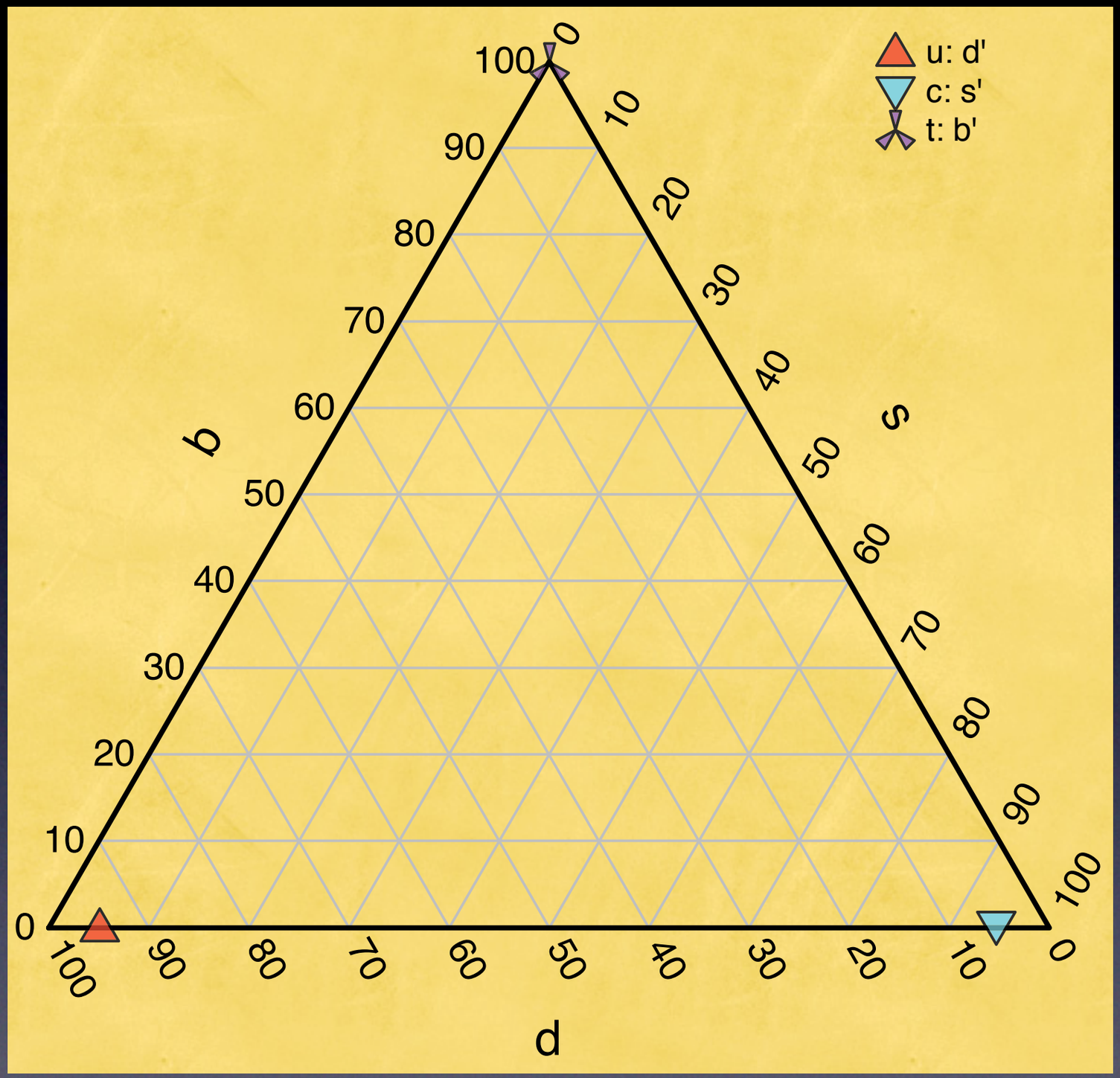
Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\mathsf{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase (+ Majorana . . .)
26^+	arbitrary parameters

Flavor physics may be where we see, or diagnose, the break in the SM.

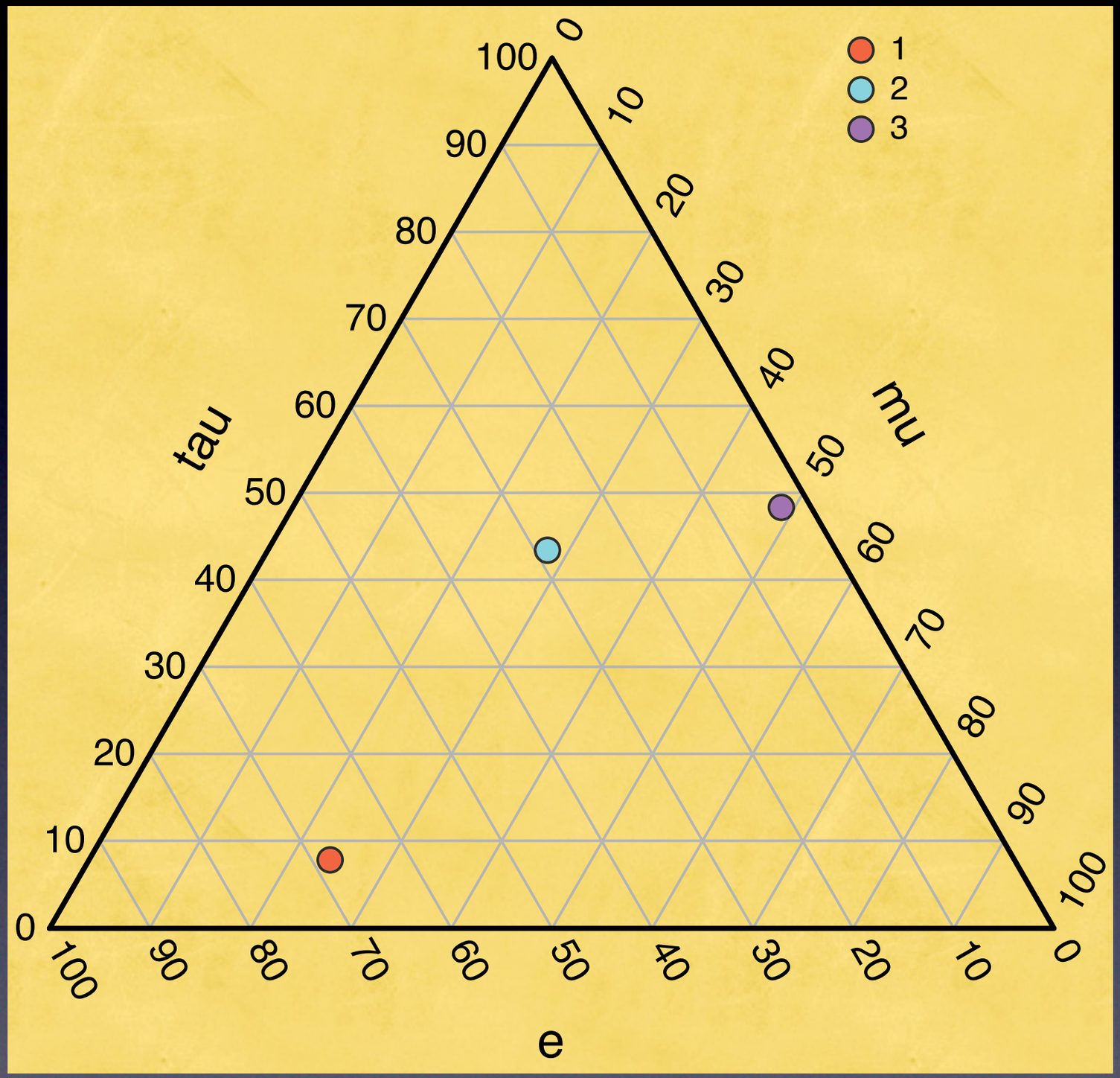

charged leptons
up quarks
down quarks
Mass / Weak Scale
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
t
b
τ
c
μ
s
d
u
e

Quark family patterns: *generations*

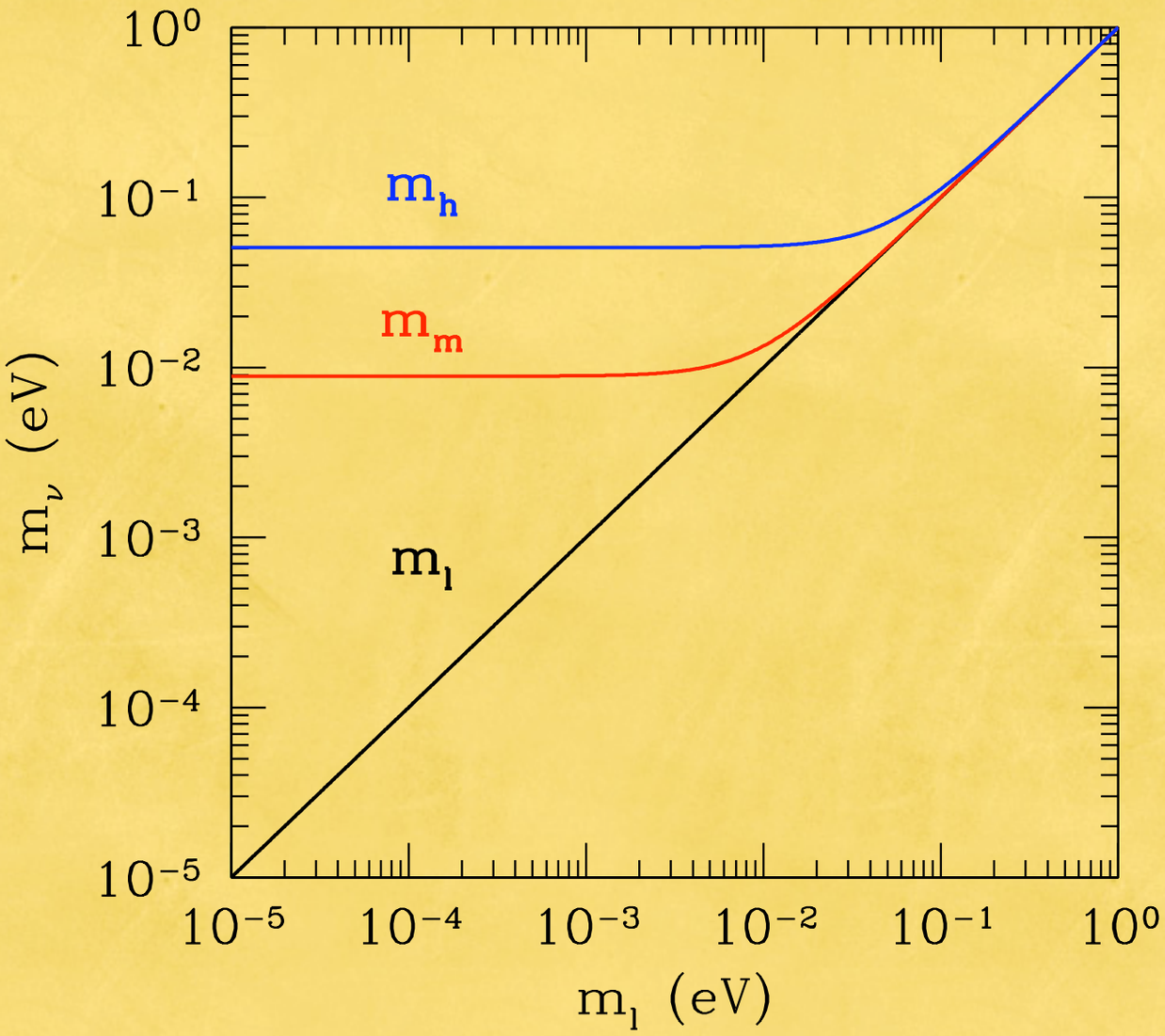


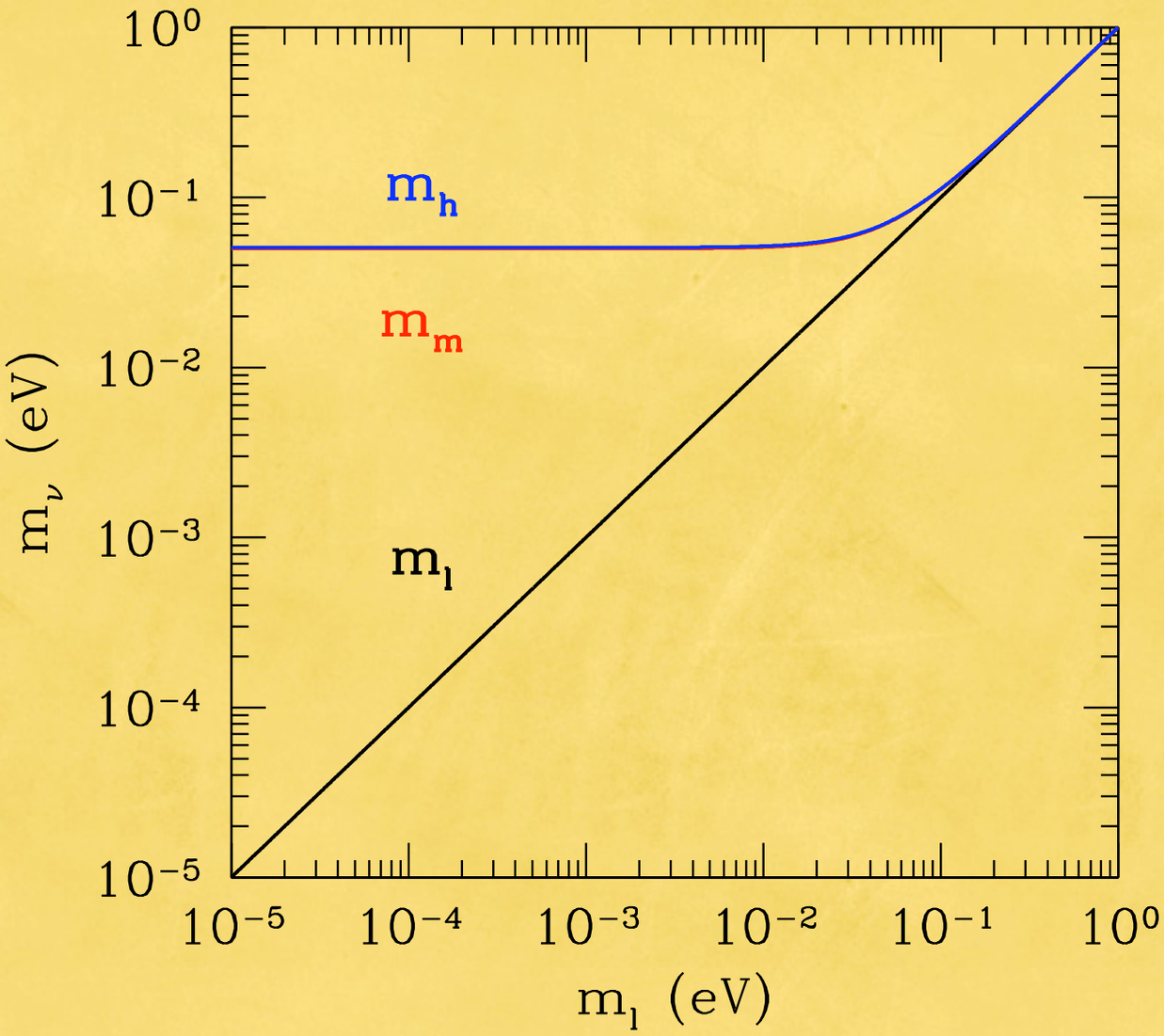
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns (an example)



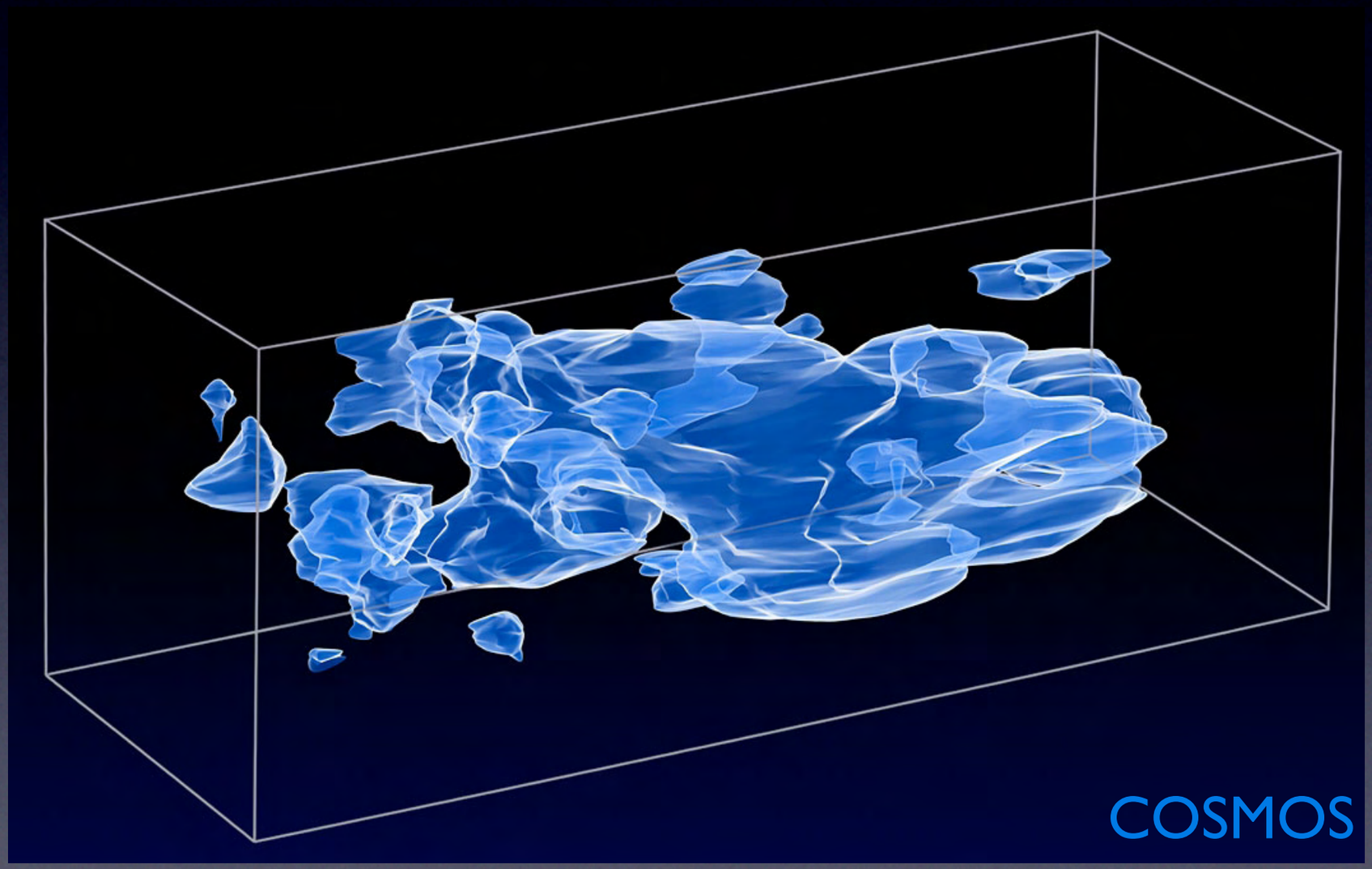
Neutrino Masses



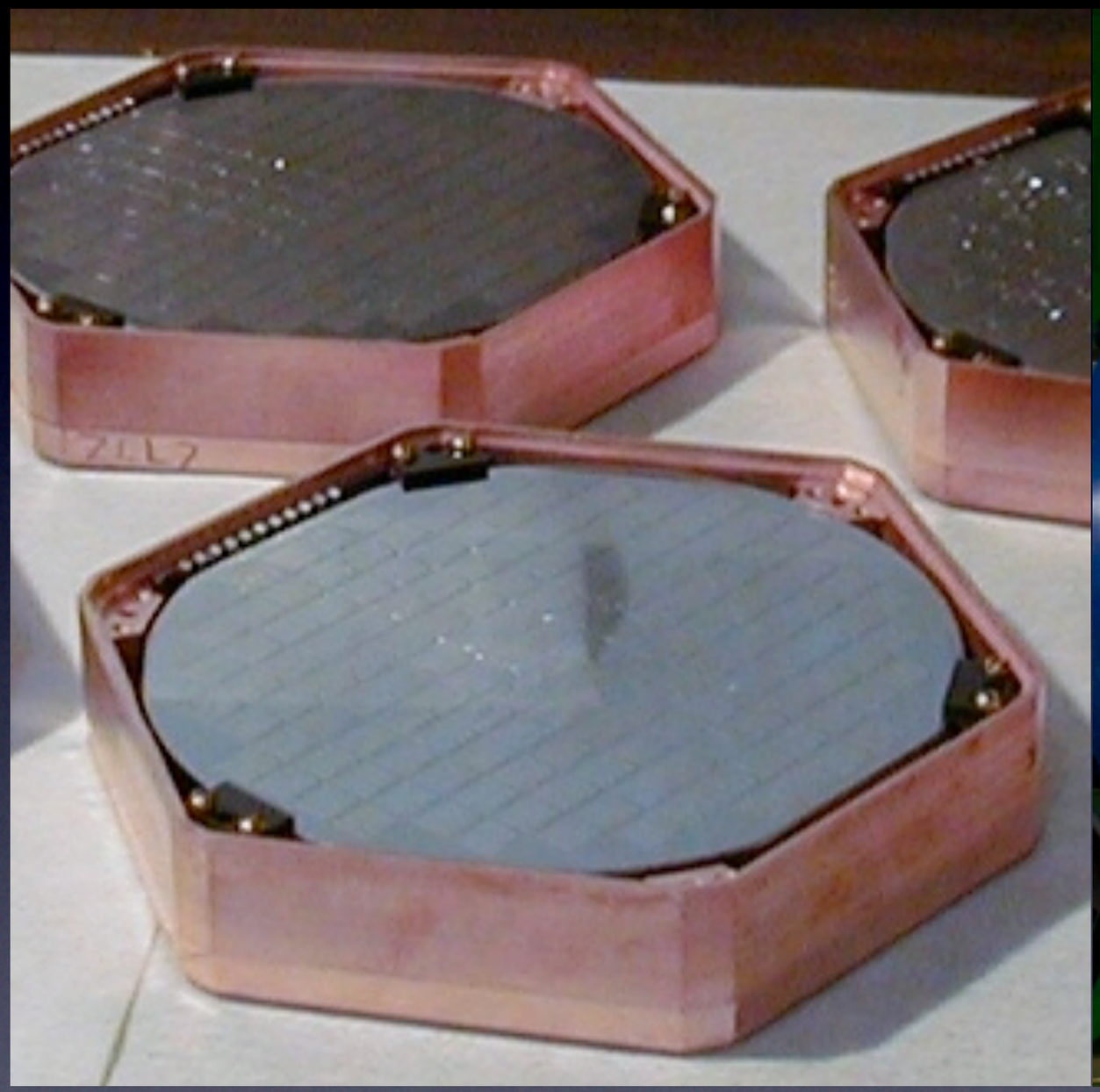


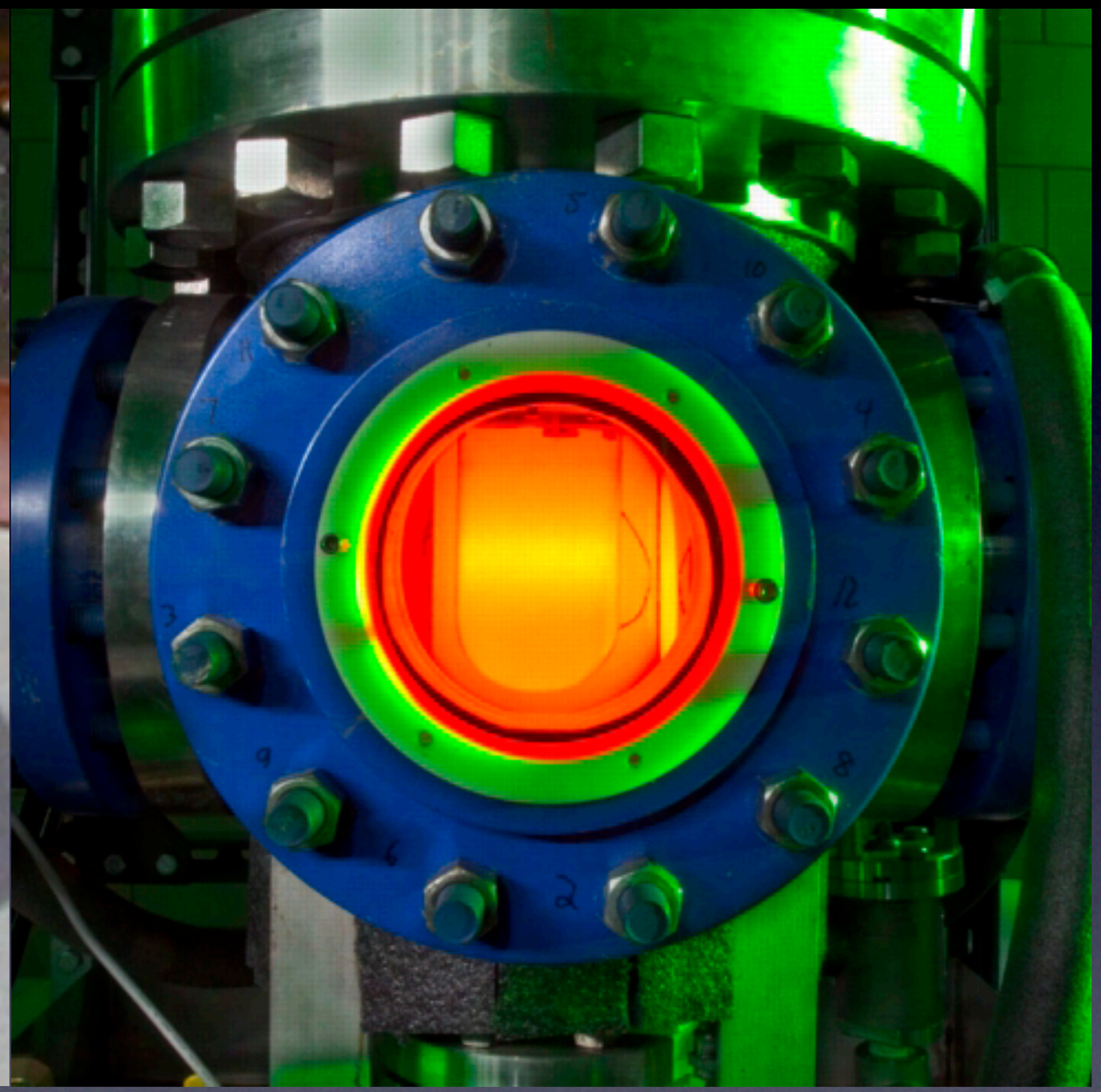
More New Physics on the Fermi Scale?

If dark matter interacts weakly …



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





Many extensions to EW theory entail dark matter candidates

Supersymmetry is highly developed, has several important consequences:

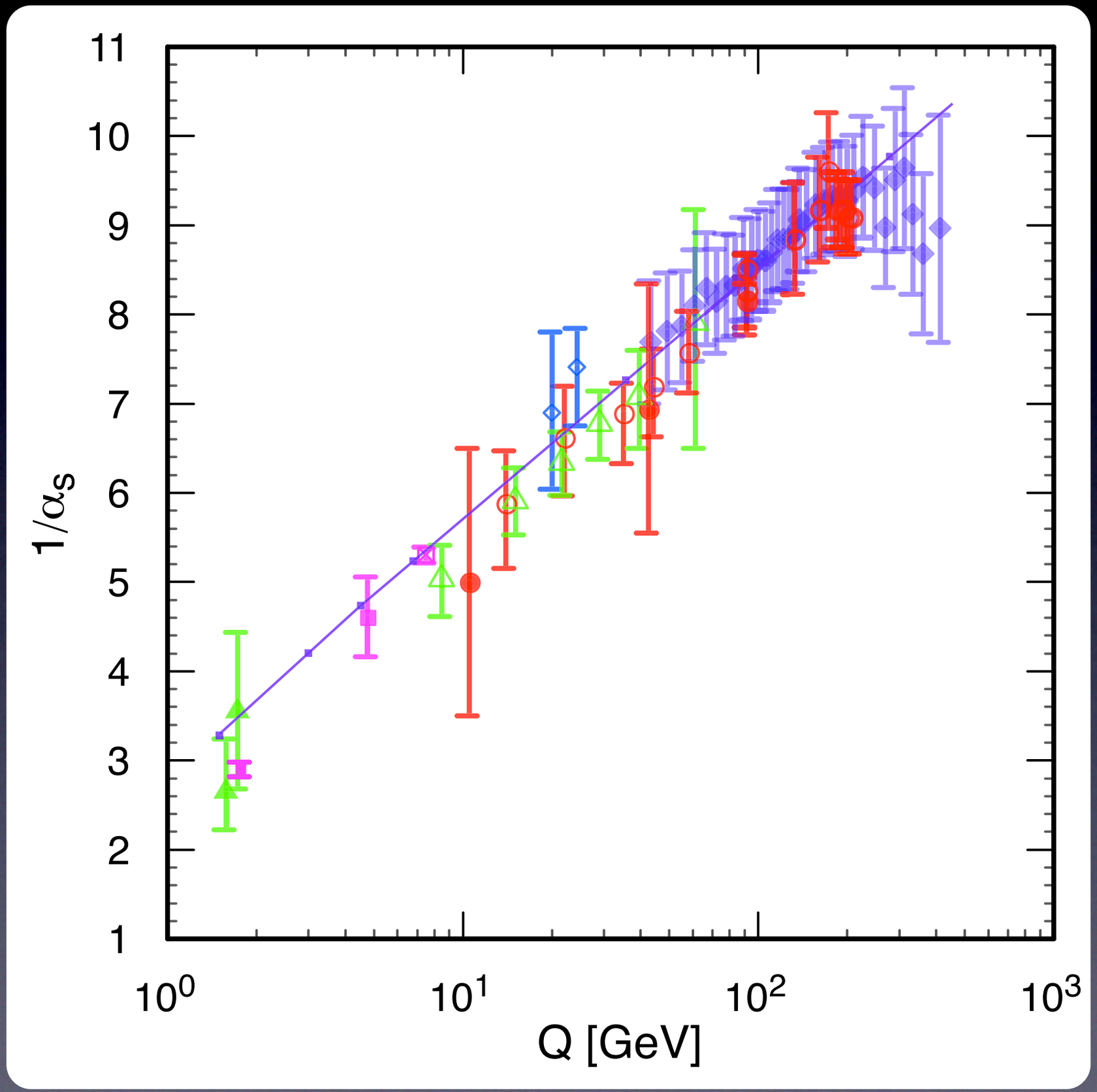
- ✳Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
- ✳Predicts a light Higgs mass
- ✳Predicts cosmological cold dark matter
- ✳In a unified theory, explains the values of standard-model coupling constants

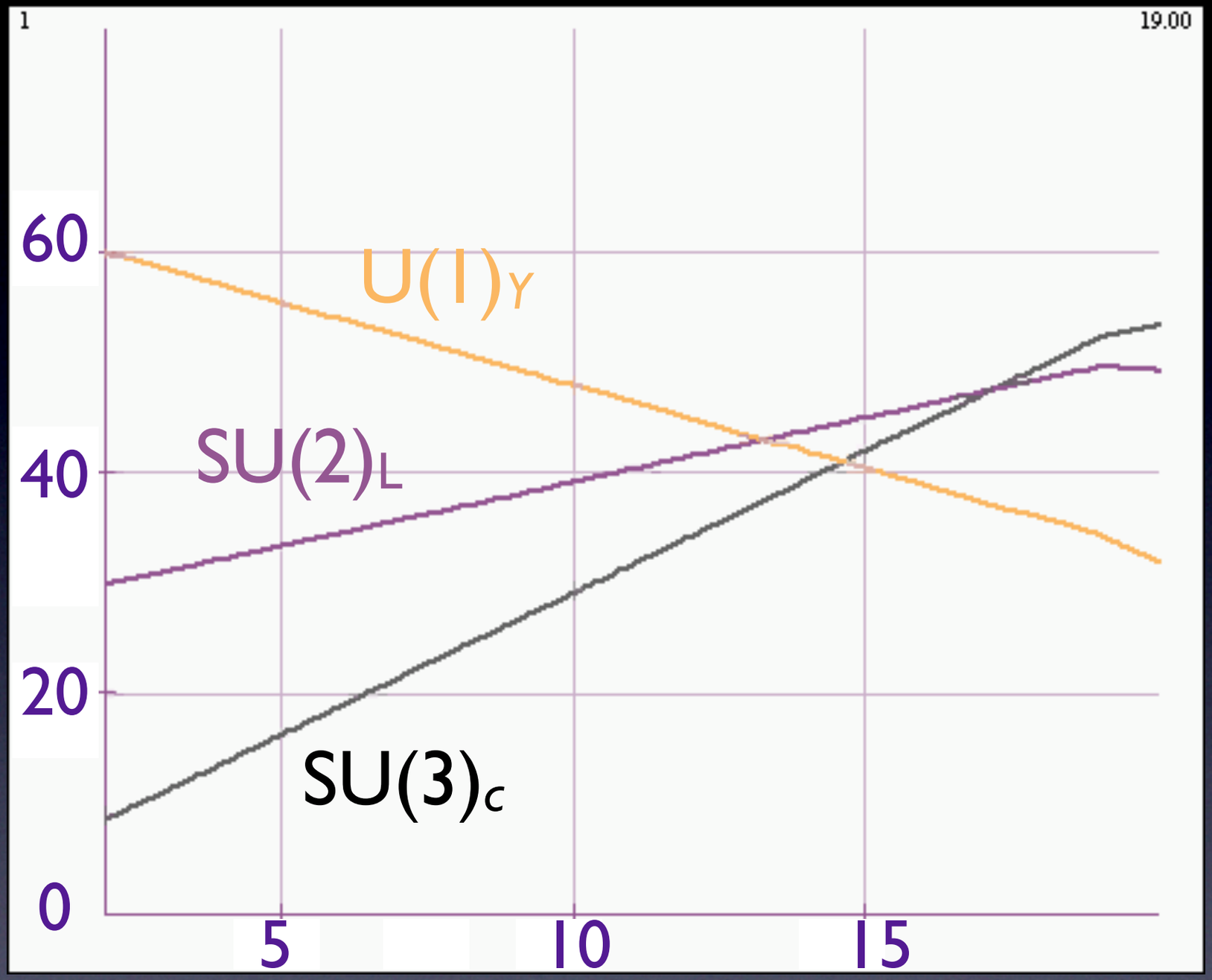
Revolution:

The Unity of Quarks & Leptons

- ▷ What do quarks and leptons have in common?
- ▷ Why are atoms so remarkably neutral?
- ▷ Which quarks go with which leptons?
- ▷ Quark-lepton extended family $\rightsquigarrow$ proton decay:
SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
- ▷ Unified theories $\rightsquigarrow$ coupling constant unification
- ▷ Rational fermion mass pattern at high energy?
(Masses run, too)

Evolution of the strong coupling "constant"




1
19.00
60
40
20
0
5
10
15
$U(1)_Y$
$SU(2)_L$
$SU(3)_c$
$1/\alpha$
$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$

Particle Physics rejoins Gravity rejoins Particle Physics

Natural to neglect gravity in particle physics

$$G_{\text{Newton}} \textit{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV } \textit{large}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

But gravity is not always negligible ...

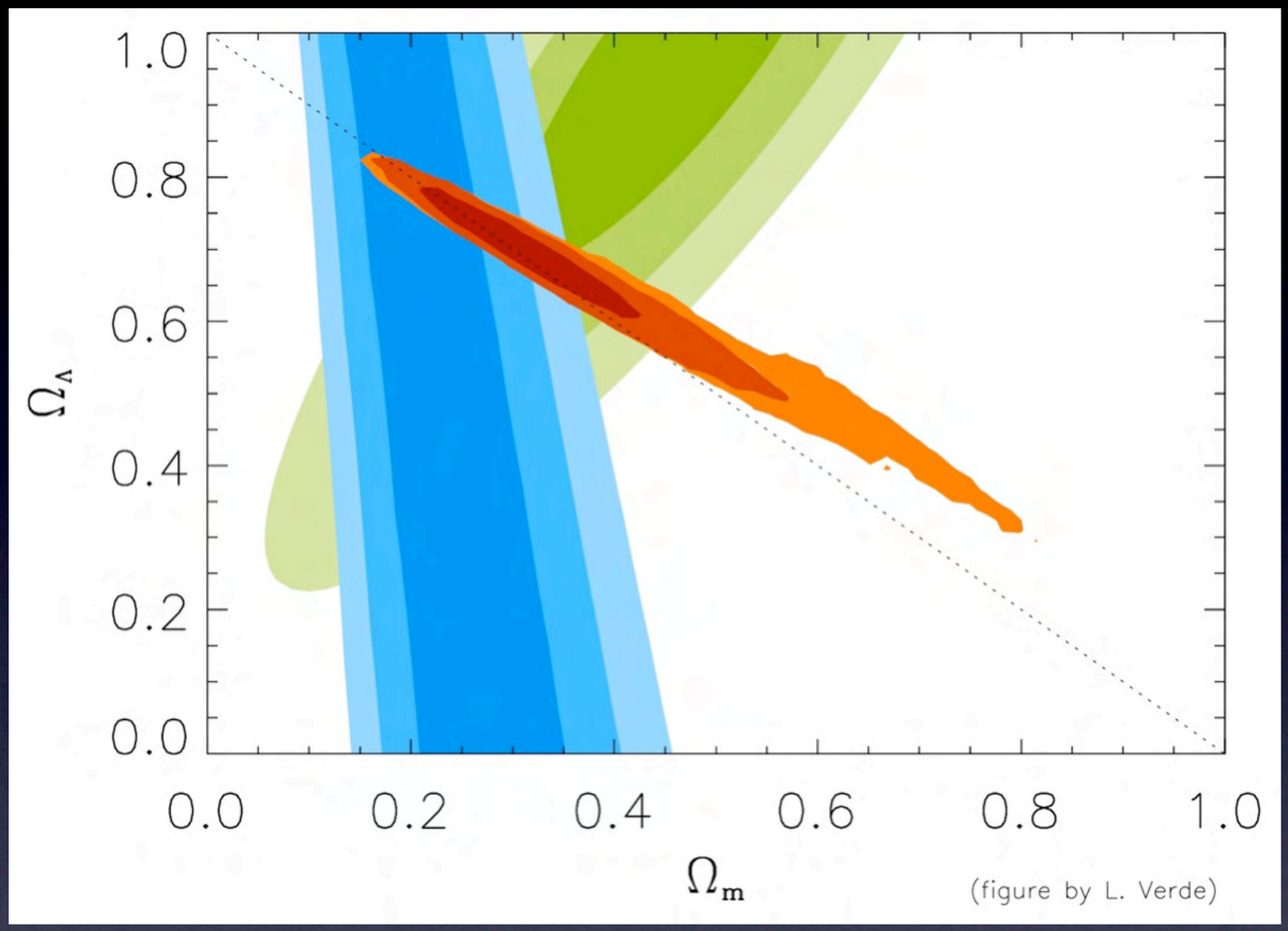
Higgs field contributes uniform vacuum energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{24} \text{ g cm}^{-3}$$

Observed vacuum energy density $\varrho_{\text{vac}} \leq 10^{-46}$ GeV^4

Mismatch by 54 orders of magnitude

Evidence that vacuum energy is present …



recasts old problem, gives us properties to measure

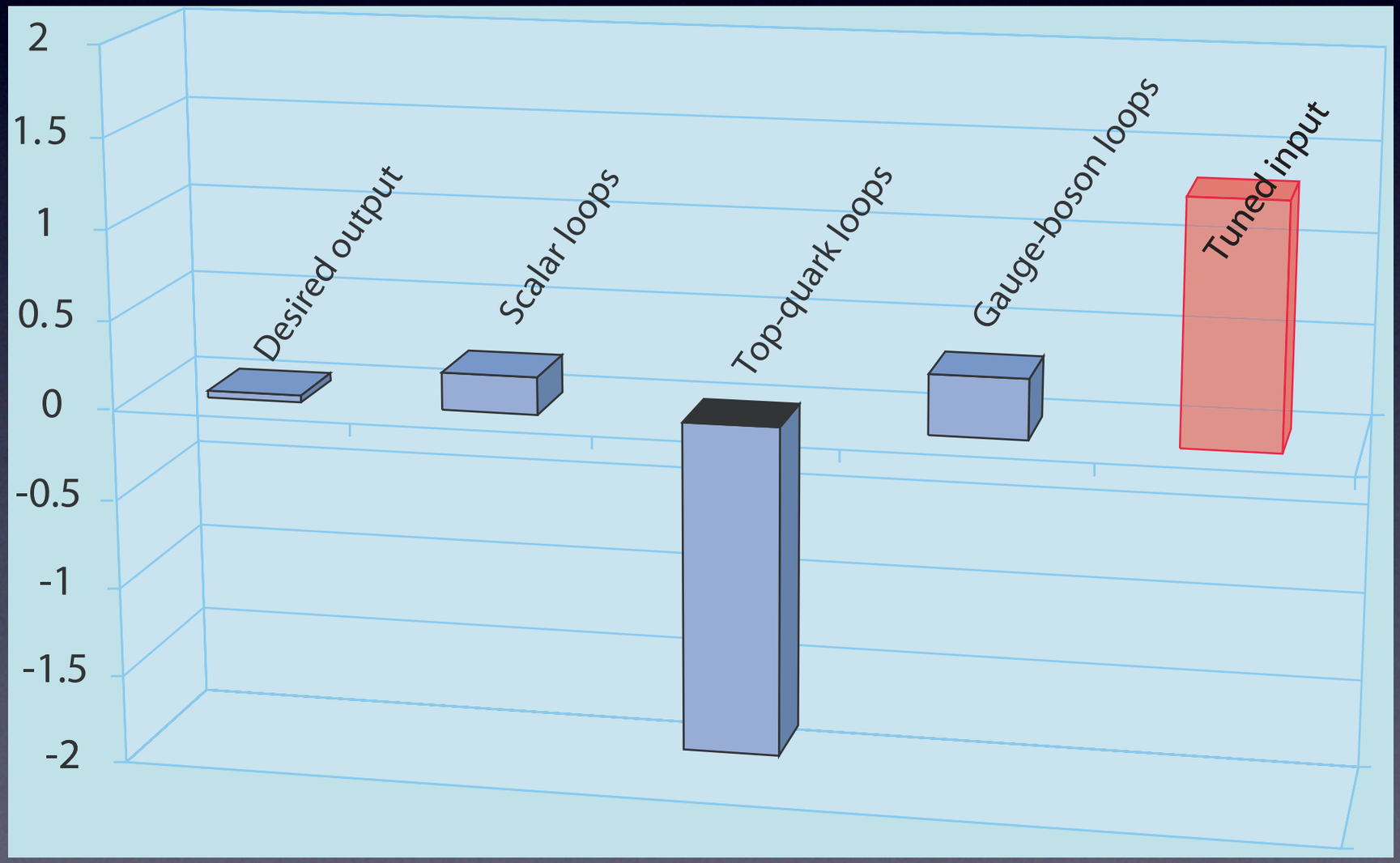
A chronic dull headache for thirty years …

Why is empty space so nearly massless?

How to separate EW, higher scales?

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



5 TeV

How to separate EW, higher scales?

Traditional: change electroweak theory to understand why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

composite Higgs boson

technicolor / topcolor

supersymmetry

…

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Ask instead why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale

Revolution:

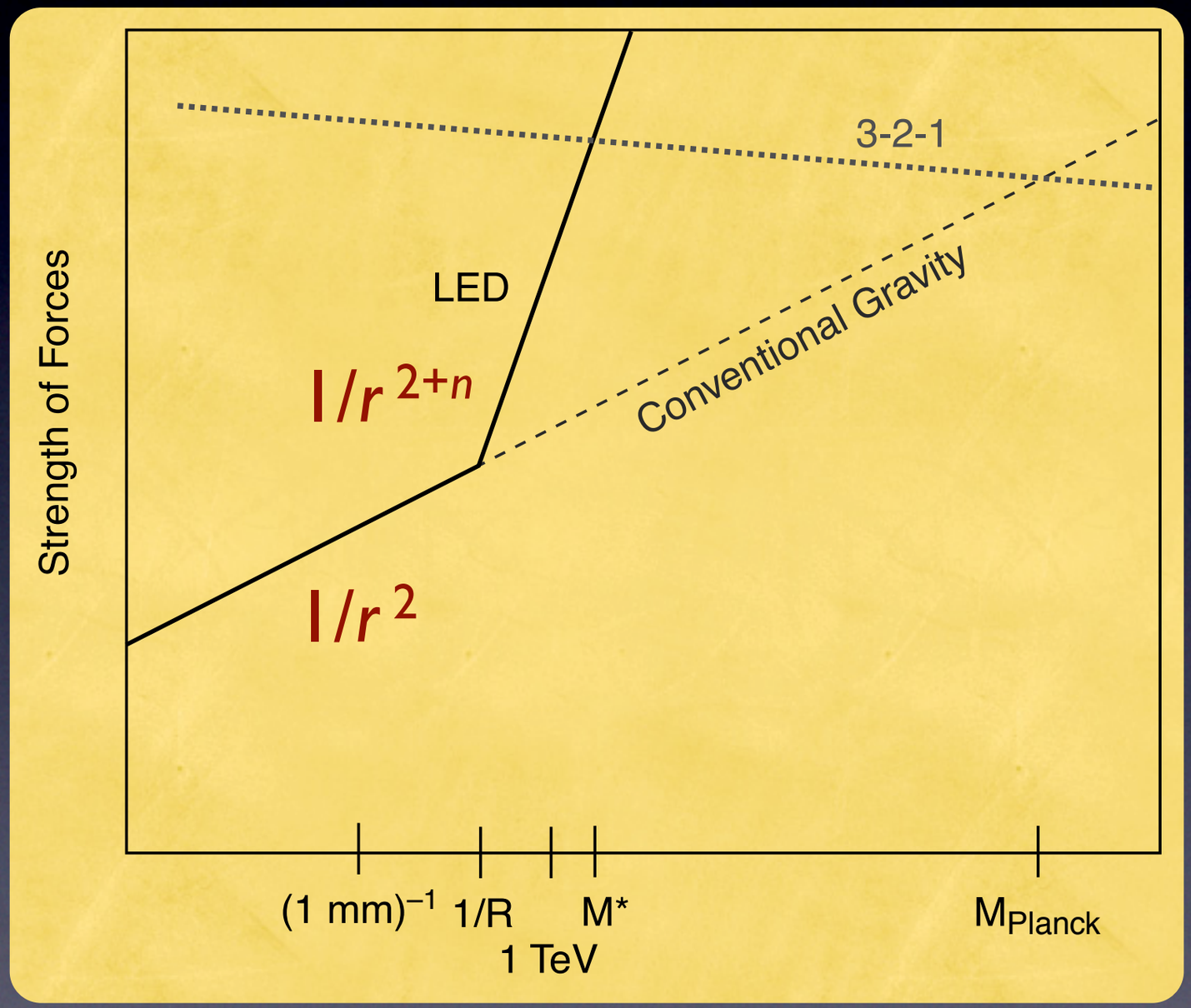
A New Conception of Spacetime

- Could there be more space dimensions than we have perceived?
- What is their size? Their shape?
- How do they influence the world?
- How can we map them?

string theory needs 9 or 10

Suppose at scale *R* … gravity propagates in 4+*n* dimensions

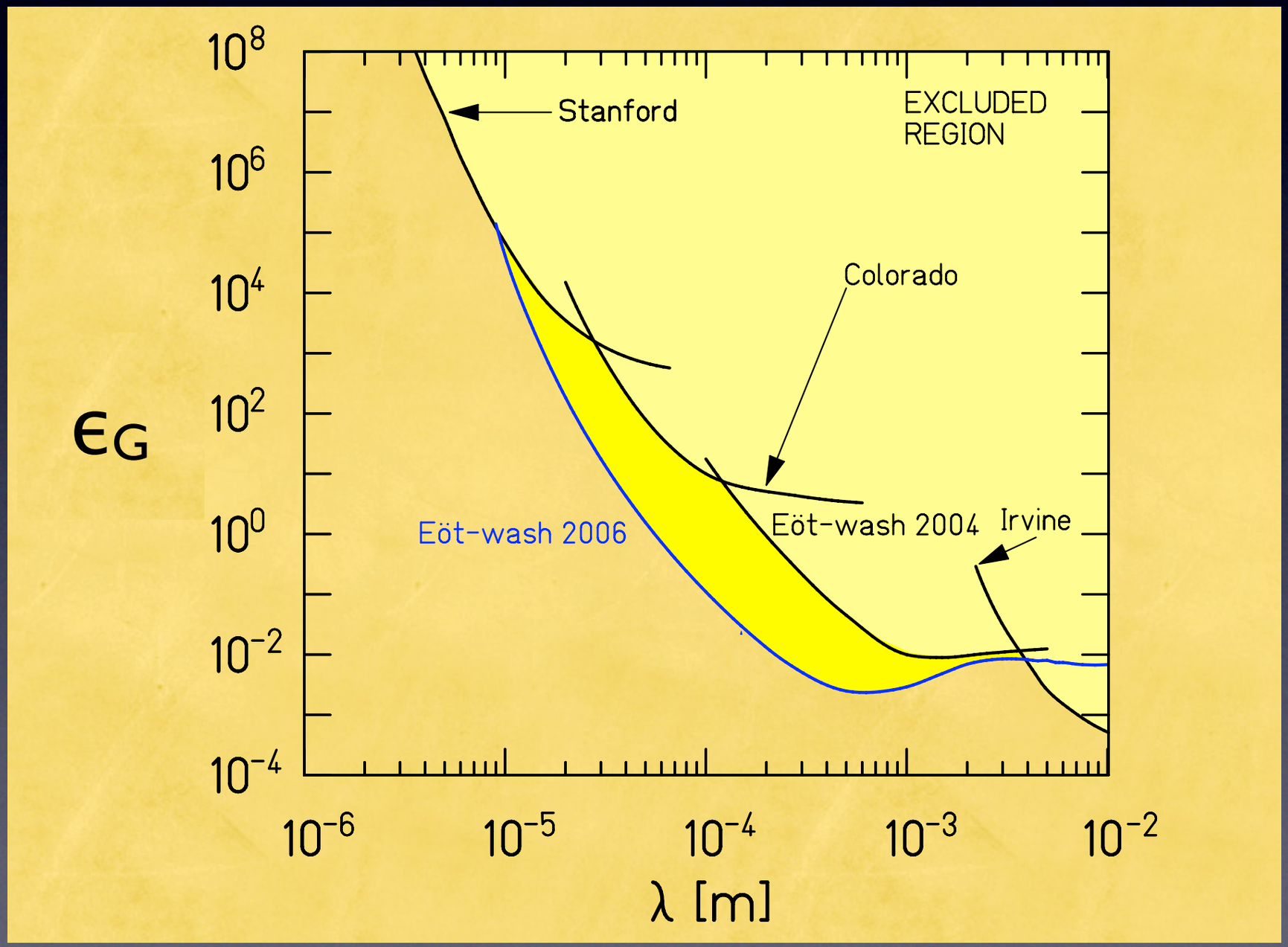
Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ M^* : gravity's true scale



M_{Planck} would be a mirage!

Gravity follows Newtonian force law down to $\lesssim$ 1 mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}}\left[1 + \varepsilon_{\text{G}}\exp(-r_{12}/\lambda_{\text{G}})\right]$$



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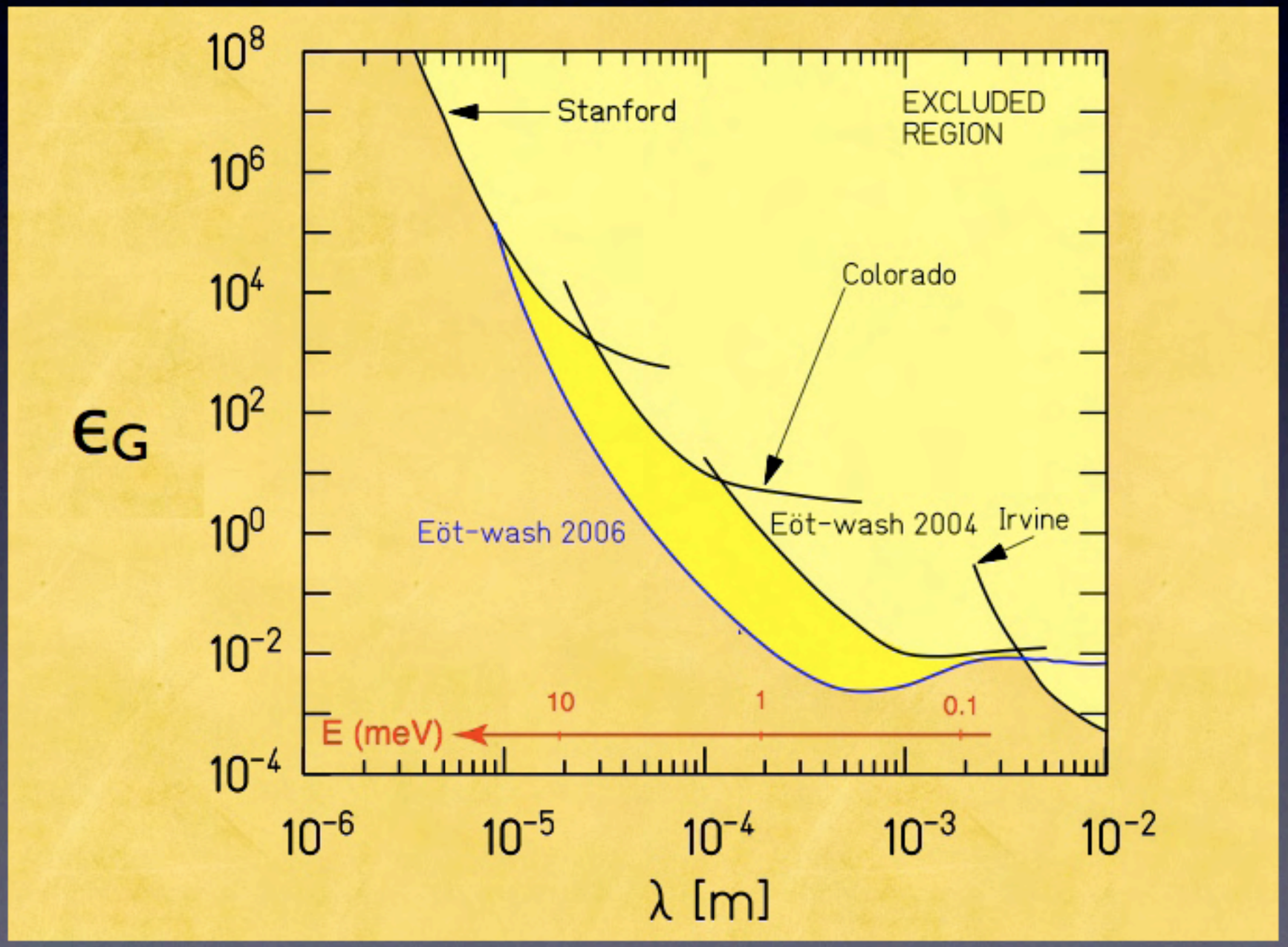

Connections …

In a decade or two, we can hope to …

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in *B* decays
Exploit rare decays (*K*, *D*, …)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

… learn the right questions to ask
… and rewrite the textbooks!