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I would like to know …

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?

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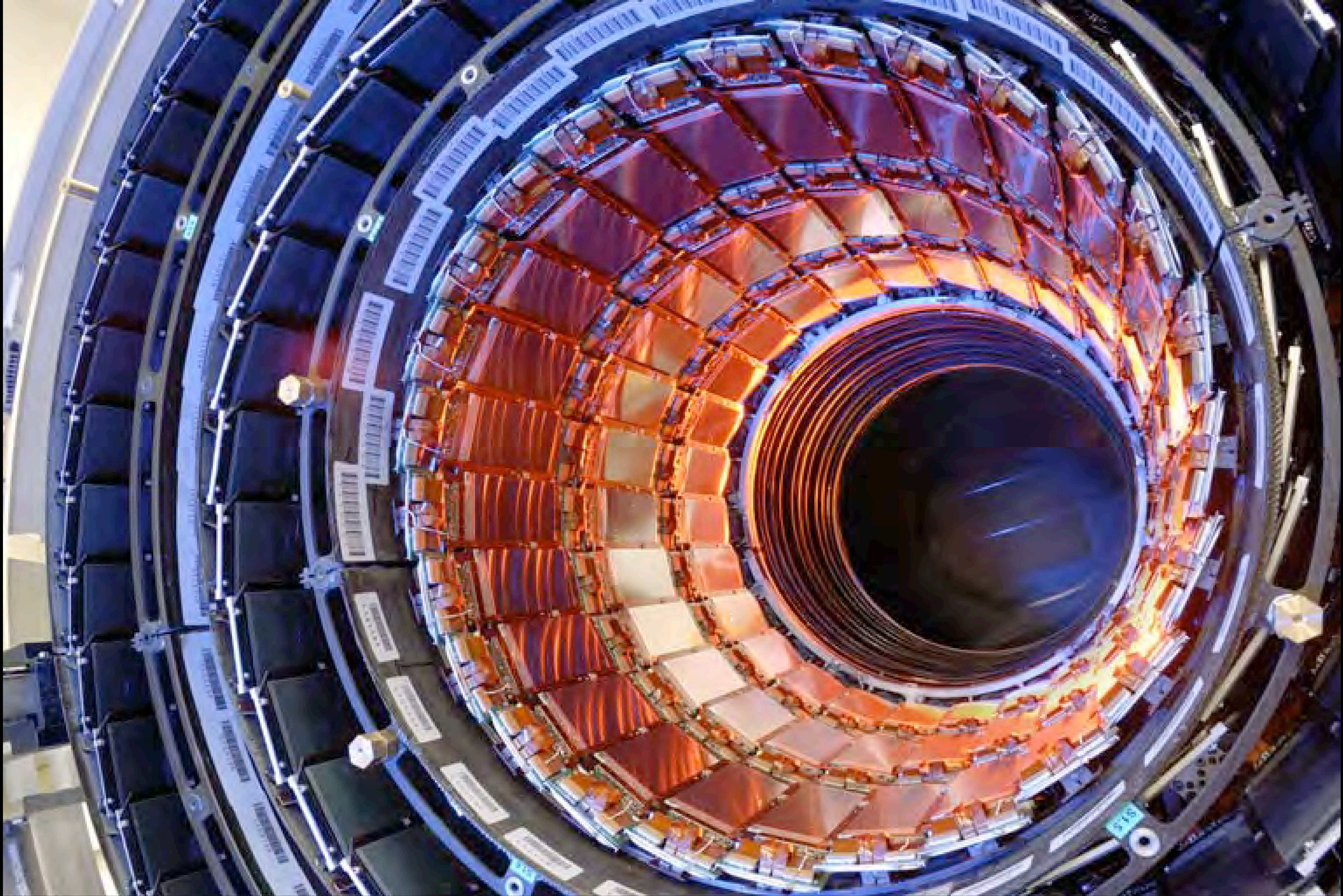
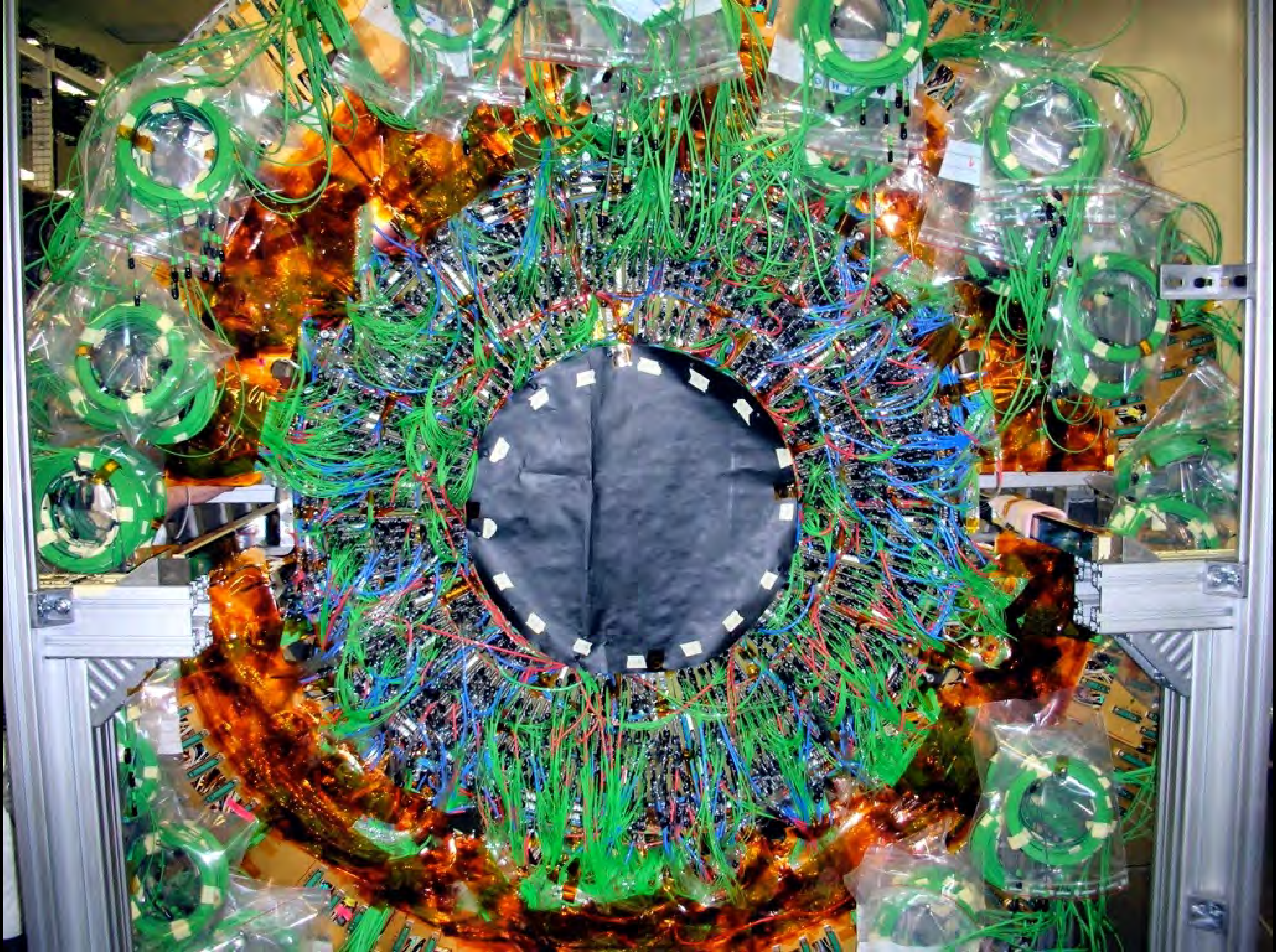




Problems of High-Energy Physics (NAL Design Report, January 1968)

We would like to have answers to many questions. Among them are the following:

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of "elementary" particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

What is the connection, if any, of electromagnetism and strong interactions?

Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

Is there some new particle underlying the action of the "weak" forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do "weak" interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem true? Do the total cross sections become constant at high energy? Will new symmetries appear, or old ones disappear, at higher energy?

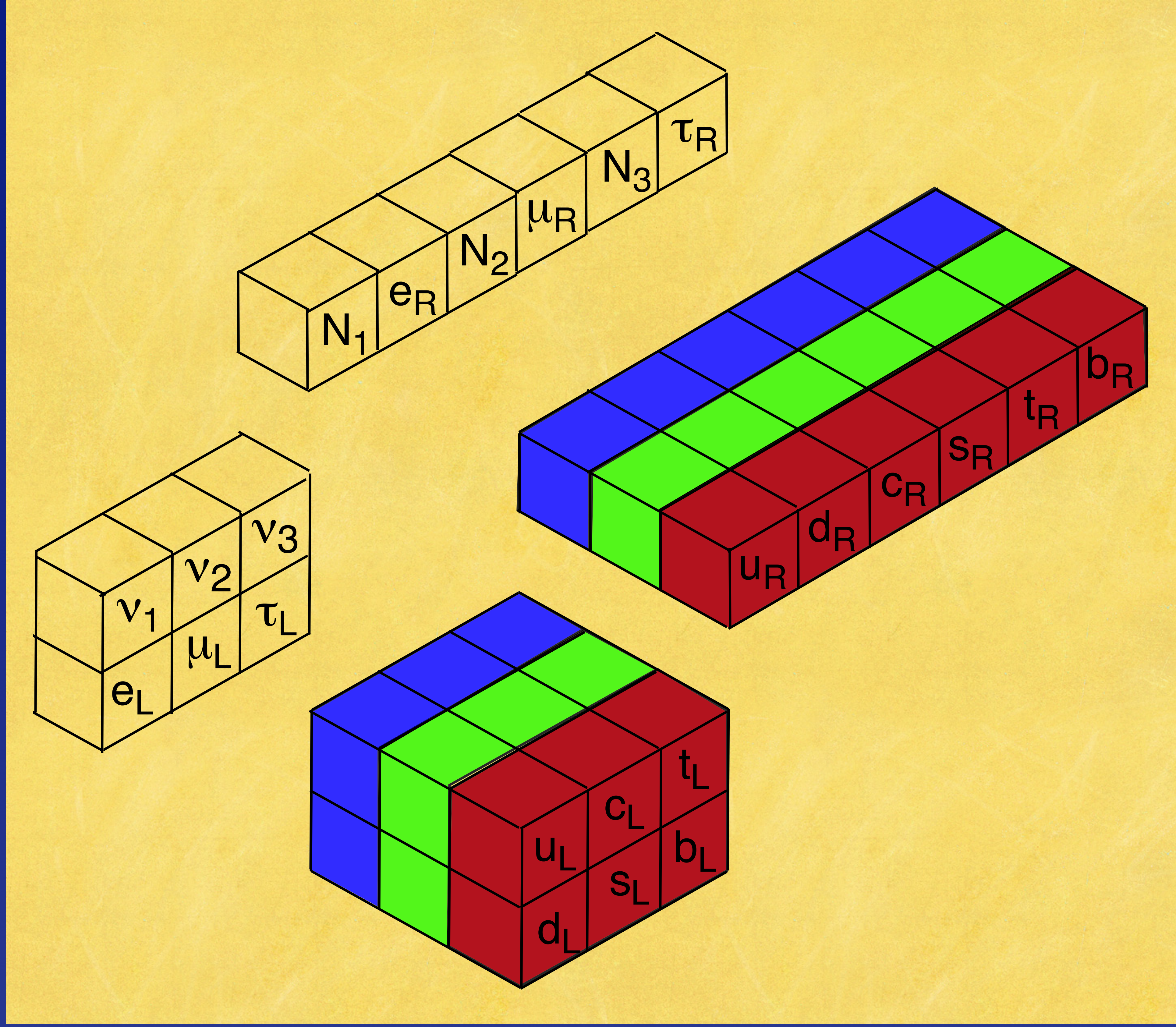
To-do / wish list for particle physics & friends, from 2005

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly study CP violation in B decay
Exploit rare decays (K, D, . . .)
Observe n EDM, pursue e^- EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover QCD's full implications
Observe proton decay
Understand the baryon excess
Catalogue matter & 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 dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate problem of identity

Before LHC

Two then-new Laws of Nature + pointlike *quarks* & *leptons*

We do not know
what the Universe
at large is made of.



Mendele'ev
did not know of
the noble gases.

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

8 gluons

Quantum Chromodynamics

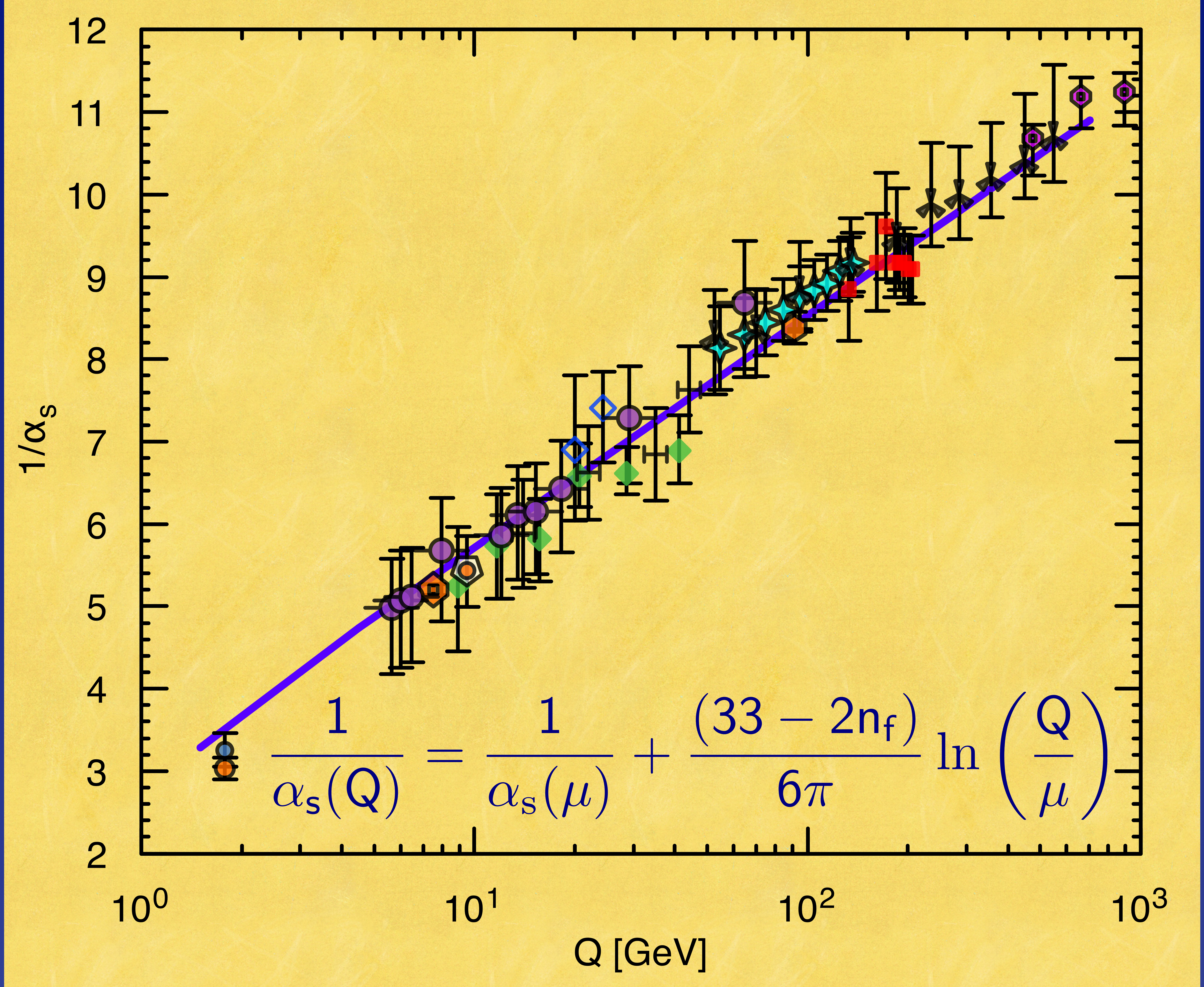
Dynamical basis for quark model

Gluons (vector force particles) mediate interactions among the quarks and experience strong interactions.

Contrast *photons*, which mediate interactions among charged particles, not among themselves.

Quark, gluon interactions $\Rrightarrow$ nuclear forces

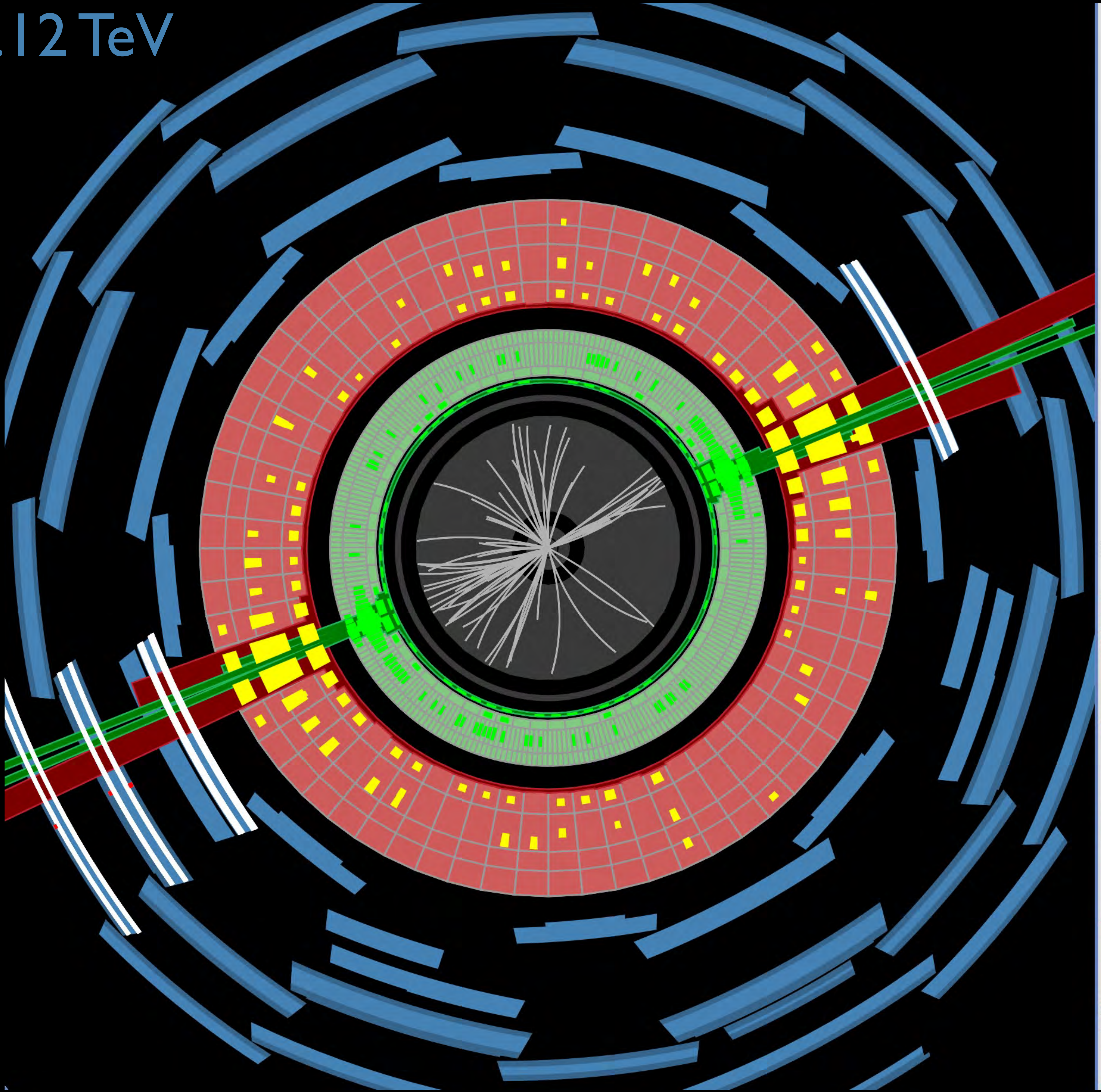
Antiscreening evolution of the strong coupling "constant"

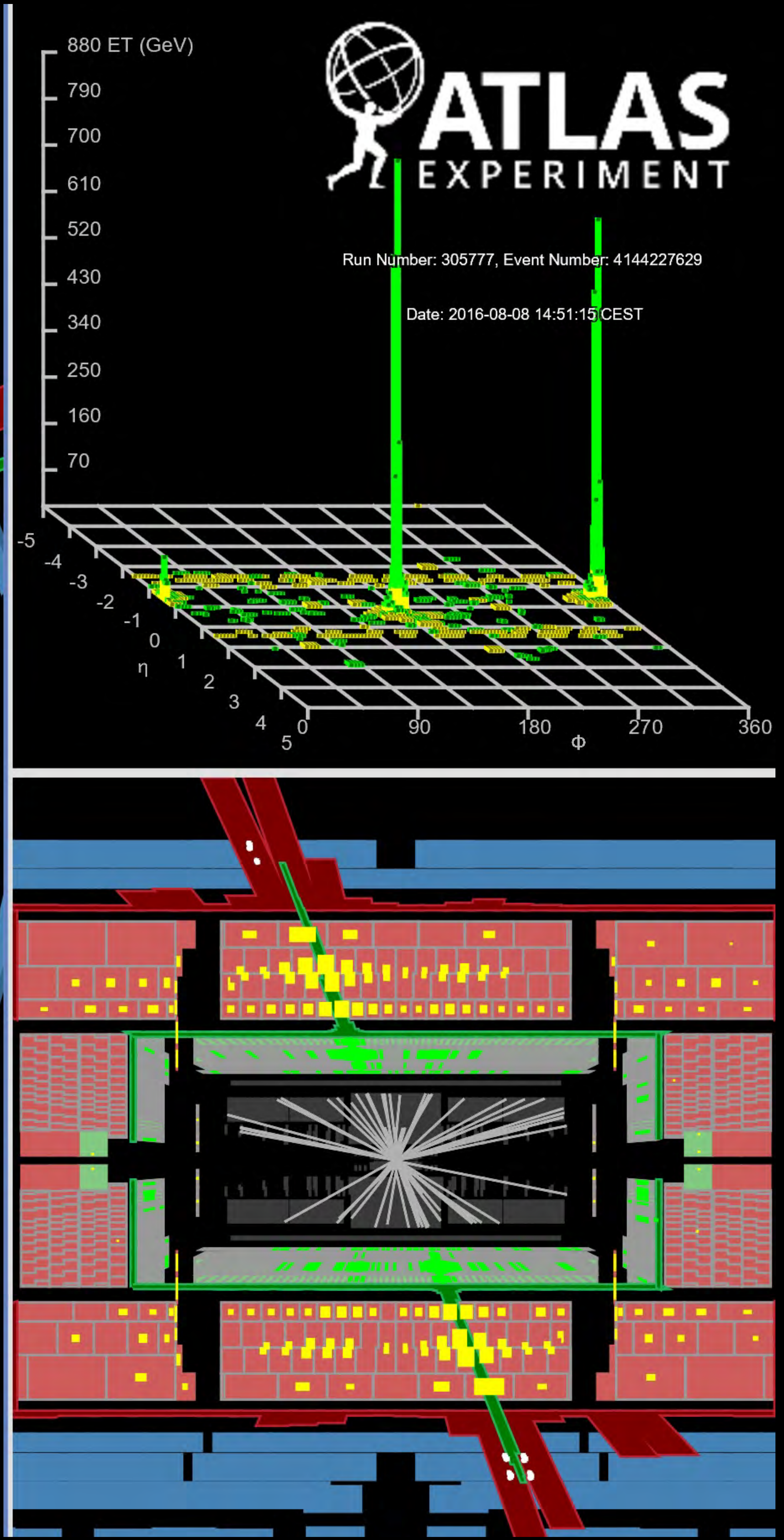


The World's Most Powerful Microscopes

nanonanophysics

8.12 TeV





sum of parts

rest energy

Nucleon mass (~940 MeV): exemplar of $m = E_0/c^2$

up and down quarks contribute few %

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

χPT: $M_N \hookrightarrow$ 870 MeV for massless quarks

QCD could be complete,* up to M_{Planck}

… but that doesn't prove it must be

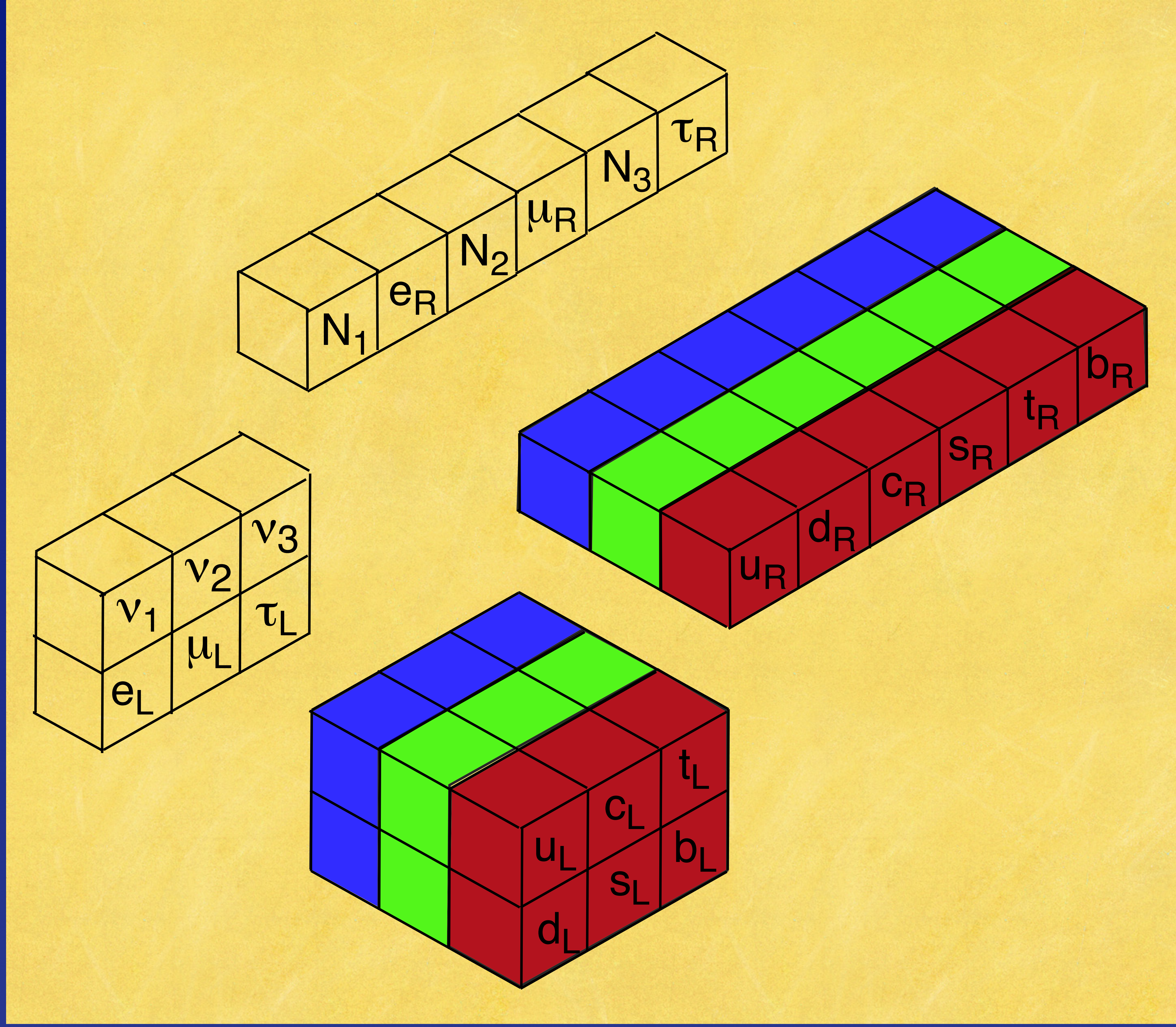
Prepare for surprises!

How might QCD Crack?

(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing QCD – *massive gluon partners?*

*modulo Strong CP Problem

Electroweak Symmetry Breaking



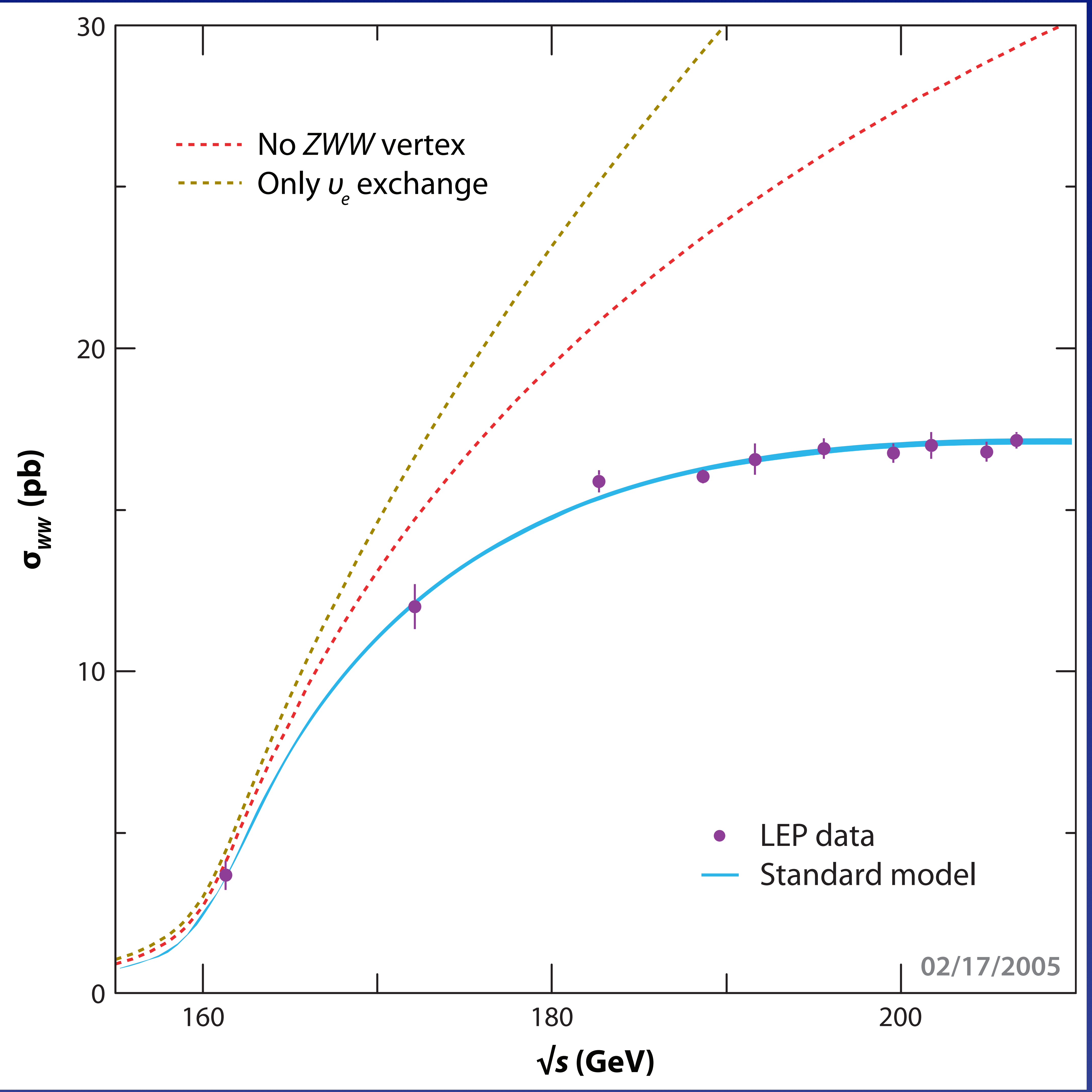
$U(1)_{EM}$

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

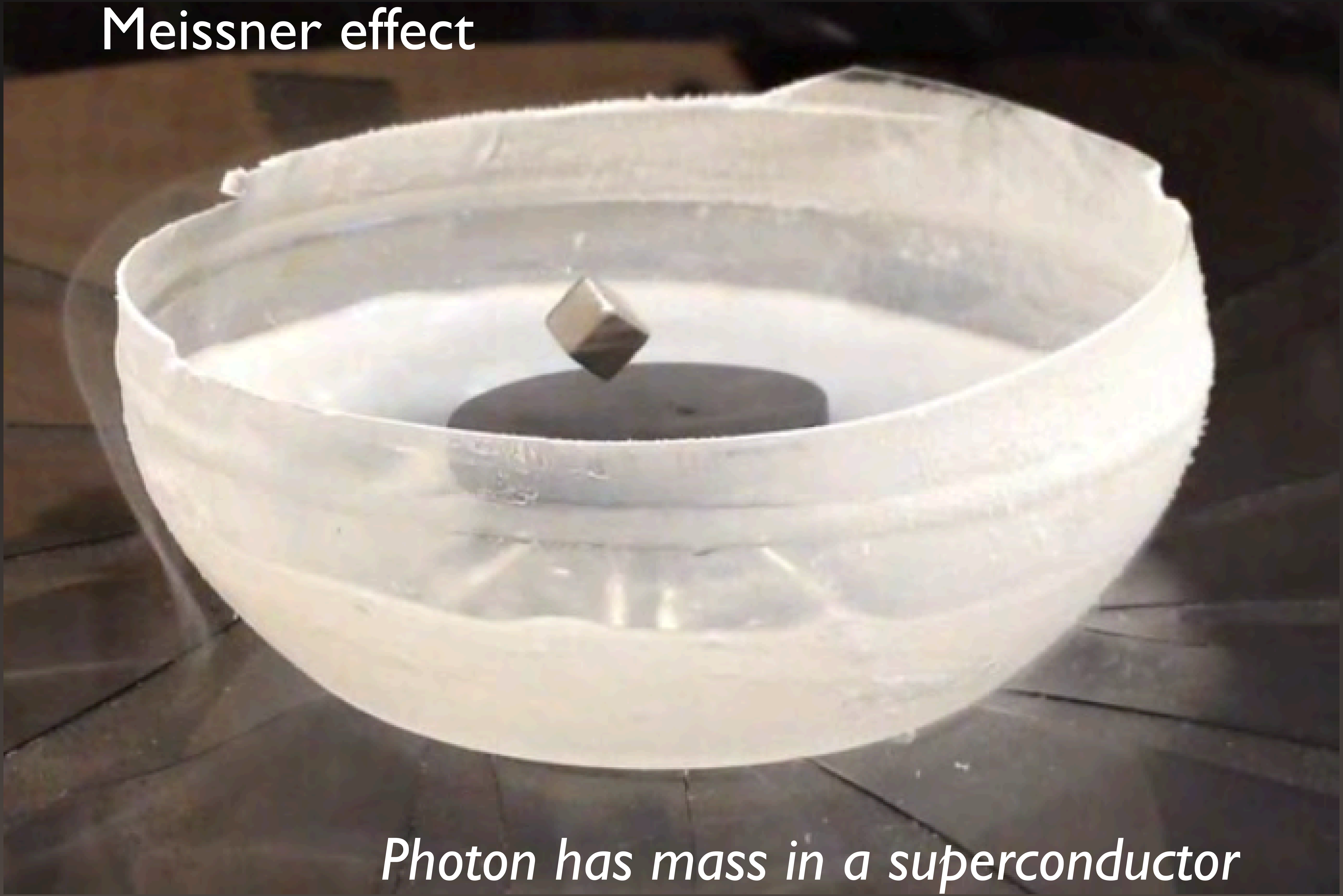
8 gluons $W^{\pm} \cdot Z^0 \cdot$ □

Gauge symmetry (group-theory structure) tested in

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



Meissner effect



Photon has mass in a superconductor

Spontaneous symmetry breaking

Higgs Kibble† Guralnik† Hagen Englert Brout†

1964– : Goldstone theorem doesn't apply to gauge theories!
Each would-be massless NGB joins with a would-be massless gauge boson to form a massive gauge boson.

Simplest example: Abelian Higgs model
= Ginzburg–Landau in relativistic notation

Yields massive photon
+
a massive scalar particle
“Higgs boson”

No mention of weak interactions.

No question of origin of fermion masses
(not an issue for Yang–Mills theory or QED).

An *a priori* unknown agent 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

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

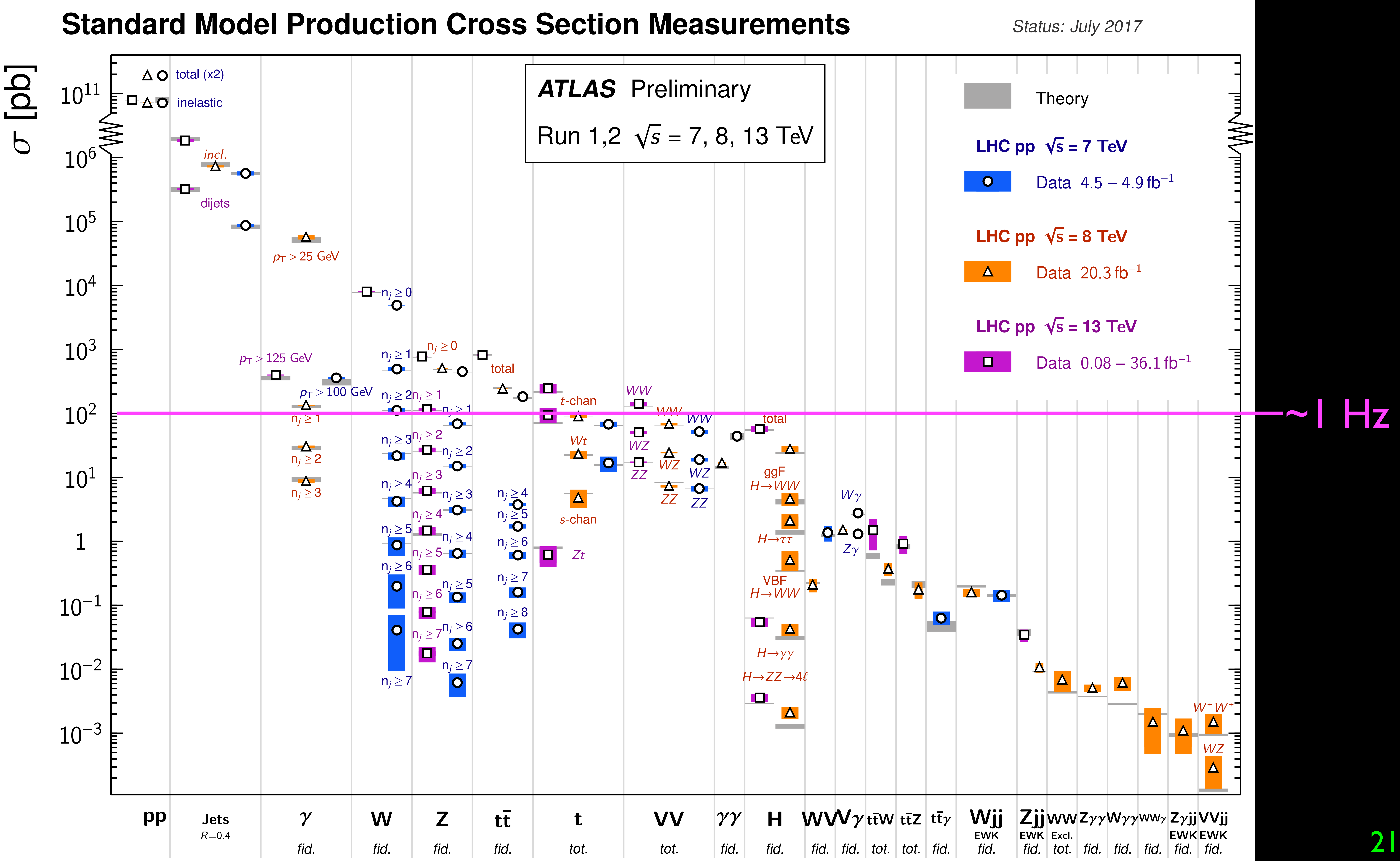
provided $M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1$ TeV

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

Large Hadron Collider


Standard Model Production Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 36.1 fb⁻¹
σ [pb]
~1 Hz
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
WV fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Wjj EWK fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
WWγ fid.
Zγjj EWK fid.
VVjj EWK fid.

What the LHC has told us about H so far

Evidence is developing as it would for
a “standard-model” Higgs boson

Unstable neutral particle near 125 GeV

$M_H = 125.09 \pm 0.24$ GeV

Motivates HL-LHC,
electron–positron Higgs factory

decays to $\gamma\gamma$, W^+W^-, ZZ

dominantly spin-parity 0^+

$Hf\bar{f}$ couplings
not universal

evidence for $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$; $\mu^+\mu^-$ limited

Only third-generation fermions tested

Why does discovering the agent matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

Electron and quarks would have no mass via Higgs

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… no template for life.

arXiv:0901.3958

What we expect of the standard-model Higgs sector

Hide electroweak symmetry

Give masses to *W*, *Z*, *H*

Regulate Higgs-Goldstone scattering

Motivates VLHC

Account for quark masses, mixings

Account for charged-lepton masses

} ΦBSM

A role in neutrino masses?

Fully accounts for EWSB (*W*, *Z* couplings)?

Couples to fermions?

t from production, $Ht\bar{t}$

need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings $\propto$ masses?

Are there others?

Quantum numbers? ($J^P = 0^+$)

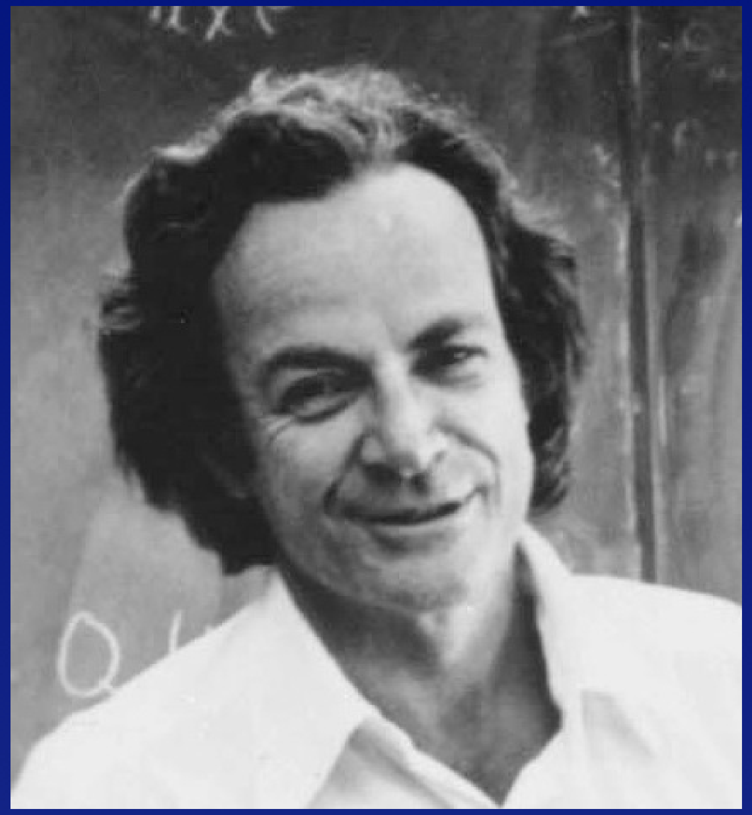
SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e \left[(\bar{e}_L \Phi) e_R + \bar{e}_R (\Phi^\dagger e_L) \right] \rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$

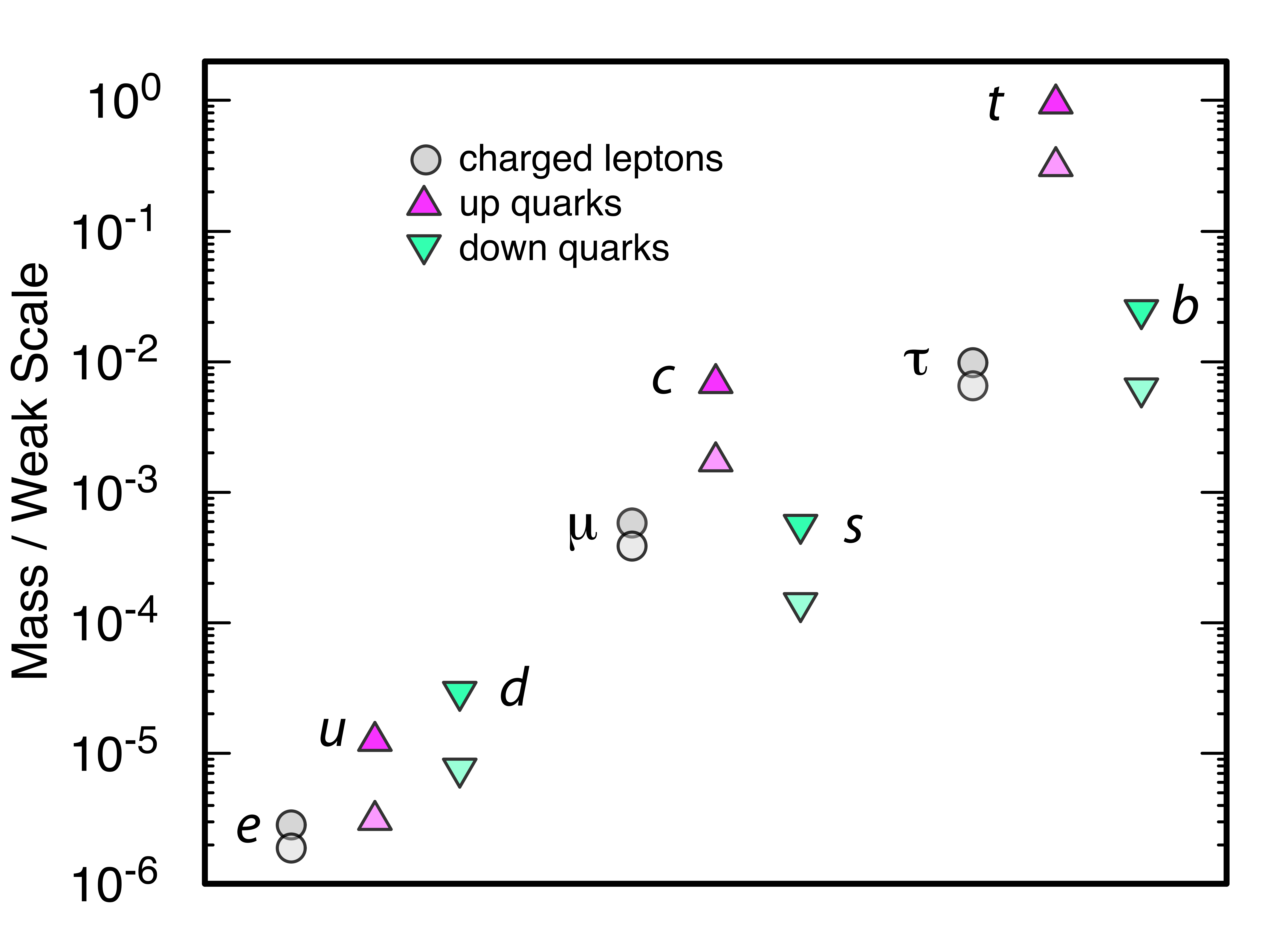
after spontaneous symmetry breaking

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

fermion mass implies physics beyond the standard model

Charged Fermion Masses



Running mass $m(m)$ … $m(U)$

0 … 1 … ∞

The Problem of Identity

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

Why three families?

Neutrino oscillations give us another take.
Clue to matter excess in the universe?

Might new kinds of matter unlock the pattern?

More new physics on the TeV scale?

WIMP dark matter

“Naturalness”

Hierarchy problem: EW scale ≪ Unification or Planck scale

Vacuum energy problem

Clues to origin of EWSB

Supersymmetry could respond to many SM problems, but (as we currently understand it) it is largely unprincipled!

R-parity (overkill for proton stability)
gives dark-matter candidate
μ problem (getting TeV scale right)
Taming flavor-changing neutral currents
All these are added by hand!

Very promising: search in EW production modes
reexamine squark + EWino, too.

How have we misunderstood the hierarchy problem?

If other physical scales are present, there is something to understand

We originally sought once-and-done remedies, such as supersymmetry or technicolor

Go in steps, or reframe the problem?

Hierarchy Problem – a second look

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Nuclear Physics B (Proc. Suppl.) 140 (2005) 3–19

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The Origins of Lattice Gauge Theory

K.G. Wilson

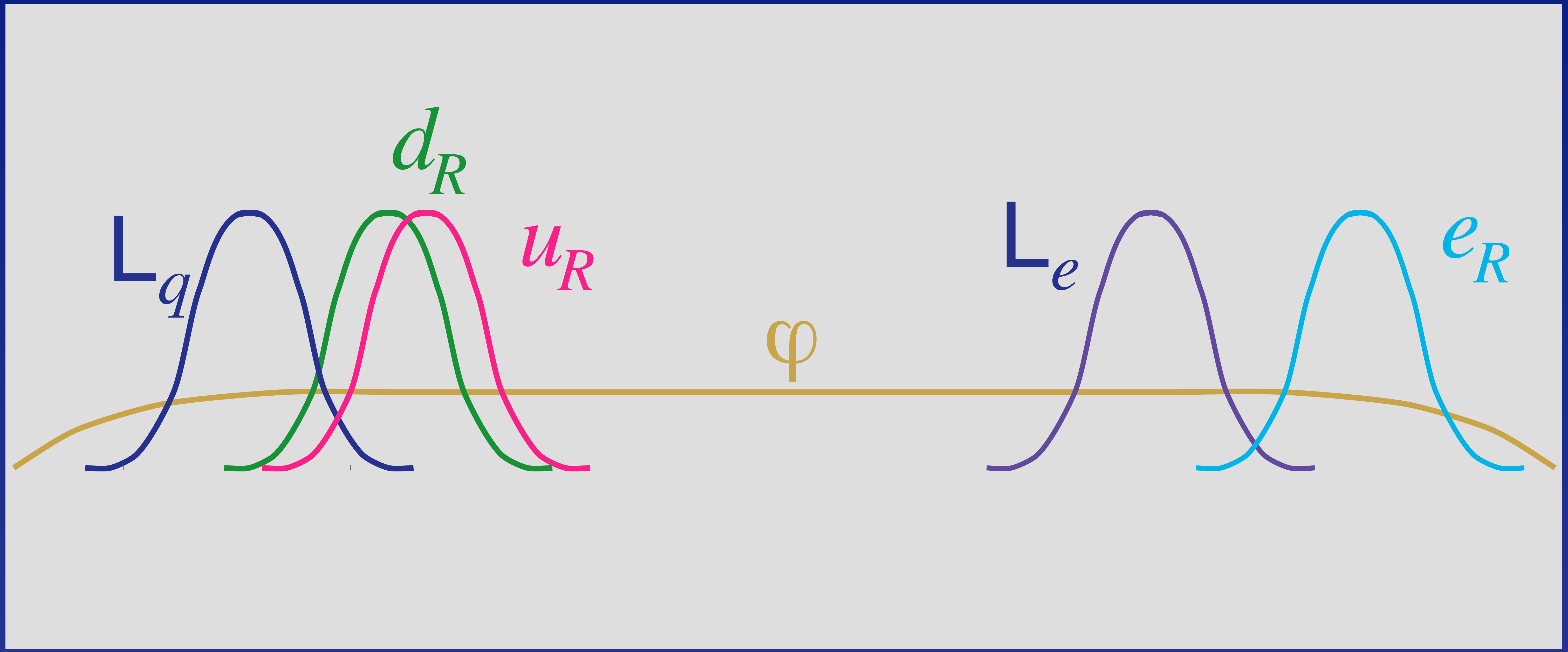
Smith Laboratory, Department of Physics, The Ohio State University, 174 W. 18th Ave., Columbus, OH 43210

The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large. An early example was the very large distance to the nearest star as compared to the distance to the Sun, as needed by Copernicus, because otherwise the nearest stars would have exhibited measurable parallax as the Earth moved around the Sun. Within elementary particle physics, one has unexpectedly large ratios of masses, such as the large ratio of the muon mass to the electron mass. There is also the very small value of the weak coupling constant. In the time since my paper was written, another set of unexpectedly small masses was discovered: the neutrino masses. There is also the riddle of dark energy in cosmology, with its implication of possibly an extremely small value for the cosmological constant in Einstein's theory of general relativity.

This blunder was potentially more serious, if it caused any subsequent researchers to dismiss possibilities for very large or very small values for parameters that now must be taken seriously. But I

How might ratios far from unity arise?

Might extra dimensions explain the range of fermion masses?



Fermions ride separate tracks in 5th dimension

Small offsets in x_4: exponential differences in masses

Arkani-Hamed & Schmaltz (2000)

Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2\theta_W$
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.

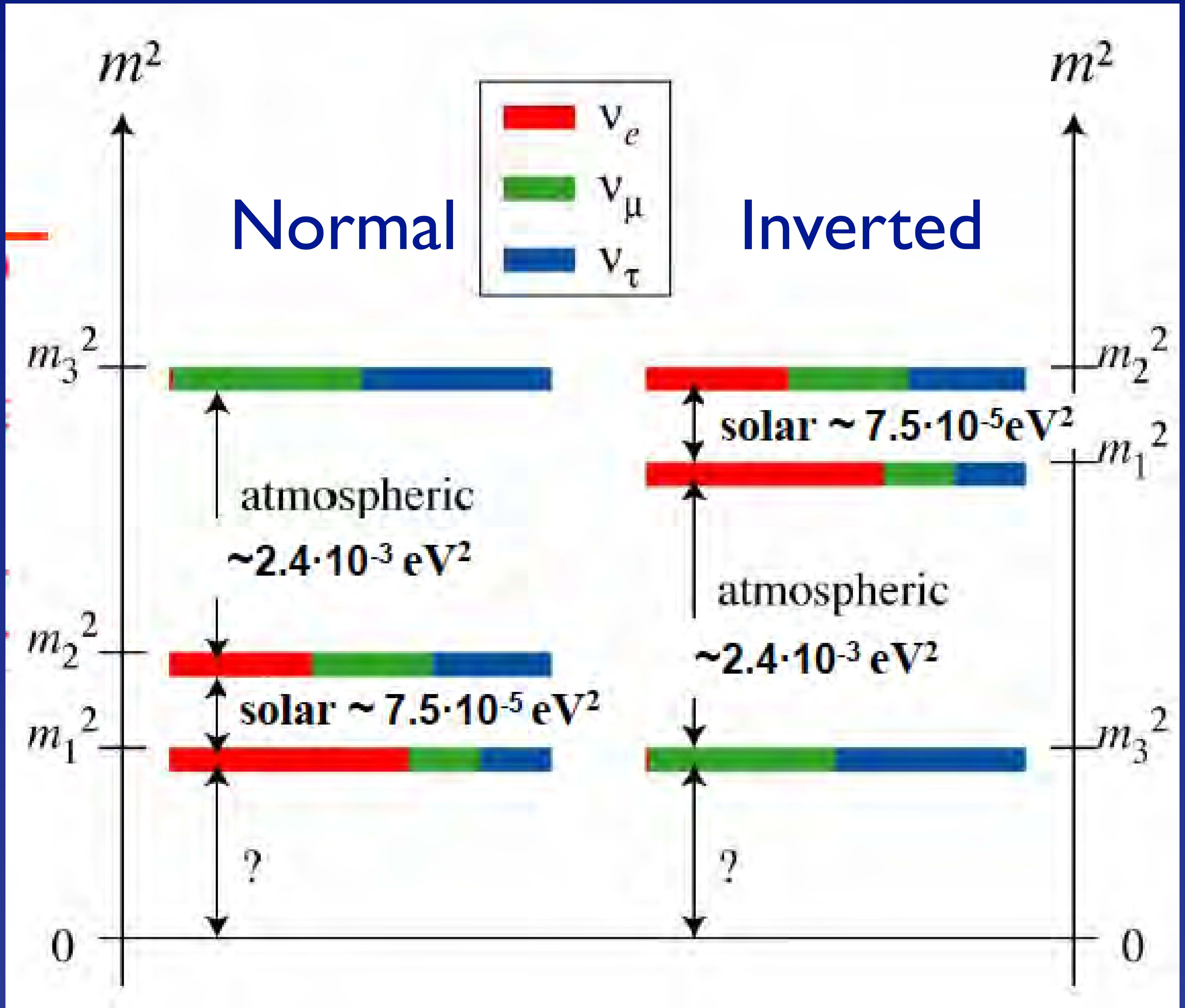
Will the fermion masses and mixings reveal symmetries or dynamics or principles?

Some questions now seem to us the wrong questions:
Kepler's obsession – Why six planets in those orbits?

Landscape interpretation as environmental parameters

Might still hope to find equivalent of Kepler's Laws!

Some outstanding questions in ν physics



NOνA, T2K ν_e appearance *begin to hint* normal hierarchy

Some outstanding questions in ν physics

CP Violation?

T2K disfavors $0 < \delta < \pi$ at 90% CL

NOνA shows some sensitivity

Are neutrinos Majorana particles?

Search for $(Z,A) \rightarrow (Z+2,A) + ee$: $\beta\beta_{0\nu}$

Do 3 light neutrinos suffice?

Are there light sterile ν?

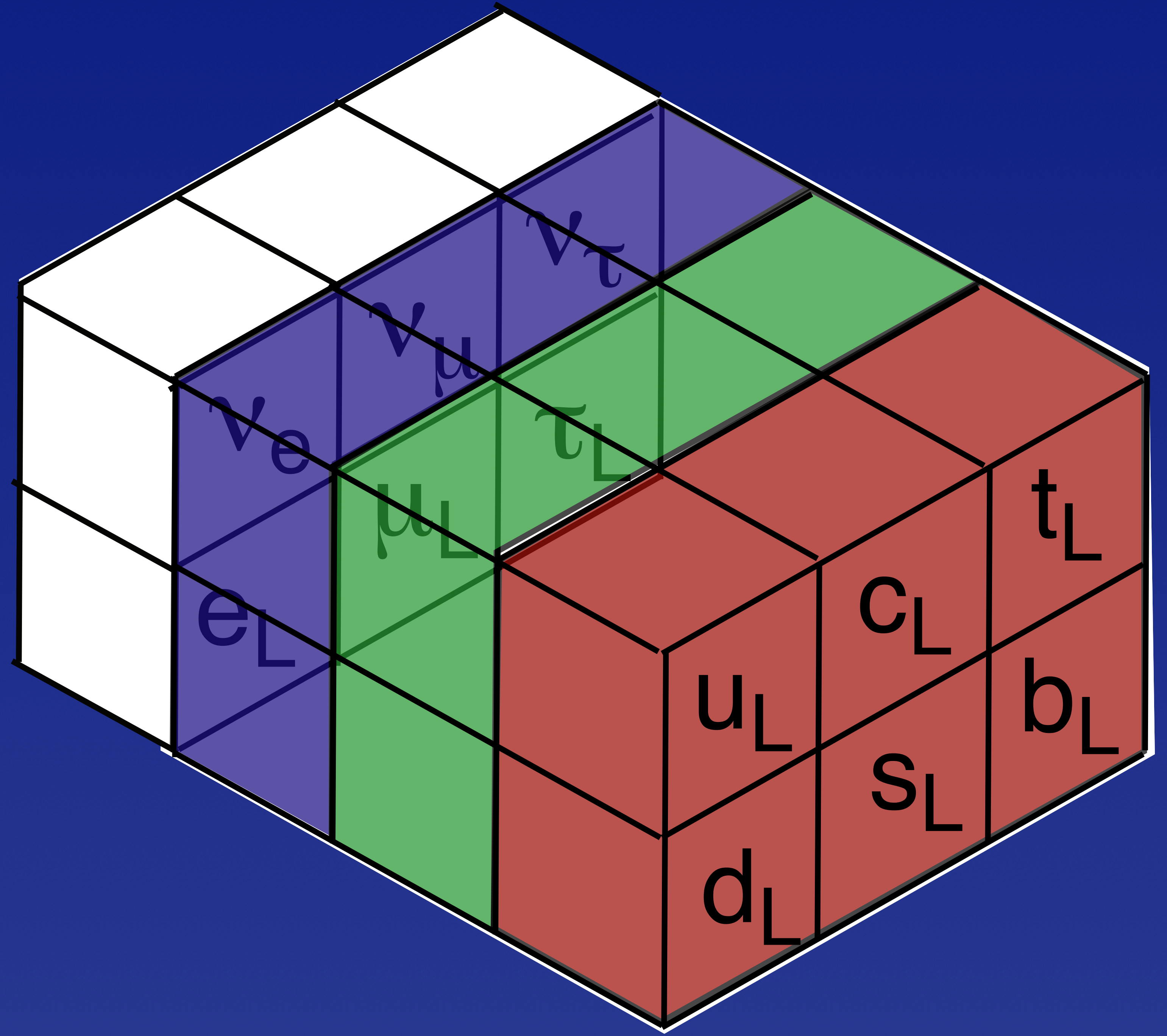
Short baseline ν experiments test for light steriles

Might neutrinos decay?

Can we detect the cosmic ν background?

A Unified Theory?

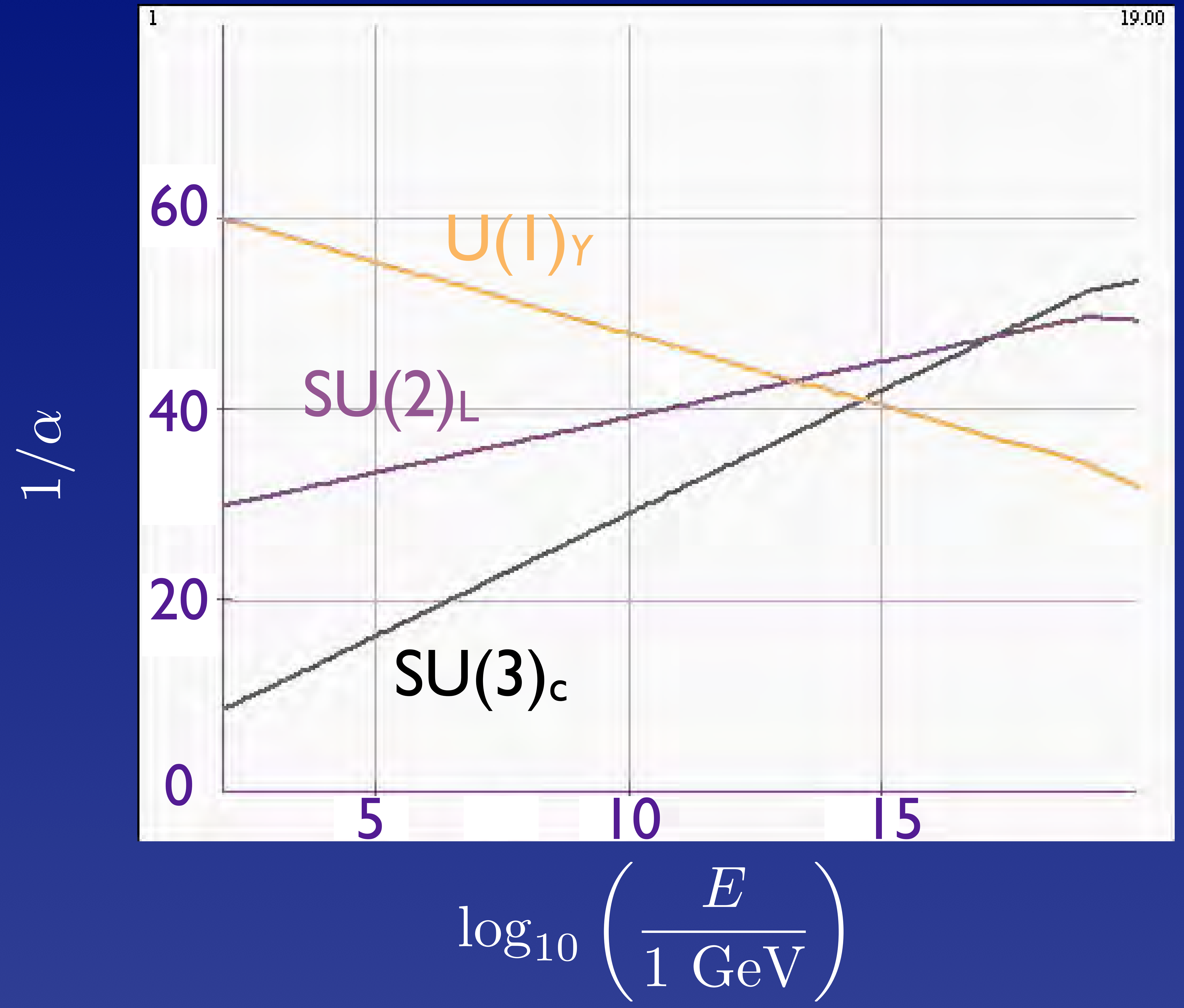
Why are atoms so remarkably neutral?



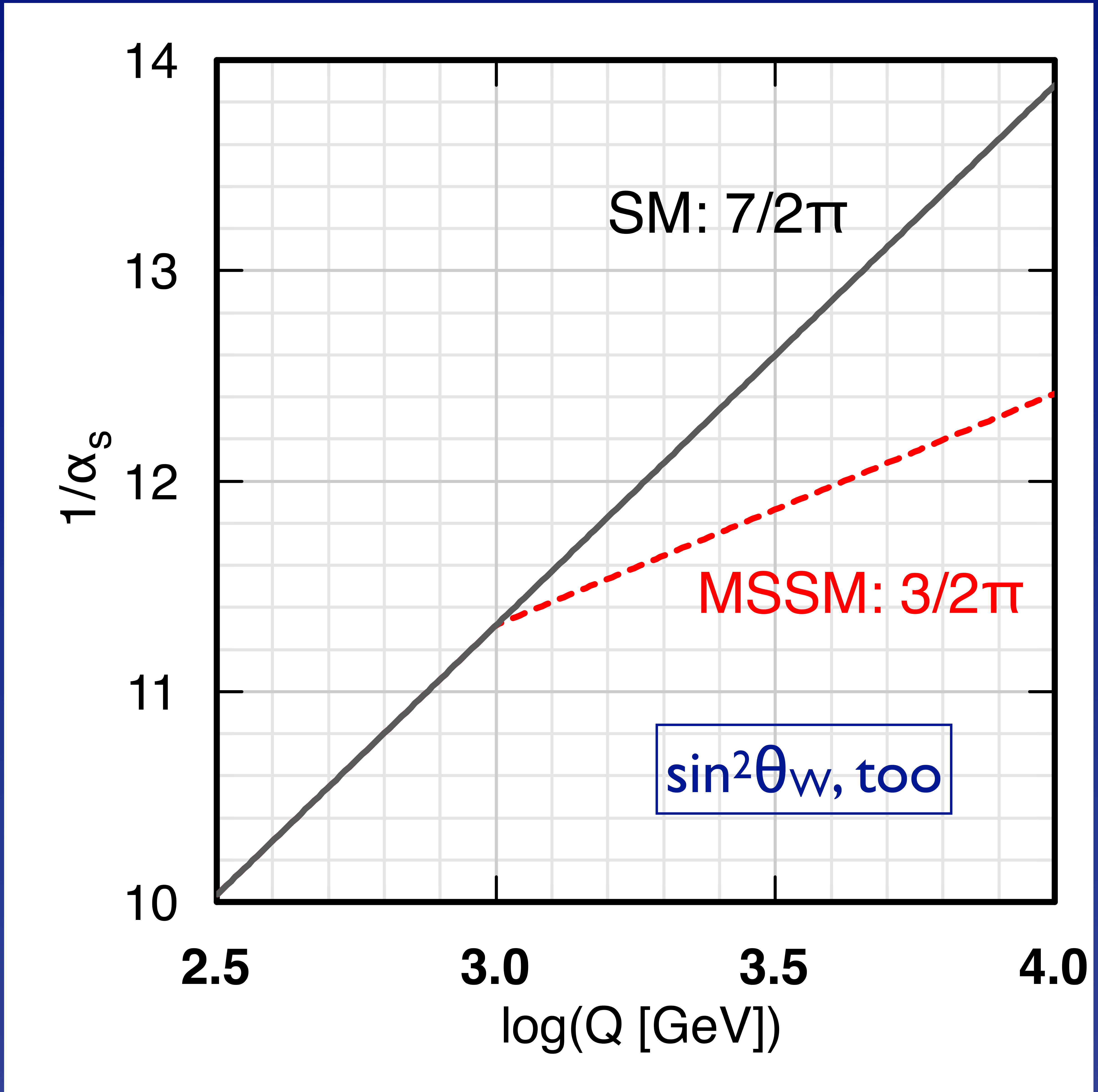
Coupling constant unification?

Extended quark–lepton families:
proton decay! n–n̄ oscillations

Unification of Forces?



Might (HE-)LHC (or 100-TeV) see change in evolution?



Tabletop precision experiments

Electric dipole moment d_e: CP/T violation

$|d_e| < 8.7 \times 10^{-29}$ e · cm

ACME Collaboration, ThO

$|d_e| < 1.3 \times 10^{-28}$ e · cm

NIST, trapped $^{180}Hf^{19}F^{+}$

(SM phases: $d_e < 10^{-38}$ e · cm)

Tabletop precision experiments

(Anti)proton magnetic moments: CPT test

$\mu_{\bar{p}}$ = – 2.792 847 344 1(42) μ_N

vs.

μ_p = + 2.792 847 344 62 (82) μ_N

BASE Collaboration @CERN Antiproton Decelerator

Issues for the Future *(Starting now!)*

1. *There is a Higgs boson!* Might there be several?
2. Does the Higgs boson regulate *WW* scattering?
3. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
4. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
5. Are there new flavor symmetries that give insights into fermion masses and mixings?
6. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

7. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
8. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
9. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why? At what scale?
10. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
11. What resolves the strong CP problem?

Issues for the Future (Now!)

12. What are the dark matters? Any flavor structure?
13. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
14. Is EWSB related to gravity through extra spacetime dimensions?
15. What resolves the vacuum energy problem?
16. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?

Issues for the Future (Now!)

17. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
18. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
19. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
20. At what scale are the neutrino masses set? Do they speak to the TeV, unification, Planck scale, …?
21. Could our laws of nature be environmental?

22. How are we prisoners of conventional thinking?

?