Mass, Electroweak Symmetry Breaking, and the Fermi Scale

Chris Quigg

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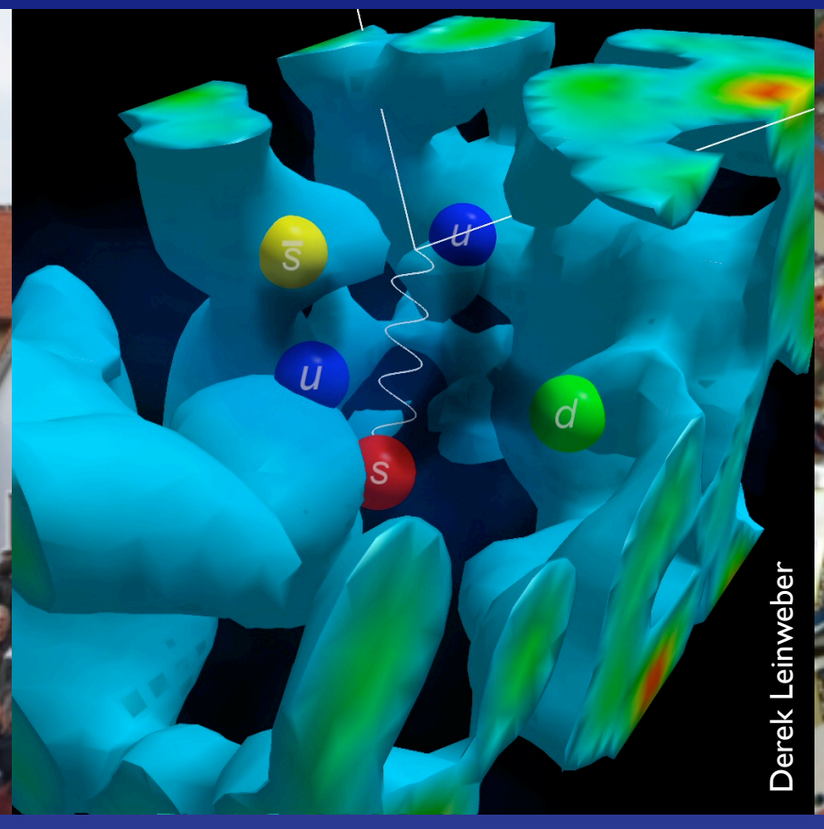


Foundations of Quantum Physics · Bad Honnef · 23.9.2008

I. Newton (1687)

Quantitas Materiæ eſt menſura ejuſdem orta ex illius Denſitate & Magnitudine conjunctim.

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

In Newton's world, mass does not arise, it simply is.

Nineteenth century: attention to a consistent definition of mass

↪ *Mach's operational definition (1867)*

Isolated bodies A & B (masses m_A & m_B) interact (attract or repel)

Ratio of masses is inverse ratio of accelerations:

$$\frac{m_A}{m_B} = -\frac{a_B}{a_A}$$

What determines inertia / mass?

1893 · "Mach's Principle" (named by Einstein):

hypothesis that inertial forces experienced by a body in nonuniform motion are determined by the quantity and distribution of matter in the universe

(1881 · J. J. Thomson: "electromagnetic mass")

1897 · electron discovered

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?

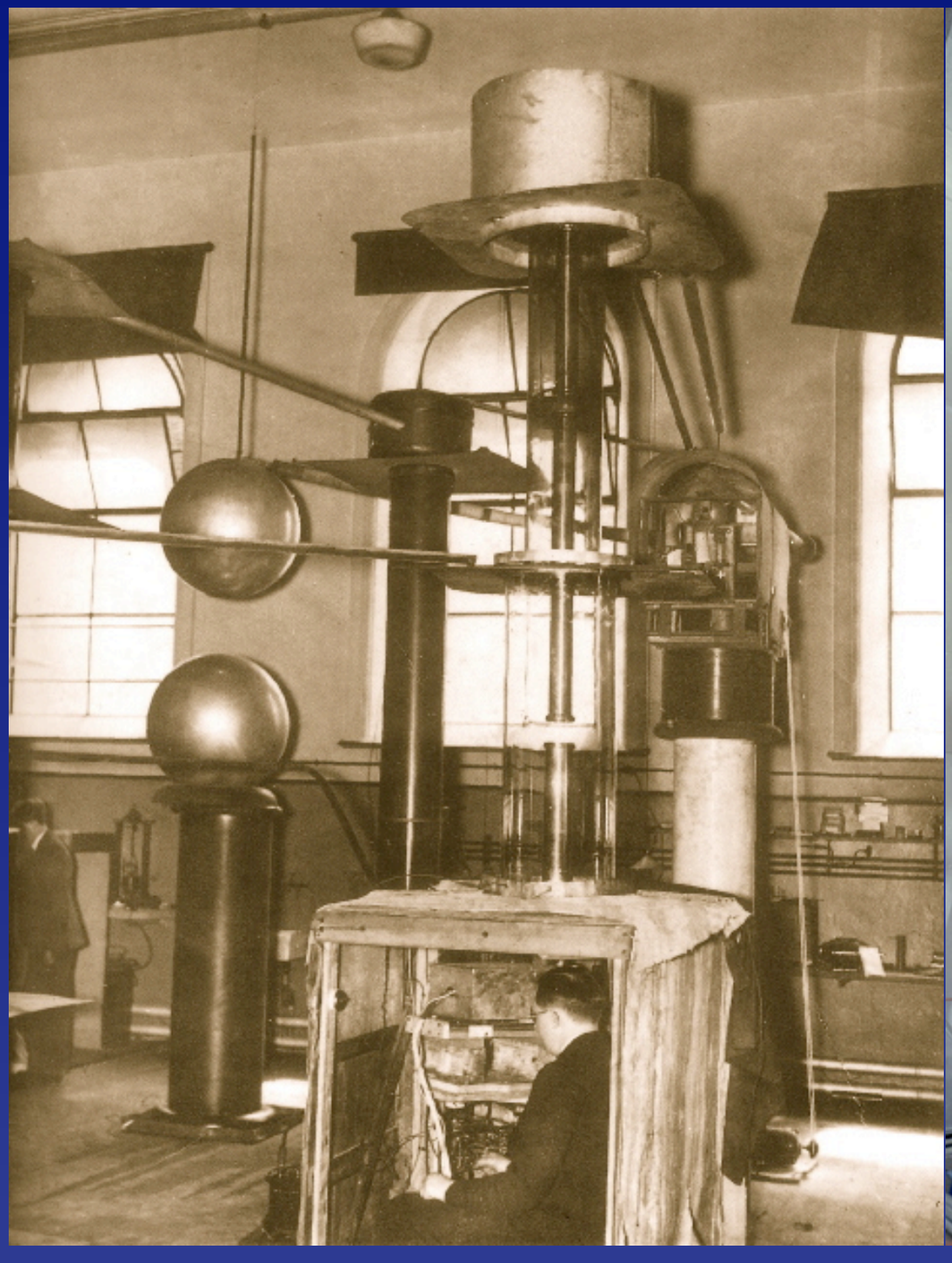
The mass of a body is a measure of its energy content;

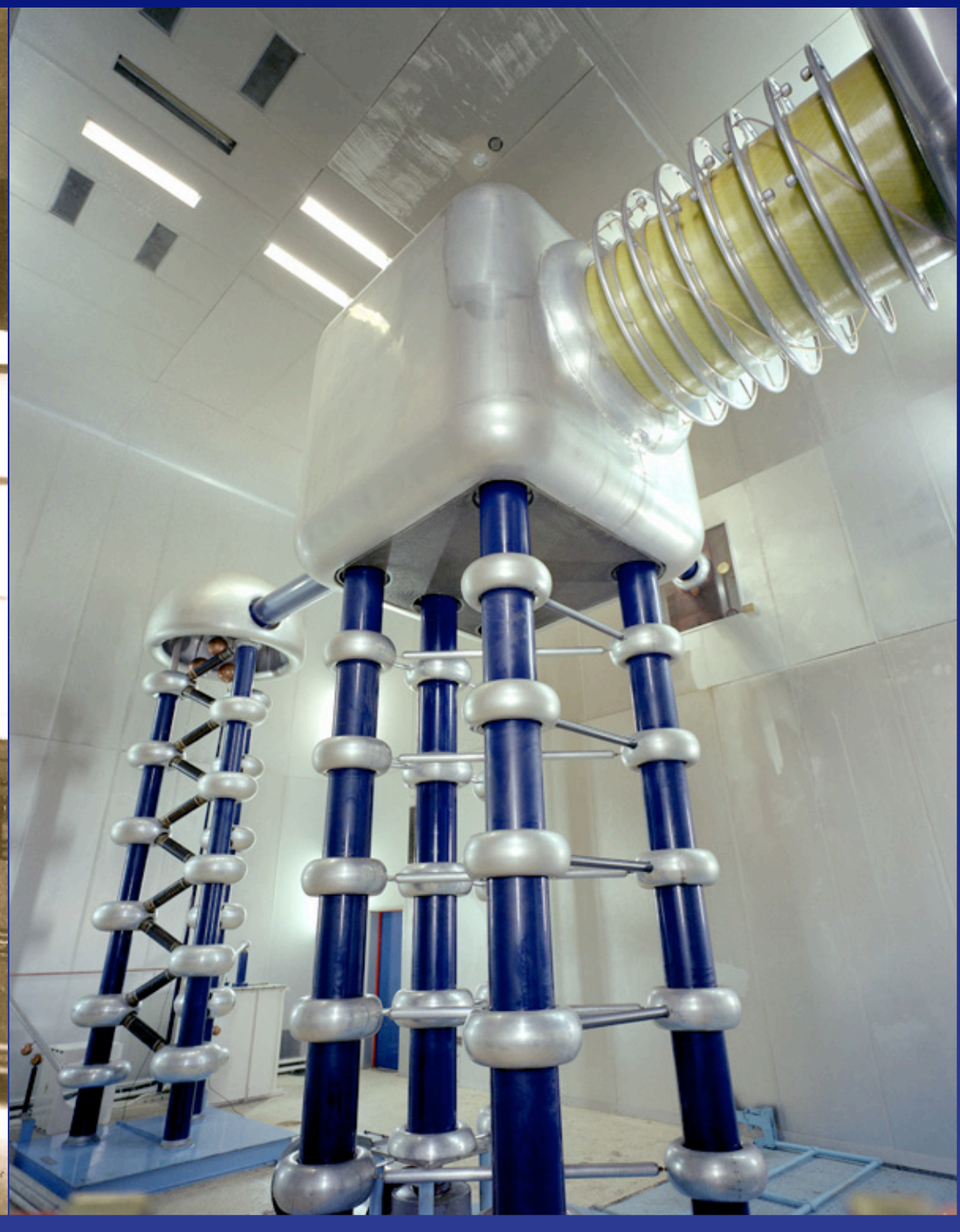
Mass is rest energy

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

Albert Einstein Historic Recordings 1930-1947, British Library NSACD 23

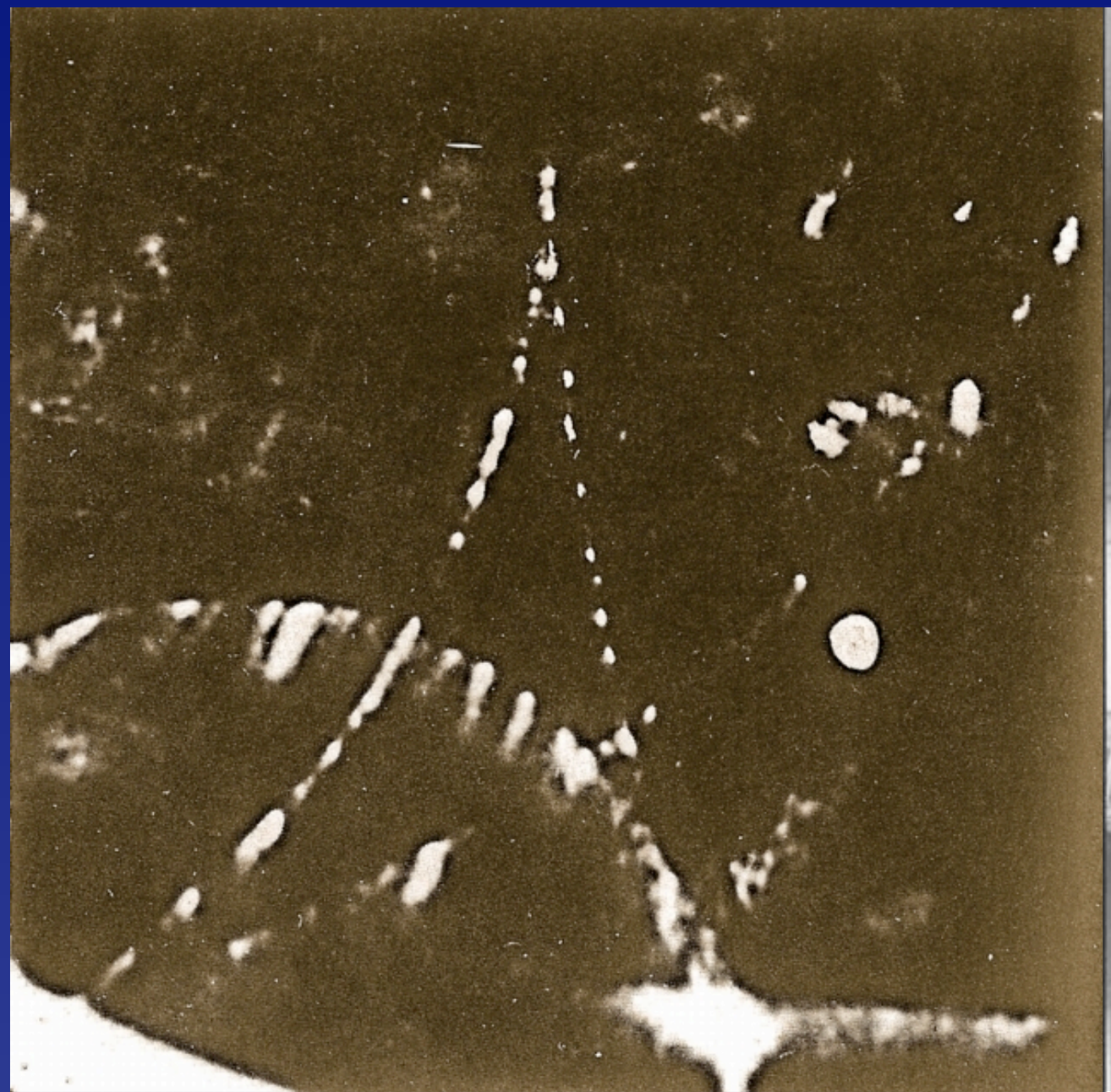
Cockcroft & Walton liberate energy from ^{7}Li (1932)





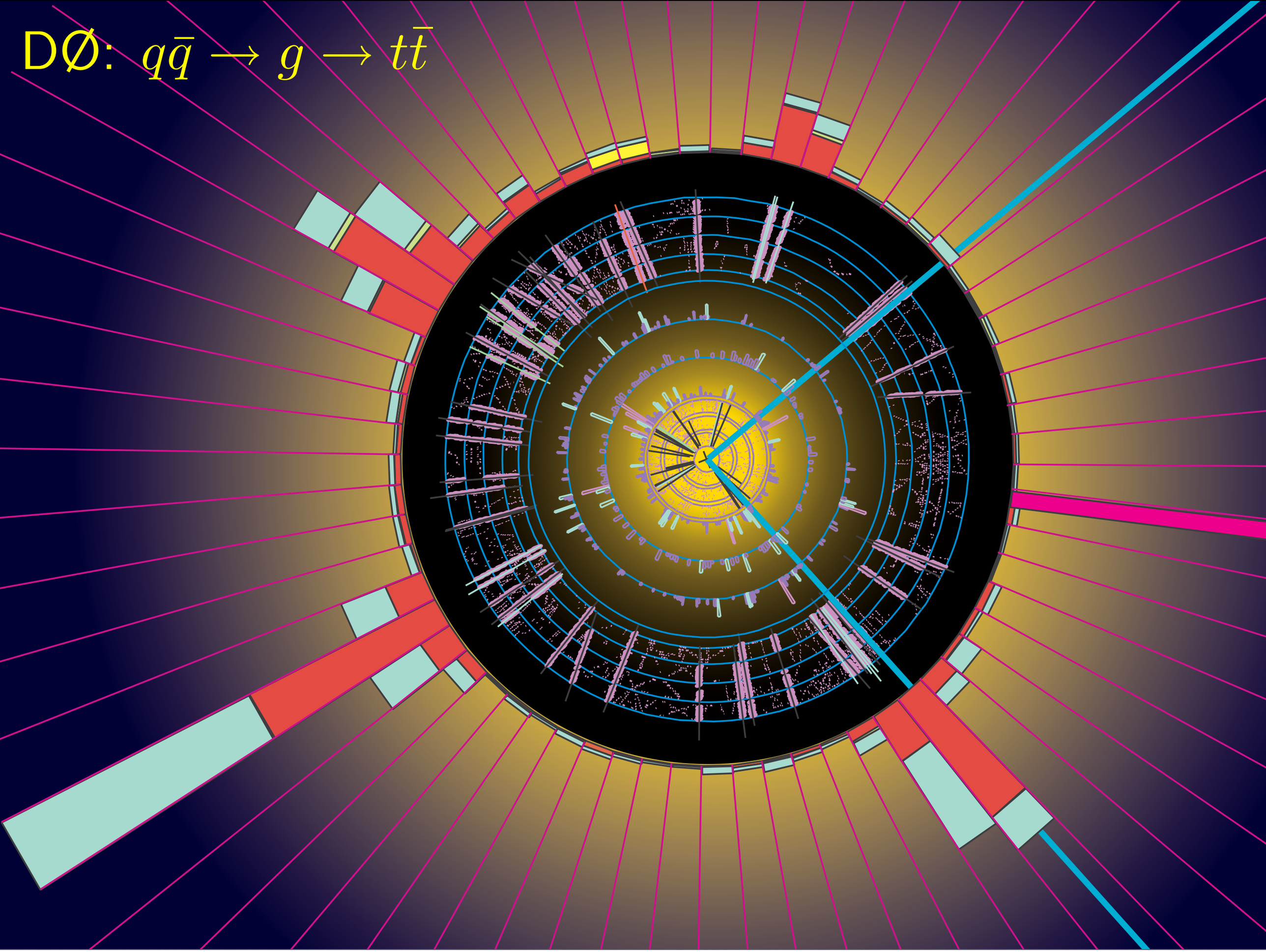
p (125 KeV) + $^{7}Li \rightarrow \alpha + \alpha$ + 17.2 MeV

I. & F. Joliot-Curie observe pair production (1933)



Energetic photon materializes as electron + positron

DØ: $q\bar{q} \rightarrow g \rightarrow t\bar{t}$



sum of parts

rest energy

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

$2H_2 + O_2 \rightarrow 2H_2O$: $\Delta M \approx 10^{-10}$

fossil-fuel economy feeds on such tiny deviations

Quantum

sum of parts ?

Fermionic matter: $E(N) \sim -N$

two lumps, $-2N$

one big lump, $-2N$

Bosonic matter: $E(N) \sim -N^{7/5}$

two lumps, $-2N^{7/5}$

one big lump, $-(2N)^{7/5} \ll -2N^{7/5}$

An insatiable amorphous shrinking blob!

Dyson, Lieb

sum of parts

rest energy

Nuclei: nucleon masses + nuclear forces

Mass defect of ^{4}He: ¾%

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 few %

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

Einstein's "rest energy" of the proton includes kinetic energy–energy of motion–of the quarks!

1905 · A. Einstein:

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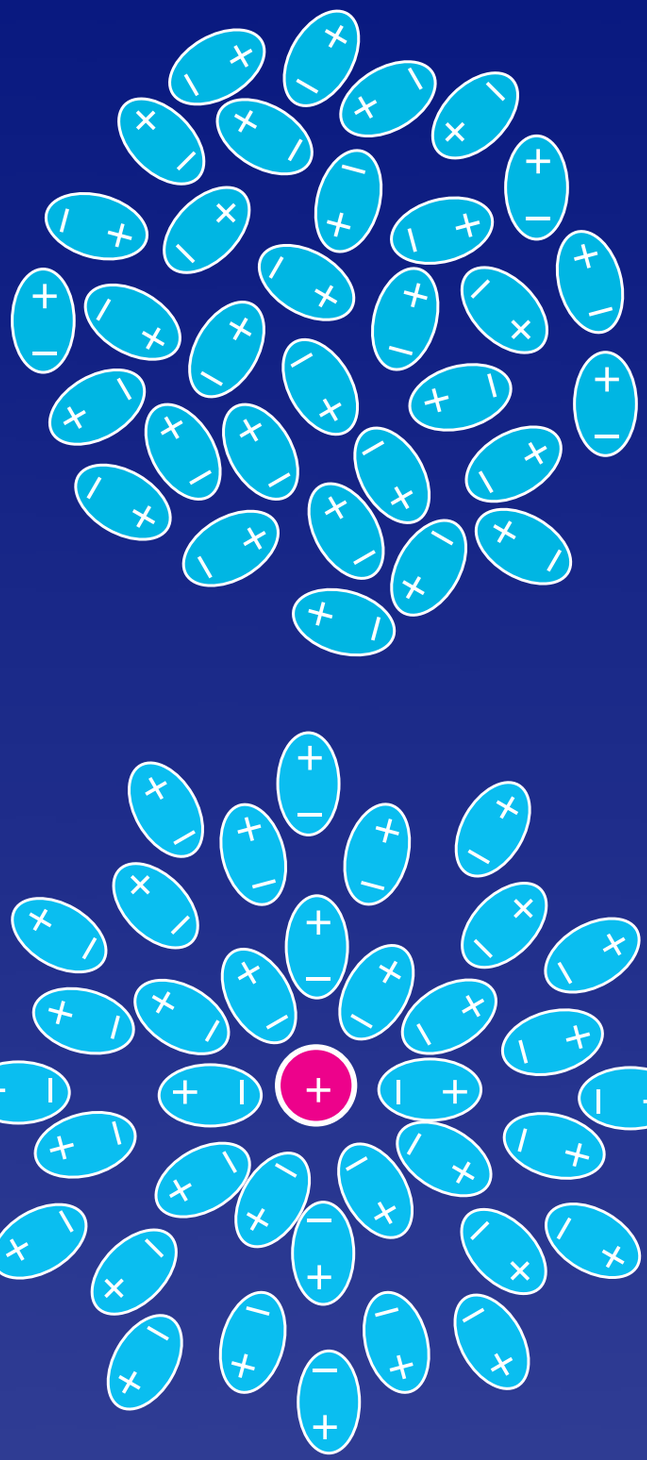
Mass is rest energy

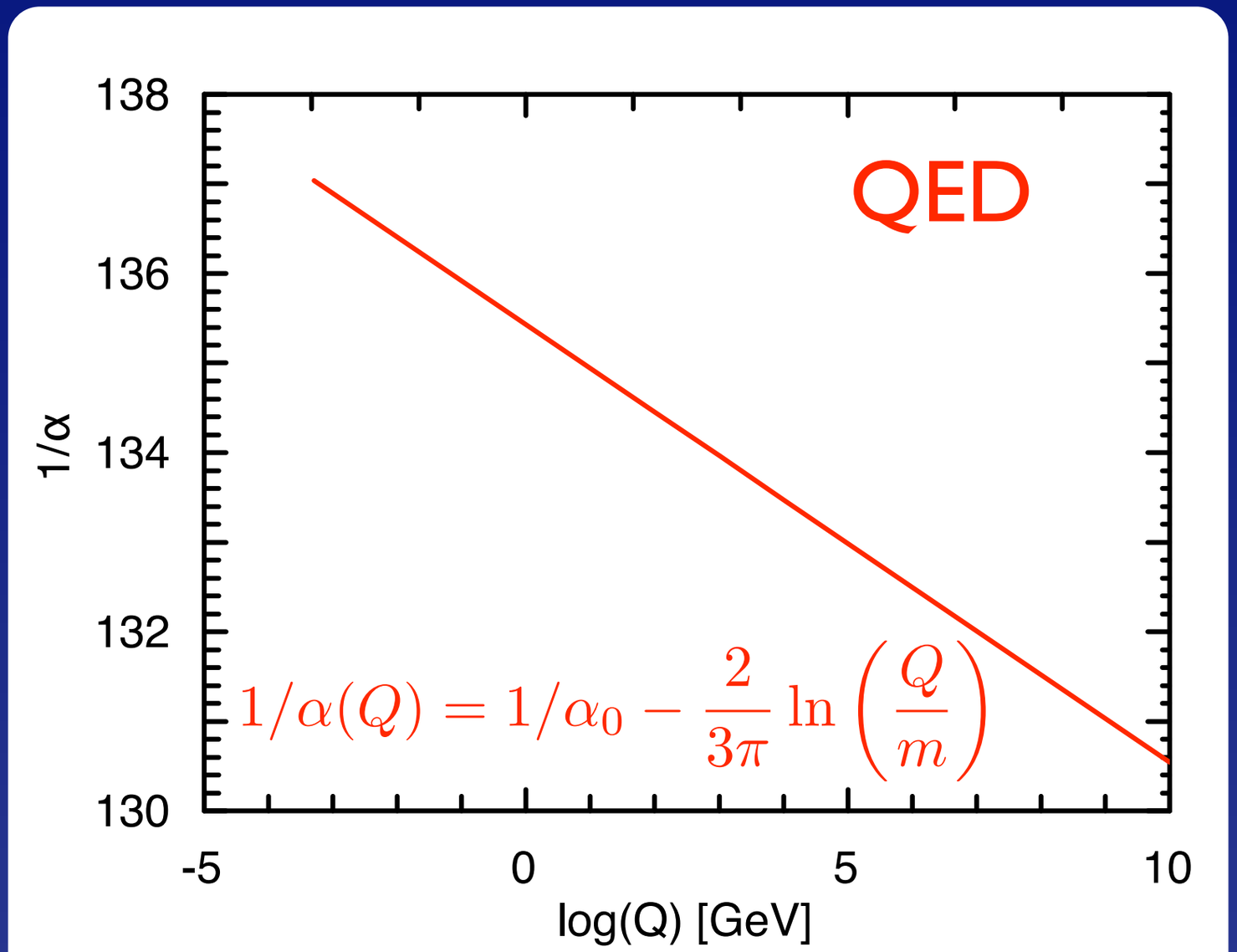
$$m = E_0/c^2; \qquad m = (1/c^2)\sqrt{E^2 - p^2c^2}$$

Invitation to consider the origins of mass

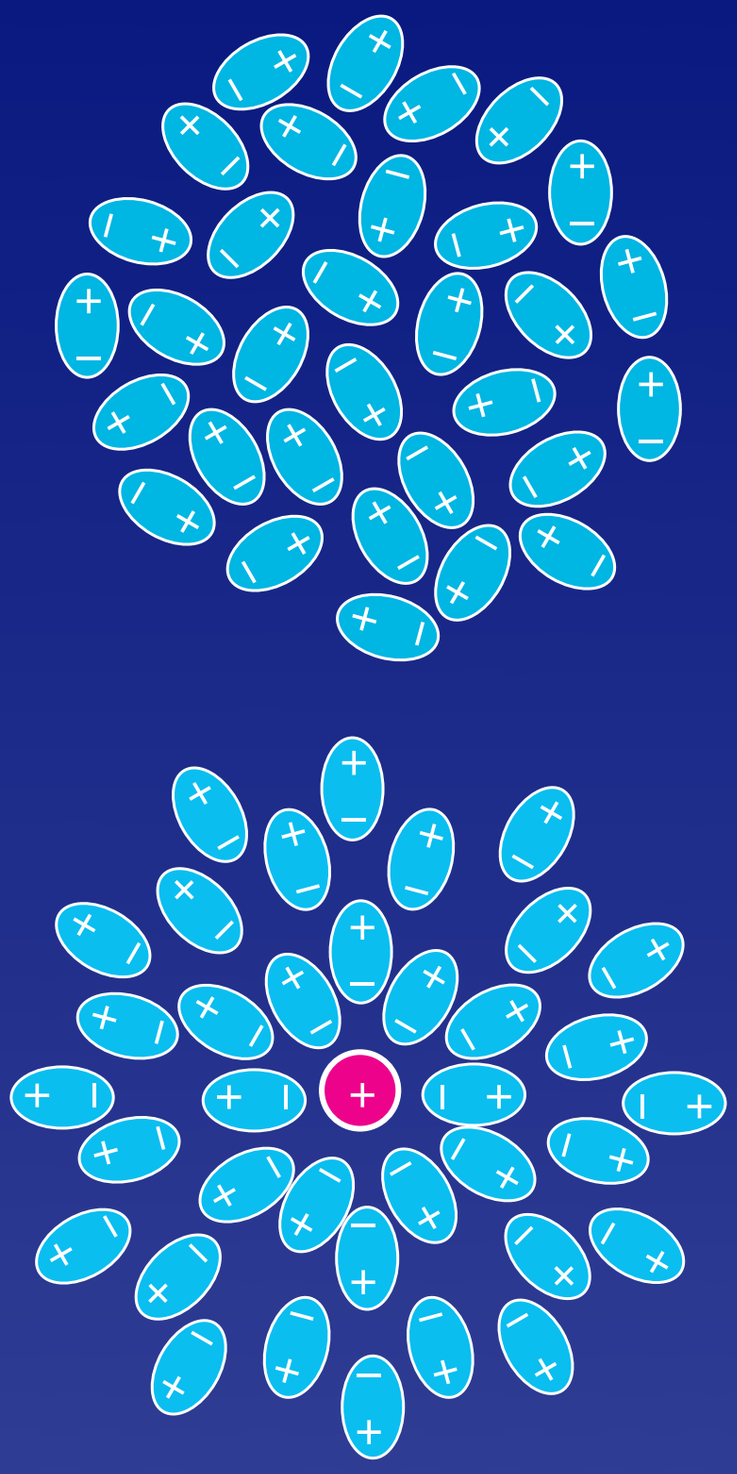
Charge screening behavior of electrodynamics

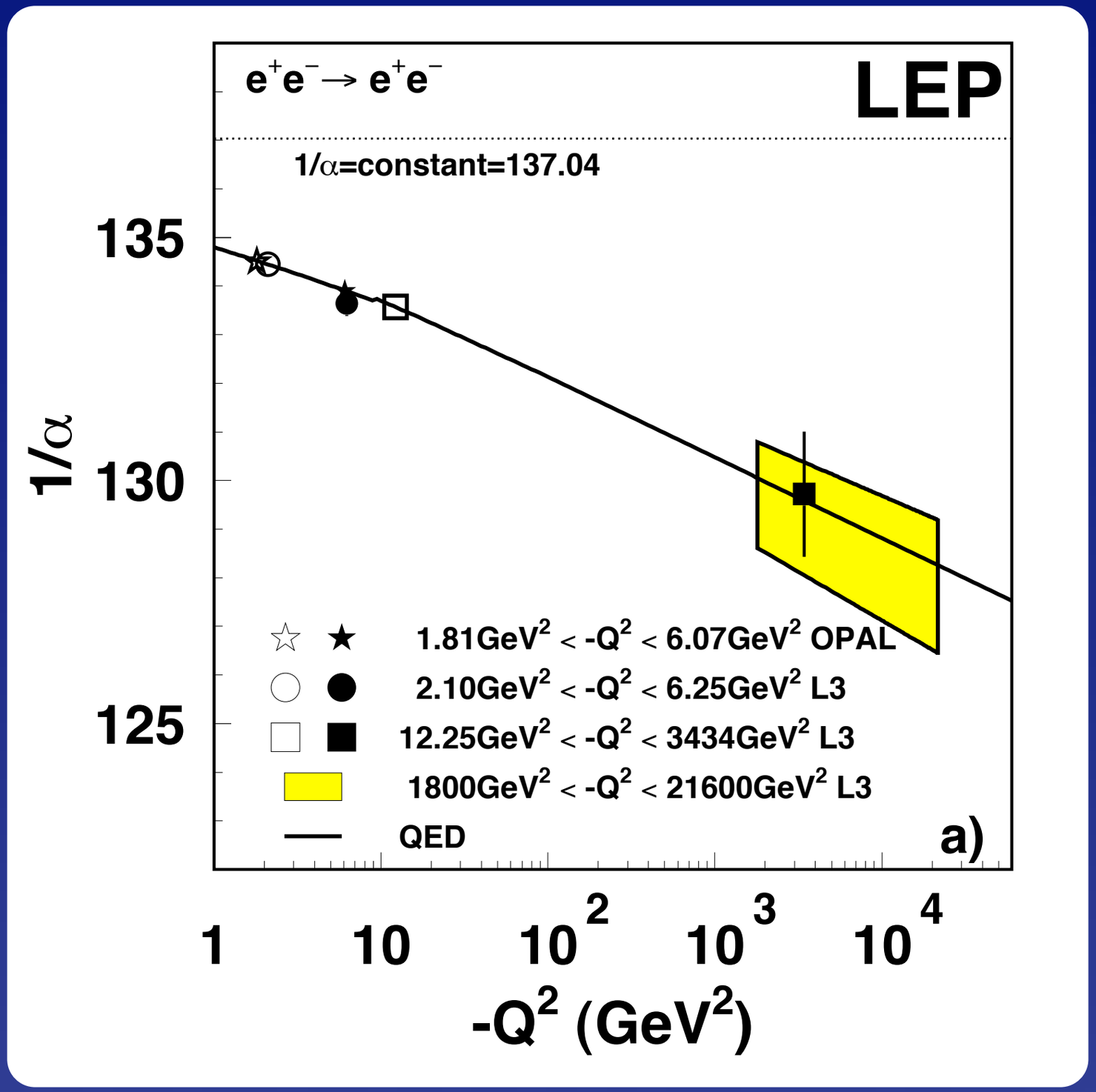


$Q_{eff} = Q/\epsilon$, $\epsilon > 1$



Charge screening behavior of electrodynamics





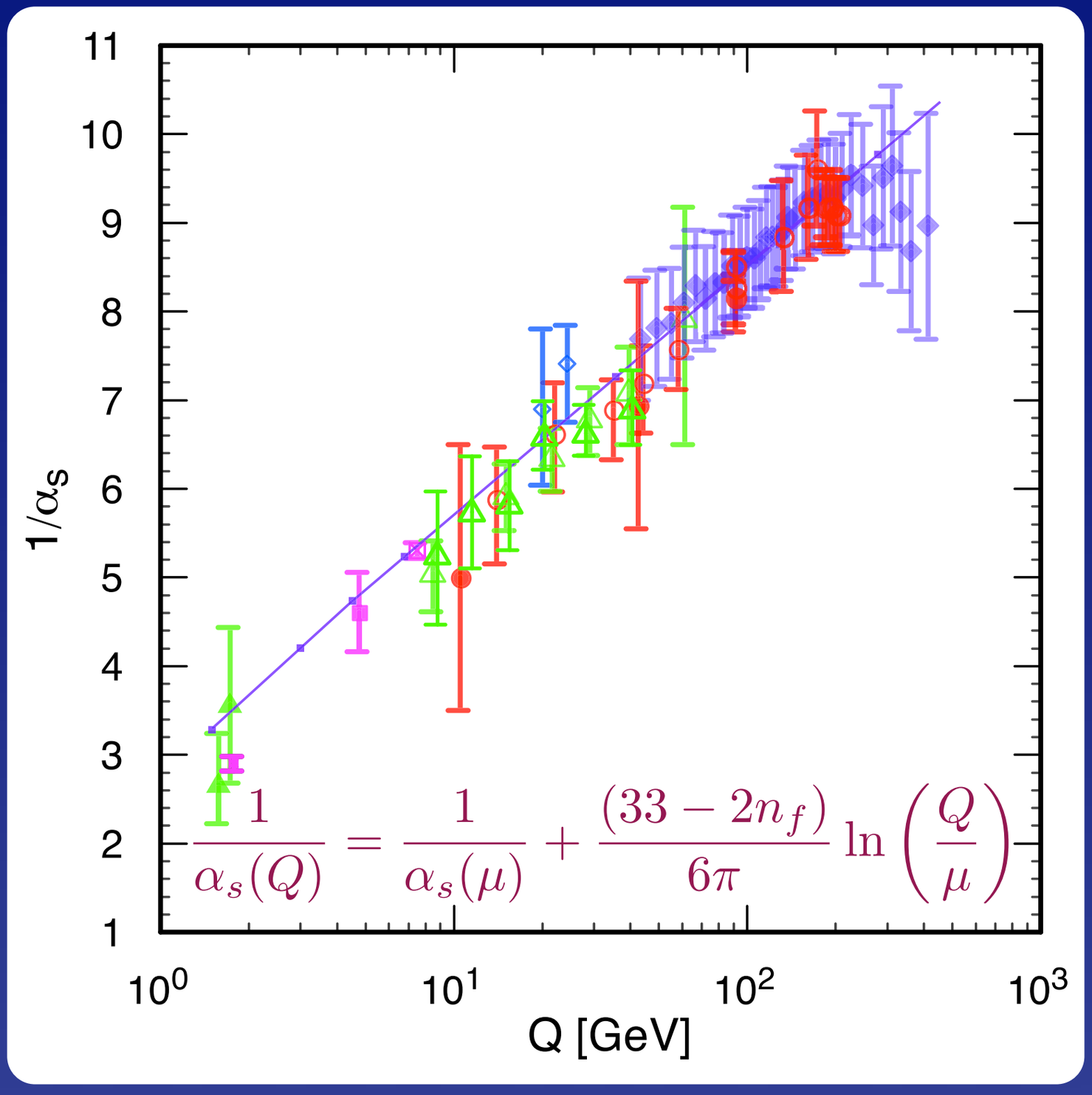
$Q_{eff} = Q/\epsilon$, $\epsilon > 1$

S. Mele, hep-ex/0601045

Color *antiscreening* behavior of chromodynamics

Color screening from quark pairs, camouflage from gluon cloud.

$\epsilon_{QCD} < 1$



S. Bethke, hep-ex/0606035

Classical picture: dielectric *constant* ϵ
a property of the medium

Quantum picture: *running* ϵ
a property of the vacuum
depends on resolution (*Q* or *r*)

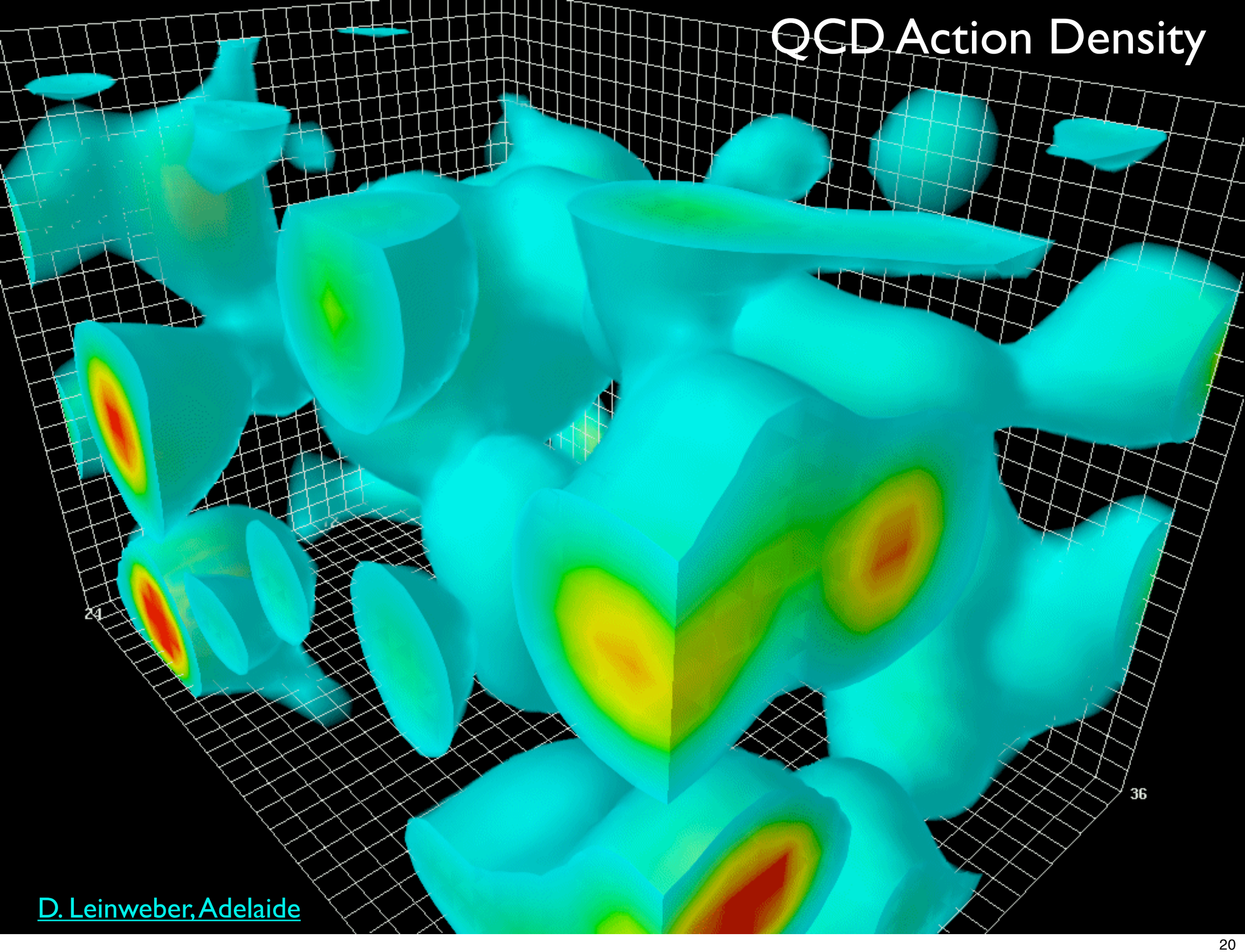
Horror vacui?

Aristotle's interpretation of suction
"Nature abhors a vacuum"

Torricelli *barometer*
Pascal *vide dans le vide*
Guericke *Magdeburg hemispheres*

↪ the vacuum exists, air has weight

QCD Action Density

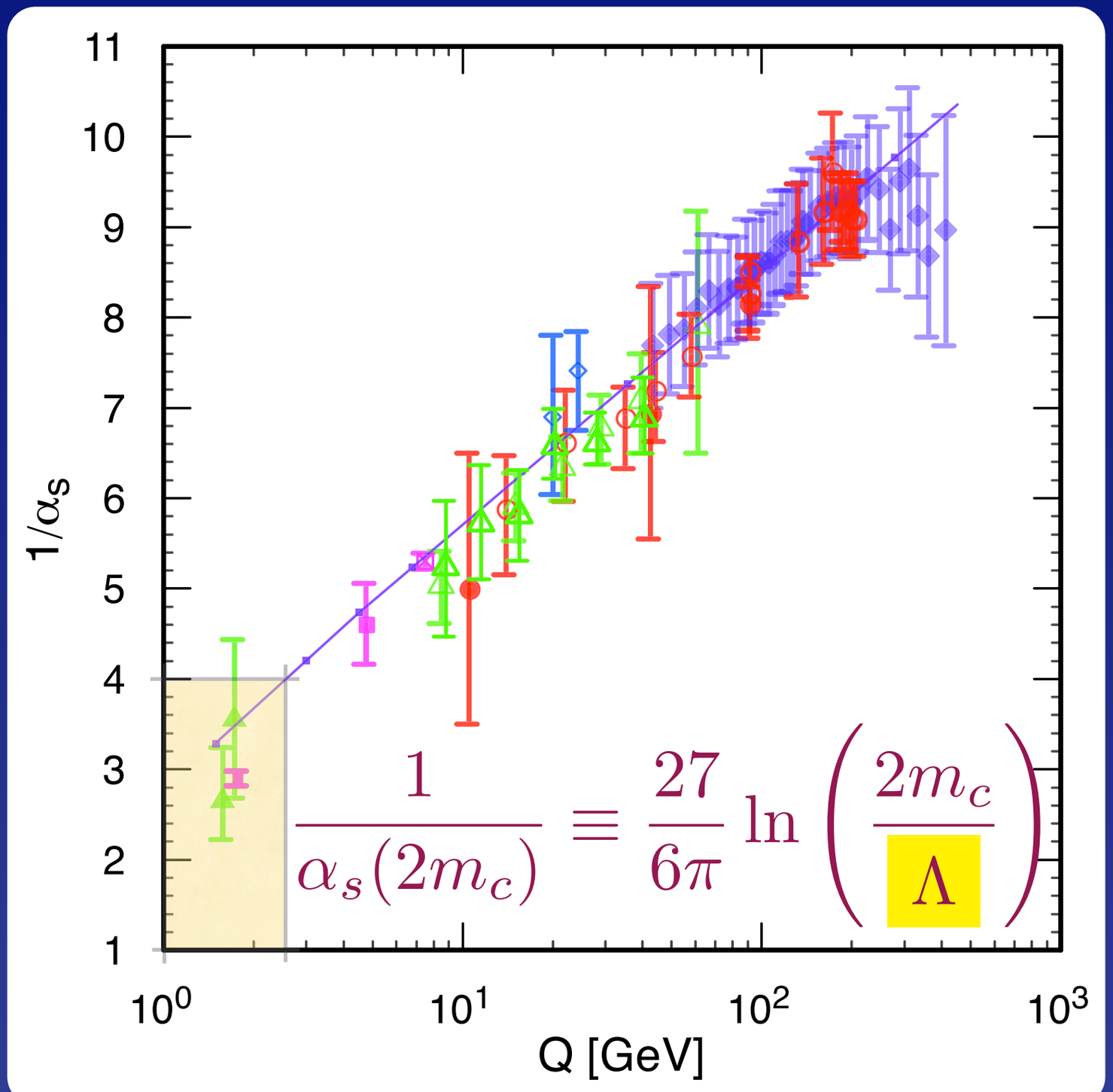


D. Leinweber, Adelaide

Dimensional transmutation

A dimensionful parameter is associated to the value of a dimensionless coupling constant

$$\Lambda^{(5)}_{\overline{\text{MS}}} \approx 220 \text{ MeV}$$
$$\Lambda^{(4)}_{\overline{\text{MS}}} \approx 305 \text{ MeV}$$
$$\Lambda^{(3)}_{\overline{\text{MS}}} \approx 346 \text{ MeV}$$



S. Bethke, hep-ex/0606035

Insight from QCD

$$M_{\text{proton}} = C \cdot \Lambda + \ldots$$

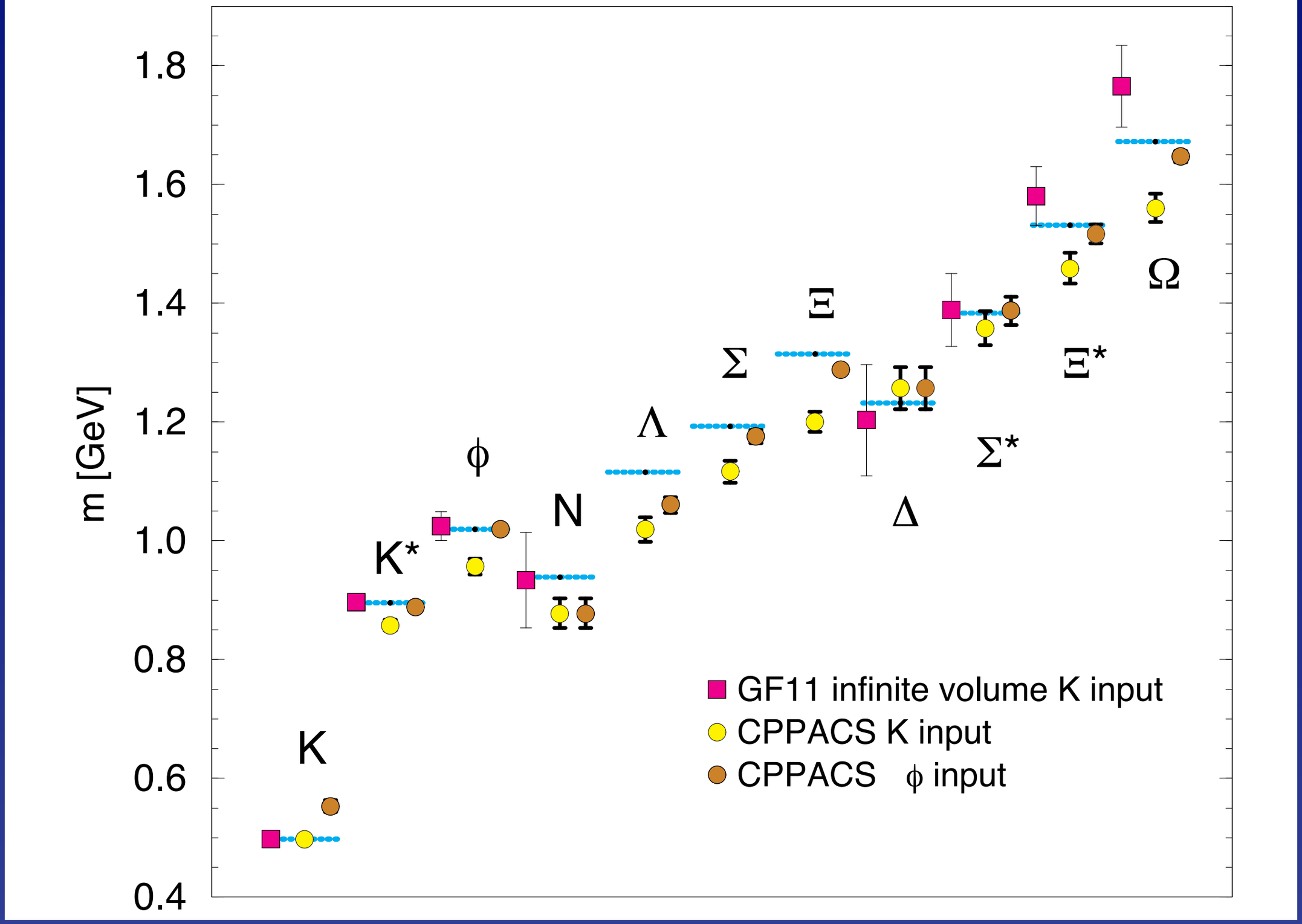
calculable on lattice

from dimensional transmutation

quark masses, EM self-energy

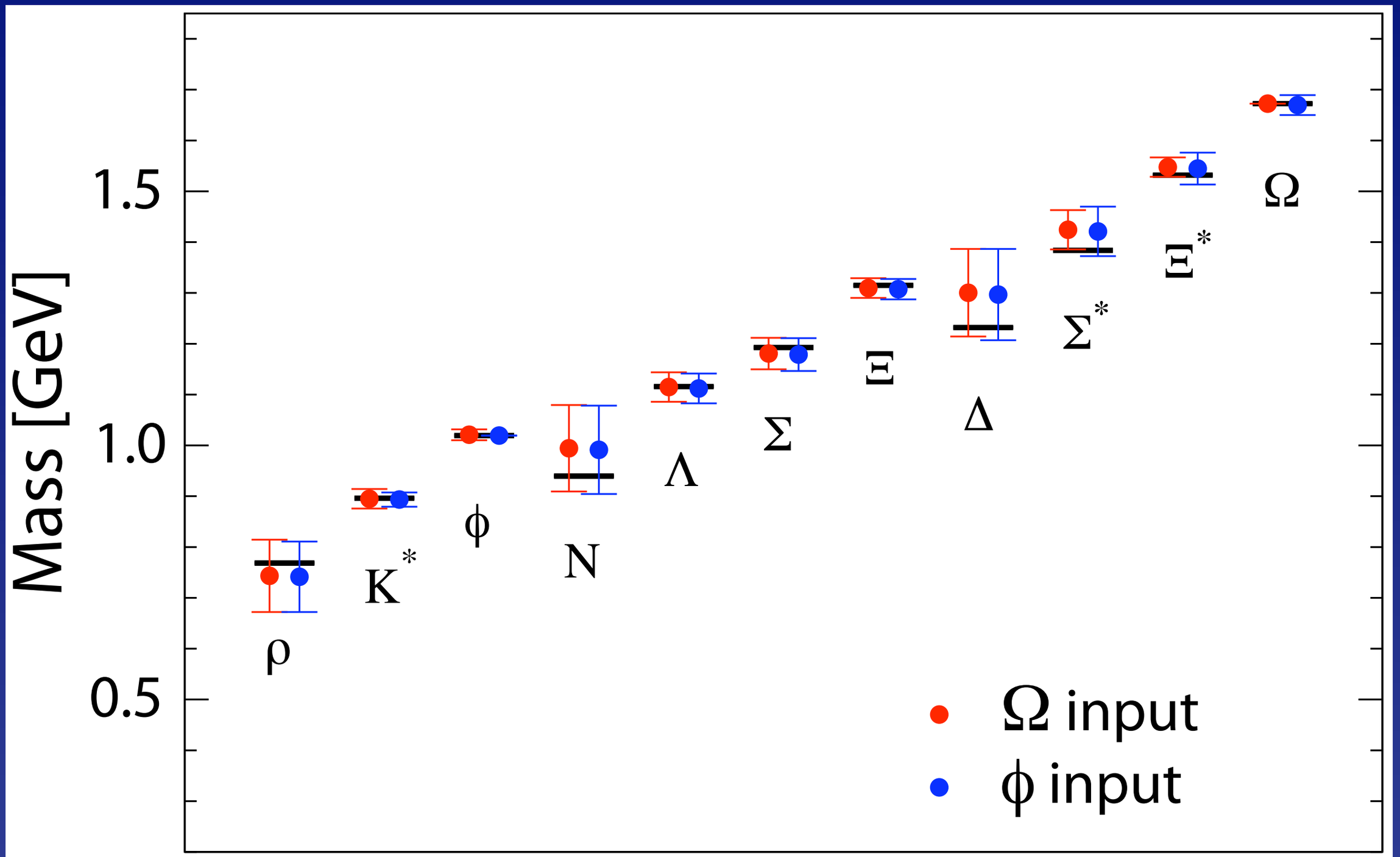
"Mass without Mass"

CP-PACS: no dynamical quark flavors ~1998



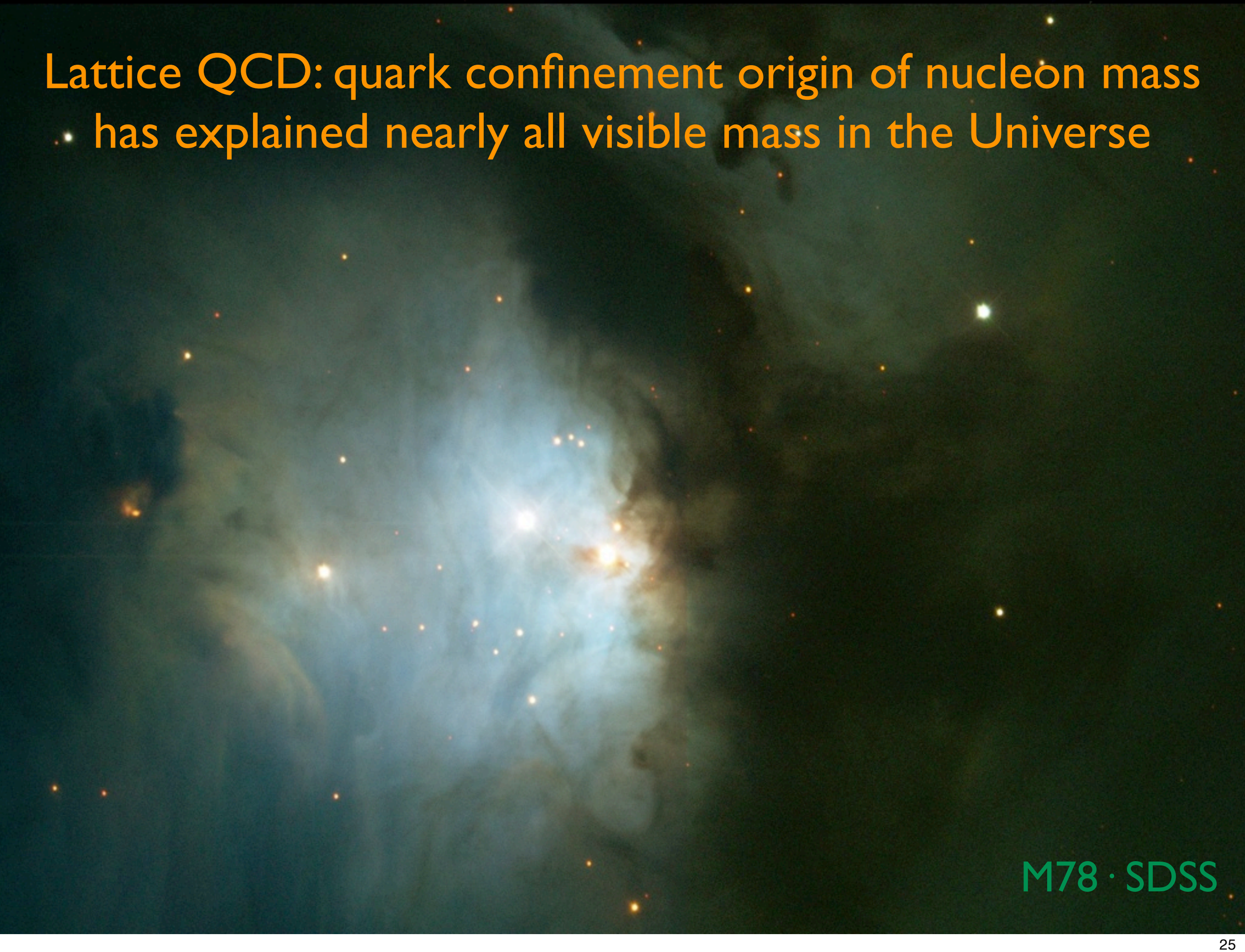
hep-lat/0206009

PACS-CS: 2+1 dynamical quark flavors ~ 2007

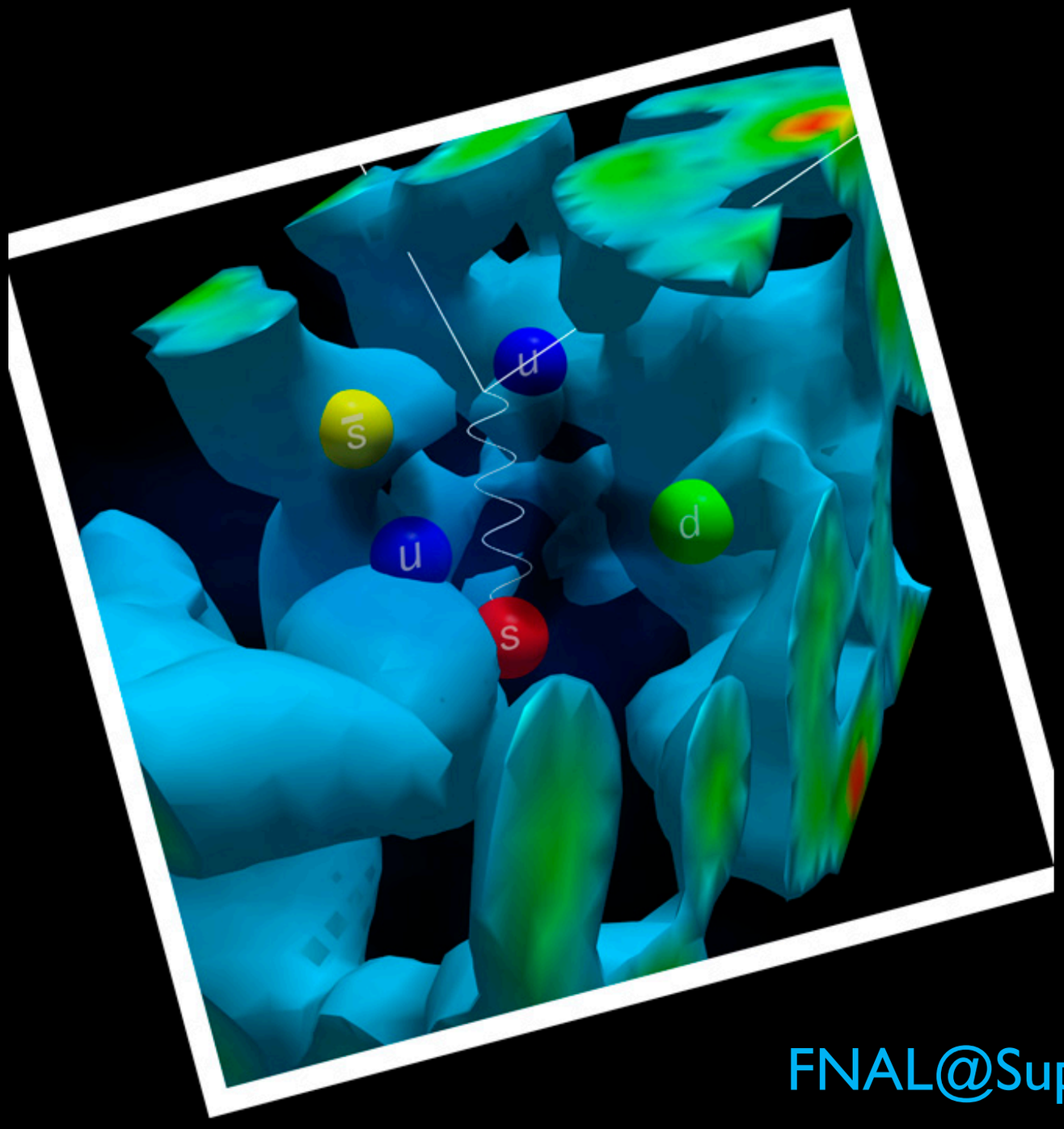


arXiv:0710.3467

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

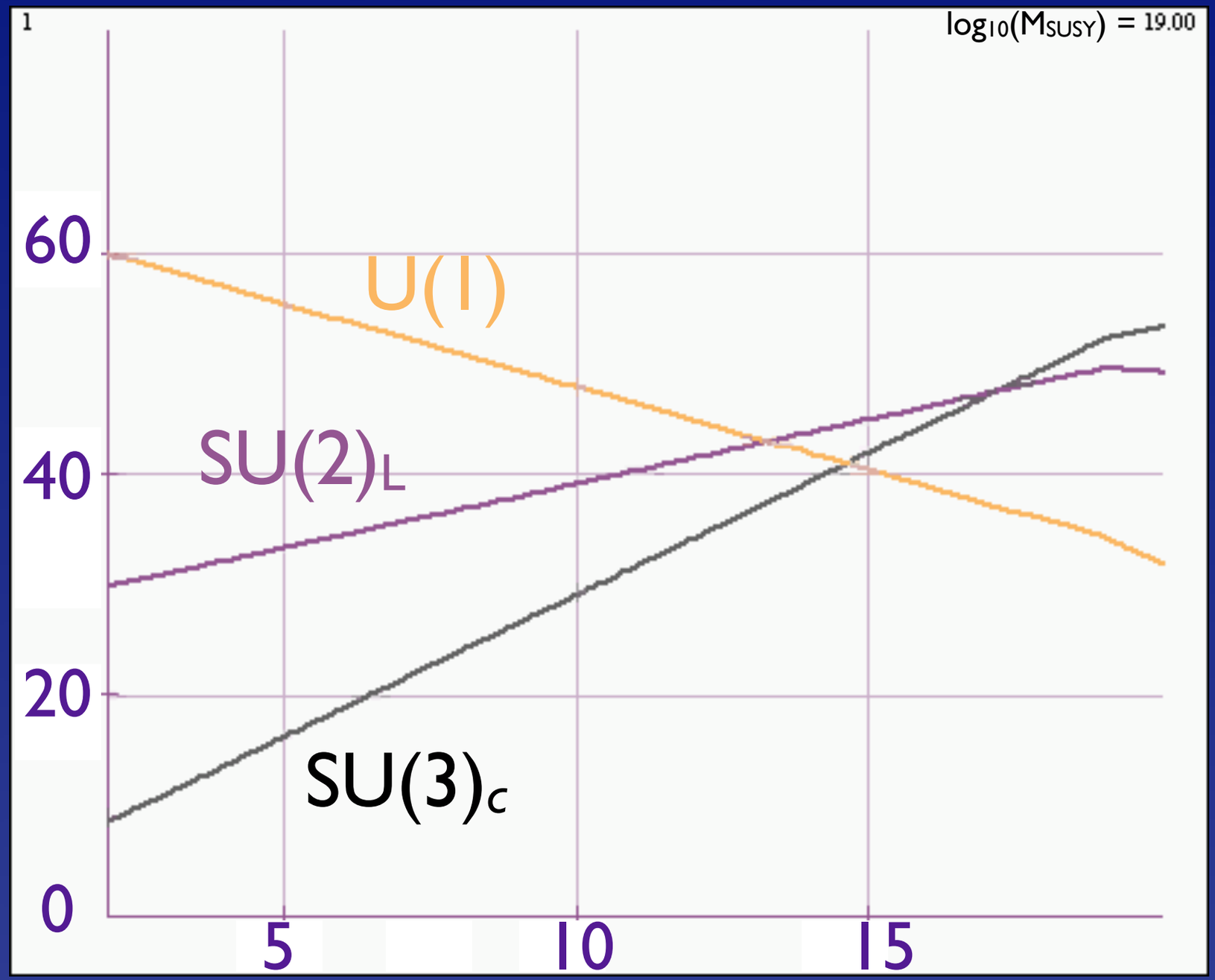


The source of your weight problem is quantum chromodynamics



FNAL@Supercomputing 2007

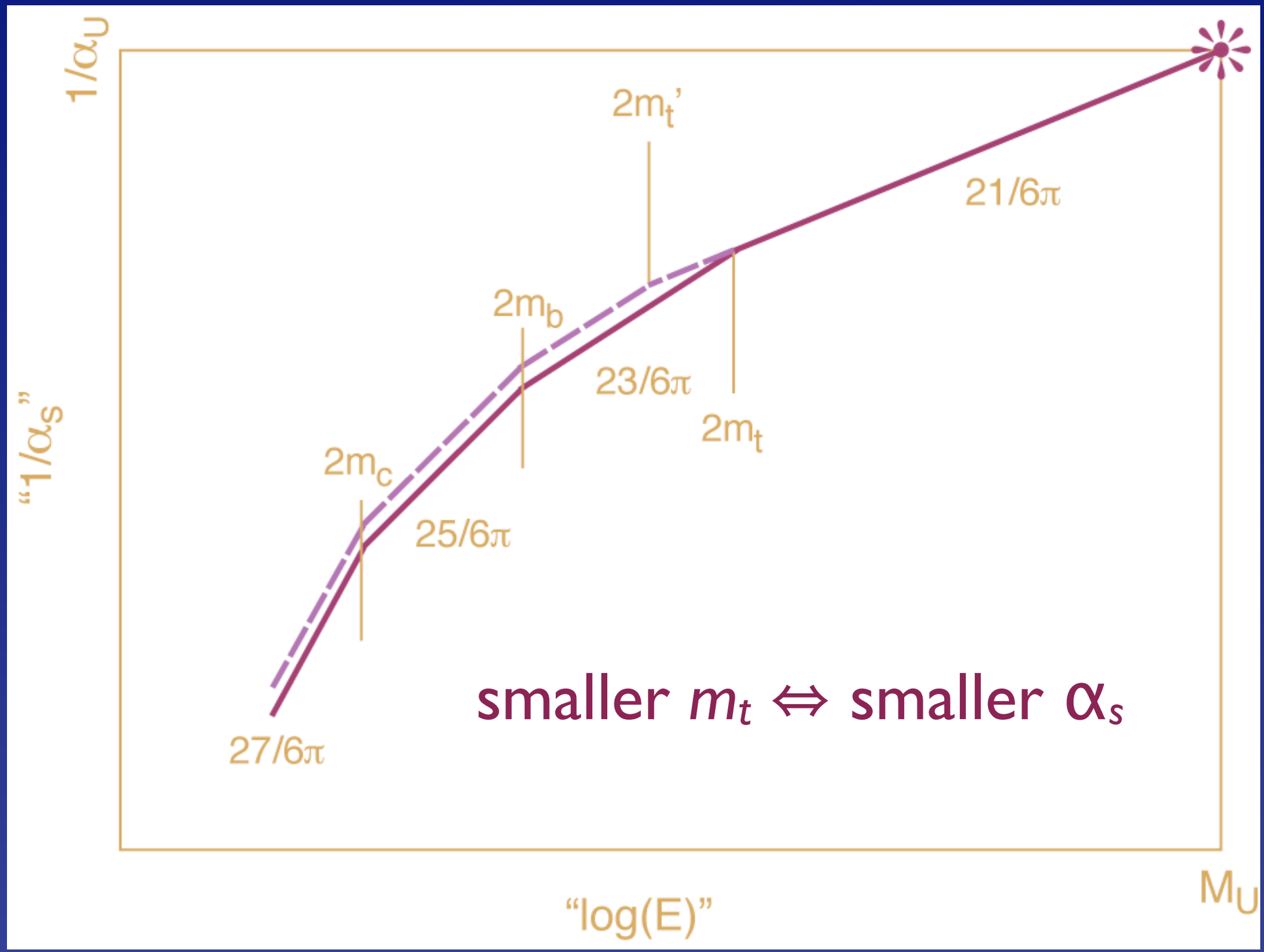
Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$ gives possibility of coupling constant unification



$$\alpha^{-1} = \tfrac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

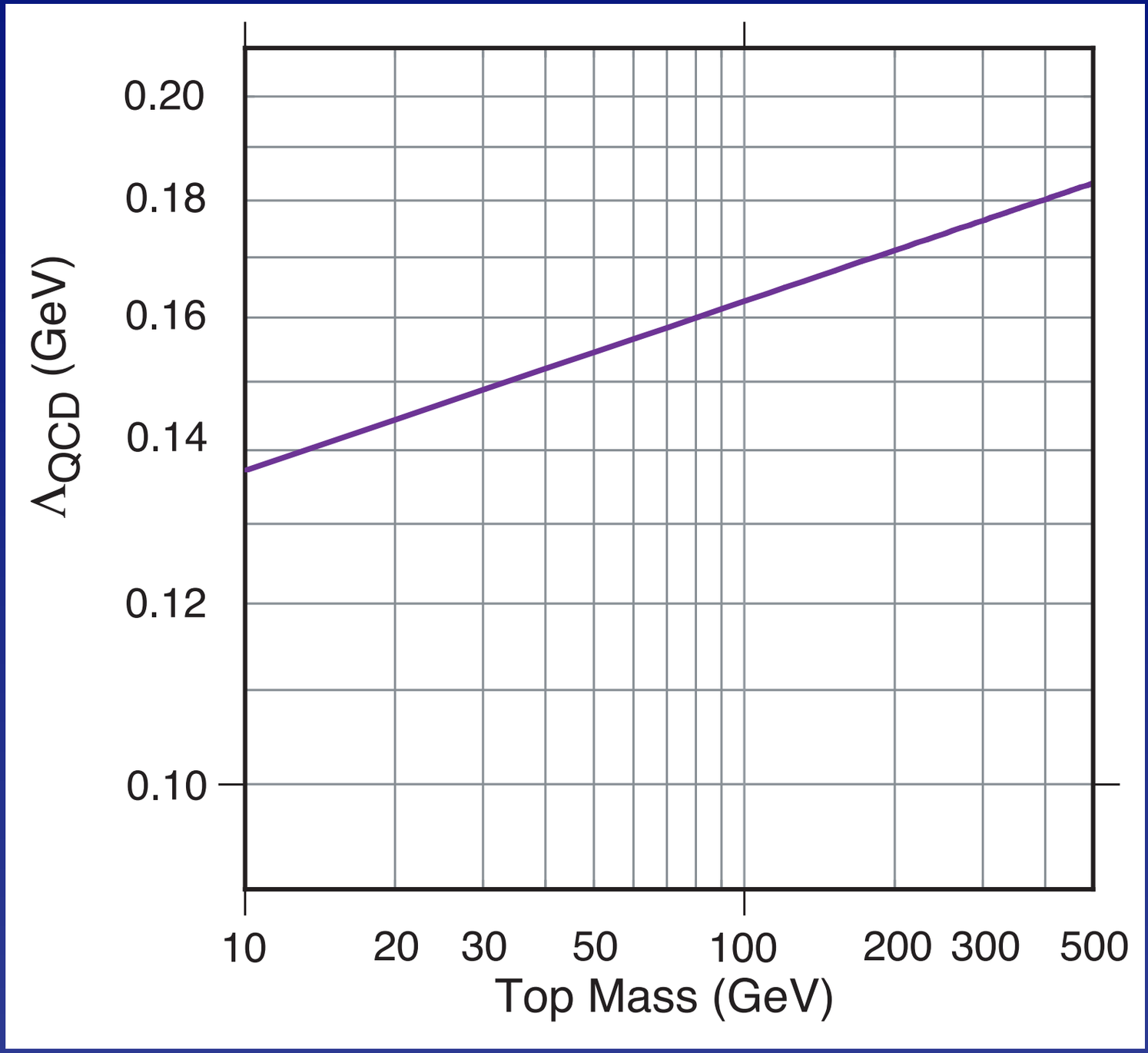
Top matters!

m_t influences low-energy value of α_s



smaller $m_t \Leftrightarrow$ smaller α_s

$$1/\alpha_s(2m_c) \equiv (27/6\pi)\ln(2m_c/\Lambda)$$



$$\Lambda_{\mathsf{QCD}}(\mathsf{GeV}) = \mathsf{const.}\left(\frac{m_t}{1\ \mathsf{GeV}}\right)^{2/27}$$

In a unified-theory framework,

$$M_{\text{proton}} \propto m_t^{2/27}$$

(for $m_b < m_t <$ New Physics)

QCD Lagrangian

$$\mathcal{L}_{\mathsf{QCD}} = \bar{q}^c_f \left[i\gamma^\mu \mathcal{D}_\mu \mathbf{I} - \mathbf{m} \right] q^c_f - \tfrac{1}{2} \mathsf{tr} \left(G_{\mu\nu} G^{\mu\nu} \right)$$

$$\mathbf{m} = \begin{pmatrix} m_u & 0 & 0 & 0 \\ 0 & m_d & 0 & 0 \\ 0 & 0 & m_s & 0 \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Mass terms connect left & right:

$$\begin{aligned} m\ \bar{q}^c q^c &= m\bar{q}^c \left[\tfrac{1}{2}(1+\gamma_5) + \tfrac{1}{2}(1-\gamma_5) \right] q^c \\ &= m \left[\bar{q}^c_{\mathrm{L}} q^c_{\mathrm{R}} + \bar{q}^c_{\mathrm{R}} q^c_{\mathrm{L}} \right] \end{aligned}$$

n massless quarks $\Rightarrow$ SU(***n***)$_{\mathsf{L}} \otimes$ SU(***n***)$_{\mathsf{R}}$ chiral symmetry

n massless quarks $\Rightarrow$ SU(n)$_L \otimes$SU(n)$_R$ chiral symmetry

Soft-pion theorems: SU(2)$_L \otimes$SU(2)$_R$ ✓

Current algebra: SU(3)$_L \otimes$SU(3)$_R$ ✓

Excellent approximation: $m_u, m_d = 0$

Good approximation: $m_u, m_d, m_s = 0$

Infer very light u, d + not-as-light s

Near the confinement scale …

$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_V$

Nambu-Goldstone bosons $\pi^+ \; \pi^0 \; \pi^-$

(residual) isospin symmetry broken by EM, $m_d - m_u$

The irony of isospin:

Motivated Yang-Mills theory,
seems an accident of $m_u \approx m_d \approx 0$,
external to QCD!

up and down quark masses are crucial

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

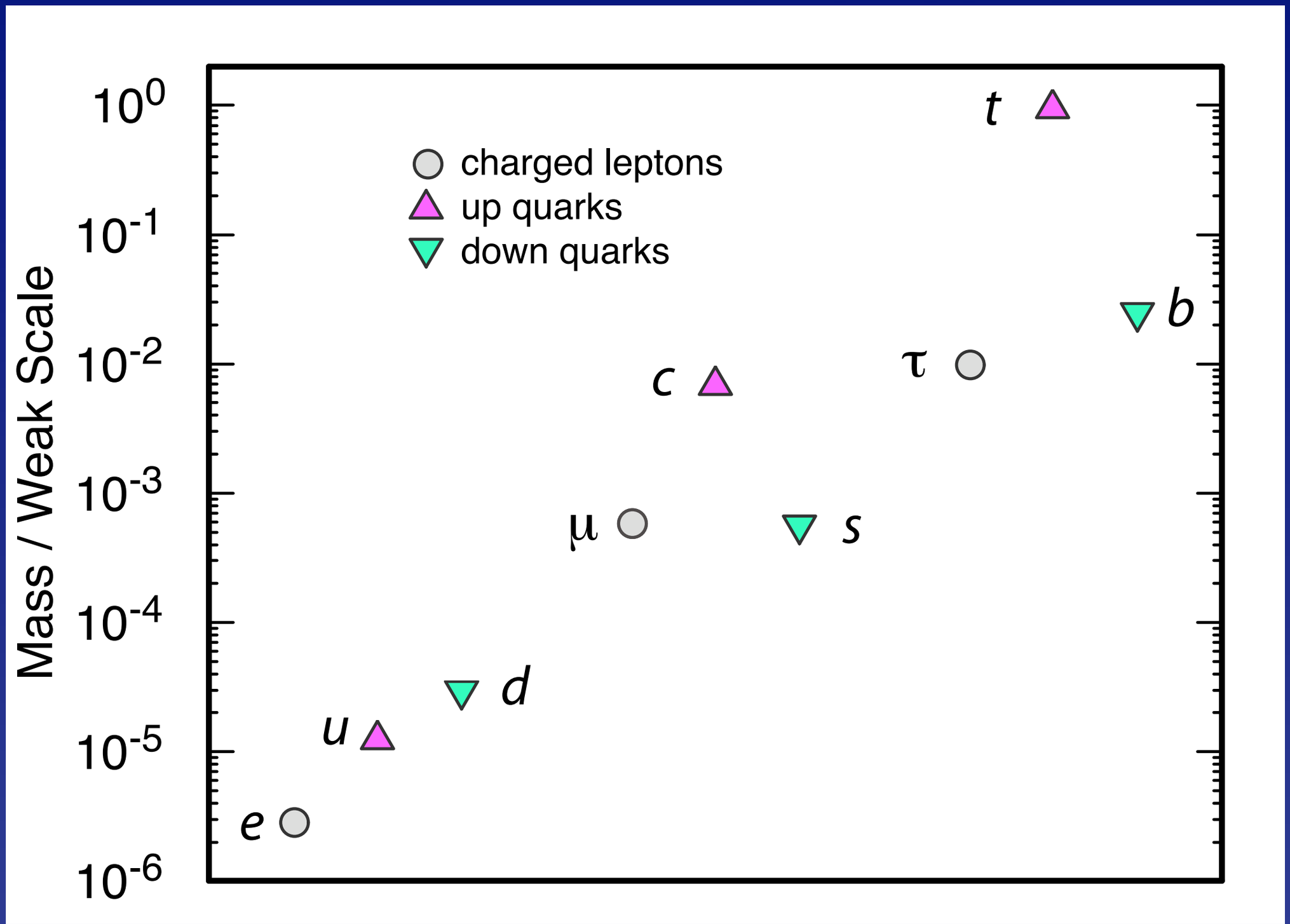
$m_d > m_u$ overcomes electromagnetic self-energy,

so proton is lightest nucleus

p = uud, n = udd

Where do quark (and lepton) masses come from?

Fermion Masses



Running mass $m(m)$

QCD & QED

Fermion masses allowed

Gauge-boson masses forbidden

Photon mass term

$$\frac{1}{2} m_\gamma^2 A^\mu A_\mu$$

violates gauge invariance:

$$\boxed{A^\mu A_\mu \to (A^\mu - \partial^\mu \Lambda)(A_\mu - \partial_\mu \Lambda) \neq A^\mu A_\mu}$$

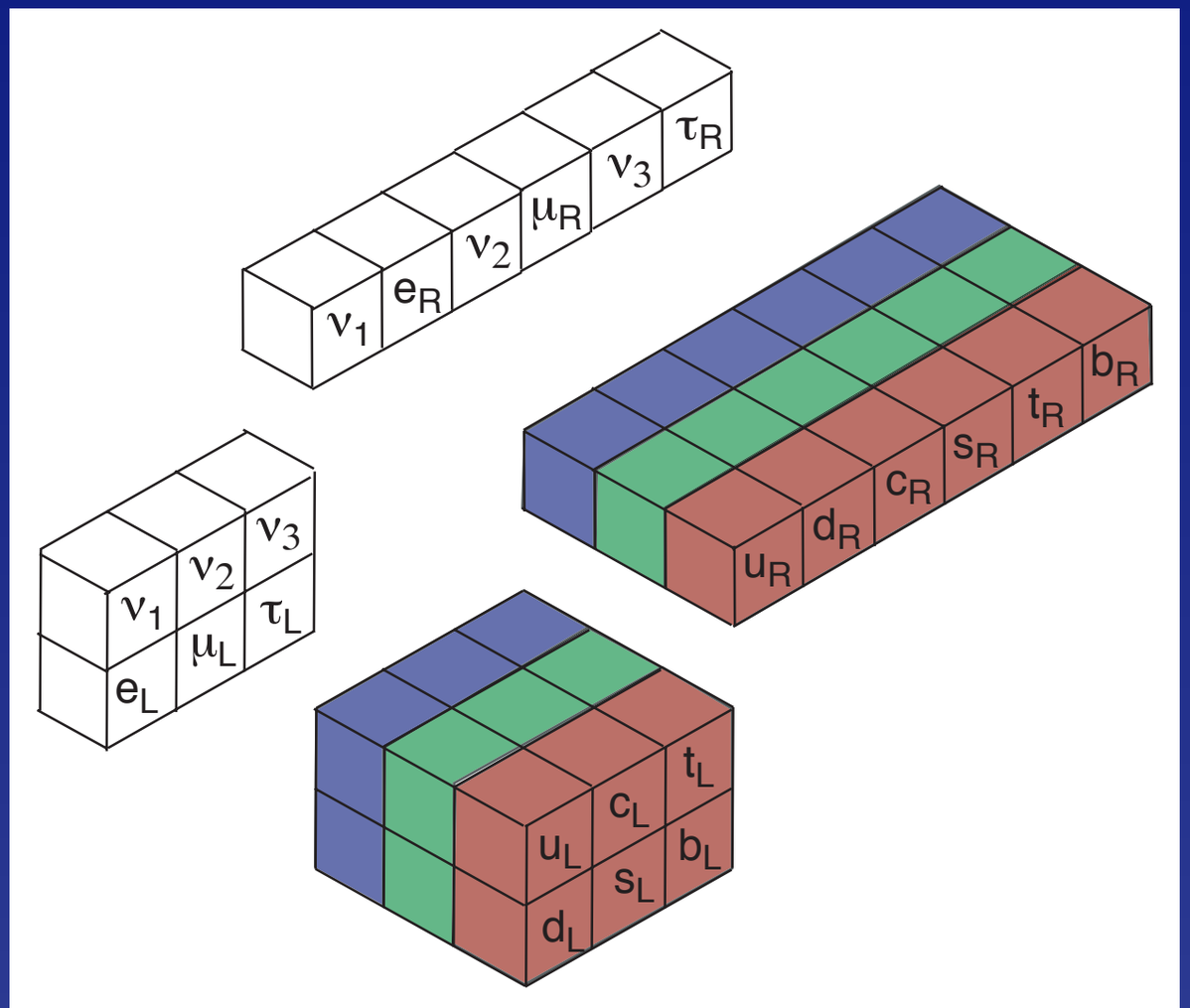
Massless photon and gluon predicted

observed: $m_\gamma \lesssim 10^{-22}\, m_e$

Electroweak theory

Fermion masses forbidden

Gauge-boson masses forbidden



LH, RH fermions respond differently to symmetries

Scalar masses allowed: $\mu^2 \Phi^\dagger \Phi \rightarrow \mu^2 \Phi^\dagger \Phi$

Hide EW symmetry to give masses to quarks, leptons, and gauge bosons

"Higgs mechanism" breaks

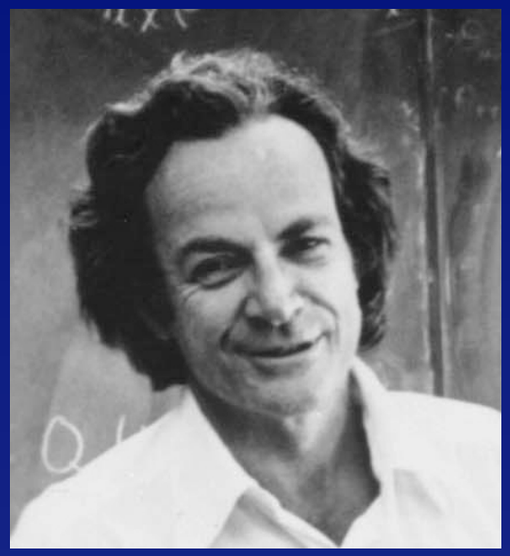
$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

g g'

$M_W = gv/2$

$M_Z = M_W/\cos\theta$

$\tan\theta = g'/g$ $v = 246$ GeV



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e \left[(\overline{e_{\mathsf{L}}} \Phi) e_{\mathsf{R}} + \overline{e_{\mathsf{R}}} (\Phi^\dagger e_{\mathsf{L}}) \right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

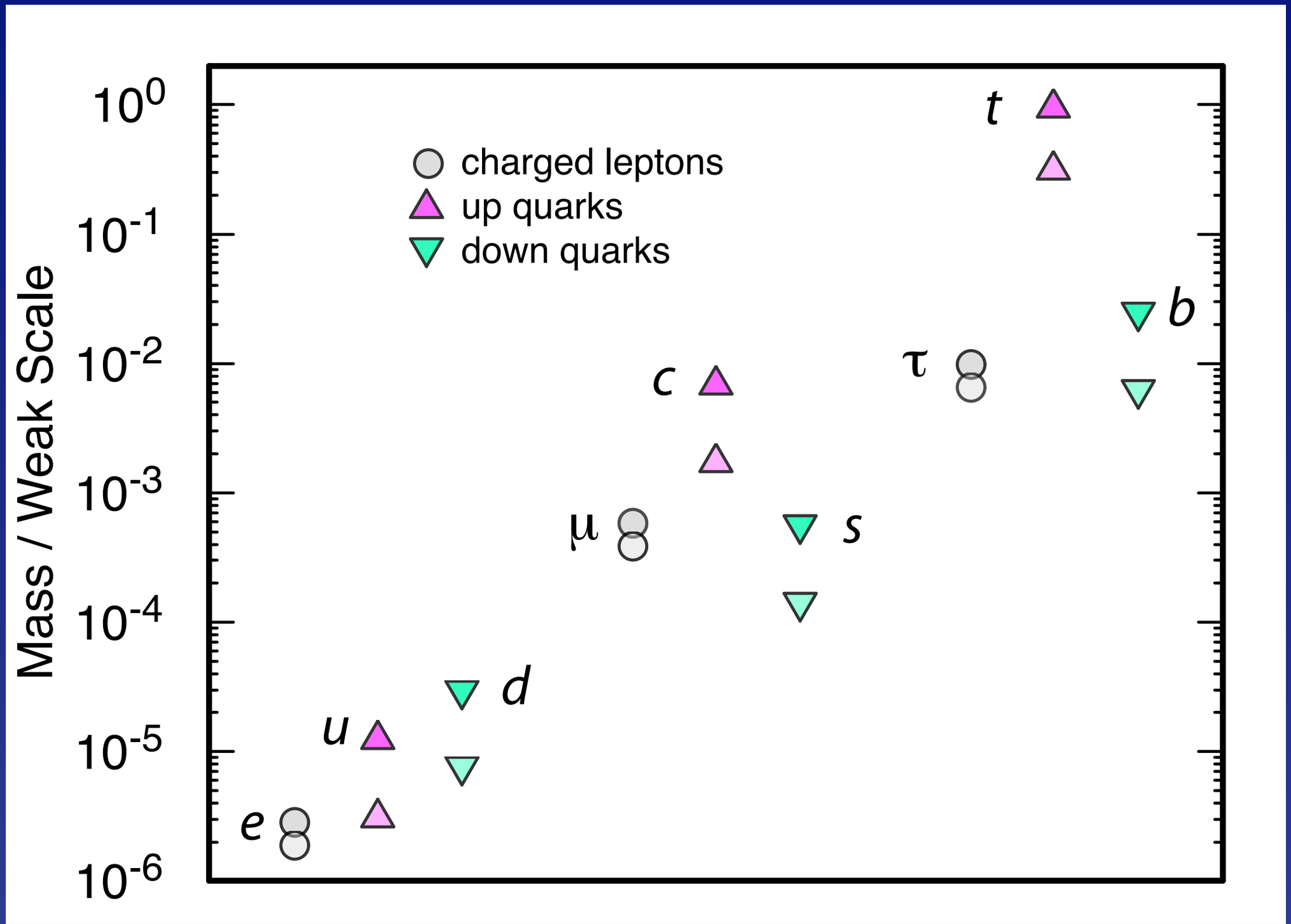
after SSB

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

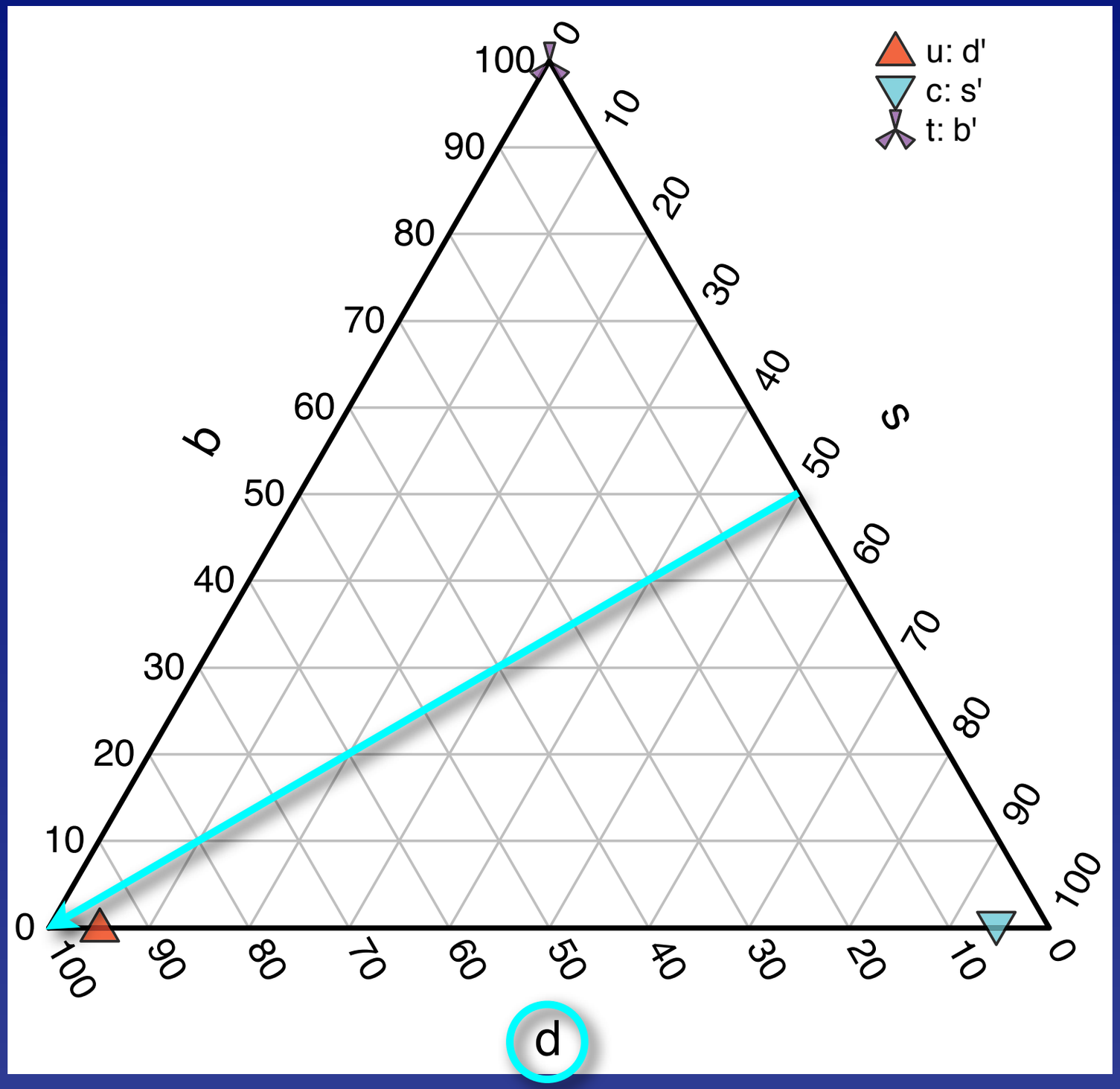
fermion mass implies physics beyond the standard model

Fermion Masses Run



Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*



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

Mass, Electroweak Symmetry Breaking, and the Fermi Scale

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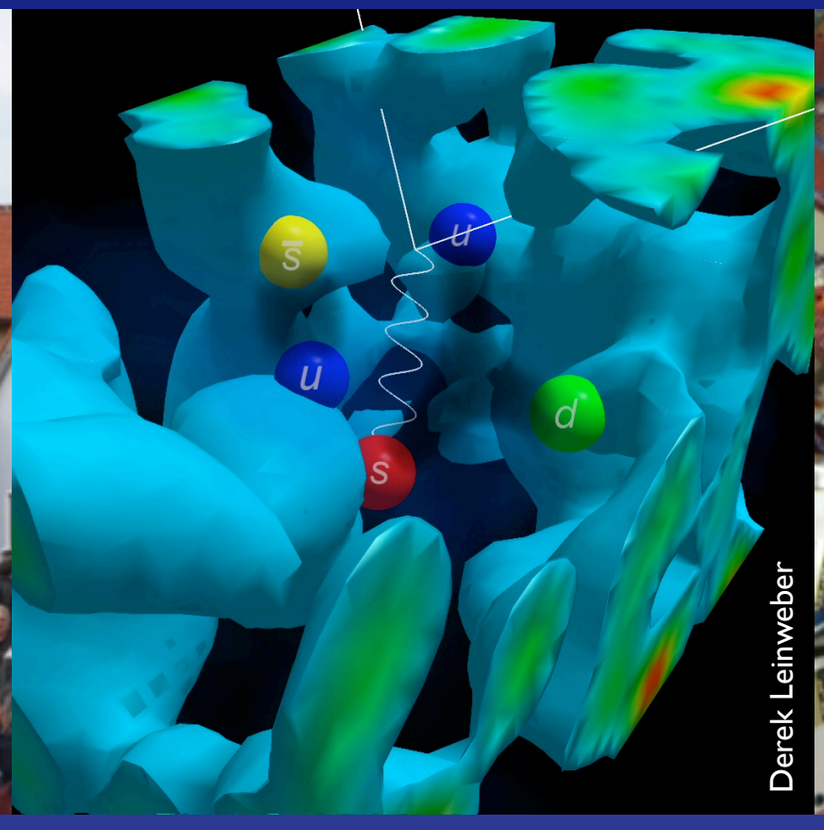

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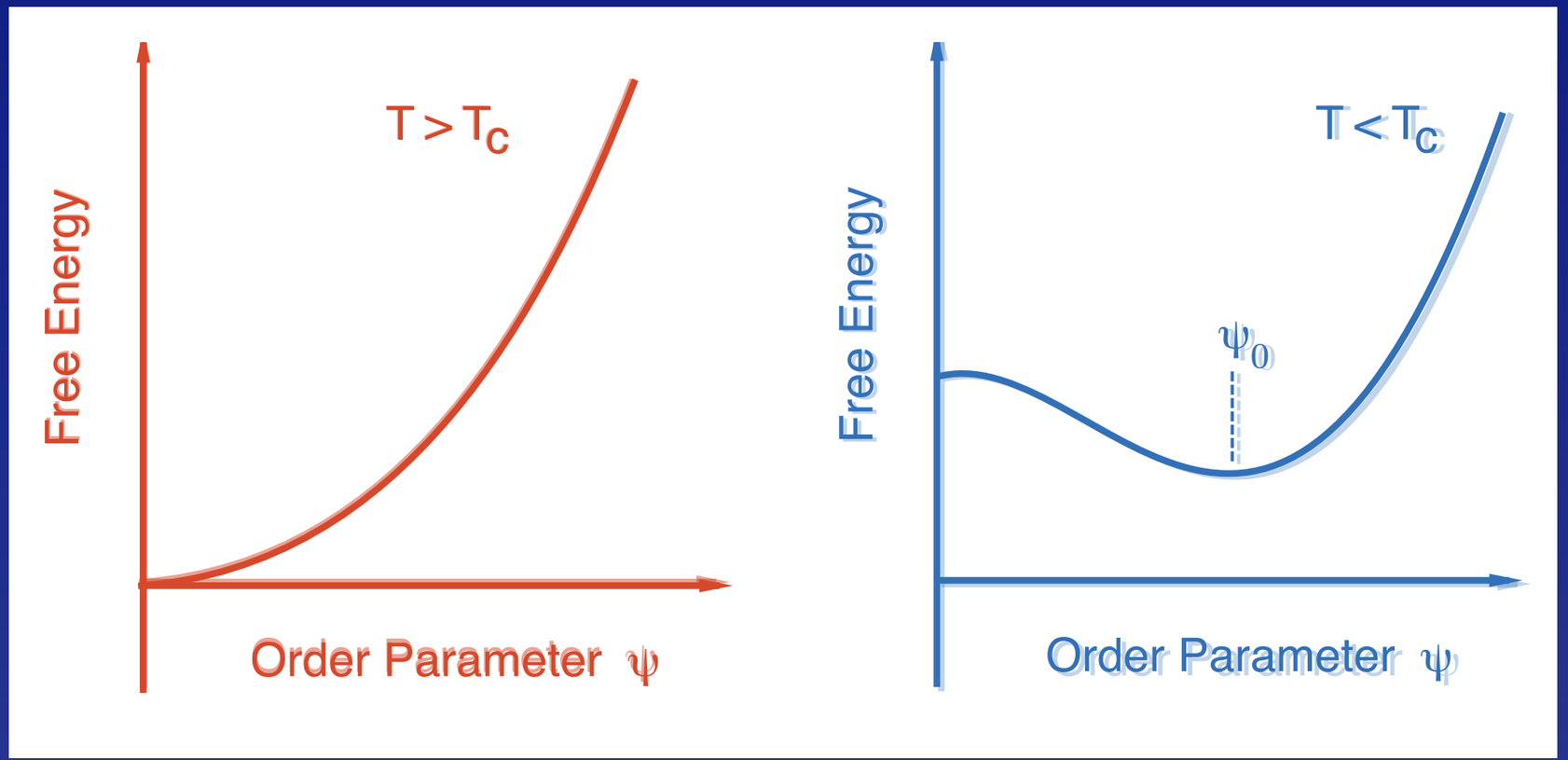
GEN NITROGEN NIT

Ginzburg–Landau Phenomenology

Ordinary charge carriers + resistance-free carriers



$$\mathbf{B} = 0: \qquad G_{\mathsf{super}}(0) = G_{\mathsf{normal}}(0) + \alpha|\psi|^2 + \beta|\psi|^4$$

$$T \gtrless T_c: \quad \alpha \gtrless 0 \quad \langle|\psi|^2\rangle_0 \neq 0$$

In a nonzero magnetic field …

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*}\left| -i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi\right|^2$$

$$\left.\begin{array}{c} e^* = -2 \\ m^* \end{array}\right\} \text{ of superconducting carriers}$$

Weak, slowly varying field: $\psi \approx \psi_0 \neq 0,\ \nabla\psi \approx 0$

Variational analysis ⇒ wave eqn of massive photon

$$M_\gamma = \lambda^{-1} = e^\star |\langle\psi\rangle_0| / \sqrt{m^\star c^2}$$

origin of Meissner effect

Higgs boson

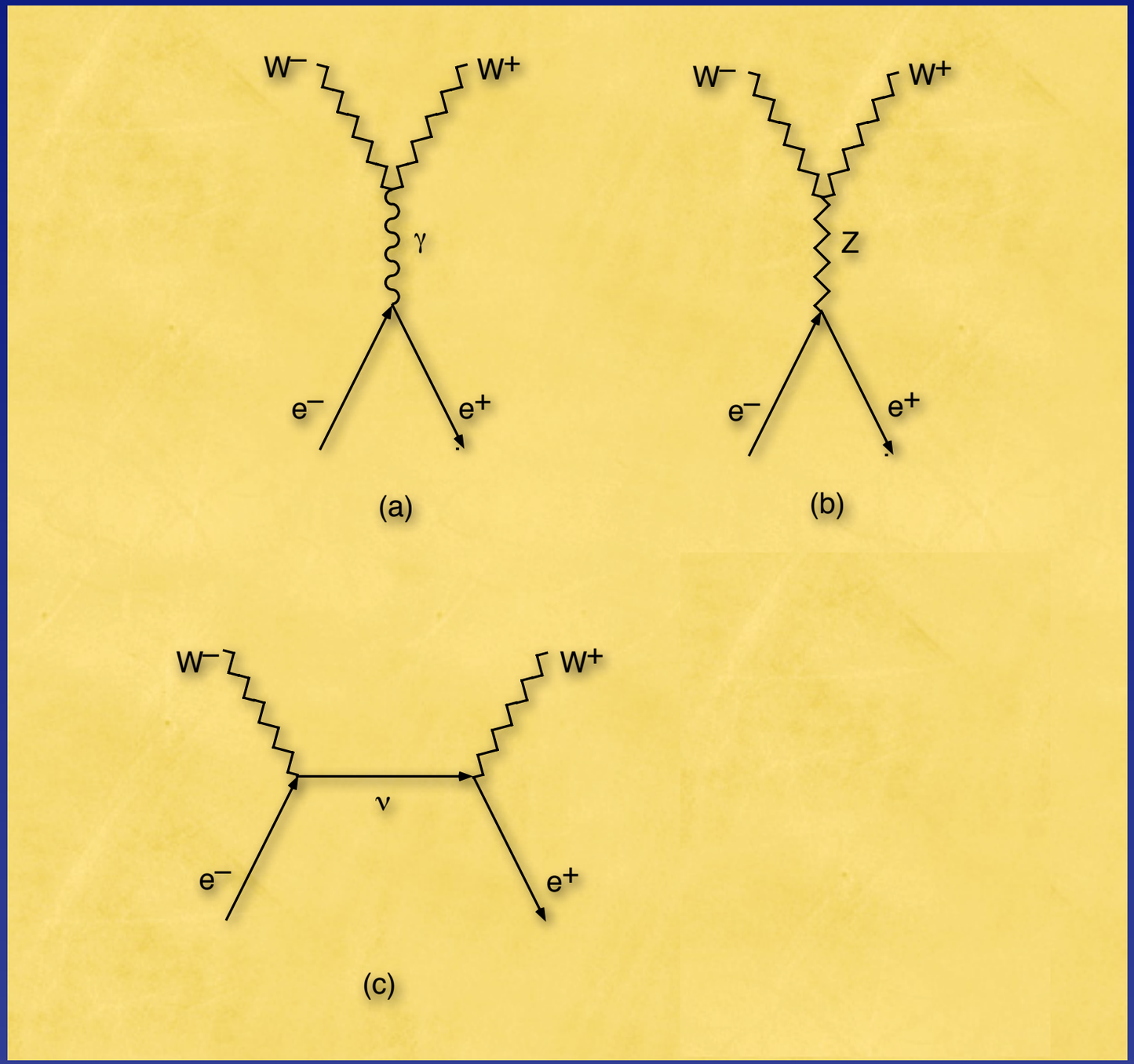
3 of 4 scalars become longitudinal W^+, W^-, Z
1 becomes massive H: $M_H \neq 0$, *not predicted*

"H" needed for consistent HE theory,
whether or not it is agent of EWSB:
$M_H \lesssim 1$ TeV

Higgs boson influence seen in vacuum,
in couplings to W & Z, not yet fermions

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \longrightarrow W^+W^-$$



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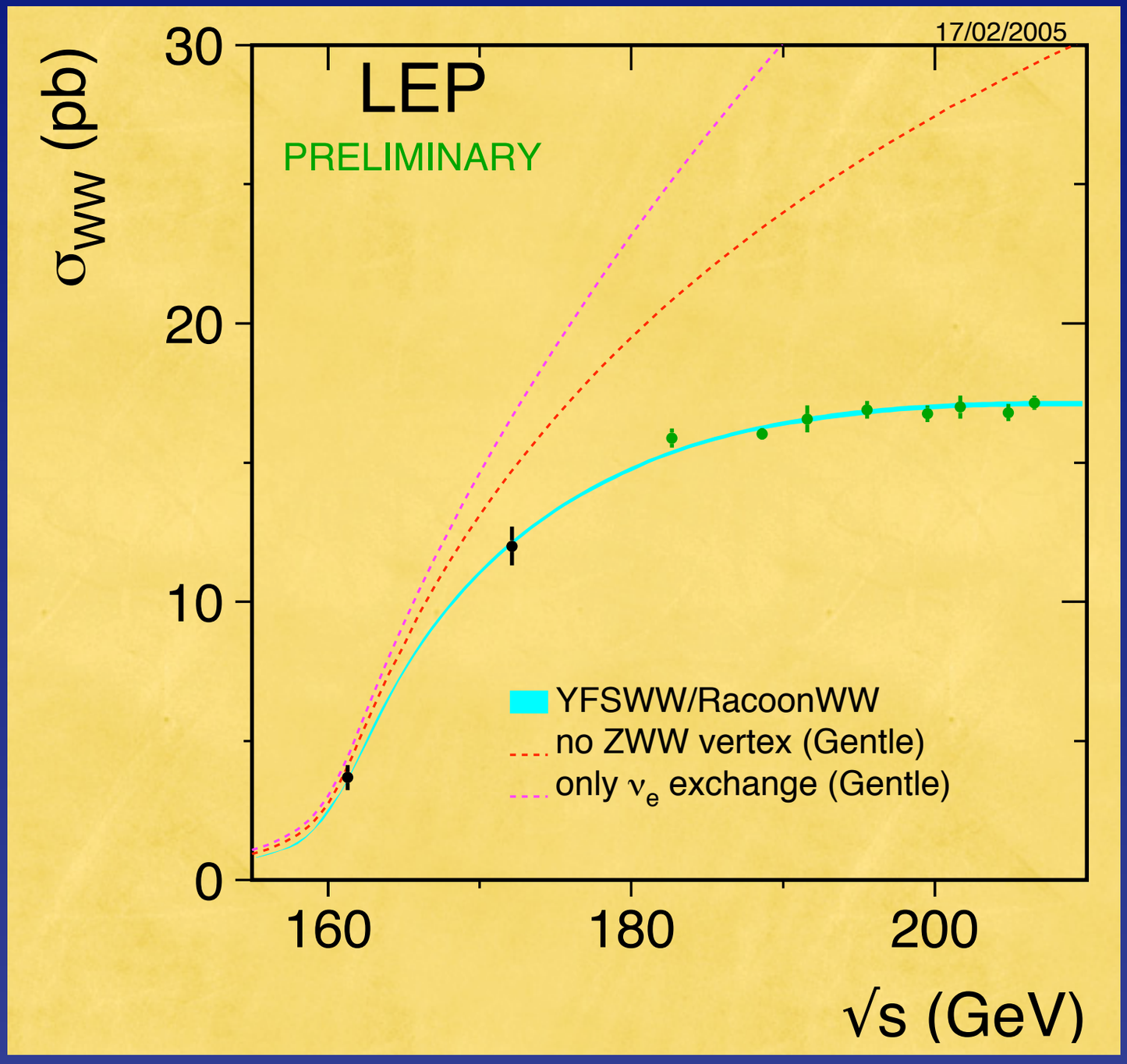

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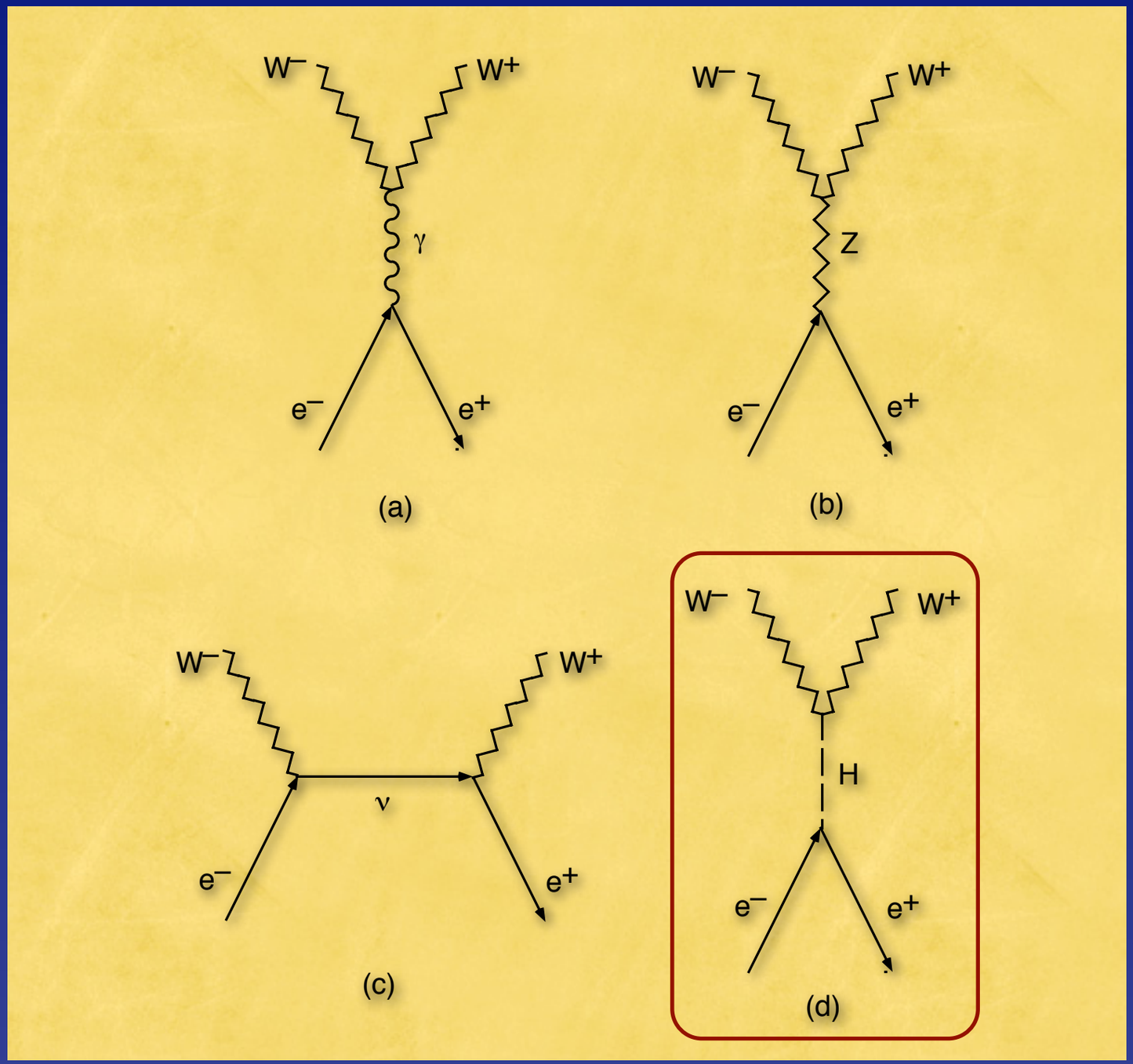
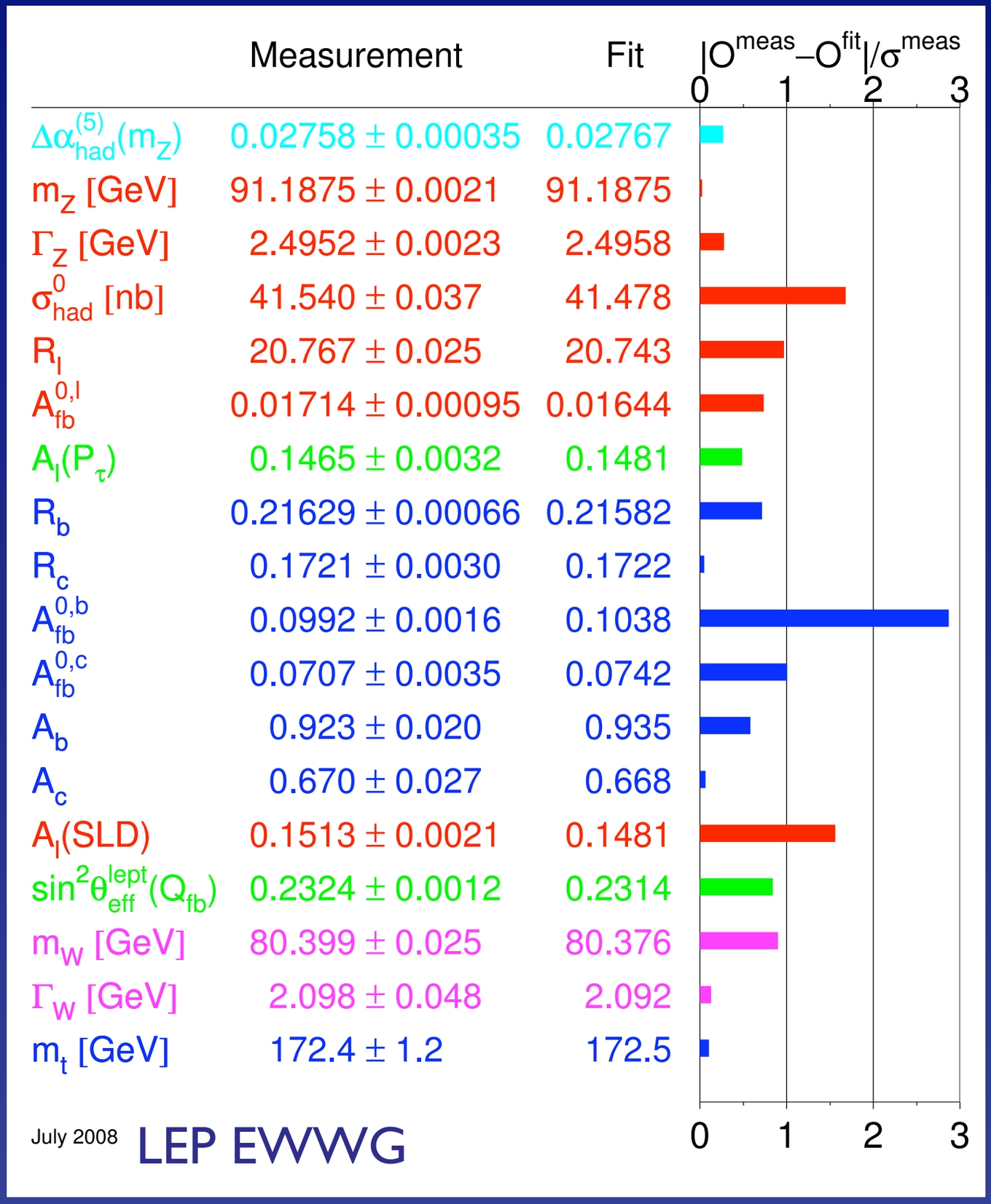


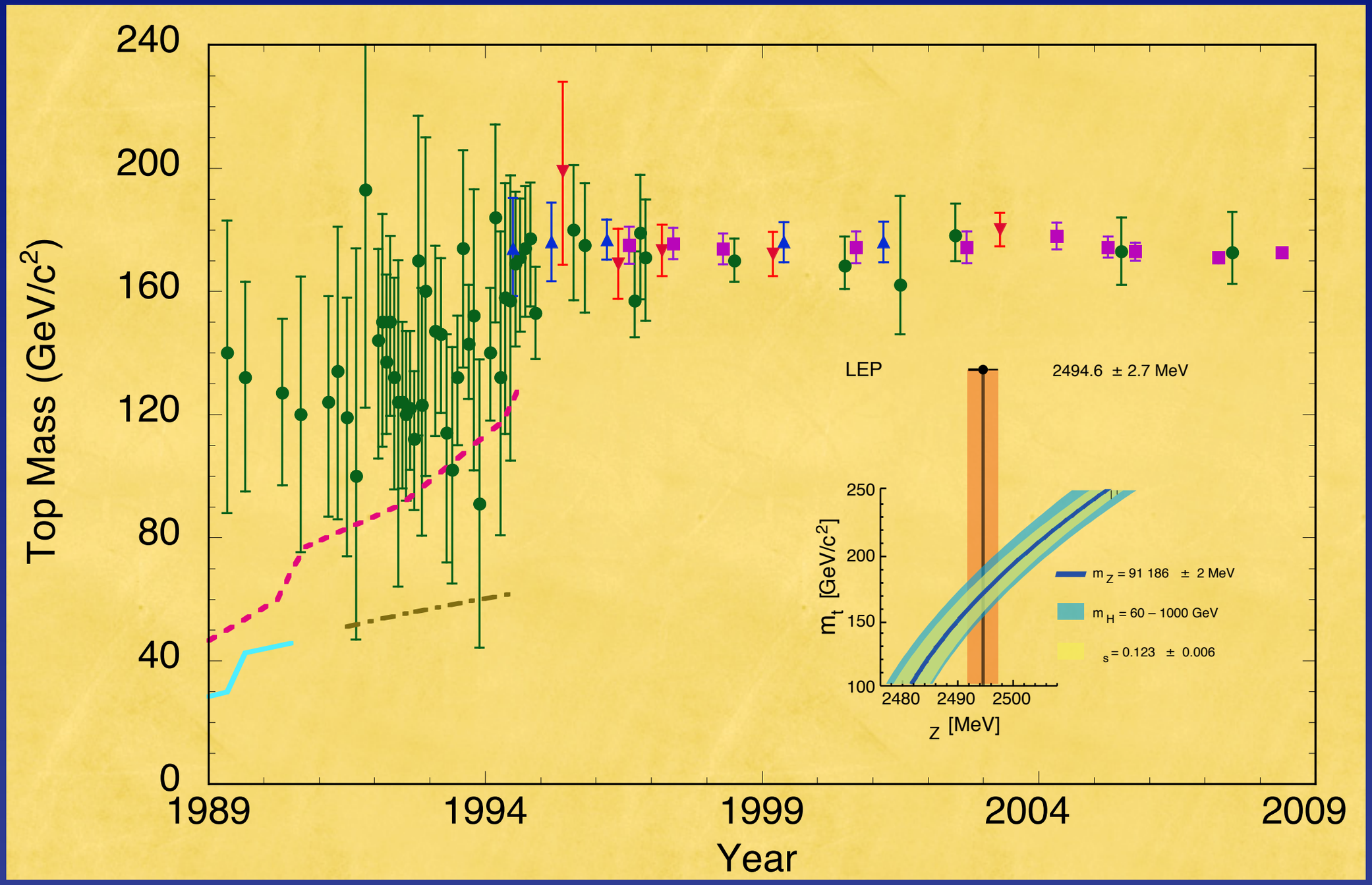
Massive weak bosons: Higgs boson

Meissner effect

Precision Measurements Test the Theory …



… and determine unknown parameters



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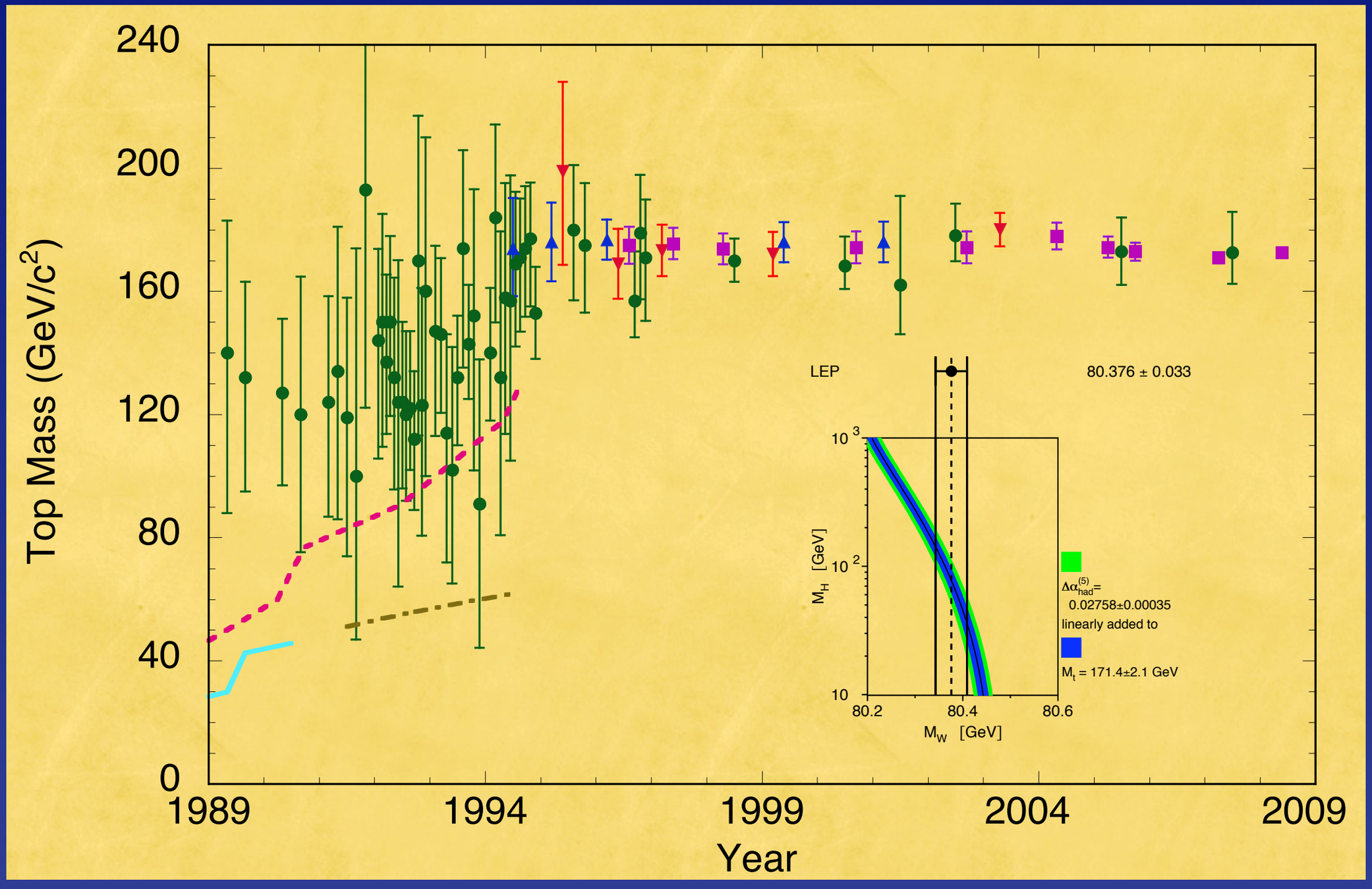
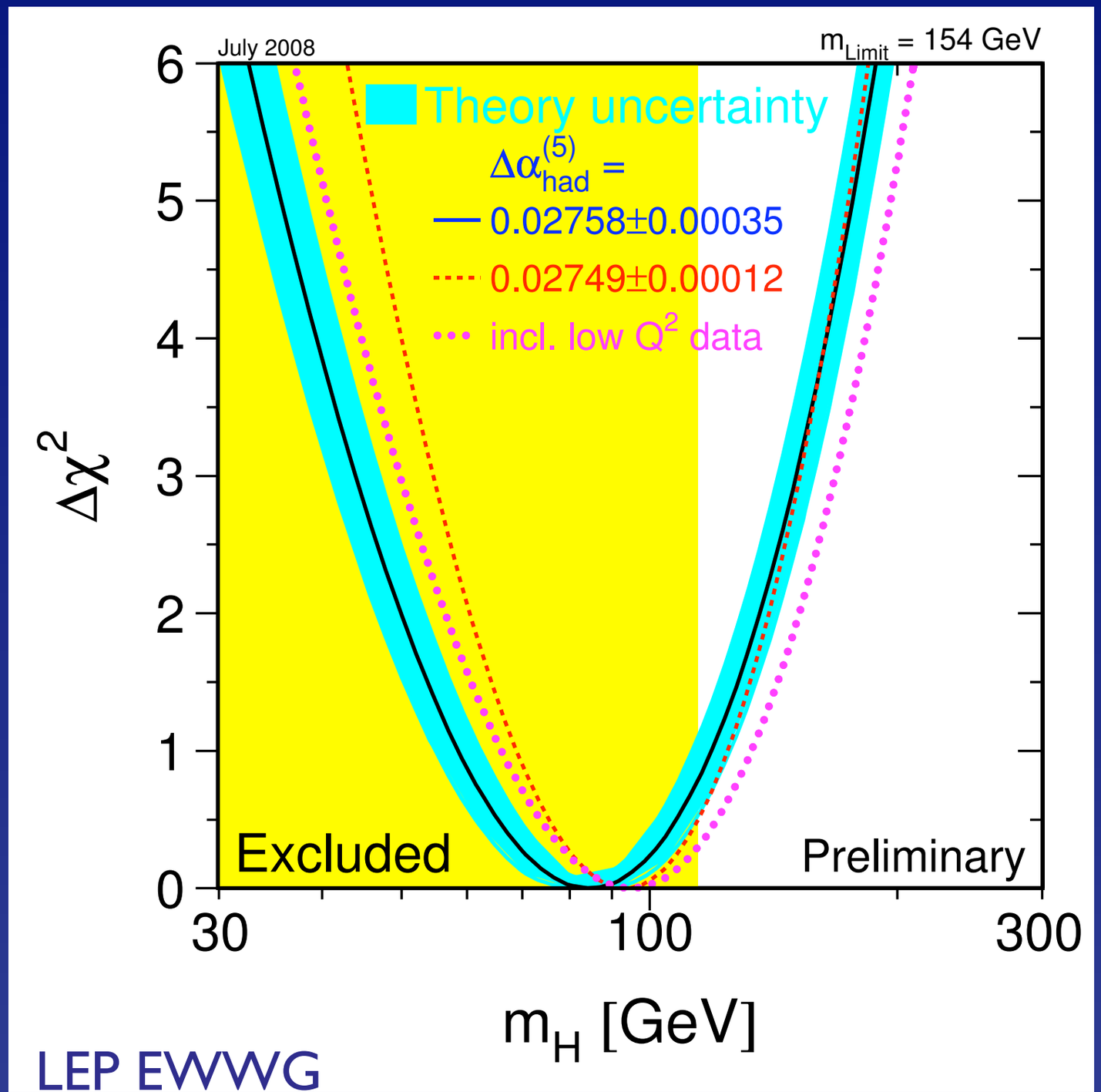
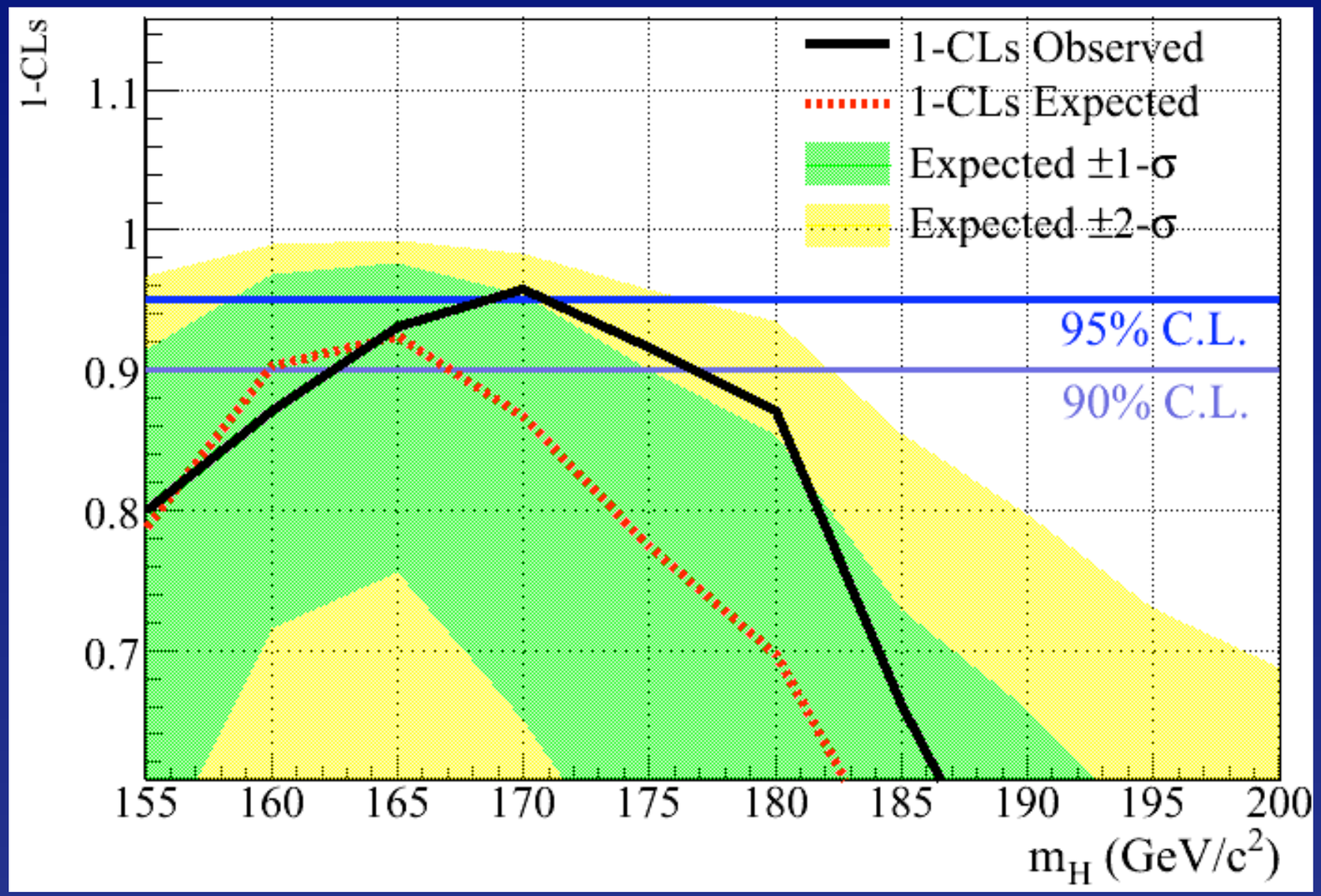


Indirect constraints on M_H

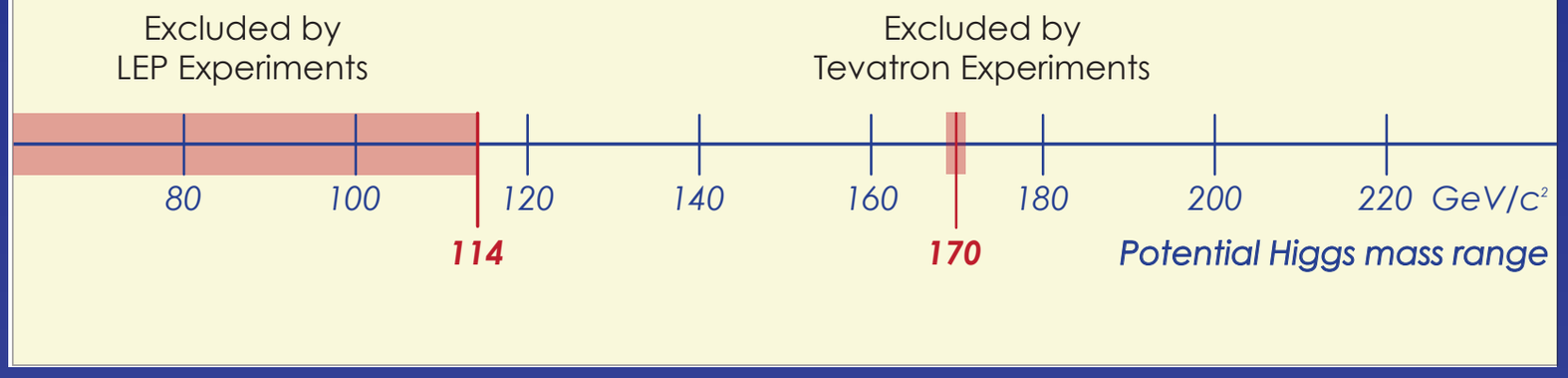


⇒ M_H < 185 GeV, within standard EW theory

Tevatron Combined Higgs Exclusion



Higgs Mass Exclusion



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

Hiding electroweak symmetry: another path

Modeled EWSB on Ginzburg–Landau description of superconducting phase transition; new, elementary scalars

GL is not the last word on superconductivity: *dynamical* Bardeen–Cooper–Schrieffer theory

Elementary fermions – electrons – and gauge interactions – QED – needed to generate scalar bound states are already present in the case of superconductivity

Could a scheme of similar economy account for EWSB?

Recall QCD with massless up and down quarks

Spontaneous chiral symmetry breaking
broken generators ⇔ 3 axial currents

couplings to π ⇔ pion decay constant f_π

Turn on $SU(2)_L \otimes U(1)_Y$:

EW gauge bosons couple to axial currents,
acquire masses of order gf_π

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4} \qquad (W^+, W^-, W_3, \mathcal{A})$$

Diagonalize:

$$M_W^2 = g^2 f_\pi^2/4,\ M_Z^2 = (g^2 + g'^2) f_\pi^2/4,\ M_A^2 = 0$$

$$\frac{M_Z^2}{M_W^2} = \frac{(g^2 + g'^2)}{g^2} = \frac{1}{\cos^2 \theta_W}$$

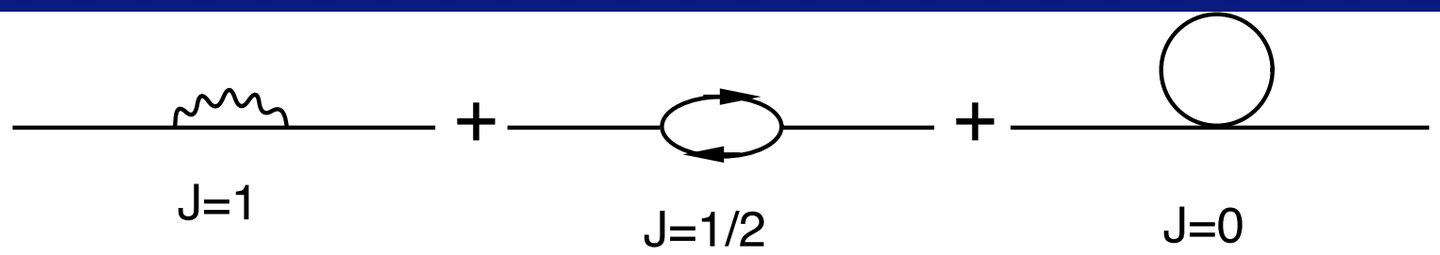
Massless pions disappear from physical spectrum, to become longitudinal components of weak bosons.

$M_W \approx 30$ MeV

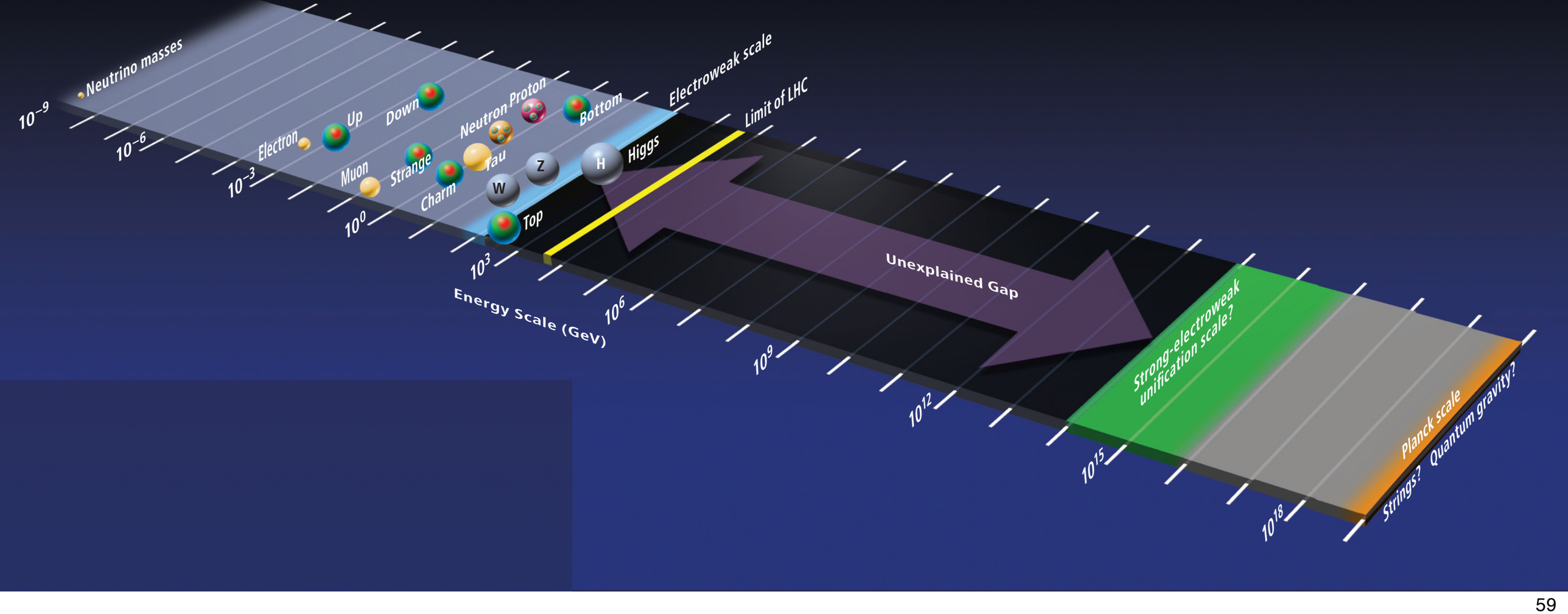
No fermion masses …

The Hierarchy Problem: Quantum Corrections to M_H

$$M_H^2(p^2) = M_H^2(\Lambda^2) +$$



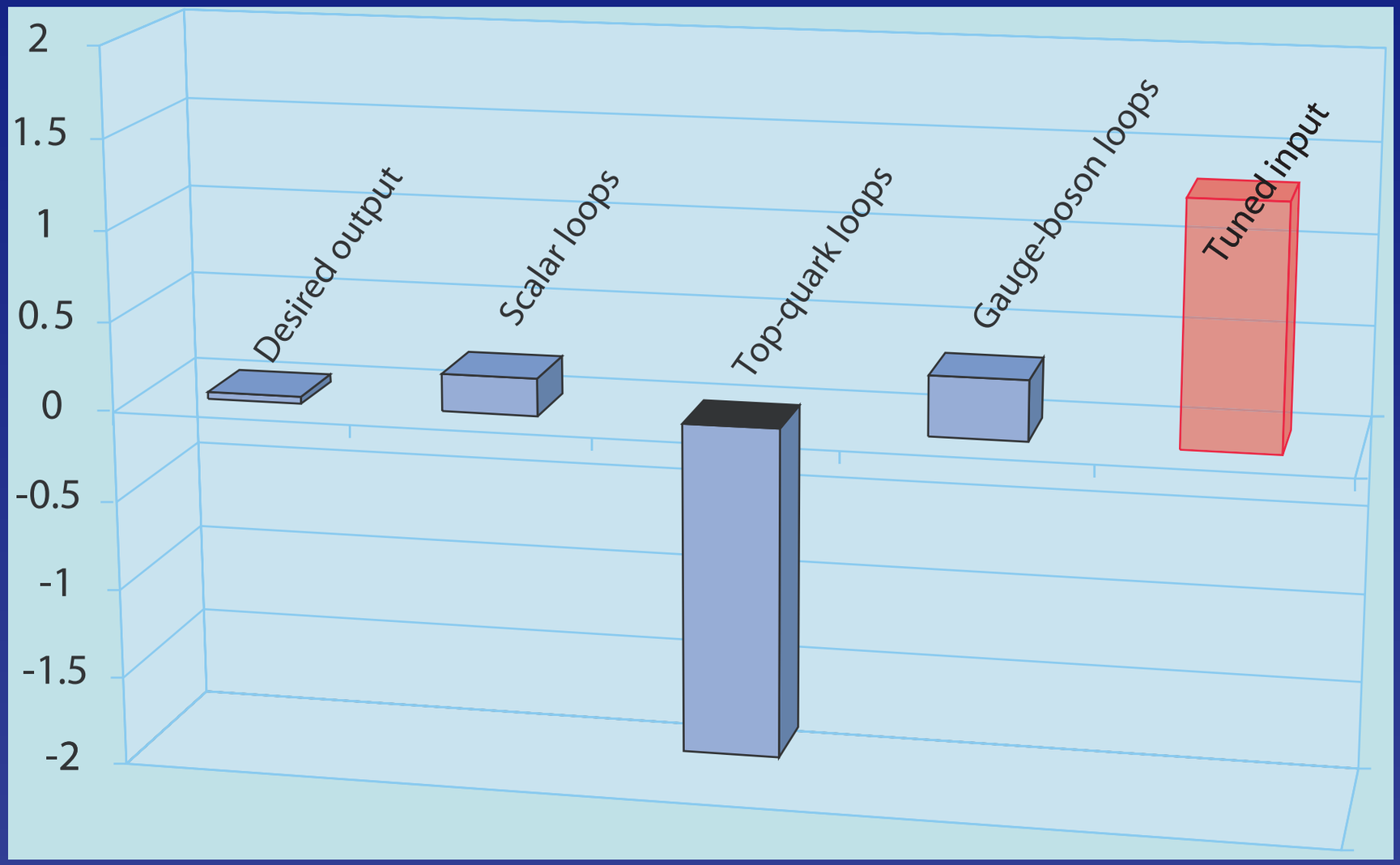
$$M_H^2(p^2) = M_H^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots$$



Symmetries protect gauge boson & fermion masses, no symmetry protects Higgs boson mass

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



5 TeV

Imagine a world without a Higgs mechanism

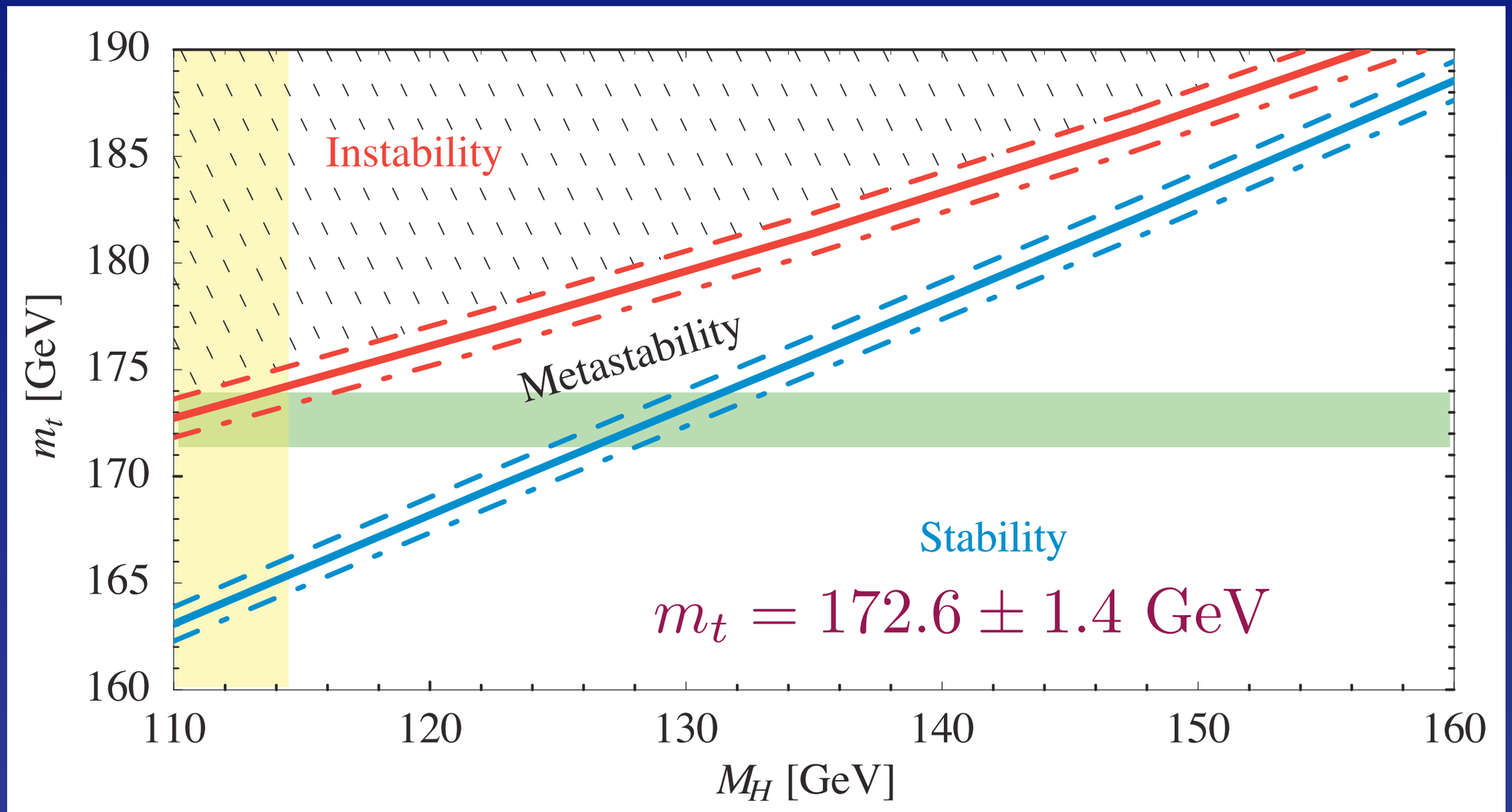
If electroweak symmetry were not hidden …

- 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; $U(1)_{EM}$ remains
- *p outweighs n:* rapid β-decay
  $\Rightarrow$ 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

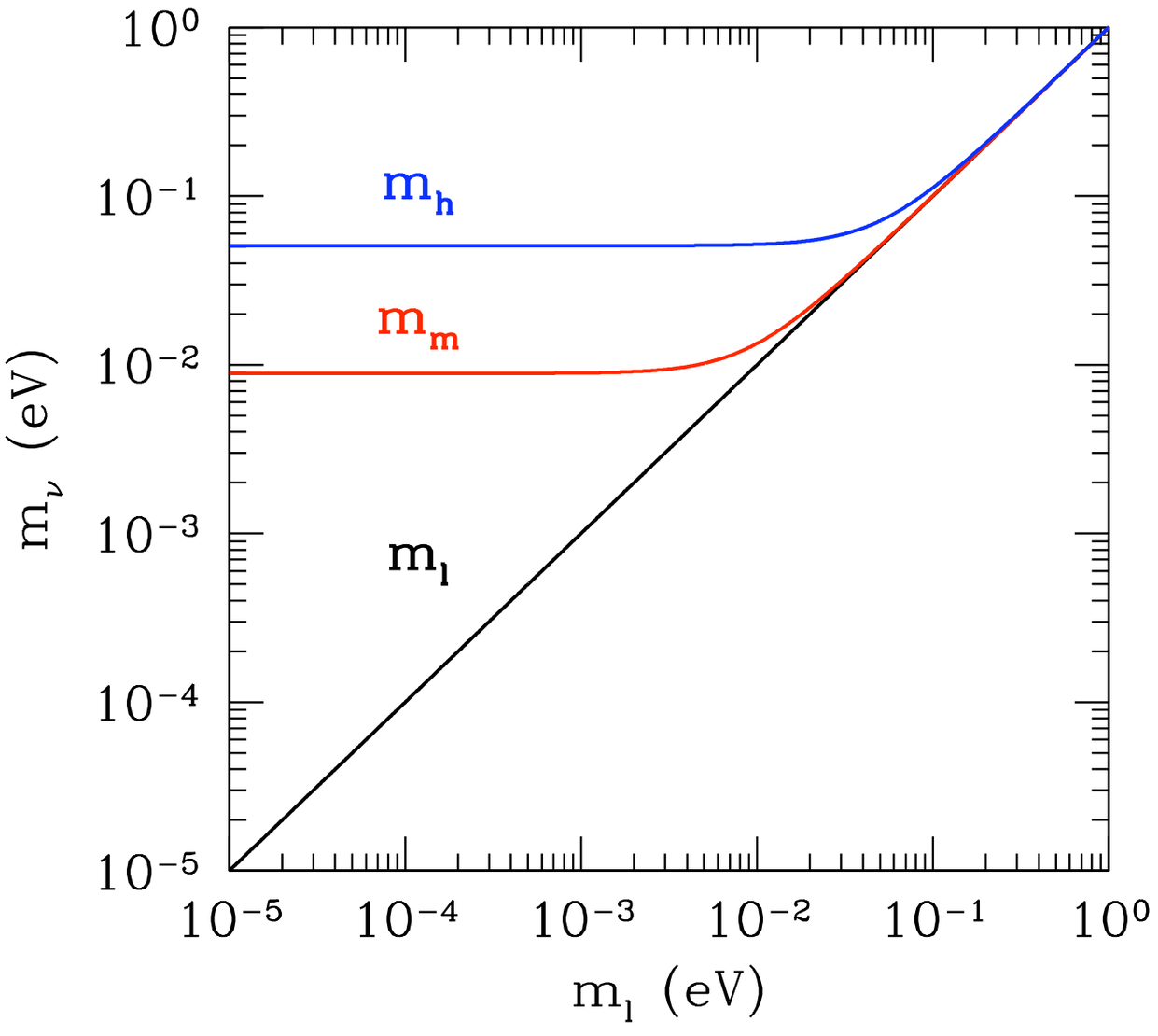
M_H has consequences

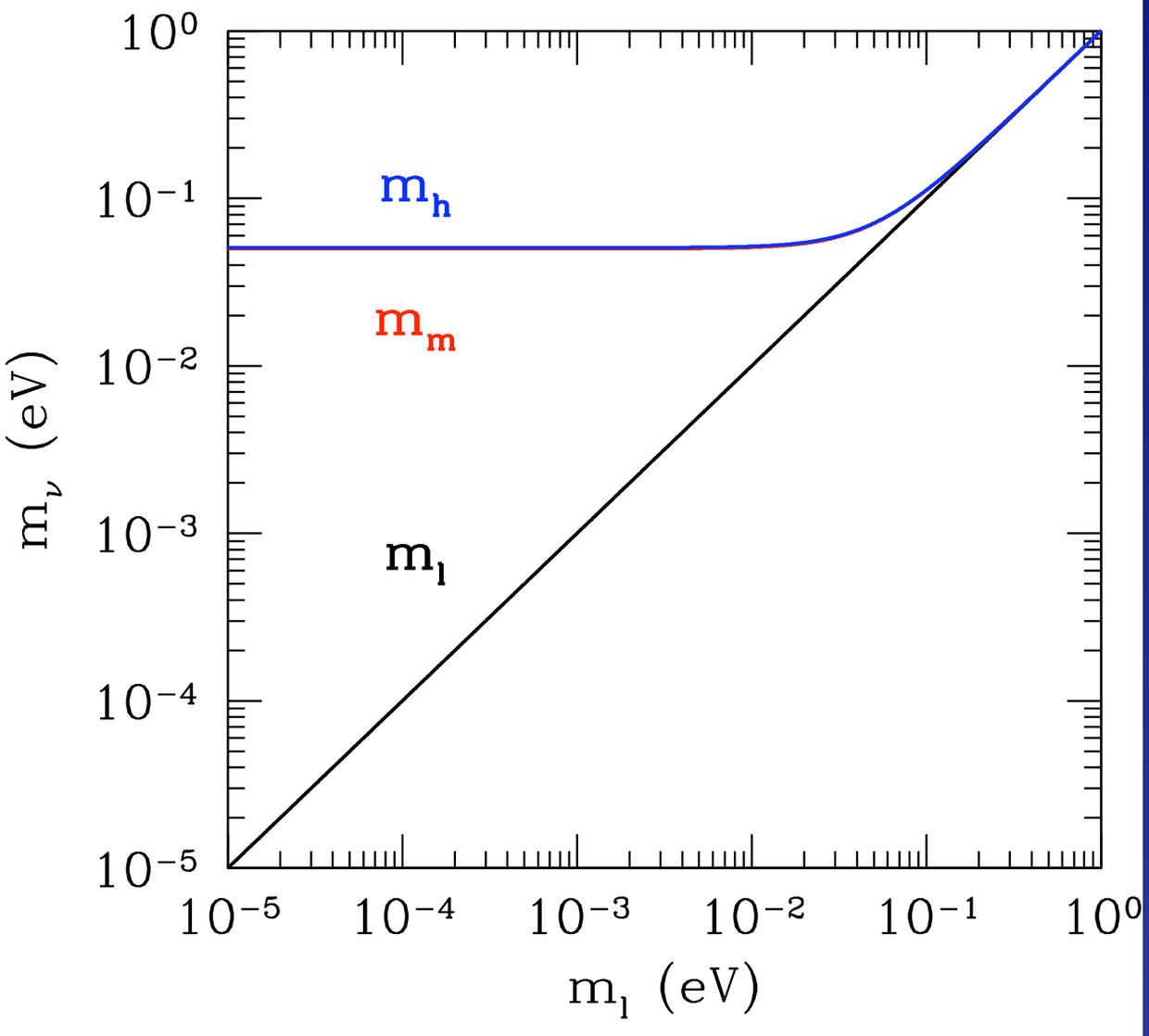
A metastable vacuum?



+ completeness / domain of EW theory

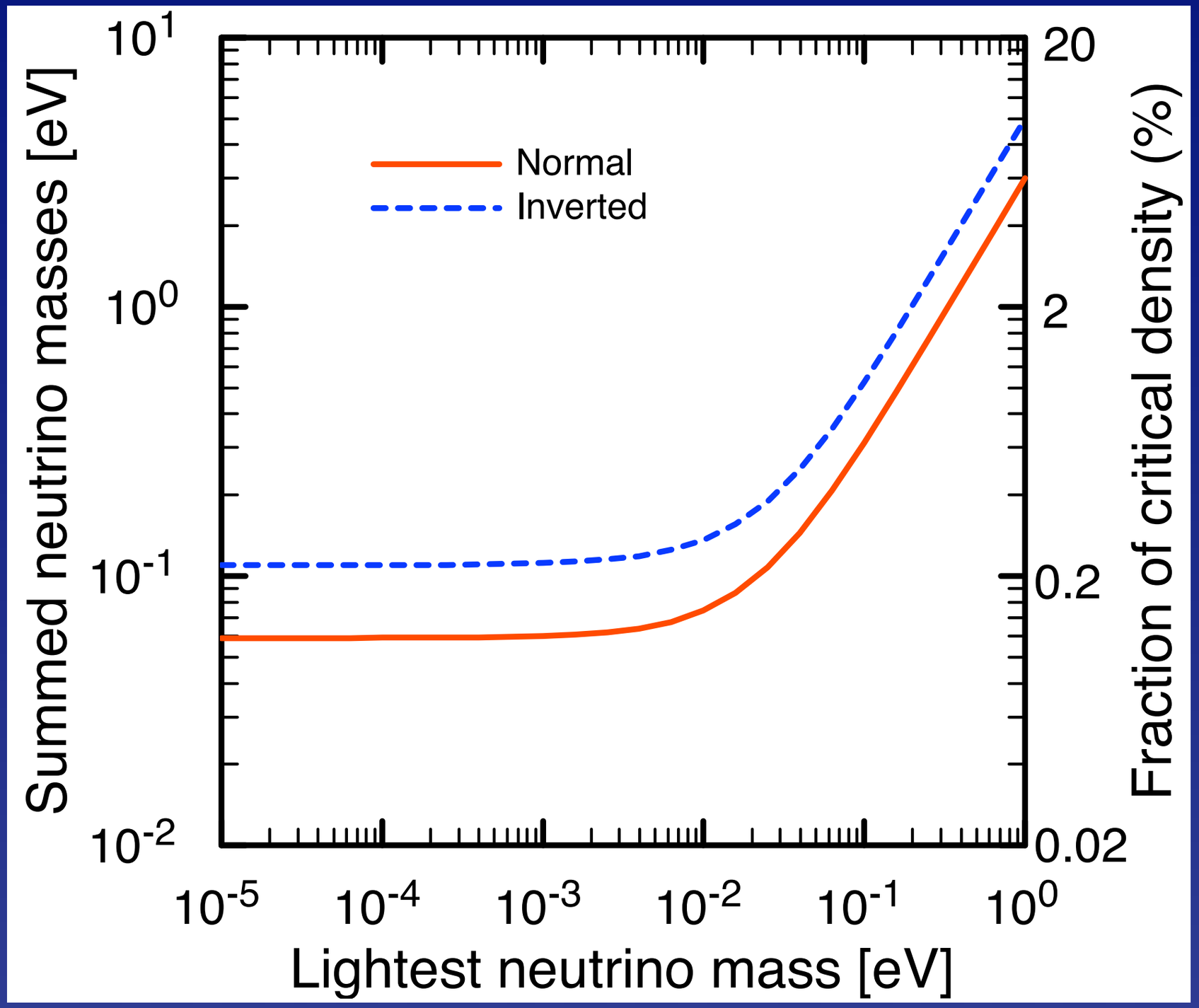
Neutrino Masses: oscillations determine Δm_ν^2, not m_ν





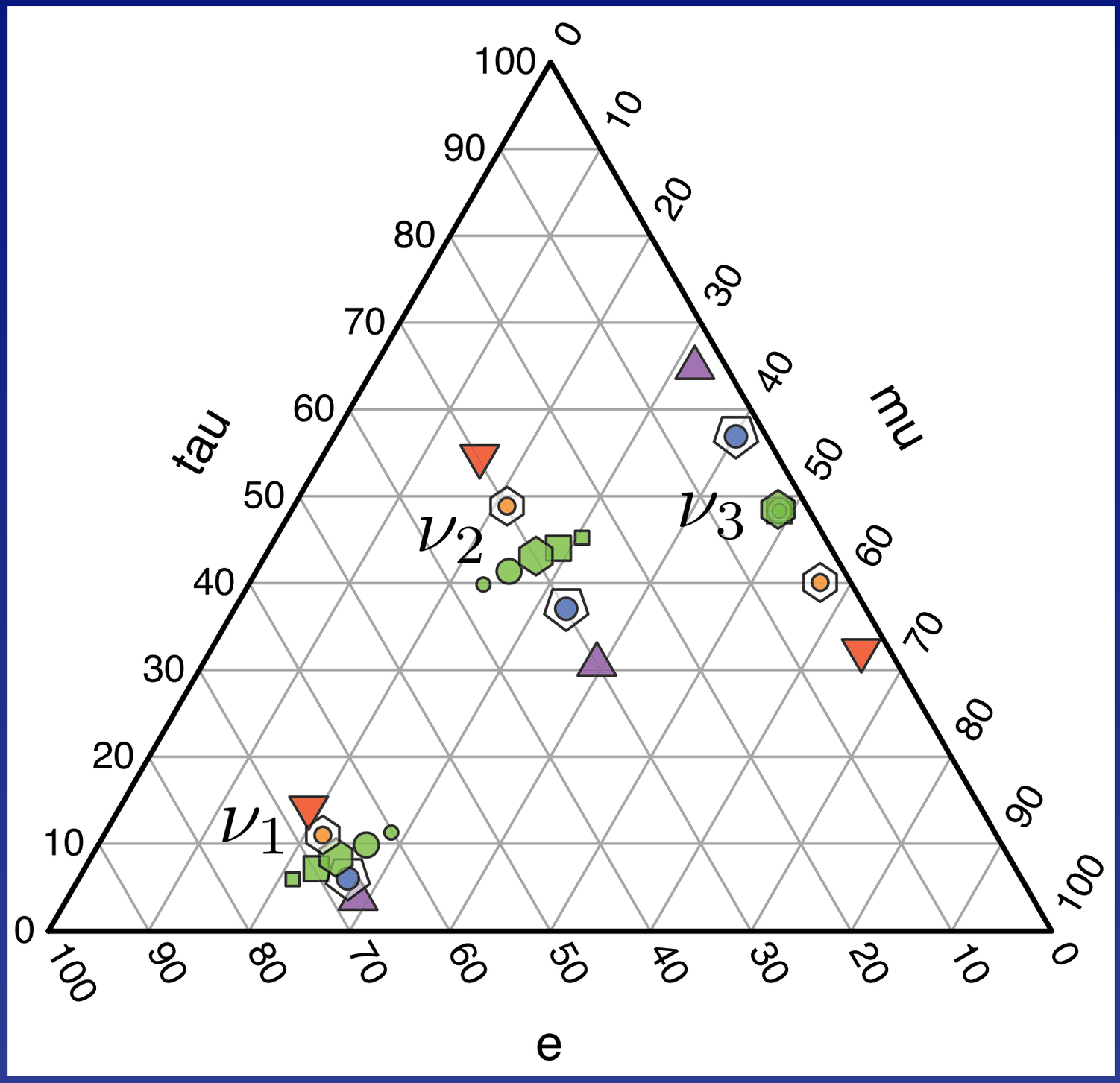
Absolute scale not known, but $m_\nu \lesssim 10^{-5}\ m_e$

Relic ν contributions to mass density of Universe



KATRIN aims at 0.2 eV

Neutrino family patterns (uncertainties)



How could neutrino mass arise?

Add N_R: $SU(2)_L$ singlet with $Y = 0$ — *sterile*
couple ν_L, N_R in Dirac mass term, $\varsigma_\nu \lesssim 10^{-11}$

ν has no charge or color,
so $\nu \equiv \overline{\nu}$ is possible (Majorana)

Dirac & Majorana: explain m_ν ?

Neutrino mass as physics beyond standard model:
may connect with ultrahigh scales (seesaw)
but might also implicate TeV scale

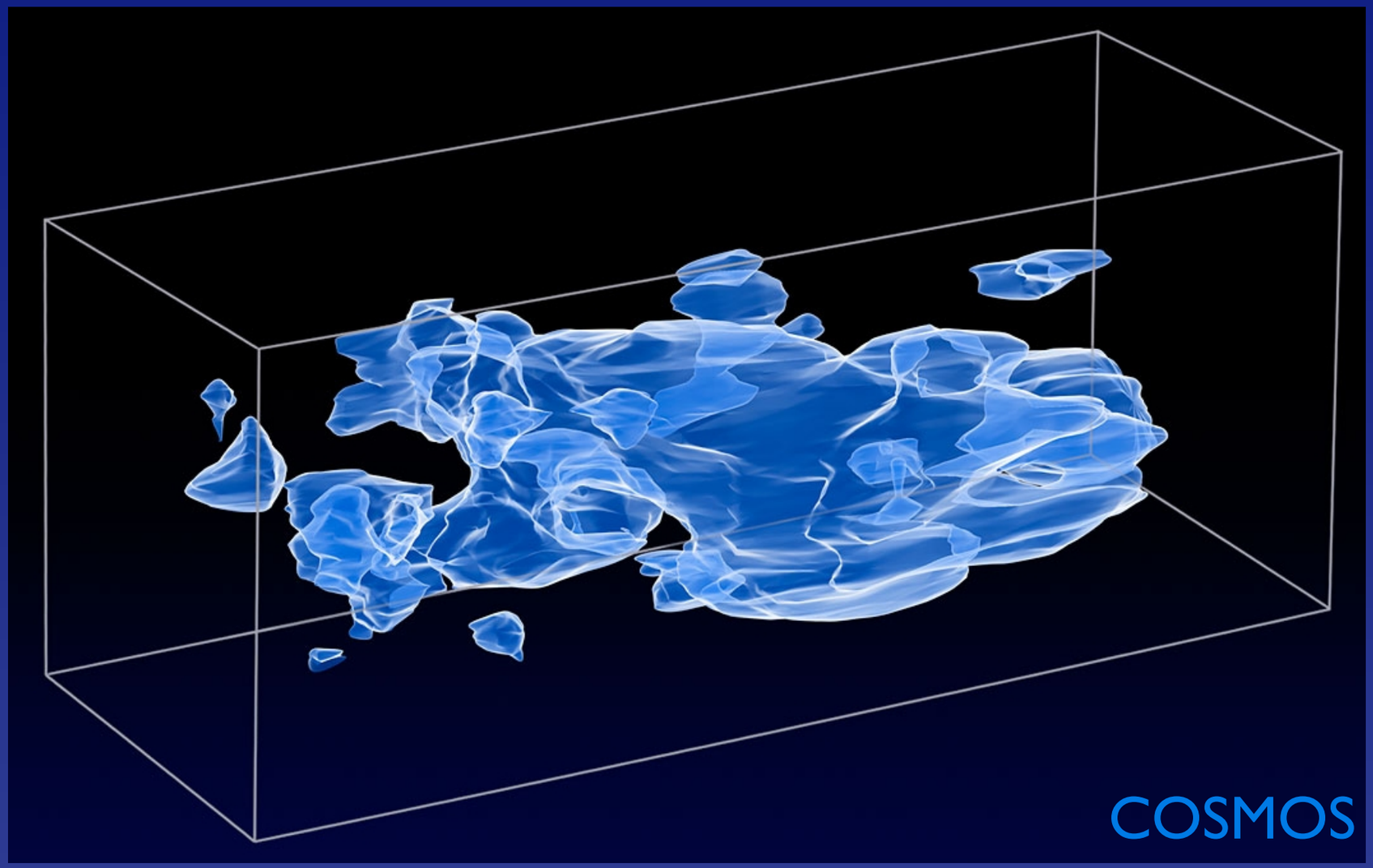
Dark Matter Precedent:
Discovery of the Noble Gases

"Nitrogen" from atmosphere
1/2% heavier than extracted
from N-bearing compounds.
Hypothesis: an unknown
ingredient in the air.
"… the improbability that a
gas surrounding us on all
sides, and present in
enormous quantities, could
have remained so long
unsuspected."

Lord Rayleigh

Much evidence for dark matter, many candidates

If dark matter interacts weakly …



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

Mass of the vacuum

Natural to neglect gravity in particle physics

Gravitational ep interaction $\approx 10^{-41}$ EM

But gravity is not always negligible …

Higgs field contributes uniform vacuum energy density

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

Critical density $\varrho_c \equiv \dfrac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-29} \text{ g cm}^{-3}$

Where do we stand?

The Higgs boson is not the source of all mass

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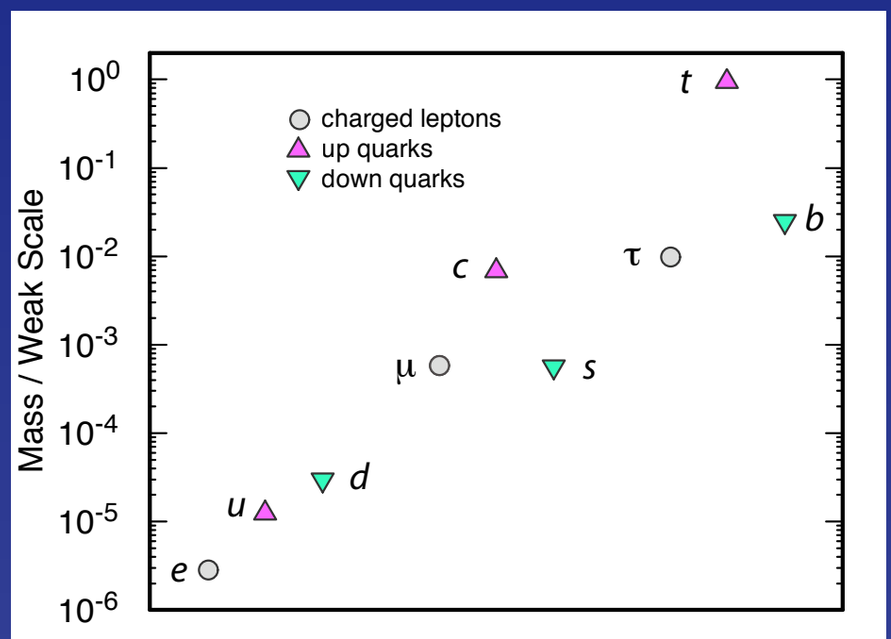
Where do we stand?

Exploration of the 1-TeV scale will reveal the agent of electroweak symmetry breaking

M_W, M_Z given by EWSB – Higgs, DSB, … (?)

Discovery of Higgs boson *may establish* Higgs interactions as origin of fermion mass

What accounts for the pattern of fermion masses and mixings?



Where do we stand?

Is Higgs boson the source of its own mass?

What stabilizes M_H < 1 TeV?

What sets the value of M_H?

How many Higgs bosons?
What are their properties?

composite … supersymmetric … ?

Where do we stand?

Neutrino mass could be special, if $\nu \equiv \bar{\nu}$

Determine absolute scale of m_ν

Connection to ultrahigh scales,
or to new physics nearby?

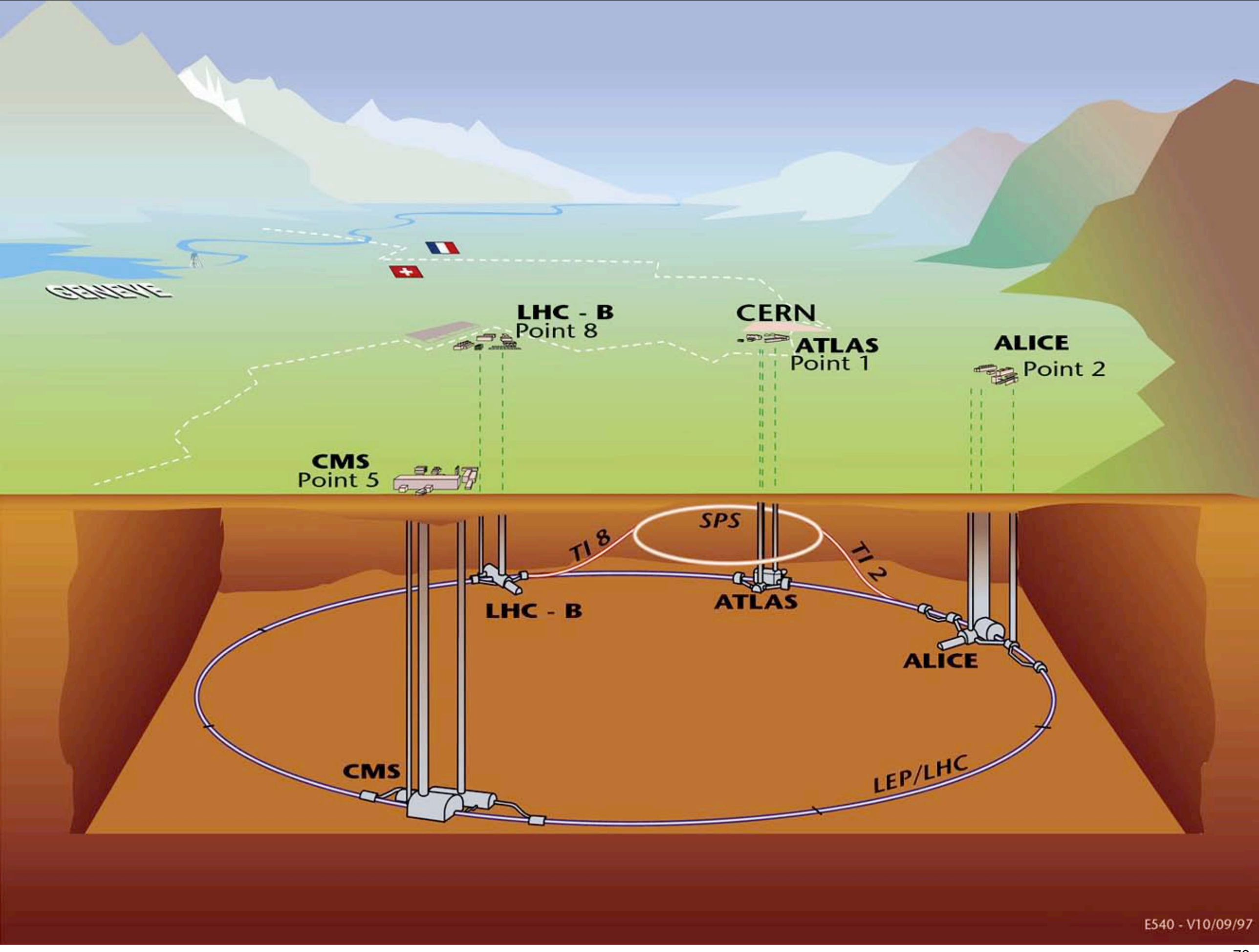
Where do we stand?

What are the dark matters,
how do their masses arise?

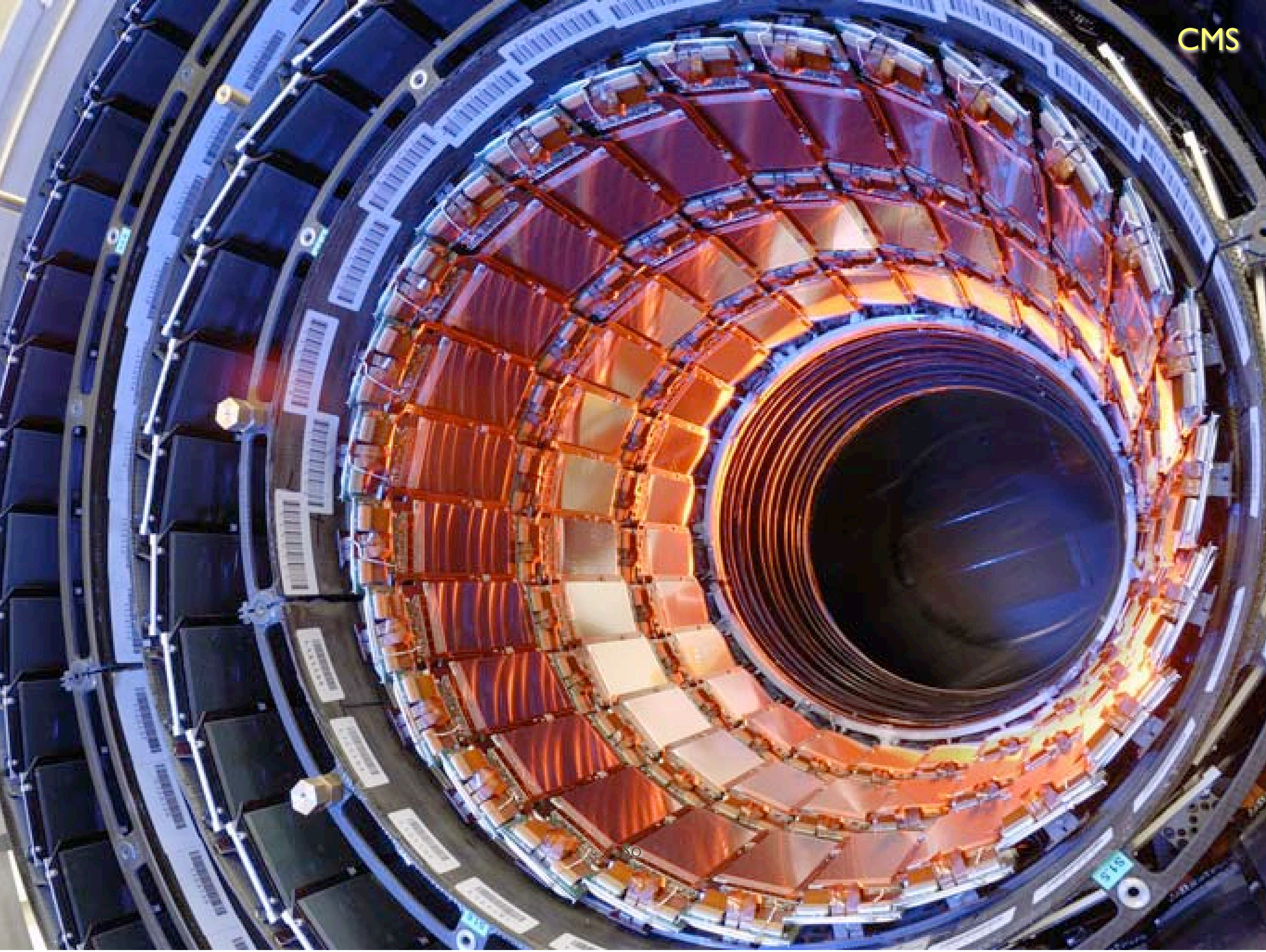
Why is empty space so nearly massless?

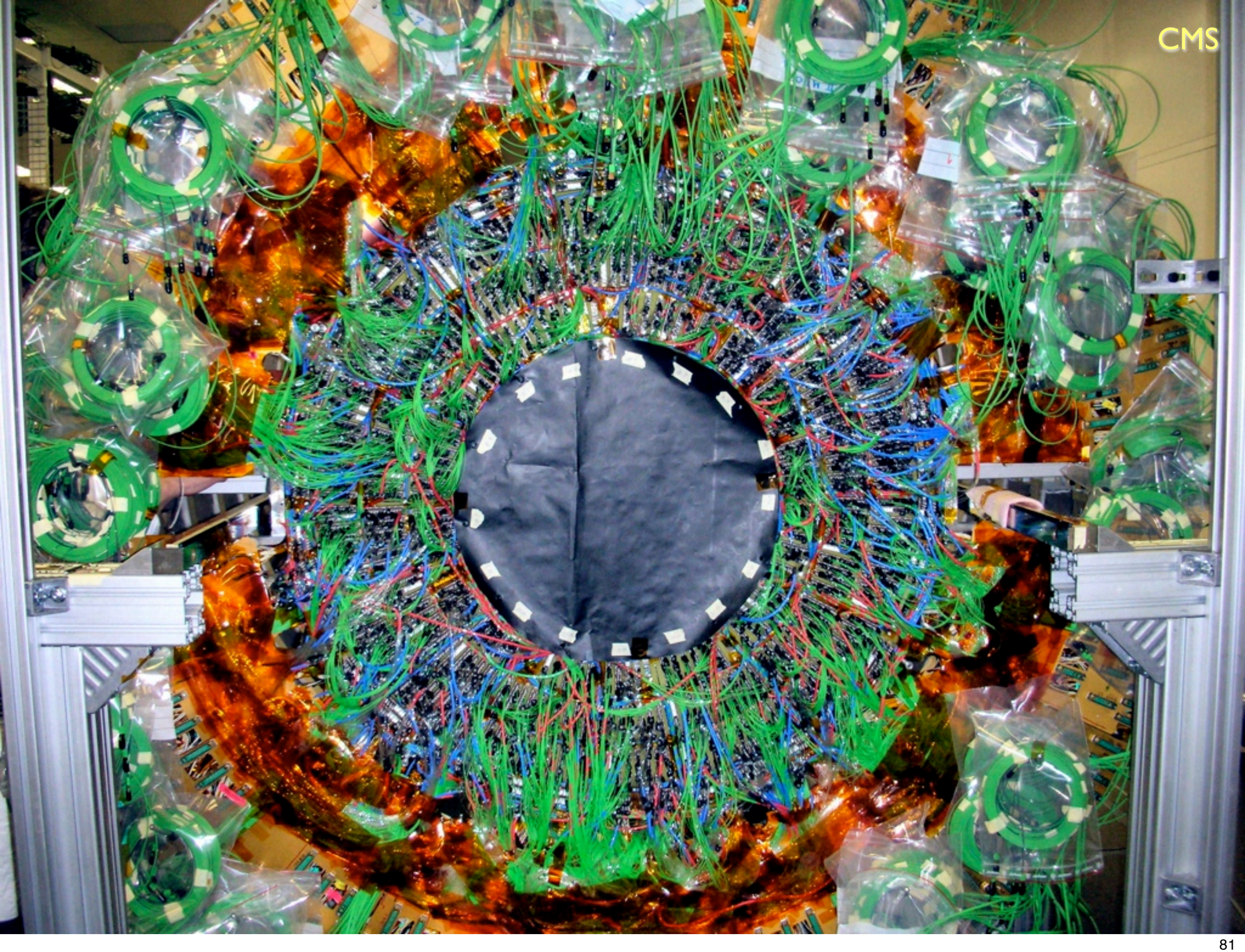
Vacuum energy problem is related to
EWSB, the source of W, Z mass,
and (perhaps) of fermion masses

New kinds of matter?


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

CMS


CMS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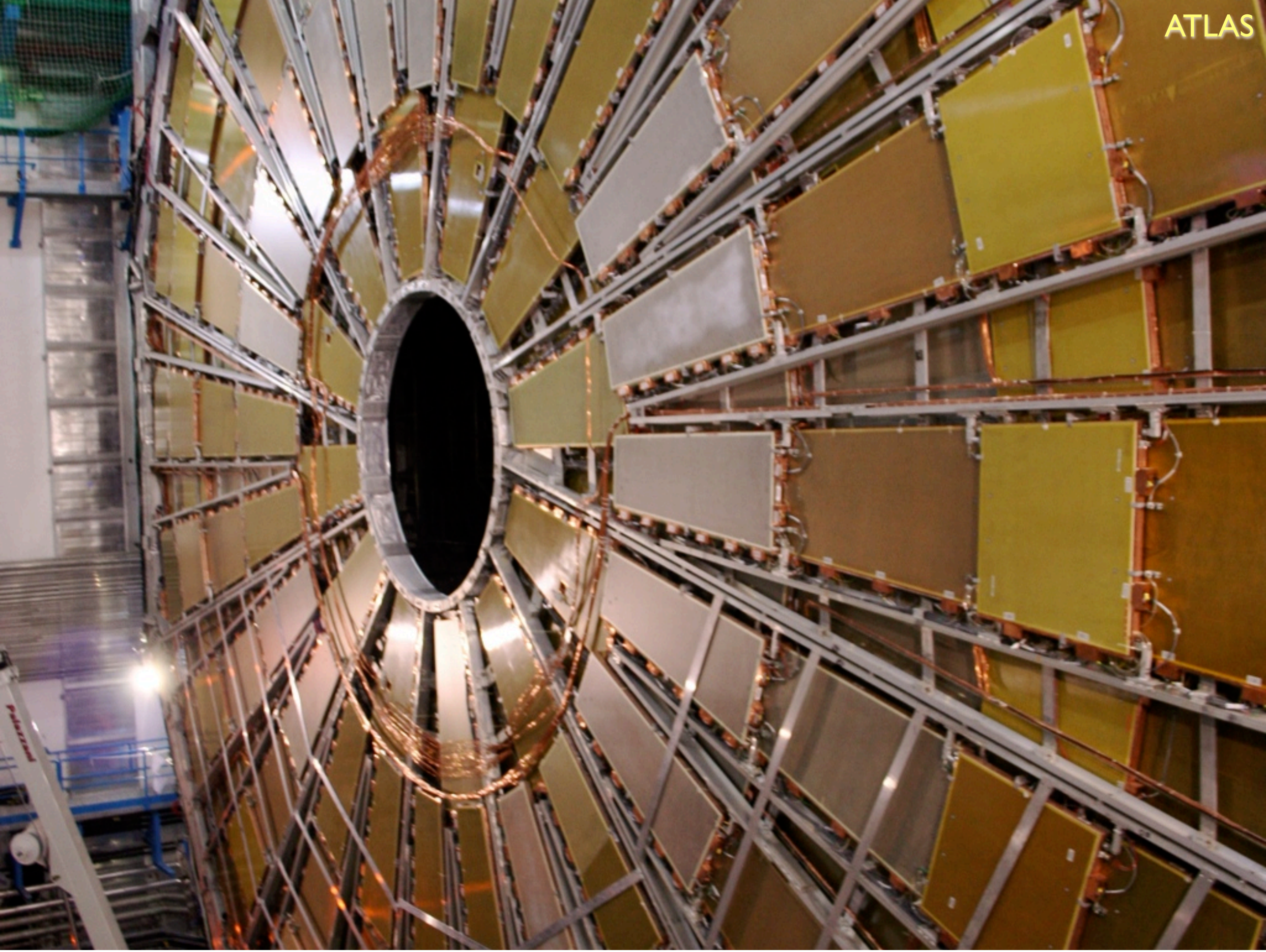
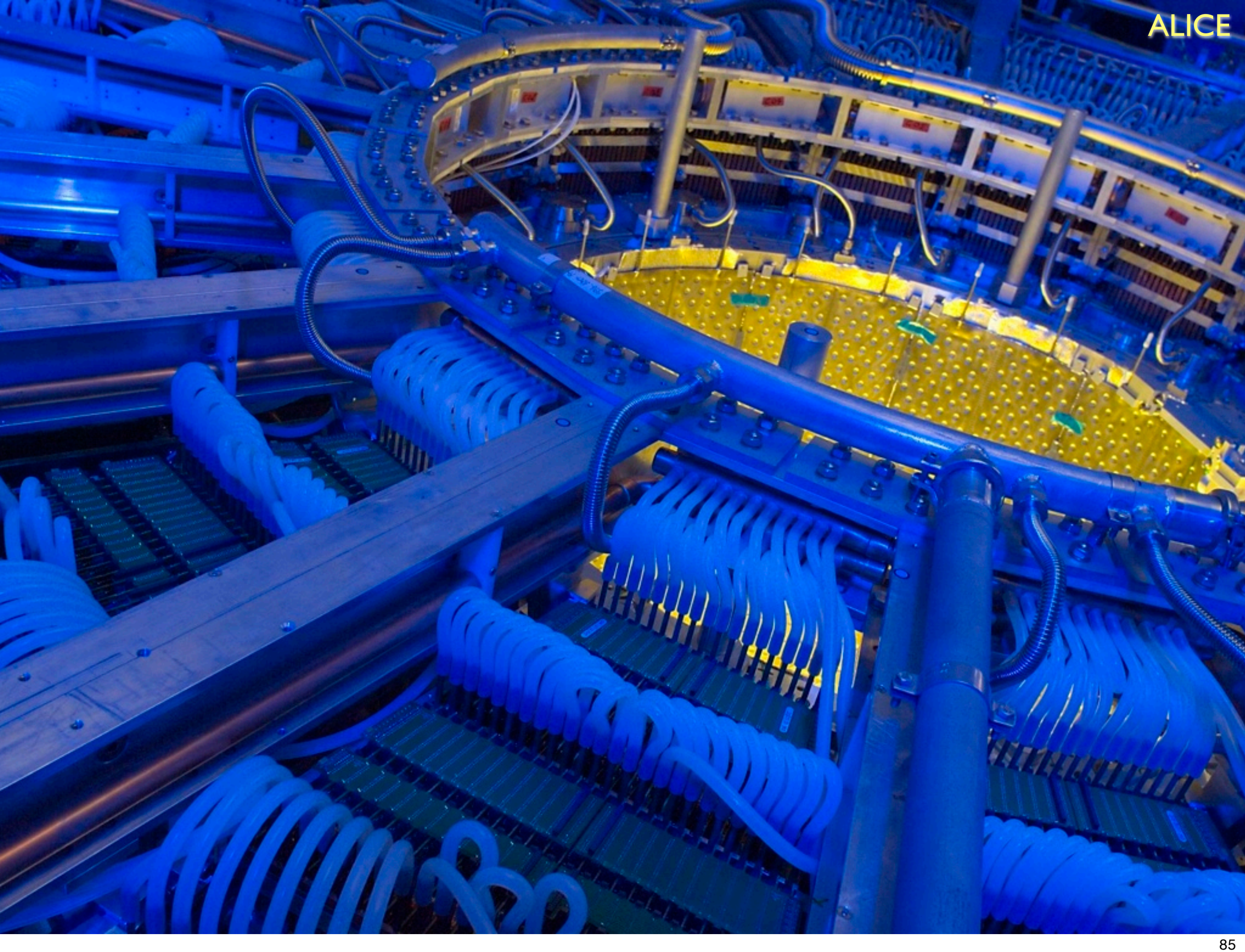
ATLAS

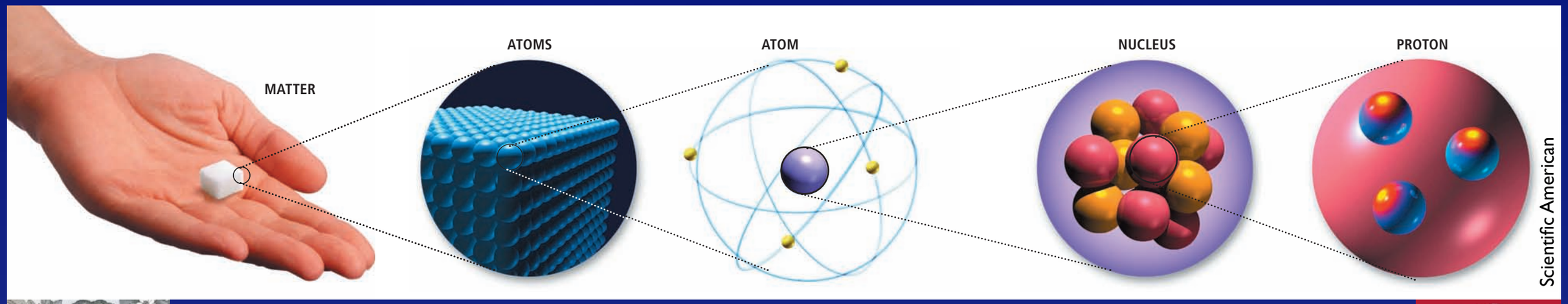





JIB18


LHCb

Where do we stand?



sum of parts · · · · · · · · · · · · · rest energy

QCD explains visible mass of the universe

Gauge symmetry explains massless photon & gluon

These lectures:
http://lutece.fnal.gov/Talks/Honnef.pdf

Scientific American, Feb. 2008 *Rep. Prog. Phys.* 70, 1019 (2007)

Spektrum der Wissenschaft, Nov. 2008

Short course on EW theory:
http://lutece.fnal.gov/Talks/CQSMPaphos.pdf