How the world is built

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Physics: motion and matter

- One aspect of physics deals with the laws of motion: classical or quantum, slow or relativistic, field theory, string theory, etc.
- Another aspect of physics studies the basic properties of matter: particles and their interactions, symmetry properties and conservation laws etc.
- Physical theories contain both aspects: some experiments are used to extract particle properties, then laws of motion are used to predict new properties.

The beginning of particle physics

The world is discrete

- There are atoms (Dalton's law of chemical combination). They move (gas laws). Atoms have weight (Avogadro number).
- Atoms are not featureless (chemical valency)
- 18th century physics of atoms further refined through the 19th century by Boltzmann, Maxwell and others later
- Deviations from continuum fluid theory: Brownian motion (Einstein: 1905)

Constituents of matter

- Electrons discovered by Thompson (1897)
- Atomic nucleus discovered by Rutherford: 1911
- The neutron discovered by Chadwick: 1932.
- Positron postulated by Dirac (1928) discovered by Anderson (1932)
- Muon discovered in 1936 by Anderson
- Pion postulated by Yukawa (1935) and discovered in 1947
- Neutrino postulated by Pauli (1930) and discovered in 1956 (Reines, Cowan).

Dirac uses symmetry

- Dirac found that relativity allows not only scalars, vectors, tensors (which describe bosons) but new objects called spinors (describing fermions).
- Spinor wavefunctions unify the different spin components with a particle-antiparticle symmetry.
- First use of symmetry for unification and prediction of new particles.
- Extension of Wigner's methods

Yukawa uses uncertainty

- In quantum mechanics $\Delta E \Delta t \geq h$. In relativity $E^2=m^2c^4+p^2c^2$
- This implies that particles can emit other particles for a short while: $\Delta E=E(p+\pi)-E(p)$
- Conservation of electric charge implies that pions can be either charge ±1 or 0.
- If there are contact interactions only, then spin of pion is 0.
- Exchange of heavy particles give short ranged forces.

Pauli uses conservation laws

- In weak decay of neutrons, protons and electrons are observed. Charge is conserved.
- Conservation of momentum implies that the electron (and proton) have a fixed energy in the rest frame of the neutron. This contradicts what is seen.
- Pauli postulated that there must be another uncharged particle produced in the reaction: the neutrino.
- Emmy Noether: conservation = symmetry

The methods of particle physics

Field theory discovered

- Quantum mechanics and relativity together build quantum field theory. Provide description of particle interactions: creation or absorption of particles.
- Symmetries play an essential role in classifying the kinds of fields (wave functions) possible. Dictate conservation laws. Gauge symmetry: local
- Quantum electrodynamics: 1930s and 1940s, Yukawa theory, etc.

Perturbative method

- In quantum field theory, the electron charge can be made dimensionless: e^2/hc. This has value less than 10^{-2}.
- Try to expand any quantity in a power series in this dimensionless coupling: perturbation theory. Incomplete, but successful since the coupling is small.
- If the coupling is large (say 1) then perturbation is unsuccessful.

Renormalization arrives

- Creation and annihilation of particle pairs makes the vacuum a polarizable medium.
- In a polarizable medium charge is always renormalized: e^2 becomes €e^2
- Furthermore, charge becomes distance dependent: like Debye screening.
- Masses can also be renormalized because of the medium.
- Solves the problem of classical Lorentz theory

Renormalization today: lattice

- Classical field theory has no scale (dimensionless coupling is constant)
- Renormalization introduces a scale: dimensionless coupling becomes distance dependent.
- Introduce a non-physical scale: use a lattice in space time instead of a continuum.
- Trade this lattice spacing for the physical scale measured by the coupling.

Lattice field theory

- Path-integral method: “sum over paths” of the quantum field theory. Replace classical equation of motion by an integral over paths.
- No perturbation expansion needed. Use exact numerical methods to do the integrals.
- Intense supercomputing demands: need a CRAY or IBM Blue Gene: 10s of Tflops of computing speed needed.

The tools of field theory

The standard model of particle physics

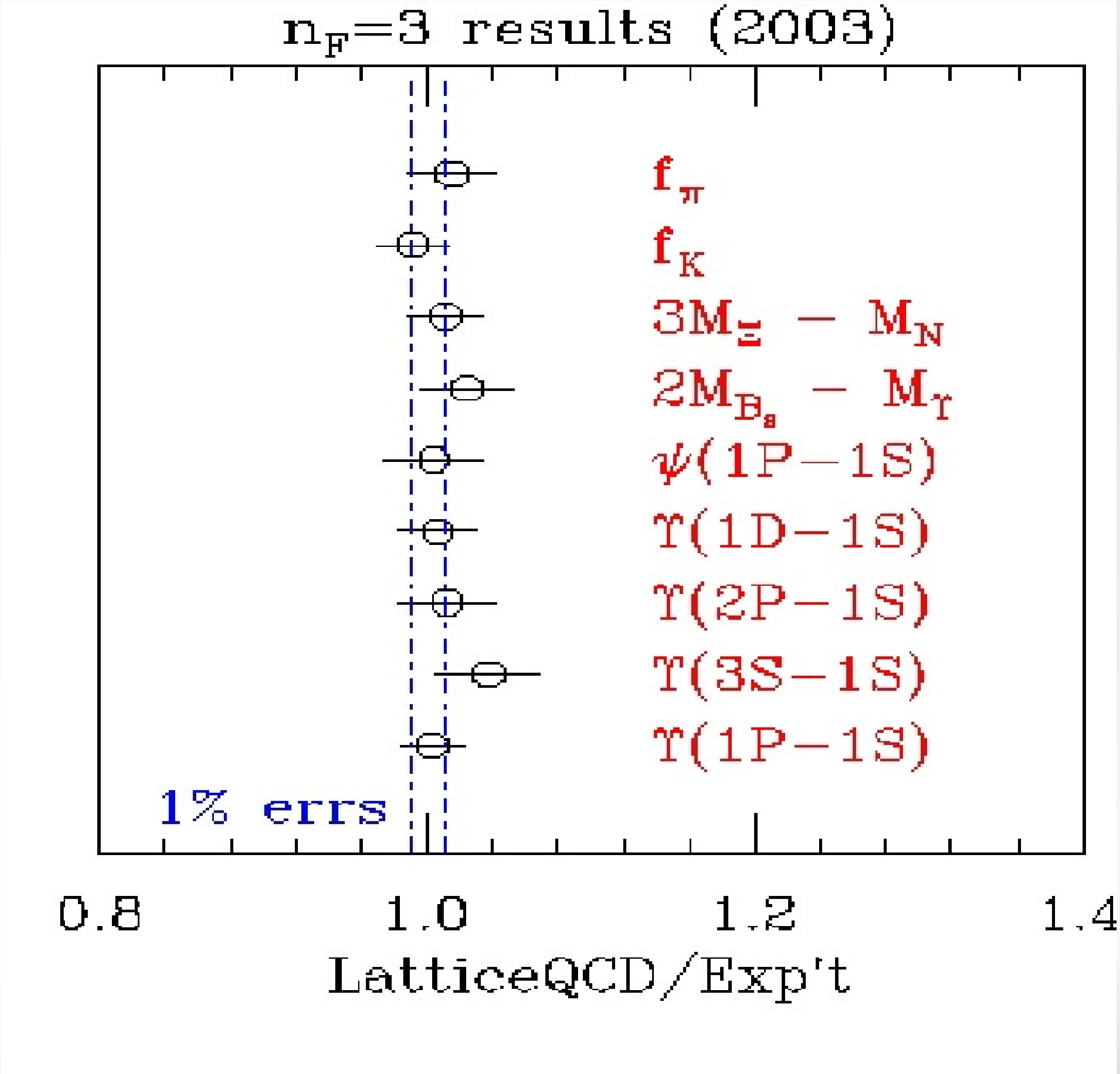
One remaining problem

- Too many hadrons: p, n, pi, K, rho, sigma, cascade. Are they all elementary?
- Yukawa theory seems to be an adequate description of these particles, but this theory is not renormalizable.
- A new symmetry discovered: flavour symmetry. Classifies hadrons, postulates components of hadrons called quarks: 1967
- Are they real?

Rutherford experiment again

- High energy electrons have small Compton wavelengths. Electron scattering is a “microscope”.
- Scattering electrons off protons one saw pointlike structures inside protons: quarks seen (1969)
- QCD: Quarks interact by exchanging particles called gluons. Gluons seen directly in 1970s

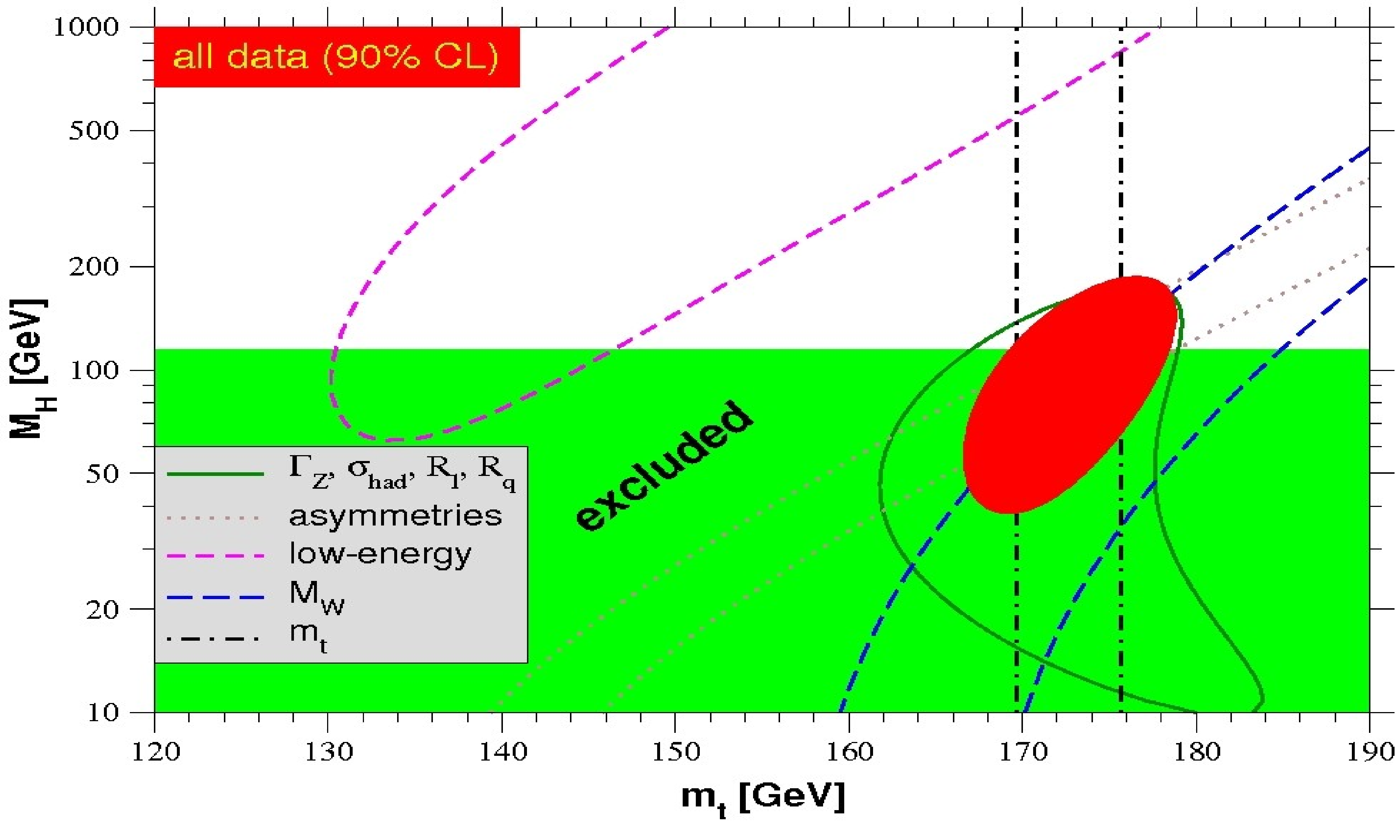
Hadron masses from QCD



The standard model

- A gauge theory of all matter: the unified theory of particle physics, completed in 1970s
- Many unseen particles postulated: W and Z bosons discovered in 1983.
- Charm (1974), bottom (1977), top (1995) quarks discovered
- Tau (1977) and neutrinos discovered
- Higgs boson remains to be discovered: LHC starts up in 2008.

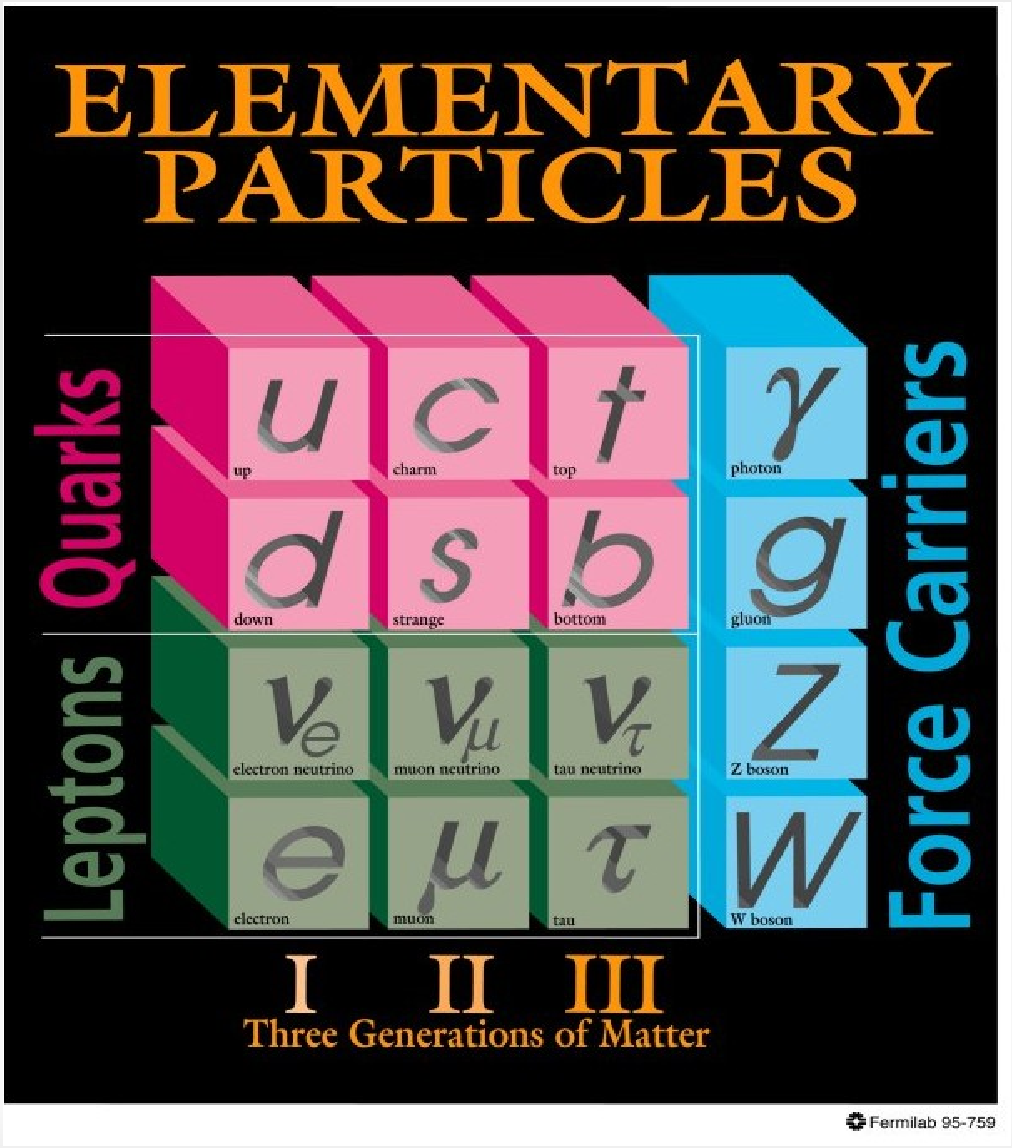
The Higgs boson



Everything is made of ...

- 6 leptons and their antiparticles: e, mu, tau and their associated neutrinos. Neutrinos are left handed.
- 6 quarks and their antiparticles: (u,d), (s,c) and (b,t)
- the electroweak gauge bosons: photon, $W^{\pm}$, Z.
- the QCD gauge boson: gluons
- the symmetry breaker: Higgs boson

Particles in the SM



New directions in particle physics

Is this the true theory?

- Tested extensively in the 1990s and found to be correct to at least one part in 10^3!
- The theory of photons and electrons true to one part in 10^9
- The theory of photons and muons incorrect at one part in 10^5! Why? Quark pairs have to be included.
- QCD not fully tested: quantum perturbation theory fails. Lattice methods needed.

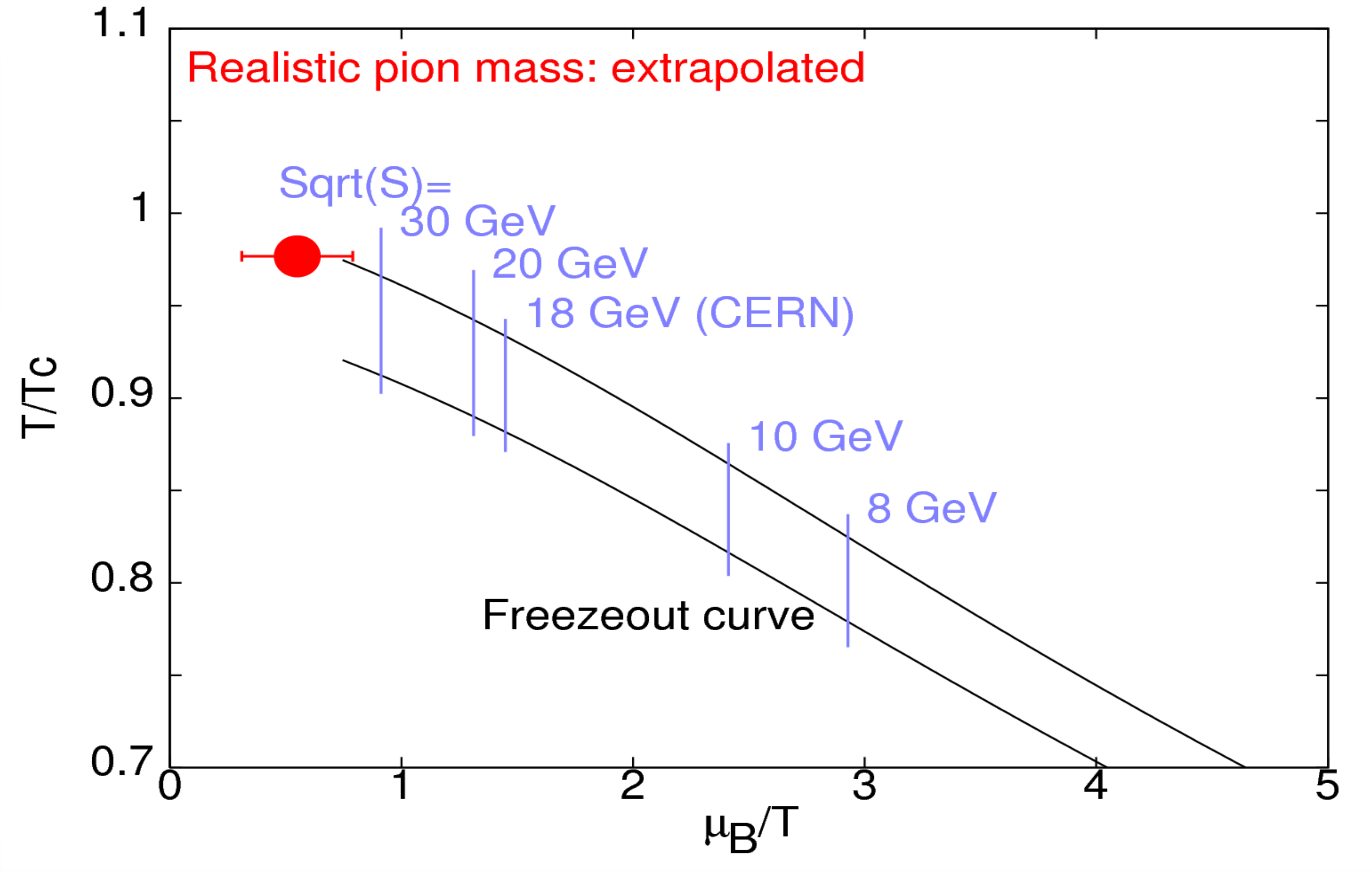
Is this the final theory?

- Neutrinos have mass: outside the standard model, but could be incorporated with some modification.
- QFT has a symmetry called CPT. CP violation of quarks may need new particles.
- Theoretical niceties demand new physics; some allowed by relativistic invariances.
- Electroweak and strong couplings could become equal at distances of 10^{-28} m

Windows into new physics

- CP violations of hadrons
- Neutrinos
- Possible strong interactions of Higgs
- Direct search for new particles
- Condensed elementary particles: quark matter, supernova remnants, the early universe

The phase diagram of QCD



Conclusions: an exciting time

- A great era of discovery in the 1970s and 1980s, completed by an era of consolidation in the 1990s: the standard model
- New era of discovery beginning now: LHC and neutrino facilities
- New areas of condensed particle matter: quark matter at LHC, RHIC, CBM
- Applications to astrophysics and cosmology: phase transitions