

A Half Century of the STANDARD THEORY

Higgs Hunting 2026
Results and prospects in the electroweak symmetry breaking sector

16-18 September
Orsay/Paris

16TH HIGGS HUNTING International Advisory Committee

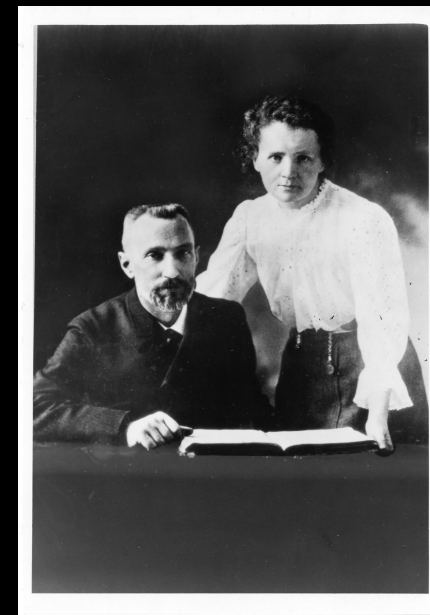
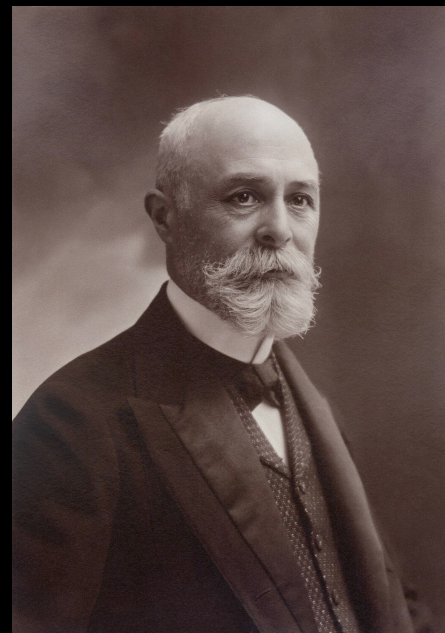
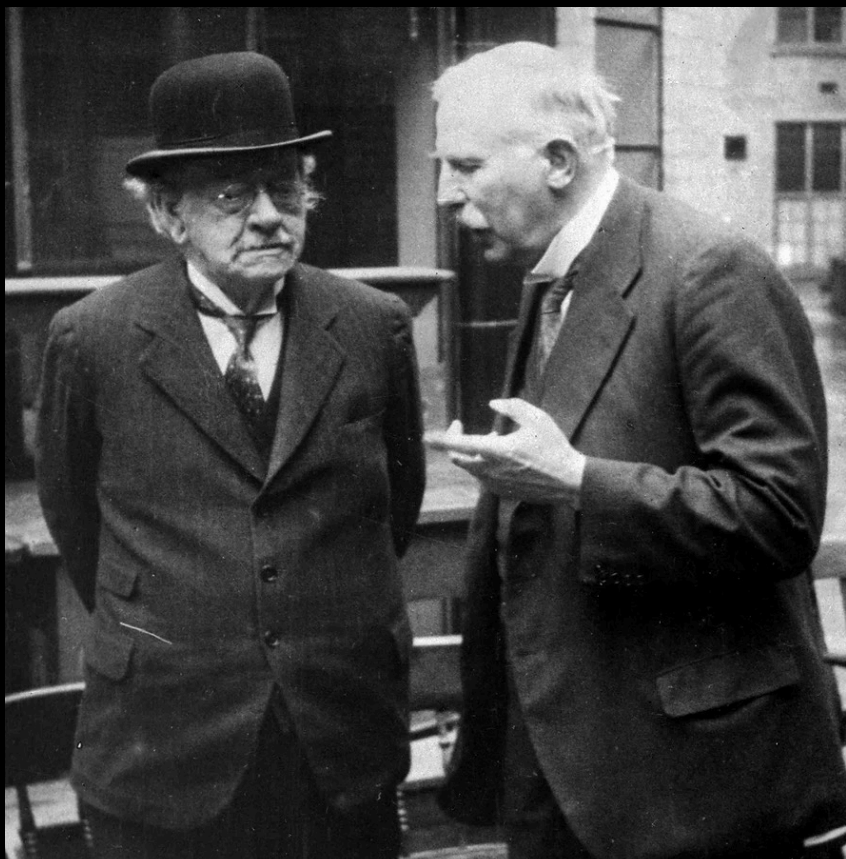
Organising Committee

www.higgshunting.fr

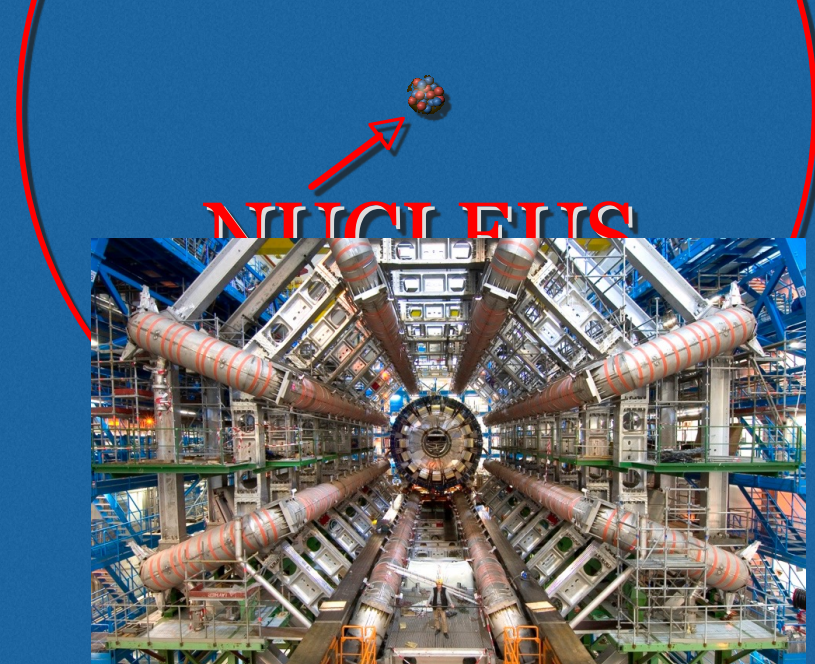
DAVID GROSS

Kavli Institute
for
Theoretical
Physics





Rutherford's Discovery of the Nucleus 1911

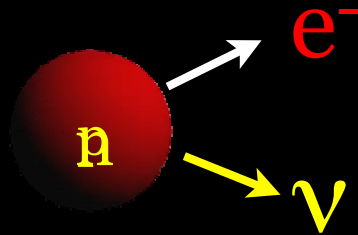


THE WEAK AND THE STRONG

(1930's--1950's)

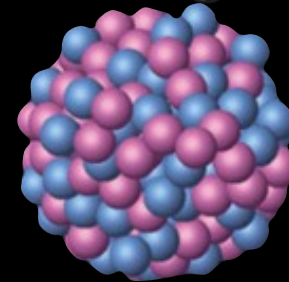
The forces operating in the nucleus are of two kinds:
WEAK INTERACTIONS **STRONG INTERACTIONS**

Responsible for radioactivity Responsible for holding
the nucleus together



Fermi theory 1928

$$H = G_F \bar{\Psi} \Gamma_a \Psi \bar{\Psi} \Gamma^a \Psi$$



Meson theory

Yukawa

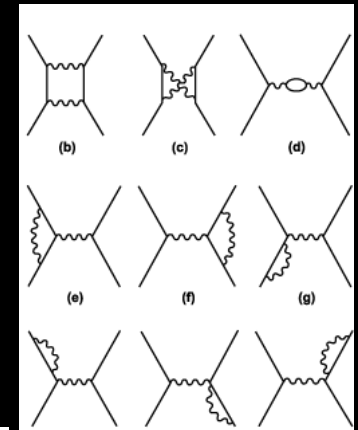
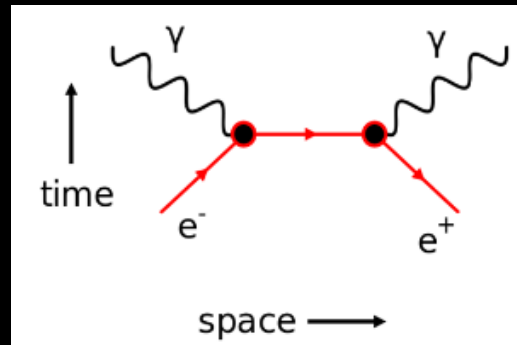
1947-1951 Quantum Electrodynamics

Feynman, Schwinger, Tomonaga, Dyson 1947-51

Renormalization theory

What we measure, and hence, what we must take account of with our equations, and what the solutions must account for, are the "renormalized mass" and the "renormalized charge" of a particle.

Feynman Diagrams



Anomalous magnetic moment
of the electron $a_e = (g-2)/2$

$$a_e = 0.001\,159\,652\,181\,643(764) \text{ Theory}$$

$$a_e = 0.001\,159\,652\,180\,59(13) \text{ Measurement}$$

NON-Abelian Gauge Theory

PHYSICAL REVIEW

VOLUME 96, NUMBER 1

OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS

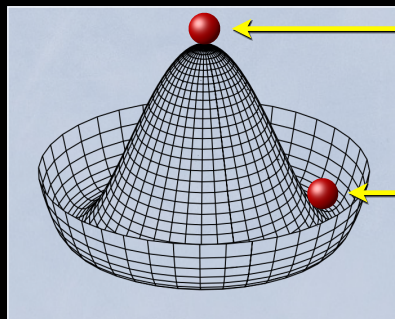
Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistent with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a $\mathbf{b}$ field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The $\mathbf{b}$ field satisfies nonlinear differential equations. The quanta of the $\mathbf{b}$ field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

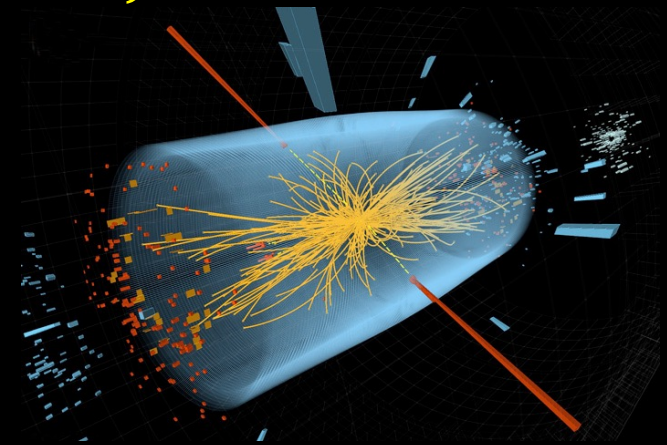
WEAK : HOW TO BREAK SYM?

HIGGS (BEH) MECHANISM



Symmetric
unstable

Asymmetric
stable



THE STRONG FORCE

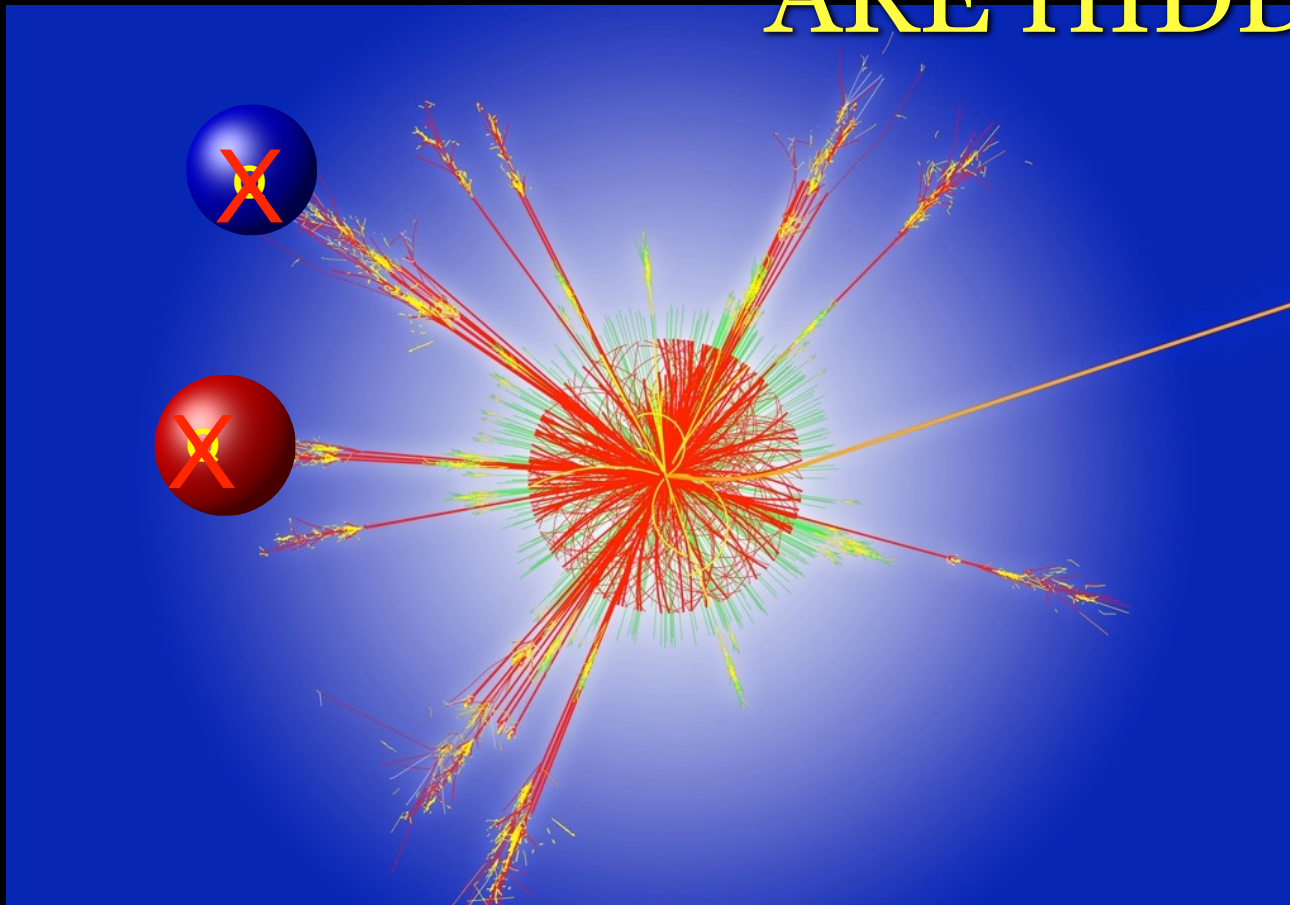
Was Especially Intractable

- Which particles are elementary ?
- What principle determines the dynamics?
- How to calculate?

DYSON: The correct theory will not be found in the next one hundred years. (1960)

A REVOLUTION WAS NEEDED

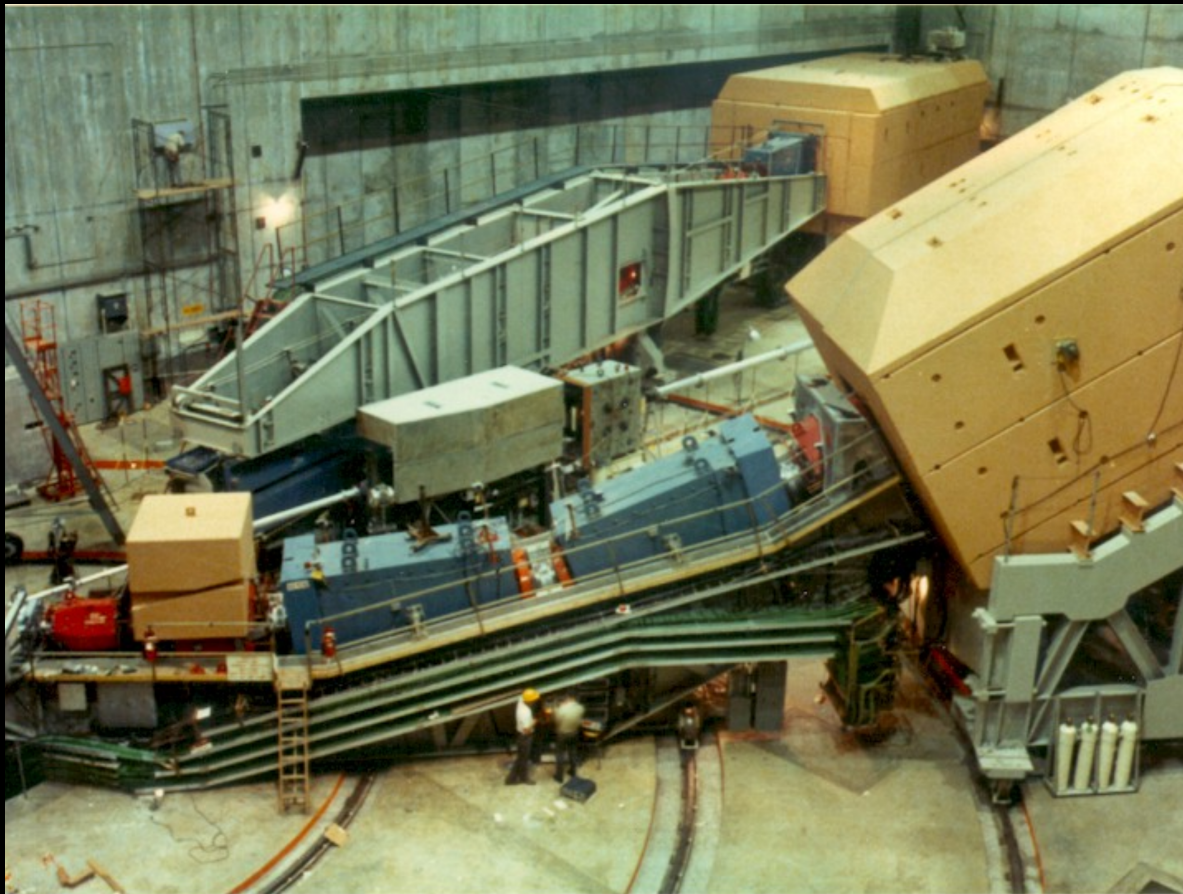
THE CHARGES (COLORED QUARKS AND GLUONS) ARE HIDDEN



NO
QUARKS

Deep-Inelastic Scattering at SLAC

Discovered that the proton looked as if it were made of freely moving quarks. 1968



Scaling = Free
Pointlike Behavior.

Quark model
sum rules worked.

1990

J. Friedman

H. Kendall

R. Taylor



Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross[†] and Frank Wilczek

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 27 April 1973)

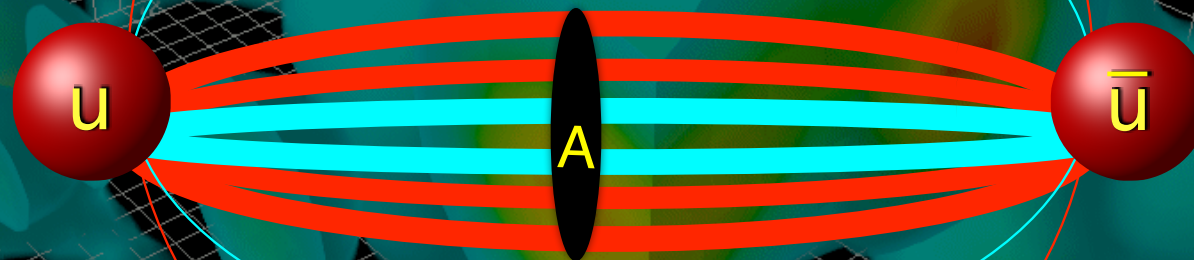
It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.¹ In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. we have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,^{2,3} which for a theory involving one field (say $g\phi^4$) are

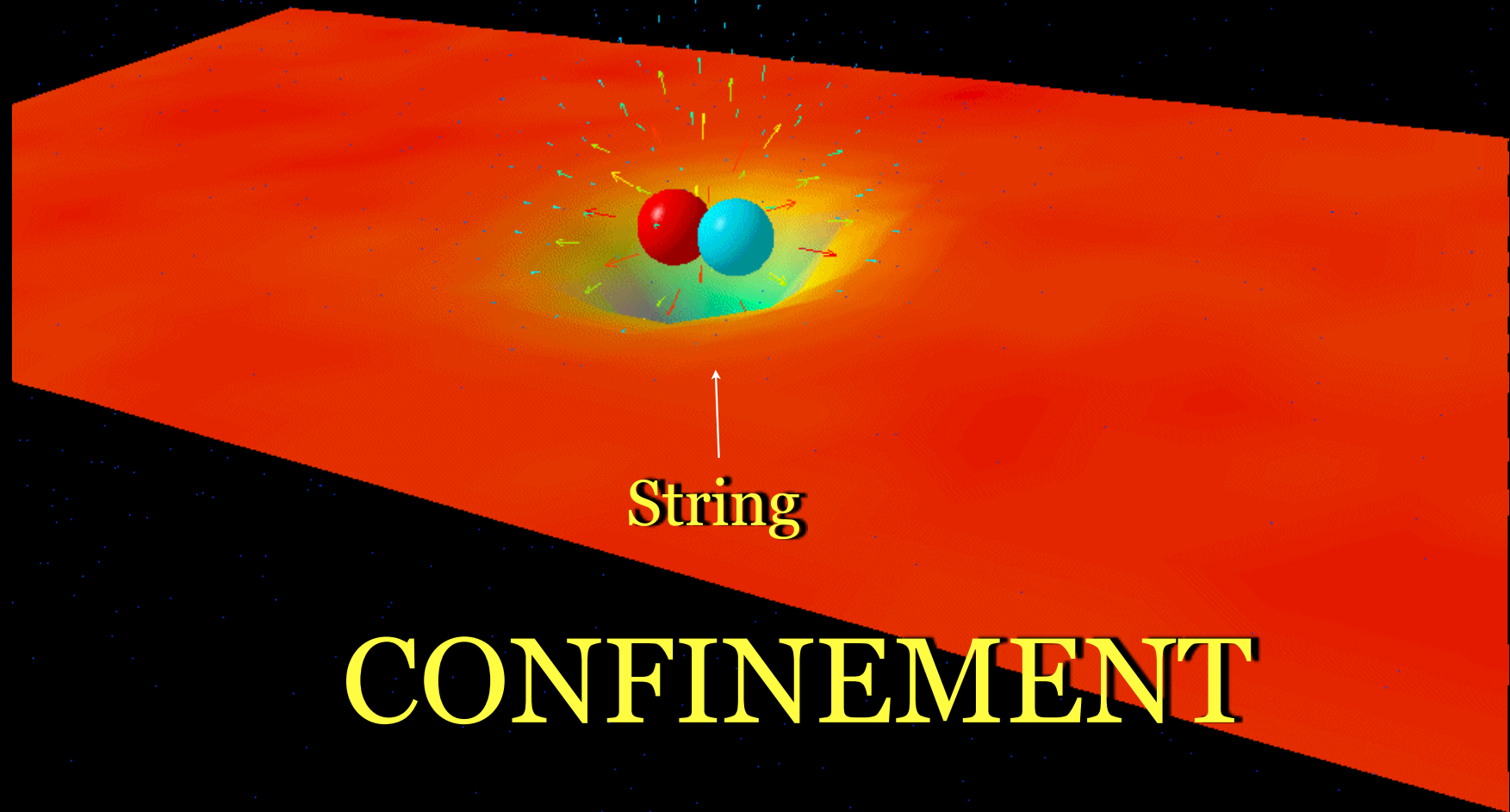
$$[m\partial/\partial m + \beta(g)\partial/\partial g - n\gamma(g)]\Gamma_{\text{asy}}^{(n)}(g; P_1, \dots, P_n) = 0. \quad (1)$$

STRONG FORCE MEDIATED BY THE CHROMODYNAMIC FIELD



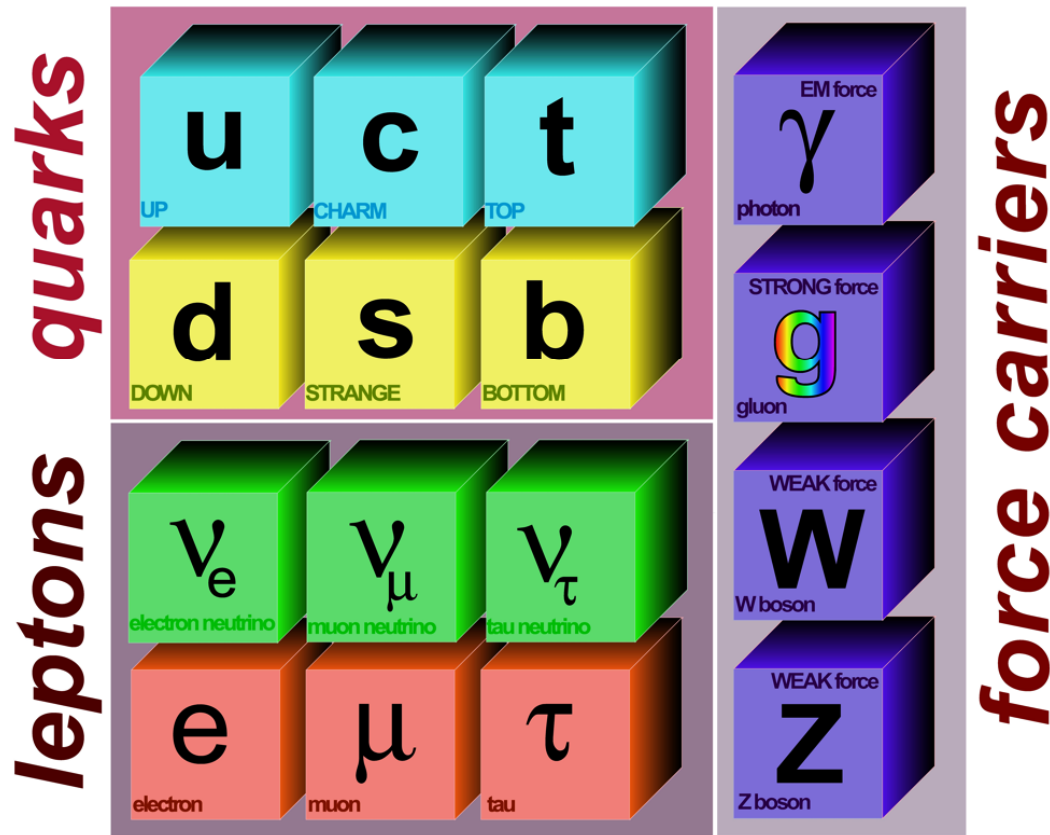
CONFINEMENT

THE MESON IN QCD



THE STANDARD MODEL

The Standard Model of Elementary Particles



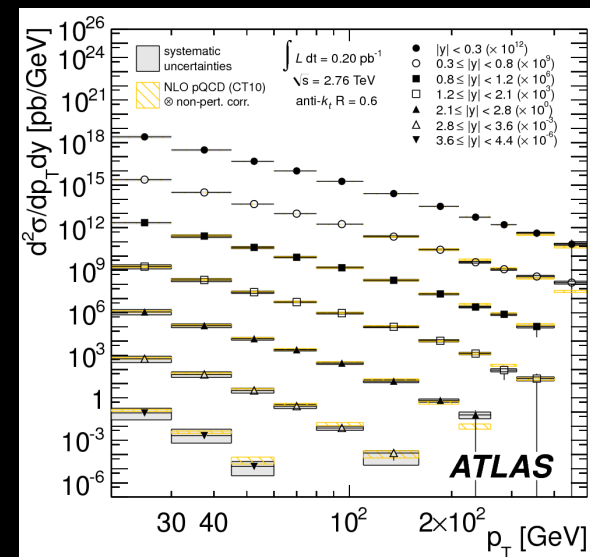
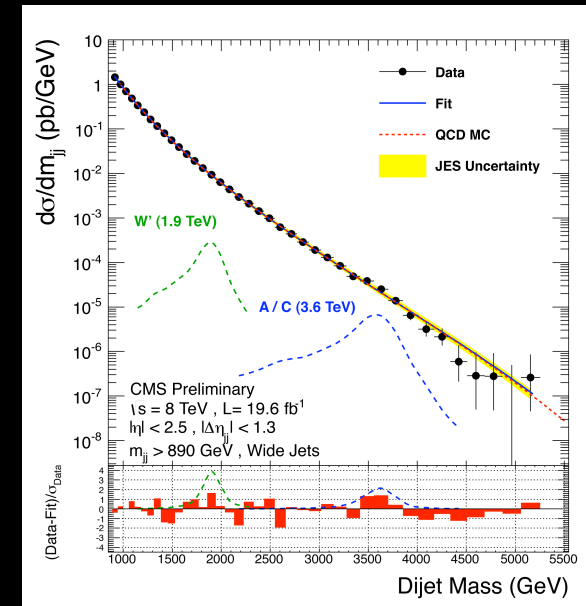
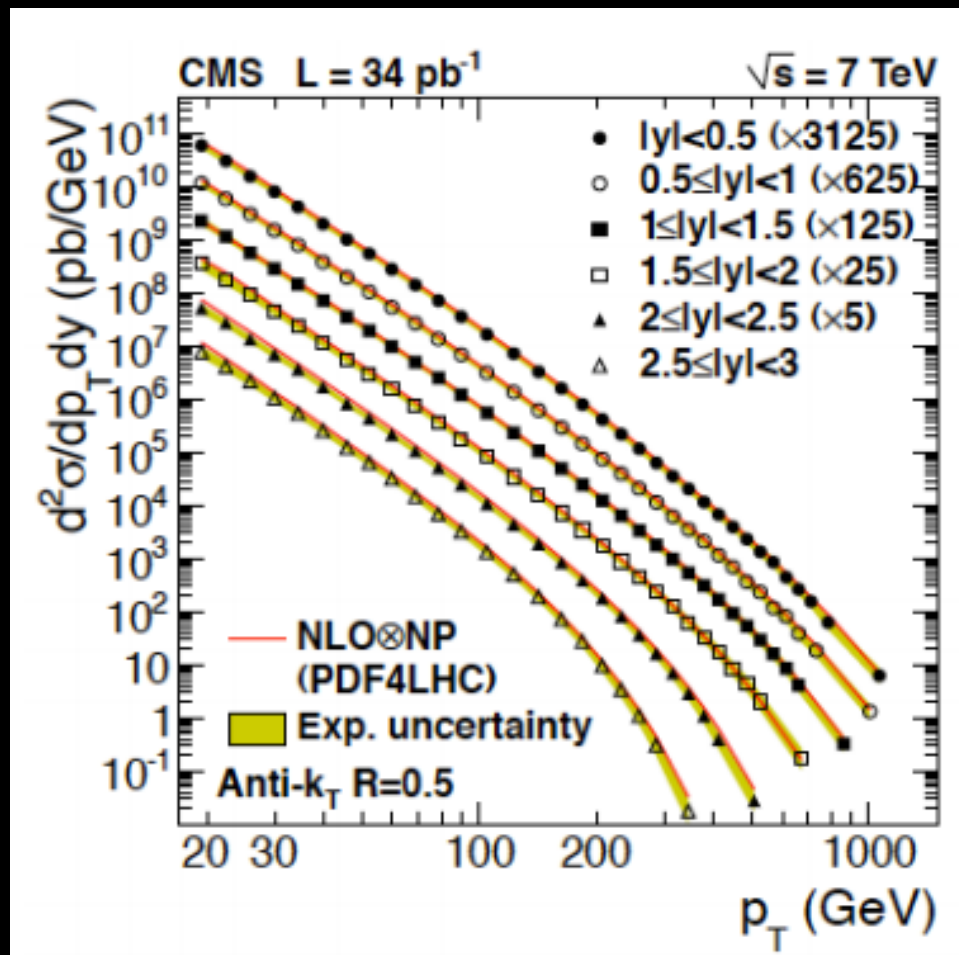
1 E & M

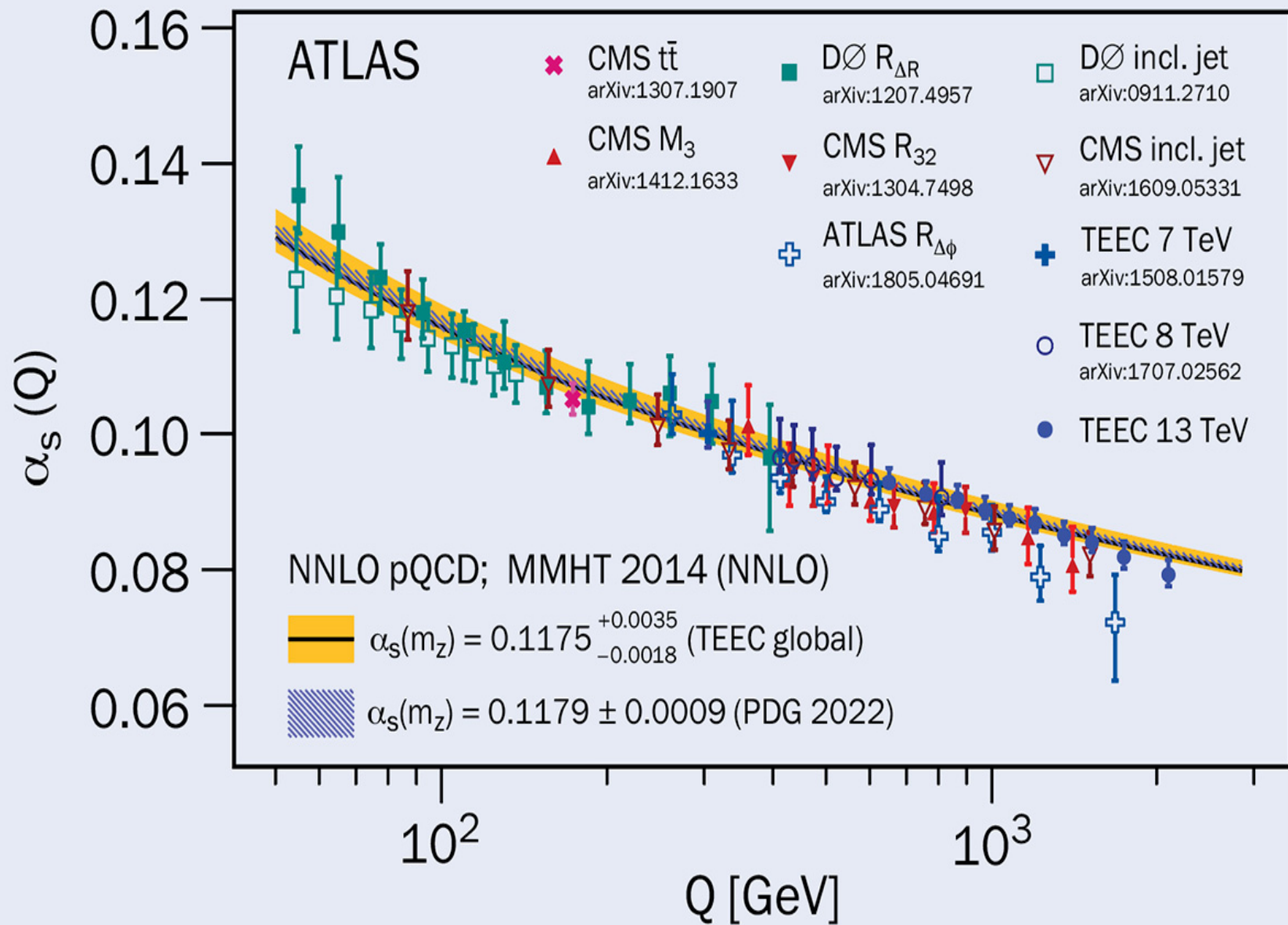
2 WEAK

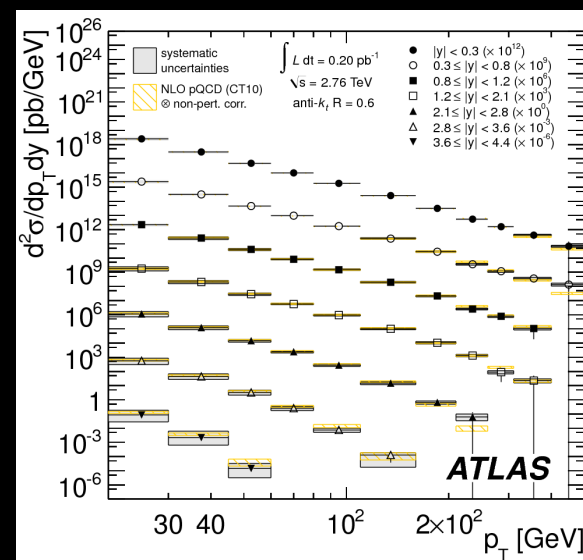
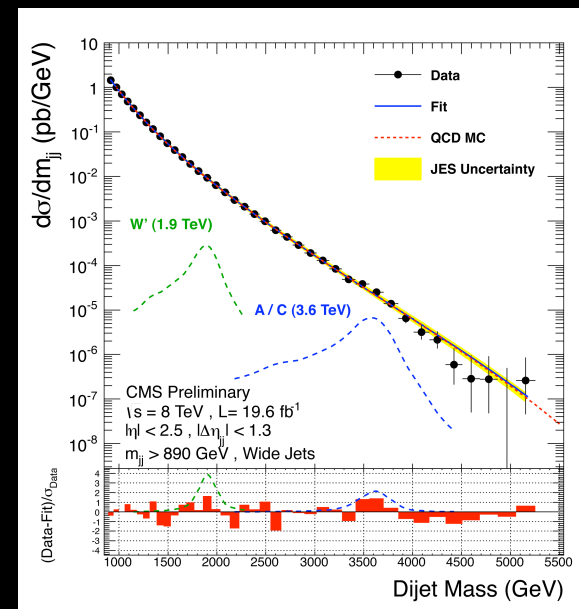
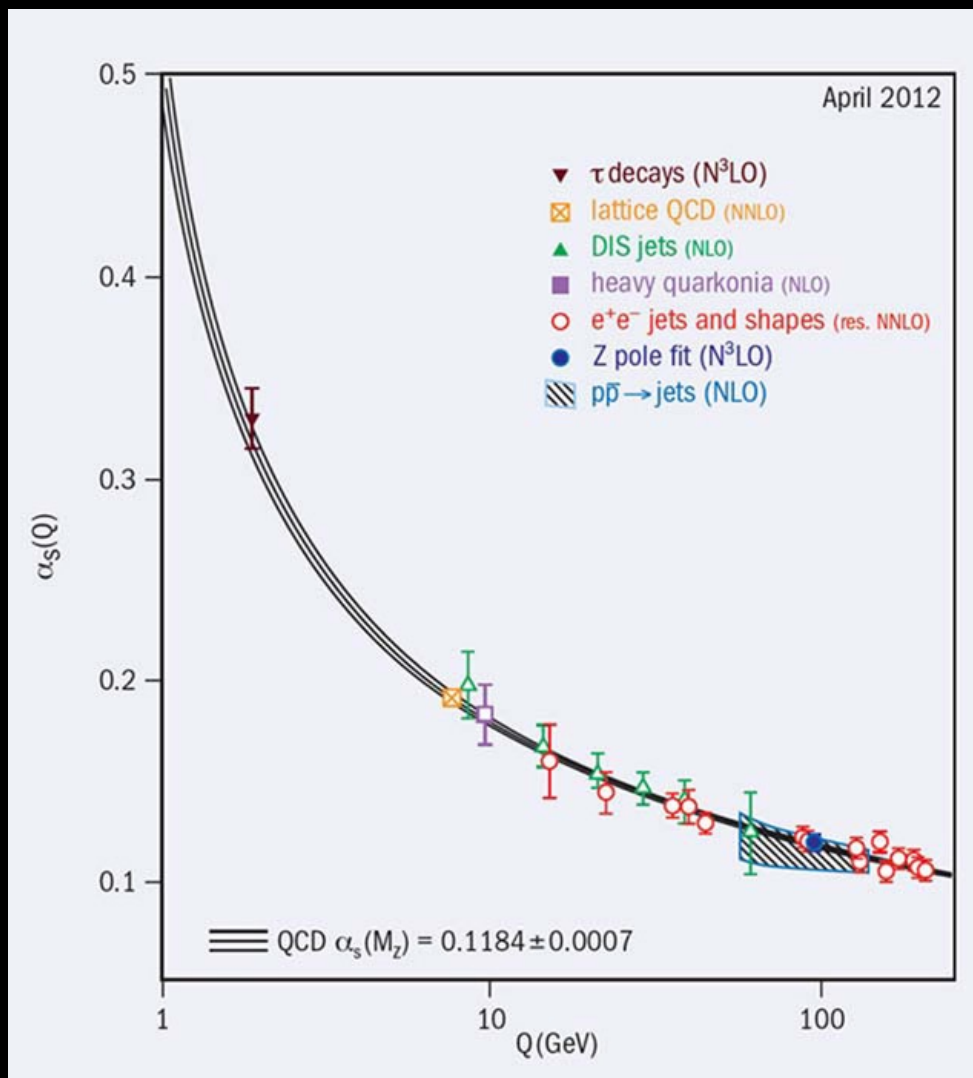
3 STRONG

HIGGS

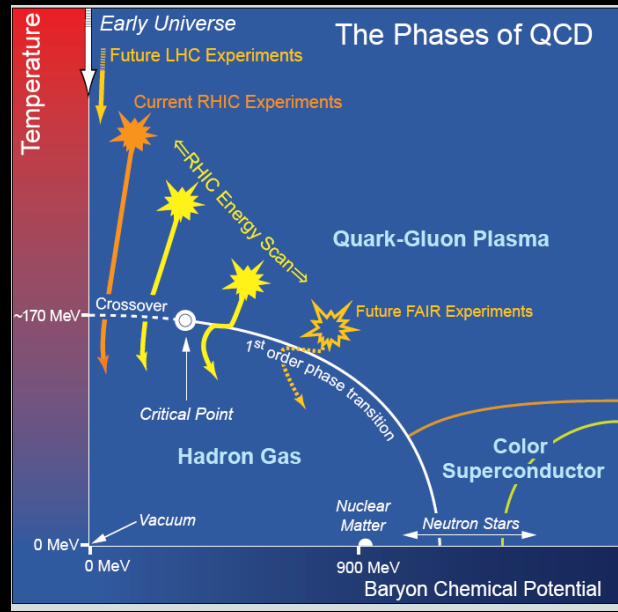
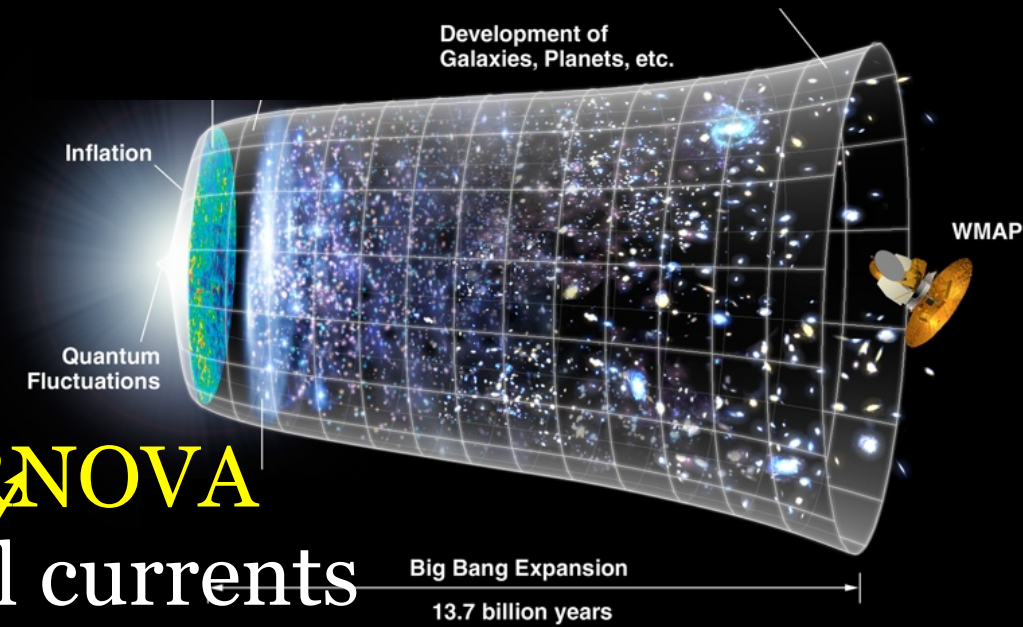
Impressive Tests







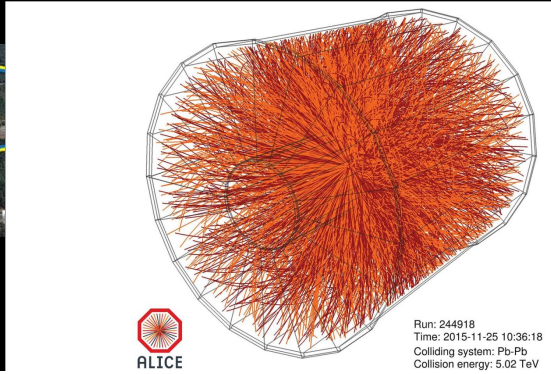
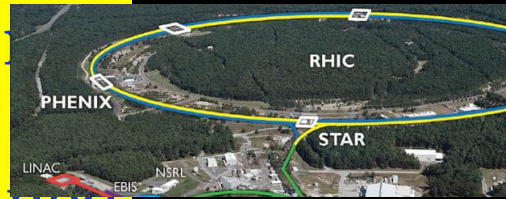
QCD opened up the early Universe for theoretical speculation, transforming it from a hadron hell to quark soup!



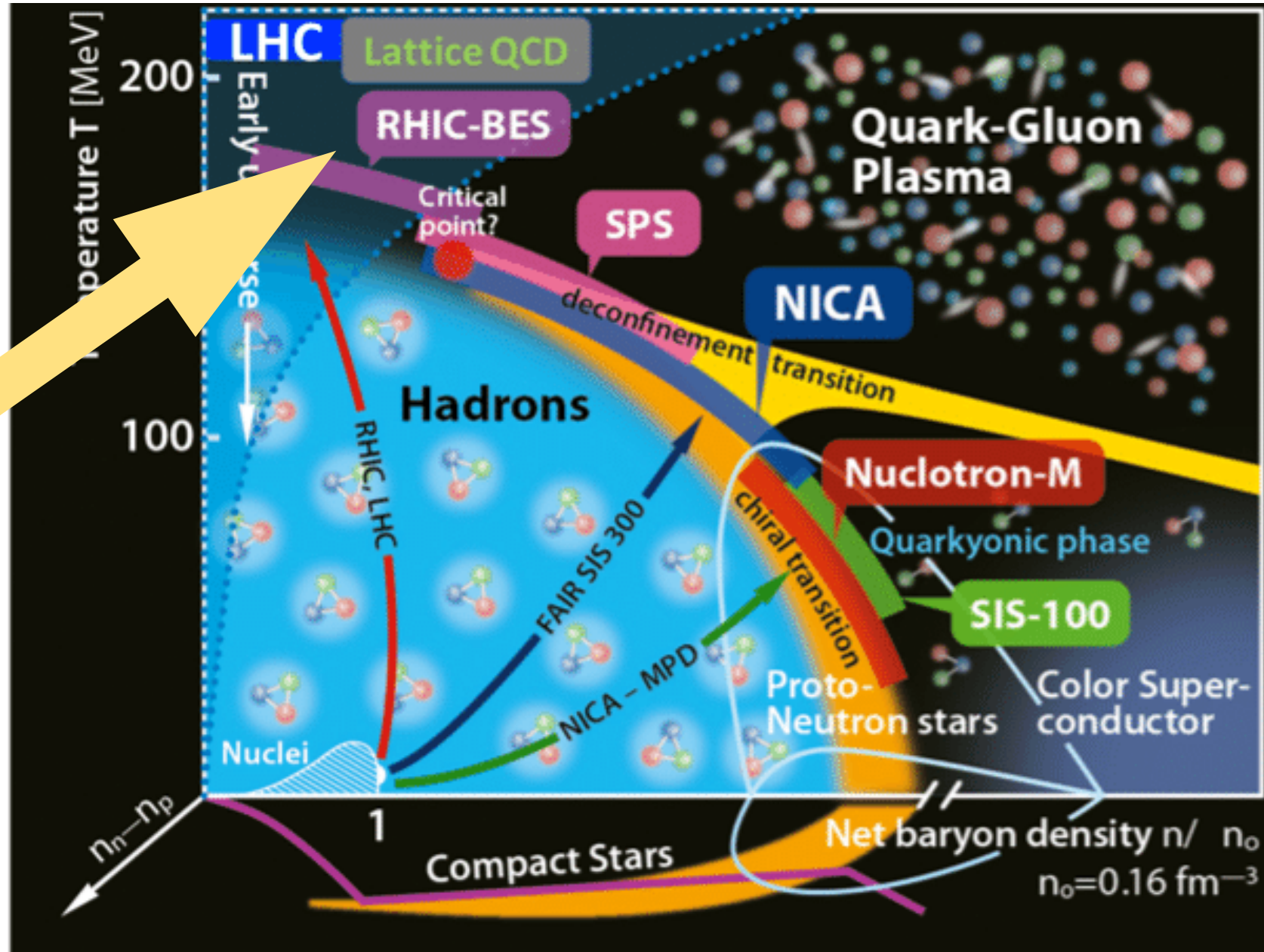
ALICE/ CERN

SUPERNOVA
Neutral currents

Quark-Gluon Phase Transition
 $T > 120 \text{ MeV}$, $t < 10^{-6} \text{ sec}$. Quark-Gluon plasma
 $T < 120 \text{ MeV}$, $t > 10^{-6} \text{ sec}$. Quarks confined in Nuclei



Perfect
Fluid



QCD: A PERFECT THEORY

NO INFINITIES

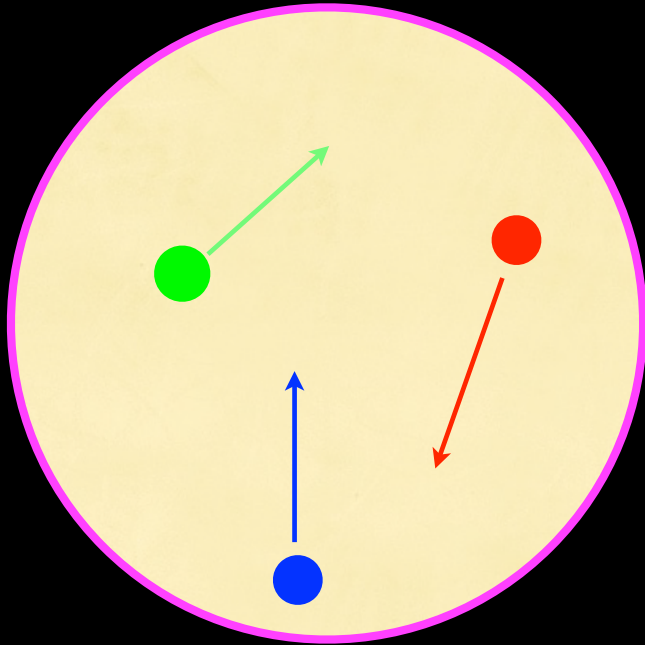
NO NEW PHYSICS AT SHORT DISTANCES OR
HIGH ENERGIES

NO ADJUSTABLE PARAMETERS

BUT:

Why $N = 3$? Quarks masses and mixing?
& there are other forces in nature -- GRAVITY

NO ADJUSTABLE PARAMETERS

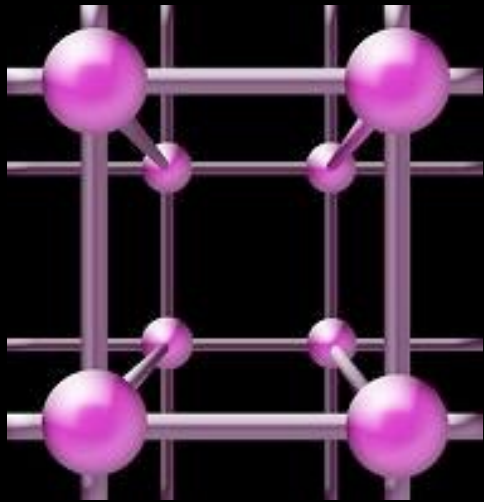


$$M = \frac{E}{c^2}$$

Most of the mass of the proton arises from the energy of the confined gluon field and the kinetic energy of the quarks.

ALL MASS RATIOS
ARE CALCULABLE

The strong coupling at the
scale of M_p is calculable!!

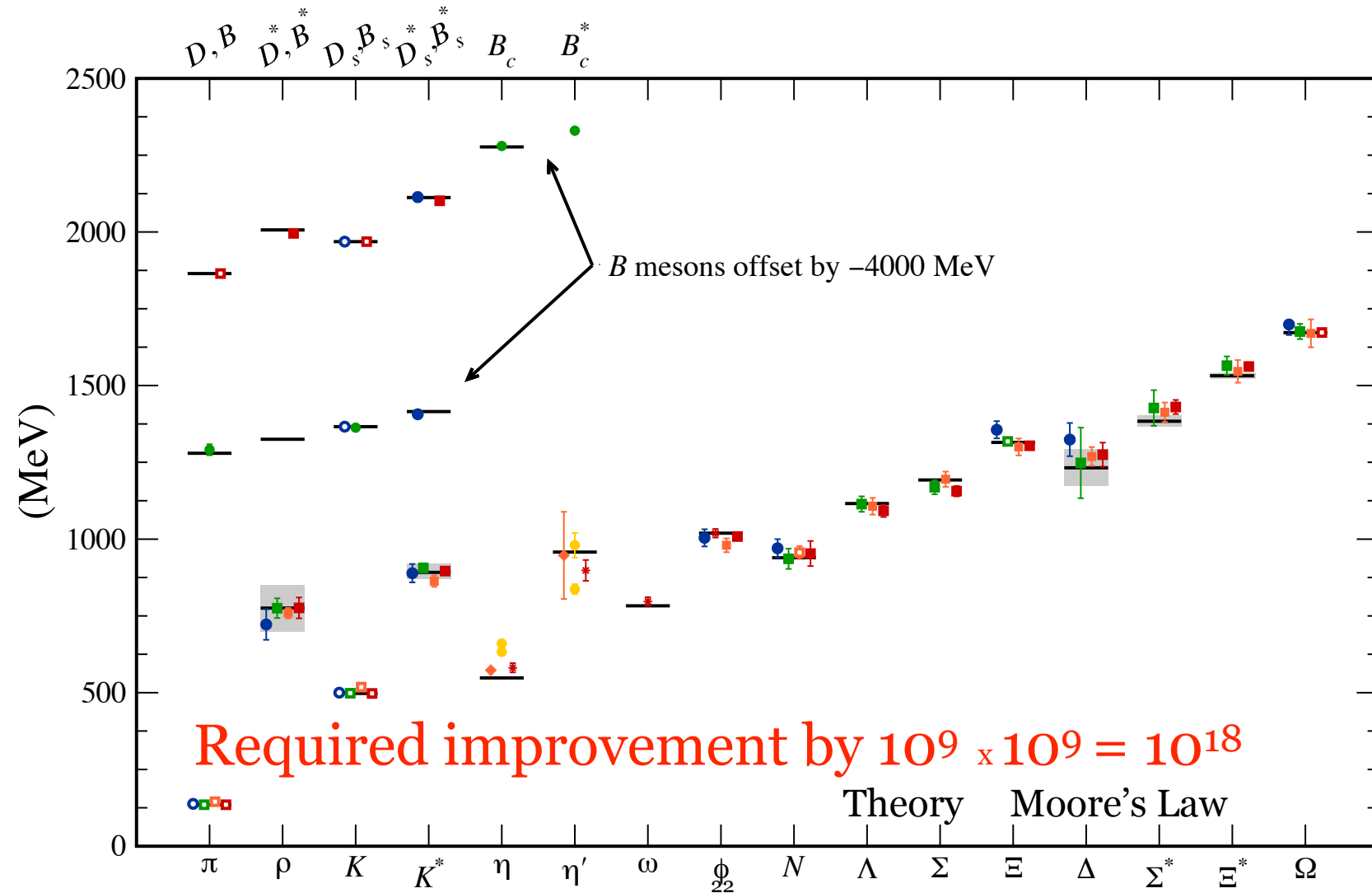


LATTICE QCD

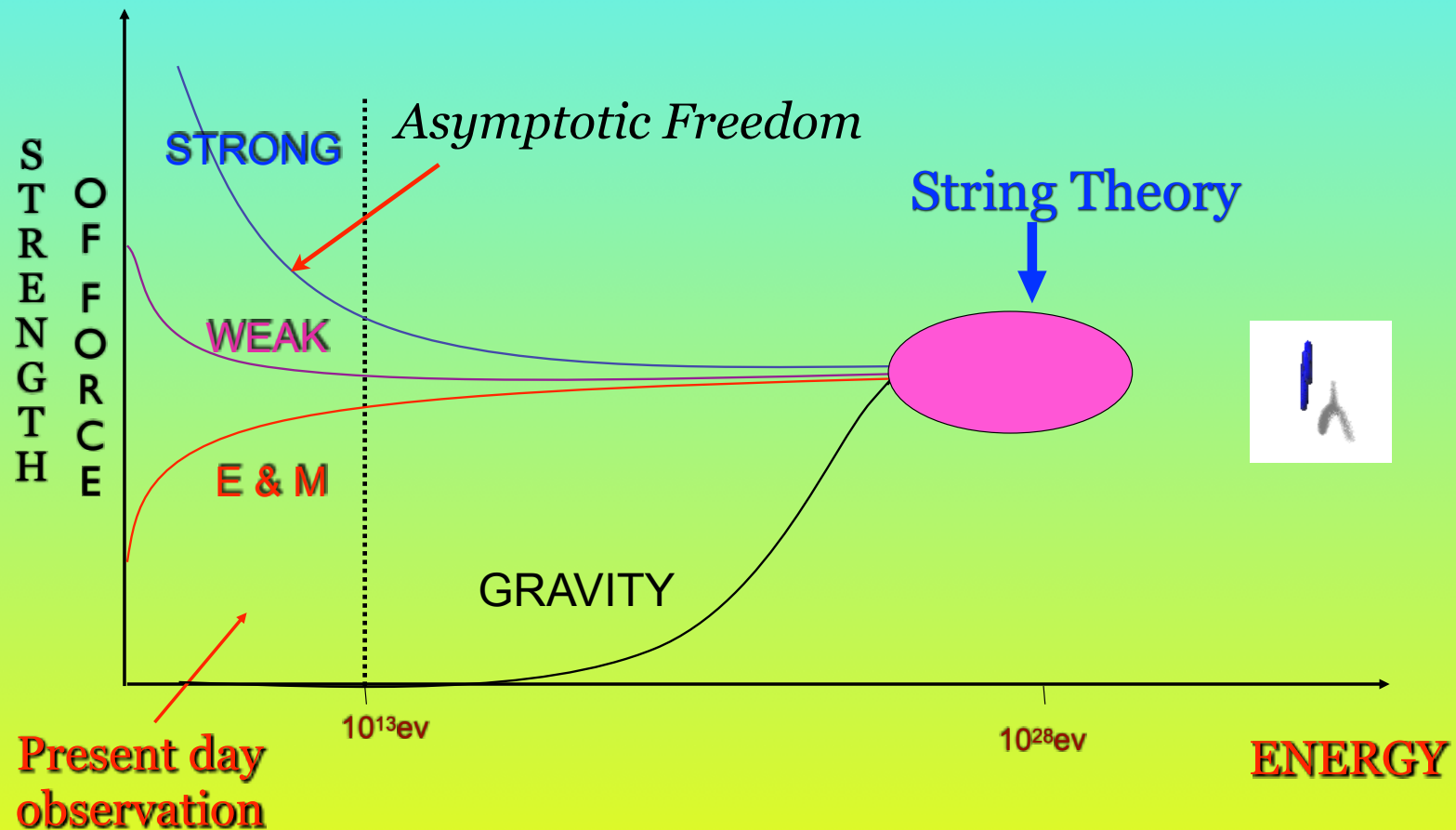
Remains the only tool for precise, controllable, first principle calculations of static hadronic properties.

In the future: QUANTUM COMPUTERS

The Light Hadron Spectrum Of Qcd

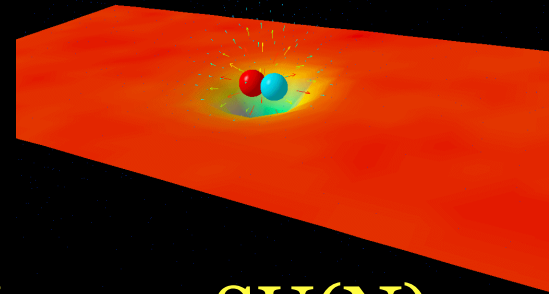


HOW DO THE FORCES UNIFY?



STRING THEORY

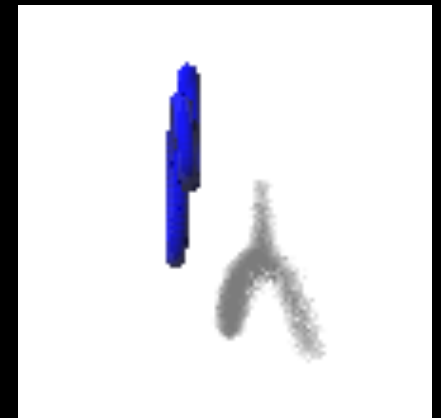
$i = 1 \dots N$



Open Strings $\sim$ $SU(N)$
Gauge Mesons

GAUGE THEORY = STRING THEORY

Closed Strings $\sim$ Gravitons



ARE ALL PARTICLES DIFFERENT VIBRATIONS OF A SUPERSTRING ?

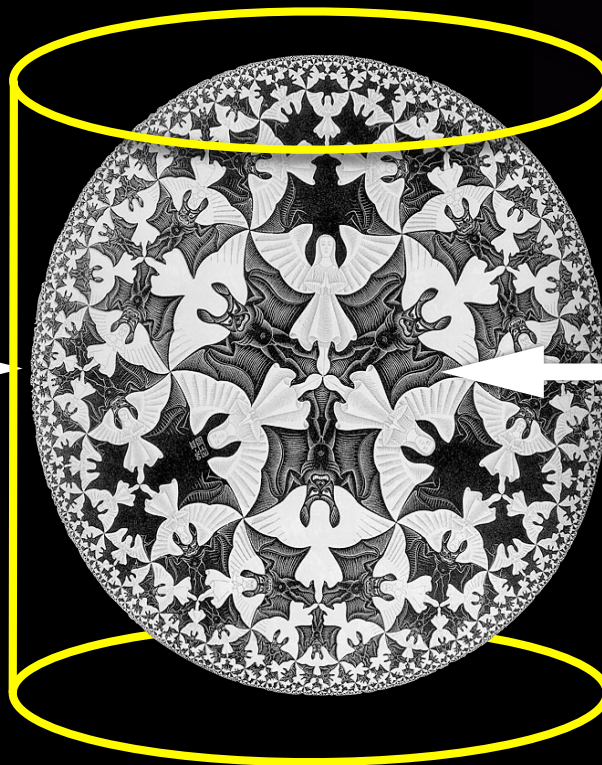


10^{-35} meters

DUALITY



QM in M_4



STRINGS
in AdS_5

EMERGENCE OF SPACE-TIME

Many examples where some or all space is emergent.

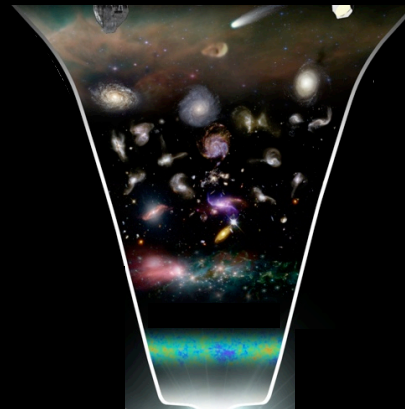
The structure of dynamical space : geometry is dual to the entanglement structure of QM dual state.

TIME IS HARDER!

WHAT
ARE THE
RULES ?

B
O
U
N
D
A
R
Y

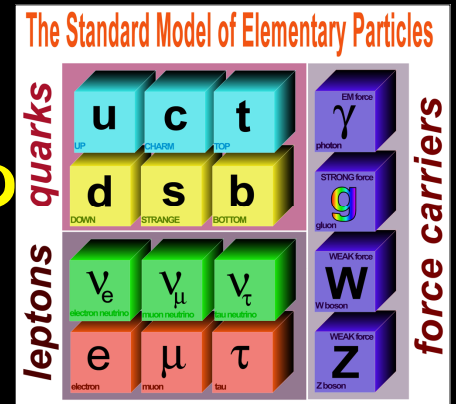
THE
END



THE
BEGINNING

THE
UNIVERSE
=
SPACETIME
HISTORY

WHAT HAVE WE LEARNED FROM THE STANDARD MODEL?



MATTER = Charged Spin 1/2 Fermions

FORCES - Described by Quantum Gauge Field Theories

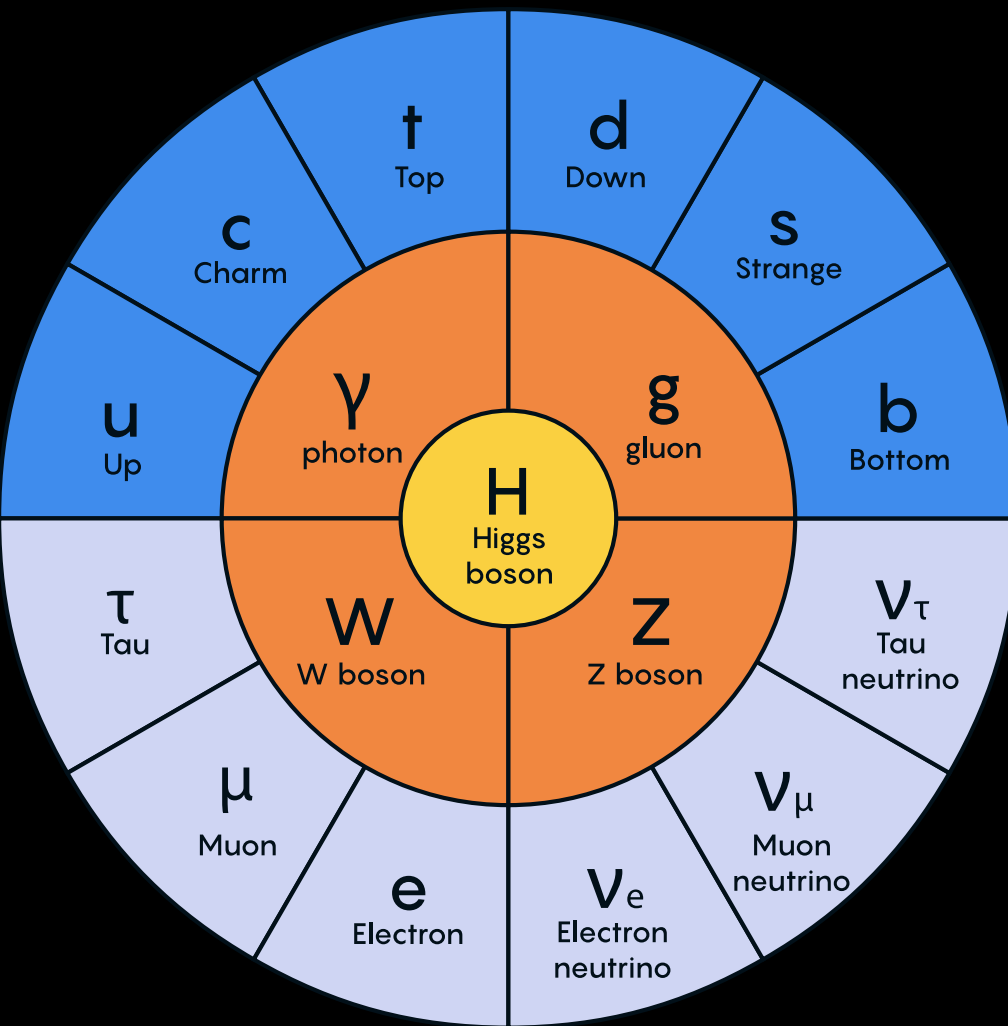
Three Phases :

1. EM: $U(1)$ Coulomb—Long Range
2. WEAK: $SU(2)$ Screened or Higgsed
by an unnatural scalar field sector
3. STRONG: $SU(3)$ Confined

AFTER 50 YEARS WHAT HAVE WE LEARNED FROM QCD?

QCD IS THE THEORY OF THE NUCLEAR FORCE
DYNAMICS CAN DETERMINE
ALL MASSES AND COUPLINGS
GAUGE-STRING DUALITY

The Standard Model



FERMIONS (MATTER)

BOSONS (FORCE CARRIERS)

● QUARKS

● LEPTONS

● GAUGE BOSONS

● HIGGS BOSON

HIGGS

- Electroweak scale, “hierarchy”
- Flavor masses, mixings, generation
- Neutrino Masses (Majorana?)
- Baryon Asymmetry

COSMOLOGY

- Cosmic Acceleration — Dark Energy

STRING THEORY

- Unification - Quantum Gravity

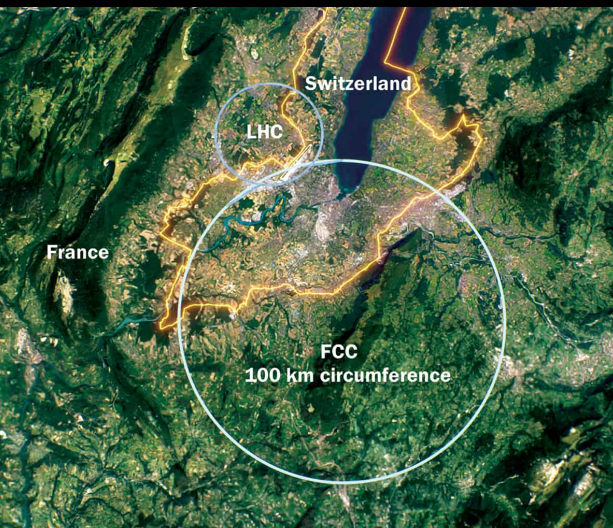
In the FUTURE

Perturbative: Amplitudes, Amplitudes, Amplitudes...

Numerical: Hamiltonian Truncation, Q-Computers

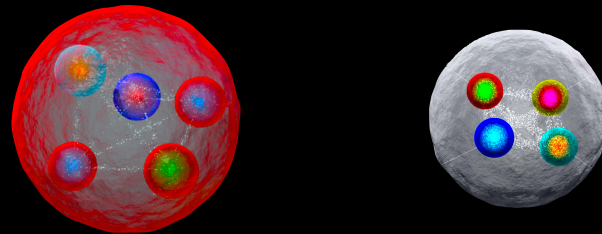
Non-Perturbative: fragmentation, diffraction,...

LHC-FCC

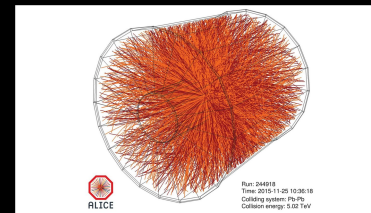


Experiment

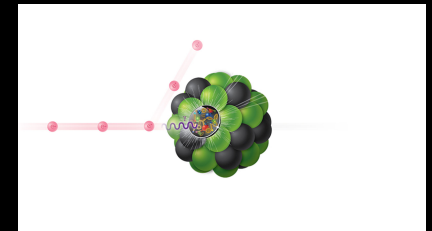
LHCB



ALICE



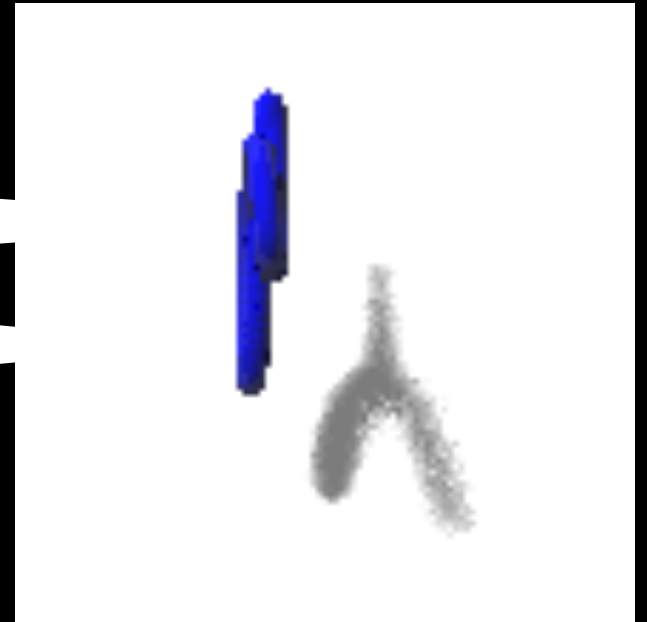
EIC



THE FRAMEWORK OF THEORETICAL PHYSICS

QUANTUM
FIELD
FRAMEWORK

Standard Theory



ALL PARAMETERS ARE DYNAMICAL
BUT THERE ARE 10^{500} “VACUA”

Particle Physics

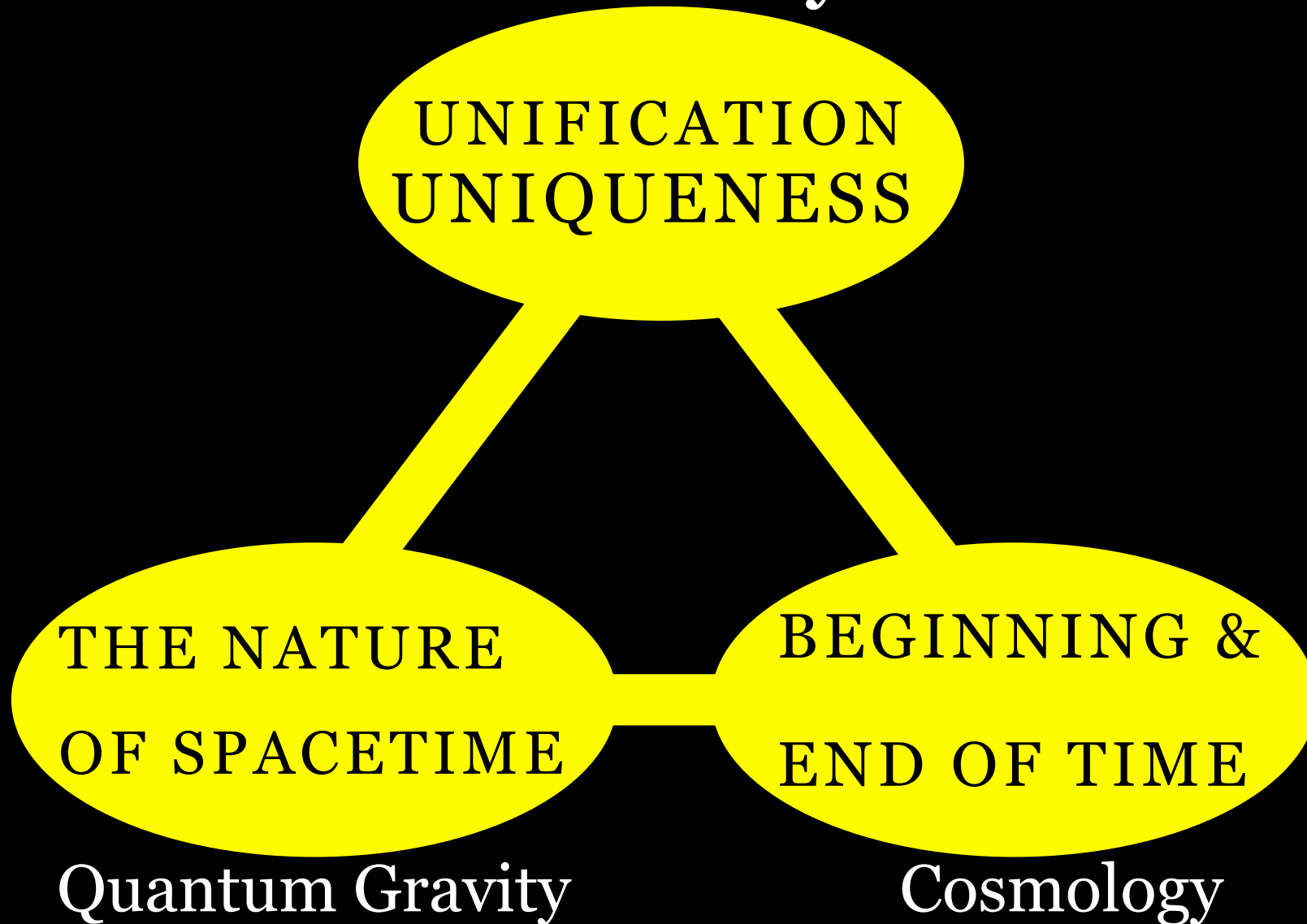
UNIFICATION
UNIQUENESS

WHAT PICKS THE
THEORY FROM THE FRAMEWORK?

BEGINNING &
END OF TIME

Cosmology

Particle Physics

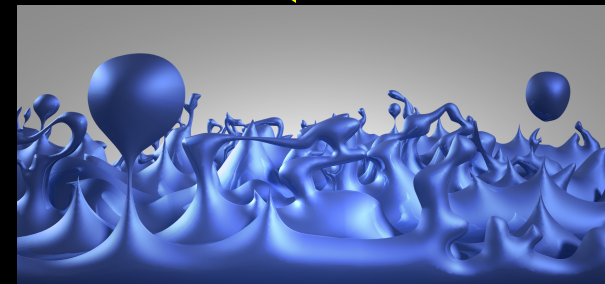
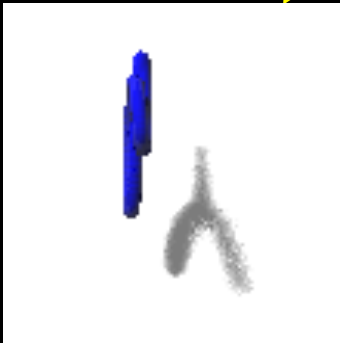


QCD

NON-ABELIAN GAUGE THEORY

The Standard Model of Elementary Particles

quarks	u UP	c CHARM	t TOP	force carriers	γ photon EM force
	d DOWN	s STRANGE	b BOTTOM		g gluon STRONG force
leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino		W W boson WEAK force
	e electron	μ muon	τ tau		Z Z boson WEAK force



EMERGENT SPACETIME

OPTIMISM

ONCE A FUNDAMENTAL QUESTION
BECOMES A WELL FORMULATED
SCIENTIFIC QUESTION

APPROACHABLE BY EXPERIMENT,
OBSERVATION AND
MATHEMATICAL MODELING

IT WILL BE ANSWERED IN
YOUR LIFETIME

THE

END

NOT THE END OF

