Electroweak Theory and Higgs Physics

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Fermilab Academic Lectures · 1 – 17 November 2005

A Decade of Discovery Past ...

- Electroweak theory → law of nature
- Higgs-boson influence observed in the vacuum
- Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$
- Understanding QCD
- Discovery of top quark
- Direct $\mathcal{CP}$ violation in $K \to \pi\pi$
- B-meson decays violate $\mathcal{CP}$
- Flat universe dominated by dark matter, energy
- Detection of ν_τ interactions
- Quarks & leptons structureless at TeV scale

A Decade of Discovery Past . . .

- ▷ Electroweak theory → law of nature
  $[Z,\ e^+e^-,\ \bar{p}p,\ \nu N,\ (g-2)_\mu,\ \ldots]$
- ▷ Higgs-boson influence observed in the vacuum
  [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$,
  $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}, reactors]
- ▷ Understanding QCD
  [heavy flavor, Z^0, $\bar{p}p$, νN, ep, ions, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct $\mathcal{CP}$ violation in $K \to \pi\pi$ [fixed-target]
- ▷ B-meson decays violate $\mathcal{CP}$ [$e^+e^- \to B\bar{B}$]
- ▷ 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]

Goal: Understanding the Everyday

- ▷ Why are there atoms?
- ▷ Why chemistry?
- ▷ Why stable structures?
- ▷ What makes life possible?

Goal: Understanding the Everyday

- ▷ Why are there atoms?
- ▷ Why chemistry?
- ▷ Why stable structures?
- ▷ What makes life possible?

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

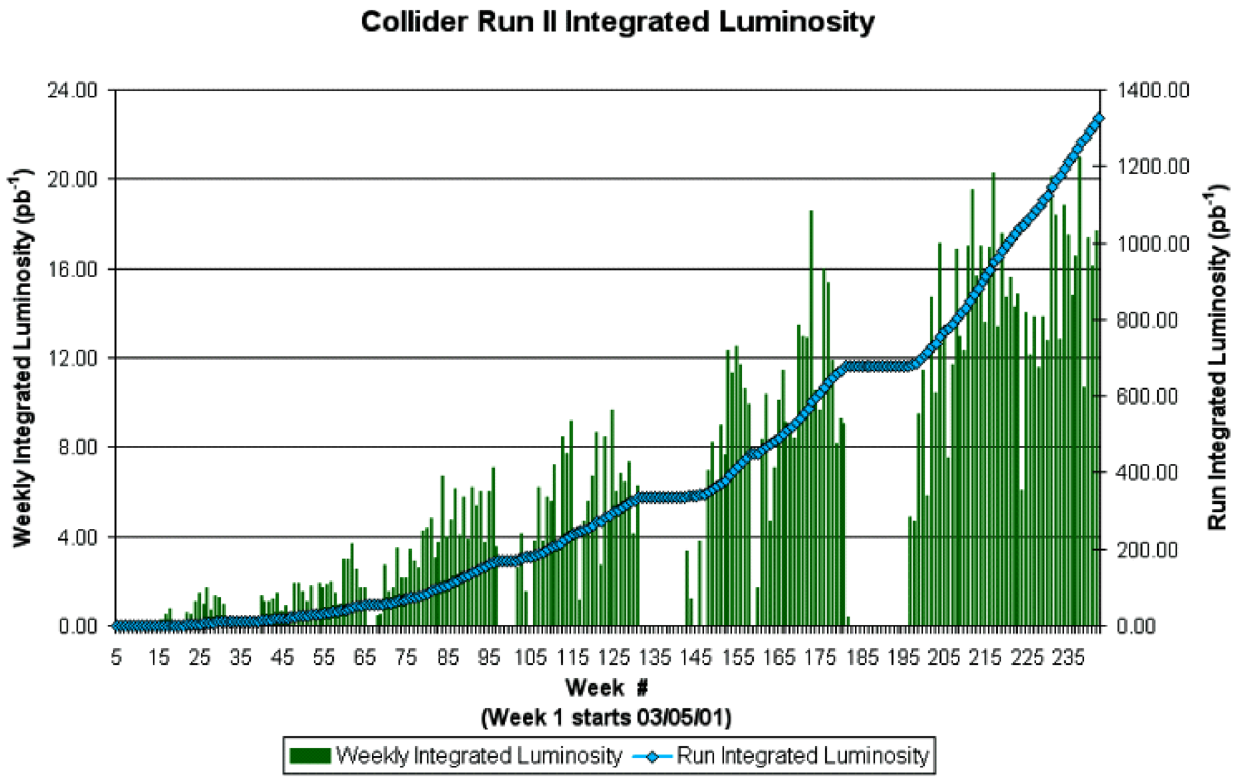
Searching for the mechanism of electroweak symmetry breaking, we seek to understand

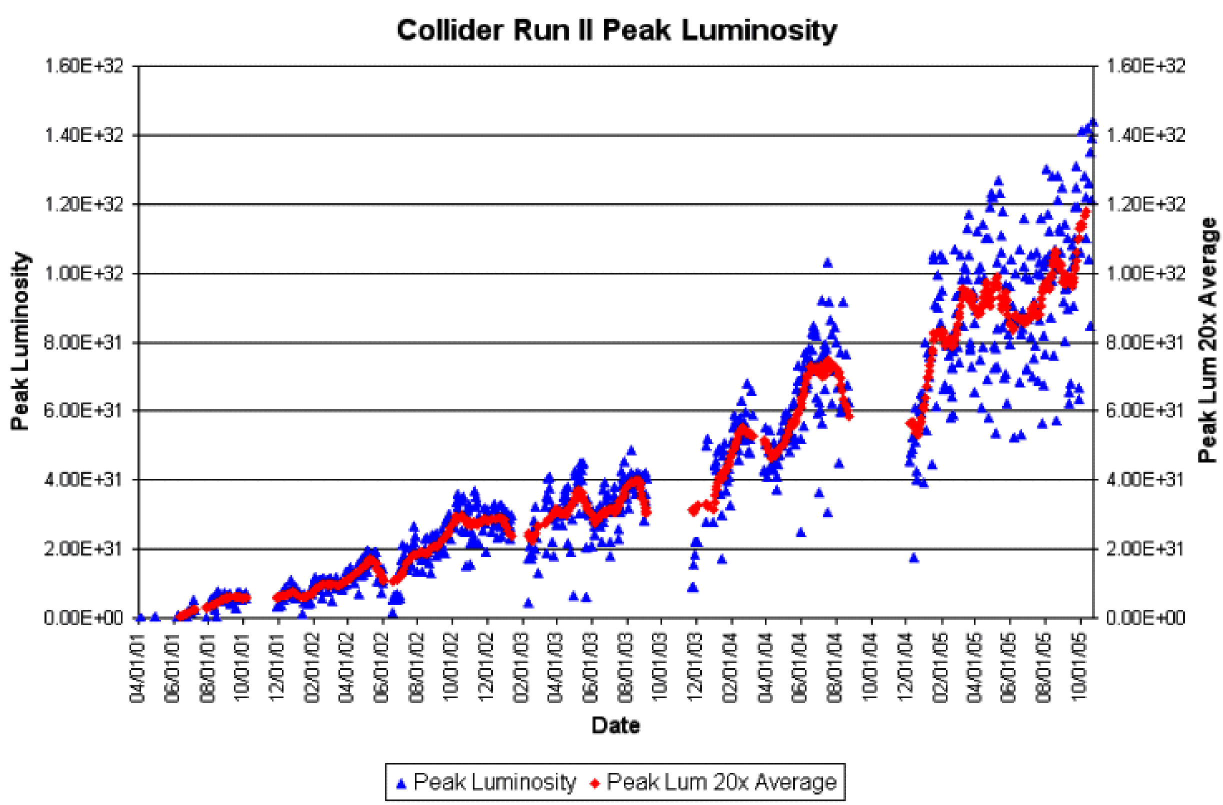
why the world is the way it is.

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

it is coming within the reach of particle physics.

Tevatron Collider is running *now*, breaking new ground in sensitivity


Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb^{-1})
Run Integrated Luminosity (pb^{-1})
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity


Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
Date
Peak Luminosity
Peak Lum 20x Average

Tevatron Collider in a Nutshell

980-GeV protons, antiprotons

(2π km)

frequency of revolution $\approx 45\,000$ s^{-1}

392 ns between crossings

($36 \otimes 36$ bunches)

collision rate $= \mathcal{L} \cdot \sigma_{\text{inelastic}} \approx 10^7$ s^{-1}

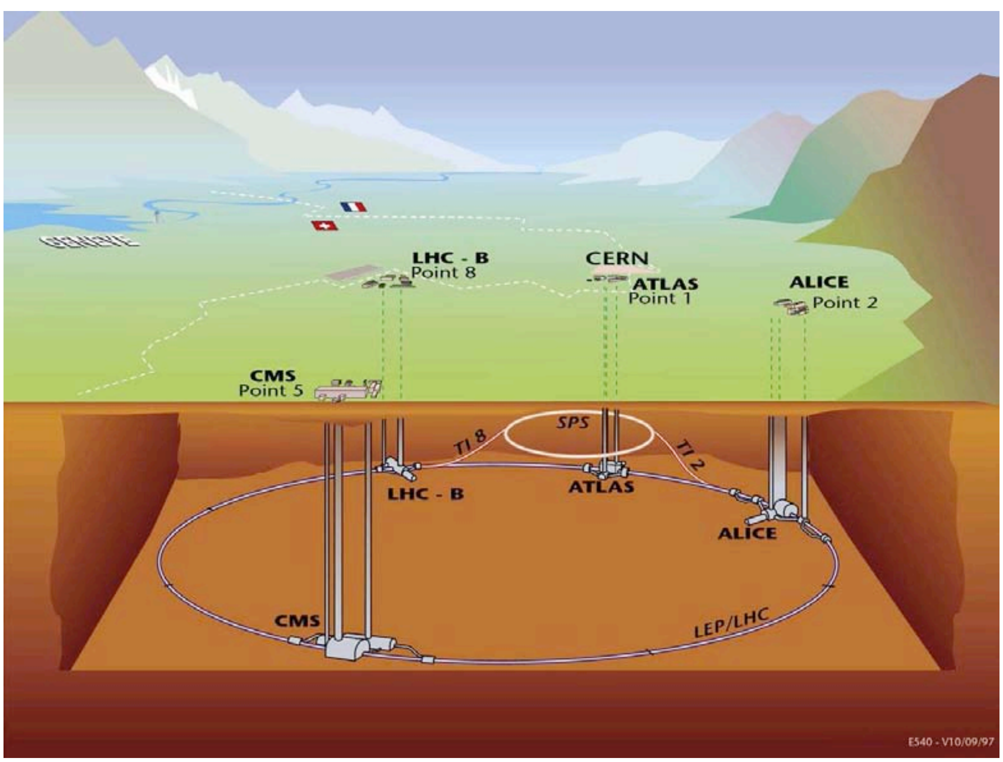
$c \approx 10^9$ km/h; $v_p \approx c - 495$ km/h

Record $\mathcal{L}_{\text{init}} = 1.64 \times 10^{32}$ cm^{-2} s^{-1}

[CERN ISR: pp, 1.4]

Maximum $\bar{p}$ at Low β: 1.661×10^{12}

The LHC will operate *soon*, breaking new ground in energy and sensitivity



LHC in a nutshell

7-TeV protons on protons (27 km);

$v_p \approx c - 10$ km/h

Novel two-in-one dipoles (≈ 9 teslas)

Startup: 43 $\otimes$ 43 $\longrightarrow$ 156 $\otimes$ 156 bunches, $\mathcal{L} \approx 6 \times 10^{31}$ cm^{-2} s^{-1}

Early: 936 bunches, $\mathcal{L} \gtrsim 5 \times 10^{32}$ cm^{-2} s^{-1} [75 ns]

Next phase: 2808 bunches, $\mathcal{L} \rightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

25 ns bunch spacing

Eventual: $\mathcal{L} \gtrsim 10^{34}$ cm^{-2} s^{-1}: 100 fb^{-1}/year

Tentative Outline . . .

▷ Preliminaries

Current state of particle physics

A few words about QCD

Sources of mass

▷ Antecedents of the electroweak theory

What led to EW theory

What EW theory needs to explain

▷ Some consequences of the Fermi theory

μ decay

νe scattering

. . . Outline . . .

- ▷ $SU(2)_L \otimes U(1)_Y$ theory

  Gauge theories

  Spontaneous symmetry breaking

  Consequences: $W^{\pm}$, Z^0/NC, H, m_f?

  Measuring $\sin^2\theta_W$ in νe scattering

  GIM / CKM

- ▷ Phenomena at tree level and beyond

  Z^0 pole

  W mass and width

  Atomic parity violation

  Vacuum energy problem

. . . Outline

- ▷ The Higgs boson and the 1-TeV scale
  - Why the Higgs boson must exist
  - Higgs properties, constraints
  - How well can we anticipate M_H?
  - Higgs searches
- ▷ The problems of mass
- ▷ The EW scale and beyond
  - Hierarchy problem
  - Why is the EW scale so small?
  - Why is the Planck scale so large?
- ▷ Outlook

General References

- C. Quigg, "Nature's Greatest Puzzles," hep-ph/0502070
- C. Quigg, "The Electroweak Theory," hep-ph/0204104 (TASI 2000 Lectures)
- C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*
- I. J. R. Aitchison & A. J. G. Hey, *Gauge Theories in Particle Physics*
- R. N. Cahn & G. Goldhaber, *Experimental Foundations of Particle Physics*
- G. Altarelli & M. Grünewald, "Precision Electroweak Tests of the SM," hep-ph/0404165
- F. Teubert, "Electroweak Physics," ICHEP04
- S. de Jong, "Tests of the Electroweak Sector of the Standard Model," EPS HEPP 2005

Problem sets: http://lutece.fnal.gov/TASI/default.html

Our picture of matter

Pointlike constituents ($r < 10^{-18}$ m)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

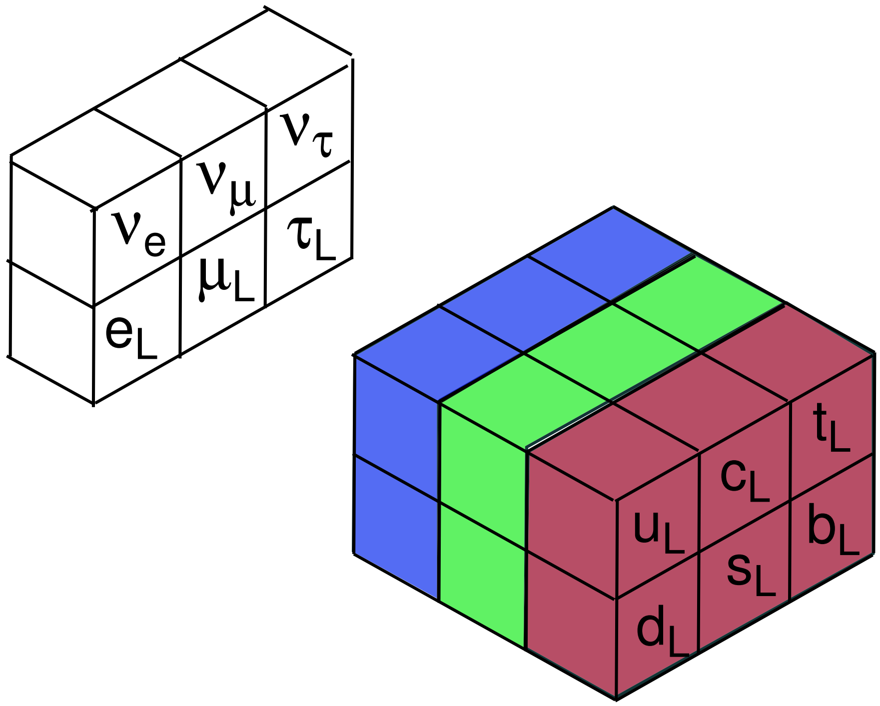
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Few fundamental forces, derived from gauge symmetries

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

Electroweak symmetry breaking

Higgs mechanism?


ν_e
ν_μ
ν_τ
e_L
μ_L
τ_L
u_L
c_L
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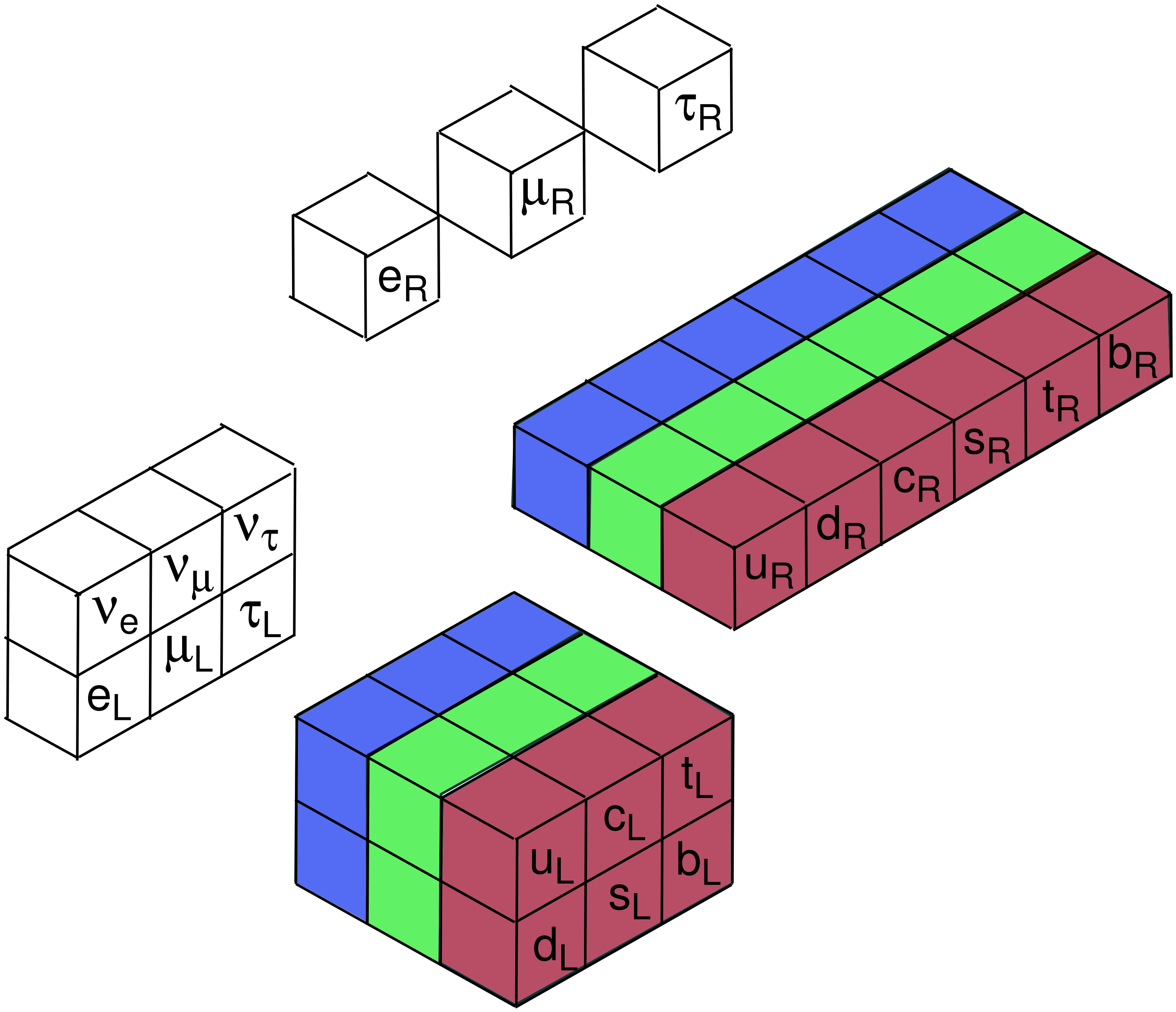
d_L
s_L
b_L



τ_R
μ_R
e_R
b_R
t_R
s_R
c_R
d_R
u_R
ν_τ
ν_μ
ν_e
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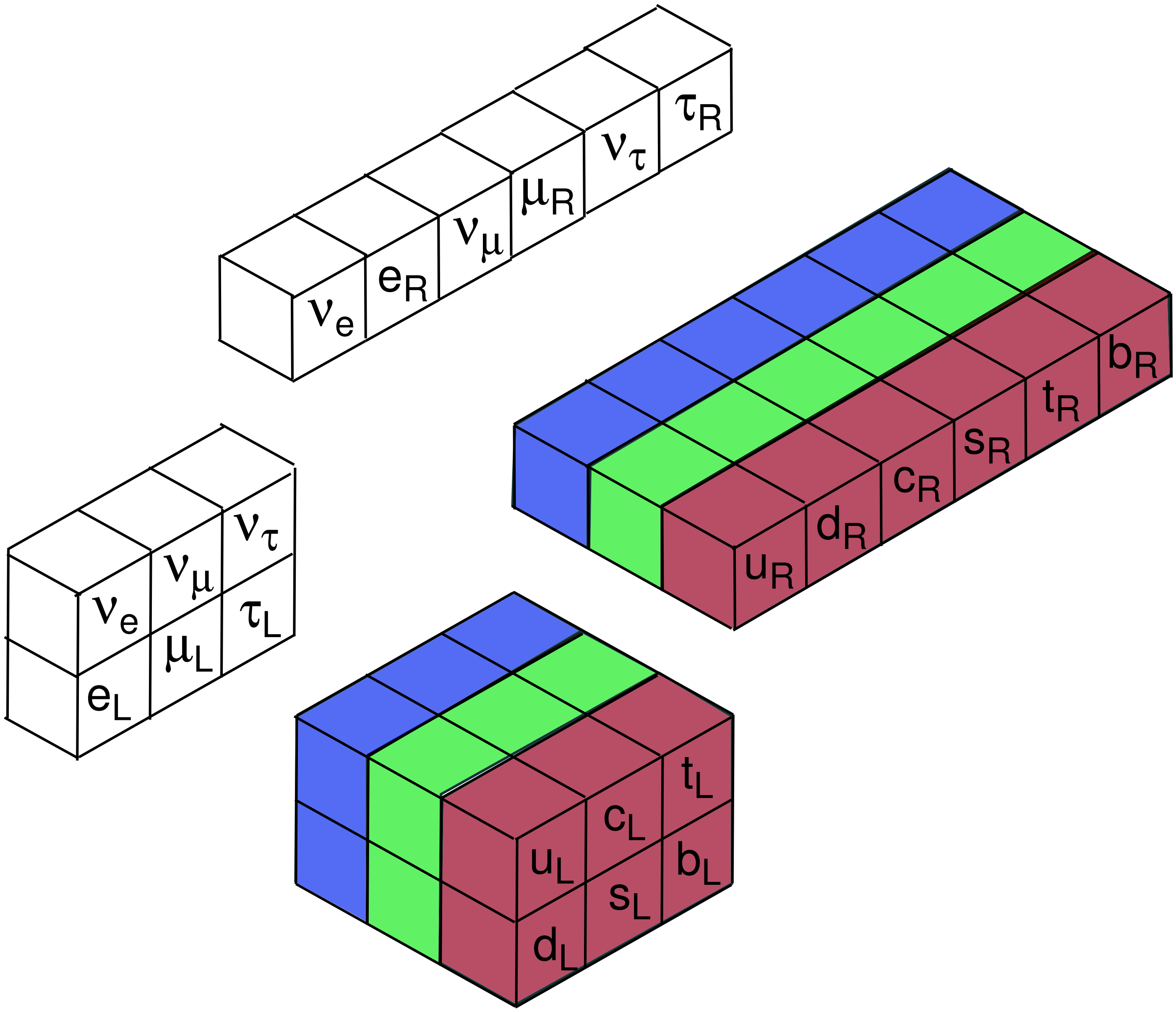
ν_e
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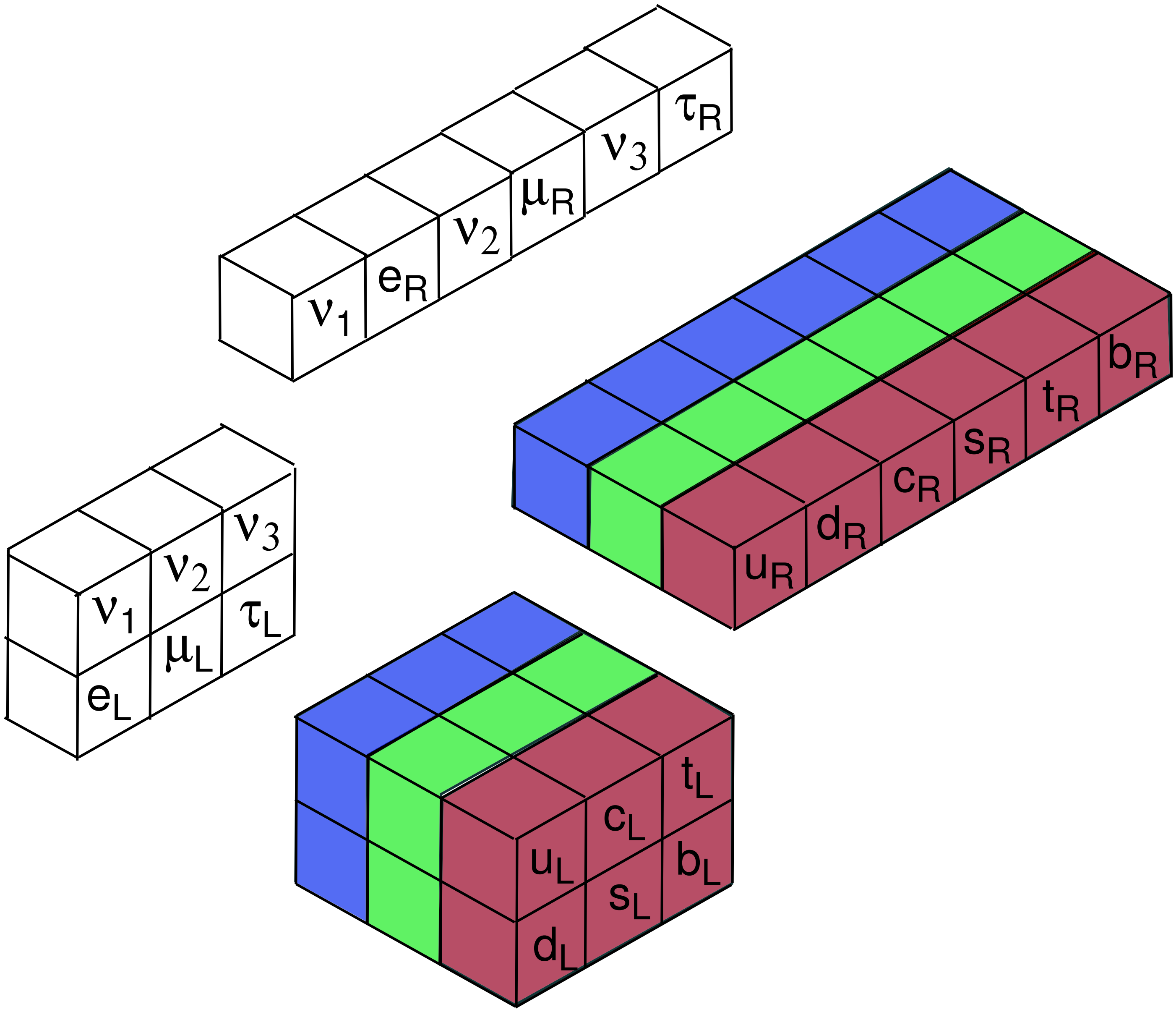

ν_1
e_R
ν_2
μ_R
ν_3
τ_R
u_R
d_R
c_R
s_R
t_R
b_R
ν_1
ν_2
ν_3
e_L
μ_L
τ_L
u_L
c_L
t_L
d_L
s_L
b_L

Elementarity

▷ Are quarks and leptons structureless?

Symmetry

▷ Electroweak symmetry breaking and the 1-TeV scale

▷ Origin of gauge symmetries

▷ Meaning of discrete symmetries

Unity

▷ Coupling constant unification

▷ Unification of quarks and leptons

(neutrality of atoms $\Rightarrow$ new forces!);

of constituents and force particles

▷ Incorporation of gravity

Identity

▷ Fermion masses and mixings; CP violation; ν oscillations

▷ What makes an electron an e and a top quark a t?

Topography

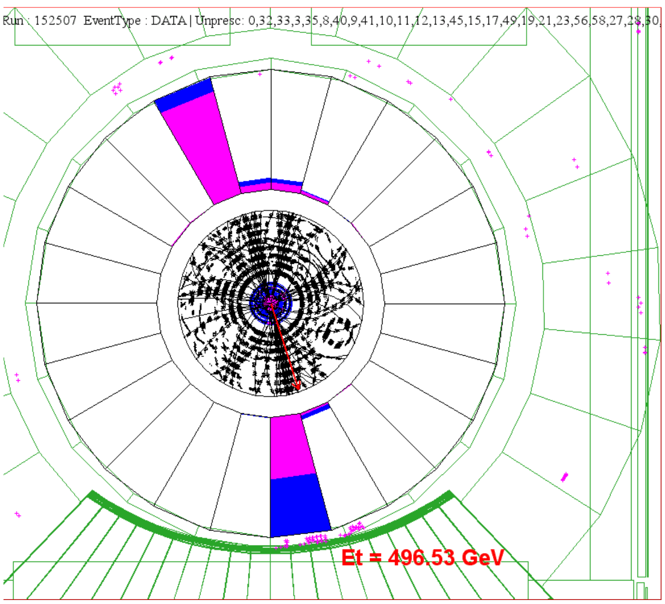
▷ What is the fabric of space and time?

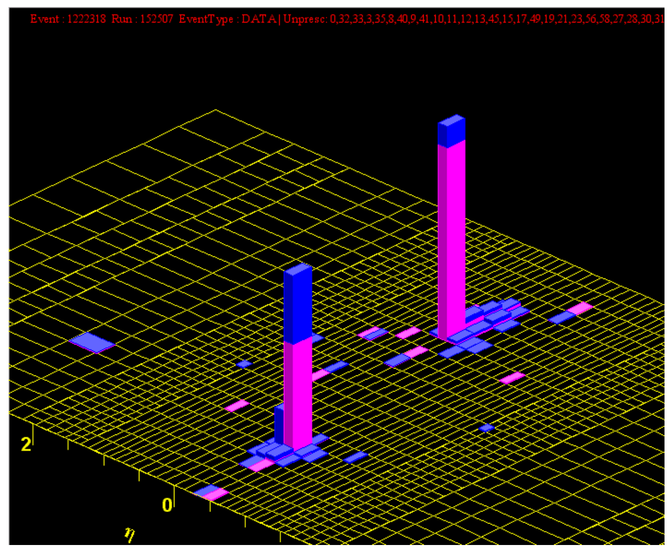
. . . the origin of space and time?

Elementarity

The World's Most Powerful Microscopes

nanonanophysics





CDF dijet event ($\sqrt{s} = 1.96$ TeV):

$E_T = 1.364$ TeV

$q\bar{q} \longrightarrow \text{jet} + \text{jet}$

Elementarity

If the Lagrangian has the form $\pm \frac{g^2}{2\Lambda^2} \overline{\psi}_L \gamma_\mu \psi_L \overline{\psi}_L \gamma^\mu \psi_L$ (with $g^2/4\pi$ set equal to 1), then we define $\Lambda \equiv \Lambda^\pm_{LL}$. For the full definitions and for other forms, see the Note in the Listings on Searches for Quark and Lepton Compositeness in the full *Review* and the original literature.

$\Lambda^+_{LL}(eeee)$	$>$	8.3 TeV, CL = 95%
$\Lambda^-_{LL}(eeee)$	$>$	10.3 TeV, CL = 95%
$\Lambda^+_{LL}(ee\mu\mu)$	$>$	8.5 TeV, CL = 95%
$\Lambda^-_{LL}(ee\mu\mu)$	$>$	6.3 TeV, CL = 95%
$\Lambda^+_{LL}(ee\tau\tau)$	$>$	5.4 TeV, CL = 95%
$\Lambda^-_{LL}(ee\tau\tau)$	$>$	6.5 TeV, CL = 95%
$\Lambda^+_{LL}(\ell\ell\ell\ell)$	$>$	9.0 TeV, CL = 95%
$\Lambda^-_{LL}(\ell\ell\ell\ell)$	$>$	7.8 TeV, CL = 95%
$\Lambda^+_{LL}(eeuu)$	$>$	23.3 TeV, CL = 95%
$\Lambda^-_{LL}(eeuu)$	$>$	12.5 TeV, CL = 95%
$\Lambda^+_{LL}(eedd)$	$>$	11.1 TeV, CL = 95%
$\Lambda^-_{LL}(eedd)$	$>$	26.4 TeV, CL = 95%
$\Lambda^+_{LL}(eecc)$	$>$	1.0 TeV, CL = 95%
$\Lambda^-_{LL}(eecc)$	$>$	2.1 TeV, CL = 95%
$\Lambda^+_{LL}(eebb)$	$>$	5.6 TeV, CL = 95%
$\Lambda^-_{LL}(eebb)$	$>$	4.9 TeV, CL = 95%
$\Lambda^+_{LL}(\mu\mu qq)$	$>$	2.9 TeV, CL = 95%
$\Lambda^-_{LL}(\mu\mu qq)$	$>$	4.2 TeV, CL = 95%
$\Lambda(\ell\nu\ell\nu)$	$>$	3.10 TeV, CL = 90%
$\Lambda(e\nu qq)$	$>$	2.81 TeV, CL = 95%
$\Lambda^+_{LL}(qqqq)$	$>$	2.7 TeV, CL = 95%
$\Lambda^-_{LL}(qqqq)$	$>$	2.4 TeV, CL = 95%
$\Lambda^+_{LL}(\nu\nu qq)$	$>$	5.0 TeV, CL = 95%
$\Lambda^-_{LL}(\nu\nu qq)$	$>$	5.4 TeV, CL = 95%

Two views of Symmetry

1. *Indistinguishability*

One object transformed into another

Familiar (and useful!) from

Global Symmetries: isospin, $SU(3)_f$, ...

Spacetime Symmetries

Gauge Symmetries

"EQUIVALENCE"

Idealize more perfect worlds, the better to understand our diverse, changing world

Unbroken unified theory: perfect world of equivalent forces, interchangeable massless particles ... *Perfectly boring?*

Symmetry ⇔ *Disorder*

A Perfect World

Two views of Symmetry

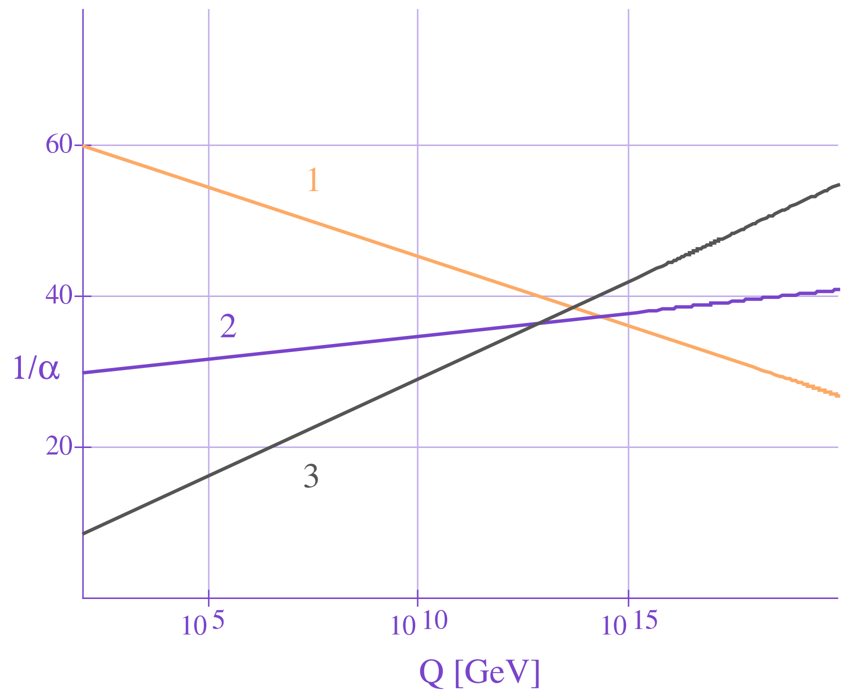
2. *Unobservable*

Goodness of a symmetry means something cannot be measured

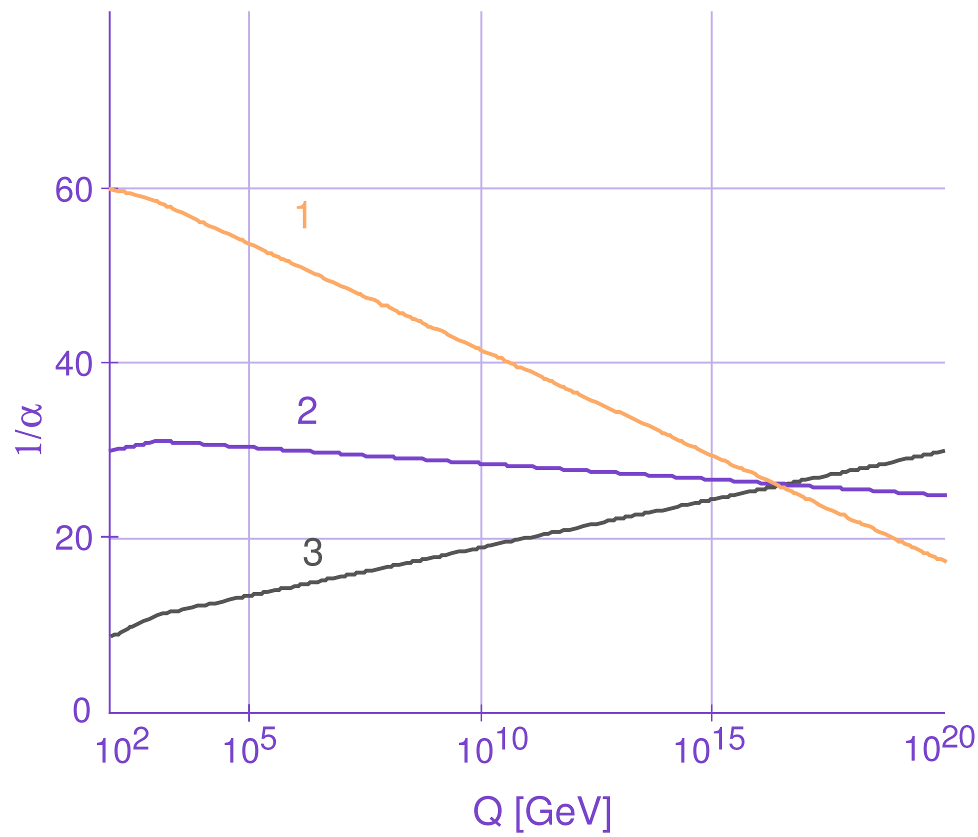
e.g., vanishing asymmetry

Un observable	Transformation	Conserved
Absolute position	$\vec{r} \to \vec{r} + \vec{\Delta}$	$\vec{p}$
Absolute time	$t \to t + \delta$	E
Absolute orientation	$\hat{r} \to \hat{r}'$	$\vec{L}$
Absolute velocity	$\vec{v} \to \vec{v} + \vec{w}$	
Absolute right	$\vec{r} \to -\vec{r}$	P
Absolute future	$t \to -t$	T
Absolute charge	$Q \to -Q$	C
Absolute phase		
⋮		

Unity



60
40
20
1/α
1
2
3
10 5
10 10
10 15
Q [GeV]



60
40
20
0
1/α
1
2
3
10^2
10^5
10^{10}
10^{15}
10^{20}
Q [GeV]

QCD is part of the standard model

. . . a remarkably simple, successful, and rich theory

Wilczek, hep-ph/9907340

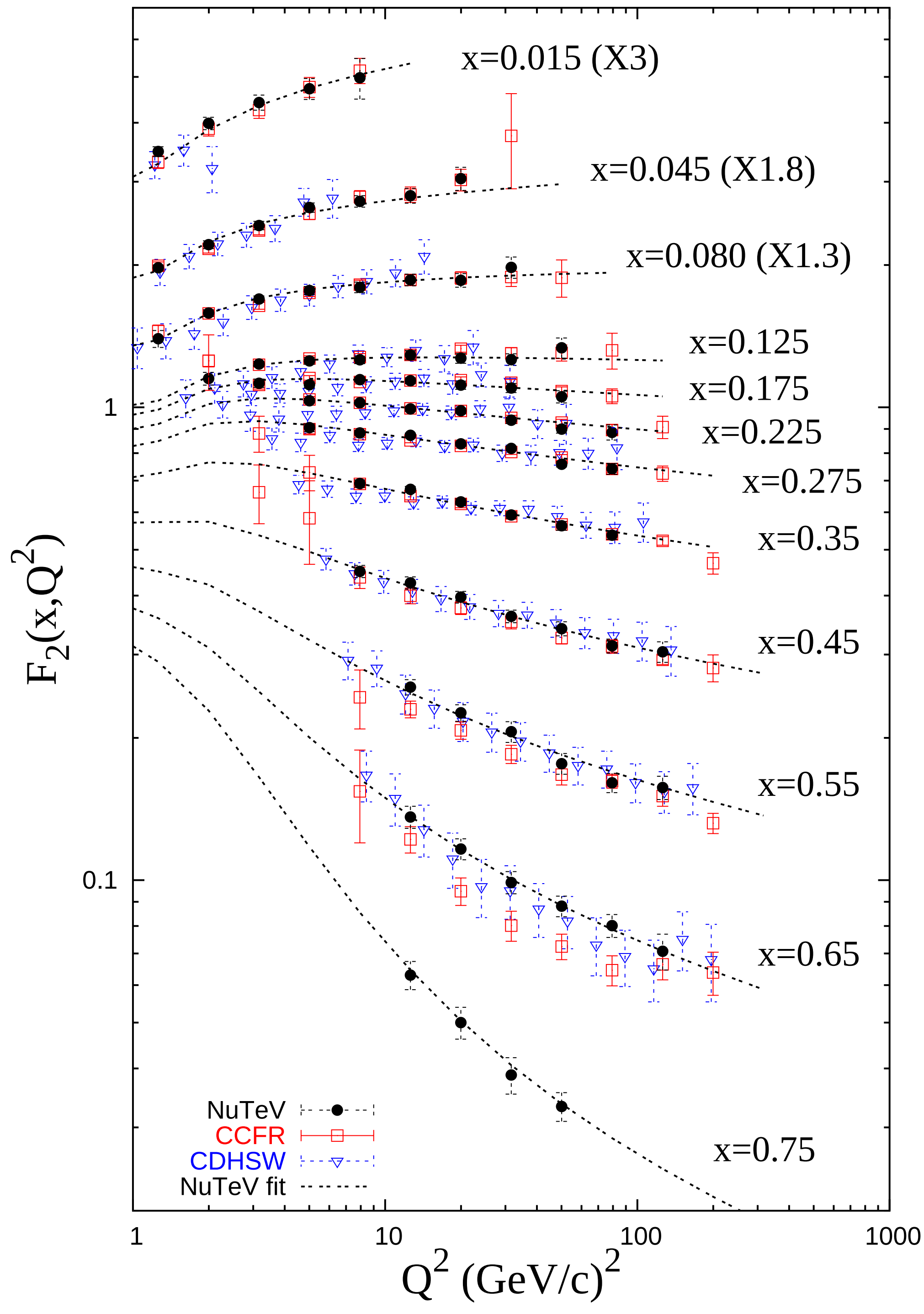
▷ Perturbative QCD

- Exists, thanks to asymptotic freedom
- Describes many phenomena in quantitative detail:
  - ▷ Q^2-evolution of structure functions
  - ▷ Jet production in $\bar{p}p$ collisions
  - ▷ Many decays, event shapes, . . .
- We can measure the running of α_s *(engineering value for unification)*

▷ Nonperturbative (lattice) QCD

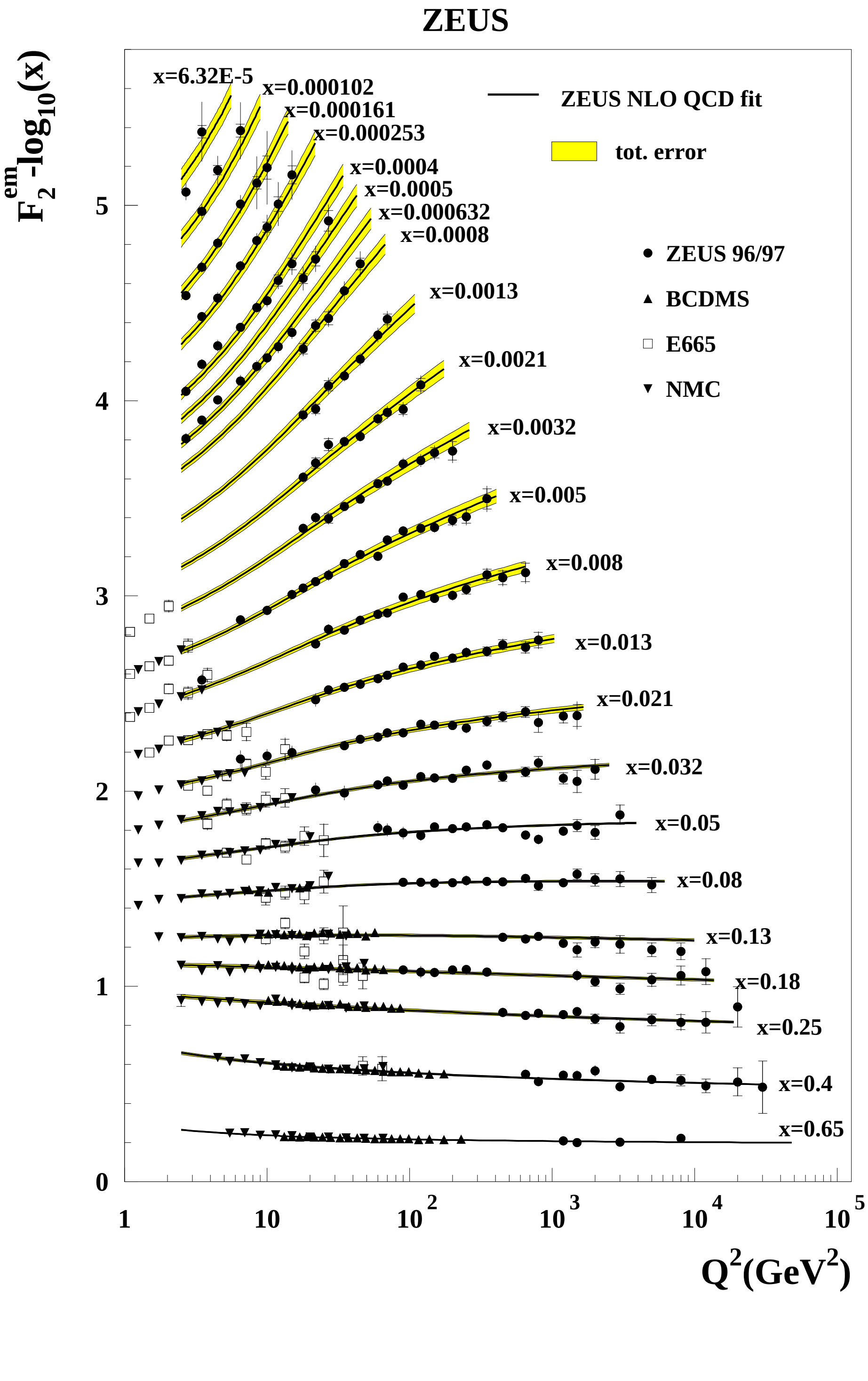
- Predicts the hadron spectrum
- Gives our best information on quark masses, etc. El-Khadra & Luke, hep-ph/0208114

$F_2(x, Q^2)$ in $\nu\mathrm{Fe}$ interactions (NuTeV)



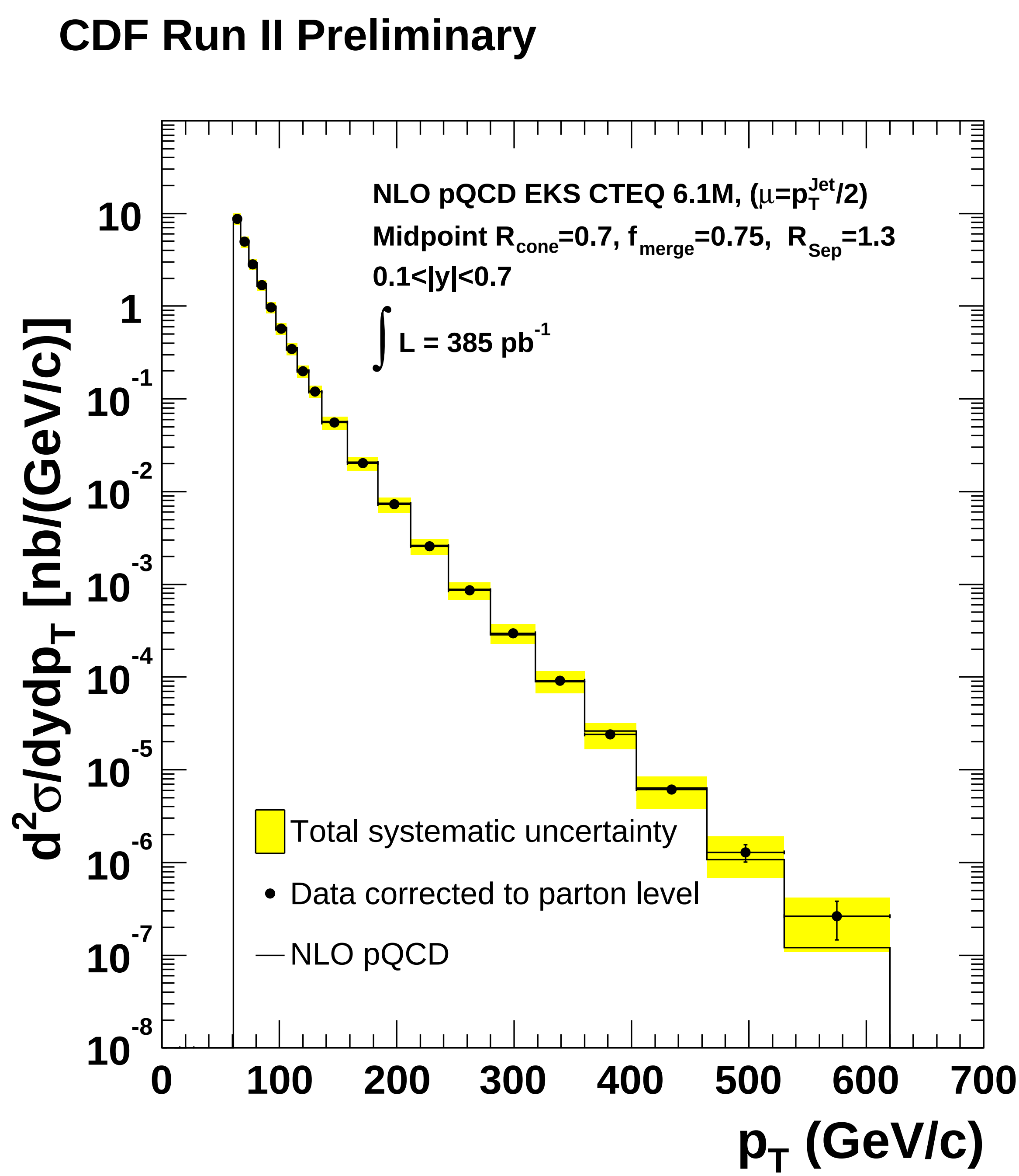
hep-ex/0509010

$F_2(x, Q^2)$ in ℓN interactions (ZEUS)

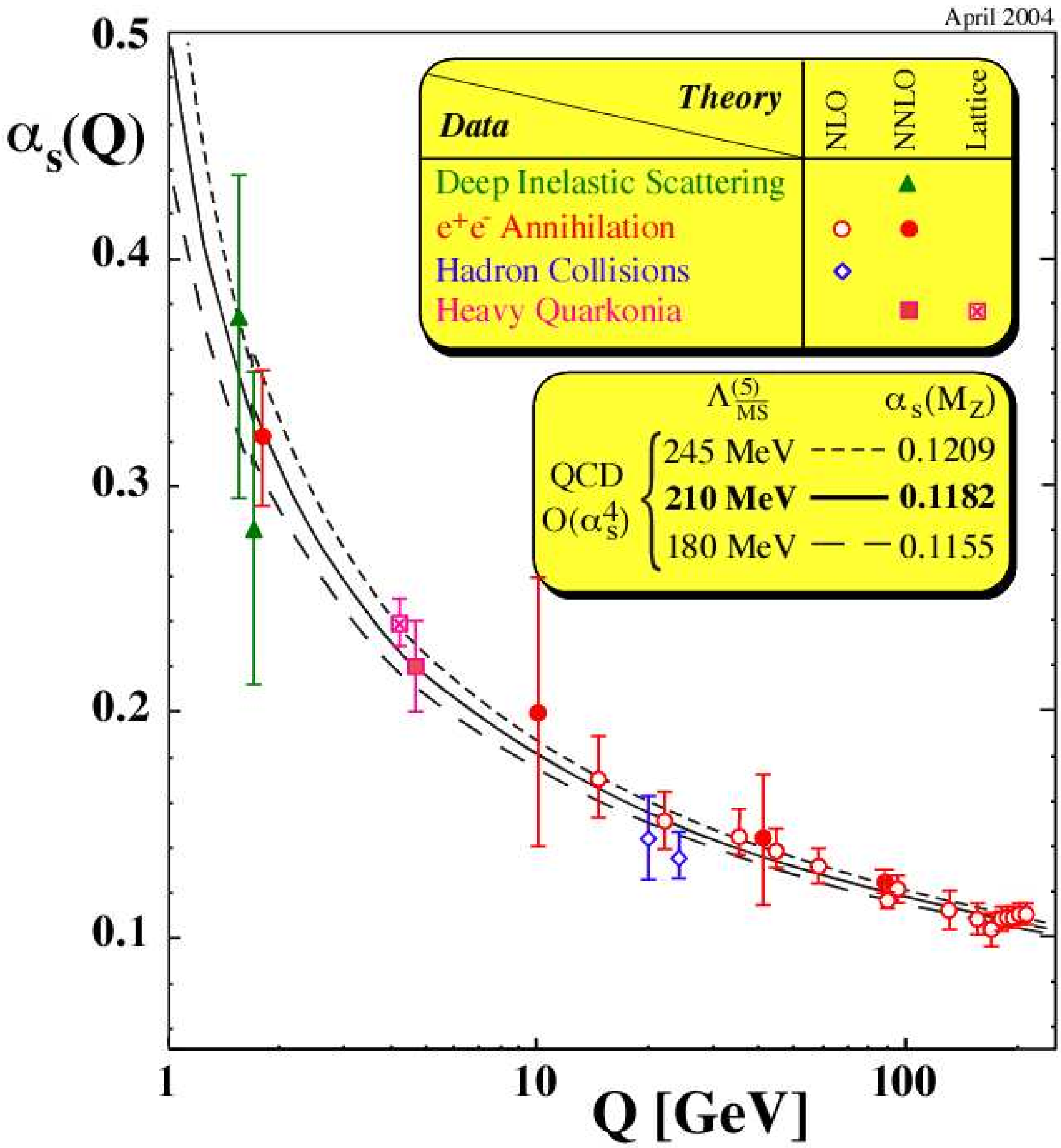


ZEUS, hep-ex/0208023.

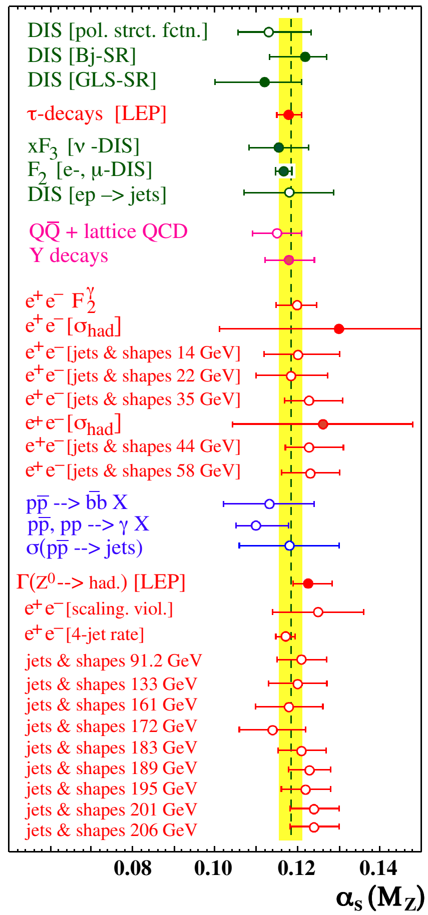
Inclusive jet cross section at $\sqrt{s} = 1.96$ TeV (CDF-II)



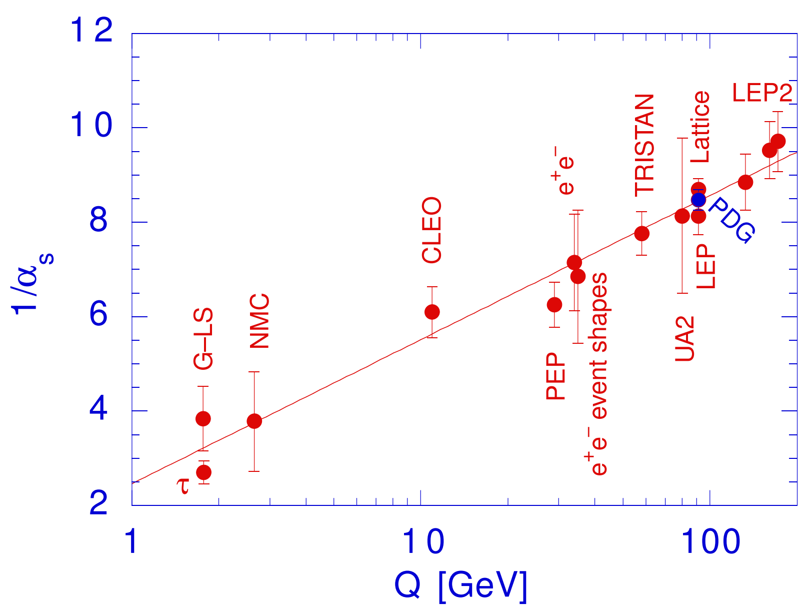
Running $\alpha_s(Q)$



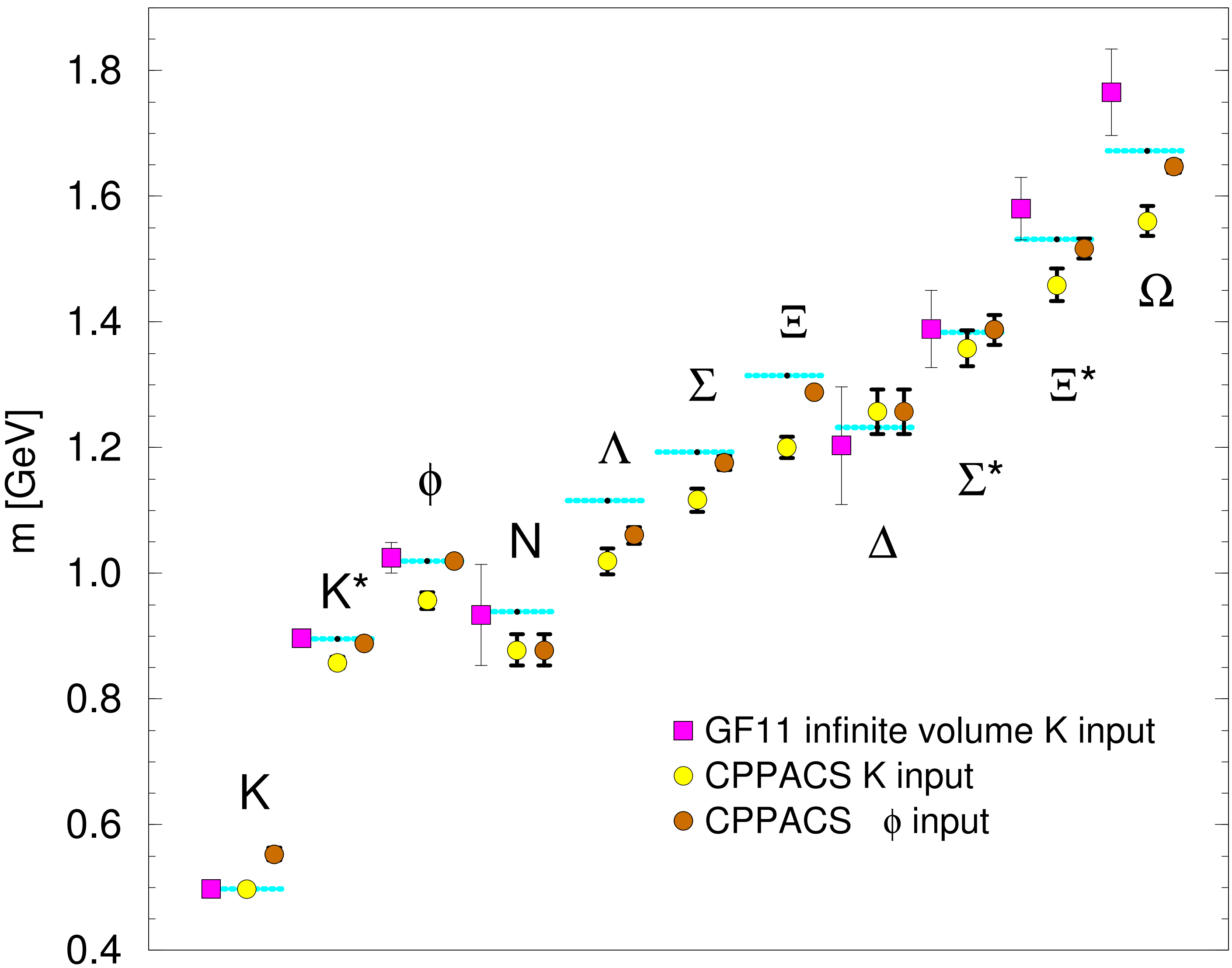
Comprehensive survey: W. de Boer, hep-ex/0407021



hep-ex/0407021



Quenched hadron spectrum



S. Aoki, *et al.* (CP–PACS), *Phys. Rev. Lett.* **84**, 238 (2000)

(No dynamical fermions)

$2+1$ dynamical flavors: A. Ukawa, Beijing QCD 2005,

http://www.phy.pku.edu.cn/~qcd/transparency/20-plen-m/Ukawa.pdf.

The Origins of Mass

(masses of nuclei "understood")

$p, [\pi], \rho$ understood: QCD

confinement energy is the source

"Mass without mass"

Wilczek, *Phys. Today* (November 1999)

We understand the visible mass of the Universe

... without the Higgs mechanism

W, Z electroweak symmetry breaking

$M_W^2 = \frac{1}{2}g^2v^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W$

$M_Z^2 = M_W^2/\cos^2\theta_W$

$q, \ell^{\mp}$ EWSB + Yukawa couplings

ν_ℓ EWSB + Yukawa couplings; new physics?

All fermion masses $\Leftrightarrow$ physics beyond standard model

H ?? fifth force ??