The Coming Revolutions in Particle Physics

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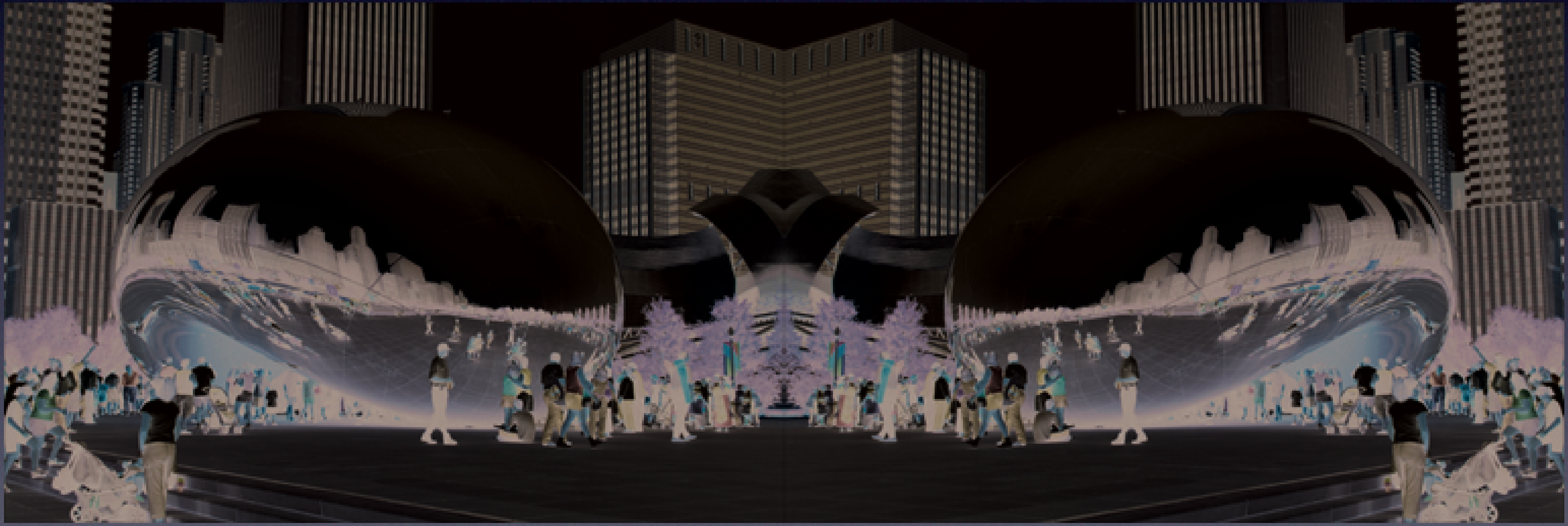


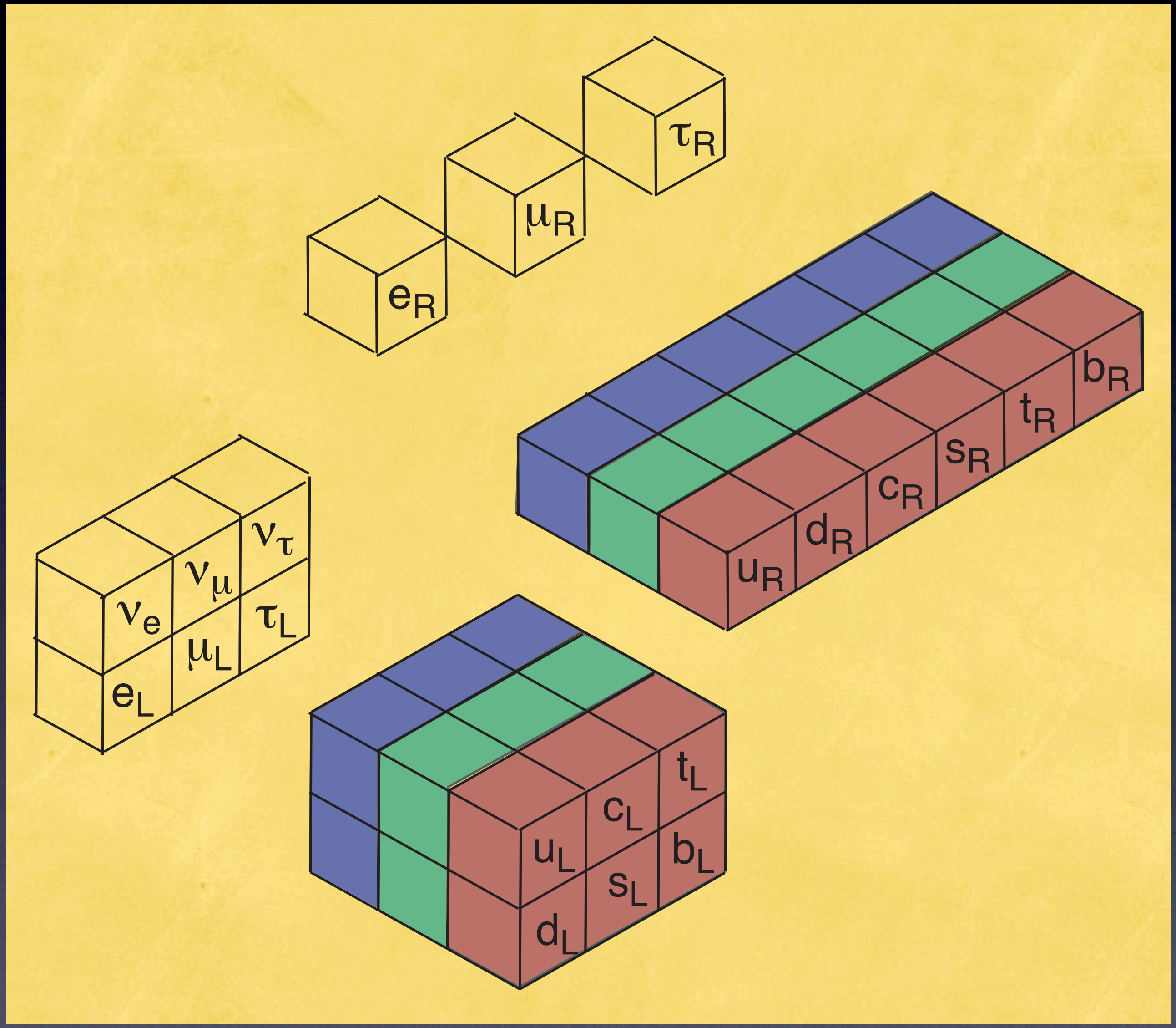
Tsinghua University Physics Colloquium · 9 November 2006

A Decade of Discovery Past

- ▷ Electroweak theory $\longrightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, $\ldots$]
- ▷ 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}]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate 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]

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) quarks and leptons



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

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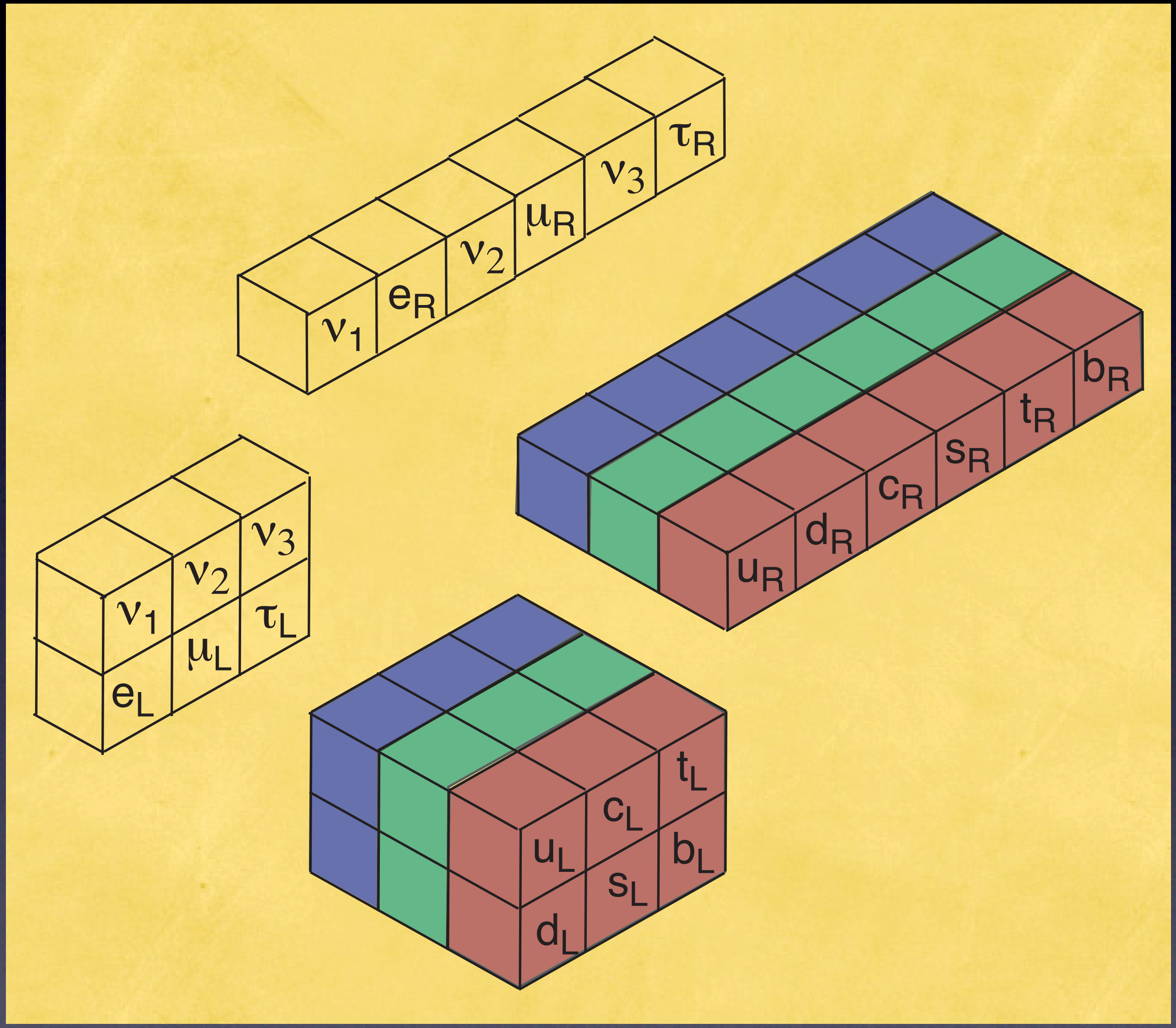


Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

The World's Most Powerful Microscopes

nanonanophysics

Fermilab's Tevatron Collider & Detectors

900-GeV protons: $c - 586$ km/h

980-GeV protons: $c - 495$ km/h

Improvement: 91 km/h!

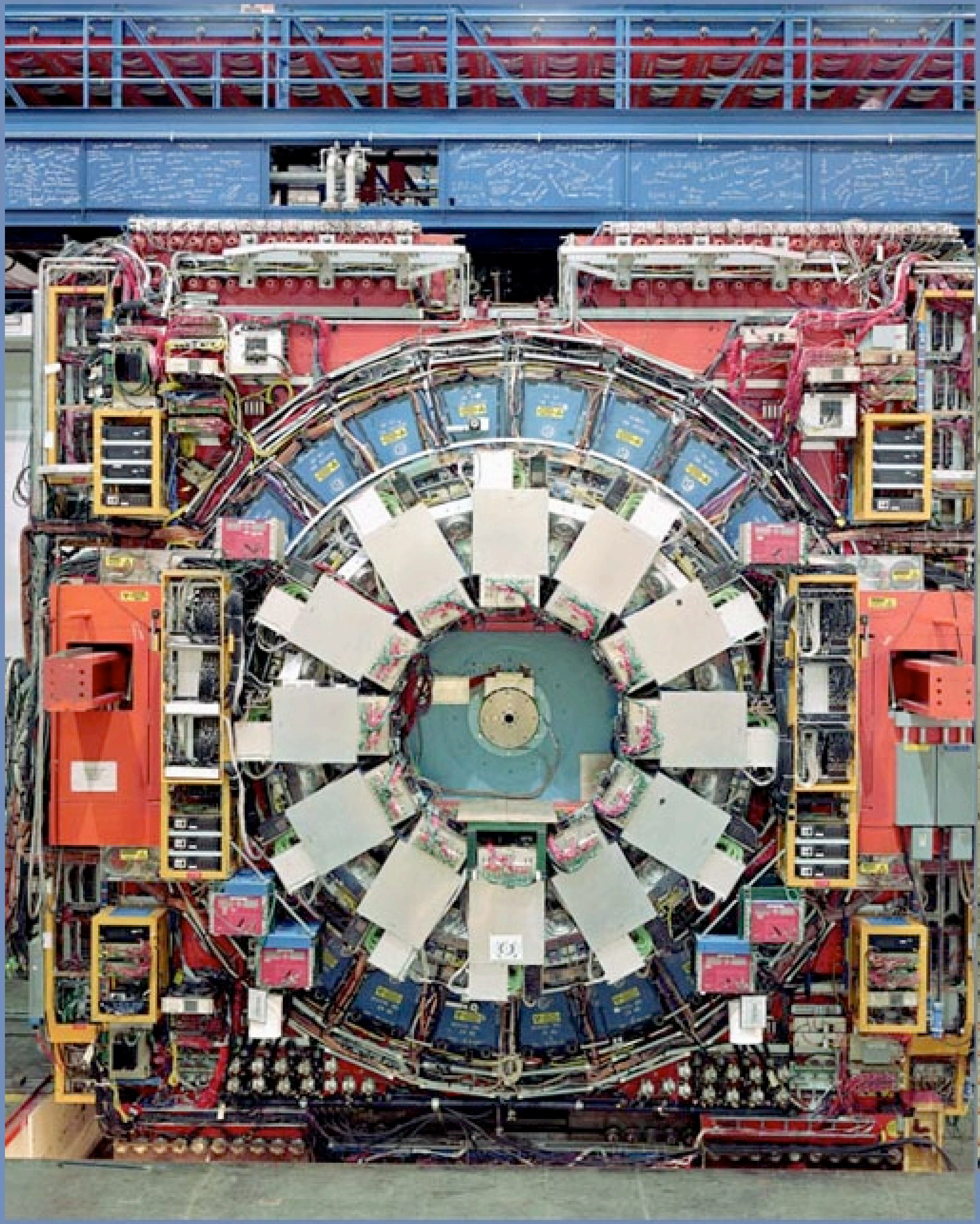
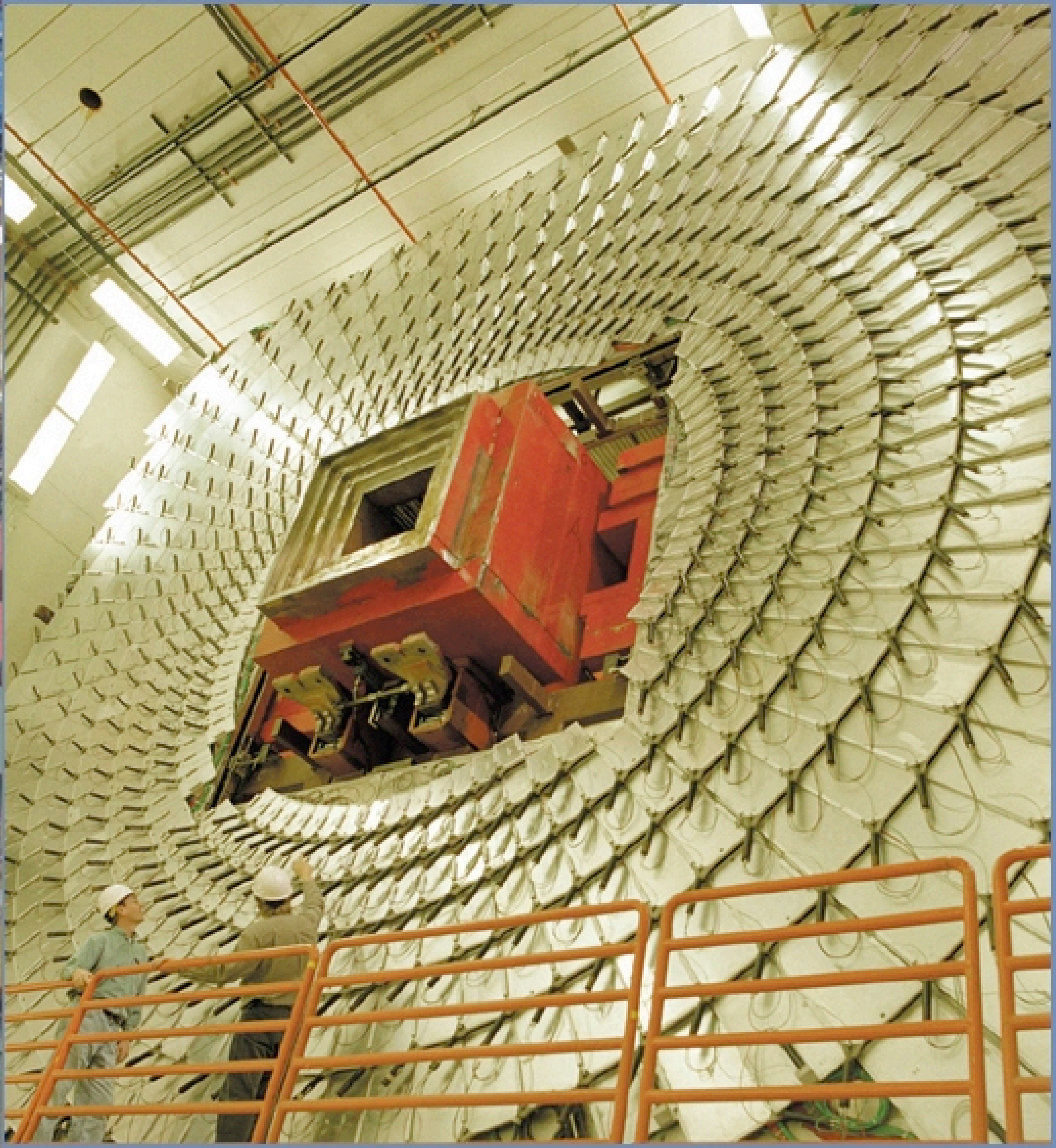
Protons, antiprotons pass my window 45 000 times / second

achieved

. . . working toward $20 \times$ increase in luminosity

$\Rightarrow 10^7$ collisions / second

CERN's Large Hadron Collider, 7-TeV protons: $c - 10$ km/h

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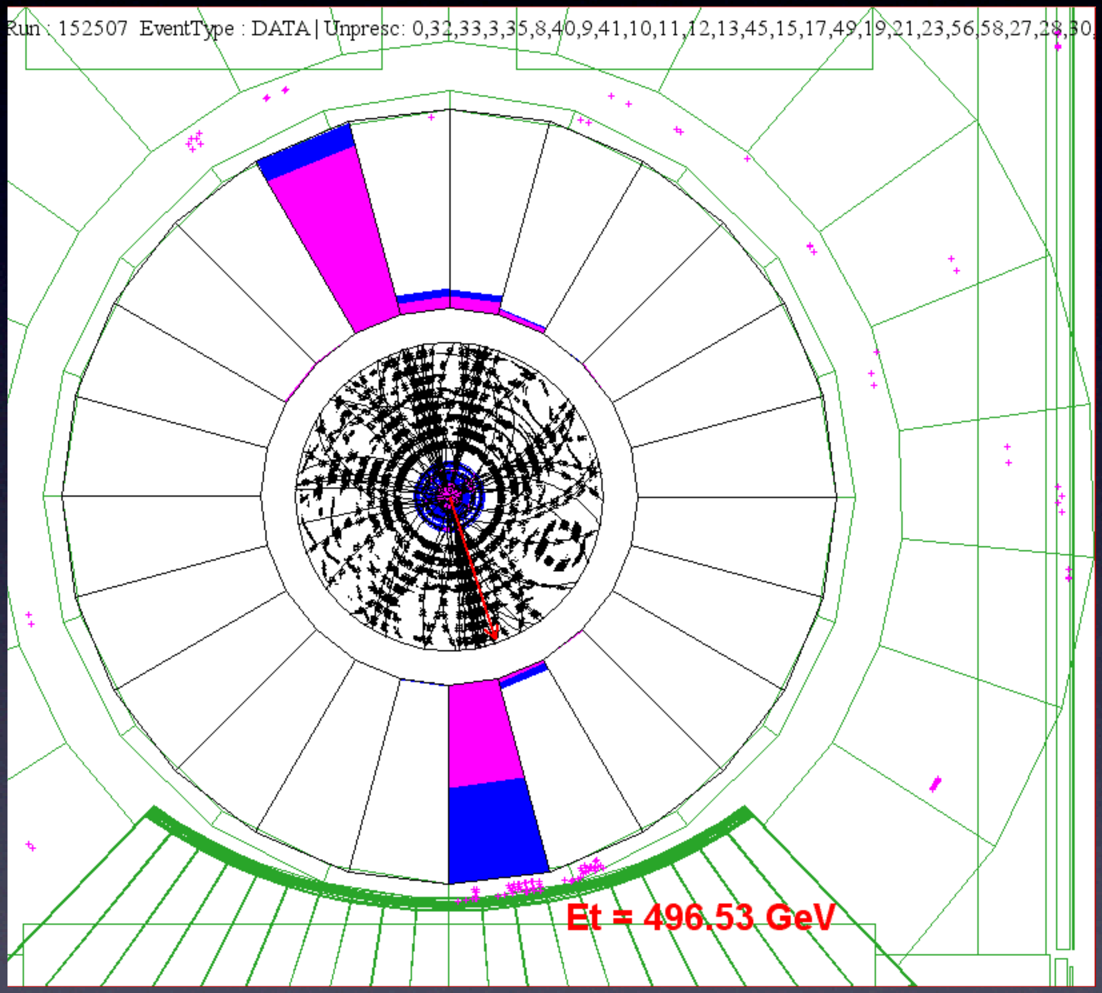
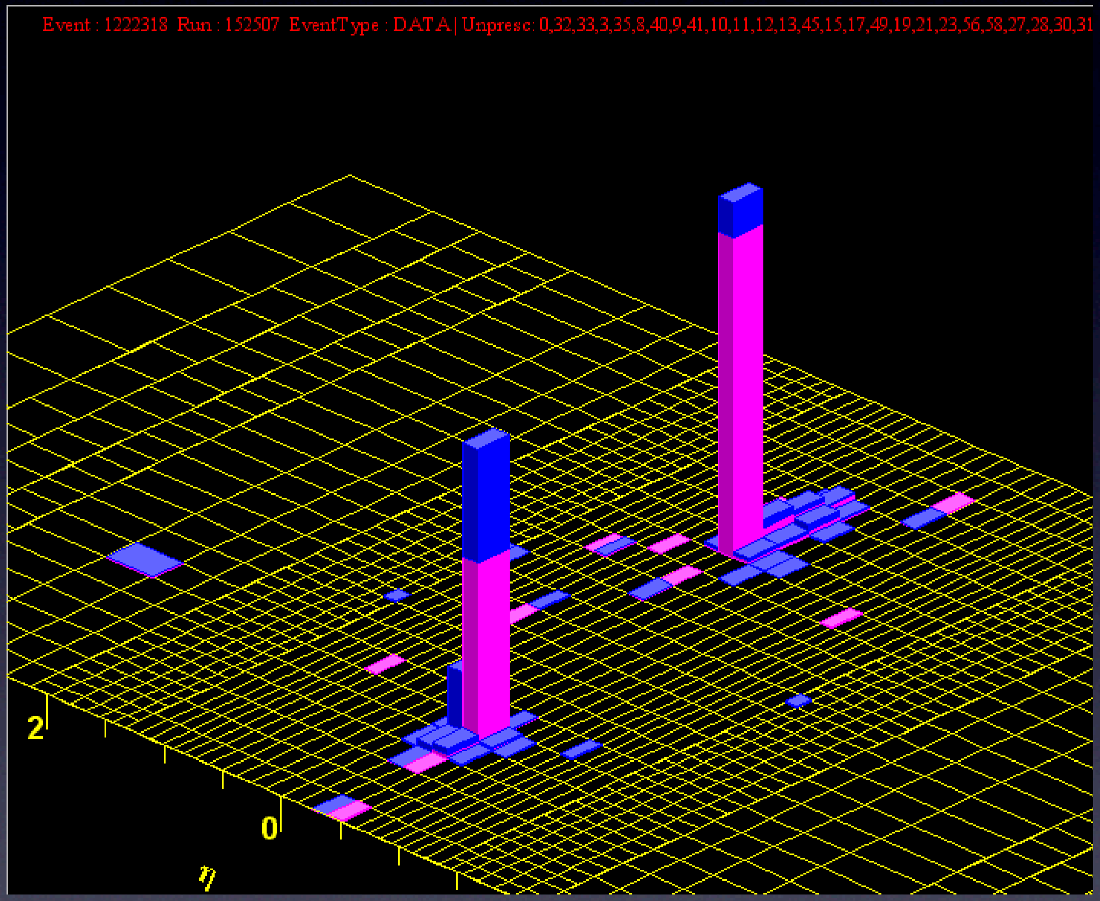
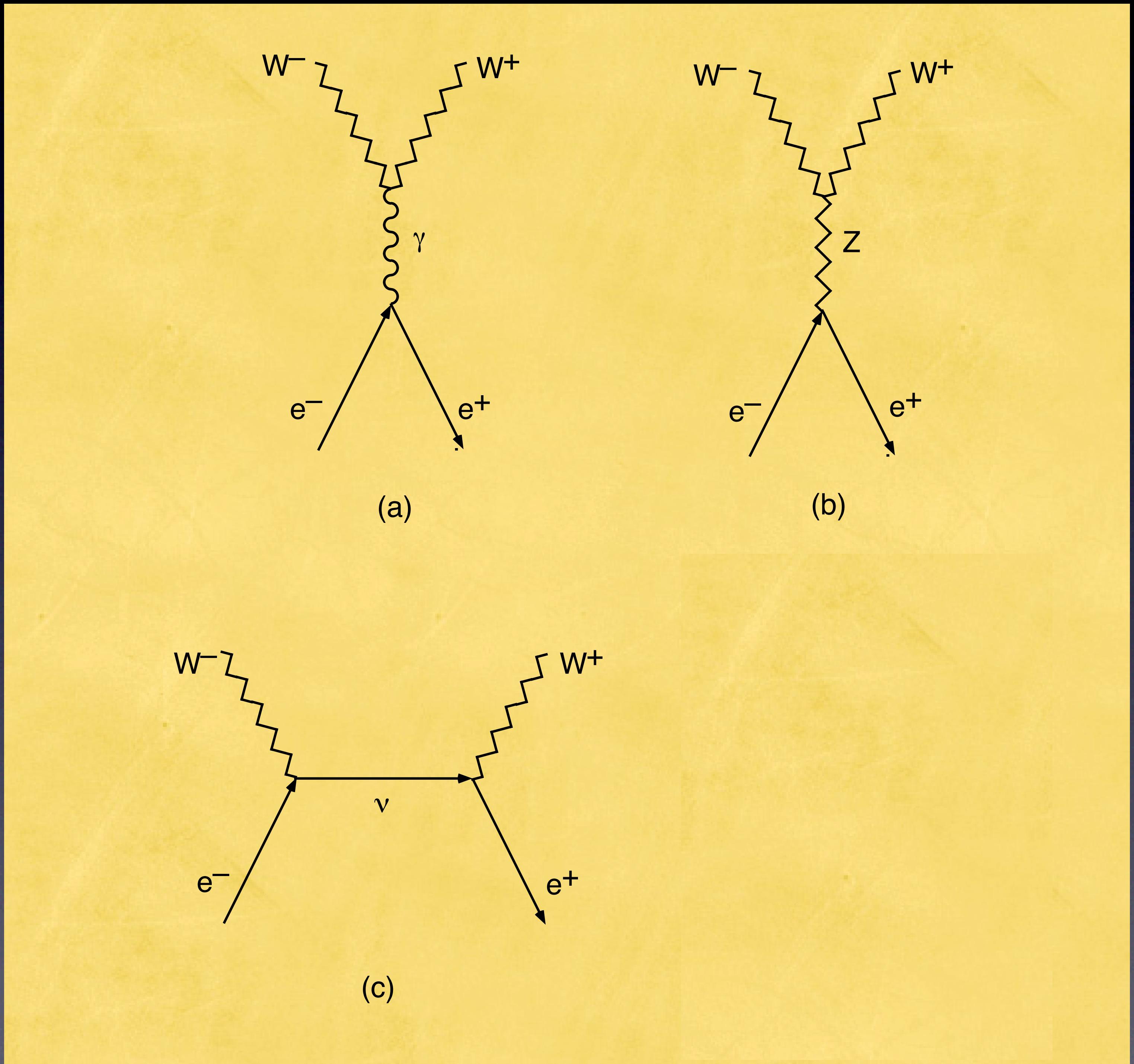




CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

Gauge symmetry (group-theory structure) tested in

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



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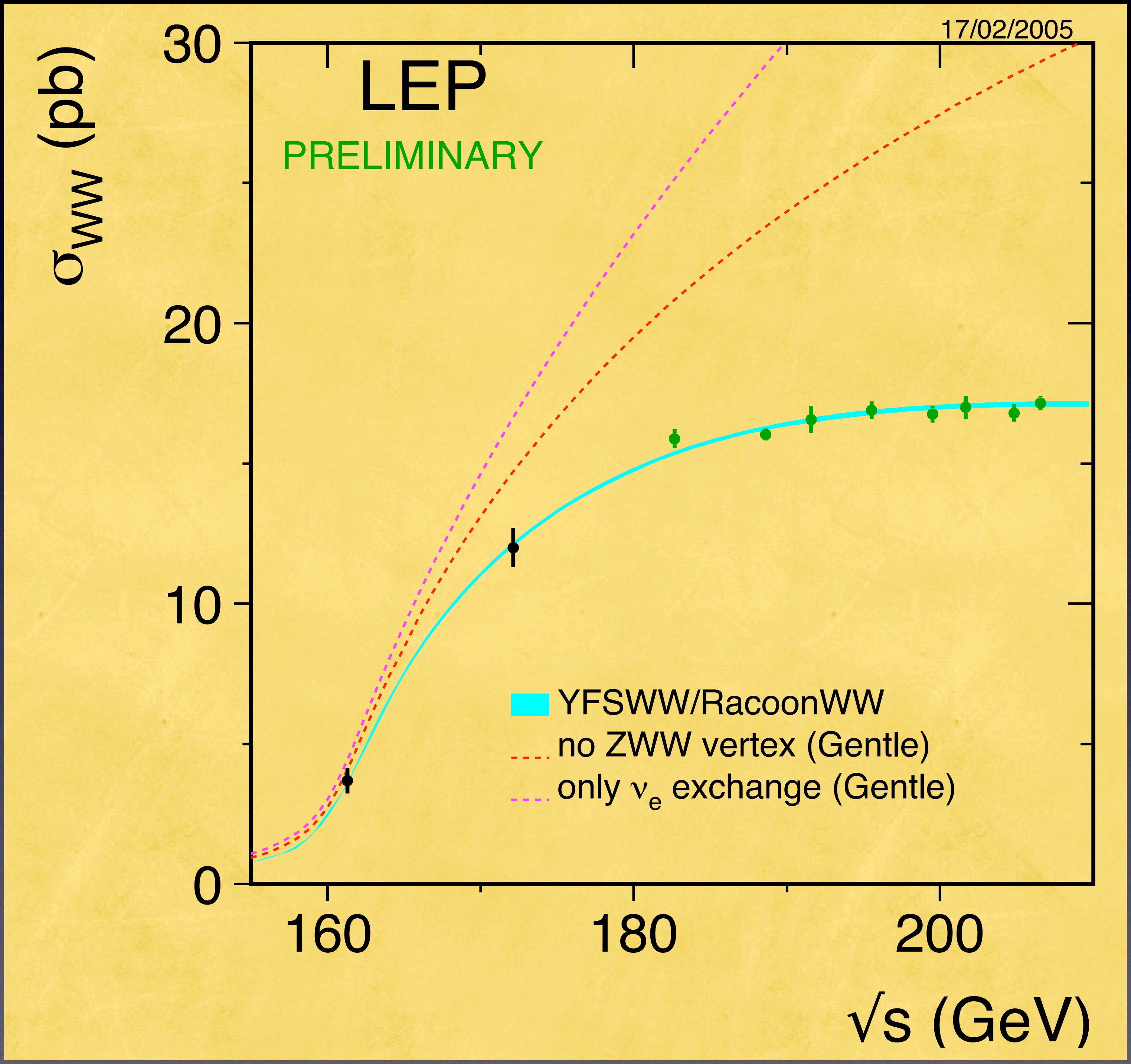


The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

$W_L^+ W_L^-, Z_L^0 Z_L^0, HH, HZ_L^0$ satisfy *s*-wave unitarity,

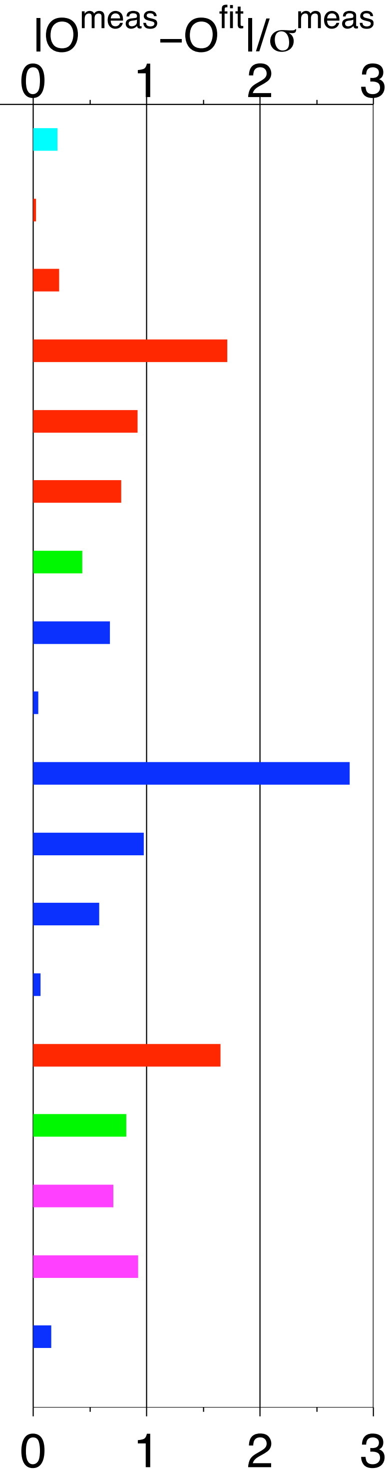
provided $$M_H \leq \left(8\pi\sqrt{2}/3G_F\right)^{1/2} = 1 \text{ TeV}$$

- 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

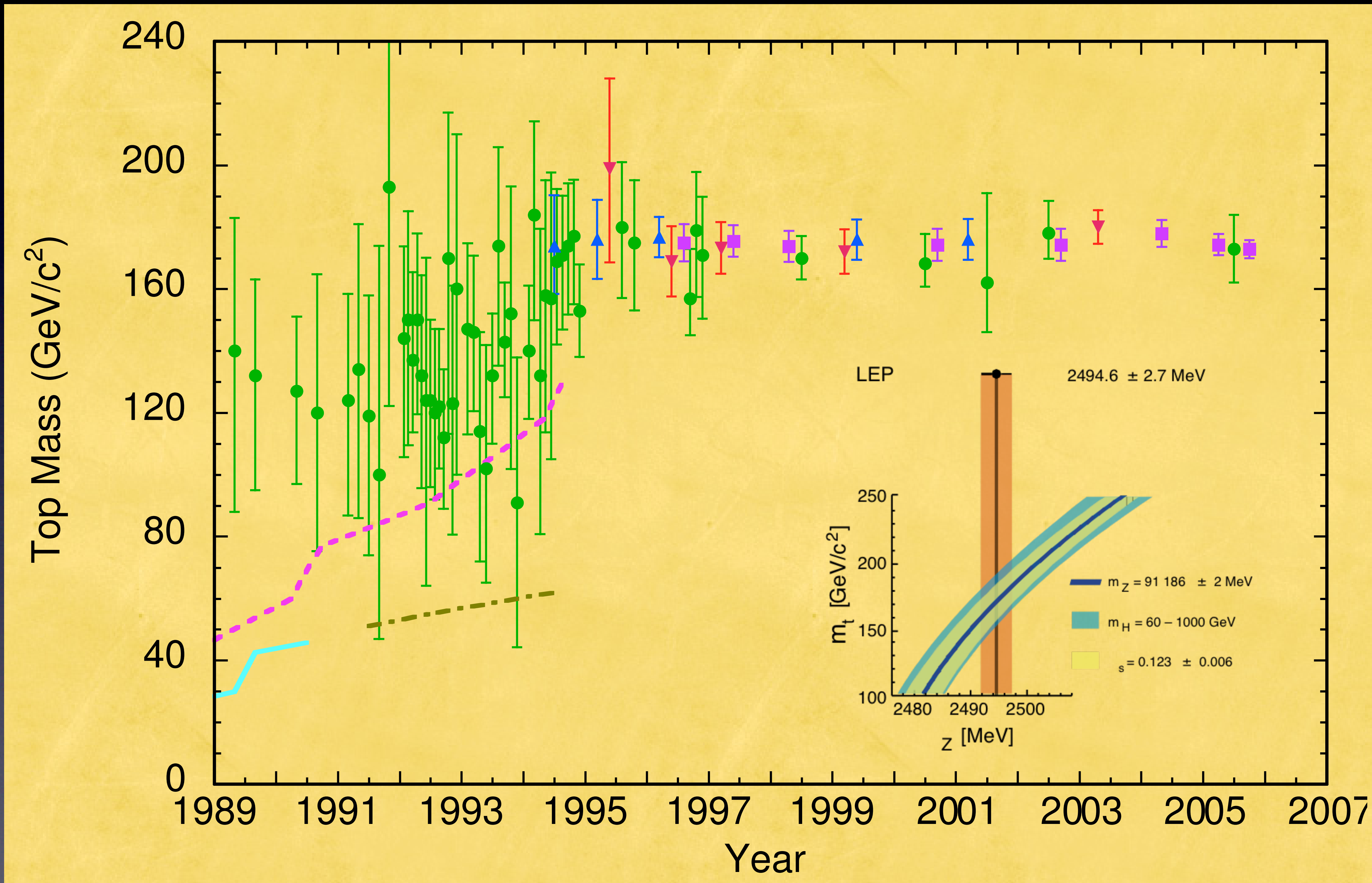
Precision Measurements Test the Theory …

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



LEP EWWG

… and determine unknown parameters



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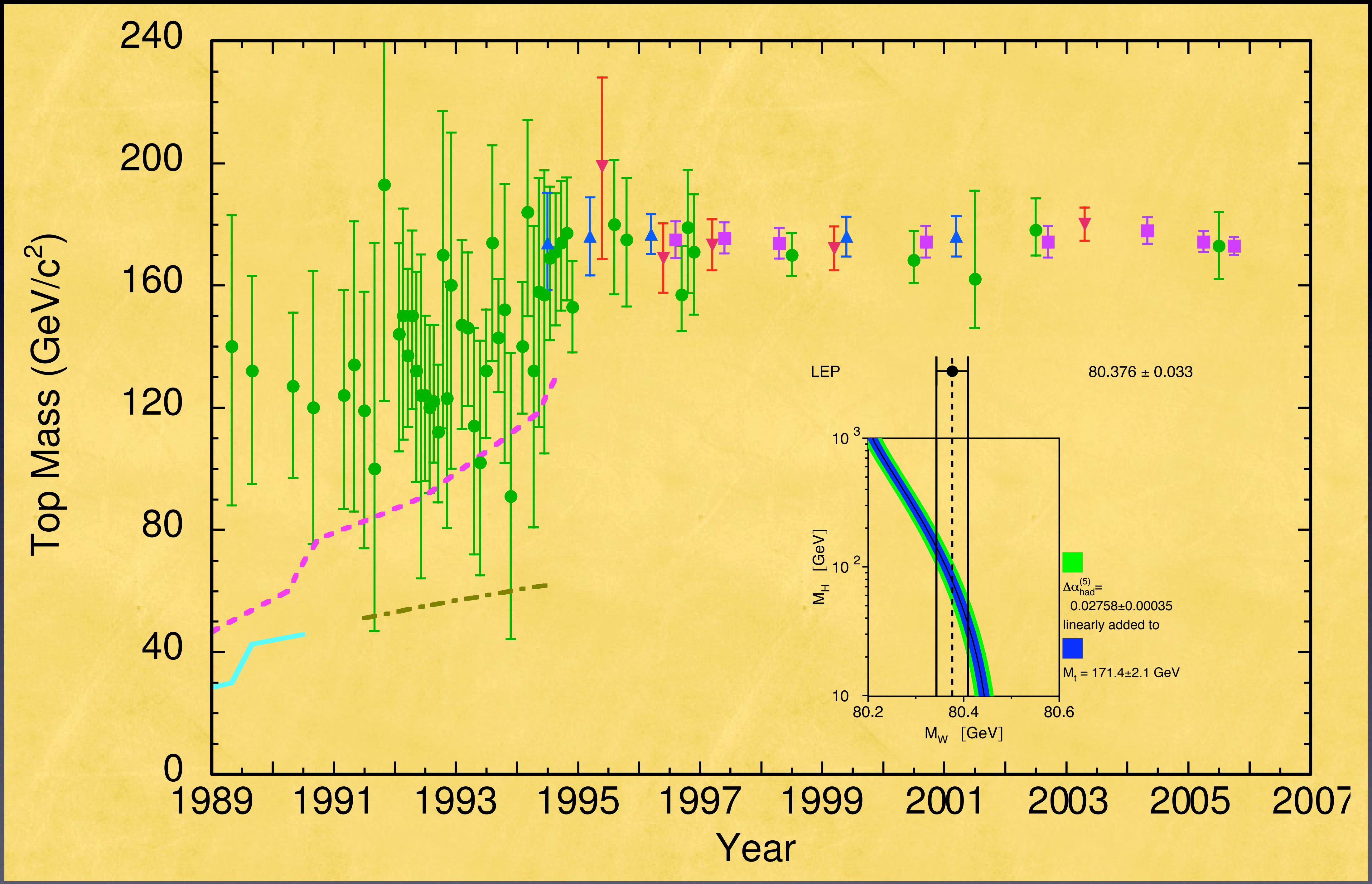


Revolution:

Understanding the Everyday

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

Imagine a world without a Higgs mechanism

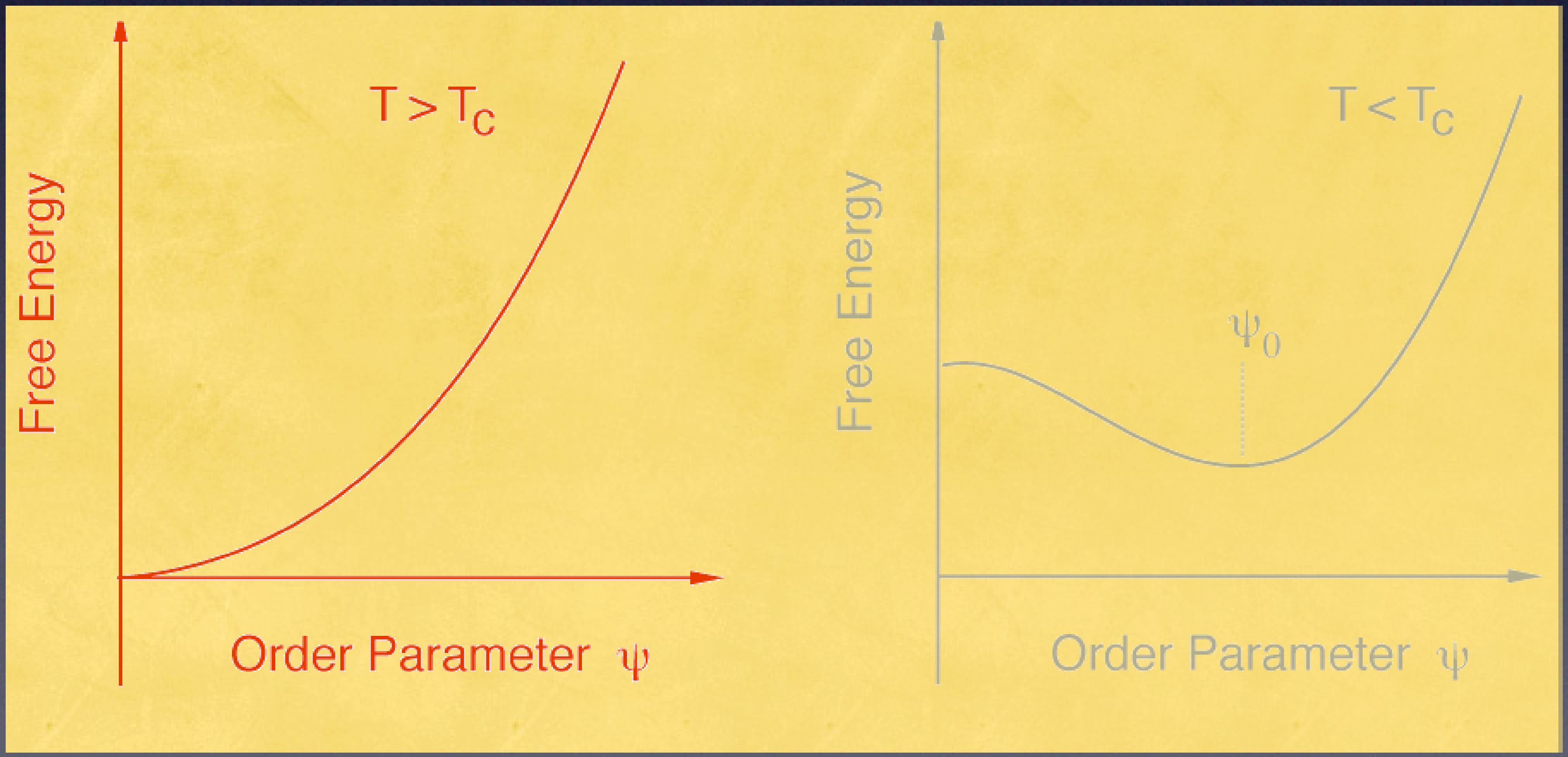
If electroweak symmetry were not hidden . . .

$\triangleright$ Quarks and leptons would remain massless
$\triangleright$ QCD would confine them into color-singlet hadrons
$\triangleright$ *Nucleon mass would be little changed,*
$\triangleright$ QCD breaks EW symmetry, gives $(1/2500\times$observed$)$ masses to W, Z, so weak-isospin force doesn't confine
$\triangleright$ Proton outweighs neutron: rapid β-decay $\Rightarrow$ lightest nucleus is one neutron; no hydrogen atom
$\triangleright$ (?) some light elements in BBN, but ∞ Bohr radius
$\triangleright$ No atoms (as we know them) means no chemistry, no stable composite structures like solids, liquids we know

. . . the character of the physical world would be profoundly changed

The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV …

We do not know the nature of the new force.



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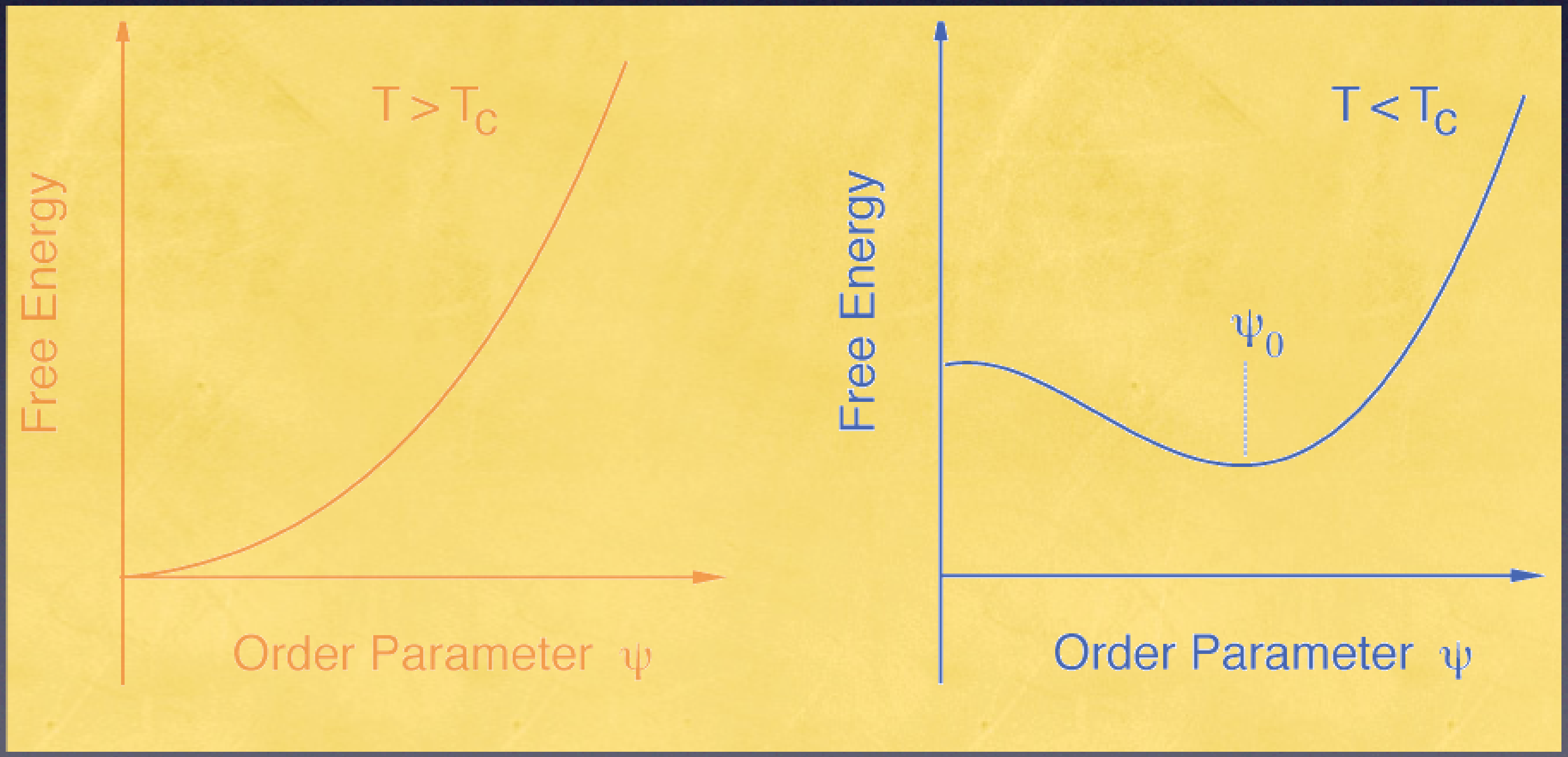


What is the nature of the mysterious new force that hides electroweak symmetry?

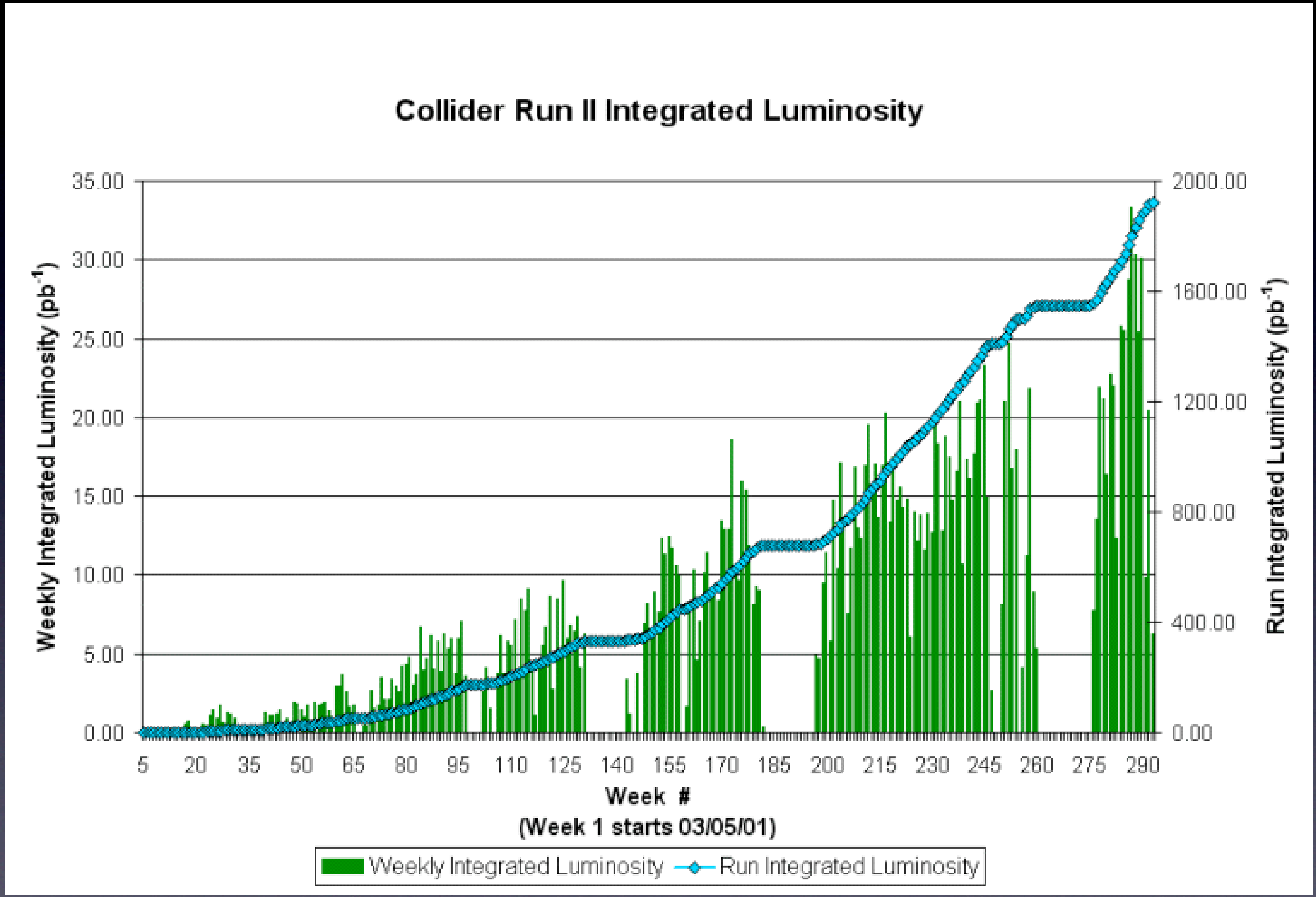
- ✶A force of a new character, based on interactions of an elementary scalar
- ✶A new gauge force, perhaps acting on undiscovered constituents
- ✶A residual force that emerges from strong dynamics among electroweak gauge bosons
- ✶An echo of extra spacetime dimensions

Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

- Is it there? How many?
- Verify $J^{PC} = 0^{++}$
- Does H generate mass for gauge bosons and for fermions?
- How does H interact with itself?

Finding the Higgs boson starts a new adventure!



Collider Run II Integrated Luminosity
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Weekly Integrated Luminosity (pb-1)
2000.00
1600.00
1200.00
800.00
400.00
0.00
Run Integrated Luminosity (pb-1)
5 20 35 50 65 80 95 110 125 140 155 170 185 200 215 230 245 260 275 290
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity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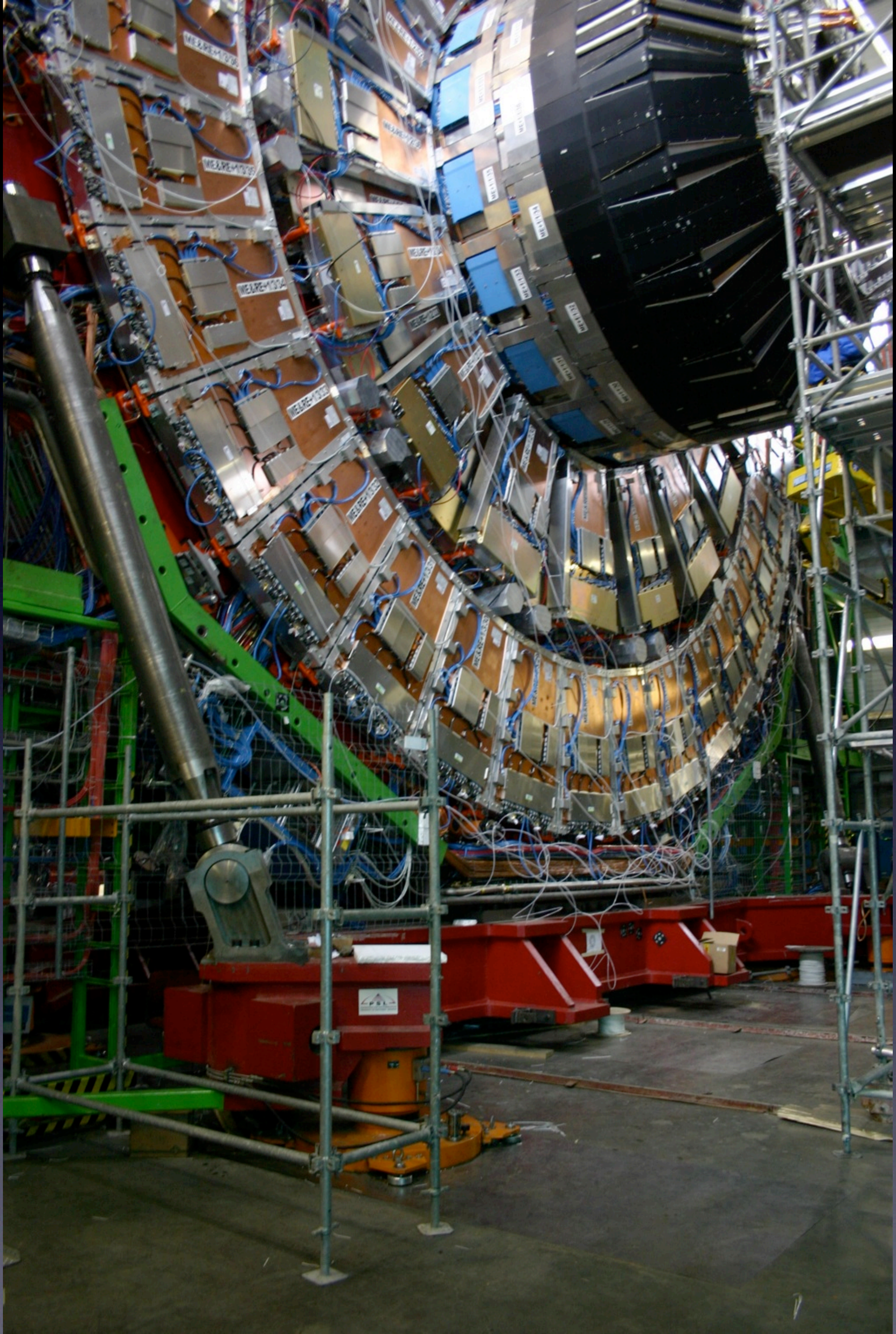

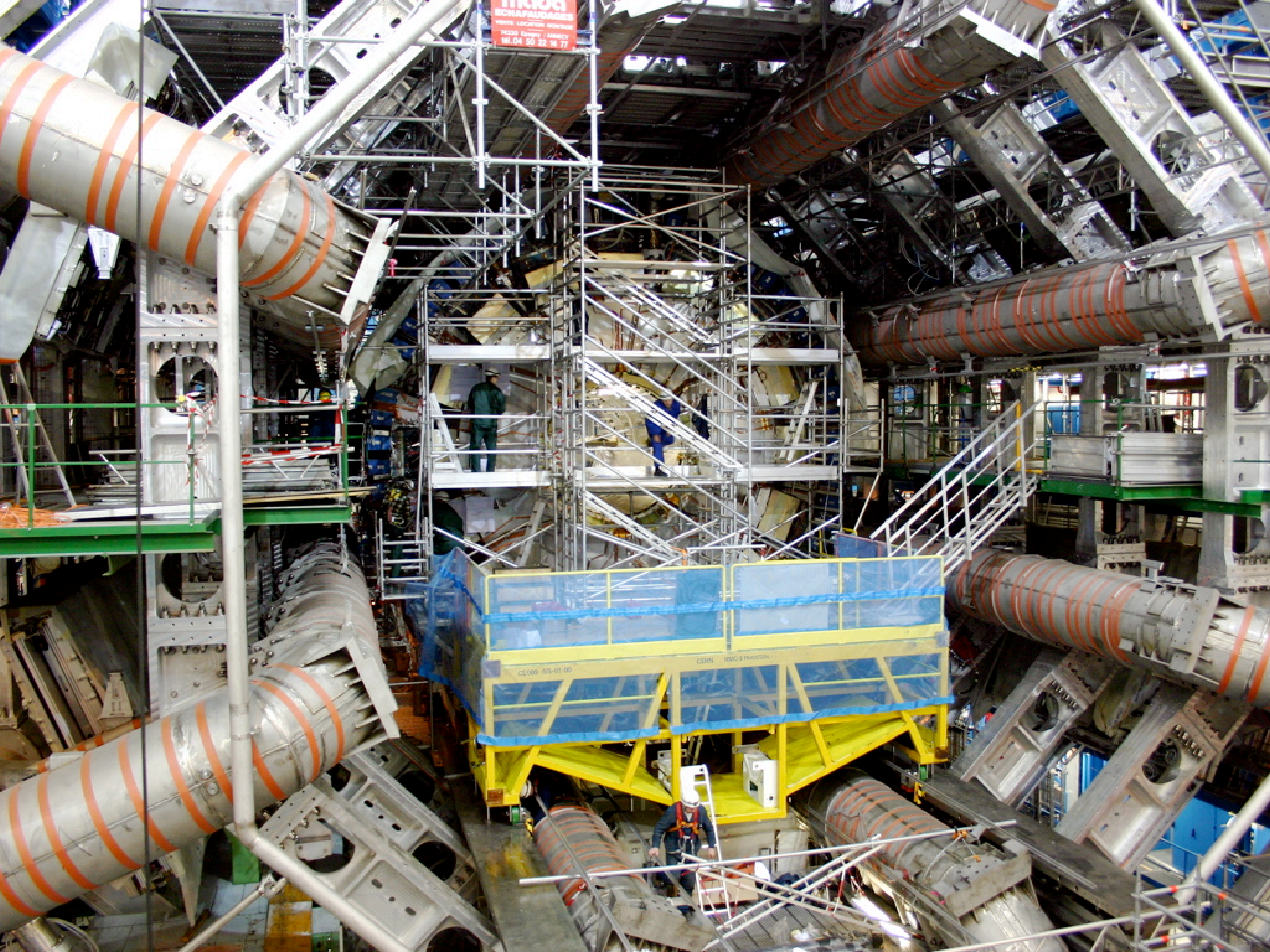
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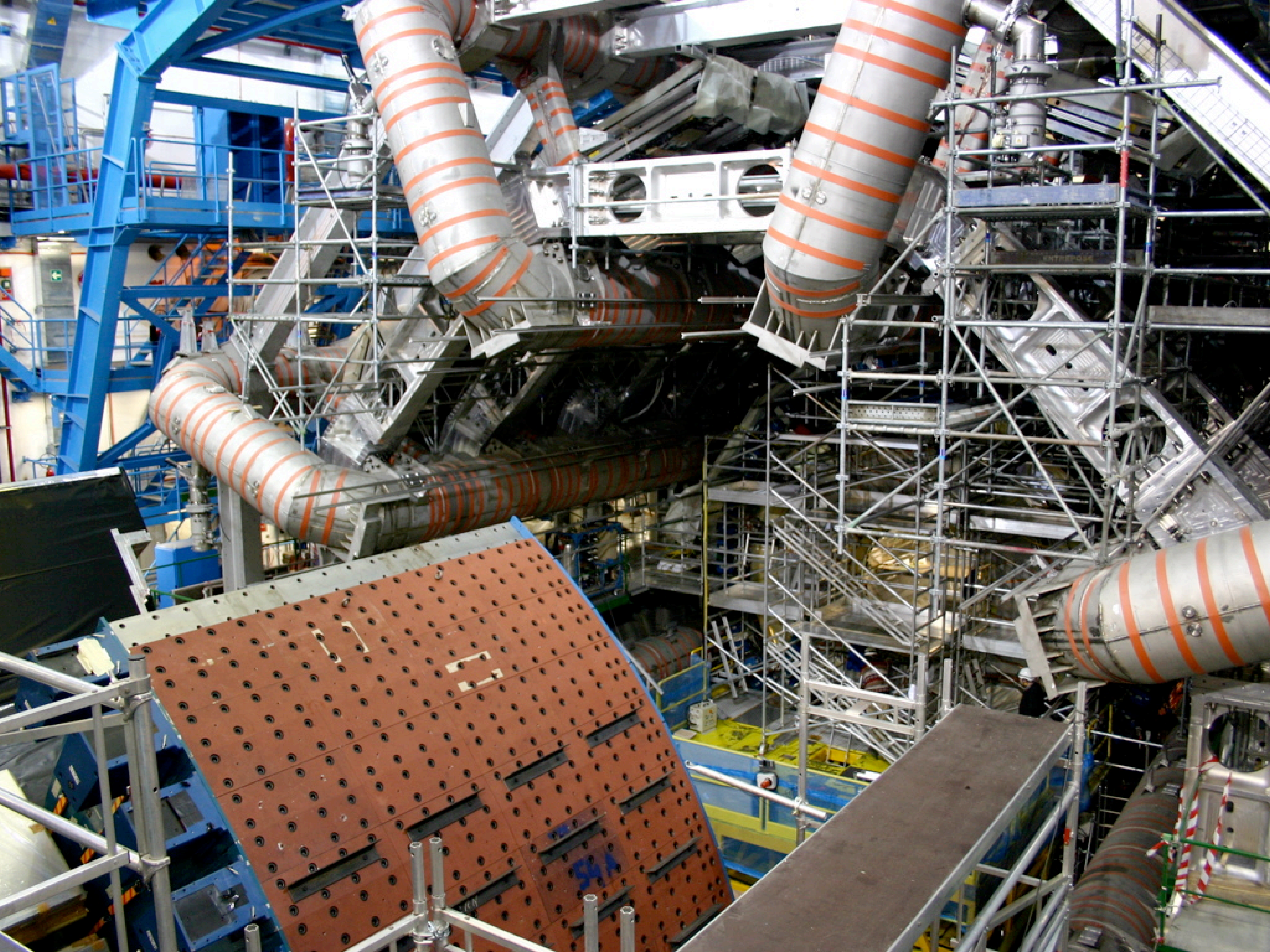


Revolution:

The Meaning of Identity

Varieties of matter

▷ What sets masses and mixings of quarks and leptons?

▷ What is $\mathcal{CP}$ violation trying to tell us?

▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the Universe.

All fermion masses and mixings mean new physics

▷ Will new kinds of matter help us to see the pattern?

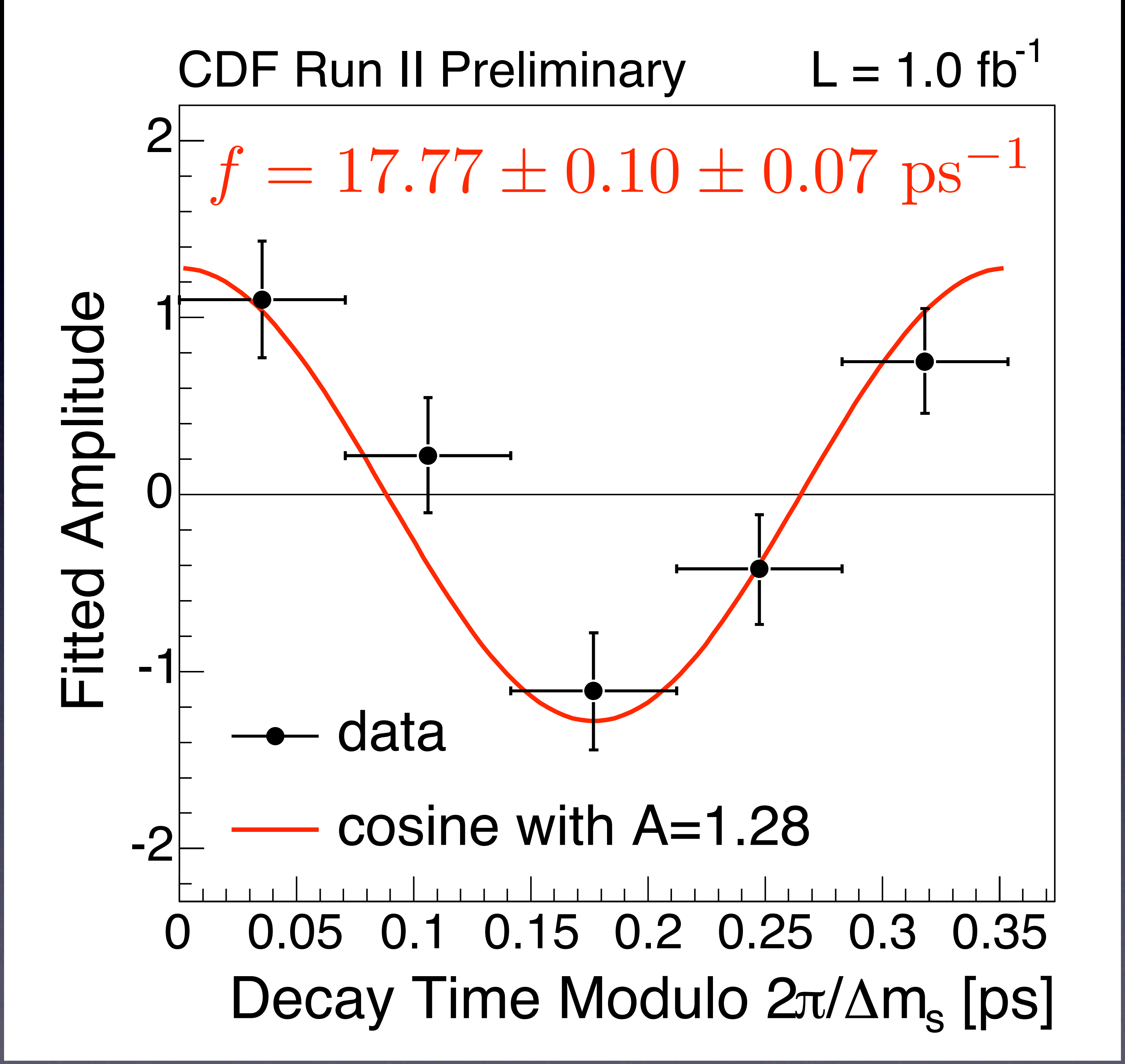
Parameters of the Standard Model

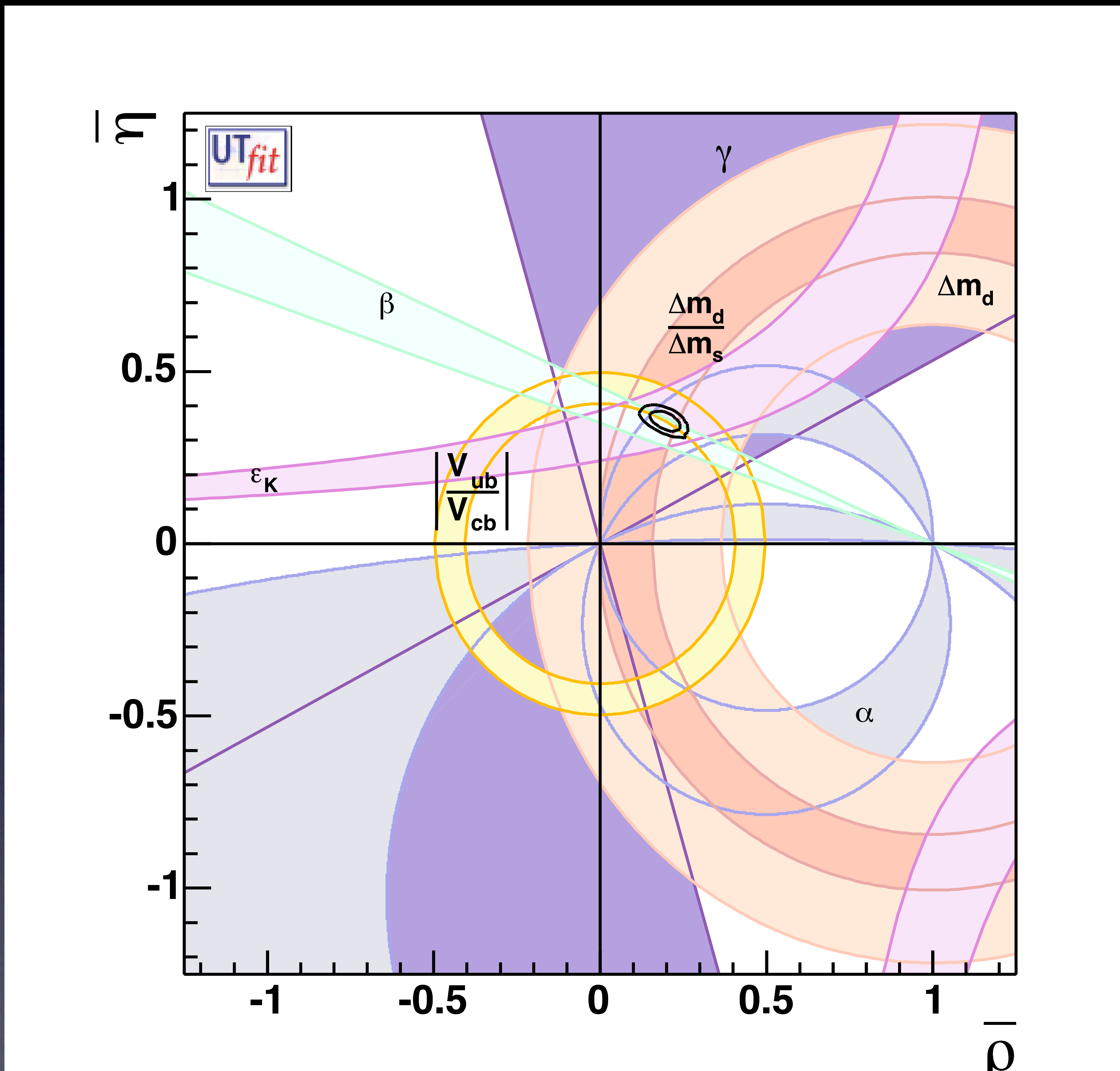
3	coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase (+ Majorana . . .)
26^+	arbitrary parameters

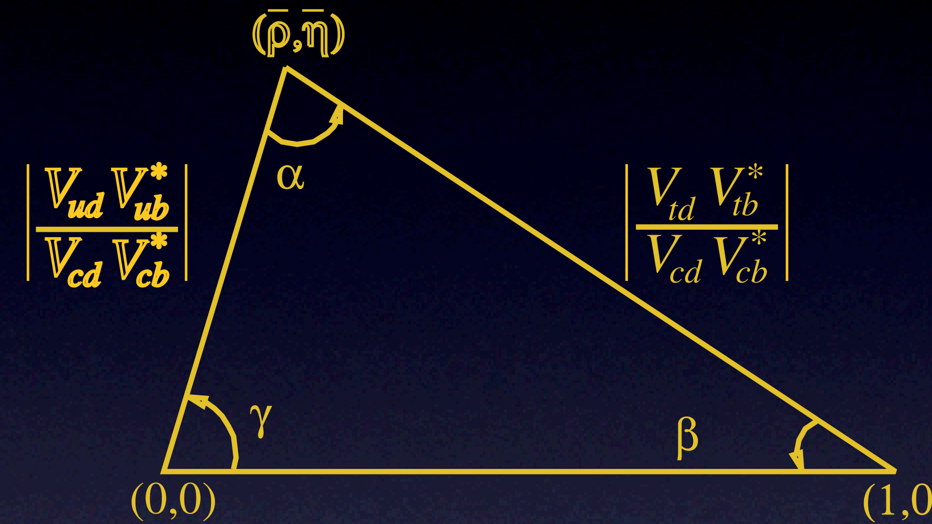
Flavor physics may be where we see, or diagnose, the break in the SM.

count not improved by strong, weak, EM unification

B_s - $\bar{B}_s$ Oscillations: $s\bar{b} \leftrightarrow \bar{s}b$




UTfit
γ
β
Δm_d
$\frac{\Delta m_d}{\Delta m_s}$
ε_K
$\left|\frac{V_{ub}}{V_{cb}}\right|$
α
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
$\bar{\eta}$
$\bar{\rho}$


$(\bar{\rho},\bar{\eta})$
α
γ
β
(0,0)
(1,0)
$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$
$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$

Revolution:

The Meaning of Identity

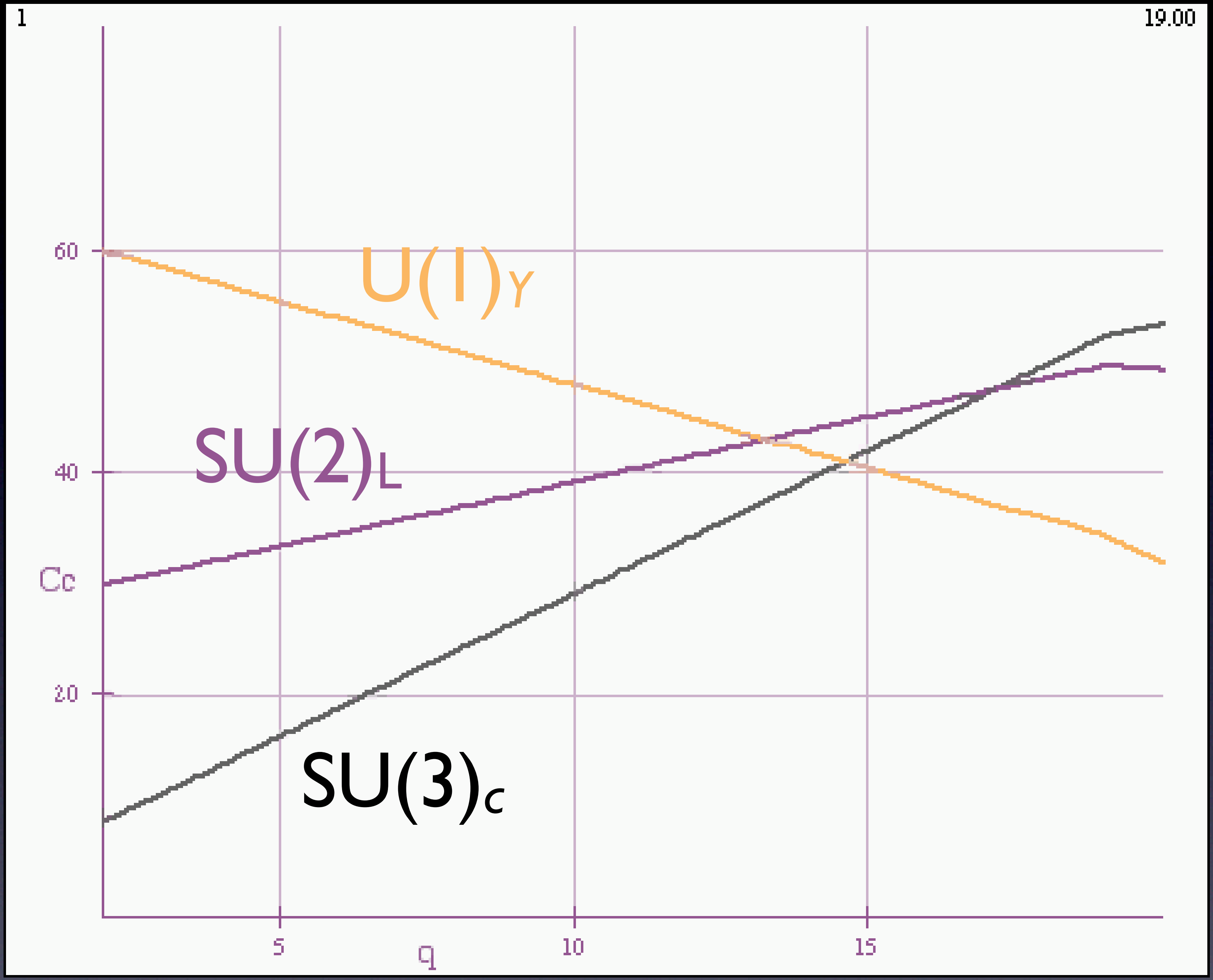
What makes
a top quark a top quark,
an electron an electron,
and a neutrino a neutrino?

A Revolution in the Making …

Revolution:

The Unity of Quarks & Leptons

- ▷ What do quarks and leptons have in common?
- ▷ Why are atoms so remarkably neutral?
- ▷ Which quarks go with which leptons?
- ▷ Quark-lepton extended family $\rightsquigarrow$ proton decay: SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
- ▷ Unified theories $\rightsquigarrow$ coupling constant unification
- ▷ Rational fermion mass pattern at high energy? (Masses run, too)



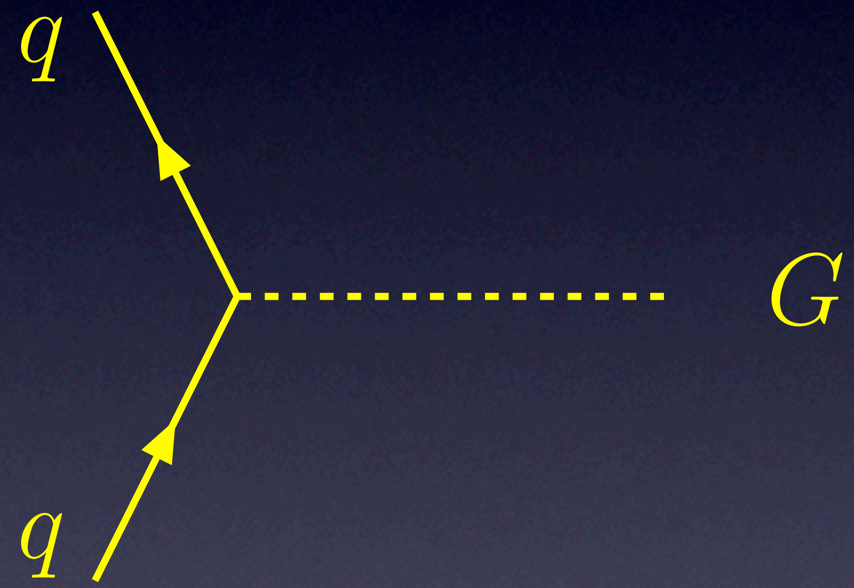
$1/\alpha$

$$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$$

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

$$G_{\text{Newton}} \ \textit{small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV } \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

Estimate $B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$

But gravity is not always negligible …

Higgs potential $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$

At the minimum, $V(\langle\varphi^\dagger\varphi\rangle) = \dfrac{\mu^2 v^2}{4} = -\dfrac{|\lambda|\,v^4}{4} < 0.$

Identify $M_H^2 = -2\mu^2$

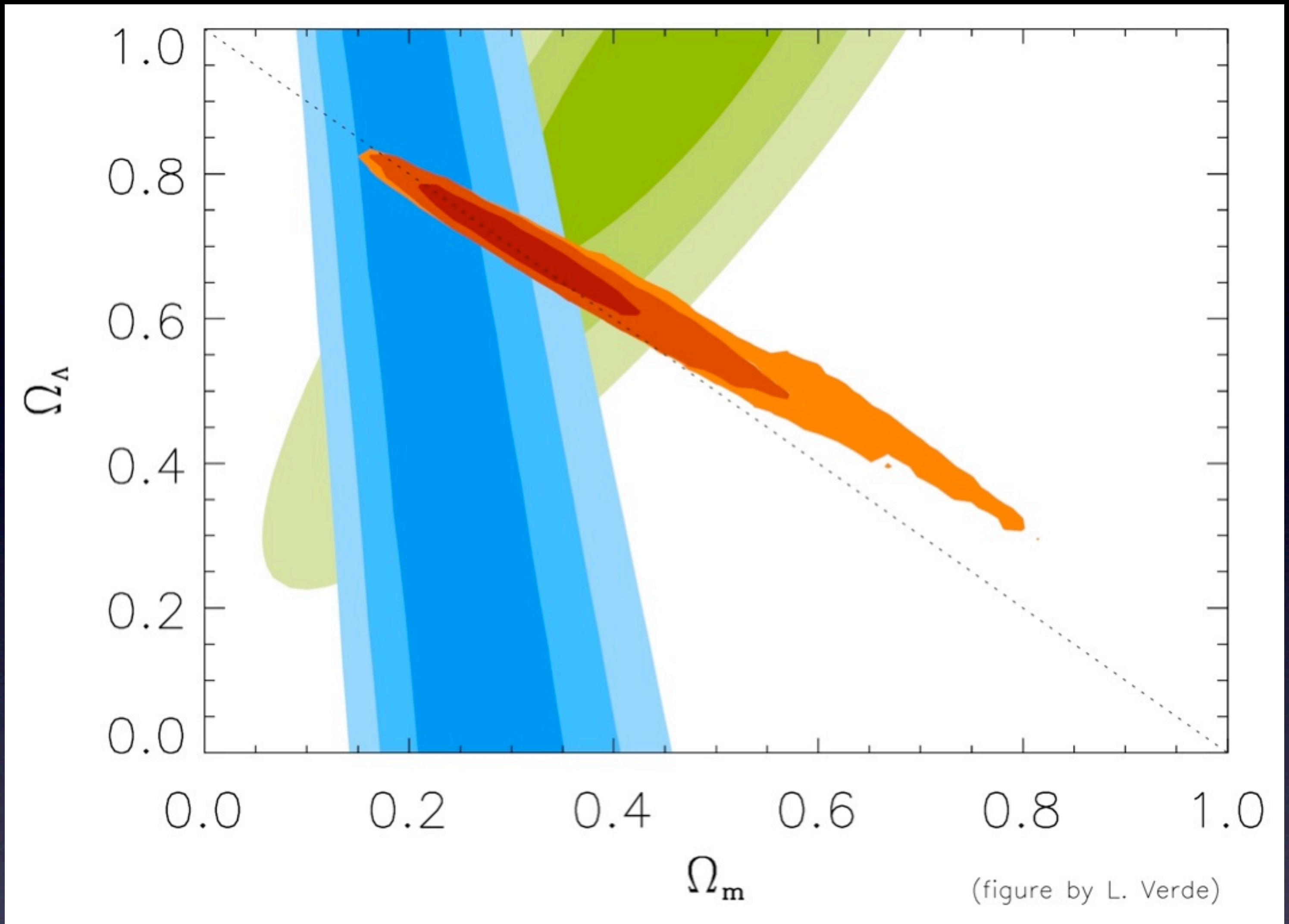
$V \neq 0$ contributes position-independent vacuum energy density

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

Observed vacuum energy density $\varrho_{\text{vac}} \leq 10^{-46}\ \text{GeV}^4$

Mismatch by 54 orders of magnitude

Evidence that vacuum energy is present …



recasts old problem, gives us properties to measure

A chronic dull headache for thirty years …

Why is empty space so nearly massless?

How to separate EW, higher scales?

Traditional: change electroweak theory to understand why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model

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

- composite Higgs boson
- technicolor / topcolor
- supersymmetry
- …

Newer approach: ask why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale

Revolution:

A New Conception of Spacetime

▷ Could there be more space dimensions than we have perceived?

▷ What is their size? Their shape?

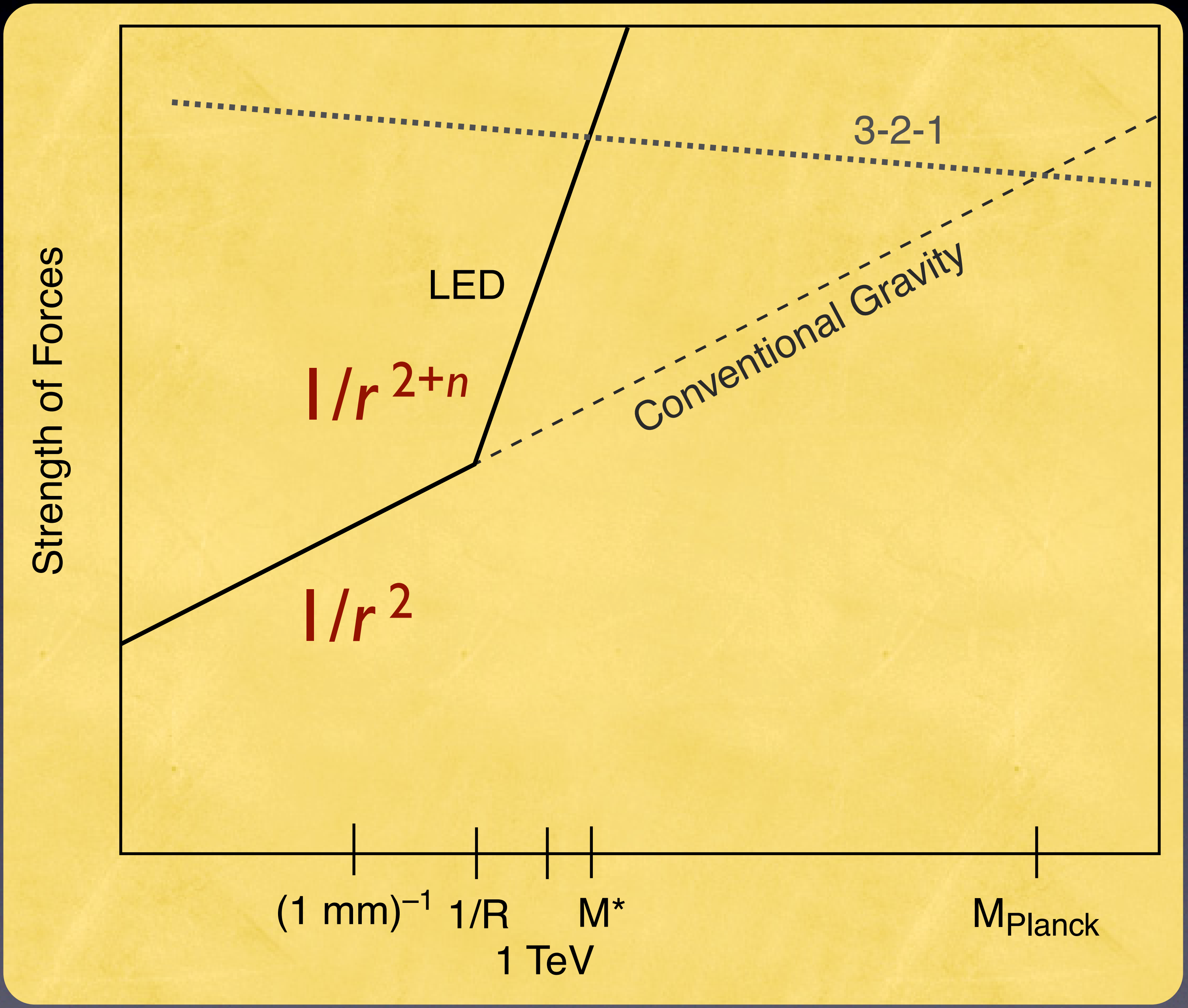
▷ How do they influence the world?

▷ How can we map them?

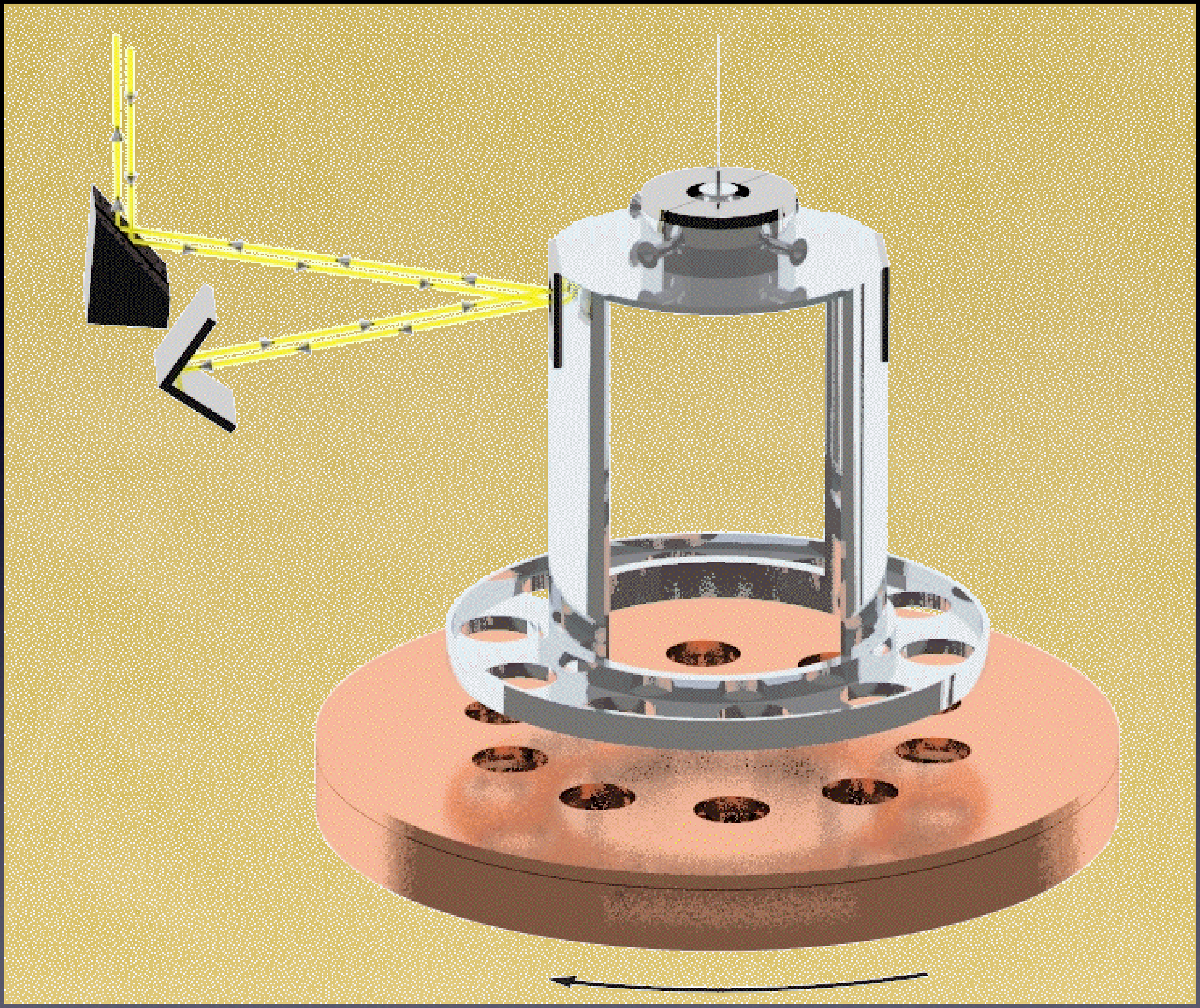
string theory needs 9 or 10

Suppose at scale R … gravity propagates in 4+n dimensions

Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ M^* : gravity's true scale

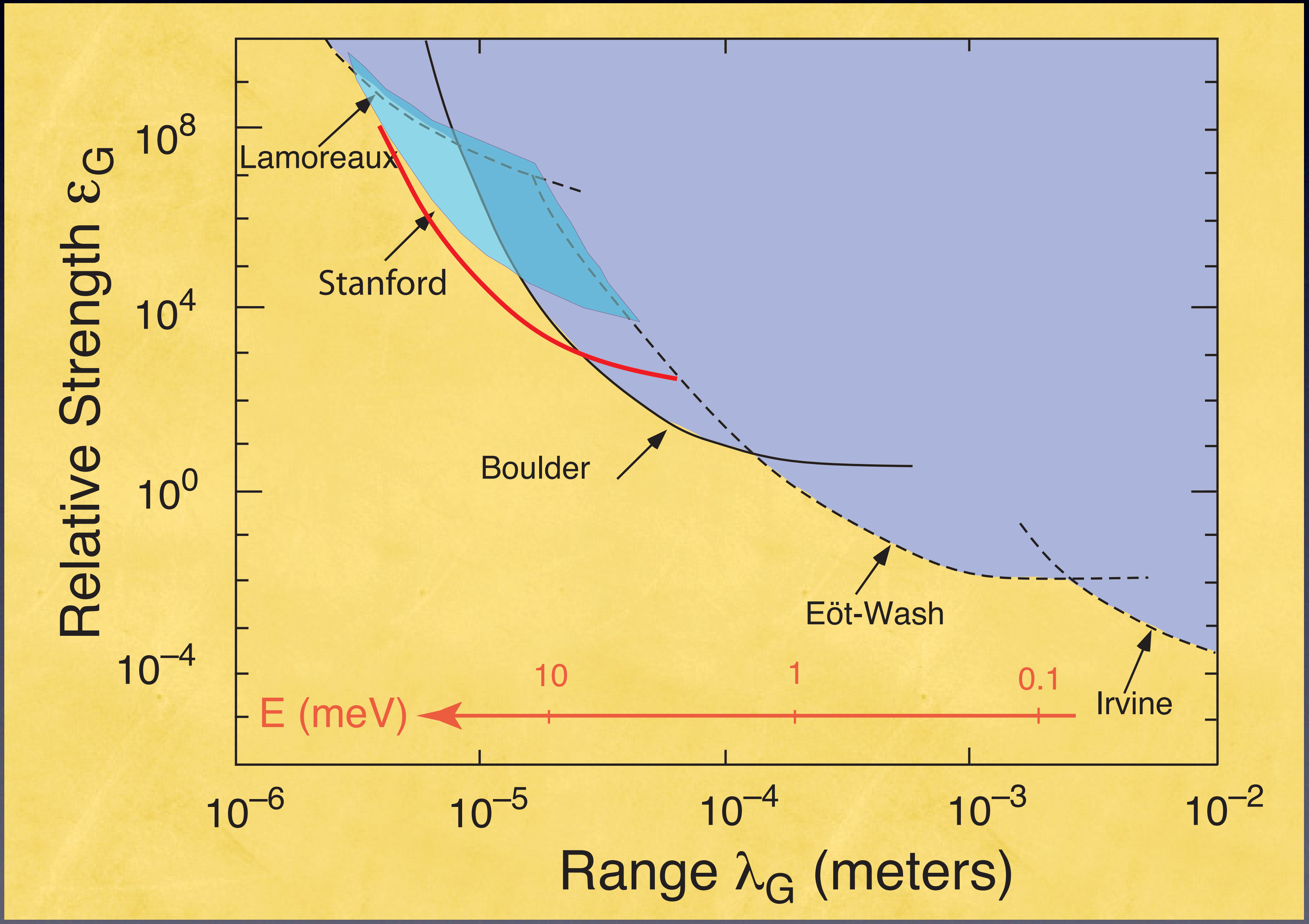


M_{Planck} would be a mirage!



Gravity follows Newtonian force law down to $\lesssim$ 1 mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}} \rho(r_1) \rho(r_2)}{r_{12}} \left[1 + \varepsilon_G \exp(-r_{12}/\lambda_G)\right]$$



Other extradimensional delights …

(provided gravity is intrinsically strong)

- Graviton emission (E_{missing} signatures) or graviton exchange (angular distributions)
- Resonances spaced at TeV intervals
- If extra dimensions are 1/TeV-scale, tiny black holes: collider hedgehogs, spectacular cosmic-ray showers

Reminders that we haven't seen (or imagined) everything yet

A Decade of Discovery Ahead

- ▷ Higgs search and study; EWSB / 1-TeV scale [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ CP violation (B); Rare decays (K, D, ...) [e^+e^-, $p^{\pm}p$, fixed-target]
- ▷ Neutrino oscillations [$\nu_{\odot}$, ν_{atm}, reactors, ν beams]
- ▷ Top as a tool [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ New phases of matter; hadronic physics [heavy ions, ep, fixed-target]
- ▷ Exploration! [colliders, precision measurements, tabletop, ...]
  Extra dimensions / new dynamics / SUSY / new forces & constituents
- ▷ Proton decay [underground]
- ▷ Composition of the universe [SN Ia, CMB, LSS, underground, colliders]

Need to prepare many revolutions …

- ✳ Experiments at the energy frontier
- ✳ High-sensitivity experiments
- ✳ Fundamental physics with “found beams”
- ✳ Astrophysical / cosmological observations
- ✳ Scale diversity!

The most ambitious accelerators drive our science

Refine e,p · Exotic technologies · Exotic particles

Connections …

In a decade or two, we can hope to ...

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, ...)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the 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 the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

...learn the right questions to ask ...

...and rewrite the textbooks!