The Coming Revolutions in Particle Physics

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LMU · Munich · 1 February 2006

The Great Lesson of Twentieth-Century Science

The human scale of space and time is *not privileged* for understanding Nature …

… and may even be disadvantaged

From the 1898–99 University of Chicago catalogue:

"While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. . . . An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals."

Röntgen, Becquerel, Curies, Thomson, Planck, … Einstein

A Decade of Discovery Past

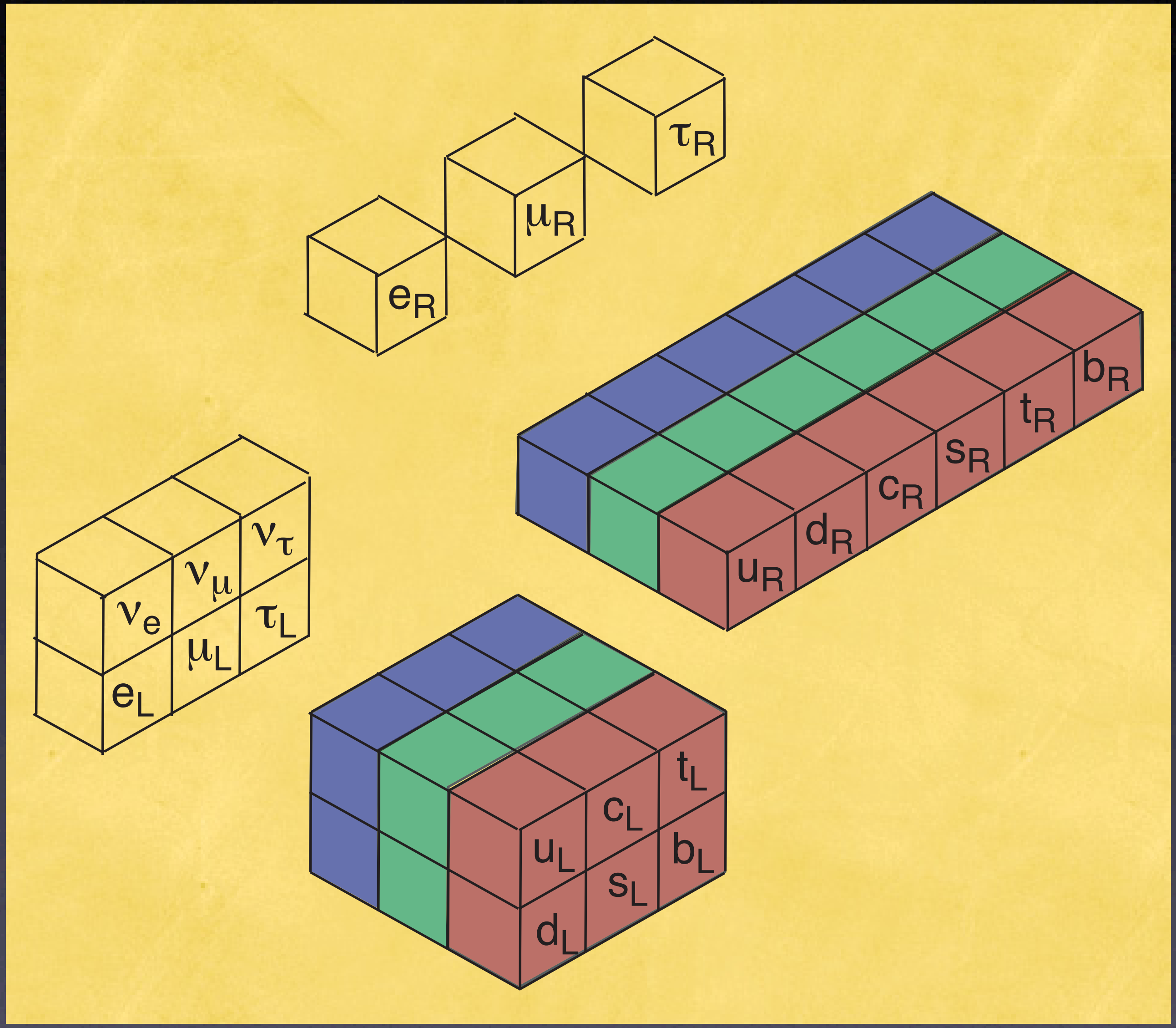
- ▷ Electroweak theory $\rightarrow$ law of nature
- ▷ Higgs-boson influence observed in the vacuum
- ▷ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$
- ▷ Understanding QCD
- ▷ Discovery of top quark
- ▷ Direct CP violation in $K \rightarrow \pi\pi$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

A Decade of Discovery Past

- $\triangleright$ Electroweak theory $\rightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, ...]
- $\triangleright$ Higgs-boson influence observed in the vacuum [EW experiments]
- $\triangleright$ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- $\triangleright$ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- $\triangleright$ Discovery of top quark [$\bar{p}p$]
- $\triangleright$ Direct CP violation in $K \rightarrow \pi\pi$ decay [fixed-target]
- $\triangleright$ B-meson decays violate CP [$e^+e^- \rightarrow B\bar{B}$]
- $\triangleright$ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- $\triangleright$ Detection of ν_τ interactions [fixed-target]
- $\triangleright$ 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: $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetries

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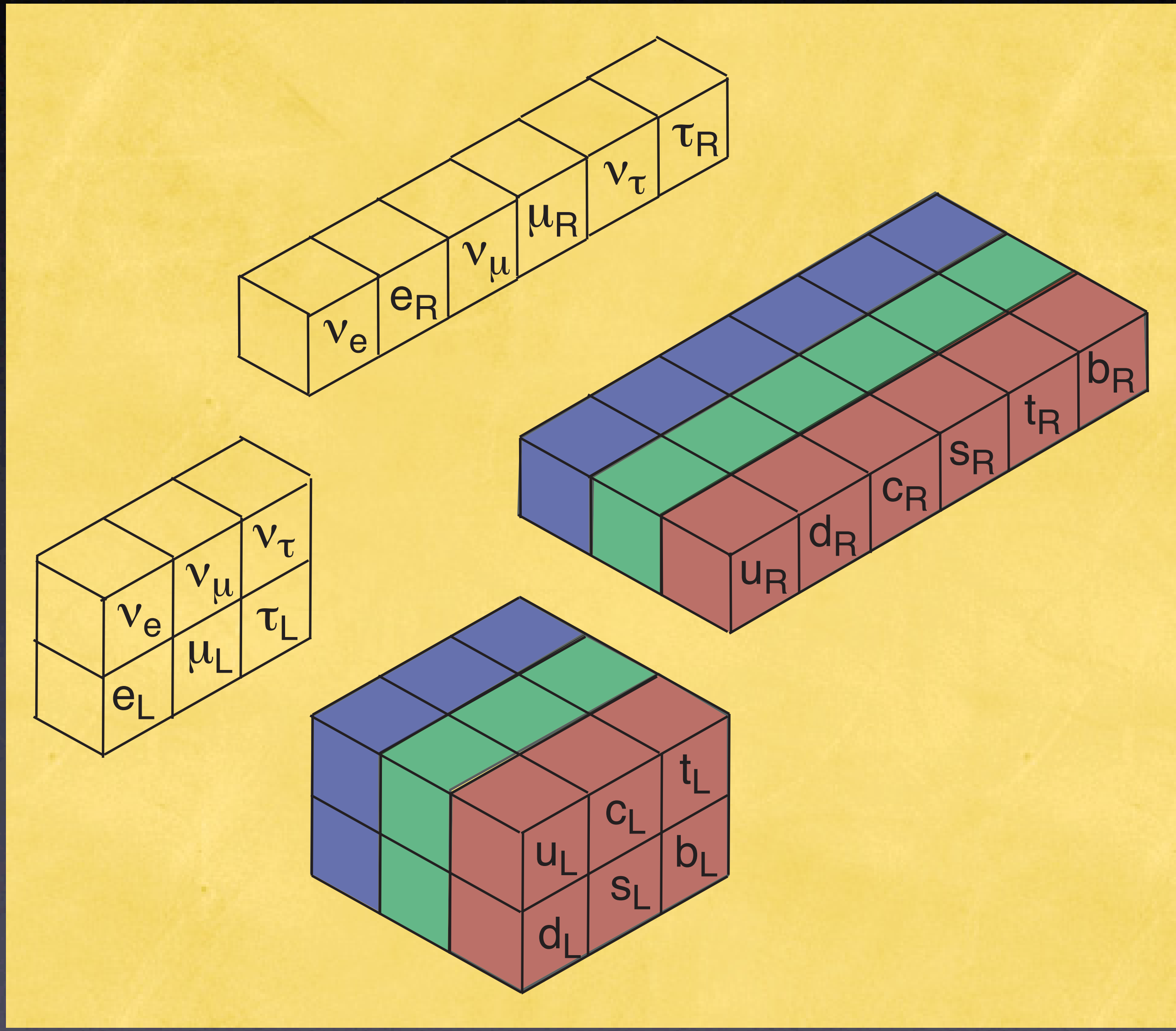

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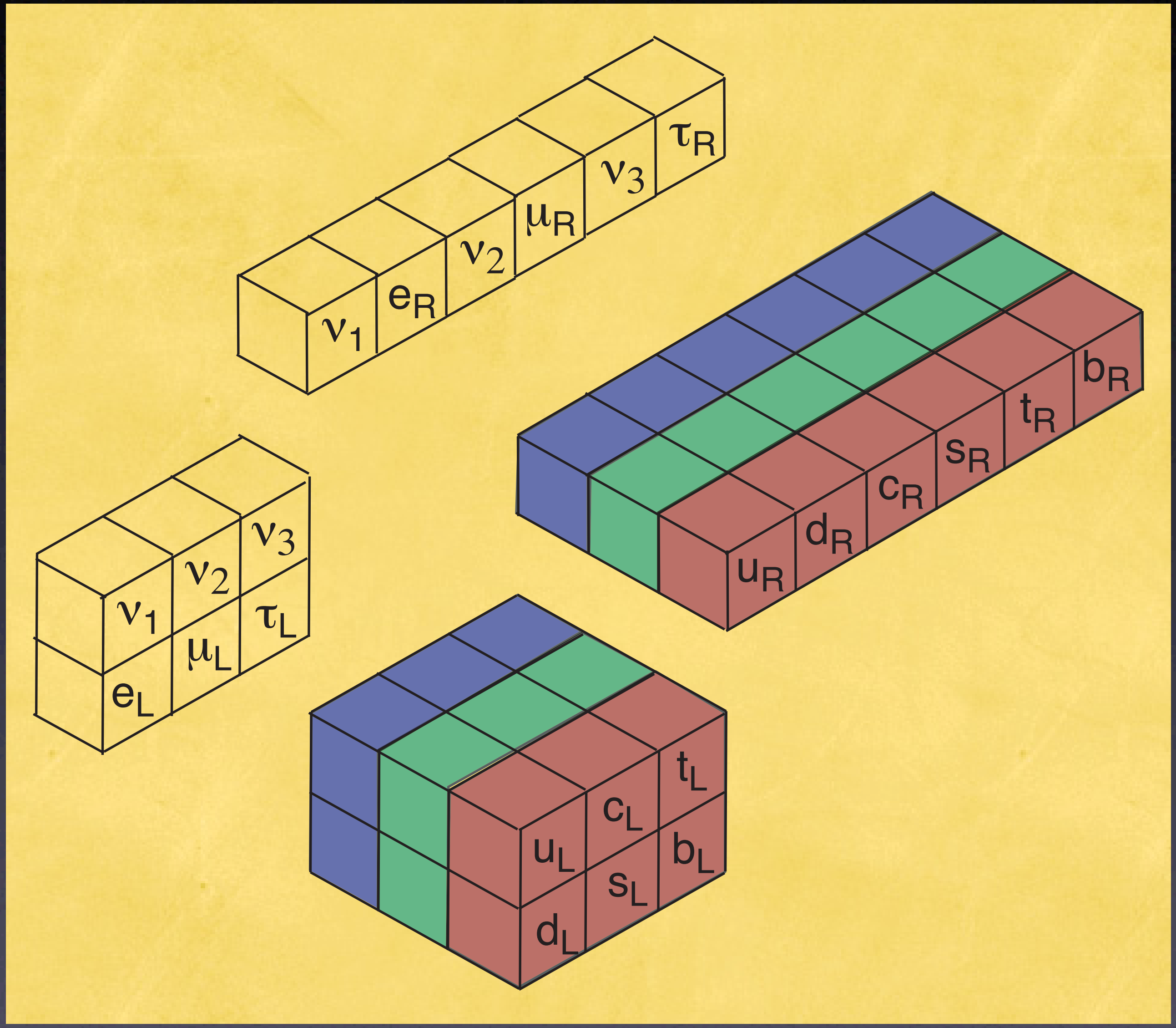


Interactions: $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetries

The World's Most Powerful Microscopes

nanonanophysics

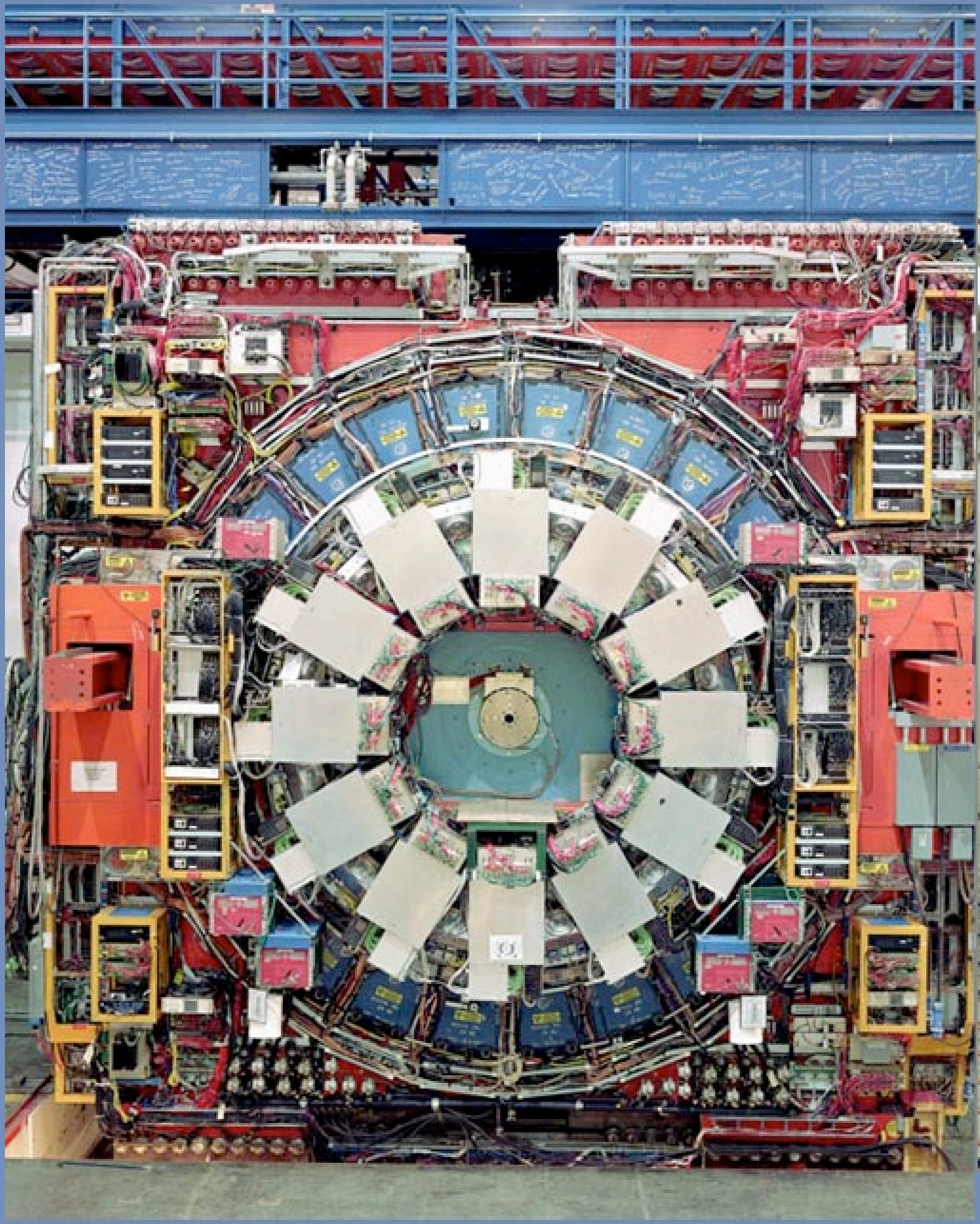
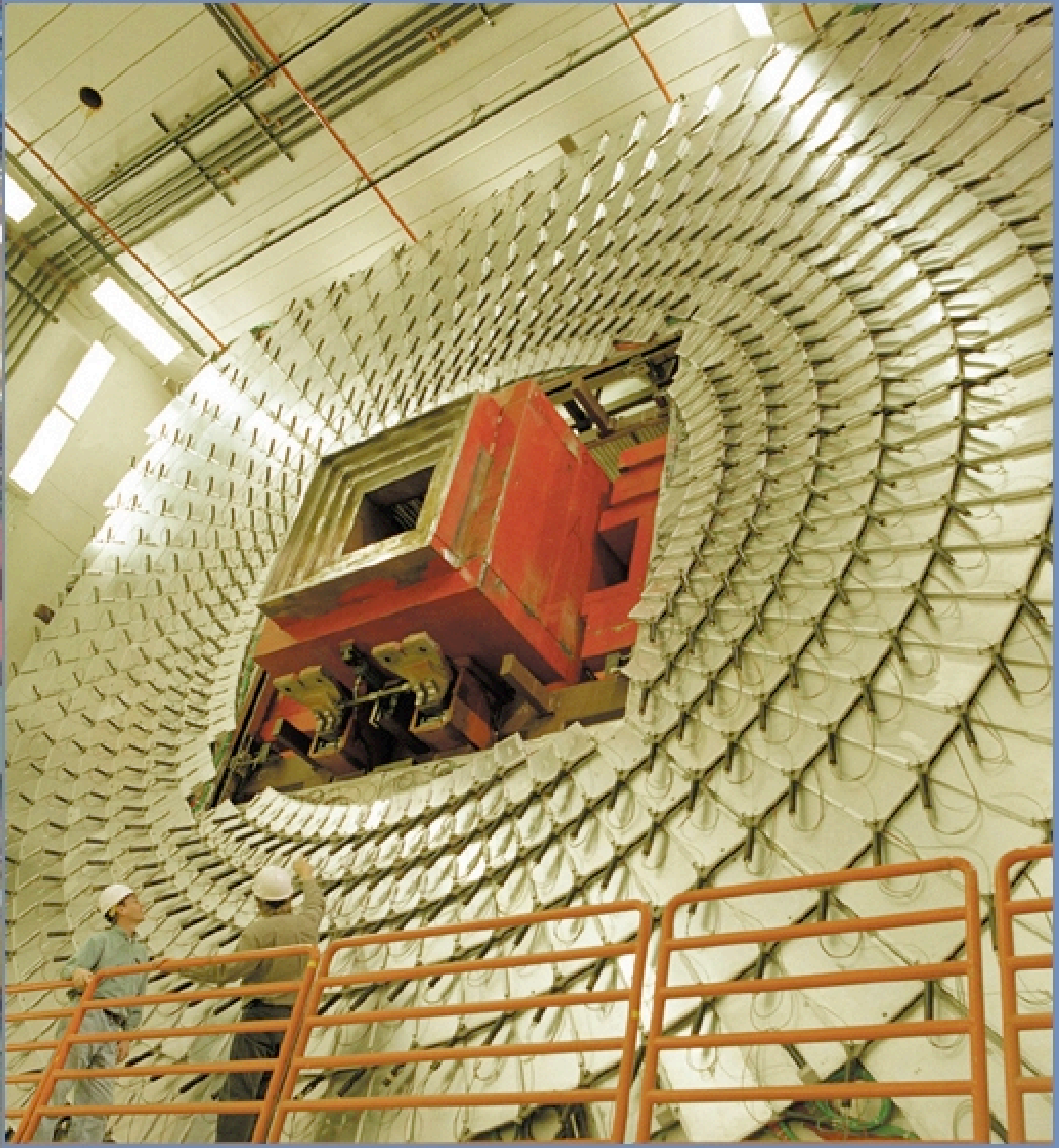
Fermilab's Tevatron Collider & Detectors

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

. . . 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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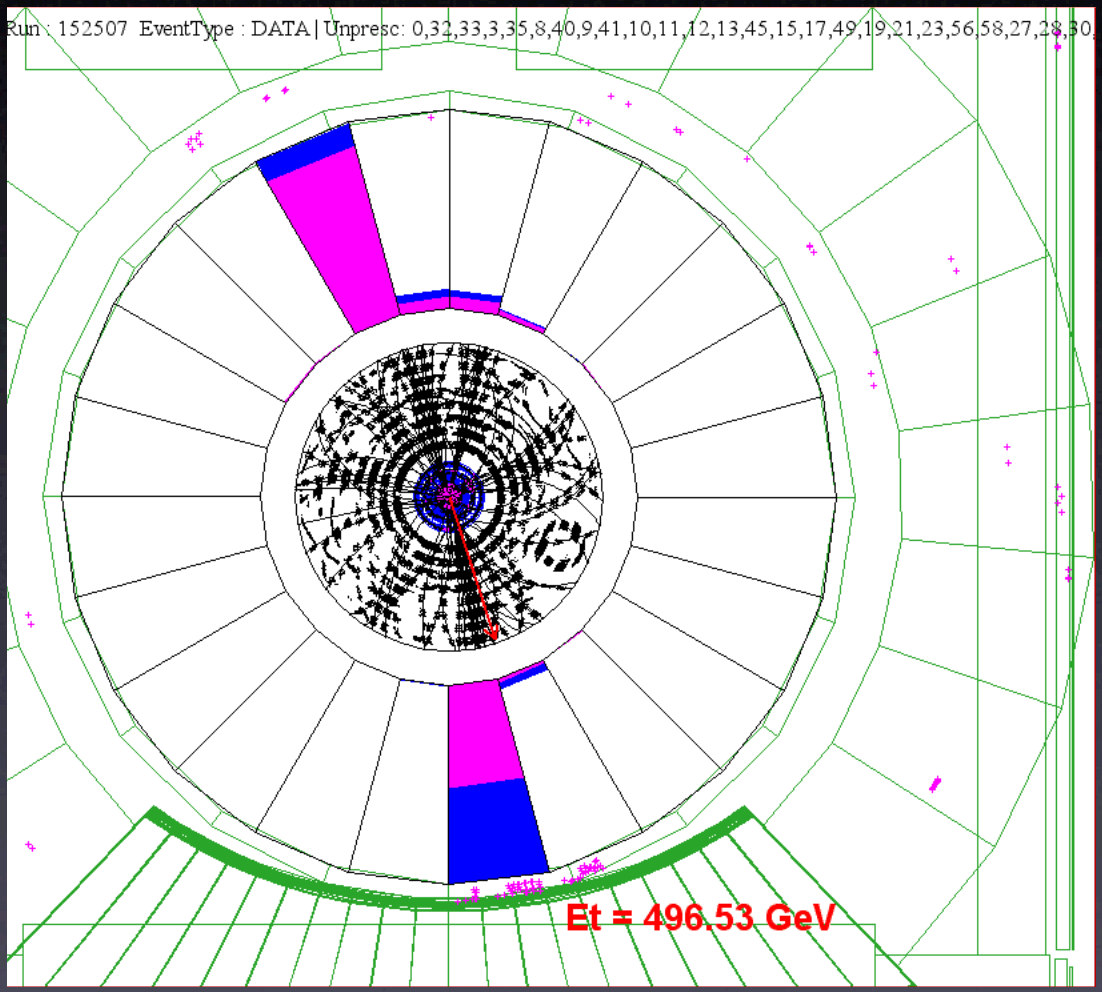
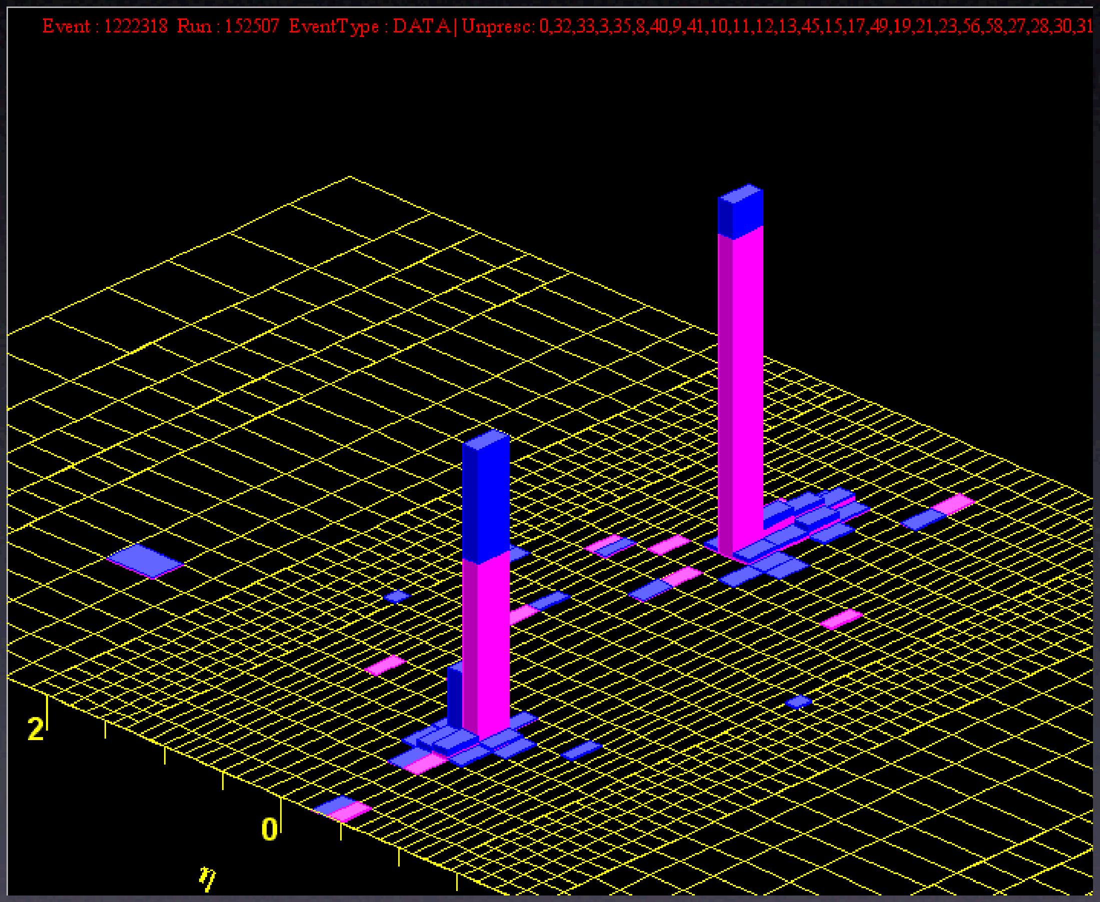
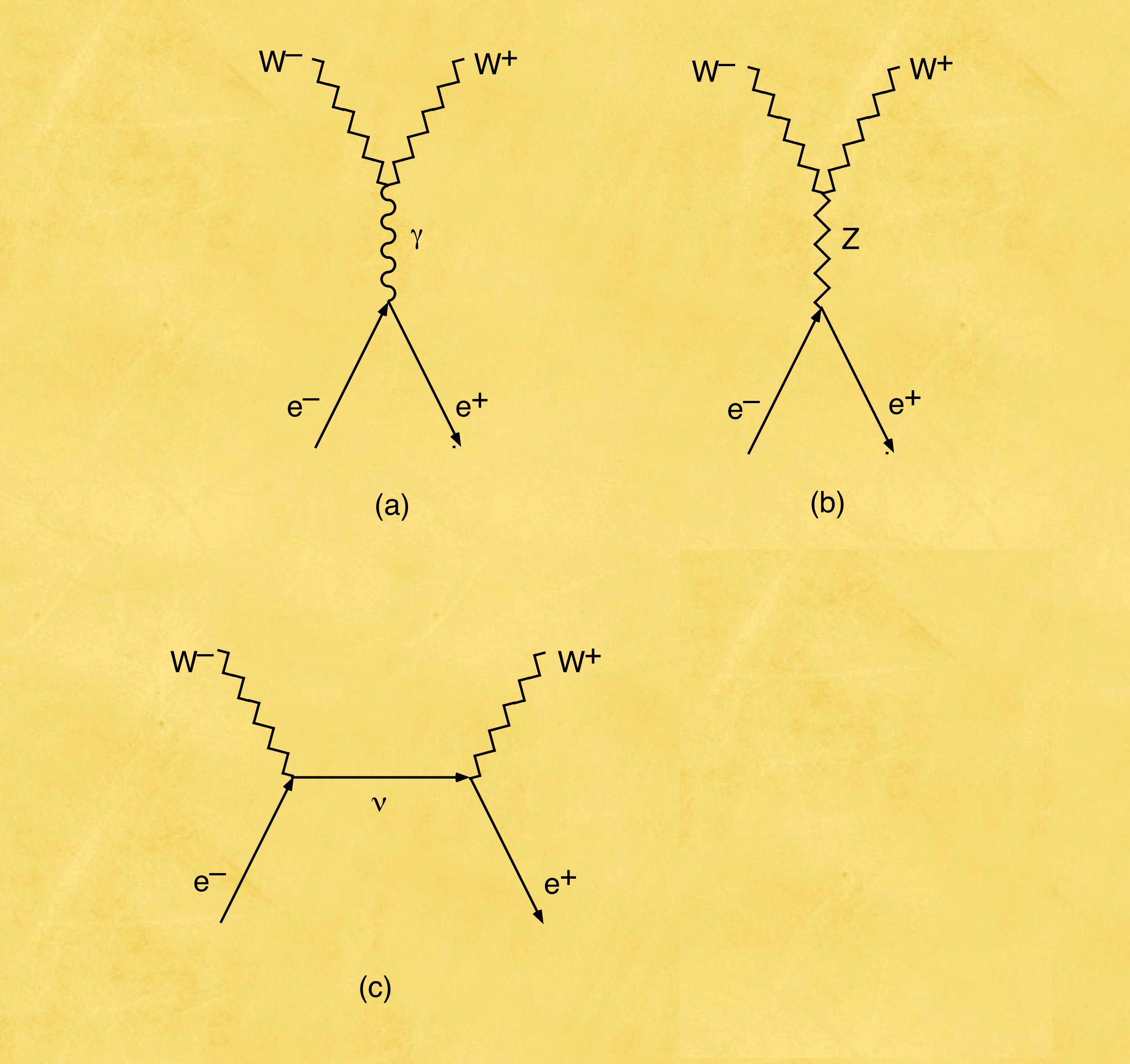




CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

Gauge symmetry (group-theory structure) tested in

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



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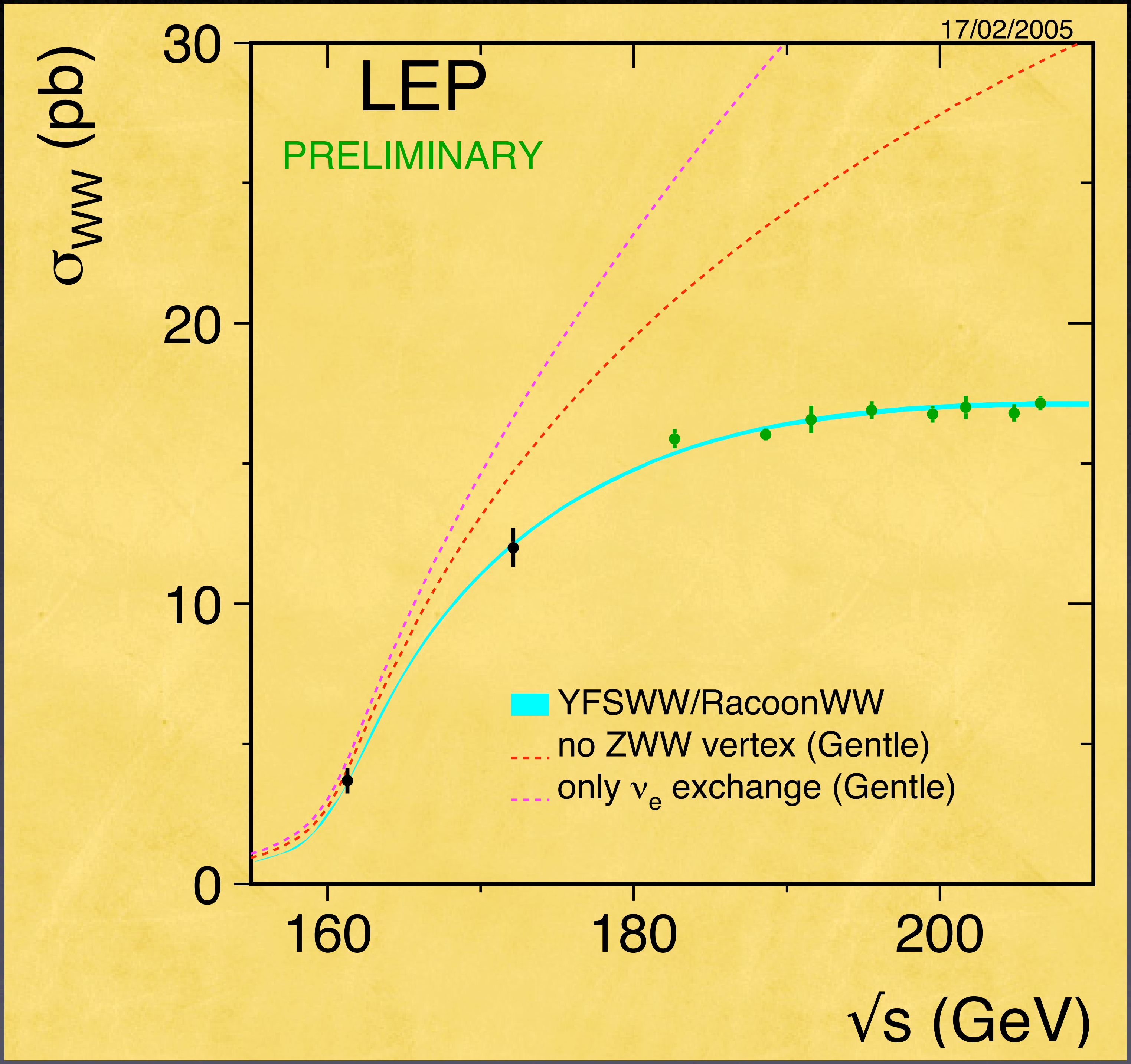


The importance of the 1-TeV scale

▷ Conditional *upper bound* on M_H from Unitarity in EW theory

Compute amplitudes $\mathcal{M}$ for gauge boson scattering at high energies, make a partial-wave decomposition

$$\mathcal{M}(s,t) = 16\pi \sum_J (2J+1) a_J(s) P_J(\cos\theta)$$

Most channels decouple: pw amplitudes small at all energies (except very near particle poles, or at exponentially large energies) for any M_H.

Four interesting channels:

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0/\sqrt{2} \quad HH/\sqrt{2} \quad HZ_L^0$$

L: longitudinal, $1/\sqrt{2}$ for identical particles

In HE limit, s-wave amplitudes $\propto G_F M_H^2 \propto s^0$

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Require largest eigenvalue respect pw unitarity: $|a_0| \leq 1$

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

condition for perturbative unitarity

Convenient to calculate using *Goldstone-boson equivalence theorem*, which reduces dynamics of longitudinally polarized gauge bosons to scalar field theory with interactions given by $\mathcal{L}_{\text{int}} = -\lambda v h (2w^+w^- + z^2 + h^2) - (\lambda/4)(2w^+w^- + z^2 + h^2)^2$, with $1/v^2 = G_F\sqrt{2}$ and $\lambda = G_F M_H^2/\sqrt{2}$.

▷ If the bound is respected

⋆ weak interactions remain weak at all energies

⋆ perturbation theory is everywhere reliable

▷ If the bound is violated

⋆ perturbation theory breaks down

⋆ weak interactions among $W^{\pm}$, Z, H become strong on the 1-TeV scale

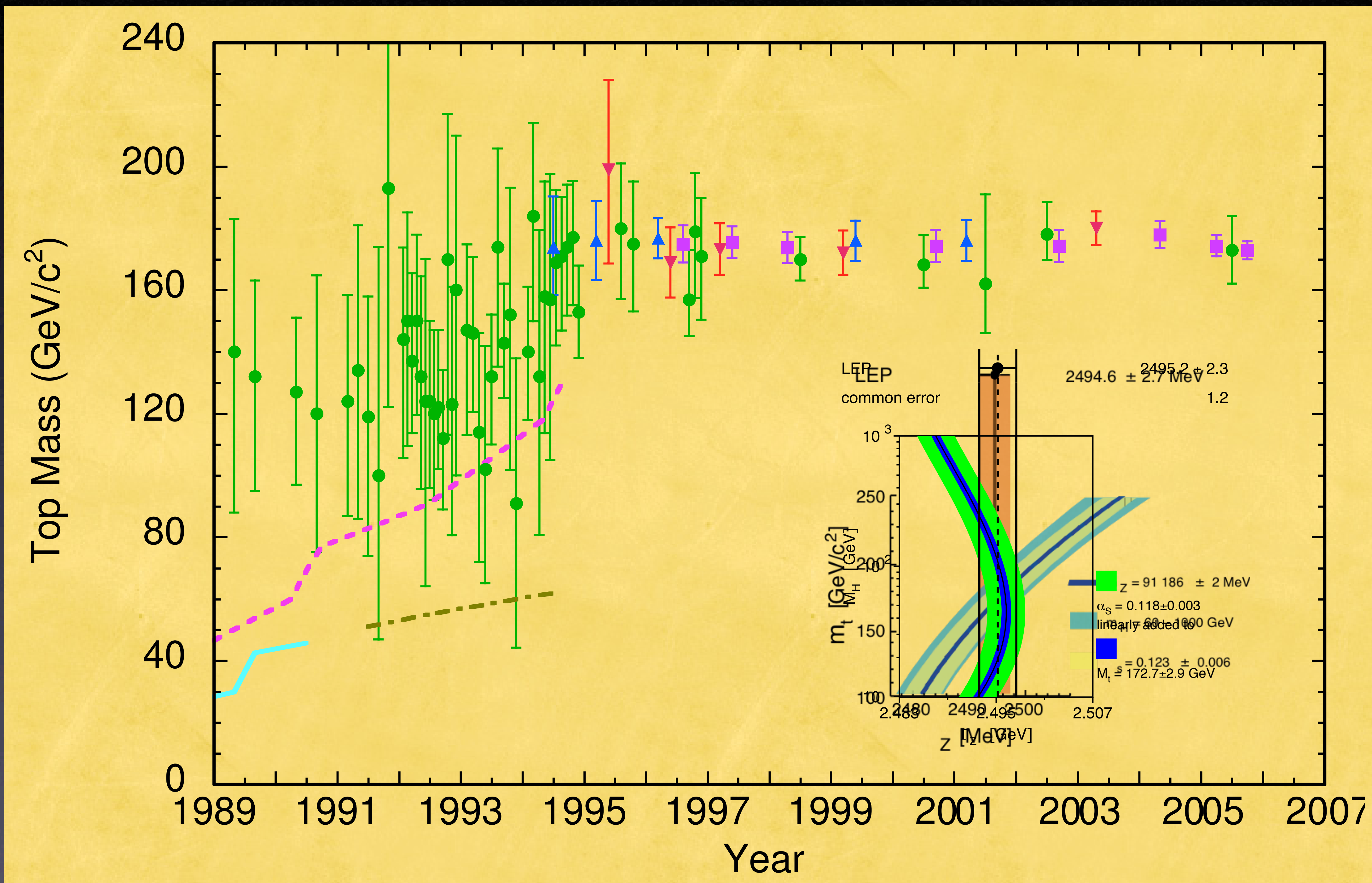
$\Rightarrow$ features of *strong* interactions at GeV energies will characterize *electroweak* gauge boson interactions at TeV energies

New phenomena in electroweak interactions at energies not much larger than 1 TeV $\Rightarrow$ Explore the 1-TeV scale!

Precision Measurements Test the Theory …

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3

… and determine unknown parameters



Revolution:

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?

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

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

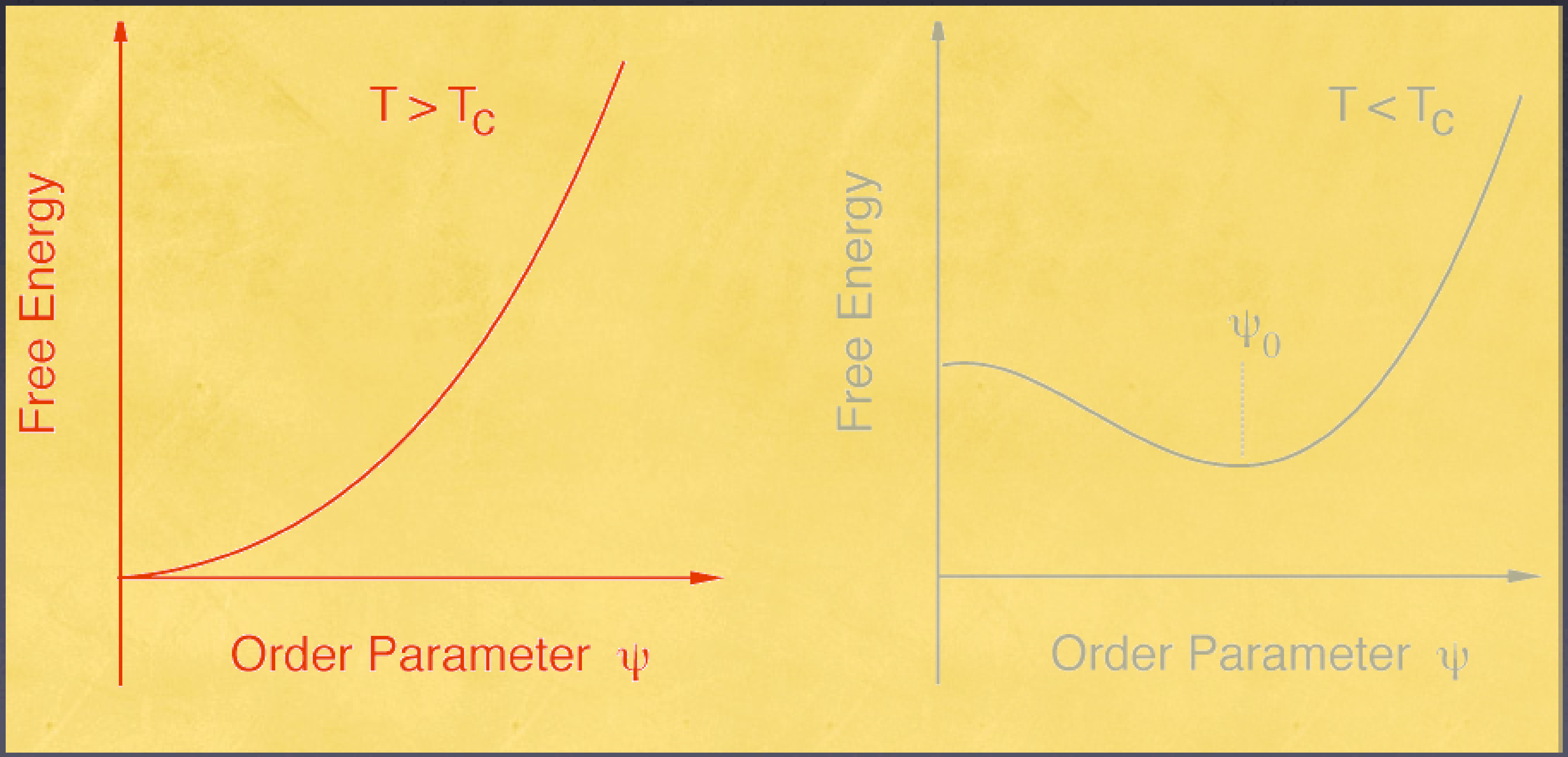
why the world is the way it is.

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

it is coming within the reach of particle physics.

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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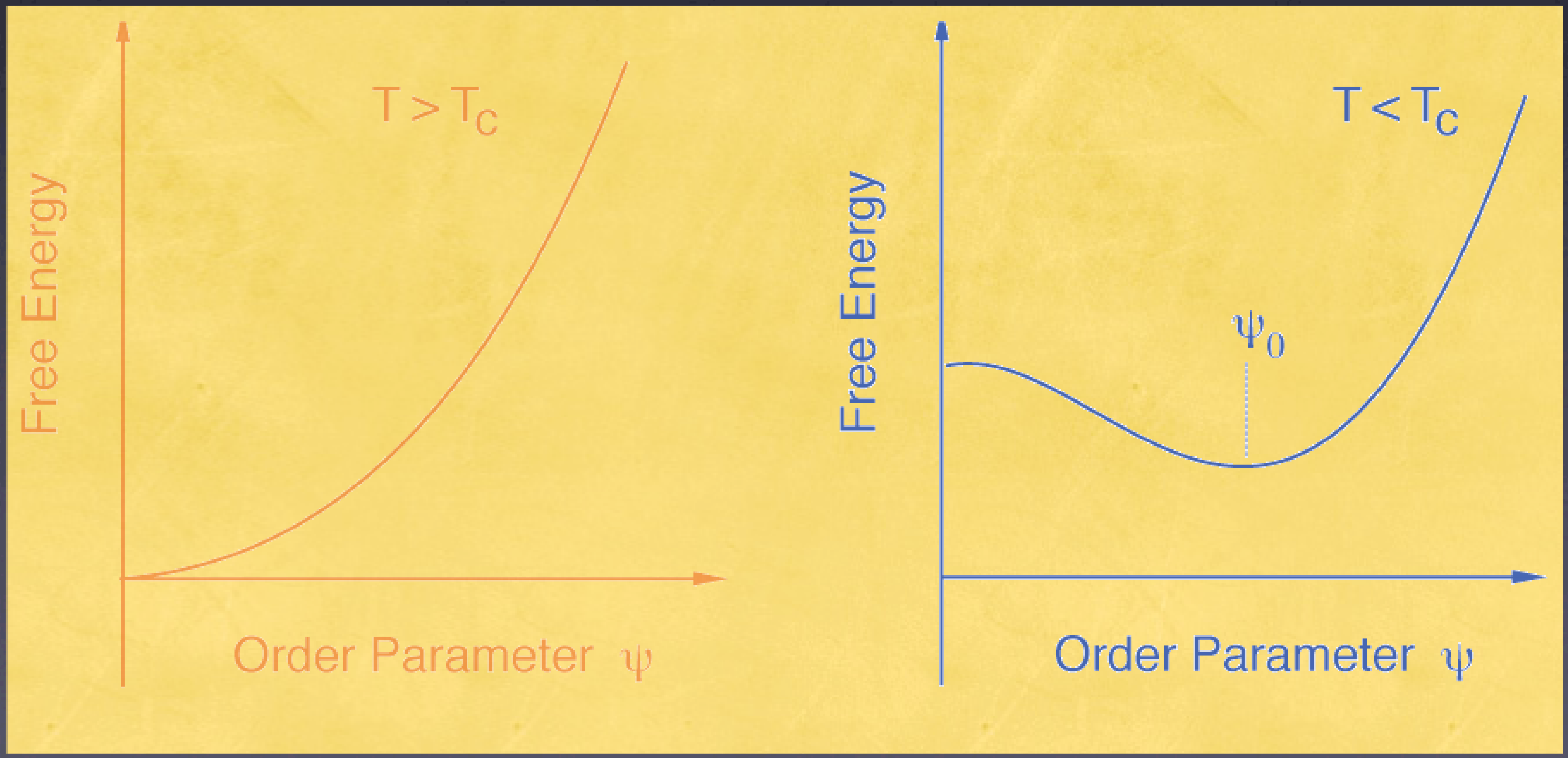


What is the nature of the mysterious new force that hides electroweak symmetry?

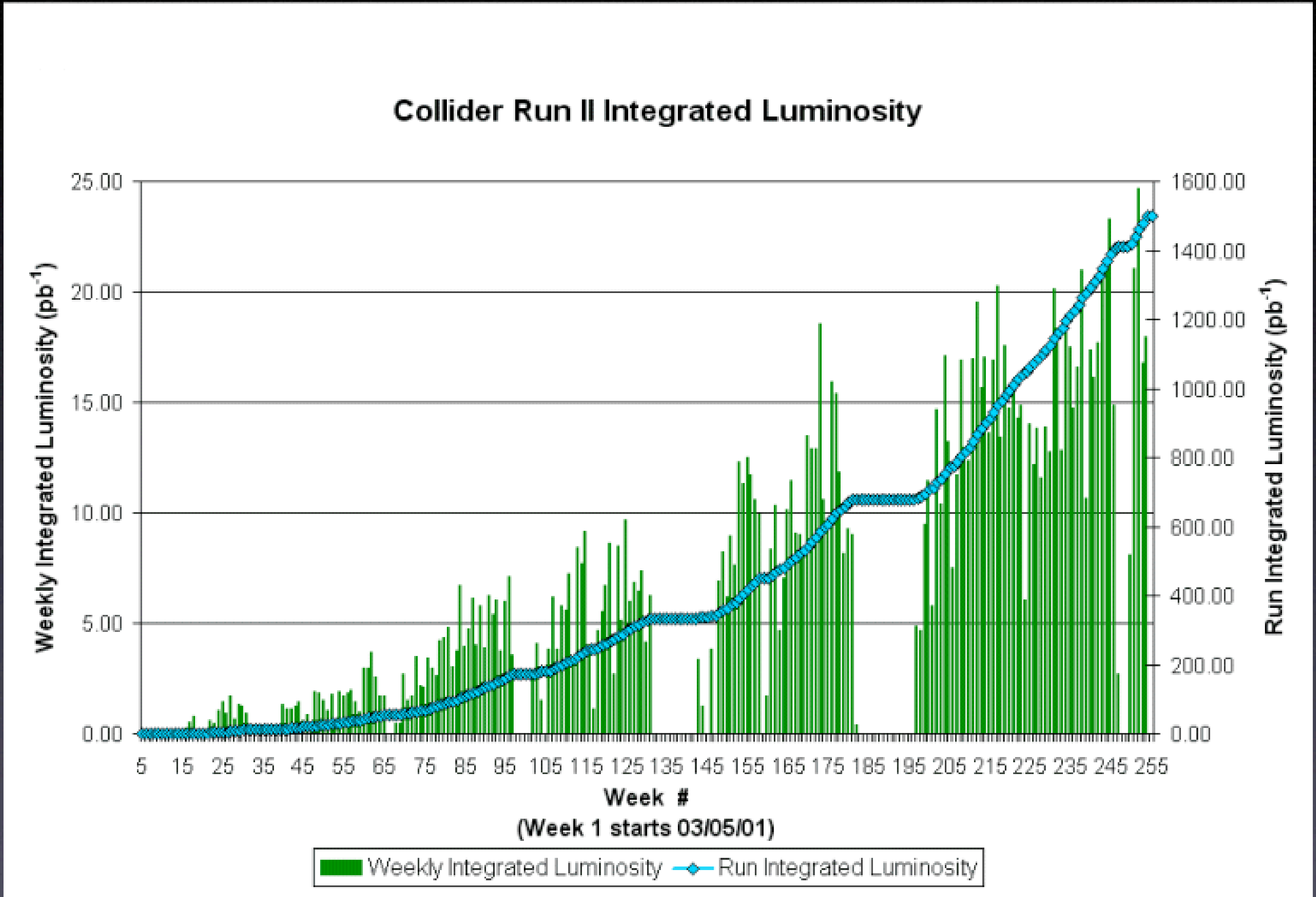
- ✳ A force of a new character, based on interactions of an elementary scalar
- ✳ A new gauge force, perhaps acting on undiscovered constituents
- ✳ A residual force that emerges from strong dynamics among electroweak gauge bosons
- ✳ An echo of extra spacetime dimensions

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!



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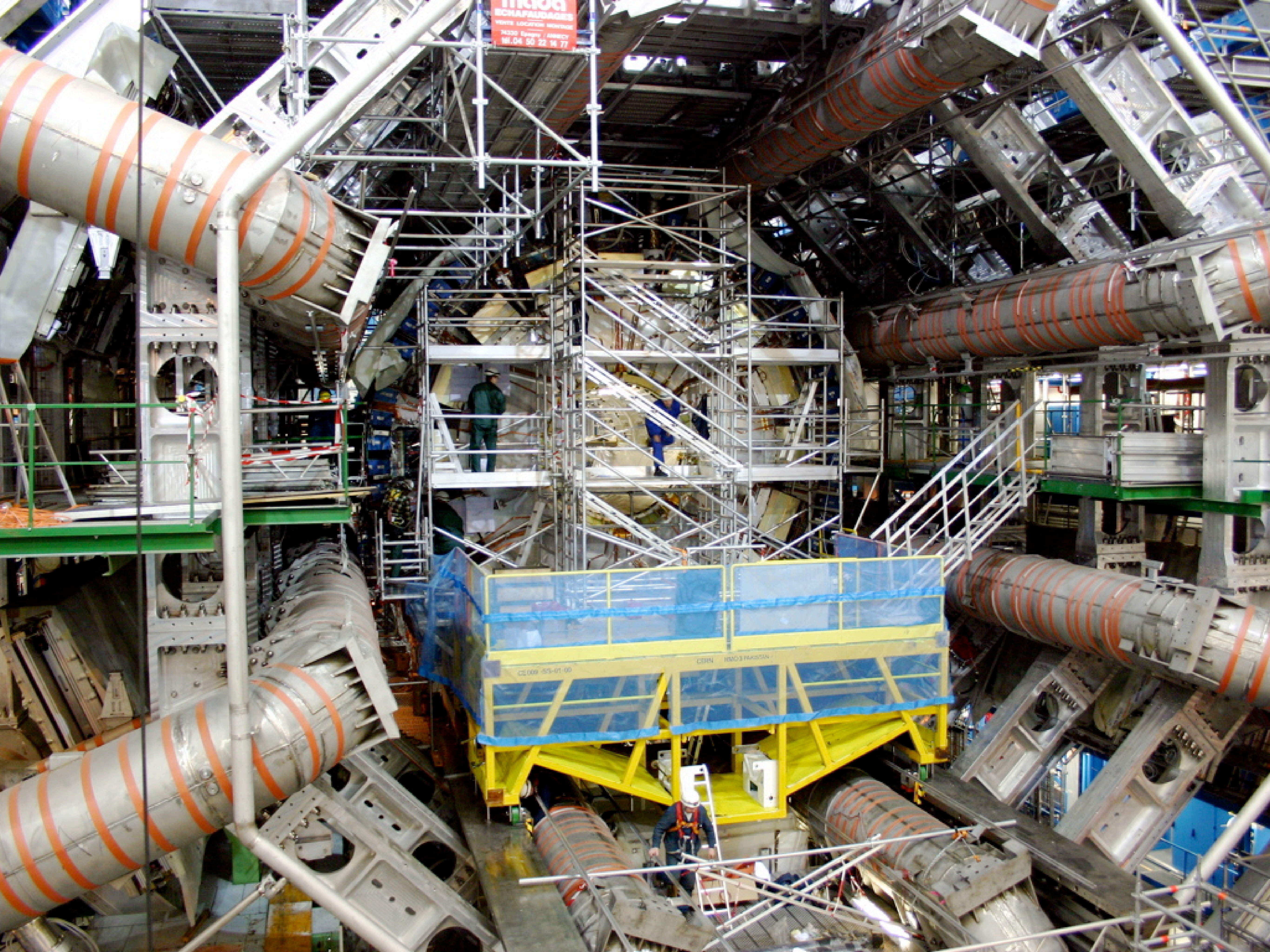
Run Integrated Luminosity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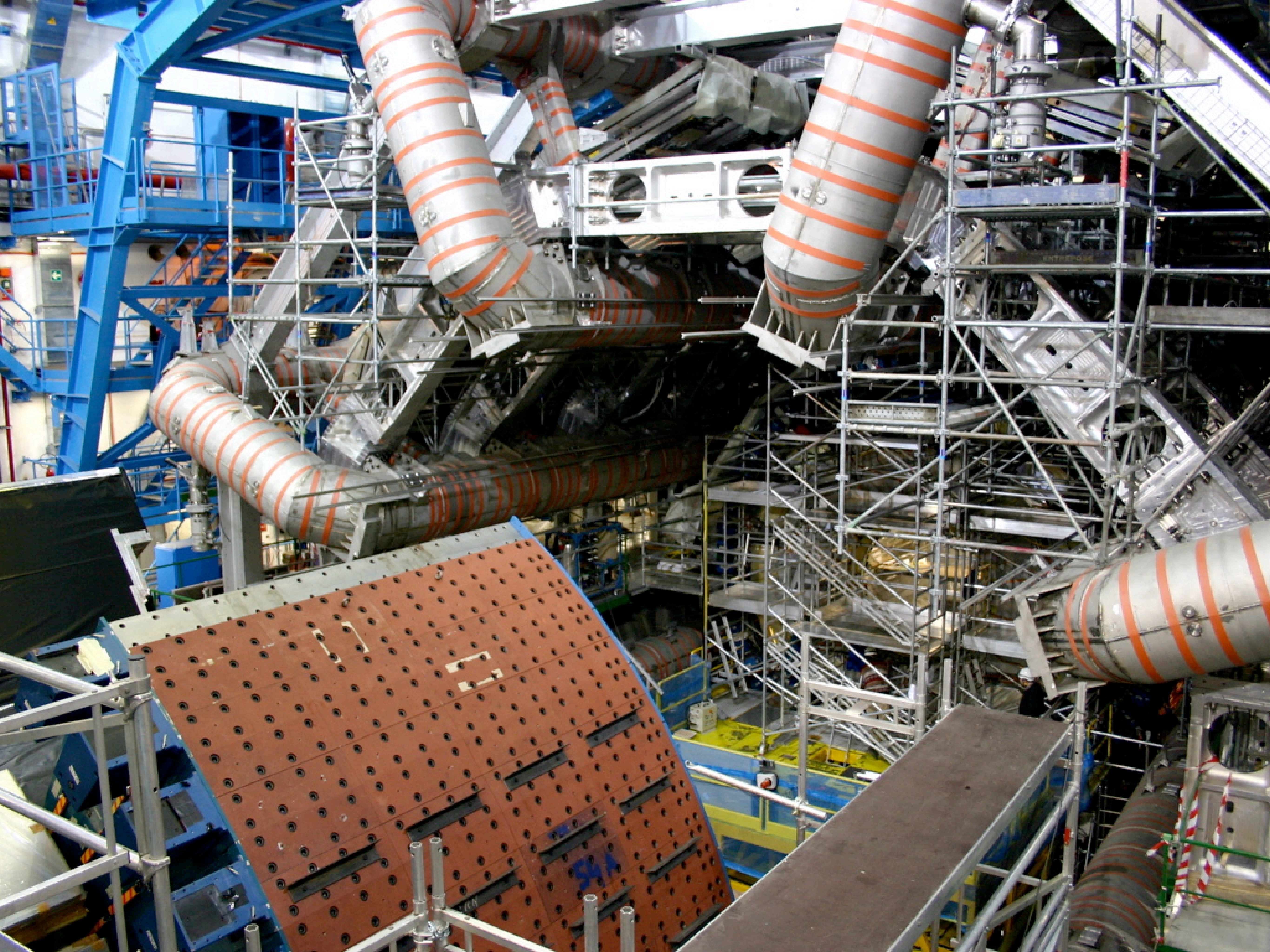


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Revolution:

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?

Many extensions to EW theory entail dark matter candidates

Supersymmetry is highly developed, has several important consequences:

- ✳ Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
- ✳ Predicts a light Higgs mass
- ✳ Predicts cosmological cold dark matter
- ✳ In a unified theory, explains the values of standard-model coupling constants

Revolution:

The Meaning of Identity

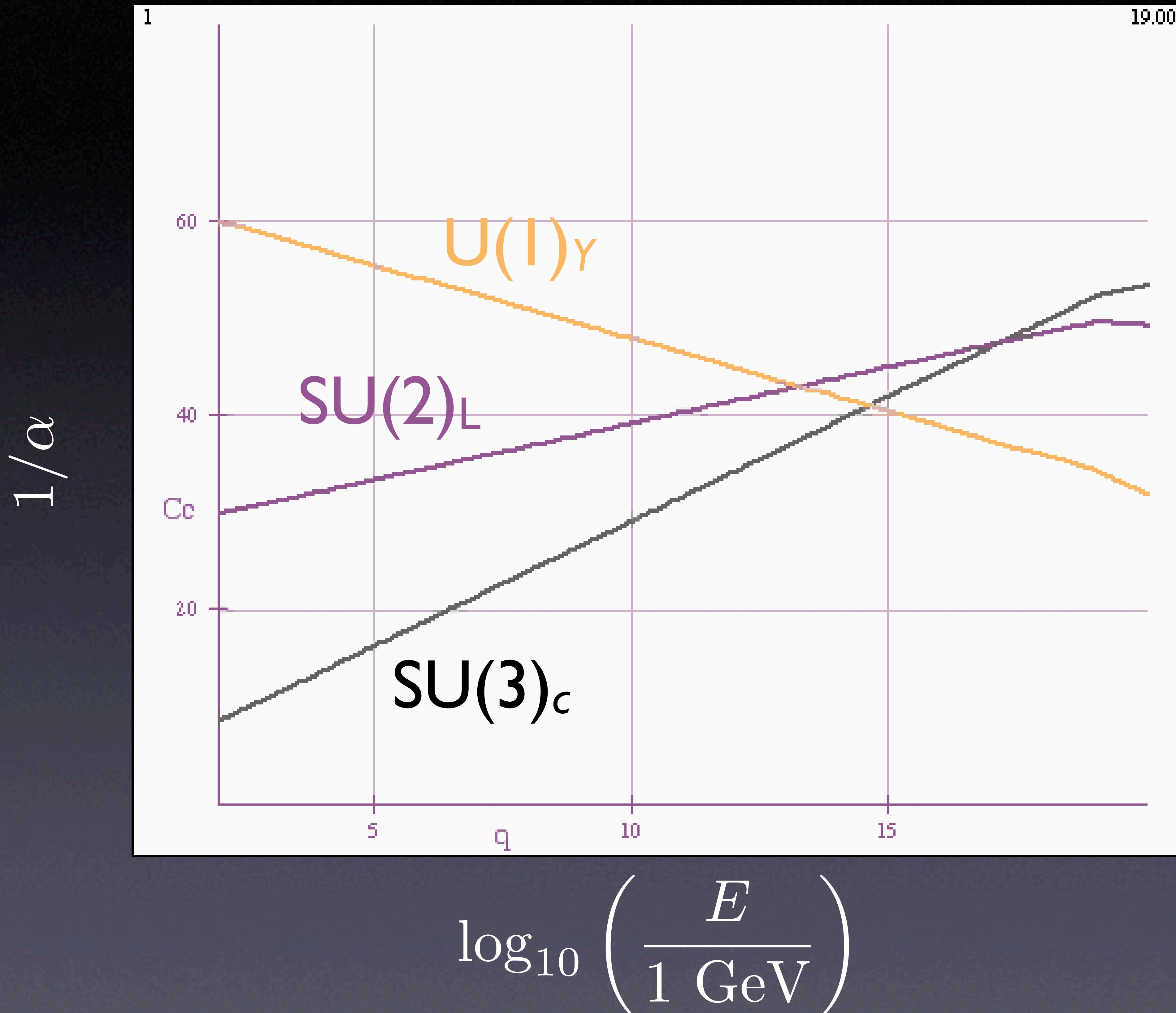
What makes
a top quark a top quark,
an electron an electron,
and a neutrino a neutrino?

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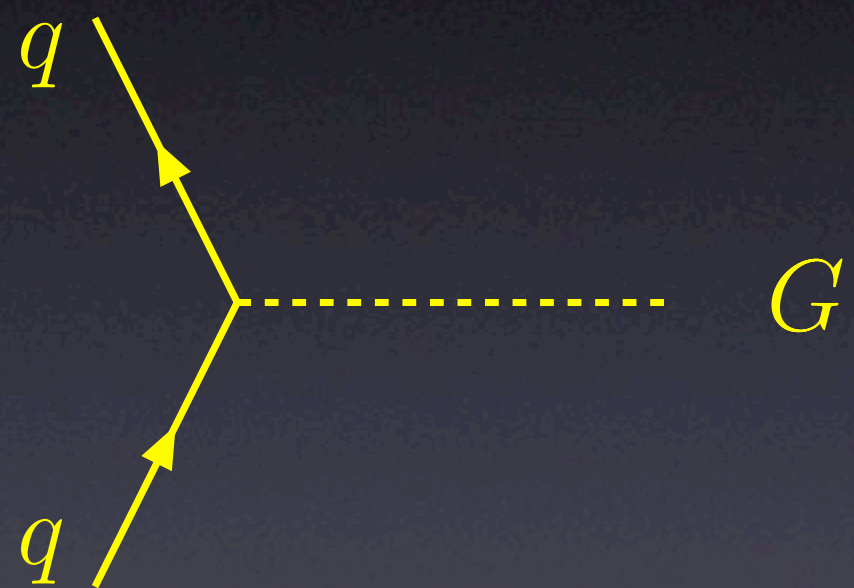
$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$

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,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$$

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

vacuum energy density $\varrho_H \equiv \frac{M_H^2 v^2}{8} \rightsquigarrow \Lambda$

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = \frac{8\pi G_{\text{Newton}}}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \quad \Lambda = \frac{8\pi G_{\text{Newton}}}{c^4}\varrho_{\text{vac}}$$

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

≈ 10 MeV$/\ell$ or 10^{-29} g cm^{-3}

But $M_H \geq 114$ GeV $\Rightarrow$

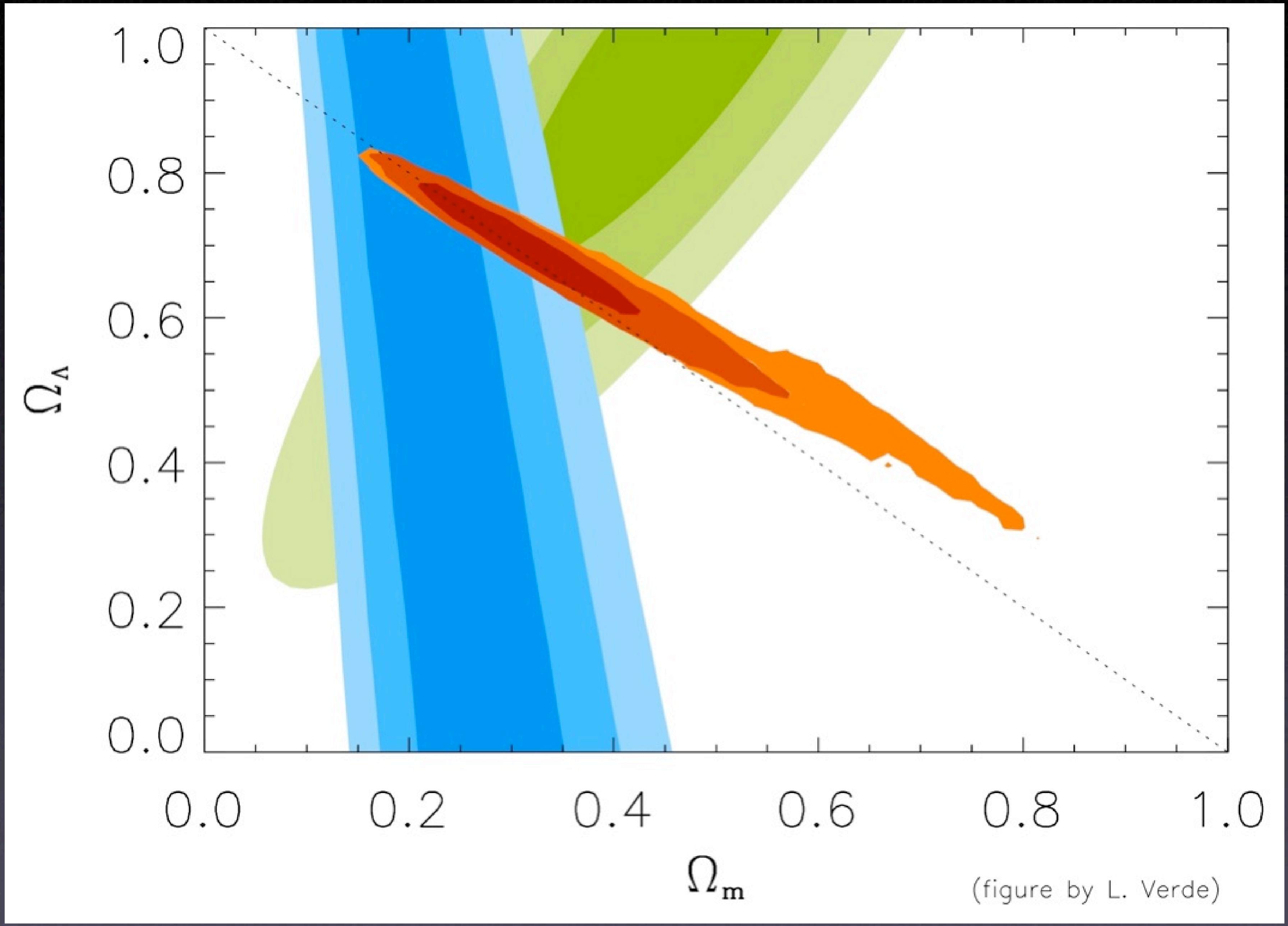
$\varrho_H \geq 10^8$ GeV^4

Mismatch by 54 orders of magnitude

A chronic dull headache for thirty years …

Why is empty space so nearly massless?

Evidence that vacuum energy is present …



recasts old problem, gives us properties to measure

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:

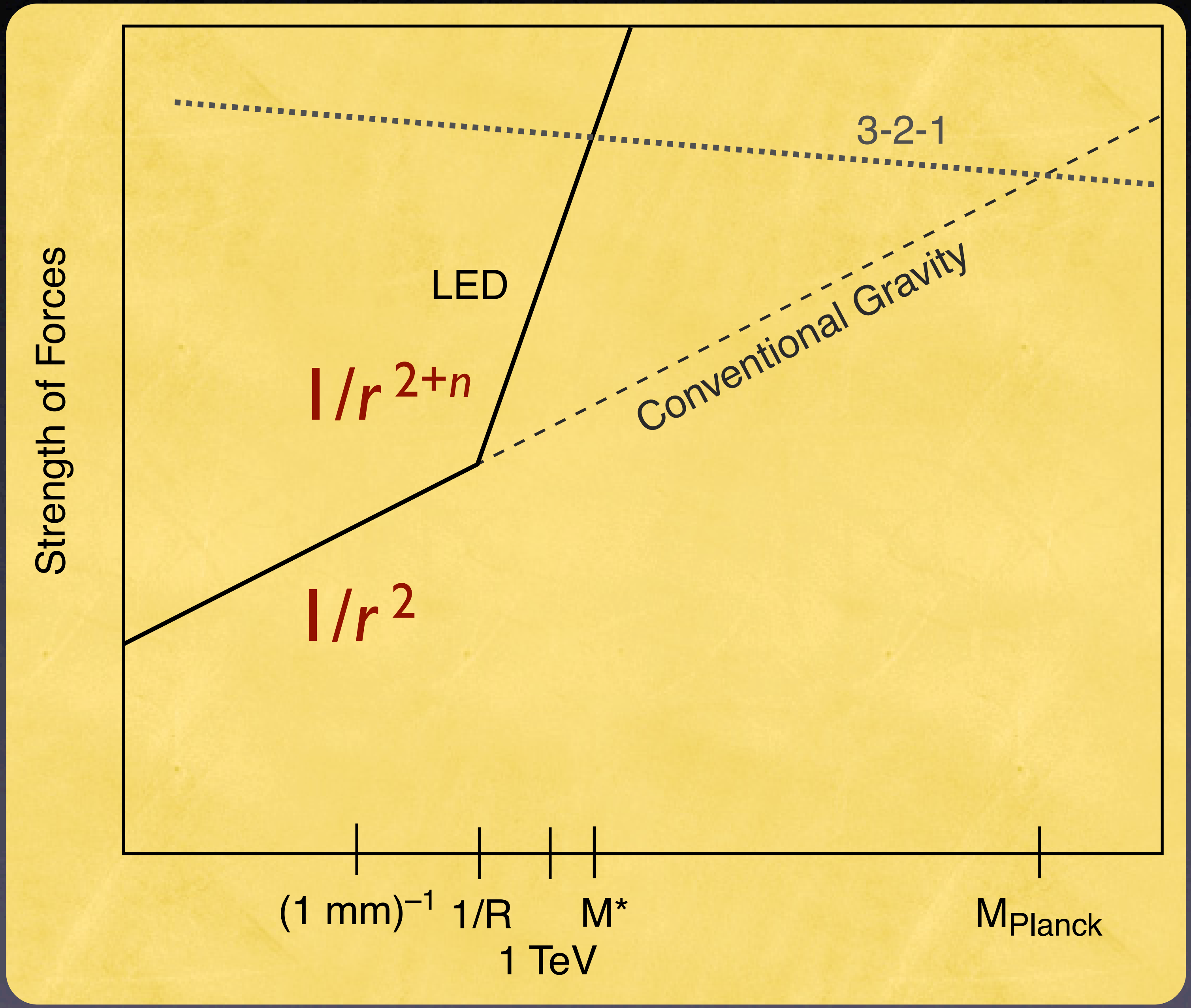
A New Conception of Spacetime

- ▷ 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

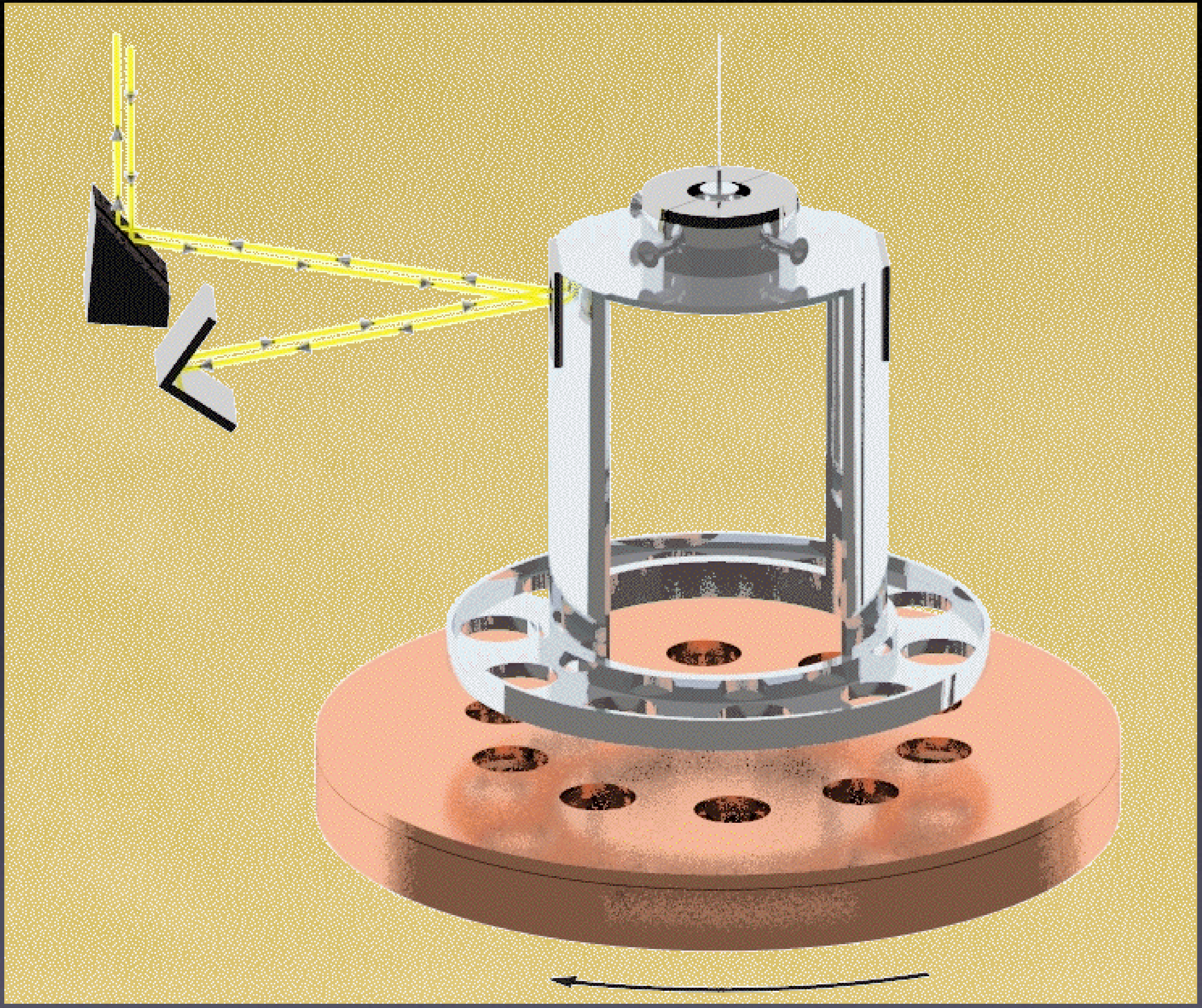
Suppose at scale *R* … gravity propagates in 4+*n* dimensions

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



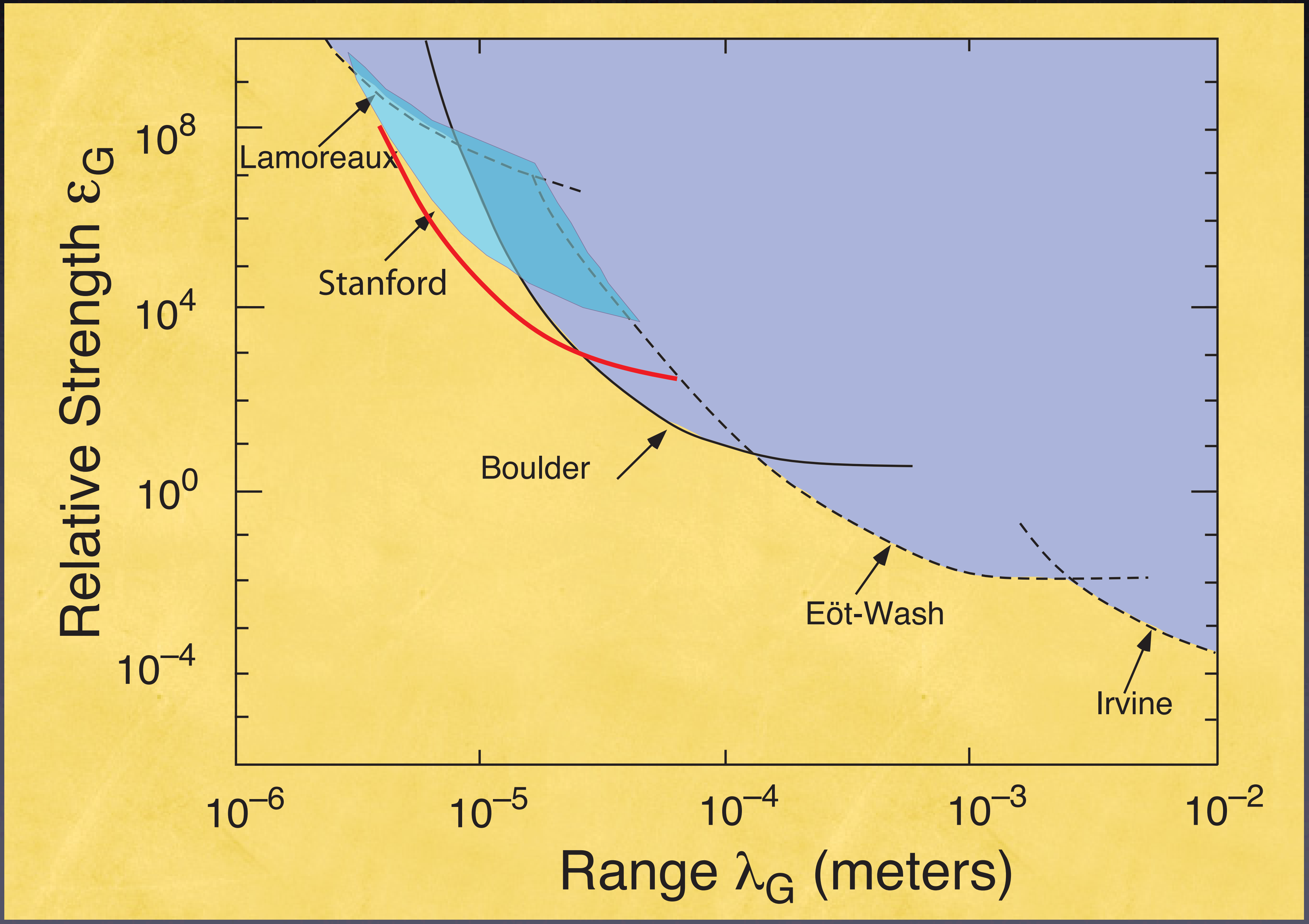
M_{Planck} would be a mirage!


$M_P^2 = M_*^{n+2} R^n$



Gravity follows Newtonian force law down to ≲ 1 mm

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



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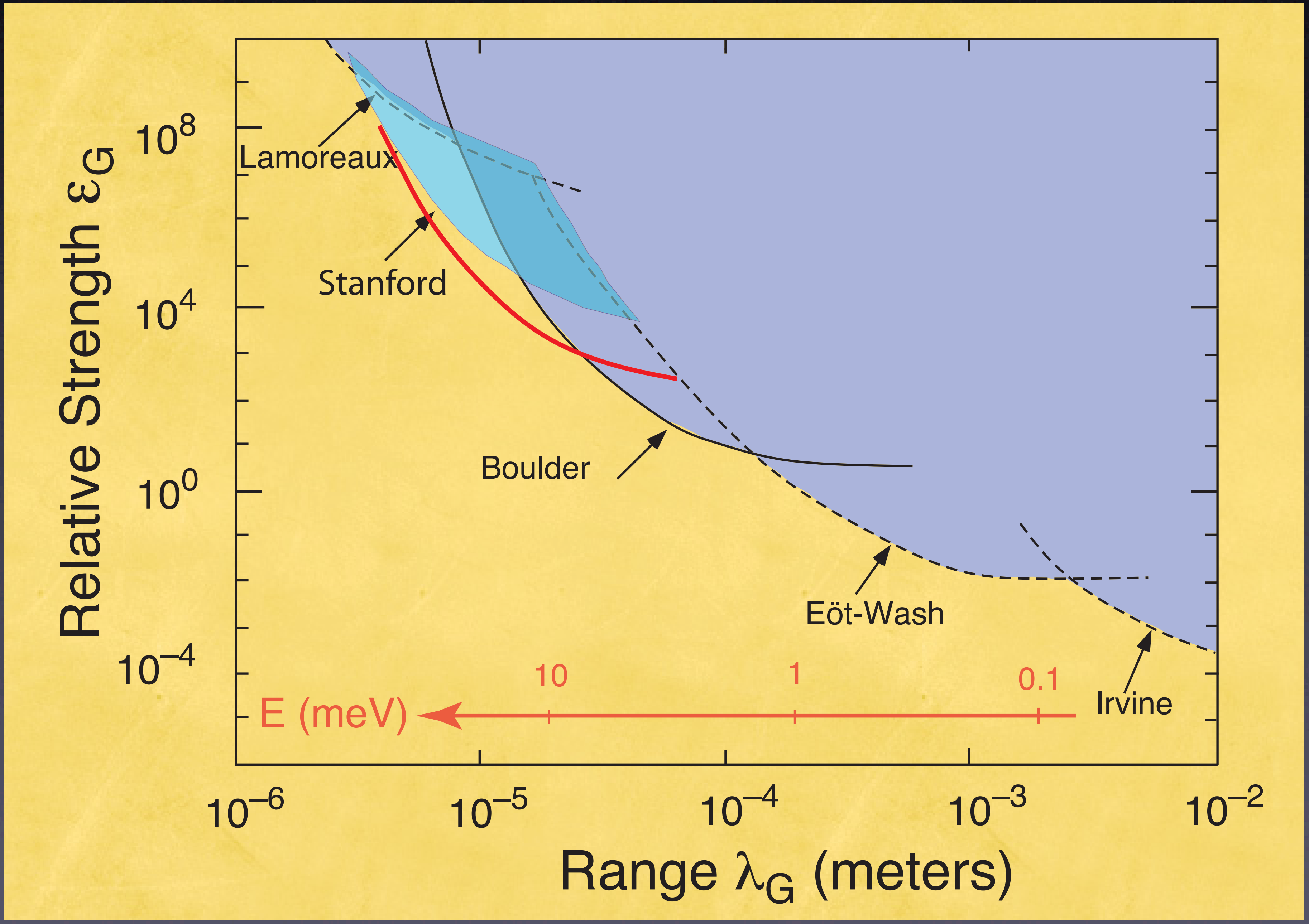
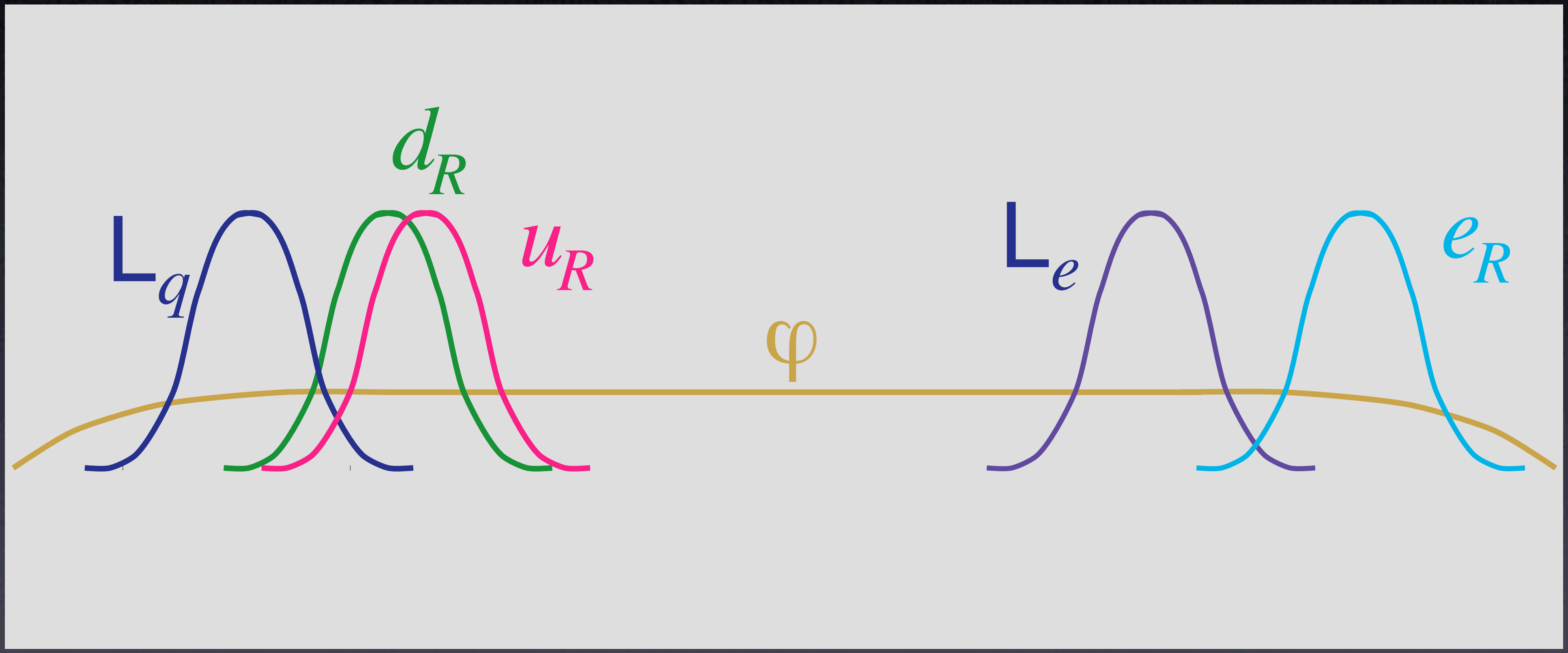


Might extra dimensions explain the range of fermion masses?



fermions ride separate tracks in 5th dimension

small offsets in $x_5 \Rightarrow$ exponential mass ratios

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
- ▷ CP violation (B); Rare decays (K, D, ...)
- ▷ Neutrino oscillations
- ▷ Top as a tool
- ▷ New phases of matter; hadronic physics
- ▷ Exploration!
  Extra dimensions / new dynamics / SUSY / new forces & constituents
- ▷ Proton decay
- ▷ Composition of the universe

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

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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 . . .

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

. . . and rewrite the textbooks!

Reserve slides on the new accelerators

Muon Accelerators

Possible path to a few-TeV $\ell^+\ell^-$ collider
to study electroweak symmetry breaking, explore

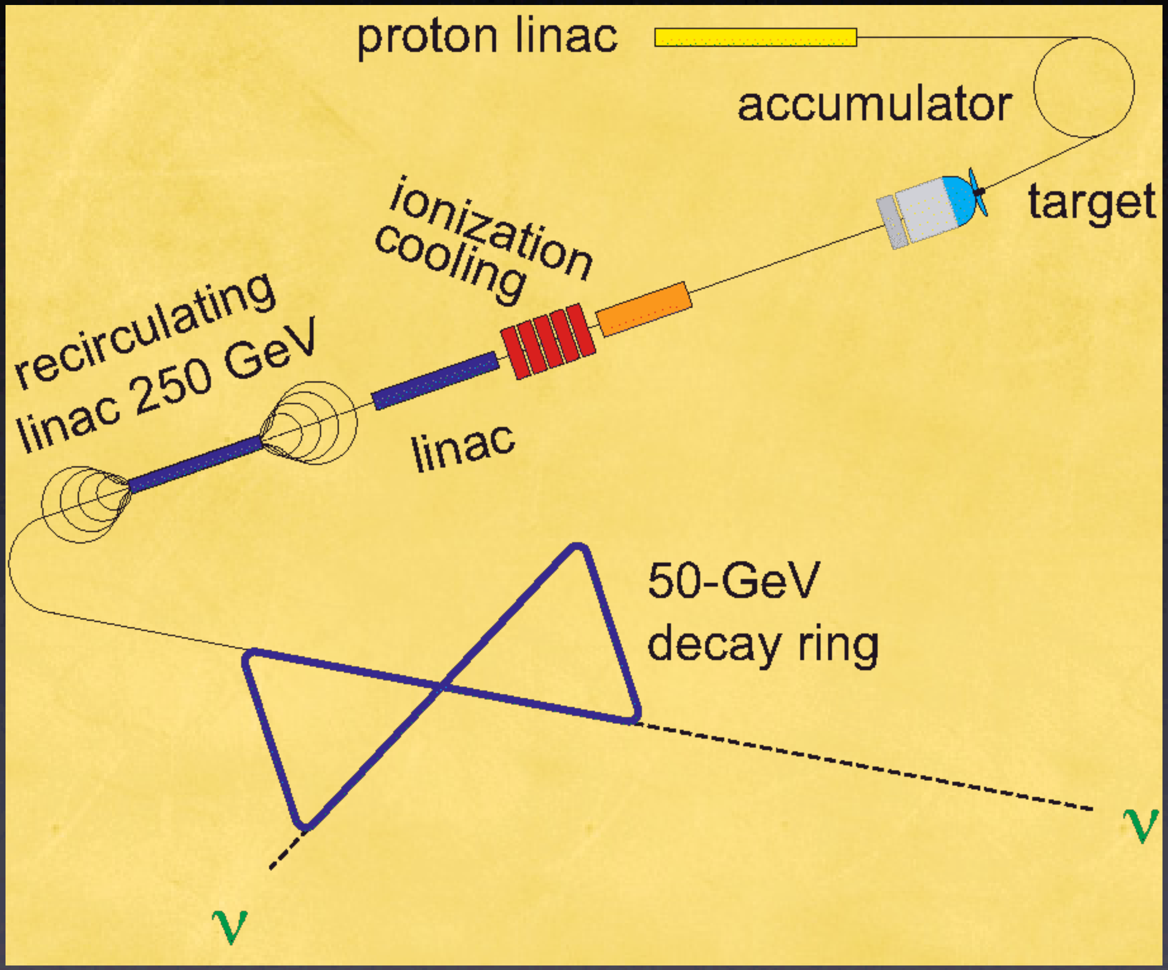
μ: elementary lepton, so energy efficient
synchrotron radiation not crippling

small collider would reach 1-TeV scale
?? modest size ↔ modest cost ??

But muons decay – must move fast!
Fierce detector, machine environment

The Ultimate Neutrino Source?

Muon storage ring with a millimole of muons per year



Beam from μ^- contains ν_μ, $\bar{\nu}_e$, but no $\bar{\nu}_\mu$, ν_e, ν_τ, or $\bar{\nu}_\tau$.

oscillation studies, scattering on thin targets

Beyond the LHC: a Very Large Hadron Collider

LHC Discoveries could point to much higher energies

- ✳ Heavy Higgs boson
- ✳ New strong dynamics
- ✳ New gauge bosons
- ✳ Hints of large extra dimensions

VLHC is the one multi-TeV machine we know we can build

Pointlike cross sections $\propto 1/E_{\text{cm}}^2 \Rightarrow$
$$\mathcal{L}^\star = 10^{32\text{-}33}\ \text{cm}^{-2}\ \text{s}^{-1}\,(E_{\text{cm}}/40\ \text{TeV})^2$$

For $E_{\text{cm}} = 100$ TeV, target $\mathcal{L}^\star \approx 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$

e^+e^- Linear Collider

A lovely idea! (40 years in the making)

- ✳ Multi-TeV to match LHC reach: CLIC
- ✳ Detailed studies of Higgs, top, light SUSY: 500 GeV
- ✳ Additional Higgs, sleptons, EW gauginos: 1 TeV
- ✳ Ultraprecision: 10^9 Z bosons

Advantages: point particle, little background
Challenges: reaching high energy, high luminosity

International Linear Collider Goals

$E_{cm} \approx 1$ TeV, first operation at 500 GeV
Luminosity : 1/2 ab^{-1} per year
$\gtrsim$ 80% electron polarization

Science opportunities:

Past decade sharpened case for exploring 1-TeV scale

TeV LC is an ideal complement to LHC, a Higgs lab

Higgs lifetime, J^{PC}, for $M_H \lesssim 200$ GeV

Higgs contributions to W, Z, b, c, τ masses, $M_H \lesssim 2\,M_W$

Probe Higgs-boson self interactions