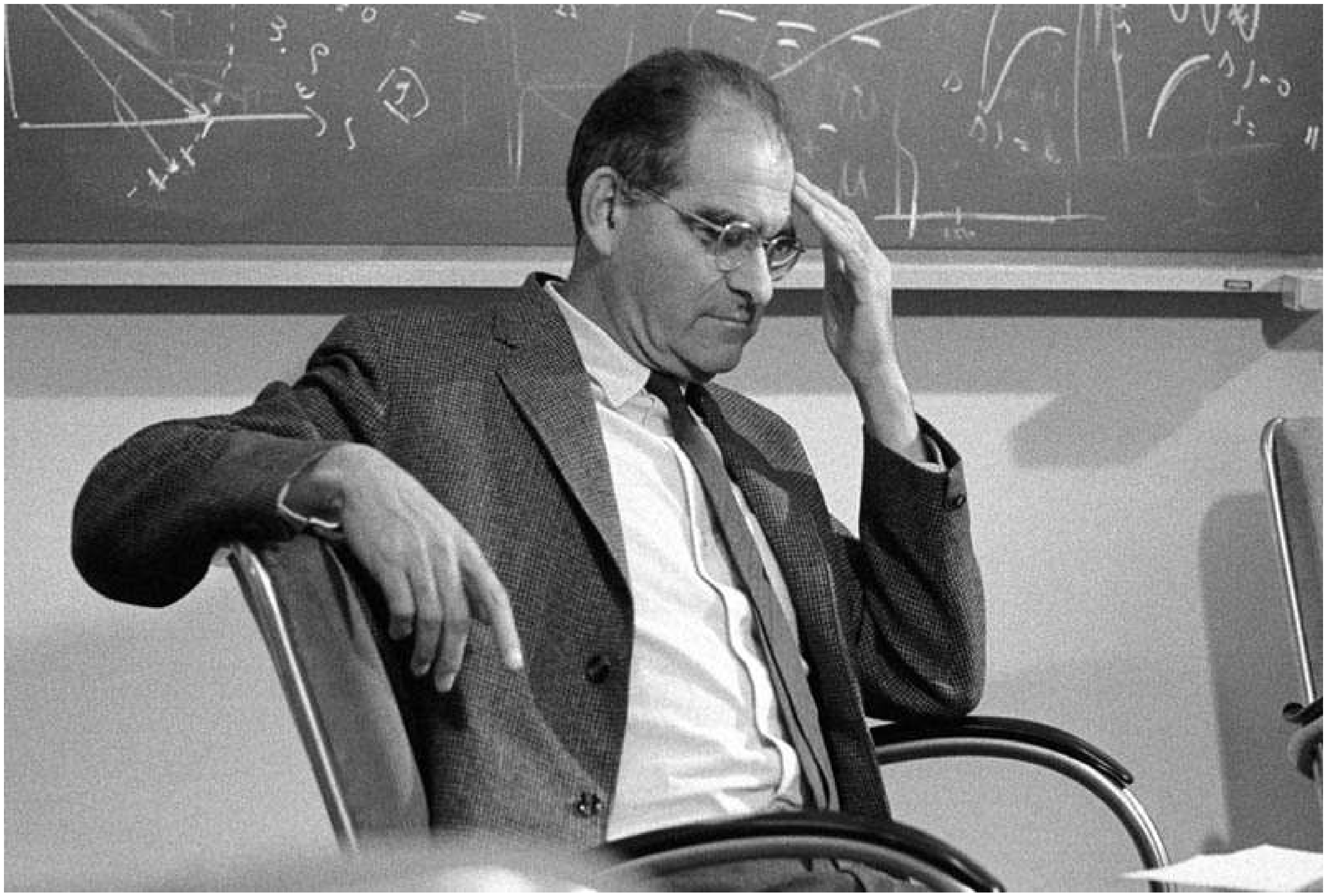
Revolutions and Revelations

Chris Quigg
Fermilab

LHC Physics Symposium · Vienna · July 17, 2004

Viki Weisskopf

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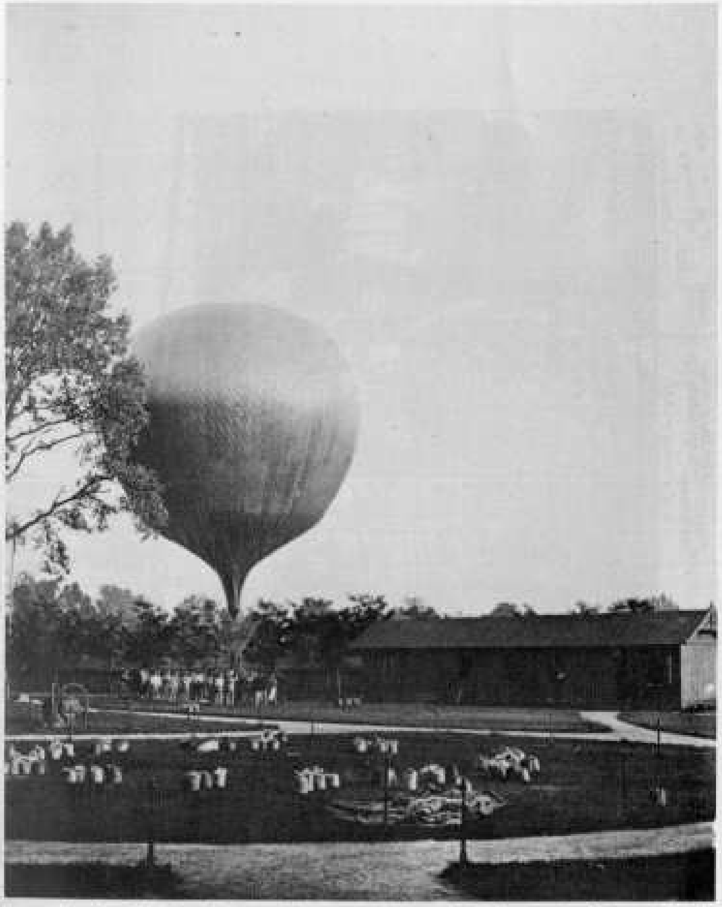
Who loves SuSy?

Ausgezeichnet!

Victor Hess im Prater

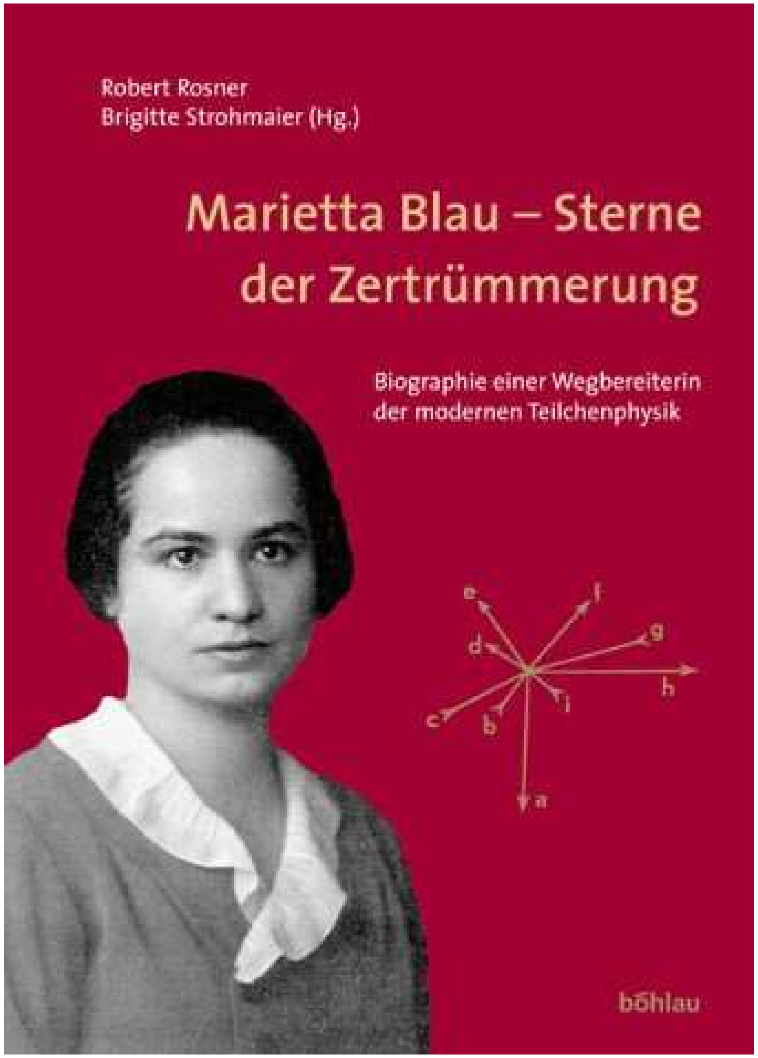


Aeronautisches Gelande im Wiener Prater, von dem aus V. F. Hess in den Jahren 1911/12 seine ersten Freiballon-Forschungsfahrten unternommen hatte. (Courtesy of Heeresgeschichtliche Museum, Vienna)

<Ed> Contributed by R. Steinmaurer. See p. 17.

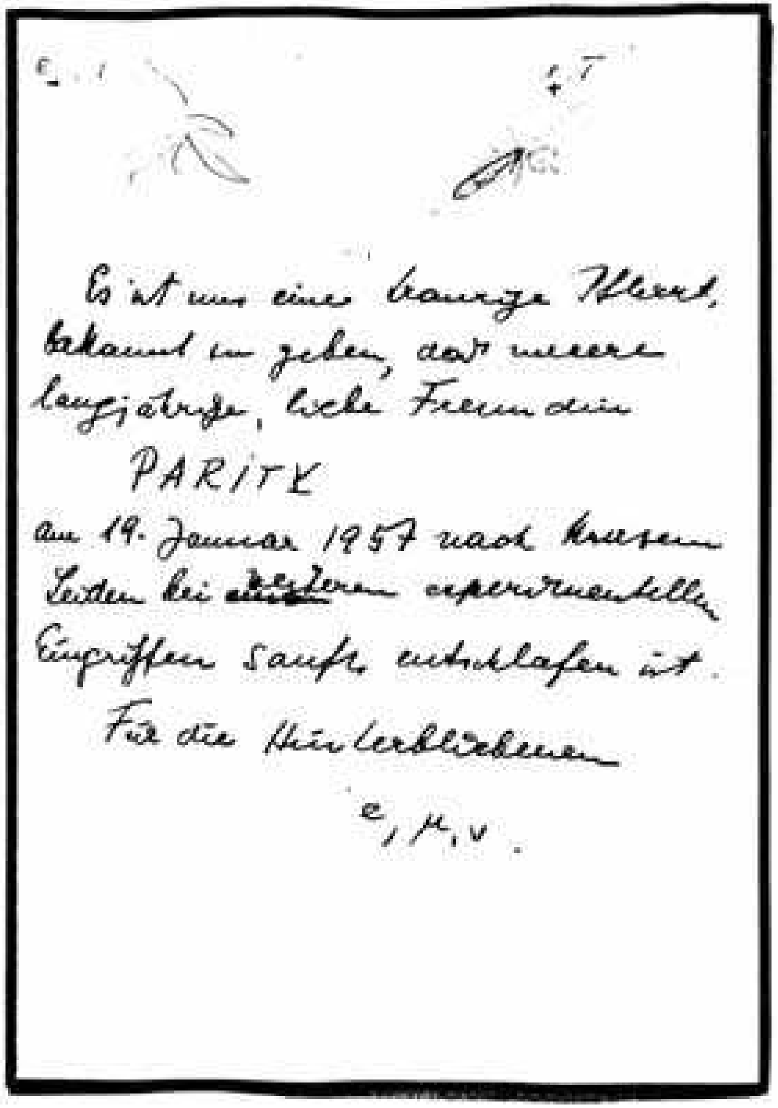
conductivity of atmosphere . . .

Marietta Blau



Wolfgang Pauli's Assertiveness Training

Pauli's Sensitive Side



Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige, liebe Freundin

PARITY

am 19. Januar 1957 nach kurzem Leiden bei weiteren experimentellen Eingriffen sanft entschlafen ist.

Für die Hinterbliebenen

e, μ, ν.

A Decade of Discovery Past . . .

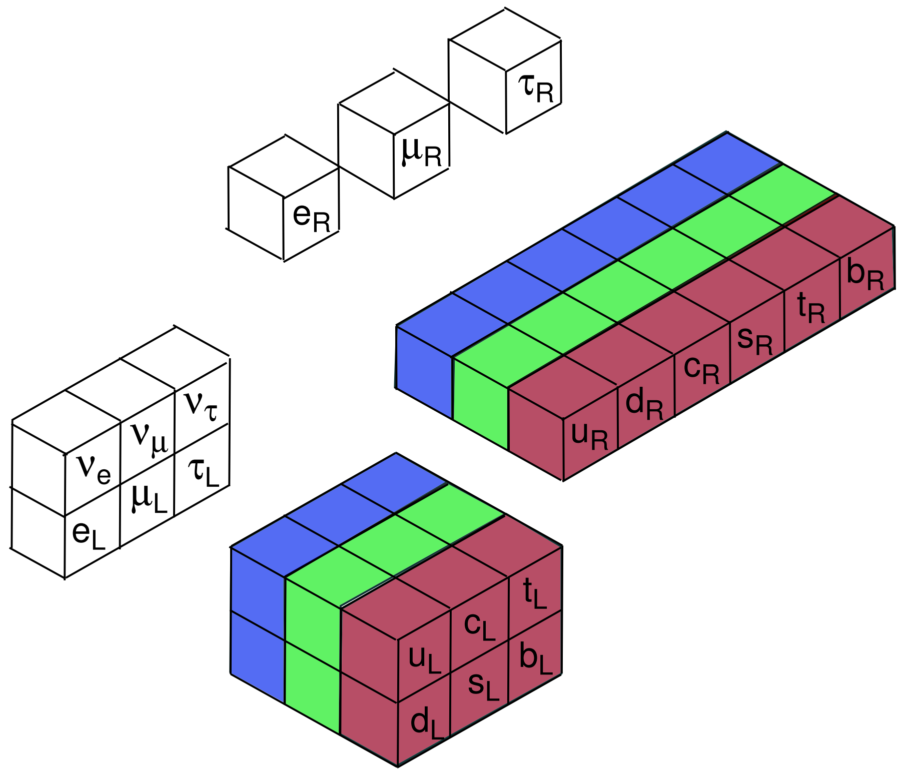
- $\triangleright$ Electroweak theory $\longrightarrow$ law of nature
- $\triangleright$ Higgs-boson influence observed in the vacuum
- $\triangleright$ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$
- $\triangleright$ Understanding QCD
- $\triangleright$ Discovery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

Our Picture of Matter (the Revolution Just Past)

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



with interactions specified by

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

gauge symmetries . . .

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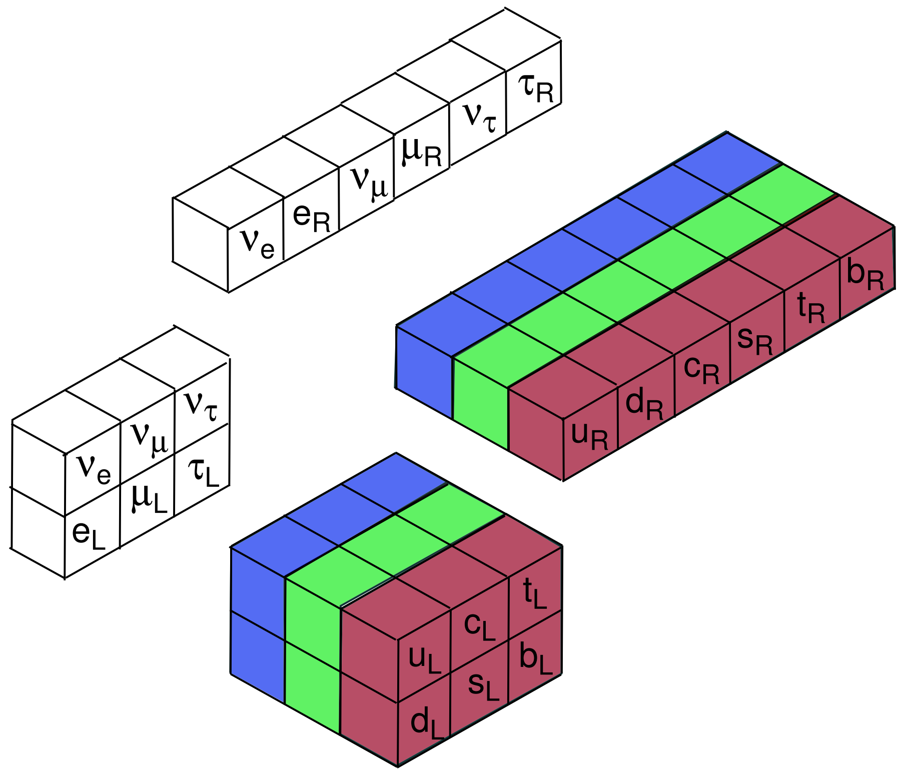

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gauge symmetries . . .

The World's Most Powerful Microscopes

Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

cos θ* = 0.30

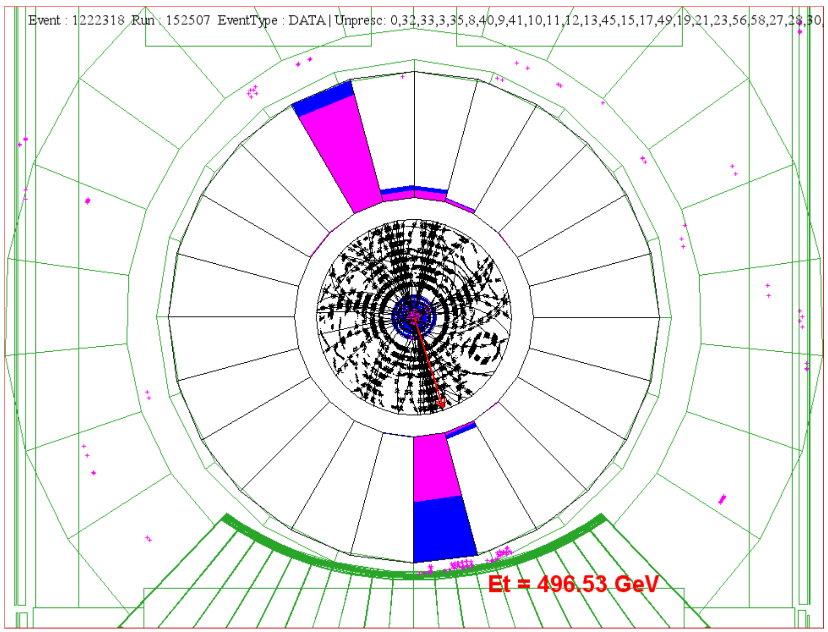
z vertex = -25 cm

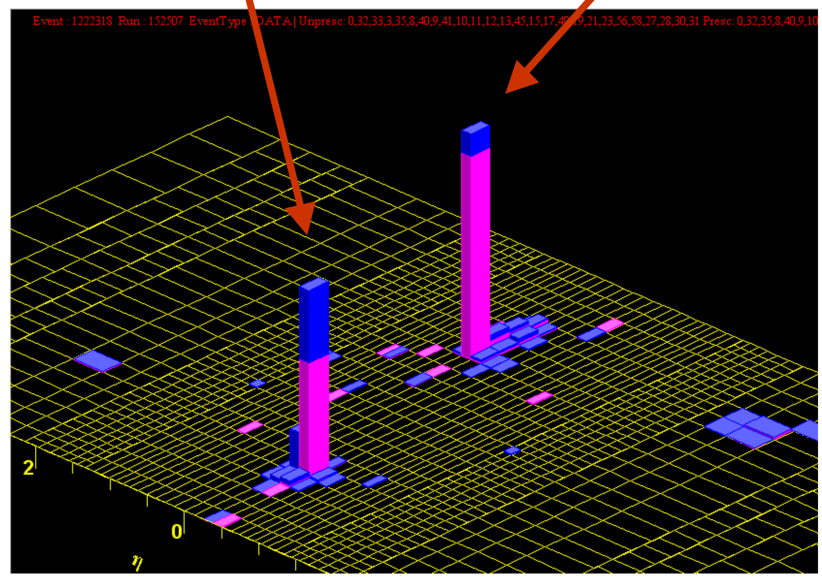
J2 E_T = 633 GeV (corr)
546 GeV (raw)

J2 η = -0.30 (detector)
= -0.19 (correct z)

J1 E_T = 666 GeV (corr)
583 GeV (raw)

J1 η = 0.31 (detector)
= 0.43 (correct z)



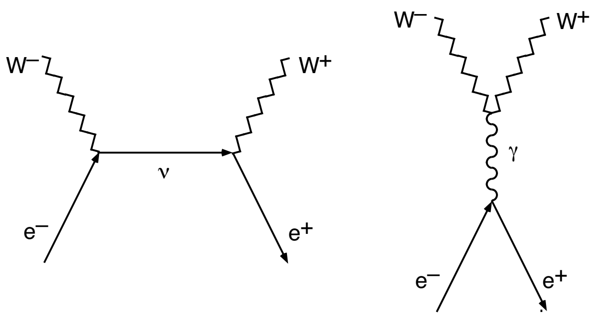


CDF Run 2 Preliminary

Tevatron at Fermilab: 980-GeV protons: $c - 495$ km/h

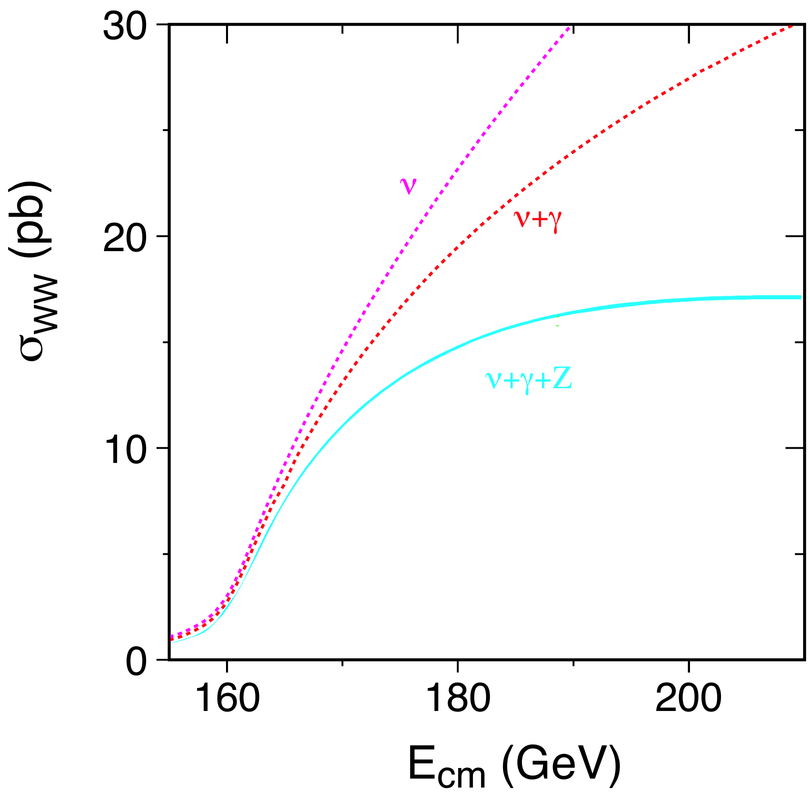
Large Hadron Collider at CERN, 7-TeV protons: $c - 10$ km/h

Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



each grows unacceptably . . .

but the sum
is well-behaved



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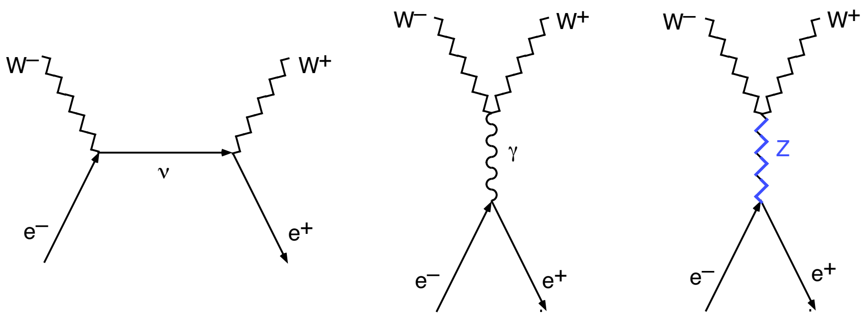

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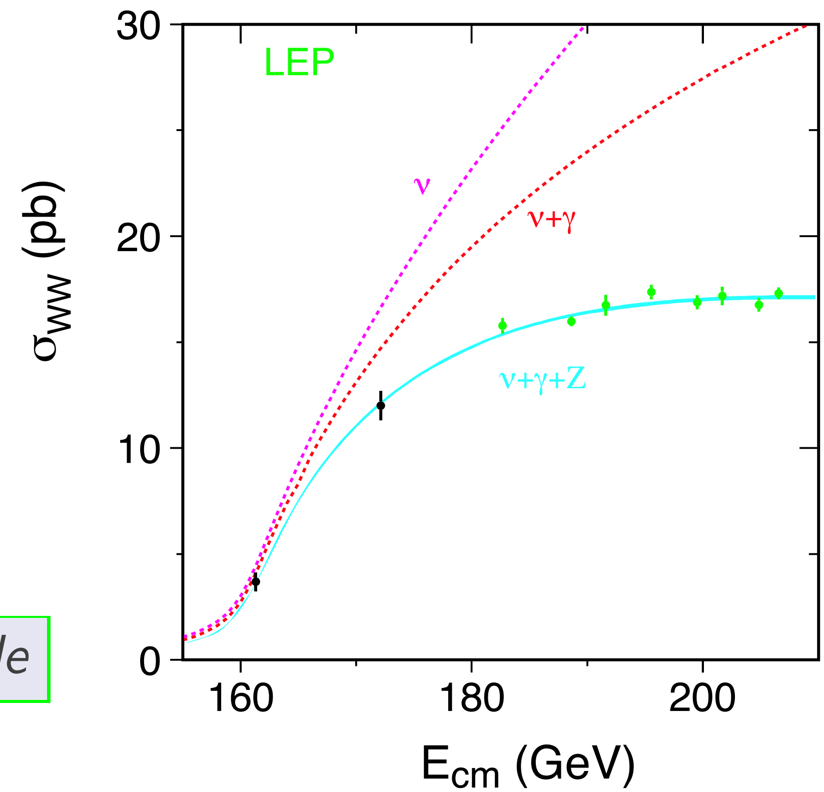


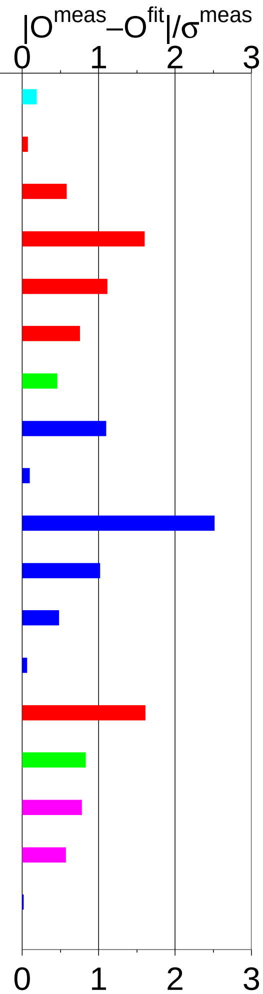
. . . and describes Nature!

New physics on TeV scale

Precision measurements test the theory . . .

Winter 2004

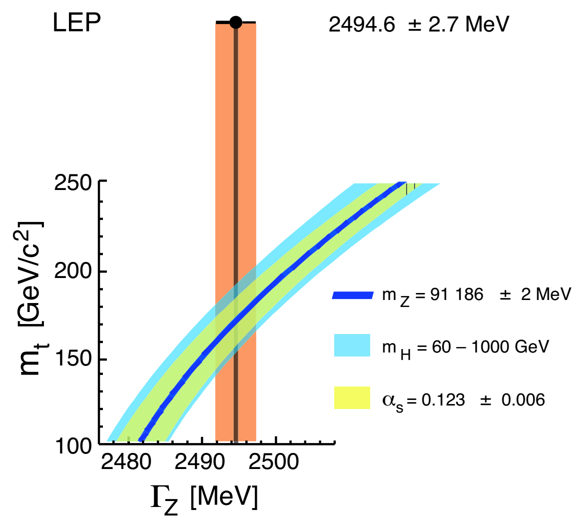
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1

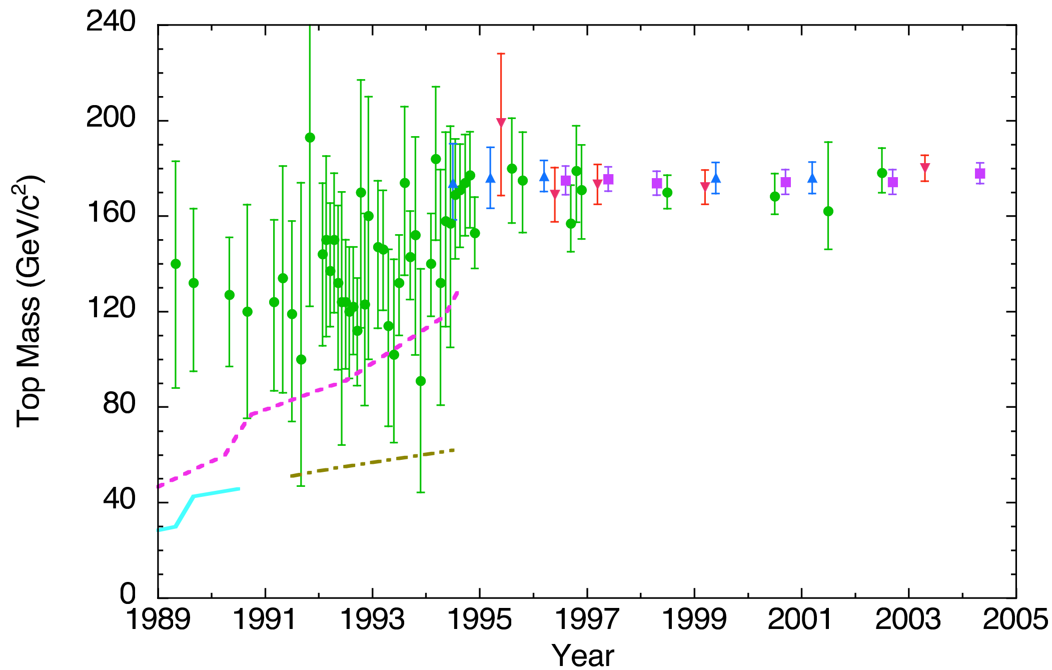


LEP Electroweak Working Group

Precision measurements determine unknown parameters . . .

Infer top mass through quantum corrections:





Revolution:

Understanding the Everyday

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

If electroweak symmetry were not hidden . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them into color-singlet hadrons

▷ *Nucleon mass would be little changed,* but proton outweighs neutron

▷ QCD breaks EW symmetry, gives $(1/2500\times$observed) masses to W, Z, so weak-isospin force doesn't confine

▷ Rapid! β-decay $\Rightarrow$ lightest nucleus is one neutron; no hydrogen atom

▷ Probably some light elements in BBN, but ∞ Bohr radius

▷ No atoms (as we know them) means no chemistry, no stable composite structures like the solids and liquids we know

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

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.

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.

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

- ▷ A fundamental 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 the weak 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, fermions?
- ▷ How does H interact with itself?

Finding the Higgs boson starts a new adventure!

Revolution:

The Meaning of Identity

Varieties of Matter

▷ What sets masses & mixings of quarks & 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 see the pattern?
sterile neutrinos, superpartners, dark matter . . .

Many extensions to EW theory entail dark matter candidates.

Supersymmetry is highly developed, and has several important consequences:

▷ Predicts that the Higgs field condenses (breaking EW symmetry), if the top quark is heavy

▷ Predicts a light Higgs mass

▷ Predicts cosmological cold dark matter

▷ In a unified theory, explains the values of the standard-model coupling constants

Revolution:

The Unity of Quarks & Leptons

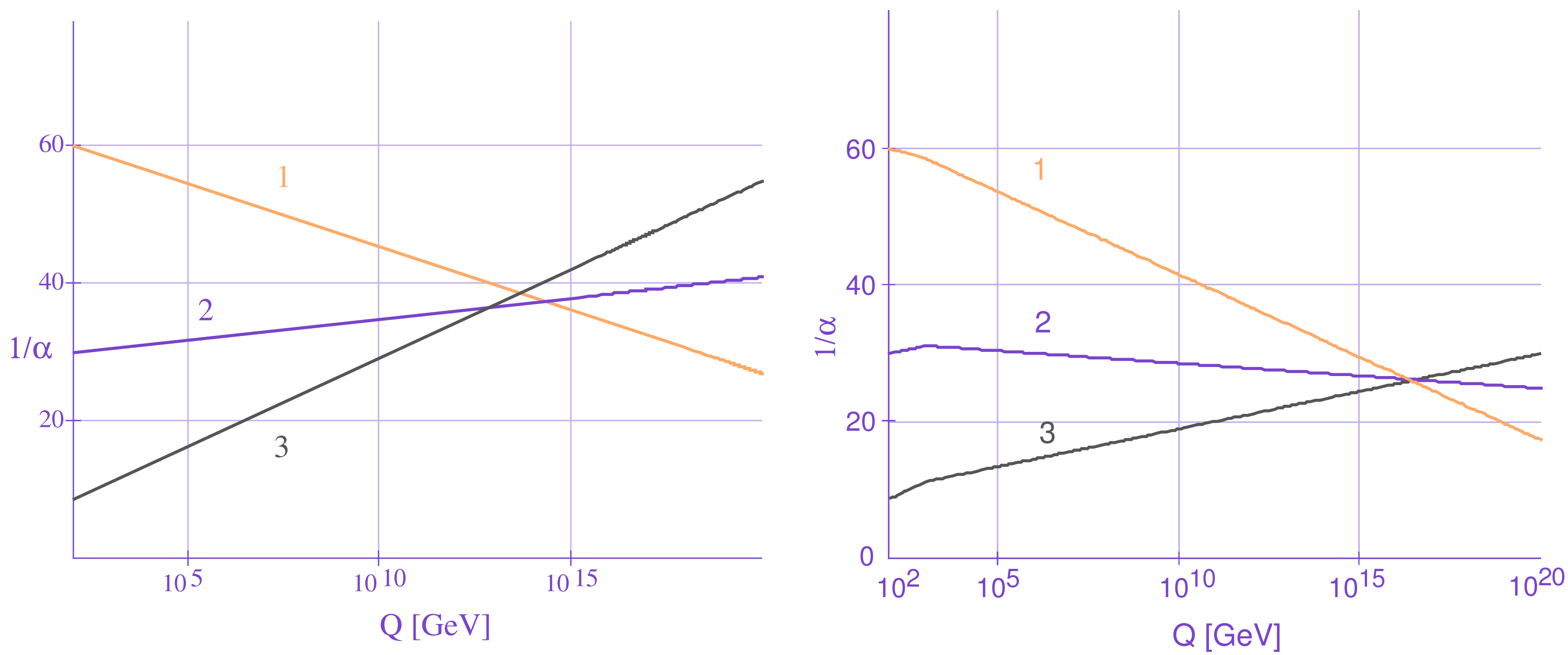
$\triangleright$ What do quarks and leptons have in common?

$\triangleright$ Why are atoms so remarkably neutral?

$\triangleright$ Which quarks go with which leptons?

$\triangleright$ Quark-lepton extended family $\rightsquigarrow$ proton decay:
SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y

$\triangleright$ Unified theories $\rightsquigarrow$ coupling constant unification
$\triangleright$ Rational fermion mass pattern at high energy?
(Masses run, too)



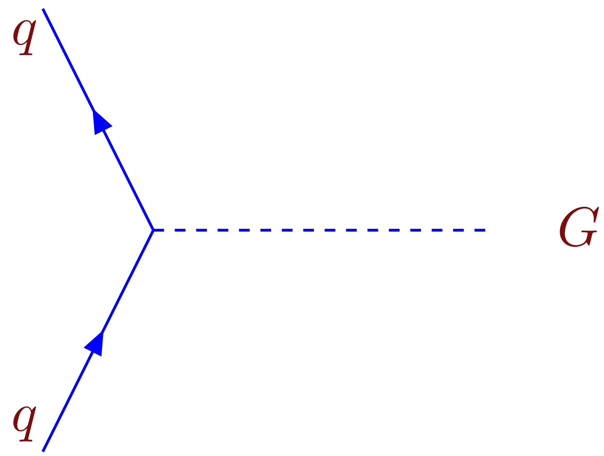
60
40
20
0
1/α
1
2
3
10 5
10 10
10 15
10 2
10 20
Q [GeV]

Revolution:

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

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

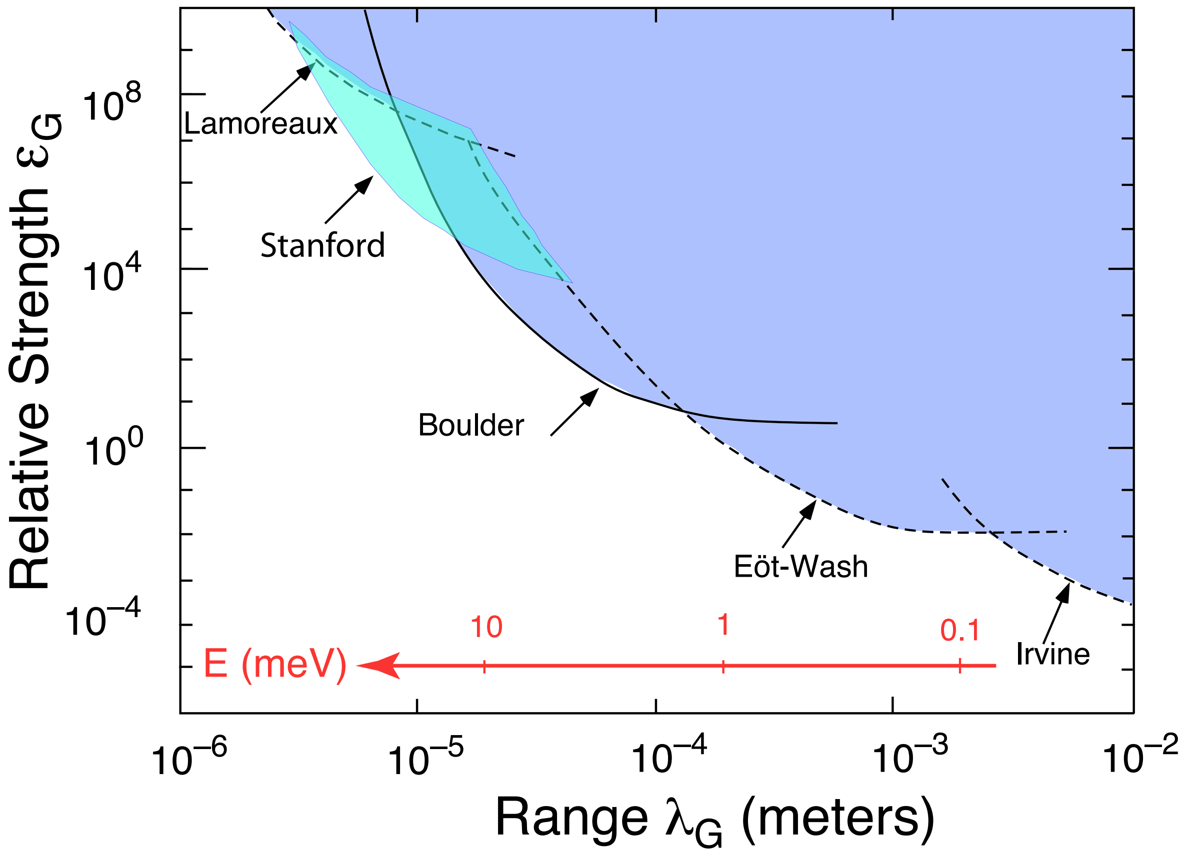


$$\sim \frac{E}{M_{\text{Planck}}}$$

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

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

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



(long-distance alternatives to dark matter)

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

contributes field-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8}}$$

Adding vacuum energy density $\varrho_{\mathrm{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

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

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

≈ 10 MeV$/\ \ell$ or 10^{-29} g cm^{-3}

But $M_H \gtrsim 114$ GeV $\Rightarrow$

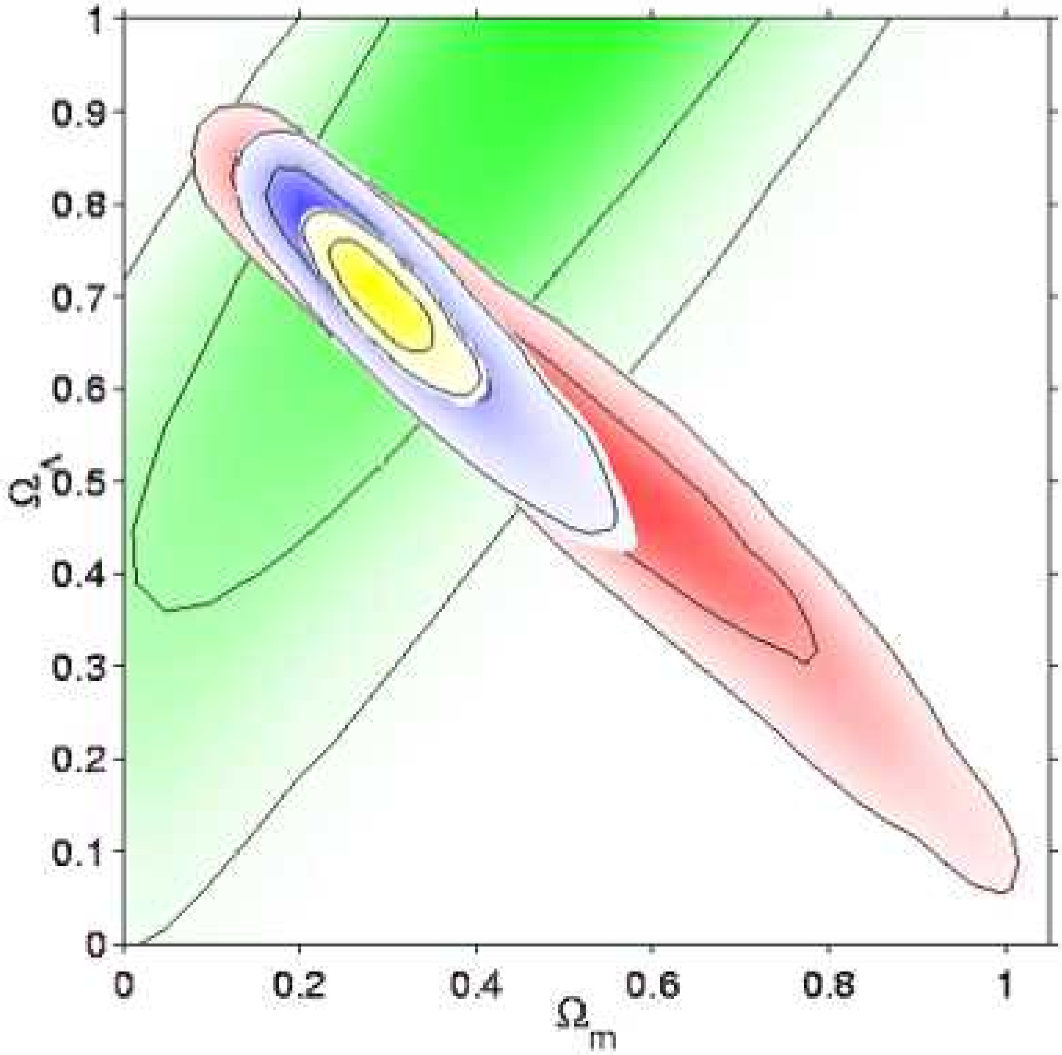
$$\varrho_H \gtrsim 10^8 \text{ GeV}^4$$

MISMATCH BY 54 ORDERS OR MAGNITUDE

A chronic dull headache for thirty years . . .

Why is empty space so nearly massless?

Evidence that vacuum energy is present . . .



. . . recasts the old problem and gives us properties to measure

How to separate EW scale from higher scales?

Conventional approach: change electroweak theory to understand

why M_H, electroweak scale $\ll M_{\mathsf{Planck}}$

To resolve the hierarchy problem: *extend the standard model*

$$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \begin{cases} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{cases}$$

Newer approach: ask why gravity is so weak

why $M_{\mathsf{Planck}} \gg$ electroweak scale

Revolution:

A New Conception of Spacetime

Revolution:

A New Conception of Spacetime

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

▷ What is their size?

▷ What is their shape?

▷ How do they influence the world?

▷ How can we map them?

9 or 10 needed for consistency of string theory

Suppose at scale R ... Gravity propagates in $4+n$ dimensions

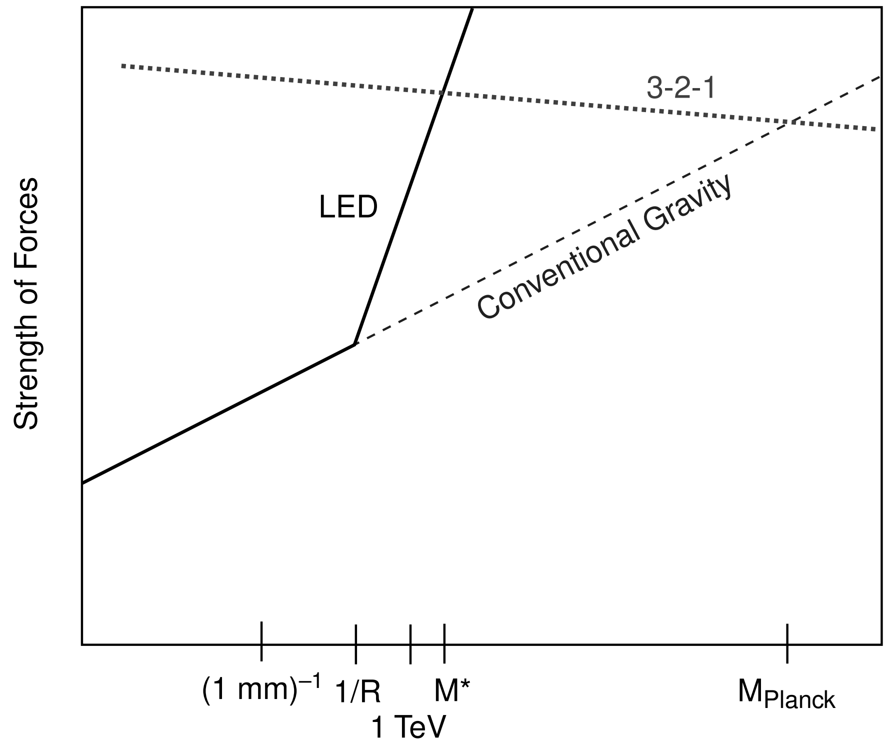
Force law changes:

Gauss's law $\Rightarrow$ $G_{\text{N}} \sim M_{\text{Pl}}^{-2} \sim M^{\star\,-n-2} R^{-n}$ $M^\star$: gravity's true scale

Example: $M^\star = 1$ TeV $\Rightarrow R \lesssim 10^{-3}$ m for $n = 2$

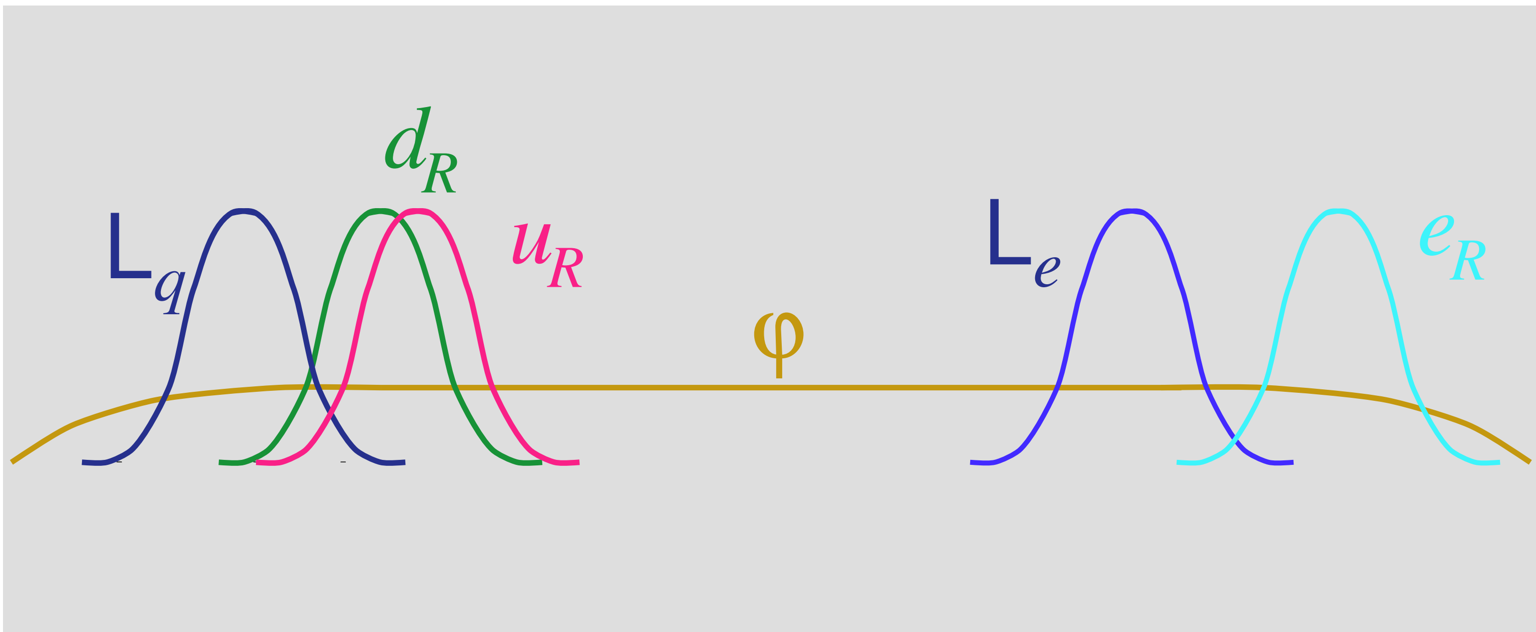
Traditional: Use 4-d force law to extrapolate gravity to higher energies; $M_{\text{P}} \sim$ scale where Gravity, SM forces are of comparable strength

IF Gravity probes extra dimensions for $E \lesssim 1/R$, Gravity meets other forces at $E = M^\star \ll M_{\text{P}}$



M_{P} is a mirage (false extrapolation)!

Might Extra Dimensions Explain the Range of Fermion Masses?



Different fermions ride different tracks in the fifth dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

Other extradimensional delights . . .

(provided gravity is intrinsically strong)

▷ If the size of extra dimensions is close to 10^{-19} m, tiny black holes might be formed in high-energy collisions: explosive evaporation ⇒ collider hedgehogs, spectacular UHECR showers

▷ Collider experiments can detect graviton radiation (missing-energy signatures) or graviton exchange (angular distributions)

(Cf. Dyson v. Greene, http://www.nybooks.com/articles/17094)

Gravity is here to stay!

(Double Simplex)

Need to Prepare Many Revolutions!

- Experiments at the energy frontier
- Experiments at high sensitivity
- Fundamental physics with “found beams”
- Astrophysical observations
- The importance of scale diversity for a healthy and productive future

Observations, opportunities, concerns

In the spirit of Jos Engelen's messages to "friendly laboratories"

- ▷ To CERN: Keep your focus on the LHC to make it a glorious success—*soon!* You carry the hopes and dreams of us all. Beware inattention.
- ▷ To CERN and ECFA and EPS: Please find ways to welcome others into Europlanning. (Example of Snowmass 2001)
- ▷ To *all* the rulers of the particle physics universe: We thrive on competition, but hyperunilateralism will be our common undoing. We all have a stake in a healthy program around the world.

Observations, opportunities, concerns

- ▷ To the LHC community: Respect the Tevatron, hope for some vigorous competition, and
  learn from the Tevatron experience.

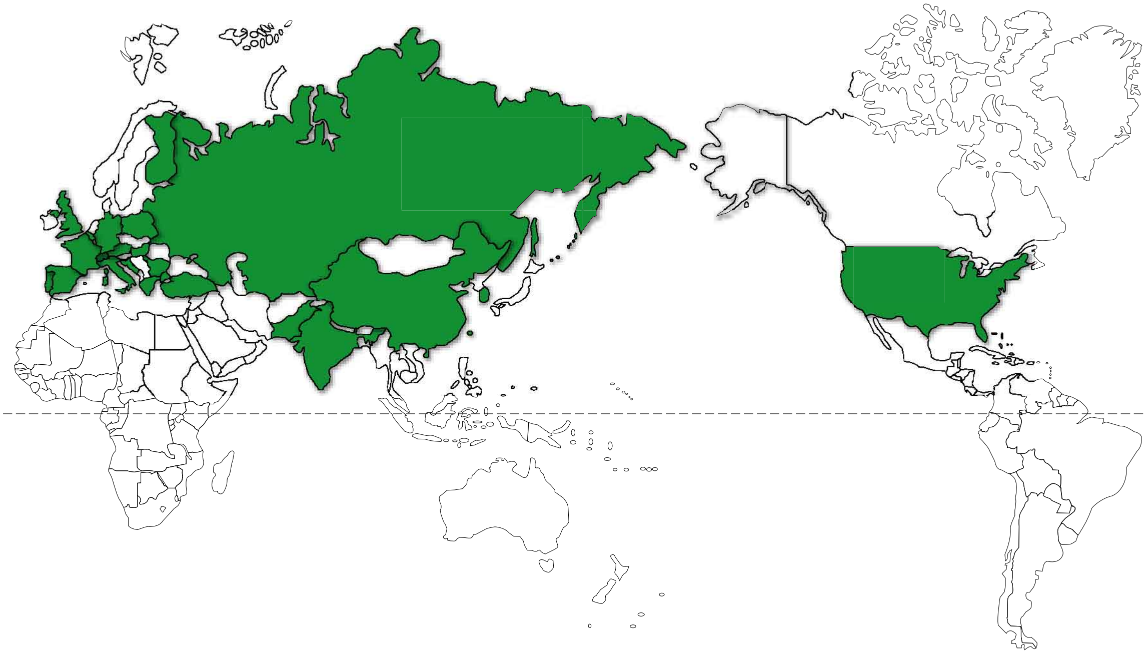
TeV4LHC Workshop, September 16–18 at Fermilab

  Improve simulations to enhance LHC analyses

- ▷ To all of us: We have an obligation to involve more people in the adventure of our science, our trust in experiment over authority, and our shared belief in the power of reason and the importance of doubt.

CMS Collaboration

31 Nations, 150 Institutions, 1870 Scientists and Engineers




Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
China
Germany
Danmark
Spain
Finland
France
Georgia
Greece
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Japan
Kazakhstan
Morocco
Norway
Netherlands
Portugal
Poland
Romania
Russia
Sweden
Switzerland
Slovenia
Slovakia
Taiwan
Turkey
UK
USA
ATLAS
Collaboration
DEB 97

Observations, opportunities, concerns

- ▷ To the LHC community: How will we actually *do physics* at the LHC? Can everyone who wants / needs to participate be accommodated at CERN? What would be required for people to participate effectively at regional analysis centers? (Of the centers? of CERN? of the experiments?)

- ▷ To all of us: How can we advance the commissioning of the Right Linear Collider? Must we execute projects in sequence? Can we optimize scientific return by executing in parallel, through cooperation and global networks?

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]

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

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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!