*XXII Nordic Particle Physics Meeting*

# Potential Discoveries at the Large Hadron Collider

Chris Quigg

*Fermilab*

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# Potential Discoveries at the Large Hadron Collider


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Lecture I

# Two New Laws of Nature +

Pointlike ($r < 10^{-18}$ m) quarks & leptons

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

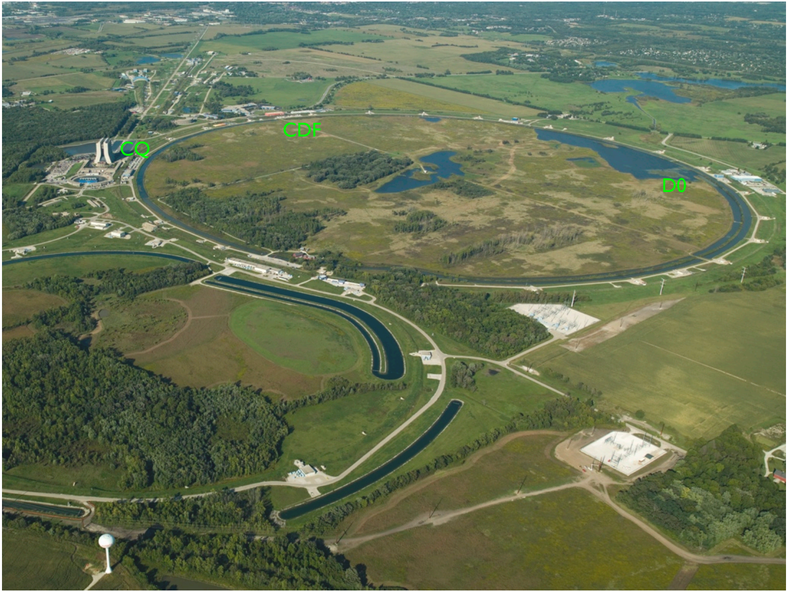
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Interactions derived from gauge symmetries

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

Electroweak symmetry breaking: Higgs mechanism?

# Tevatron: $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV



# Tevatron Highlights

CERN Courier October 2011

Collider physics

## Long live the Tevatron

As the Tevatron closes down, the data analysis continues, but there are already many areas in which the experiments have delivered results of enduring importance. **Chris Quigg** surveys some highlights.

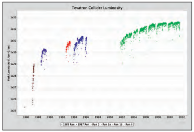



*Fig. 1. Initial luminosity for all fills in the Tevatron collider. The peak luminosity reached $4.3 \times 10^{32}\,cm^{-2}s^{-1}$ – about 30 million collisions per second.*

A quarter-century of experimentation has come to a close at Fermilab's Tevatron collider, a pioneering instrument that advanced the frontiers of accelerator science and particle physics alike, setting the stage for the LHC at CERN. The world's first high-energy superconducting synchrotron, the Tevatron served as the model for the proton ring in the HERA collider at DESY and as a key milestone towards the development of the LHC. In its final months of operation the Tevatron's initial luminosity for proton–antiproton collisions at 1.96 TeV averaged more than $3.5 \times 10^{32}\,\mathrm{cm^{-2}s^{-1}}$. The integrated luminosity delivered at 1.96 TeV approached $12\,\mathrm{fb^{-1}}$, with approximately $10\,\mathrm{fb^{-1}}$ recorded by the CDF and DØ experiments. A long line of innovations and much perseverance made possible the evolution of luminosity shown in figure 1 (Holmes *et al*. 2011).

The legacy of the Tevatron experiments includes many results for which the high energy of a hadron collider was decisive. Chief among these is the discovery of the top quark, which for 15 years could be studied only at the Tevatron. Exacting measurements of the masses of the top quark and the W boson and of the frequency of $B_s$ oscillations punctured the myth that hadron colliders are not precision instruments. Remarkable detector innovations such as the first hadron-collider silicon vertex detector and secondary vertex trigger, and multilevel triggering are now part of the standard experimental toolkit. So, too, are robust multivariate analysis techniques that enhance the sensitivity of searches in the face of challenging backgrounds. CDF and DØ exemplify one of the great strengths of particle physics: the high value of experimental collaborations whose scientific interests and capabilities expand and deepen over time – responding to new opportunities and delivering a harvest of results that were not imagined when the detectors were proposed.

### Early days

The CDF logbook records the first collision event in the Tevatron at 02.32 a.m. on 13 October 1985, at an energy of 800 GeV per beam. The estimated luminosity was $2 \times 10^{25}\,\mathrm{cm^{-2}s^{-1}}$, more than seven orders of magnitude below the machine's performance in 2011. By the afternoon, the Tevatron complex was shut down for 18 months to construct the DØ interaction region and complete the CDF detector. CDF's pilot run in 1987 yielded the first wave of physics papers, including measurements and searches. During 1988 and 1989 CDF accumulated $4\,\mathrm{pb^{-1}}$, now at 1.8 TeV in the centre of mass. (Two special-purpose experiments also published results from this run. Experiment 710 measured elastic scattering and the total cross-sections; Experiment 735 sought evidence of a deconfined quark–gluon plasma.) The peak luminosity delivered to CDF surpassed $10^{30}\,\mathrm{cm^{-2}s^{-1}}$ in collisions of six proton bunches on six antiproton bunches. Papers from these early runs are worth rereading as reminders of how little we knew, and how a tentative but growing respect for the Standard Model brought coherence to the interpretation of results. It is also interesting to see how the experimenters went about gaining confidence in their detector and their analysis techniques.

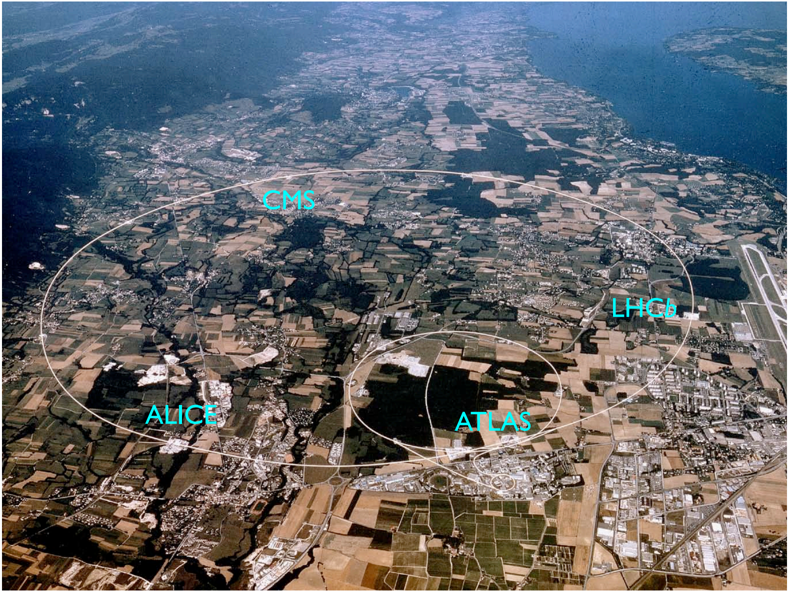
**The legacy of the Tevatron includes many results for which the high energy of a hadron collider was decisive.**

Both DØ and CDF took data at 1.8 TeV in the extended Run 1 between 1992 and 1996, recording $120\,\mathrm{pb^{-1}}$. An important enabler of increased luminosity was the move to helical orbits, which eliminated collisions outside the two interaction regions. During this period, a small test experiment called MiniMax (T864) searched for disordered chiral condensates and other novel phenomena in the far-forward region. This was a time of high excitement, not only ▷

[1]

R. Dixon: *The Machine*

# Large Hadron Collider: $pp$ at $\sqrt{s} \to 14$ TeV



# Setting the Scene

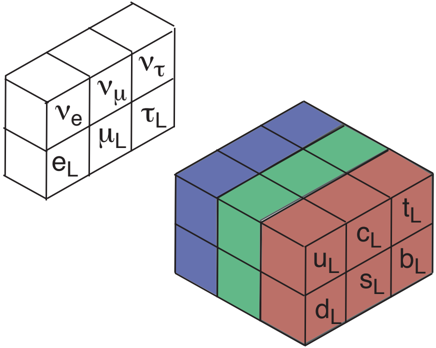
- ▷ Electroweak theory validated [$Z$, $e^+e^-$, $\bar{p}p$, $\nu N$, …]
- ▷ Higgs-boson influence observed [EW experiments]
- ▷ Neutrino oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, $\nu_{\mathrm{atm}}$]
- ▷ QCD [heavy flavor, $Z^0$, $\bar{p}p$, $\nu N$, $ep$, lattice]
- ▷ 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 U, mostly dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of $\nu_\tau$ interactions [fixed-target]
- ▷ Constituents structureless at TeV scale [mainly colliders]

Explore

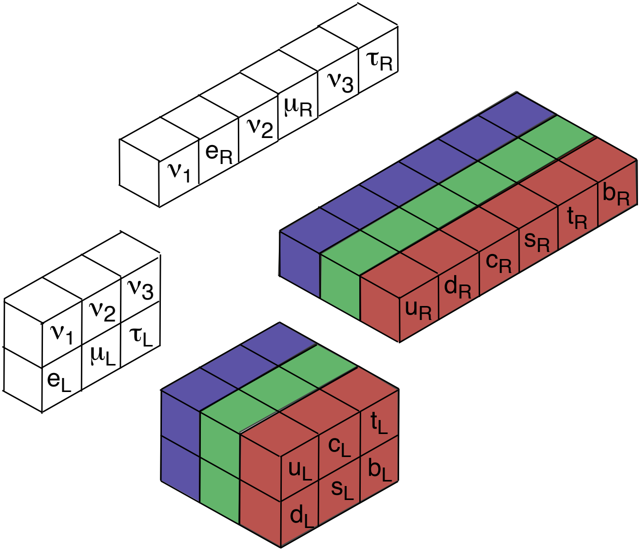
Search

Measure

# Our Picture of Matter



# Our Picture of Matter



# Quantum Chromodynamics: Yang-Mills theory for $SU(3)_c$

Single quark flavor:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m)\psi - \frac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu})$$

composite spinor for color-**3** quarks of mass $m$

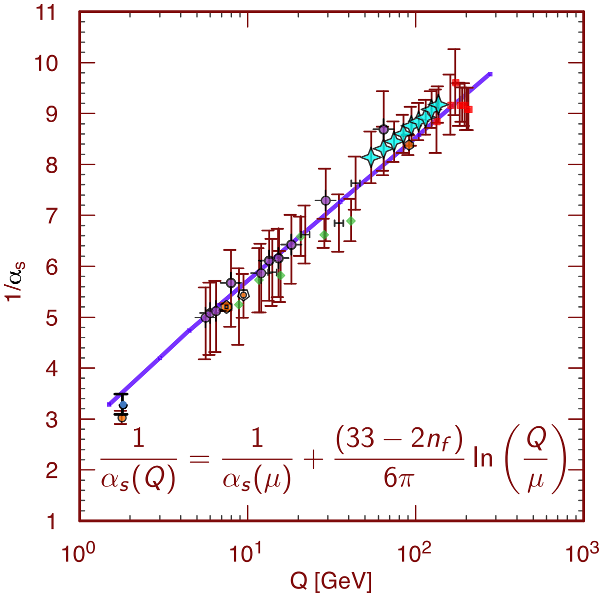
$$\psi = \begin{pmatrix} q_{\text{red}} \\ q_{\text{green}} \\ q_{\text{blue}} \end{pmatrix}$$

Gauge-covariant derivative:

$$\mathcal{D}_\mu = I\partial_\mu + igB_\mu$$

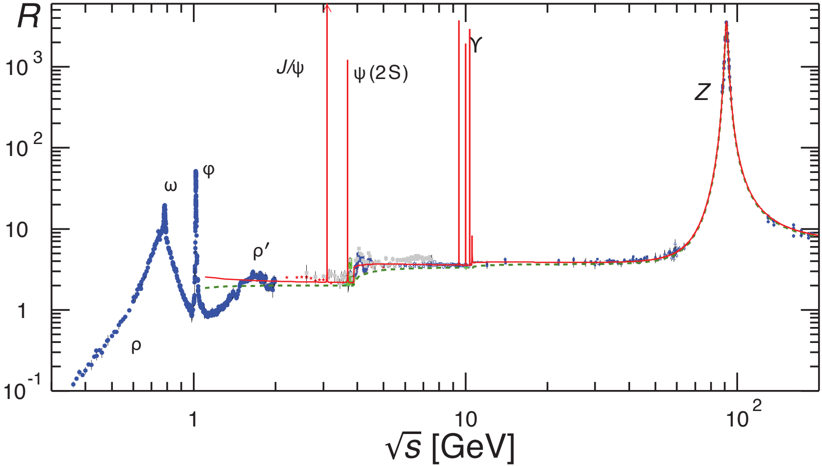
$g$: strong coupling; $B_\mu$: $3 \times 3$ matrix in color space formed from 8 gluon fields $B_\mu^\ell$ and $SU(3)_c$ generators $\frac{1}{2}\lambda^\ell$ ...

# QCD Tests: Asymptotic Freedom

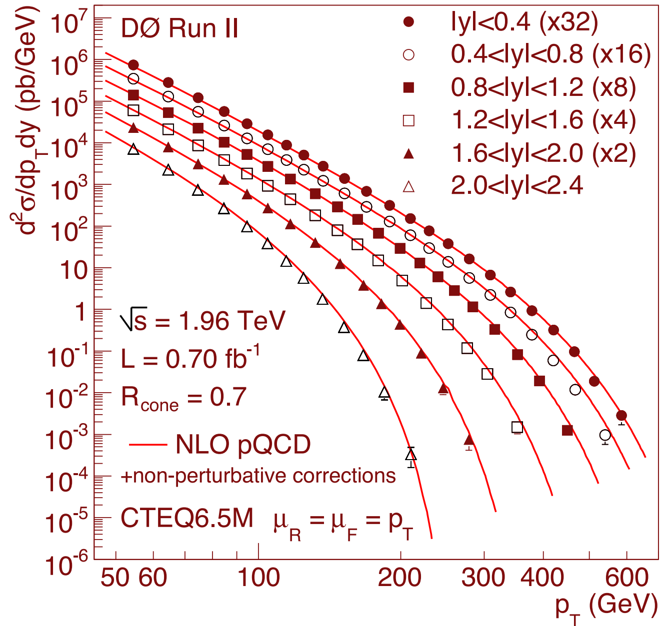



$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33 - 2n_f)}{6\pi} \ln\left(\frac{Q}{\mu}\right)$$

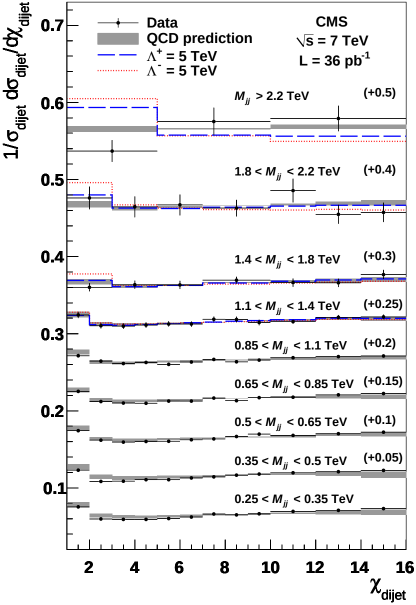
# QCD Tests: $e^+e^- \to$ hadrons



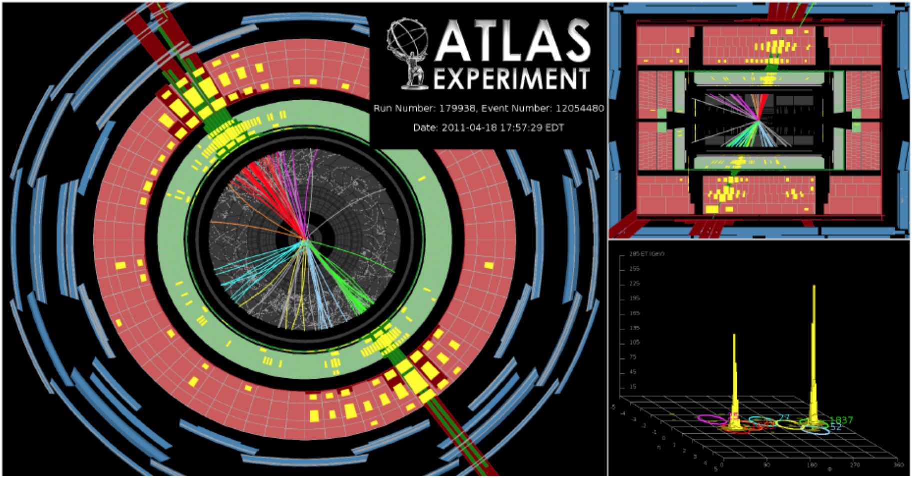
# QCD Tests: $\bar{p}p \longrightarrow$ jets



# QCD Tests: $pp \to$ jets $\quad \chi \equiv (1 + \cos\theta)/(1 - \cos\theta)$

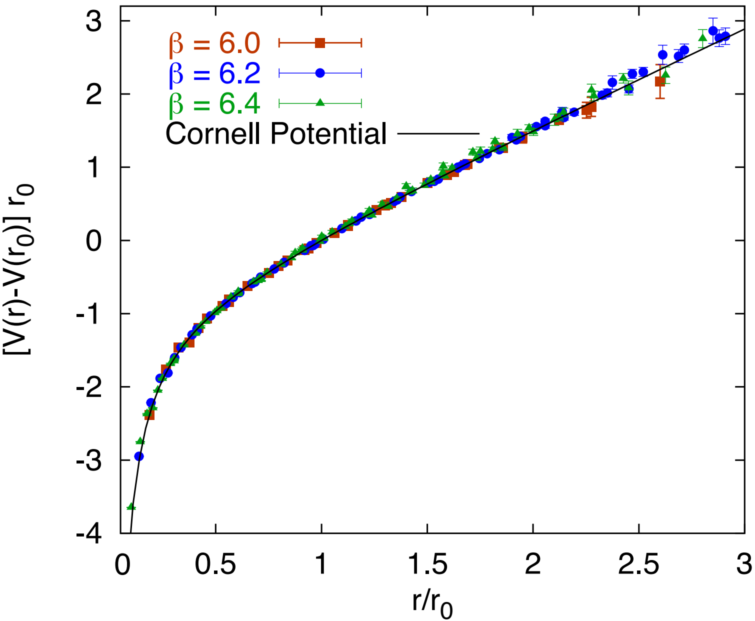


# QCD Tests: $pp \to$ jets *Nanonanophysics*

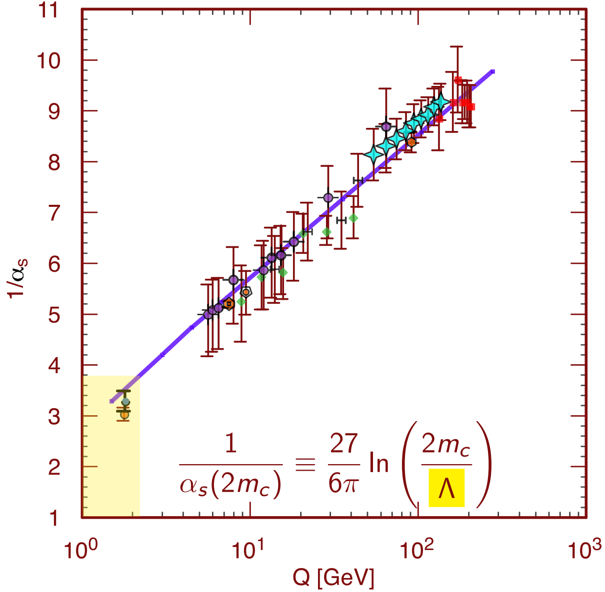



$p_\perp$: 1.8 TeV + 1.8 TeV · Dijet mass: 4 TeV

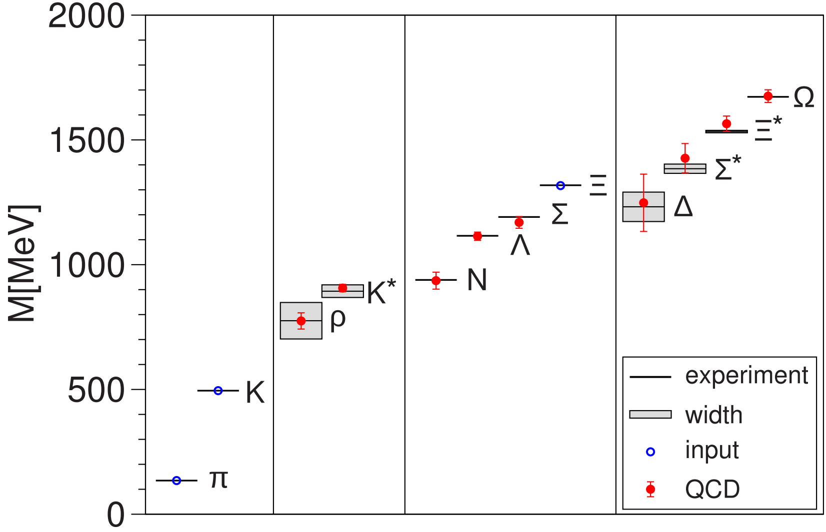
# QCD Tests: Quark Confinement



# Dimensional Transmutation

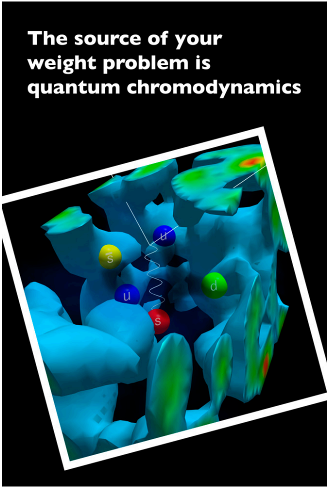


# Hadron Masses from Lattice QCD: $M = E_0/c^2$




BMW, *Science* **322,** 1224 (2008)

# QCD accounts for (most) visible mass in Universe




(*not* the Higgs boson)

# New Worlds Opened by the LHC

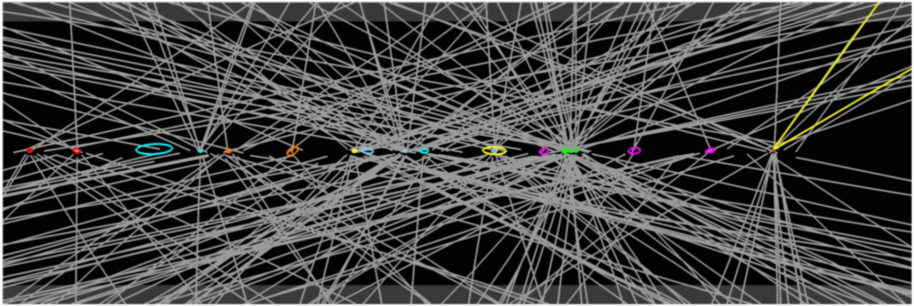
*Don't know what the new wave of exploration will reveal*

*True for lightly triggered events*
*as well as high mass scales*

Staged commissioning of LHC: opportunity to map gross features of particle production over a wide energy range

- Validate assumptions that underlie searches for new phenomena in hard-scattering events
- Develop intuition: LHC experimenters (+ theorists!)
- Opportunity for exploration and discovery

# Large Sample of Zero-bias Events?



# Exploring the New Landscape

CLNS-131
November 1970
September 1973

(Preliminary Version)

Some Experiments on Multiple Production*

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University,

Ithaca, New York 14850

A program of experiments is described mainly on secondary particle spectra to test scaling hypotheses derived from the multiperipheral model. It is assumed that diffraction dissociation and multiperipheral processes are distinct effects, and the consequences of this for the scaling laws are explained. Feynman's analogy linking multiple production to the statistical mechanical distribution functions of a gas is outlined, and based on this analogy it is suggested that one look for a correlation length in the two particle spectrum of secondaries.

# Wilson's Experiments in Multiple Production

*Some Experiments in Multiple Production*

- Multiplicities: diffractive + multiperipheral?
- Feynman scaling: $\rho_1(x \equiv k_z/E, k_\perp, E)$ indep. of $E$?
- Factorization: $\pi p$, $pp$ same in backward hemisphere?
- $dx/x$ spectrum (flat rapidity plateau)?
- Double Pomeron exchange?
- Short-range order:
  $\rho_2(y_1, y_2) - \rho_1(y_1)\rho_1(y_2) \propto \exp(-|y_1 - y_2|/L)$?
- Factorization test with central trigger (no diffraction)

# Isn't "Soft" Particle Production Settled Knowledge?

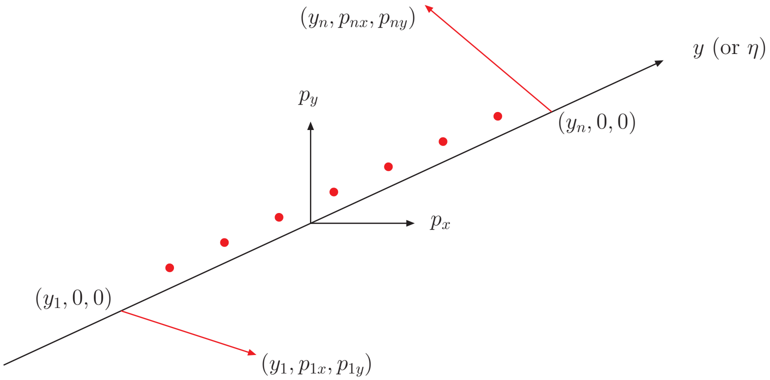
Diffractive scattering + short-range order

- (Not exhaustively studied at Tevatron)
- Long-range correlations?
- High density of $p_z = 5$ to 10 GeV partons
  $\rightsquigarrow$ hot spots, thermalization, ...?
- Multiple-parton interactions, perhaps correlated
  $q(qq)$ in impact-parameter space, ...
- PYTHIA tunes miss 2.36-TeV data (ATLAS & CMS)

Few percent of minimum-bias events ($\sqrt{s} \gtrsim 1$ TeV)
might display an unusual event structure
We should look! How?

# An Informative Event Display

## (Avoid pathological attachment to blind analysis!)




(unwrapped LEGO plot for particles)

Bjorken, SLAC-PUB-0974 (1971)

# Example Event Displays from CDF Run II

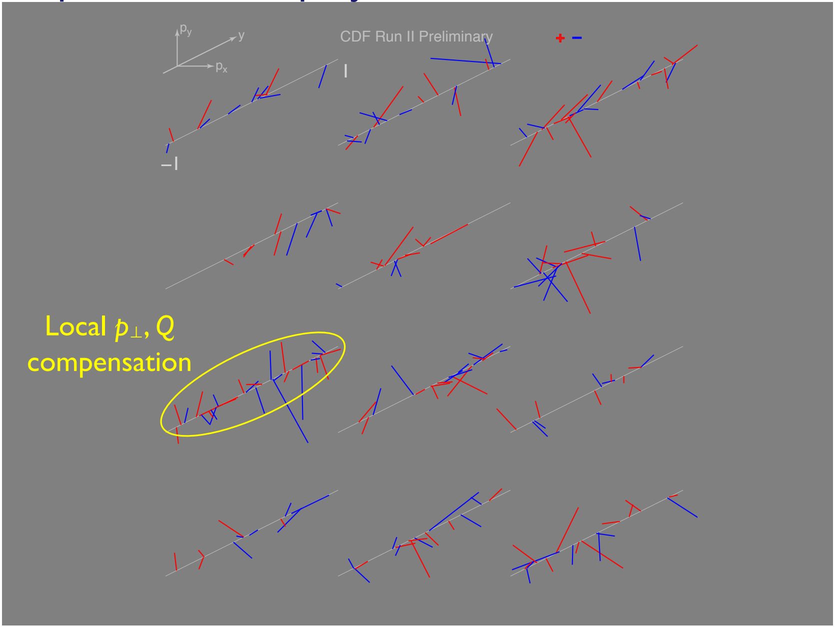
## 1.88 Million “zero-bias” events

Selection for these examples:

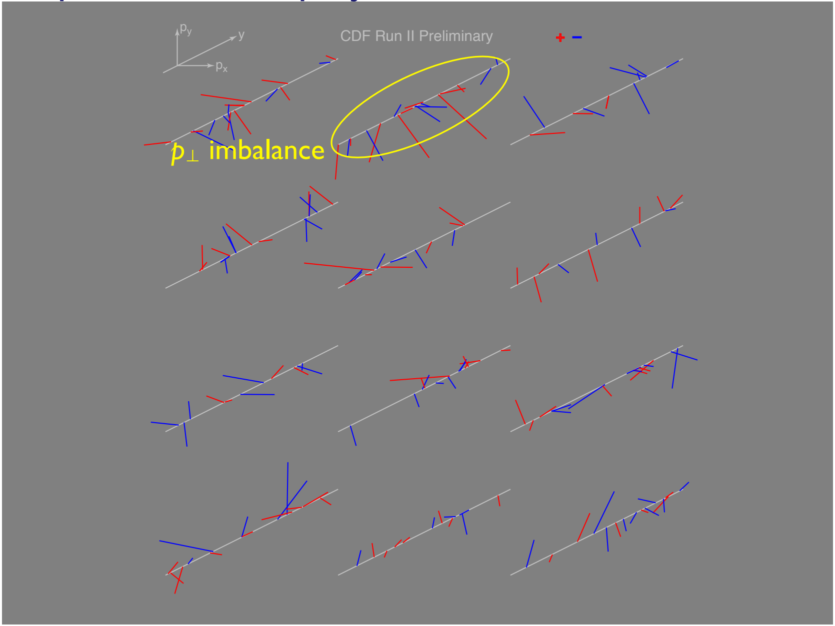
- $\geq 10$ tracks in $-1 \leq y \leq 1$ (excludes $\gamma\gamma$, $\mathbb{PP}$ candidates)
- One primary vertex

Compare N. Moggi, La Thuile 09

# Example Event Displays from CDF Run II



# Example Event Displays from CDF Run II



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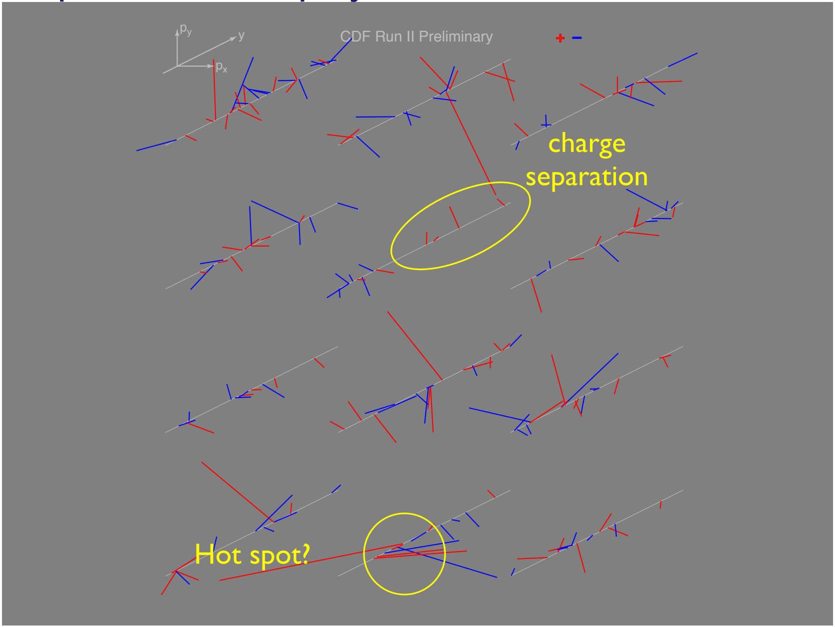
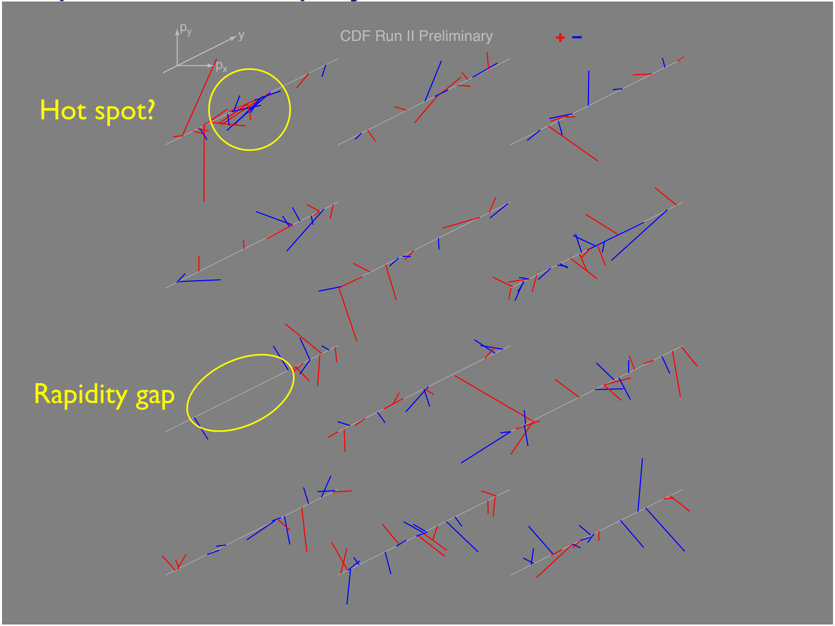


# Example Event Displays from CDF Run II



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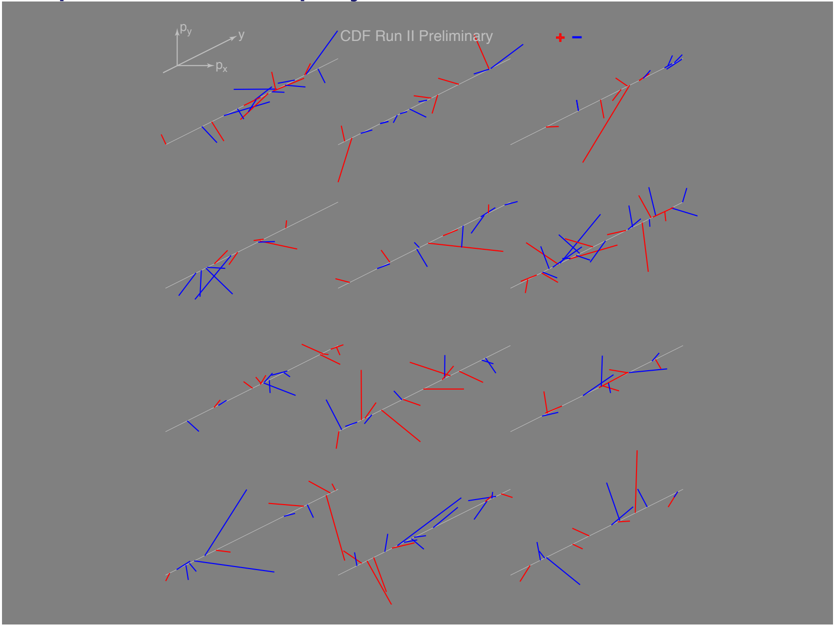

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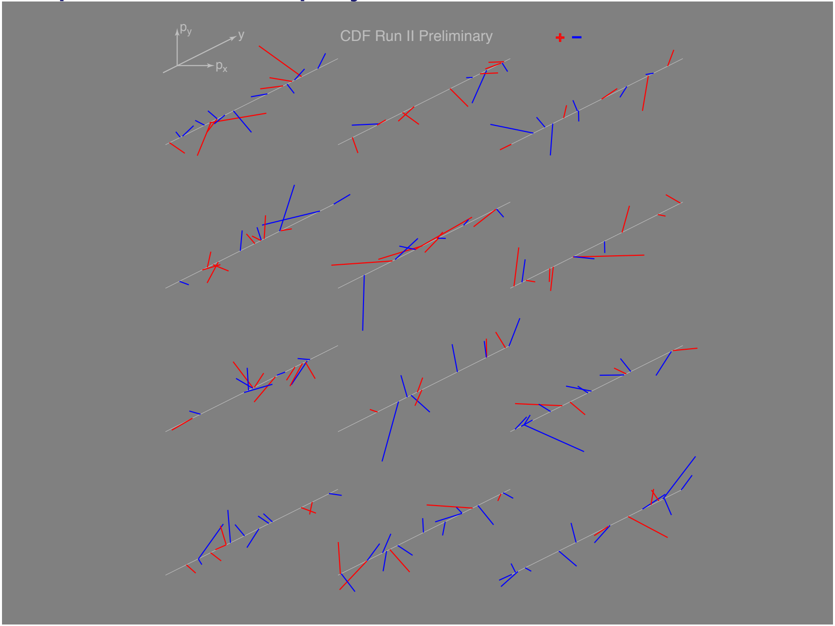

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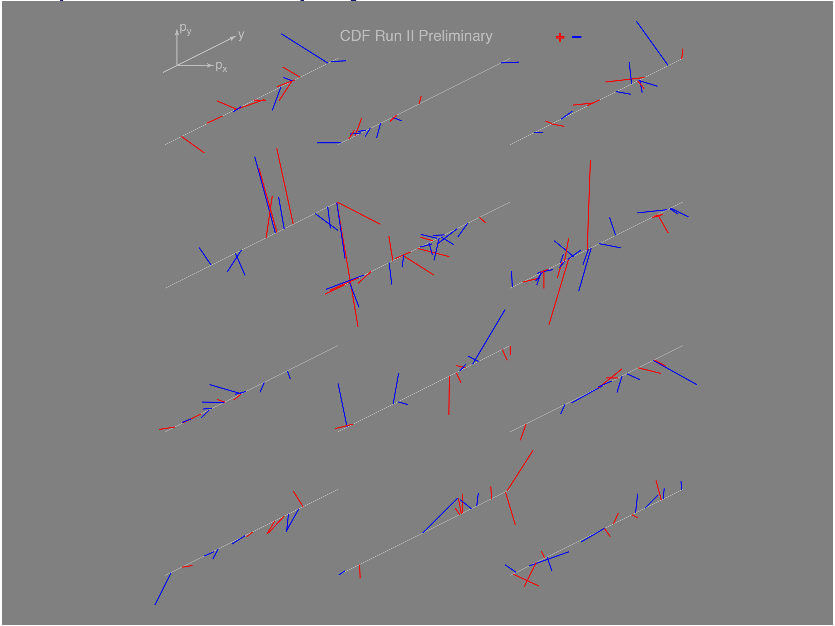

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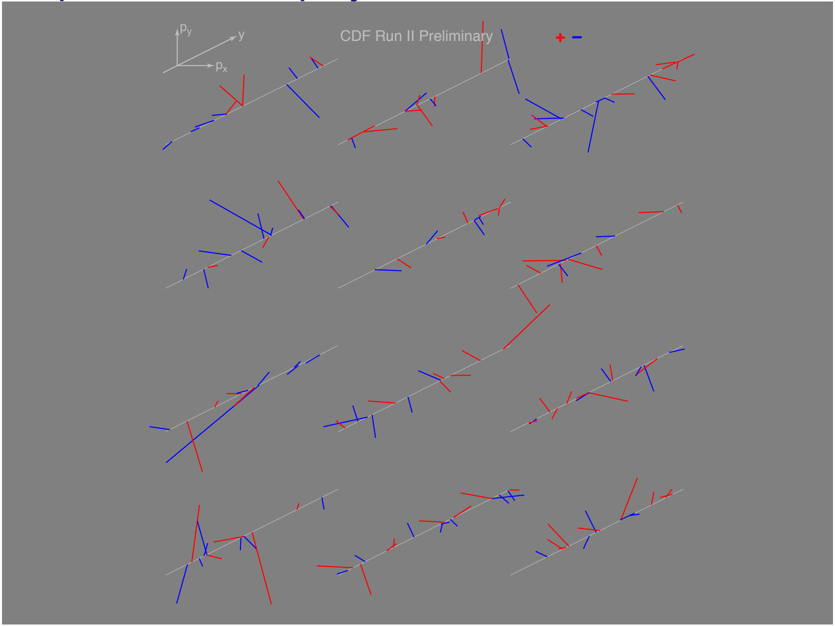


# A Modest Proposal

*I encourage LHC collaborations to produce live streams of* $(y, \vec{p}_\perp)$ *representations, along with the online displays of events that show the structure in terms of detector elements in ordinary space.*

More is to be learned
from the river of events
than from a few specimens!

*Changes in event structure vs.* $\sqrt{s}$*, or the onset of new features, might raise important questions.*

# Opportunity for Exploration and Discovery

- Minimum-bias, triggered (underlying event) samples
- Revisit early multiple-production studies (particles): multiplicity distributions, (semi-)inclusive correlations, charge-transfer across hemispheres or rapidity intervals
- *For some classes of events,* bulk properties: elliptic flow, thermodynamic parameters as at RHIC
- Looking at events, in appropriate coordinates, may identify new event classes (new studies), point to shortcomings in the Monte Carlo programs

Each step in energy is a new world!

# My speculation . . .

*Event structure not a simple extrapolation of Tevatron*

LHC's first surprise in this area: not a crack in the foundations, but something perhaps buried within QCD that we have not been clever enough to anticipate.

Some unusual structure in a few percent of events? High-multiplicity hedgehog events? Sporadic event structures? Dozens of small jets or other manifestations of multiple parton collisions?

*Soft collisions + underlying events*
$\rightsquigarrow$ *understanding multiple production, parton showers*

# Exploring the New Landscape

QCD could be complete, up to ultrahigh energies

. . . *Doesn't mean it must be!*

*No structural deficiencies (strong CP problem remains)*

*Perhaps . . .*

- *(Breakdown of factorization)*
- *Free quarks / unconfined color*
- *new kinds of colored matter beyond quarks gluons (and maybe their superpartners)*
- *quarks might be composite in an unexpected manner*
- $\mathrm{SU}(3)_c$ *gauge symmetry might be vestige of a larger, spontaneously broken, color symmetry.*

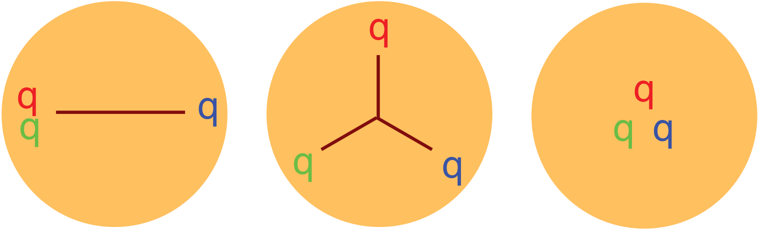
# New phenomena within QCD?

Multiple production $\neq$ diffraction $+$ short-range order?

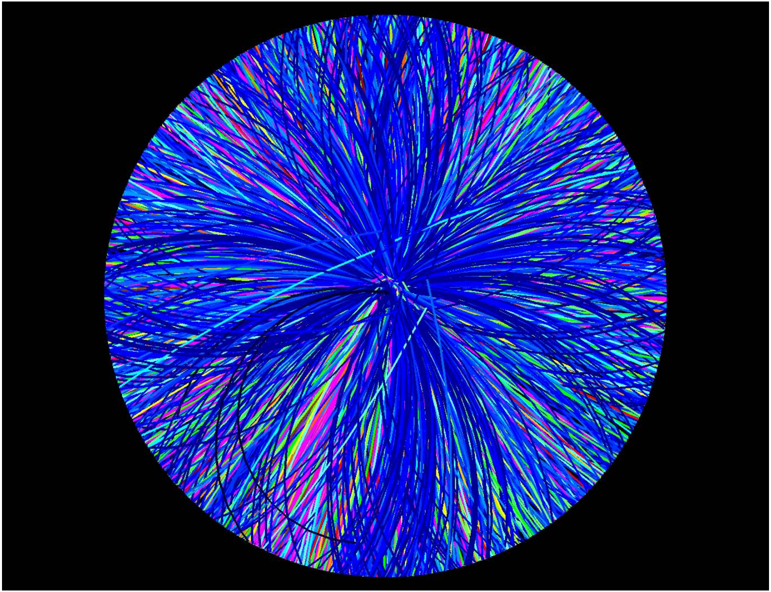
High density of *few-GeV* partons . . . thermalization?

Long-range correlations in $y$?

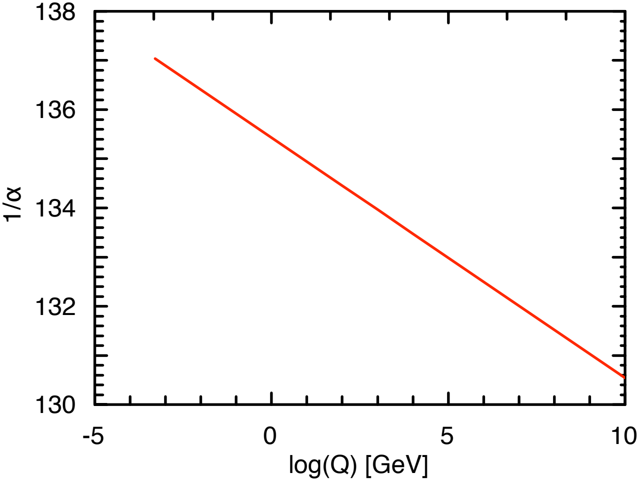
Unusual event structures (Bj, 2010) . . .



# 2.76 TeV/A $^{208}$Pb $^{208}$Pb: ALICE

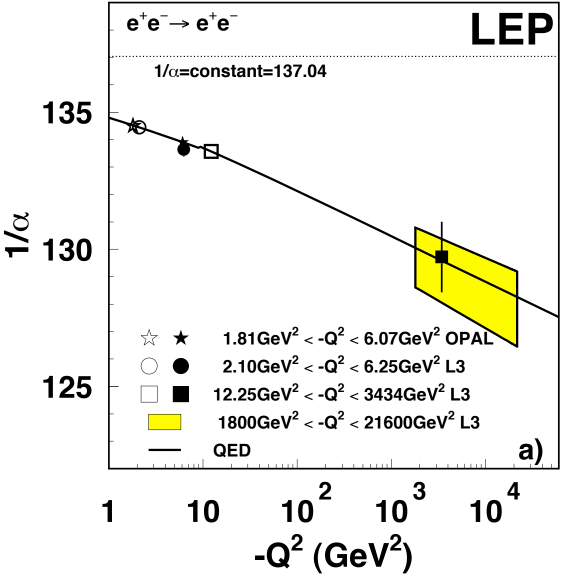


# Charge screening in QED (electrons + photons)

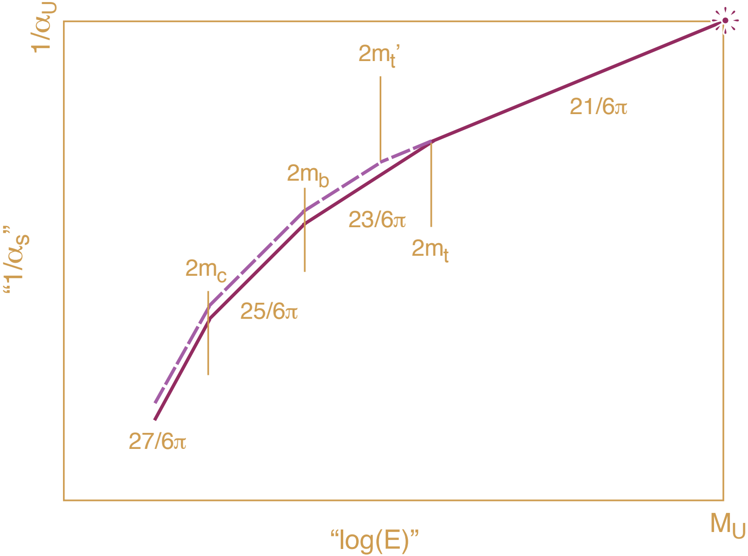



$$1/\alpha(Q) = 1/\alpha_0 - \frac{2}{3\pi} \ln\left(\frac{Q}{m}\right)$$

# Charge screening in QED (real world)

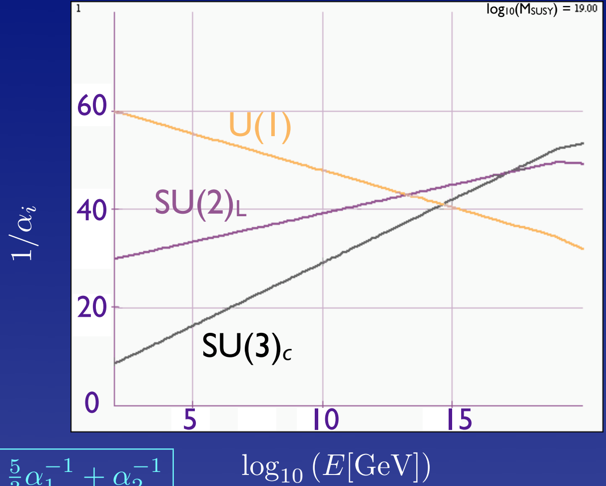


# Evolution of $\alpha_s(Q^2)$: Influence of $m_t$



# Coupling Constant Unification

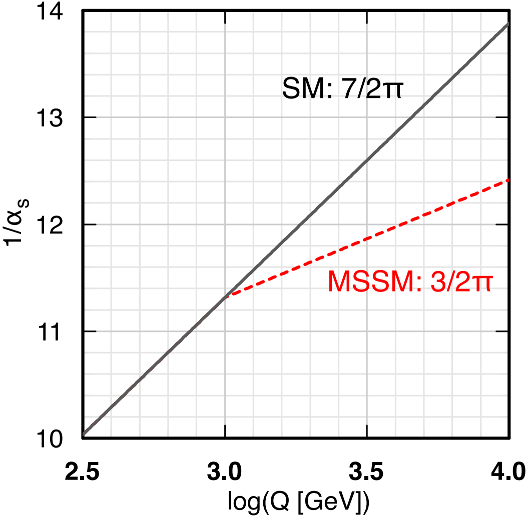
Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$
gives possibility of coupling constant unification




$$\boxed{\alpha^{-1} = \tfrac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}}$$

# Can LHC See Change in Evolution?

## Sensitive to new colored particles




(sharp threshold illustrated)

. . . also for $\sin^2\theta_W$

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# Potential Discoveries at the Large Hadron Collider

Chris Quigg

*Fermilab*

Lecture II

# Electroweak Physics



## Unanswered Questions in the Electroweak Theory

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**Key Words**

electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

**Abstract**

This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

505

# A theory of leptons

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \mathsf{R} \equiv e_R$$

weak hypercharges $Y_L = -1$, $Y_R = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ gauge group $\Rightarrow$ gauge fields:

- weak isovector $\vec{b}_\mu$, coupling $g$ $\quad \boxed{b_\mu^\ell = b_\mu^\ell - \varepsilon_{jk\ell}\alpha^j b_\mu^k - (1/g)\partial_\mu\alpha^\ell}$
- weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$ $\quad \boxed{\mathcal{A}_\mu \to \mathcal{A}_\mu - \partial_\mu\alpha}$

Field-strength tensors

$$F_{\mu\nu}^\ell = \partial_\nu b_\mu^\ell - \partial_\mu b_\nu^\ell + g\varepsilon_{jk\ell} b_\mu^j b_\nu^k \qquad \mathrm{SU(2)_L}$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu \qquad \mathrm{U(1)_Y}$$

# Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}$$

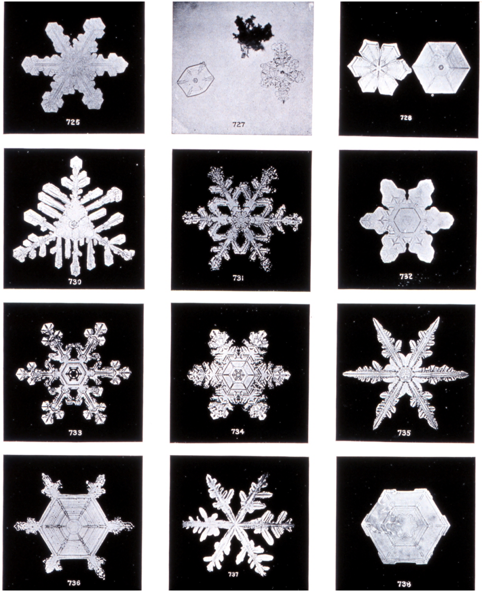
$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{4} F^{\ell}_{\mu\nu} F^{\ell\mu\nu} - \tfrac{1}{4} f_{\mu\nu} f^{\mu\nu},$$

$$\begin{aligned} \mathcal{L}_{\text{leptons}} &= \overline{\mathsf{R}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu} Y\right)\mathsf{R} \\ &+ \overline{\mathsf{L}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu} Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu}\right)\mathsf{L}. \end{aligned}$$

Mass term $\mathcal{L}_e = -m_e(\bar{e}_{\mathsf{R}} e_{\mathsf{L}} + \bar{e}_{\mathsf{L}} e_{\mathsf{R}}) = -m_e \bar{e} e$ violates local gauge inv.

Theory: 4 massless gauge bosons ($\mathcal{A}_{\mu}$ $b^1_{\mu}$ $b^2_{\mu}$ $b^3_{\mu}$); Nature: 1 ($\gamma$)

# Symmetry of laws $\not\Rightarrow$ symmetry of outcomes




# Electroweak theory antecedents

*Lessons from experiment and theory*

- Parity-violating $V - A$ structure of charged current
- Cabibbo universality of leptonic and semileptonic processes
- Absence of strangeness-changing neutral currents
- Negligible neutrino masses; left-handed neutrinos
- Unitarity: four-fermion description breaks down at $\sqrt{s} \approx 620$ GeV $\quad \nu_\mu e \to \mu \nu_e$
- $\nu\bar{\nu} \to W^+W^-$: divergence problems of *ad hoc* intermediate vector boson theory

# Electroweak theory consequences

- Weak neutral currents
- Need for charmed quark
- Existence and properties of $W^{\pm}$, $Z^0$
- No flavor-changing neutral currents at tree level
- No right-handed charged currents
- CKM Universality
- KM phase dominant source of CP violation
- Existence and properties of Higgs boson (but not $M_H$)
- Higgs interactions determine fermion masses, *but ...*
- (Massless neutrinos: no neutrino mixing)

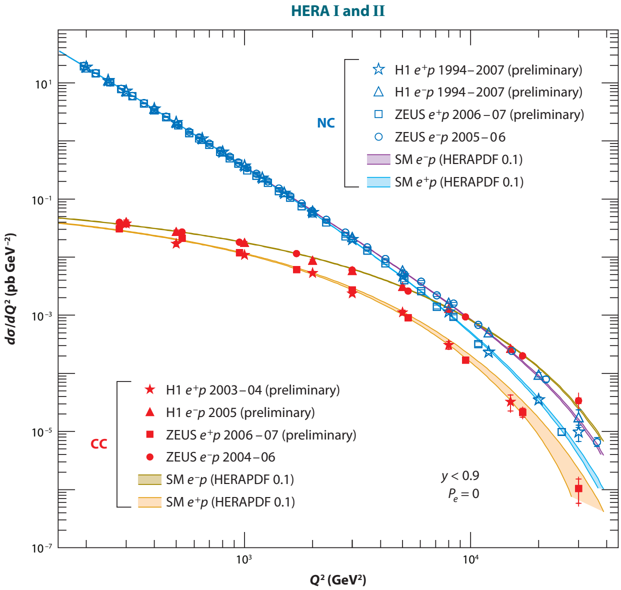
# Electroweak theory tests: tree level

- $W^{\pm}$, $Z^0$ existence and properties verified
- $Z$-boson chiral couplings to quarks and leptons agree with $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ theory
- Third generation of quarks and leptons discovered
- Constraints on a fourth generation
- $M_{Z'} \gtrsim 1.83$ TeV (ATLAS), 1.94 TeV (CMS)
- $M_{W'} \gtrsim 2.15$ TeV (ATLAS), 2.27 TeV (CMS)
- $M_{W_\mathrm{R}} \gtrsim 715$ GeV, $g_\mathrm{L} = g_\mathrm{R}$
- Strong suppression of FCNC:

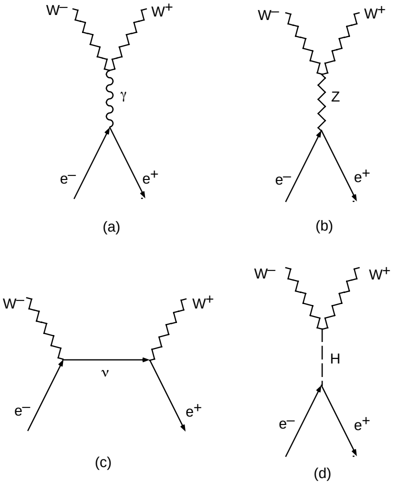
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10};$$

$$\text{SM expectation} = (0.85 \pm 0.07) \times 10^{-10}$$

# Electroweak theory tests: tree level

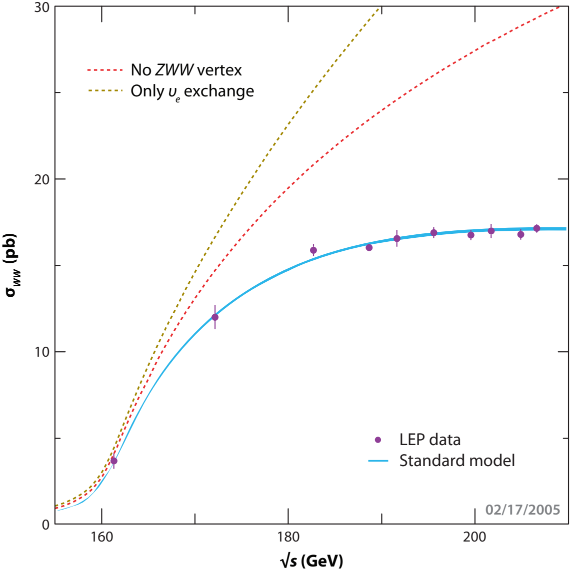


# Electroweak theory tests: $e^+e^- \to W^+W^-$




Individual $J = 1$ partial-wave amplitudes $\mathcal{M}_{\gamma}^{(1)}$, $\mathcal{M}_{Z}^{(1)}$, $\mathcal{M}_{\nu}^{(1)}$ have unacceptable high-energy behavior ($\propto s$)

# Gauge cancellation in $e^+e^- \to W^+W^-$



# Why the Higgs boson must exist

$J = 0$ amplitude exists because electrons have mass, and can be found in "wrong" helicity state

$$\mathcal{M}_{\nu}^{(0)} \propto s^{\frac{1}{2}} \quad : \text{unacceptable HE behavior}$$

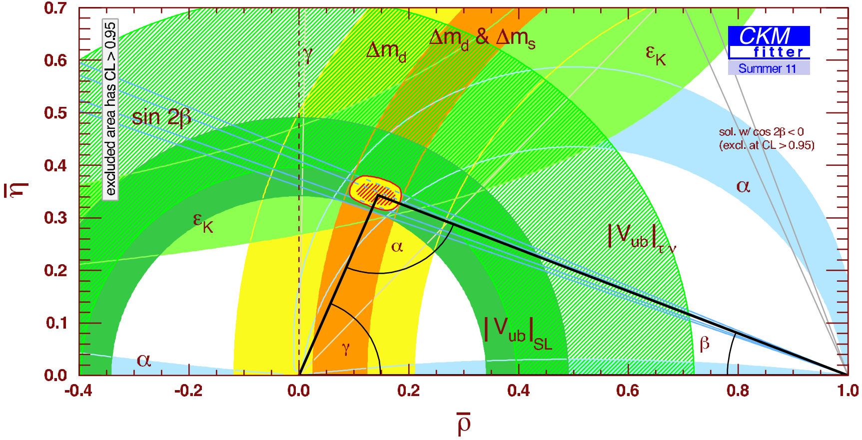
Divergence canceled by Higgs-boson contribution

$$\boxed{\Rightarrow He\bar{e} \text{ coupling must be} \propto m_e,}$$

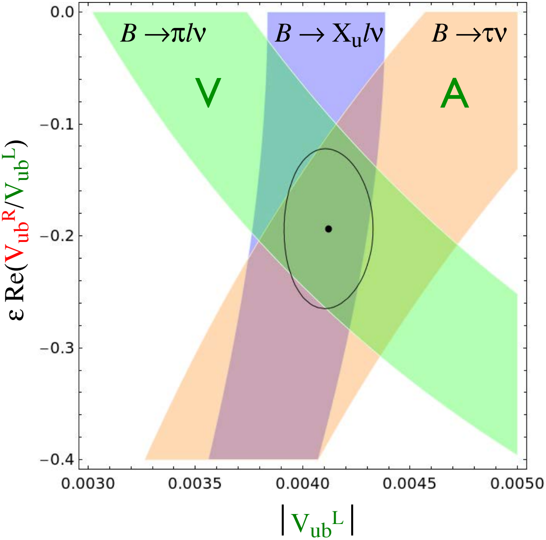
because "wrong-helicity" amplitudes $\propto m_e$

*If the Higgs boson did not exist, something else would have to cure divergent behavior*

# Electroweak theory tests: CKM paradigm

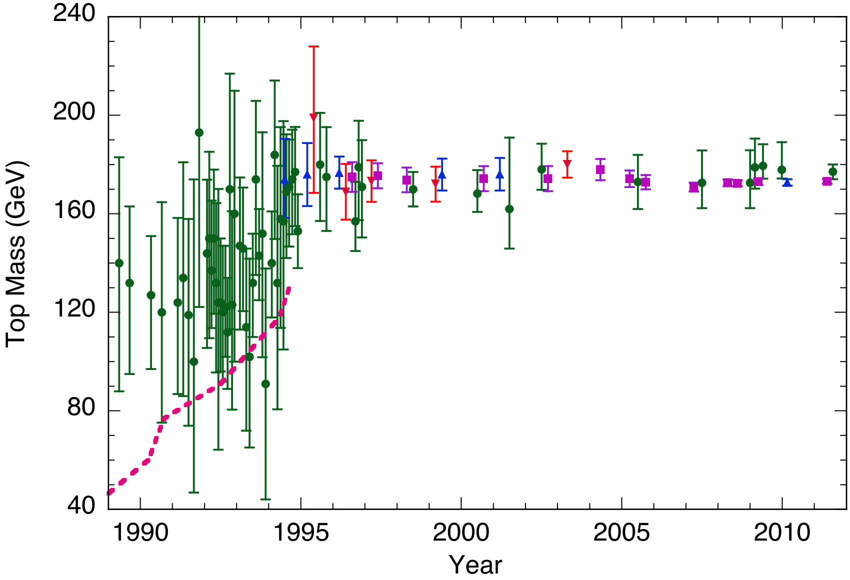


# $|V_{ub}|$ puzzle resolved by RH current?

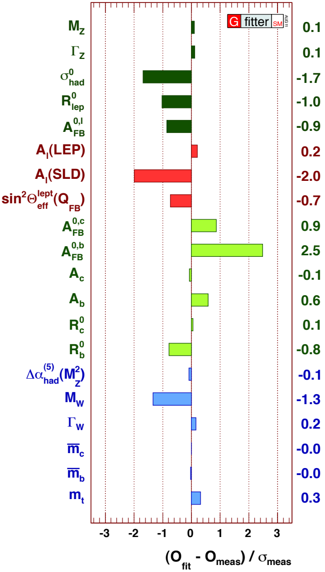



Buras/Gemmler/Isidori 1007.1993

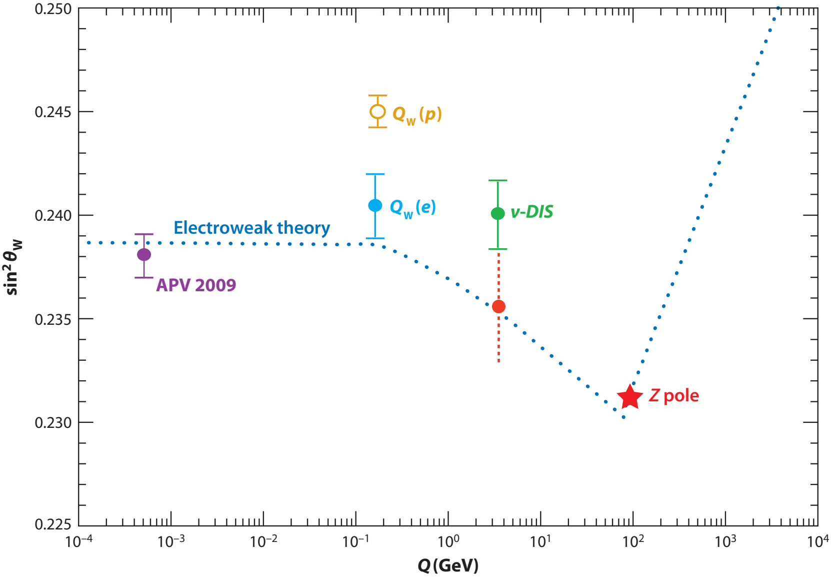
# Electroweak theory tests: loop level



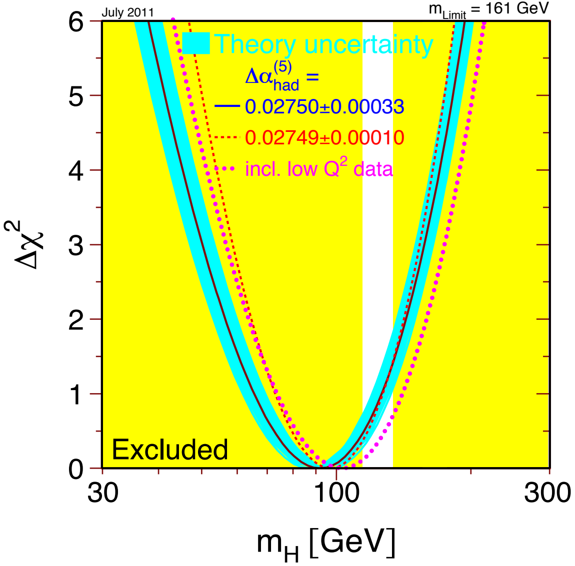
# Electroweak theory tests: loop level



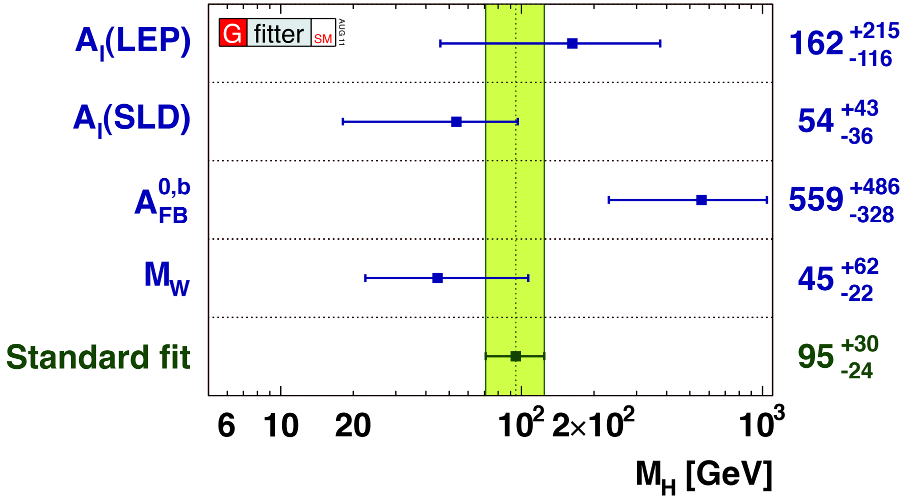
# Electroweak theory tests: low scales [$Z'$]



# Electroweak theory tests: Higgs influence



# Electroweak theory tests: Higgs consistency?



# Electroweak theory successes

$\rightsquigarrow$ search for unknown *agent provocateur* of EWSB

IOP PUBLISHING REPORTS ON PROGRESS IN PHYSICS

Rep. Prog. Phys. **70** (2007) 1019–1053 doi:10.1088/0034-4885/70/7/R01

**Spontaneous symmetry breaking as a basis of particle mass**

**Chris Quigg**

# Is electroweak symmetry broken by . . .

- 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?

# Higgs (then)

# Kibble, Guralnik, Hagen, Englert, Brout (2010)

▸ 1-TeV Scale

# Hiding EW Symmetry

*Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition*

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger \phi) = \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2}$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R}\right]$

- Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$
  Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

Hides (breaks) $SU(2)_L$ and $U(1)_Y$

but preserves $U(1)_{\mathrm{em}}$ invariance

Invariance under $\mathcal{G}$ means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

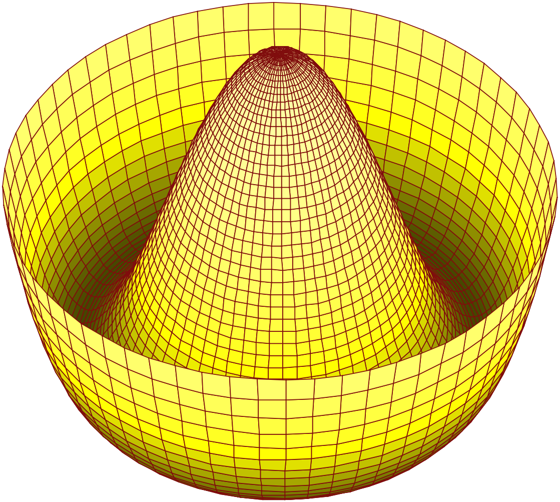
$$\tau_1\langle\phi\rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2\langle\phi\rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3\langle\phi\rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y\langle\phi\rangle_0 = Y_\phi\langle\phi\rangle_0 = +1\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

# Symmetry of laws $\not\Rightarrow$ symmetry of outcomes



Examine electric charge operator $Q$ on the (neutral) vacuum

$$\begin{aligned} Q\langle\phi\rangle_0 &= \tfrac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\ &= \tfrac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix}\langle\phi\rangle_0 \\ &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \textit{unbroken!} \end{aligned}$$

Four original generators are broken, *electric charge is not*

- $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \rightarrow U(1)_{\mathrm{em}}$ (will verify)
- Expect massless photon
- Expect gauge bosons corresponding to

$$\tau_1,\ \tau_2,\ \tfrac{1}{2}(\tau_3 - Y) \equiv K \quad \text{to acquire masses}$$

# Expand about the vacuum state

Let $\phi = \begin{pmatrix} 0 \\ (v+\eta)/\sqrt{2} \end{pmatrix}$; in *unitary gauge*

$$\begin{aligned} \mathcal{L}_{\text{scalar}} &= \tfrac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \mu^2 \eta^2 \\ &\quad + \frac{v^2}{8}[g^2 \left| b_\mu^1 - i b_\mu^2 \right|^2 + (g' \mathcal{A}_\mu - g b_\mu^3)^2] \\ &\quad + \text{interaction terms} \end{aligned}$$

"Higgs boson" $\eta$ has acquired (mass)$^2$ $M_H^2 = -2\mu^2 > 0$

$$\text{Define } W_\mu^\pm = \frac{b_\mu^1 \mp i b_\mu^2}{\sqrt{2}}$$

$$\frac{g^2 v^2}{8}(\left|W_\mu^+\right|^2 + \left|W_\mu^-\right|^2) \Longleftrightarrow M_{W^\pm} = gv/2$$

$(v^2/8)(g'\mathcal{A}_\mu - g b^3_\mu)^2 \ldots$

Now define orthogonal combinations

$$Z_\mu = \frac{-g'\mathcal{A}_\mu + g b^3_\mu}{\sqrt{g^2 + g'^2}} \qquad A_\mu = \frac{g\mathcal{A}_\mu + g' b^3_\mu}{\sqrt{g^2 + g'^2}}$$

$$M_{Z^0} = \sqrt{g^2 + g'^2}\, v/2 = M_W \sqrt{1 + g'^2/g^2}$$

$$\boxed{A_\mu \text{ remains massless}}$$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\zeta_e \frac{(v+\eta)}{\sqrt{2}}(\bar{e}_{\text{R}} e_{\text{L}} + \bar{e}_{\text{L}} e_{\text{R}}) \\ &= -\frac{\zeta_e v}{\sqrt{2}}\bar{e}e - \frac{\zeta_e \eta}{\sqrt{2}}\bar{e}e\end{aligned}$$

electron acquires $m_e = \zeta_e v/\sqrt{2}$

Higgs-boson coupling to electrons: $m_e/v$ ($\propto$ mass)

Desired particle content . . . plus a Higgs scalar

Values of couplings, electroweak scale $v$?

Then analyze interactions . . .

# The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass,

but partial-wave unitarity defines tipping point

*Gedanken* experiment: high-energy scattering of

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

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

# The importance of the 1-TeV scale . . .

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

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

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \leq 1$

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

condition for perturbative unitarity

# The importance of the 1-TeV scale . . .

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 1-TeV scale

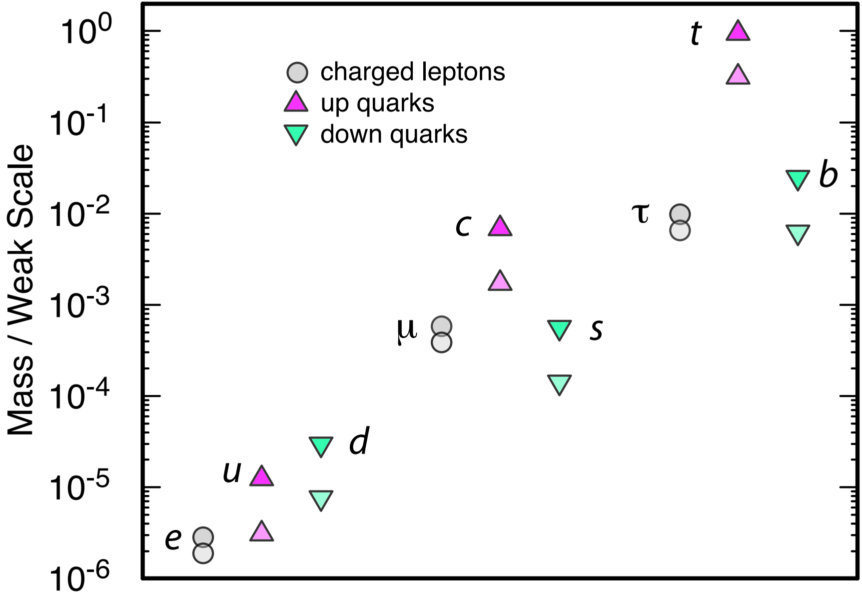
New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

# Electroweak Questions for the LHC

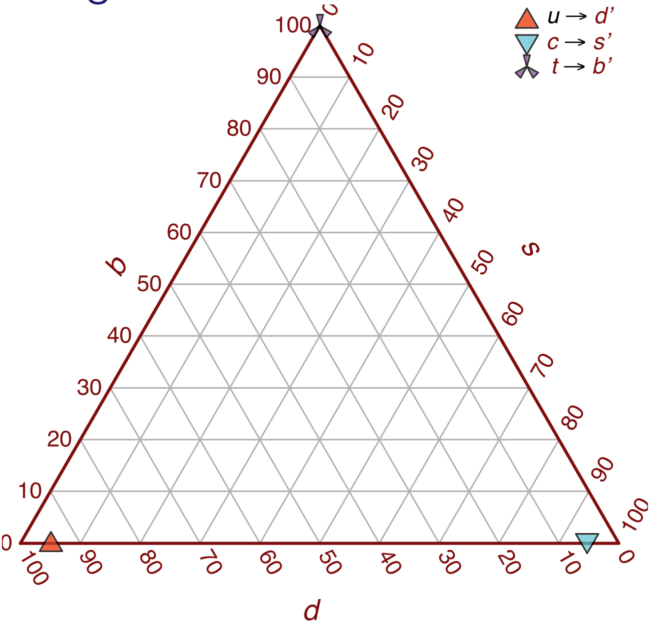
- What hides electroweak symmetry: a Higgs boson, or new strong dynamics?
- If a Higgs boson: one or several?
- Elementary or composite?
- Is the Higgs boson indeed light, as anticipated by the global fits to EW precision measurements?
- Does $H$ only give masses to $W^{\pm}$ and $Z^0$, or also to fermions?
- Are the branching fractions for $f\bar{f}$ decays in accord with the standard model?

If all this: what sets the fermion masses and mixings?

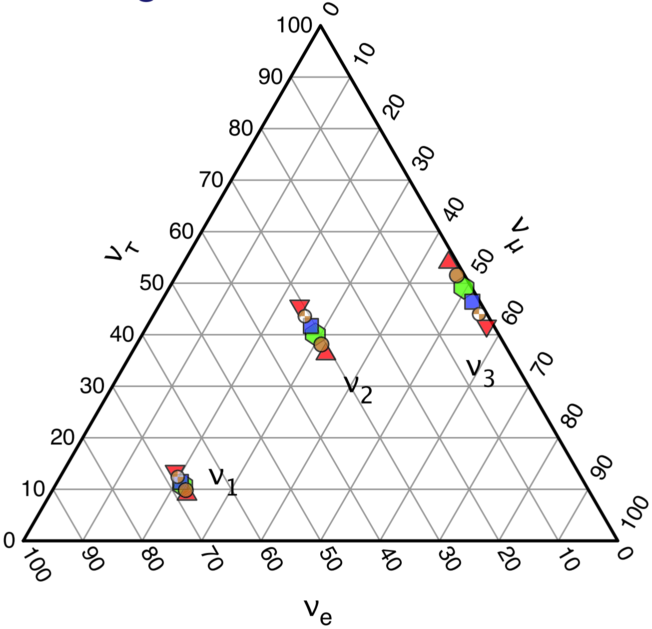
# Fermion Mass Generation = Physics beyond SM



# Quark Mixing



# Neutrino Mixing



*XXII Nordic Particle Physics Meeting*

# Potential Discoveries at the Large Hadron Collider


Chris Quigg

*Fermilab*


Lecture III

▸ Tevatron Higgs Searches

# Search for the Standard-Model Higgs Boson

$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass; $\propto \beta^3$ for scalar

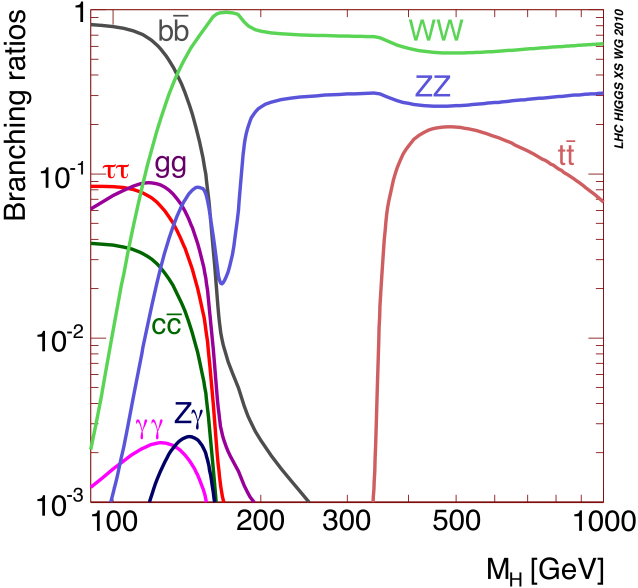
$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}}(1-x)^{1/2}(4 - 4x + 3x^2) \quad x \equiv 4M_W^2/M_H^2$$

$$\Gamma(H \to Z^0Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}}(1-x')^{1/2}(4 - 4x' + 3x'^2) \quad x' \equiv 4M_Z^2/M_H^2$$

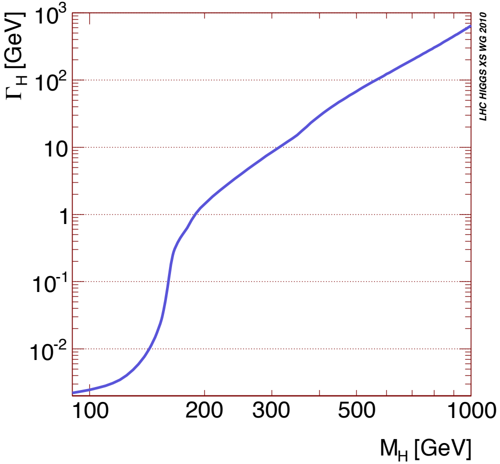
asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively

$2x^2$ and $2x'^2$ terms $\Leftrightarrow$ decays into transverse gauge bosons
Dominant decays for large $M_H$: pairs of longitudinal weak bosons

# SM Higgs Boson Branching Fractions



# Total width of the standard-model Higgs boson




Below $W^+W^-$ threshold, $\Gamma_H \lesssim 1$ GeV

Far above $W^+W^-$ threshold, $\Gamma_H \propto M_H^3$

# A few words on Higgs production ...

$e^+e^- \to H$: hopelessly small
$\mu^+\mu^- \to H$: scaled by $(m_\mu/m_e)^2 \approx 40\,000$
$e^+e^- \to HZ$: prime channel

Hadron colliders:
$gg \to H \to b\bar{b}$: background !!
$gg \to H \to \tau\tau, \gamma\gamma$: rate ?!

$gg \to H \to W^+W^-$: best Tevatron sensitivity now
$\bar{p}p \to H(W, Z)$: prime Tevatron channel for light Higgs

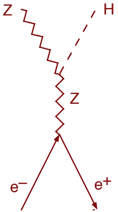
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

# Higgs search in $e^+e^-$ collisions

$\sigma(e^+e^- \to H \to \text{all})$ is *minute*, $\propto m_e^2$

Even narrowness of low-mass $H$ is not enough to make it visible . . . Sets aside a traditional strength of $e^+e^-$ machines—*pole physics*

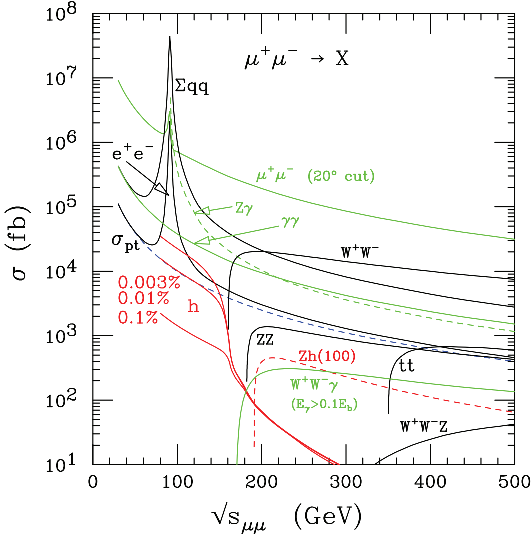
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)




$$\boxed{\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \quad x_W^2(1 - x_W)^2}}$$

$K$: c.m. momentum of $H$ $\qquad x_W \equiv \sin^2\theta_W$

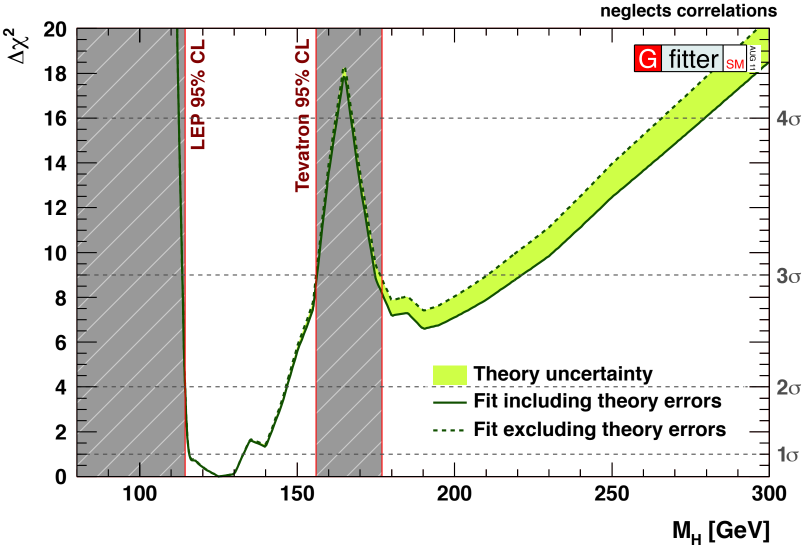
# $\ell^+\ell^- \to X \ldots$



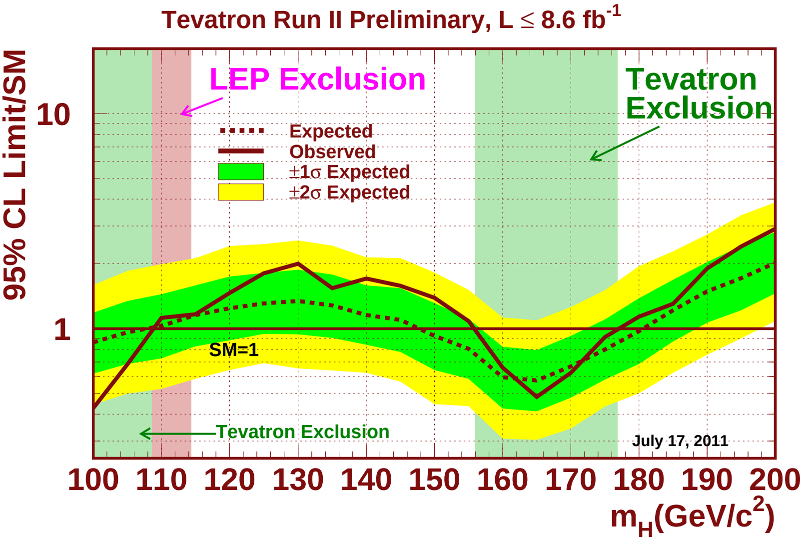

$$\sigma(e^+e^- \to H) = (m_e/m_\mu)^2\sigma(\mu^+\mu^- \to H) \approx \sigma(\mu^+\mu^- \to H)/40\,000$$

# Electroweak theory projection

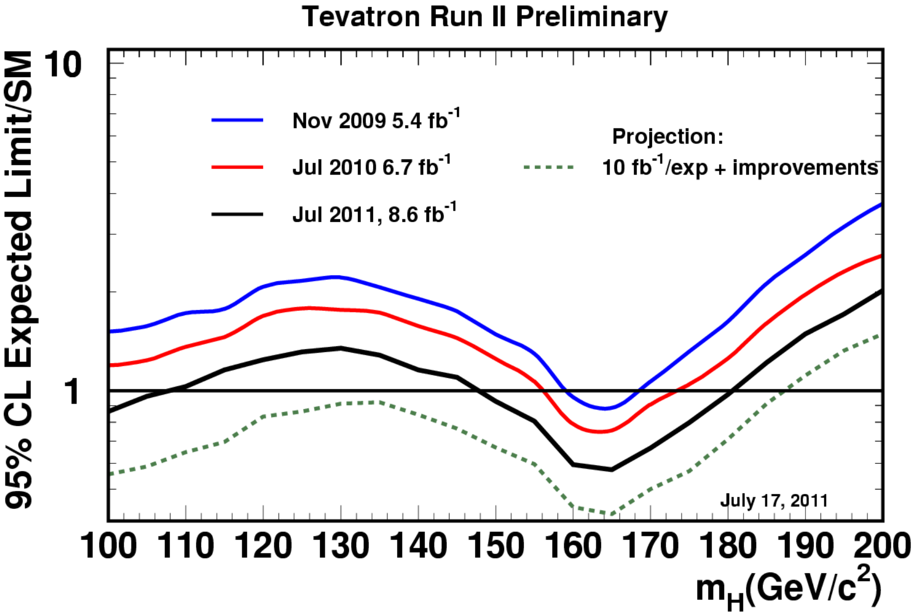
*Global fit + LEP & Tevatron exclusions*



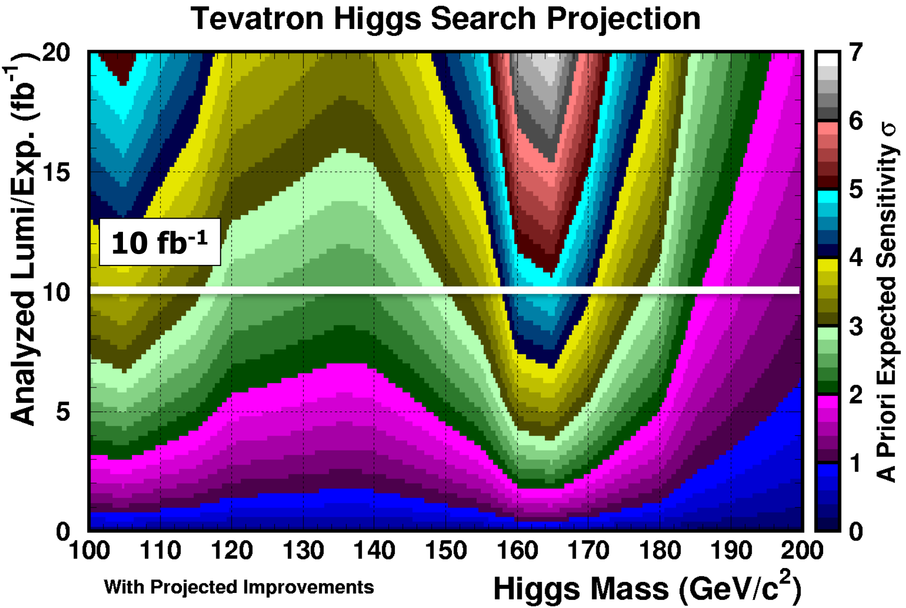
# Current Tevatron Sensitivity



# Tevatron prospects . . .



# Tevatron prospects . . .

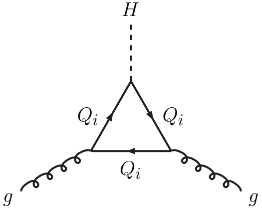


# The Origin of Fermion Mass

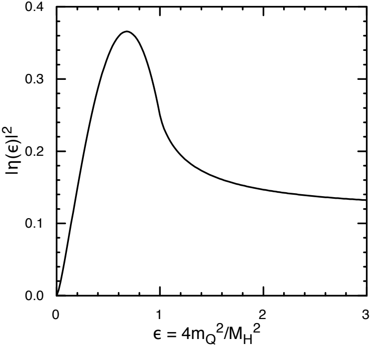
We do not know that the agent of electroweak symmetry breaking gives mass to fermions.

We do not know what determines fermion masses and mixings.

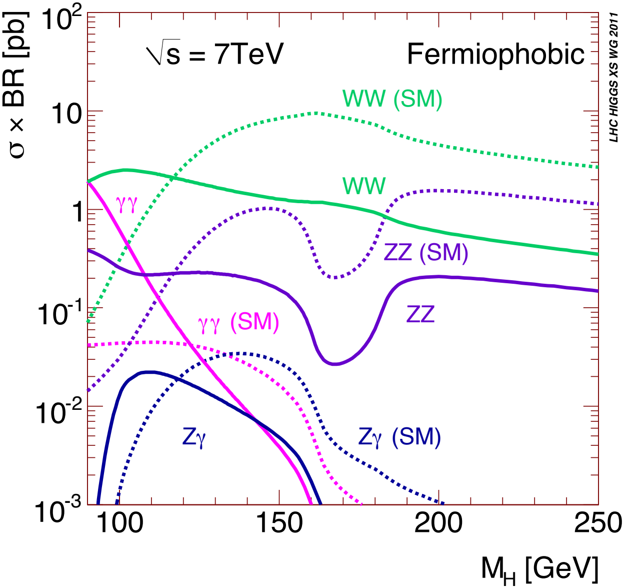
# $H$ couples to gluons through quark loops




Only heavy quarks matter: heavy 4th generation ??



# Distinguishing SM, bosogamous Higgs bosons



# Why Electroweak Symmetry Breaking Matters

PHYSICAL REVIEW D **79,** 096002 (2009)

## Gedanken worlds without Higgs fields: QCD-induced electroweak symmetry breaking

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To illuminate how electroweak symmetry breaking shapes the physical world, we investigate toy models in which no Higgs fields or other constructs are introduced to induce spontaneous symmetry breaking. Two models incorporate the standard $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ gauge symmetry and fermion content similar to that of the standard model. The first class—like the standard electroweak theory—contains no bare mass terms, so the spontaneous breaking of chiral symmetry within quantum chromodynamics is the only source of electroweak symmetry breaking. The second class adds bare fermion masses sufficiently small that QCD remains the dominant source of electroweak symmetry breaking and the model can serve as a well-behaved low-energy effective field theory to energies somewhat above the hadronic scale. A third class of models is based on the left-right-symmetric $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \otimes \mathrm{U(1)}$ gauge group. In a fourth class of models, built on $\mathrm{SU(4)_{PS}} \otimes \mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ gauge symmetry, the lepton number is treated as a fourth color and the color gauge group is enlarged to the $\mathrm{SU(4)_{PS}}$ of Pati and Salam (PS). Many interesting characteristics of the models stem from the fact that the effective strength of the weak interactions is much closer to that of the residual strong interactions than in the real world. The Higgs-free models not only provide informative contrasts to the real world, but also lead us to consider intriguing issues in the application of field theory to the real world.

DOI: 10.1103/PhysRevD.79.096002 PACS numbers: 11.15.−q, 12.10.−g, 12.60.−i

# Challenge: Understanding the Everyday World

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

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!
$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$

# Modified Standard Model: No Higgs Sector

$\mathbf{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ with massless $u$, $d$, $e$, $\nu$

(treat $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

$$M_p = C \cdot \Lambda_{\mathrm{QCD}} + \dots$$

$$3\,\frac{m_u + m_d}{2} = (7.5 \text{ to } 15)\ \mathrm{MeV}$$

Small contribution from virtual strange quarks

$M_N$ decreases by $< 10\%$ in chiral limit: $939 \rightsquigarrow 870$ MeV

# Modified Standard Model: No Higgs Sector

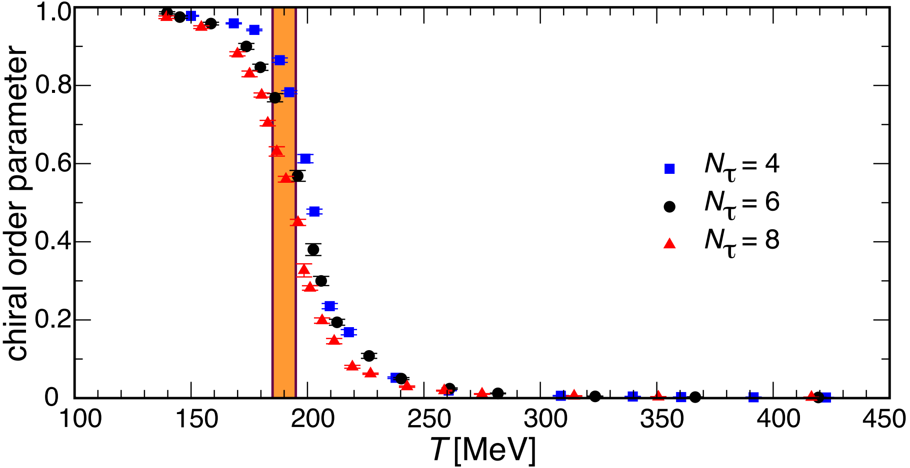
QCD has exact $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\mathrm{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \to \mathrm{SU(2)_V}$$

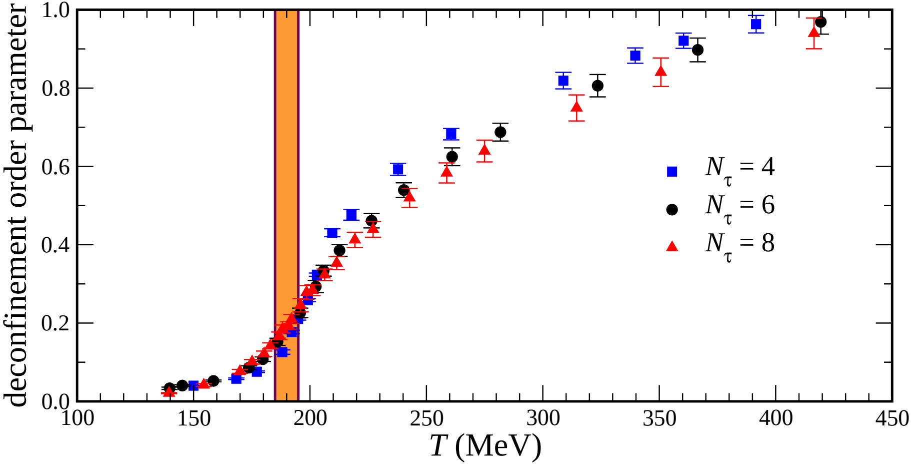
$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

# Chiral Symmetry Breaking on the Lattice




Review and lattice QCD references

# Deconfinement on the Lattice




A. Polyakov, *Phys. Lett.* **B72,** 477 (1978)

# Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

$$1 = \tfrac{1}{2}(1 + \gamma_5) + \tfrac{1}{2}(1 - \gamma_5)$$

$$\mathrm{Q}^a_{\mathrm{L}} = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_{\mathrm{L}} \qquad u^a_{\mathrm{R}} \quad d^a_{\mathrm{R}}$$

$$(\mathrm{SU}(3)_{\mathrm{c}}, \mathrm{SU}(2)_{\mathrm{L}})_Y\!: \; (\mathbf{3}, \mathbf{2})_{1/3} \qquad (\mathbf{3}, \mathbf{1})_{4/3} \quad (\mathbf{3}, \mathbf{1})_{-2/3}$$

transforms as $\mathrm{SU}(2)_{\mathrm{L}}$ doublet with $|Y| = 1$

# Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Broken generators: 3 axial currents; couplings to $\pi$: $\bar{f}_\pi$

*Turn on* $SU(2)_L \otimes U(1)_Y$*:*

Weak bosons couple to axial currents, acquire mass $\sim g\bar{f}_\pi$

$$g \approx 0.65,\ g' \approx 0.34,\ f_\pi = 92.4\ \text{MeV} \rightsquigarrow \bar{f}_\pi \approx 87\ \text{MeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{\bar{f}_\pi^2}{4} \qquad (w_1, w_2, w_3, \mathcal{A})$$

*same structure* as standard EW theory

# Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned} \overline{M}_W^2 &= g^2 \bar{f}_\pi^2/4 \\ \overline{M}_Z^2 &= (g^2 + g'^2)\bar{f}_\pi^2/4 \\ \overline{M}_A^2 &= 0 \end{aligned}$$

$$\overline{M}_Z^2/\overline{M}_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

NGBs become longitudinal components of weak bosons.

$$\boxed{\overline{M}_W \approx 28 \text{ MeV} \qquad \overline{M}_Z \approx 32 \text{ MeV}}$$

$$(M_W \approx 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV})$$

# Strong coupling in $\overline{\text{SM}}$

SM with (very) heavy Higgs boson:

$s$-wave $W^+W^-$, $Z^0Z^0$ scattering as $s \gg M_W^2, M_Z^2$:

$$a_0 = \frac{s}{32\pi v^2}\begin{bmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 0 \end{bmatrix}$$

Largest eigenvalue: $a_0^{\max} = s/16\pi v^2$

$$|a_0| \leq 1 \Rightarrow \sqrt{s^\star} = 4\sqrt{\pi}v \approx 1.74 \text{ TeV}$$

$$\boxed{\overline{\text{SM}}\text{: } \sqrt{s^\star} = 4\sqrt{\pi}\bar{f}_\pi \approx 620 \text{ MeV}}$$

$\overline{\text{SM}}$ becomes strongly coupled on the hadronic scale

# What about atoms?

*Suppose* some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

# Massless fermion pathologies . . .

Vacuum readily breaks down to $e^+e^-$ plasma

. . . persists with GUT-induced tiny masses

"hard" fermion masses: explicit $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ breaking

NGBs $\longrightarrow$ pNGBs

$$\mathrm{SM}m\text{: } a_J(f\bar{f} \to W_L^+ W_L^-) \propto G_\mathrm{F} m_f E_\mathrm{cm}$$

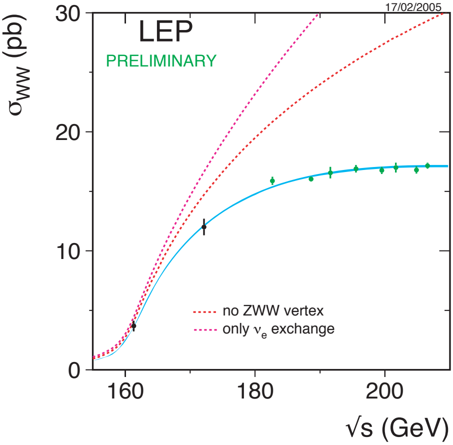
saturate p.w. unitarity at

$$\sqrt{s_f} \simeq \frac{4\pi\sqrt{2}}{\sqrt{3\eta_f}\, G_\mathrm{F} m_f} = \frac{8\pi v^2}{\sqrt{3\eta_f}\, m_f}$$

$\eta_f = 1(N_\mathrm{c})$ for leptons (quarks)

“Hard” electron mass: $\sqrt{s_e} \approx 1.7 \times 10^9$ GeV . . .

Gauge cancellation need not imply renormalizable theory




“Hard” top mass: $\sqrt{s_t} \approx 3$ TeV

# Stability bounds

*Quantum corrections to* $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$

Triviality of scalar field theory bounds $M_H$ from above

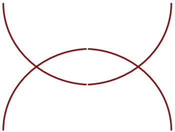
- Only *noninteracting* scalar field theories make sense on all energy scales
- Quantum field theory vacuum is a dielectric medium that screens charge
- $\Rightarrow$ *effective charge* is a function of the distance or, equivalently, of the energy scale

$\boxed{\text{running coupling constant}}$

▸ Graph

# Bounding $M_H$ from above . . .

In $\lambda\phi^4$ theory, calculate variation of coupling constant $\lambda$ in perturbation theory by summing bubble graphs



$\lambda(\mu)$ is related to a higher scale $\Lambda$ by

$$\frac{1}{\lambda(\mu)} = \frac{1}{\lambda(\Lambda)} + \frac{3}{2\pi^2} \log\left(\Lambda/\mu\right)$$

(Perturbation theory reliable only when $\lambda$ is small, lattice field theory treats strong-coupling regime)

# Bounding $M_H$ from above . . .

For stable Higgs potential (*i.e.*, for vacuum energy not to race off to $-\infty$), *require* $\lambda(\Lambda) \geq 0$

Rewrite RGE as an inequality

$$\frac{1}{\lambda(\mu)} \geq \frac{3}{2\pi^2} \log\left(\Lambda/\mu\right)$$

. . . implies an *upper bound*

$$\boxed{\lambda(\mu) \leq 2\pi^2/3 \log\left(\Lambda/\mu\right)}$$

# Bounding $M_H$ from above ...

If we require the theory to make sense to arbitrarily high energies—or short distances—then we must take the limit $\Lambda \to \infty$ while holding $\mu$ fixed at some reasonable physical scale. In this limit, the $\boxed{\text{bound}}$ forces $\lambda(\mu)$ to zero.

$\longrightarrow$ free field theory "trivial"

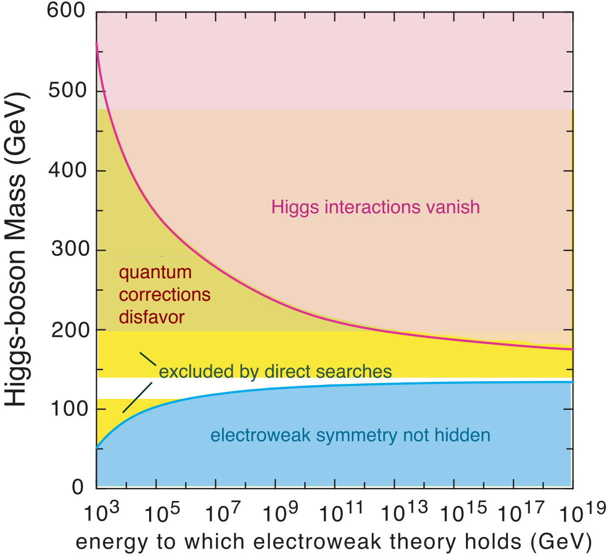
Rewrite as bound on $M_H$:

$$\Lambda \leq \mu \exp\left(\frac{2\pi^2}{3\lambda(\mu)}\right)$$

Choose $\mu = M_H$, and recall $M_H^2 = 2\lambda(M_H)v^2$

$$\boxed{\Lambda \leq M_H \exp\left(4\pi^2 v^2 / 3M_H^2\right)}$$

# Bounding $M_H$ from above . . .



# Requiring $V(v) < V(0)$ gives *lower* bound on $M_H$

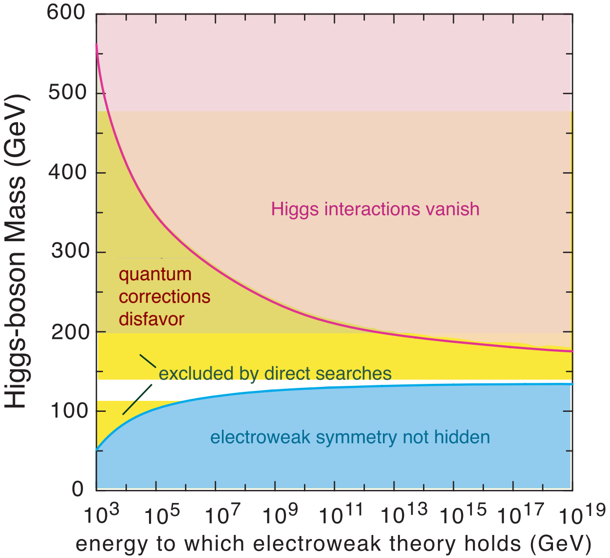
Requiring that $\langle\phi\rangle_0 \neq 0$ be an absolute minimum of the one-loop potential up to a scale $\Lambda$ yields the vacuum-stability condition . . . (for $m_t \lesssim M_W$)

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2}(2M_W^4 + M_Z^4 - 4m_t^4)\log(\Lambda^2/v^2)$$

(No illuminating analytic form for heavy $m_t$)

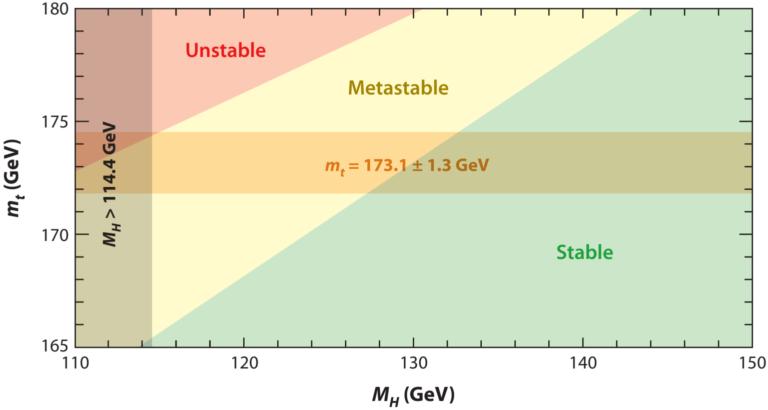
If Higgs boson is relatively light (which would require explanation) then theory can be self-consistent up to very high energies

# Consistent to $M_{\text{Planck}}$ if 134 GeV $\lesssim M_H \lesssim$ 177 GeV



# Living on the Edge?

*Require cosmological tunneling time, not absolute stability*



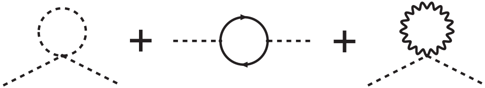

Isidori, *et al.*, hep-ph/0104016

# SM shortcomings

- No explanation of Higgs potential
- No prediction for $M_H$
- Doesn't predict fermion masses & mixings
- $M_H$ unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

# The Hierarchy Problem
## *Evolution of the Higgs-boson mass*

$M_H^2(p^2) = M_H^2(\Lambda^2) +$ 

quantum corrections from particles with $J = 0, \frac{1}{2}, 1$

Potential divergences:

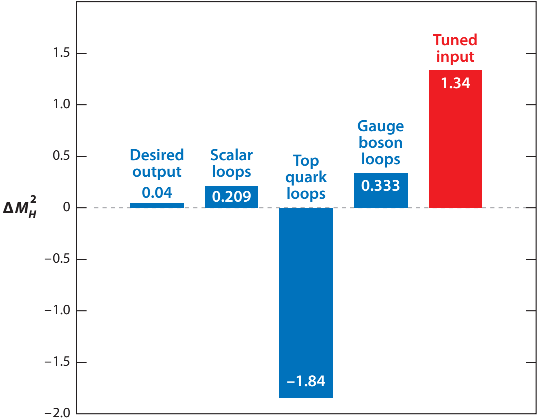
$$M_H^2(p^2) = M_H^2(\Lambda^2) + \mathcal{C}g^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots \ ,$$

$\Lambda$: naturally large, $\sim M_{\text{Planck}}$ or $\sim U \approx 10^{15-16}$ GeV

How to control quantum corrections?

# A Delicate Balance . . . even for $\Lambda = 5$ TeV

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$




Light Higgs + no new physics: LEP Paradox

# The Hierarchy Problem
*Possible paths*

- Fine tuning
- A new symmetry (supersymmetry)
  fermion, boson loops contribute with opposite sign
- Composite "Higgs boson" (technicolor . . . )
  form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

$\boxed{\text{All but first require new physics near the TeV scale}}$

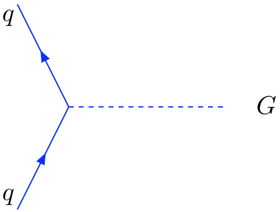
▸ . . .

# Why is empty space so nearly massless?

## Natural to neglect gravity in particle physics ...

Gravitational *ep* interaction $\approx 10^{-41} \times$ EM

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




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

300 years after Newton: Why *is* gravity weak?

# But gravity is not always negligible . . .

$$\boxed{V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2}$$

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

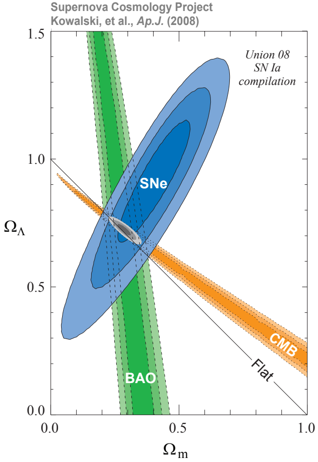
Identify $M_H^2 = -2\mu^2$

Position-independent vacuum energy density

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

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

# Observed $\varrho_{\text{vac}} \lesssim 10^{-46}\ \text{GeV}^4$




$\varrho_H \gtrsim 10^8\ \text{GeV}^4$: mismatch by $10^{54}$

A chronic dull headache for thirty years . . .

*The unreasonable effectiveness of the standard model*

# Puzzle #1:

Expect New Physics on TeV scale

to stabilize Higgs mass,

solve hierarchy problem,

but no sign of flavor-changing neutral currents.

*Minimal flavor violation a name, not yet an answer*

Great interest in searches for

forbidden or suppressed processes

# Example: $B_s \to \mu^+\mu^-$

$$\text{SM: BR}(\mathrm{B_s} \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

$$\text{MSSM: BR}(\mathrm{B_s} \to \mu^+\mu^-) \propto \frac{\mathrm{m_b^2 m_t^2}}{\mathrm{M_A^4}} \tan^6 \beta$$

$$\text{LHCb: BR}(\mathrm{B_s} \to \mu^+\mu^-) < 1.5 \times 10^{-8}$$

# Puzzle #2:

Expect New Physics on TeV scale

to stabilize Higgs mass,

solve hierarchy problem,

but no quantitative failures of EW theory.

No departures from established physics

have turned up in early running at LHC

# More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the "Higgs boson" elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of $H$ reveal new kinds of matter?
- What would discovery of $> 1$ Higgs boson imply?
- What stabilizes $M_H$ below 1 TeV?
- How can a light $H$ coexist with absence of new phenomena?
- Is EWSB related to gravity through extra spacetime dimensions?

# More Electroweak Questions for the LHC$^{\text{bis}}$

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of $H$?
- Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

# More Electroweak Questions for the LHC$^{\text{ter}}$

- What will be the next symmetry recognized in Nature? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

# A New World Is Coming

Explore

Search

Measure

*How are we prisoners of conventional thinking?*

Thank you and good luck!