Hadron Collider Physics:

Measurement, Search, & Discovery at the High-Energy Frontier

Chris Quigg
Fermilab

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A Decade of Discovery Past . . .

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

A Decade of Discovery Past . . .

- ▷ Electroweak theory $\rightarrow$ 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: $\nu_\mu \rightarrow \nu_\tau,\ \nu_e \rightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, 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 $K \rightarrow \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate $\mathcal{CP}$ [$e^+e^- \rightarrow B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Goal: Understanding the Everyday

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

Goal: Understanding the Everyday

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

What would the world be like without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons? *Consider the effects of all the* $\mathrm{SU(3)}_c \otimes \mathrm{SU(2)}_\mathrm{L} \otimes \mathrm{U(1)}_Y$ *gauge symmetries.*

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!

Tevatron Collider in a Nutshell

980-GeV protons on 980-GeV antiprotons (2π km)

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

392 ns between crossings (36 $\times$ 36 bunches)

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

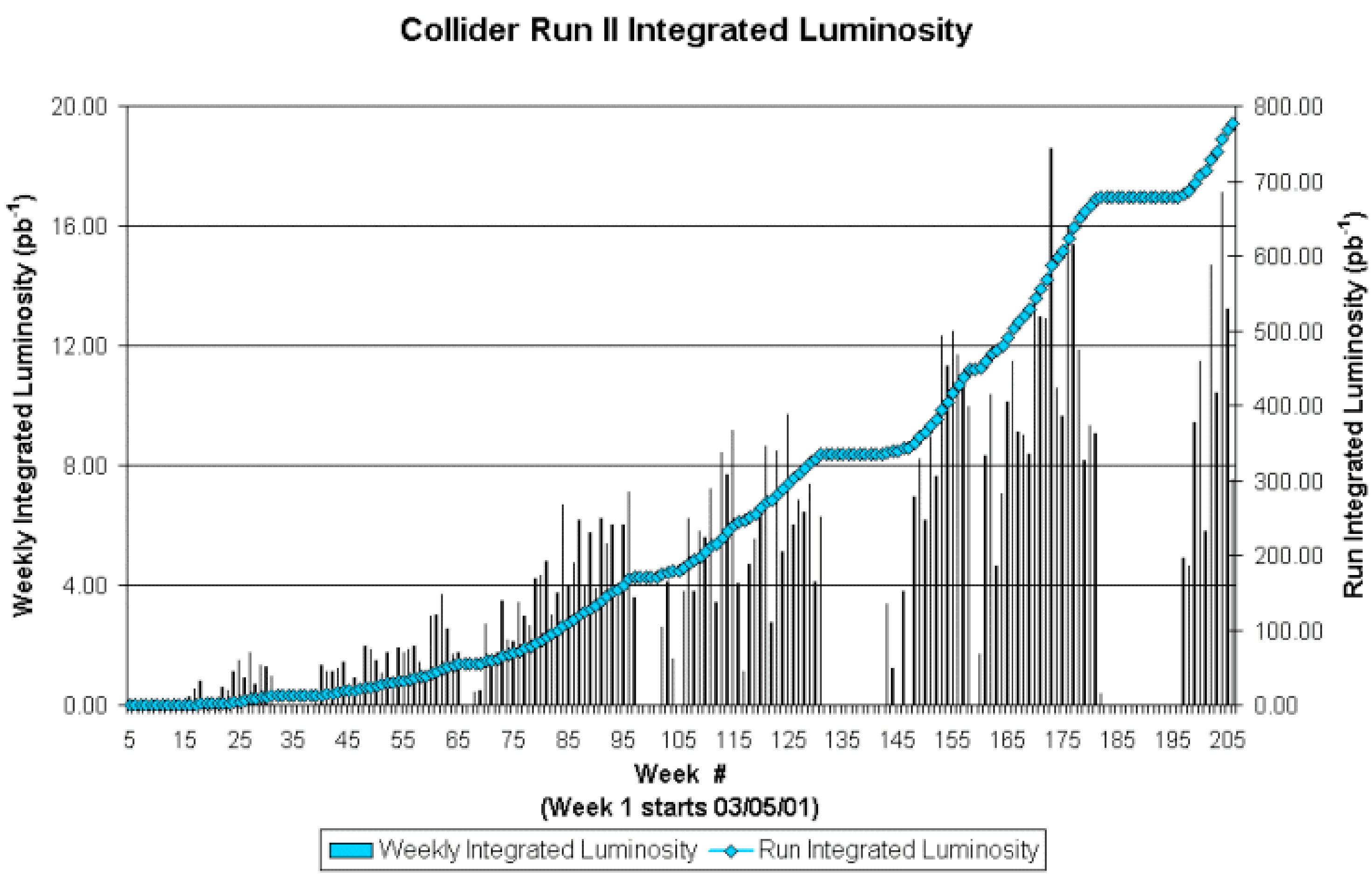
$c \approx 10^9$ km/h; $v_p \approx c - 495$ km/h

Record $\mathcal{L}_{\text{init}} = 1.0742 \times 10^{32}$ cm^{-2} s^{-1} [ISR: pp, 1.4]

Record integrated luminosity / store: 5.055 pb^{-1}

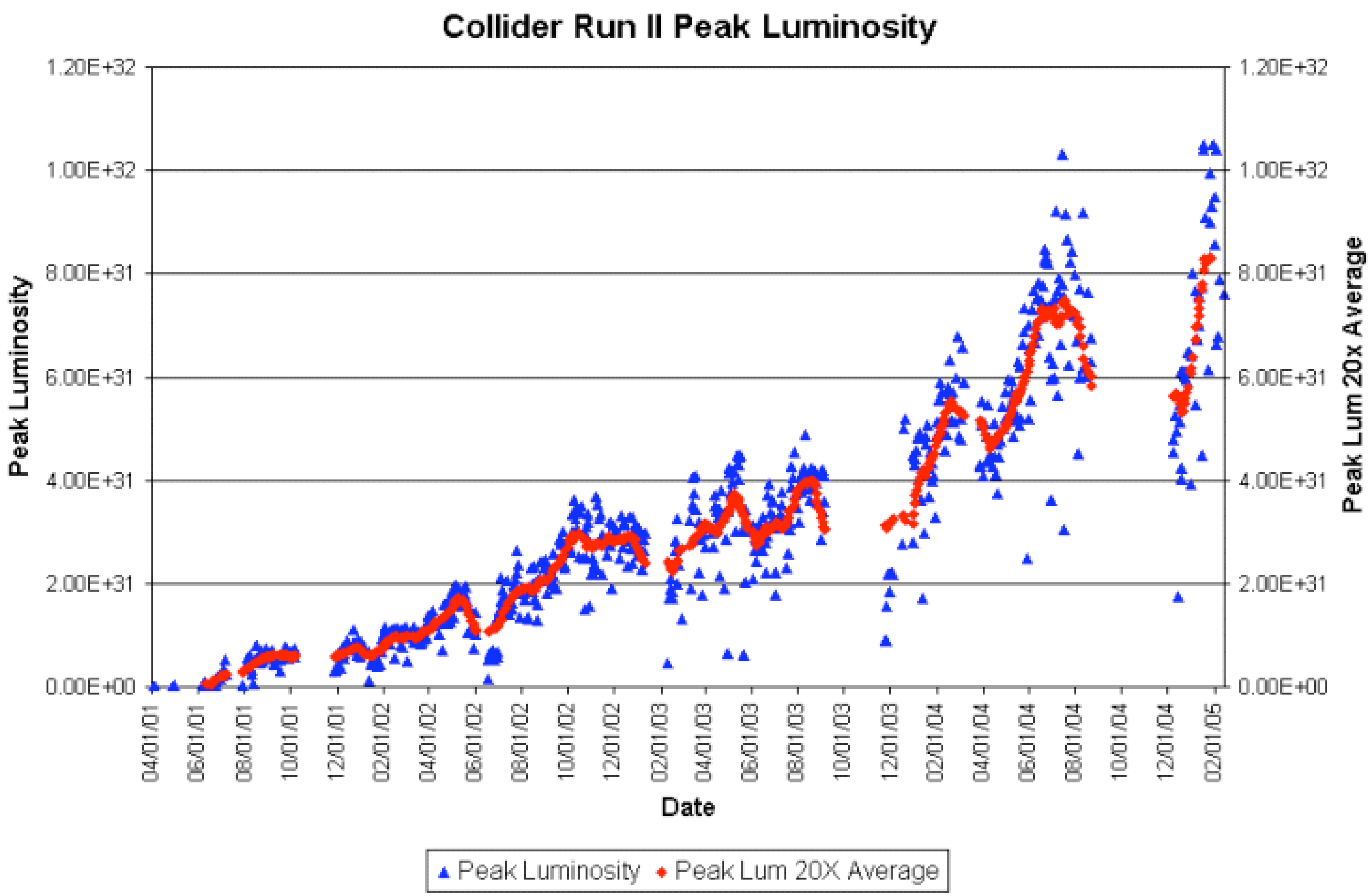
Maximum $\bar{p}$ at Low β: 1.661×10^{12}

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



$\mathcal{L}_{\text{init}} \approx 10^{32}$ cm^{-2} s^{-1} not rare, 0.8×10^{32} routine

working toward 2×10^{32} cm^{-2} s^{-1}



The Large Hadron Collider will operate *soon*, breaking new ground in energy and sensitivity

LHC in a nutshell

7-TeV protons on protons (27 km)

Novel two-in-one dipoles (≈ 9 teslas)

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

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

First year? 2808 bunches, $\mathcal{L} \to 2 \times 10^{33}$ cm^{-2} s^{-1}

25 ns bunch spacing

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

Much more from Philippe Bloch

Why the LHC is so exciting (I)

- Even low luminosity opens vast new terrain:
  10 pb^{-1} *(few days at initial $\mathcal{L}$)* yields
  8000 top quarks, 10^5 W-bosons,
  100 QCD dijets beyond Tevatron kinematic limit
  Supersymmetry could be found in a few weeks

- The antithesis of a one-experiment machine;
  enormous scope and versatility beyond high-$p_\perp$

- $\mathcal{L}$ upgrade extends $\gtrsim$10-year program . . .

Our picture of matter

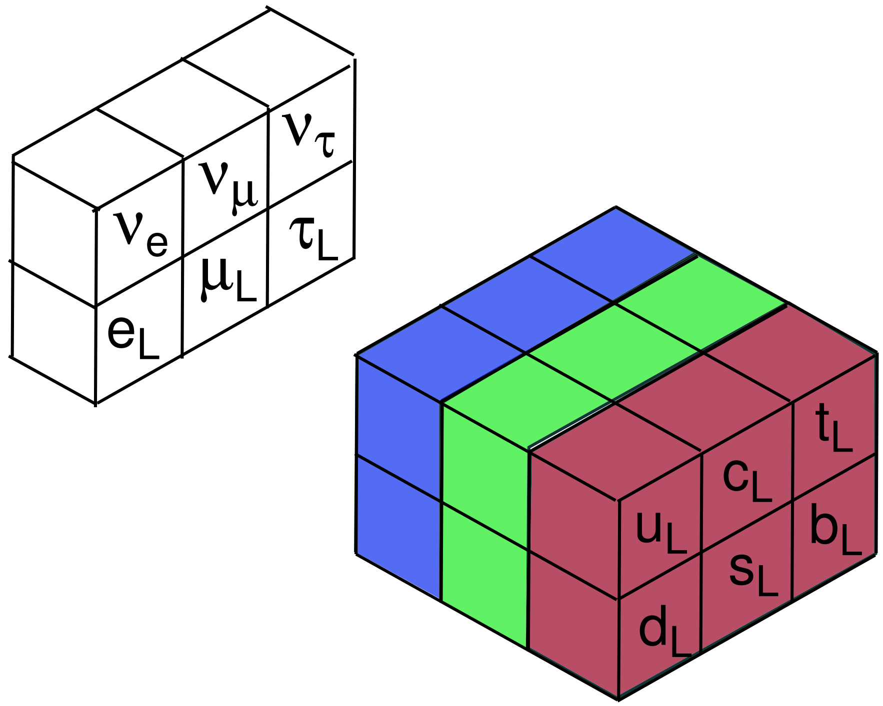
Pointlike constituents ($r < 10^{-18}$ m)

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

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

Few fundamental forces, from gauge symmetries

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


ν_e
ν_μ
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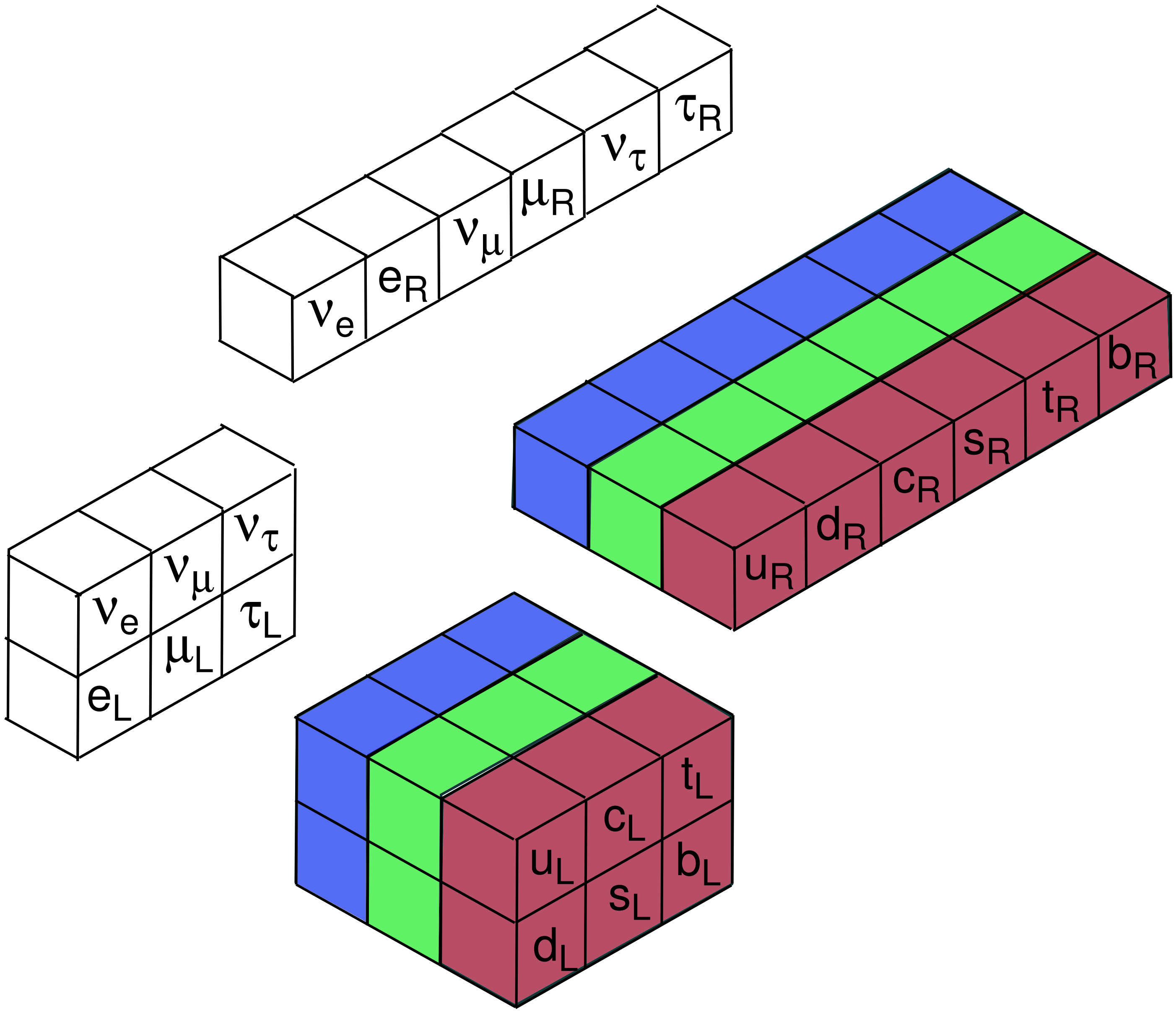
c_L
t_L
d_L
s_L
b_L



ν_e
e_R
ν_μ
μ_R
ν_τ
τ_R
ν_e
ν_μ
ν_τ
e_L
μ_L
τ_L
u_R
d_R
c_R
s_R
t_R
b_R
u_L
c_L
t_L
d_L
s_L
b_L

Recall electroweak theory . . .

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

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:

$\star$ weak isovector $\vec{b}_\mu$, coupling g $\quad$ $\star$ weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$

Field-strength tensors

$$F^{\ell}_{\mu\nu} = \partial_\nu b^{\ell}_\mu - \partial_\mu b^{\ell}_\nu + g\varepsilon_{jk\ell} b^j_\mu b^k_\nu \;, SU(2)_L$$

and

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

$$\mathcal{L} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm leptons} \;,$$

with

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

and

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

Electron mass term $\mathcal{L}_e = -m_e(\bar{e}_{\mathsf{R}}e_{\mathsf{L}} + \bar{e}_{\mathsf{L}}e_{\mathsf{R}}) = -m_e\bar{e}e$

would violate local gauge invariance

Theory has four massless gauge bosons

$$\mathcal{A}_{\mu} \quad b^1_{\mu} \quad b^2_{\mu} \quad b^3_{\mu}$$

Nature has but one (γ)

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition (Meissner effect)

▷ 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 $\rightsquigarrow$ broken symmetry: $\mu^2 < 0$

Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|} = (G_F\sqrt{2})^{-1/2} \approx 246 \text{ GeV}$$

Hides (breaks) $\mathrm{SU(2)_L}$ and $\mathrm{U(1)}_Y$ but preserves $\mathrm{U(1)_{em}}$ 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 in laws doesn't imply symmetry in outcomes . . .

- Electromagnetism is mediated by a massless photon, coupled to the electric charge;
- Mediator of charged-current weak interaction acquires a mass $M_W^2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W$,
- Mediator of (new!) neutral-current weak interaction acquires mass $M_Z^2 = M_W^2/\cos^2\theta_W$;
- Massive neutral scalar particle, the Higgs boson, appears, but its mass is not predicted;
- Fermions can acquire mass—value not predicted.

The importance of the 1-TeV scale

▷ Conditional *upper bound* on M_H from Unitarity

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 are 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,[a] 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 that largest eigenvalue respect pw unitarity condition $|a_0| \leq 1$

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

condition for perturbative unitarity

[a] Convenient to calculate using *Goldstone-boson equivalence theorem*, which reduces dynamics of longitudinally polarized gauge bosons to scalar field theory with interaction Lagrangian 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 1-TeV scale

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

New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV $\Rightarrow$ Explore the 1-TeV scale!

Lee, Quigg, Thacker, *Phys. Rev.* D**16**, 1519 (1977).

Why hadron colliders?

Rich diversity of elementary processes at high energy

Benchmark: $q\bar{q}$ interactions at 1 TeV ...

$$\langle x \rangle = \tfrac{1}{6} \rightsquigarrow pp \text{ collisions at } \sqrt{s} \approx 6 \text{ TeV}$$

Fixed-target: $p \approx 2 \times 10^4$ TeV $= 2 \times 10^{16}$ eV

$$r = \frac{10}{3} \cdot \left(\frac{p}{1 \text{ TeV}}\right) / \left(\frac{B}{1 \text{ tesla}}\right) \text{ km.}$$

$B = 2$ T (iron magnets) $\Rightarrow r = \frac{1}{3} \times 10^5$ km.

$\frac{1}{12}\times$ lunar orbit!

SC magnets (10 T) $\Rightarrow r \approx R_{\oplus} = 6.4 \times 10^3$ km

Breakthrough: Colliding beams!

To reach $3 \oplus 3$ TeV, require

$$r_{3\ \mathrm{TeV}} = \frac{10\ \mathsf{T}}{B}\ \mathsf{km}.$$

$\times 2$ (straight sections, quads, correctors) $\ldots$

10-T dipoles: radius of practical machine ≈ 2 km

$\approx 2\times$ Tevatron

SC magnets greatly reduce operating cost

Key advances in accelerator technology

- The idea of colliding beams.
- Alternating-gradient ("strong") focusing
- Superconducting accelerator magnets.
- Vacuum technology. In 20 hours, protons travel $\approx 2 \times 10^{10}$ km, $\approx 150\times$ Earth – Sun
- Large-scale cryogenic technology
- Active optics
- Intense antiproton sources

Competing technologies?

None for quark–gluon interactions

None for highest energies (derate composite protons)

Lepton–lepton collisions: LEP ($\sqrt{s} \approx 0.2$ TeV) was the last great electron synchrotron? Synchrotron radiation $\Rightarrow$ linear colliders for higher energies.

Challenge to reach 1 TeV; $\mathcal{L}$ *a great challenge*
$\leadsto$ International Linear Collider (François Richard)
Can we surpass 1 TeV? CLIC . . .

Competing technologies?

Lepton–hadron collisions: HERA ($e^{\pm}p$) as example;
energy intermediate between e^+e^-, pp
$e^{\pm}(u, d)$ leptoquark channel, proton structure, γp

High $\mathcal{L}$ a challenge: beam profiles don't match

(Far) future: $\mu^{\pm}p$ collider?

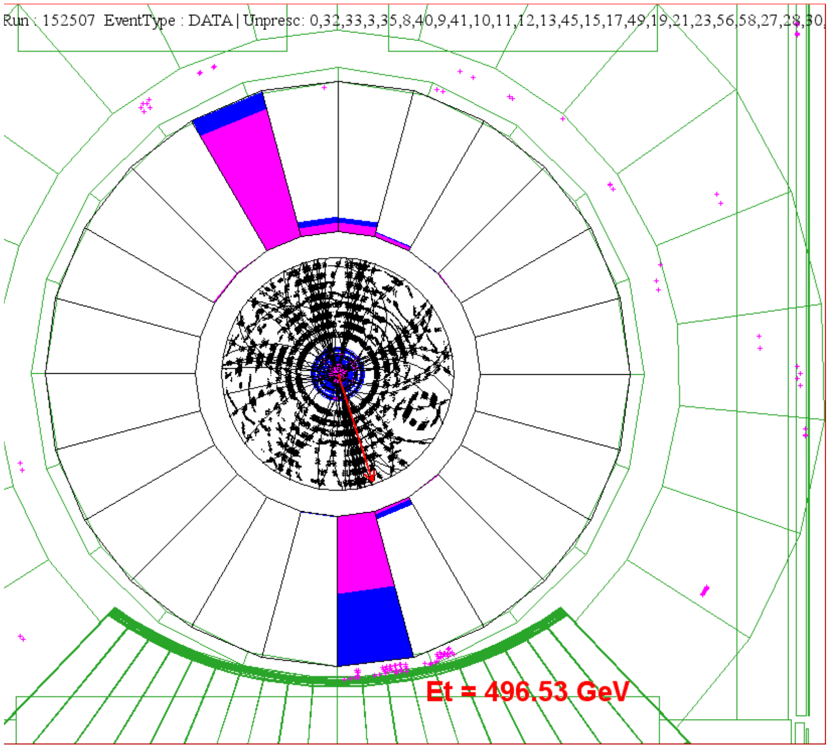
Heavy-ion collisions: RHIC the prototype; LHC
modest energy per nucleon;
quark-gluon plasma; new phases of matter

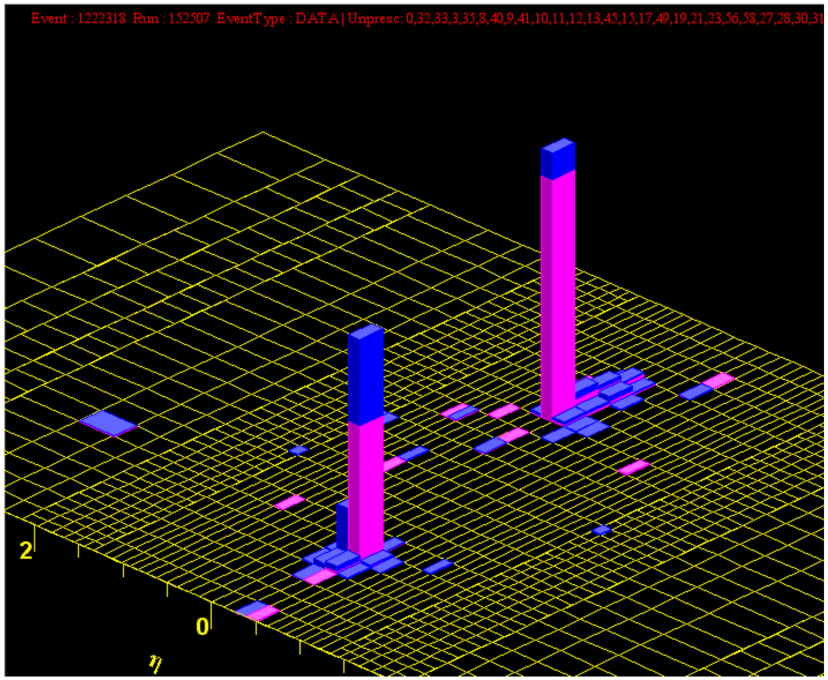
Unorthodox projectiles?

$\gamma\gamma$ Collider: Backscattered laser beams;
enhancement of linear collider capabilities

$\mu^+\mu^-$ collider: Advantage of elementary particle,
disadvantage of muon decay (2.2μs).
Small ring to reach very high effective energies?
Muon storage ring (neutrino factory) would turn bug into feature!

The World's Most Powerful Microscopes





CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV

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

What is a proton?

(For hard scattering) a broad-band, unselected beam of quarks, antiquarks, gluons, and perhaps other constituents characterized by parton densities

$$f_i^{(a)}(x_a, Q^2),$$

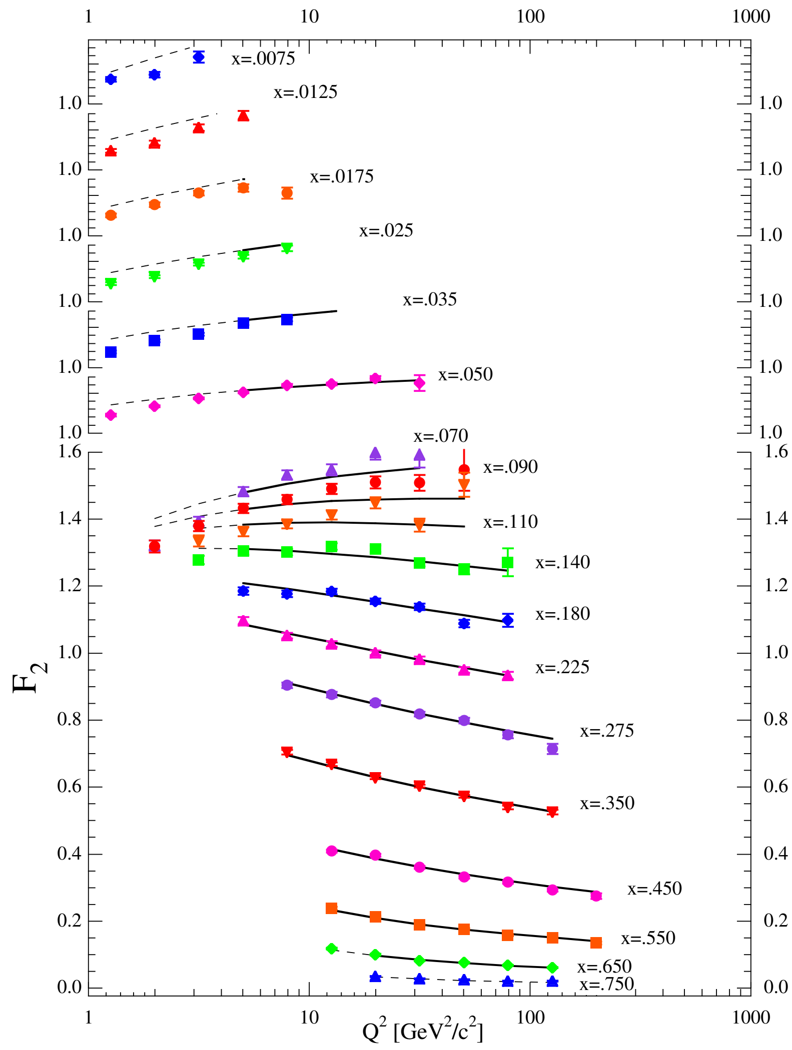
... number density of species i

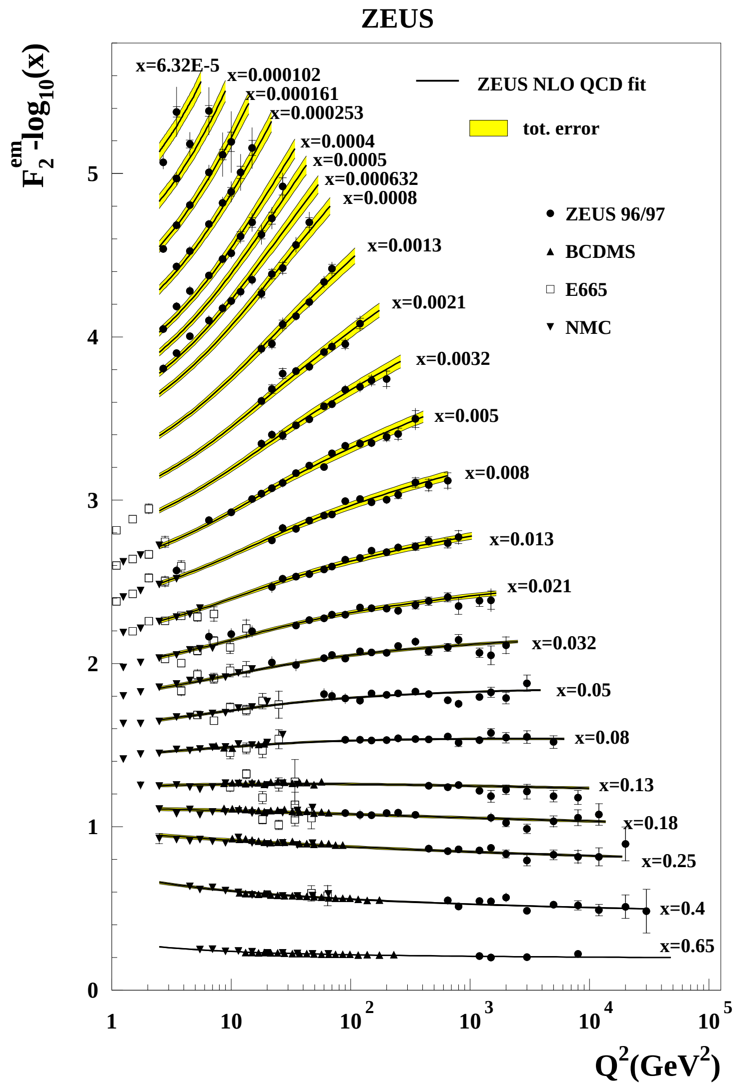
with momentum fraction x_a of hadron a seen by probe with resolving power Q^2.

Q^2 evolution given by QCD perturbation theory

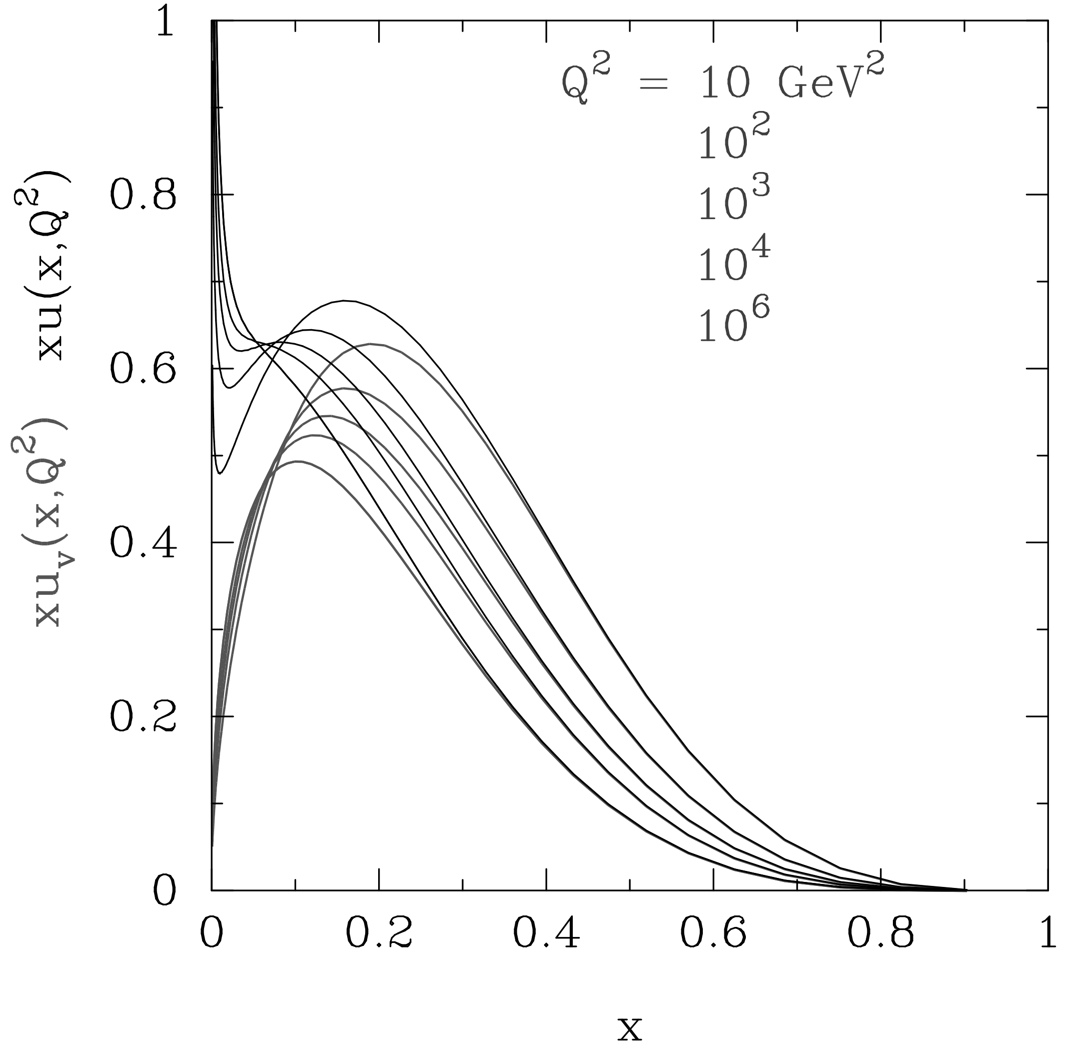
$f_i^{(a)}(x_a, Q_0^2)$: nonperturbative

PDFs determined from deeply inelastic scattering . . .

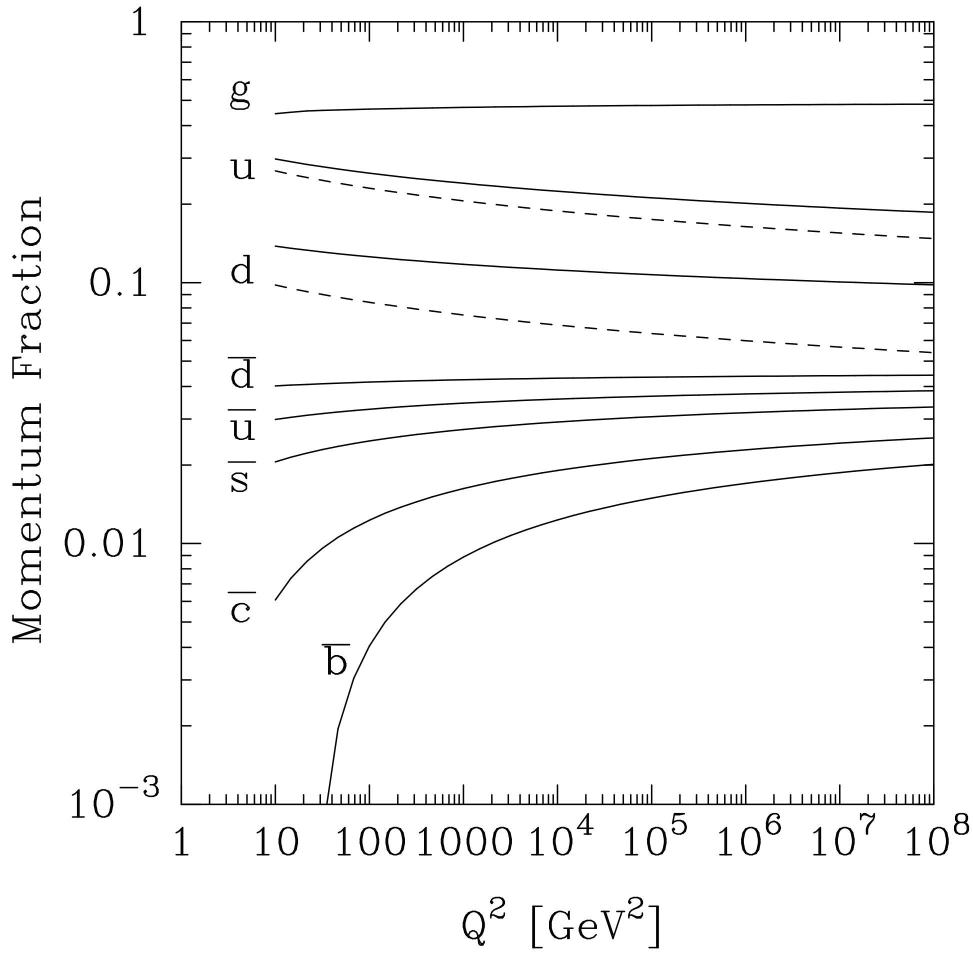




What is a proton?



Flavor content of the proton: $\int_0^1 dx\, x\, f_i(x, Q^2)$



Asymptotic limit ($Q^2 \to \infty$): $g : \frac{8}{17}$; $q_s : \frac{3}{68}$; $q_v : 0$

Hard-scattering cross sections

$$d\sigma(a+b \to c+X) = \sum_{ij} \int dx_a dx_b \cdot f_i^{(a)}(x_a, Q^2) f_j^{(b)}(x_b, Q^2) d\hat{\sigma}(i+j \to c+X),$$

$d\hat{\sigma}$: elementary cross section at energy $\sqrt{\hat{s}} = \sqrt{x_a x_b s}$

Define differential luminosity ($\tau = \hat{s}/s$)

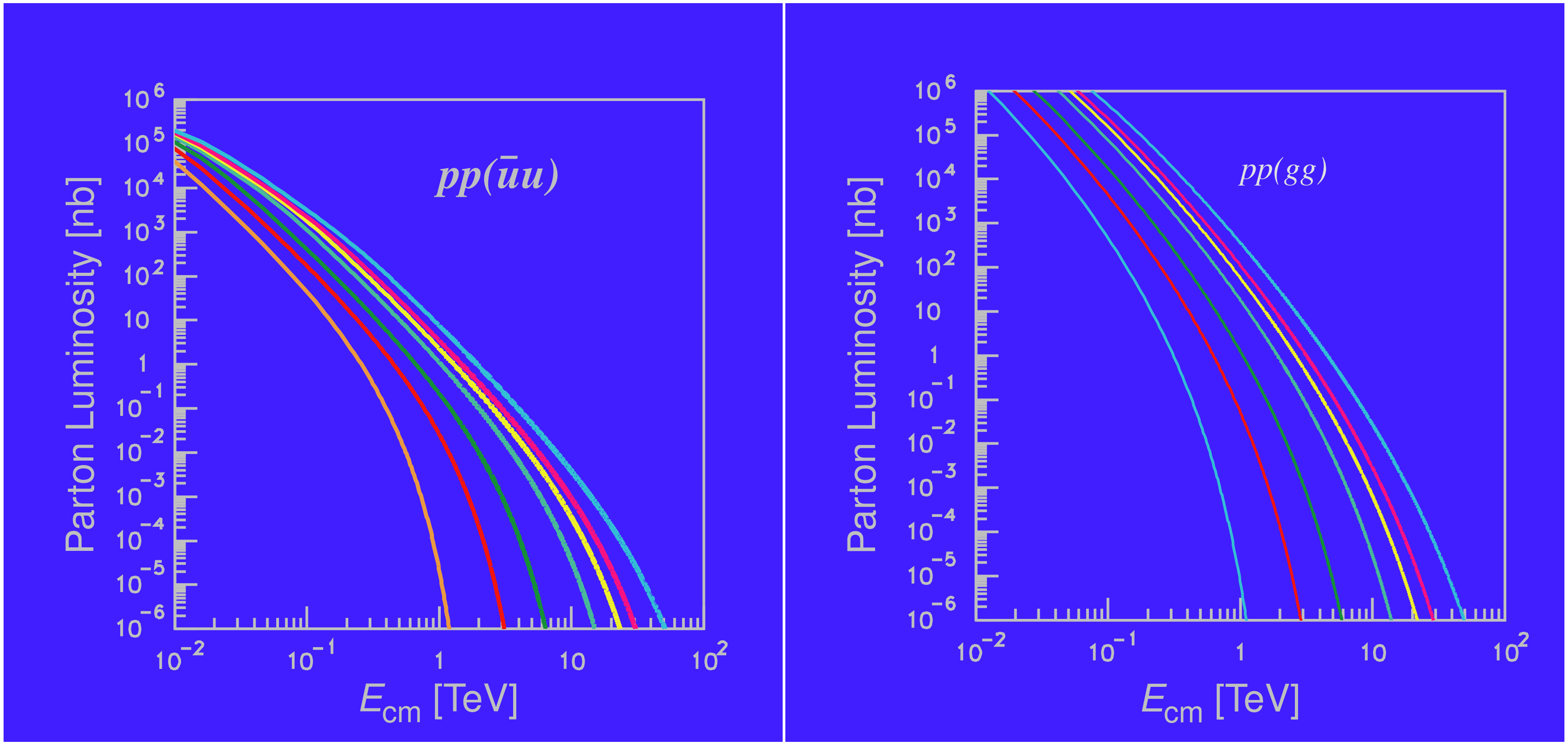
$$\frac{d\mathcal{L}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_\tau^1 dx \left[f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x) \right]$$

parton i-parton j collisions in $(\tau, \tau + d\tau)$ per ab collision

$$d\sigma(a+b \to c+X) = \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau} \hat{\sigma}(i+j \to c+X)$$

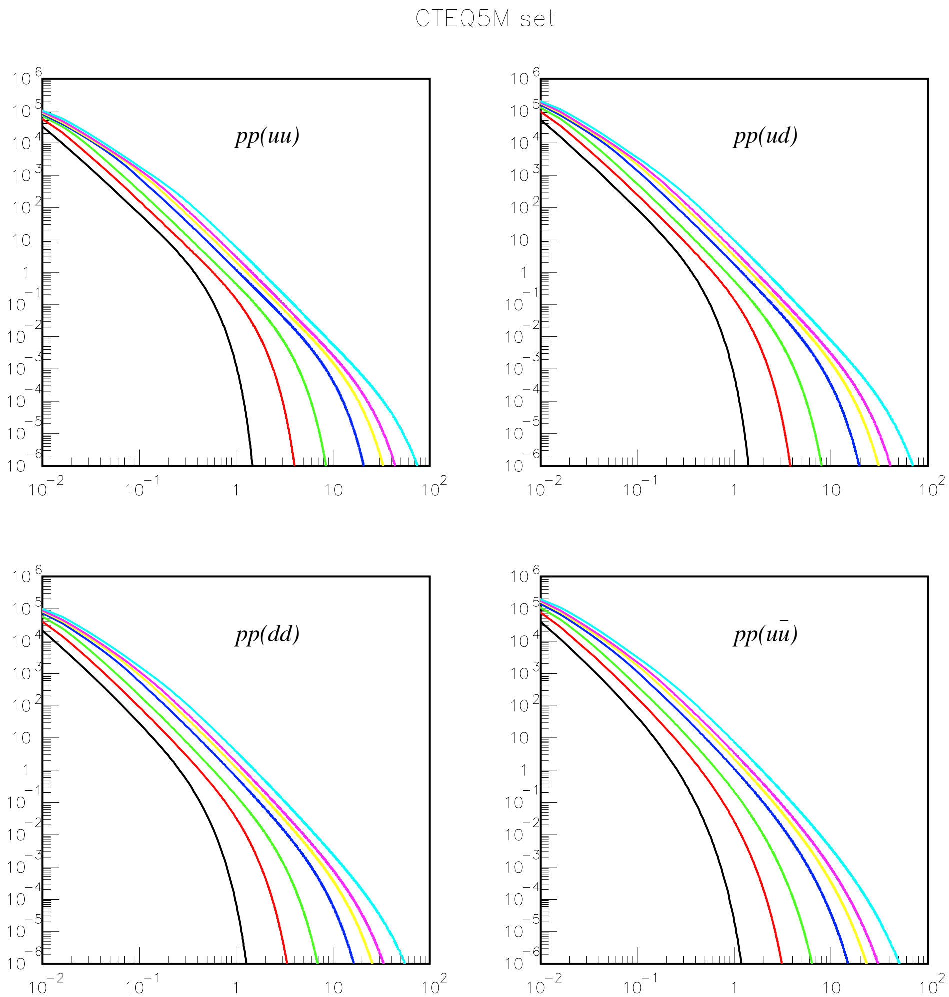
Hard scattering: $\hat{\sigma} \propto 1/\hat{s}$; Resonance: $\hat{\sigma} \propto \tau$; form $(\tau/\hat{s}) d\mathcal{L}/d\tau$

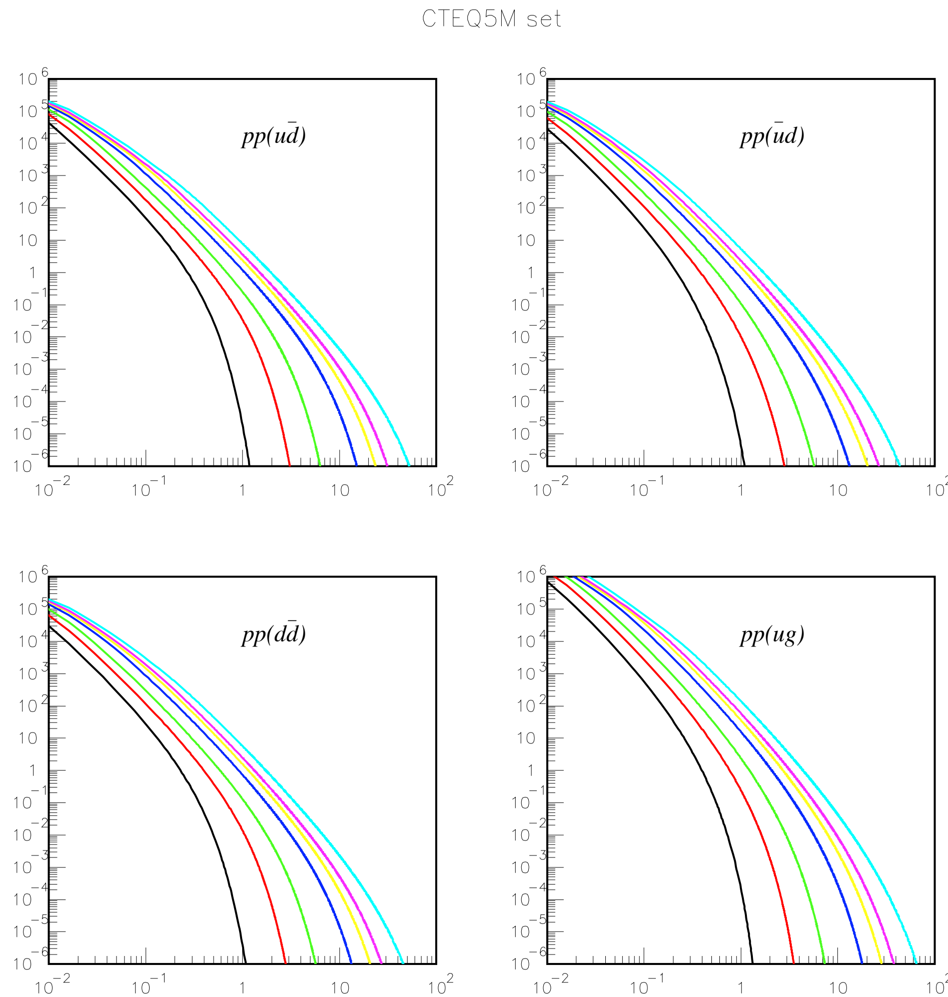
Parton Luminosities $(\tau/\hat{s})d\mathcal{L}/d\tau$

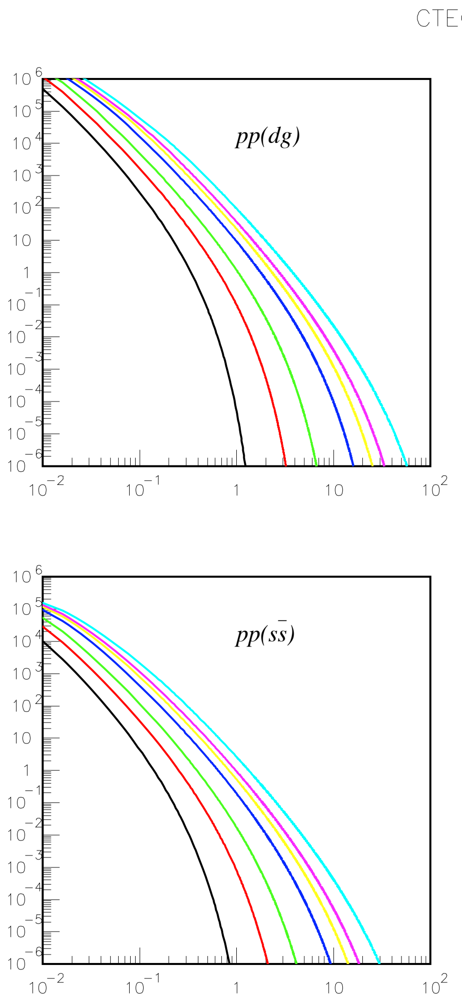


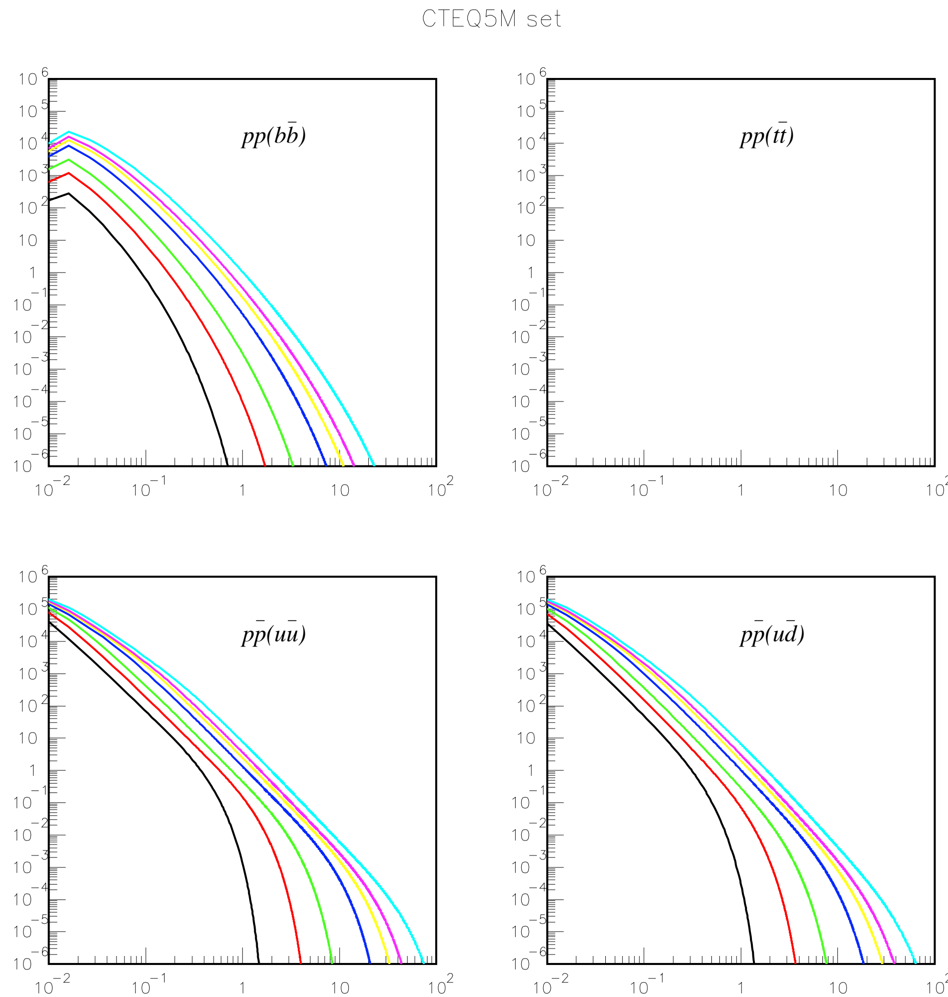
at $\sqrt{s} = 2, 6, 14, 40, 70, 100, 200$ TeV

Background: E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, *Rev. Mod. Phys.* **56**, 579 (1984). (CTEQ5 parton distributions)

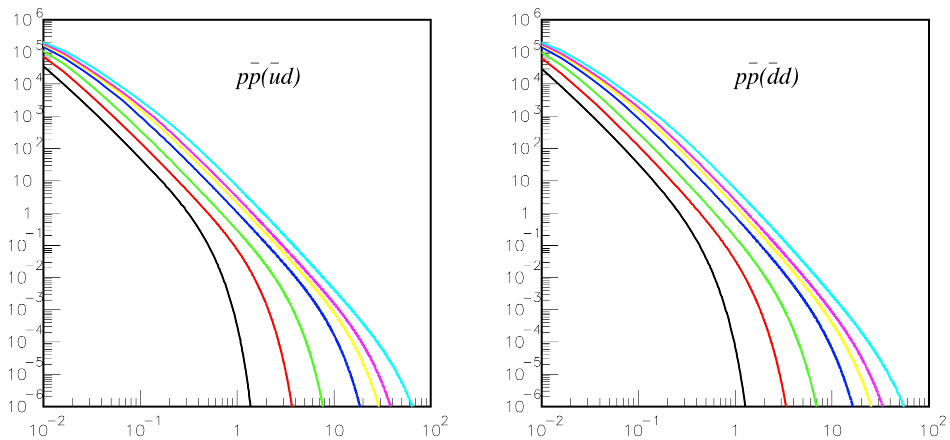

CTEQ5M set
pp(uu)
pp(ud)
pp(dd)
pp(uū)


CTEQ5M set
pp(ud̄)
pp(ūd)
pp(dd̄)
pp(ug)


CTEQ5M set
$pp(dg)$
$pp(gg)$
$pp(s\bar{s})$
$pp(c\bar{c})$


CTEQ5M set
$pp(b\bar{b})$
$pp(t\bar{t})$
$p\bar{p}(u\bar{u})$
$p\bar{p}(u\bar{d})$

CTEQ5M set


$p\bar{p}(\bar{u}d)$
$p\bar{p}(\bar{d}d)$
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-2
10^-1
1
10
10^2

Why a Higgs Boson Must Exist

Canceling HE divergences

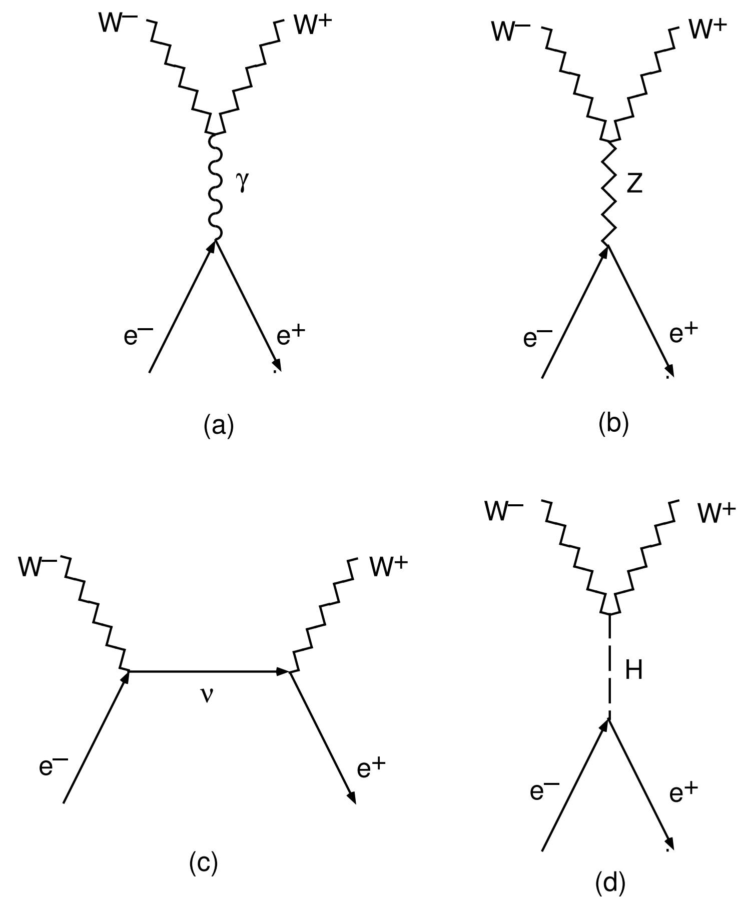
S-matrix: $e^+e^- \to W^+W^-$

$J = 1$ amplitudes

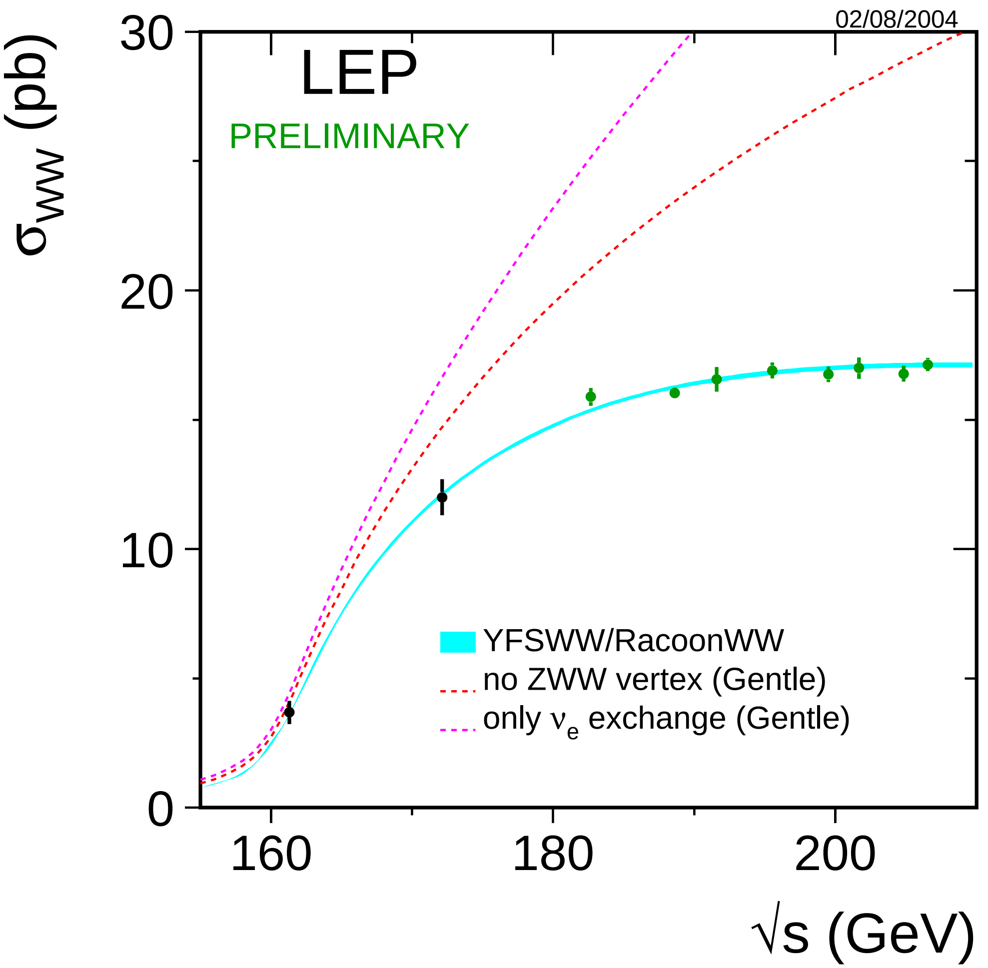
$$\mathcal{M}_\gamma^{(1)},\ \mathcal{M}_Z^{(1)},\ \mathcal{M}_\nu^{(1)}$$

each has unacceptable high-energy behavior ($\propto s$)

. . . but sum is well-behaved



"Gauge cancellation" observed at LEP2, Tevatron



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

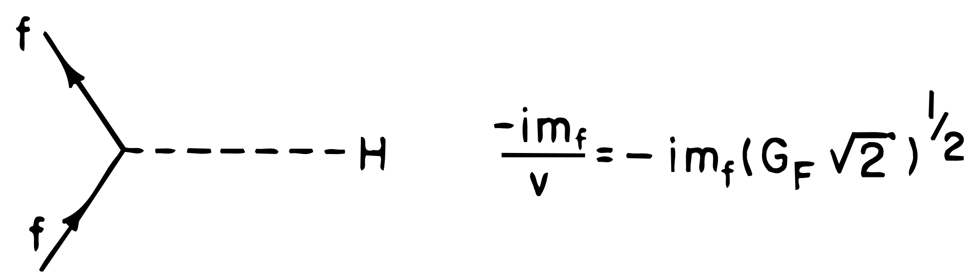
$$\mathcal{M}_{\nu}^{(0)} \propto s^{\frac{1}{2}}$$: unacceptable HE behavior

(no contributions from γ and Z)

This divergence is canceled by the Higgs-boson contribution

$\Rightarrow He\bar{e}$ 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

If the gauge symmetry were unbroken . . .

- ▷ no Higgs boson
- ▷ no longitudinal gauge bosons
- ▷ no extreme divergences
- ▷ no wrong-helicity amplitudes

. . . and no viable low-energy phenomenology

In spontaneously broken theory . . .

- ▷ gauge structure of couplings eliminates the most severe divergences
- ▷ lesser—but potentially fatal—divergence arises because the electron has mass

  . . . due to the Higgs mechanism
- ▷ SSB provides its own cure—the Higgs boson

A similar interplay and compensation *must exist* in any acceptable theory

▷ Triviality of scalar field theory

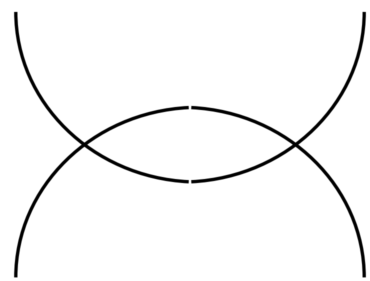
Only *noninteracting* scalar field theories make sense on all energy scales

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

running coupling constant

In $\lambda\phi^4$ theory, it is easy to calculate the variation of the coupling constant λ in perturbation theory by summing bubble graphs



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

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

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

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

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

implies an *upper bound*

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

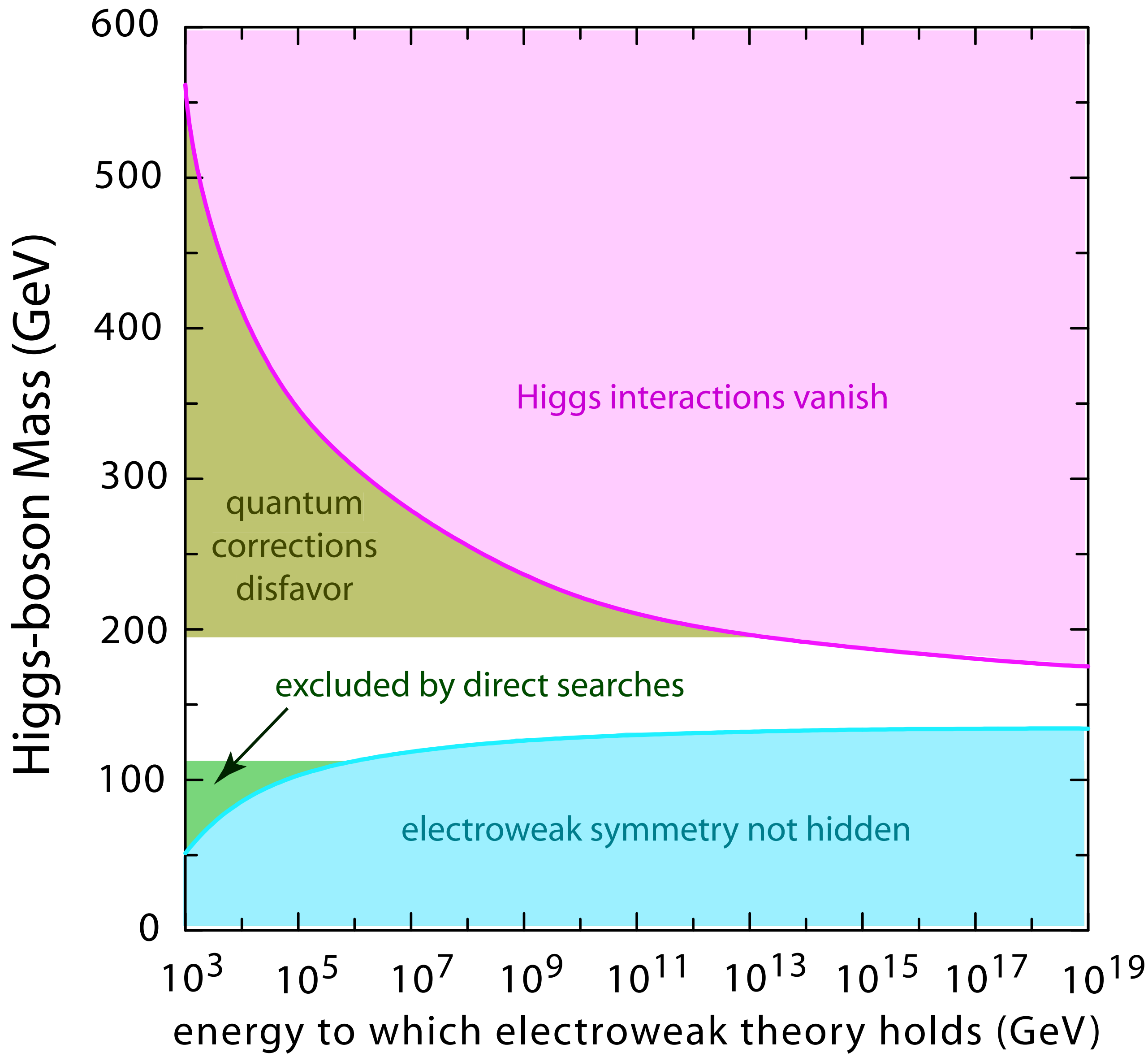
If we require the theory to make sense to arbitrarily high energies—or short distances—then we must take the limit $\Lambda \to \infty$ while holding μ fixed at some reasonable physical scale. In this limit, the bound forces $\lambda(\mu)$ to zero. $\longrightarrow$ free field theory "trivial"

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 $M_H^2 = 2\lambda(M_H)v^2$

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



Higgs-boson Mass (GeV)
600
500
400
300
200
100
0
Higgs interactions vanish
quantum
corrections
disfavor
excluded by direct searches
electroweak symmetry not hidden
10^3 10^5 10^7 10^9 10^11 10^13 10^15 10^17 10^19
energy to which electroweak theory holds (GeV)

Moral: For any M_H, there is a *maximum energy scale* $\Lambda^\star$ at which the theory ceases to make sense.

The description of the Higgs boson as an elementary scalar is at best an effective theory, valid over a finite range of energies

Perturbative analysis breaks down when $M_H \to 1$ TeV/c^2 and interactions become strong

Lattice analyses $\Longrightarrow M_H \lesssim 710 \pm 60$ GeV/c^2 if theory describes physics to a few percent up to a few TeV

If $M_H \to 1$ TeV EW theory lives on brink of instability

▷ *Lower bound* by requiring EWSB vacuum

$V(v) < V(0)$

Requiring that $\langle\phi\rangle_0 \neq 0$ be an absolute minimum of the one-loop potential up to a scale Λ yields the vacuum-stability condition

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

. . . for $m_t \lesssim M_W$

(No illuminating analytic form for heavy m_t)

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

If EW theory is to make sense all the way up to a unification scale $\Lambda^\star = 10^{16}$ GeV, then

$$134 \text{ GeV}/c^2 \lesssim M_H \lesssim 177 \text{ GeV}/c^2$$

The EW scale and beyond

EWSB scale, $v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246$ GeV, sets

$$M_W^2 = g^2v^2/2 \qquad M_Z^2 = M_W^2/\cos^2\theta_W$$

But it is not the only scale of physical interest

quasi-certain: $M_{\text{Planck}} = 1.22 \times 10^{19}$ GeV

probable: $\mathrm{SU(3)}_c \otimes \mathrm{SU(2)}_\mathrm{L} \otimes \mathrm{U(1)}_Y$ unification scale $\sim 10^{15-16}$ GeV

somewhere: flavor scale

How to keep the distant scales from mixing in the face of quantum corrections?

OR

How to stabilize the mass of the Higgs boson on the electroweak scale?

OR

Why is the electroweak scale small?

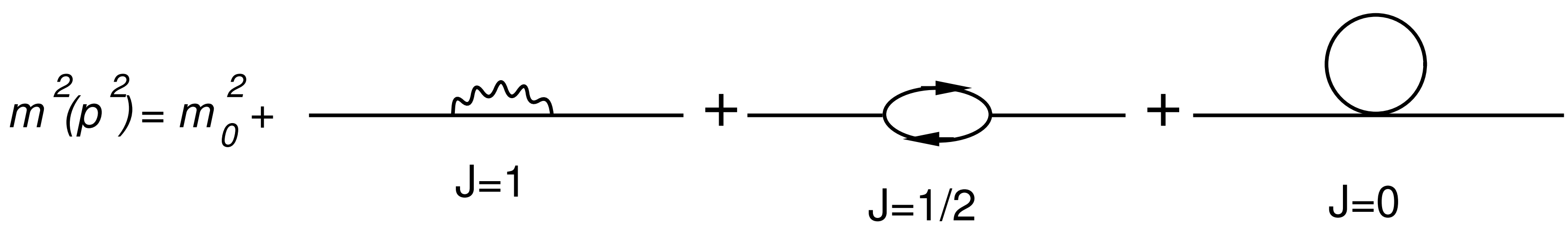
“The hierarchy problem”

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

$\mu^2 < 0$: $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y \to U(1)_\mathrm{em}$, as

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ \sqrt{-\mu^2/2|\lambda|} \end{pmatrix} \equiv \begin{pmatrix} 0 \\ \underbrace{(G_F\sqrt{8})^{-1/2}}_{175\ \mathrm{GeV}} \end{pmatrix}$$

Beyond classical approximation, quantum corrections to scalar mass parameters:



Loop integrals are potentially divergent.

$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots$$

Λ: reference scale at which m^2 is known

g: coupling constant of the theory

C: coefficient calculable in specific theory

For the mass shifts induced by radiative corrections to remain under control (not greatly exceed the value measured on the laboratory scale), *either*

- ▷ Λ must be small, *or*
- ▷ new physics must intervene to cut off integral

BUT natural reference scale for Λ is

$$\Lambda \sim M_{\mathsf{Planck}} = \left(\frac{\hbar c}{G_{\mathsf{Newton}}}\right)^{1/2} \approx 1.22 \times 10^{19}\ \mathsf{GeV}$$

for $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$

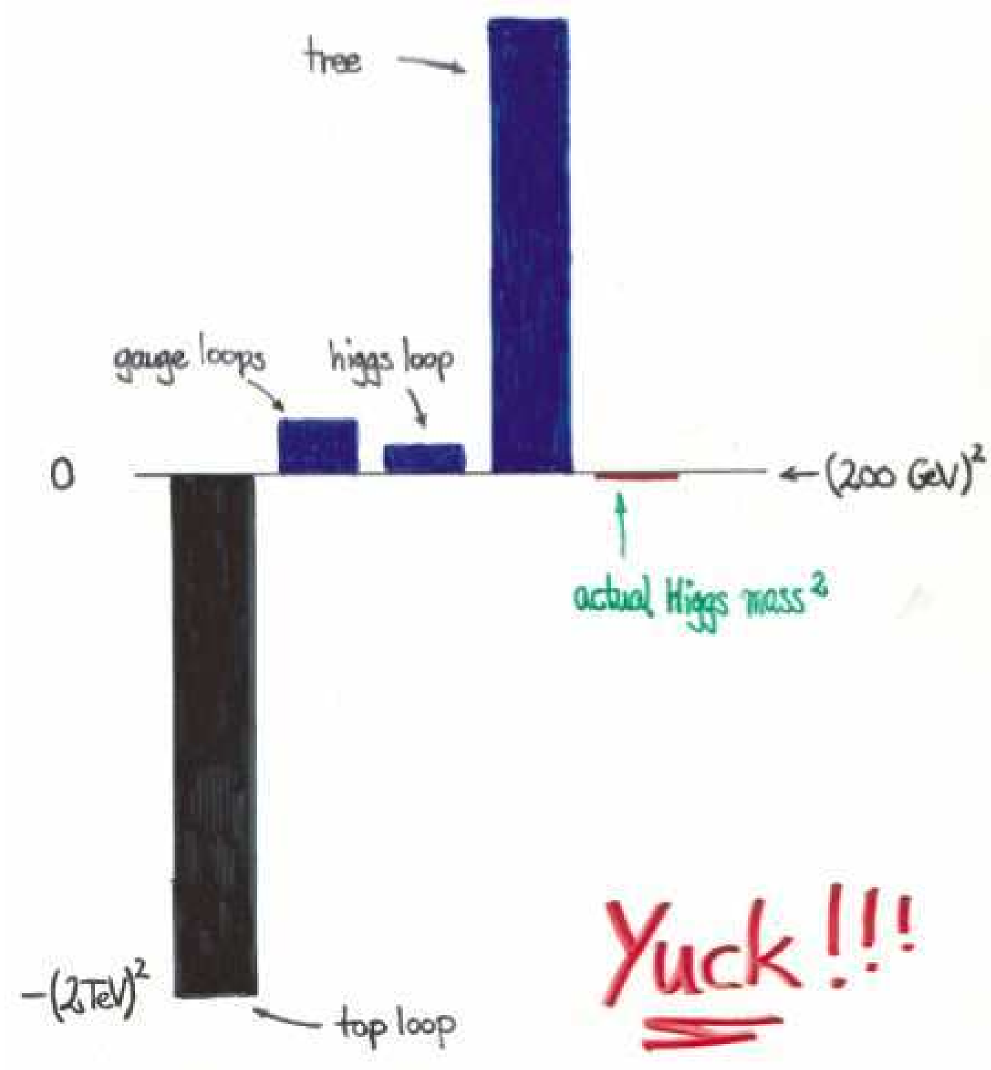
OR

$$\Lambda \sim M_U \approx 10^{15}\text{-}10^{16}\ \mathsf{GeV}$$

for unified theory

Both $\gg v/\sqrt{2} \approx 175$ GeV $\Longrightarrow$

New Physics at $E \lesssim 1$ TeV



Martin Schmaltz, ICHEP02

Only a few distinct scenarios . . .

▷ Supersymmetry: balance contributions of fermion loops (-1) and boson loops $(+1)$

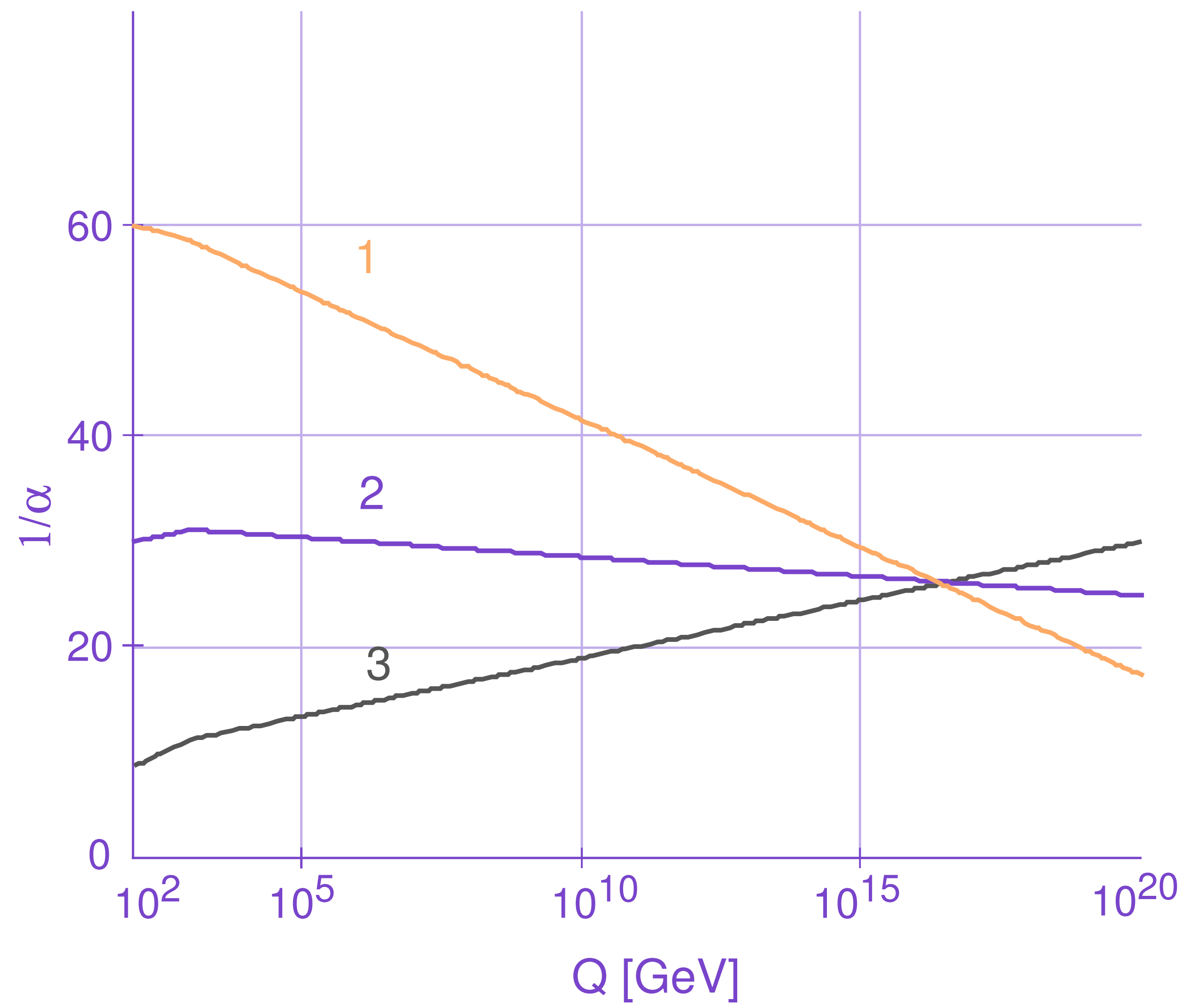
Exact supersymmetry,

$$\sum_{i=\substack{\text{fermions}\\+\text{bosons}}} C_i \int dk^2 = 0$$

Broken supersymmetry, shifts acceptably small if superpartner mass splittings are not too large

$g^2\Delta M^2$ "small enough" $\Rightarrow \widetilde{M} \lesssim 1$ TeV/c^2

Coupling constant unification?



Only a few distinct scenarios . . .

- ▷ Composite scalars (technicolor): New physics arises on scale of composite Higgs-boson binding,

$$\Lambda_{\mathsf{TC}} \simeq O(1\ \mathsf{TeV})$$

"Form factor" cuts effective range of integration

- ▷ Strongly interacting gauge sector: WW resonances, multiple W production, probably scalar bound state "quasiHiggs" with $M < 1$ TeV

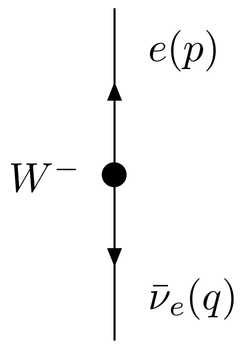
Only a few distinct scenarios . . .

- ▷ Extra spacetime dimensions:
  pseudo-Nambu–Goldstone bosons, extra particles to cancel integrand, . . .

- ▷ Planck mass is a mirage, based on a false extrapolation of Newton's $1/r^2$ force law

W-boson properties

Leptonic decay $W^- \to e^- \nu_e$



$$p \approx \left(\frac{M_W}{2}; \frac{M_W \sin\theta}{2}, 0, \frac{M_W \cos\theta}{2}\right)$$

$$q \approx \left(\frac{M_W}{2}; -\frac{M_W \sin\theta}{2}, 0, -\frac{M_W \cos\theta}{2}\right)$$

$$\mathcal{M} = -i\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^{\frac{1}{2}} \bar{u}(e,p)\gamma_\mu(1-\gamma_5)v(\nu,q)\,\varepsilon^\mu$$

$\varepsilon^\mu = (0; \hat{\varepsilon})$: W polarization vector in its rest frame

$$|\mathcal{M}|^2 = \frac{G_F M_W^2}{\sqrt{2}} \mathrm{tr}\left[\not{\varepsilon}(1-\gamma_5)\not{q}(1+\gamma_5)\not{\varepsilon}^*\not{p}\right] ;$$

$$\mathrm{tr}[\cdots] = \left[\varepsilon\cdot q\,\varepsilon^*\cdot p - \varepsilon\cdot\varepsilon^*\,q\cdot p + \varepsilon\cdot p\,\varepsilon^*\cdot q + i\epsilon_{\mu\nu\rho\sigma}\varepsilon^\mu q^\nu \varepsilon^{*\rho} p^\sigma\right]$$

Decay rate is independent of W polarization; look first at longitudinal pol. $\varepsilon^{\mu} = (0;0,0,1) = \varepsilon^{*\mu}$, eliminate $\epsilon_{\mu\nu\rho\sigma}$

$$|\mathcal{M}|^2 = \frac{4G_F M_W^4}{\sqrt{2}} \sin^2\theta$$

$$\frac{d\Gamma_0}{d\Omega} = \frac{|\mathcal{M}|^2}{64\pi^2}\,\frac{\mathcal{S}_{12}}{M_W^3}$$

$$\mathcal{S}_{12} = \sqrt{[M_W^2 - (m_e + m_\nu)^2][M_W^2 - (m_e - m_\nu)^2]} = M_W^2$$

$$\frac{d\Gamma_0}{d\Omega} = \frac{G_F M_W^3}{16\pi^2\sqrt{2}} \sin^2\theta$$

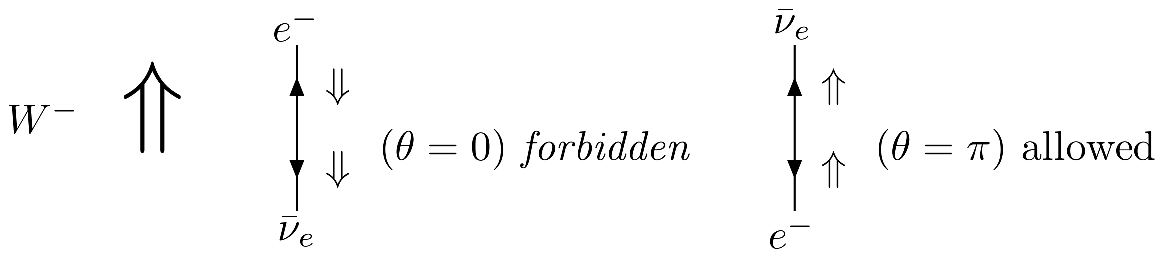
and

$$\boxed{\Gamma(W \to e\nu) = \frac{G_F M_W^3}{6\pi\sqrt{2}}}$$

Other helicities: $\varepsilon^{\mu}_{\pm 1} = (0; -1, \mp i, 0)/\sqrt{2}$

$$\frac{d\Gamma_{\pm 1}}{d\Omega} = \frac{G_F M_W^3}{32\pi^2\sqrt{2}}(1 \mp \cos\theta)^2$$

Extinctions at $\cos\theta = \pm 1$ are consequences of angular momentum conservation:



(situation reversed for $W^+ \to e^+\nu_e$)

e^+ follows polarization direction of W^+

e^- avoids polarization direction of W^-

important for discovery of $W^\pm$ in $\bar{p}p$ $(\bar{q}q)$ C violation

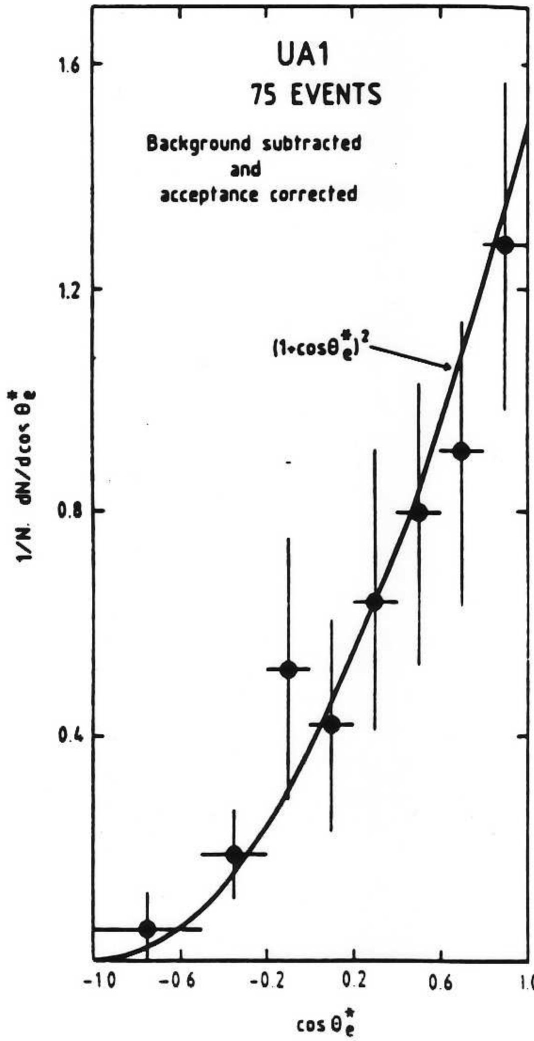


Fig. 2. The W decay angular distribution of the emission angle θ^* of the electron (positron) with respect to the proton (antiproton) direction in the rest frame of the W. Only those events for which the lepton charge and the decay kinematics are well determined have been used. The curve shows the ($V - A$) expectation of $(1 + \cos\theta^*)^2$.

Higgs-Boson Properties

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

$\propto M_H$ in the limit of large Higgs mass

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

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

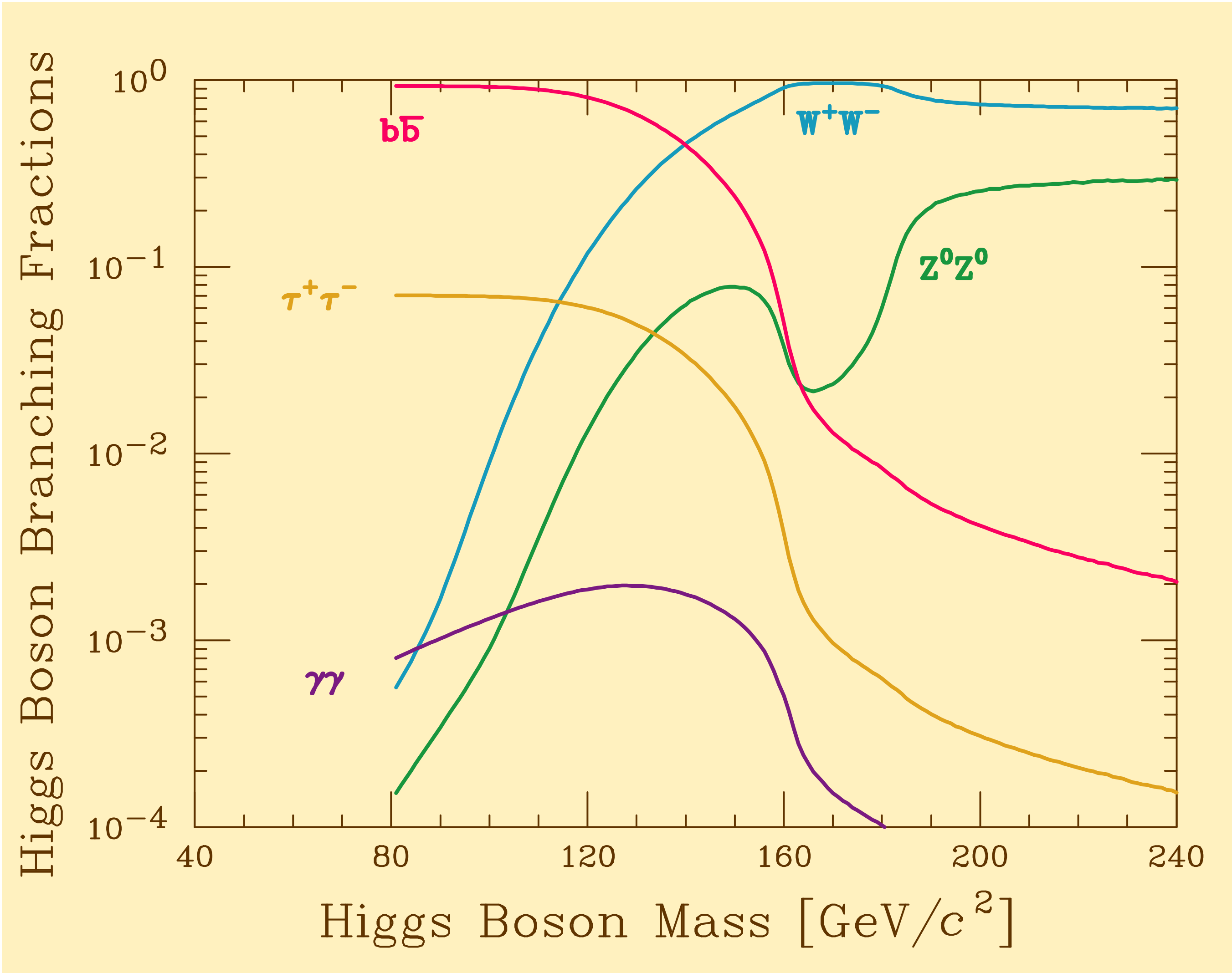
$x \equiv 4M_W^2/M_H^2$, $x' \equiv 4M_Z^2/M_H^2$

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

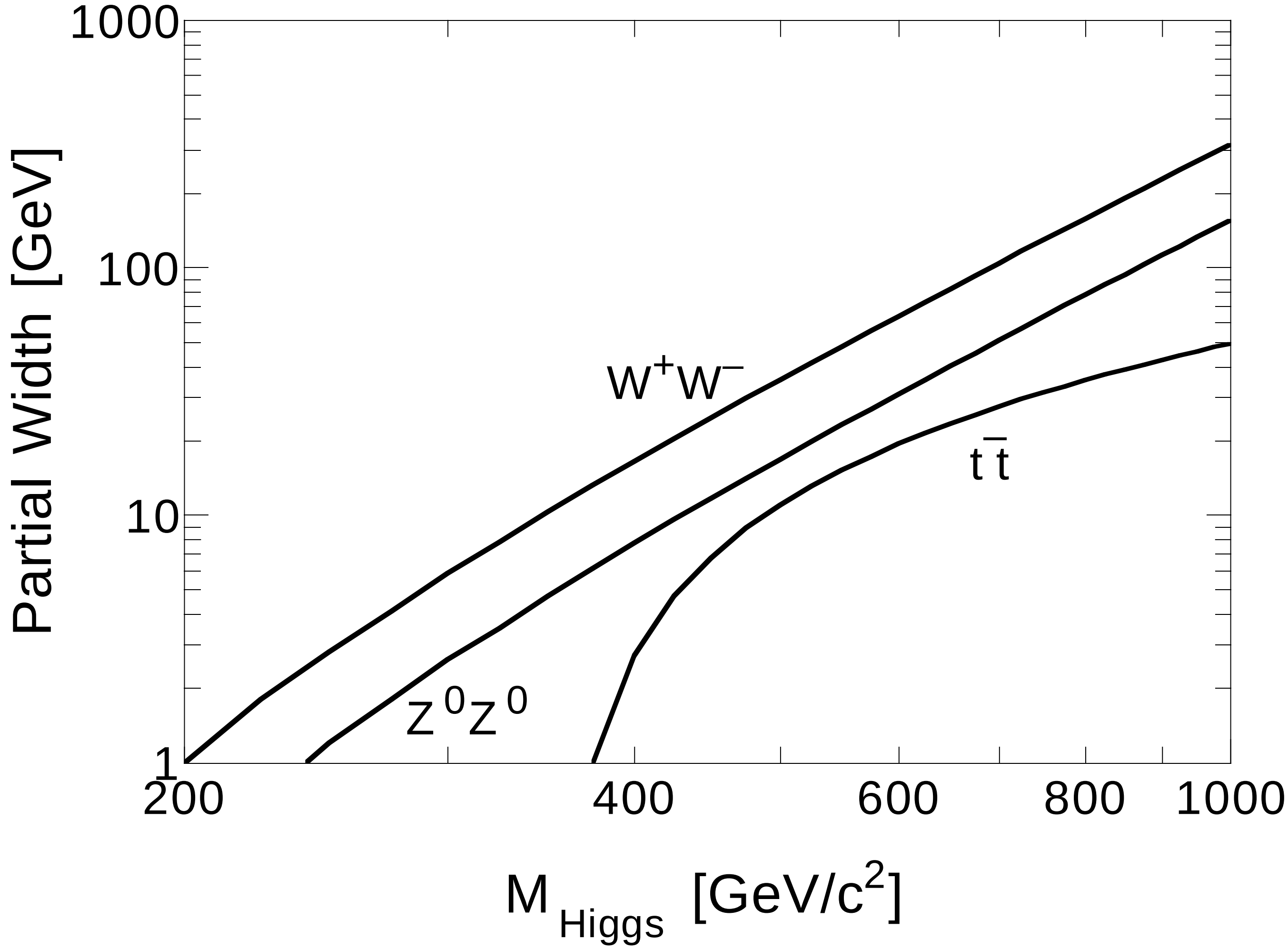
($\frac{1}{2}$ from weak isospin)

$2x^2$ and $2x'^2$ terms $\Leftrightarrow$ decays into transversely polarized gauge bosons

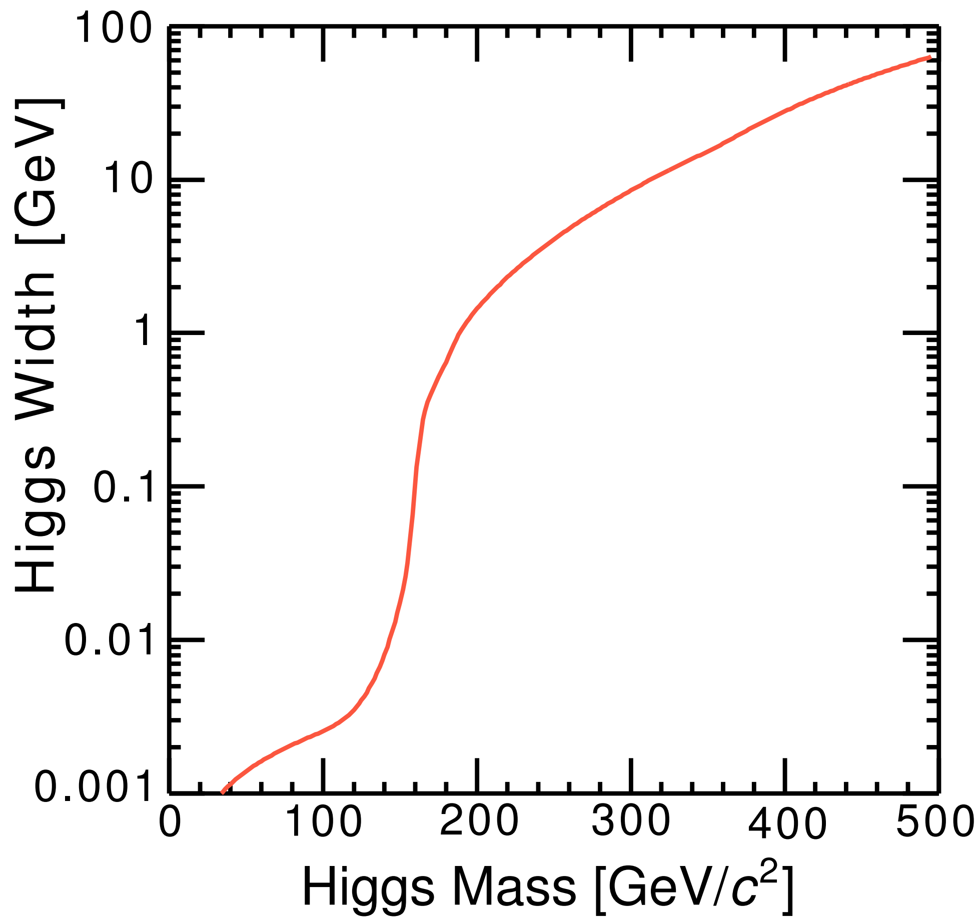
Dominant decays for large M_H into longitudinally polarized weak bosons



Higgs Boson Branching Fractions
Higgs Boson Mass [GeV/c²]
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
40
80
120
160
200
240
bb̄
W⁺W⁻
Z⁰Z⁰
τ⁺τ⁻
γγ



1000
100
10
1
Partial Width [GeV]
200
400
600
800
1000
M_{Higgs} [GeV/c^2]
W^+W^-
Z^0Z^0
$t\bar{t}$



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

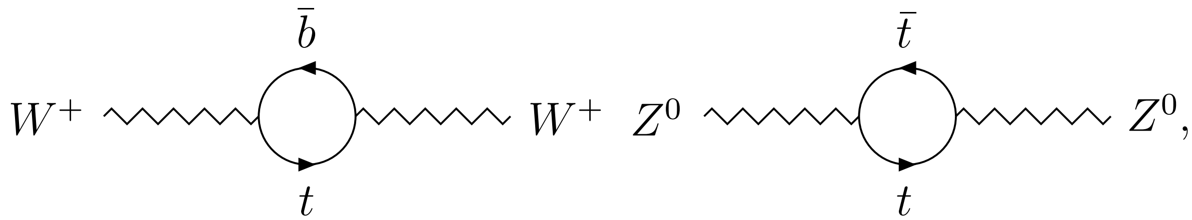
Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

For $M_H \to 1$ TeV/c^2, Higgs boson is an *ephemeron*, with a perturbative width approaching its mass.

Clues to the Higgs-boson mass

Sensitivity of EW observables to m_t gave early indications for massive top

quantum corrections to SM predictions for M_W and M_Z arise from different quark loops



...alter the link between M_W and M_Z:

$$M_W^2 = M_Z^2 \left(1 - \sin^2\theta_W\right)(1 + \Delta\rho)$$

where $\Delta\rho \approx \Delta\rho^{(\text{quarks})} = 3G_F m_t^2/8\pi^2\sqrt{2}$

strong dependence on m_t^2 accounts for precision of m_t estimates derived from EW observables

Tevatron measures m_t to $\pm 3\%$: 178.0 ± 4.3 GeV

$\Longrightarrow$ look beyond the quark loops to next most important quantum corrections: Higgs-boson effects

H quantum corrections smaller than t corrections, exhibit more subtle dependence on M_H than the m_t^2 dependence of the top-quark corrections

$$\Delta\rho^{(\mathrm{Higgs})} = \mathcal{C} \cdot \ln\left(\frac{M_H}{v}\right)$$

M_Z known to 23 ppm, m_t and M_W well measured

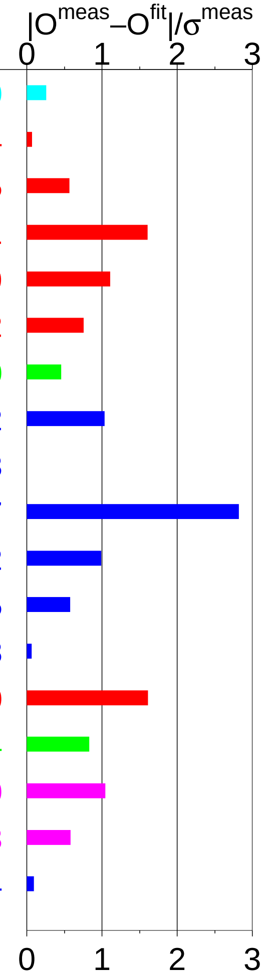
so examine dependence of M_W upon m_t and M_H

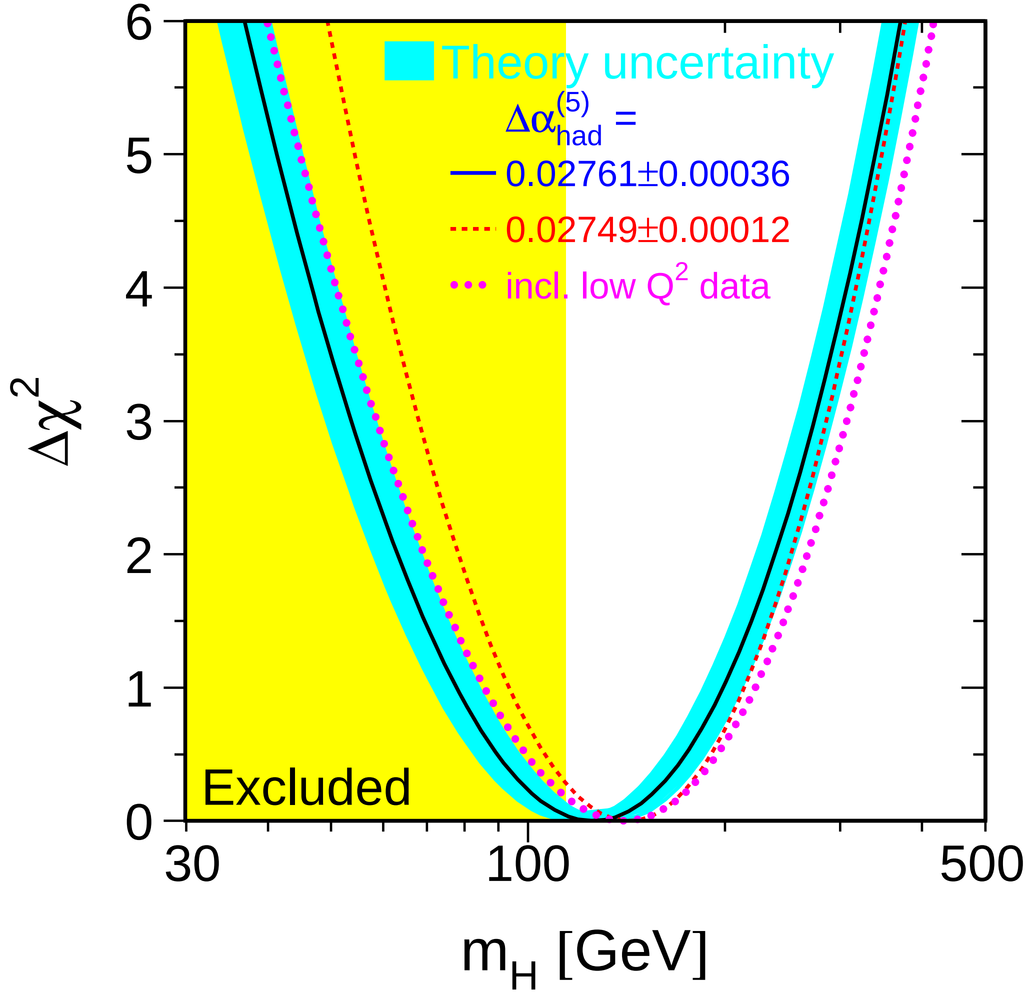
Direct, indirect determinations agree reasonably
Both favor a light Higgs boson,

within framework of SM analysis.

Fit to a universe of data

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
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	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4





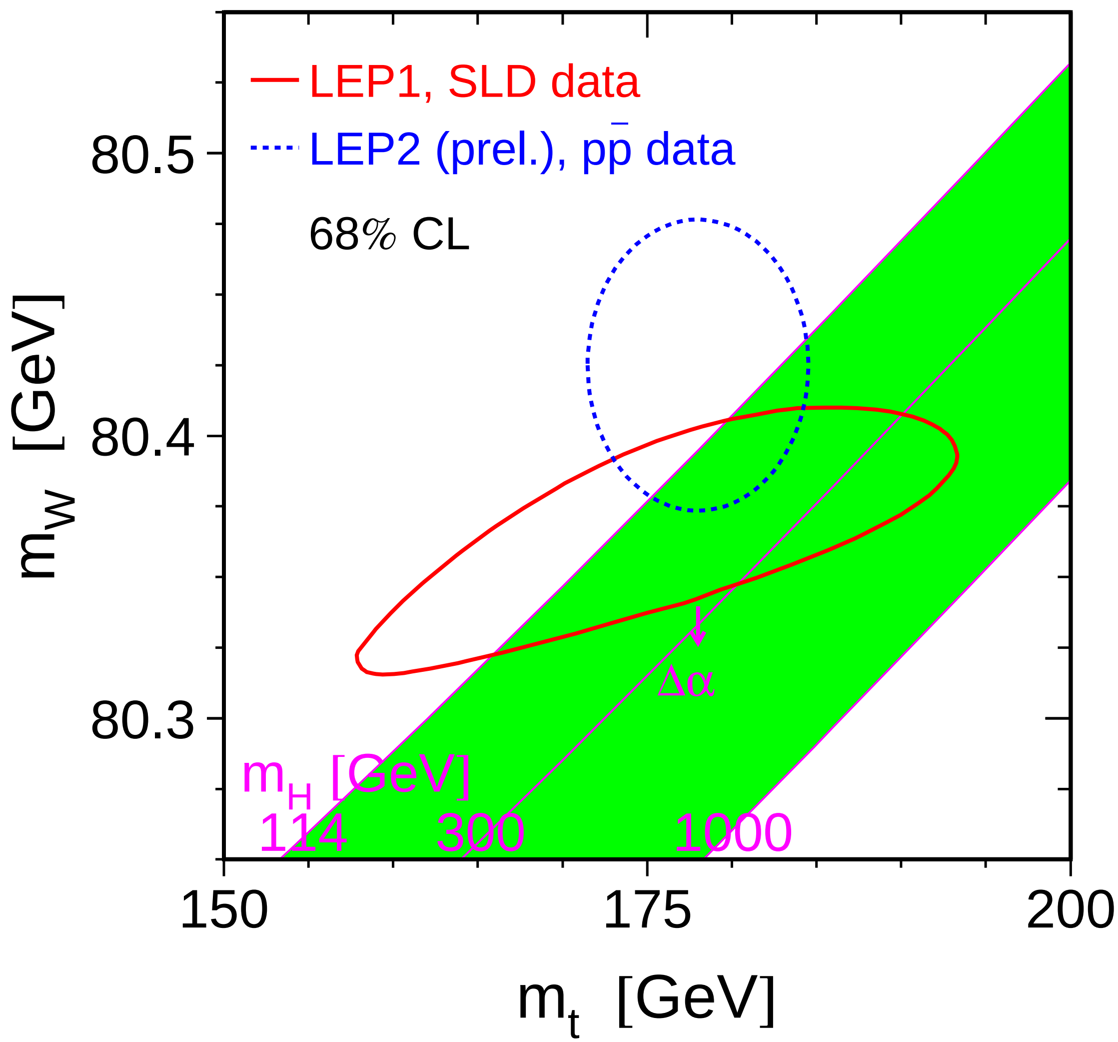
$M_H < 280$ GeV 95% CL (up from 193 GeV)

Within SM, LEPEWWG deduce a 95% CL upper limit, $M_H \lesssim 280$ GeV/c^2.

Direct searches at LEP $\Rightarrow M_H > 114.4$ GeV/c^2, eating into the favored region

Either the Higgs boson is nearby, or SM analysis is misleading

Expect progress from M_W-m_t-M_H correlation



LEP1, SLD data
LEP2 (prel.), pp̄ data
68% CL
Δα
mH [GeV]
114
300
1000
80.5
80.4
80.3
mW [GeV]
150
175
200
mt [GeV]

▷ Tevatron and LHC measurements will determine m_t within 1 or 2 GeV/c^2

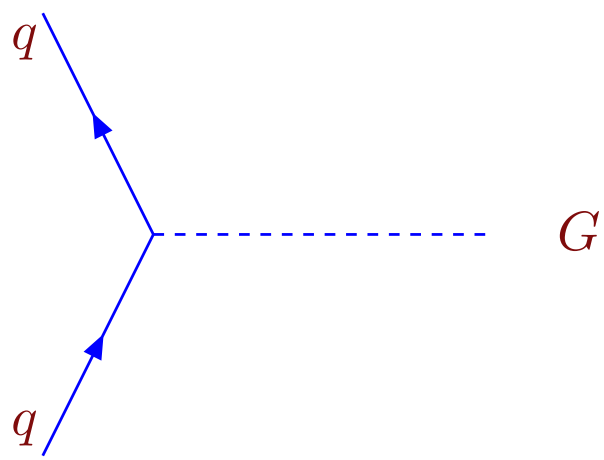
▷ ...and improve δM_W to about 15 MeV/c^2

▷ As the Tevatron's integrated luminosity approaches 10 fb^{-1}, CDF and DØ will explore the region of M_H not excluded by LEP

▷ ATLAS and CMS will carry on the exploration of the Higgs sector at the LHC; could require a few years, at low mass; full range accessible, $\gamma\gamma, \ell\ell\nu\nu, b\bar{b}, \ell^+\ell^-\ell^+\ell^-, \ell\nu jj, \tau\tau$ channels.

Natural to neglect gravity in particle physics

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

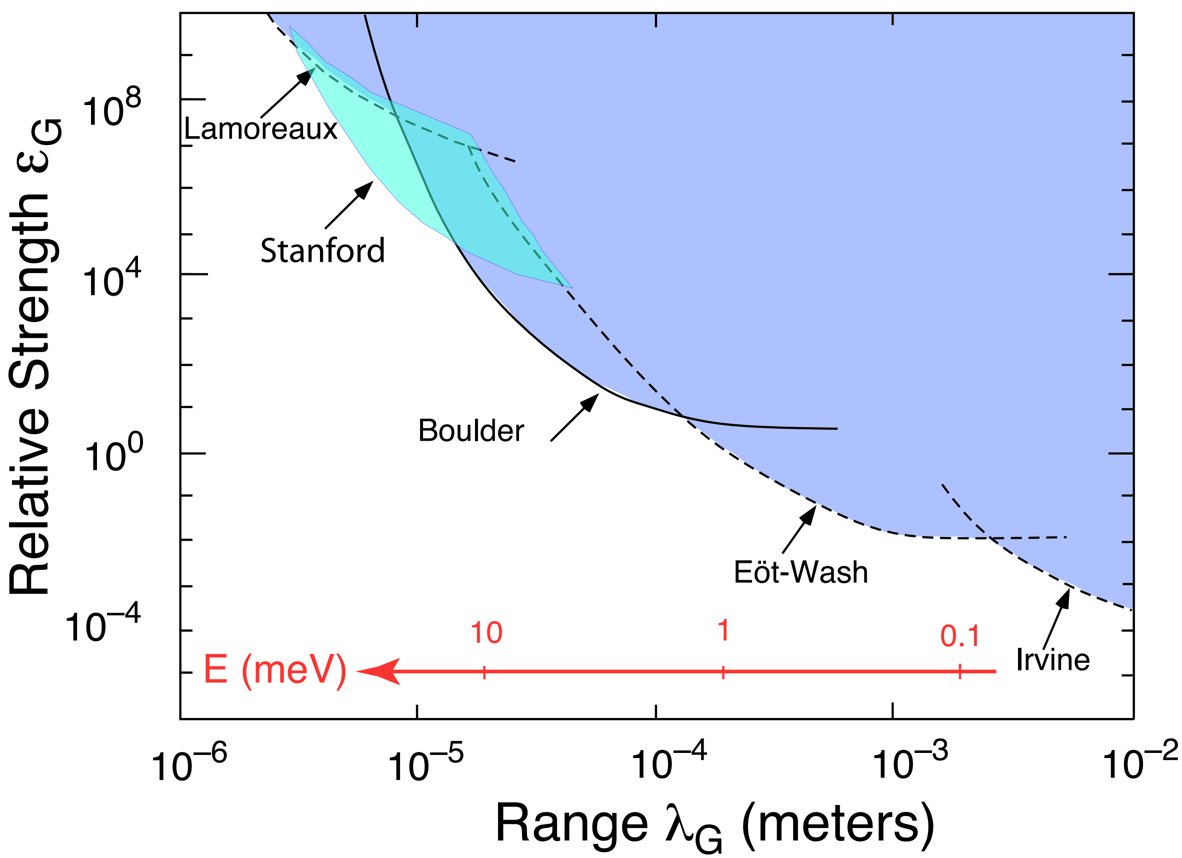


$$\sim \frac{E}{M_{\text{Planck}}}$$

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

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 . . .

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

At the minimum,

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

$$\text{Identify } M_H^2 = -2\mu^2$$

contributes field-independent vacuum energy density

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

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

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

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

≈ 10 MeV$/\ell$ or 10^{-29} g cm^{-3}

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

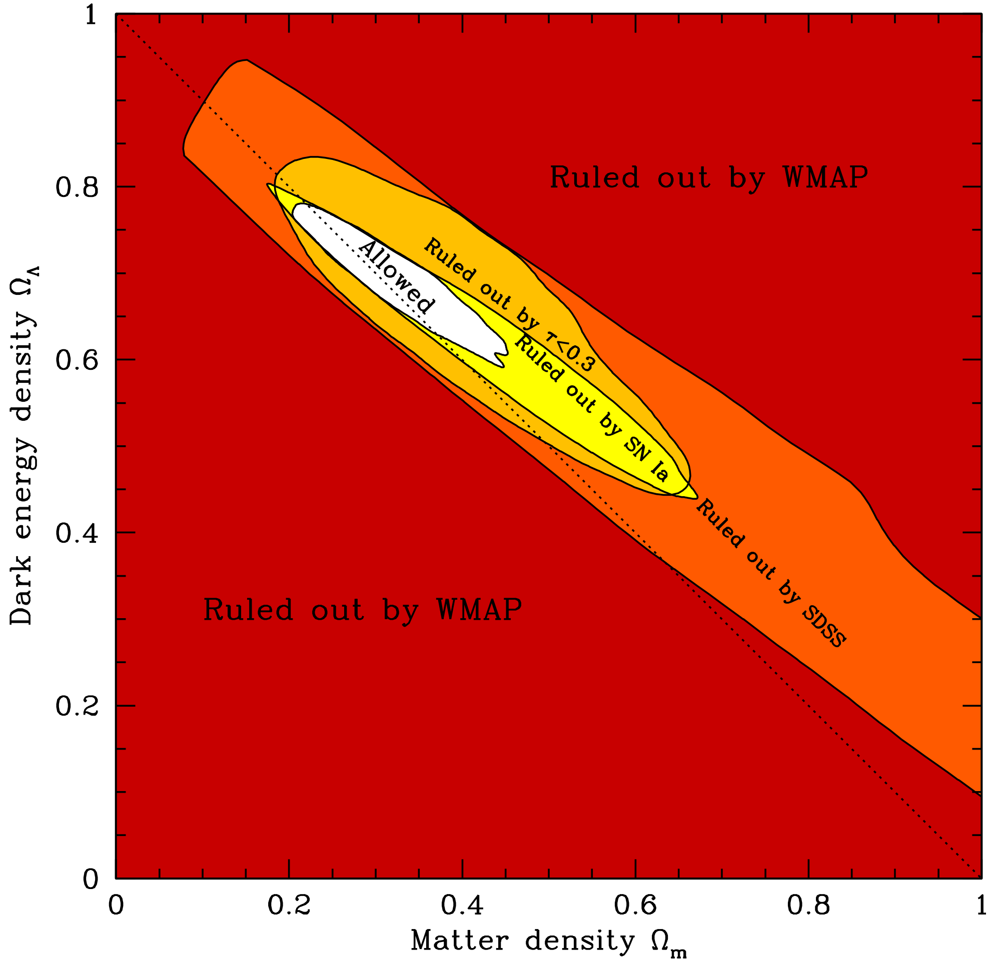
$$\varrho_H \gtrsim 10^8 \text{ GeV}^4 \approx 10^{25} \text{ g cm}^{-3}$$

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 the old problem and gives us properties to measure

Boselab

Why Supersymmetry?

▷ Closely approximates the standard model

▷ Unique extension of Poincaré invariance

▷ A path to the incorporation of gravity: local supersymmetry
$\longrightarrow$ supergravity

▷ Solution to the naturalness problem: allows light scalar

▷ (+ unification): $\sin^2\theta_W$, coupling constant unification

▷ (+ universality): Can generate SSB potential

▷ (+R-parity): LSP as dark matter candidate (only one?)

What is supersymmetry?

A fermion-boson symmetry that arises from new *fermionic* dimensions

Most general symmetry of S-matrix: SUSY + Poincaré invariance + internal symmetries

Relates fermion to boson degrees of freedom: roughly, each particle has a superpartner with spin offset by $\frac{1}{2}$

SUSY relates interactions of particles, superpartners

Known particle spectrum contains no superpartners $\Rightarrow$ SUSY doubles the spectrum

SUSY invariance or anomaly cancellation requires two Higgs doublets to give masses to $I_3 = \pm\frac{1}{2}$ particles

Yukawa terms consistent with SUSY induce dangerous lepton- and baryon-number violations:

$$\lambda_{ijk} L^i L^j E^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda'' \bar{U}^i \bar{D}^j \bar{D}^k$$

45 free parameters . . . Transitions like

$$\mathcal{L}_{LLE} = \lambda_{ijk}\, \tilde{\nu}^i_L e^i_L \bar{e}^k_R + \ldots$$

To banish these, impose symmetry under R-parity:

$$R = (-1)^{3B+L+S}$$

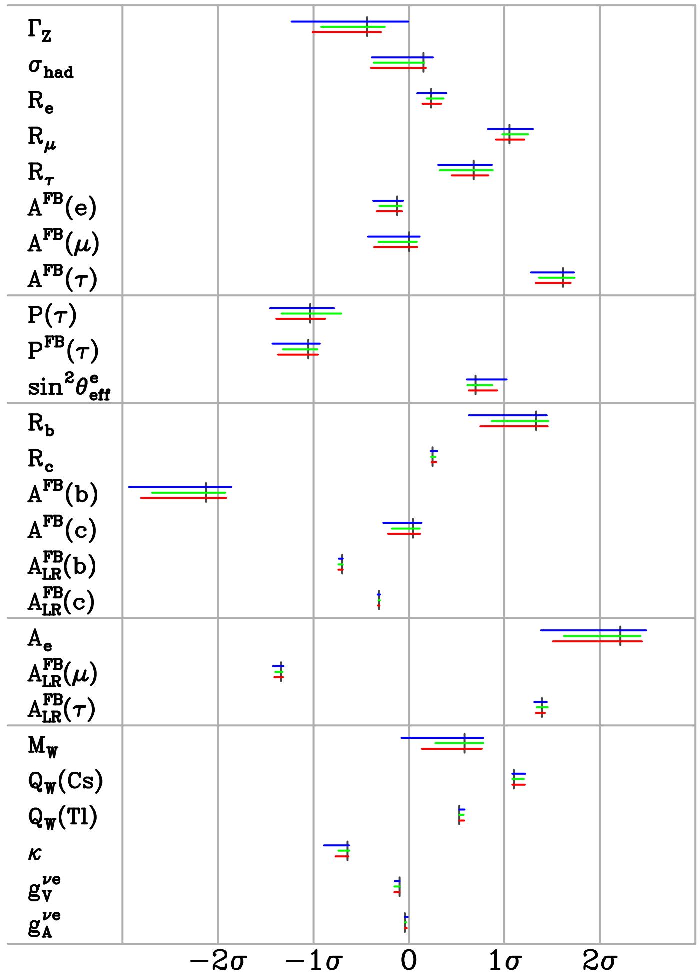
. . . even for particles, odd for superpartners.

Superpartners produced in pairs

Lightest superpartner is stable

Five physical Higgs bosons: CP even h^0, H^0; CP odd $A^0; H^{\pm}$

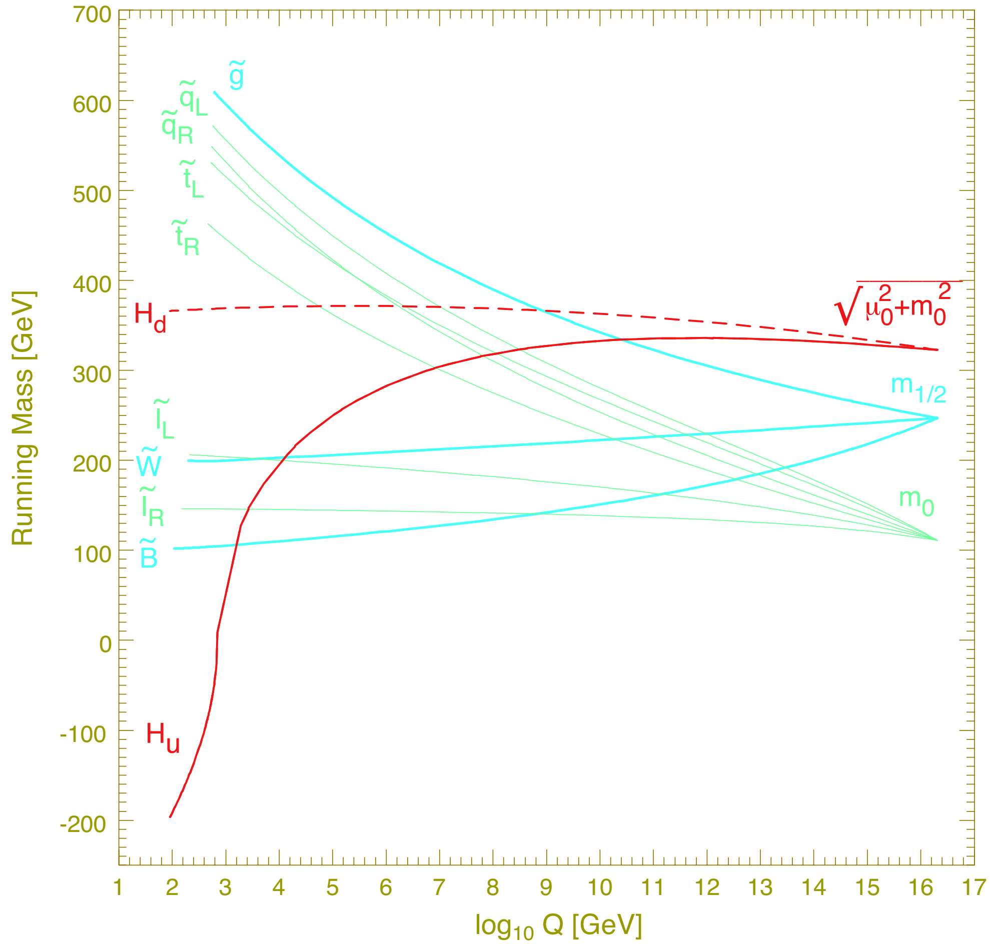
MSSM closely resembles the standard EW Theory



Erler & Pierce: SUSY *vs.* SM, hep-ph/9801238 Cho & Hagiwara, hep-ph/9912260

| SM — SUGRA — $5 \oplus 5^\star$ GMSB — $10 \oplus 10^\star$ GMSB

For heavy top, SSB may follow naturally in SUSY



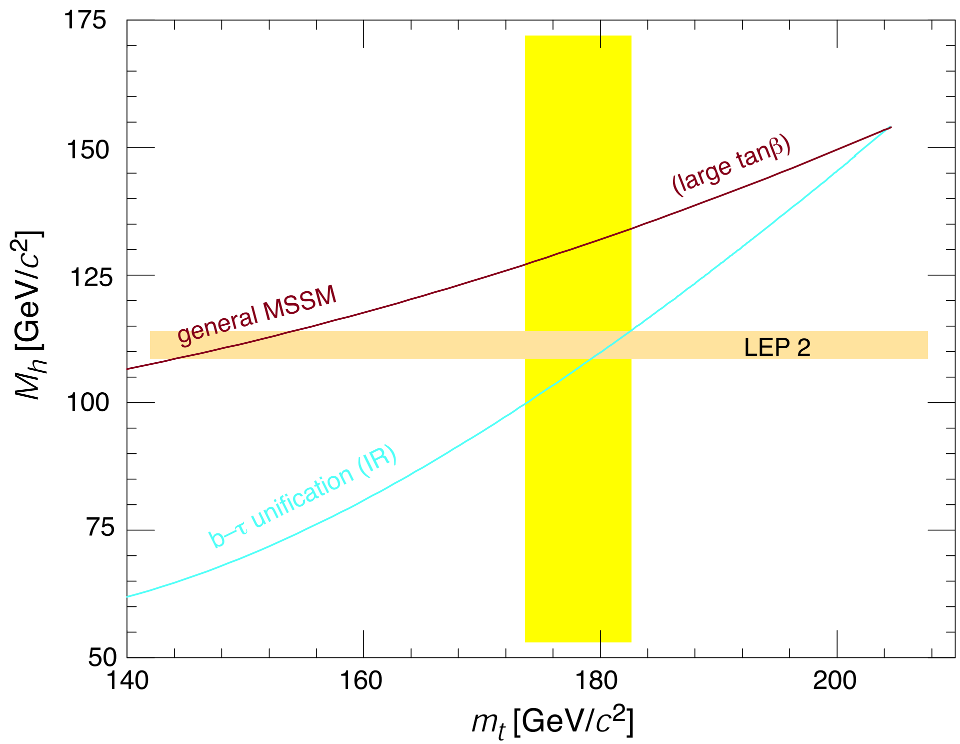
... (sign of M^2 indicated)

Kane, *et al.* (hep-ph/9312272, *Phys. Rev. D* **49**, 6173 (1994))

Upper bounds on M_h in the MSSM

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \cdots\right] \lesssim \left(130\ \text{GeV}/c^2\right)^2$$

Upper bound on $M_h \Leftrightarrow$ large M_A limit, $(M_s = 1$ TeV$)$



Carena, *et al.*, *Phys. Lett.* **B355**, 209 (1995)

Nonminimal SUSY Higgs couplings perturbative up to M_U: $M_h \lesssim 150$ GeV

If $m_{\tilde{e}} < m_e \ldots$

... no Pauli principle to dictate integrity of molecules

Dyson & Lieb: If basic constituents of matter were bosons, individual molecules would join into a

shrinking

insatiable

undifferentiated

B L O B !

Supersymmetry menaces us

with an amorphous death

Full understanding of SUSY would show us why we live in a world ruled by the *Exclusion Principle*

SUSY Challenges . . .

▷ Extra dynamics needed to break SUSY

"Soft" SUSY breaking $\Longrightarrow$

MSSM with $\boxed{124}$ parameters

Contending schemes for SUSY breaking:

Gravity mediation. SUSY breaking at a very high scale, communicated to standard model by supergravity interactions

Gauge mediation. SUSY breaking nearby ($\lesssim 100$ TeV), communicated to standard model by (nonperturbative ?) gauge forces.

. . .

None meets all challenges

. . . SUSY Challenges

- ▷ Weak-scale SUSY protects M_H, but does not explain the weak scale ("μ problem")
- ▷ Global SUSY must deal with the threat of FCNC
- ▷ (Like SM) Clear predictions for gauge-boson masses, not so clear for squarks and sleptons
- ▷ So far, SUSY is well hidden Contortions for $M_H \gtrsim 115$ GeV
- ▷ Disappointing that SUSY didn't relate particles & forces, but doubled spectrum
- ▷ Baryon- and lepton-number violating interactions arise naturally, are abolished by decree

. . . SUSY Challenges

- ▷ SUSY introduces new sources of CP violation that are potentially too large.
- ▷ We haven't found a convincing and viable picture of the TeV superworld.

This long list of challenges doesn't mean that Supersymmetry is wrong, or even irrelevant to the 1-TeV scale.

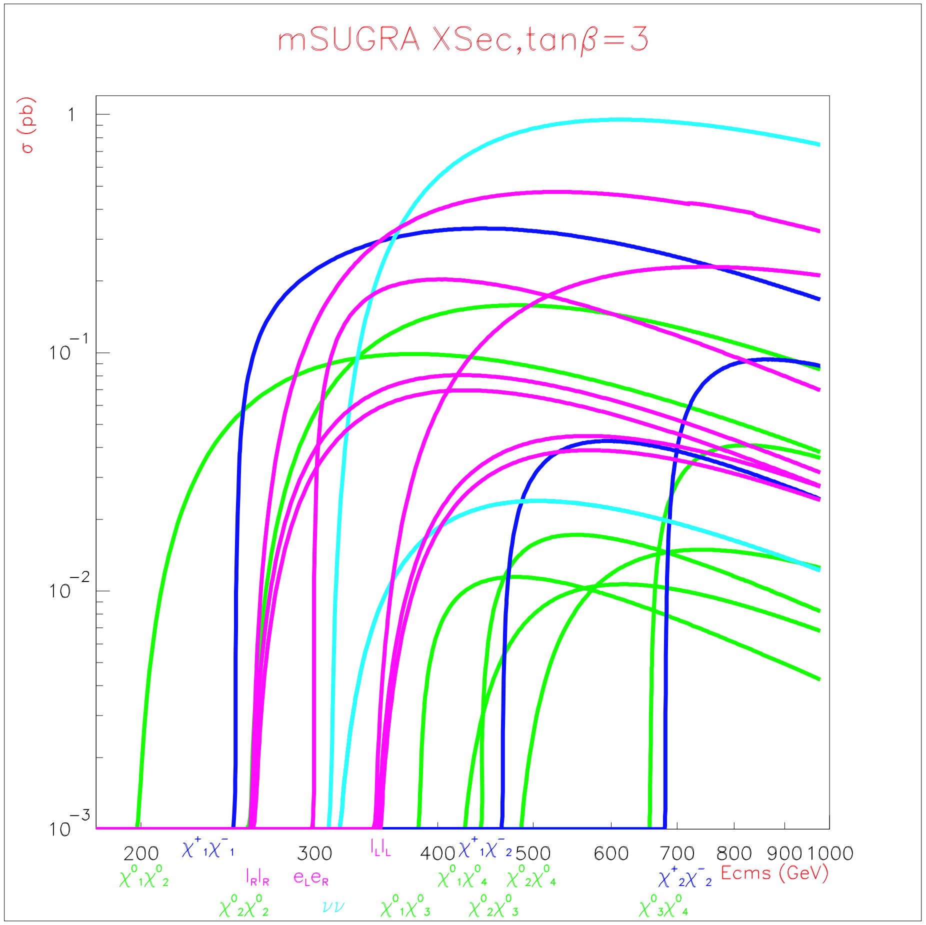
But SUSY is not automatically right, either!

If SUSY does operate on the 1-TeV scale, then Nature must have found solutions to all these challenges . . .

. . . and we will need to find them, too.

If weak-scale SUSY is present, we should see it soon

. . . in the Higgs sector and beyond



SUSY thresholds in e^+e^-

Grahame Blair

We have many interesting theoretical ideas . . .

Supersymmetry, New strong dynamics, Extra dimensions, Composite fermions, String theory, . . .

Progress requires experimental discoveries . . .

We have many interesting theoretical ideas . . .

Supersymmetry, New strong dynamics, Extra dimensions, Composite fermions, String theory, . . .

Progress requires experimental discoveries . . .

Nothing is too wonderful to be true,
if it be consistent with the laws of nature . . .

Experiment is the best test . . .

Michael Faraday
Research notes, 19th March 1849

Why the LHC is so exciting (II)

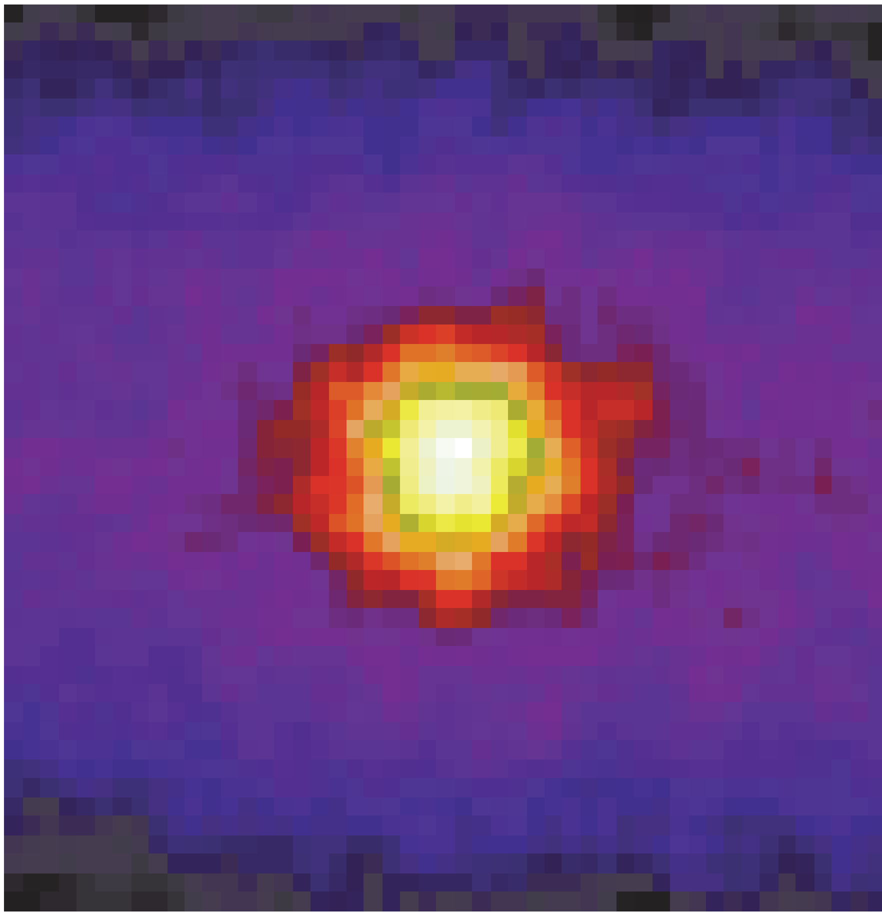
- ▷ Electroweak theory (unitarity argument) tells us the 1-TeV scale is special: Higgs boson or other new physics (strongly interacting gauge bosons)
- ▷ Hierarchy problem $\Rightarrow$ other new physics nearby
- ▷ Our ignorance of EWSB obscures our view of other questions (identity problem, for example). Lifting the veil at 1 TeV will change the face of theoretical physics

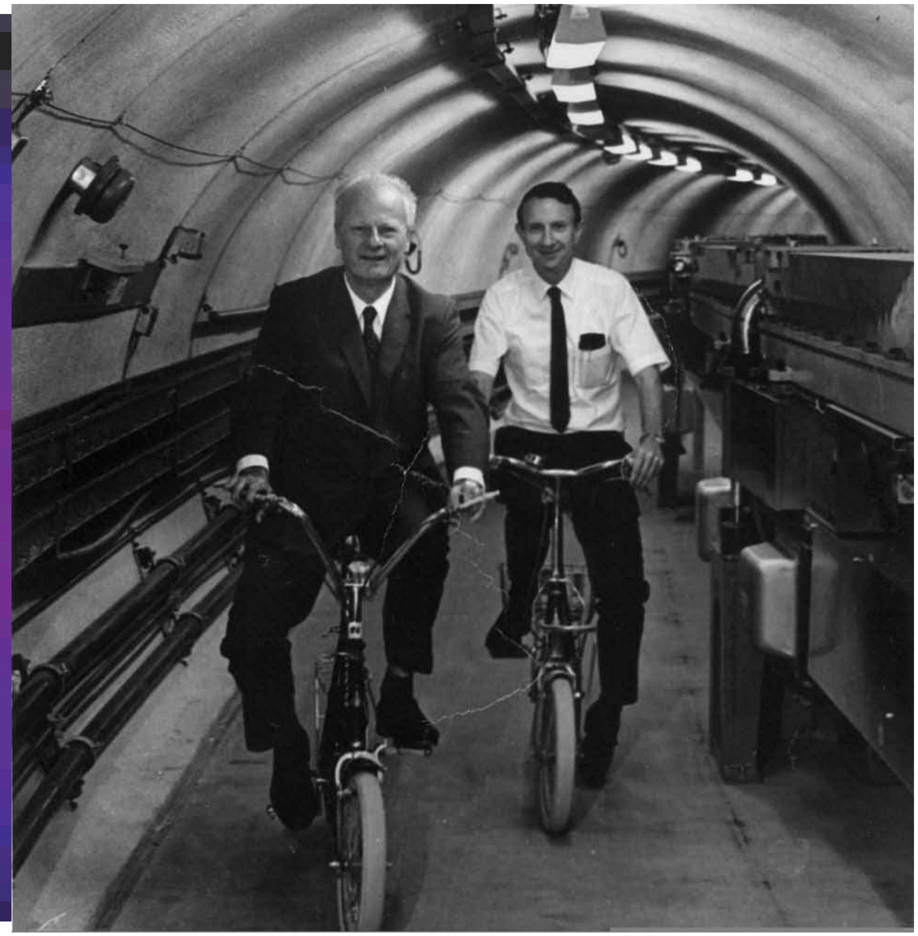
Expect important results from the Tevatron

- Biggest changes in the way we think about LHC experiments have come from the Tevatron: the large mass of the top quark and the success of silicon microvertex detectors: heavy flavors
- Top quark is a unique window on EWSB and of interest in its own right: single top production
- Entering new terrain for new gauge bosons, new strong dynamics, SUSY, Higgs, B_s mixing, ...

The cosmic connection

- ▷ Observational cosmology is like paleontology: reading the fossil record. Only a few layers are preserved, can we find more?
- ▷ Our reading of the fossil record is influenced by our world-view / theoretical framework.
- ▷ Cosmology shows us the world we must explain, provides questions and constraints; the answers will come from particle physics.





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

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, . . .)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

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

. . . and rewrite the textbooks!

Año Mundial de la
FÍSICA
2005