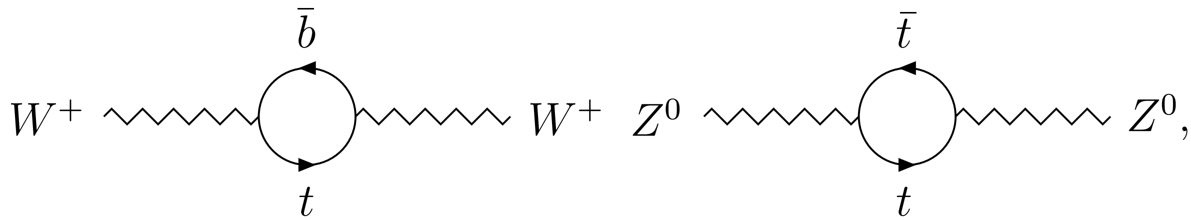
Clues to the Higgs-boson mass

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 link between the 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

m_t known to $\pm 1.7\%$ from Tevatron . . .

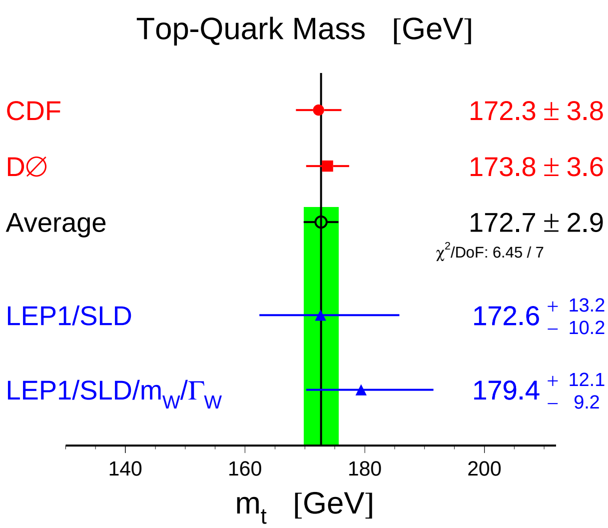
$\Longrightarrow$ look beyond the quark loops to next most important quantum corrections:

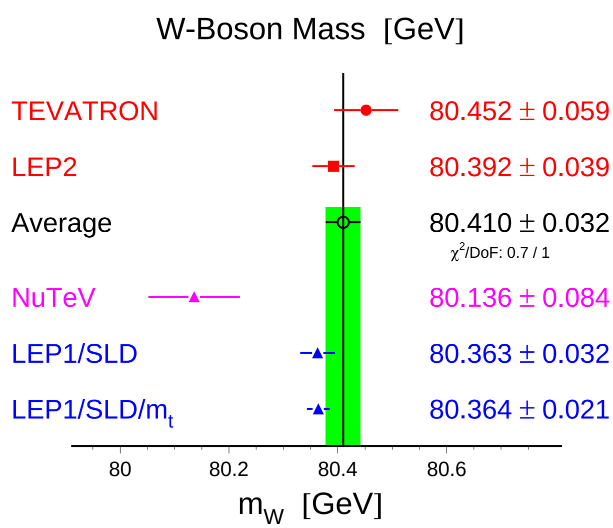
Higgs-boson effects

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

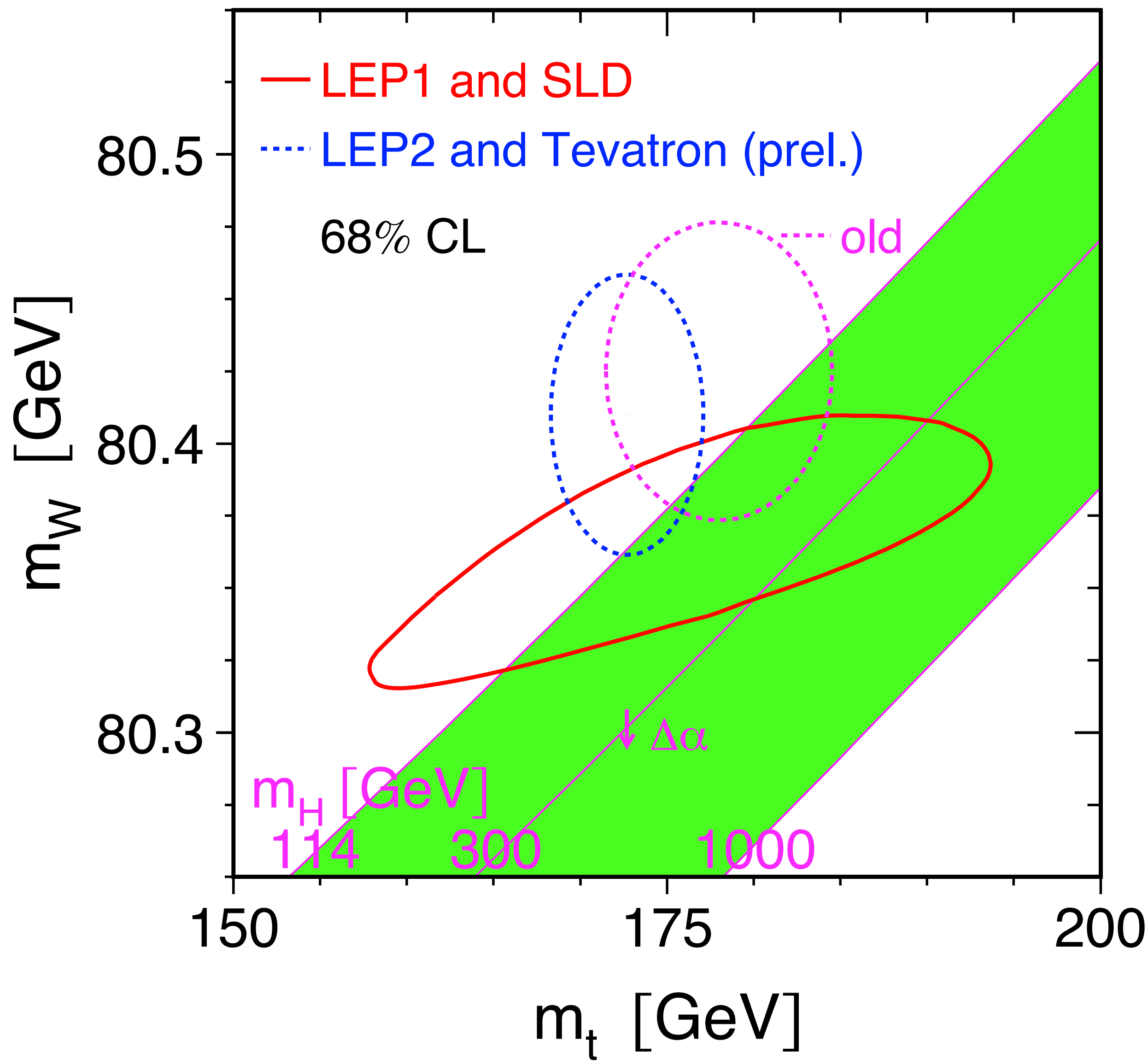
$$\Delta\rho^{(\text{Higgs})} = \mathcal{C} \cdot \ln\left(\frac{M_H}{v}\right)$$

M_Z known to 23 ppm, m_t and M_W well measured



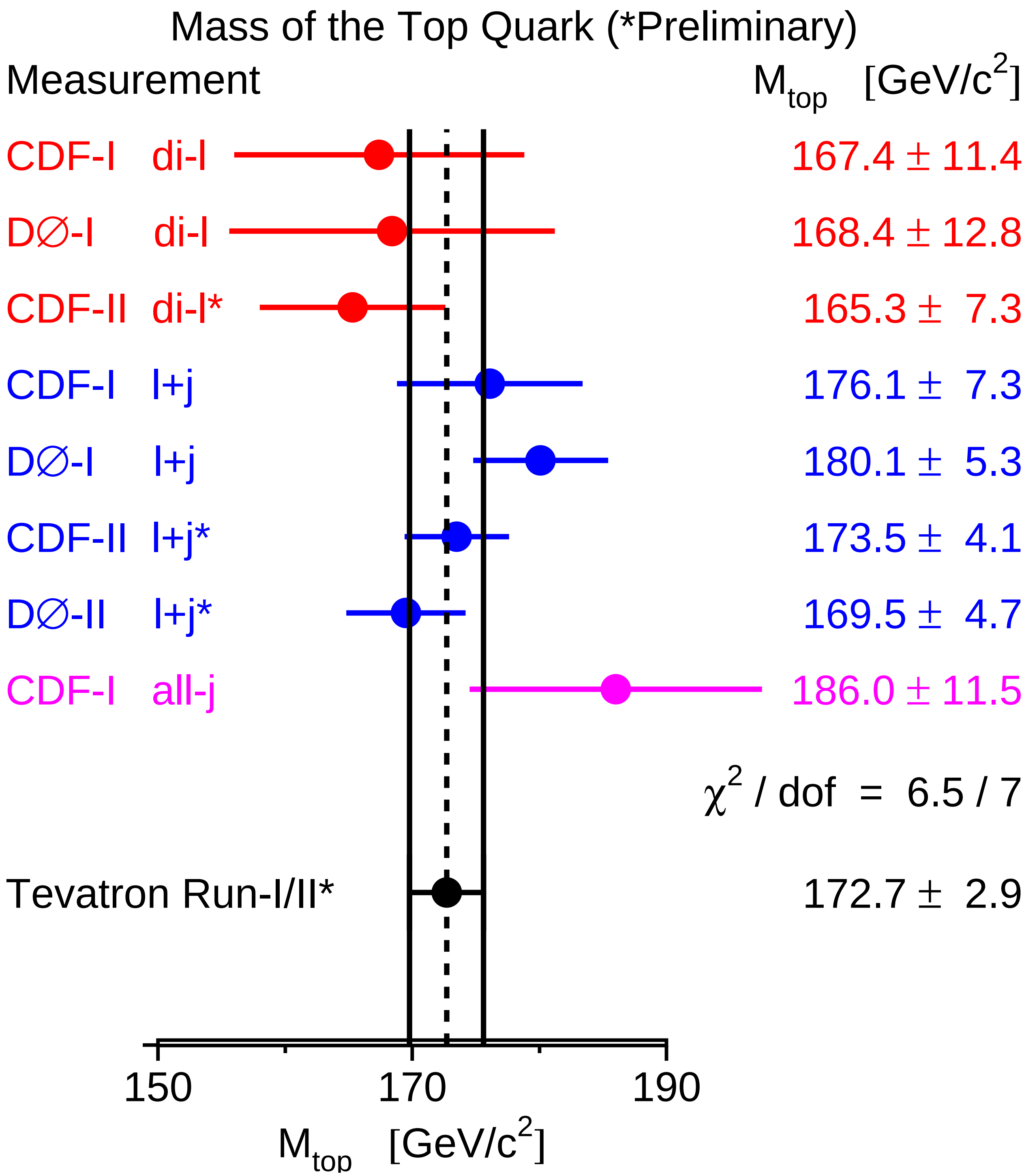


so examine dependence of M_W upon m_t and M_H

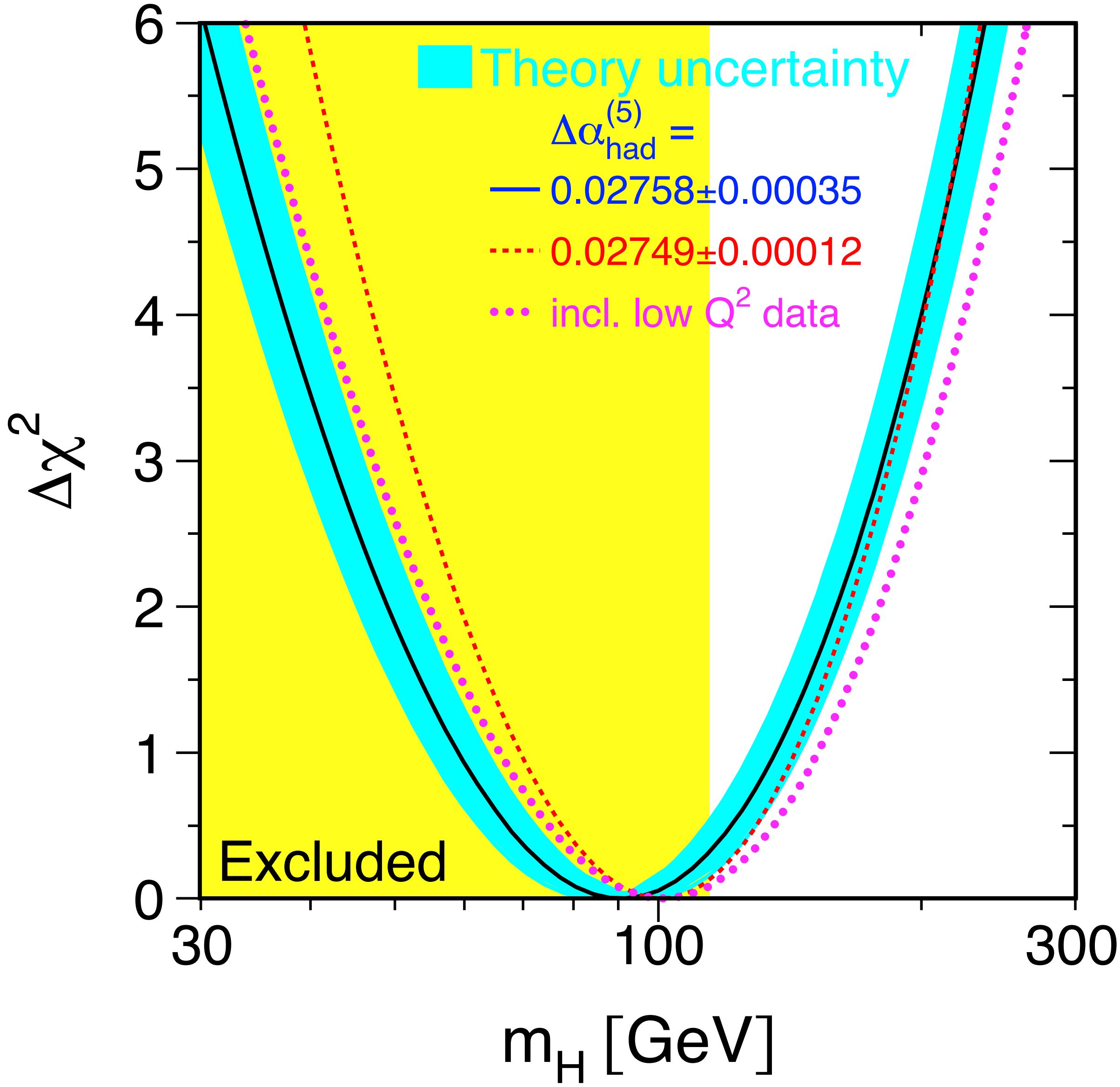


Direct, indirect determinations agree reasonably
Both favor a light Higgs boson,

within framework of SM analysis.


Mass of the Top Quark (*Preliminary)
Measurement
M_top [GeV/c²]
CDF-I di-l
167.4 ± 11.4
DØ-I di-l
168.4 ± 12.8
CDF-II di-l*
165.3 ± 7.3
CDF-I l+j
176.1 ± 7.3
DØ-I l+j
180.1 ± 5.3
CDF-II l+j*
173.5 ± 4.1
DØ-II l+j*
169.5 ± 4.7
CDF-I all-j
186.0 ± 11.5
χ² / dof = 6.5 / 7
Tevatron Run-I/II*
172.7 ± 2.9
150
170
190
M_top [GeV/c²]

Fit to a universe of data



Within SM, LEPEWWG deduce a 95% CL upper limit, $M_H \lesssim 219$ GeV/c^2.

Direct searches at LEP $\Rightarrow M_H > 114.4$ GeV/c^2, excluding much of the favored region

either the Higgs boson is just around the corner, or SM analysis is misleading

Things will soon be popping!

$\boxed{\text{Expect progress from } M_W\text{-}m_t\text{-}M_H \text{ correlation}}$

- ▷ 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 begin to 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

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 ?!
$gg \to H \to \gamma\gamma$: rate ?!

$\bar{p}p \to H(W,Z)$: prime Tevatron channel

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

Aside: varieties of neutrino mass

Chiral decomposition of Dirac spinor:

$$\psi = \tfrac{1}{2}(1-\gamma_5)\psi + \tfrac{1}{2}(1+\gamma_5)\psi \equiv \psi_{\mathrm{L}} + \psi_{\mathrm{R}}$$

$$\psi^c \equiv C\bar{\psi}^{\mathrm{T}};\ C = i\gamma^2\gamma^0$$

Charge conjugate of RH field is LH:

$$\psi^c_{\mathrm{L}} \equiv (\psi^c)_{\mathrm{L}} = (\psi_{\mathrm{R}})^c$$

Possible forms for mass terms

Dirac connects LH, RH components of *same field*

$$\mathcal{L}_D = D(\bar{\psi}_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}) = D\bar{\psi}\psi$$

$\Longrightarrow$ mass eigenstate $\psi = \psi_{\mathrm{L}} + \psi_{\mathrm{R}}$

(invariant under global phase rotation $\nu \to e^{i\theta}\nu$, $\ell \to e^{i\theta}\ell$, so that lepton number is conserved)

Possible forms for mass terms (cont'd)

Majorana connects LH, RH components of *conjugate fields*

$$\begin{aligned} -\mathcal{L}_{\mathrm{MA}} &= A(\bar{\psi}^c_{\mathrm{R}}\psi_{\mathrm{L}} + \bar{\psi}_{\mathrm{L}}\psi^c_{\mathrm{R}}) = A\bar{\chi}\chi \\ -\mathcal{L}_{\mathrm{MB}} &= B(\bar{\psi}^c_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi^c_{\mathrm{L}}) = B\bar{\omega}\omega \end{aligned}$$

for which the mass eigenstates are

$$\begin{aligned} \chi &\equiv \psi_{\mathrm{L}} + \psi^c_{\mathrm{R}} = \chi^c = \psi_{\mathrm{L}} + (\psi_{\mathrm{L}})^c \\ \omega &\equiv \psi_{\mathrm{R}} + \psi^c_{\mathrm{L}} = \omega^c = \psi_{\mathrm{R}} + (\psi_{\mathrm{R}})^c \end{aligned}$$

$\mathcal{L}_{\mathrm{M}}$ violates lepton number by two units

$\Rightarrow$ Majorana ν can mediate $\beta\beta_{0\nu}$ decays

$$(Z, A) \to (Z+2, A) + e^- + e^-$$

Detecting $\beta\beta_{0\nu}$ would offer decisive evidence for the Majorana nature of ν

EWSB: another path?

Modeled EWSB on Ginzburg–Landau description of SC phase transition

had to introduce new, elementary scalars

GL is not the last word on superconductivity: *dynamical* Bardeen–Cooper–Schrieffer theory

The elementary fermions—electrons—and gauge interactions—QED—needed to generate the scalar bound states are already present in the case of superconductivity. Could a scheme of similar economy account for EWSB?

$$\boxed{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y + \text{massless } u \text{ and } d}$$

Treat $SU(2)_L \otimes U(1)_Y$ as perturbation

$m_u = m_d = 0$: QCD has exact $SU(2)_L \otimes SU(2)_R$ chiral symmetry. At an energy scale $\sim \Lambda_{\mathrm{QCD}}$, strong interactions become strong, fermion condensates appear, and $SU(2)_L \otimes SU(2)_R \to SU(2)_V$

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

Broken generators: 3 axial currents; couplings to π measured by pion decay constant f_π

Turn on $SU(2)_L \otimes U(1)_Y$: EW gauge bosons couple to axial currents, acquire masses of order $\sim g f_\pi$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{f_\pi^2}{4}\,,$$

$(W^+,\, W^-,\, W_3,\, \mathcal{A})$

same structure as standard EW theory. Diagonalize: $M_W^2 = g^2 f_\pi^2/4$, $M_Z^2 = (g^2 + g'^2) f_\pi^2/4$, $M_A^2 = 0$, so

$$\frac{M_Z^2}{M_W^2} = \frac{(g^2 + g'^2)}{g^2} = \frac{1}{\cos^2\theta_W}$$

Massless pions disappear from physical spectrum, to become longitudinal components of weak bosons

$$\boxed{M_W \approx 30 \text{ MeV}/c^2}$$

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No fermion masses . . .

With no Higgs mechanism . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them in 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

Assessment

$SU(2)_L \otimes U(1)_Y$: 25 years of confirmations

- $\star$ neutral currents; $W^{\pm}$, Z^0
- $\star$ charm

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- $\star$ τ, ν_τ
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$\star$ charm

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$\star$ τ, ν_τ

$\star$ b, t

$+$ experimental surprises

$\star$ narrowness of ψ, ψ'

$\star$ long B lifetime; large B^0–$\bar{B}^0$ mixing

$\star$ heavy top

10 years of precision measurements...

...find no significant deviations

quantum corrections tested at $\pm 10^{-3}$

No "new physics" ...yet!

Theory tested at distances

from 10^{-17} cm

to $\sim 10^{22}$ cm

origin	Coulomb's law (tabletop experiments)
smaller	Atomic physics $\rightarrow$ QED high-energy expts. $\rightarrow$ EW theory
larger	$M_\gamma \approx 0$ in planetary ... measurements

Is EW theory true?

Complete ??

The EW scale and beyond

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

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

But it is not the only scale of physical interest

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

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

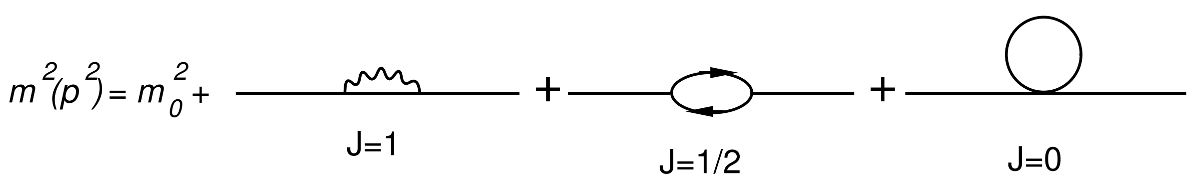
$\boxed{\text{“The hierarchy problem”}}$

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

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

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

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

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

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

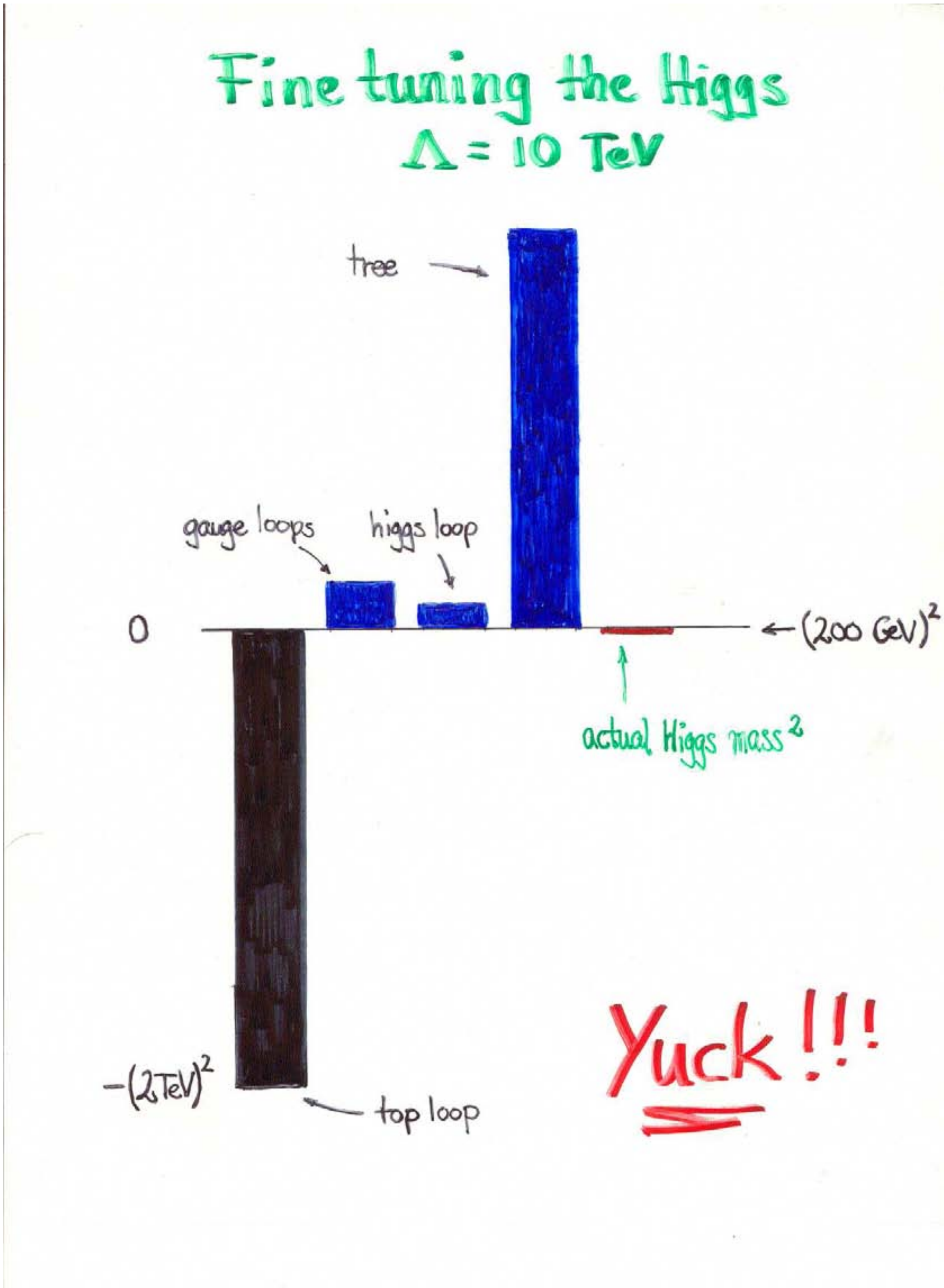
OR

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

for unified theory

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

$\boxed{\text{New Physics at } E \lesssim 1 \text{ TeV}}$



Martin Schmaltz, ICHEP02

Only a few distinct scenarios . . .

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

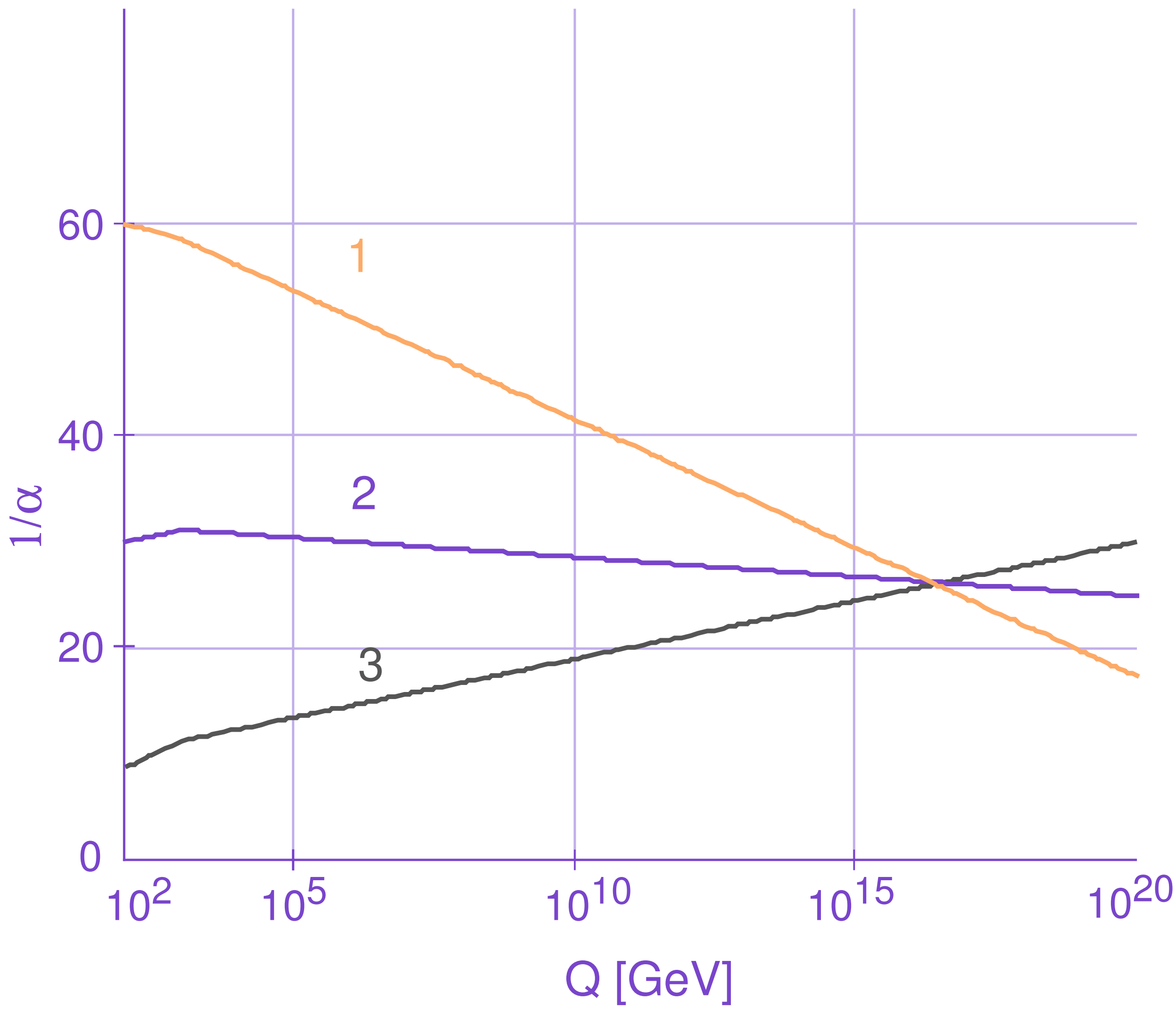
Exact supersymmetry,

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

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

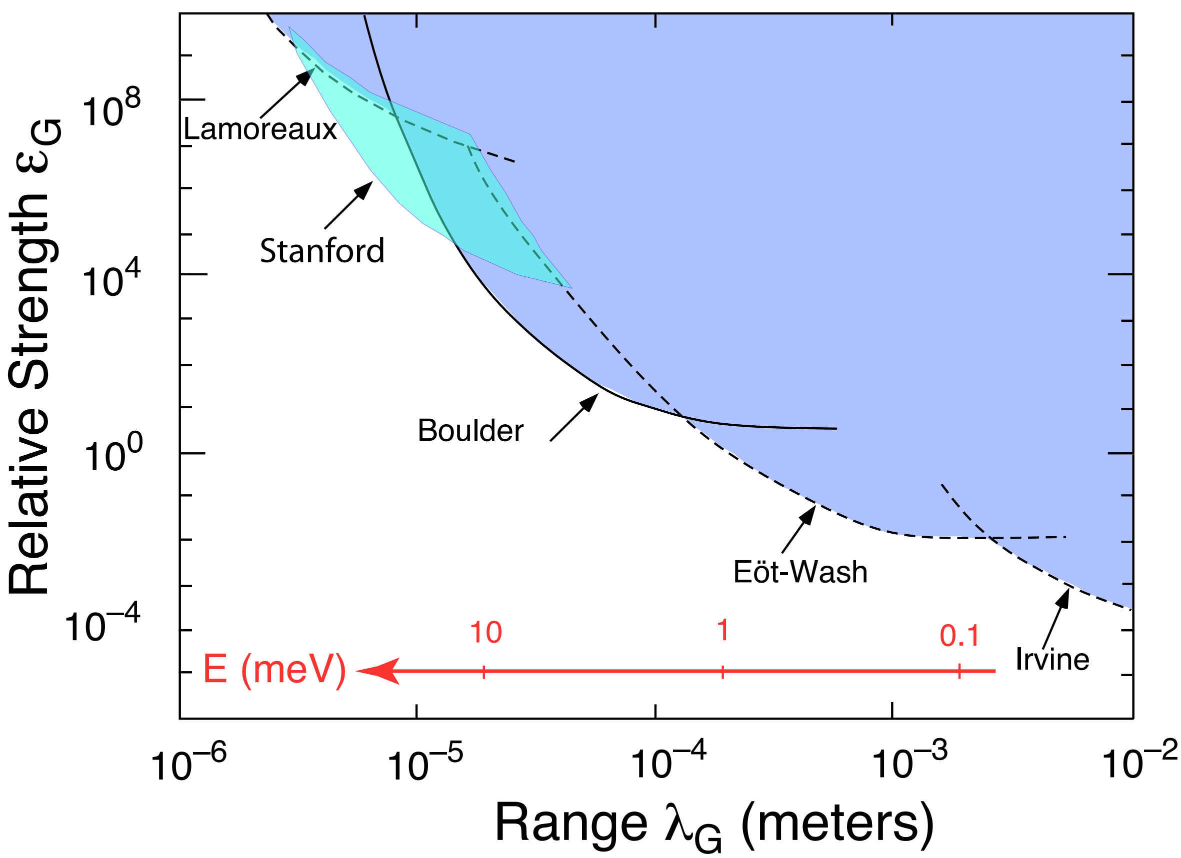
Only a few distinct scenarios . . .

- ▷ 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

Gravity follows $1/r^2$ law down to $\lesssim 1$ mm (few meV)

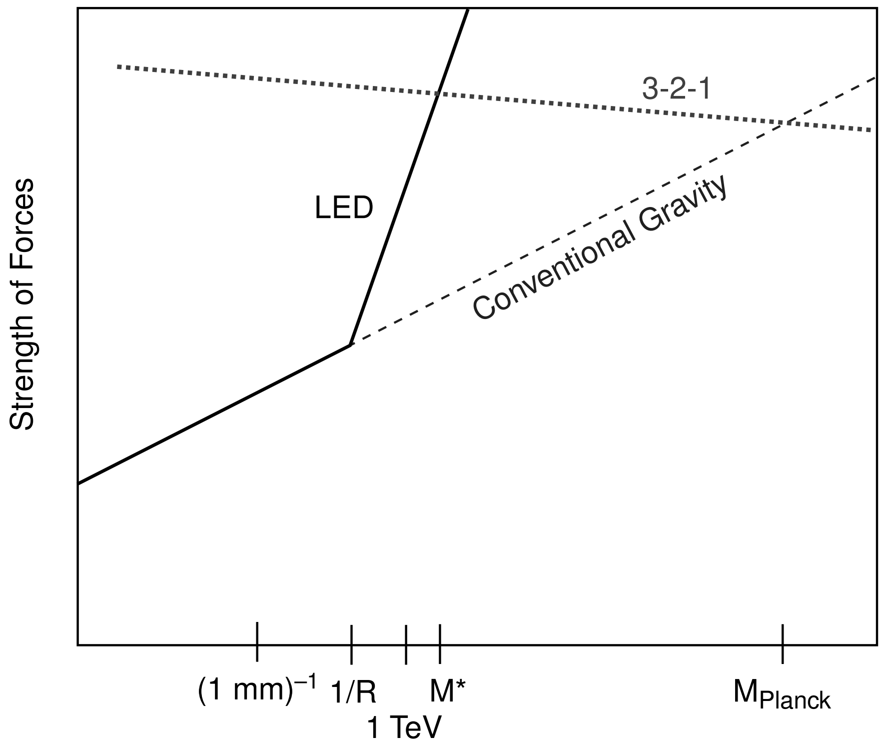
$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\mathrm{N}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_{\mathrm{G}} \exp(-r_{12}/\lambda_{\mathrm{G}})\right]$$



Experiment leaves us free to consider modifications to Gravity even at (nearly) macroscopic distances

Suppose at scale R Gravity propagates in $3+n$ spatial dimensions

Force law changes: $F \propto 1/r^{2+n}$



$$G_{\mathrm{N}} \sim M_{\mathrm{Pl}}^{-2} \sim M^{\star\,-n-2} R^{-n}$$

$M^{\star}$: gravity's true scale

Example:

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

$\boxed{M_{\mathrm{P}} \text{ is a mirage (false extrapolation)!}}$

Why the LHC is so exciting (I)

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

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

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 physics

High expectations for 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, strong dynamics, SUSY, Higgs, B_s mixing, ...

Fermilab Academic Lectures 2005 – 2006

Course 2

Tests of the Electroweak Theory · Six Lectures
Paul Langacker (Fermilab Frontier Fellow; Penn)
November 29 – December 15, 2005

This set of lectures will further develop the electroweak theory, emphasizing the precision tests that have established the standard model and the framework of renormalizable gauge theory, determined its parameters, and constrained the possibilities for new physics at the TeV scale. Included will be discussions of the weak charged and neutral currents; Z-pole physics; properties of the W and Z; CP violation and the CKM matrix; rare B, K, and lepton decays; gauge self-interactions; and neutrino mass and mixing. An introduction to radiative corrections and electroweak renormalization schemes will be included.

Lecture slides will be available on line.

Lecture dates and times: Tuesdays and Thursdays at 11:00 am in One West.
The December 1 and 6 lectures will be held in Curia II.

Live video stream!
Fermilab Visual Media Services provides live streaming video of Academic Lectures in progress. Click on "live stream" in the lower left corner. Please contact VMS on x3343 if you need assistance.