LAL Cours d'automne 2009

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

Lecture 3: Standard Model Opportunities
Themes of Contemporary Particle Physics

- Elementarity: *structureless quarks and leptons?*
- Symmetry: *EWSB and the 1-TeV scale; new forces*

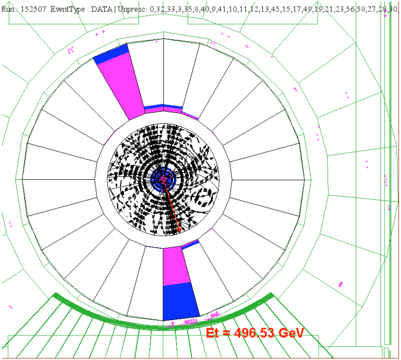
  (origin of gauge symmetries; discrete symmetries)
- Unity: *quarks + leptons; gauge symmetries*

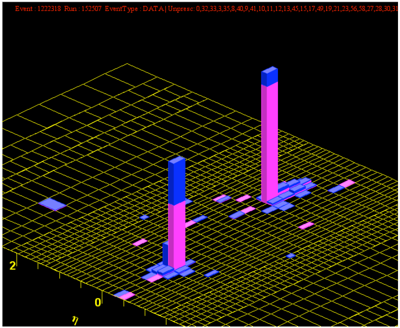
  (constituents + forces; incorporation of gravity)
- Identity: *fermion masses, mixings; CP violation*

  (Majorana ν?)
- Topography: *fabric of space and time*

Elementarity
The World's Most Powerful Microscopes

nanonanophysics



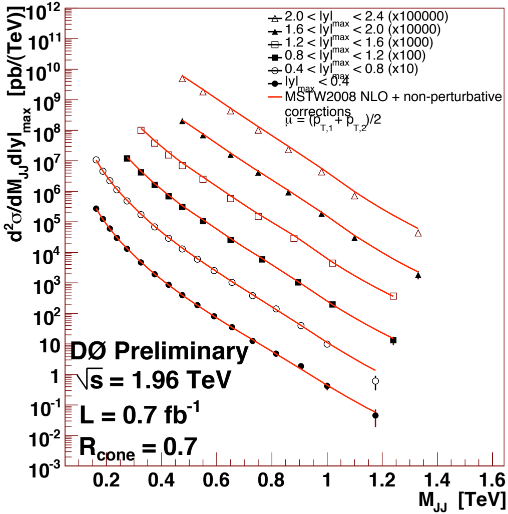


CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV

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

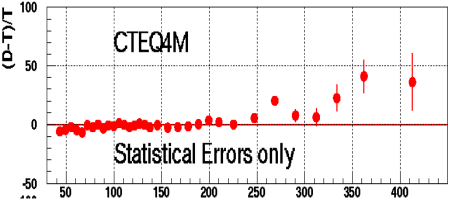
Elementarity

DØ Jet Cross Sections



Elementarity

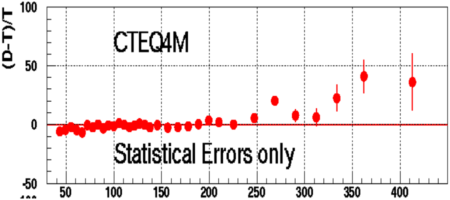
The CDF Experience



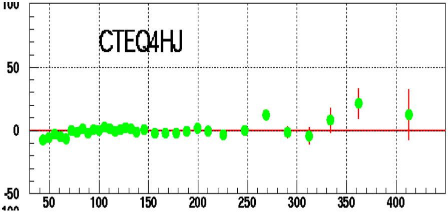
E_T jet (GeV)

Elementarity

The CDF Experience



E_T jet (GeV)



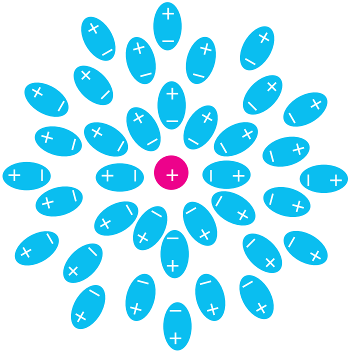
E_T jet (GeV)

Charge screening in electrodynamics

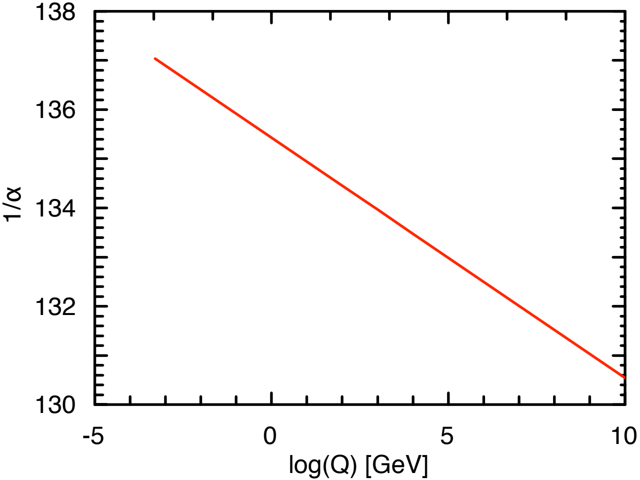
Dielectric (polarizable) medium . . .

Charge screening in electrodynamics

Dielectric (polarizable) medium . . .

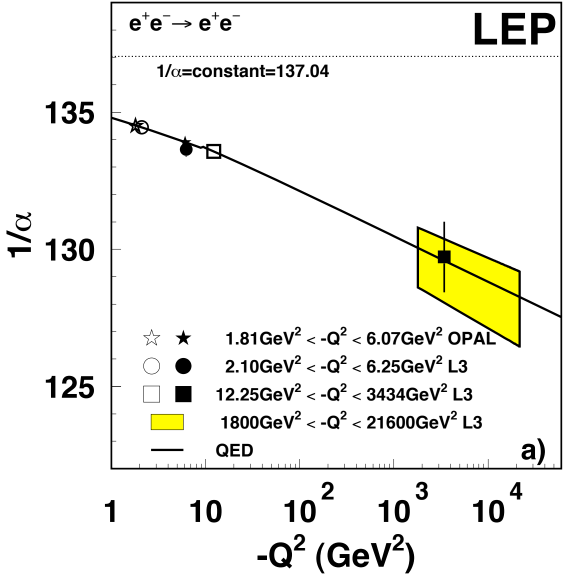


Charge screening in QED (electrons + photons)

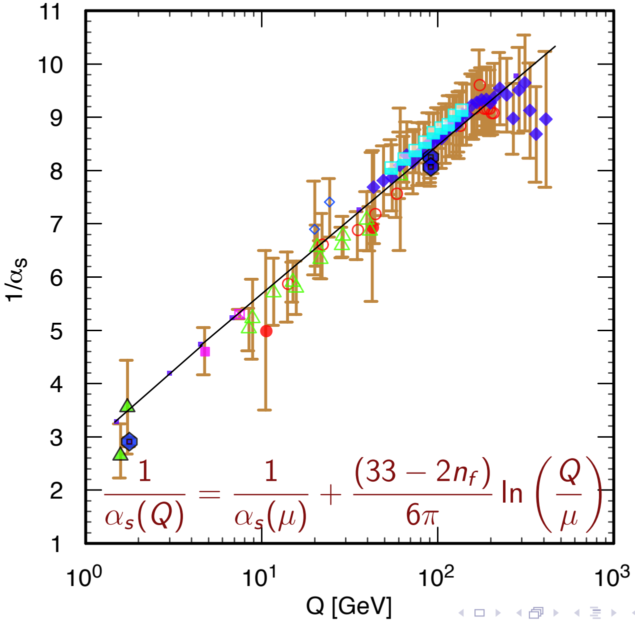


$$1/\alpha(Q) = 1/\alpha_0 - \frac{2}{3\pi} \ln\left(\frac{Q}{m}\right)$$

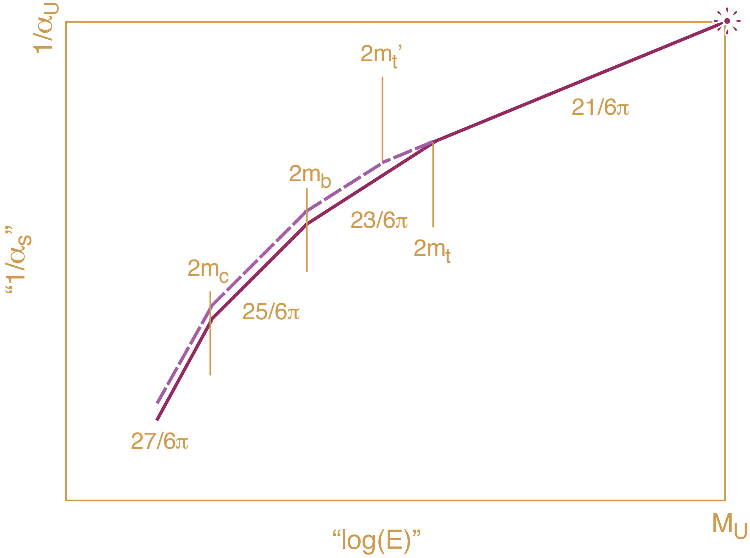
Charge screening in QED (real world)



Evolution of $\alpha_s(Q^2)$

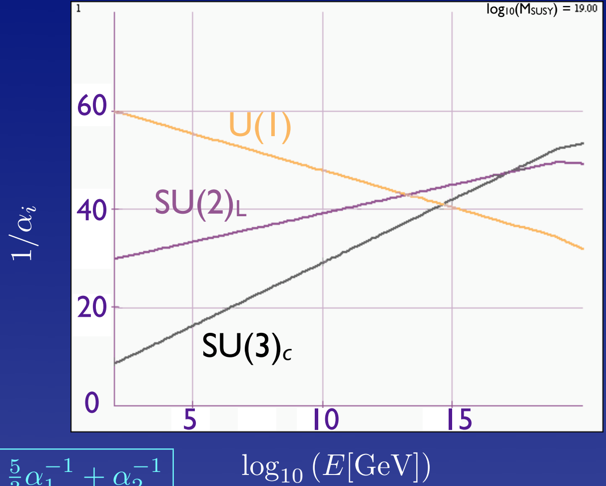


Evolution of $\alpha_s(Q^2)$
Influence of m_t



Coupling Constant Unification

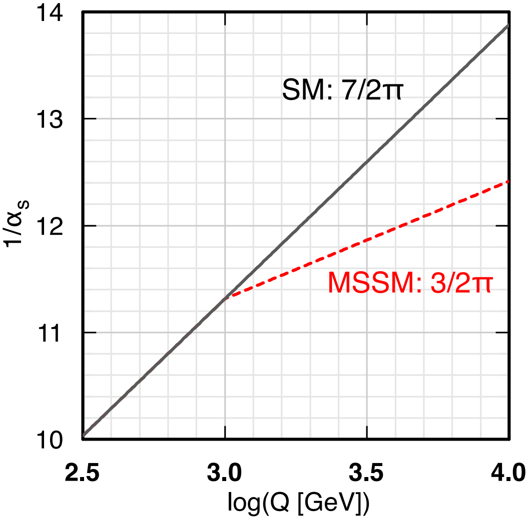
Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$
gives possibility of coupling constant unification



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

Can LHC See Change in Evolution?

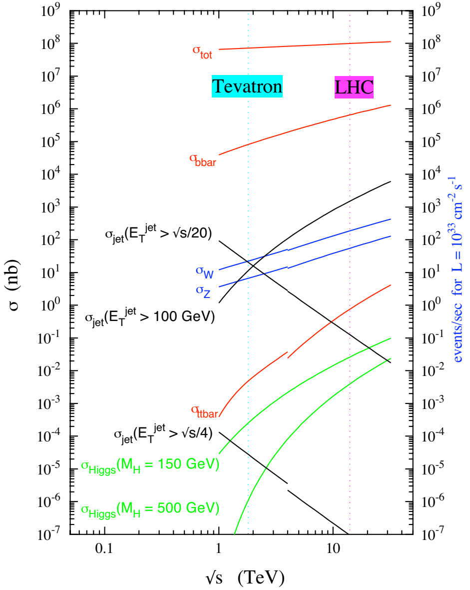
Sensitive to new colored particles



(sharp threshold illustrated)

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

Sample event rates in $p^{\pm}p$ collisions



Supermodels

New physics possibilities in very early running

Supermodels for early LHC

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[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720*
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[4] *Center for the Fundamental Laws of Nature, Jefferson Physical Laboratory, Harvard University, Cambridge, MA 02138*

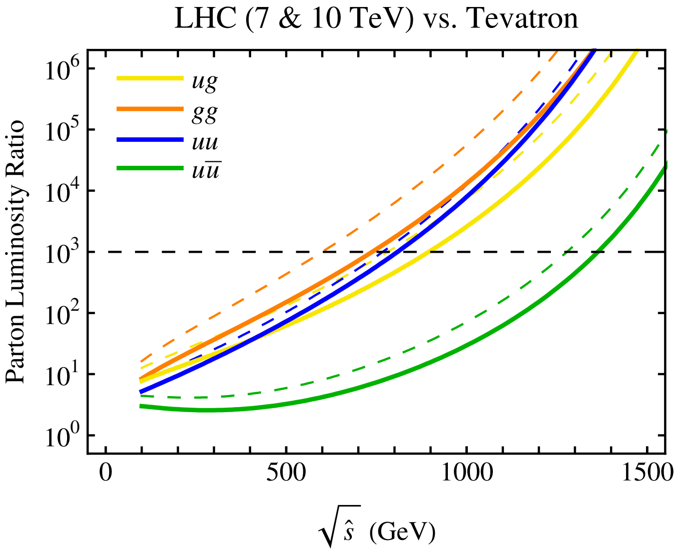
We investigate what new physics signatures the LHC can discover in the 2009–2010 run, beyond the expected sensitivity of the Tevatron data by 2010. We construct "supermodels", for which the LHC sensitivity even with only 10 pb^{-1} is greater than that of the Tevatron with 10 fb^{-1}. The simplest supermodels involve s-channel resonances in the quark-antiquark and especially in the quark-quark channels. We concentrate on easily visible final states with small standard model backgrounds, and find that there are simple searches, besides those for Z' states, which could discover new physics in early LHC data. Many of these are well-suited to test searches for "more conventional" models, often discussed for multi-fb^{-1} data sets.

Rules of the game:

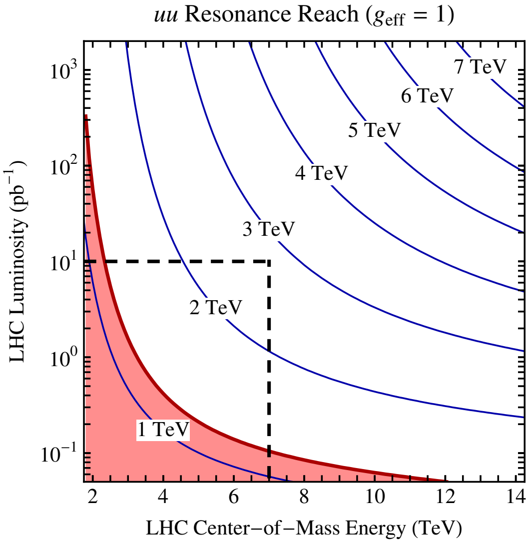
- $\gtrsim$ 10 signal events in 10 pb^{-1} at LHC (25 better)
- No signal in 10 fb^{-1} at Tevatron
- Easily detected, low-background decay channel
- Consistent with existing constraints

Supermodels

Need 10^3 advantage in parton luminosities



Supermodels
Example: strongly coupled qq resonance



Supermodels

To observe diquark, require decays beyond qq

An example: color-**6** diquark D + leptodiquark L (!)

$$uu \rightarrow D \hookrightarrow \ell^- L \hookrightarrow \ell^+ jj$$

Doesn't respond to any needs, but . . .

final state familiar from W_R searches

Don't assume there is nothing to find at low $\int \mathcal{L}dt$

Electroweak Questions for the LHC. I

- 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? (Infer $t\bar{t}H$ from production)
- 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?

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

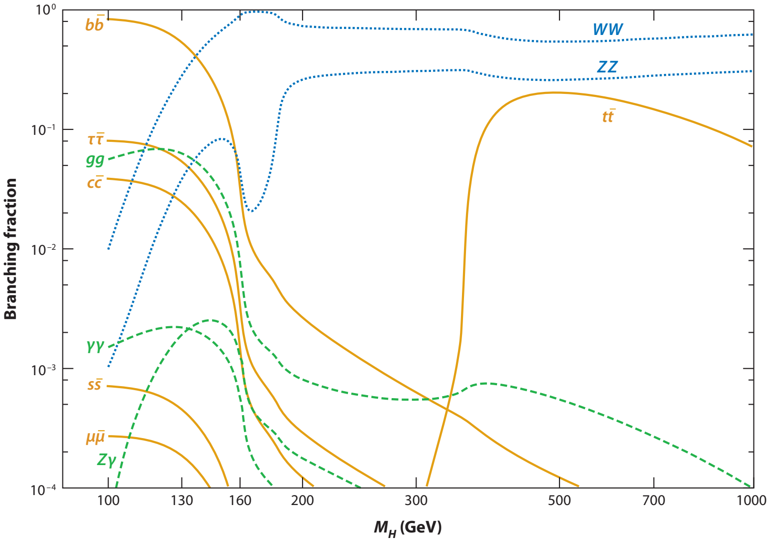
$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}}(1-x)^{1/2}(4 - 4x + 3x^2) \quad x \equiv 4M_W^2/M_H^2$$

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

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

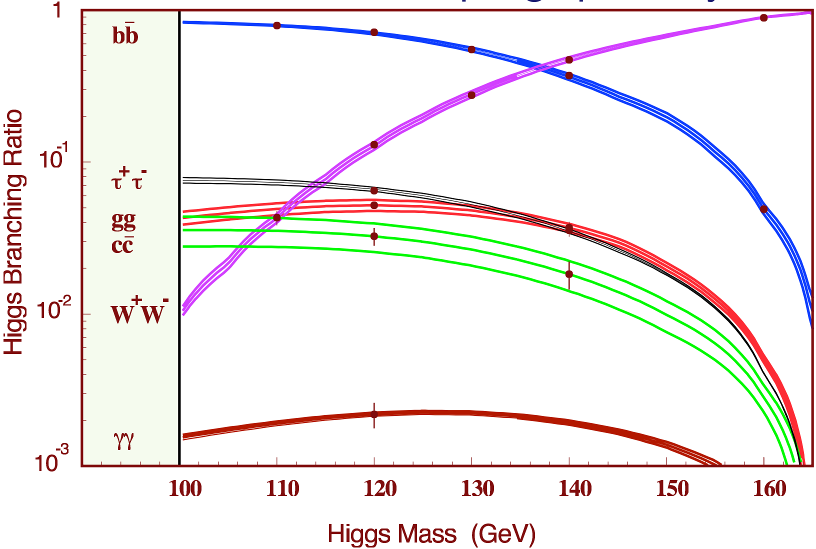
$2x^2$ and $2x'^2$ terms $\Leftrightarrow$ decays into transverse gauge bosons
Dominant decays for large M_H: pairs of longitudinal weak bosons

SM Higgs Boson Branching Fractions



Djouadi, hep-ph/0503172

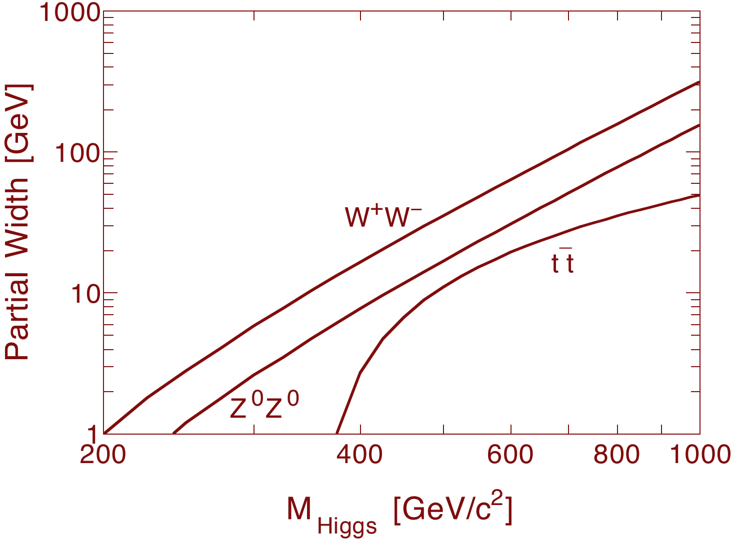
ILC would measure $Hf\bar{f}$ couplings precisely



Points: 500 fb^{-1} @ 350 GeV   Bands: theory uncertainty (m_b)

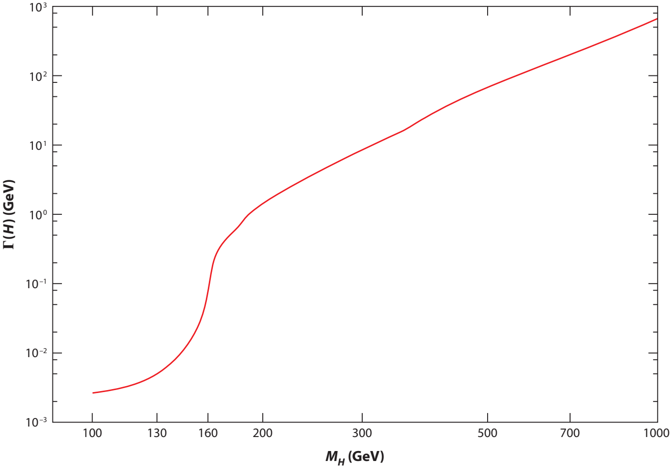
Battaglia

Dominant decays at high mass



For $M_H \to 1$ TeV, Higgs boson is *ephemeral:* $\Gamma_H \to M_H$.

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

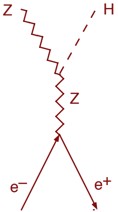
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

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*

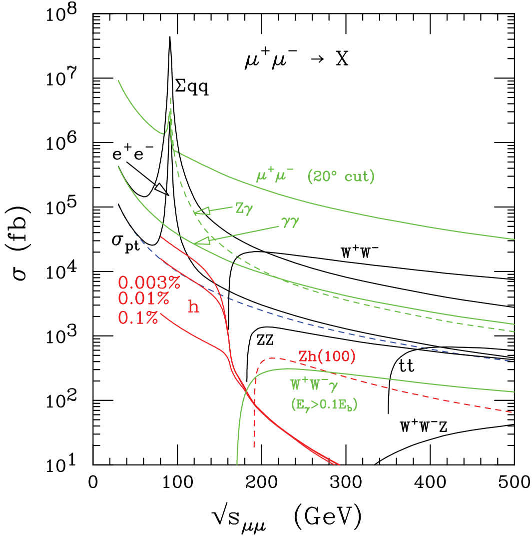
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)



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

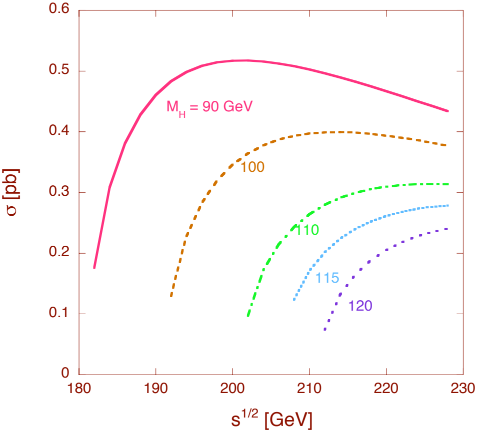
K: c.m. momentum of H $\qquad x_W \equiv \sin^2\theta_W$

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



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

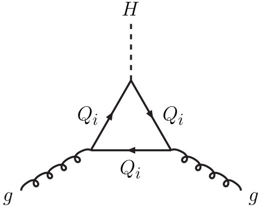
LEP Range Excitation Curves (ISR not included)



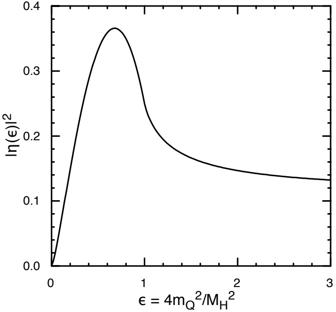
LEP 2: sensitive nearly to kinematical limit $M_H^{\max} = \sqrt{s} - M_Z$

LC: sensitive for $M_H \lesssim 0.7\sqrt{s}$

H couples to gluons through quark loops

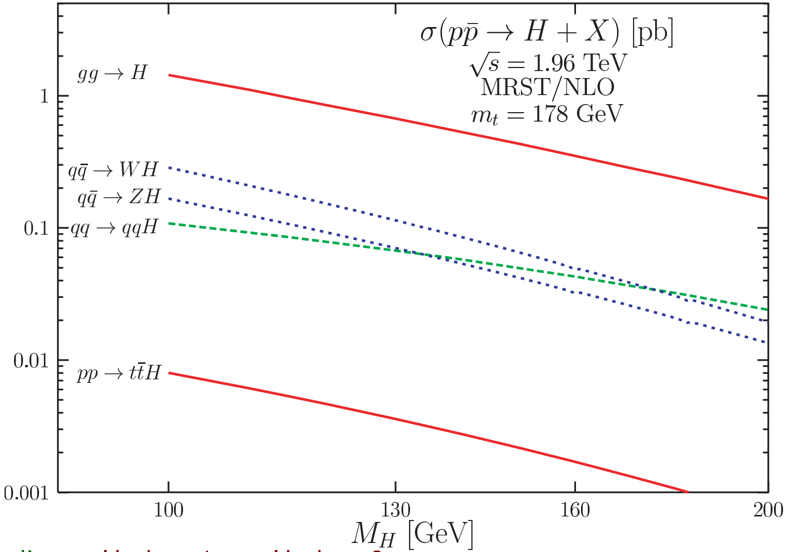


Only heavy quarks matter:



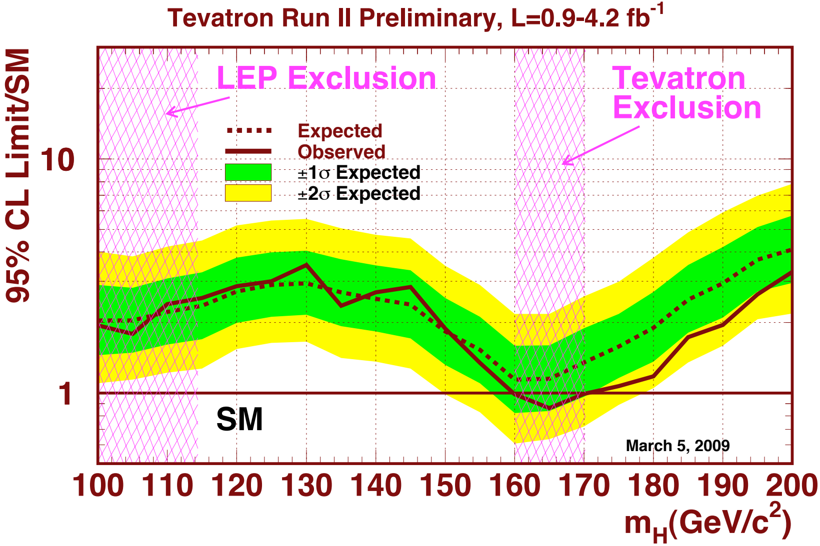
heavy 4th generation would have a big effect

Higgs-boson production at the Tevatron



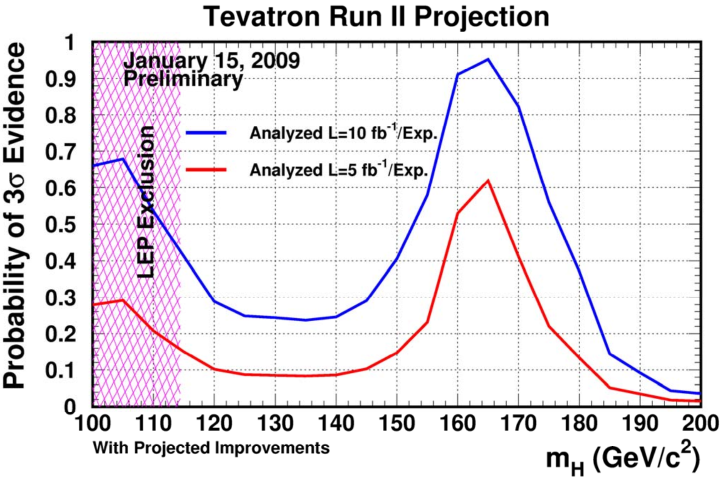
Djouadi Update 1 Update 2

Current Tevatron Sensitivity



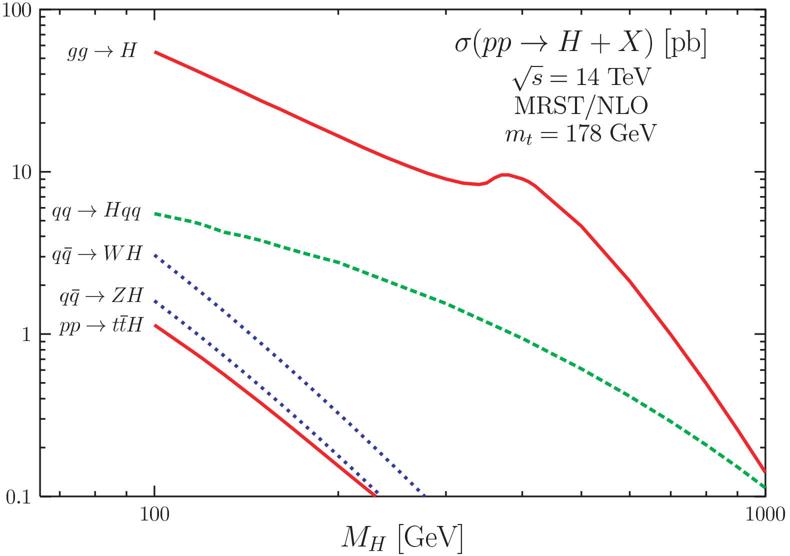
combining experiments, channels: Winter 2009

Tevatron prospects . . .



> 40% probability to have a 3 sigma evidence for m_H =115 GeV Higgs with L=10 fb^{-1}

LHC cross sections . . .



Djouadi

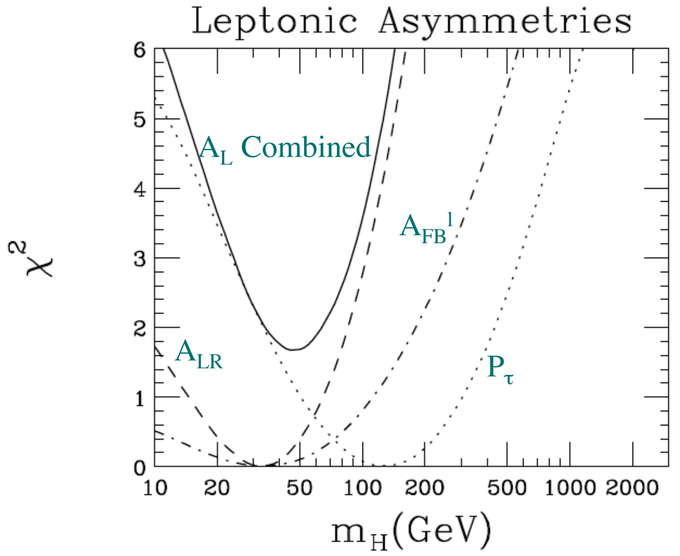
A Cautionary Note

- A^b_{FB}, which exerts the greatest "pull" on the global fit, is most responsible for raising M_H above the range excluded by direct searches.
- Leptonic and hadronic observables point to different best-fit values of M_H
- Many subtleties in experimental and theoretical analyses

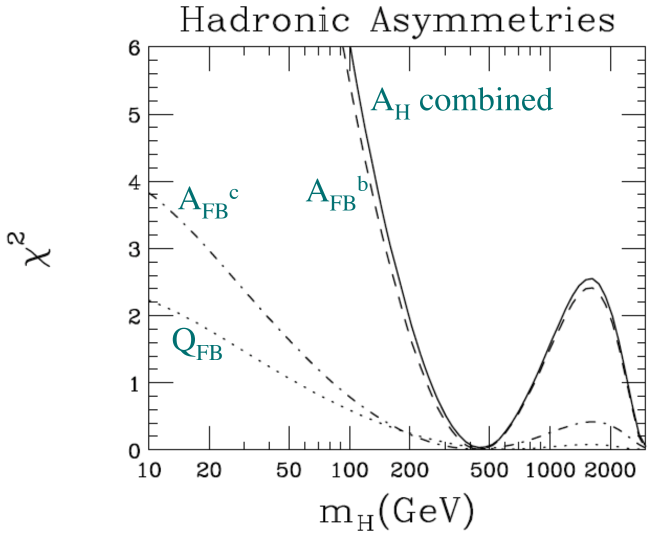
M. Chanowitz, arXiv:0806.890

Introduction to global analyses: J. L. Rosner, hep-ph/0108195; hep-ph/0206176

χ^2 Distributions: Leptonic Asymmetries



χ^2 Distributions: Hadronic Asymmetries



The EW scale and beyond

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

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

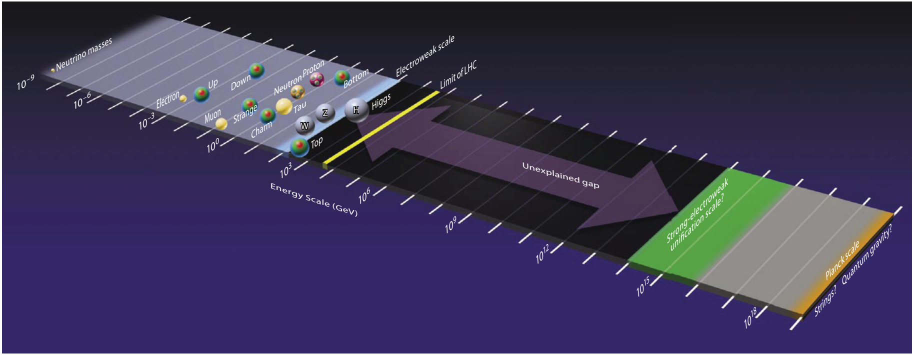
But it is not the only scale of physical interest

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

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

somewhere: flavor scale?

The Hierarchy Problem



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?