Hadron Collider Physics: Present and Future

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- Opening Remarks
- Hadron Colliders—the Why and How
- Expectations for Run II of the Tevatron Collider
- Aspirations for Tevatron Run III
- The Opportunity of the LHC
- Beyond the LHC?
- Inventing Our Futures

For a more expansive view of what is to come, see "Physics Opportunities in Fermilab's Futures," from my Wine & Cheese Seminar at Fermilab, 15 January 1999, available in PDF form or in gzipped PostScript at http://lutece.fnal.gov/Talks/. Hard copies are available as FERMILAB–FN–676.

Why Hadron Colliders?

Make available a rich diversity of elementary processes at the highest accessible energies.

To study quark-quark collisions at $\sqrt{s} = 1$ TeV:

If three quarks share half the proton's momentum ($\langle x \rangle = \frac{1}{6}$), we require pp collisions at $\sqrt{s} = 6$ TeV.

How to achieve?

Fixed-target machine with beam momentum $p \approx 2 \times 10^4$ TeV $= 2 \times 10^{16}$ eV, (*cf.* highest-energy cosmic rays). Ring radius is

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

Conventional copper magnets ($B = 2$ teslas) $\rightsquigarrow$

$$r \approx \tfrac{1}{3} \times 10^5\ \text{km}.$$

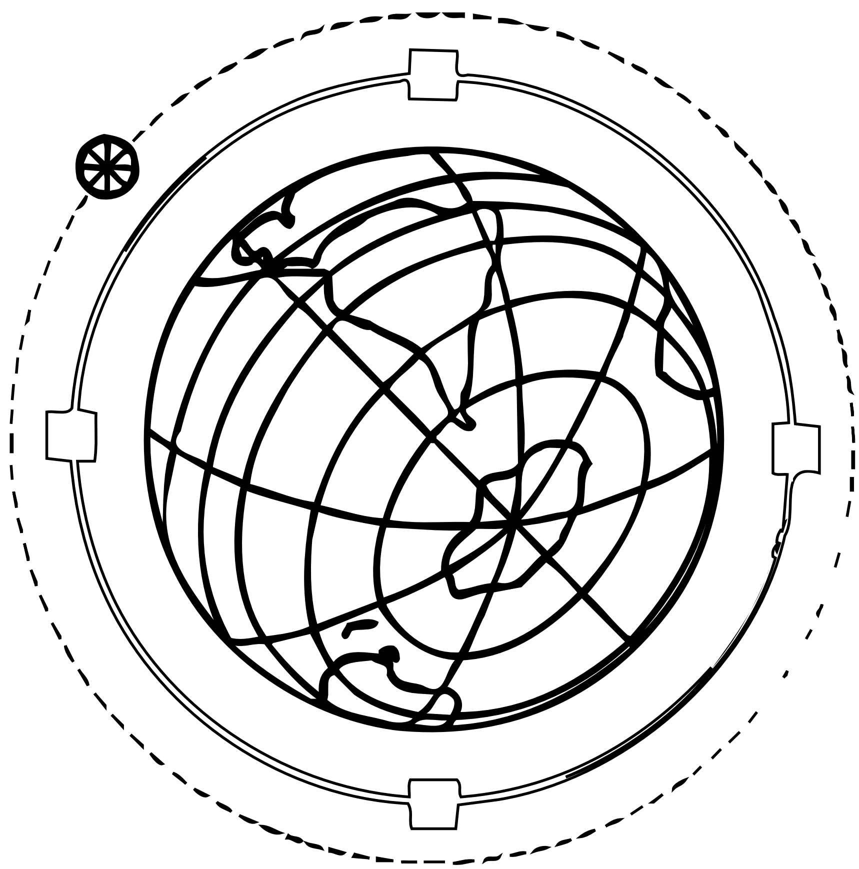
$$\approx \tfrac{1}{12}\ \text{size of Moon's orbit}$$

10-tesla field reduces the accelerator to mere Earth size ($R_\oplus = 6.4 \times 10^3$ km).

Fermi's Dream Machine (1954)

5000-TeV protons to reach $\sqrt{s} \approx 3$ TeV

2-tesla magnets at a radius of 8000 km



Projected operation 1994, cost \$170 billion
(inflation assumptions not preserved)

No technological innovations!

New Technology Telescopes

The development of new strategies for reaching higher energies has parallels in the development of new tools for optical astronomy.

The 2.5-m Telescope on Mount Wilson, with a mirror made of plate glass, was the largest in the world for 30 years.

The invention of Pyrex in the 1930s made practical the casting of a 5-m mirror for the Hale Telescope on Mount Palomar, where observations began in 1949.

Telescopes built over the next four decades—except the 6-m telescope on Mount Pastukhov in the Caucasus, commissioned in 1976—all were substantially smaller.

Recent innovations have broken the 5-m barrier.

- Multiple-mirror telescopes, with effective apertures much larger than can be obtained with a single mirror.
- Active optics, embodied in the idea of the "rubber telescope" that corrects its figure in real time to respond to variations in the density of the column of air above it.
- Segmented mirrors, in which a mosaic of mirrors of manageable size is positioned under microprocessor control.
- New fabrication methods that promise large, lightweight mirrors shaped in a spinning oven, like a potter's wheel, and mirrors with nonspherical surfaces, made by the technique of stressed-mirror polishing.
- Open-air telescopes that minimize aberrations caused by temperature gradients within the protective tube of traditional instruments.

The two 10-m Keck Telescopes, each made of 36 hexagonal segments 1.8 m across, commissioned (1993, 1996) in Hawaii.

Key Advances in Accelerator Technology

- The idea of colliding beams.
- Alternating-gradient ("strong") focusing, invented by Christofilos, Courant, Livingston, and Snyder.

Before and After . . .

Synchrotron	Beam Tube	Magnet Size
Bevatron (6.2 GeV/c)	1 ft × 4 ft	$9\frac{1}{2}$ ft × $20\frac{1}{2}$ ft
Main Ring (400 GeV/c)	∼ 2 in × 4 in	14 in × 25 in
LHC (7 TeV/c)	56 mm	

- Superconducting accelerator magnets. We owe to materials scientists the discovery of practical "type-II" superconductors, including the NbTi used in all superconducting machines to date, and the brittle Nb_3Sn, which may find use in special applications. The superconducting cable used in accelerator magnets has roots in pioneering work carried out at the Rutherford Laboratory, and essential early steps in the development of robust magnet structures were taken at Fermilab.
Applied Superconductivity Center at UW–M

Key Advances . . .

- The evolution of vacuum technology. Accelerator beams stored for approximately 20 hours must travel approximately 2×10^{10} km, about 150 times the distance from Earth to Sun, without encountering a stray air molecule.

- The development of large-scale cryogenic technology, to maintain many kilometers of magnets at a few kelvins.

- Active optics to achieve real-time corrections of the orbits of particles in the accelerator has yielded the benefits of "cooling," or phase-space compaction of stored antiprotons. Makes it possible to build reliable, highly tuned accelerators from magnets with small apertures.

Hadron Colliders through the Ages

- CERN Intersecting Storage Rings: pp collider at $\sqrt{s} \to 63$ GeV. Two rings of conventional magnets.

- S$\bar{p}p$S Collider at CERN: $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV (ramped to 900 GeV) in a conventional-magnet synchrotron, the SPS.

- Fermilab Tevatron Collider: $\bar{p}p$ collsions at $\sqrt{s} = 1.8$ TeV (soon 2.0 TeV) in the first superconducting synchrotron. 4-tesla magnets in a 2π-km tunnel.

- Superconducting Super Collider: planned as a 40-TeV pp collider, using 6.6-tesla magnets in an 87-km tunnel. Abandoned in 1993.

- Large Hadron Collider at CERN: 14-TeV pp collider under construction in the 27-km LEP tunnel, using 9-tesla magnets operating at 1.8 K.

- Relativistic Heavy-Ion Collider at Brookhaven will operate part of each year with polarized pp collisions at $\sqrt{s} = 400$ GeV.

Expectations for Tevatron Run II

Fermilab Tevatron + Main Injector
$\bar{p}p$ collisions at 2 TeV
CDF and DØ detectors

- Run I: 100 pb^{-1} @ 1.8 TeV 1994–1996
- Run II: 2 fb^{-1} @ 2 TeV in 2000–2002
- Run III: 30 fb^{-1} by 2006

Goals:

- Discover CP violation in $B^0 \to \psi K_s$
- Exploit the physics of the top quark
  Begin to determine $|V_{tb}|$ in $q\bar{q} \to W^\star \to t\bar{b}$
- Refine M_W
- Search for superpartners and new strong dynamics
- Explore!

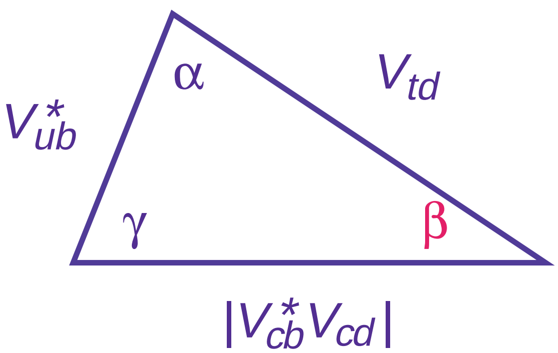
The Problem of Identity

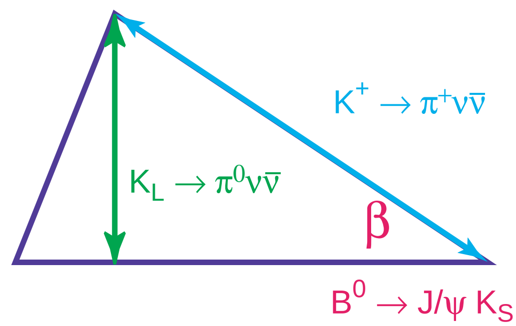
Part of the physics that determines
the machine beyond the LHC.

Accessible soon: CP violation, ν mass, ...

Three-generation unitarity:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$





Tevatron can be first to $\sin 2\beta$ from $B^0 \to \psi K_{\mathrm{S}}$, though BaBar and belle will have a head start.

- Large asymmetry expected
- Ample rate: 10 – 20 kHz $b\bar{b}$ in Run II
- CDF has developed tagging techniques and measured $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ in 400 ψK_{S} events.

Measuring $|V_{tb}|$

CDF measures

$$B_b \equiv \frac{\Gamma(t \to bW)}{\Gamma(t \to qW)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99 \pm 0.29$$

With three generations,

$$\Rightarrow |V_{tb}| > 0.76 \ \ (95\%\ \mathrm{CL})$$

Without the unitarity constraint, learn only that

$$|V_{tb}| \gg |V_{td}|, |V_{ts}|$$

Expected improvements in δB_b:

Run II: $\pm 10\%$ Run III: $\pm$ few % LHC: $\pm 1\%$

Direct measurement of $|V_{tb}|$ in single-top production

$$\bar{q}q \to W^\star \to t\bar{b} \qquad gW \to t\bar{b}$$

$$\sigma(t) \propto |V_{tb}|^2$$

Expect $\delta|V_{tb}| = \pm(10\%, 5\%)$ in Run II and III, using both $W^\star$ and gW fusion.

LHC: gW fusion cross section is $100\times$ larger

S. Willenbrock, "Top Quark Physics for Beautiful and Charming Physicists," hep-ph/9709355.

Top and W Measurements

- $\delta m_t \approx 3$ GeV/c^2 in Run II, 1 GeV/c^2 in Run III, LHC
- $\delta M_W \approx 40$ MeV/c^2 in Run II (each experiment)
- $\Rightarrow$ infer $\delta M_H / M_H \lesssim 40\%$
- $\delta\sigma(t\bar{t}) \approx 8\%$ in Run II, 3% in Run III, $\pm$ few % at LHC
- $\delta \dfrac{\Gamma(t \to bW)}{\Gamma(t \to qW)}$ will improve to $\pm 10\%$ in Run II, $\pm$ few % in Run III, $\pm 1\%$ at LHC
- $\delta |V_{tb}| \approx \pm 10\%$ in Run II, $\pm 5\%$ in Run III
- Searches are under way for $t\bar{t}$ resonances, rare decays, and other signs of new physics.

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thinkshop: top-quark physics for Run II.
QCD and Weak Boson Physics Workshop: first meeting March 4–6, 1999.
Links at http://www-theory.fnal.gov/.

Run II: Extensive search for light-scale supersymmetry

Now is the time to find supersymmetry!

LEP 2

Tevatron Run II

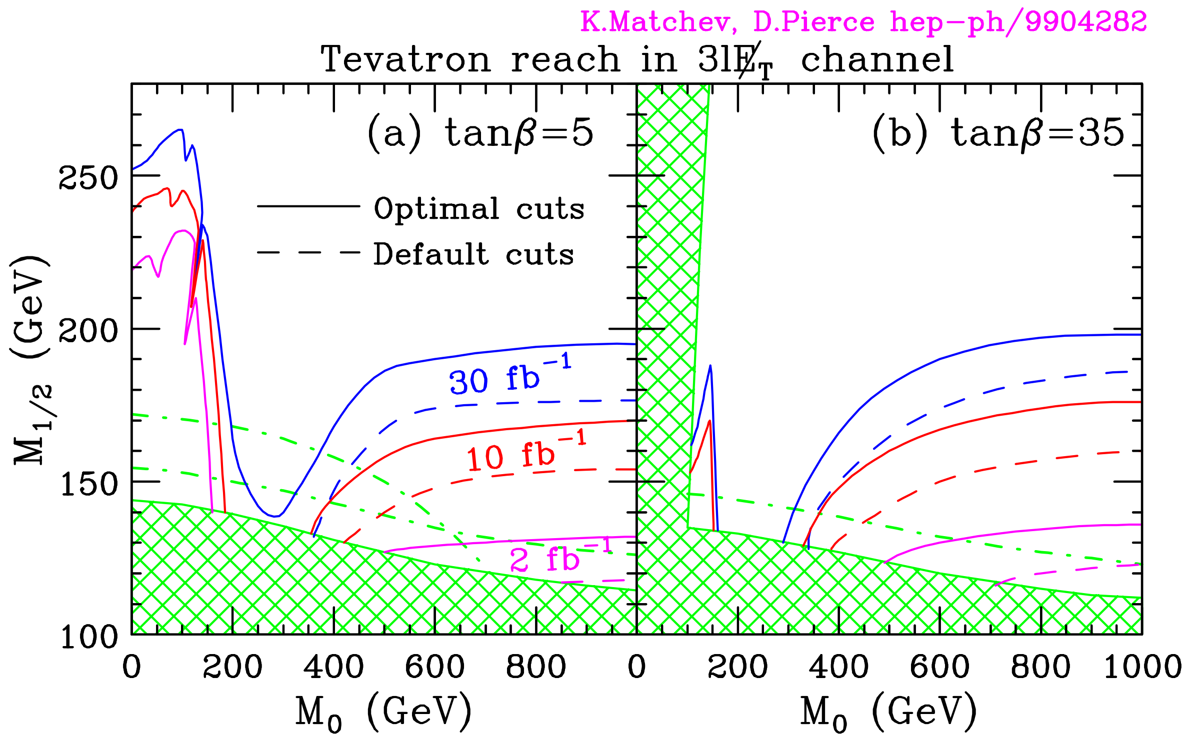
Run II Workshops: Supersymmetry & Higgs

- New simulation tools & improvements to old
- Analysis schemes
- New signatures
  - R-parity–violating decays
  - Signatures of extra dimensions
  - Search for long-lived particles (macroscopic decay lengths) by photon pointing or heavy ionization
  - τ modes

First draft of "Yellow Book" chapters due 1/29.
SUSY99 at Fermilab, 14-19 June 1999
Links at http://www-theory.fnal.gov/.

Improved analysis of signals and backgrounds . . .

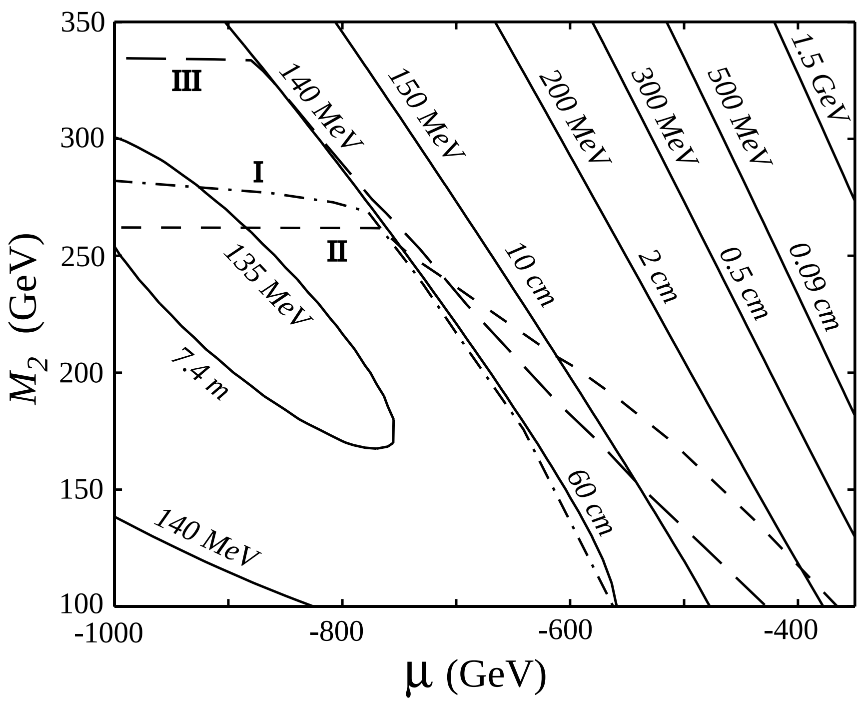
Minimal Supergravity Models with $\mu > 0$, $A_0 = 0$



Wino LSP Scenarios

Search for macroscopically displaced vertices

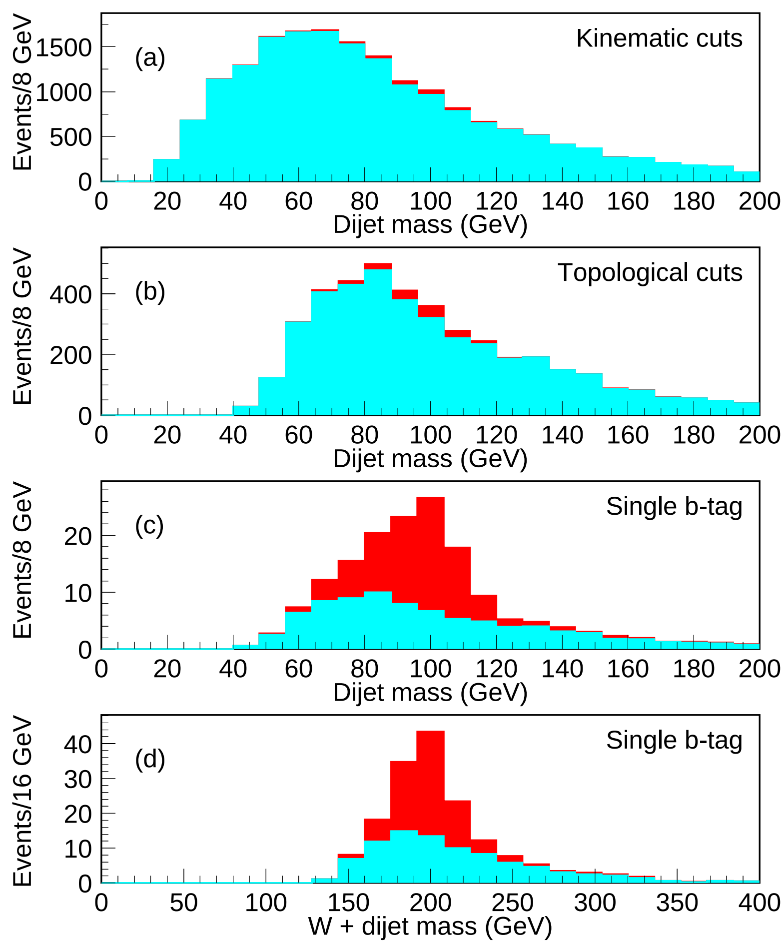
nearly degenerate $\tilde{\chi}^{\pm}$, $\tilde{\chi}_1^0$ ...



Feng, Moroi, Randall, Strassler, & Su, hep-ph/9904250.

Low-Scale Technicolor Search

$$\rho_T^+ \quad \rightarrow \quad W^+ \pi_T^0$$
$$\hookrightarrow b\bar{b}$$



Eichten, Lane, & Womersley, "Finding low-scale technicolor at hadron colliders," *Phys. Lett.* **B405**, 305 (1997), hep-ph/9704455.
Workshop on New Strong Dynamics: next meeting April 9-10, 1999.
Link at http://www-theory.fnal.gov/.

Search for "Large" Extra Dimensions

§ String theory requires 10-ish spacetime dimensions.

Assumed natural to take

$$R_{\text{unobserved}} \simeq 1/M_{\text{Planck}} \simeq 10^{-31}\ \text{cm}$$

What goes on there does affect the observable world:

Excitations of Calabi–Yau manifolds determine spectrum of quarks and leptons.

(Fermion mass problem lives in curled-up dimensions)

§ New wrinkle

- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge fields (+ necessary extensions) live on branes
- Gravity lives in the bulk (extra dimensions)

If gravity lives in $4+n$ dimensions (n with radius R), Gauss's law $\rightsquigarrow$

$$G_N = \frac{1}{4\pi} M^{-n-2} R^{-2}$$

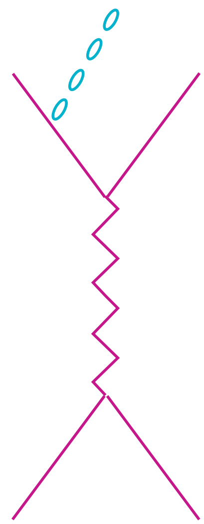
Could extra dimensions be quasimacroscopic?

If $M \sim 1$ TeV, then $R \lesssim 1$ mm for $n \geq 2$.

Remarkably, might have escaped detection ...

Examine real and virtual effects of

♠ GRAVITON EXCITATION OF TOWERS OF EXTRADIMENSIONAL ("KAŁUZA–KLEIN") MODES



New signatures, like

$$pp \quad \rightarrow \quad \text{jet} + \not{E}_T \;\; (\text{parton} + \text{graviton})$$
$$\ell^+\ell^- + \not{E}_T \;\; (\ell^+\ell^- + \text{graviton})$$

Informative metaphor of collider as ultramicroscope
Are extra dimensions large enough to see?

NEED A NAME FOR ♠
provatons $<$ *πρόβατο*

(sheep, as in a flock)

Develop a Plan for Run III

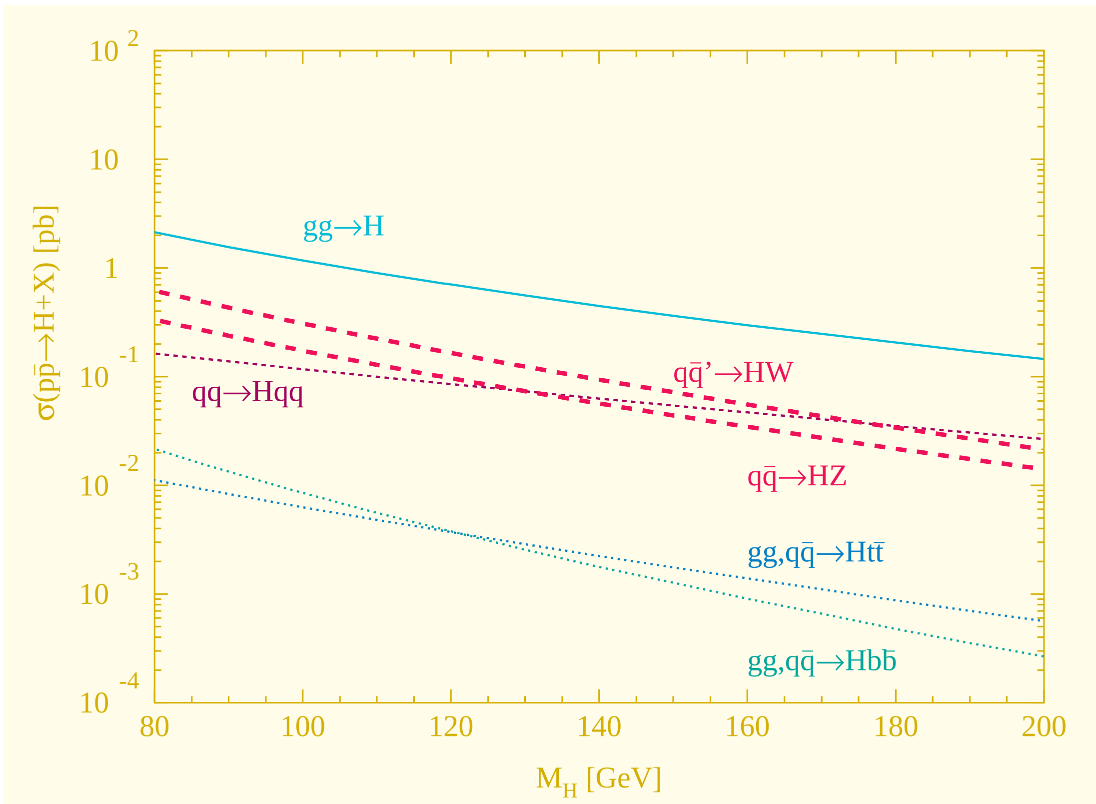
Increased $\mathcal{L}$ improves discovery reach

Target: 30 fb^{-1} by 2006

$\mathcal{L}$ motivated by search for light Higgs boson in the region favored by supersymmetry

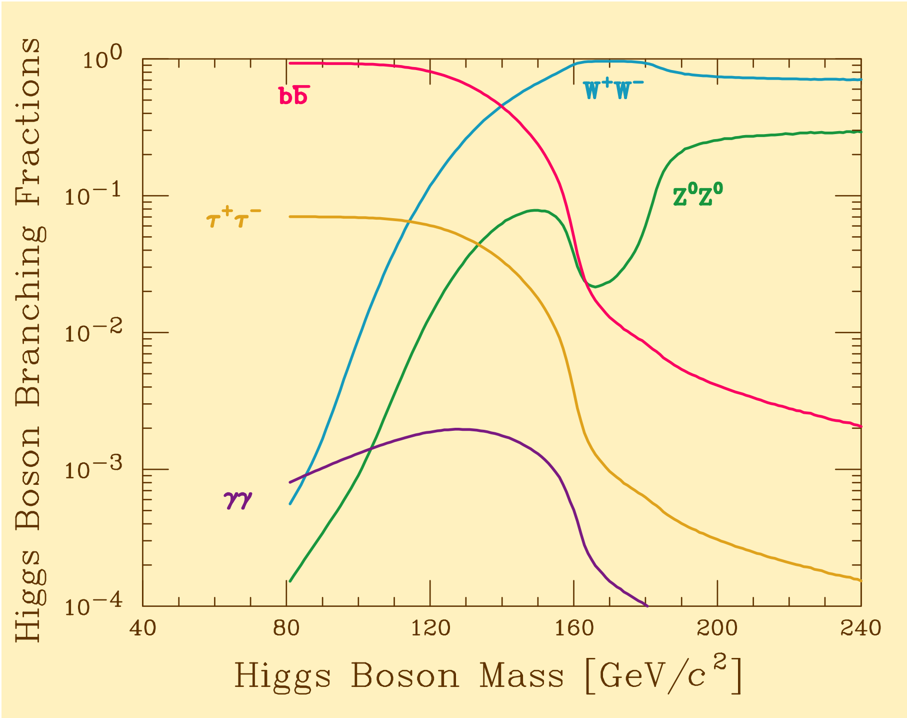
- Improvements in m_t, M_W
- Study of top production and decay
- Single-top production and $|V_{tb}|$
- Extend study of CP violation
- $B_s - \bar{B}_s$ mixing
- B_c, b-baryon spectroscopy
- Supersymmetry: extend search or exploit discovery
- Continue search for new strong dynamics

Higgs-boson production sets luminosity target



Many processes become accessible once $\mathcal{L}$ exceeds a few fb.

Search for a not-too-heavy Higgs boson



- Tevatron:

$$q\bar{q} \quad \to \quad H(W,Z) \\ \hookrightarrow b\bar{b}$$

- LHC:

$$gg \to H \to \gamma\gamma,$$

$$q\bar{q} \quad \to \quad HW \\ \hookrightarrow b\bar{b},\ WW^\star,\ ZZ^\star$$

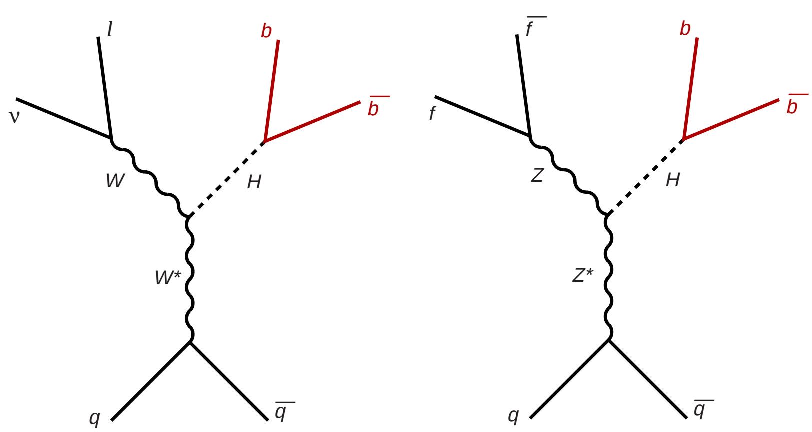
Tevatron Search Strategies

- $gg \to H \to b\bar{b}$ is swamped by QCD production of $b\bar{b}$.
  Even with 30 fb^{-1}, only $<$ 1-σ excess.
  By-product: $Z^0 \to b\bar{b}$ observable in Run II.

- Special topologies improve signal/background and significance:

$$\bar{p}p \quad \to \quad HW + \text{anything} \quad (W \hookrightarrow \ell\nu,\ \text{jets};\ H \hookrightarrow b\bar{b})$$

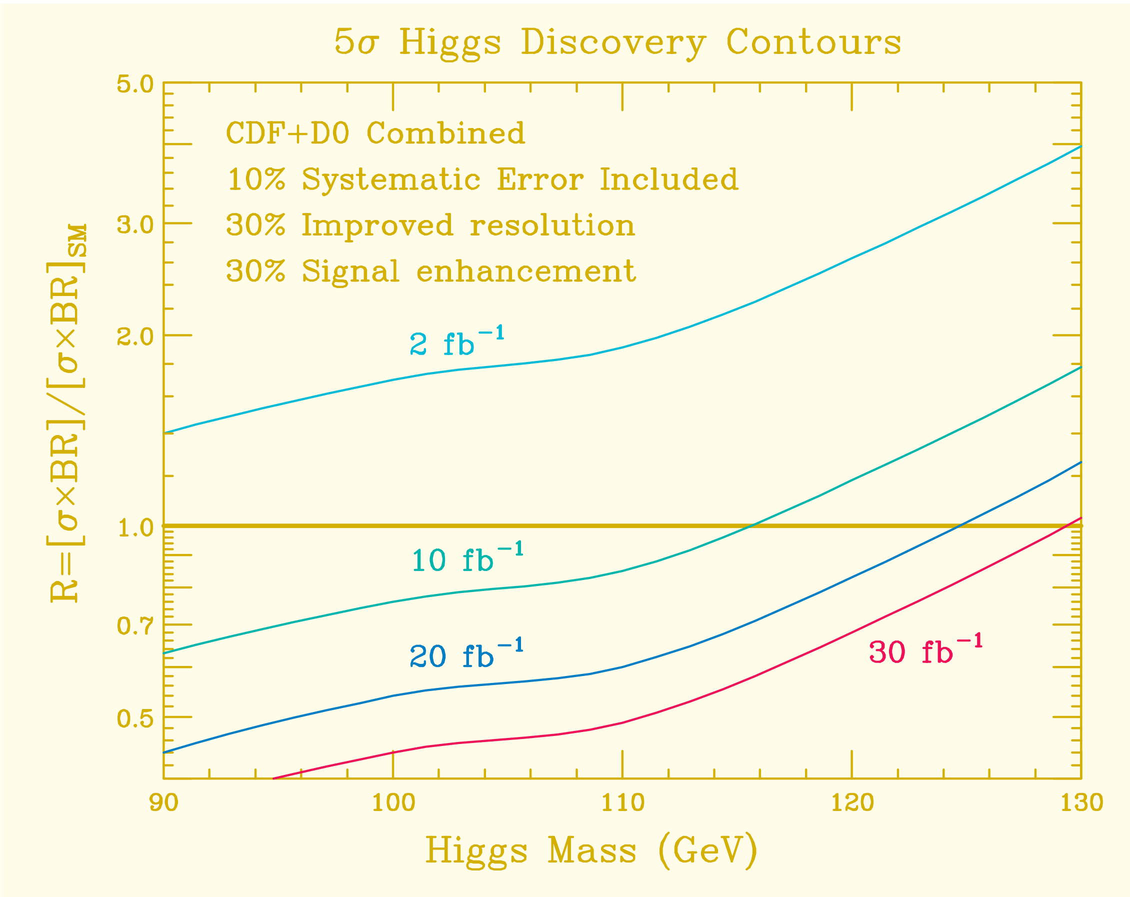
$$\bar{p}p \quad \to \quad HZ + \text{anything} \quad (Z \hookrightarrow \ell^+\ell^-,\ \nu\bar{\nu};\ H \hookrightarrow b\bar{b})$$



A. Stange, W. Marciano and S. Willenbrock, *Phys. Rev. D* **49**, 1354 (1994); *Phys. Rev. D* **50**, 4491 (1994).

Higgs boson sensitivity

- Combine CDF and DØ
- Combine W and Z channels

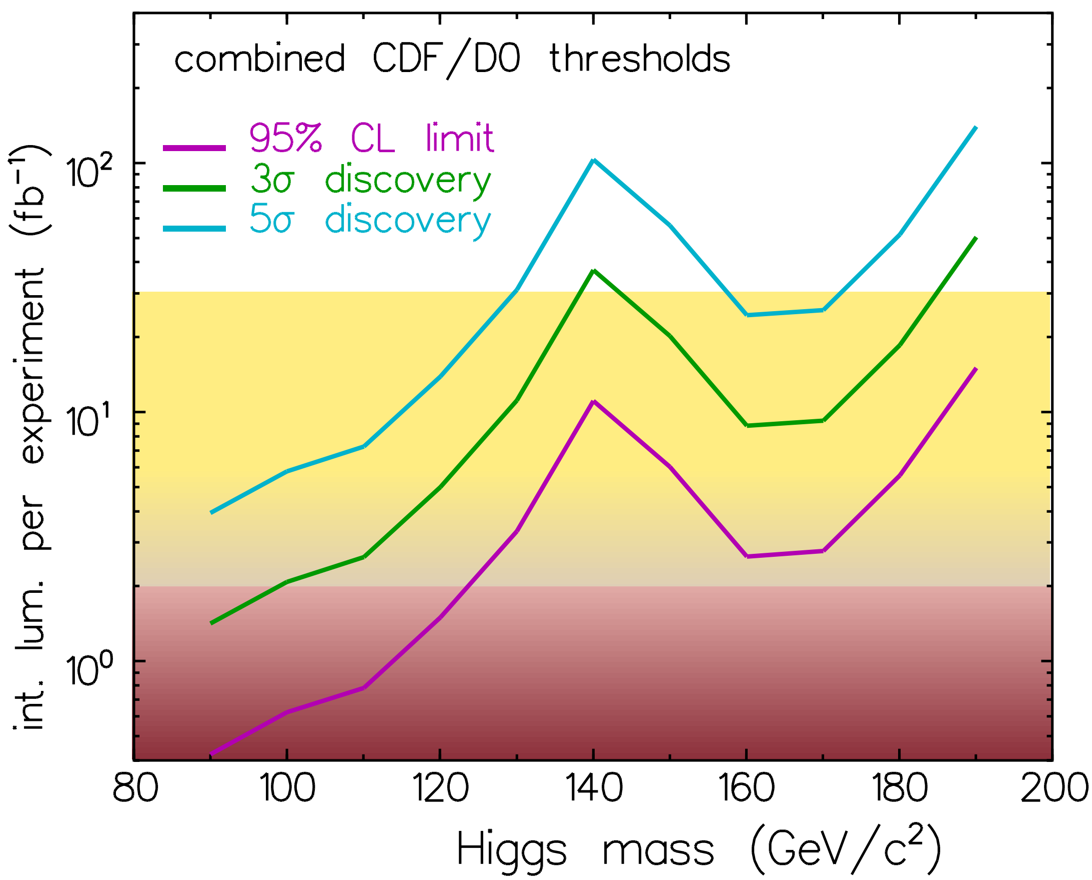


Supersymmetry/Higgs Workshop, http://fnth37.fnal.gov/susy.html.

Higgs boson search & discovery

Extend reach using $H \to WW^*$ mode?

Initial studies are promising.



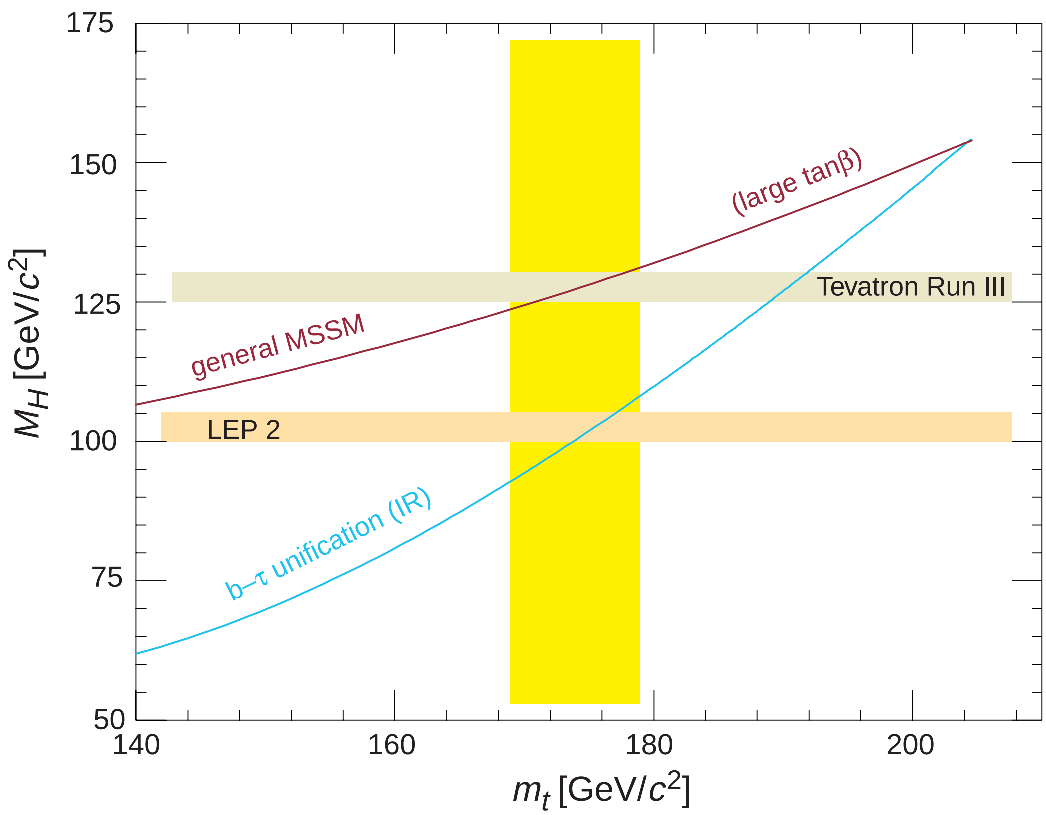
Tao Han, André S. Turcot, and Ren-Jie Zhang, hep-ph/9812275.

Precision EW data prefer a light Higgs boson, which demands new physics nearby.

SUSY solves naturalness problem of SM Higgs sector, allows perturbative unification, and provides a source of new physics that demands a light Higgs boson.

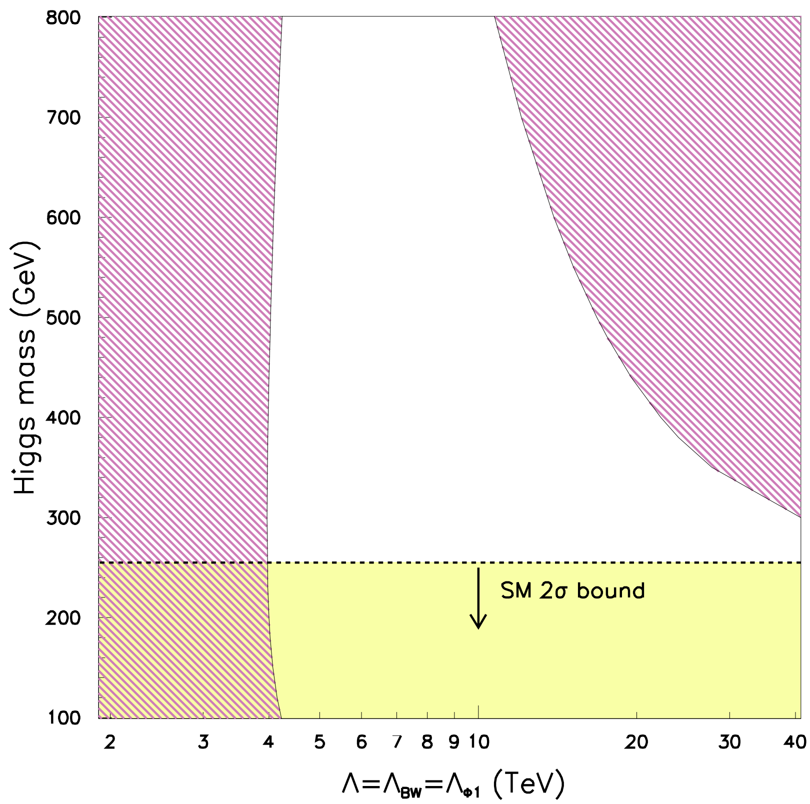
$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \cdots\right] \lesssim \left(130 \text{ GeV}/c^2\right)^2$$

Upper bound on $m_h \Longleftrightarrow$ large m_A limit, ($M_s = 1$ TeV):



M. Carena, J. R. Espinosa, M. Quirós, and C. Wagner, *Phys. Lett.* **B355**, 209 (1995).

EWSB and Large Extra Dimensions



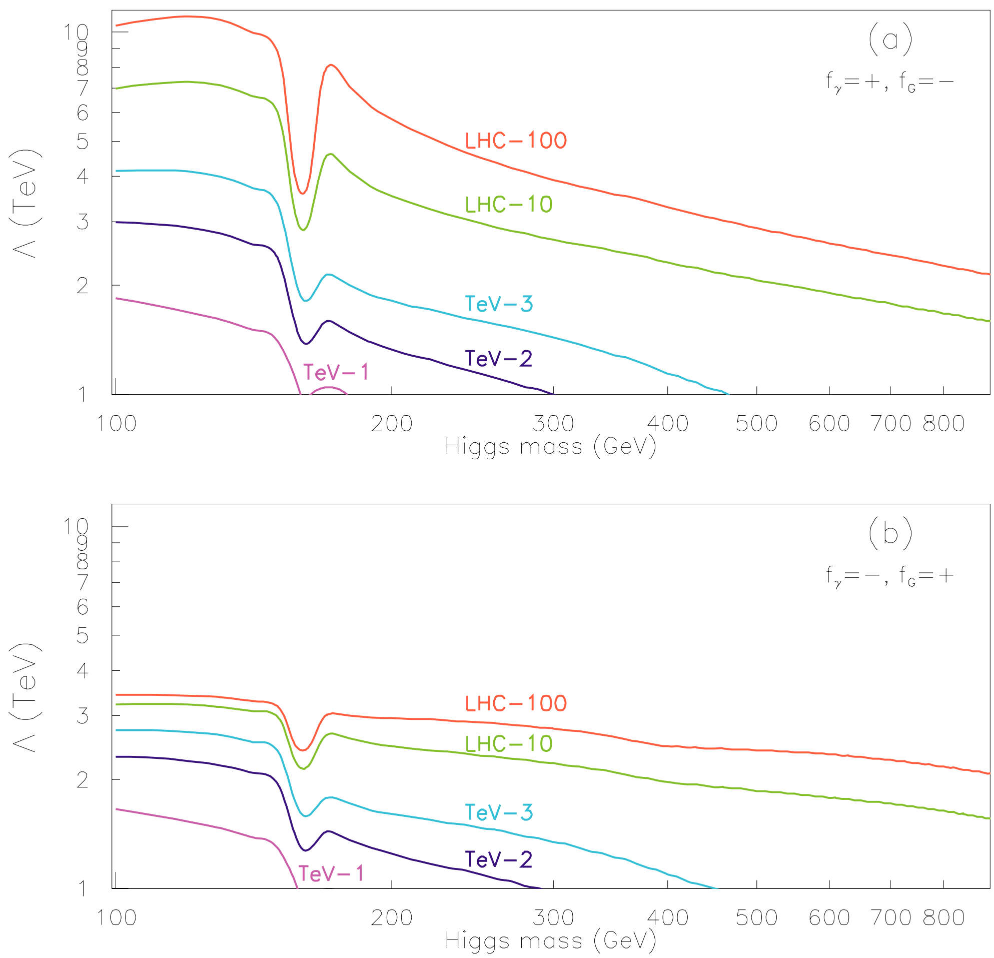
almost an existence proof for escaping SM Higgs constraints . . .

Does situation arise in any real theory?

Hall & Kolda, hep-ph/9904236.

5-σ limits on $h \to \gamma\gamma$

Example of nonstandard Higgs with enhanced production and $\Gamma(h \to \gamma\gamma)$



Hall & Kolda, hep-ph/9904236.

How to Realize Run III?

Be prepared to exploit Run II discoveries

(a) High peak $\mathcal{L} \to 2 \times 10^{33}$ cm^{-2} s^{-1}, or

(b) "Level" $\mathcal{L} \approx 5 \times 10^{32}$ cm^{-2} s^{-1}?

Avoid a long shutdown while Tevatron defines the energy frontier.

What detector upgrades are required?

If modest upgrades suffice, will CDF & DØ have adequate forces?

Total cost?

Can we do this?

Physics at the LHC

pp collisions at 14 TeV

$\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$ in 2005–2009

ATLAS and CMS detectors

The Energy Frontier and EWSB

Tevatron experiments have changed the way we think about LHC physics.

- The great mass of the top quark
- The success of b-tagging in the hadron-collider environment: τ, c channels?
- High sensitivity from high integrated luminosity

CDF & DØ (+ LEP) will define the physics context.

Big Questions for Future Accelerators

- What machines are possible?
  When?
  At what cost?
- What are the physics opportunities?
- Can we do physics in the environment?
  (What does it take?)
- How will these experiments add to existing knowledge *when they are done?*

The SSC was the right answer

Central problem in particle physics:
understand the mechanism of electroweak symmetry breaking.

$\Rightarrow$ Explore the 1-TeV scale
Search for the Higgs boson

40-TeV *pp* collider with 10^{33} cm^{-2} s^{-1} would have been the ideal instrument.

Still the *best practical idea* we've had . . .

. . . but it's not going to happen.

Complicates the task of developing a new vision

Luckily, LHC is a very capable machine.

Challenge:

- Develop better practical ideas
- Look to physics beyond EWSB
- Imagine ways to pursue LEP2 – Tevatron – LHC discoveries

Beyond the LHC

Discoveries at LHC could point to energies well above the 1-TeV scale $\Rightarrow \sqrt{s} \gg 14$ TeV.

- Heavy Higgs boson
- New strong dynamics
  strong WW scattering
  Technicolor (analogue of BCS)
  Gauge-mediated SUSY breaking
- New gauge boson

A Very Large Hadron Collider is the one multi-TeV machine we know we can build.

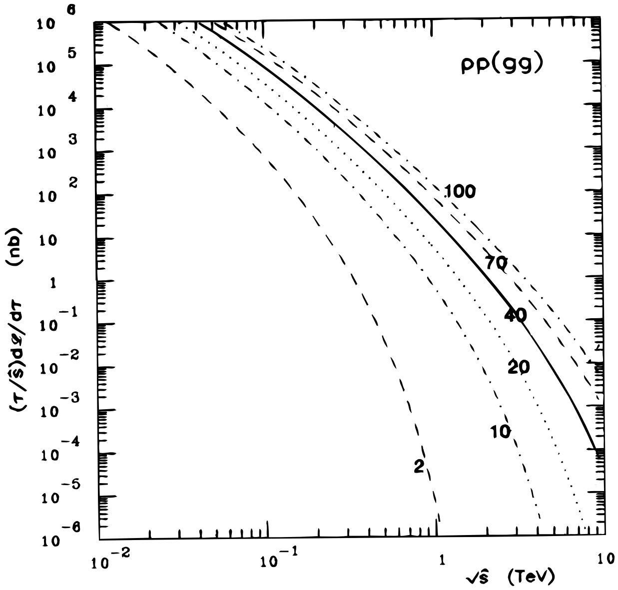
Pointlike cross sections $\propto 1/s$

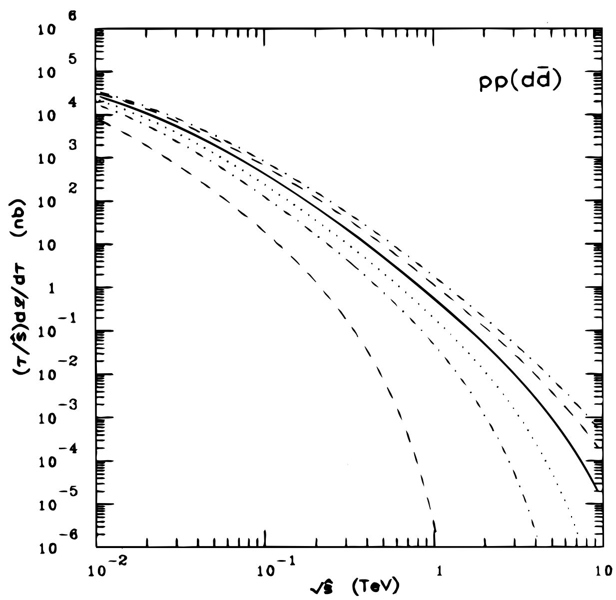
$\Rightarrow$ Luminosity goal:

$$\mathcal{L}^\star = 10^{32\text{-}33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \left(\frac{\sqrt{s}}{40\ \mathrm{TeV}}\right)^2$$

For $\sqrt{s} = 100$ TeV, target $\mathcal{L}^\star \approx 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Parton Luminosities





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

Possible physics targets

- nonstandard heavy Higgs boson
- strong WW scattering without low-lying resonances
- few-TeV messengers of gauge-mediated SUSY breaking
- huge reach for leptoquarks, excited quarks, ...

The idea of "large" extra dimensions reminds us how uncertain we are that nothing is there.

Toward the VLHC

Cost reduction essential to go beyond SSC

Example pp machine:
$\sqrt{s} = 100$ TeV, $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1}

¶ Explore magnet alternatives

- superferric (2 teslas) “transmission line”
- moderate field (7 – 8 teslas) à la LHC
- high field ($\sim$ 10 teslas)
- very high field (14 – 15 teslas)
- high-T_c superconductors for dipoles or specials

¶ Encourage appropriate conductor R & D

¶ Look for limitations to accelerator performance à la 1979 ICFA Report

¶ Optimize cost of machine: technical + conventional components

¶ Aim at a set of reference designs (but not too soon)

Be aware of evolving physics goals
and energy /luminosity tradeoffs for detectors

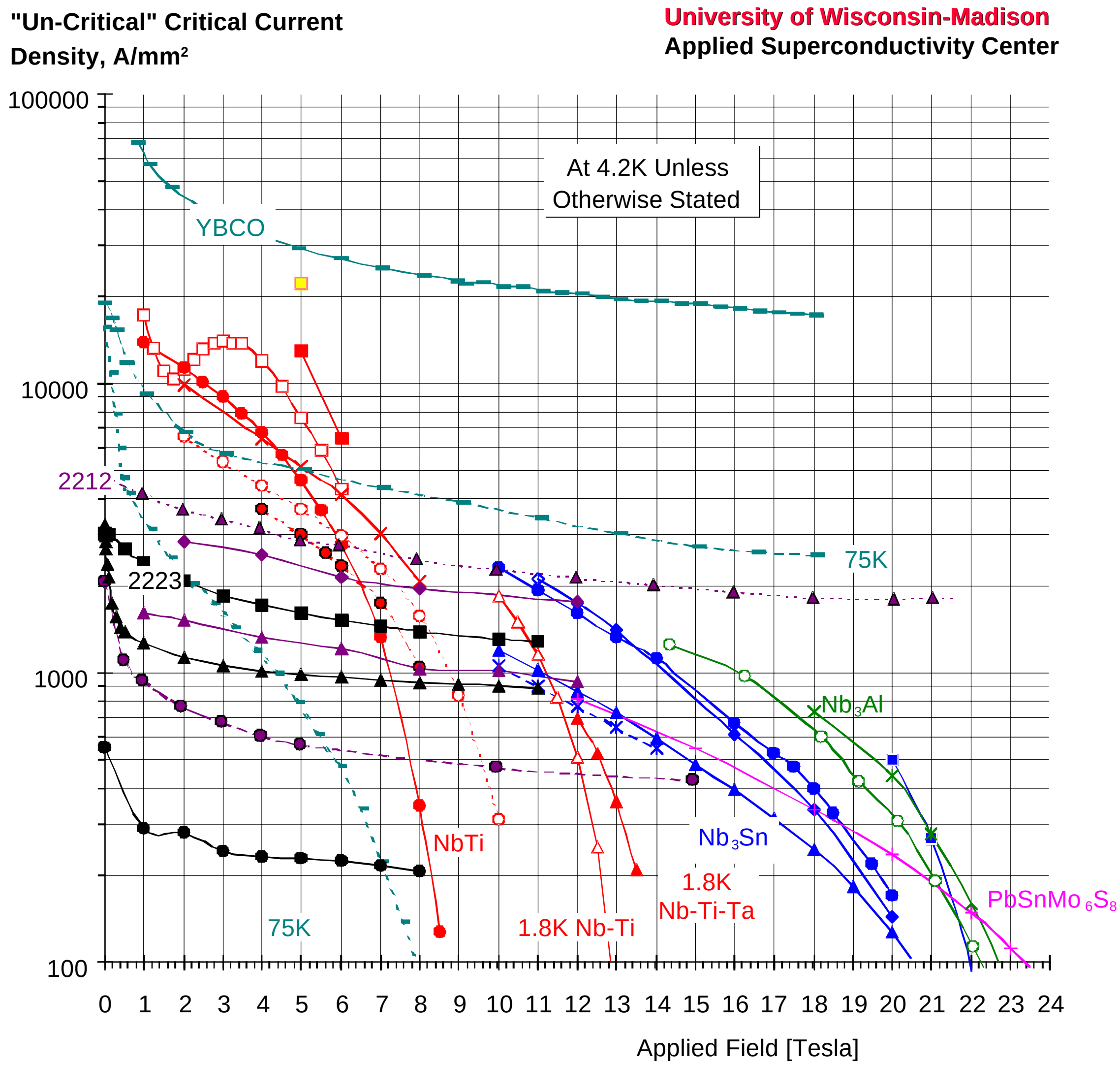
VLHC Steering Committee (http://vlhc.org)

Snowmass Parameters List

VLHC Machine parameters

Parameter	High field-new technology	Low Field	Units
CM Energy	100	100	TeV
Dipole field	12.6	1.8	T
Circumference	104	646	km
Revolution frequency	2.89	.46	kHz
Injection energy	3	3	TeV
Synchrotron radiation damping time (horizontal amplitude)	2.6	*antidamped*	hr
Equilibrium rms emittance	144.2	---	π nm
Energy loss/turn	3678	526	keV
Synchrotron radiation power/ring	189	48	kW
Initial/peak luminosity	.35/1.2	1./1.	10^{34} cm^{-2}sec^{-1}
Protons/bunch	0.5	0.94	10^{10}
Bunch spacing	16.7	16.7	nsec
Number of bunches	20794	129240	
Total protons/ring	1.1	12.2	10^{14}
Beam stored energy	.89	9.73	GJ
Injected rms normalized emittance	1.	1.	π μm
β^*	20	20	cm
Rms relative energy spread(collision)	15.6 (50)	39.0	10^{-6}
Total current	.05	.09	Amp
Peak current(injection)	3.6	4.2	Amp
$\langle\beta\rangle$	255	382	m
Tune	65	269	
Half cell length (assumed 90°cells)	200	300	m
Beam pipe radius	1.65	1.0	cm
Beam pipe	Cold, Cu	Warm, Al	

High-field magnets will require new superconductors



. . . but we can always dream

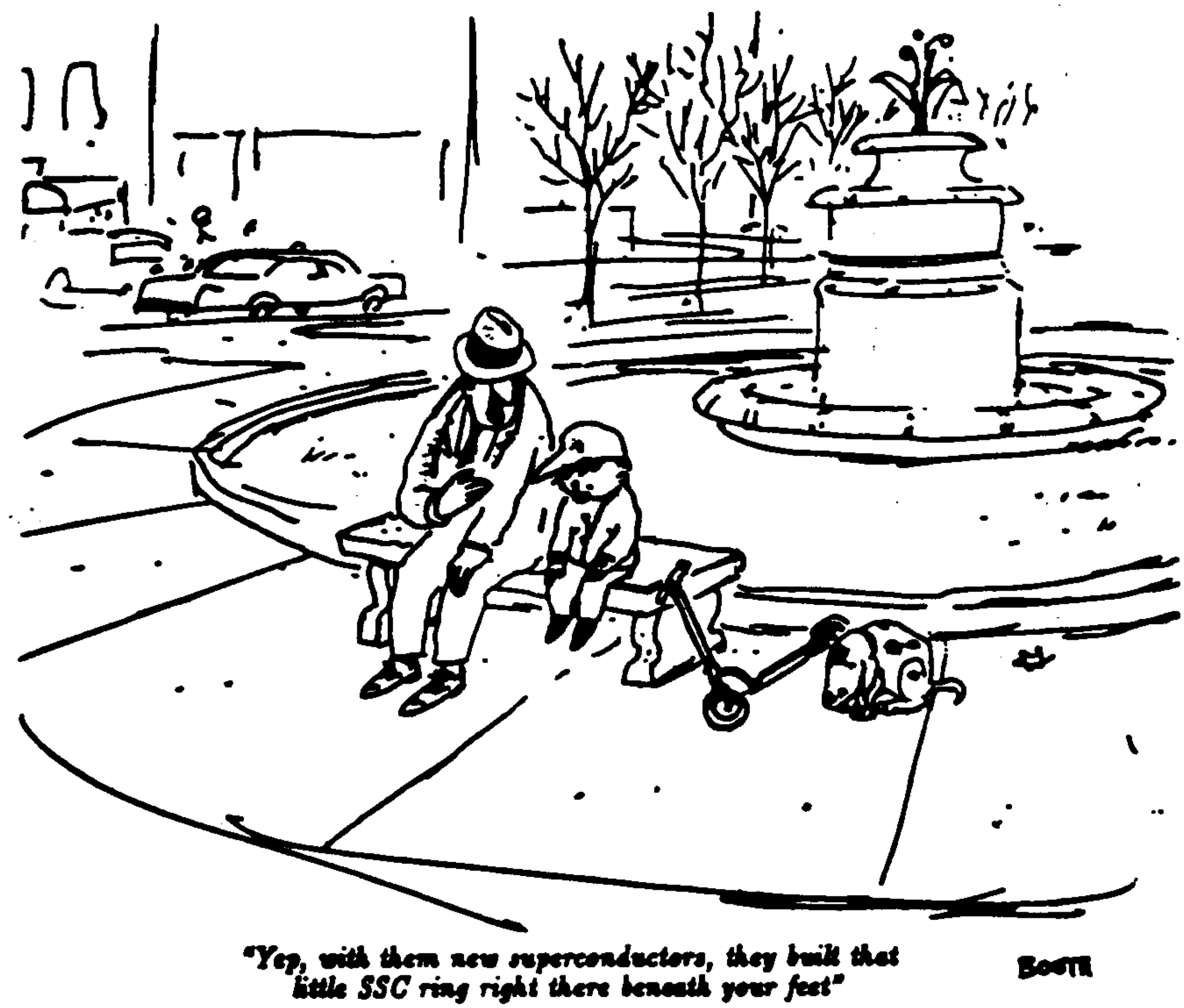


Illustration for the poster advertising a talk on high-T_c superconductors at the SSC Central Design Group.

Technical Challenges for a VLHC

COST, COST, COST!

HIGH FIELD ($B \gtrsim 10$ T)

- Make a cheap magnet with good enough field, especially at injection.
  + Cost(Nb_3Sn $\approx 4\times$ Cost(NbTi)
  + "Snapback" – persistent currents with strange time constants
  + Simplify, simplify!

- Vacuum and cryogenic problems caused by synchrotron radiation.
  + Damping is a plus (constant $\mathcal{L}$)

LOW FIELD (SUPERFERRIC, $B \lesssim 2$ T)

- Tunnel cost (550 km ?!)

- Beam stability in a mammoth ring

- Develop a good, reliable (combined-function) magnet

Inventing Our Futures

Near future looks very exciting:

LEP2 · HERA · SuperK

NA48 · KTeV · E787 · DAΦNE/KLOE

BaBar · BELLE

Tevatron Run II

- Can we do Tevatron Run III?
- Ensure the success of LHC
- Definitive accelerator experiments for ν oscillations

  Mini-BOONE · MINOS · Gran Sasso

  ? ν Factory (store $10^{20\text{ - }21}$ muons/year)

  νFact '99 · Lyon · July 5–9

- We need to plan the Right Linear Collider
  Energy and luminosity? Decision (yes or no) in 4–5 years
- Prepare our long-term future by developing possibilities of $\mu^+\mu^-$ collider, VLHC