Physics Opportunities in Fermilab's Futures

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- Opening remarks
- Expectations for Run 2
- Aspirations for Run 2^{bis}
- Fermilab and the LHC
- e^+e^- linear collider
- The path to a $\mu^+\mu^-$ collider
  $\rightsquigarrow$ a neutrino factory?
- Beyond the LHC
- Strengthening Our Institutions

Late Night Thoughts on Listening to Bruckner's Fourth Symphony*

Multiple time scales
Overlapping time scales
The importance of patience

¶ I will not mention every important physics issue.

¶ I will not bless or curse individual experiments.

¶ I will focus on issues we need to think about—and work on—together.

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*With apologies to Lewis Thomas.

Optimize the Physics Program

- A golden age for Fermilab:
  Tevatron is the highest energy collider; fixed-target experiments advance the sensitivity frontier.
  Both have great discovery potential.

- Today's physics influences tomorrow's experiments and accelerators.

- **Success is rewarded!**

Develop Tomorrow's Technologies

- We are the National Accelerator Laboratory

Many Promising Ideas

Much Work to Do

Elementarity

▷ Are quarks and leptons structureless?

Symmetry

▷ Electroweak symmetry breaking and the 1-TeV scale

Unity

▷ Coupling constant unification
▷ Unification of Quarks and Leptons
▷ Unification of Constituents and Force Particles
▷ Incorporation of Gravity

Identity

▷ Fermion masses and mixings
▷ CP violation
▷ Neutrino oscillations
▷ What makes an electron an electron and a top quark a top quark?

One Aspect of the Problem of Identity:
The Origins of Mass

- $\triangleright$ π, ρ — understood: QCD
- $\triangleright$ W, Z — electroweak symmetry breaking
- $\triangleright$ $q, \ell^{\mp}$ — EWSB + Yukawa couplings
- $\triangleright$ ν_ℓ — EWSB + Yukawa couplings;

  + new physics?

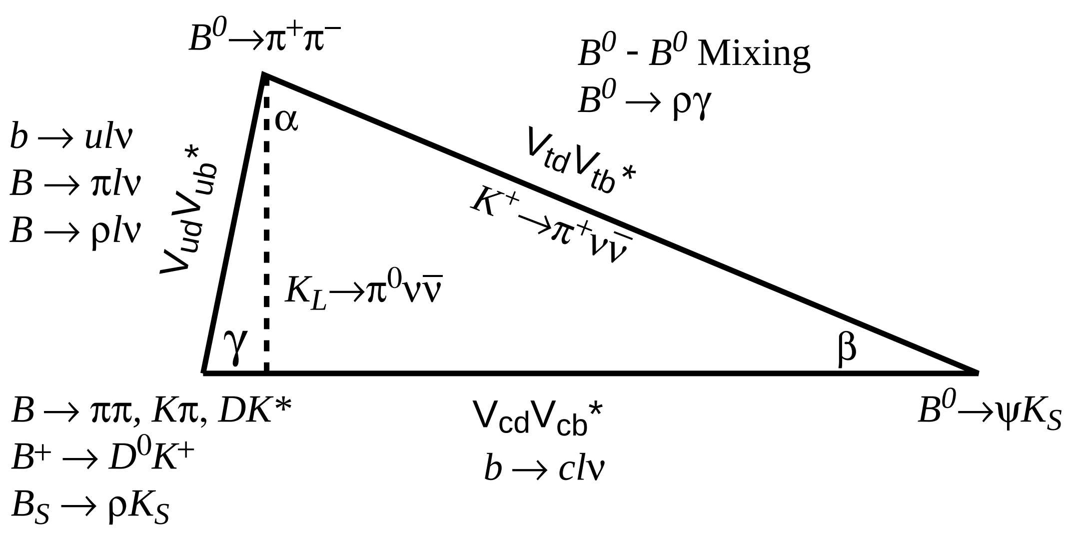
The Problem of Identity

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

Accessible soon: K and B CP violation, ν mass, ...

Three-generation unitarity:

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



Tevatron can measure $\sin 2\beta$ from $B^0 \to \psi K_S$, though BaBar and BELLE have a head start.

- Large asymmetry expected
- CDF has developed tagging techniques and measured $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ in 395 ± 31 ψK_S events
  ($\sin 2\beta > 0$ at 93% CL)
- Ample rate: 10 – 20 kHz $b\bar{b}$ in Run 2

Future Measurements of $K \to \pi\nu\bar{\nu}$

SM expectations

$$B(K^+ \to \pi^+\nu\bar{\nu}) = (0.8 \pm 0.3) \times 10^{-10}$$
$$B(K^0 \to \pi^0\nu\bar{\nu}) = (2.8 \pm 1.1) \times 10^{-11}$$

$K^+ \to \pi^+\nu\bar{\nu}$

- BNL E787: BR $= 1.5^{+3.5}_{-1.3} \times 10^{-10}$
- Evolution to BNL E949, single-event sensitivity (0.8 to 1.4)$\times 10^{-11}$
- CKM at Fermilab aims for 10% measurement of BR

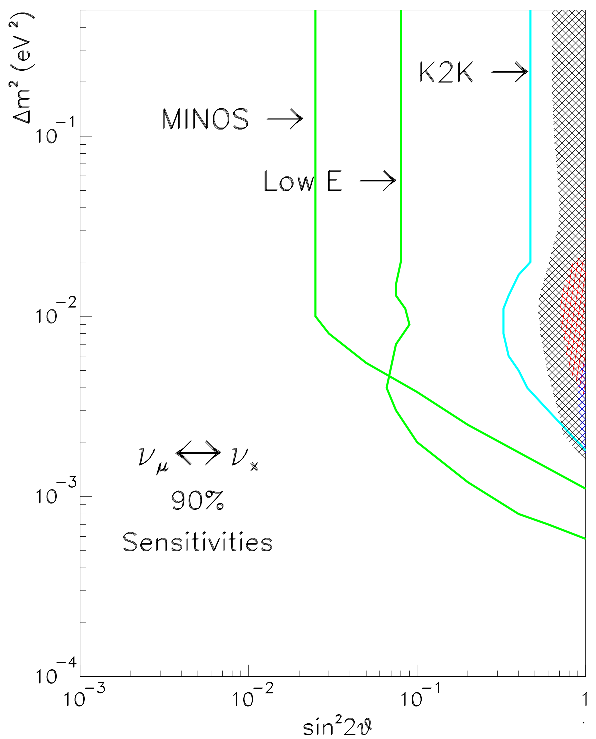
$K^0 \to \pi^0\nu\bar{\nu}$

- KEK E391 aims for 10^{-10} sensitivity (2001)
- BNL 926 $\equiv$ KOPIO aims for 50 events at SM rate
- KAMI at Fermilab aims for 10% measurement of η + other rare decays to 10^{-13} level.

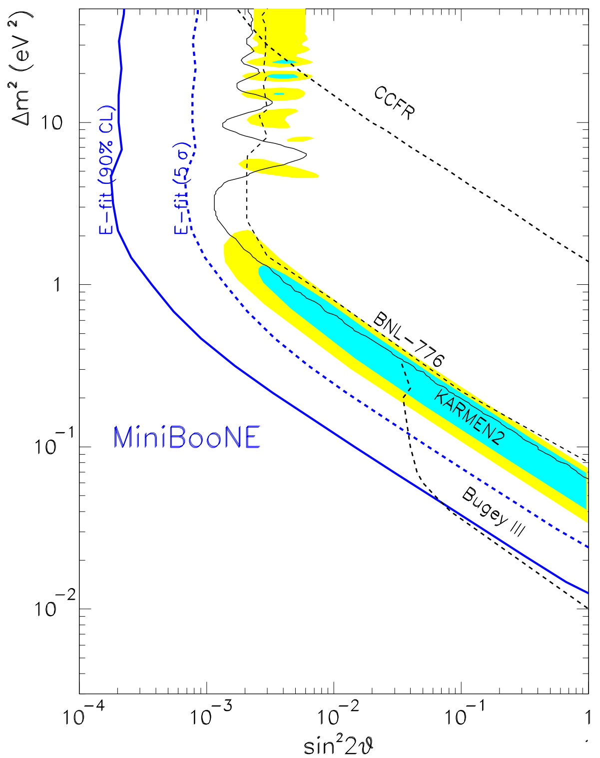
Neutrino Oscillations

Need to progress from observations to experiments!

Atmospheric ν Anomaly



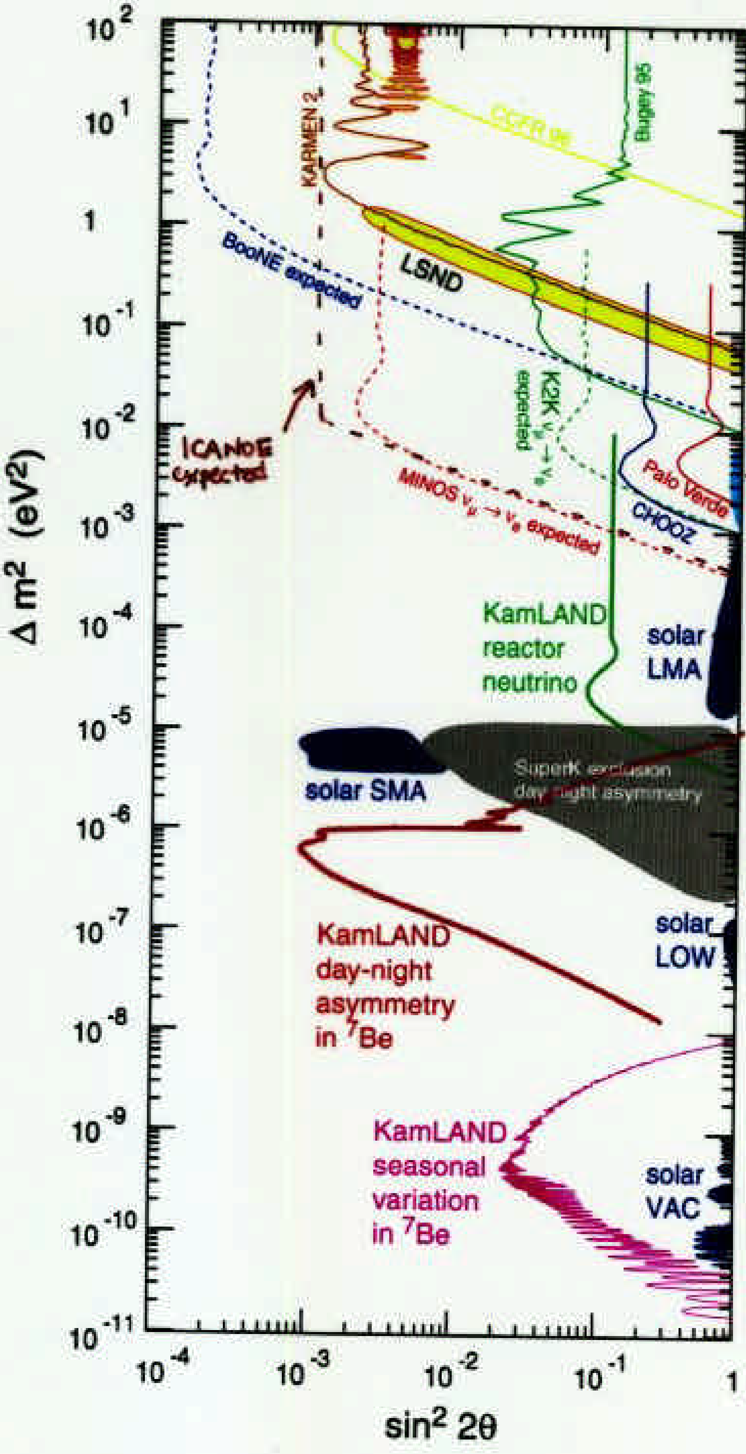
LSND Effect



K2K ($L = 250$ km) startup; MINOS ($L = 732$ km) begins 2003.

CERN to Gran Sasso ($L = 730$ km) appearance experiments

MiniBooNE: data taking in 2002–2003.



Δm^2 (eV^2)
$\sin^2 2\theta$
KARMEN 2
CCFR 96
Bugey 95
LSND
BooNE expected
K2K $\nu_\mu \to \nu_e$ expected
ICANOE expected
MINOS $\nu_\mu \to \nu_e$ expected
Palo Verde
CHOOZ
SuperK
KamLAND reactor neutrino
solar LMA
solar SMA
SuperK exclusion day-night asymmetry
solar LOW
KamLAND day-night asymmetry in ^{7}Be
KamLAND seasonal variation in ^{7}Be
solar VAC

Expectations for Tevatron Run 2

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

- Run 1: 100 pb^{-1} @ 1.8 TeV 1994–1996
- Run 2: 2 fb^{-1} @ 2 TeV in 2001–2003
  $\rightsquigarrow \sigma(t\bar{t}) \times 1.4$
- Run 2^{bis}: 30 fb^{-1} by 2007 ($>$ 15 fb^{-1})

Run 2 Goals:

- Study CP violation in $B^0 \to \psi K_s$ (BaBar, belle)
- Observe B_s - $\bar{B}_s$ oscillations, measure $\Delta m_s \lesssim 41\ \text{ps}^{-1}$
  ($x_s \lesssim 63$)
- 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 (LEP)
- Search for superpartners, new strong dynamics (LEP)
- Explore!

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,

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

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

- $\delta m_t \approx 3 \to 2$ GeV/c^2 in Run 2, 1 GeV/c^2 in Run 2^{bis}, LHC

- $\delta M_W \approx 40$ MeV/c^2 in Run 2

  $\Rightarrow$ infer $\delta M_H / M_H \approx 40\%$

- $\delta\sigma(t\bar{t}) \approx 8\%$ in Run 2, 3% in Run 2^{bis}, $\pm$ few % at LHC

- $\delta \dfrac{\Gamma(t \to bW)}{\Gamma(t \to qW)}$ will improve to $\pm 10\%$ in Run 2, $\pm$ few % in Run 2^{bis}, $\pm 1\%$ at LHC

- $\delta|V_{tb}| \approx \pm 10\%$ in Run 2, $\pm 5\%$ in Run 2^{bis} from single-top production

- Searches for $t\bar{t}$ resonances, rare decays, and other signs of new physics.

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thinkshop: top-quark physics for Run 2, QCD and Weak Boson Workshop.
Links at http://www-theory.fnal.gov/.

Run 2: Extensive Search for Light-Scale Supersymmetry

Now is the time to find supersymmetry!

LEP 2 · Tevatron Run 2

Run 2 Workshops: Supersymmetry & Higgs

Using Run 1 experience to devise new and improved triggers and searches. Many channels analyzed in detail.

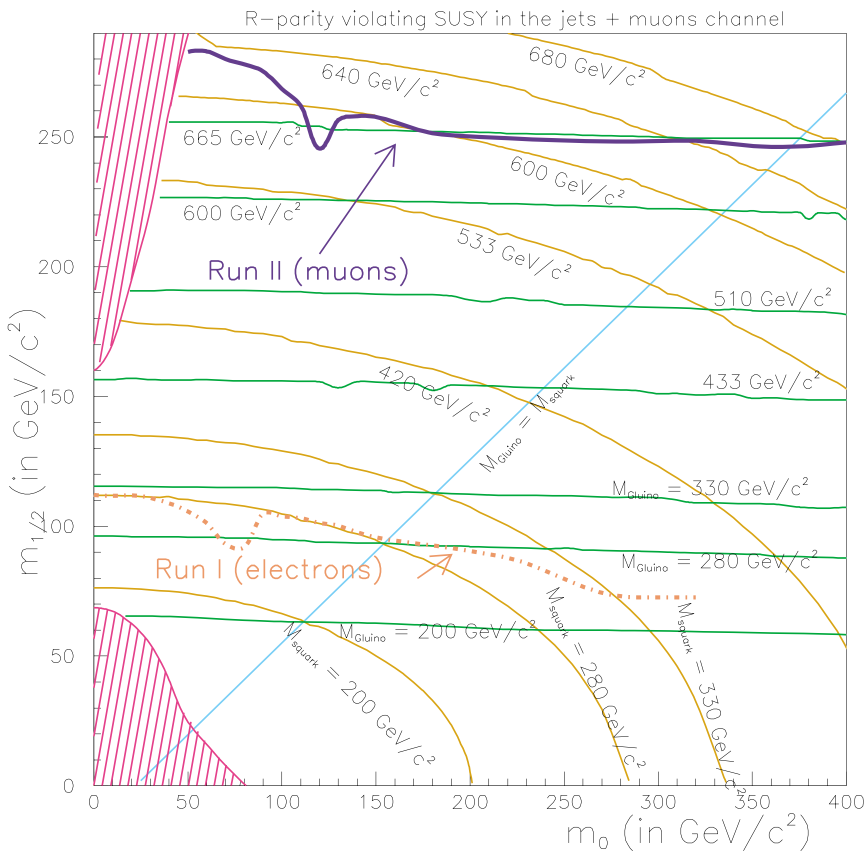
- New simulation tools
- Analysis schemes
- New signatures
  - ▷ R-parity–violating decays
  - ▷ τ modes
  - ▷ Search for long-lived particles (macroscopic decay lengths) by photon pointing, ionization, or TOF
  - ▷ Signatures of extra dimensions

SUSY99 at Fermilab, 14-19 June 1999

Yellow Book draft complete, Links at http://fnth37.fnal.gov.

R-parity violating SUSY

No missing energy: reconstruct $\mu +$ jets



Improvements from

- Increased energy and luminosity
- Detector upgrades
- Cannier trigger and analysis

Develop a Plan for Run 2^{bis}

Increased $\mathcal{L}$ improves discovery reach

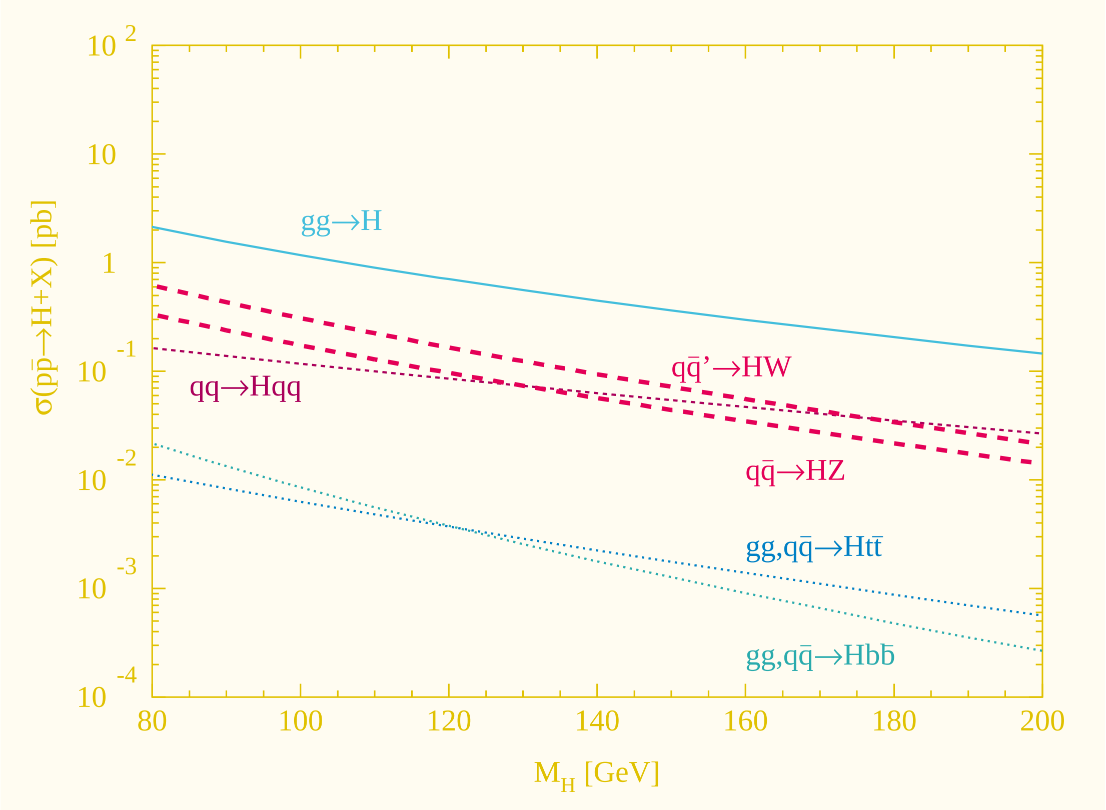
Every factor of two opens new discovery possibilities

Target: 30 fb^{-1} by 2007

$\mathcal{L}$ 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

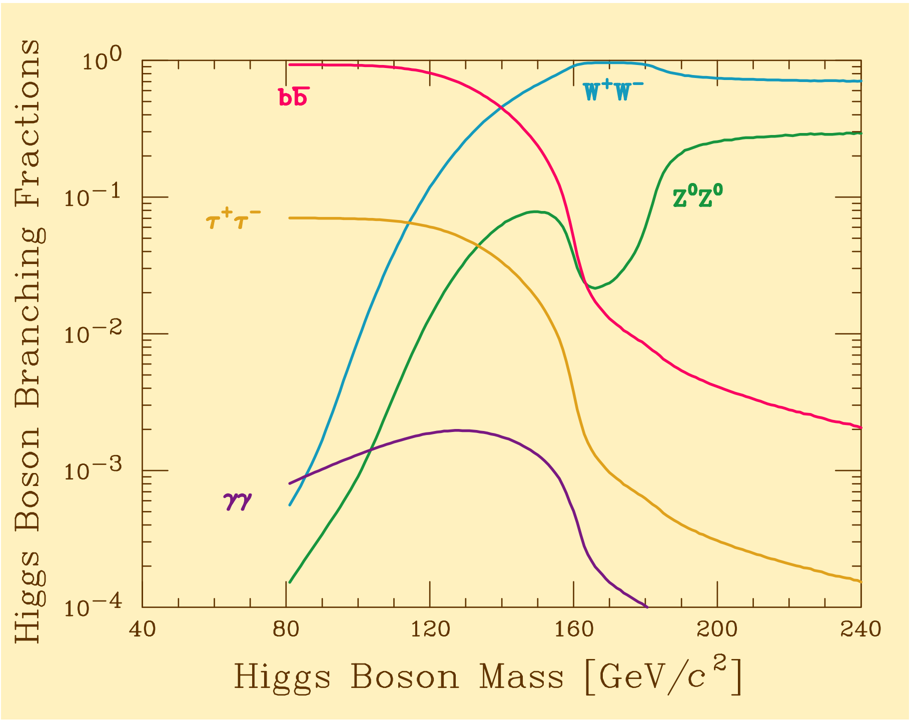
Higgs-Boson Production Sets Luminosity Target



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

See TeV33, TeV2000 Studies

Search for a not-too-heavy Higgs boson



- Tevatron:

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

- LHC:

$$gg \rightarrow H \rightarrow \gamma\gamma,$$

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

Tevatron Search Strategies

- $gg \rightarrow H \rightarrow b\bar{b}$ is swamped by QCD production of $b\bar{b}$. Even with 30 fb^{-1}, only < 1-σ excess. $Z^0 \rightarrow b\bar{b}$ calibrates $b\bar{b}$ resolution in Run 2.

- Special topologies improve signal/background and significance:

$$\bar{p}p \quad \rightarrow \quad HW + \text{anything}$$

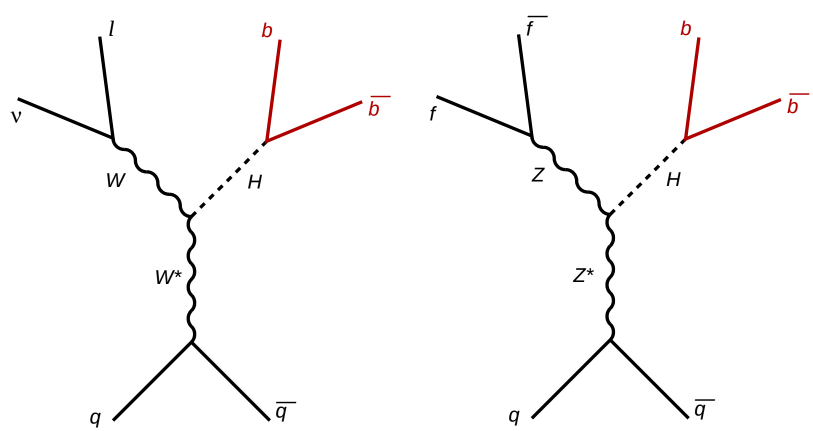
$$W \hookrightarrow \ell\nu,\ \text{jets}$$

$$H \hookrightarrow b\bar{b}$$

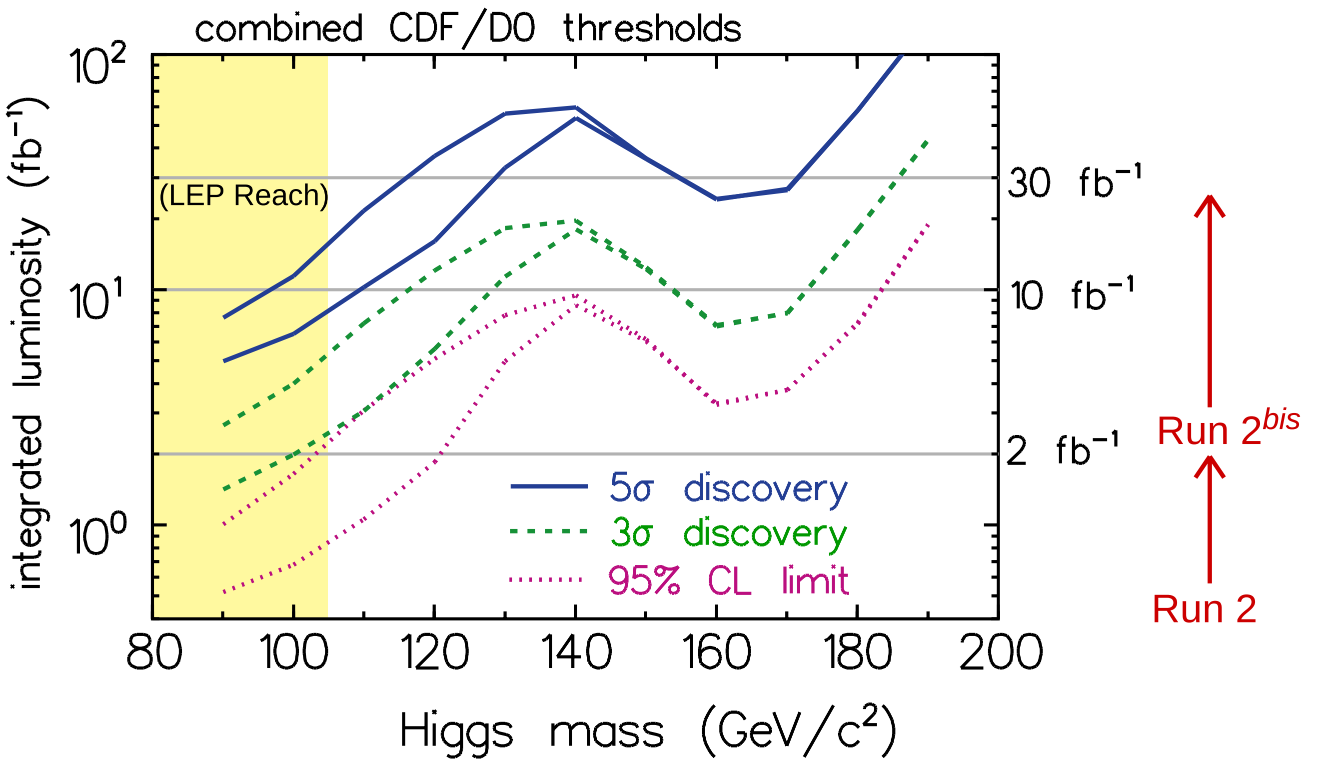
$$\bar{p}p \quad \rightarrow \quad HZ + \text{anything}$$

$$Z \hookrightarrow \ell^+\ell^-,\ \nu\bar{\nu}$$

$$H \hookrightarrow b\bar{b}$$



Higgs Boson Search & Discovery



- 10% $b\bar{b}$ mass resolution
- SHW fast simulation or SHW plus neural-net
- Systematics: 10% background or $1/\sqrt{\mathcal{L}\cdot \mathrm{Bgd}}$
- Bayesian combination of CDF & DØ

Extend reach using $H \to WW^*$? Initial studies promising.

Ela Barberis, Wasiq Bokhari, Pushpalatha Bhat, Russell Gilmartin, Harrison Prosper, Weiming Yao, Regina Demina, David Hedin, Rick Jesik, Ben Kilminster, Mark Kruse, Vladimir Sirotenko, Anna Goussiou, John Hobbs, Juan Valls, Rocio Vilar, Michael Albrow, Dmitri Litvintsev, Andrey Rostovsev, Tao Han, Arnaud Lucotte, Michael Schmitt, André S. Turcot, Ren-Jie Zhang, John Conway.

Higgs at the Tevatron: Summary

- If $M_H \approx 100$ GeV/c^2:

  Higgs observed independently in WH and ZH with $\int \mathcal{L}dt \lesssim 13$ fb^{-1}, or in combined channels with ~ 7 fb^{-1}.

- If Higgs is inaccessible at LEP:

  5-σ discovery possible independently in WH and ZH with 30 fb^{-1} up to $M_H \approx 120$ GeV/c^2; in combined channels, up to $M_H \approx 125$ GeV/c^2

  New information on g^2_{WWH}/g^2_{ZZH}

  If g_{ZZH} and $B(H \to b\bar{b})$ are known from LEP, new information on g_{WWH}.

M_H determined to $\pm$(1-3) GeV/c^2

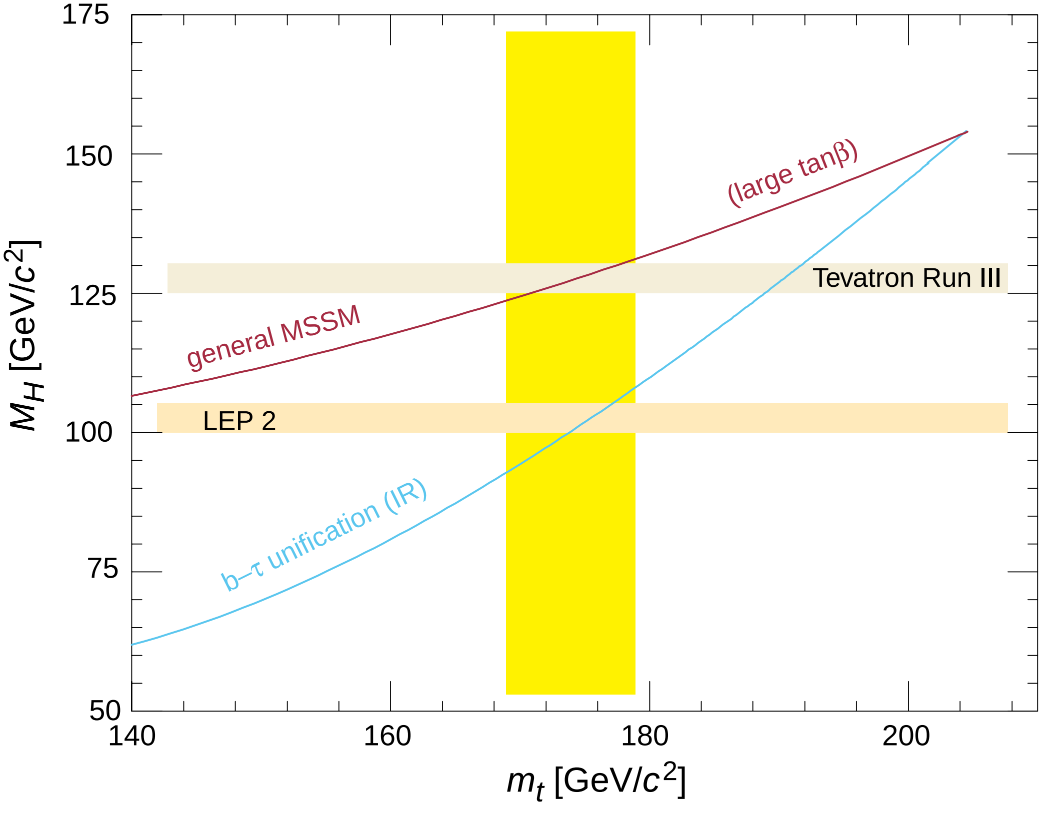
Run 2 Workshops: Supersymmetry & Higgs

http://fnth37.fnal.gov/higgs.html

Boselab

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

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

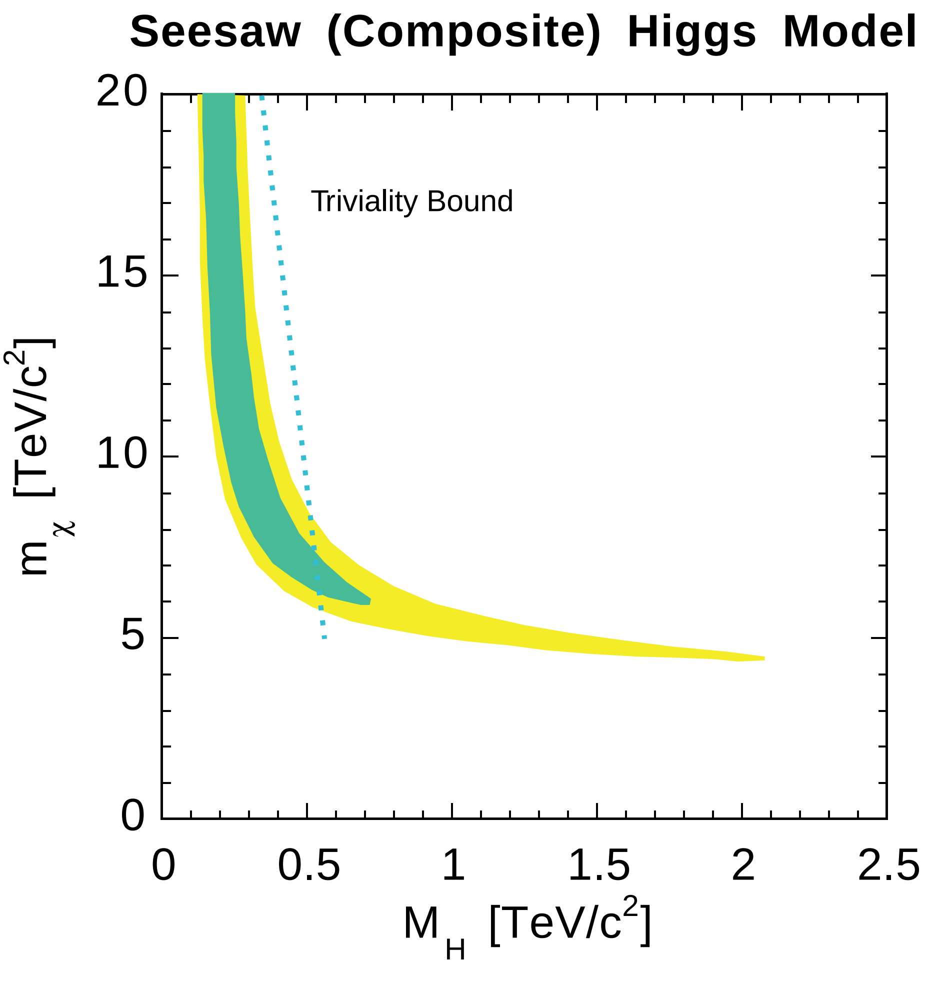


M. Carena, J. R. Espinosa, M. Quirós, and C. Wagner, *Phys. Lett.* **B355**, 209 (1995).

How much can we trust SM bounds on M_H?

- Hall & Kolda, hep-ph/9904236, include higher-dimensional operators suggested by extra space dimensions. constraints evaporate! Weakness—not shown to be the outcome of a real theory.

- Collins–Grant–Georgi, hep-ph/9908330, Topcolor seesaw model (1 additional heavy weak-**1** fermion χ with $Y = 4/3$): $M_H \gtrsim 300$ GeV/c^2 for $m_\chi \approx 5$ to 7 TeV/c^2.



How to Realize Run 2^{bis}?

Be prepared to exploit Run 2 discoveries

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

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

Avoid a long shutdown while Tevatron defines the energy frontier.

Can some high-field magnets gain needed elbow room in the Tevatron?

What detector upgrades are required?

(Silicon ≡ emulsion)

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

Total cost?

Interaction with a third experiment in CØ?

Can we do this?

Physics at the LHC

pp collisions at 14 TeV

$\int \mathcal{L} dt = 100 \text{ fb}^{-1}$ 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.

- We should be strongly engaged in magnets, machine design, commissioning, detectors, physics.
- LHC Physics School at Fermilab in 2002?

LHC involvement can enhance Fermilab, not sap it.

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?*

Circle Line Tours Seminar Series

http://www-theory.fnal.gov/CircleLine/

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.

Our challenge:

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

e^+e^- Linear Collider

A lovely idea!

Fermilab accelerator links to SLAC & DESY

Possible goals:

- multi-TeV to complement LHC studies of EWSB
- detailed studies of t or H or SUSY $\lesssim 500$ GeV?
- threshold scans of any new channel $\lesssim 1$ TeV?

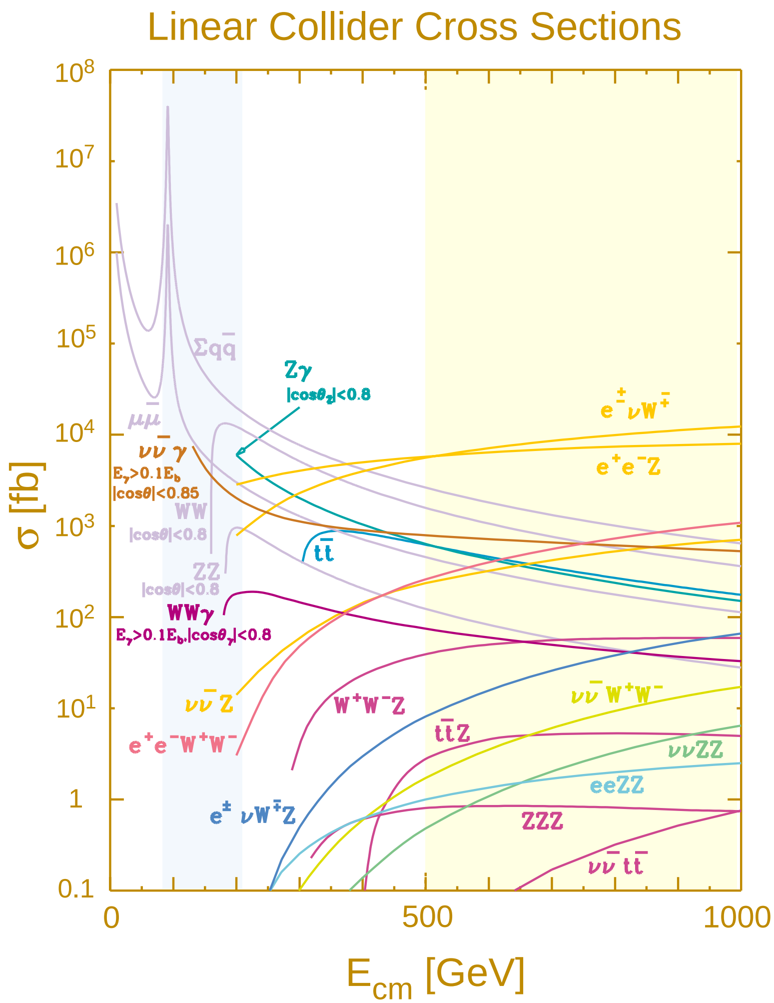
Traditional advantages:

- Point particle means full E_{cm} is available
- No background from the underlying event

Traditional challenges:

- Hard to reach very high energies
- Small cross sections demand high luminosity

Away from resonance peaks,
cross sections are small . . .



. . . but many interesting cross sections
are significant fractions of σ_{total}

H. Murayama and M. Peskin, "Physics Opportunities of e^+e^- Linear Colliders," *Ann. Rev. Nucl. Part. Sci.* **46,** 533 (1996).

E. Accomando, et al., "Physics with e^+e^- Linear Colliders," *Phys. Rep.* **299,** 1 (1998), hep-ph/9705442.

Gilman subpanel recommendation:

The Subpanel recommends that SLAC continue R&D with Japan's KEK toward a common design for an electron-positron linear collider with a luminosity of at least 10^{34} cm^{-2} s^{-1} and an initial capability of 1 TeV in the center of mass, extendible to 1.5 TeV. The Subpanel recommends that SLAC be authorized to produce a Conceptual Design Report for this machine in close collaboration with KEK.

This is not a recommendation to proceed with construction. A decision on whether to construct a linear collider should only follow the recommendation of a future subpanel convened after the CDR is complete. The decision will depend on what is known about the technology of linear colliders and other potential facilities, costs, international support, and advances in our physics understanding.

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My belief:

The US (and worldwide) HEP community will decide within five years whether to proceed with a linear collider—on its own, and not in competition with any other machine.

This decision must be based on an informed assessment of the scientific opportunities, technical risk, and cost. Building an inadequate machine "because we need a project" would be calamitous.

We Cannot Stand Apart

- Only informed opinions will carry any weight.
- We have the standing to check claims about physics and accelerator science.
  Example: How long does it take to carry out the physics menu of a 500-GeV linear collider?
- The entire community must define the Right Linear Collider: E, $\mathcal{L}$, and technology.
- Much physics is in common with the physics of a muon collider. (Profit from LC studies, learn what it takes to compete.)
- Fermilab is a possible site for a linear collider at the energy frontier.
- We can take a fresh look at competing—and developing—technologies.
- We can build bridges to users, and to other labs.

Can we invent a machine we want to build?

Physics Return vs. Cost and Technical Risk

(time sensitive)

Very interesting suggestions

TESLA team: $\mathcal{L} \to 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

$\Rightarrow$ Explore physics reach vs. $\mathcal{L}$

CLIC team: Evolved two-beam scheme

$\Rightarrow$ Explore physics reach vs. E_{cm}

Fermilab studies of physics vs. E_{cm} and $\mathcal{L}$

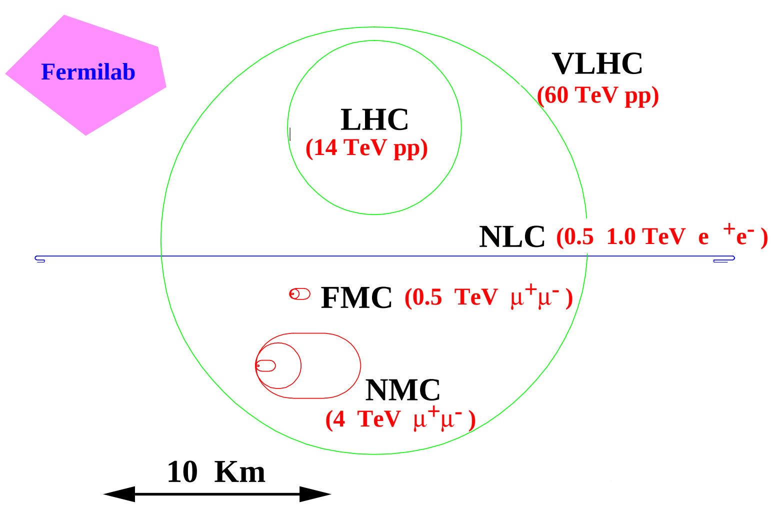
- Coordinators: Andreas Kronfeld & Sławek Tkaczyk

$\mu^+\mu^-$ collider

Possible path to a few-TeV $\ell^+\ell^-$ collider
to study electroweak symmetry breaking
and explore ...

μ: an elementary lepton $\Rightarrow$ energy efficient
synchrotron radiation not crippling

$\Rightarrow$ small device reaches 1-TeV scale



?? modest size $\Rightarrow$ modest cost ??

Ultimate goal is $\sqrt{s} \sim 4$ TeV

(keep eye on ball)

But ... How to start?

Fermilab Workshop on Physics at the First Muon Collider and at the Front End of a Muon Collider

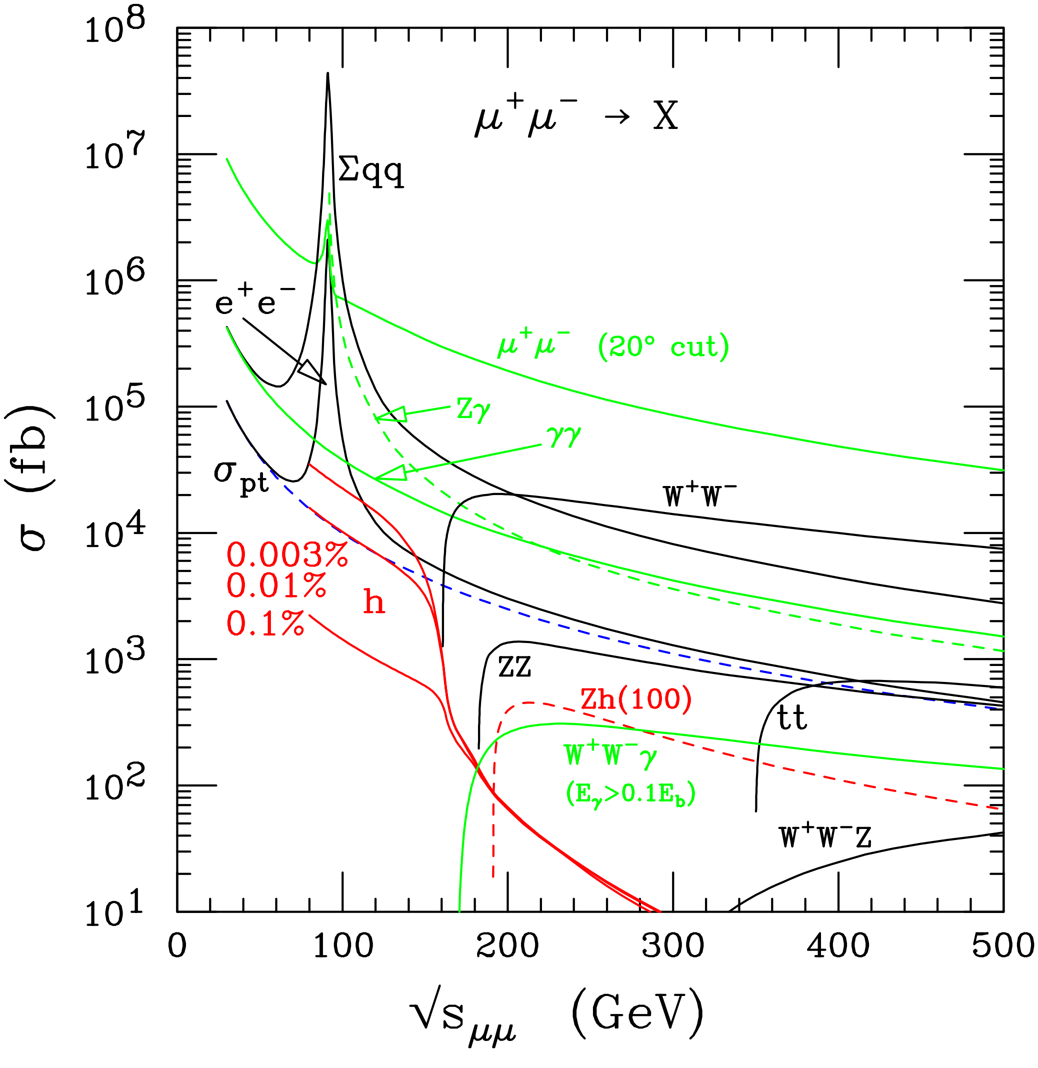
¶ A First Muon Collider?

- high-luminosity Z factory
- Higgs factory
- W^+W^- threshold
- $t\bar{t}$ threshold
- $\sqrt{s} \approx \frac{1}{2}$ TeV to explore SUSY or Techni world

¶ Front-end physics

- intense low-energy hadron beams
- a copious source of low-energy muons
- intense ν_μ and $\bar{\nu}_e$ or $\bar{\nu}_\mu$ and ν_e beams

$\mu^+\mu^-$ Cross Sections



(h labels envelope of Higgs peak cross sections)

Is $\mu^+\mu^- \to h \to b\bar{b}$ observable?

The Ultimate Neutrino Source?

Muon storage ring with a millimole of muons per year.

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e \text{ OR } \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

μ charge, momentum, polarization determine
ν composition, spectrum.

Beam from μ^- contains ν_μ, $\bar{\nu_e}$, but no $\bar{\nu}_\mu$, ν_e, ν_τ, or $\bar{\nu}_\tau$.

- Oscillation studies over a wide range of distance/energy and at very great distances
- Deeply inelastic scattering on thin targets

Requires less muon cooling than a $\mu^+\mu^-$ collider.

νFact '99 · Lyon · July 5–9
νFact 2000 · Monterey · May 22–26

Fermilab Activities . . .

Mike Witherell commissioned two six-month studies:

- Neutrino Physics with a Muon Storage Ring
  S. Geer, H. Schellman, M. Shaevitz
  $\leq$ 50-GeV muons
  $\lesssim 10^{21}$ muons per year
  Oscillation + nonoscillation physics
  Low-energy μ physics left aside for now

- Muon Decay Ring
  N. Holtkamp
  50-GeV muons, $\sim 10^{21}$ muons per year
  inclined at 13°, directed to BaBar Hall

Long-Baseline Possibilities

¶ Muon storage ring of two semicircular arcs + two equal straight sections ⇒ 25% of νs emitted in desired direction.

¶ Sources can be small:

$$\text{Arc length} \approx 75\ \text{m} \times \left(\frac{p_\mu}{40\ \text{GeV}/c}\right)$$

Can slant at steep angles without going very deep.

¶ Distinguish expected reactions

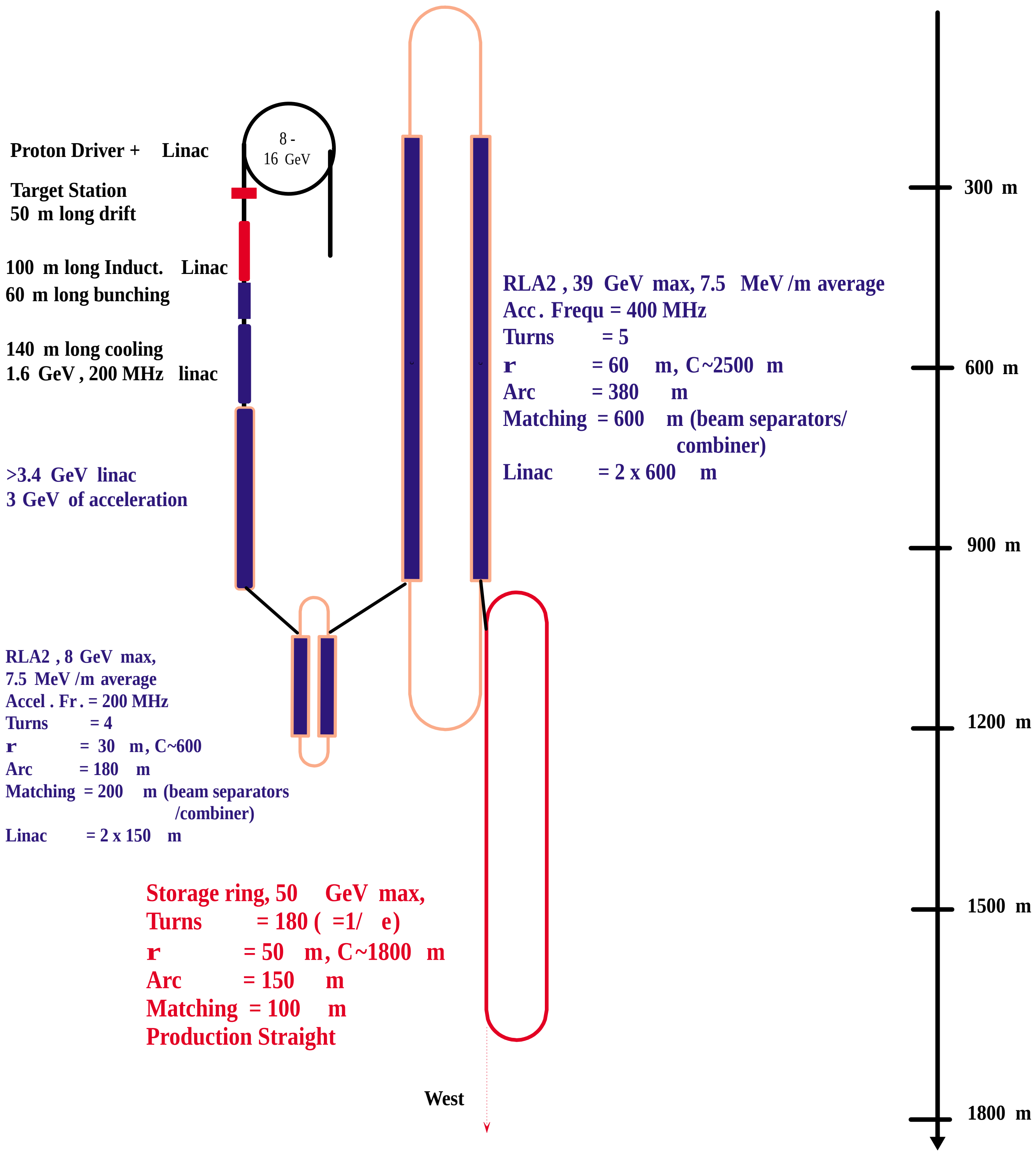
$$\begin{aligned} \nu_\mu N &\rightarrow \mu^- + \text{anything} \\ \bar{\nu}_e N &\rightarrow e^+ + \text{anything} \end{aligned}$$

from the oscillation-induced reactions

$$\begin{aligned} (\nu_\mu \rightarrow \nu_e)N &\rightarrow e^- + \text{anything} \\ (\nu_\mu \rightarrow \nu_\tau)N &\rightarrow \tau^- + \text{anything} \\ (\bar{\nu}_e \rightarrow \bar{\nu}_\mu)N &\rightarrow \mu^+ + \text{anything} \\ (\bar{\nu}_e \rightarrow \bar{\nu}_\tau)N &\rightarrow \tau^+ + \text{anything}\ . \end{aligned}$$

¶ Oscillations characterized by

$$\sin^2\left(1.27\,\frac{\Delta m^2}{1\ \text{eV}^2}\cdot\frac{L}{1\ \text{km}}\cdot\frac{1\ \text{GeV}}{E}\right)$$

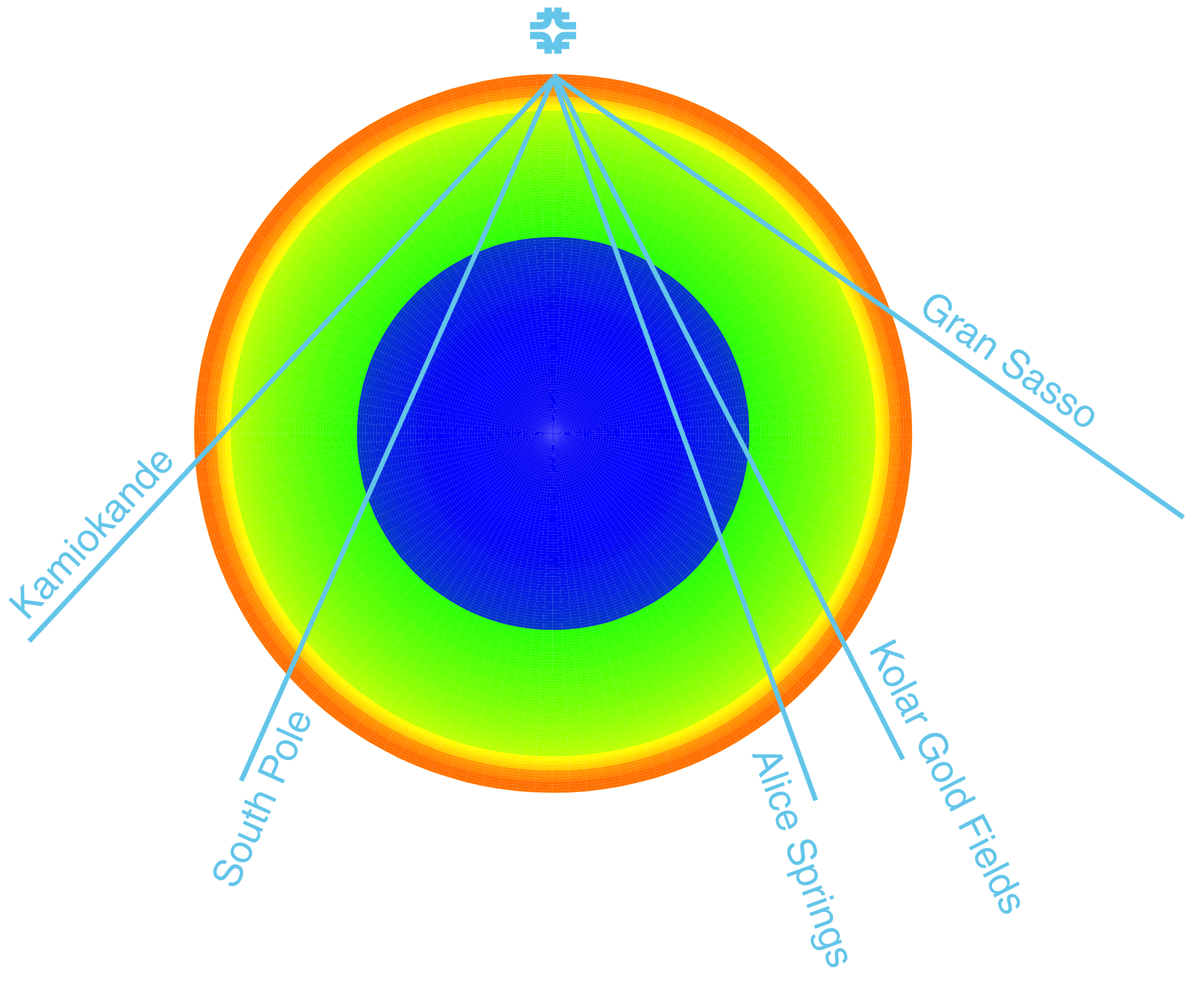


Proton Driver + Linac
8 - 16 GeV
Target Station
50 m long drift
100 m long Induct. Linac
60 m long bunching
140 m long cooling
1.6 GeV , 200 MHz linac
>3.4 GeV linac
3 GeV of acceleration
RLA2 , 39 GeV max, 7.5 MeV /m average
Acc. Frequ = 400 MHz
Turns = 5
r = 60 m, C~2500 m
Arc = 380 m
Matching = 600 m (beam separators/ combiner)
Linac = 2 x 600 m
RLA2 , 8 GeV max,
7.5 MeV /m average
Accel . Fr. = 200 MHz
Turns = 4
r = 30 m, C~600
Arc = 180 m
Matching = 200 m (beam separators /combiner)
Linac = 2 x 150 m
Storage ring, 50 GeV max,
Turns = 180 (=1/ e)
r = 50 m, C~1800 m
Arc = 150 m
Matching = 100 m
Production Straight
West
300 m
600 m
900 m
1200 m
1500 m
1800 m

20-GeV muon beam ⇒

- few $\times 10^{10}$ ν/m^2/year at Gran Sasso or Kamioka
- about 100 charged-current events / kiloton-year

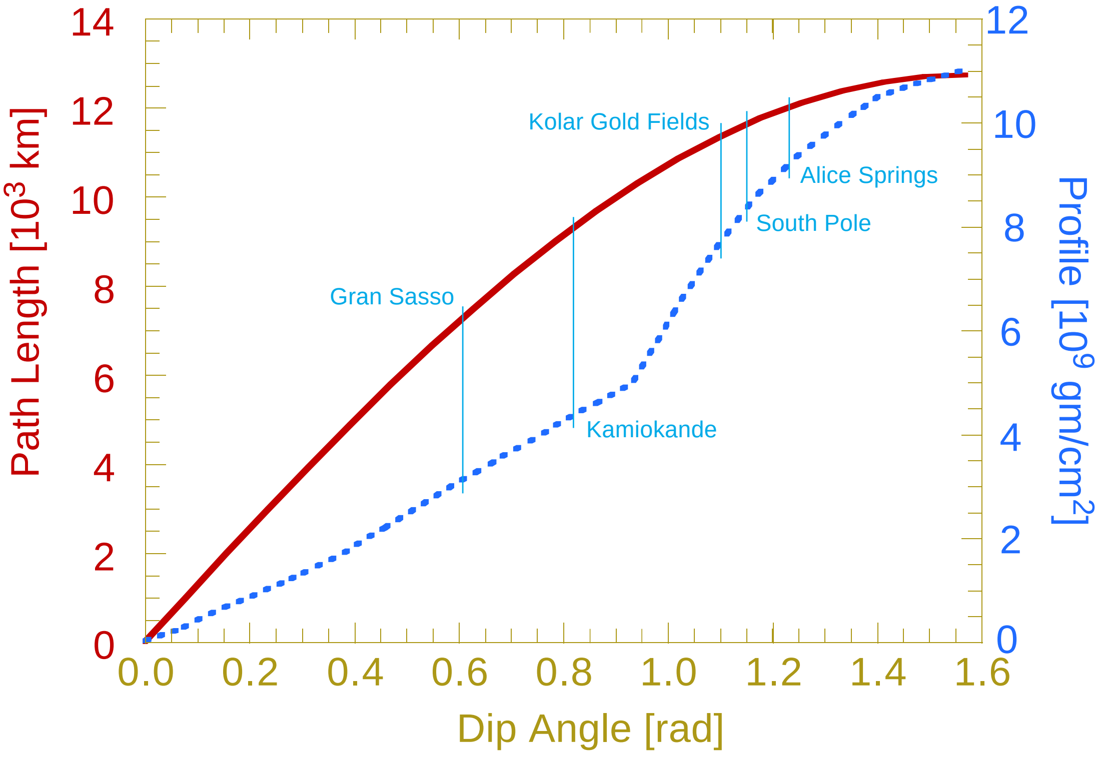
$$\text{Rate} = \Phi \times \sigma \propto E_\mu^3/L^2$$

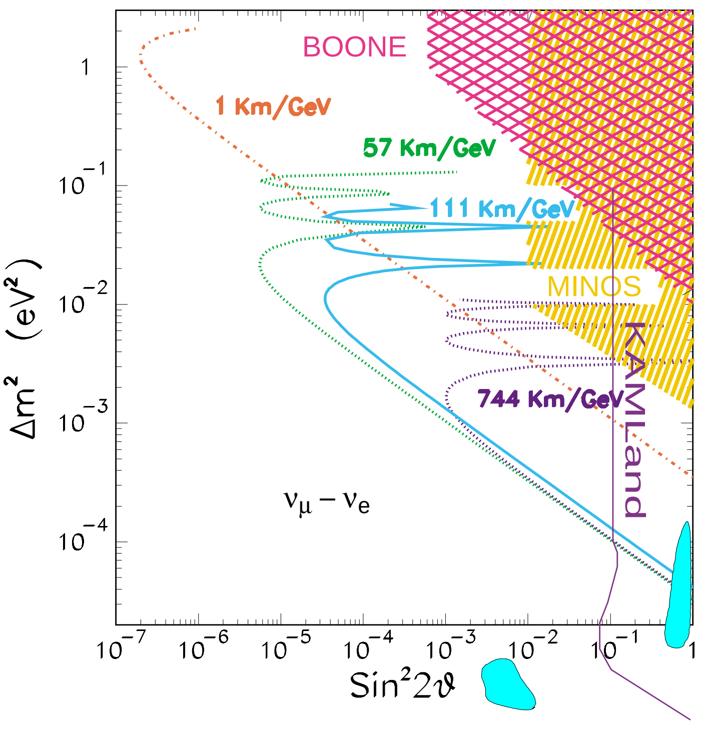


A growth path for MINOS?

Detector design needed: identify e, μ, τ, and measure charges

Must detectors be underground?





Background: S. Geer, "Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential," hep-ph/9712290, *Phys. Rev. D*57, 6989-6997 (1998), **59**, 039903 (1999); C. Quigg, "Questions of Identity," hep-ph/9908357.

Gilman subpanel recommendation:

The Subpanel recommends that an expanded program of R&D be carried out on a muon collider, involving both simulation and experiments. This R&D program should have central project management, involve both laboratory and university groups, and have the aim of resolving the question of whether this machine is feasible to build and operate for exploring the high-energy frontier. The scale and progress of this R&D program should be subject to additional review in about two years.

European interest:

- Report to ECFA, "Prospective Study of Muon Storage Rings in Europe"
- CERN–SPSC/98-30, "Physics Opportunities at a CERN-based Neutrino Factory"

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My belief:

The muon collider path needs a plausible first step that is rich in physics. If a neutrino source can be built by the time the LHC turns on, it could offer a diverse program of experiments, including a broad assault on neutrino mass and mixing—without committing us to the muon collider as our machine on the energy frontier.

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 bosons
- Hints of large extra dimensions

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

Pointlike cross sections $\propto 1/s$

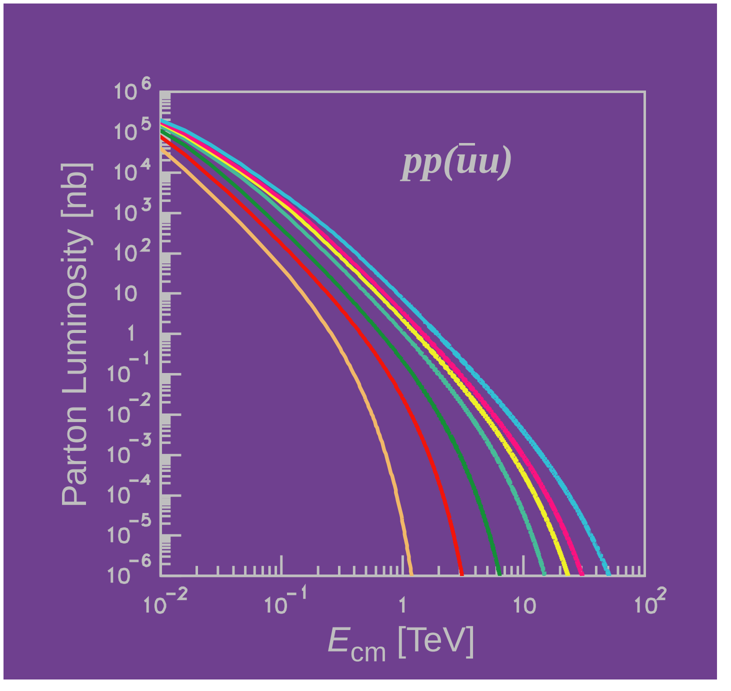
$\Rightarrow$ Luminosity goal:

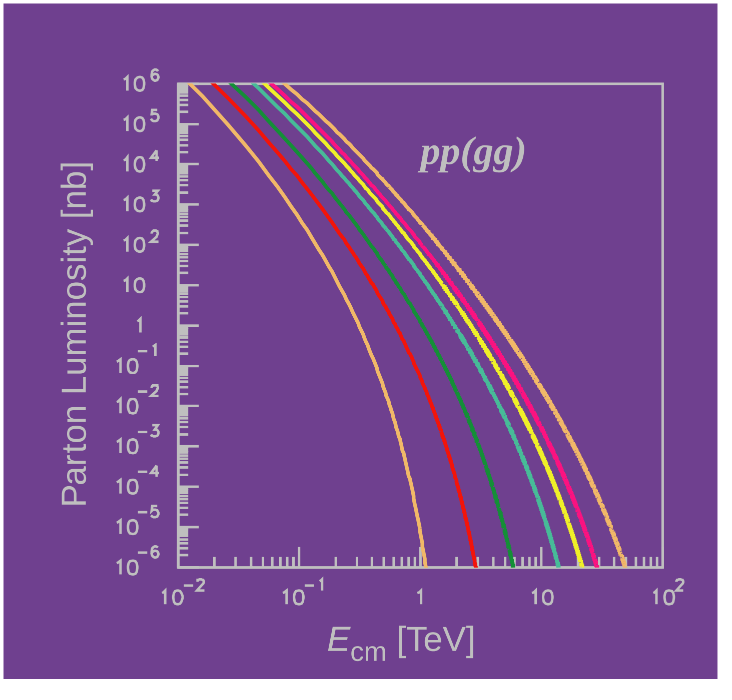
$$\mathcal{L}^\star = 10^{32\text{-}33}\ \text{cm}^{-2}\ \text{s}^{-1} \left(\frac{\sqrt{s}}{40\ \text{TeV}}\right)^2$$

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

Parton Luminosities

at $2, 6, 14, 40, 70, 100, 200$ TeV





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

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, ...
- production of black holes if the scale of strong gravity is nearby

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

Search for "Large" Extra Dimensions

▷ String theory requires 10-ish spacetime dimensions.

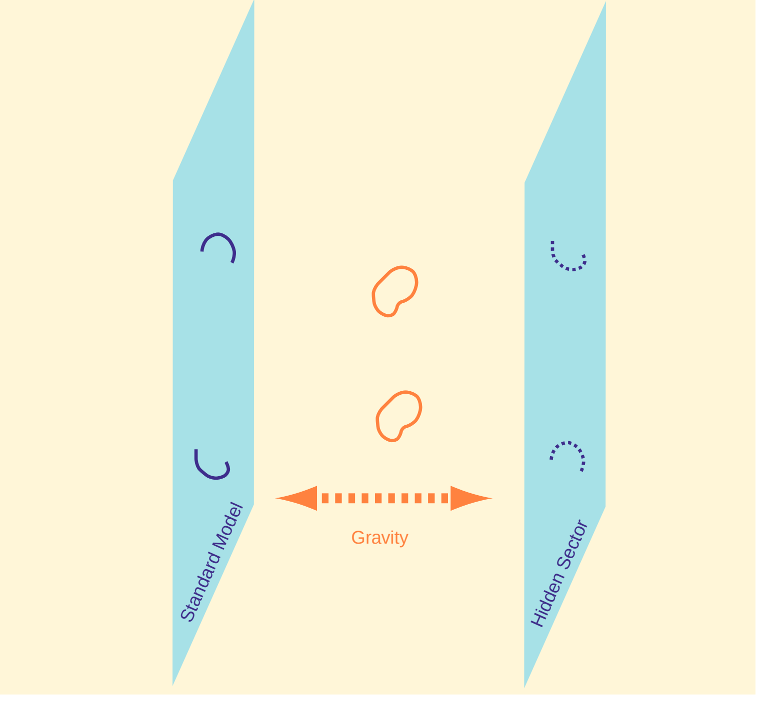
Assumed natural to take

$$R_{\text{unobserved}} \simeq \frac{1}{M_{\text{Planck}}} = \frac{1}{1.22 \times 10^{19}\ \text{GeV}/c^2} = 1.6 \times 10^{-35}\ \text{m}$$

What goes on there does affect the observable world: Excitations of Calabi–Yau manifolds determine fermion spectrum.

(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, cannot propagate in bulk. Gravity lives in the bulk (extra dimensions).



Could extra dimensions be quasimacroscopic?

Remarkably, might have escaped detection . . .

Exciting Compact Dimensions

Any particle can radiate a graviton into extra dimensions.

An extradimensional graviton is gravitationally coupled.
$\Longrightarrow$ won't interact with detector.

Gravitons go off into extra dimensions and are lost.

Their signature is missing energy, $\not{E}_T$.

These processes, individually tiny, may be observable because the number of excitable modes is very large.

Examine real and virtual effects of provatons*:
Graviton excitation of semi-infinite towers of extradimensional ("Kałuza–Klein") modes

* **provatons** < $\pi\rho\acute{o}\beta\alpha\tau o$ (sheep, as in a flock)

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

Tevatron Collider is already on the case!

Gilman subpanel recommendation:

> The Subpanel recommends an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC. These efforts should be coordinated across laboratory and university groups with the aim of identifying design concepts for an economically and technically viable facility. The scale and progress of this R&D program should be subject to additional review in about two years.

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

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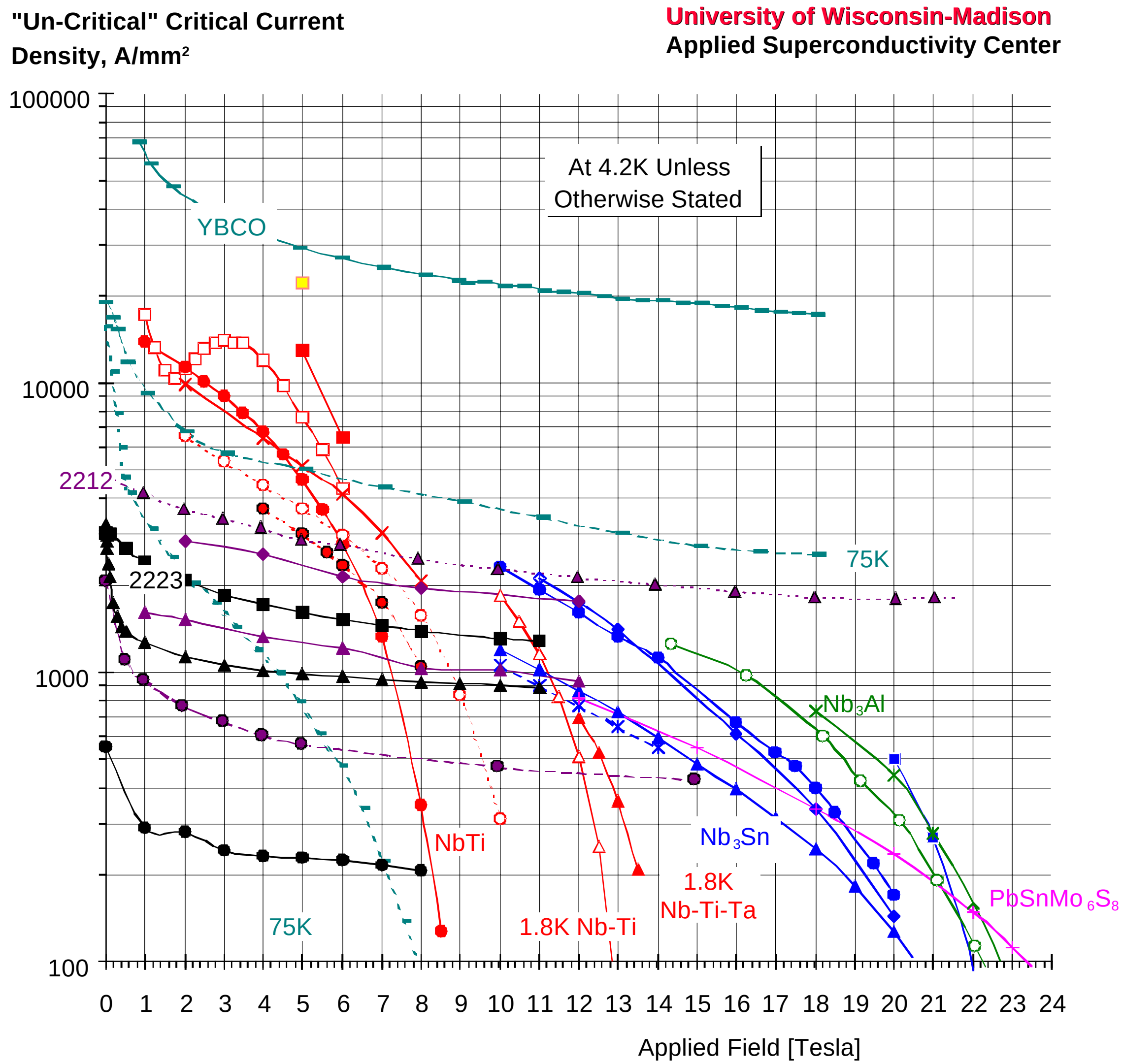
My belief:

We need to identify compelling physics targets before any machine proposal will be taken seriously by our colleagues or the funding agencies.

High-field magnets will require new superconductors



... but we can always dream

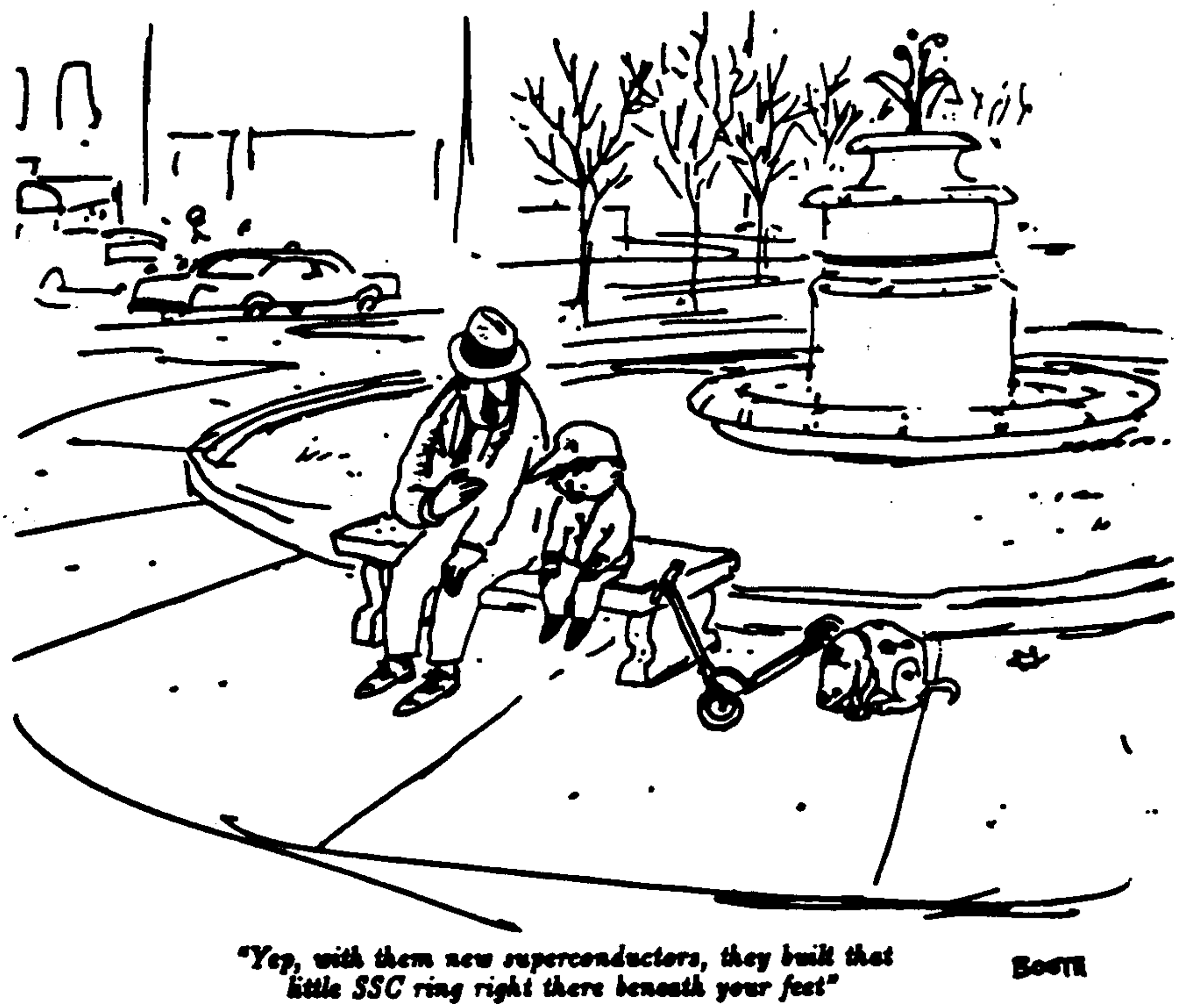


Illustration for the poster advertising a talk on high-T_c superconductors at the SSC Central Design Group.

Toward a VLHC

Cost reduction essential to go beyond SSC

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

¶ 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

¶ Look for applications of new magnet technologies in our existing accelerator complex

¶ 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

Inventing Our Futures

Near future looks very exciting:

LEP2 · HERA

SuperK · K2K · SNO · KamLAND

NA48 · KTeV · E787 · DAΦNE/KLOE · Hyper-CP

BaBar · belle

Tevatron Run 2

Main Injector fixed-target experiments?

But it is not enough!

- Can we do Tevatron Run 2^{bis}?
- Ensure the success of LHC and CMS ⊕ ATLAS.
  Keep the energy frontier at Fermilab metaphorically, if not geographically.
- Definitive accelerator experiments for ν oscillations

  K2K · Mini-BooNE · minos · CERN to Gran Sasso

  ? ν Factory (store $10^{20\text{ - }21}$ muons/year)
- We need to plan the Right Linear Collider
  Energy and luminosity? Technology?
  Decision (yes or no) in 4–5 years
- Prepare our long-term future by developing possibilities of $\mu^+\mu^-$ collider, VLHC

Strengthening Our Institutions

The Theory Crisis in Universities

- String fever: the retreat from experiment
- Detachment from the future of particle physics
- Diminished particle-physics culture in the universities:
  damaging to students in HEP and other fields
  reduces respect for what you do

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What Can We Do?

- ▷ You must demand better!
  If your department would not hire the young Hans Bethe
  because he is too practical, you have a big problem.
- ▷ DOE and NSF could ask,
  "What are you doing for the future of the field?"
- ▷ Reinvent SSC Fellowships to support young theorists (and
  experimenters and accelerator physicists) who want to help
  build the future.

Strengthening Our Institutions

Ask More of the Government

- The will to join together and undertake challenging and important causes is not in evidence . . .
  an aberration in American history

- In a time of unparalleled prosperity, every section of every appropriations bill begins, "Because of severe budgetary constraints . . ."

- We are still waiting for the peace dividend

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What Can We Do?

- You must demand better!
  The public believes in science and exploration
- Basic research (particle physics) is a superb investment on many levels. Don’t be timid (but be sensible)

  Many people are dining out on the World Wide Web, an unprogrammed dividend of a tiny fraction of the world’s investment in particle physics