Discoveries Ahead in Particle Physics

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Where we are

Theoretical insights developed 30+ years ago showed the path to three decades of experimental discoveries that established the Standard Model.

The Standard Model of Particle Physics

- is fairly simple;
- agrees in detail with an enormous amount of precise data;
- and explains why a number of things do not occur.

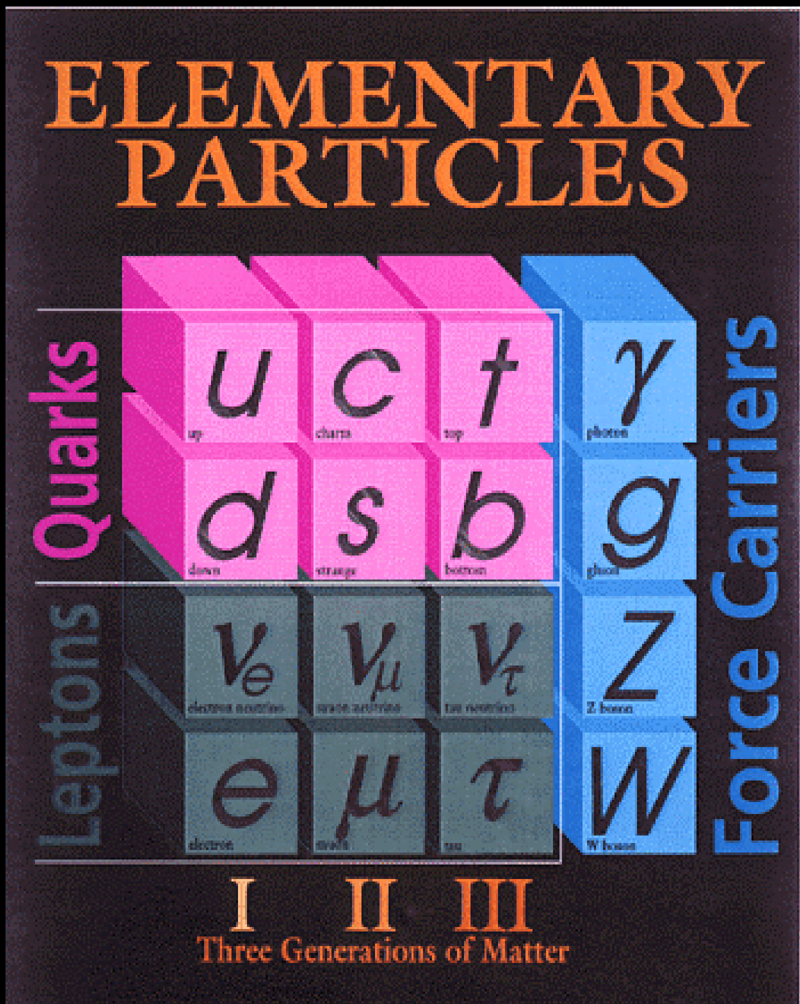
At the same time, we are confident that the Standard Model is not the complete picture.

Experiment must lead.

Within 10 years the Standard Model will be replaced by a new theory of matter and forces.

- Experiment must lead the way.
  - Theory tells us what questions are the most important, but not what the answer will be.
- The change in our picture of matter and time will be revolutionary, not evolutionary.

The Known Elementary Particles



The Standard Model includes quantum field theories for 3 forces: strong, electromagnetic, and weak; and 3 generations of quarks and leptons.

- Gravity famously difficult to integrate
- An effective model that breaks down at higher energy
  - We believe the energy at which the new physics turns on is of order 1 TeV.

Four areas of particle physics with compelling questions

A. Unification of forces
- How do we integrate gravity with quantum mechanics?

B. Electroweak Symmetry Breaking
- What causes the Higgs field?

C. Three generations
- Why are there 3 generations of quarks and leptons?
- Why do the neutrinos have such small masses?

D. Particles and the Cosmos
- What is Dark Matter?
- What is Dark Energy?

The Great Questions

A. Unification of forces

How do we integrate gravity with quantum mechanics?

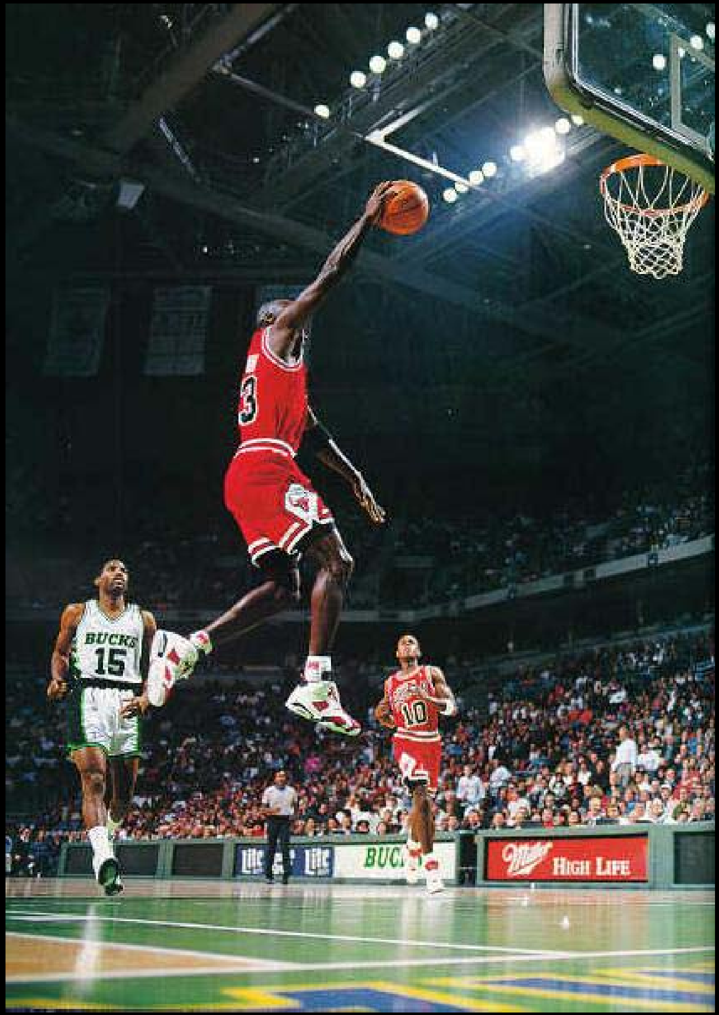
Why is gravity so weak?

Why is $F_{grav} \approx 10^{-42} \times F_{elec}$?

Why are M_W, $M_{Higgs} << M_{Pl}$?

10^2 GeV << 10^{19} GeV

The key to this is probably new physics at the TeV scale.



The Great Questions

B. Electroweak Symmetry Breaking

– Gravity and electric force are long-ranged, but the weak force has range 10^{-16} cm.

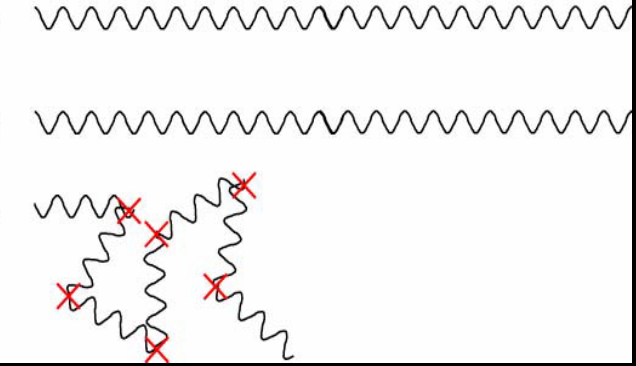
– In the SM, the scalar Higgs field gives mass to the W,Z boson.

Forces

gravitational

electric

weak



We do not know what the Higgs is.

- What causes the Higgs field?
- Why is there only one scalar particle?
- Is it an elementary particle or a composite?
- Are there multiple scalar bosons, as in supersymmetry?

The inadequacy of the Standard Model

Ed Witten formulated this clearly at the recent Lepton Photon Symposium, 8/2003:

Most physicists (including me) remain convinced that the minimal Standard Model with only the Higgs is unlikely to be the full story.

- A scalar field ϕ can have a bare mass term m^2.
- … in the Standard Model, the renormalization of m^2 is quadratically divergent, so that if the Standard Model is somehow cut off at a mass scale M, the one-loop renormalization is of order αM^2.
- Unnatural for $m^2 << \alpha M^2$

More

- In a model with spontaneous electroweak symmetry breaking, the problem … (also) affects the masses of other particles …the W and Z, and the quarks and charged leptons.
- So everyone seems to agree on one thing: we want from accelerators not just a Higgs boson, but a mechanism that will “stabilize” the scale of electroweak symmetry breaking and explain why the Higgs boson, and the rest of the particles, are not much heavier.

- But what?

Three of the possible answers

- Hidden Extra Dimensions
  - They can be used to disperse the intrinsic strength of gravity, making it seem weak to us.
  - Ultimate scale of physics: quantum gravity
- Supersymmetry
  - It stabilizes the Higgs mass.
  - It is necessary in string theory.
  - It leads to unification of gauge forces.
- Technicolor and variations
  - Higgs boson may be fermion-pair composite, analogous to Cooper pairs

The Great Questions

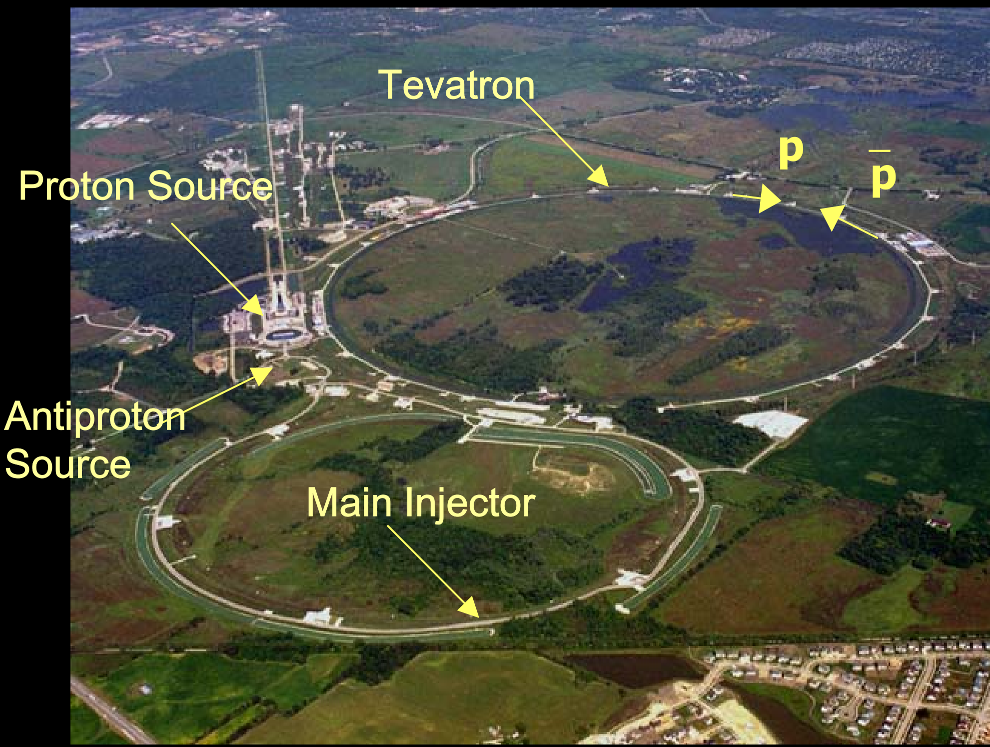
A. Unification of forces

B. Electroweak Symmetry Breaking

For both of these areas, the questions are addressed in colliders operating at the highest energy.

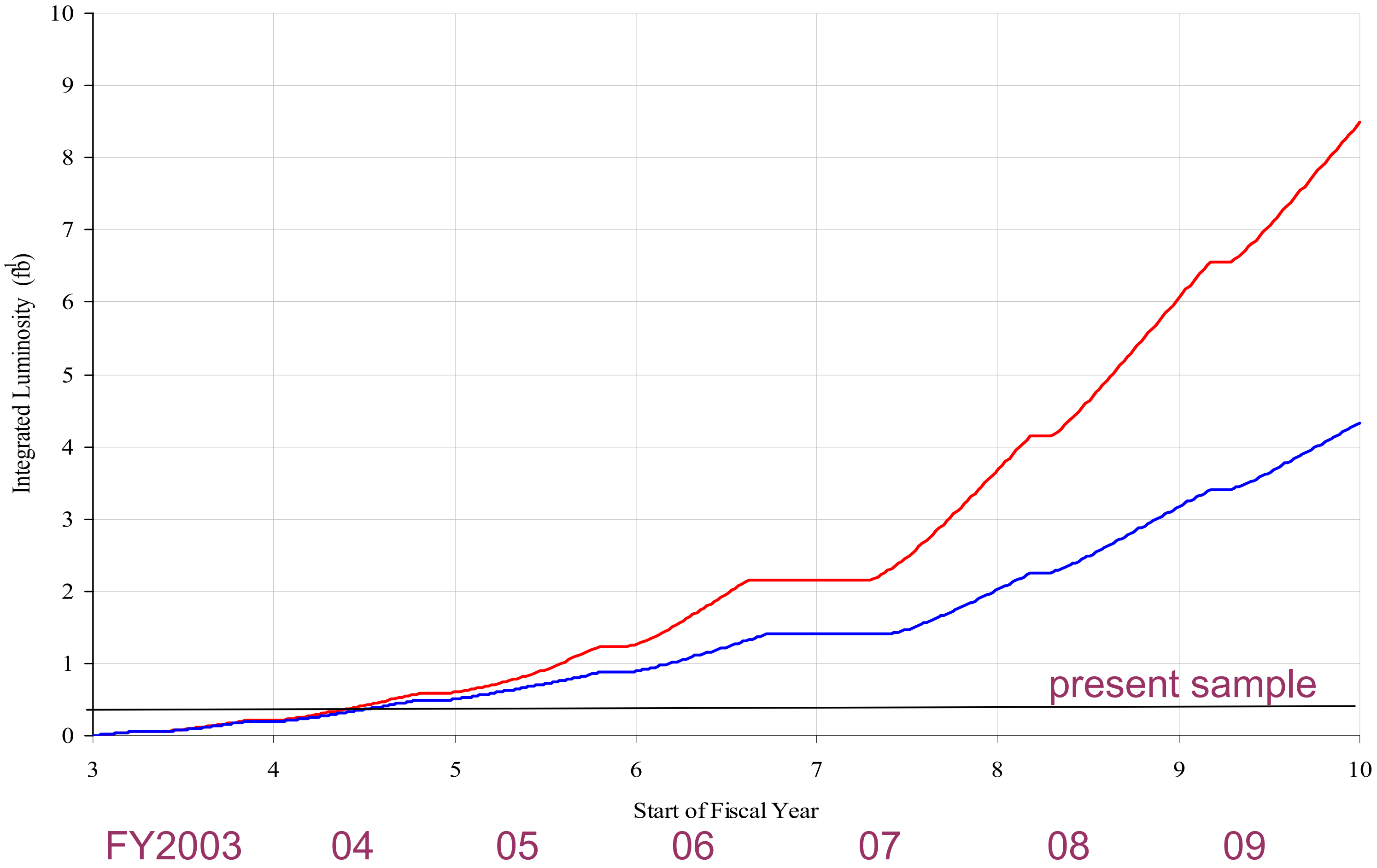
Now: the Tevatron

Soon: the Large Hadron Collider

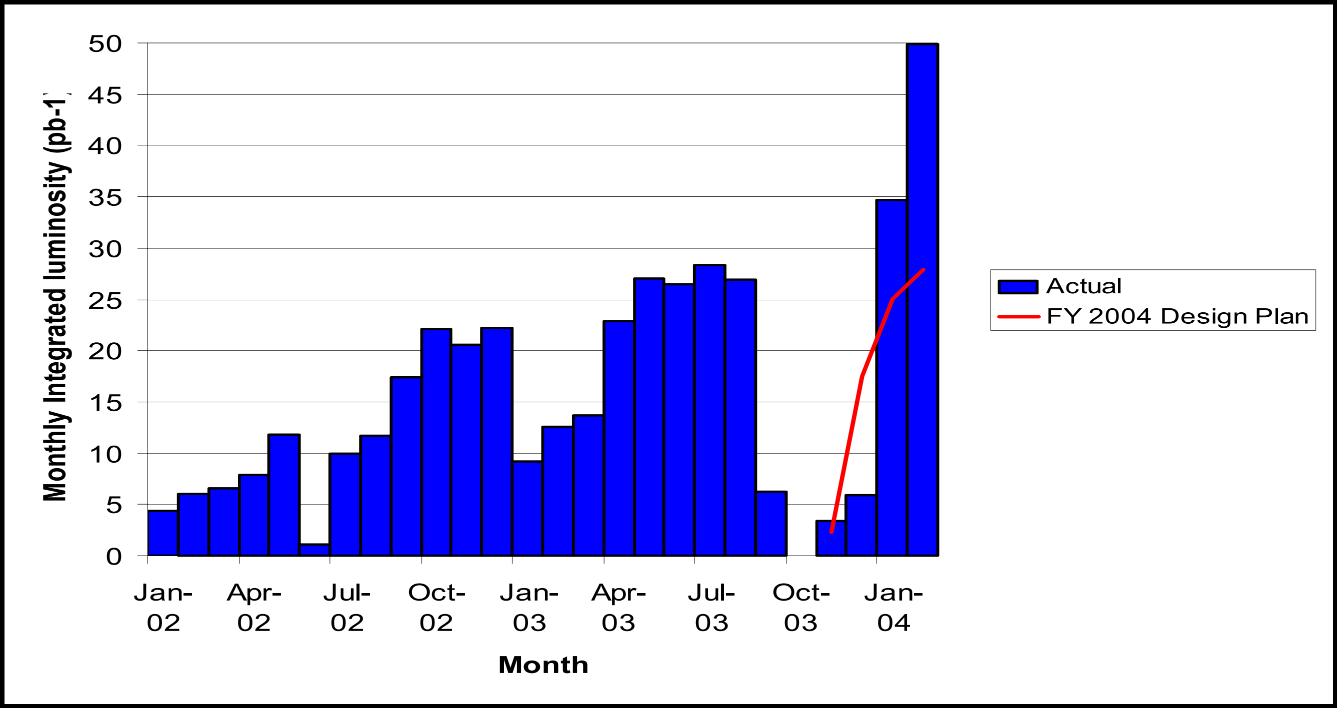


$\bar{p}$ – p collisions with E_{cm} = 2 TeV

A growing data sample



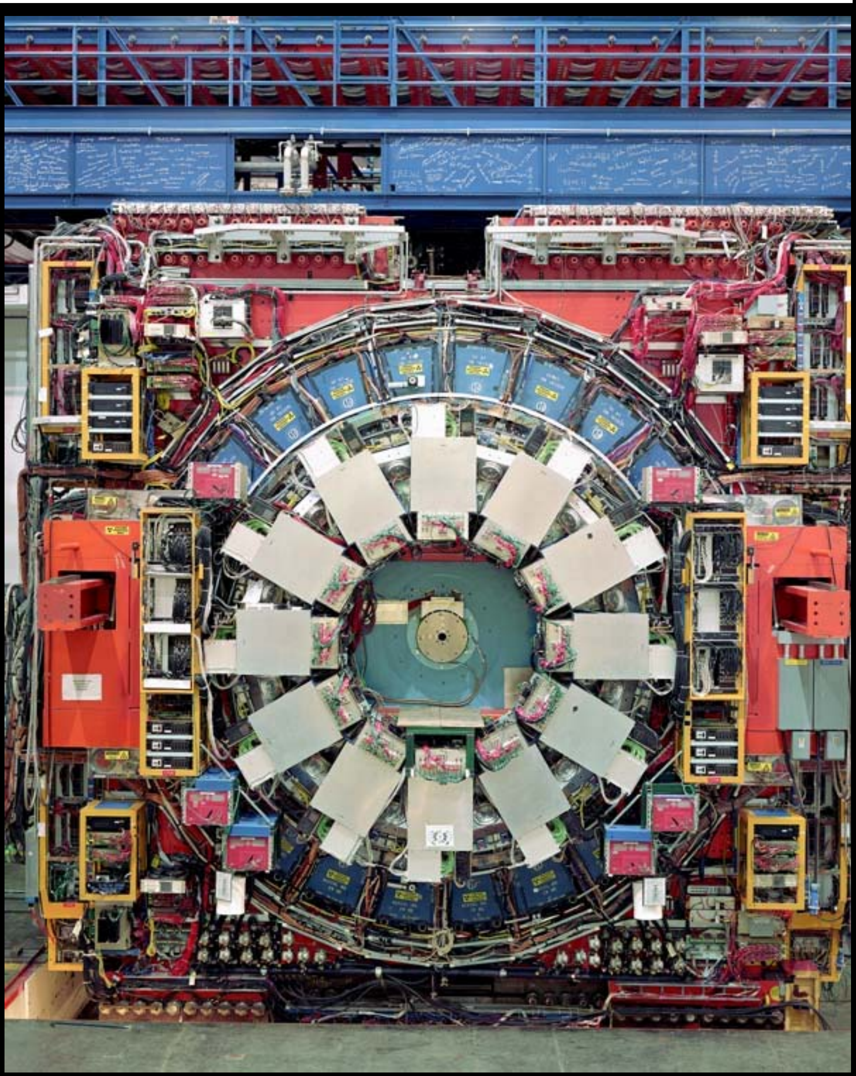
Breakthroughs at the Tevatron in 2004



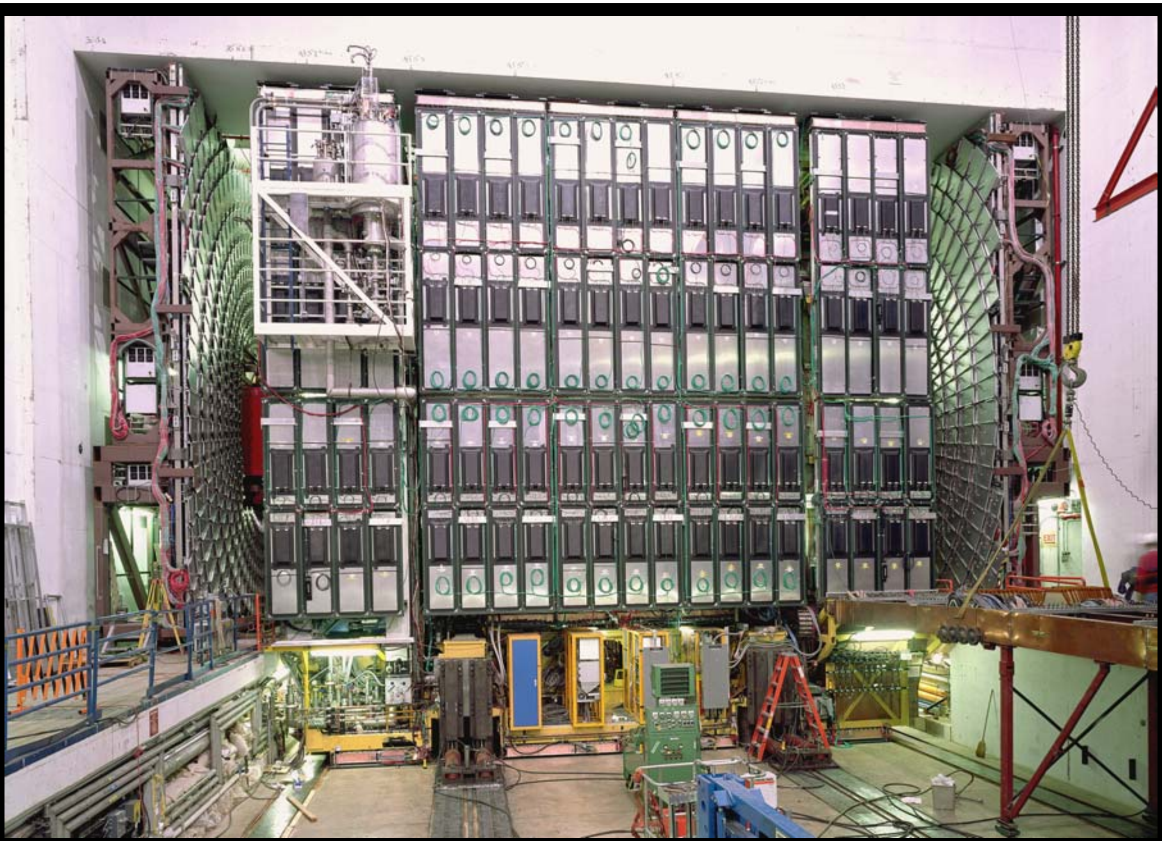
- The accelerator complex broke every record for performance and reliability in February.

CDF at the Tevatron

- Physics goals
  - Precise study of the known quanta of the Standard Model
  - Search for particles, forces beyond those known

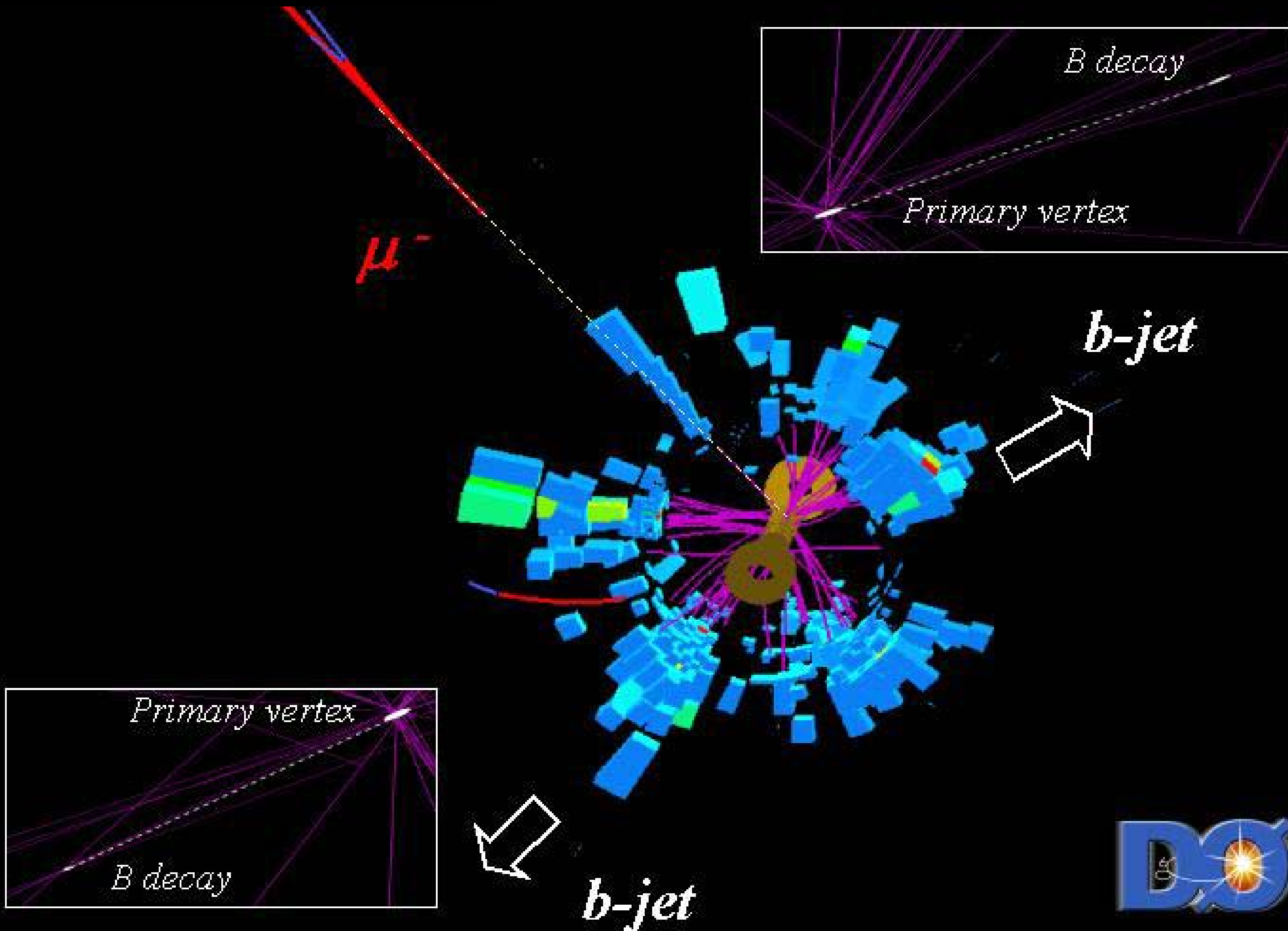


DØ at the Tevatron



- Physics goals
  - Precise study of the known quanta of the Standard Model
  - Search for particles, forces beyond those known

Run II top candidate



What causes the Higgs field?

In the Standard Model (SM), the Higgs fills the universe with a Bose-Einstein condensate, giving weak bosons their mass.

It also gives the quarks and leptons mass. The top quark feels the Higgs field most strongly.

Is there really a Higgs?

Is there one?

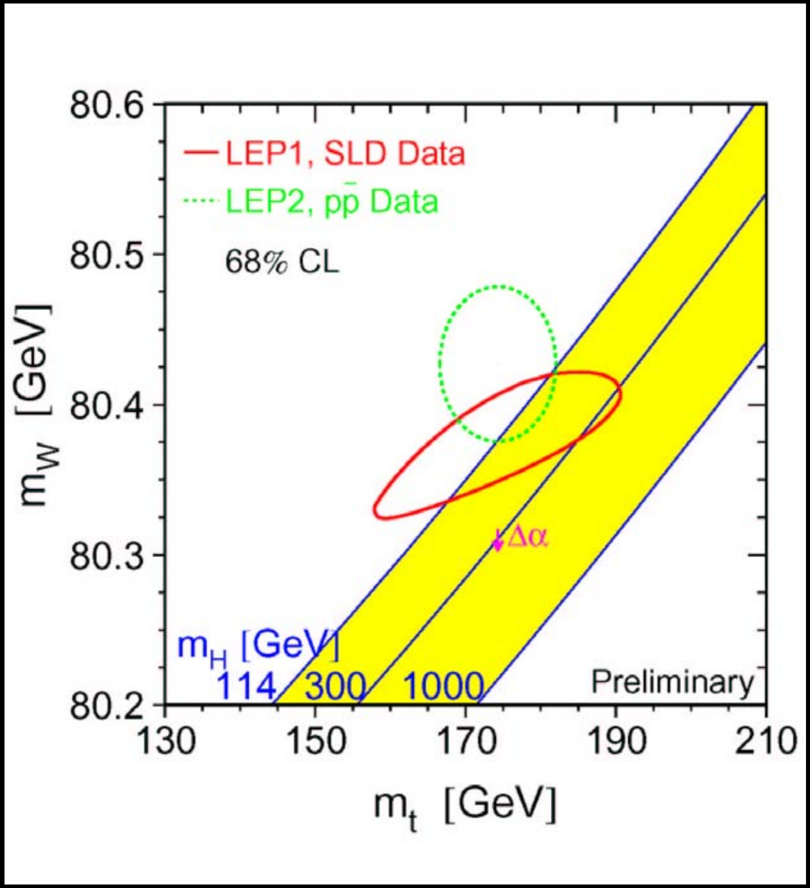
Are there five?!

We can predict the Higgs mass well, in the SM, using precise measurements including the properties of the top quark and the W and Z bosons.

Tracking the Higgs

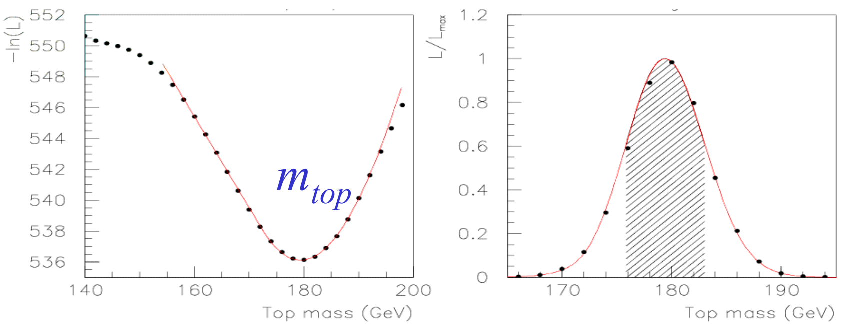
The future of Higgs physics:

- Measure top, W mass more precisely at the Tevatron.
  - consistent with SM Higgs?
- Observe Higgs production directly.
  - Exclusion or indication of low-mass Higgs at Tevatron
  - Discovery throughout the range at LHC.



Top mass

- **New DØ Run I lepton+ jets mass measurement:**



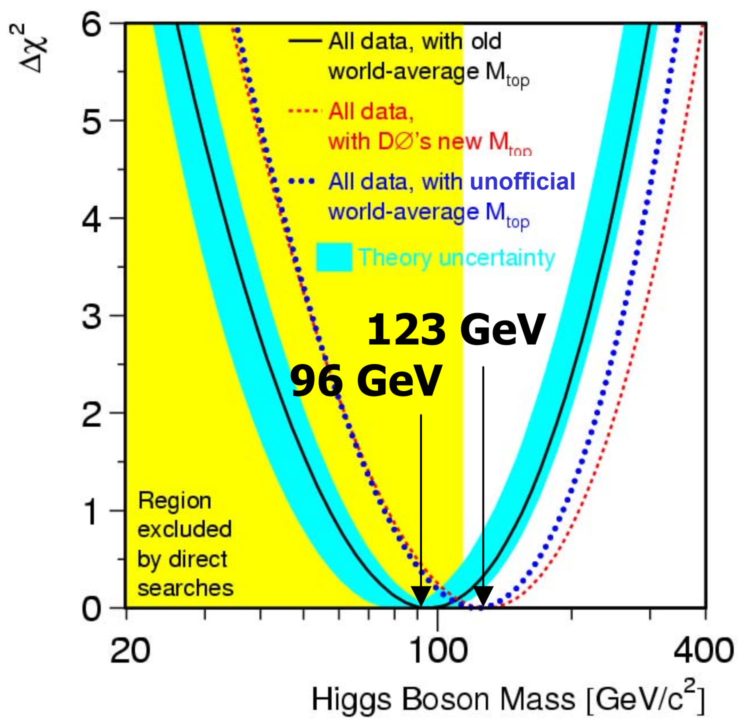
Run II mass analysis in progress, using this technique, the classic (Run I) technique, and a newly developed one
anticipated stat. error 6-8 GeV

m_{top} = 179.0 ± 5.1 GeV (DØ combined)

m_{top} = 178.0 ± 4.3 GeV (my unofficial average)

Precise m_{top} is important! *example…*

Top mass	2003 World Ave	New DØ combined	Unofficial average
Higgs mass best fit	**96 GeV + 60 – 38**	**123 GeV + 76 – 50**	**117 GeV + 67 – 45**
95% CL upper limit	**219 GeV**	**277 GeV**	**251 GeV**



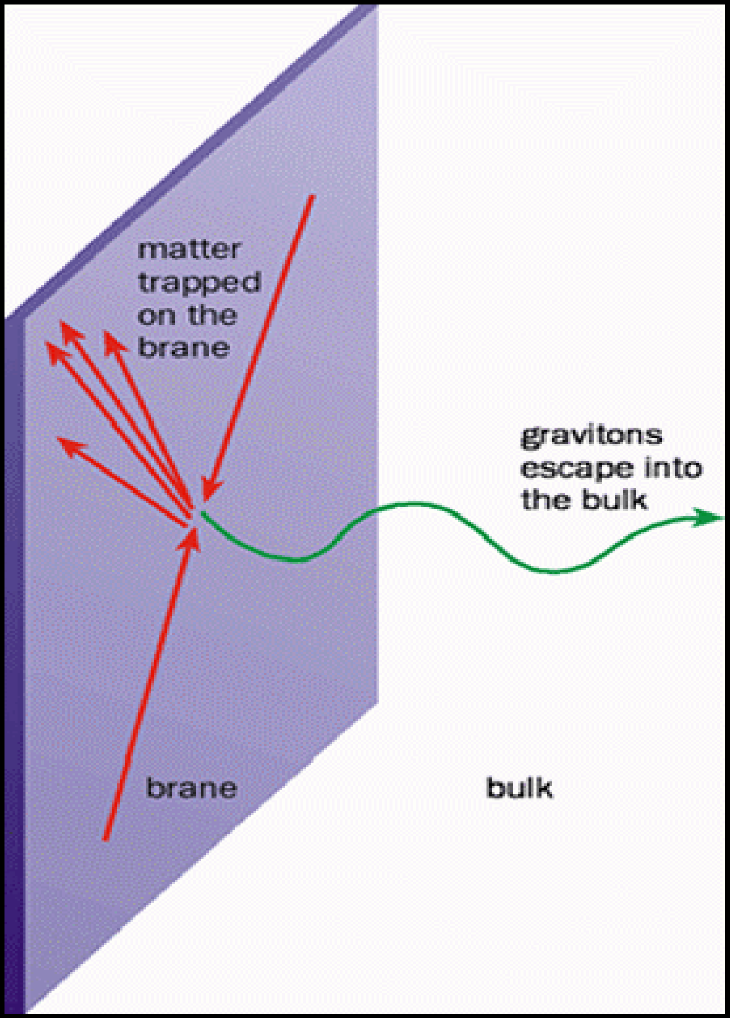
Extra Dimensions

Naively, the size for the extra dimensions should be the Planck length ~10^{-33} cm.

But they could be much larger, up to ~10^{-16} cm.

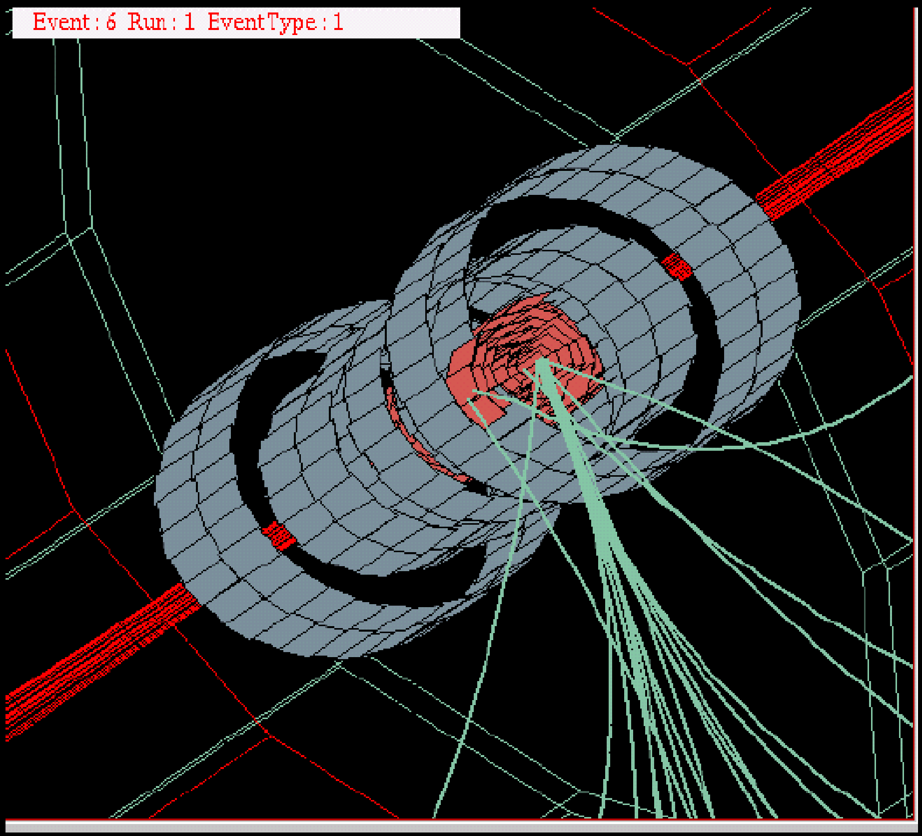
In another variant, the extra dimensions are large, but we are trapped on a 4-dimensional membrane in an 11-dimensional space-time.

Only gravity acts in the extra dimensions, which can be of macroscopic size.



Search for extra dimensions

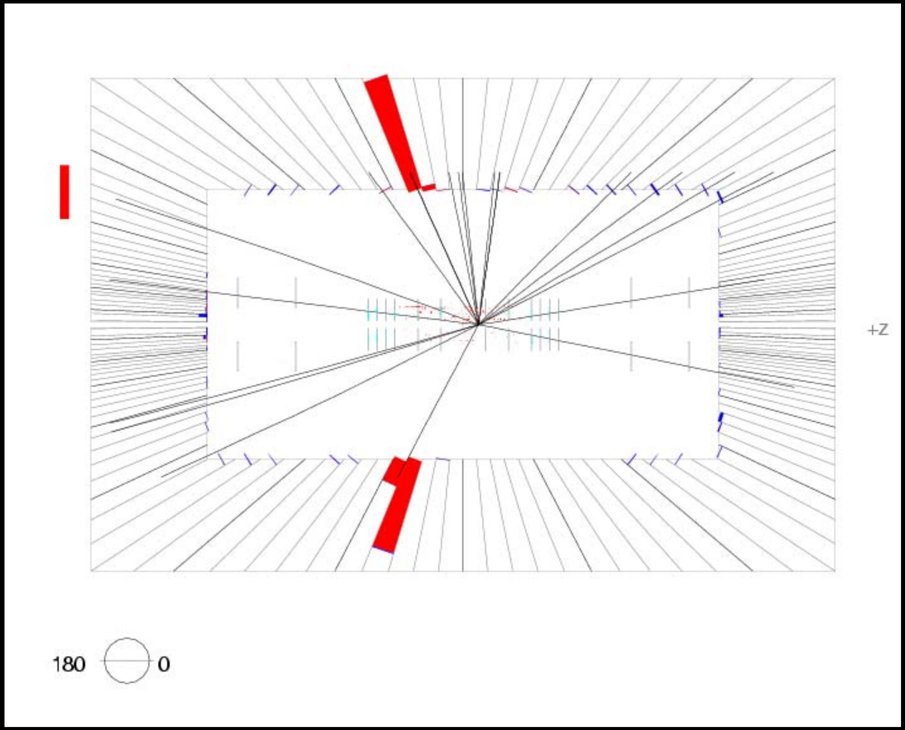
- For some models of extra dimensions, the characteristic signature is a deviation from the gravitational force law at distances less than 1 mm.
- For other models, the signature is the production of Kaluza-Klein gravitons.
  - We could see a jet of high-energy particles, with nothing balancing its energy and momentum.
  - The high-energy graviton going in the other direction would disappear.



Search for extra dimensions

- We can also search for large extra spatial dimensions through virtual graviton effects

- Signal would be an excess of ee, μμ, γγ events at large mass and large angle, due to virtual graviton exchange



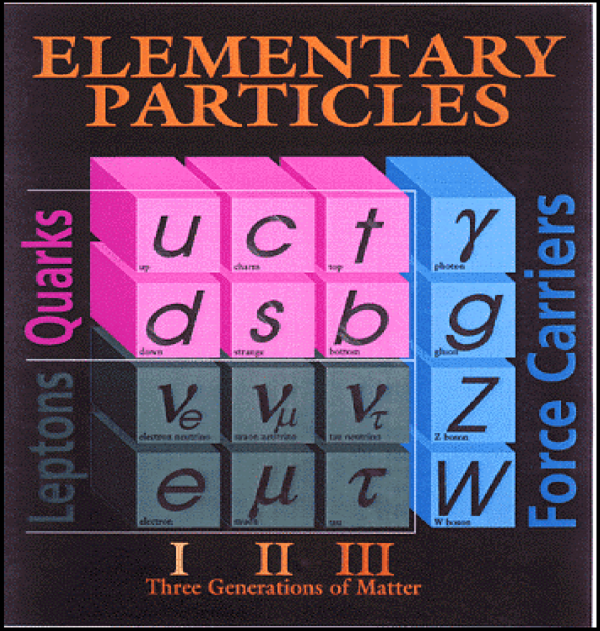
Latest DØ limits from $\bar{p}p \rightarrow$ ee, μμ, γγ
Mass Scale > 1.4 TeV

Is nature supersymmetric?

Supersymmetry looks attractive because

- stabilizes Higgs mass
- is necessary for string theory
- leads to equal gauge couplings at unification scale
- has a natural dark matter candidate (lightest supersymmetric particle)

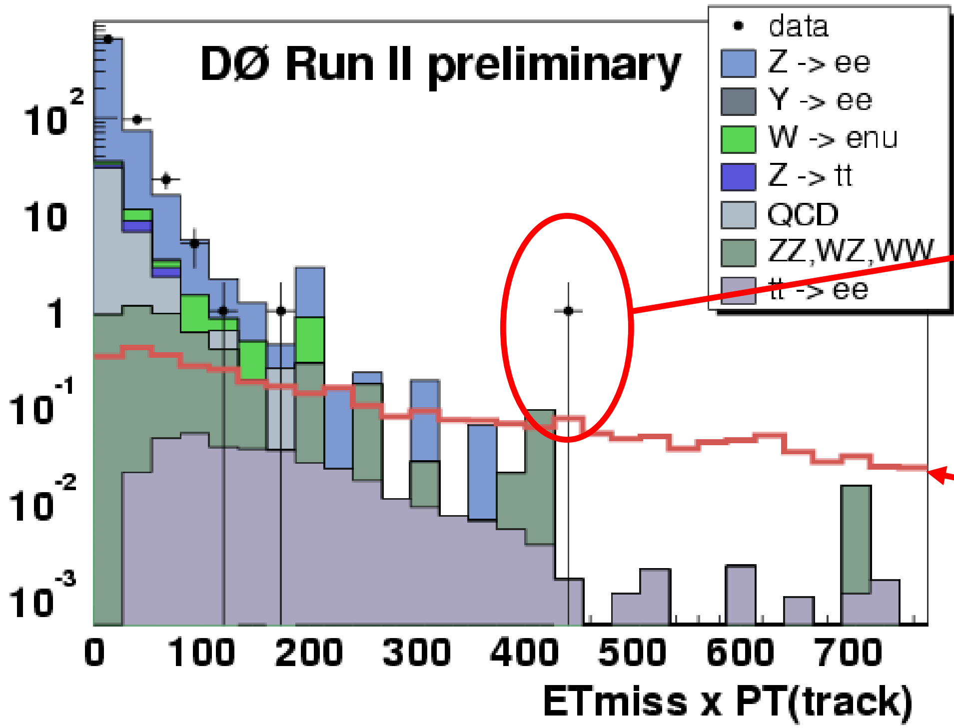
particle	superpartner
quark	squark
gluon	gluino
photon	photino



But we need experimental evidence.

Things are starting to be fun

- With 250 pb^{-1} in Run II, it is no longer crazy to imagine that new physics may be present in our data at the few event level



1 trilepton candidate event
Expected background fairly small
Expected SUSY signal 1-2 events

One of our mSUGRA reference points

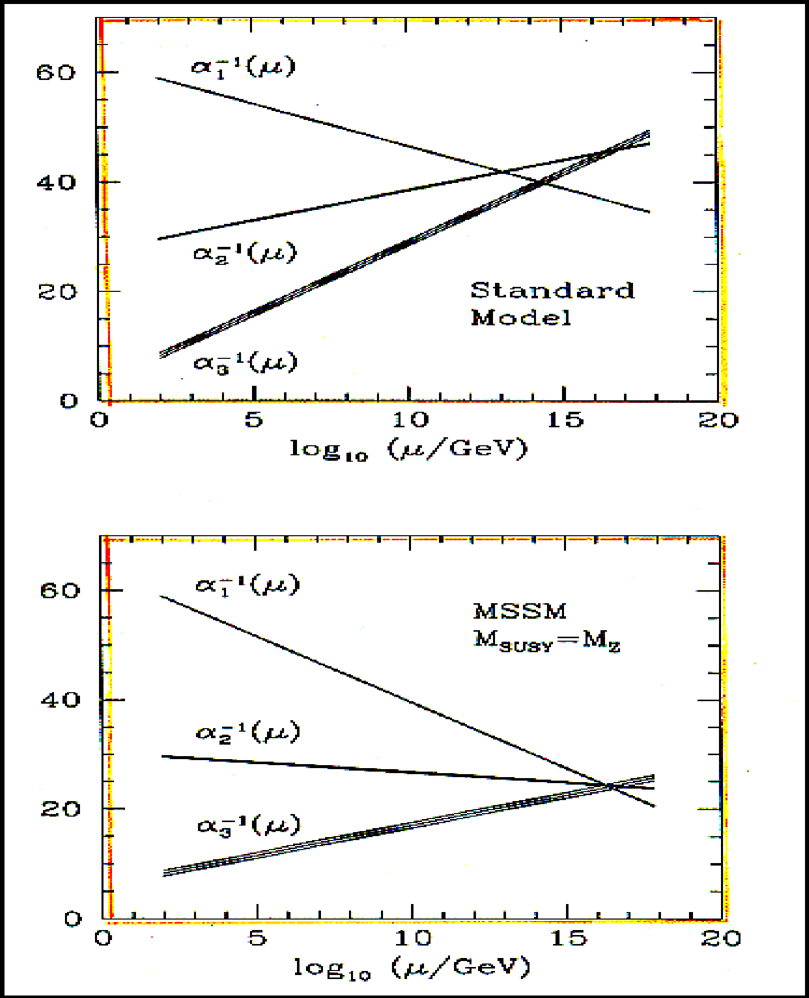
m_0=76 $m_{1/2}$=170 A_0=0 tan β=3 μ > 0
m(χ^0_1 χ^0_2 $\chi\pm$) = 59, 106, 101 GeV

… also find 1 like-sign muon event
Expected background fairly small

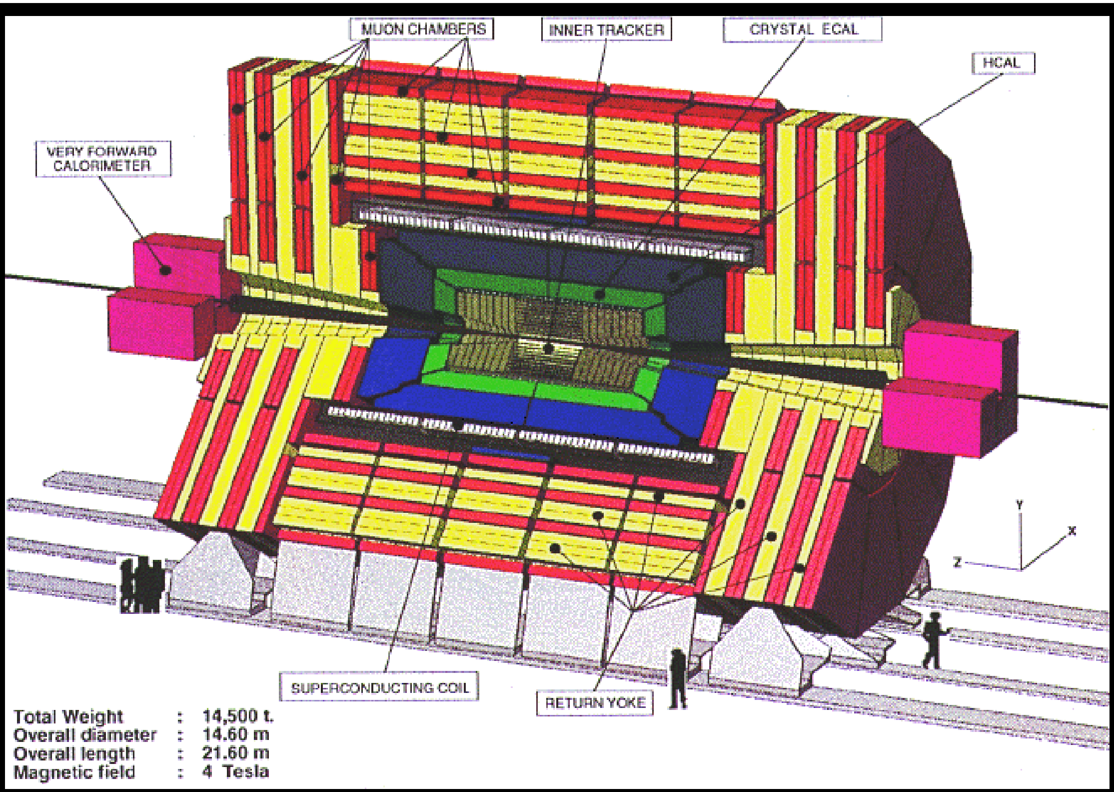
Unification of gauge couplings

- The gauge couplings of strong, electromagnetic, and weak interactions evolve logarithmically with the energy scale.

- With supersymmetric corrections, they coincide at E $\simeq 10^{16}$ GeV, the GUT scale.



Producing and observing supersymmetric particles



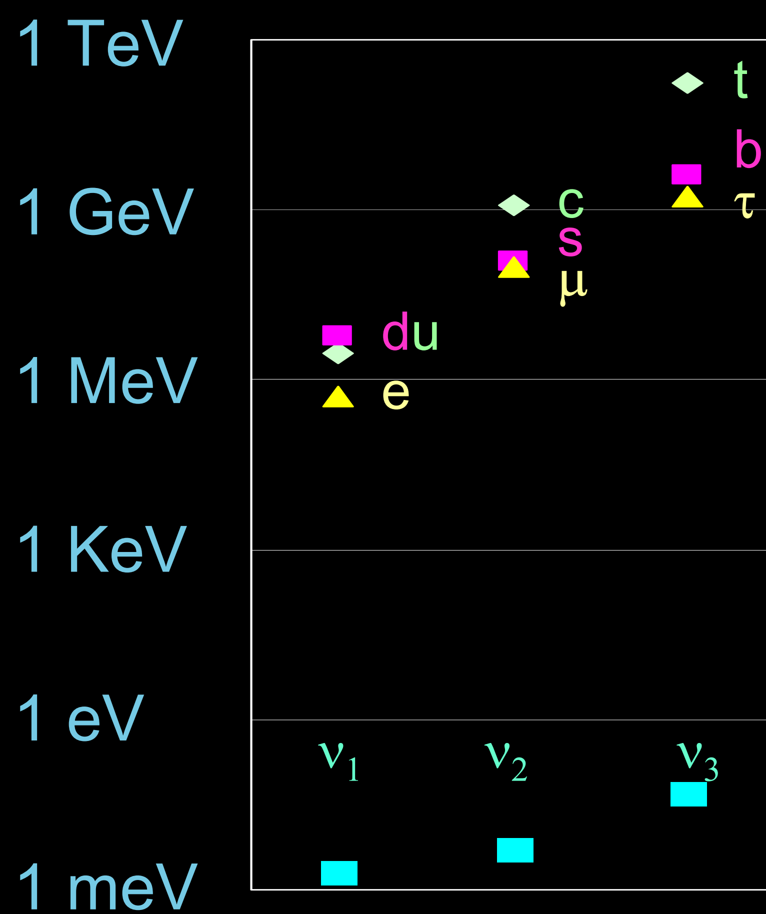
CMS experiment at the Large Hadron Collider

If supersymmetry is connected with stabilizing the Higgs mass, it will be discovered at the LHC.

The Great Questions

C. Three generations

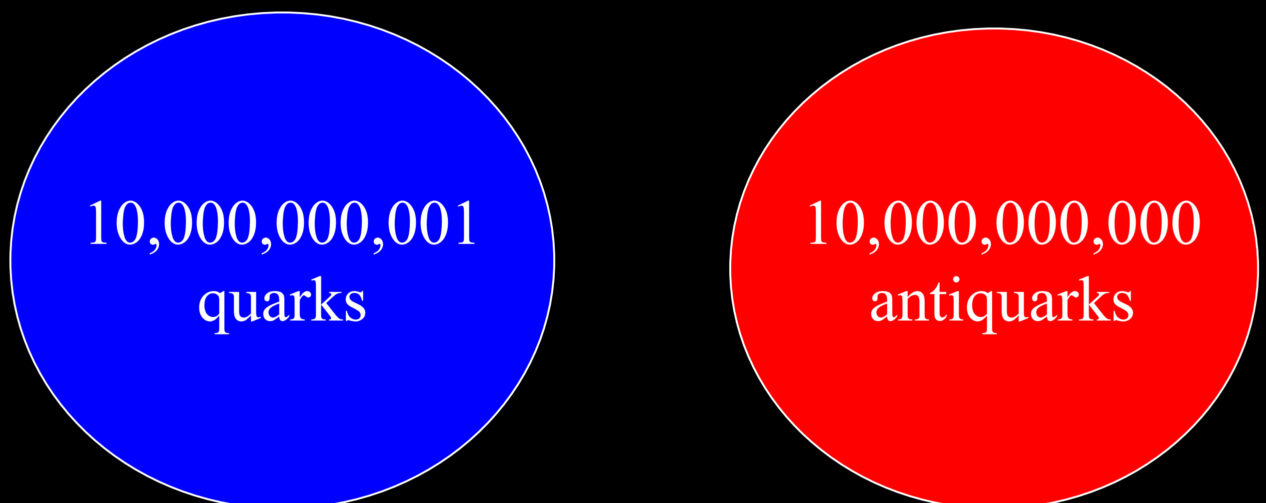
- Why 3 generations?
- What physics determines the masses?
- What are the origins of CP violation?
- What is the origin of the matter-antimatter asymmetry in the universe?
- Is the top quark mass particularly important?
- Why do the neutrinos have such small masses?



Masses of the quarks and leptons

Quark Asymmetry in the Early Universe

Matter and antimatter were created in equal quantities in the Big Bang.
But a small asymmetry in properties led to:



Quarks and antiquarks got together…

Quark Asymmetry in the Early Universe

1 Quark

They have all annihilated away except for the tiny difference.

Why is any matter left in the universe?

What created the small excess of matter in the early universe?

Requirements

- Nonconservation of quark or lepton number
- CP violation (asymmetry in properties of matter and antimatter)
- Departure from equilibrium

The CP violation well measured in B decays is not enough to explain baryogenesis.

We need another source of CP violation.

- Supersymmetric particles?
- Neutrinos?`

Quark Flavor Physics

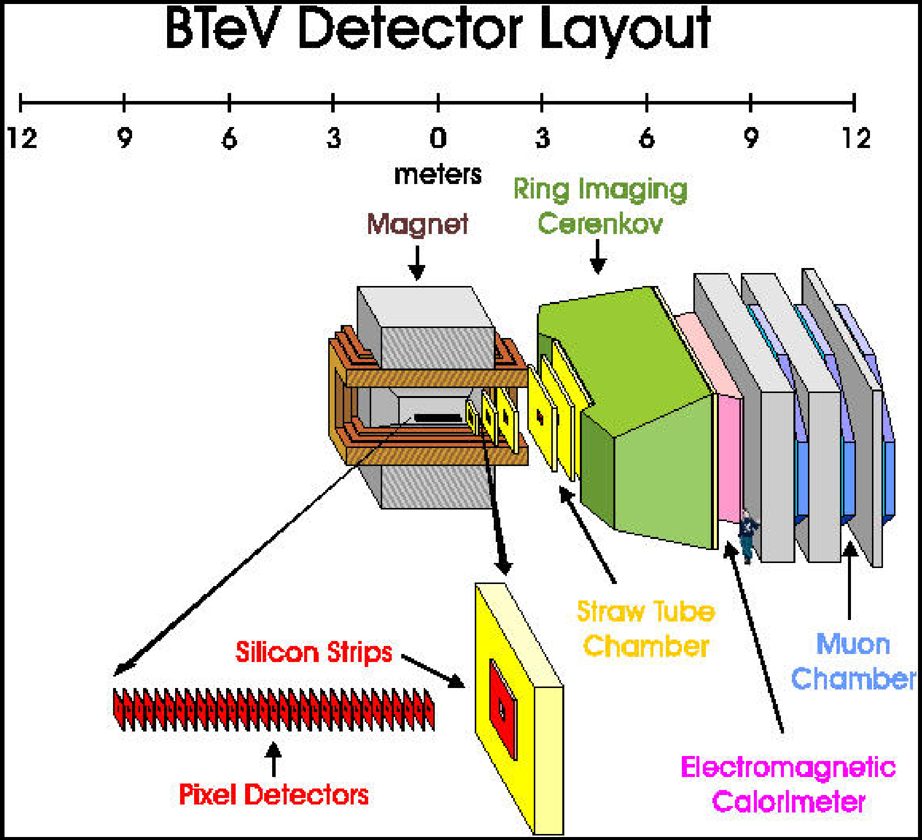
- The Standard Model flavor structure is particular.
  - Universality of the charged current interaction
  - Flavor Changing Neutral Currents are highly suppressed
- Any New Physics model (e.g., supersymmetry) must not destroy these successful SM features.

Many proposed models of new physics lead to anomalies observable by comparing the mixing and decays of K, B_d, and B_s mesons.

- CP violation is very sensitive to new physics at a very high energy.
- The first sign of the top quark was the discovery of CP violation in K decays, 30 years before the top quark discovery.

BTeV

- BTeV is a novel detector designed to use efficiently the prodigious production of B mesons at the Tevatron.
  - It represents the generation beyond the very successful B-factories.
  - BTeV was recently endorsed by advisory panel, DOE facilities plan, and FY 2005 budget.

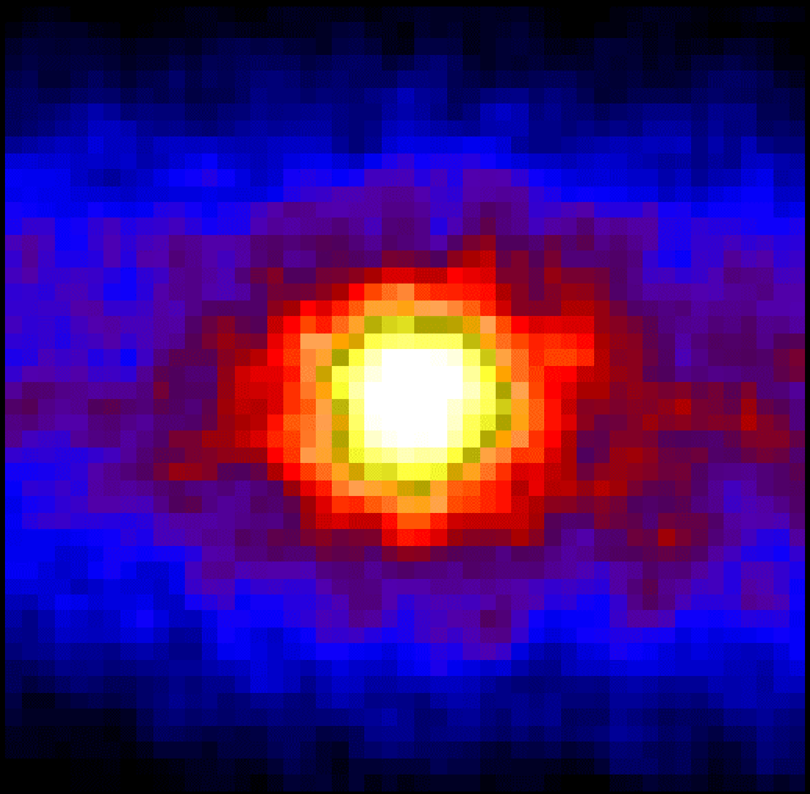


start of operation in 2009.

Surprising Neutrinos

Neutrino oscillations are the greatest experimental surprise of the last decade.

- large mixing among the three neutrino flavors
- possibility of observing a new instance of CP violation
- possible connection through the see-saw mechanism to a very high mass scale
- sterile neutrinos?



The sun as seen with neutrinos

Recent Progress

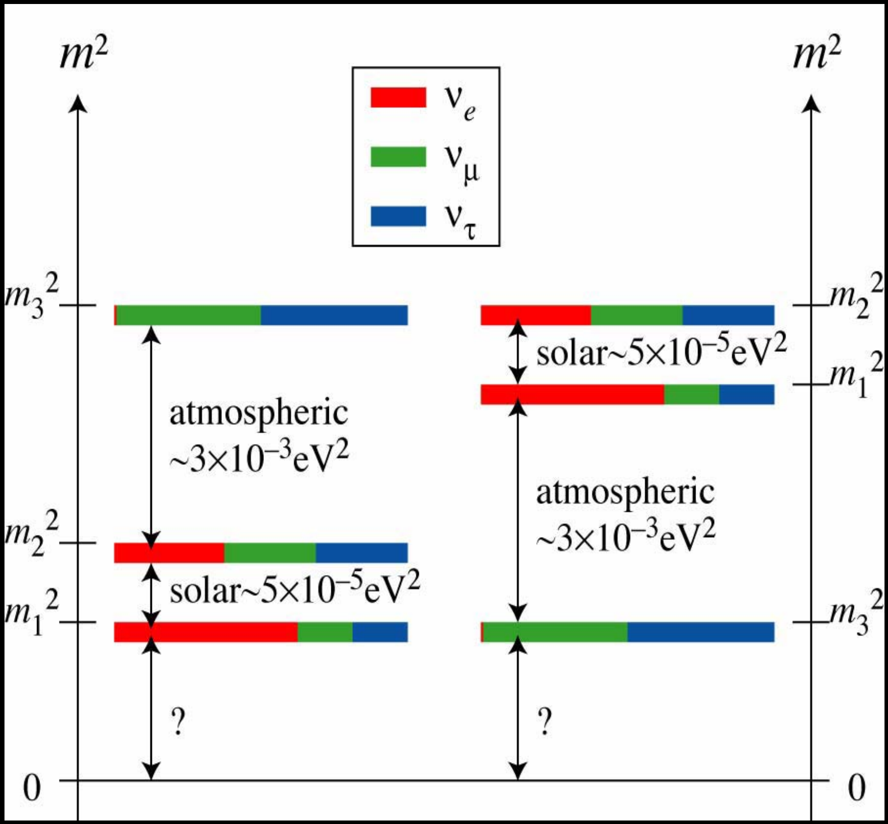
1998 SuperK: atmospheric ν_μ changes to another flavor

2002 SNO: solar ν_e changes to another flavor

2002 Kamland: the Large Mixing Angle solution for solar νs

The two observed mixing angles are very large.

If the third angle is not too small, it opens the chance to study a new source of CP violation in the neutrino sector.

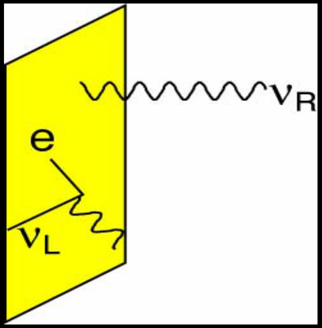


mass eigenstates ≠ flavor eigenstates

Why is neutrino mass of special importance?

No right-handed neutrino $\Rightarrow$ Neutrino massless in SM

1. Could be ν_R is very weakly coupled, e.g. because of extra dimensions.



2. Neutrinos might get their mass from super-heavy neutrinos with masses near 10^{15} GeV.

   LH massless ν + RH super-heavy ν

   $\Rightarrow$ LH ν gains a tiny mass: $m_\nu \approx m_L^2/M$

   If $m_L \sim m_{top}$, $M \sim 10^{15}$ GeV (GUT), then $m_\nu \sim 10^{-(1-2)}$ eV

   Decays of these heavy neutrinos in the early universe could have led to the small baryon excess today.

Sterile neutrinos

- Three observations of neutrino oscillations
  1. Solar — large mixing — $\Delta m^2 \approx 10^{-4}$ eV^2
  2. Atmospheric — large mixing — $\Delta m^2 \approx 10^{-3}$ eV^2
  3. LSND — small mixing — $\Delta m^2 \approx 1$ eV^2

This requires either violation of CPT or a fourth neutrino, which would be sterile. (A sterile neutrino does not have standard weak interactions.)

Who ordered that?

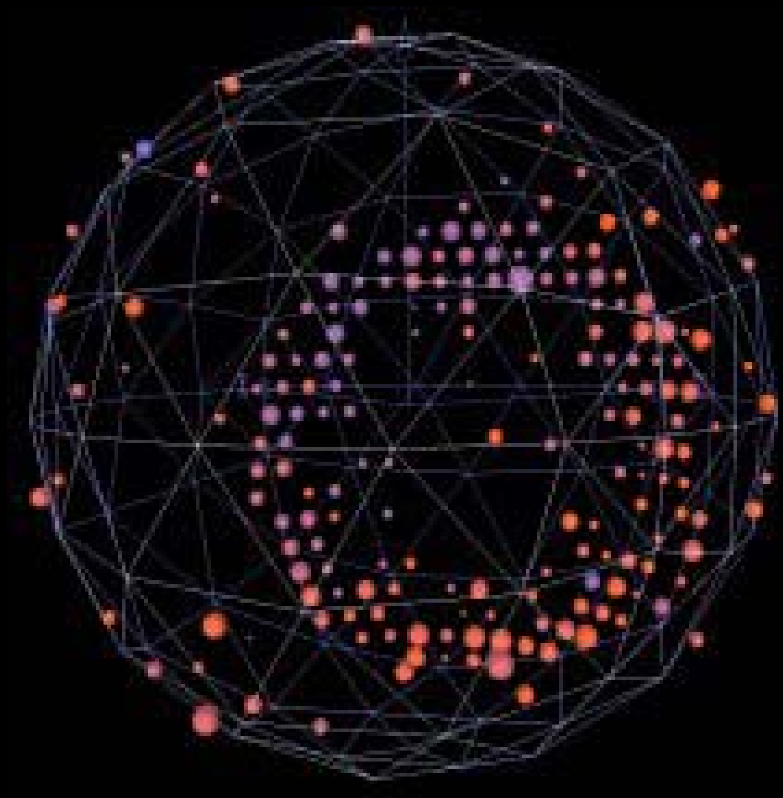
MiniBooNE

MiniBooNE is designed to follow up on the LSND evidence of a $\nu_\mu - \nu_e$ oscillation at high Δm^2, requiring a sterile neutrino.

Theorists expect no light, sterile neutrinos.

Good news: Expectations have been wrong at every step.

If MiniBooNE confirms LSND, it will cause another neutrino revolution.



Long-baseline neutrinos

In the 3-neutrino world, if MiniBooNE reverses LSND, the goals are

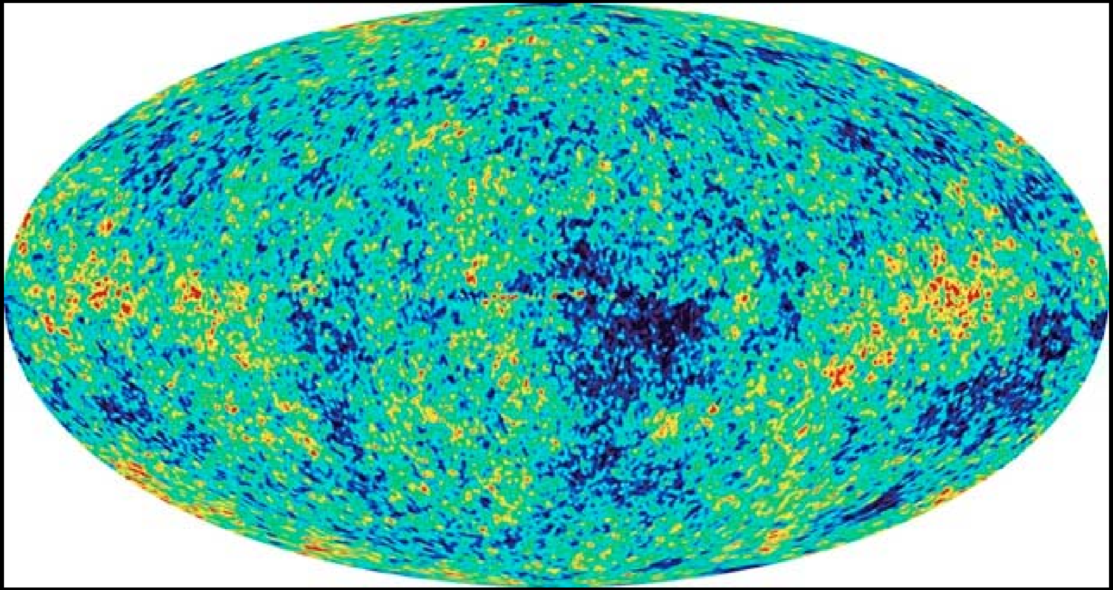
- measure θ_{13}
- observe CP violation
- determine the mass hierarchy.

Experimental steps

- K2K, MINOS about to start
- Next J-PARC, Off-axis NuMI, reactor experiment
- Then even more protons, much larger detectors

MINOS: Interstate Neutrinos

The Great Questions



D. Particles and the Cosmos

What is Dark Matter?

What is Dark Energy?

- Results from WMAP et al. point to new particle physics.

Composition of the universe

Other elements	0.03%
Neutrinos	0.3%
Stars	0.5%
Free H and He	4%
Dark matter	23%
Dark energy	72%
Antimatter	0%
(Higgs condensate	10^{62}% ??)

Dark Matter

We observe Dark Matter through its gravitational effects.

But its properties do not fit any of the standard particles.

We need to determine the nature of dark matter by experiment.

The larger, blue objects are images of a distant galaxy.
The yellow galaxy cluster in the foreground and its associated dark matter halo act as a gravitational lens.

What is the nature of Dark Matter?

To understand dark matter we need to study dark matter particles in controlled experiments.

We want to detect their very weak interactions in the laboratory.

– Establish that they are around us

We want to produce them with colliders and observe their decays.

– Measure their properties

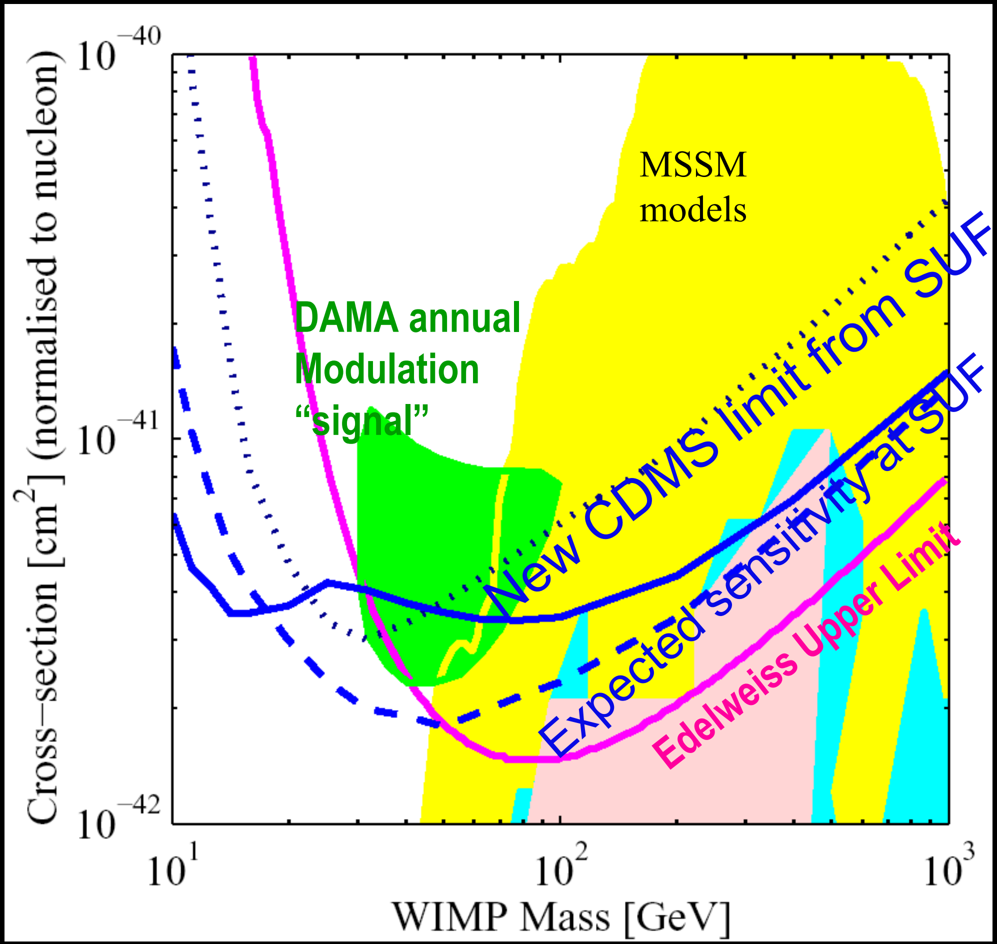
Dark matter could be supersymmetric

The lightest supersymmetric particle (LSP) is also an ideal dark matter candidate.

- probably stable
- needed properties consistent with LSP

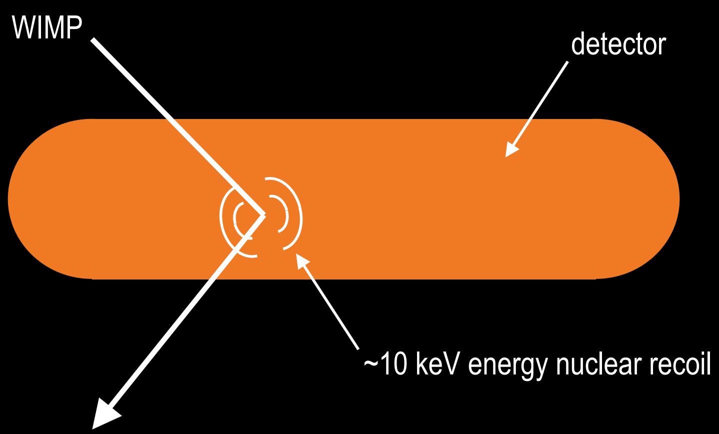
Dark matter scatters are hard to see.

- ~1 interaction per pound of material per year, depositing ~20 keV in recoil energy

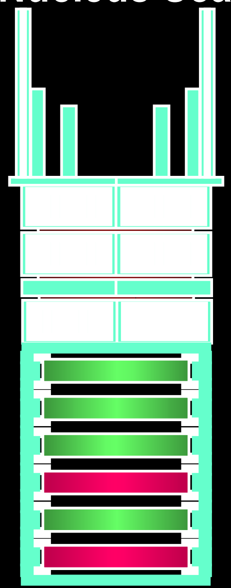


Observing dark matter in the wild

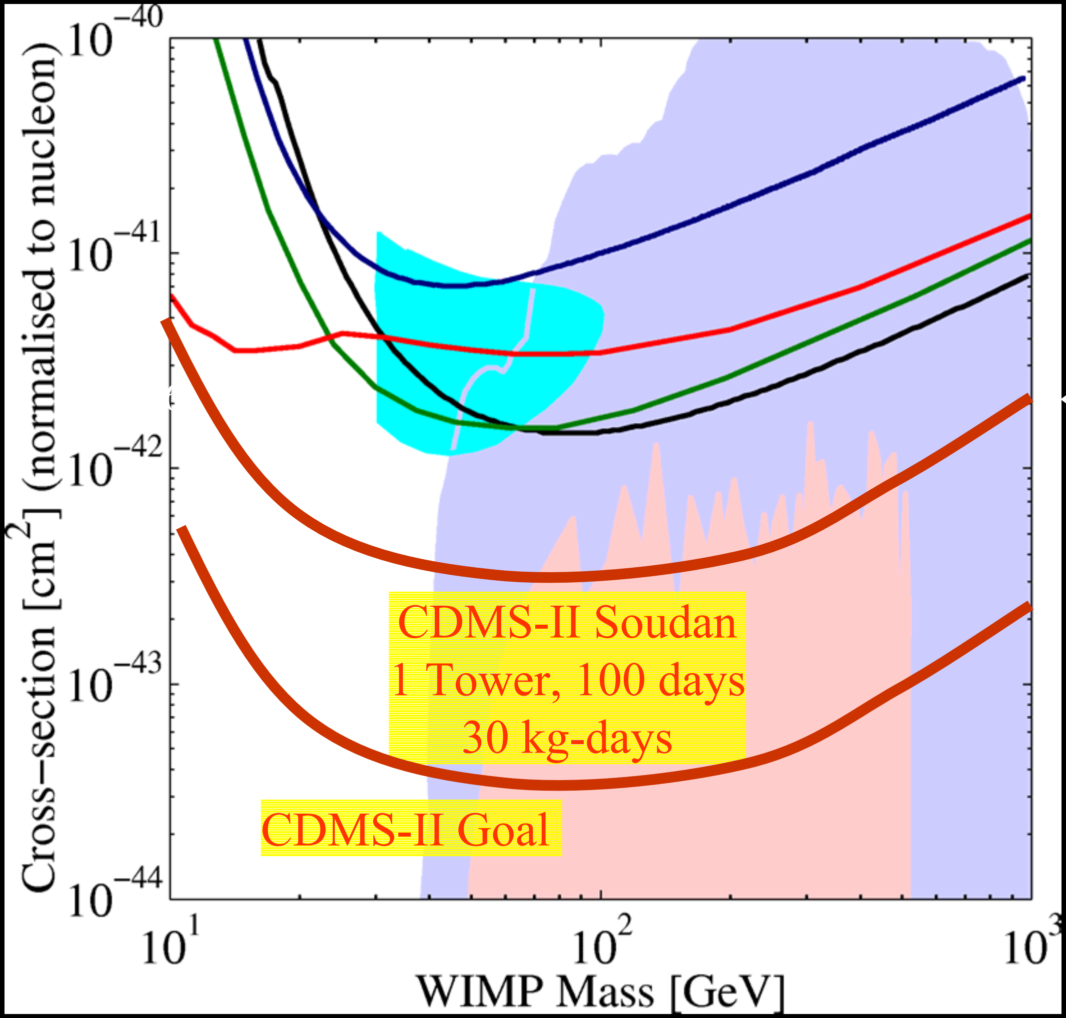
- Cryogenic Dark Matter Search detectors operate at T=20 mK.
  - They measure ionization energy and recoil energy separately to reduce dominant radioactive backgrounds.
- CDMS II has collected its first physics data sample in Soudan.
  - 2 towers, 6 Ge + 6 Si detectors
  - reduced neutron background from ~1/kg/day to ~4/kg/year



WIMP-Nucleus Scattering



CDMS-II Goals in Soudan



Existing limits

By this summer, if no signal is observed, the limits will move to about here.

Dark Energy from particle physics

- To know the future evolution of the universe we need to know the nature of dark energy.
  - Sources of vacuum energy abound in particle physics.
  - The difficulty is getting them to be small enough.

- Theoretical understanding is needed, in addition to experimental guidance.
  - In this case, theory does not need to wait for experiment.

Opportunities for discovery over the next ten years

- Unification of forces and Electroweak symmetry
  - D0 and CDF will dominate the new experimental results for some years.
  - Atlas and CMS will certainly cause a revolution.
- Quarks
  - B-factories and CDF/D0 explore B physics now.
  - BTeV is the next generation.
  - KOPIO

(Fermilab is host laboratory.)

- Neutrinos
  - MiniBooNE
  - MINOS and other long-baseline experiments
  - SNO, Kamland
  - Double beta decay
  - $\mu \Rightarrow e$: MECO
- Particle Astrophysics
  - Dark matter: CDMS
  - Highest energy cosmic rays: Auger, HiRes
  - WMAP, Sloan DSS…
  - ν astrophysics: Ice Cube
  - Gamma rays: GLAST, Veritas
  - Dark Energy: JDEM

Conclusions

- The energy scale of 0.2-1 TeV is richer than just a Higgs boson.
  - Supersymmetry, extra dimensions, hierarchy problem
- Many flavor problems appear ripe for discovery.
  - Neutrino masses, sterile neutrinos, new physics in B mixing
- Important cosmic questions will be addressed with several different approaches.
  - Dark Matter, Dark Energy
- New discoveries are generating new understanding of QCD.
  - pentaquarks, long-lived heavy mesons
- The field is positioned well for new discoveries over the next decade.
- The linear collider will make possible additional breakthroughs beyond the next ten years.

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