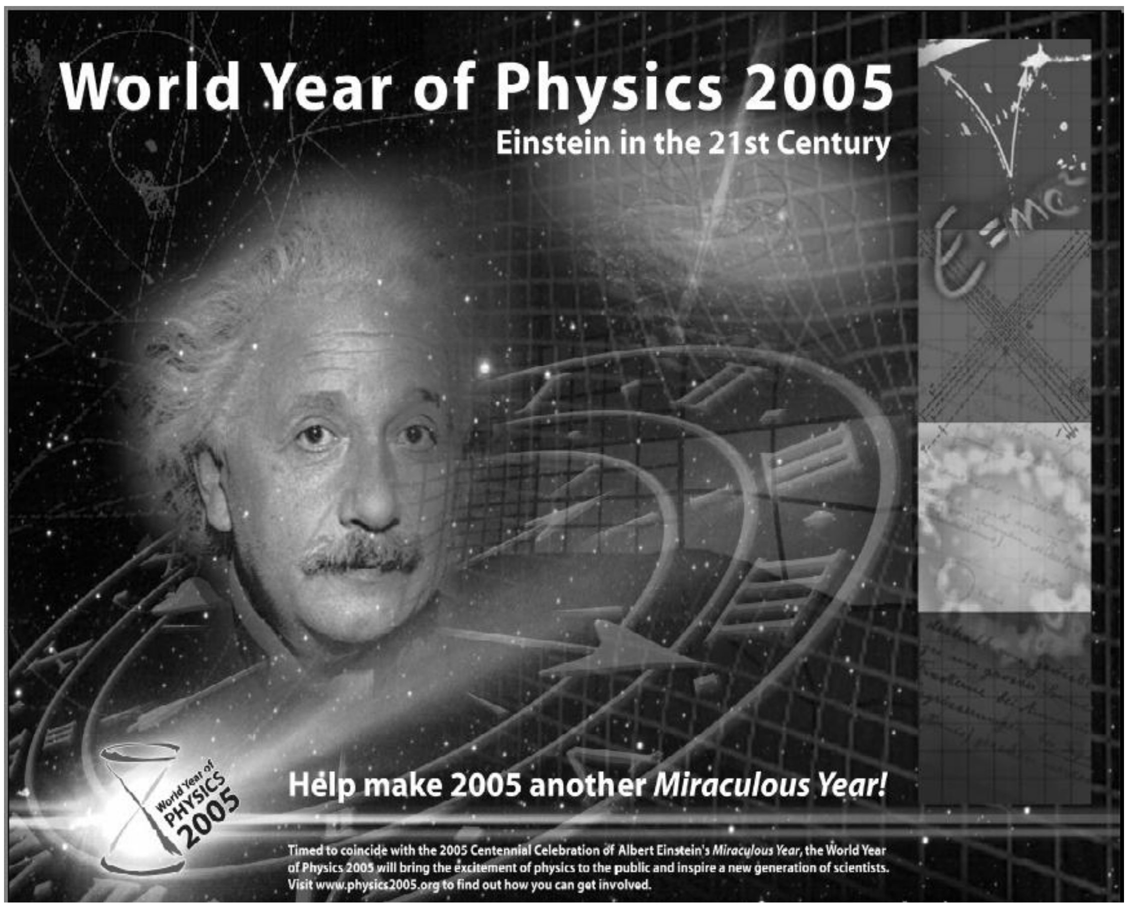
Revolutions in Particle Physics

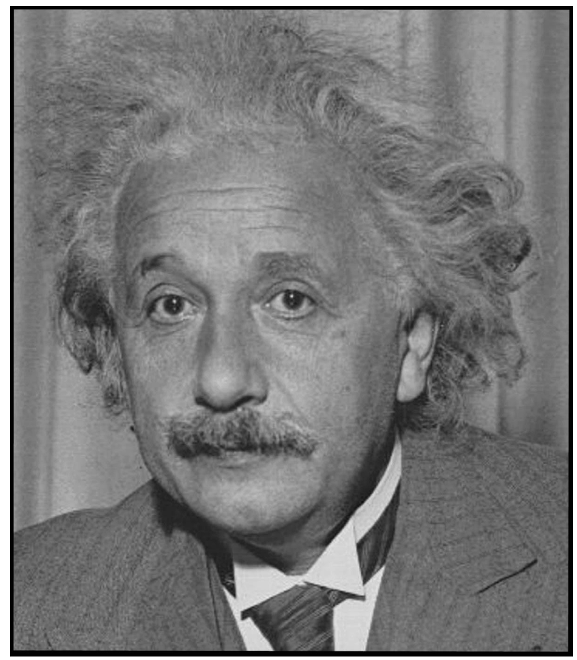
Sally Dawson
BNL

The First Revolution



Einstein's Dream

- Is there an underlying simplicity in the laws of nature?
- Einstein dreamed of a unified picture
- He failed to unify electromagnetism and gravity



A Decade of Discovery

- Electroweak Theory
- Neutrino flavor oscillations
  - Three separate neutrino species
- Understanding QCD
- Discovery of top quark
- B meson decays violate CP
- Flat universe dominated by dark matter & energy
- Quarks and leptons structureless at TeV scale

Discoveries have us poised for next revolution

EM and Weak Theory in 1960




- Dirac introduced theory of electron - 1926
- Theoretical work of Feynman, Schwinger, Tomonga resulted in a theory of electrons and photons with precise predictive power
- Example: magnetic dipole of the electron [(g-2)/2] $\mu = g \, (e\hbar/2mc) \, S$
    - <u>current values of electron (g-2)/2</u>

theory: $0.5\,(\alpha/\pi) - 0.32848\,(\alpha/\pi)^2 + 1.19\,(\alpha/\pi)^3 + ..$

$= (115965230 \pm 10) \times 10^{-11}$

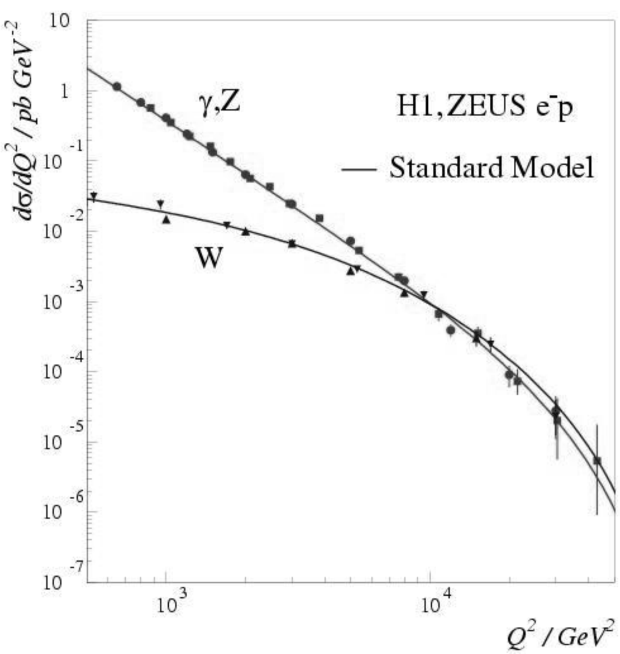
experiment $= (115965218.7 \pm 0.4) \times 10^{-11}$

We can calculate!

Slide from Jim Brau

Desire for Unification is a Guiding Theme

HERA



Charged and neutral currents unify at 100 GeV

Model requires Higgs boson or something like it for consistency!

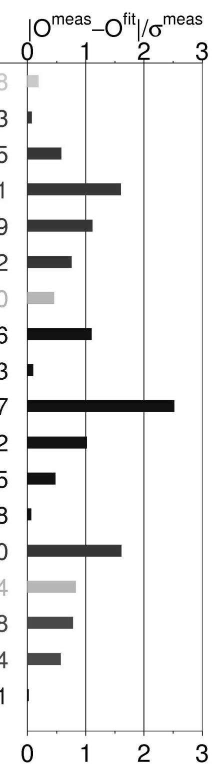
Electroweak Theory is Precision Theory

We have a model….
And it works to the 1% level

Gives us confidence to predict the future!

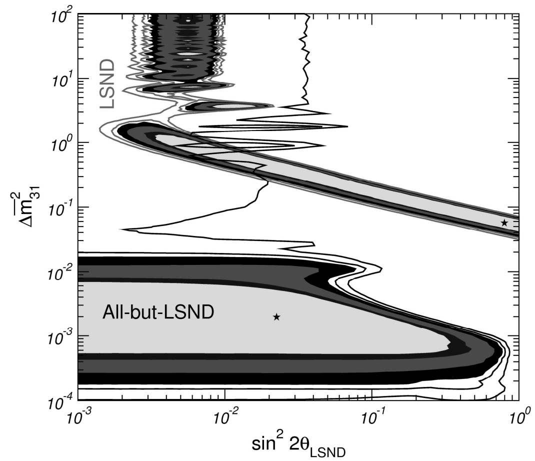
Winter 2004

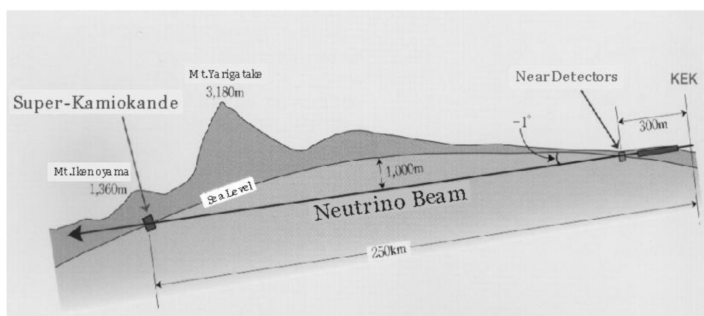
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



Neutrinos have Mass

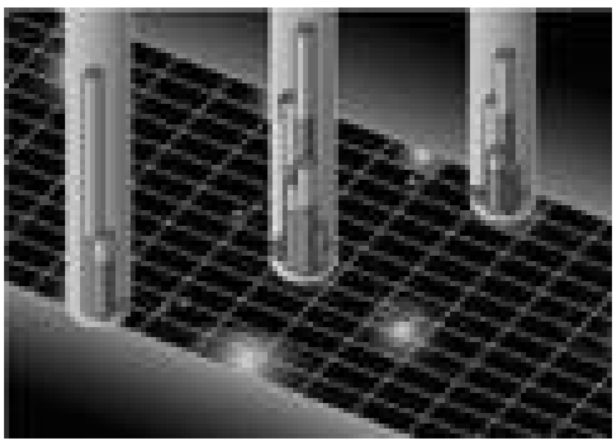
- Irrefutable evidence accumulated in last decade
- Neutrinos change their type
- But our (incredibly successful) model doesn’t accommodate neutrino masses

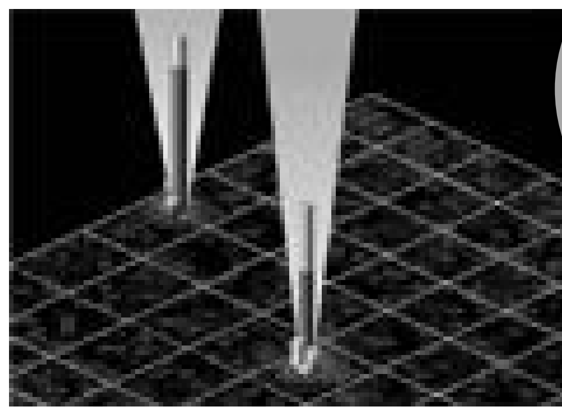




Understanding QCD

- Protons are made of quarks and gluons
- 2004 Nobel prize to Gross, Politzer, Wilczek

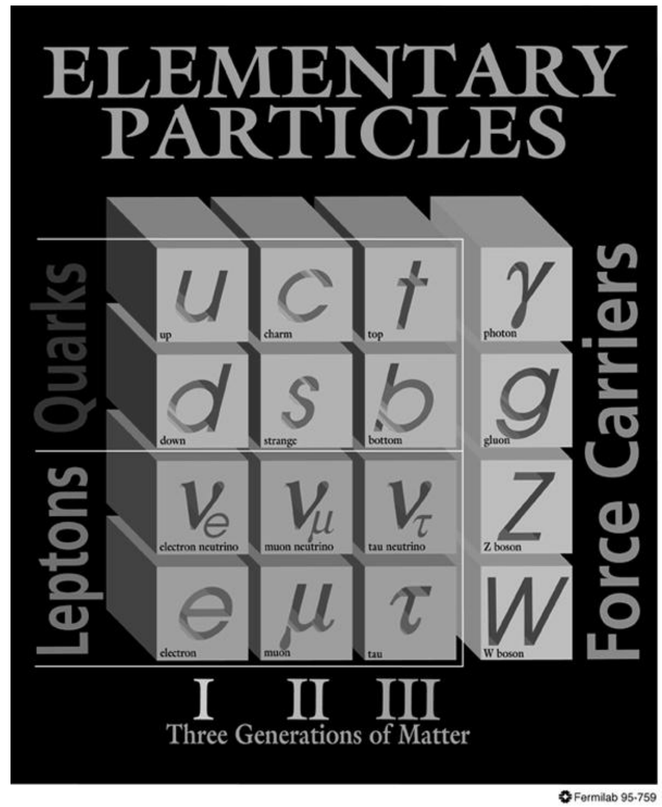




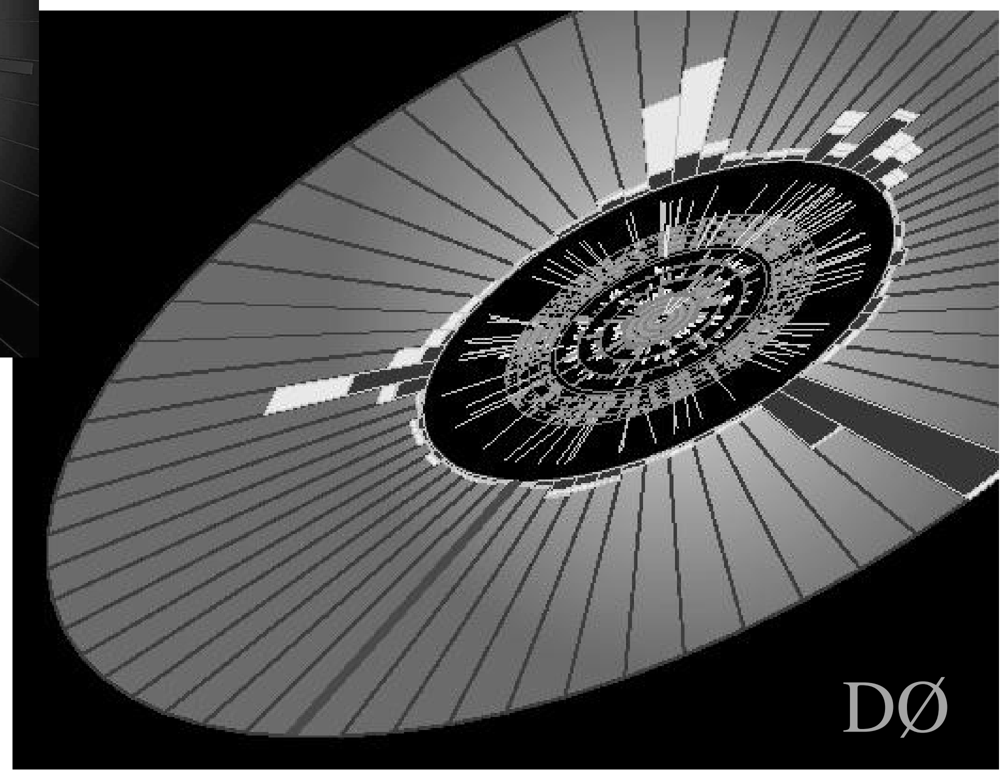
Quarks and gluons act like pointlike particles

Model Needs Top Quark

- Top quark completes 3rd generation
  - Why are there 3 generations, anyways?
- Theory inconsistent without top



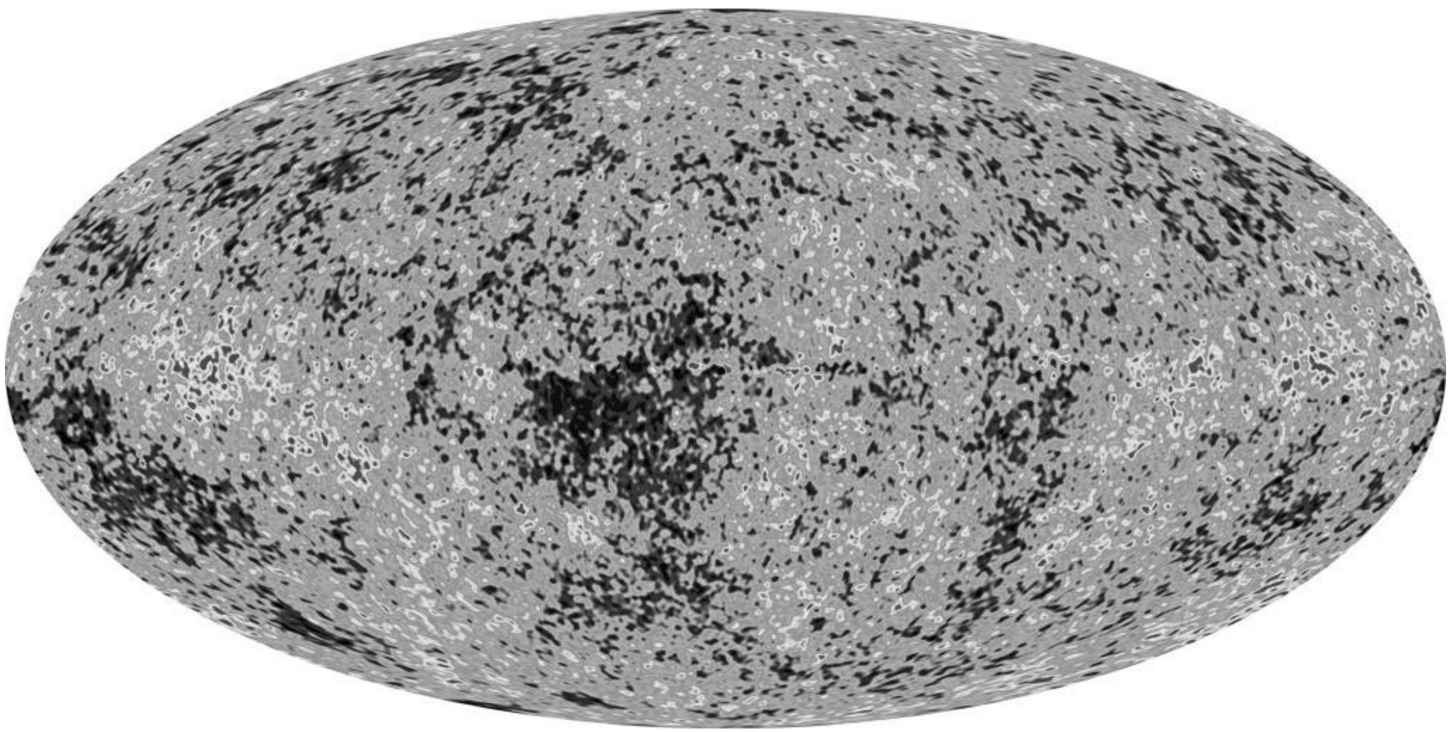
Top Quark Discovered at Fermilab



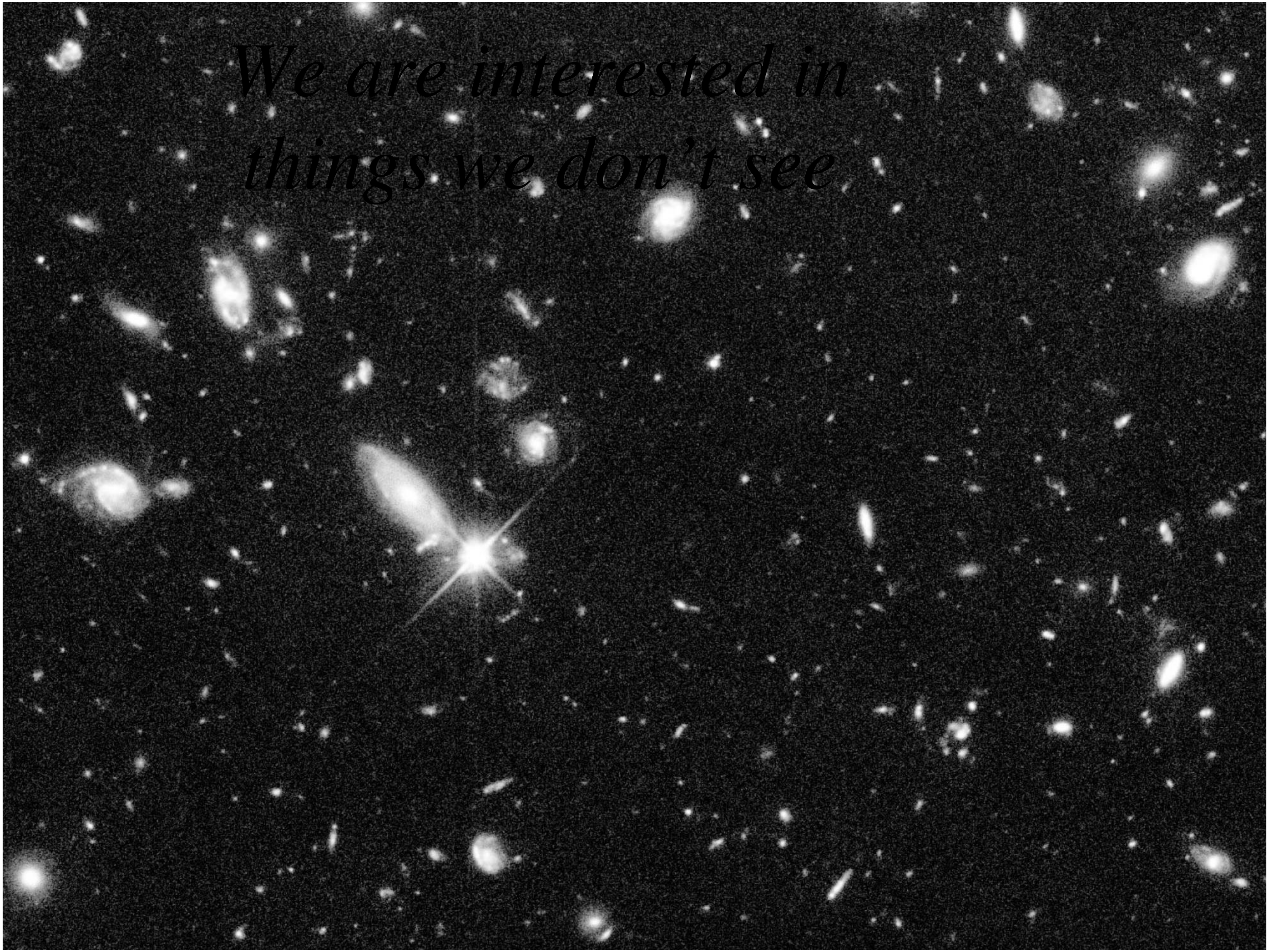
Why is it so heavy?

M_t=175 GeV

We live in special times

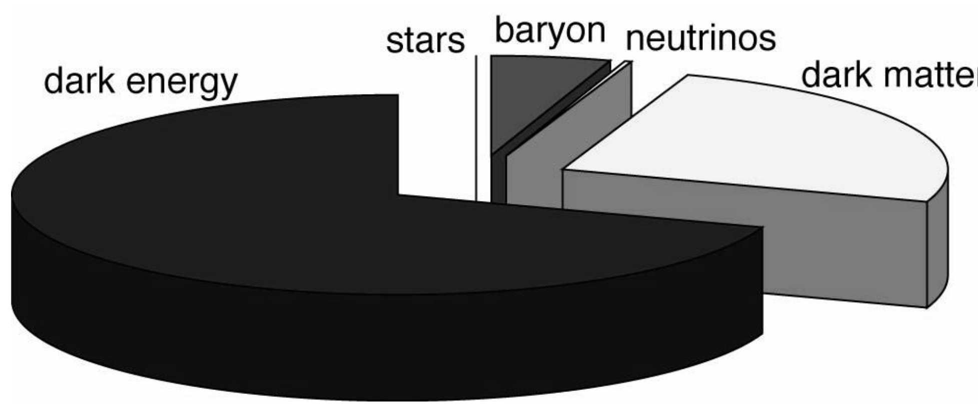


We have a census of the universe


We are interested in
things we don’t see

The Universe has an Energy Budget Crisis

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%



The Cosmic Questions

- What is Dark Matter?
- What is Dark Energy?
- How much is the neutrino component?
- What is the evidence for dark matter and dark energy? How do we know there is missing mass?

These questions connect particle physics and cosmology in an inescapable way

Discoveries of last decade point to new discoveries

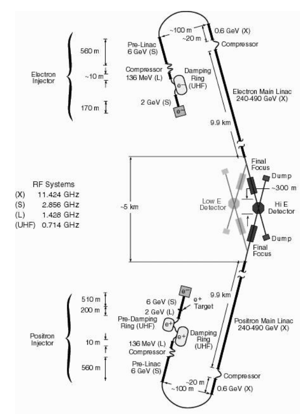
- Incredibly successful model
- Our model cannot explain dark matter, dark energy, neutrino masses, why the top quark is so heavy……
- It points to an energy scale of 1 TeV as place where physics explaining our questions might lurk

Explaining why 1 TeV is special is central point of this talk!

Science Timeline

Tevatron | LHC | LHC Upgrade | ILC

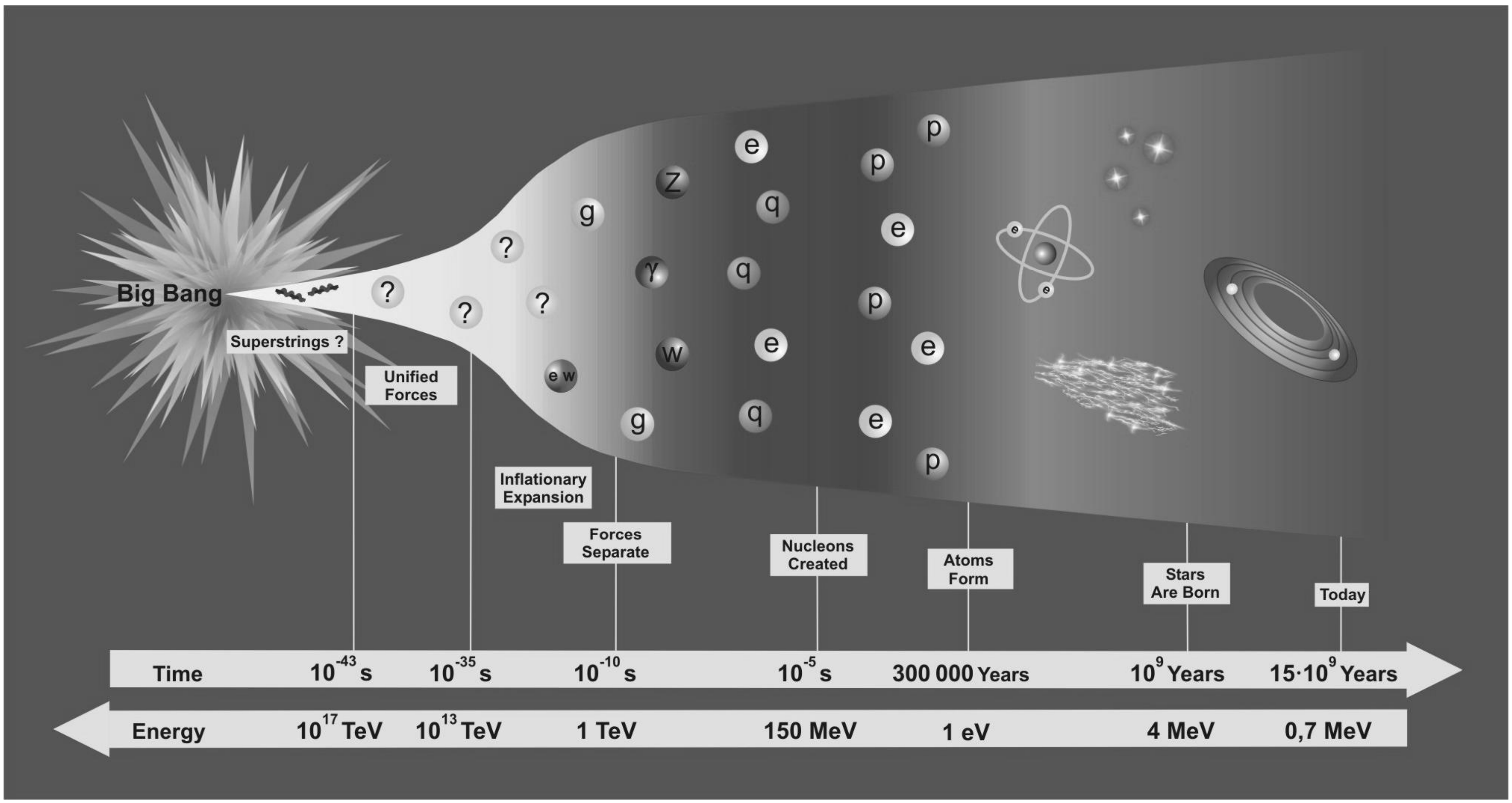
2003 | 2007 | 2012



Large Hadron Collider (LHC)

- proton-proton collider at CERN (2007)
- 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf*. 2TeV @ Fermilab
  (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV

High Energy Probes Early Universe



Linear Collider is Next

- Initial design, $\sqrt{s} = 500\ GeV$
- Luminosity $\approx 10^{34}\ /\ cm^2\ /\ \sec$

  $\rightarrow 300\ fb^{-1}\ /\ year$

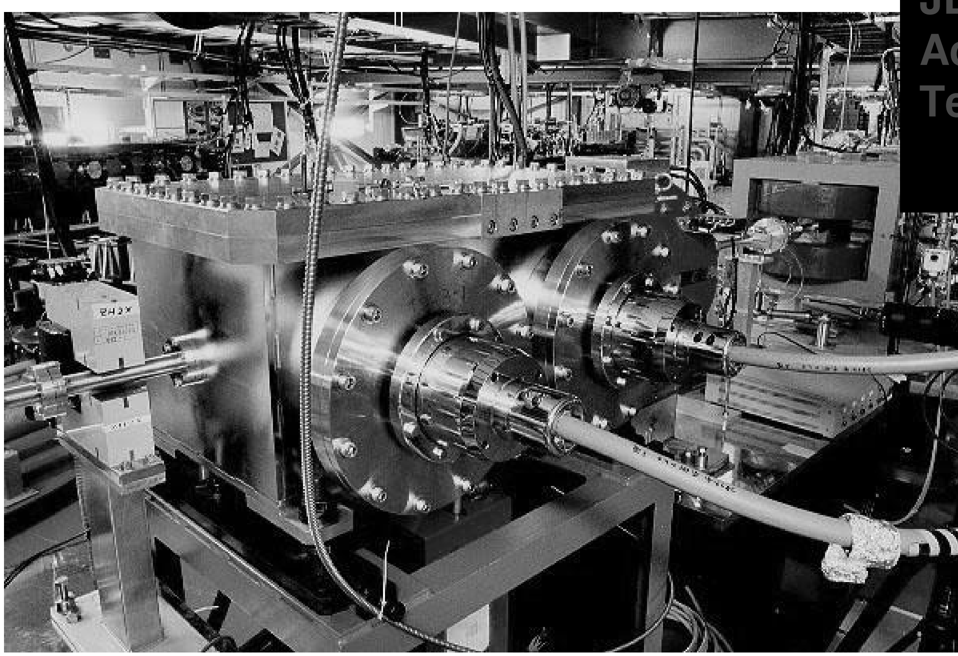
- $\approx$ 15 miles long
- International project
- 80% e^- polarization
- Physics arguments for 1 TeV energy scale

  Energy upgrade a must!

e^+e^- collisions are pointlike

The international accelerator community believes that a TeV-scale linear collider can be successfully built

NLC
High Power
Klystron



JLC
Accelerator
Test Facility

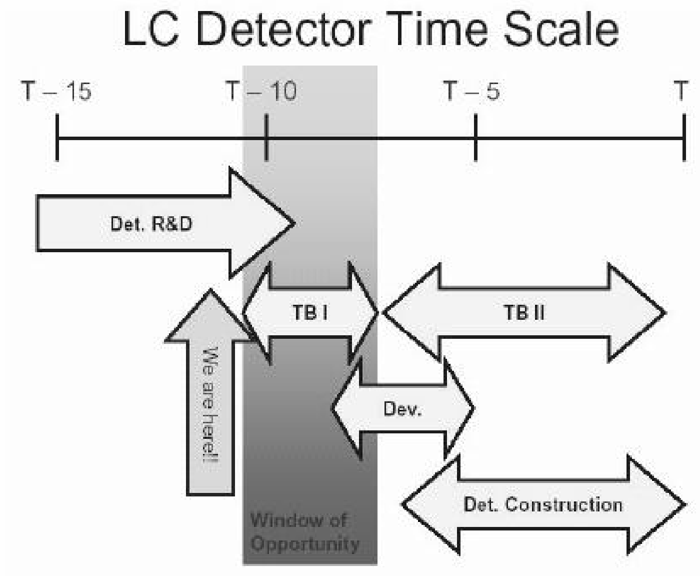
TESLA
Superconducting
Cavity

Progress on the International Front

- International Team recommended cold technology in August, 2004
- Global Design Effort (GDE) for International Linear Collider (ILC)
  - Barry Barish, Chair
- Regional Centers in Asia, Europe, North America
  - Site independent design
- Optimistic time frame has construction decision in 2009, physics in 2015

LHC results *before* construction decision

Long Lead Time for ILC



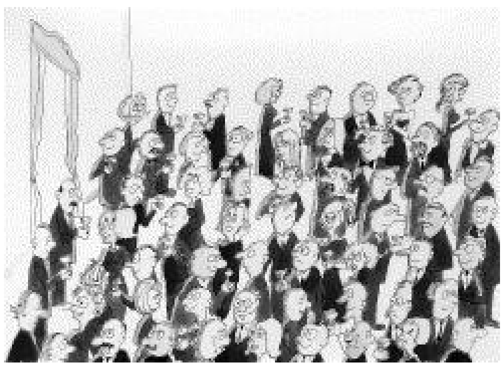
Time	T=2015	Tasks
T – >10~11	Before 2005	Detector R&D
T – 10~11	2005~6	Test Beam I
T – 8~9	2006~7	•Detector Technology chosen. •Detector Development and design begins
T – 6	2009	Detector Construction begins Test Beam II (Calibration)
T	2015	LC and Detector ready

Unanswered Questions and the LHC/ILC Connection

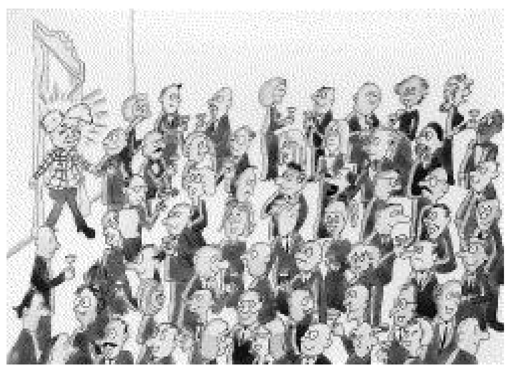
- Why is the top quark so heavy?
- Can we understand the patterns of fermion and gauge boson masses?
- Simplest explanation for masses is Higgs mechanism

The Higgs Mechanism for Dummies

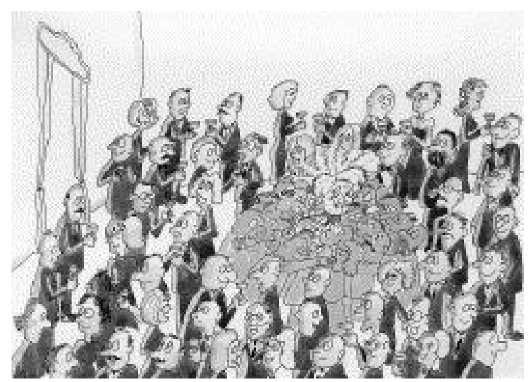
Cocktail party…room full of people…like Higgs field



A celebrity walks in…



…people crowd around celebrity…resisting his movement…like acquiring Mass.



Is Mass Due to a Higgs Boson?

- Higgs couplings of SM fixed

$$g_{ffh} = \frac{m_f}{246\,GeV}$$
$$g_{WWh} = gM_W$$

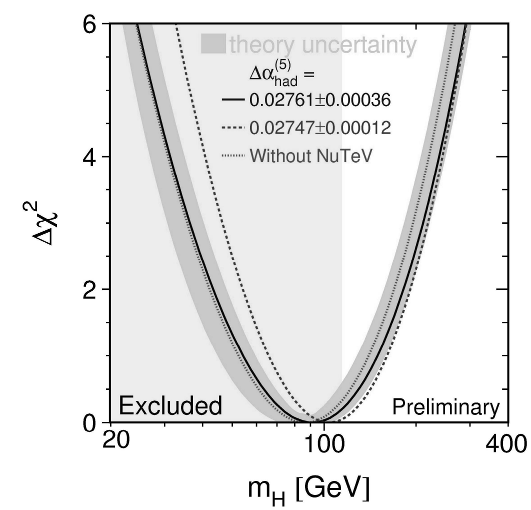
- Production rates at LEP, Tevatron, LHC fixed in terms of mass
- Direct search limit from LEP:

$$M_h > 114\,GeV \text{ @ } 95\%\, cl$$

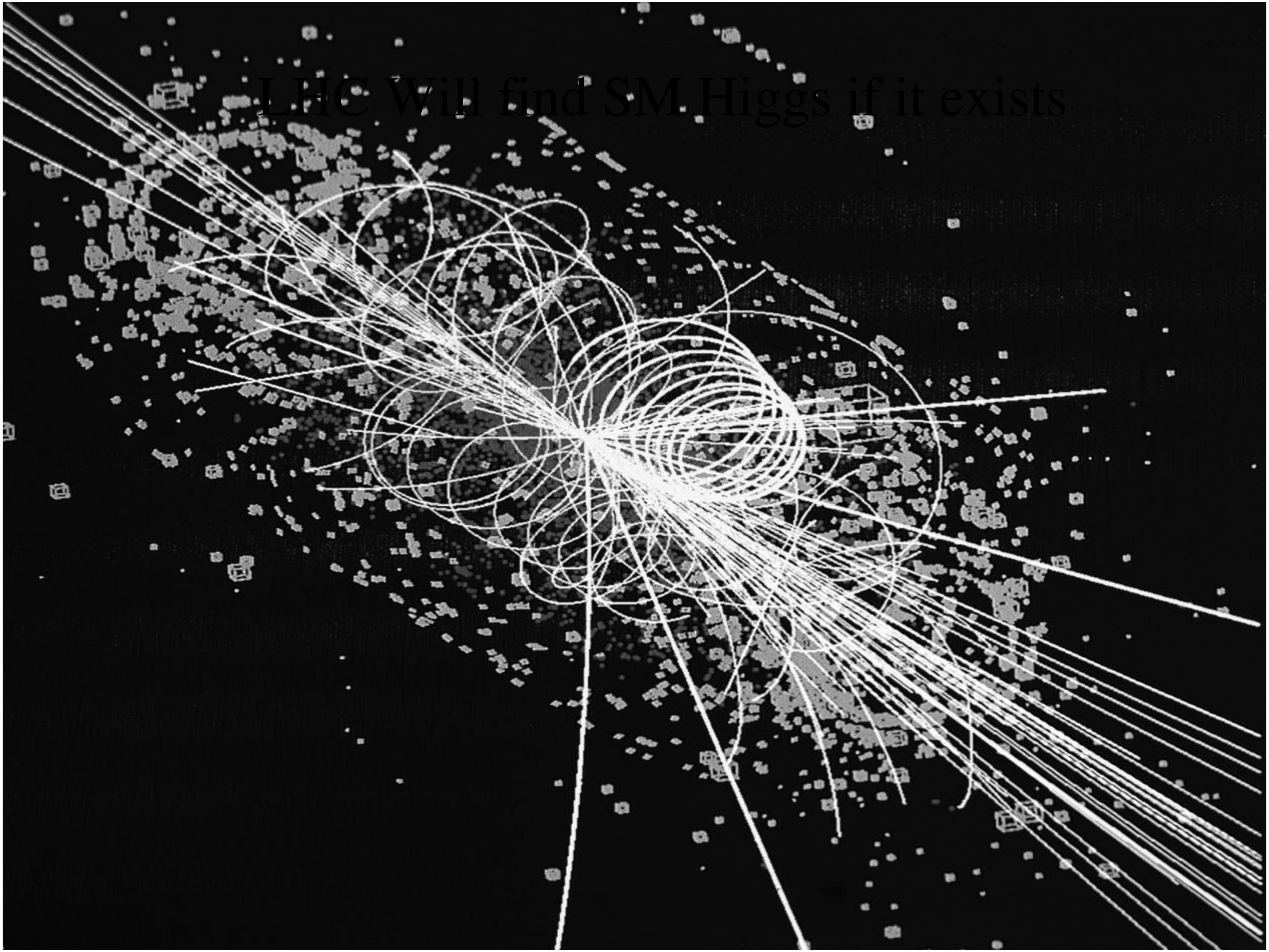
- Higgs contributions to precision measurements calculable

Precision measurements:

$$M_h < 219\,GeV \text{ @ } 95\%\, cl$$

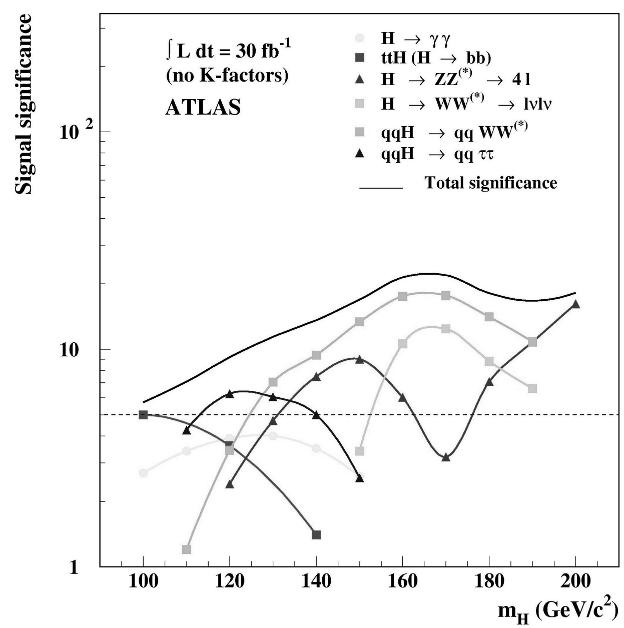


LHC Will find SM Higgs if it exists



LHC and the Higgs

- LHC will discover Higgs boson if it exists
- Sensitive to M_h from 100-1000 GeV
- Higgs signal in just a few channels
- Physics circa 2007



Discovery isn't Enough

- Is this a Higgs or something else?
- Linear Collider can answer critical questions
  - Does the Higgs generate mass for the W,Z bosons?
  - Does the Higgs generate mass for fermions?
  - Does the Higgs generate its own mass?

Two Paths to Discovery

- High Energy
  - Operating at the energy frontier
  - Direct discovery of new particles
  - Tevatron and LHC
- High Precision
  - Infering new physics effects from high energy scales through precision measurements at low energy

Combining both stategies gives much more complete understanding than either one alone

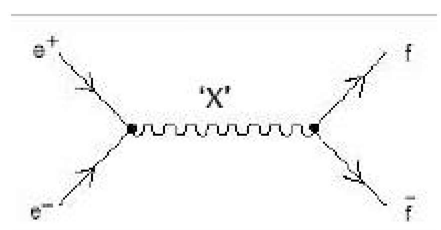
Footprints of Heavy Particles

- Skilled tracker can determine
  - Type, size, speed of animal
- Without direct observation of animal
  - Even if animal is extinct

Slide from JoAnne Hewett

ILC probes footprints of Heavy Particles

- ILC sensitive to X much heavier than ILC energy scale
- Tools to detect X
  - Deviations in production rates
  - Deviations in production properties



Is it a Higgs?

- Measure couplings to fermions & gauge bosons

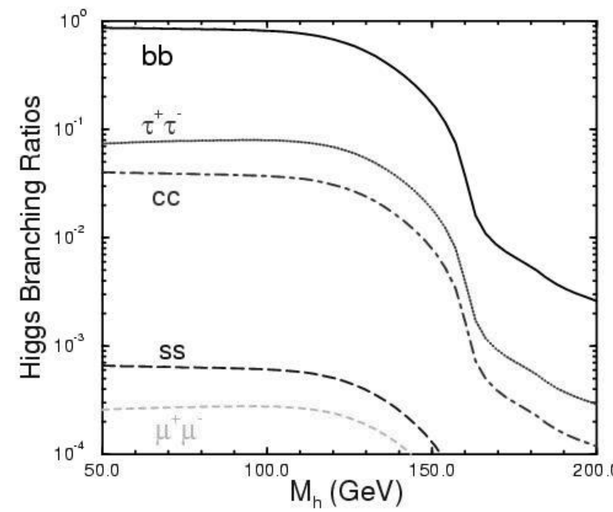
$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

- Measure self interactions

$$V = \frac{M_h{}^2}{2}h + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$



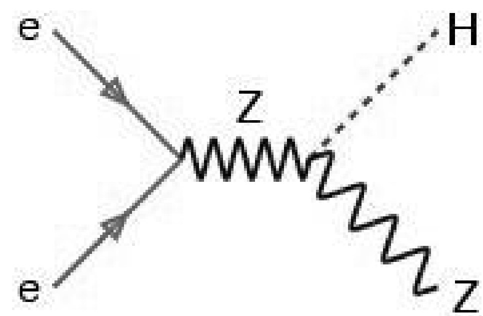
Measuring these rates tracks heavy particles and possible new physics

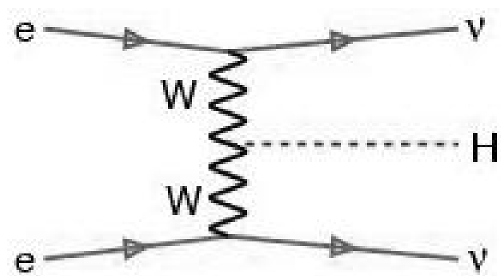
Linear Collider is a Higgs Factory

- $e^+e^- \to Zh$ produces 40,000 Higgs/yr
- Clean initial state gives precision Higgs mass measurement

$$M_h^2 = s - 2\sqrt{s}E_Z + M_Z^2$$

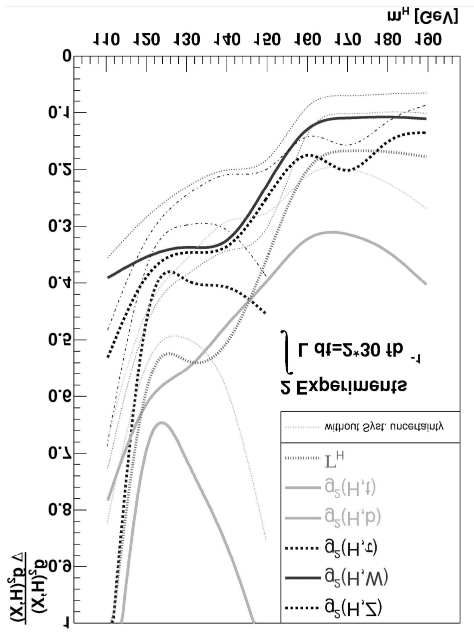
- Model independent Higgs branching ratios
- Clean probe of underlying model





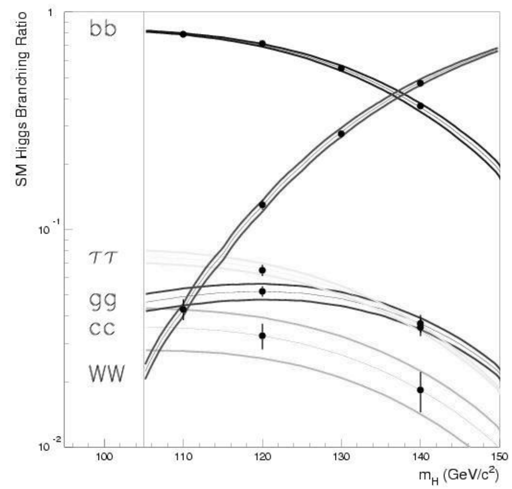
Does the Higgs Generate Mass?

LHC



Duhrssen, Rainwater…., hep-ph/0407190

Note scales



e^+e^- LC at $\sqrt{s}$=350 GeV

L=500 fb^{-1}, M_h=120 GeV

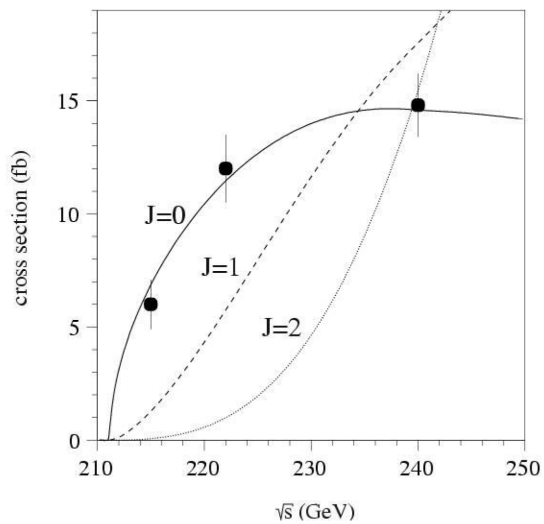
Linear Collider is the place!

Battaglia & Desch, hep-ph/0101165

Measuring the spin of the Higgs

Threshold behavior measures spin

[20 fb^{-1} /point]



Linear collider can change initial state energy to do energy scans

Very hard to do at the LHC

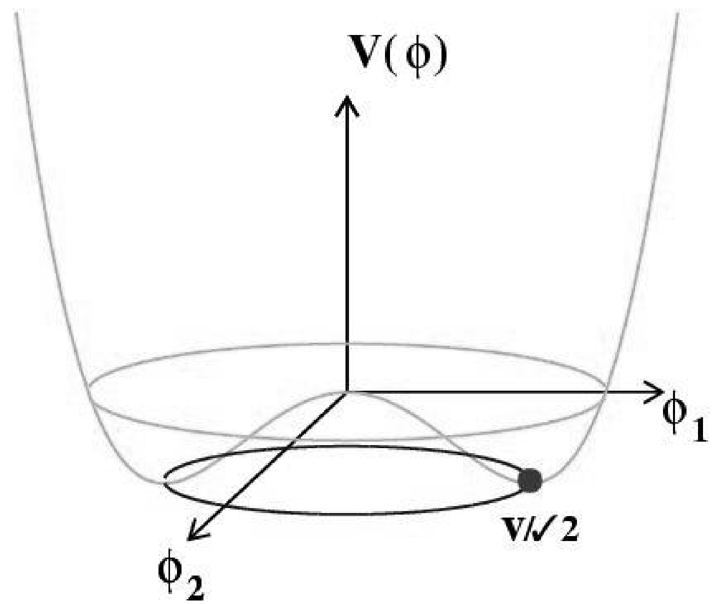
Does the Higgs Generate its own Mass?

$$V = \frac{M_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

Fundamental test of model!

SM: $\lambda_3 = \lambda_4 = M_h^2 / 2v^2$

Requires production of multiple Higgs bosons



We need both λ_3 and λ_4

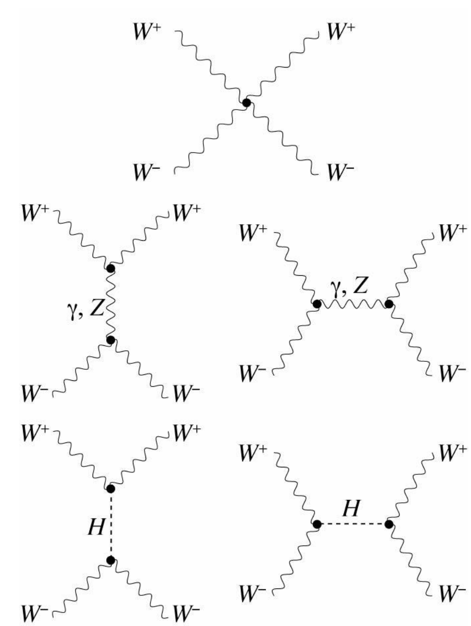
Challenging at both the LHC and an ILC

The Higgs and the TeV Scale

- Without Higgs, *W*-boson scattering grows with energy

  $$A \sim G_F s$$

  - Violates conservation of probability at E=1.8 TeV (unitarity)
- SM Higgs has just the right couplings to restore unitarity



LHC measures WW scattering

Win/win situation: Light Higgs or new physics at the TeV scale!

Problem with this Picture…..

- Fundamental Higgs is not natural
- Quantum corrections to M_h are quadratically divergent

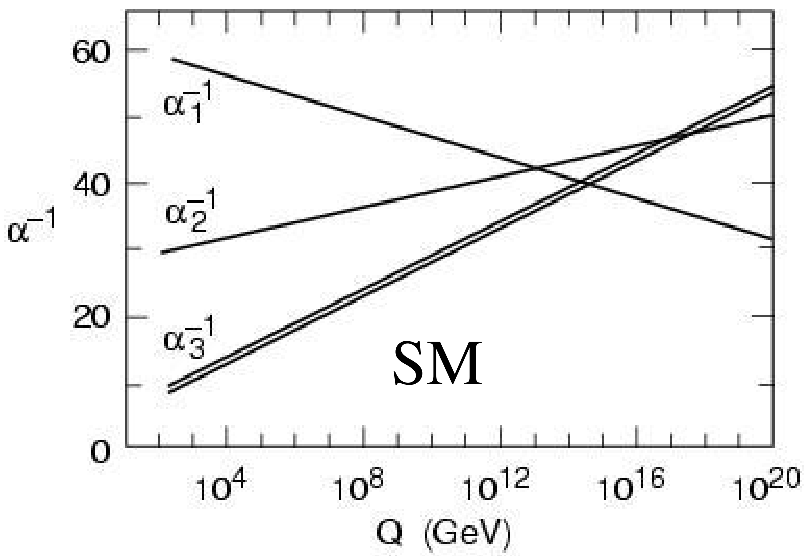
$$\delta M_h^2 \approx \Lambda^2$$

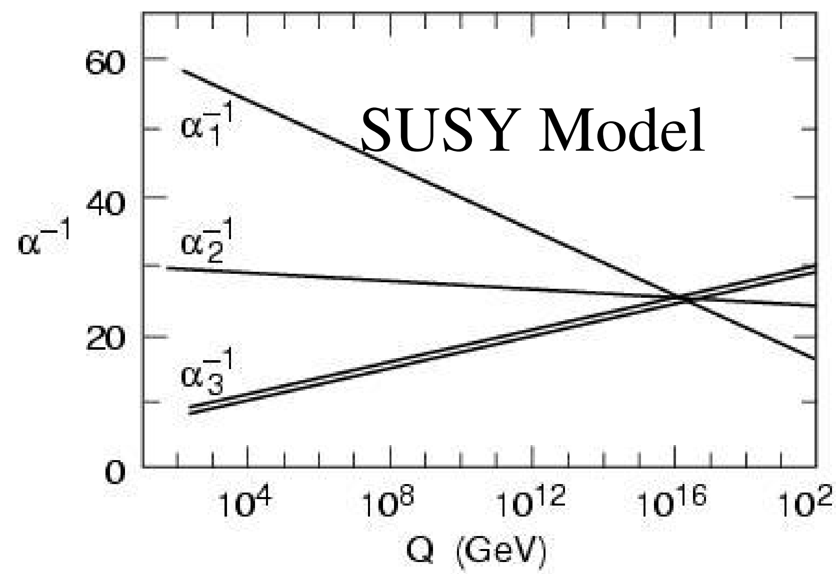
- So enormous fine-tuning needed to keep Higgs light

$$\delta M_h^2 \backslash M_h^2 \approx M_W^2 \backslash M_{pl}^2 \approx 10^{-32}$$

Einstein's Dream of Unification

- Coupling constants change with energy





Supersymmetric Theories

- Predict many new undiscovered particles (>29!)
- Very predictive models
  - Can calculate particle masses, interactions, everything you want in terms of a few parameters
  - ***Solve naturalness problem of SM***
- Any Supersymmetric particle eventually decays to the lightest supersymmetric particle (LSP) which is stable and neutral!!!

Dark Matter Candidate

Supersymmetry Raises More Questions

- Can we find it?
- Can we tell what it is?
- Masses of new particles depend on mechanism for breaking Supersymmetry
- Couplings of new particles predicted in terms of few parameters
- Simplest version has 105 new parameters

Many New Particles in Supersymmetric Models

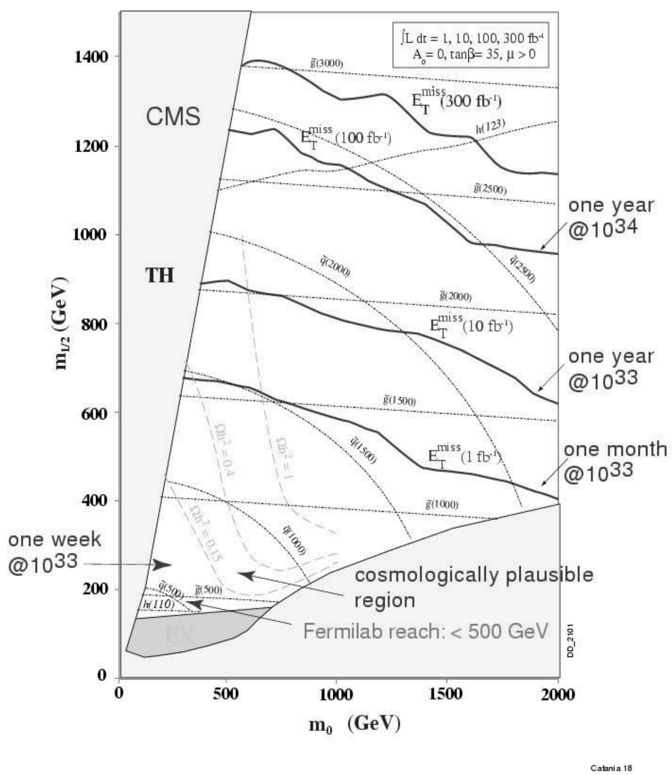
- Spin ½ quarks $\Rightarrow$ spin 0 squarks
- Spin ½ leptons $\Rightarrow$ spin 0 sleptons
- Spin 1 gauge bosons $\Rightarrow$spin ½ gauginos
- Spin 0 Higgs $\Rightarrow$spin ½ Higgsino

Experimentalists dream….many particles to search for!

What mass scale?

Supersymmetry is broken….no scalar with mass of electron

LHC will find Supersymmetry



Catania, CMS

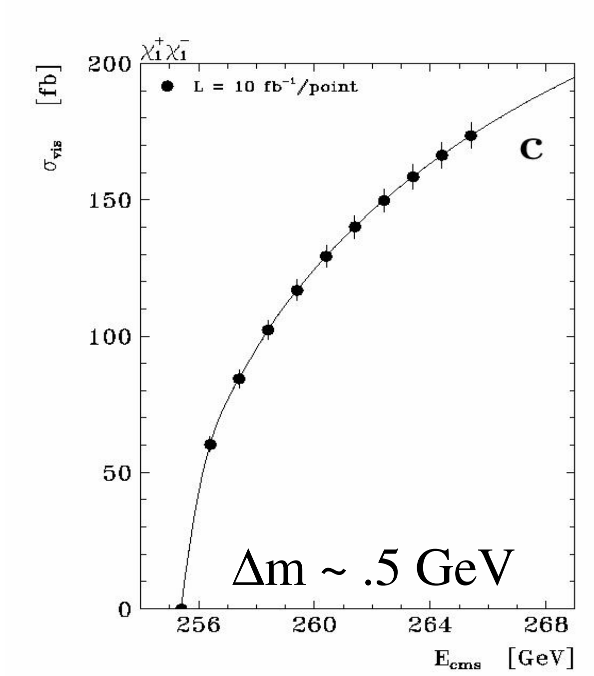
- Discovery of many SUSY particles is straightforward
- Untangling spectrum is difficult

  ⇒ all particles produced together
- SUSY mass differences from complicated decay chains

Linear Collider can change its Energy

- Precision measurements of masses by tuning energy to sit at threshold

Chargino Pair Production at LC

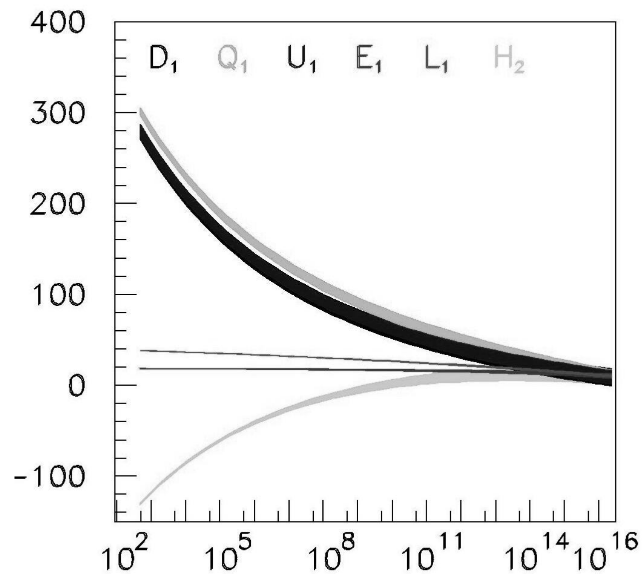


Slope of curve very sensitive to mass

Combine LHC/ILC masses to get window to high scale

- Different masses measured at LHC and ILC

Do masses unify?



The New York Times

July 23, 2008

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

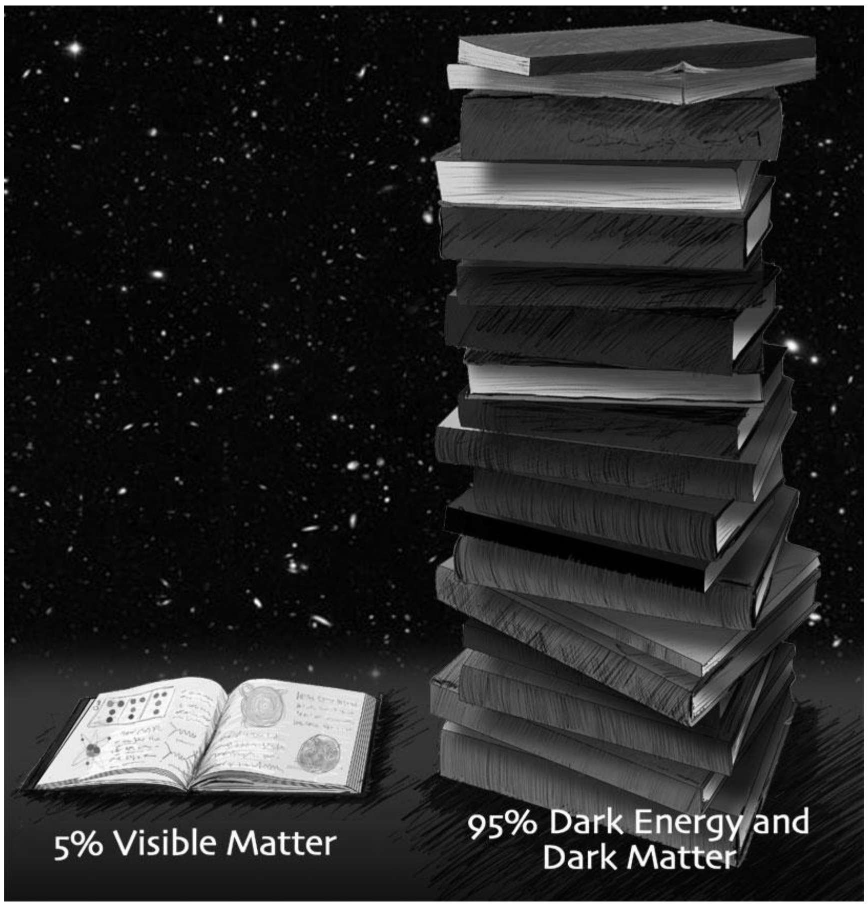
still a long way to

"Halliday-Resnick" level confidence

"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Slide from Hitoshi Murayama

Dark Matter and Supersymmetry



Can we produce dark matter in a collider and study all its properties?

Supersymmetry has Dark Matter Candidate

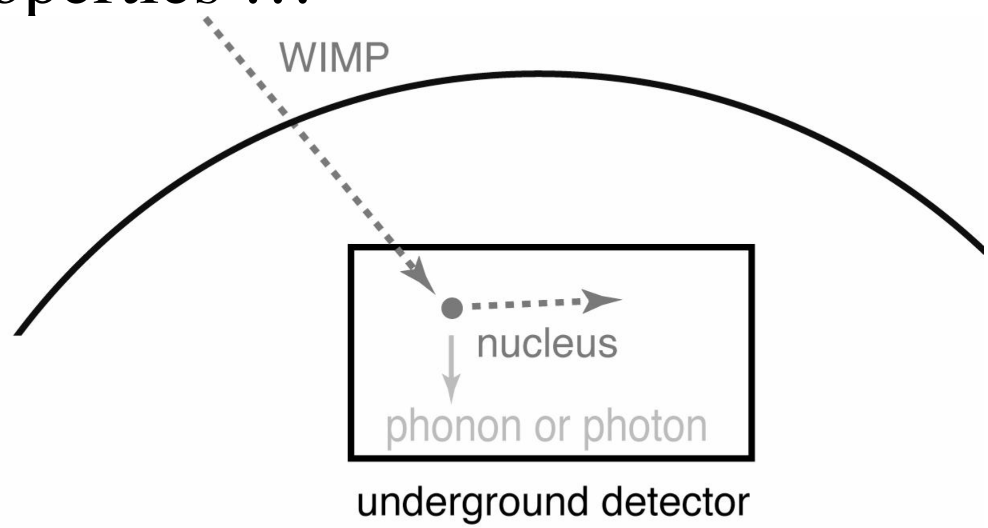
- Supersymmetric models have natural dark matter candidate
- Lightest supersymmetric particle (LSP) is neutral and weakly interacting
- On general grounds, LSP contributes correct amount of dark matter if its mass is 300 GeV-1 TeV
- Supersymmetric particles within reach of LHC and a Linear Collider

Particle Dark Matter

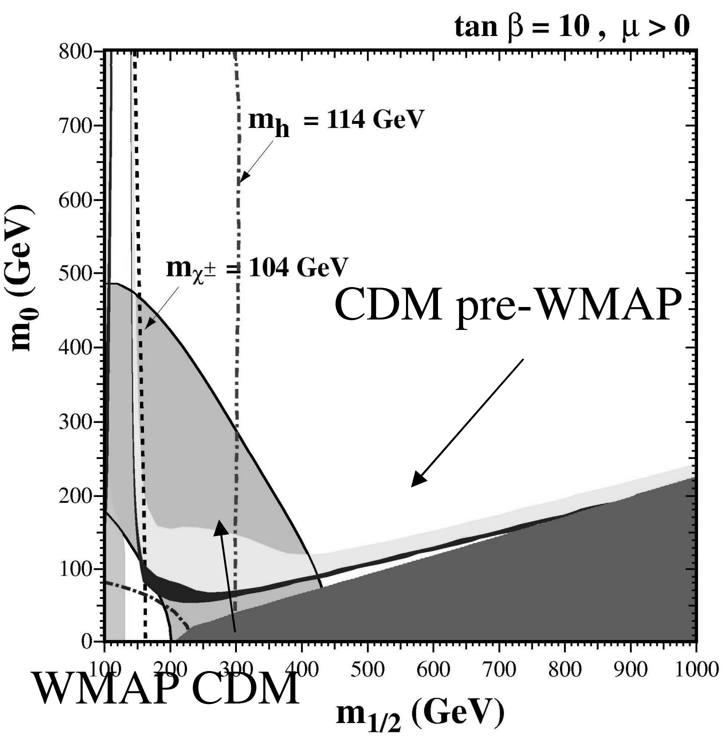
- We'd like to detect WIMPs in the lab
  - To show they're in the galactic halo …
- And to produce them at an accelerator
  - To measure their properties …

WIMP: Weakly Interacting Massive Particle

aka: dark matter candidate



Example: Put it all together



Assume dark matter is LSP

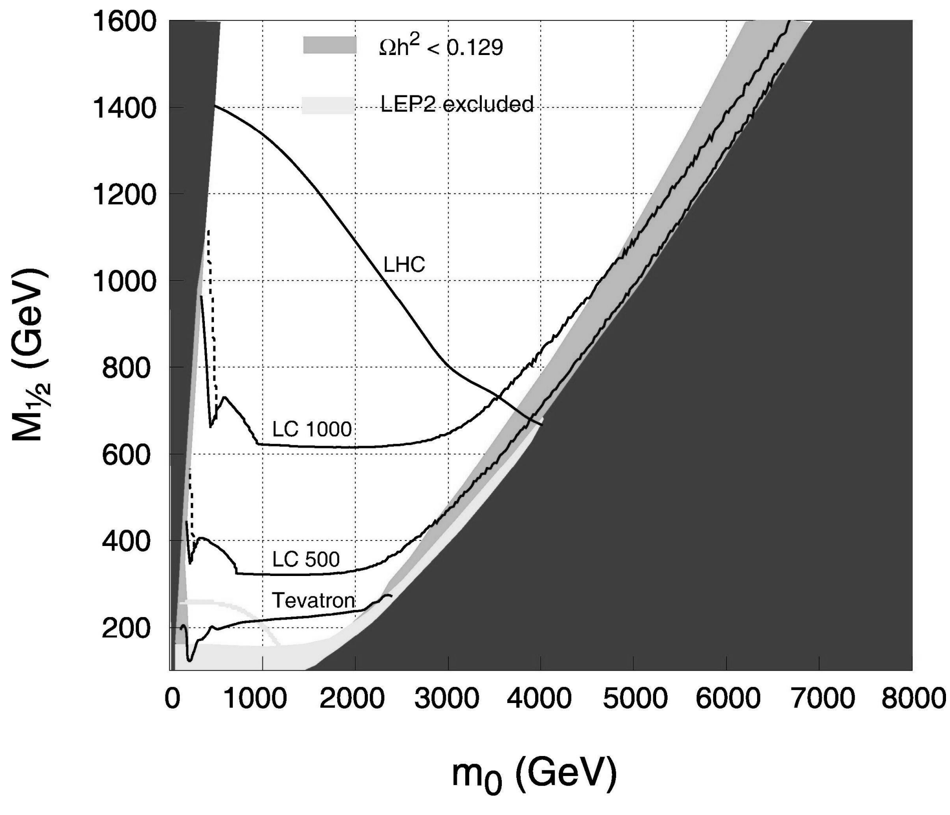
M(LSP) ≈ .4 $m_{1/2}$

Simple Supersymmetric theory
with 2 parameters

Pink is (g-2) assuming e^+e^- solution
for hadronic contribution

Blue is cosmologically preferred
region

If LSP is dark matter, LHC and Linear Collider will see plethora of supersymmetric particles



Dark matter inescapably links particle physics and astrophysics

A major goal of LHC and Linear Collider is to produce the LSP (supersymmetric dark matter candidate) and measure everything about it

Discoveries Ahead!