The Case for a Linear Collider

S. Dawson

BNL

April, 2004

- Asian, European, and American communities all agree
- High Energy Linear Collider is next large accelerator
- ***WHY???***

Why build a linear collider now?

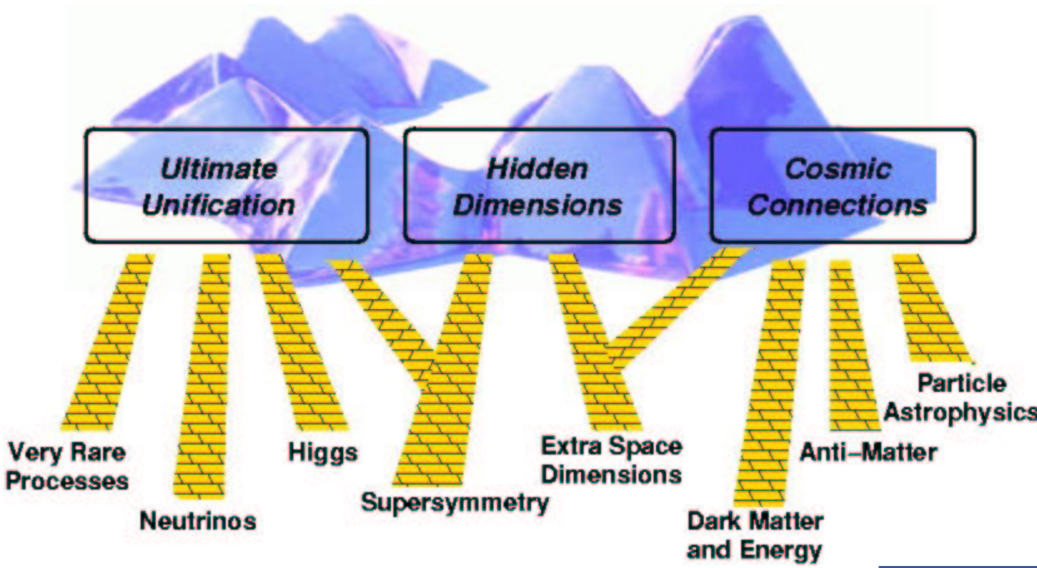
Why not wait and see what the LHC tells us?

Where are we going?

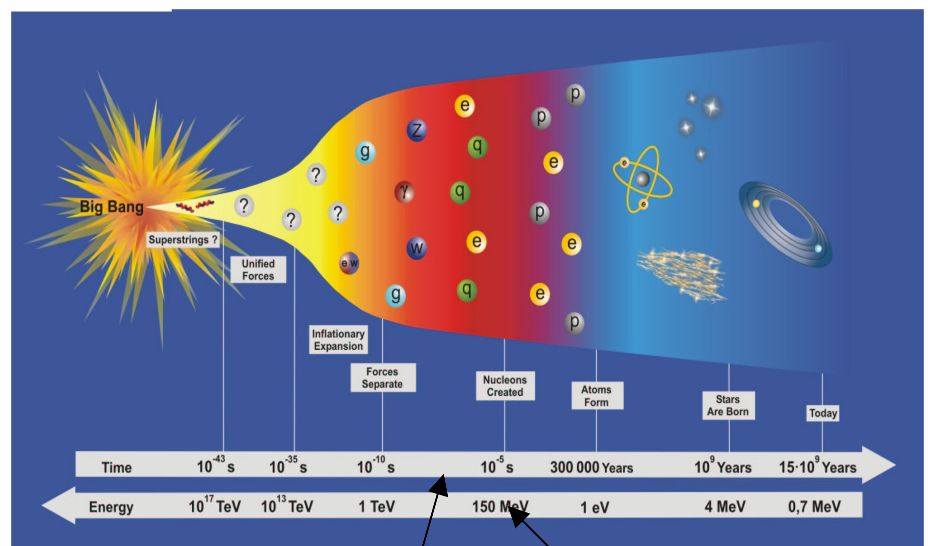
- US high energy community completed long range planning process 2 years ago
- 20 year roadmap for the future
- HEPAP subpanel:

> We recommend that the highest priority of the U.S. program be a high-energy, high-luminosity, electron-positron linear collider, wherever it is built in the world

The Challenge: Connecting the Energy Scales



With what we know now, how can we best decide where to go next?



Tevatron RHIC

Linear Collider is Next

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

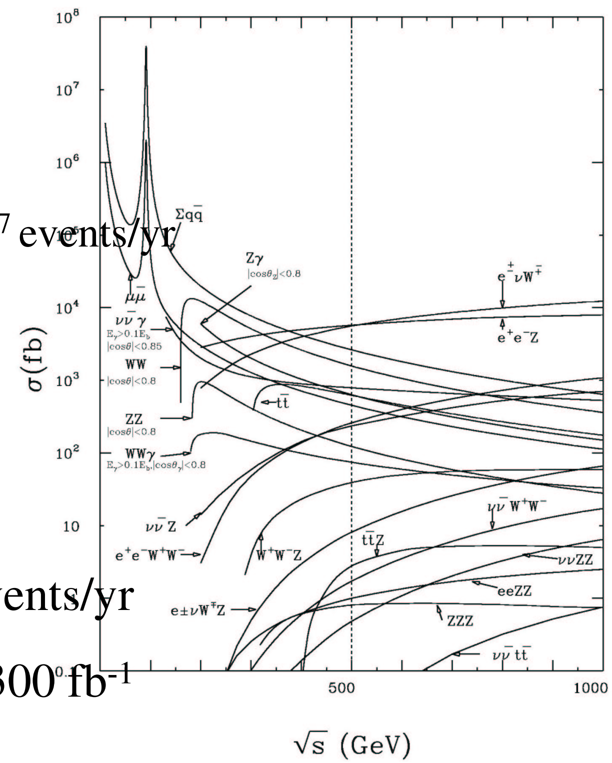
  $\rightarrow 300\, fb^{-1} / year$
- ≈ 15 miles long
- International project
- 80% e^- polarization
- Physics arguments for 1 TeV energy scale

Energy upgrade a must!

e^+e^- collisions are pointlike

Combination of LHC/LC physics probes source of masses

Event Rates:



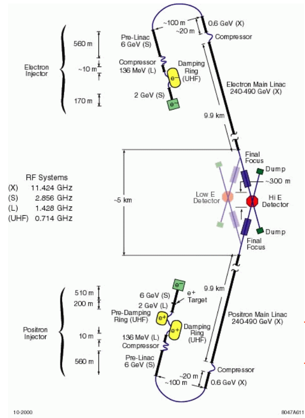
3 x 10^7 events/yr

300 events/yr

with 300 fb^{-1}

$\sqrt{s}$ (GeV)	~500 fb^{-1}	~1000-2000 fb^{-1}
350-400	low-mass h: production rates, BRs, spin; tt production; low-mass SUSY	
500	WW fusion, hWW more SUSY	rare h BRs ($h \to \gamma\gamma, h \to \mu^+\mu^-$) h self coupling
800	charged Higgs; HA better SUSY spectra	tth production; rare h decays
1000-1500	heavy H,A,charged Higgs; SUSY model parameters strongly interacting WW	ttH; Higgs self-couplings heavier Higgs particles

Science Timeline



LC

VLHC

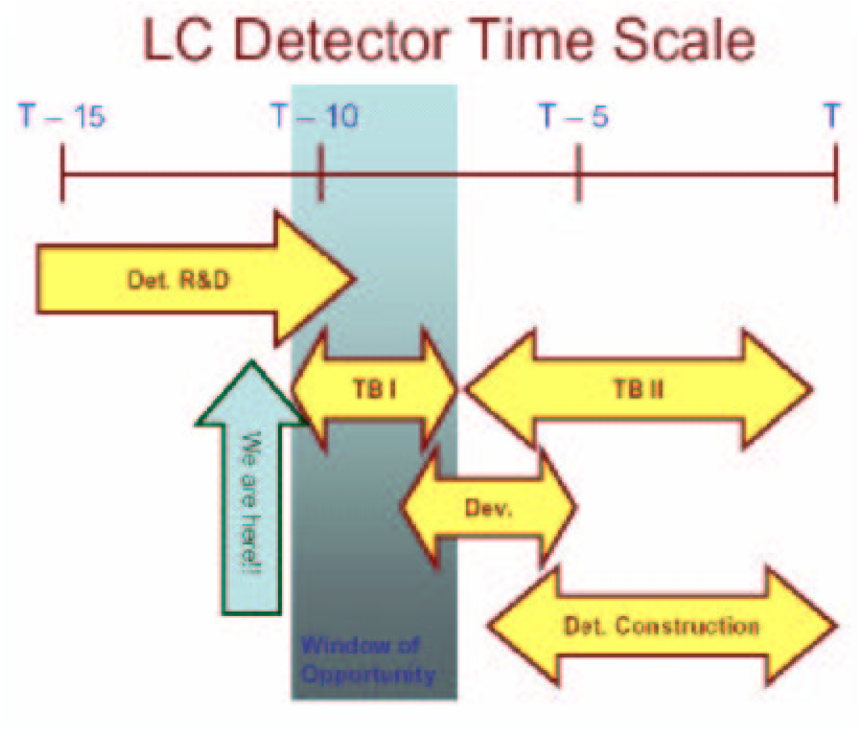
CLIC

Tevatron LHC LHC Upgrade

2003 2007 2012 202x

??????

Must Start Now!!!



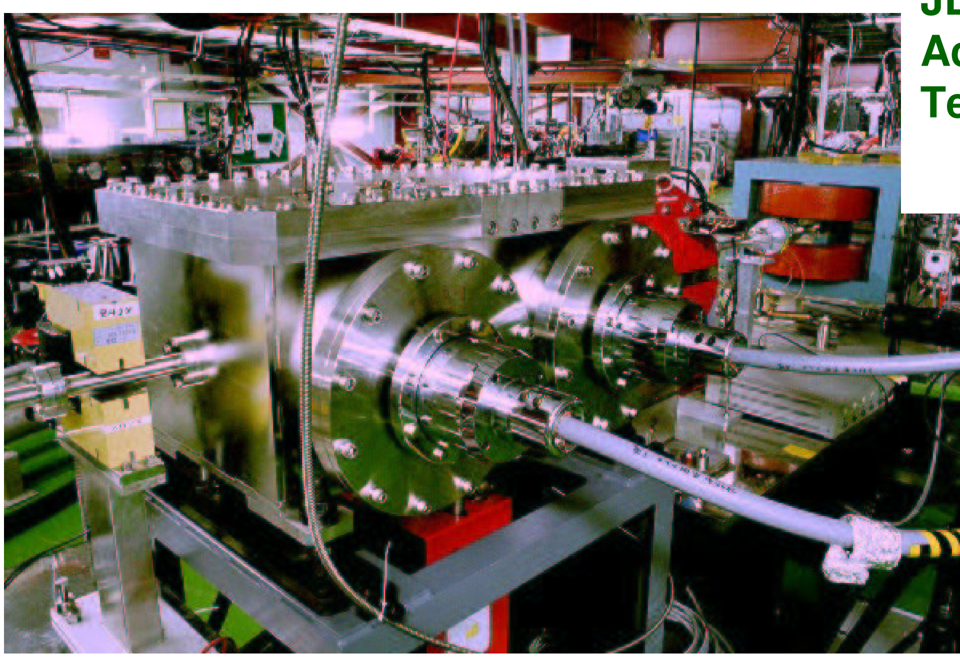
Time	T=2015	Tasks
T – >10~11	Before 2005	Detector R&D
T – 10~11	2005~6	Test Beam I
T – 8~9	2006~7	·Detector Technology chosen. ·Detector Development and design begins
T – 6	2009	Detector Construction begins Test Beam II (Calibration)
T	2015	LC and Detector ready

Progress towards a Linear Collider

- The past two years have seen many important advances toward realizing the linear collider
  - Regional Steering Groups Formed
  - International Steering Committee Formed
  - Scope Defined Internationally
  - Consensus Document Expressed Physics Goals and Drove Scope
  - TRC Evaluation of Technologies
  - ITRP Commissioned and Working
  - Global Design Group Being Planned
  - US (and Japanese) Technology Option Comparisons
  - OECD and Governmental Attention and Deliberation

NLC
High Power
Klystron

- The international accelerator community believes that a TeV-scale linear collider can be successfully built
- Technology choice by end of 2004



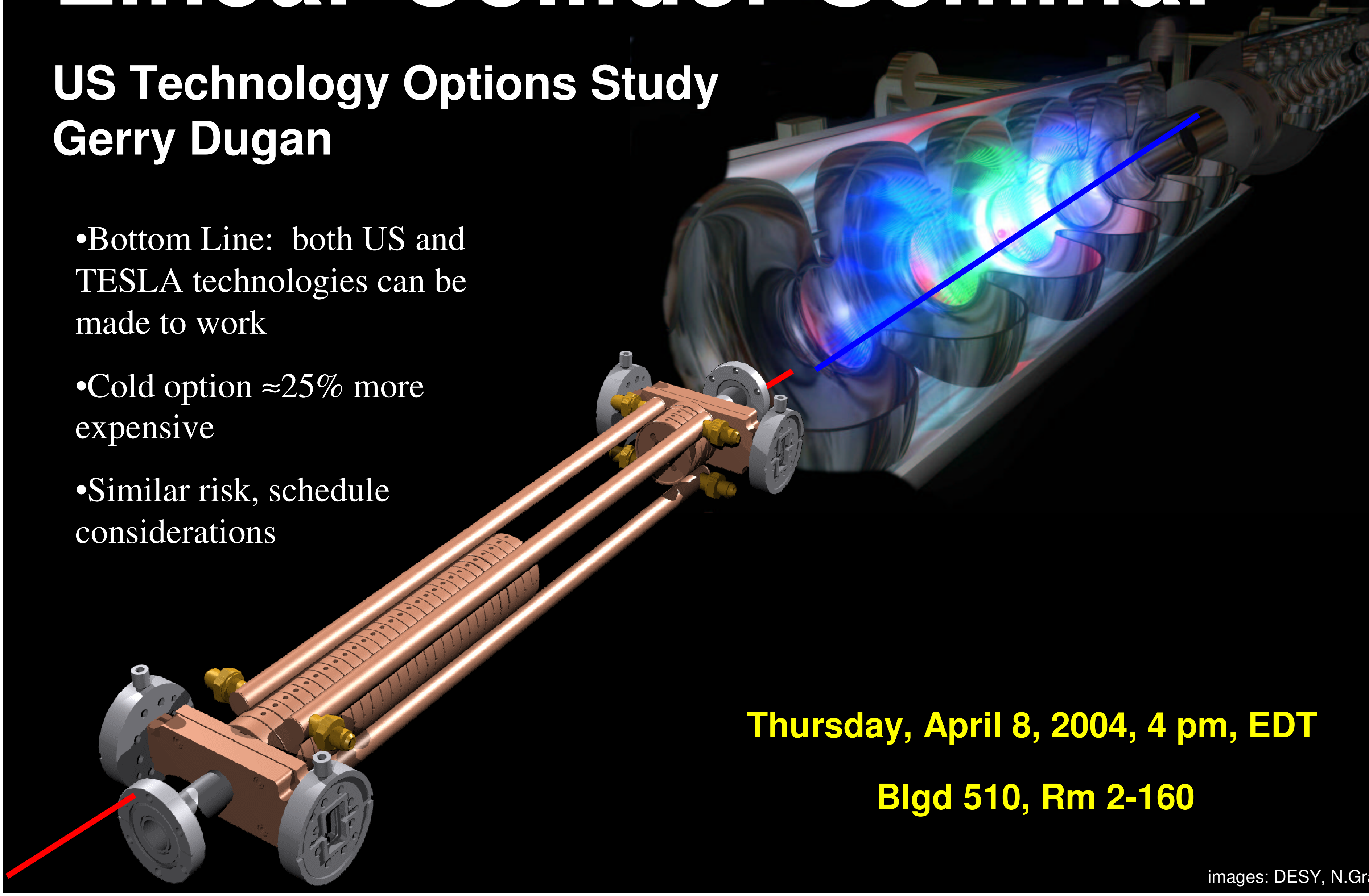
JLC
Accelerator
Test Facility

TESLA
Superconducting
Cavity

Linear Collider Seminar

US Technology Options Study
Gerry Dugan

- Bottom Line: both US and TESLA technologies can be made to work
- Cold option ≈25% more expensive
- Similar risk, schedule considerations



Thursday, April 8, 2004, 4 pm, EDT

Blgd 510, Rm 2-160

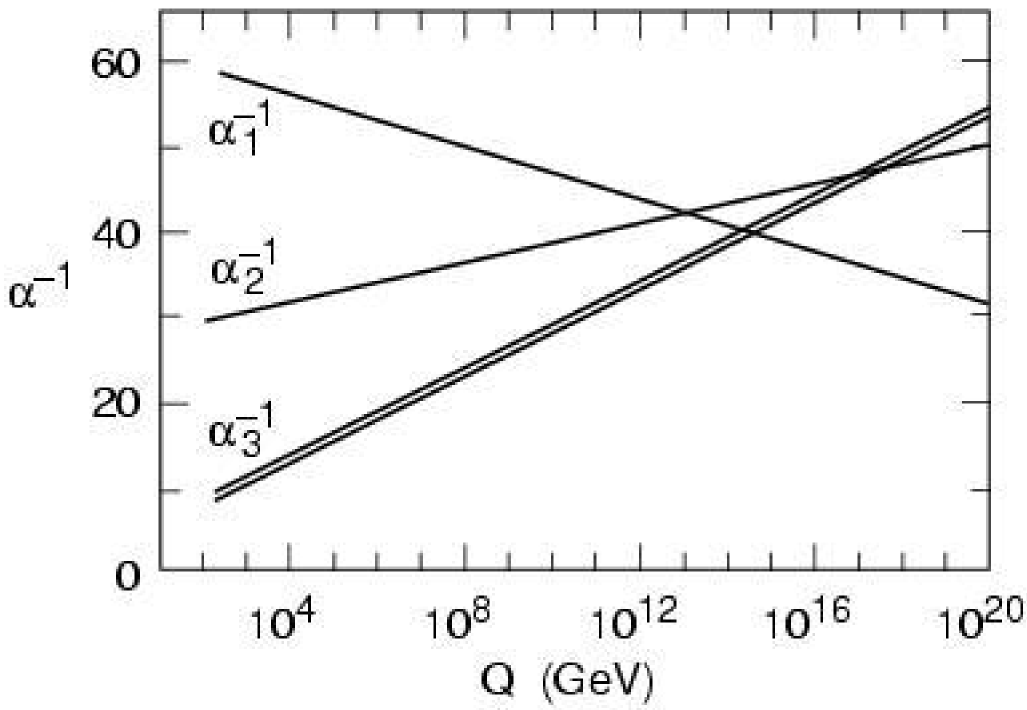
images: DESY, N.Graf

?????

- What are the big questions we want to answer?
- Why do we think we can predict where we want to go?
  - *What do we know now?*
  - *What do we expect to learn from the Tevatron and LHC?*
  - *What questions will remain unanswered?*

The Big Questions?

- What is the origin of mass?
- Do protons decay?
- Do forces unify at a large scale?
- Are there more than four dimensions?
- Why are there 4 forces?

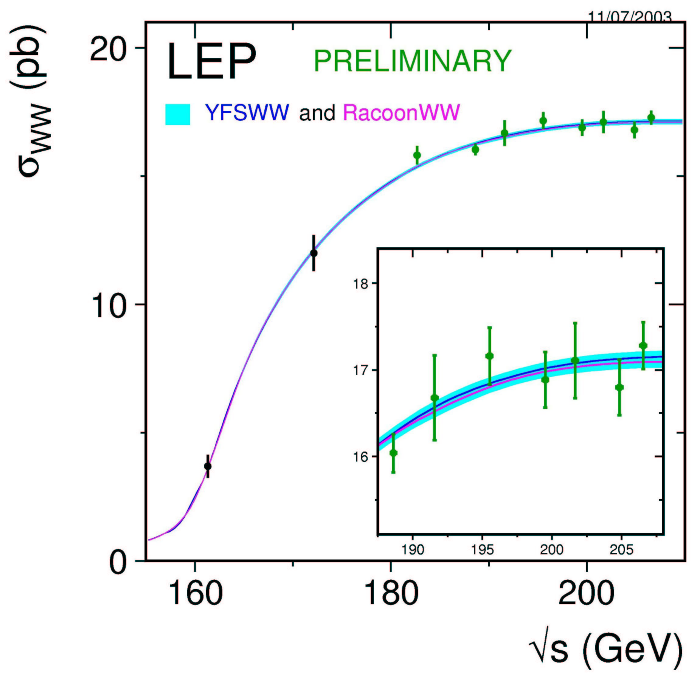


No unification of couplings in SM

Standard Model is Gauge theory

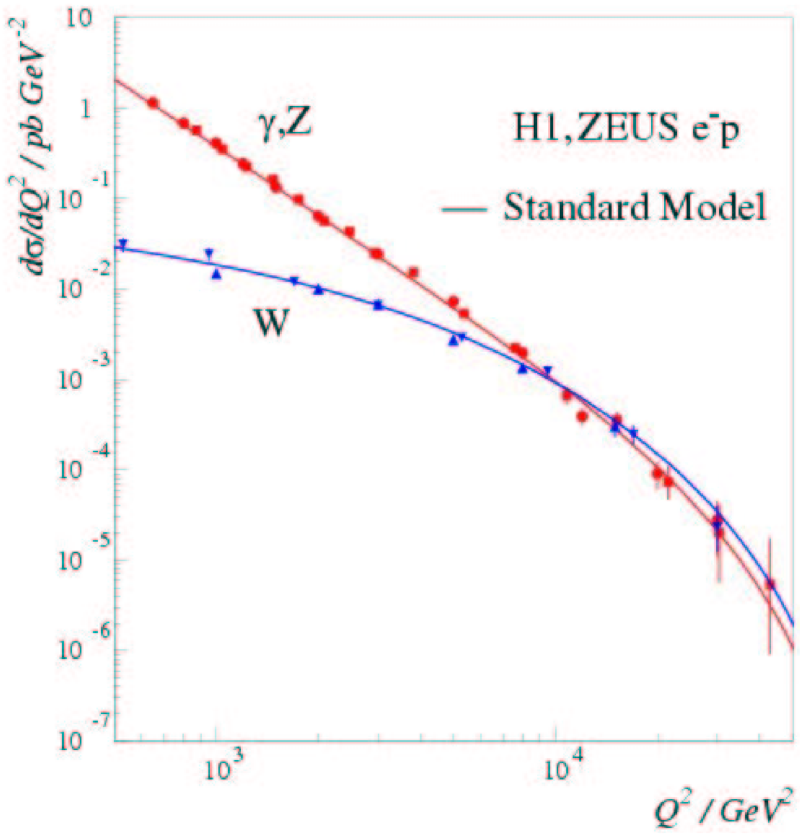
- SU(2) x U(1)
  - Massive W and Z gauge bosons
  - Massless photon
- At ≈100 GeV, SU(2) X U(1)→U(1)$_{EM}$

- Example: $e^+e^- \to W^+W^-$
- Sensitive to details of SU(2) X U(1)→U(1)$_{EM}$



We've seen SU(2) x U(1) gauge unification

HERA



Charged and neutral currents unify at 100 GeV

Model requires Higgs boson or something like it for consistency!

The Next Linear Collider and Electroweak Physics

- The Physics landscape
- Electroweak physics
  - Unification of gauge interactions
  - Predictions
  - Missing pieces
- The Hunt for the Higgs boson
  - How do we know what we've found?
- New physics
- Connections with the cosmos
  - Dark matter

Standard Electroweak Model spectacularly verified

- Precision studies at Z factories
  - LEP and SLC
- Precision W measurements at colliders
  - LEP2 and Tevatron

M_Z=91.1875± .0021 GeV
M_W=80.451 ± .033 GeV

- Precision measurements test Standard Model
  - LEP2 and Tevatron

A Precision Science…

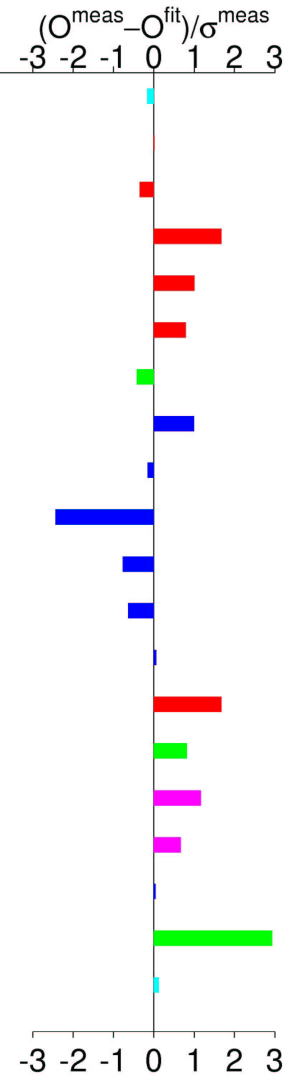
Experimental successes of past decade put us on firm footing

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

Gives us confidence to predict the future!

Winter 2003

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12



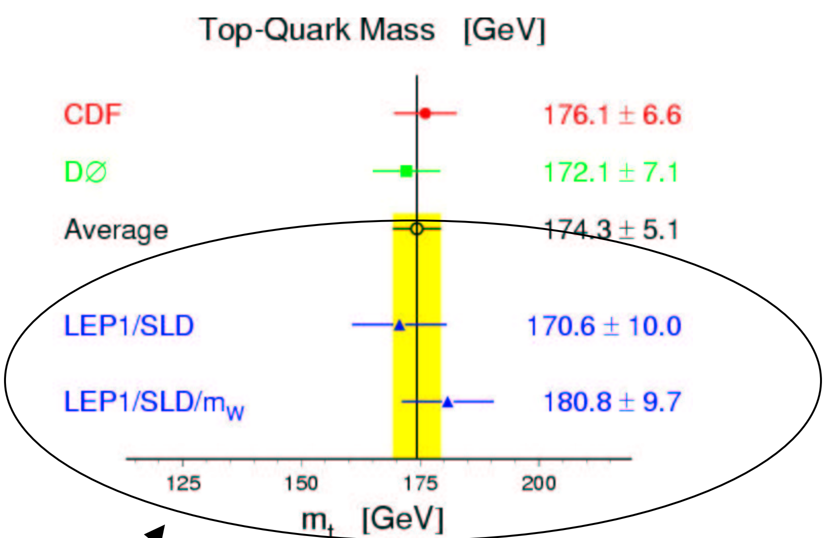
Standard Model tested at the level of Quantum Fluctuations

Higgs and top quark enter into quantum corrections

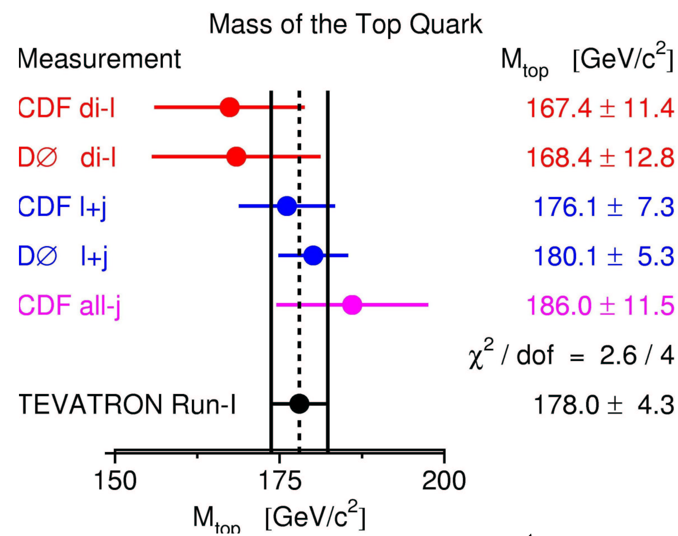
$\approx M_t^2, \log(M_h)$

Precision Measurements sensitive to top quark before it was discovered!

Situation last week

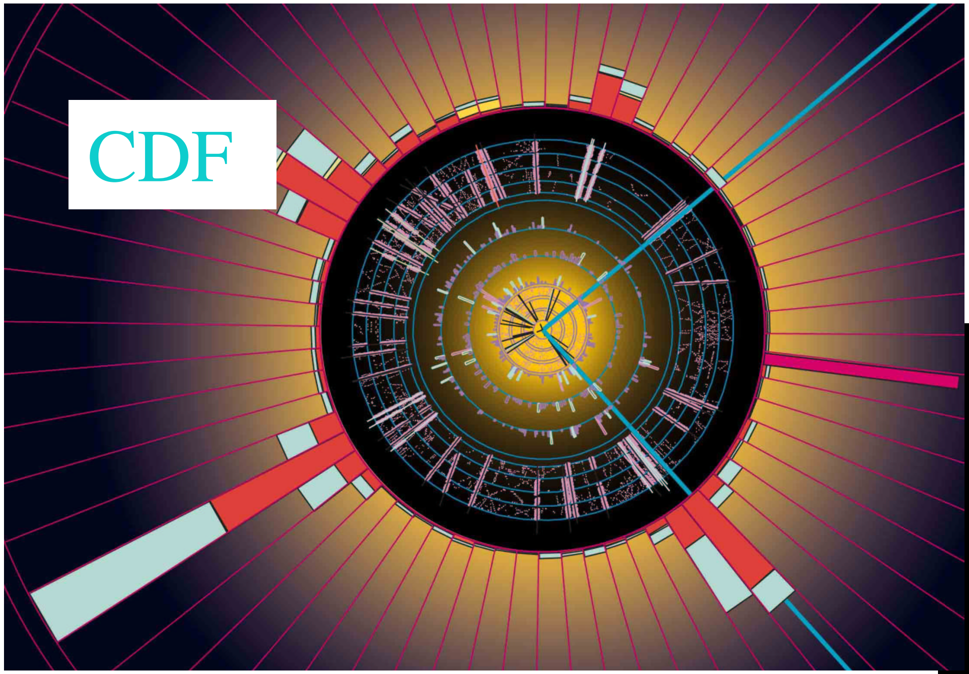


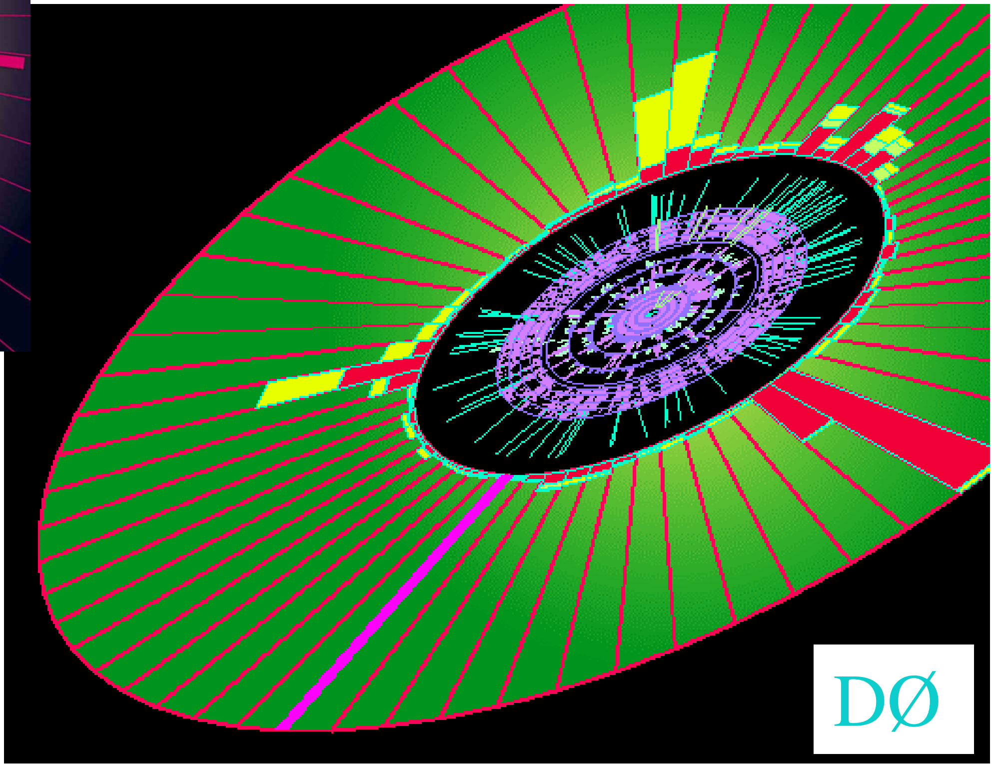
Inferred from precision measurements



Hot New Result: Combined CDF/D0 Run I result

Top Discovered at Fermilab in 1995





Why is it so heavy?

M_t=175 GeV

Planning for the Future Based on Success of last 20 years….

- Model of electroweak physics verified at 1% level
- The problem of mass remains
- W and Z masses aren't small

What is the source of mass?

Why is Mass a Problem?

- Lagrangian for gauge field (spin 1):

$$L=-\frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu$$

- L is invariant under transformation:

$$A_\mu (x) \rightarrow A_\mu(x)-\partial_\mu \eta(x)$$

- Gauge invariance is guiding principle
- Mass term for gauge boson

$$\frac{1}{2} m^2 A_\mu A^\mu$$

- Violates gauge invariance
- So we understand why photon is massless

Simplest possibility for Origin of Mass is Higgs Boson

- Higgs mechanism gives gauge invariant masses for $W^{\pm}$, Z
- Requires physical, scalar particle, h, with unknown mass
- Observables predicted in terms of:
  - M_Z=91.1875±.0021 GeV
  - G_F=1.16639(1) x 10^{-5} GeV^{-2}
  - α=1/137.0359895(61)
  - M_h
- Higgs and top quark enter into quantum corrections, $\approx M_t^2$, $\log(M_h)$

Is Mass Due to a Higgs Boson?

- Higgs couplings of SM fixed

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

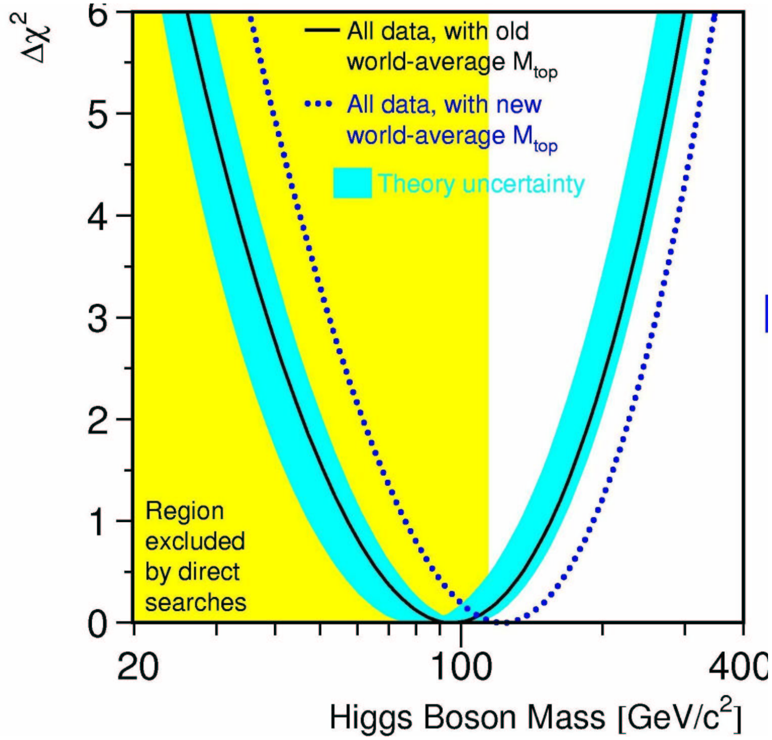
$$g_{WWh} = g M_W$$

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

$$M_h > 114\,GeV\ @\ 95\%\,cl$$

Precision measurements limit Higgs Mass

NEW



- Old:
  - $M_t = 174 \pm 5.1$ GeV
  - $M_h = 96^{+60}_{-38}$ GeV
  - $M_h < 219$ (95% cl)
- New:
  - $M_t = 178 \pm 4.3$ GeV
  - $M_h = 117^{+67}_{-45}$ GeV
  - $M_h < 251$ (95% cl)

Tantalizingly close…..

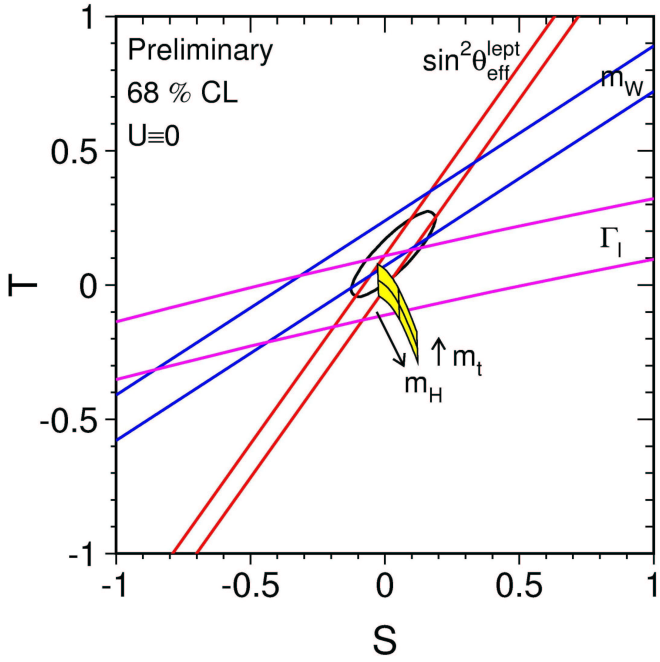
Direct limit: $M_h > 114.1$ GeV

Indirect limit: $M_h < 251$ GeV

- ***New Physics is just around the corner!***
- ***Fits assume Standard Model….if Standard Model incorrect, even more exciting new physics….***

What if there is no Higgs Boson? We still need a Linear Collider!

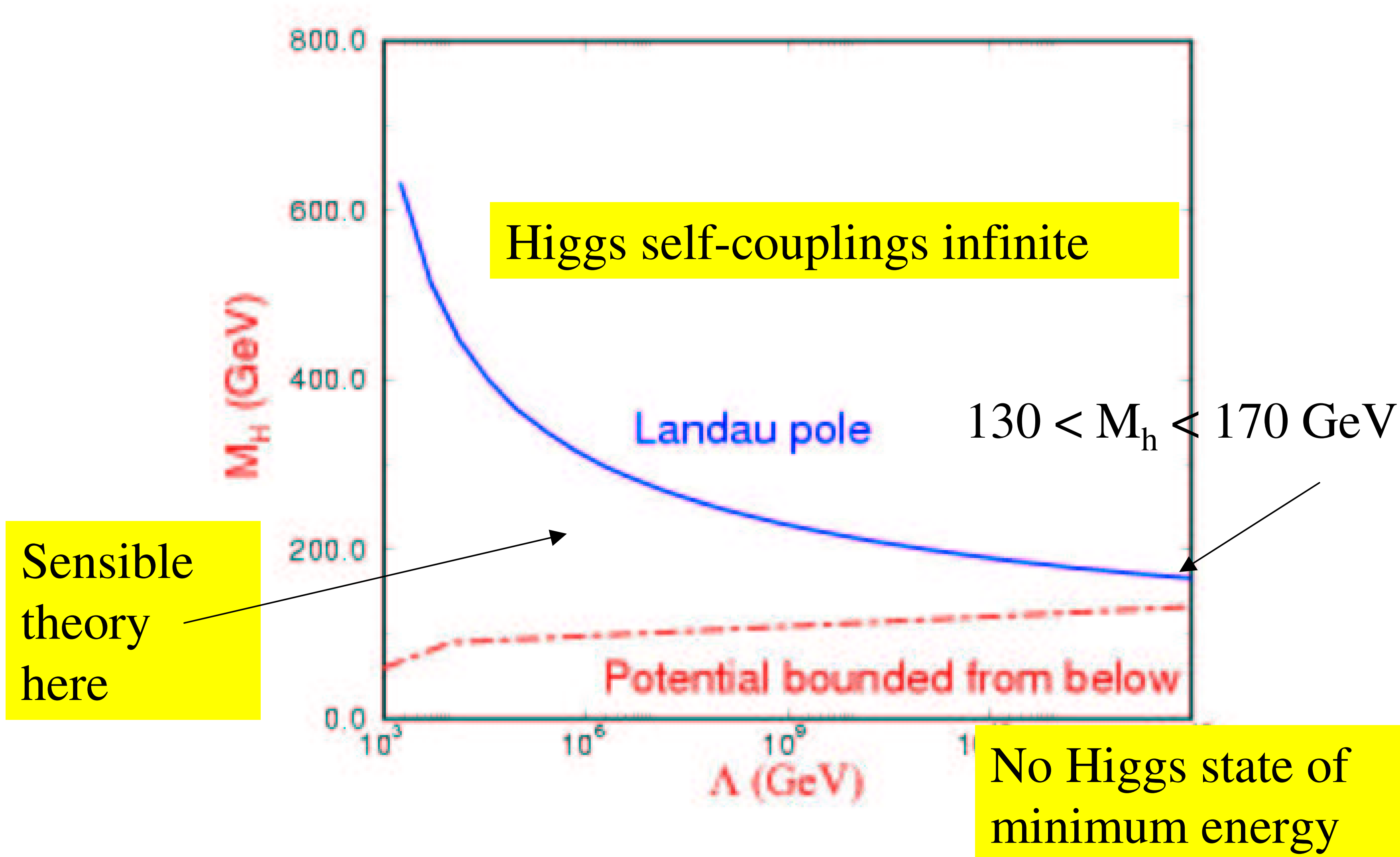
- ***Very, very, very hard to explain precision measurements without light Higgs!***



•Postulate new physics which predominantly affects W and Z boson self energies

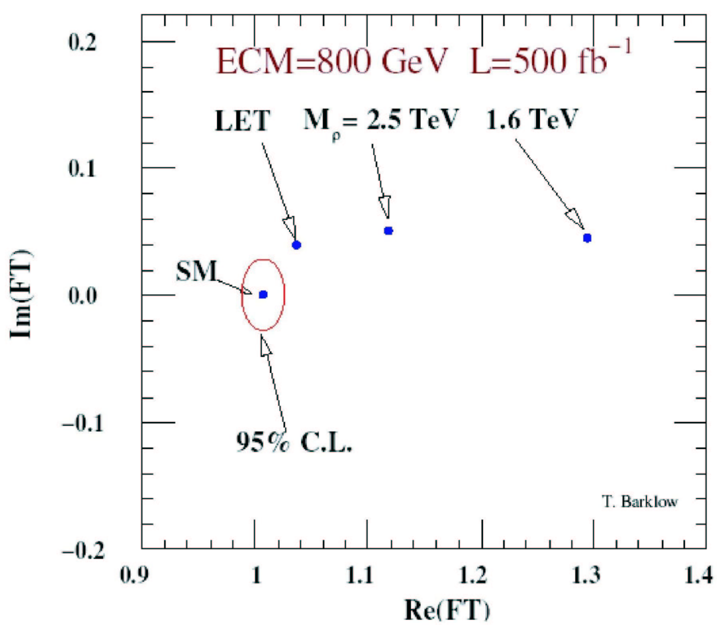
•Hard to make models which do this

Higgs mass and scale of new physics correlated…..



No Higgs….gauge boson couplings are different from SM

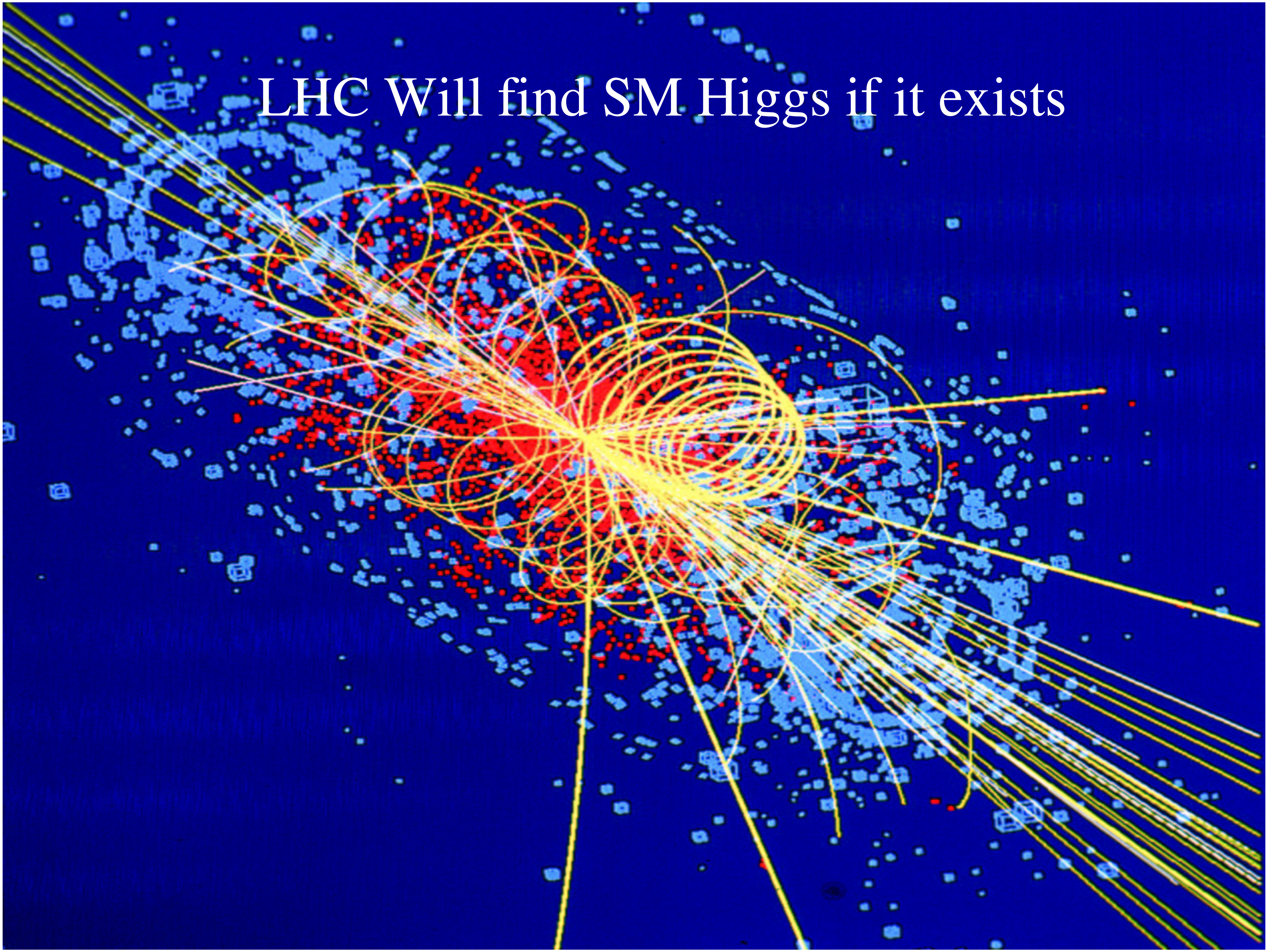
- $e^+e^- \rightarrow W^+W^-$ very different in models with no Higgs boson
- Needs high energy



Two paths to discovery

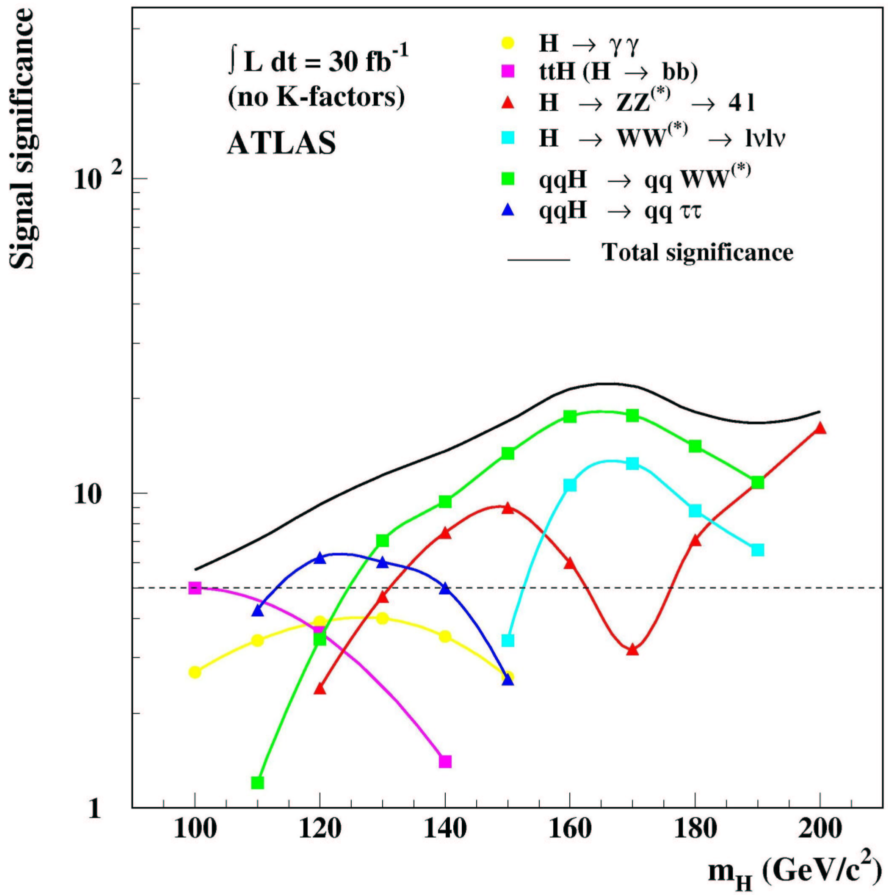
- High Energy
  - Operating at the energy frontier
  - Direct discovery of new particles
  - Tevatron and LHC
- High Precision
  - Infering new physics effects from high energy scales through precision measurements at low energy

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


LHC Will find SM Higgs if it exists

CERN Large Hadron Collider (LHC)

- pp interactions at $\sqrt{s}$ =14 TeV
- 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 happens quickly!

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?

Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

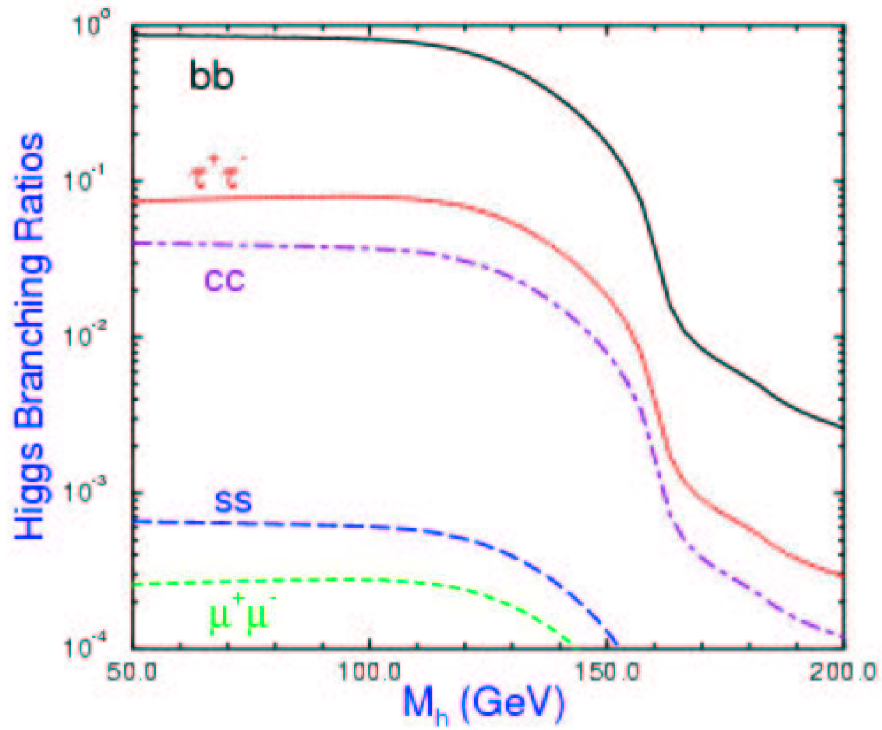
$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

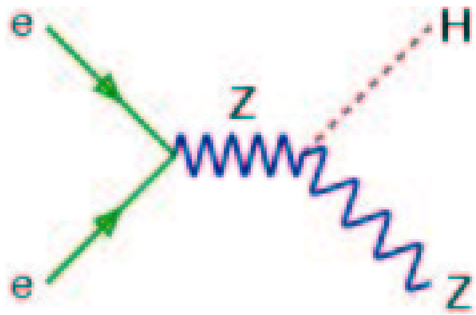
$$J^{PC} = 0^{++}$$

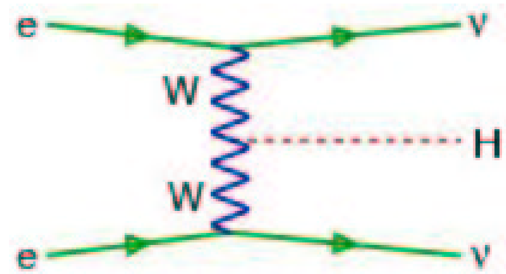
- Measure self interactions

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



Linear Collider is Higgs Factory!



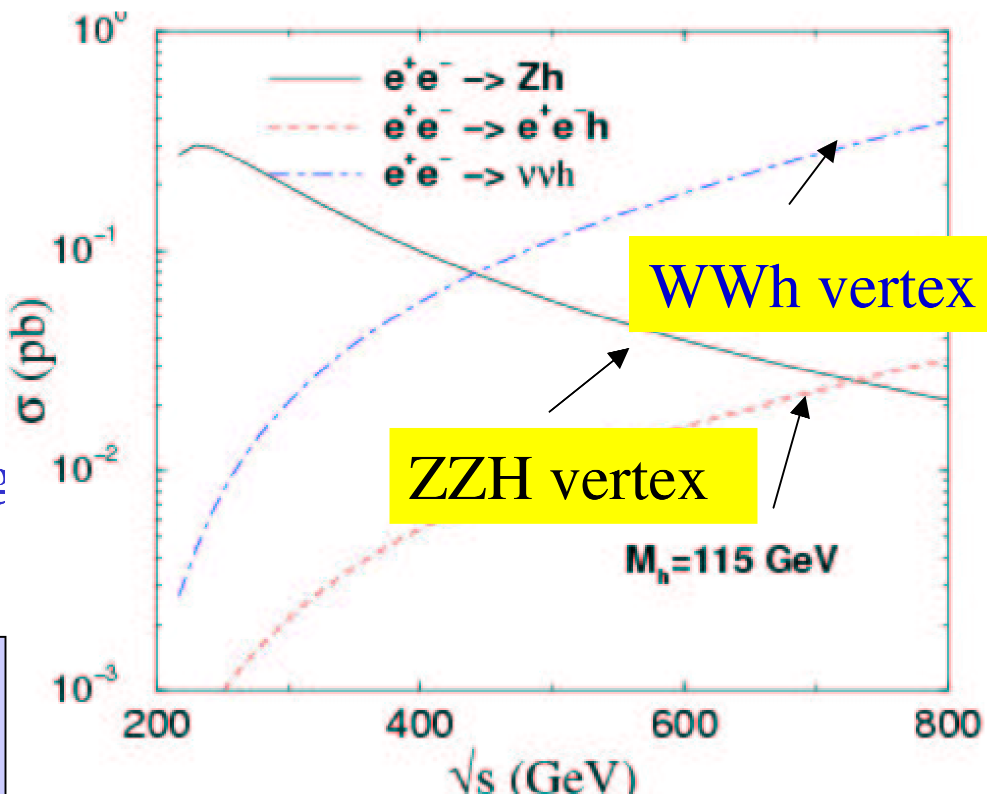


- $e^+e^- \to Zh$ produces 40,000 Higgs/yr
- Clean initial state gives precision Higgs mass measurement

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

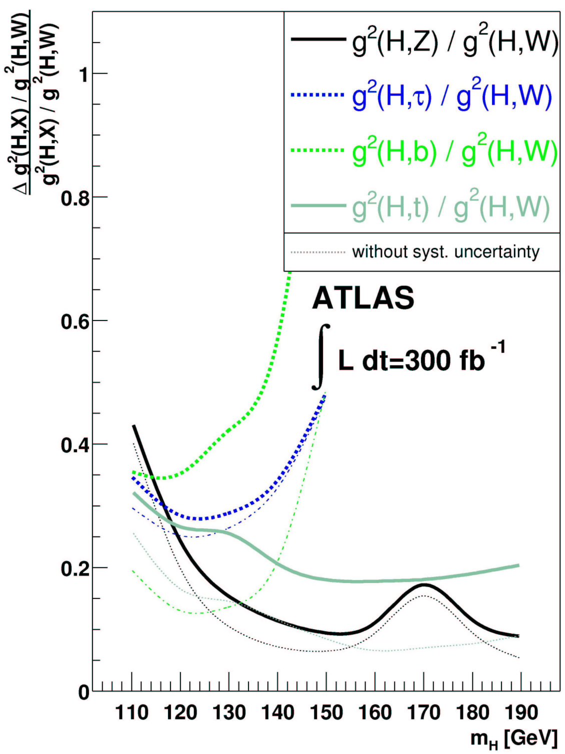
- Model independent Higgs branching ratios

Are W & Z masses result of couplings to Higgs boson?



Once we find the Higgs, we need to measure its couplings

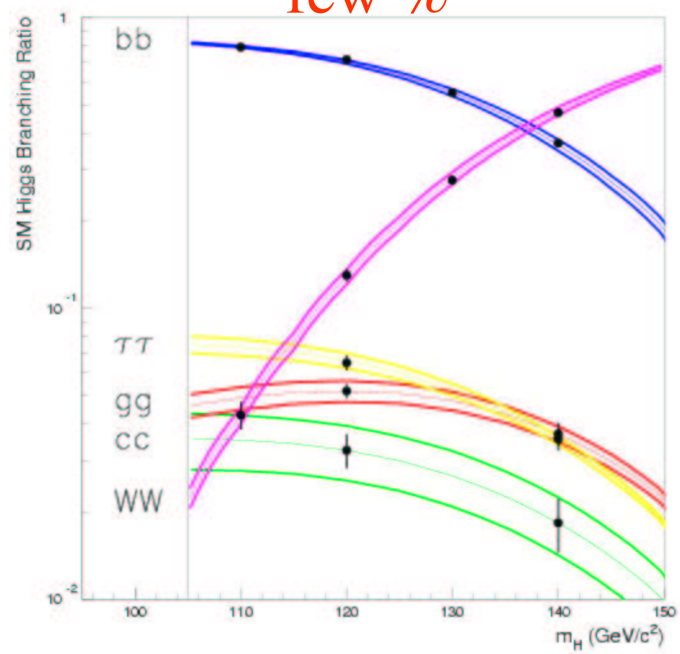
Ratios of coupling constants measured quite precisely at LHC



Duhrssen, ATL-PHYS-2003-030

Note scales

LC measures couplings to a few %



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

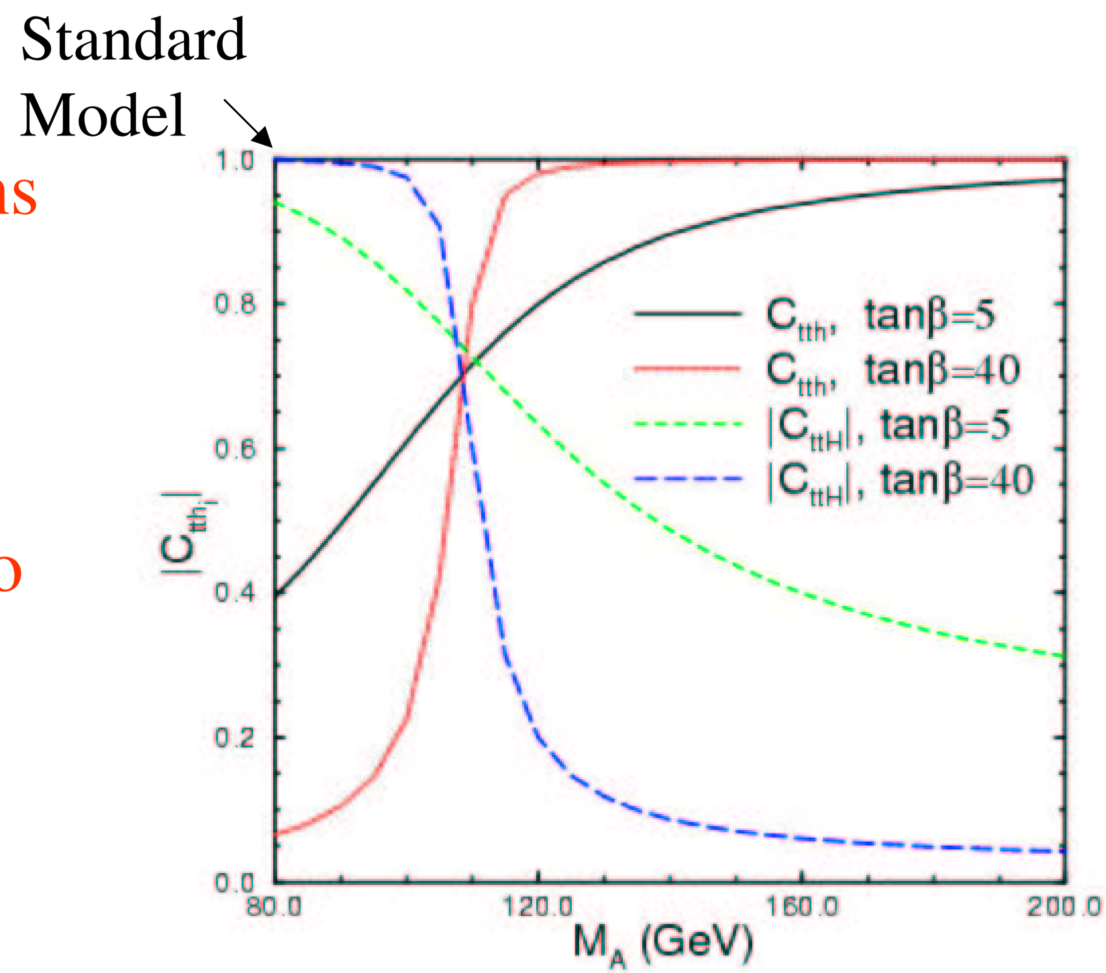
L=500 fb^{-1}, M_h=120 GeV

Battaglia & Desch, hep-ph/0101165

Linear Collider is the place!

Higgs measurements test model!

- Couplings to fermions very different in SUSY models
- LC can distinguish SM from SUSY up to M_A=600 GeV



Higgs mass measurements

LC @ 350 Gev

- LC:

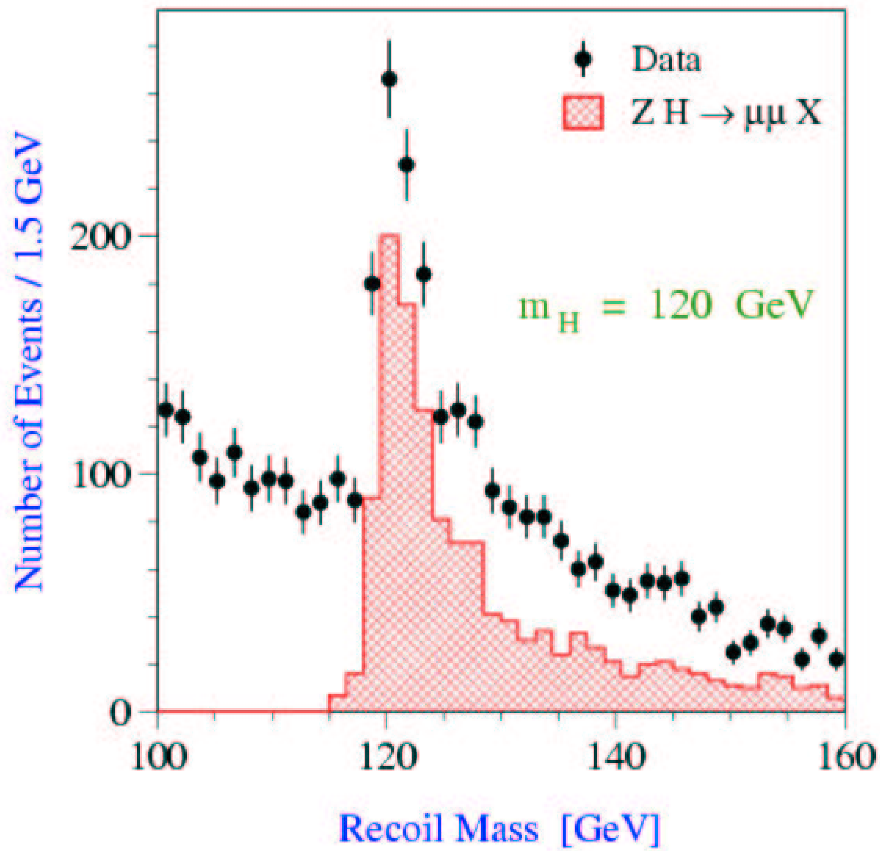
$$M_h = 120\,GeV,\ 500\,fb^{-1}$$
$$\rightarrow \delta M_h \approx 50\,MeV$$

- LHC:

Direct reconstruction of

$$h \rightarrow \gamma\gamma$$

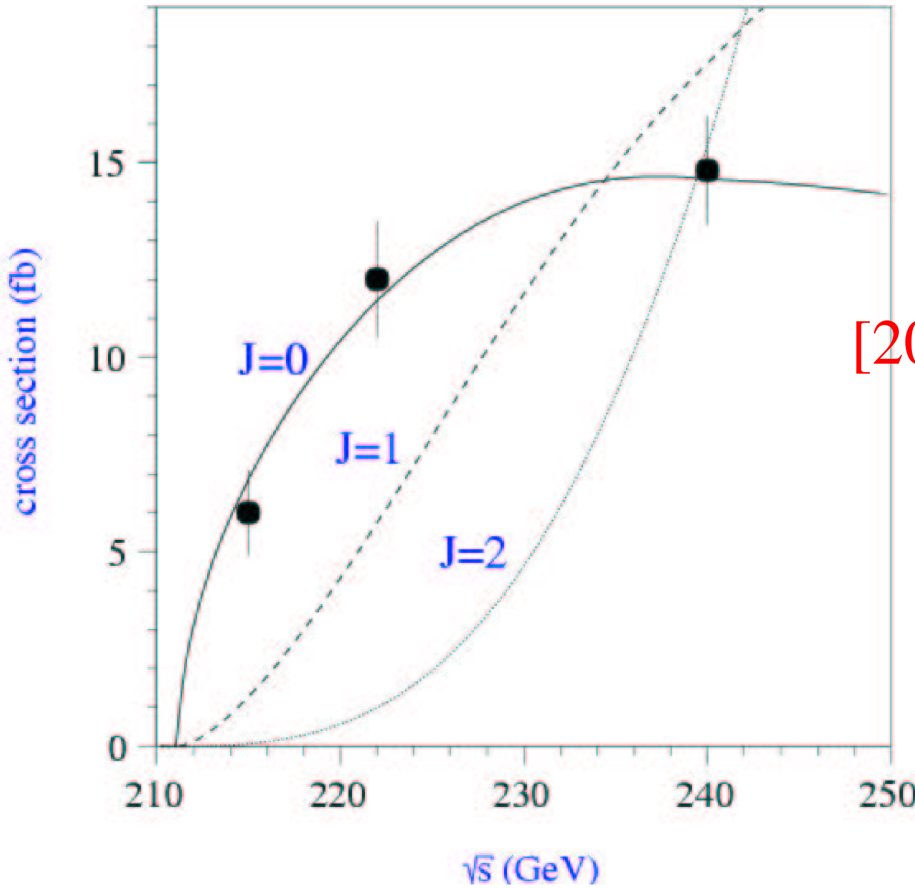
$$M_h < 150\,GeV,\ 300\,fb^{-1}$$
$$\rightarrow \delta M_h \approx 100\,MeV$$



Conway, hep-ph/0203206

Higgs spin/parity in $e^+e^- \to Zh$

Threshold behavior measures spin



[20 fb^{-1} /point]

Linear collider can change initial state energy to do energy scans

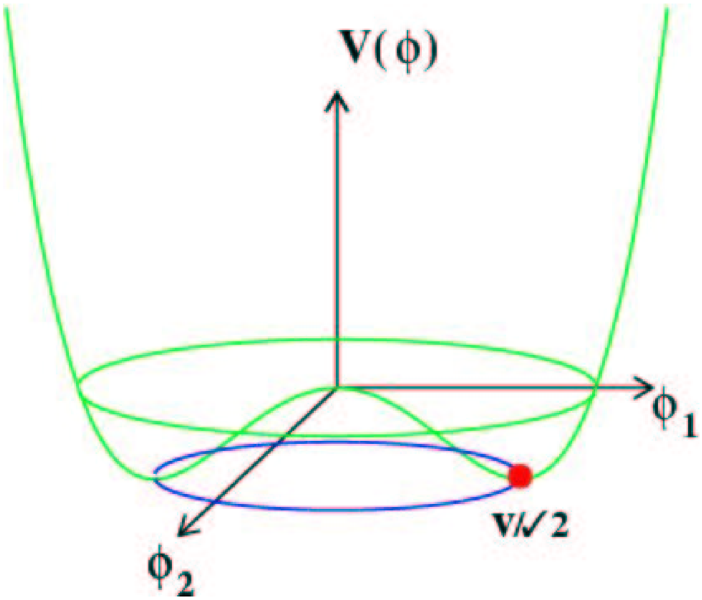
- Angular correlations of decay products distinguish scalar/pseudoscalar

Miller, hep-ph/0102023

Does the Higgs generate its own mass?

Can we reconstruct the Higgs potential?

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



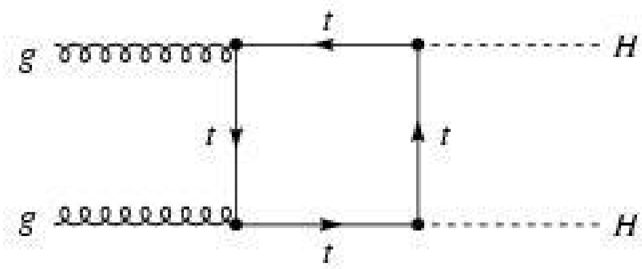
Fundamental test of model!

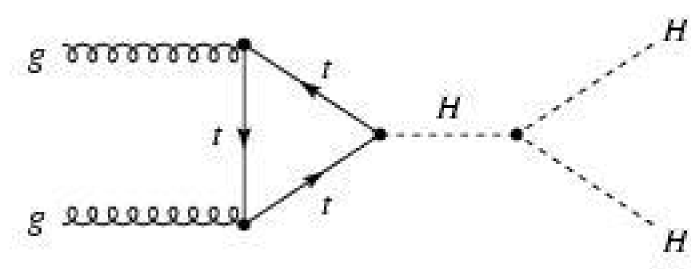
SM: $\lambda_3 = \lambda_4 = M_h^2/2v^2$

Requires production of multiple Higgs bosons

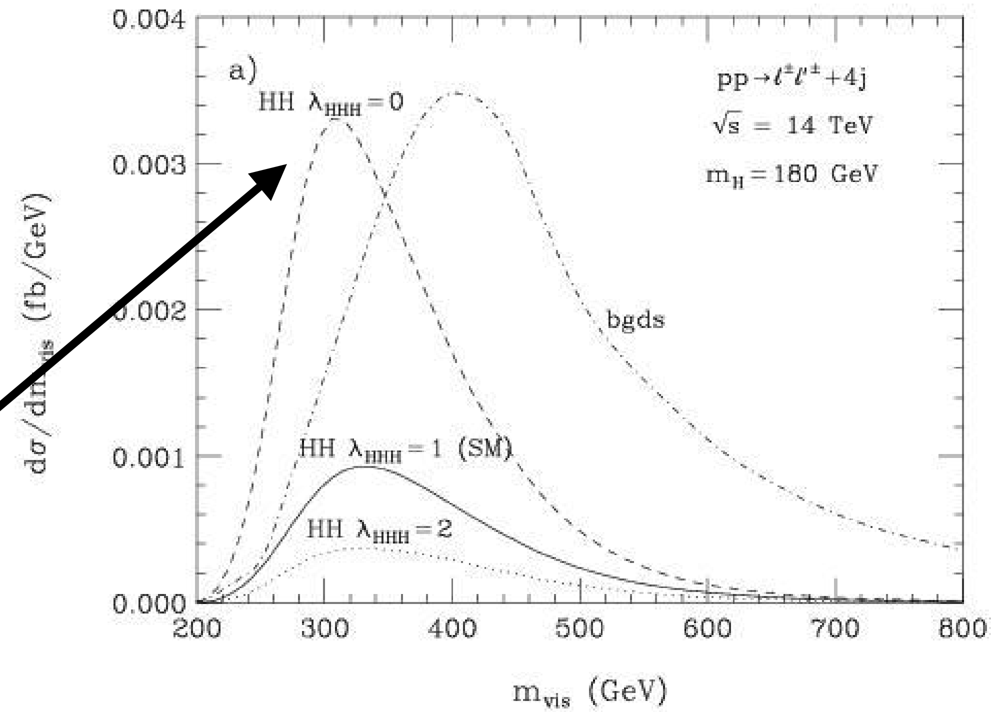
We need both λ_3 and λ_4

Reconstructing the Higgs potential





- λ_3 requires 2 Higgs production

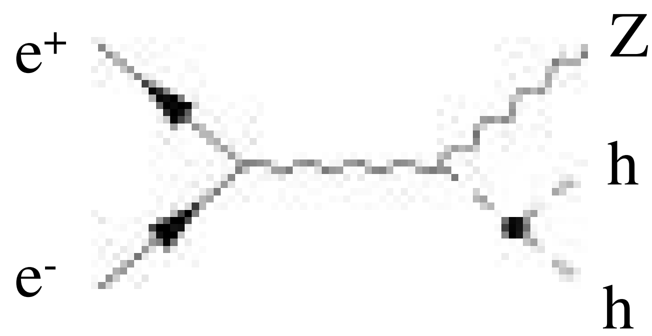


Can determine whether λ_3=0 at LHC

Baur, Plehn & Rainwater, hep-ph/0304015

Tri-Linear Higgs Coupling at e+e- Colliders

- M_h<140 Gev, $e^+e^- \rightarrow Zhh$
  - Dominant decay, $h \rightarrow bb$
  - High efficiency for identifying b's recoiling from Z
- M_h>150 GeV, $h \rightarrow W^+W^-$
  - Phase space suppression
  - $\sqrt{s}$=500 GeV optimal energy



LHC & LC are complementary:

LHC sensitive to M_h>150 GeV,
LC sensitive to lighter M_h

Castanier, hep-ex/0101028

Baur,Plehn, Rainwater, hep-ph/0304015

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

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

Solution is Supersymmetry

- Quadratic contributions to Higgs mass cancel between scalars and fermions
- To make cancellation hold to all orders need symmetry
- Bose-Fermi symmetry….supersymmetry

New particles in SUSY Theory

- Spin ½ quarks ⇒ spin 0 squarks
- Spin ½ leptons ⇒ spin 0 sleptons
- Spin 1 gauge bosons ⇒spin ½ gauginos
- Spin 0 Higgs ⇒spin ½ Higgsino

Experimentalists dream….many particles to search for!

What mass scale?

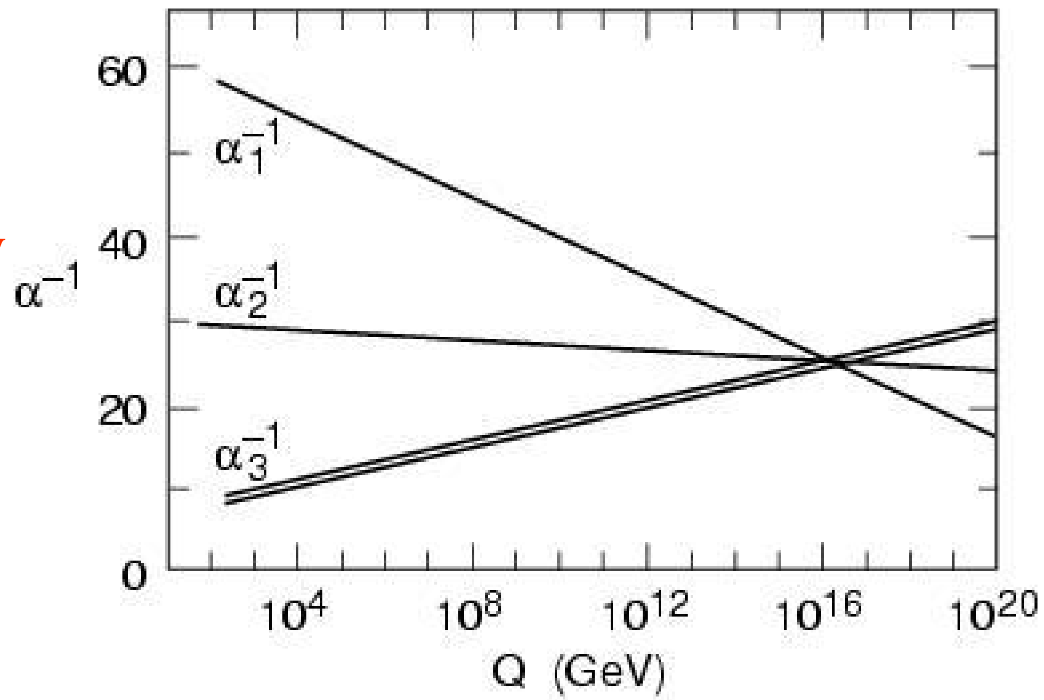
Supersymmetry is broken….no scalar with mass of electron

Supersymmetry

- 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

Do the forces unify?

- Coupling constants change with energy
- Coupling constants unify in supersymmetric models

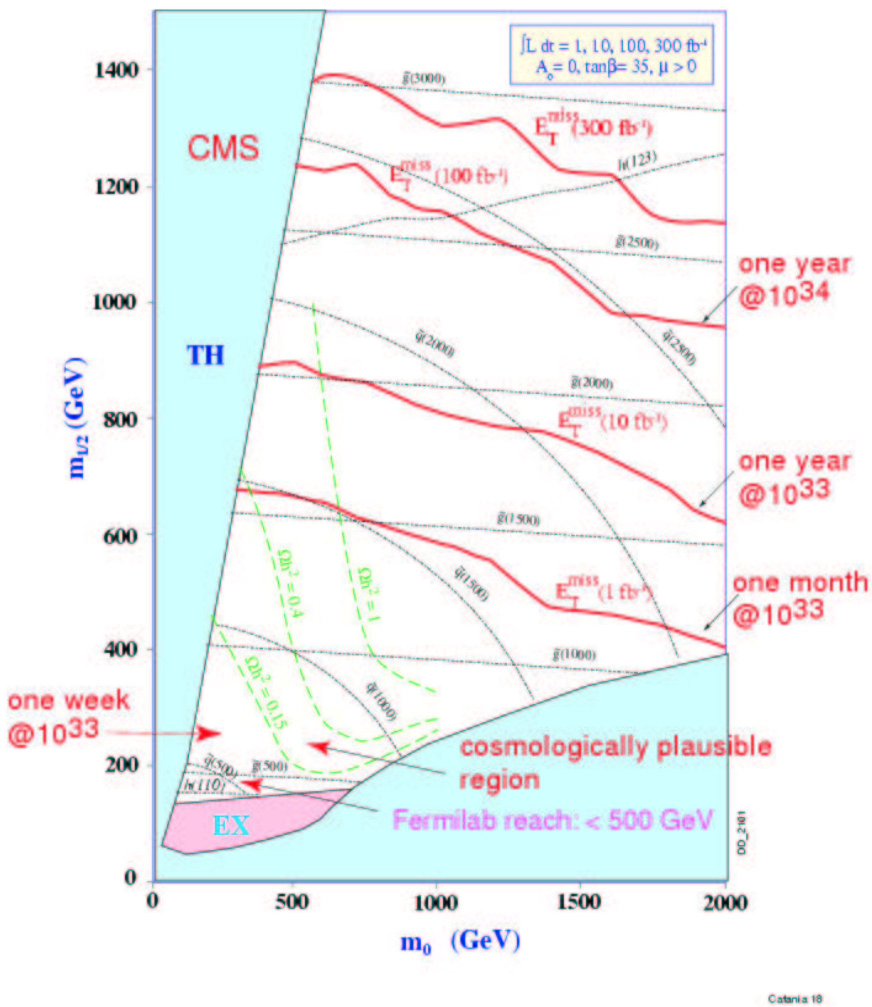


Hint for new physics?

Simplifying Assumption:

- Assume masses unify at same scale as couplings
- Everything specified in terms of scalar/fermion masses at high scale and 3 parameters
- Predictive anzatz…..

LHC/Tevatron will find SUSY



Catania, CMS

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

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

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}^{\pm} l^{\mp}$$
$$\to \tilde{\chi}_1^0 l^+ l^- q$$

- $M_{\chi 0}$ limits extraction of other masses

How do we know it's SUSY?

- Need to measure masses, couplings
- Observe SUSY partners, eg

$$\tilde{e}_L, \ \tilde{e}_R$$

In a SUSY model, couplings of electron and scalar partner are equal

- Polarization can help separate states
- Discovery is straightforward

$$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$$

$$\tilde{e} \rightarrow e\tilde{\chi}^0$$

$\tilde{\chi}_0$ is lightest SUSY particle;

Stable, non-interacting

Dark matter candidate

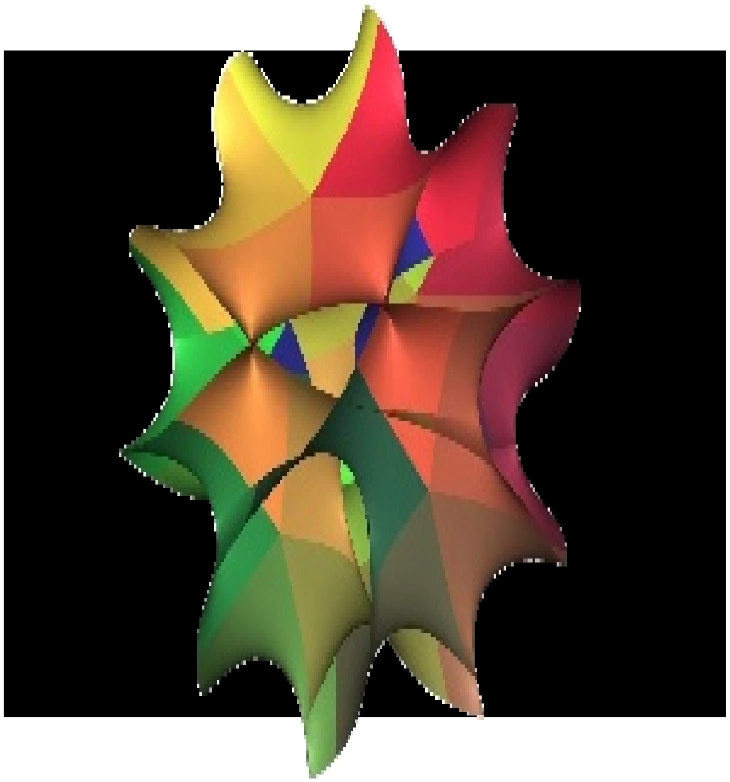
- $e^{\pm}$ energies measure masses

$$M_{\tilde{e}}^{\ 2} = E_{CM}^{\ \ 2} \frac{E_{e,\max} E_{e,\min}}{(E_{e,\max} + E_{e,\min})^2}$$

LHC & LC together can do precision exploration of TeV Scale!

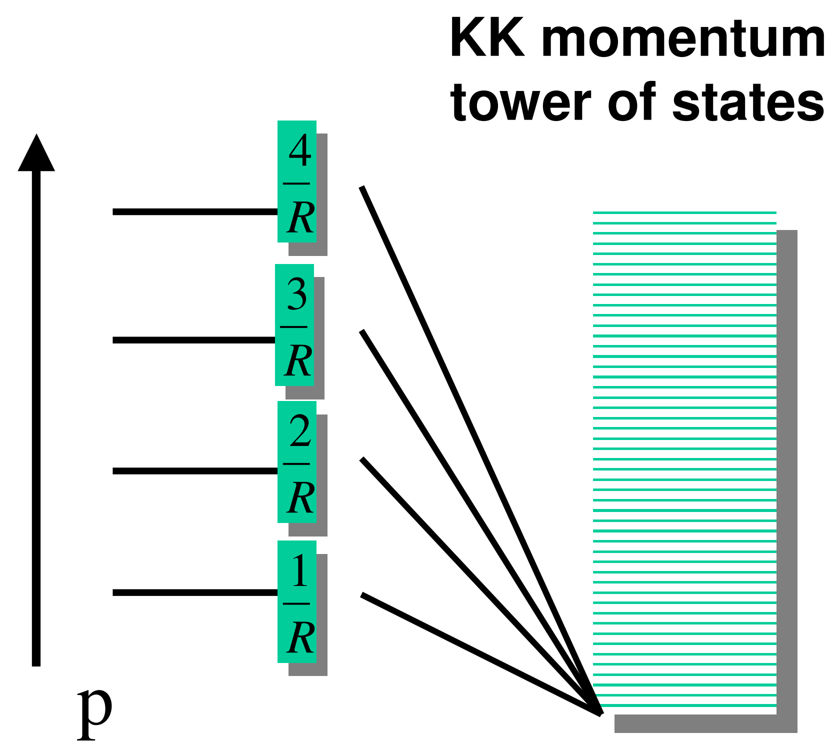
Hidden Dimensions

- The idea of extra dimensions not new
- Today, the idea receives additional support from string theory, which predicts new spacetime dimensions



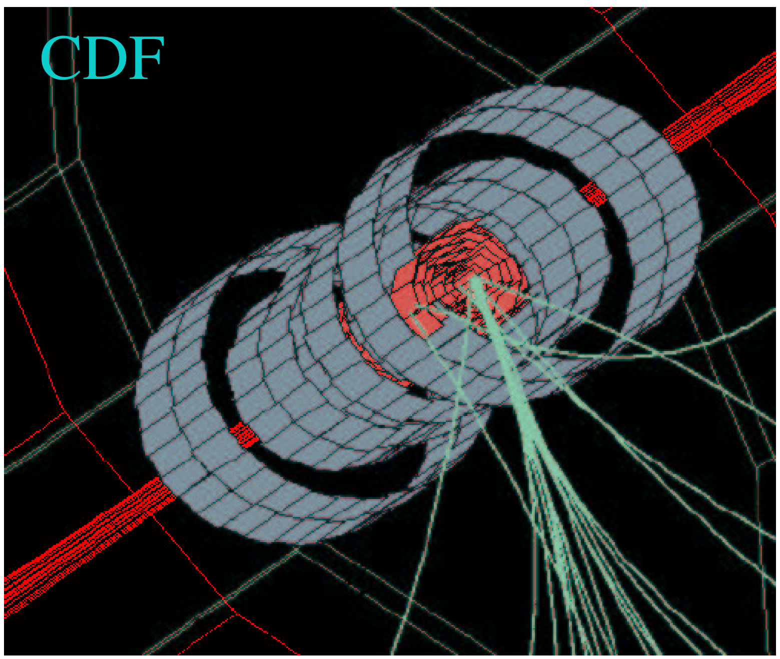
Kaluza-Klein Particles

- Extra dimensions give rise to a tower of new Kaluza-Klein particles, with new physics at the TeV scale
  - New particles
  - Events with missing energy and momentum
  - SUSY?

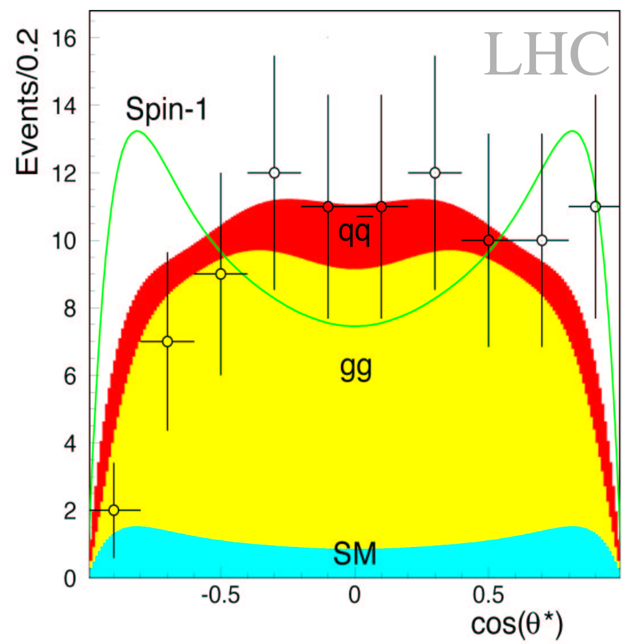


Kaluza-Klein Particles

- We need to detect the Kaluza-Klein particles and measure their properties



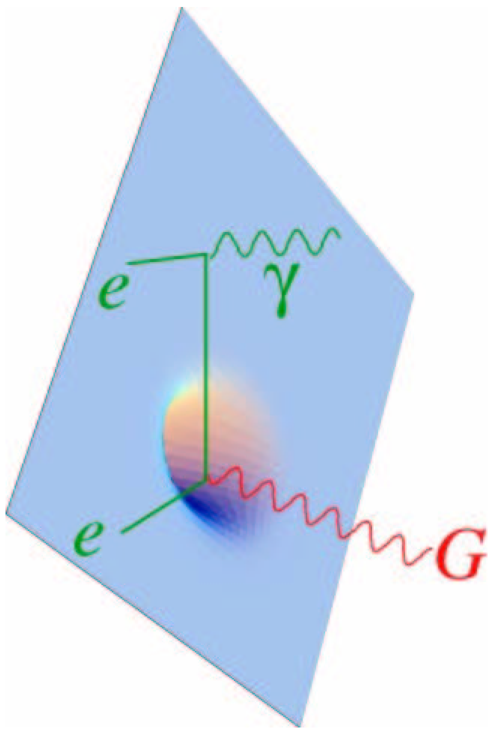
Spirapolou

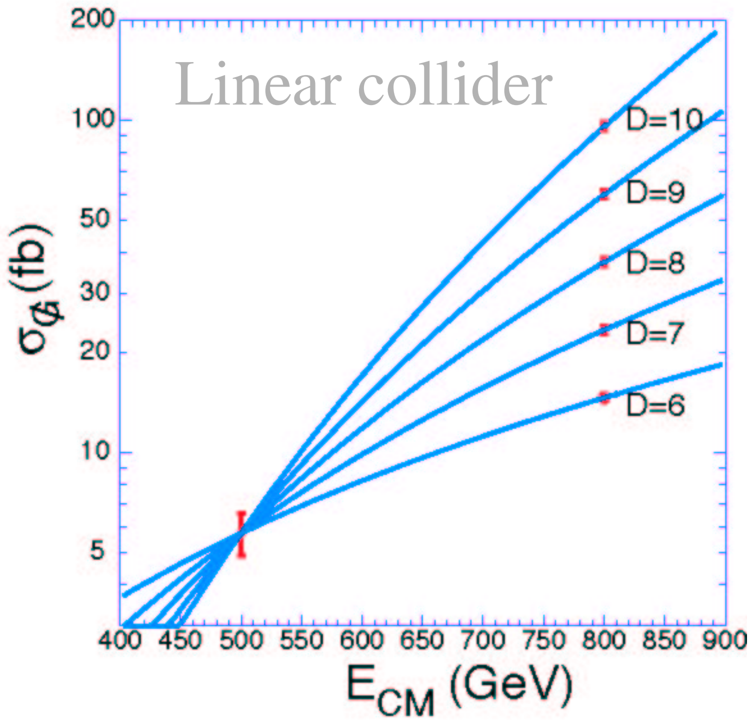


Allanach, Odagiri, Parker, Webber

How Many?

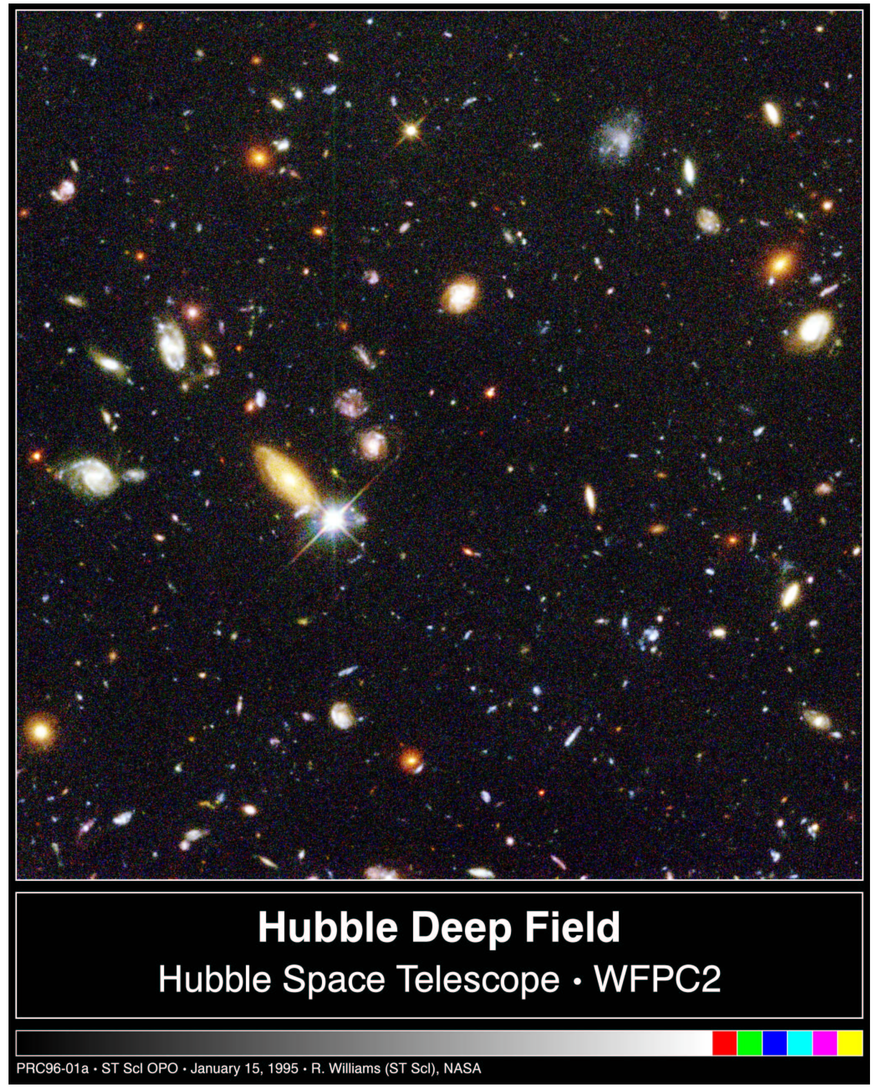
- Graviton emission can measure the number of hidden dimensions





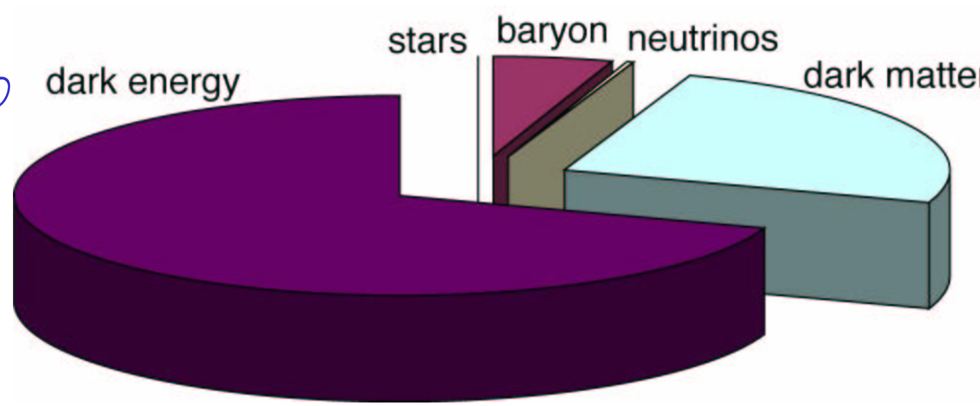
Cosmic Connections

- What is dark matter?
- How are particle physics & cosmology connected?
- What is dark energy?
- Where did the anti-matter go?



What is the universe made of?

- Stars and galaxies are only 0.1%
- Neutrinos are ~0.1–10%
- Electrons and protons are ~5%
- Dark Matter ~25%
- Dark Energy ~70%



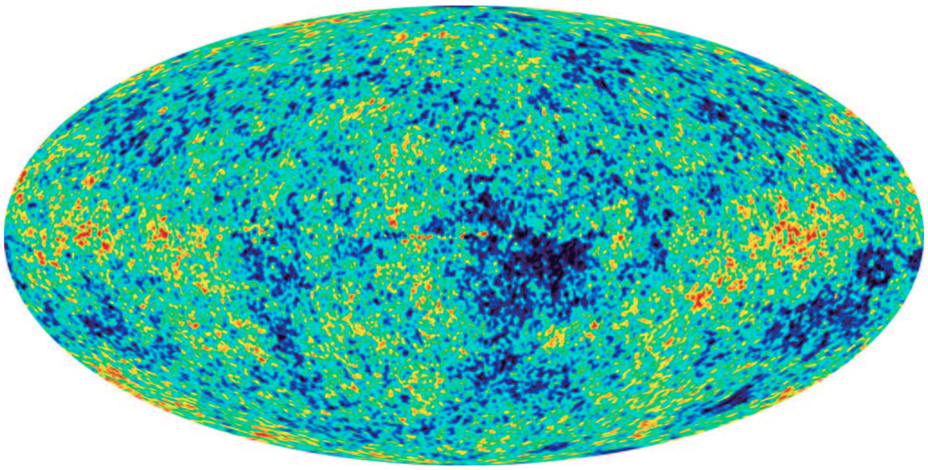
H. Murayama

The ASTRO/particle Connection

- 23% of universe is cold dark matter:

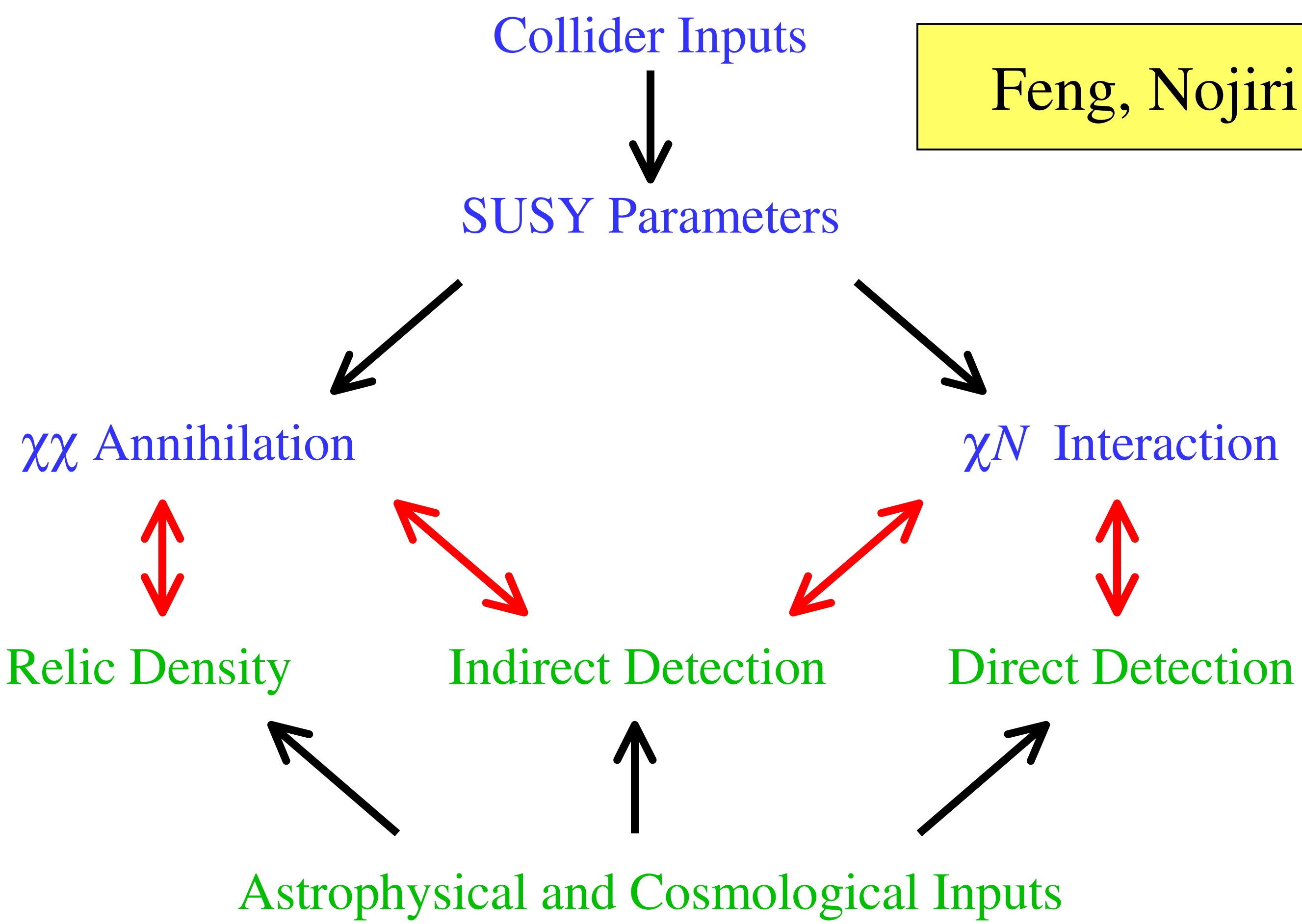
$$\Omega_{CDM}h^2 = .1126\ ^{+.0161}_{-.0181}$$

- WMAP (and others): Cosmology is a precision science → Implications for particle physics!



Connection between particle/cosmology

Feng, Nojiri

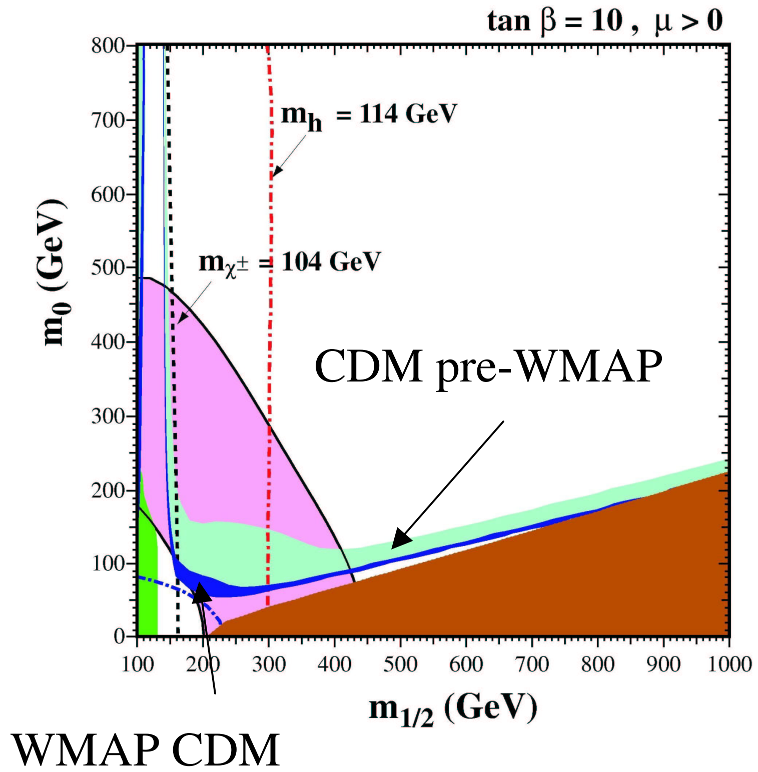


Cold dark matter points to TeV Scale

- SUSY models have natural dark matter candidate
- Lightest SUSY Particle (LSP) is neutral and weakly interacting
- On general grounds, LSP contributes correct relic density if mass is 300 GeV-1 TeV
- WMAP results imply M_χ <500 GeV for tan β < 40 in mSugra type models
- SUSY particles within reach of LHC and LC

Ellis, Olive, Santoso, & Spanos, hep-ph/0303043

WMAP suggests SUSY is just around the corner?



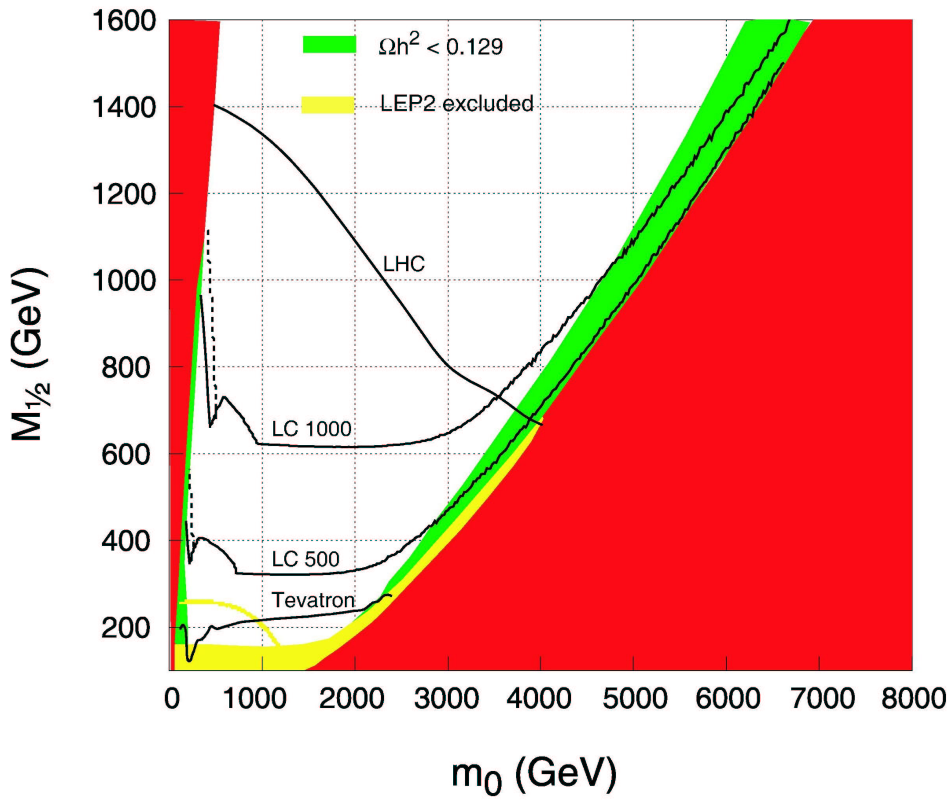
Assume dark matter is LSP of mSUGRA

Note low m_0 scale!

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

Ellis, Olive, Santoso, Spanos, hep-ph/0303043

Even small region where LC is sensitive to SUSY and LHC isn't



Exciting physics ahead

- LHC finds Higgs

  →LC makes precision measurements of couplings to determine underlying model

- LHC finds evidence for SUSY, measures mass differences

  →LC untangles spectrum, finds sleptons

  →LC makes precision measurements of couplings and masses

- etc

Precision measurements of the TeV Scale

⇒ Window to yet higher energy scales