A Roadmap for Colliders

The future…

Where are we? Why the TeV scale?

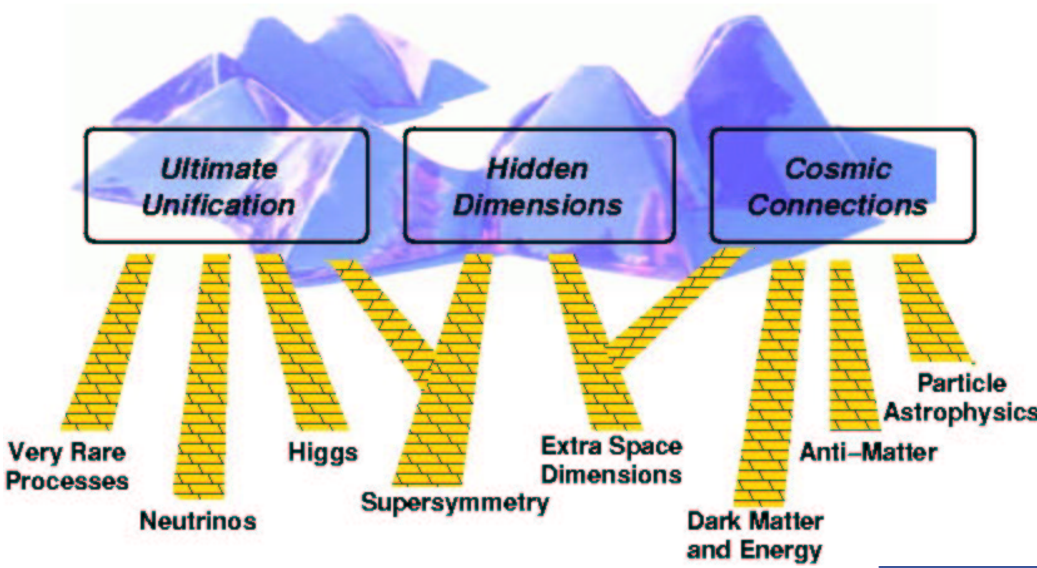
What's the next scale above a TeV?

S. Dawson, BNL

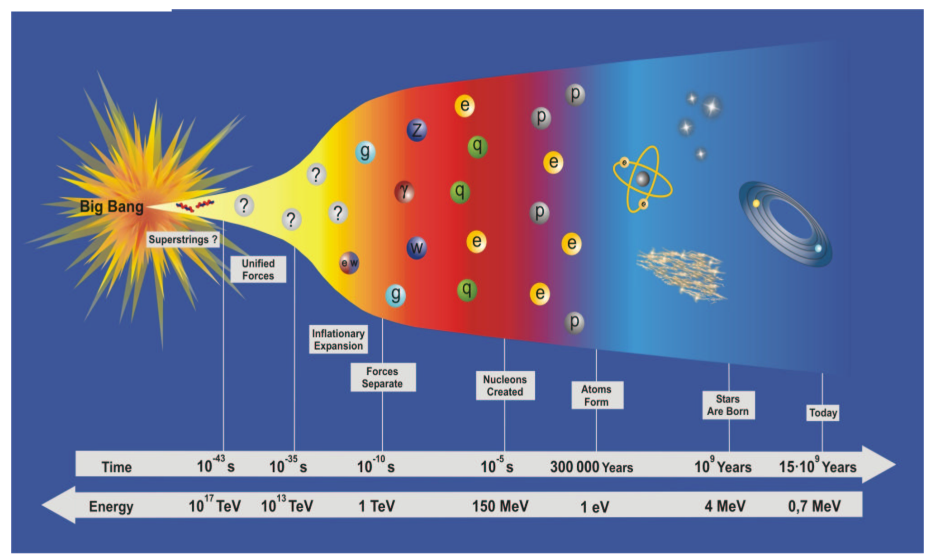
Oct. 17, 2003

Reprise of talks by A. deRoeck and F. Gianotti

The Challenge: Connecting the Energy Scales



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



Better title: ***Towards a Roadmap for Colliders***

Outline

- Machines on the market*
  - SLHC, VLHC, LC, CLIC, μ collider, γγ….
- The big questions
  - What can we expect to know after the LHC?
  - What questions will remain unanswered?
  - How to compare physics potential
- A few case studies
  - Precision measurements
    - Higgs Physics
  - New Particle searches
    - SUSY searches
    - New Z's

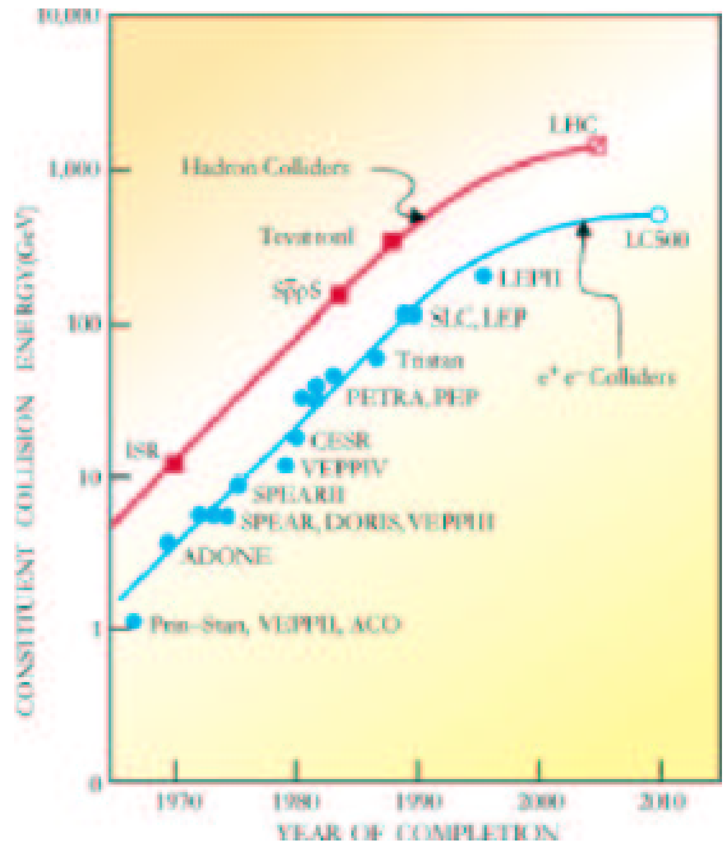
Not comprehensive study: many other examples possible

*B's and ν's are another talk

Livingstone plot

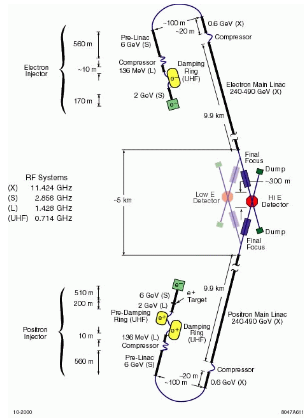
What are new entrys on
Livingstone plot?

What physics can they address?



Do curves saturate?

Science Timeline



LC

VLHC

CLIC

Tevatron LHC LHC Upgrade

2003 2007 2012 202x

Lepton Machines

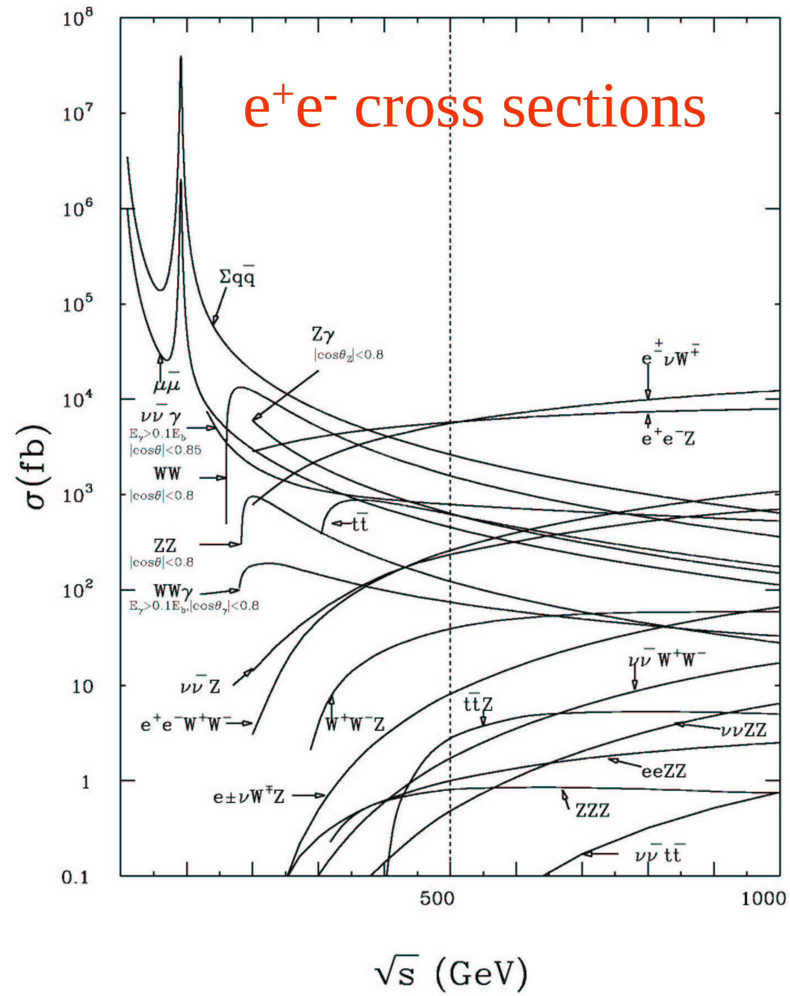
- LC: Initial energy $\sqrt{s}$=200-500 GeV at 2 x 10^{34} /cm^2/s
  - Physics demands 500-1000 fb^{-1}
  - Energy scans for precision mass measurements
- Upgrade to $\sqrt{s}$= .8-1.2 TeV
- Giga-Z for precision Z-pole measurements
- Positron polarization

Assume we have a LC before a VLHC

Progress towards setting the stage to make a technology decision for a linear collider

Physics drives accelerator requirements

- Basics of e^+e^- collisions:
  - 2→2 processes
    $\sigma \approx (1/s)$
  - Vector boson fusion
    (Zhh, $\nu\nu W^+W^-$, etc)
    $\sigma \approx \log(s)$
- LC: $\sqrt{s}$=(.5-1) TeV
  L = 1 ab^{-1}
- CLIC: $\sqrt{s}$=(1-5) TeV
  L = 3-5 ab^{-1}



The Next Steps in Hadron Machines: SLHC & VLHC

- LHC upgrade: SLHC
  - $L = 5 \times 10^{34}$-10^{35} /cm^2/sec
  - $\sqrt{s}$=14 TeV
  - Technically feasible
    - 5 years after LHC starts
- Higher still energy: VLHC
  - $\sqrt{s}$=40, 100, 200 TeV

Which energy????

Goal: 3000 fb^{-1} in 3-4 years

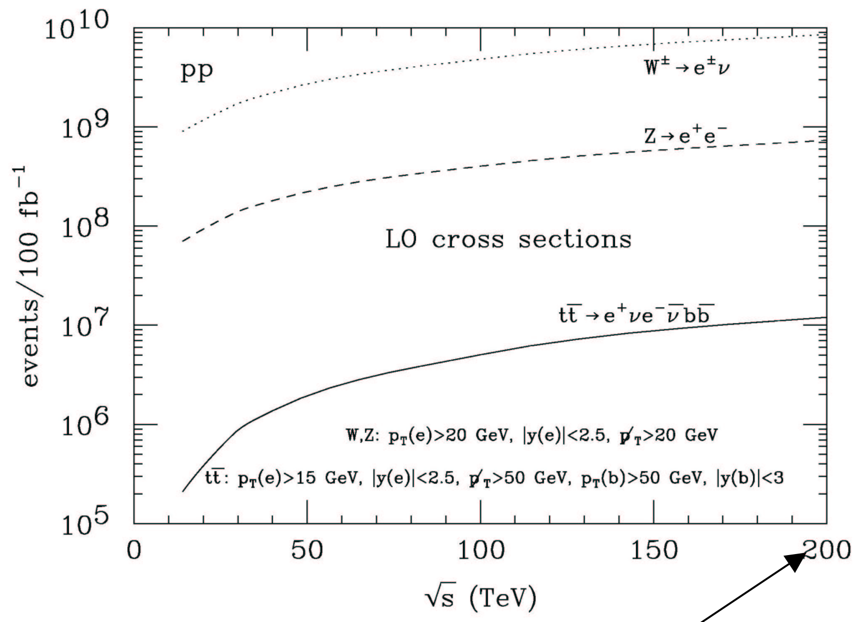
Major detector upgrades needed to exploit high luminosity

Energy upgrade of LHC much harder

Rates at the energy frontier

- Growing cross sections at high energy allow:
  – Expanded discovery reach
  – Precision measurements of rare processes
    - Eg BR($t \rightarrow WZb$)=2 x 10^{-6}

Cross sections grow with log(s) for states of fixed mass



10^9 tt pairs

Baur, Brock, & Parsons, hep-ph/0201227

Where are we now?

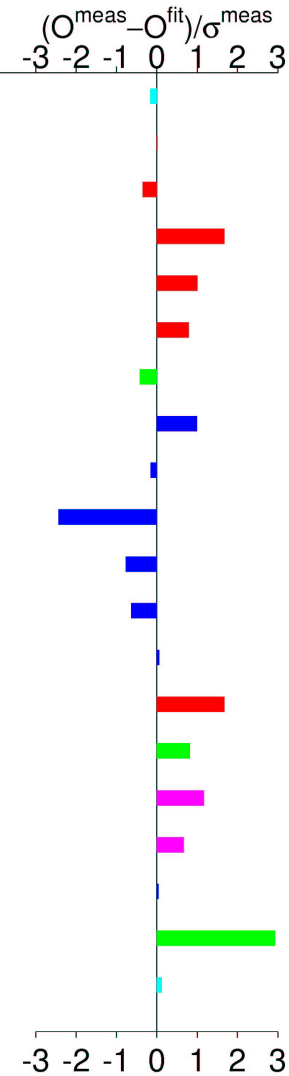
Experimental successes of past decade put us on firm footing

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

Gives us confidence to predict the future!

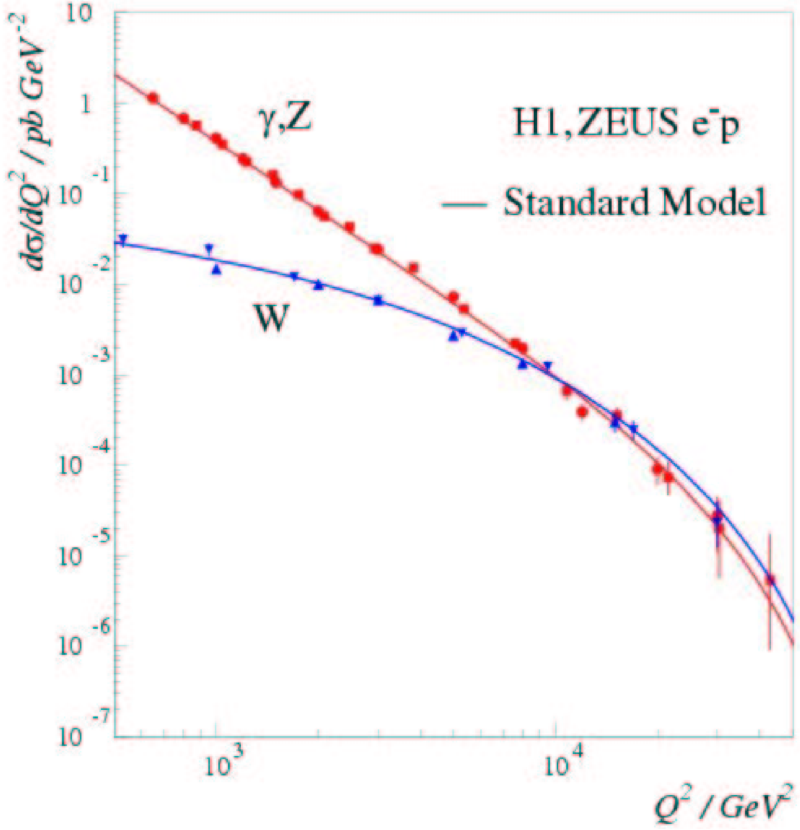
Winter 2003

	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0995 ± 0.0017	-2.43
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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



We've seen one example of gauge unification

HERA



Charged and neutral currents unify at 100 GeV

Model requires Higgs boson or something like it for consistency!

What are the big questions?

- Origin of EW Symmetry breaking
  - Fundamental Higgs?
  - Strong Dynamics?
  - Extra dimensions?
- Pattern of Fermion masses & Mixing
  - Why is top heavy?
- Origin of parity violation
- Why 3 generations?
- Why gauge symmetry?

My claim: current machines cannot answer all these questions

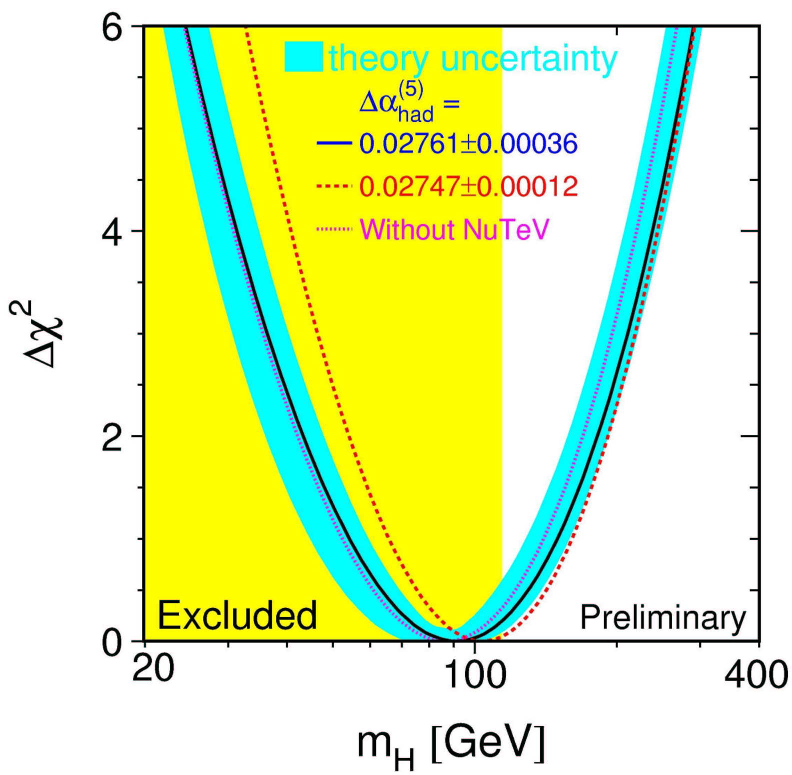
The first prong of the attack:

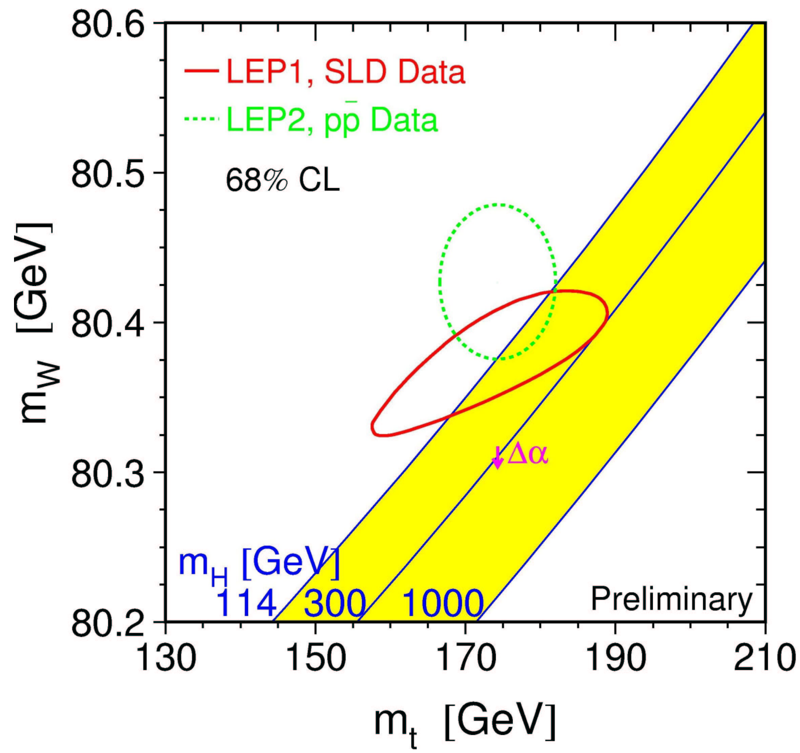
Precision measurements

The Value of M_W & M_t measurements

Precision EW Measurements:

$M_h < 219$ GeV

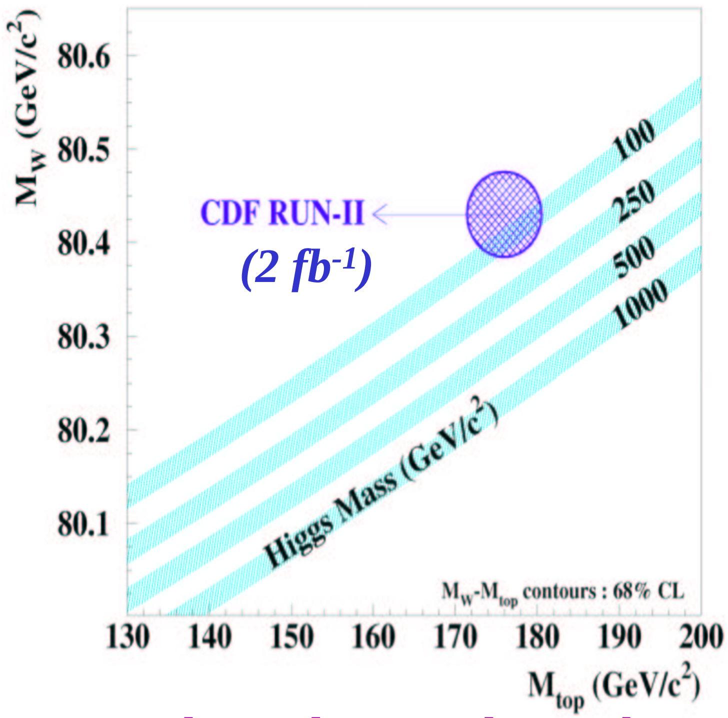




Note: Poor quality of fit

Best fit: $M_h=96^{+60}_{-38}$ GeV

The Tevatron will point the way….



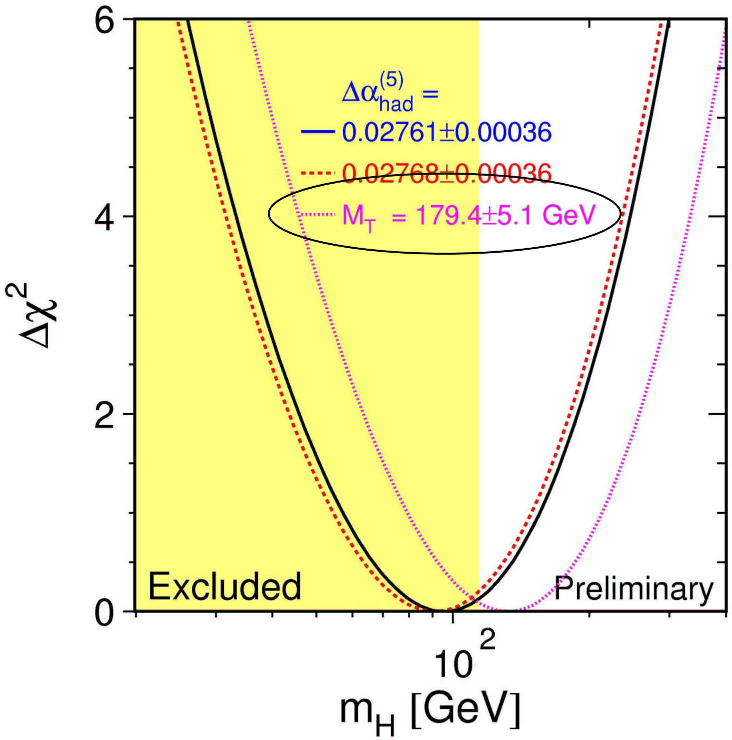
M_h dependence is logarithmic

M_t dependence is quadratic

Increasing M_t by 5 GeV increases M_h limit by 35 GeV

R. Claire, WIN03

Suppose M_t=179.4±5.1 GeV



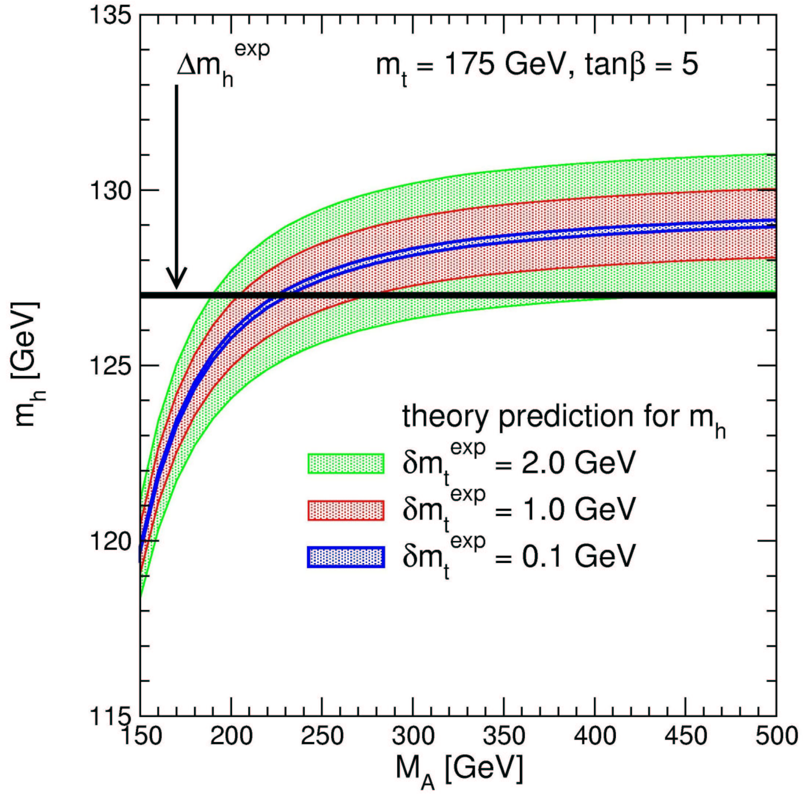
Limit on M_h goes from 219 GeV to M_h < 283 Gev

Best fit goes from 96 GeV to 126 GeV

Precise M_t measurements limit SUSY models

- Upper bound on M_h in MSSM strongly affected by M_t
- Knowing M_t precisely will limit the SUSY scale
- Note M_t^4 dependence

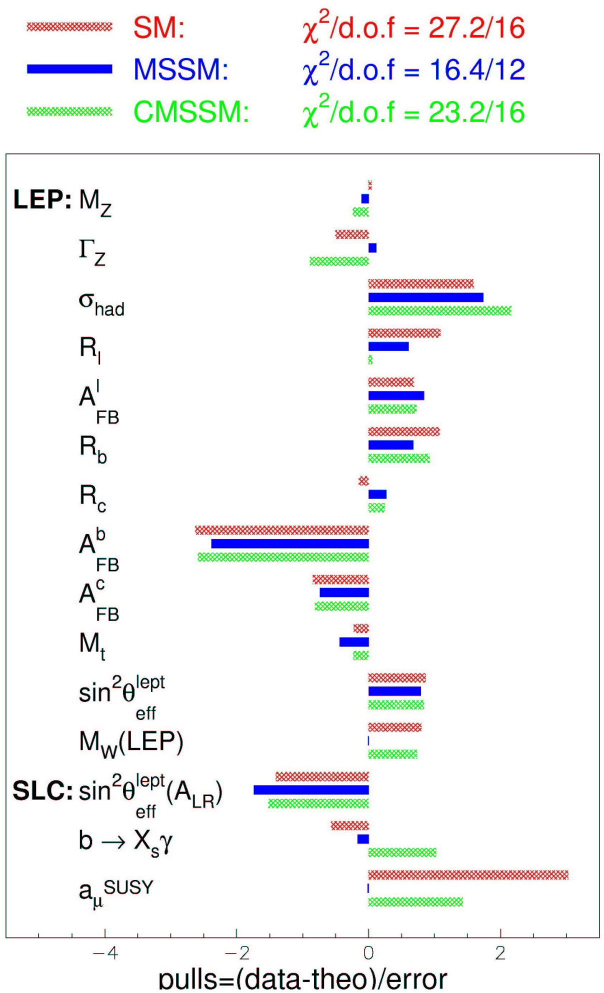
$$M_H^{\ 2} \leq M_Z^{\ 2}\cos^2 2\beta + \frac{3G_F m_t^{\ 4}}{\sqrt{2}\pi^2 \sin^2\beta}\ln\left[\frac{\tilde{m}_t^{\ 2}}{m_t^{\ 2}}\right] + \ldots$$



Heinemeyer, Kraml, Porod, Weiglein, hep-ph/0306181

Precision measurements can’t tell you source of new physics

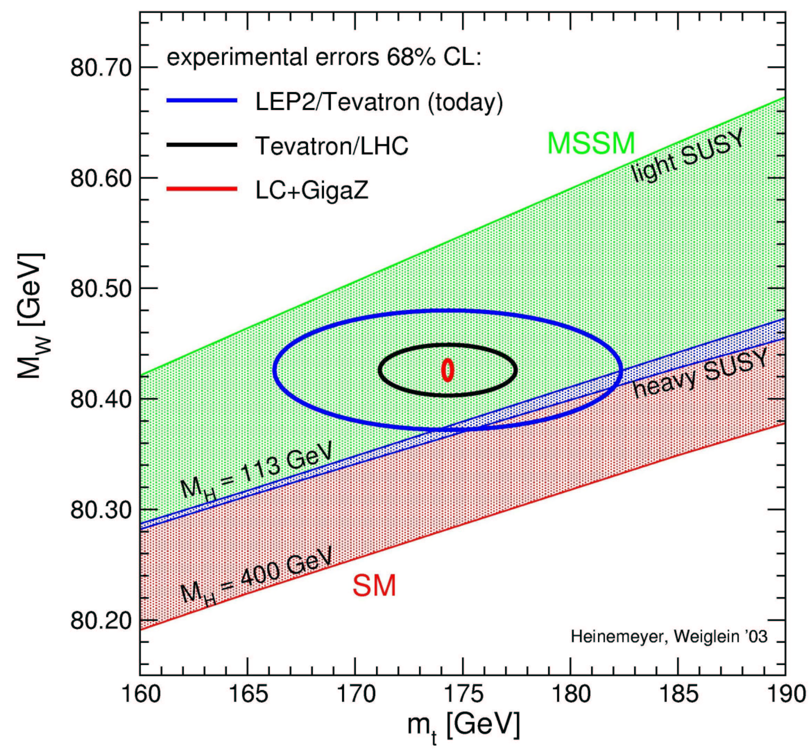
- Example: try to fit precision data to MSSM



deBoer & Sanders, hep-ph/0307049

MSSM slightly better fit (17% prob) vs SM (5% prob)

MSSM prefers “light” SUSY

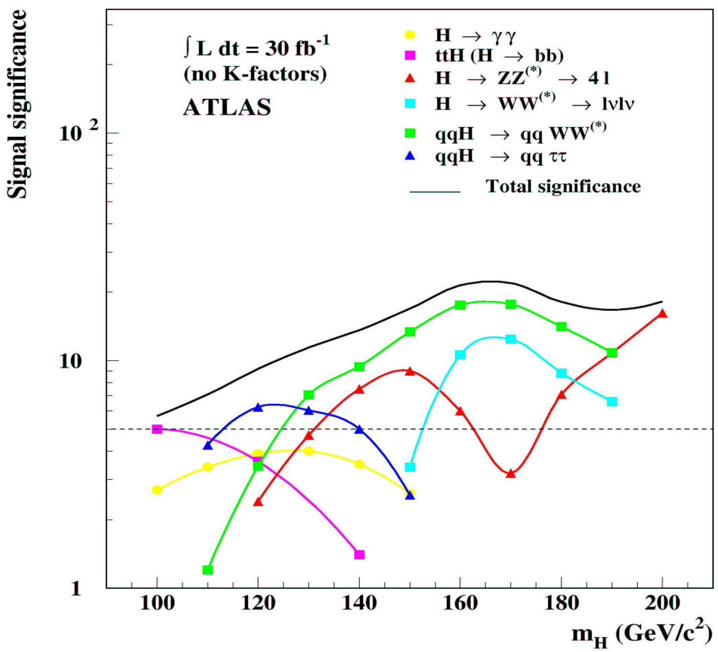


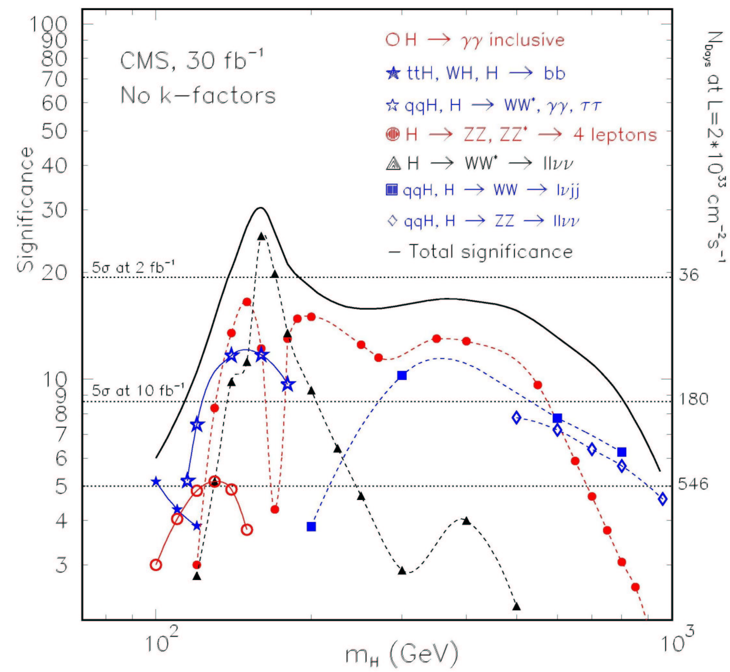
Heinemeyer & Weiglein, hep-ph/0307177

First order of business:

Find the Higgs or something like it

If there is a light SM Higgs, we'll find it at the LHC





No holes in M_h coverage

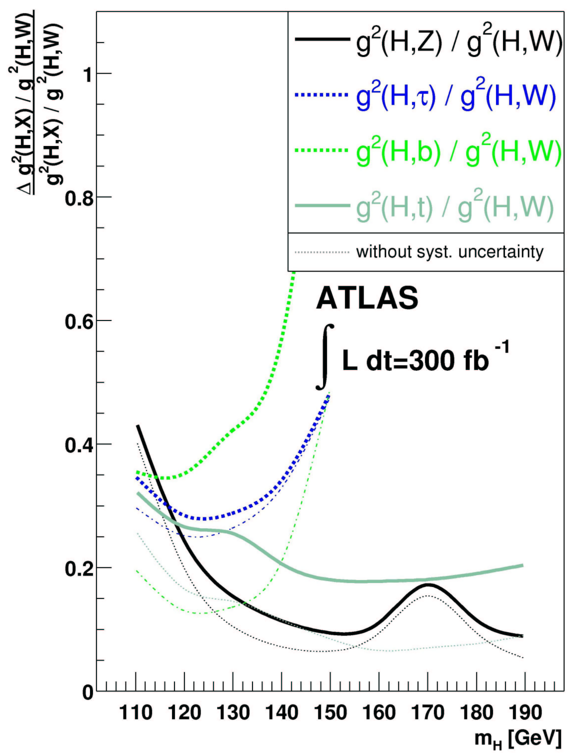
Discovery happens early in the game!

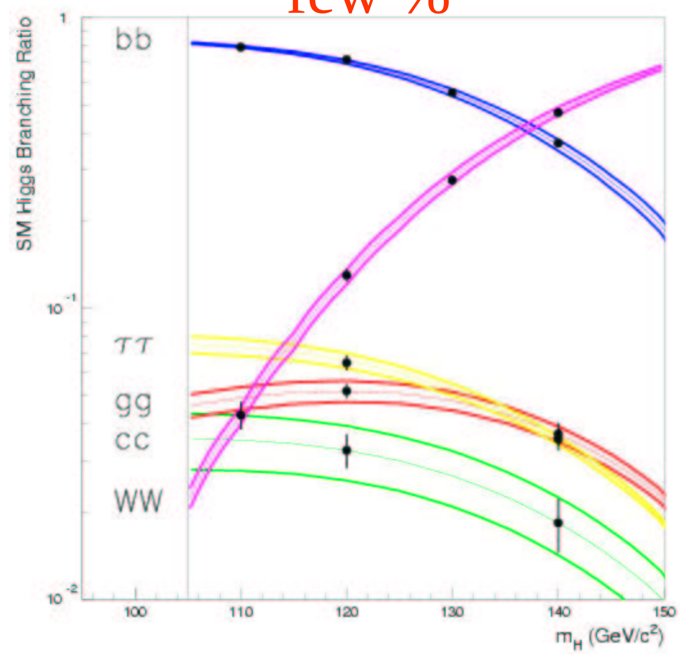
(plots are 30 fb^{-1})

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

Ratios of coupling constants measured quite precisely at LHC

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

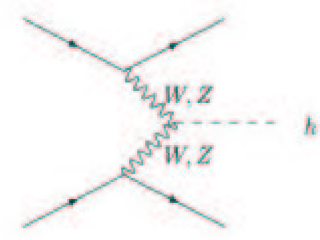
Linear Collider is the place!

Duhrssen, ATL-PHYS-2003-030

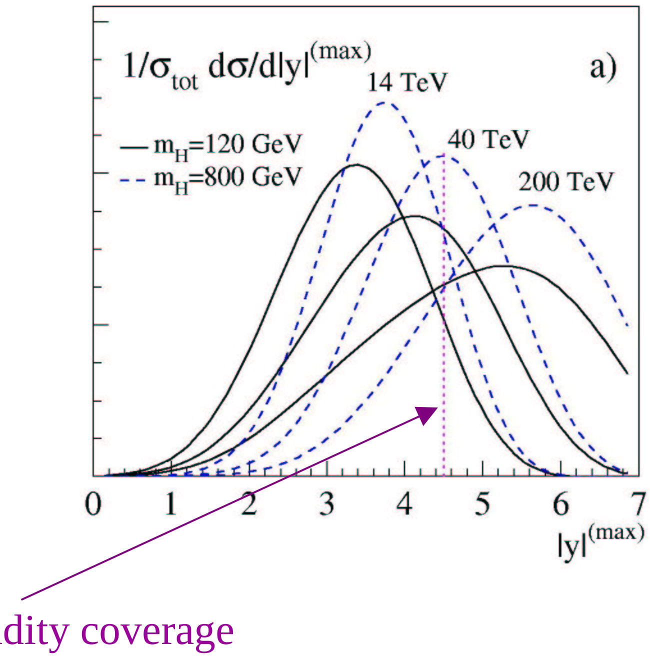
Can SLHC or VLHC improve Higgs coupling measurements?

- Critical ingredient in LHC coupling measurements is weak boson fusion
  - WBF gives 2 forward jets with large rapidity gap
  - Forward jet tagging/central jet veto crucial (degraded at SLHC)
  - Higher rate at VLHC: but need hadron calorimetry to $|y| \approx$ 6-7

SLHC improves Higgs coupling measurements by ≈ factor of 2

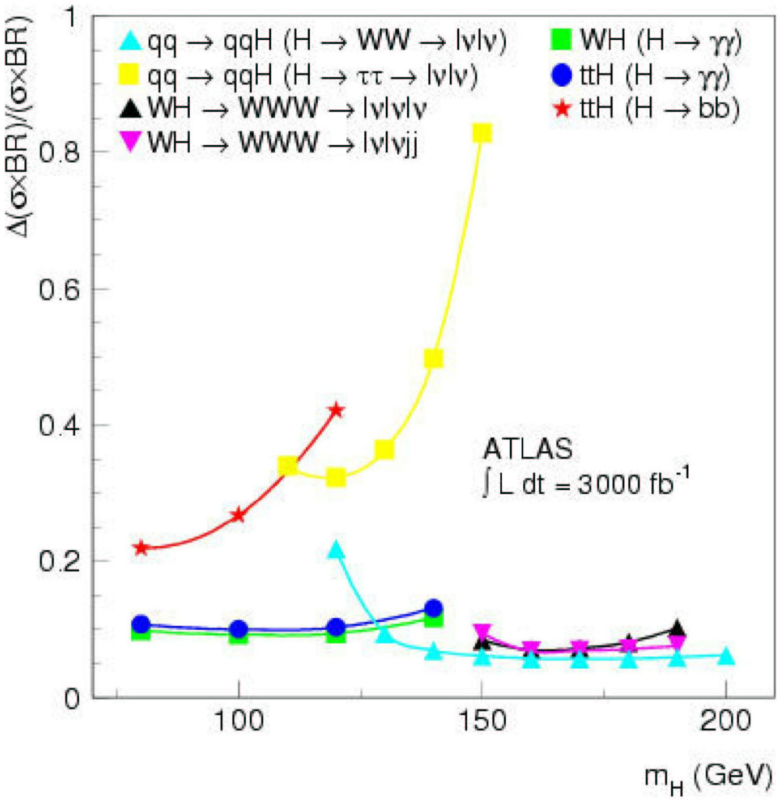


Jet rapidity distribution



Baur, Brock, & Parsons, hep-ph/0201227

Hadron machine not competitive with LC for Higgs couplings



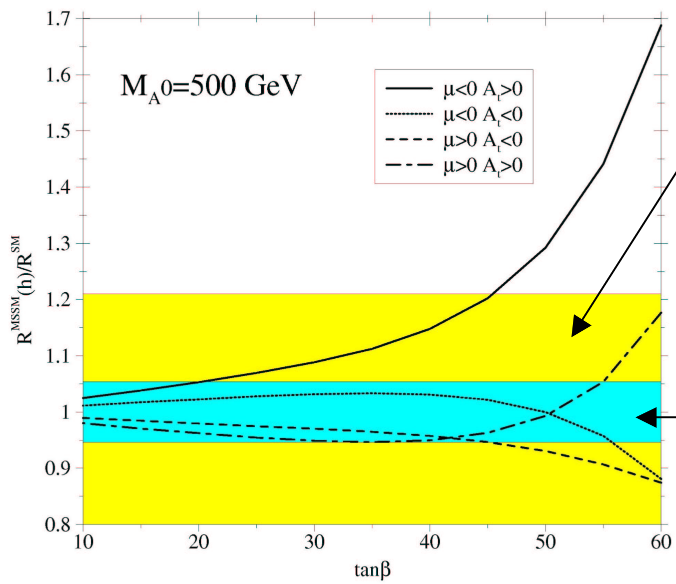
SLHC gives factor of 2 improvement over LHC in Higgs coupling measurements

Azuelos, hep-ex/0203019

How well do we need Higgs couplings?

- MSSM example:

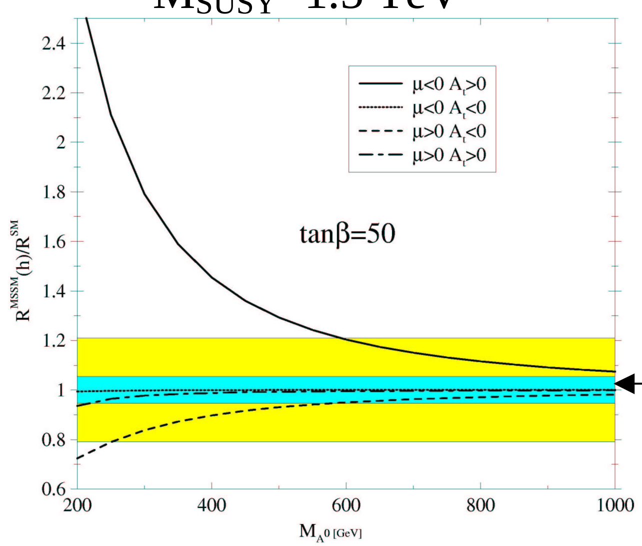
$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)}$$



21% deviation from SM

5.4% deviation from SM

M_SUSY=1.5 TeV



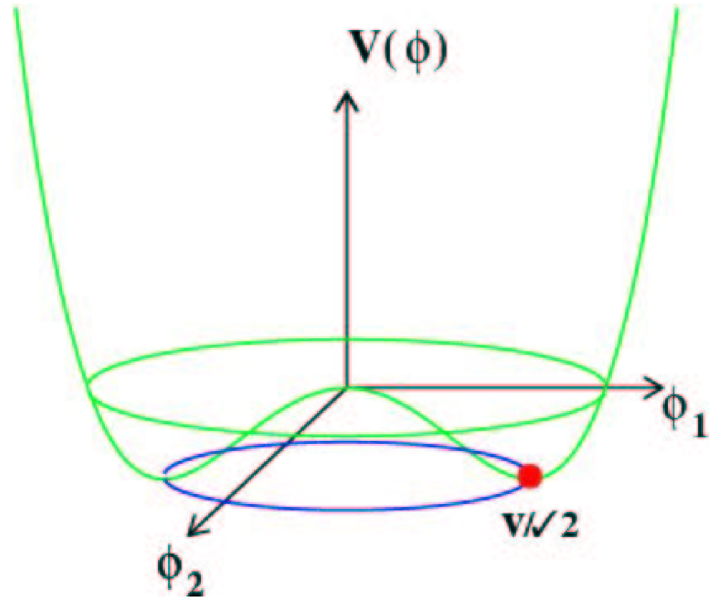
Note rapid approach to decoupling limit

Guasch, Hollik, Penaranda, hep-ph/0307012

Can we reconstruct the Higgs potential?

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

$$+ \sum_n C_n \frac{(h^2 - v^2)^n}{\Lambda^{(2n-4)}}$$

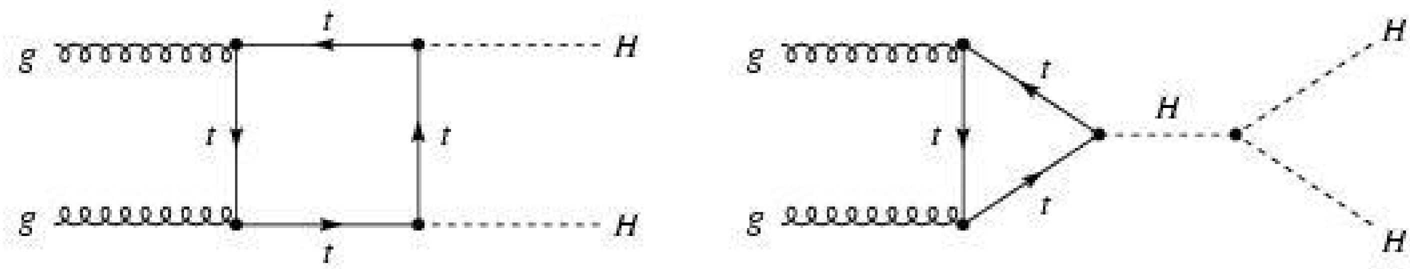


Fundamental test of model!

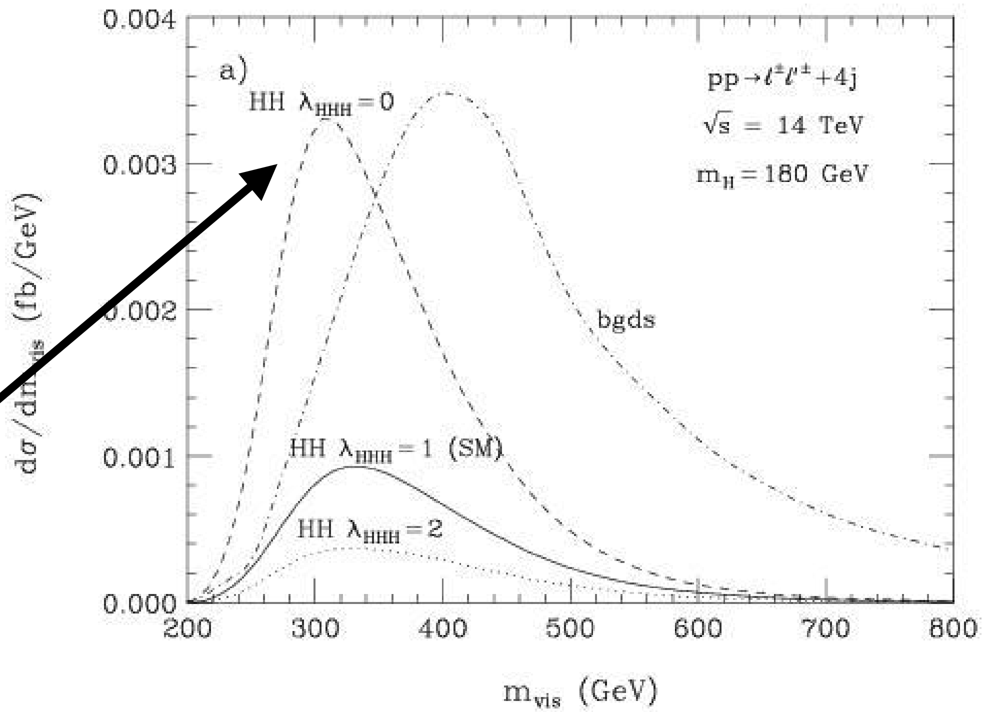
SM: $\lambda_3 = \lambda_4 = M_h^2/2v^2$

We need both λ_3 ***and*** λ_4

Reconstructing the Higgs potential



- λ_3 requires 2 Higgs production



Baur, Plehn & Rainwater, hep-ph/0304015

Can determine whether λ_3=0 at LHC

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
  - $\sigma(\nu\nu hh) \ll \sigma(Zhh)$
  - $\sqrt{s}$=500 GeV optimal energy

LHC & LC are complementary:

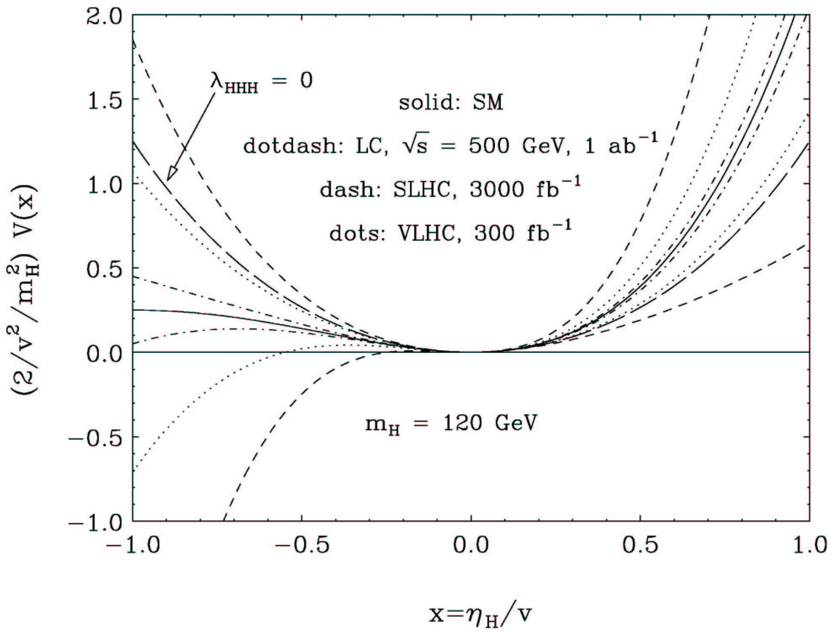
LHC sensitive to M_h>150 GeV,
LC sensitive to lighter M_h

Castanier, hep-ex/0101028

Baur,Plehn, Rainwater, hep-ph/0304015

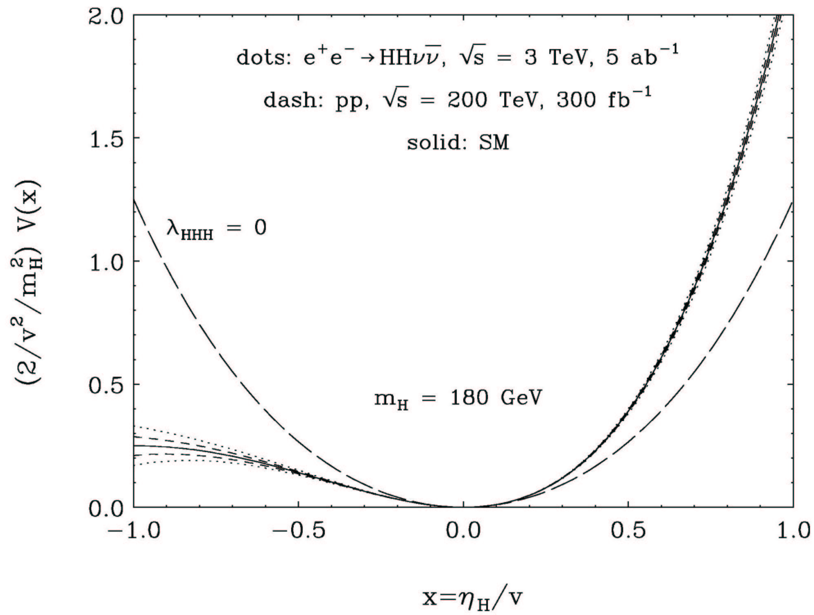
Comparison of Higgs Potential capabilities

LC, SLHC, VLHC



Significant improvement at LC for light Higgs

CLIC & VLHC similar



LC has trouble with heavier Higgs

Baur, Plehn, Rainwater, hep-ph/0304015

So….

- If the LHC gives us a light Higgs, with perhaps TeV scale SUSY…..
  - We want a linear collider to measure all the Higgs properties

Standard Model Physics isn't motivation for future hadron machine

- Electroweak physics, B-physics, top physics well known from Tevatron, B factories, LHC
- VLHC not competitive to improve SM precision measurements
- ***Argument for VLHC rests on new physics discovery potential***
  - ***LHC unlikely to tell us why the top is heavy or why the world looks 4-dimensional…..***
  - ***Although we hope it gives hints of where to look…***

Standard Model is an effective Theory

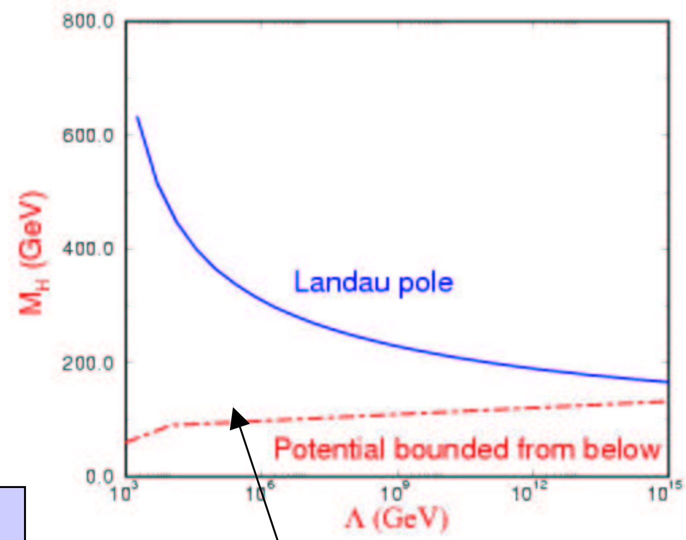
- Higgs self-coupling scales with energy

$$L_{SM} \approx -\frac{M_h^{\ 2}}{2} h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4$$

- $\lambda \to \propto$ at scale Λ

$$\frac{d\lambda}{d \log Q^2} = \frac{3\lambda^2}{4\pi^2}$$

- Heavier the Higgs ($\lambda = M_H^2/2v^2$)
  - The smaller the scale Λ
- Relatively low scale of new physics



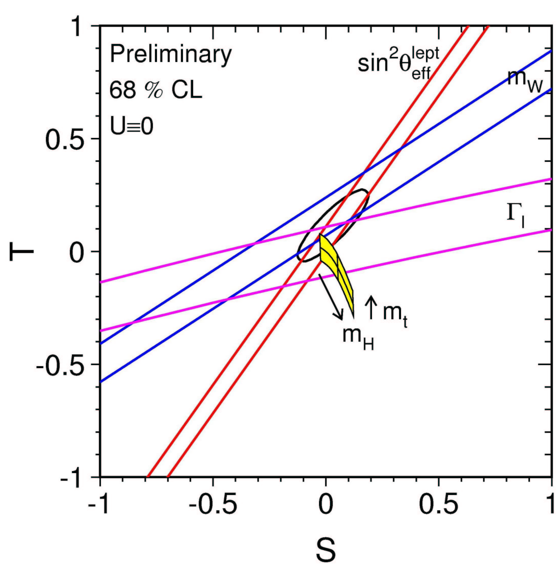
Above scale Λ, New Physics

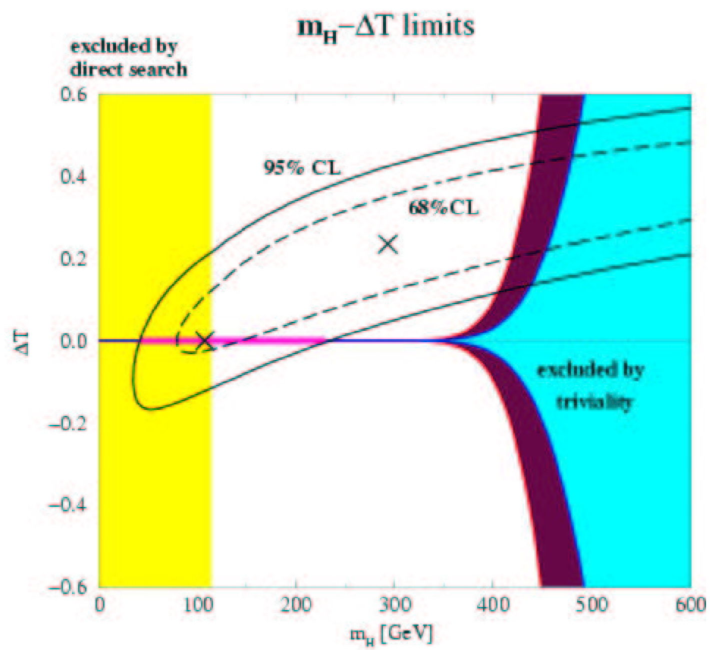
Only for small range of M_h is SM consistent at Planck scale energies!

M_h=120 GeV, $\Lambda \approx 10^6$ GeV

Higgs can be heavy with new physics

- Non-zero ΔS and/or ΔT required for heavy Higgs
- $M_h \approx$ 450-500 GeV allowed with large ΔT (isospin violation)
- Constructing a real model is the hard part





Measuring a heavy Higgs helps pinpoint the scale of new physics!

•Chivukula, Holbling, hep-ph/0110214

Beyond the Standard Model

- At some scale Λ
  - The gauge symmetry is extended
  - Or the Higgs is composite
  - Or the spectrum of supersymmetric particles begins
  - Or the Kaluza Klein resonances of extra –D models start
  - Or….
- Probe effects of new physics at scales smaller than Λ

$$L = L_{SM} + \sum \frac{f_i}{\Lambda^n} O^{(4+n)}$$

- Can fit EW precision data with f≈ 1, Λ ≈1-3 TeV

Many Possibilities for New Physics

- Supersymmetry
- Extra dimensions
- Compositeness
- Strong Electroweak symmetry breaking
- Something new?

$\Rightarrow$ Clues from the LHC

What is scale of new physics?

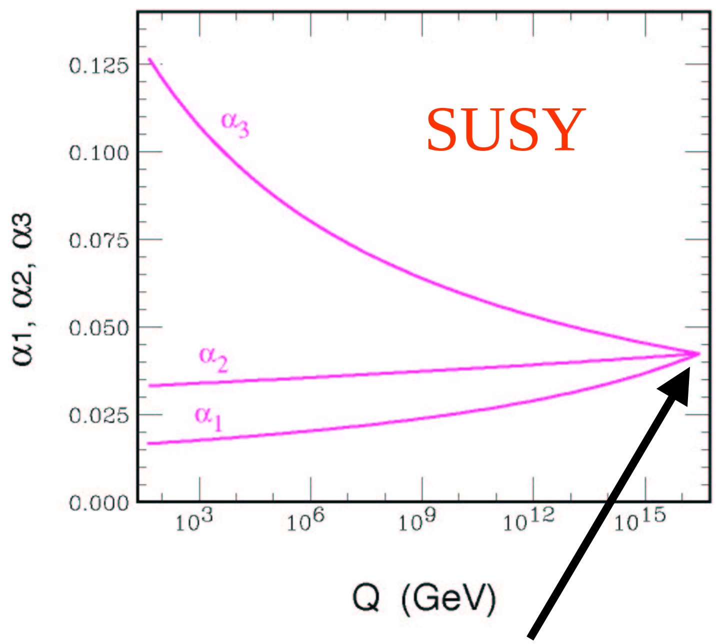
Determining source of new physics requires data

Case study:

Exploring the SUSY spectrum

Supersymmetry is a favorite candidate*

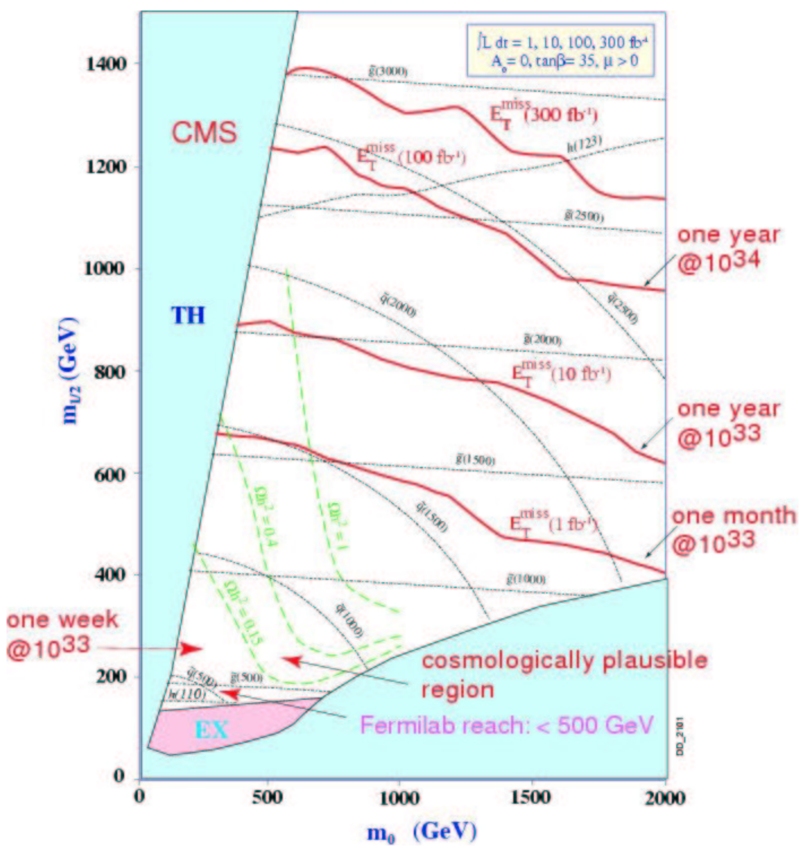
- MSSM most studied variant of SM
- Motivated by coupling unification; Higgs mass renormalization
- Definite predictions for rates, Higgs mass
- Most general model has many parameters



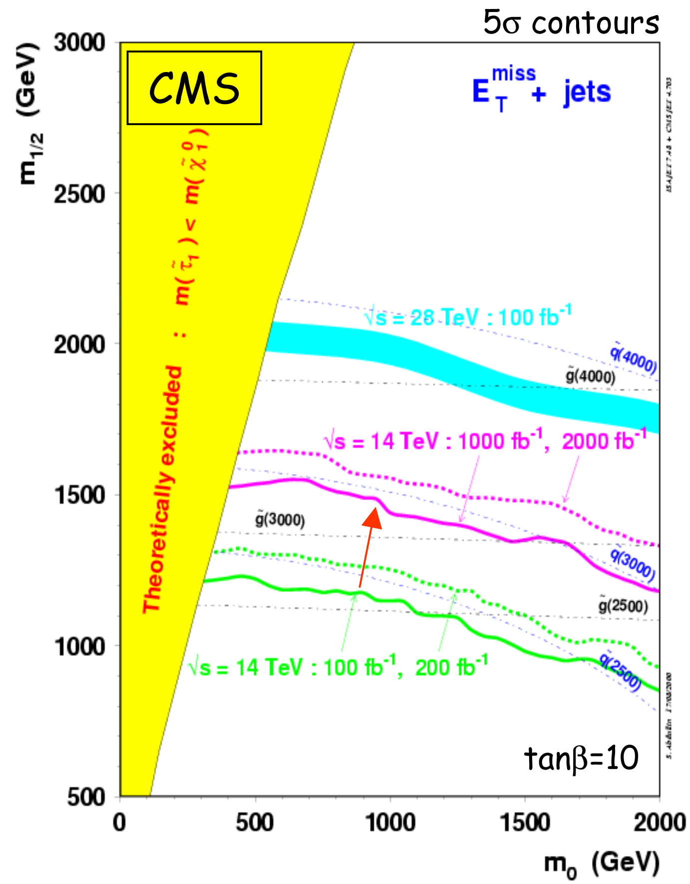
Doesn't happen in SM

*Spires has > 7800 papers after 1990 with t supersymmetry or supersymmetric

TeV Scale SUSY likely to be discovered at the Tevatron or LHC

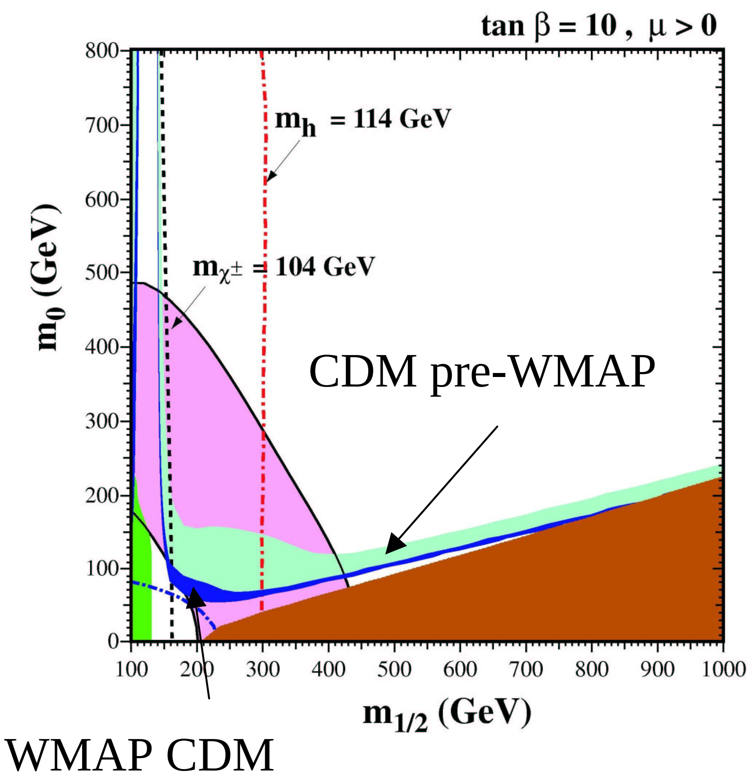


SUSY can be found with low luminosity….but what is it?



SLHC increases discovery reach by ≈ 500 GeV

WMAP suggests SUSY is just around the corner?



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

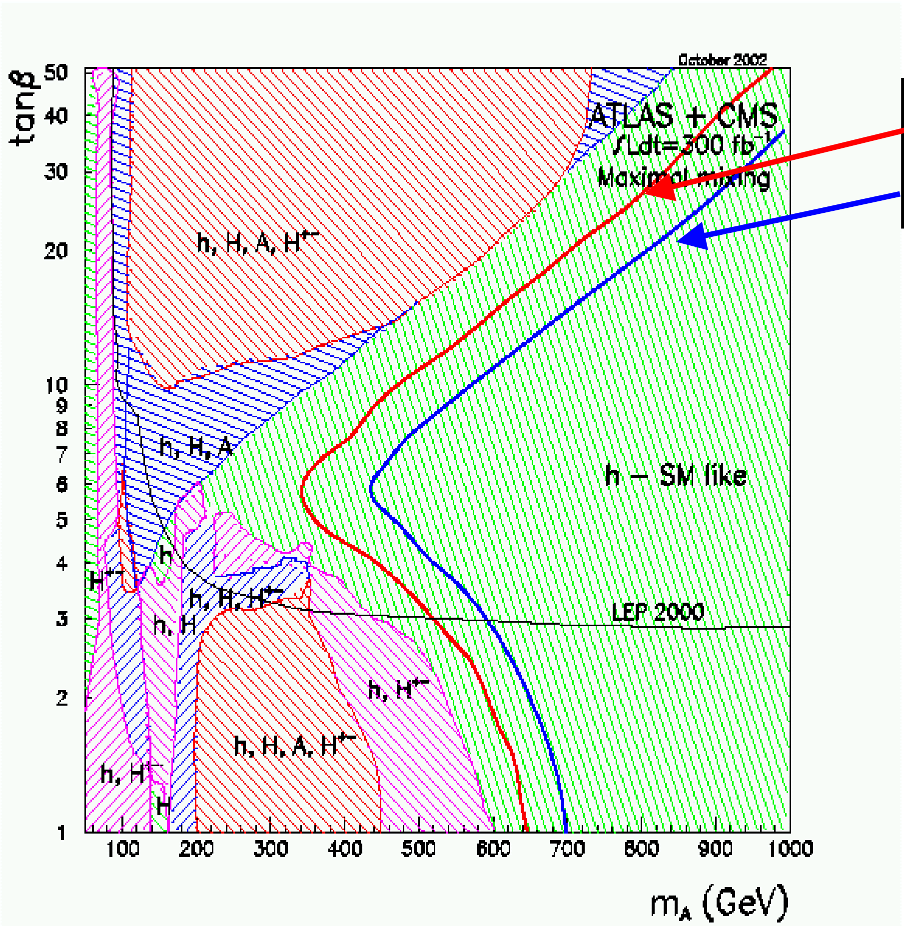
Assume dark matter is LSP of mSUGRA

Note low m_0 scale!

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

Doesn't look nearly as pretty without mSUGRA assumptions

MSSM heavy Higgs difficult in wedge region at LHC



H observable with 3000 fb^{-1}/exp
95% excl. for H with 3000 fb^{-1}/exp

Need to find not just SM Higgs, but heavy and charged Higgs, also

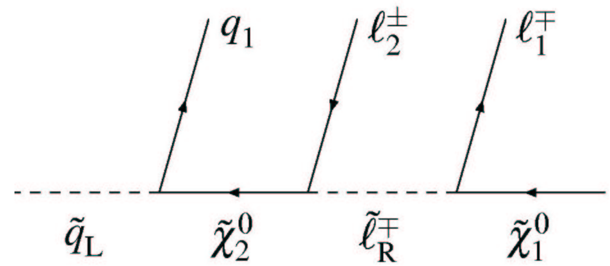
SLHC improves discovery reach by 50-100 GeV

$e^+e^- \rightarrow H^+H^-$ gets to≈ kinematic limit

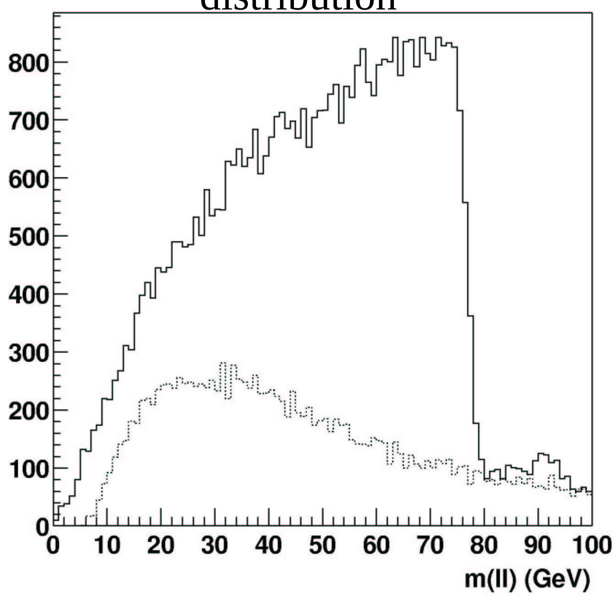
LHC can miss part of MSSM spectrum!

Measuring SUSY masses at hadron colliders

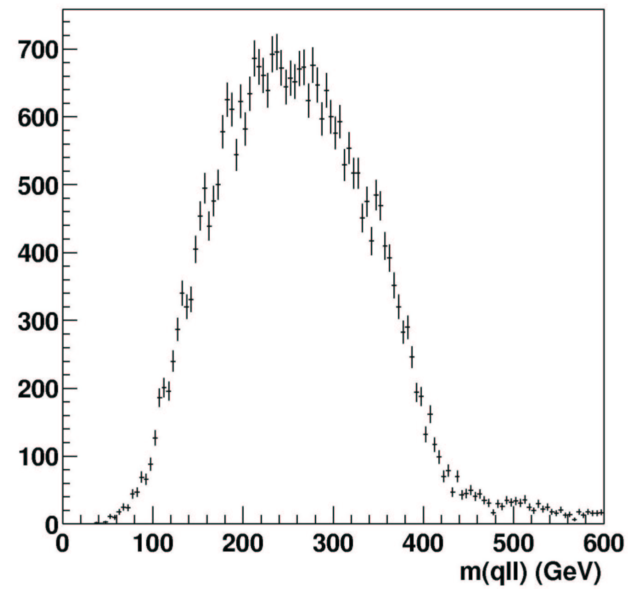
- Complicated decay chains
- Main tool: dilepton edge from $\tilde{\chi}_2^{\,0} \rightarrow l^+ l^- \tilde{\chi}_1^{\,0}$
- Sbottom/squark and gluino reconstruction
- Proportional to mass differernces: strong mass correlations



Same flavor-opposite sign lepton distribution

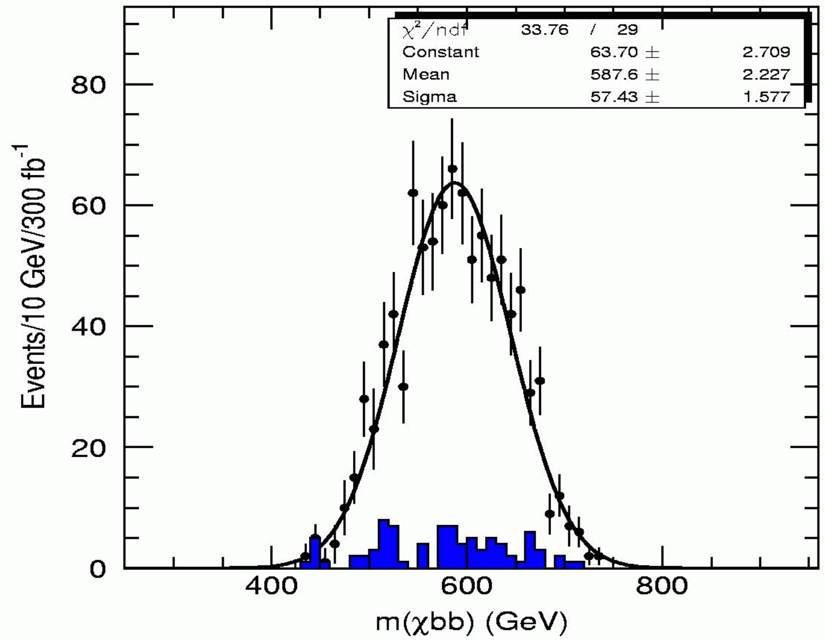


Invariant qll mass

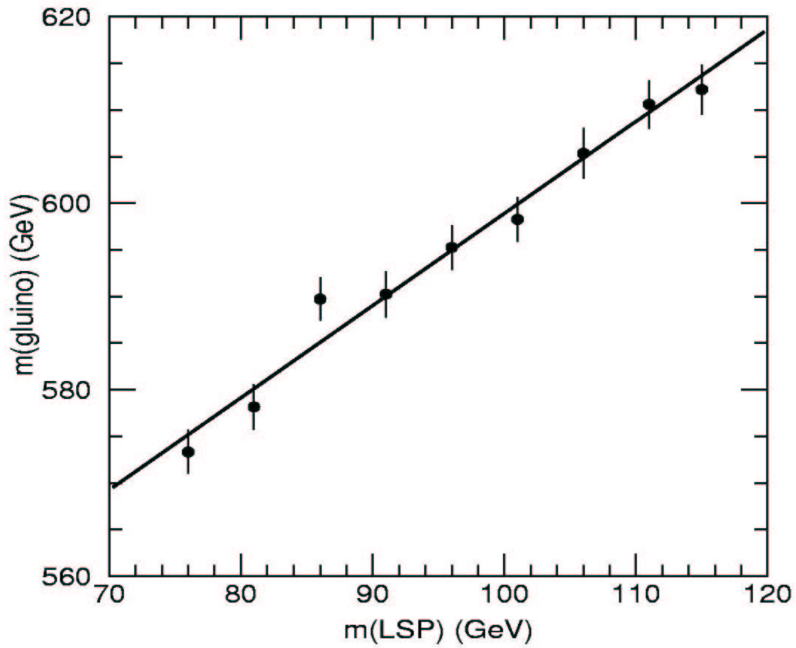


LHC: Gluino mass precision directly related to LSP mass

Gluino mass reconstruction from $\tilde{\chi}_2^0 b\bar{b}$

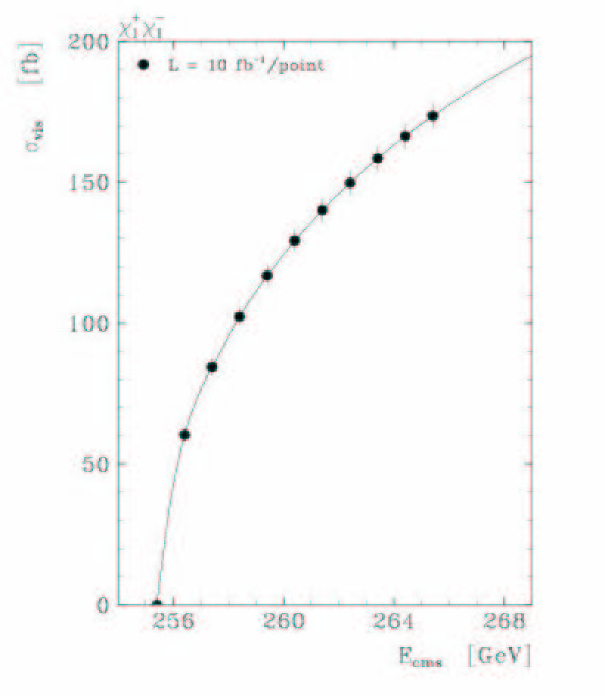


Gluino mass as function of LSP mass



$\Rightarrow \Delta m(\text{gluino}) \approx \Delta m(\text{LSP})$

LC makes precision mass measurements



- Chargino pair production, S-wave
- Rises steeply near threshold
- This example:

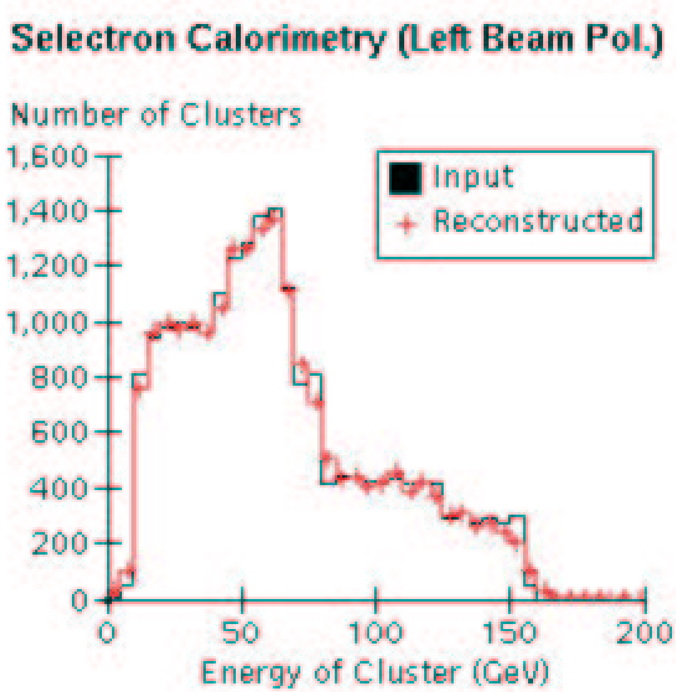
$$\frac{\delta m}{m} \approx .1\%$$

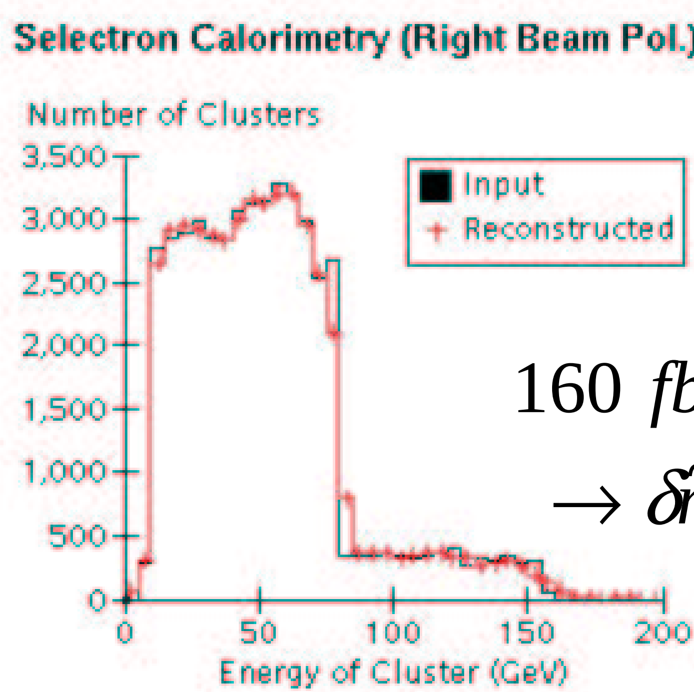
Blair, hep-ph/99910416

LC mass measurements from endpoints

$$e^+e^- \to \tilde{e}^+\tilde{e}^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$m_{\tilde{l}}^{\,2} = \frac{sE_{\max}E_{\min}}{(E_{\max}+E_{\min})^2}\,,\ \left(1-\frac{m_{\tilde{\chi}_1^0}^{\,2}}{m_{\tilde{l}}^{\,2}}\right)^2$$



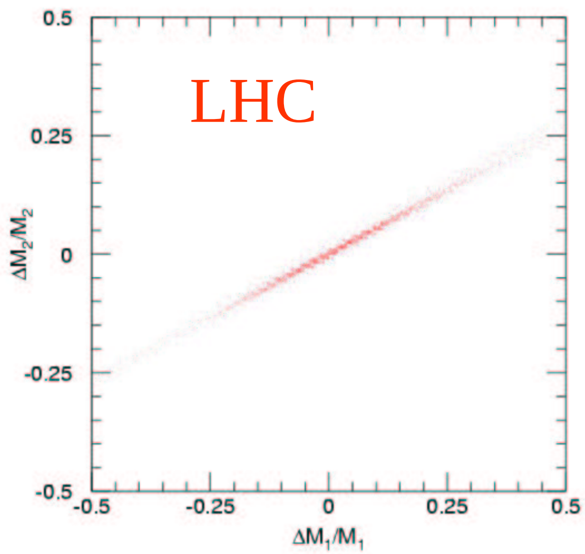


$160\ fb^{-1}$

$\to \delta\tilde{m}_e \approx .4\,GeV$

LHC & LC improves SUSY mass resolution

- LSP mass constrained at LHC at 10% level



Bachacou, Hinchliffe, Paige, hep-ph/9907518

⇒LC input improves accuracy significantly

•Take LSP mass as input from LC

(GeV)	LHC	LHC+ LC(.2%)	LHC+ LC (1%)
$\Delta m(\tilde{\chi}_1^0)$	9.2	.2	1
$\Delta m(\tilde{l}_R)$	9.2	.5	1
$\Delta m(\tilde{\chi}_2^0)$	9.0	.3	1
$\Delta m(\tilde{b}_1)$	23	17	17
$\Delta m(\tilde{q}_L)$	15	5	5

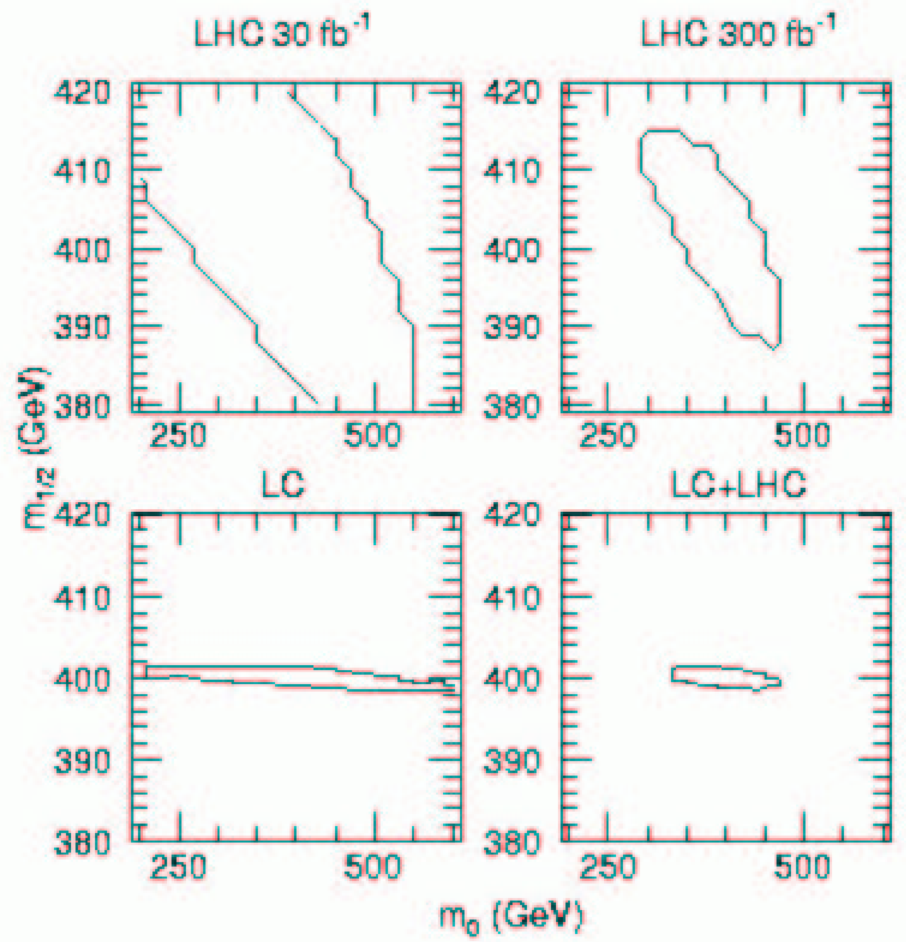
Weiglein, LHC/LC Study

Need to ask the who cares question?

SUSY: LC+LHC

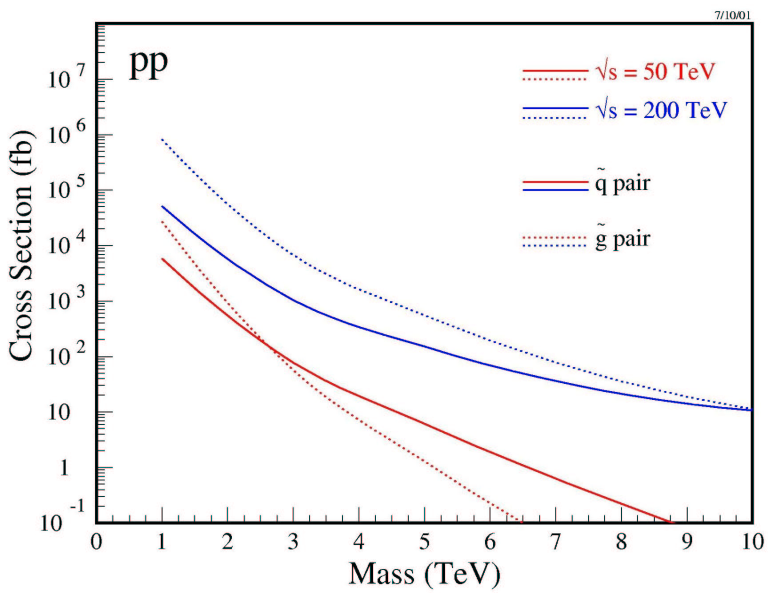
Global fit to mSUGRA parameters:

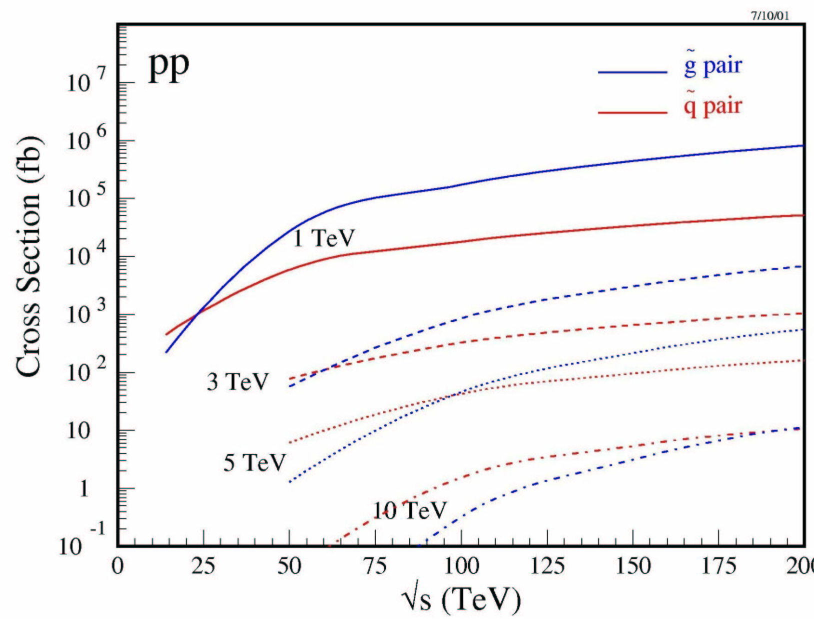
m_0, $m_{1/2}$,sign(μ), A_0, $\tan\beta$



- LHC sensitive to heavy squarks, gluinos
- Use neutralino mass, couplings from LC
- CMS study:10 fb^{-1} gives squark, gluino masses to 1-2% ***if*** neutralino mass known from LC

VLHC increases discovery reach for SUSY





Rates increase
dramatically with energy

Baur

But can we tell what underlying model is?

- Can we test models of SUSY breaking?
  - SUSY broken by VEV, F
  - Breaking communicated to Standard Model at Scale, M
  - Gauge Mediated Models, SUSY masses:

$$\tilde{m} \approx \frac{\alpha}{4\pi} \frac{F}{M}$$

$\Rightarrow$ Discovery of SUSY implies there must be a new scale, F

One Scenario

LHC finds SUSY

- Looks like Gauge Mediated SUSY (masses and decays have the right pattern)

- Lightest SUSY (LSP) particle is gravitino
  - Phenomenology described by NLSP (which decays to LSP)

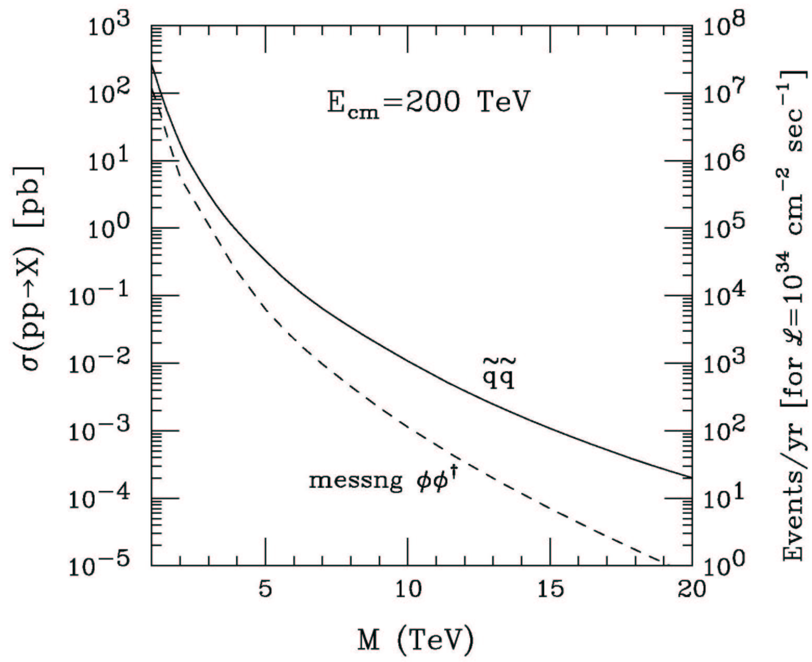
$$c\tau_{NLSP} = 100\mu m \left(\frac{100GeV}{m_{NLSP}} \right)^5 \left(\frac{\sqrt{F}}{100TeV} \right)^4$$

  - LHC measures F and SUSY masses

$\Rightarrow$ Prediction for messenger scale

VLHC looks for Messenger fields

- Discovery of messenger fields confirms GMSB



Last Example:

Finding new Z's

New Z's highly motivated

- Little Higgs models:
  - Could the Higgs be a Goldstone boson?
    - Intermediate scale, f, limited by precision measurements
  - Predict the scale after 1 TeV
    - Maybe find new fermions, gauge bosons at LHC

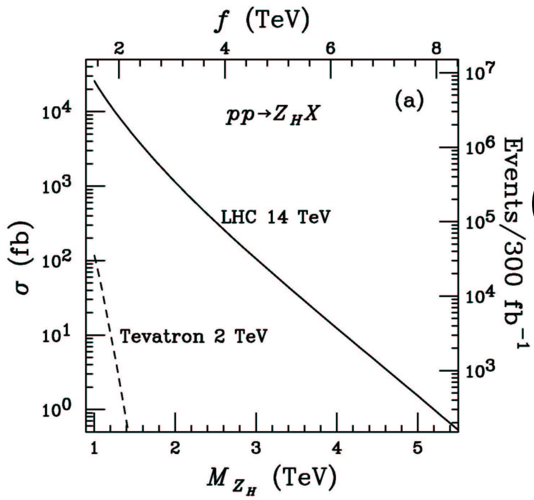
$\Lambda \approx 10$ TeV — Sigma model cut-off

$f \approx 1\text{-}5$ TeV — Charge 2/3 quark, Heavy gauge bosons, Scalar triplets

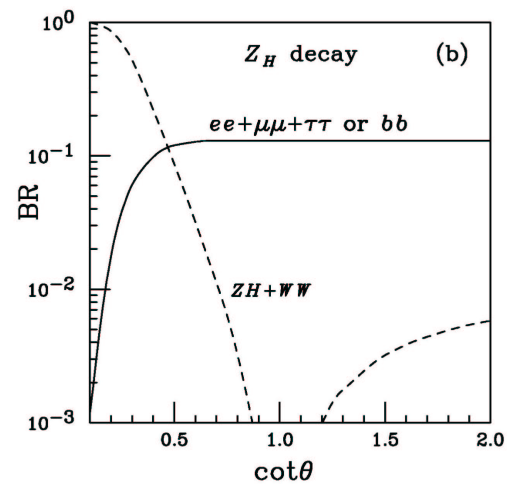
$v = 246$ GeV — 1 or 2 Higgs doublets

New Phenomenology in Little Higgs Models

- Drell-Yan production of Z_H
  - EW precision limits prefer cot θ ≈ .2 (Heavy-light gauge mixing parameter)
  - BRs very different from SM

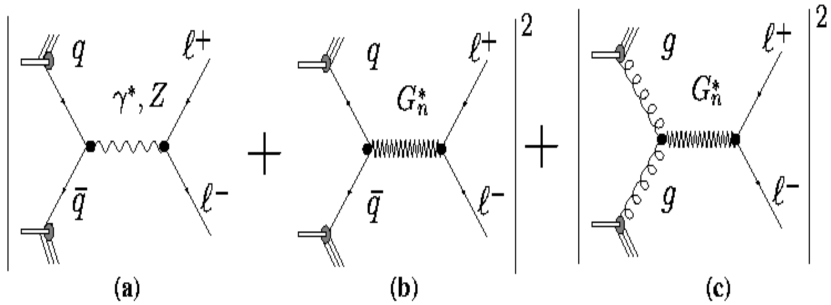


Scale down by $\cot^2\theta \approx .04$



Han,Logan,McElrath, Wang, hep-ph/0301040

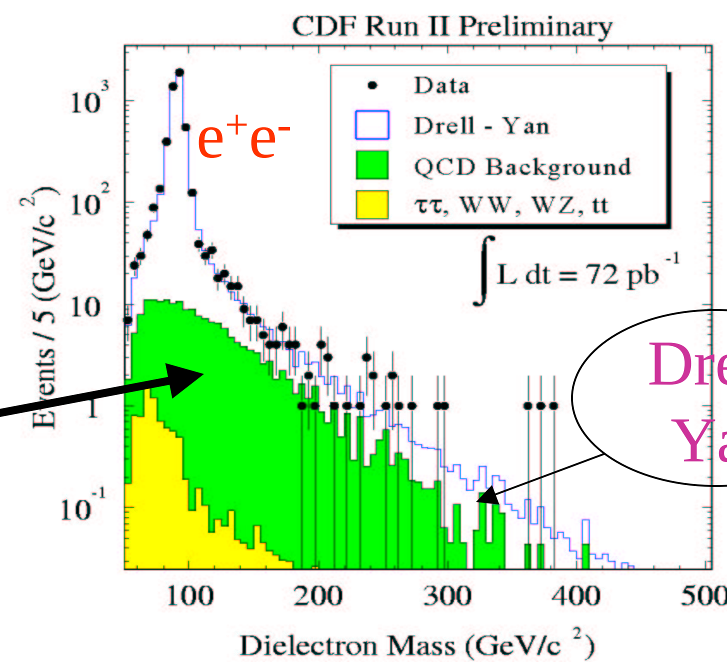
Large Extra Dimension models have new resonances in Drell-Yan



RunII search for high mass di-leptons

Sensitive to Z' and Randall-Sundrum Graviton

No excess observed

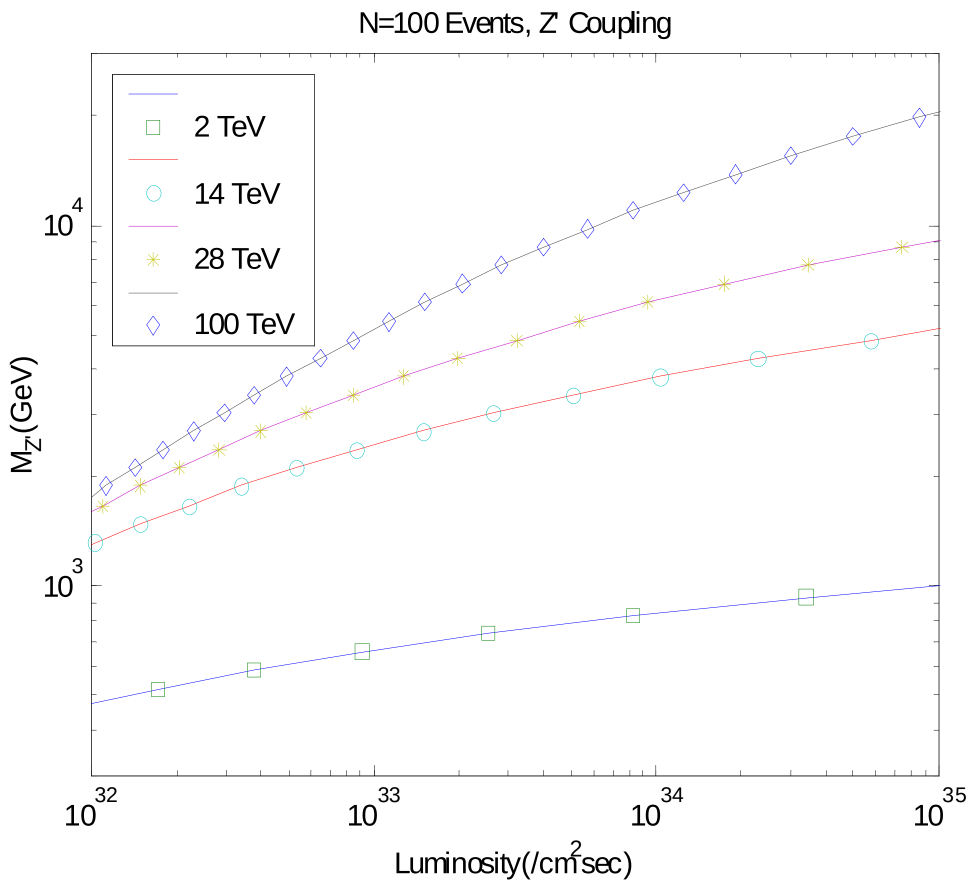


Drell-Yan

Note critical importance of understanding QCD backgrounds

Z’ Reach at Tevatron, SLHC & VLHC

Mass reach of Z’



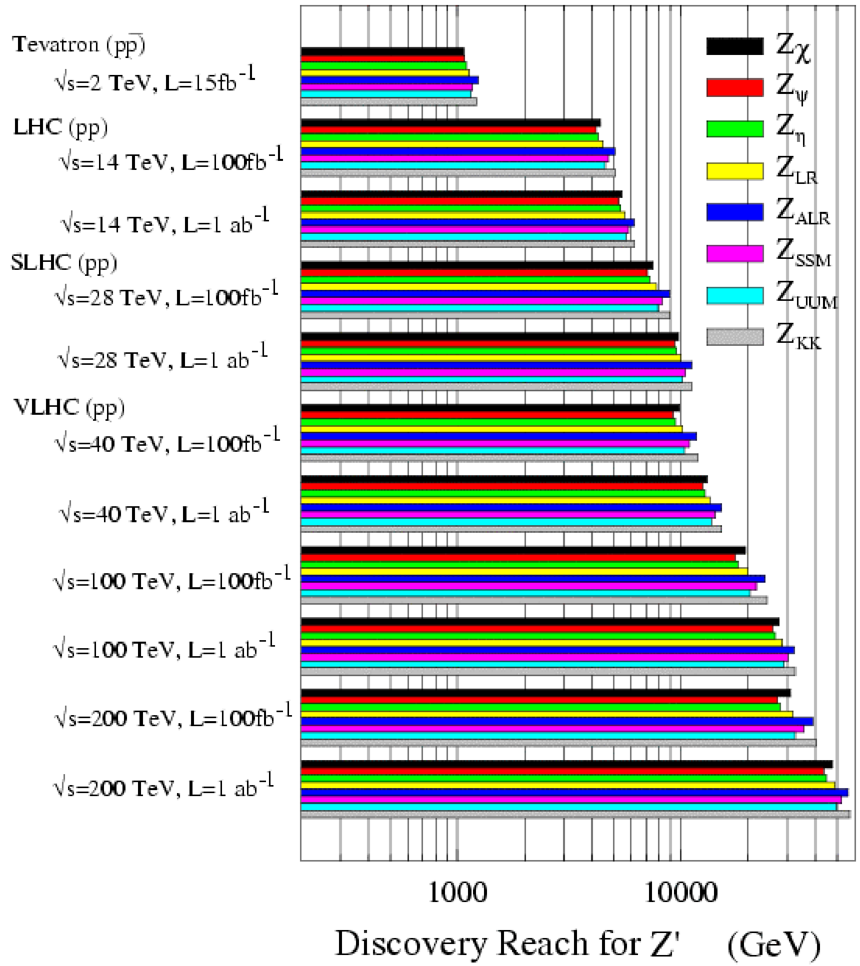
Factor 10 in luminosity extends the
Z’ reach by 1-1.5 TeV
14 TeV to 100 TeV extends reach by factor of 7-10

Comparison of Z’ Models

Many models, but at a given machine, reach is similar for all models

Assumes 10 events in e^+e^- + $\mu^+\mu^-$ channels

Energy counts!



S. Godfrey, hep-ph/0201093

I discussed 3 examples:

- SM Higgs physics
  - Because this is a program which will be largely completed by the LHC and LC
  - With the possible exception of the Higgs potential
- Supersymmetry
  - Because we are unlikely to know what causes SUSY breaking even with the LHC and LC: data will point to the next energy scale
  - If we don't find squarks and gluinos, the extra mass reach of the SLHC or VLHC could be crucial
- New Z's
  - Because this is a case where discovery reach is likely to be critical
- Many other possibilities, of course

Snowmass summary

	LHC 100 fb^{-1}	*SLHC 1 ab^{-1}*	*VLHC 40 TeV, 100 fb^{-1}*	*VLHC 200 TeV, 100 fb^{-1}*
tth coupling	13%	10%	5-10%	1-3%
gluino, squark	2 TeV	2.5 TeV	4-5.5 TeV	20 TeV
Z'	4-5 TeV	5-6 TeV	10-13 TeV	30-40 TeV
Composite ness	23 TeV	35 TeV	50 TeV	100 TeV
Strong WW	1.7 σ	1.6 σ	7 σ	18σ
Extra D, δ=4, M_D	9 TeV	12 TeV	24 TeV	65 TeV

Baur, Brock, Parsons, hep-ph/0201227

Conclusions

- Sound bites:
  - *The arguments for new physics at the TeV scale are solid and well developed*
  - *But many questions will remain unanswered by the LHC and even a LC*
  - ***There will be an energy scale of new physics beyond the TeV….determining what it is requires DATA from the LHC.***