New *(Tev scale)* Phenomenology at LHC.

♢ Current state of play on HEP.

♢ Issues which force us to think of Beyond the Standard Model (BSM), TeV scale Physics?

♢ Which BSM physics?

a Nonstandard Higgs, SUSY.....
b EW alternates: Little Higgs, Higgsless Theories...
c Braneworld: Extra Dimensions small/big,warped,...

♢ LHC and all the above.

a Take EWSB (Higgs sector) as an example to point out the exptalist-theory synergy :-)
b The possibility (need) for International Linear Collider ILC: Synergy betweeen the LHC and the ILC arXiv:hep-ph/0410364.

HEP is in a strange situation.

The usual road through which Science progresses:

Existing Theory and Unexplained Phenomena $\Rightarrow$ New Theoretical developments $\Rightarrow$ Predictions $\Rightarrow$ Testing in Experiments.

Current state in HEP

Existing Theory **No Unexplained Phenomena!**, Prejudices of the Community $\Rightarrow$ New Theoretical Developments $\Rightarrow$ Predictions $\Rightarrow$ Testing in Experiments.

We have strong theoretical reasons to believe that there is new physics at the TeV scale, Dont have *any strong* experimental evidence indicating its need.

LHC is now at the doorstep, time of reckoning at hand ! For most of us thinking of various theoretical options of BSM , necessary to know what the LHC can/can not do :-)

Generalities:

The SM Lagrangian consists of 'proved' gauge sector and **yet to be proved scalar** sector:

$$\mathcal{L} = - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\bar{\psi}\, \not{D}\psi$$
$$+ \psi^T \lambda \psi h + h.c.$$
$$+ |D_\mu h|^2 - V(h)$$

Gauge sector in good shape. Given that the Strong interaction part also got the Nobel ☺

Last few years great progress in the flavour sector: The correctness of CKM picture, ν oscillations...

SM needs to be augmented by

$$\mathcal{L}' = (\frac{1}{M} L_i \lambda^\nu_{ij} L_j h^2 \,\text{and/or}\, L_i \lambda^\nu_{ij} N_j h + h.c.) \tag{1}$$

Generalities(continued):

- ♢ Instability of the EW scale under radiative corrections, a need to get a basic understanding of the flavour problem, direct evidence for the nonzero ν masses, unfication of couplings, all indicate need to go beyond the SM and possibly with a scale of (few) TeV for this physics.

- ♢ Some of the above *need* a TeV scale resolution, for some we may postpone the solution to Planck scale :-)

In addition

- ♢ Connection with Cosmology e.g. quantitative explanation of Baryon Asymmetry requires physics beyond that in the SM, in terms of additional CP violation, lepton number violation etc.
- ♢ Dark Matter: a second important connection between HEP and Cosmology. The favourite BSM models have a DM candidate present in the theory.
- ♢ Dark Energy? Yet another connection between HEP and cosmology? Does our understanding of Gravity help here?

□ All these indicate different types of NEW physics beyond the SM.

see http://lepewwg.web.cern.ch

- Precision Measurements: fit includes LEP, Tevatron, SLC ..data
- Pull is the difference between the SM best fit value in units of the stnadard deviation of the measurement error.
- The per mill accuracy of measurements means that χ^2 of the fit is large even with quite a good fit. χ^2/dof = 16.7/14 (without nuTeV) Probability 27%.
- There are some tricky issues of discussion here. Including nuTeV data increases χ^2/dof to 25.5/15, with a probablitiy of only 4%.
- By and large most believe that this shows that the SM works *reasonably* well in explaining the EW precision data
- *May be holds also some clues of Physics beyond the SM*

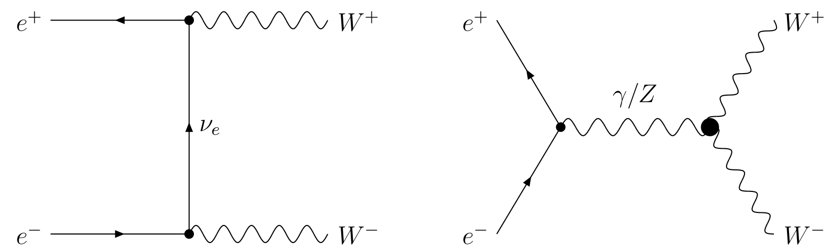
Direct 'Proof' of $SU(2) \times U(1)$

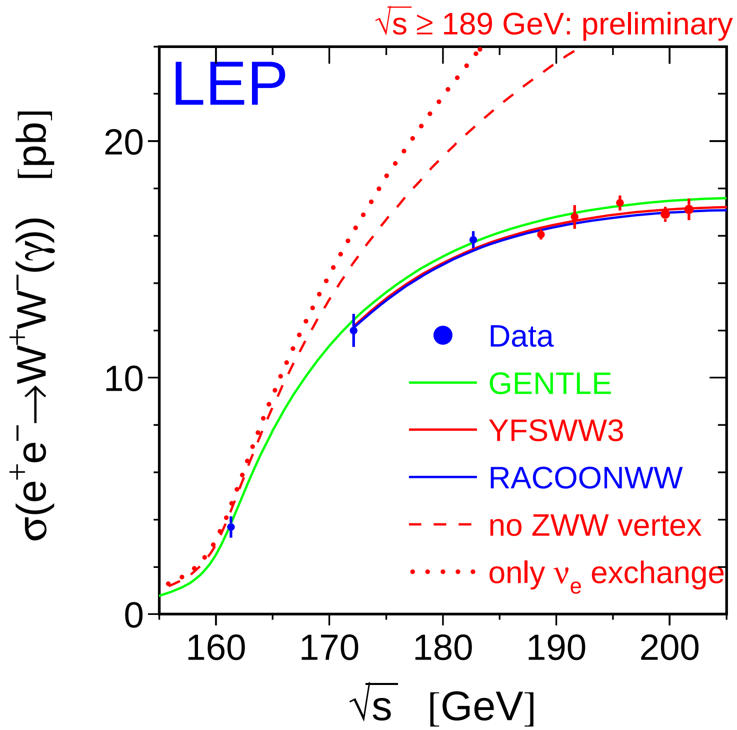
- The triple gauge boson ZWW coupling tames the bad high energy behaviour of the cross-section caused by the t-channel ν-exchange diagram.

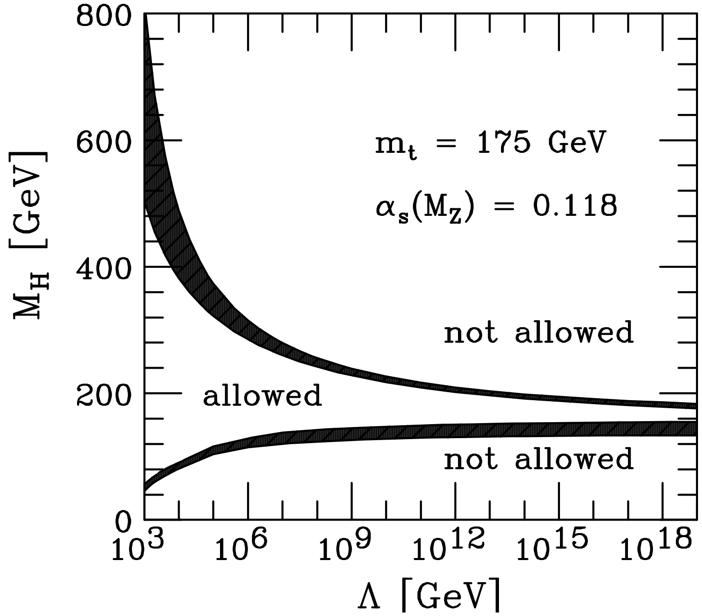
- Direct verification of the nonabelian nature of the SM.

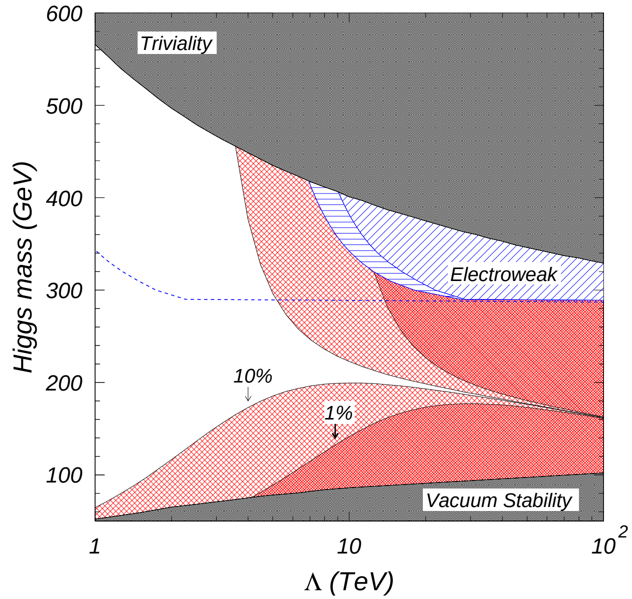
- Recall *nonabelian nature of the coupling* and particle content of the SM including the Higgs particle can be obtained by requiring 'good' high energy behaviour of the amplitude $WW \to WW$

- 'Proof' that EW symmetry exists and is spontaneously broken. What then about the Higgs?









- In the SM Higgs mass a free parameter.
- Is there is no new physics beyond the SM upto M_{pl} then m_h restricted to a narrow range. SM certainly likes a light, weakly coupled higgs. Bound is $\sim$ 800–900 Gev if $\Lambda = 1$ TeV.
- If SM is an effective theory only upto 1 TeV, i.e. there is new physics beyond 1 TeV, bound is higher. A heavier Higgs would be consistent with New Physics at lower scales.
- The Murayama/Kolda analysis adds additional higher dimensional operators.

Two kinds of bounds from Colliders.

Direct (lower) Bound:

Direct search at LEPII for h production in

$e^+e^- \to (Z^*) \to Z + h$

followed by the decay of h has yielded negative results,

In the SM $m_h >\sim 114$ GeV.

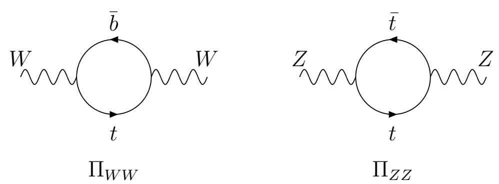
Logical steps in Precision testing of the SM and the indirect limits.

- SM has three parameters g, g' and v.
- All the SM couplings, gauge boson masses functions of these
- A large number of EW observables measured quite accurately.
- m_Z, α_{em} and G_μ are most accurately measured.
- Trade g, g' and v for these.
- All observables depend on these three apart from m_f (mainly m_t) *and* m_h, and of course α_s.
- Calculate all observables using **1 loop EW** radiative corrections.
- Compare with data, make a SM fit. Tests the SM at loop level.

Dominant loop corrections involve t/b loops.

See the effect in terms of radiative correction to ρ.
At tree level,

$\rho = m_W^2/(m_Z^2 \cos^2\theta_W)$, $(G_F\sqrt{2}) = (g^2/8m_W^2)$



$\Delta\rho \equiv$ change in ρ at one loop due to t:

$\Delta\rho = \Pi_{ZZ}(0)/m_Z^2 - \Pi_{WW}(0)/m_W^2 \simeq N_c G_F m_t^2/(8\pi\sqrt{2})$

$\Delta\rho$ is a function of m_t, depends on it quadratically.

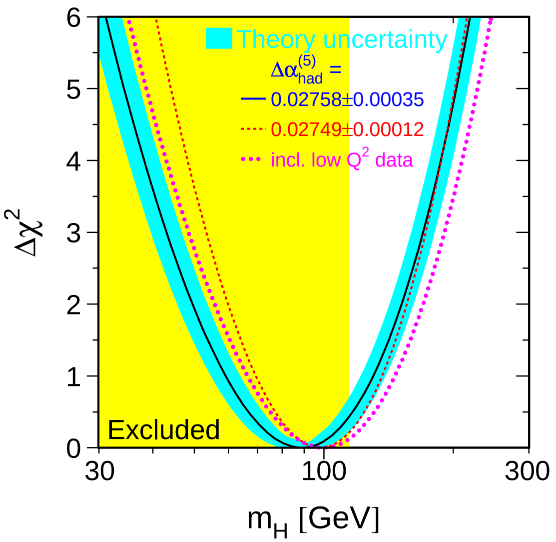
ρ measures the relative mass shift between the W and Z due to the different radiative corrections (also called T): sensitive to the weak isospin breaking.

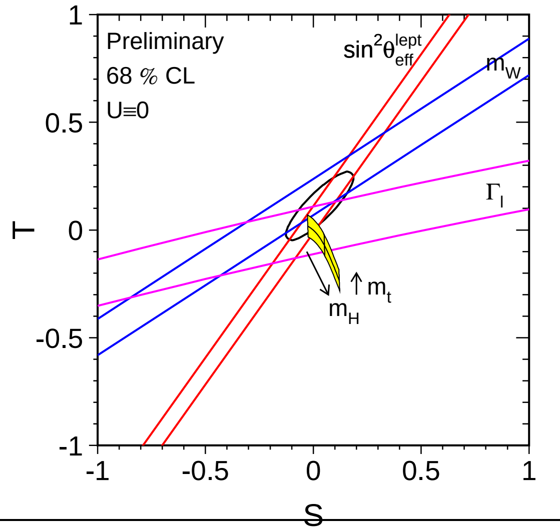
$\Delta\rho = \alpha_{em} T$

Similarly one can define two variables S, U related to the wave function renormalisation. These truly probe the Weak corrections.

Role of the Higgs

- The dominant EW corrections, are due to t/b loops. Hence the connection between these tests and the top mass.
- But Higgs will contribute to the radiative corrections via the different two point functions.
- Dependence on m_h is logarithmic.
- All the couplings and the masses of the gauge boson receive corrections.
- Use the experimental measurements of different observable to constrain m_h.
- The fits, the constraints on m_h will depend strongly on the central value of m_t and the error on it.





Tevatron and LEP/SLC data mainly contribute to the **indirect** bounds on the Higgs mass.

Analysis of precision measurements from LEP in terms of Oblique parameters constrain any **nondecoupling NEW** physics beyond the SM strongly.

- Indirect bound restricts m_h : 85 (+39 -21) GeV
- i.e. $m_h < 199$ GeV at 95% c.l., with precision measurements plus direct search limit.
- Direct lower bound $m_h > 114$ GeV.
- If SM effective theory, $180 < m_h < 200$ GeV (theoretical)
- If $195 < m_h < 215$ GeV, $\Lambda_{NP} < 10$ TeV (theoretical)

The upper limit from 'S,T,U' on the m_h can be evaded by going beyond the SM.

Partial list:

- $S < 0$:
  - a Extra $SU(2) \times U(1)$ multiplets: Dugan and Randall
  - b New singlet Majorana fermions: Gates and Terning
- $T > 0$:
  - a 4^{th} generation fermions Dobrescu and Hill
  - b 2 higgs doublet models Chankowski et al.
  - c New vector bosons Casalbouni et al, ED, little higgs
  - d A real Higgs triplet: gives contribution to T at tree level Forshaw et al

Lessons:

- The EW precision data like a light higgs, so does the theory.

- But the data can not rule out a heavier higgs. It *may* still be allowed. ANY discussion of alternate scenarios of symmetry breaking MUST always pass the **precision** test.

- Models in which heavier Higgs is allowed have been constructed. In some cases these can be tested with newer particles which will show up at the LHC.

- In some cases, real triplet example, phenomenology at LHC not very robust.

- If $m_h >$ 700/800 GeV then strongly interacting W sector will be the only signal at the LHC (Come back to this in the end if time permits).

- Should keep an open mind and open eye.

- **In some areas of parameter spaces the 'direct' experimental lower bound on 114 GeV *may* be evaded. However, there will be always associated BSM phenomenology at the LHC in this case.**

So if the SM is correct a light Higgs **must** be found at the LHC.

What if we do find it? Must explain why it is light :-)

Different explanations will imply more phenomenology which will be observed at the LHC.Item number one on LHC phenomenology agenda: infer which one of the many explanations (if any) is right.

Whar if we dont find it?

We have to find an alternate to EW symmetry breaking which passes the challenge posed by the preicsion tests as comprehensively as the SM does.Then the LHC agenda item is to check which one of these alternates, if any, is correct !

Why must the LHC agenda include more than finding a 'light' Higgs? **The hierarchy problem:**

The EW theory has been tested at 1-loop level. The Higgs mass which is a free parameter in the SM, receives large quantum corrections and the mass will approach the cutoff scale of the theory.

If, $m_{\mathrm{h}}^2 = m_{\mathrm{bare}}^2 + \delta m_{\mathrm{h}}^2$ the top loop (e.g.) gives

$$\delta m_{\mathrm{h|top}}^2 \sim -\frac{3G_{\mathrm{F}}}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2.$$

The light higgs is 'natural' then only if $\Lambda \sim$ TeV.

More general analysis : plot by Murayama and Kolda shown before.

So far NO hint of physics at the TeV scale !

Is the demand of no fine tuning just fussiness?(will talk later)

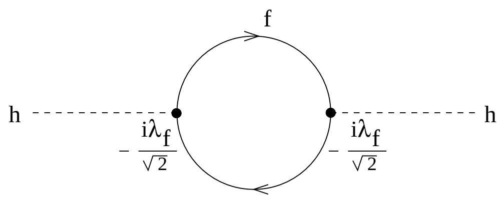
Only two ways to keep the Higgs 'naturally' light:

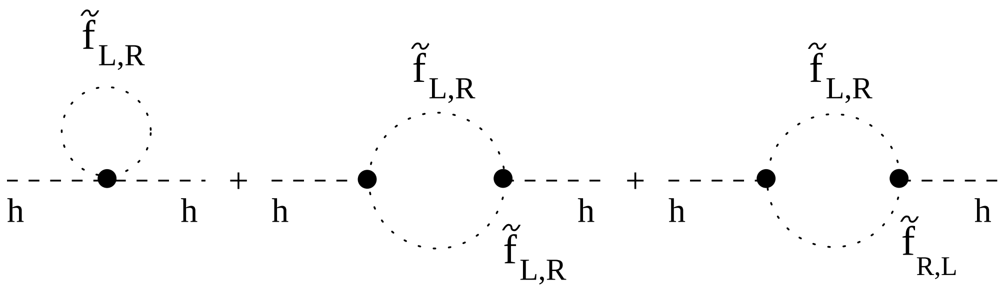
1] Introduce a symmetry: Supersymmetry : cancel the large top loop contribution by contributions from scalars. OR little Higgs models: The Higgs is a pseudo Goldstone boson and remains massless at one loop level. Gets the mass at two loops. There exist many additional fermions, gauge bosons in the theory at the TeV scale.

2] The cutoff is lowered to TeV:composite models and brane-worlds.

Theoretically extremely elegant and attractive: Spacetime symmetry, finite ultraviolet behaviour.

How is the stabilisation brought about?





Thus the sparticle loops cancel the large self energy corrections and keep the higgs mass 'naturally' small.

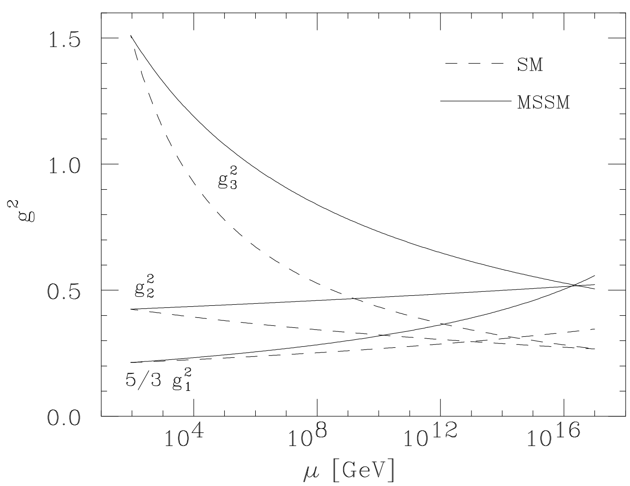
Eqally important: As we saw the data seem to *like* a light Higgs.

A ready made DM candidate in case of R-parity conservation.

Search for SUSY is the case of experiments chasing a beautiful theoretical idea.

It is *clearly* broken. ALL the experiments have so far only given NEGATIVE results, giving LOWER limits on sparticle masses.

Only one indirect evidence.



(Non)Unification of the three couplings in the (SM) MSSM.

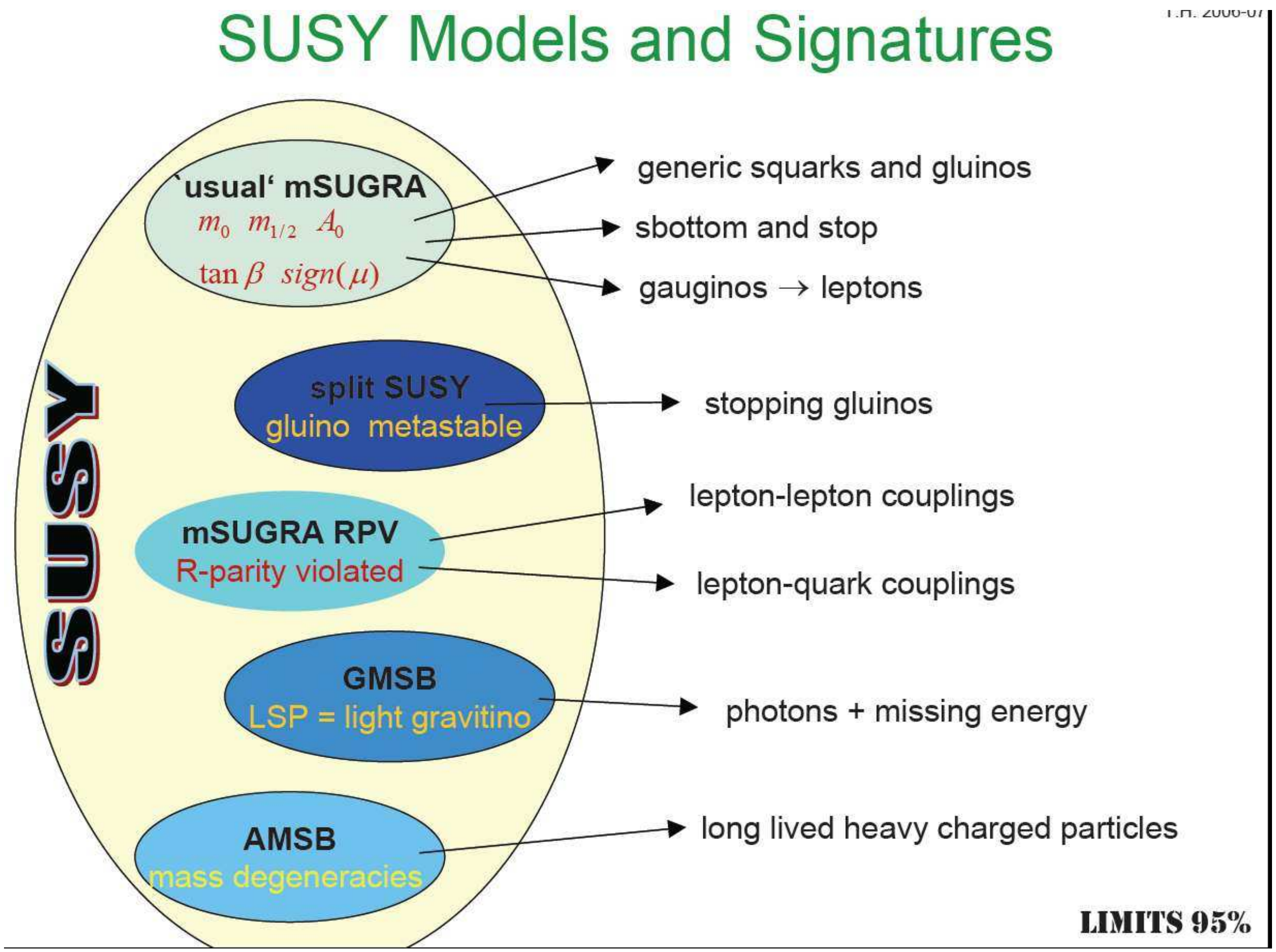
Imperative to find direct 'Proof for SUSY'

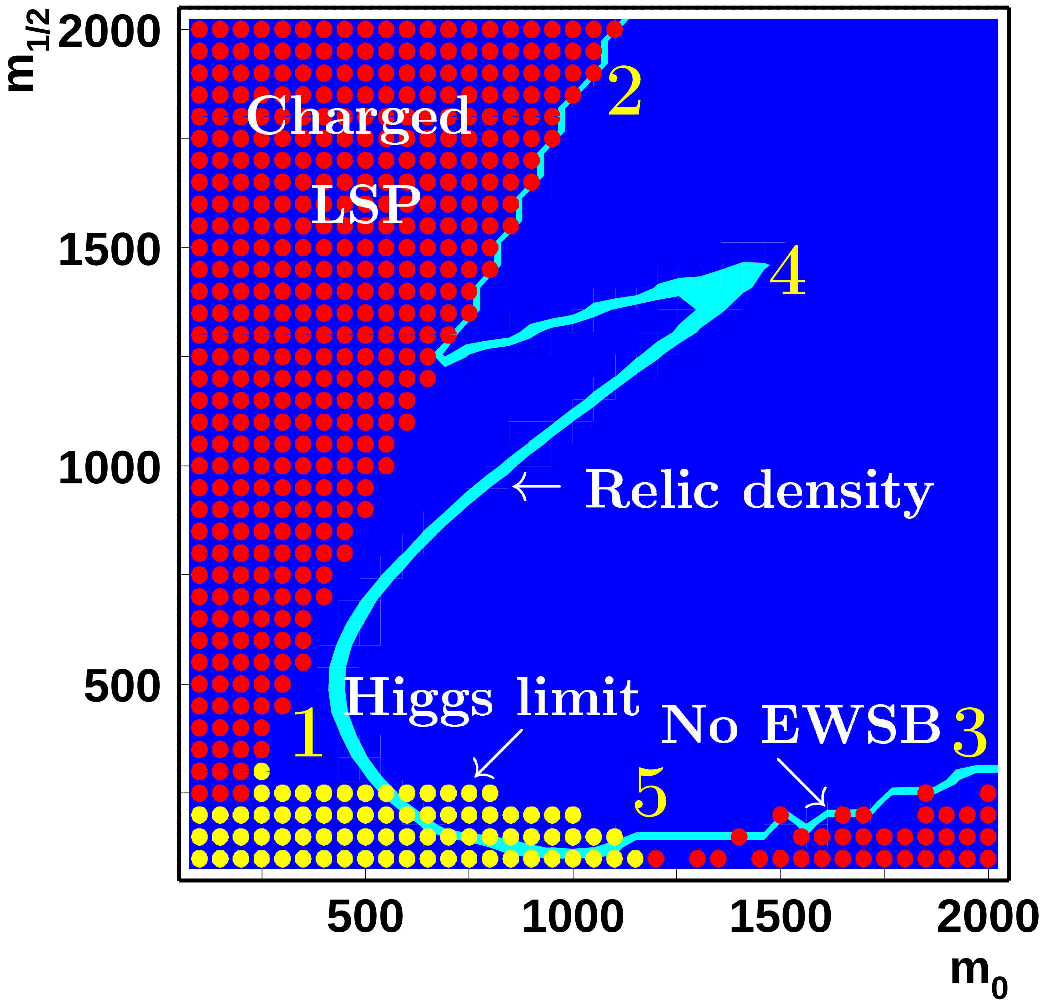
• There exist different ways of braking SUSY, each with its merits and negative points. The SUSY breaking mechanism affect the sparticle spectra, couplings and hence signatures at the LHC.

• Since at a hadronic collider like LHC it helps to know what one is looking for to isolate signal from the background, the search strategies have been designed, making certain assumptions. Interaction between theory and experiment, to understand the signal for SUSY, should it manifest itself at the LHC (as many of us hope) is a MUST.

• Participation of all parts of the HEP community, (in my definition String Theorists are necessarily included in the HEP community!) is essential to solve this kind of 'inverse' problem.

• Strategies need to be developed to see how LHC data can be used to decide which SUSY breaking mechanism has been realised in nature and to determine the sparticle spectra etc.


SUSY Models and Signatures
SUSY
`usual' mSUGRA
m_0 $m_{1/2}$ A_0
$\tan\beta$ $sign(\mu)$
generic squarks and gluinos
sbottom and stop
gauginos → leptons
split SUSY
gluino metastable
stopping gluinos
mSUGRA RPV
R-parity violated
lepton-lepton couplings
lepton-quark couplings
GMSB
LSP = light gravitino
photons + missing energy
AMSB
mass degeneracies
long lived heavy charged particles
LIMITS 95%



$m_{1/2}$
2000
1500
1000
500
Charged
LSP
2
4
← Relic density
Higgs limit
No EWSB
1
3
5
500
1000
1500
2000
m_0

However, NON-obseration of direct SUSY signal anywhere so far is not only discouraging, but also points to a problem called 'small hierarchy problem'.

LEP gives a limit on the chargino mass (which is free of any details of the SUSY models) and it also gives a limit on the mass of the lightest higgs in SUSY.

The Higgs mass limit implies rather heavy stop, which is not natural.

More generally, in SUSY models the EW symmetry breaking is radiatively induced. This means a relationship between M_Z and other SUSY parameters, masses. With sparticles as heavy as required to satisfy the Higgs mass limit a fine tuning of a percent or more is required to satisfy this relation. **Naturalness may be lost! (Guidice, Rattazi 06)** Non minimal (NMSSM) cures this problem to a large extent.

Extra Dimensions: The Universe has more than 1+3 dimensions, but the Standard Model fields (us!) are confined to a 1+3 dimensional hyper-surface (brane)

The extra dimensions are compactified. Gravity is free to propagate in the extra dimensions. Gravity is as strong as the electroweak interaction, but appears weak on the brane where the standard model fields live. TeV-scale experiments probe the 'strong gravity sector. There is new physics at a TeV.

There is no hierarchy problem.

Many versions: Large Extra Dimensions (ADD...) and Warped Extra Dimensions (Randall/Sundrum...), Universal Extra Dimensions(UED)...

Gravitons produced in a collision can fly off into the extra dimensions, carrying energy-momentum, which would seem to disappear from the brane. (missing energy-momentum signatures).

Virtual graviton exchanges can look like neutral current interactions.

UED signatures can be similar to SUSY cascade decays. These also have a DM candidate. Spin of the DM candidate here will be zero.

- Extra dimensions are an exciting idea. Very interesting that it is compatible with the data. Provide an intimate link with structure of spacetime and technical problems in particle physics

- None of the models is completely free from fine-tuning. RS the best and hence the template of almost all the ED phenomenology these days.

- There is no way to determine the number of the extra dimensions. We do not understand dynamically why some of the dimensions are compact

- Phenomenology is highly model- dependent: only spin-2 graviton is unique, if it (the spin) can be determined.

- LEP paradox still not solved. why the Higgs is light?

Personally I find it amazing that our experimental colleagues have shown that even though the detector was NOT designed with the knowledge of such models, once the possibility arose they showed that the detectors will be able to find the evidence should these exist.

Little Higgs Models

The Symmetry of the SM is enhanced. Higgs is a Pseduo Goldstone Boson.

There are massive gauge bosons W' and B' at the TeV scale radiative corrections generate (negative) Higgs mass terms (Coleman-Weinberg mechanism) Quadratic divergences in the Higgs mass generated by W and B cancel with those generated by W' and B' (negative signs are generated by group-theoretic factors)

Large Higgs mass corrections due to top quark cancelled by a heavy pair of vectorlike fermions NOT SCALARS AS IN SUSY. Hierarchy problem disappears: lots of TeV physics.

Higgs mass generated at two loops. The scale at which 'naturalness' gets into trouble is then now ~ 10 TeV instead of ~ 1 TeV as in SUSY.

The idea of Higgs as a Pseudo Goldstone Boson, combined with the warped extra dimension seems interesting. (Agashe et al)

Precision measurements cosntrain the model parameters very strongly as there is no Custodial symmetry. These constraints may sometimes push the scale to be higher than 10 TeV and again difficult to be 'natural'.

The gauge symmetry is completely ad hoc. New fields, interactions and symmetries have been thrown in as and when required Experience shows that Nature is generally simple.

Most importantly no calculability beyond 10 TeV or so, unlike SUSY. Unification ideas are also lost.

Consider fine tuning 'natural' ! Inspired by the cosmological Constant problem!

Split Supersymmetry: N. Arkani-Hamed and S. Dimopoulos, arXiv:hep-th/0405159. Philosophically can be discussed in detail and the discussion is important.

It is a narrow corner of the SUSY parameter space as far as the phenomenology is concerned. $\tilde{g}$ almost stable, infinitely heavy sfermions, fermions in the TeV range. Depending on the SUSY breaking scheme based on a braneworld scenario details of the LHC phenomenology will change. A large number of options discussed.

Maintains the good feature of SUSY: Gauge unification, DM candidate. Does not care about the 'naturalness'

• If there is no light Higgs ($\lesssim$1 TeV) the low energy theorems predict the $W_L W_L$ scattering amplitudes from the symmetries of the theory to leading order in s/m_{SB}^2.

• The specific theory of symmetry breaking then shows up to the next higher irder in s/m_{SB}^2.

• The violation of unitarity in $W_L W_L$ amplitude now is prevented in different ways. In Composite models (Technicolor and their variants) one has Techni-rhos, in Higgsless models addiitonal Massive Vector Bosons etc, i.e. additional resonances.

• In the EW Chiral Lagnrangian Models there are no resonances, but unitarisation will always build in resonance like behaviour.

• Characteristic of Higgsless models : WZ resonance. No WZ resonance in the SM!. Some masses less than 1 TeV. Accessible to LHC.

• Studies of WW, WZ scattering can be used to probe these.

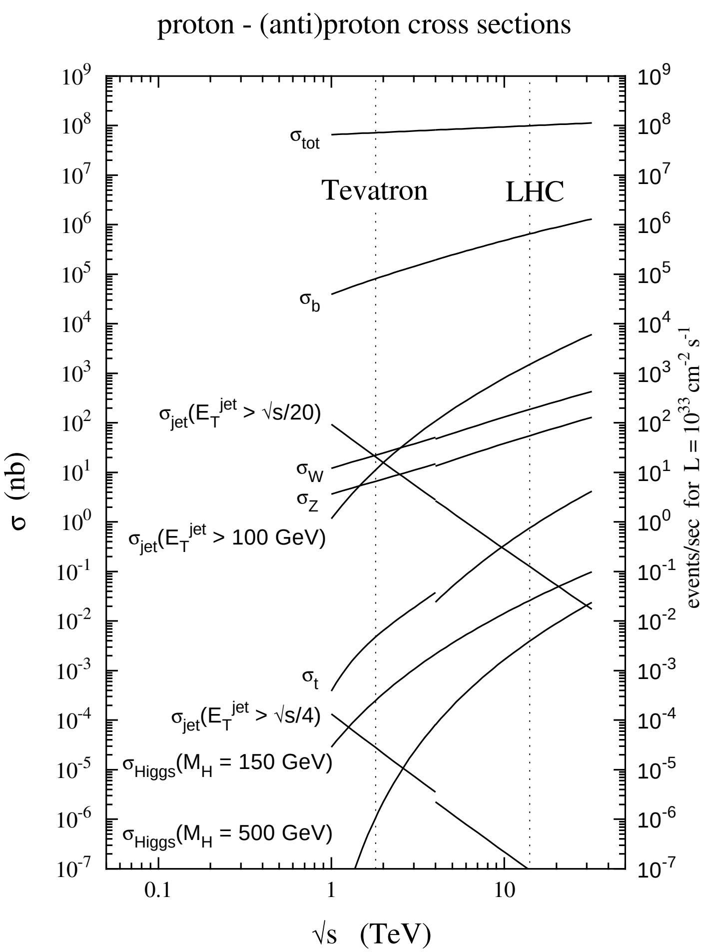
• As a thumb rule these models have trouble with precision EW measurements.

No. of events = $\mathcal{L} \times \sigma$

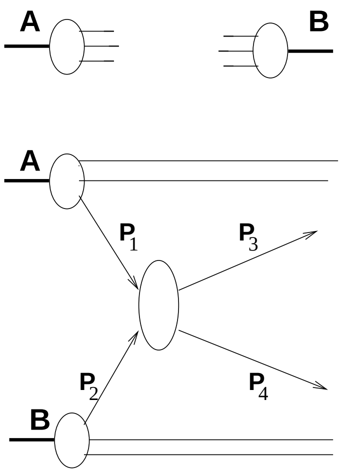
$\mathcal{L} = 10^{33} cm^{-2} sec{-}1 = 1 nb^{-1} sec^{-1} \rightarrow 10 fb^{-1}/yr$

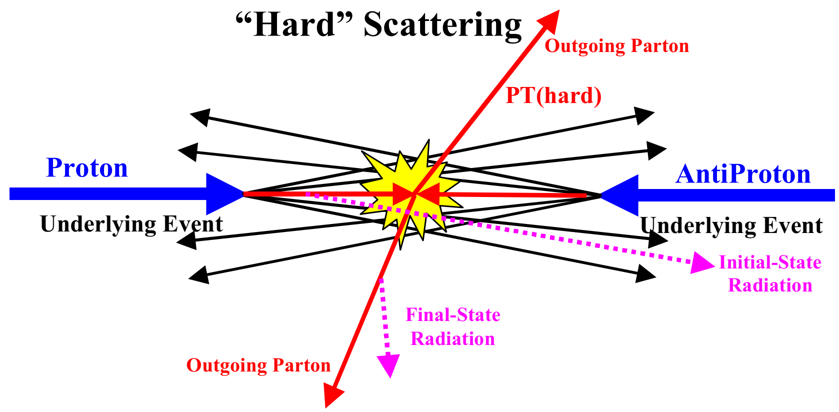
We expect to measure signals which have cross-section of $\sim$ 1 pb or so, giving 1000 events/yr.

Process	$\sigma(nb) \equiv$ # of events/sec	events/yr
Total cross-sections	10^8	10^{15}
$W^\pm \rightarrow e\nu$	20	2×10^8
$Z \rightarrow e^+e^-$	2	2×10^7
$t\bar{t}$	0.8	8×10^6
$b\bar{b}$	5×10^5	5×10^{12}
central jets ($P_T > 10 GeV$)	2.5×10^6	2.4×10^{13}
central jets ($P_T > 100 GeV$)	10^3	10^{10}
central jets ($P_T > 1000 GeV$)	1.5×10^{-3}	1.5×10^5



proton - (anti)proton cross sections
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
Tevatron
LHC
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)
0.1
1
10





QCD factorisation theorem for short distance, inlcusive processes:

$$\sigma(pp \to X + ..) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2)$$
$$\times \sigma(a + b \to X)\left(x_1, x_2, \mu_R^2, \alpha_s(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

Theoretical prediction:

Initial State	subprocess	final state
parton density distributions PDF	$\sigma(a + b \to X)$	Fragmentation Functions.

LHC requires from QCD theory:

- Precise inputs
  - α_s
  - Parton Density Functions (PDF's)
- Accurate calculations of subprocess cross-sections
  - NLO, NNLO calculations of cross-sections.
  - Resummation of large logarithms
- New physics $\rightarrow$ large masses $\rightarrow$ long decay chains Discussions of SUSY signals $\rightarrow$ Multijet final states $\rightarrow$ high order tree level matrix elements
- PT-NonPT interface
  - parton-hadron transistion fragmentation functions
  - underlying event.
  - multiple hard scattering.

Cross-sections in QCD Calculated by truncating perturbative expansion to a fixed order (FO).

$$\begin{aligned}\hat{\sigma}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_F^2) = \alpha_s^k(\mu_R^2)\Big\{&\hat{\sigma}^{(LO)}(p_1,p_2;Q,\{Q_1,\ldots\}) \\ &+\alpha_s(\mu_R^2)\,\hat{\sigma}^{(NLO)}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_R^2;\mu_F^2) \\ &+\alpha_s^2(\mu_R^2)\,\hat{\sigma}^{(NNLO)}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_R^2;\mu_F^2)+\ldots\Big\}\,.\end{aligned}$$

The LO (tree level) calculation has a strong dependence on the choice of scale Q^2. The scale dependence is reduced by going to NLO. To get a reliable esitmate of error on theoretical calculation, a NLLO calculation is necessary.

- NNLO calculation a must for all the processes for which the NLO corrections change the LO cross-sections by large K-factor.

- $|\mathcal{M}|^2$ is to be calculated for diagrams with $m \geq 0$ loops and $n \geq 2$ legs, eg. potential background for Higgs pair production, to be used for studying higgs self coupling λ directly, will need calculation of $b\bar{b}b\bar{b} + n$ jets.

- The number of diagrams to be computed increases *very* quickly with number of increasing legs. For $gg \to g_1..g_n$ for $n = 7$ is 559405.

- Therefore one requires very intelligent autmoated computation.

- Berends, Kuijf, Giele, Mangano, Kleiss, Bernd, Kosower, Dixon...

- NLO/NNLO calculations sometimes necessary also for some proecesse which are not present in LO.

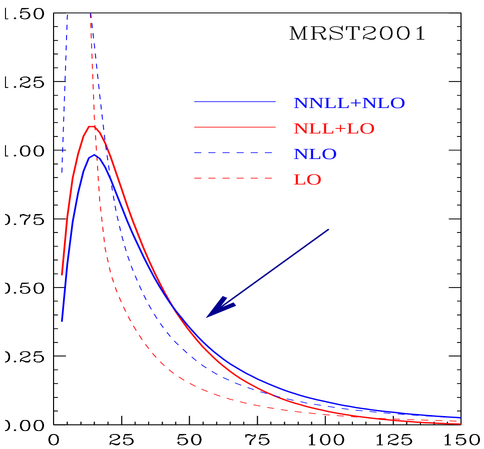
- The intricate part is cancellation of infrared and collinear singularities between the real emissions and virtual contribution.

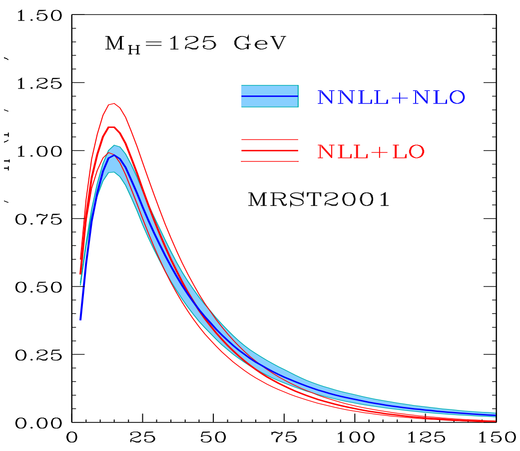
- Enormous progress in calculation of two loop amplitudes.

- New technical breakthroughs (Remmidi, Gehrmann, Binoth, Catani, Grazzini .....)

- One loop calculations for $2 \to 3$ processes now available

- n-loop Matrix Element requires AP kernel at $(n+1)$ loop level and has to be used with Str. fucntions evaluated at the same level (3-loop splitting function: Vermaseren et al)





- SM Higgs production at the NNLO has been computed. Haarlander, Kilgore, Catani, Grazzini, Van Neerven, Ravindran, Anastasiou, Melinkov....

- Different authors have used different techniques and hence cross-checks.

- K-factor for Higgs production between 2.1 to 2.5 as mass changes from 10 GeV to 300 GeV.

- Beyond fixed order, soft gluon resummation for calculating Higgs q_T also has been done.

• Developments at the interface of String Theory and QCD: Twistor Calculus.

• Initial work (Parke et al) to calculate compact expressions for mulit-ple gluoni, tree level amplitudes. Relation between Strings and Gauge Theories in Twistor space.

• Current developments: allow now to calculate loop amplitudes. Is developing to be a big tool in the computation of higher order diagrams. (Dixon, Glover,Khoze...). Already used for computing multijet events at the LHC.

- Strong reasons to believe that there is BSM physics at the TeV scale.

- SUSY still seems to be the best motivated, but seems to be 'un-natural' when it was introduced to have 'naturalness'

- Whatever is the new physics LHC should give us some hints about it and we hope some really unexplained phenomena.

- We need to be ready with our strategies how to begin to understand what LHC is telling us. Hope that nature is kind and 'natural'!