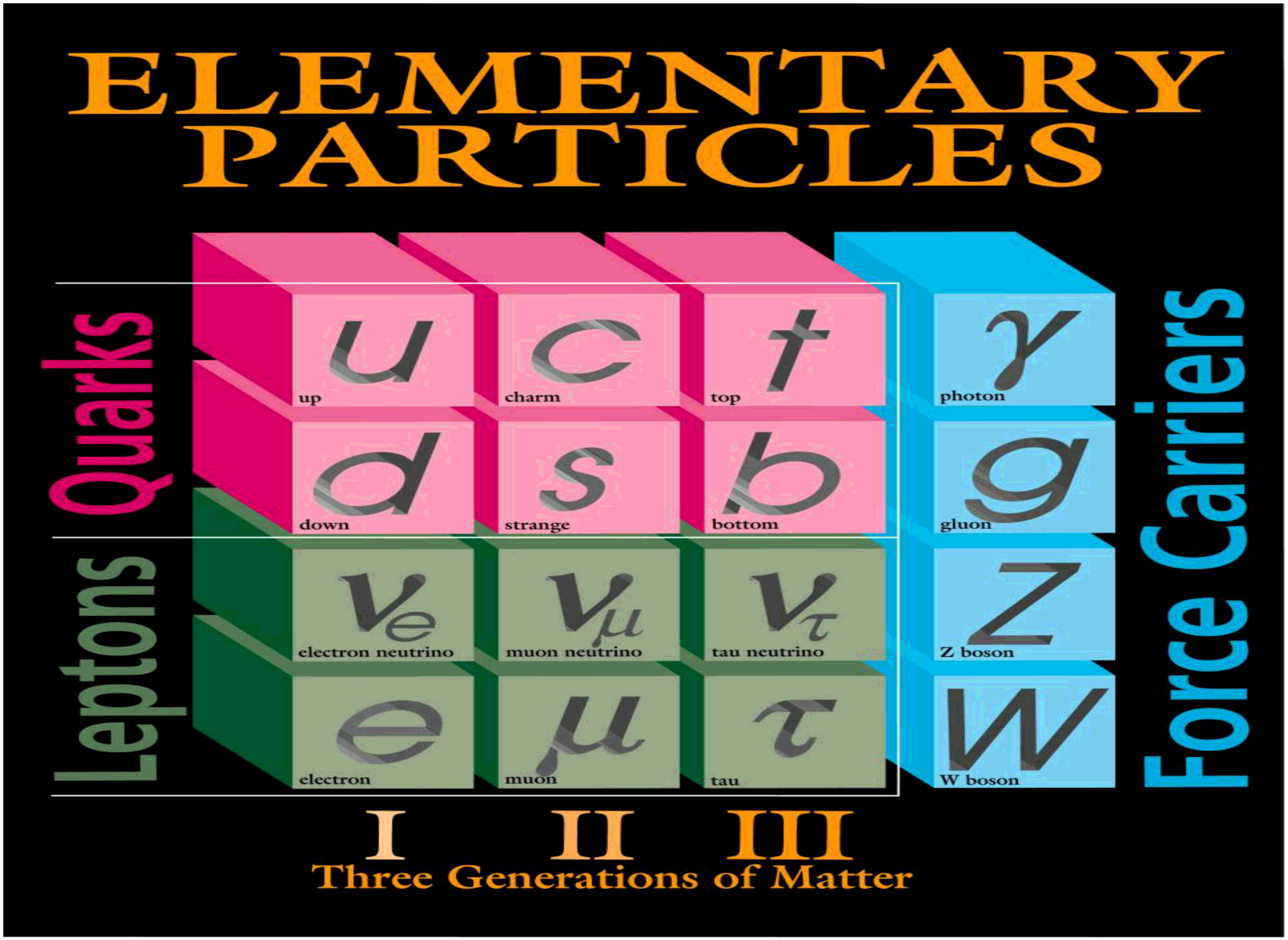
NEW PHYSICS AND THE LHC
THE THEORIST'S PREJUDICE

Biswarup Mukhopadhyaya

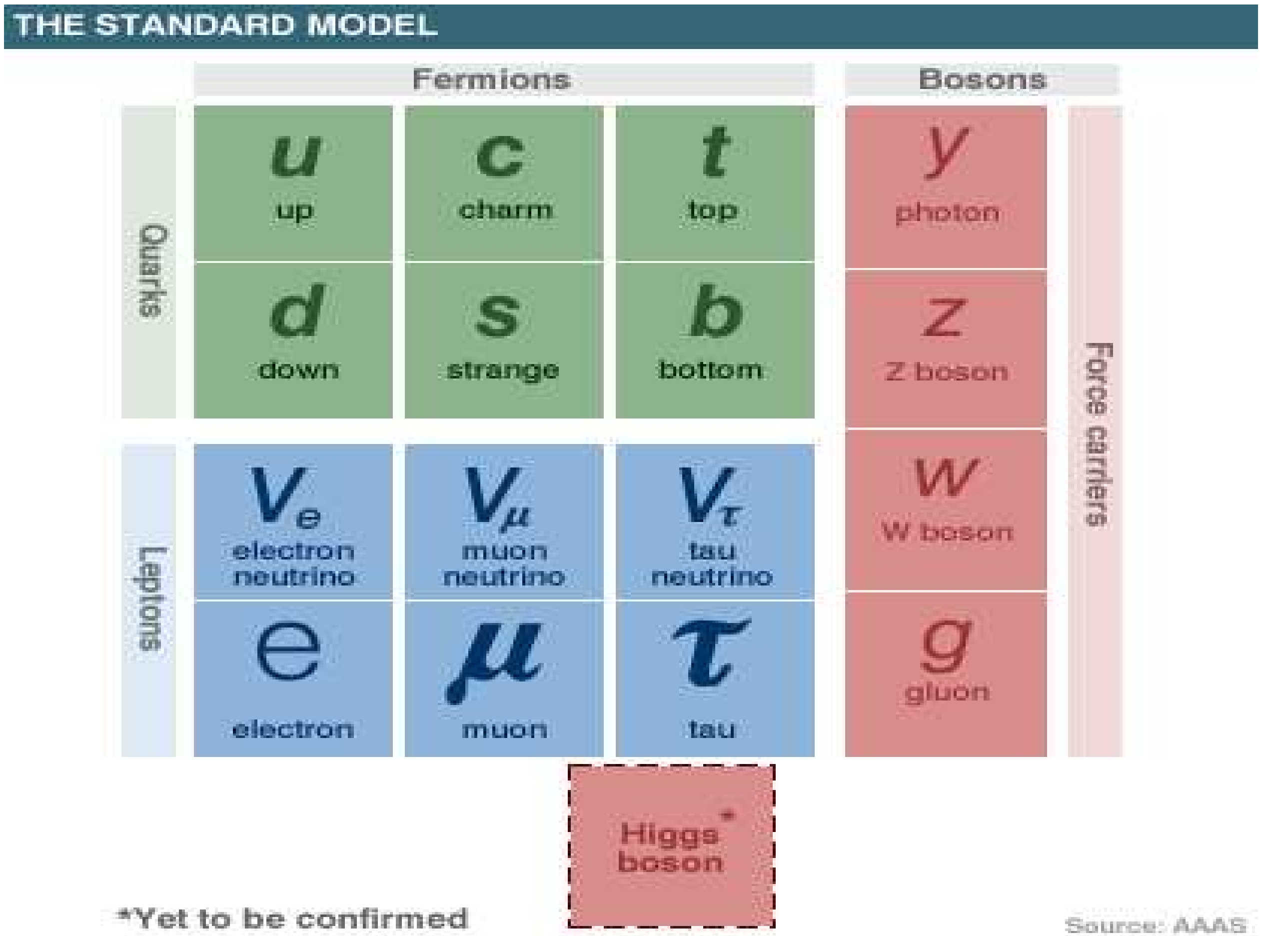
Regional Centre for Accelerator-based Particle Physics
Harish-Chandra Research Institute, Allahabad, India

We know well enough about these....



Fermilab 95-759

But for one missing component....



Still waiting for the existing theory of strong + electroweak forces to be complete !

The Standard Model (SM)....

Consider the electroweak part:
A $SU(2) \times U(1)$ gauge theory

- Practically all observations are consistent with the gauge principle

- Higher order effects verified
  $\Rightarrow$ a renormalisable quantum field theory
- Symmetry is broken still: a consistent symmetry breaking sector must be around

$SU(2) \times U(1) \rightarrow U(1)_{EM}$ has occurred

Strong indication: there is at least an 'effective' sector where spontaneous symmetry breaking has taken place

$m_W^2 \simeq m_Z^2 \cos^2\theta_W$
$\Rightarrow$ **This effect is dominated by SU(2) doublet(s)**

If it is really one fundamental scalar doublet, it is 'just Standard Model Physics'; if not, it's New Physics

Actually, it is more than that, but, before we come to it,.....

The Standard Model has inadequacies/puzzles...

Phenomenological dissatisfactions:

- Large number of unrelated free parameters
- Replication of fermion families
- The pattern of fermion masses
- Maximal P but small CP violation

The Standard Model has inadequacies/puzzles...

Theoretical/Philosophical questions:

- **No way to unify with strong interaction**
- **No clue on a quantum theory of gravity**
- *Problem of the Higgs mass (more later)*

The Standard Model has inadequacies/puzzles...

Seasonal/Volatile/Metastable issues:

- The muon anomalous magnetic moment (3 - 3.5 σ inconsistency)
- PAMELA (excess positrons $\sim$ 10 - 100 GeV from galactic halo)
- ATIC (excess galactic cosmic-ray $e^{\pm} \sim$ 300 -800 GeV)
- Fermi-LAT (excess $e^{\pm} \gtrsim$ 200 GeV)
- Tevatron multimuon events (excess multimuons, inexplicable from b-decays)

.....

.....

The Standard Model has inadequacies/puzzles...

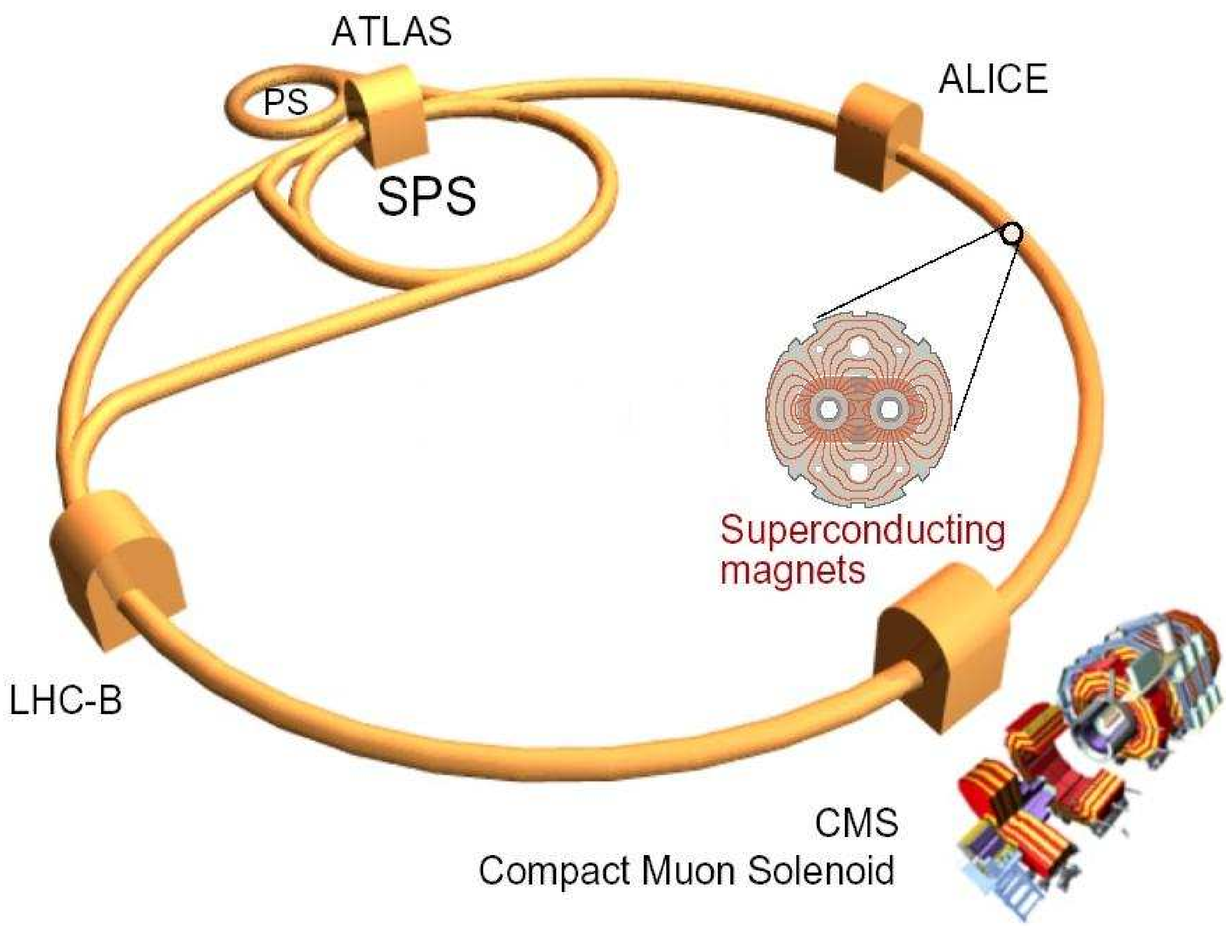
Concrete and persistent problems:

- Neutrino masses and mixing
- Cold dark matter

  (no particle physics explanation)
- Matter-antimatter asymmetry in the universe

  (B/L violation, adequate CP-violation)
- A positive cosmological constant (!)

The Large Hadron Collider



$p \Longrightarrow\Longleftarrow p$

$E_{cm} =$ **7/10/14 TeV**

Goals of the LHC....

- To discover the Higgs boson and complete the Standard Model
- To know more about top quark properties
- To understand strong interaction better
- To study B-hadrons better
- To look for quark-gluon plasma
- *Physics beyond the standard model*

Physics beyond the standard model...

Effective energy scale to be probed at the LHC: $\simeq$ 1 -2 TeV

Out of the many motivations listed, which ones definitely suggest *'something new'* **at this energy?**

Physics beyond the standard model...

- **The issue of Grand Unification**

  (very indirect!)

- **Finding a cold dark matter candidate**

  (*Somewhat imperative*)

- **The issue of the Higgs mass**
  (Quite pressing)

That brings us back to the Higgs !

The Higgs and Physics beyond the standard model..

- **Unitarity in gauge boson scattering**

  + perturbative self-coupling

$\Rightarrow \quad m_H \lesssim$ **800 GeV**

- **Triviality bound:**

λ**(Q) =** $\dfrac{\lambda(v)}{1 - \frac{3}{4\pi^3} \log \frac{Q^2}{v^2} \lambda(v)}$

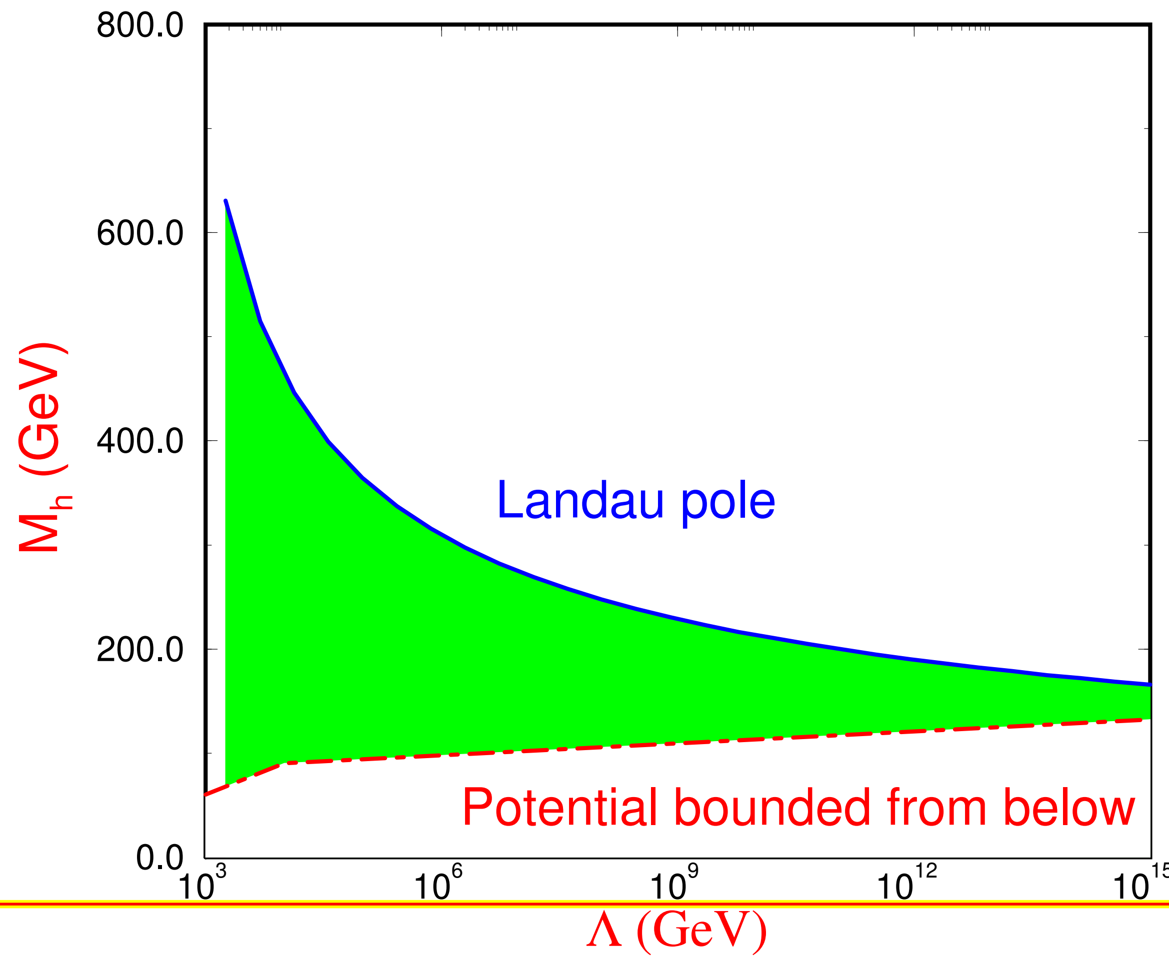
without gauge and Yukawa couplings:

a similar result including them (A pole hit unless

$\lambda(v) = 0$

The Higgs and Physics beyond the standard model..

A solution: A cut-off Λ such that the pole lies above $\Lambda \Rightarrow$ An upper limit on Higgs mass



The Higgs and Physics beyond the standard model..

Quadratically divergent corrections to the Higgs mass— no symmetry to protect large shifts:

Destabilising effects: $m_H^2 \longrightarrow m_H^2 + \Lambda^2$

(Λ = upper limit of validity of the standard model)

Higgs mass can be kept small only if $\Lambda \simeq$ TeV

$\Rightarrow$ New physics within the reach of the LHC?

An age-old analogy...

Remember: The self-energy of a classical electron blows up as $r_e \longrightarrow 0$

Even the classical electron radius shifts electron mass to $\simeq$ 10 GeV

New physics (the existence of the positron) at scale $\simeq 2m_e$ removes the divergence

But what kind of new physics can we look for?

- Something that stabilises the Higgs mass?
- Something that offers a cold dark matter candidate?
- Something that may be an effective theory embedded in whatever solves the puzzles on unification/family replication /ν-masses/baryogenesis....?

Specific signals to be identified for each option
Restricted choice, and still scenarios whose signatures can be mixed up !

Some more expected features of target scenarios

- **New particles/interactions within the TeV scale**
- **A sector that itself is not to be pushed too high up (avoid a *little hierarchy*)**
- **Compatibility with precision electroweak data**
- **A Z_2 symmetry to ensure stable massive particles?**

Some general features of expected LHC signals

- **Hard leptons/jets in the central region ($|\eta| \lesssim 2.5$)**
- **Missing transverse momentum if a dark matter candidate is there**
- **Invariant mass peaks (leptons/jet pairs) if heavy bosons are there**
- **Large effective mass ($= \sum[|p_T| + |\not{p}_T|]$)**

Some candidate theories....

- **Supersymmetry (SUSY) (a prototype of new physics!)**
- **Extra spacelike dimensions (large/warped/universal)**
- **Little Higgs (with T-parity if stable particle are required)**

Some candidate theories....

- **Hidden valley (higher-dim interactions with a new sector suppressed by the TeV scale)**
- **Unparticles (scale invariant sector of an effective field theory)**
- **‘Dark sector’ (a gauged sector comprising the dark matter candidate and some new force carrier)**
- **.....**

Supersymmetry....

New particles corresponding to the standard ones, but with different spin

Higgs mass stabilised by the symmetry itself, even when it is broken in masses but not in couplings

A dark matter candidate for conserved B/L

Supersymmetry....

Leads to schemes of neutrino mass generation

Hope for Grand Unification if the new particles are of mass $\lesssim$ TeV

Hope of gravity being a part of the game

Promise of an ultraviolet-complete superstructure

Seeing SUSY at the LHC....

In most (*but not all*) incarnations,

SUSY signals are marked by

missing $\not{E}_T$ accompanied by

hard jets/leptons/photons

Majorana character of the spin-1/2 partners

of the gauge bosons can be exploited

Missing $\not{E}_T$ distribution carries useful

information

But also makes mass reconstruction difficult

The flip side of SUSY...

Proliferation of parameters–no unique

'organising principle'

(read SUSY breaking scheme)

Makes SUSY a *Theoreticians' Anarchy*

Flavour-changing neutral current suppression

often leads to cross-currents of speculation

Usually, difficult to rule out, except by
eliminating a Higgs boson of mass $\lesssim$ 200 GeV

Extra dimensions...

Hopes to have ultraviolet completion through a 'stringy' undertone

Flat extra dimensions:

Gravity in the bulk with a flat metric

New signals with missing energy

due to a tower of gravitons

No satisfactory solution to the naturalness problem

Extra dimensions...

Hopes to have ultraviolet completion through a 'stringy' undertone

Warped extra dimensions:

Gravity in the bulk, with a metric carrying

an exponential factor of $\simeq 10^{-16}$

The warp factor can be dynamically generated

with only the Planck scale to start with

New resonances *graviton,...* at $\simeq$ TeV

Spin information must be extracted

Extra dimensions...

Hopes to have ultraviolet completion through a 'stringy' undertone

Universal extra dimensions:

All standard fields in the bulk

Kaluza-Klein towers for all of them

Effective $Z_2 \Rightarrow$ a dark matter candidate

Similar signals as SUSY

Spin information must be extracted for differentiation

Little Higgs (with T-parity)

The scalar sector as a set of

pseudo-goldstone bosons of an *effective theory*

Precision data + ***Little Hierarchy***

$\Rightarrow$ **a discrete symmetry**

Extra heavy quarks, gauge bosons, scalars...

Plus a dark matter candidate

Distinction with SUSY requires

spin information + details on spectrum

No guideline on ultraviolet completion

The advantage of multichannel analysis...

Example: SUSY with overseeing high-scale physics

(universality in gaugino/scalar masses, or departure therefrom)

Information is contained in the spectrum (both kinematics and dynamics)

The advantage of multichannel analysis...

Possible approaches (not guaranteed as successful):

- **Combining effective mass info with endpoint analysis**
- **Study event ratios in different channels (dilepton, trilepton, four-leptons...)**

A. K. Datta, S. Bhattacharya, BM (2007, 2008)

D. Choudhury, S. Bhattacharya, U. Chattopadhyay, D. Das, BM (2009)

Be prepared for totally different signals...

Suppose one has SUSY + right-handed neutrinos

The 'right sneutrinos' can often naturally be the LSP

Decay rate into LSP — $\sim m^2_{\nu_{Dirac}}$

NLSP (often the lighter stau) stable within the detector

$\Rightarrow$ *Drastically different SUSY signals*

Be prepared for totally different signals...

Not $\not\!\!E_T$ *but stable charged track-pairs*
Kinematic features to distinguish with
S. K. Gupta, S. K. Rai, BM (2007)

Neutralino, chargino mass reconstruction possible

S. Biswas, BM (2009)

Concluding remarks

- **So many interesting new physics possibilities!**
- **Signals will perhaps not be missed, but details of the scenario *may very well be***
- **The *Achilles Heel*: is it this theory or that one?**
- **Mass/spin reconstruction: crucial but difficult**
- **Caution: *Be careful before getting sold out to preconceived scenarios***

“The difficulty lies, not in the new ideas, but in escaping the old ones, which ramify ...into every corner of our minds.”

John Meynard Keynes