
THE INVISIBLE AND THE VISIBLE AT THE LHC

Biswarup Mukhopadhyaya

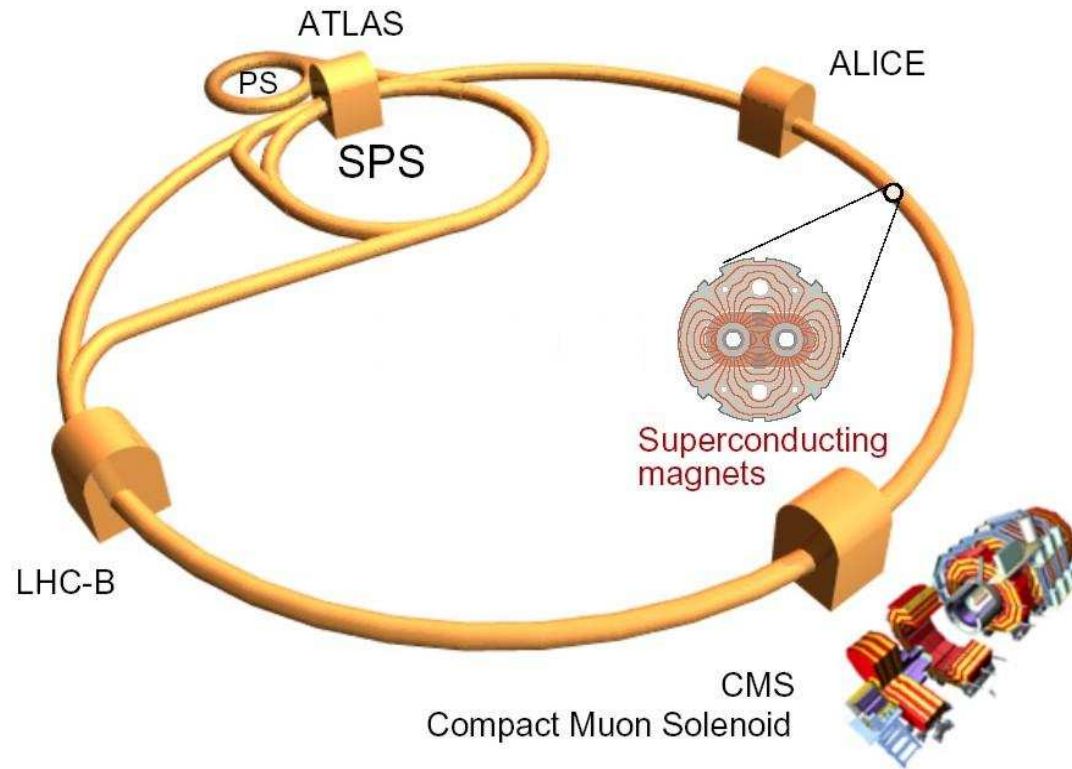
Regional Centre for Accelerator-based Particle Physics
Harish-Chandra Research Institute, Allahabad, India

The Large Hadron Collider

Geneva(Switzerland):

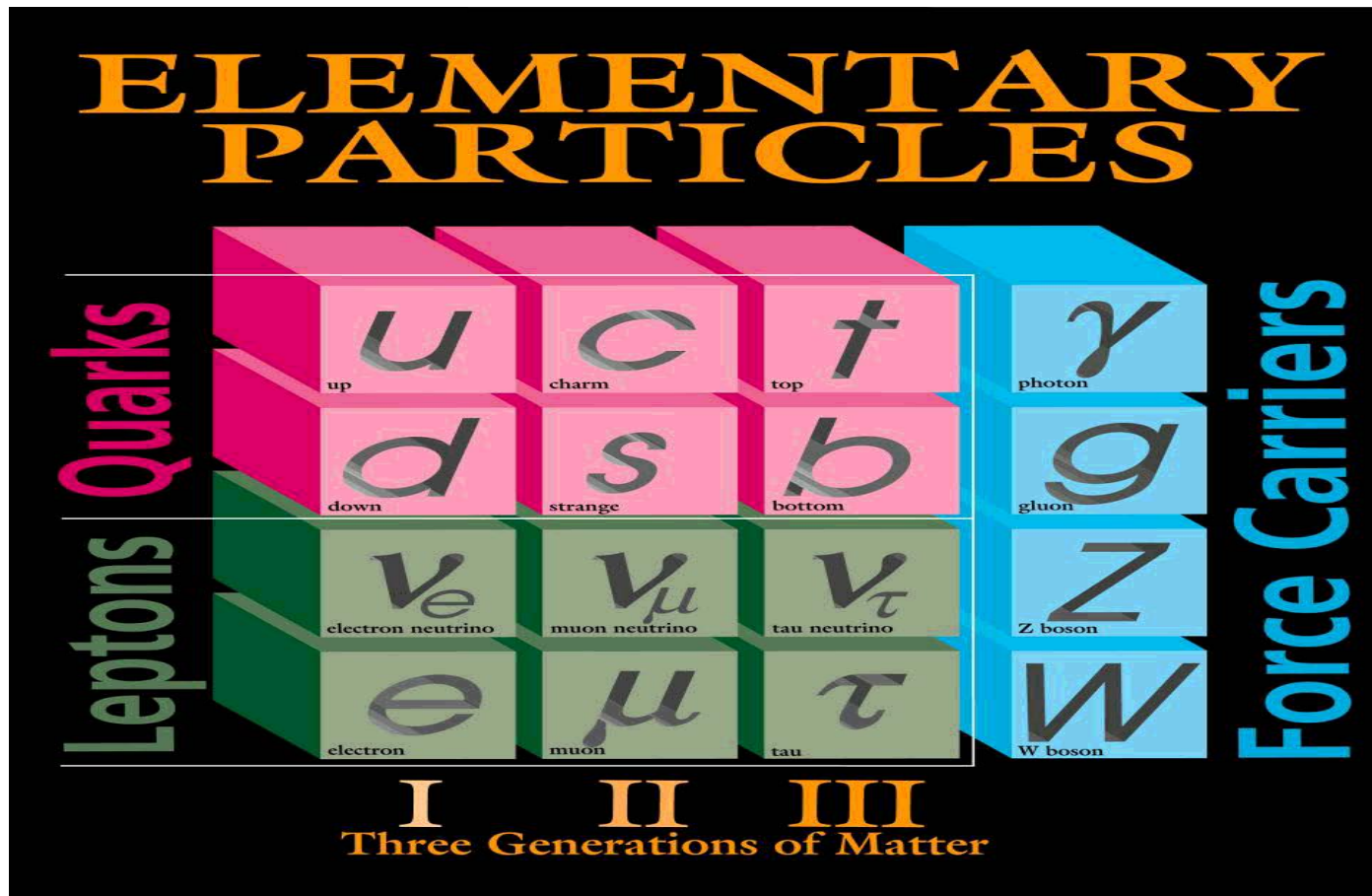


The Large Hadron Collider



$E_{cm} = 7/14\text{TeV}$: About 1 fb^{-1} of data already in store

What is there to know?



Fermilab 95-759

Relevant forces: Strong, weak, electromagnetic

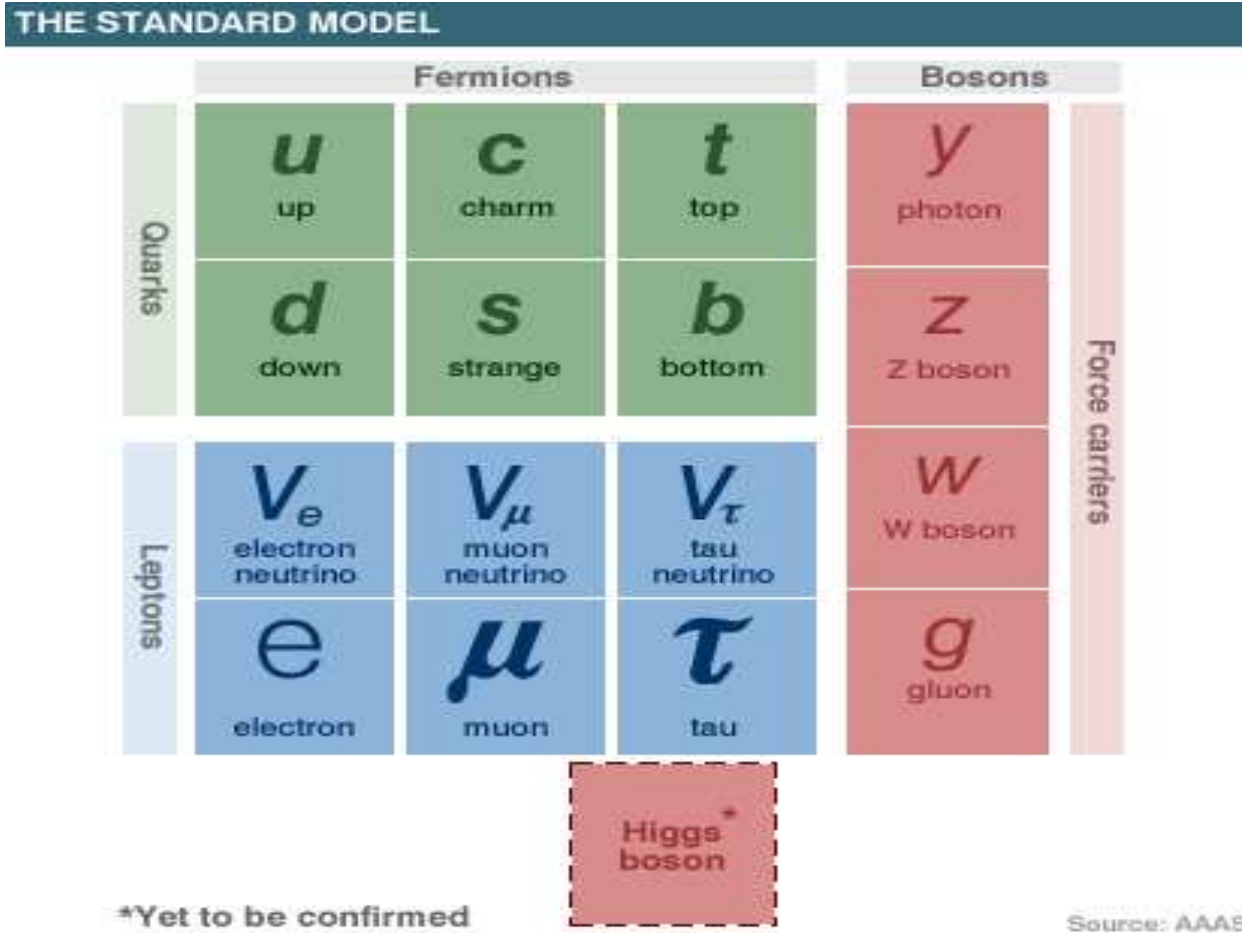
The Standard Model (SM)....

Gauge invariance: $SU(3)_c \times SU(2)_L \times U(1)_Y$

A well-tested quantum field theory describing the strong weak, and electromagnetic interactions

Everything works fine within its domain of validity,....

But for one missing component....



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

Goals of the LHC....

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

BUT....

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new physics ?**

**Why should new laws be manifest at the
LHC energy ?**

The Standard Model has inadequacies/puzzles...

Phenomenological dissatisfactions(unexplained features):

- 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
- *Divergent higher-order contributions to the Higgs boson mass*

The Standard Model has inadequacies/puzzles...

Sporadic/seasonal/volatile issues:

- The muon anomalous magnetic moment (3 - 3.5 σ inconsistency)
- PAMELA (excess positrons \sim 10 - 80 GeV from galactic halo)
- ATIC (excess galactic cosmic-ray electrons \sim 300 -800 GeV)
- Tevatron multimMuon events (excess multimMuons, inexplicable from b-decays)
- Top quark forward-backward asymmetry at Tevatron
- Wjj events at the CDF detector

.....

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
- A positive cosmological constant (!)

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

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

Why new physics at the TeV scale?

- **The issue of Grand Unification**
(very indirect!)
- **To understand why the Higgs should be within a TeV**
(somewhat pressing!)
- **Finding a cold(warm?) dark matter candidate**
(Quite imperative)

Thus the Dark matter issue is rather central to new physics search at the LHC

The most obvious signature of dark matter.

‘missing transverse momentum’

(\cancel{p}_T or \cancel{E}_T)

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Lesson: precision for the ‘visible’ and the ‘invisible’ are inter-connected

Bottomline....

We need to extend the SM with some massive particle(s) that interact at best weakly

Some candidate theories:

- **Supersymmetry (SUSY) (a boson for every existing fermion and vice versa)**
- **Universal extra spacelike dimensions (UED)**
- **Little Higgs with T-parity (LHT)**

A quick resume: Supersymmetry (SUSY)

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The lightest SUSY particle (LSP) is stable for conserved B/L: a dark matter candidate (A neutral, weakly interacting particle)

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due to the Z_2 symmetry: dark matter candidate
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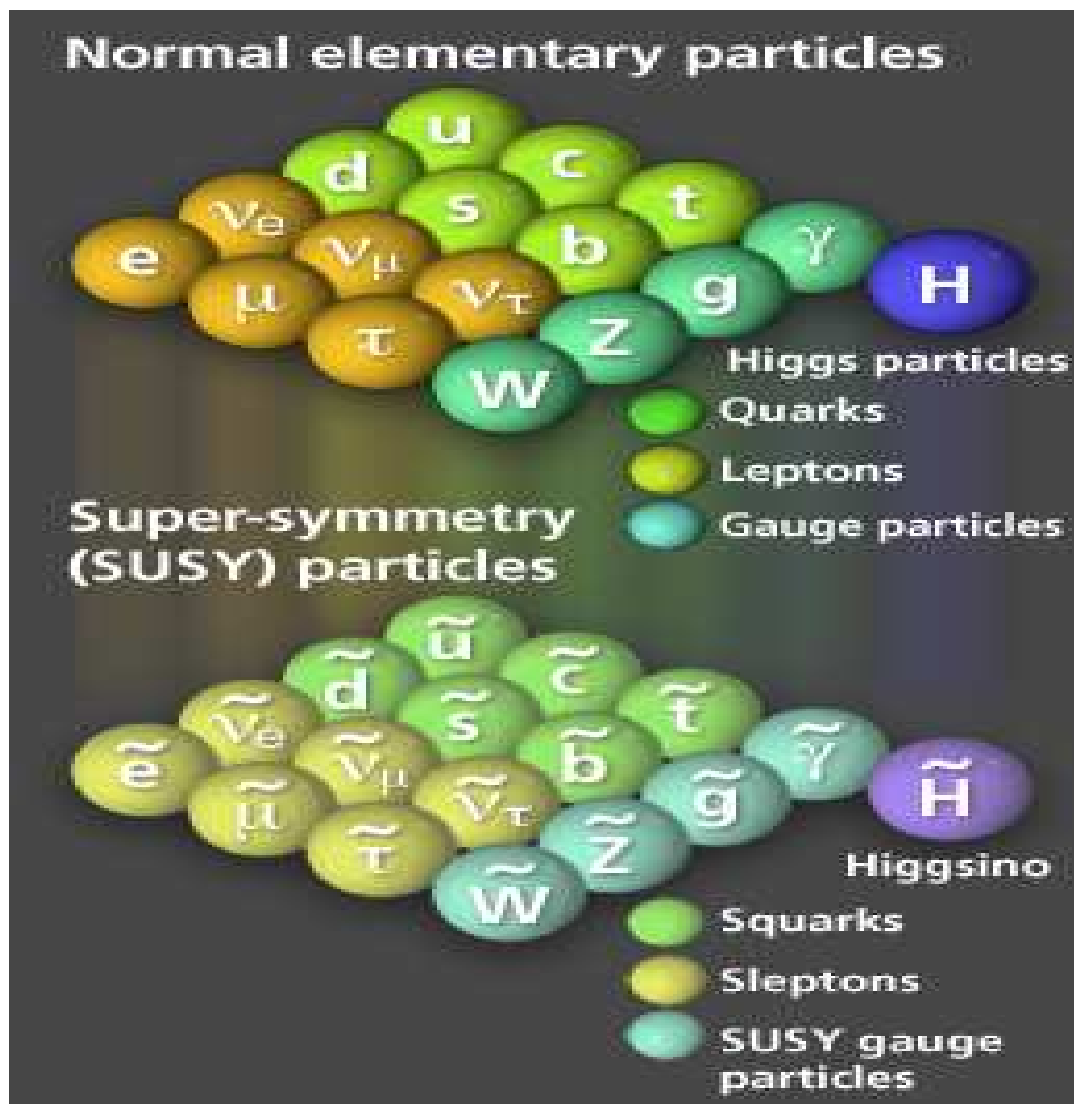
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Some basic issues...

- To identify the DM signature at the LHC
- To see if different DM candidates in the same theory lead to different signatures

We demonstrate this using SUSY as the prototype

The Minimal SUSY Standard Model (MSSM)



enlarged spectrum

The Minimal SUSY Standard Model (MSSM)

Neutralinos:

$$\chi_i^0 (i = 1 - 4) = (.)\tilde{B} + (.)\tilde{W}_3 + (.)\tilde{H}_1^0 + (.)\tilde{H}_2^0$$

Charginos:

$$\chi_i^\pm (i = 1 - 2) = (.)\tilde{W}^\pm + \tilde{H}^\pm$$

Usually, χ_1^0 is the lightest SUSY particle (LSP) and the DM candidate

Signals of Dark Matter at the LHC...

A neutralino LSP (and DM) \rightarrow expect
jets/leptons + MET

Data constraining the parameter space have
started arriving

Mass reconstruction of the χ_1^0 : a problem

One has to depend on various variables
based on transverse projections

How about alternative DM candidates?

A simple case with RH neutrinos...

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$\tilde{\nu}_R$ -dominated states can form the LSP
(and become dark matter component)

- **The low-scale sneutrino mass matrix:**

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{1}{2}m_Z^2 \cos 2\beta & y_\nu v (A_\nu \sin \beta - \mu \cos \beta) \\ y_\nu v (A_\nu \sin \beta - \mu \cos \beta) & M_{\tilde{\nu}_R}^2 \end{pmatrix}$$

$M_{\tilde{L}}$ = soft mass for the left-handed sleptons

$M_{\tilde{\nu}_R}$ = soft mass for the right-handed sneutrino

In general, $M_{\tilde{L}} \neq M_{\tilde{\nu}_R}$ because of different evolution patterns + D-term contribution for the former.

Physical states: $\tilde{\nu}_1$ (lighter), $\tilde{\nu}_2$ (heavier)

All couplings (gauge/Yukawa) for $\tilde{\nu}_1$ are proportional to

$$y_\nu \simeq 10^{-13}$$

New signals at the LHC

The LSP (dominantly a $\tilde{\nu}_R$) couples to all other SUSY particles with a strength $\sim y_\nu \sim m_\nu/m_W$

SUSY particle production

\Rightarrow cascades into the next-to-lightest SUSY particle (NLSP)

\Rightarrow Very slow decay of the NLSP to the LSP

New signals at the LHC

The LSP contributes to dark matter, but the NLSP (charged?) appears stable in collider detectors

Example: a $\tilde{\tau}$ or a \tilde{t} NLSP

The signal is *not* missing- p_T but charged tracks

*These tracks will be seen in the muon chamber
(outermost part of the detector)*

Distinguishing heavy stable particles from muons

Kinematic characteristics of heavy stable superparticles can make them conspicuous

One can reconstruct masses of unstable particles in the spectrum

$(\chi_{1,2}^0, \chi_1^\pm, \tilde{\nu}_L)$

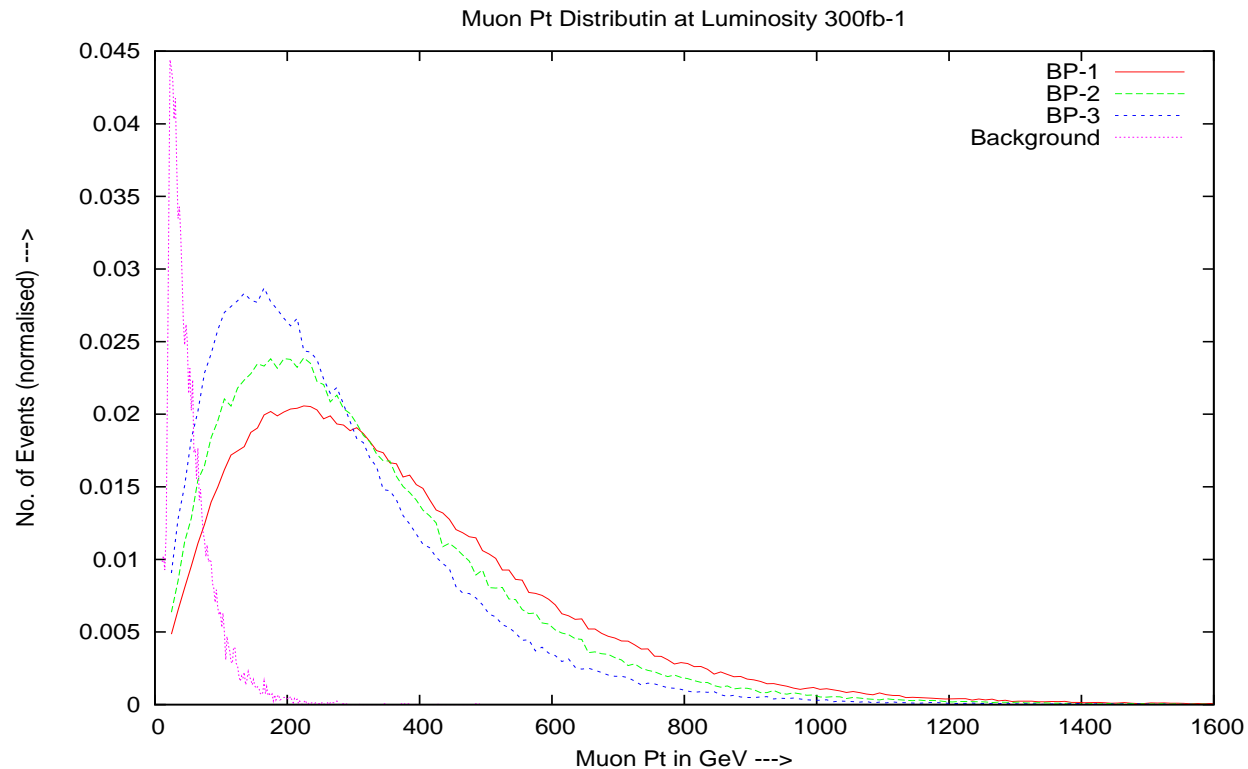
S. K. Gupta + S. K. Rai + BM, 2007

D. Choudhury + S. K. Gupta + BM, 2008

S. Biswas + BM, 2009,2010

S. Biswas, 2010

Discriminator: track p_T

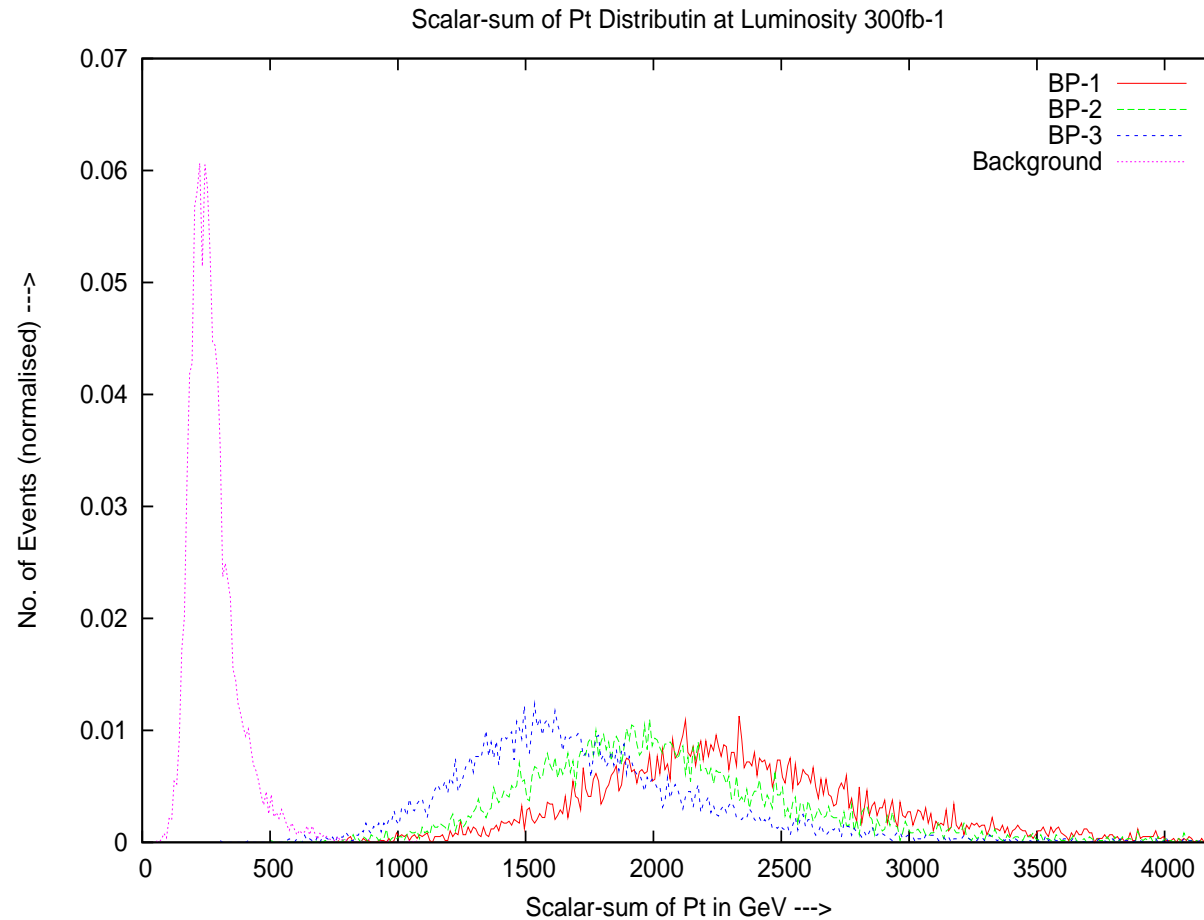


Strongly interacting new particles with mass $\sim 800 - 1400$ GeV

Stable stau with mass $\sim 125 - 200$ GeV

From S. Biswas + BM, 2009

Discriminator: Σp_T of leptons+jets+photons

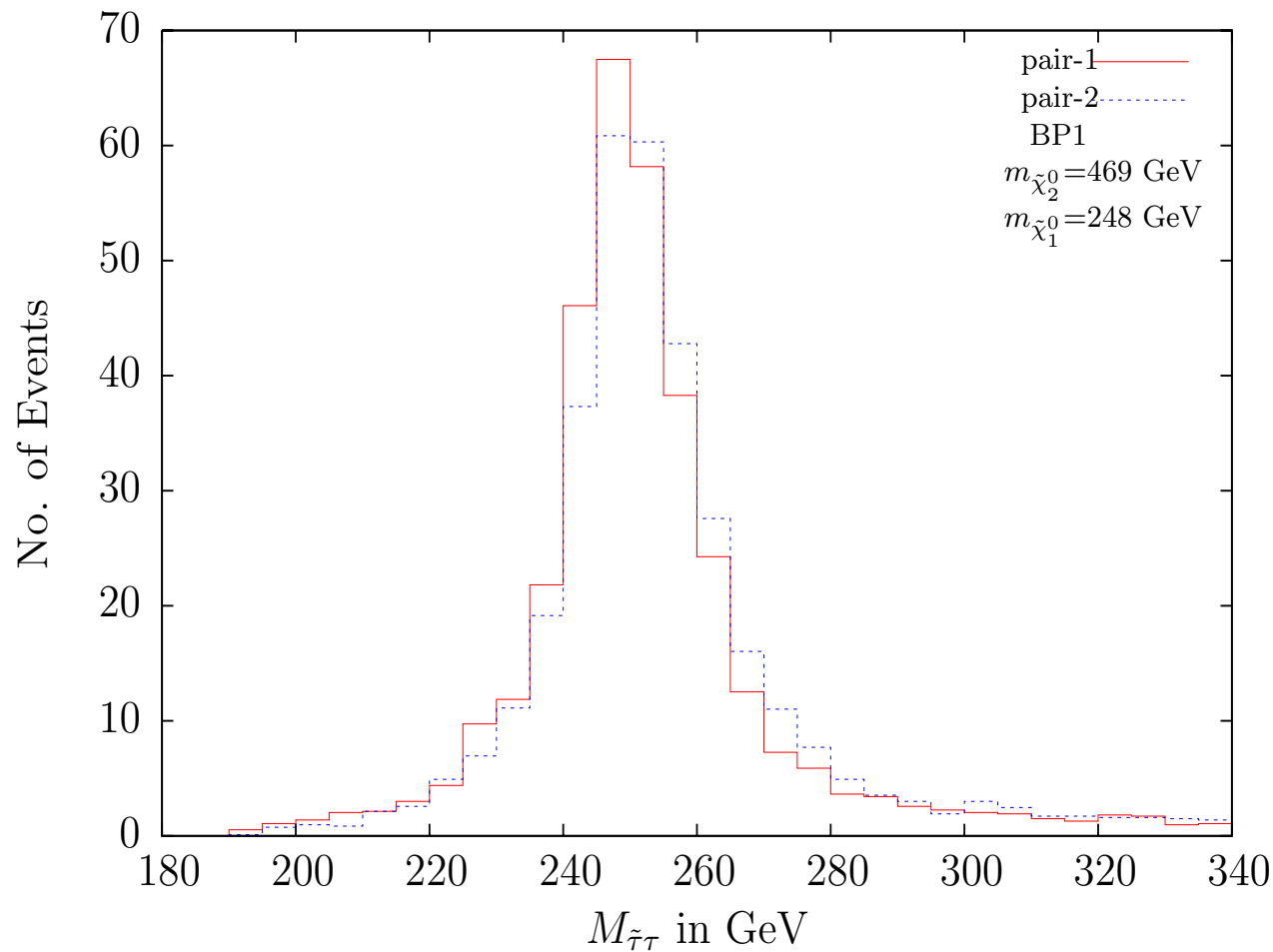


From S. Biswas + BM, 2009

Already at the 7 TeV Run, with
 $\int \mathcal{L} dt = 1 fb^{-1}$, $m_{\tilde{g}}, m_{\tilde{q}} \geq 750 \text{ GeV}$
can be probed with appropriate cuts

S. Biswas + BM, in preparation

One can reconstruct SUSY particle masses here...



χ_1^0 reconstruction: from the $\tau\tilde{\tau}$ -pair

S. Biswas + BM, 2009

Reconstruction of a χ_1^\pm

If one produces $pp \longrightarrow \chi_1^\pm \chi_1^0 \longrightarrow$
 $\tau \nu_\tau + \text{two charged tracks} + X,$

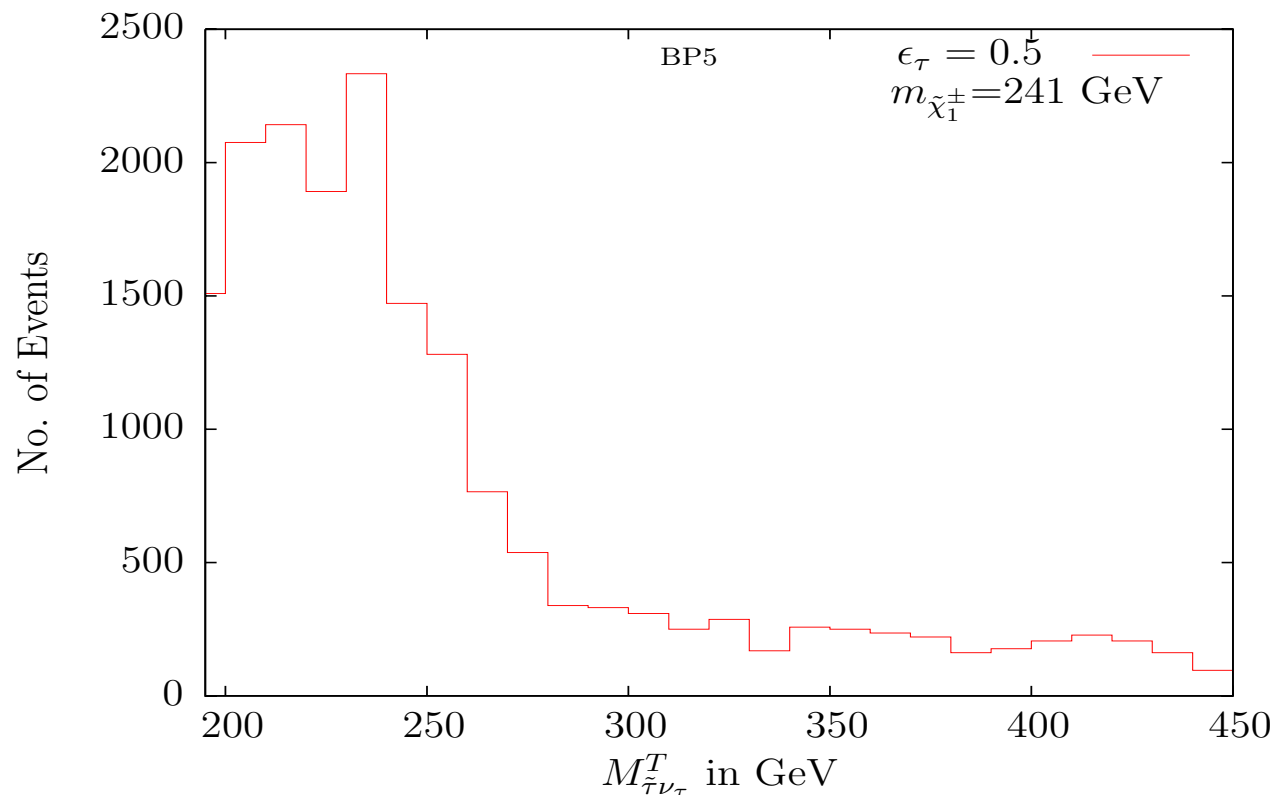
The invisible ν_τ obstructs reconstruction of the
 χ_1^\pm

One can use the transverse mass:

$$M_T^2(\tilde{\tau}, \nu_T) =$$
$$\left(\sqrt{p_T^{\tilde{\tau}2} + m_{\tilde{\tau}}^2} + |\not{p}_T| \right)^2 - (p_T^{\tilde{\tau}} + \not{p}_T)^2$$

A cut-off in the M_T distribution at $m_{\chi_1^\pm}$

Reconstruction of a χ_1^\pm



S. Biswas + BM, 2009

Tail due to combinatorial backgrounds

Select only events with opposite sign tracks

Use the track with the same sign as the τ for M_T

Another case....

Can the scalar partner of a left-handed neutrino be the LSP?

Yes, but it cannot be a dark matter candidate because of direct search limits

But the gravitino or an axino can form dark matter,

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SUSY signals in such cases:

Dictated by a spectrum where $\tilde{\nu}_L = \text{MSSM LSP}$

This mostly means $\tilde{\nu}_L < m_{\tilde{\tau}_L} < m_{\tilde{\tau}_R}$

Not usual in most SUSY breaking scenarios

LHC signal with $m_{\tilde{\tau}_L} < m_{\tilde{\tau}_R}$

S. Bhattacharya + S. Biswas + BM + M. Nojiri, 2011

$\tilde{\tau}_{(L,R)}$ production in cascades is accompanied
(followed) by $\tau_{(L,R)}$

Requisite strategy: tau-polarisation
identification

A useful discriminator in di-tau events:

$R = E_{\pi^\pm} / E_{\tau_j}$ in one-prong τ -decay

R tends to be smaller for τ_L

LHC signal with $m_{\tilde{\tau}_L} < m_{\tilde{\tau}_R}$

A theoretical scenario where this can occur:

When the Higgs masses have different origin

from spin-zero partners of quarks and leptons

Non-universal Higgs Mass (NUHM): distinct from

the minimal supergravity scenario

An example of how R can distinguish:

	NUHM-1	mSUGRA-1
$\frac{\mathcal{N}(R < 0.8)}{\mathcal{N}(R > 0.8)}$	3.35	2.45

Summary/Conclusions

- **The expectation of cold and warm dark matter point towards a number of particle physics options.**
- **LHC searches, and their difficulties are often accordingly tuned.**
- **It is however advisable to be open to different but perfectly viable scenarios.**

It is the mark of an educated mind to be able to entertain a thought without accepting it.

Aristotle