How to 'see' the 'invisible'?

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- Current state of particle physics: Hurrah for the SM!

- Is there life after the Higgs discovery?

- How to look for a Higgs boson that decays into 'invisible' particles?

Elementary Particle Physics

The accepted world view:

Fundamental Particles are the quarks, the leptons and the force carrier called bosons: the photon, the W/Z-boson, the gluons and the omnipresent, Higgs Boson.

Laws of particle physics which we have found to be functioning at distance scales of fermi's and smaller, seem to be of relevance in addressing things that happen on cosmological time scales (say beginning of the universe) and astronomical distance scales (millions of mega parsecs and above!)

How was everything formed?

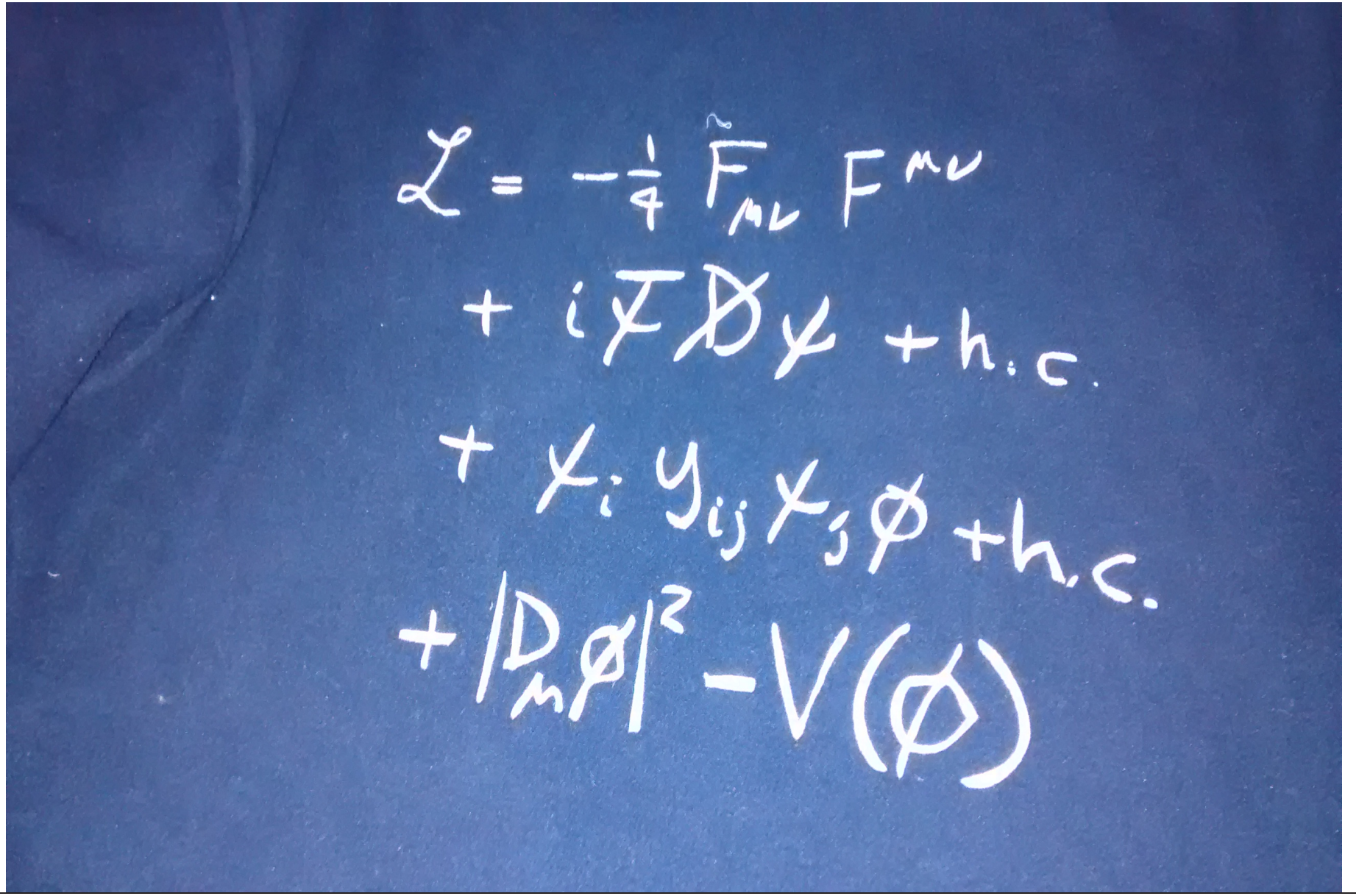
How did the nucleons form? Can we explain the relative abundance of different elements in the Universe? (stars, galaxies...)

These questions are understood in terms of known physics of the Standard Model (SM) of Particle Physics!

Not enough to know what the fundamental constituents are but also need to know how they are glued together!

What is the mortar?

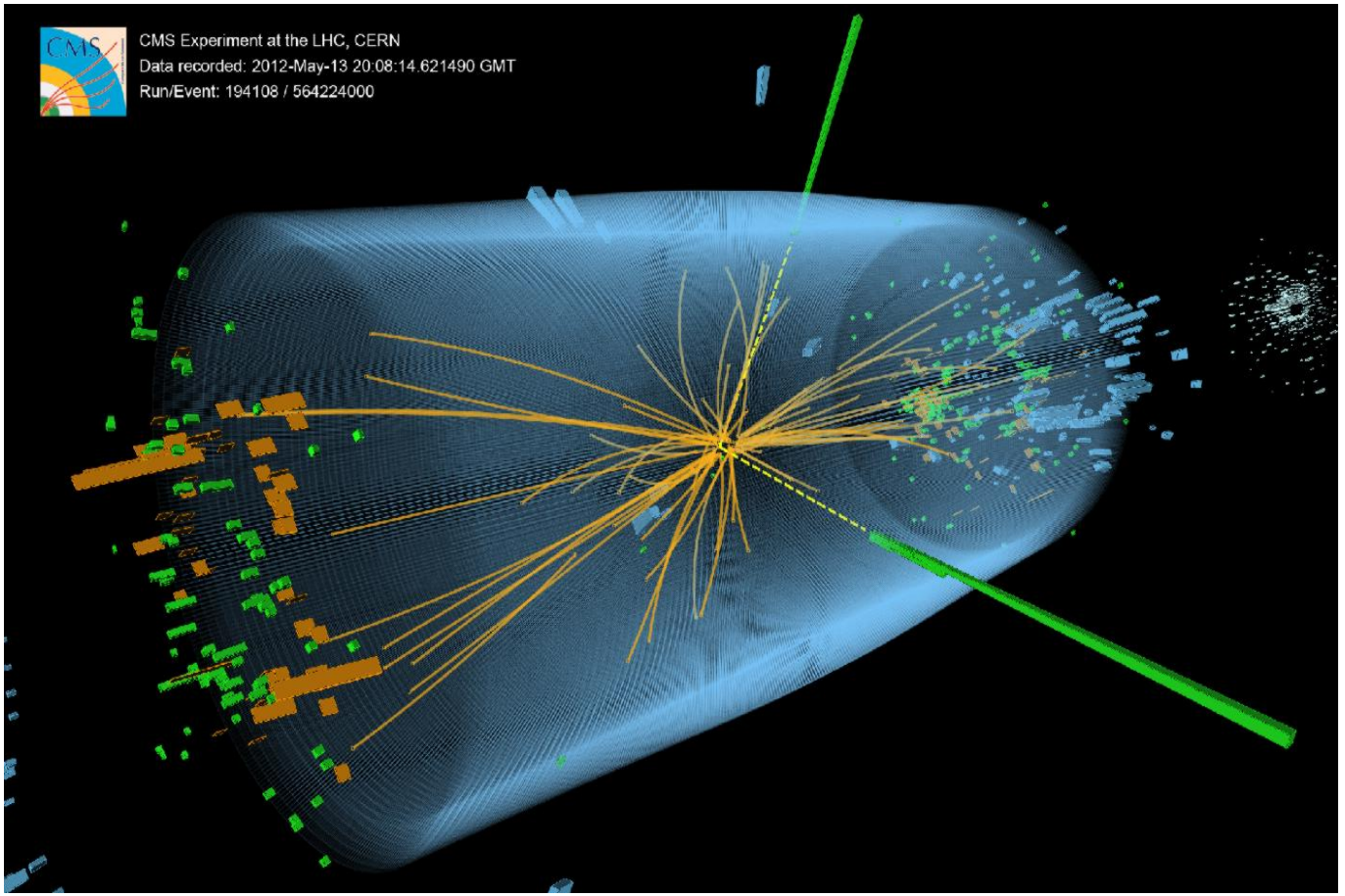
The four fundamental interactions mediated by elementary particles!


$\mathcal{L} = -\frac{1}{4}\tilde{F}_{\mu\nu}F^{\mu\nu}$
$+ i\bar{\chi}\not{D}\chi + h.c.$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

For the theoretical construct to be proven true we needed to find the Higgs boson.

The stakes were high!

The Large Hadron Collider: LHC was built to look for the Higgs boson spin 0 particle!



One of the Higgs event

Terminus for the train of the Standard Model!

Is there a life for particle physicists after the Higgs discovery?

YES!

Are we saying this just because we want to keep our jobs?

Actually not!

Particle physicists had started looking at 'what after Higgs' decades ago.

This is called 'Physics Beyond the Standard Model' : BSM

It is just that we have not yet found any 'proof' at the LHC, for any of the big ideas that the field had produced!

Particle physics finds itself in a very peculiar place.

To steal from 'A tale of two cities': (Apologies to Charles Dickens!) (and also to Sreerup from whom I stole the idea and expanded it further!)

It is the best of times , it is the worst of times

It is the epoch of belief , it is the epoch of incredulity

It is the season of 'Light' , it is the season of Darkness

It is the spring of hope, it is the winter of despair

We have everything before us, we have nothing before us.

We have found the SM Higgs, proved the SM, we have no glimmer of BSM that the Higgs properties promises!

So we all can feel a bit like Lord Kelvin (The Kelvin temperature scale is named after him) who at the end of 19 th century thought that

"There is nothing new to be discovered in physics now, All that remains is **more and more precise measurement**."

Mere mortals today:

All that remains is **more and more precise measurement** of the Higgs and top properties! *OR Higher and higher energies?*

What are the resaons for agonising? Just the arrogance of physicists? Actually no!

- Dark Matter makes up 27% of the Universe.! (Physics Nobel 2019)

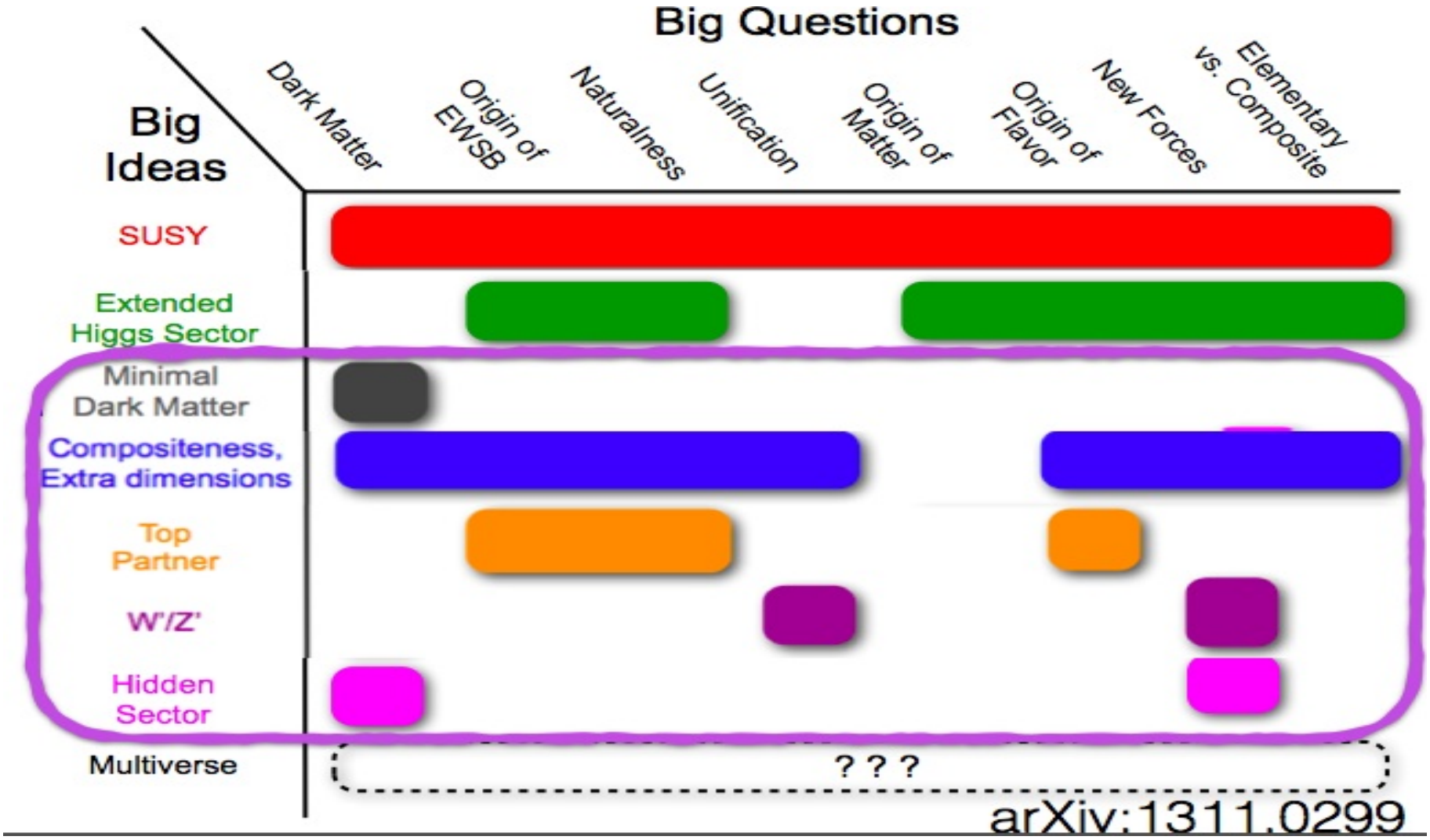
- We have direct evidence for the nonzero ν masses (Physics Nobel prize 2015)

- Need to understand why matter dominates the Universe: Matter-Antimatter Asymmetry in the Universe!

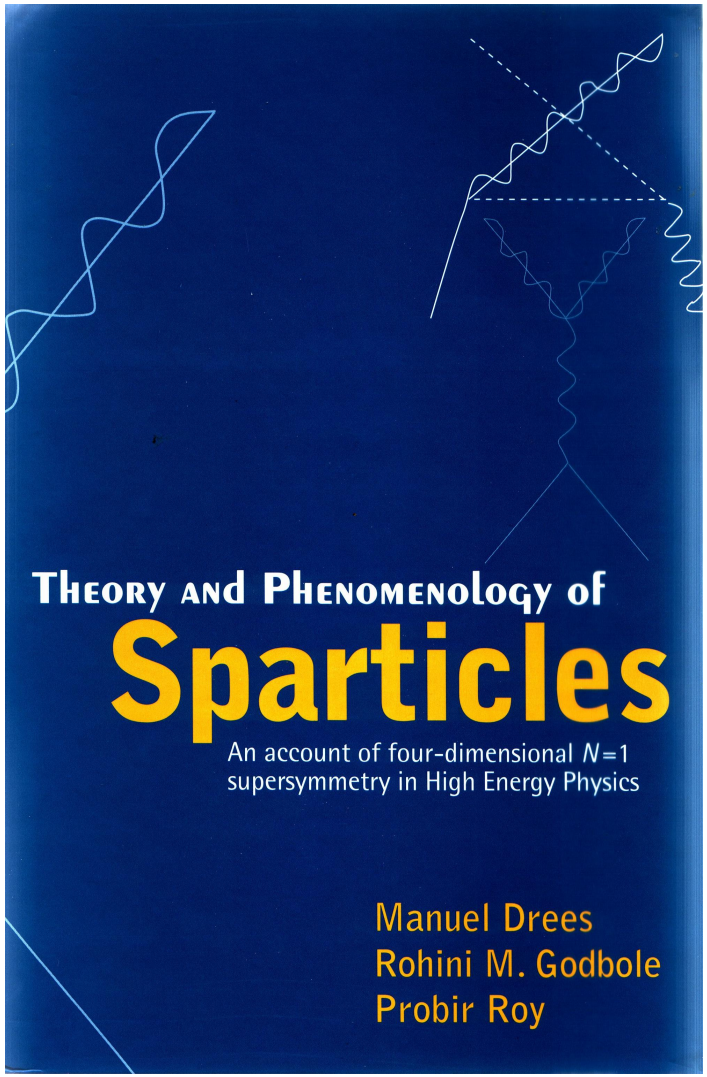
- We have found a light Higgs boson at the LHC! (Physics Nobel Prize 2013)

- We feel the force of gravity but do NOT have a QUANTUM description!

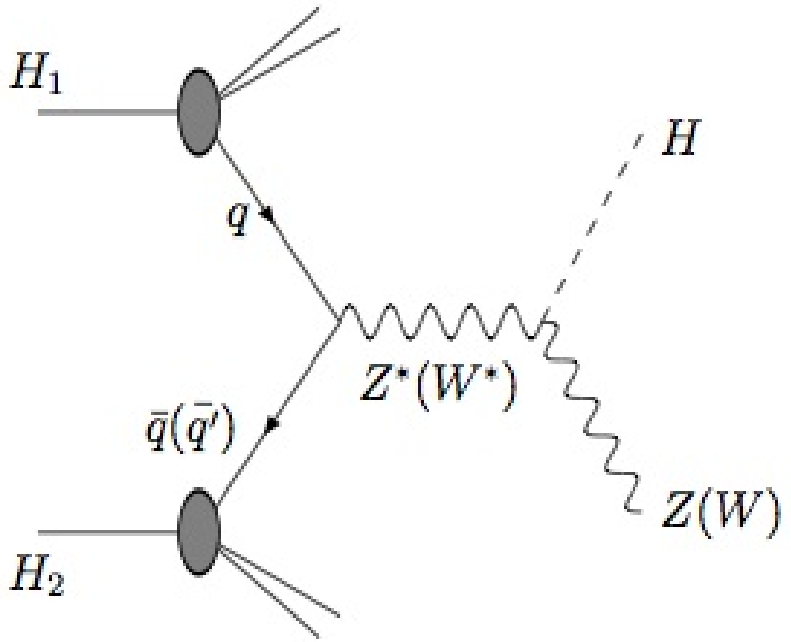
- Cosmic Acceleration. (Physics Nobel Prize 2011)


Big Questions
Big Ideas
Dark Matter
Origin of EWSB
Naturalness
Unification
Origin of Matter
Origin of Flavor
New Forces
Elementary vs. Composite
SUSY
Extended Higgs Sector
Minimal Dark Matter
Compositeness, Extra dimensions
Top Partner
W'/Z'
Hidden Sector
Multiverse
? ? ?
arXiv:1311.0299

Associated with every particle there is a supersymmetric partner! For it to solve the problems we need the partners to have a mass M such that $Mc^2 < 1000$ GeV. Looking for them at LHC was one way to probe the BSM ideas!
But we have not found any evidence so far at the LHC!
The theory has some ready made DM candidate particles.

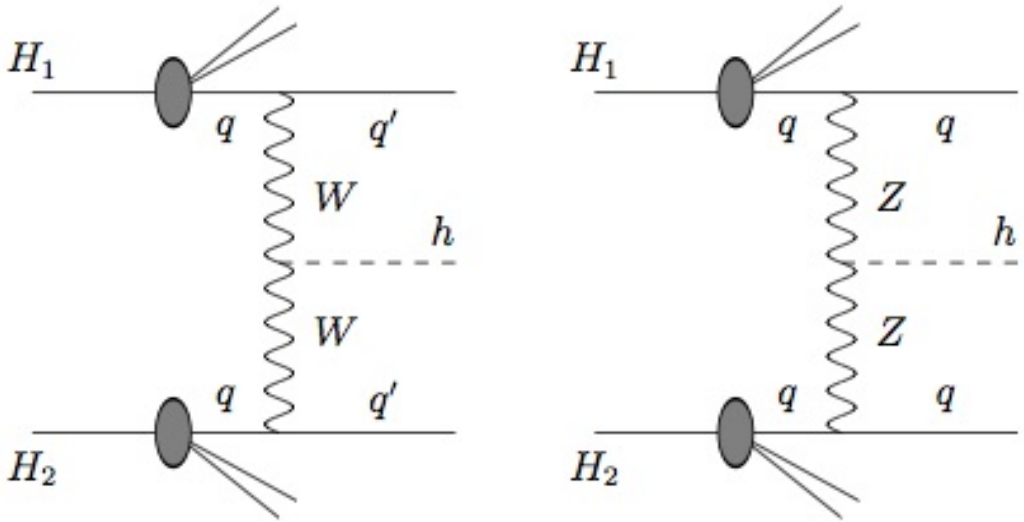


How to look for Dark Matter at the colliders through the Higgs.



R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003) "Search for 'invisible' Higgs signals at LHC via associated production with gauge bosons," *Phys. Lett. B* **571**, *pp. 184-192*

After the Higgs was discovered, we revisited the analysis, Included other processes as well.



D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, (2013) "Looking for an Invisible Higgs Signal at the LHC," Phys. Lett. B 725, arXiv:1211.7015 [hep-ph]

Process	8 TeV 20 fb^{-1}	14 TeV 30 fb^{-1}	14 TeV 100 fb^{-1}
VBF	0.34	0.32	0.17
$Z(\rightarrow l^{+}l^{-})h$	0.58	0.32	0.18
$Z(\rightarrow b\bar{b})h$(substructure)	–	–	0.5
$Z(\rightarrow b\bar{b})h$(b-jet cluster)	–	–	0.55

CMS result: Invisible Branching ratio < 0.58

European Physical Journal C: 74, 2980 (2014).

ATLAS Result: Invisible Branching ratio < 0.75

Physical Review Letters: 112, 201802, (2013).

In each model the invisible branching ratio, ie. the number of times the Higgs will decay into 'unseen' particles is related to the total number of DM particles in the Universe!

So these limits indirectly rule out some of the values of the parameters of the models.

The observed DM density in the Universe is called 'relic' density.

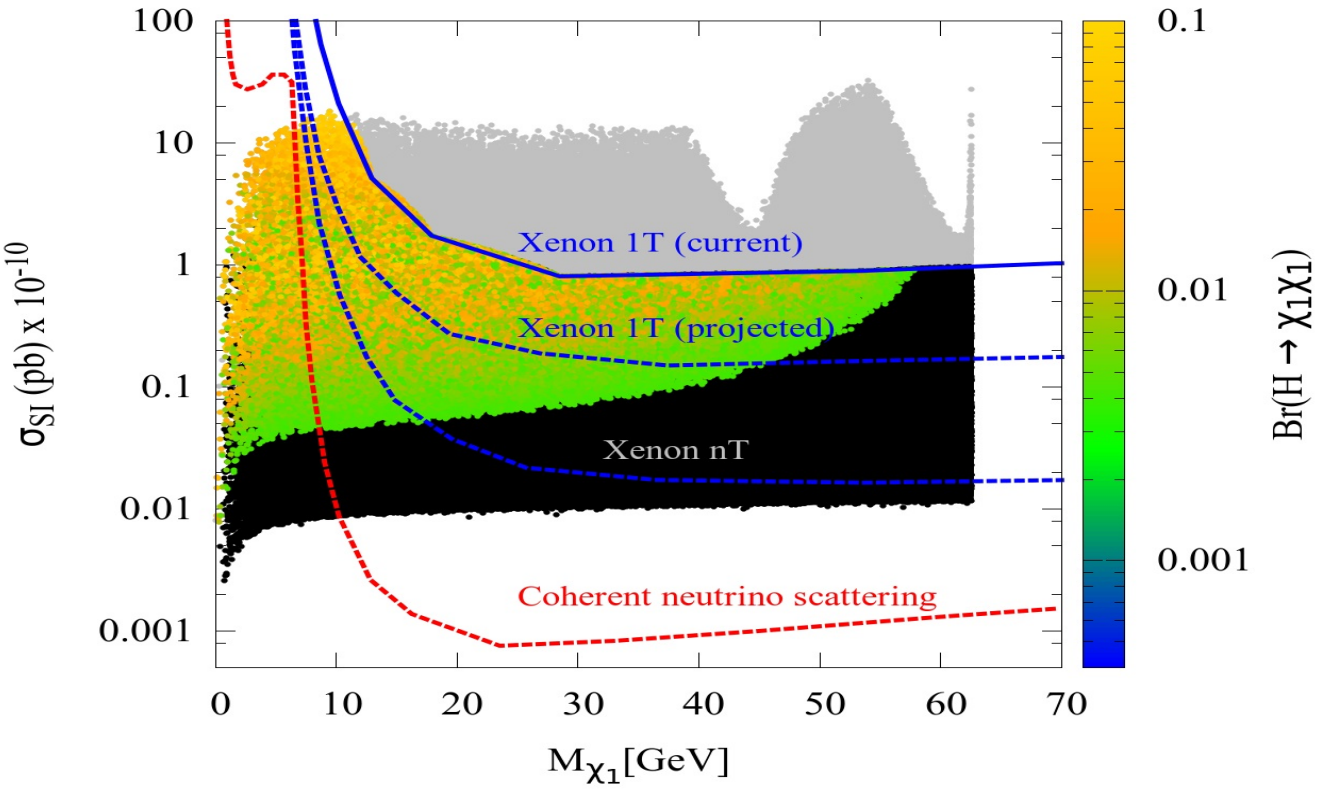
It predicted value depends on BSM model as well as the model for Cosmology.

A low mass, Lighetst Supersymmetric Particle (LSP) is still allowed in versions of SUSY models, satisfying relic constraints. For example, see R.K. Barman, G. Belanger, B. Bhattacharjee, R.G., D. Sengupta, G. Mendiratta,: PRD 95, 095018. Difft. from 1612.06333v1, **considered non thermal DM as well**.

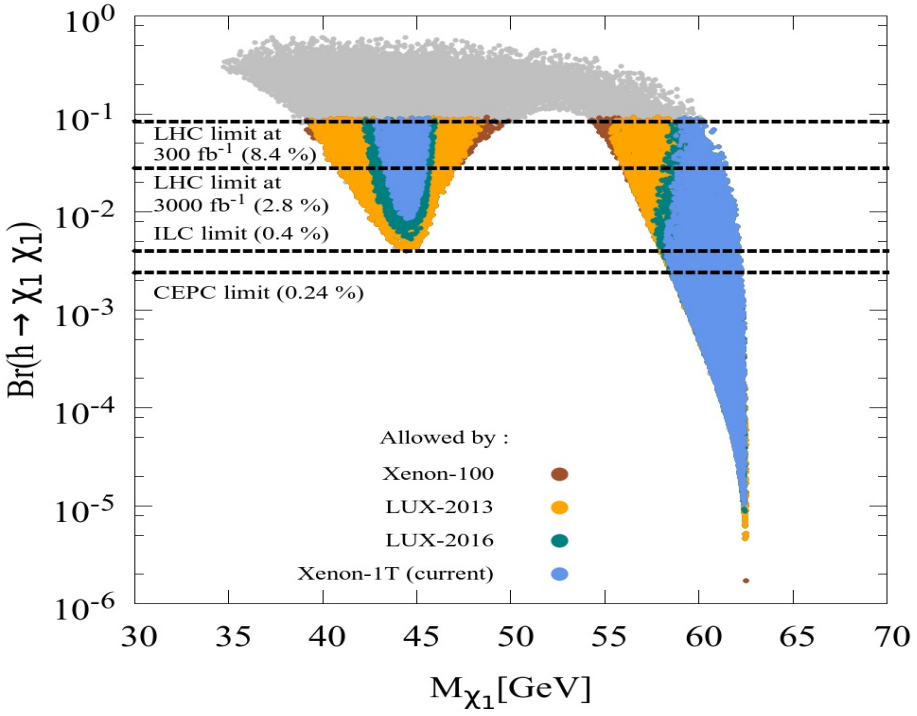
This light LSP will mean invisible decay of the Higgs. Possible to probe it at LHC and future colliders. For example, D.Ghosh, R.G., M. Guchait and K. Mohan, PLB 725, 344, 2013 .

Such a DM should be seen in the 'direct' detection experiments (not the LHC experiments) being performed all over the world.

For Nonthermal DM the light neutralinos can not be detected in the Direct Detection experiments and then invisible decay width might be the only way!



Where can we measure this?



Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:

300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

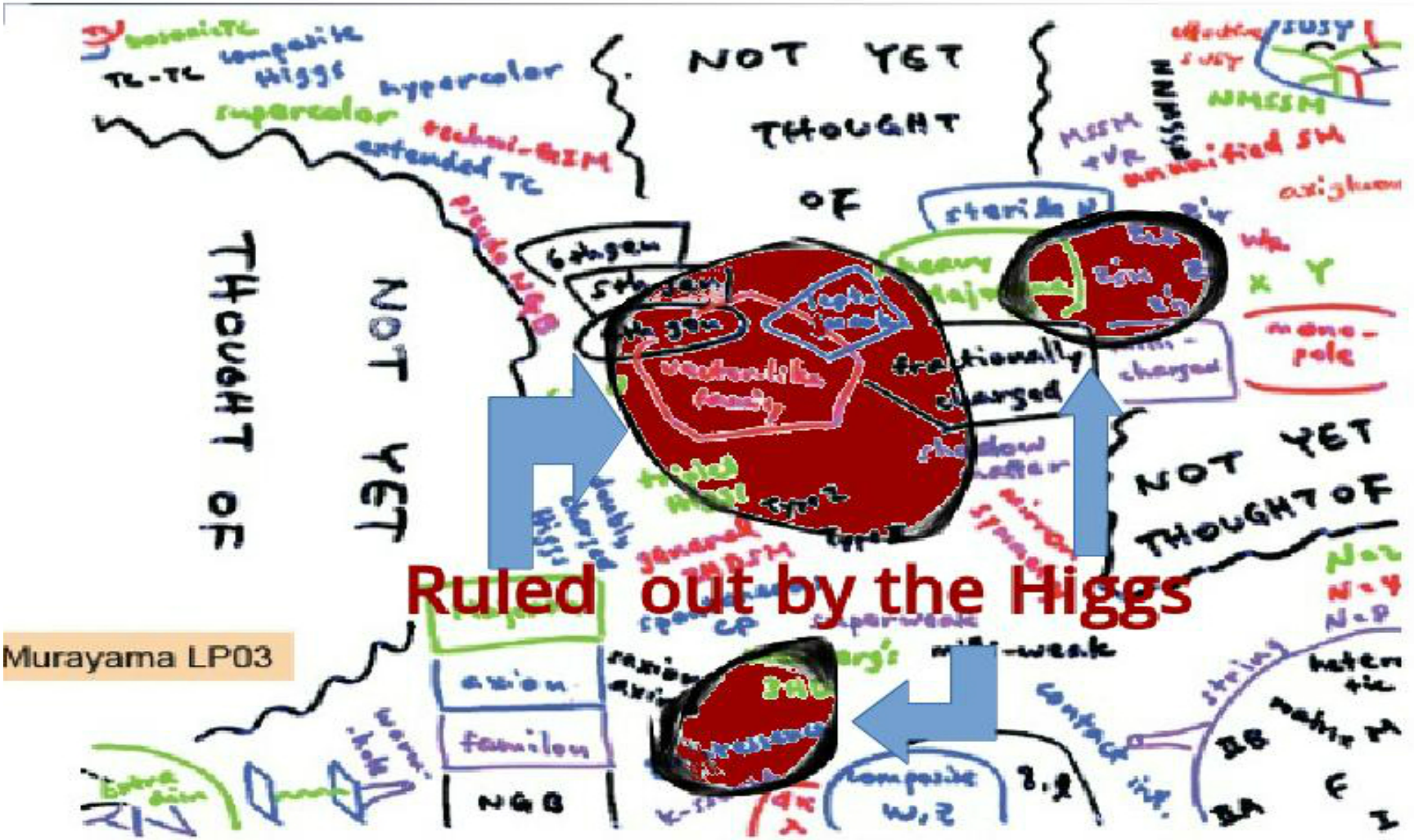
Our scan allows relic to be less than observed. Most of the times one needs additional DM component.

Searches for invisibly decaying Higgs hold promise. Green(orange) (dis)allowed by LUX. (from PRD 95, 095018)

Connection between Higgs, BSM and DM! Connections between the LHC, e^+e^- colliders and Direct detection experiments.

Peeping through the Higgs and the top window!


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
composite Higgs
TC-TC
hypercolor
supercolor
technI-BSM
extended TC
6th gen
5th gen
4th gen
vectorlike family
lepto quark
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
monopole
MSSM
NMSSM
unmotivated SM
axigluon
S.T.U
triplet Higgs
type2
TypeI
general 2HDSM
spontaneous CP
shadow matter
mirror symmetry
N=1
N=4
N=P
superweak
milli-weak
weinberg's 3HD
Majoron
axion
familon
NGB
ramon
axino
gravitino
quintessence
composite W,Z
contact
string
heterotic
Murayama LP03


NOT YET THOUGHT OF
Ruled out by the Higgs
Murayama LP03

The Quest Continues!!