Whither Particle Physics and colliders?

Rohini M. Godbole
Centre for High Energy Physics, IISc, Bangalore, India

- Nobel Prizes in Physics: 2013 and 2015
- Hurrah for the SM!
- How did colliders help us on this journey?
- Where do we go next?

a Nobel prize of 2013:

The discovery was the **final** piece of information to prove that the currently accepted description of fundamental particles and interactions among them, *viz.* **Standard Model** (SM) is the correct one ☺

b Nobel prize of 2015:

The discovery of neutrino oscillations. It gave proof that there MUST exist physics, either particles OR interactions, beyond the SM : the so called BSM physics.

The Nobel Prize in Physics 2013 was awarded jointly to Francois Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Two things about the Nobel prize:

1) The mechanism : Higgs mechanism (triumph of the theory!)

2) Confirmed by the discovery of the Higgs boson. (the confirmation of theoretical speculations by experiments!)

The experimental groups at different Universities and Institutes and also a host of theorists all over India have been involved right from the beginning, in this exercise.

Remember:

Higgs postulate : 1968

Machine design: 1984

Machine building start: 1998

Experiments : 2012!

HEP experiments need a lot of lead time to plan, not just because they are huge and costly but also because they are very complex. Also spread over many decades the cost is not too much!

Kajita and McDonald

Nobel for physics 2015


ν_τ
G. Boixader

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Among the Nobel prizes awarded for physics till to date, in 24 years they were given for experimental discoveries or theoretical breakthroughs that have contributed to the Standard Model to 47 scientists! First in 1936 and the most recent one in 2013.!

2013 : last Nobel for the SM!

2015: First Nobel for the physics beyond the Standard Model (BSM)?

Particle physics finds itself in a very peculiar place.

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

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 at the LHC of the type of BSM that the Higgs properties promise! Nonzero ν masses imply BSM physics BUT Higgs properties dont imply non zero ν masses.

So we all can feel a bit like Lord Kelvin who 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, top and B meson properties! *OR Higher and higher energies?*

Is that the path of the collider physics ahead?

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!

The 'Periodic Table' of Fundamental particles and their interactions has arrived!

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

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!

BOSONS

force carriers
spin = 0, 1, 2, ...

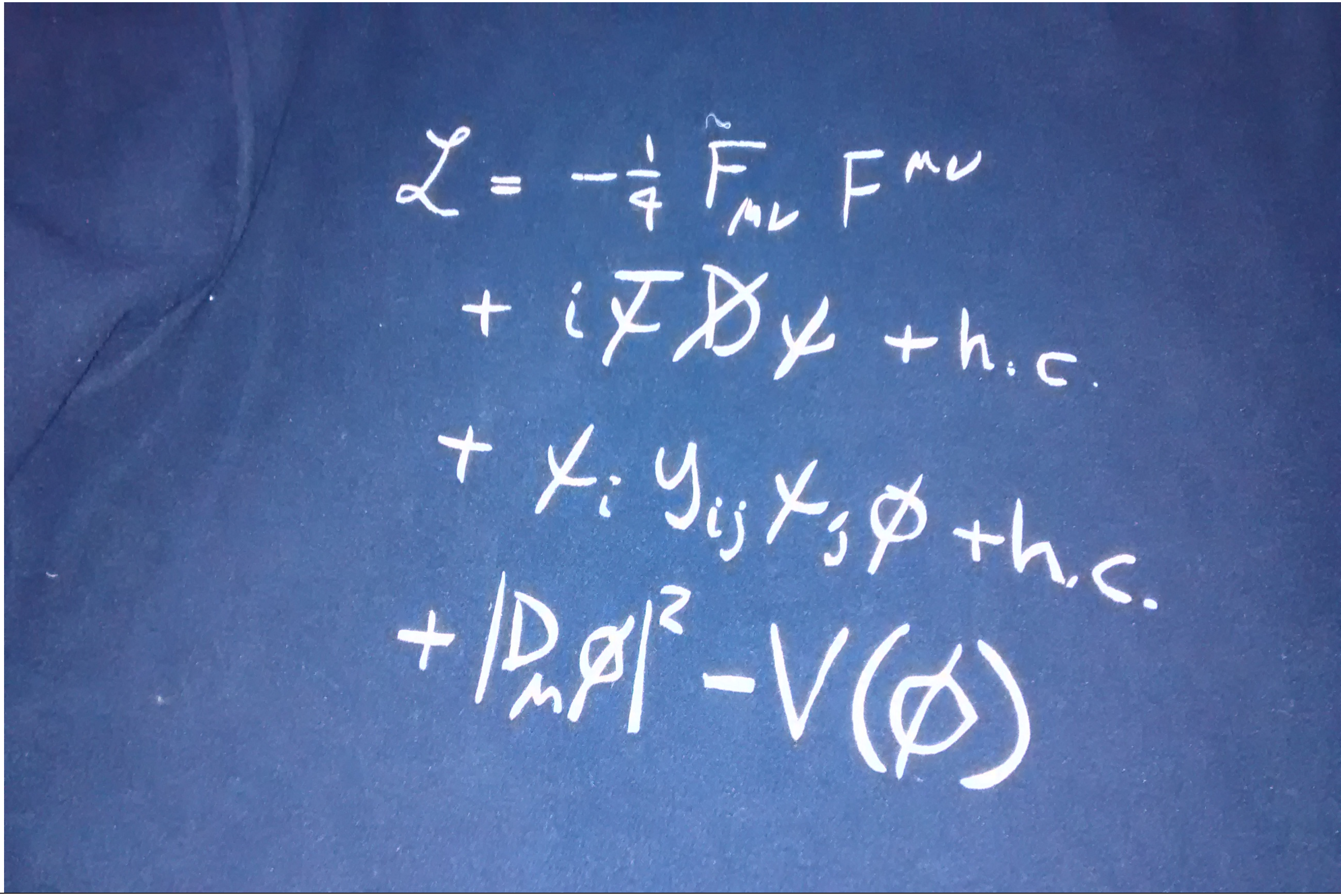
Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The force carriers are fundamental particles too!


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

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!

Cosmic Rays and Photographic emulsions, accelerator experiments and bubble chambers!

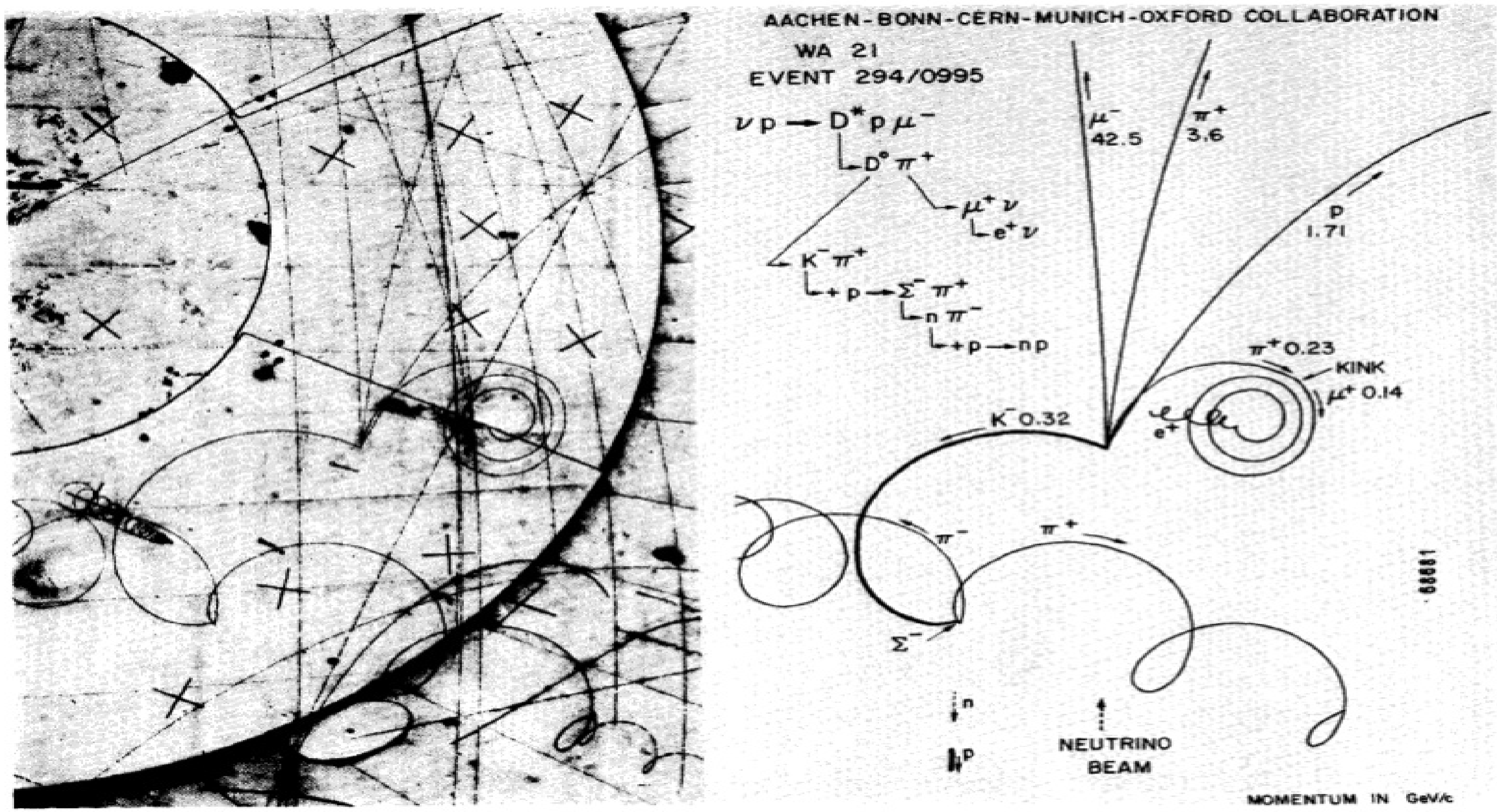
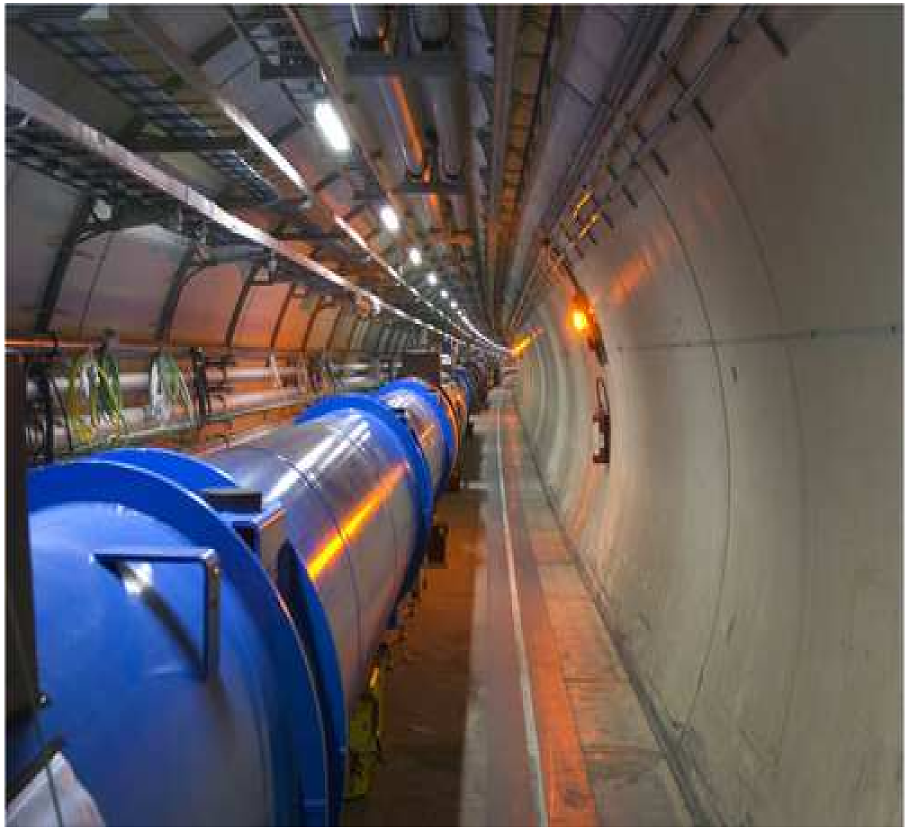


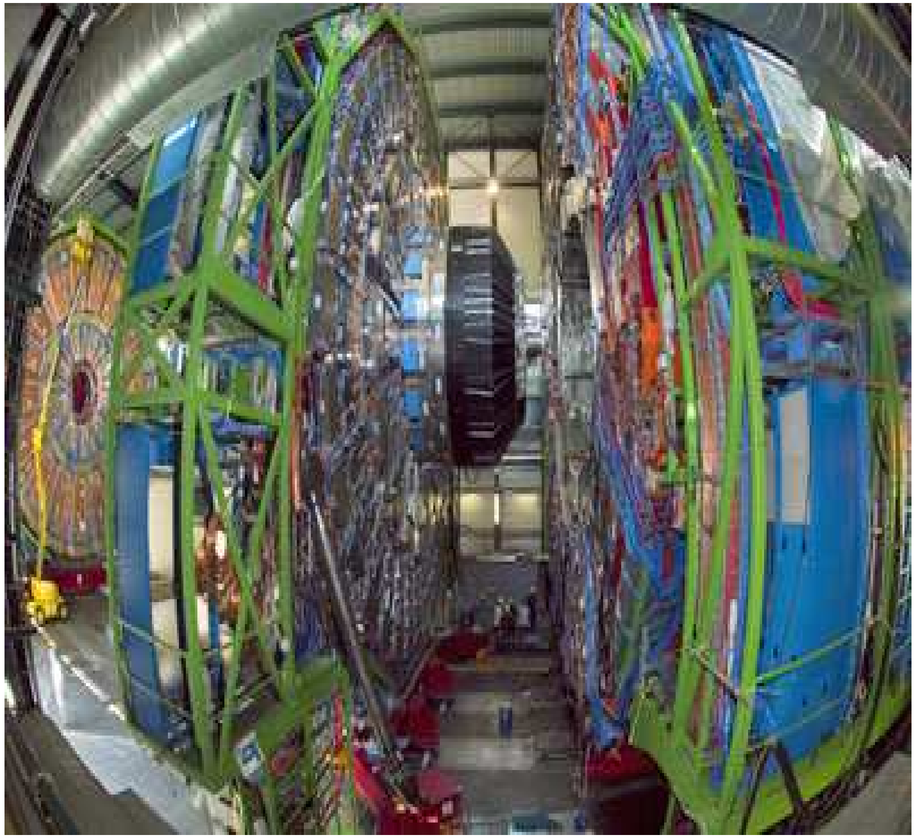
Fig. 7-12. Production and decay of a charmed meson in a neutrino–proton interaction in BEBC. A drawing of the event is shown next to the actual photograph.

78 L. Van Hove and M. Jacob, Highlights of 25 years of physics at CERN

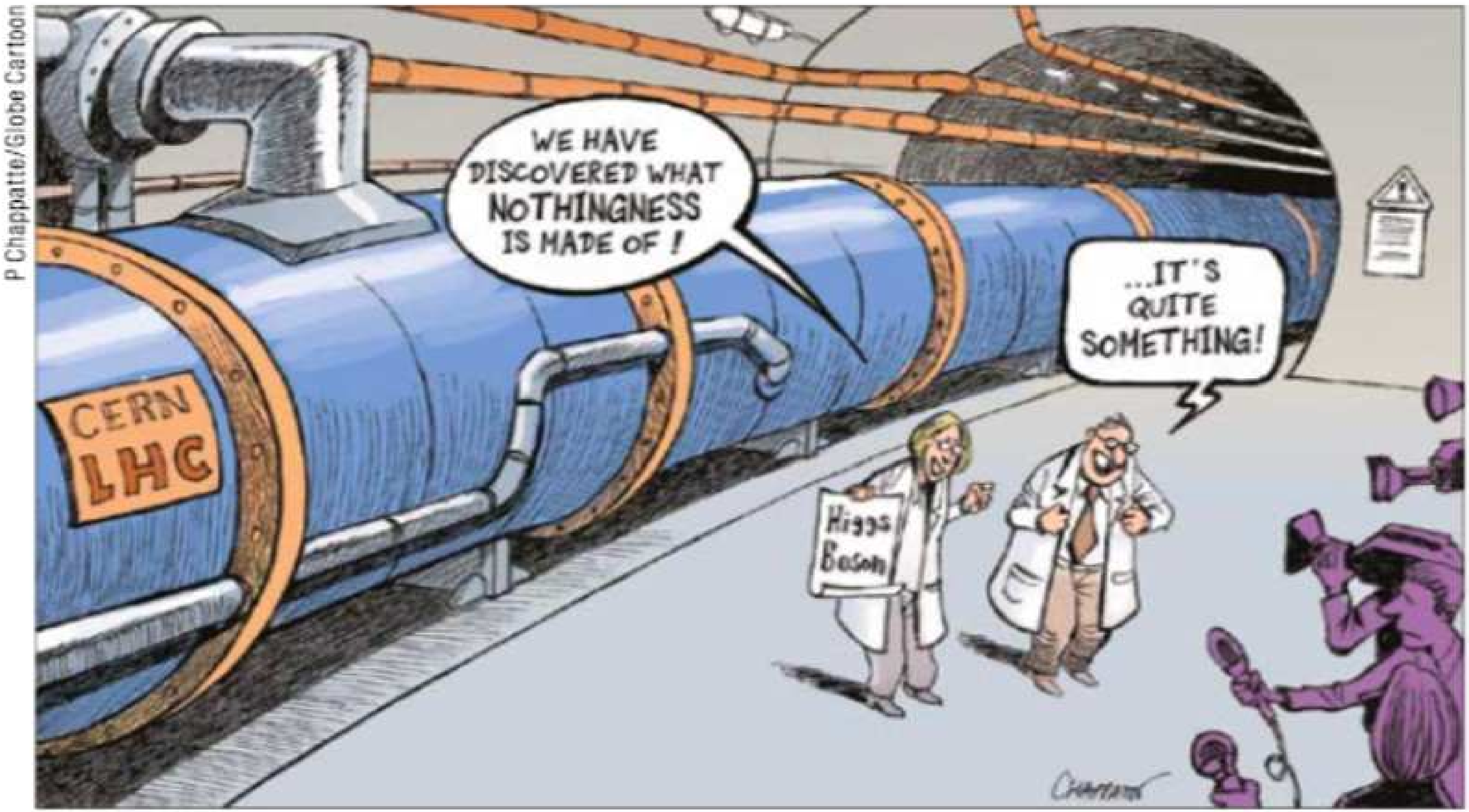
Physics Reports 62, 1980, First 25 years of CERN.

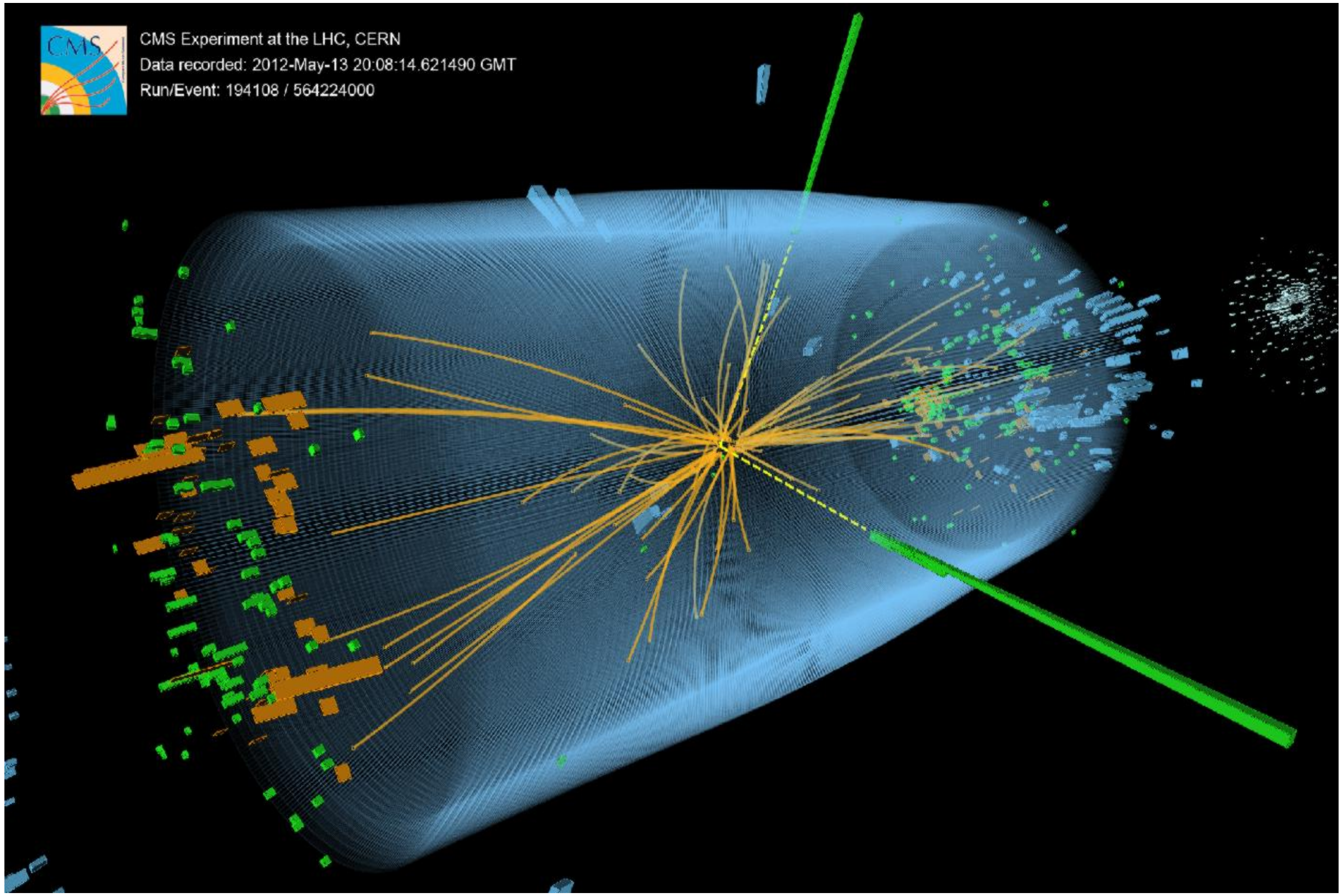


Machine



Detector


P Chappatte/Globe Cartoon
WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson

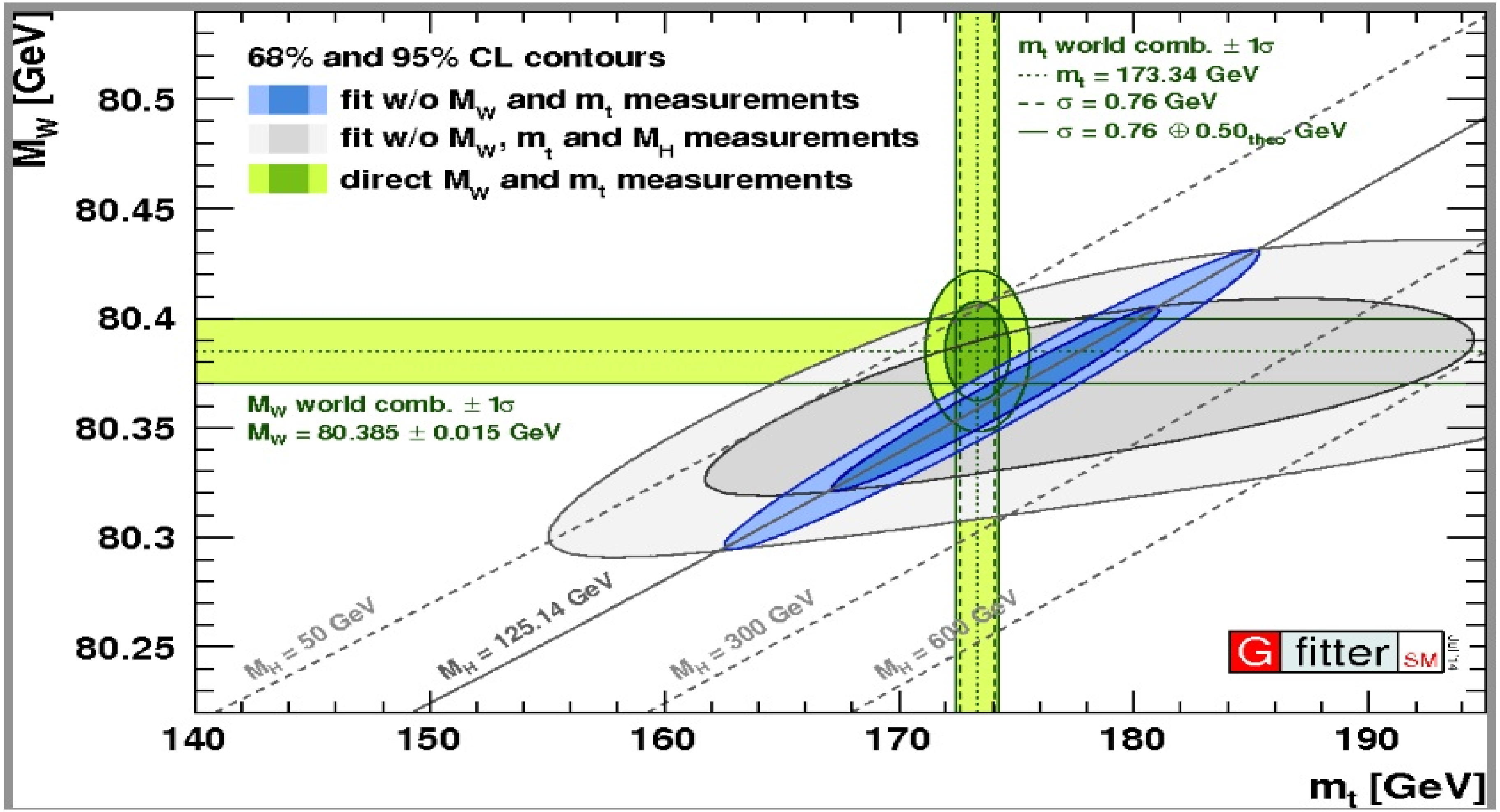


One of the Higgs event

Terminus for the train of the Standard Model!

Why did we believe the Higgs signal when it came first even if it was somewhat tenuous?

The signal had all the connections with the top that we expected the SM Higgs to have.



SM rocks! *At LOOP level* **Connection with top absolutely essential**

Three lessons to be learnt from the plot

1) SM works really spectacularly!

2) Space allowed for new physics contributions very limited. But this can be indeed the way to probe new physics! Recall after all there was a time when top quark was not found and the mass was 'predicted ' from the same precision studies!

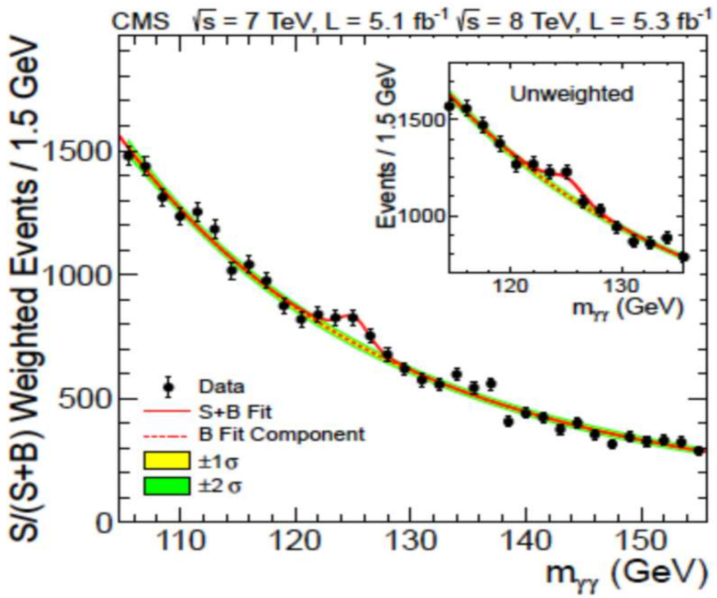
3) We know the Higgs mass as well (or better) as we will ever need for this exercise!

4)What do we need to study further then?

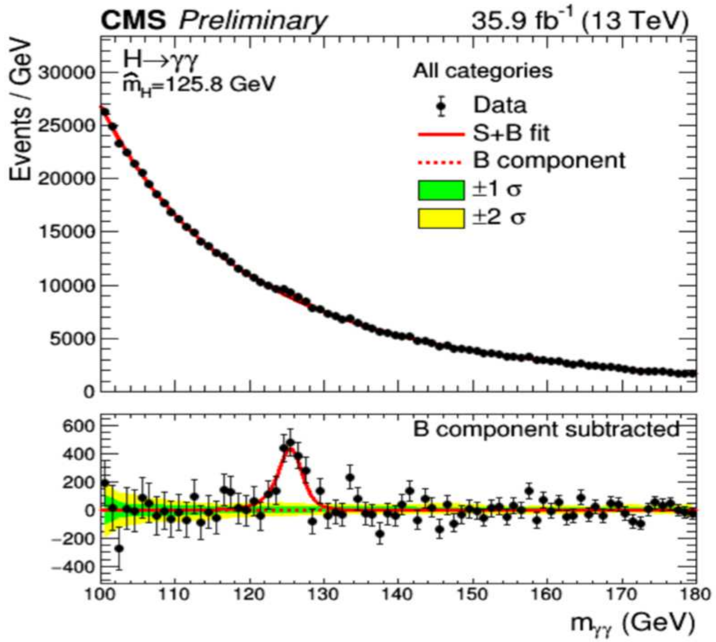
Discovery to precision

2012

H→γγ

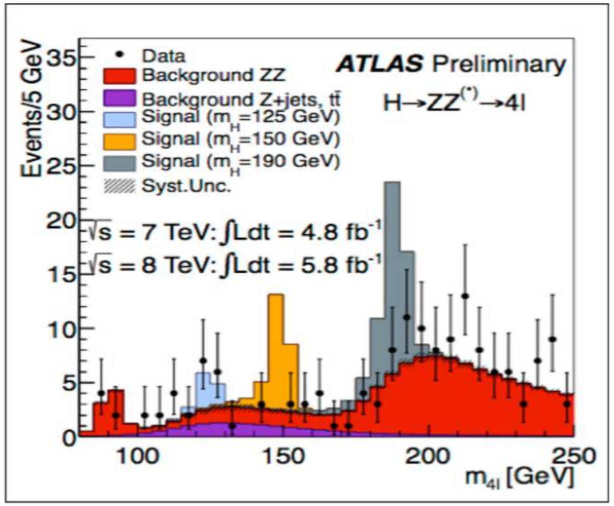


2019

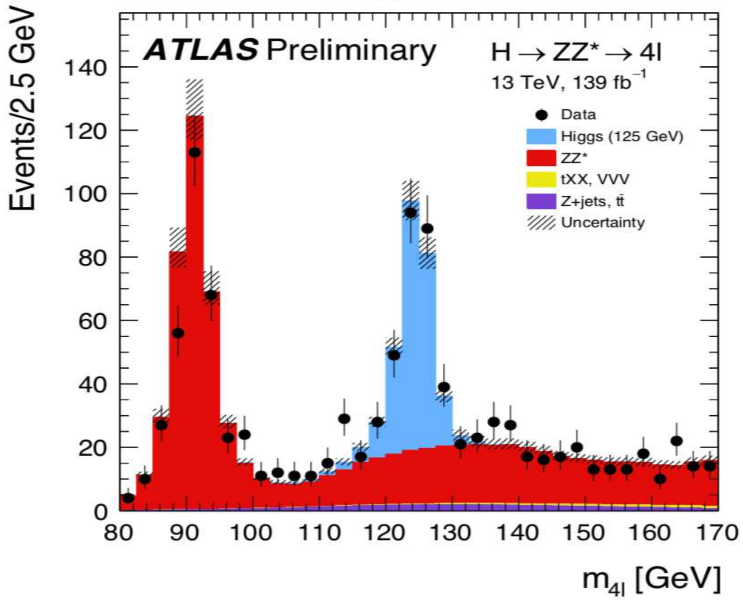


Discovery to precision

2012



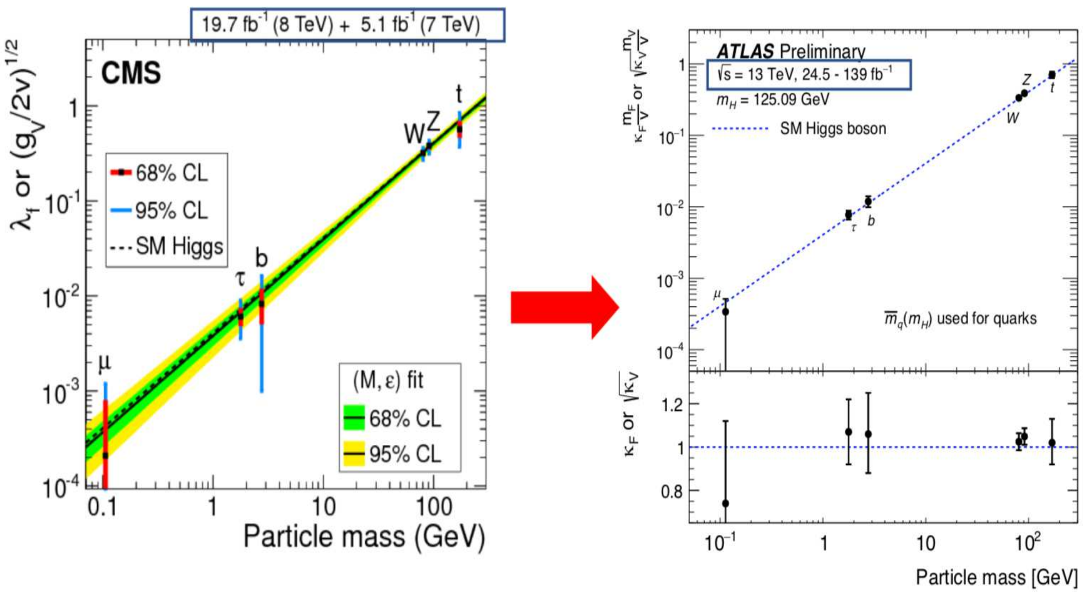
2019



H→ZZ→4l

Discovery to precision measurements

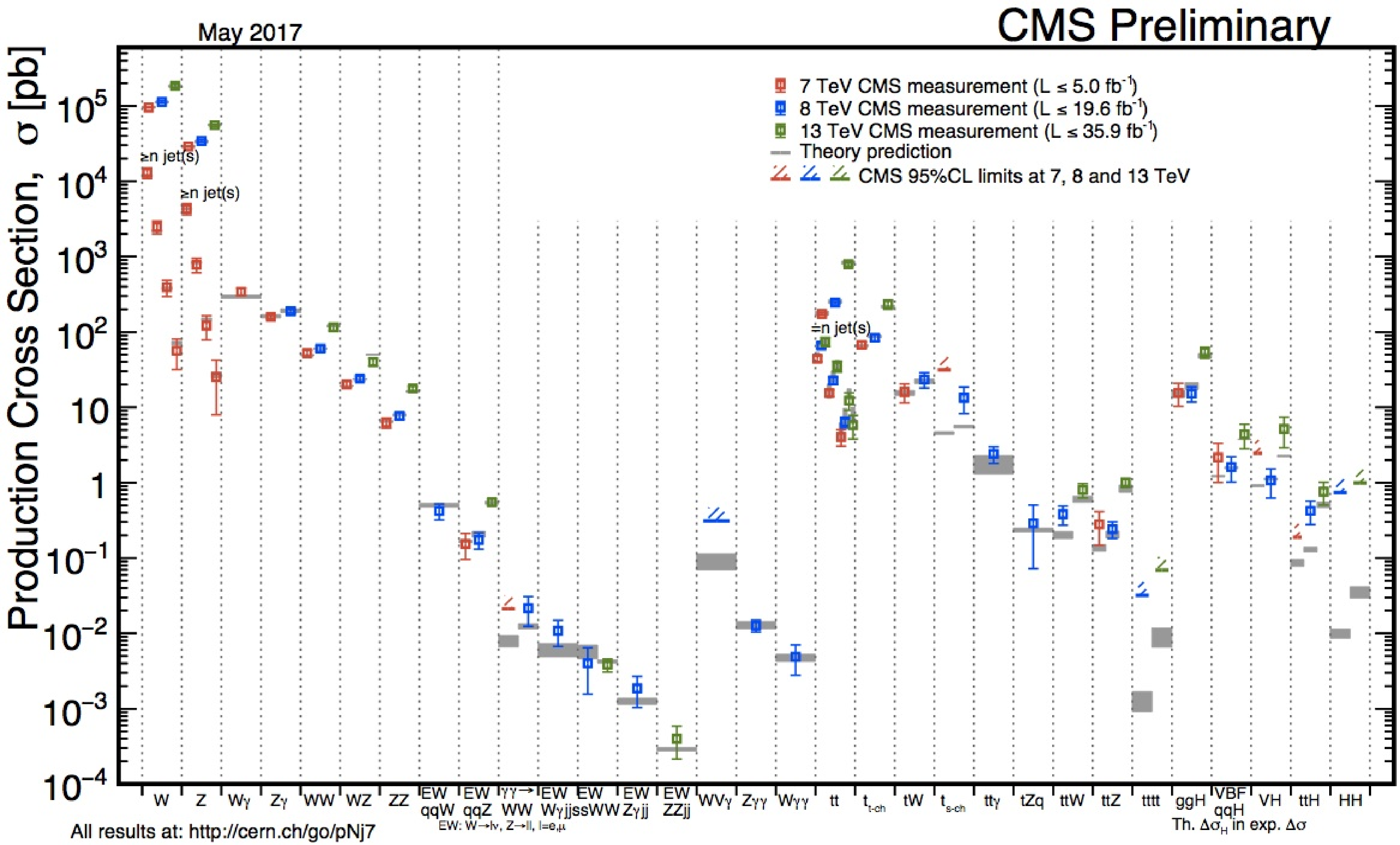
- SM has very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to gM_V
  - Higgs self-couplings proportional to M_H^2



If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

SM predictions calculated for many many processes and they agree with the measurements very well.

These are the many roads to reach the conclusion of the correctness of the SM.


May 2017
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
13 TeV CMS measurement (L ≤ 35.9 fb⁻¹)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→WW
EW Wγjj
ssWW
EW Zγjj
EW ZZjj
WVγ
Zγγ
Wγγ
tt
t t-ch
tW
t s-ch
ttγ
tZq
ttW
ttZ
tttt
ggH
VBF qqH
VH
ttH
HH
EW: W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ
All results at: http://cern.ch/go/pNj7

Is there a life for particle physicists post the Higgs and the SM validation at LHC?

YES!

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

Actually not!

Two reasons:

1) Use the Higgs boson as the tool for discovery.

2) Particle physicists have thought about ‘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!

Are we only agonising over non discovery of our beautiful theories which we think must be realised in nature because of their aesthetic beauty!

One question : Is BSM Optional?

Is it only a theorists dream or do we have observations that force us to believe that BSM HAS to exist?

We have MANY pragmatic reasons to expect physics beyond the SM : either interactions or particles

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

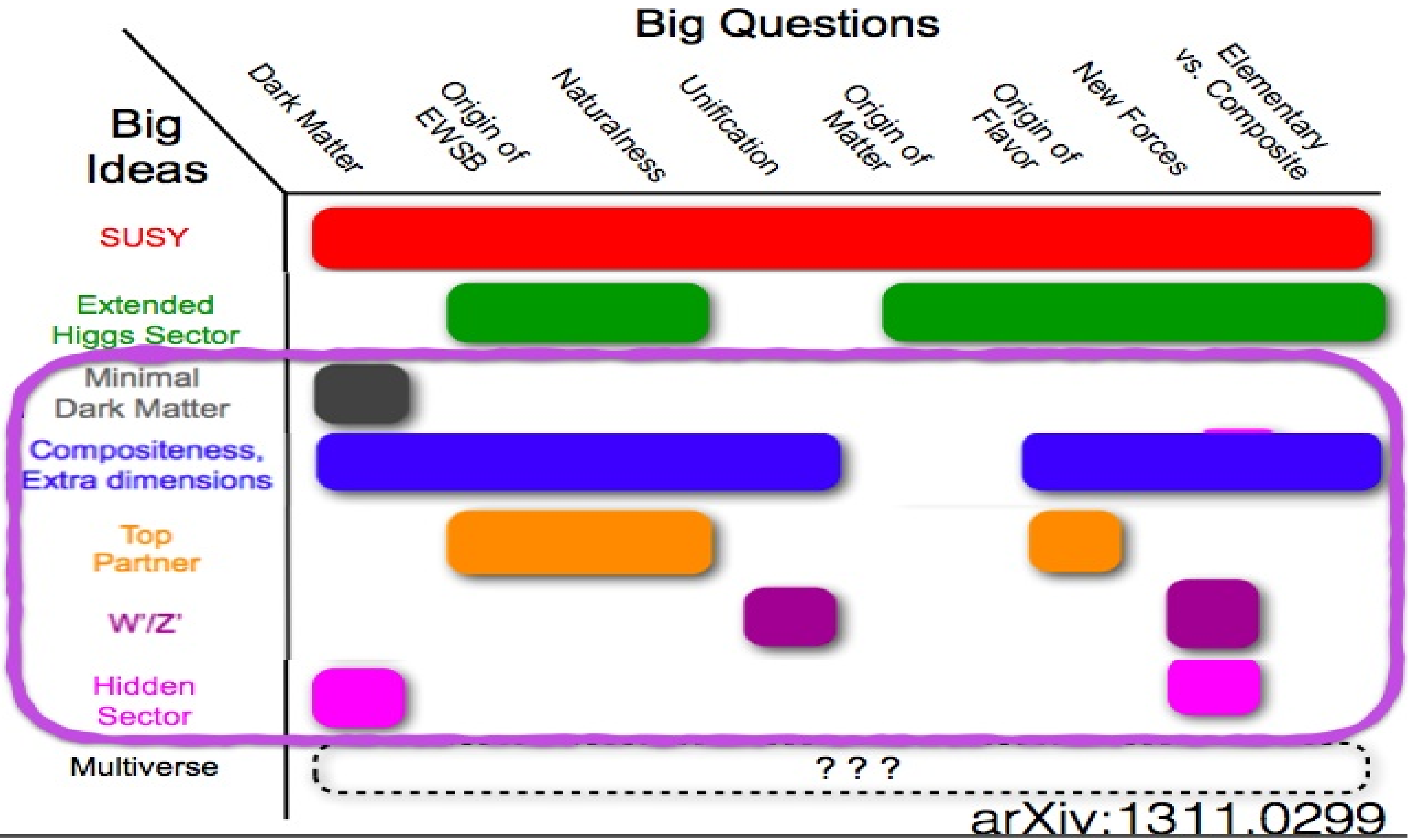
- We have direct evidence for the nonzero ν masses (Physics Nobel prize 2015)

- 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!

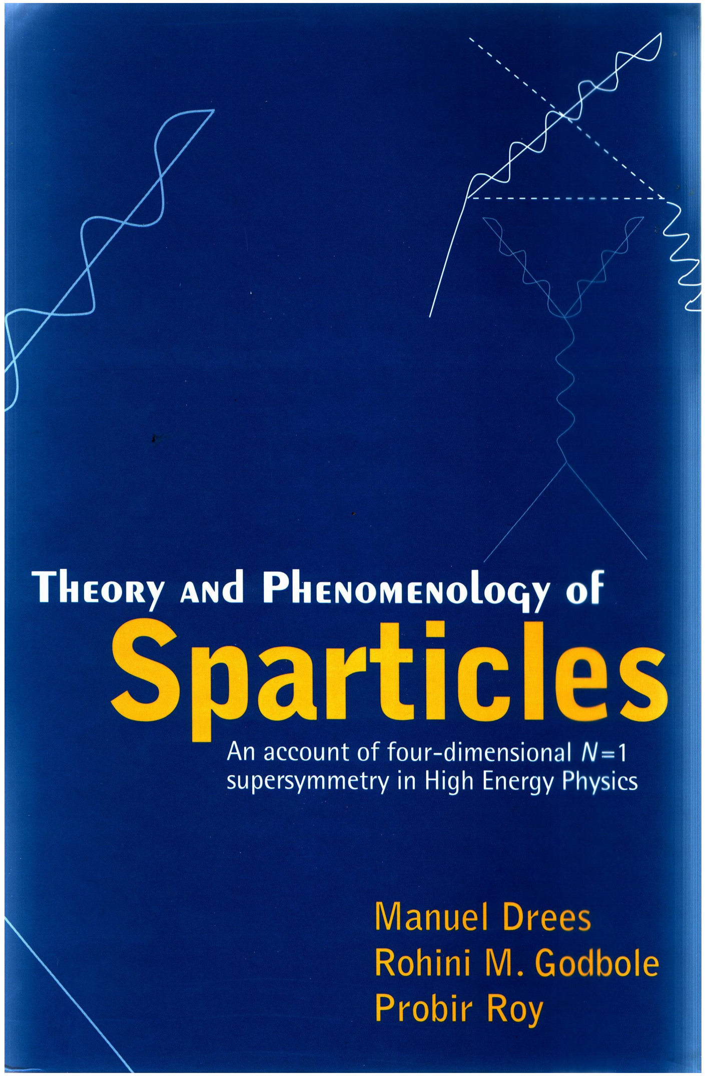
- Cosmic Acceleration.(Physics Nobel Prize 2011)


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.



A variety of mass generations:

1)Nonzero mass of the gauge boson: Spontaneous Symmetry Breakdown via the the celebrated Higgs Mechanism! Elegantly makes nonzero fermions masses also consistent with gauge invariance! The highly successful Standard Model!

2) Generation of the 'invisible' mass in the universe, picturesquely called the Dark Matter DM.

3) Mass of the Higgs boson itself! Why is it light?

4)However the masses are generated at the cost of many more free parameters of the SM. Even worse they span at least 15 orders of magnitude!. No real understanding of the generation of this hierarchy of masses! The non zero masses of neutrinos has even more additional facets. flavour issue

All these require BSM ideas!!

All the big questions gave rise to some big ideas!

Almost all of them indicated scale of physics to be TeV.

LHC results have constrained them!

Light Higgs AND NO BSM till now!

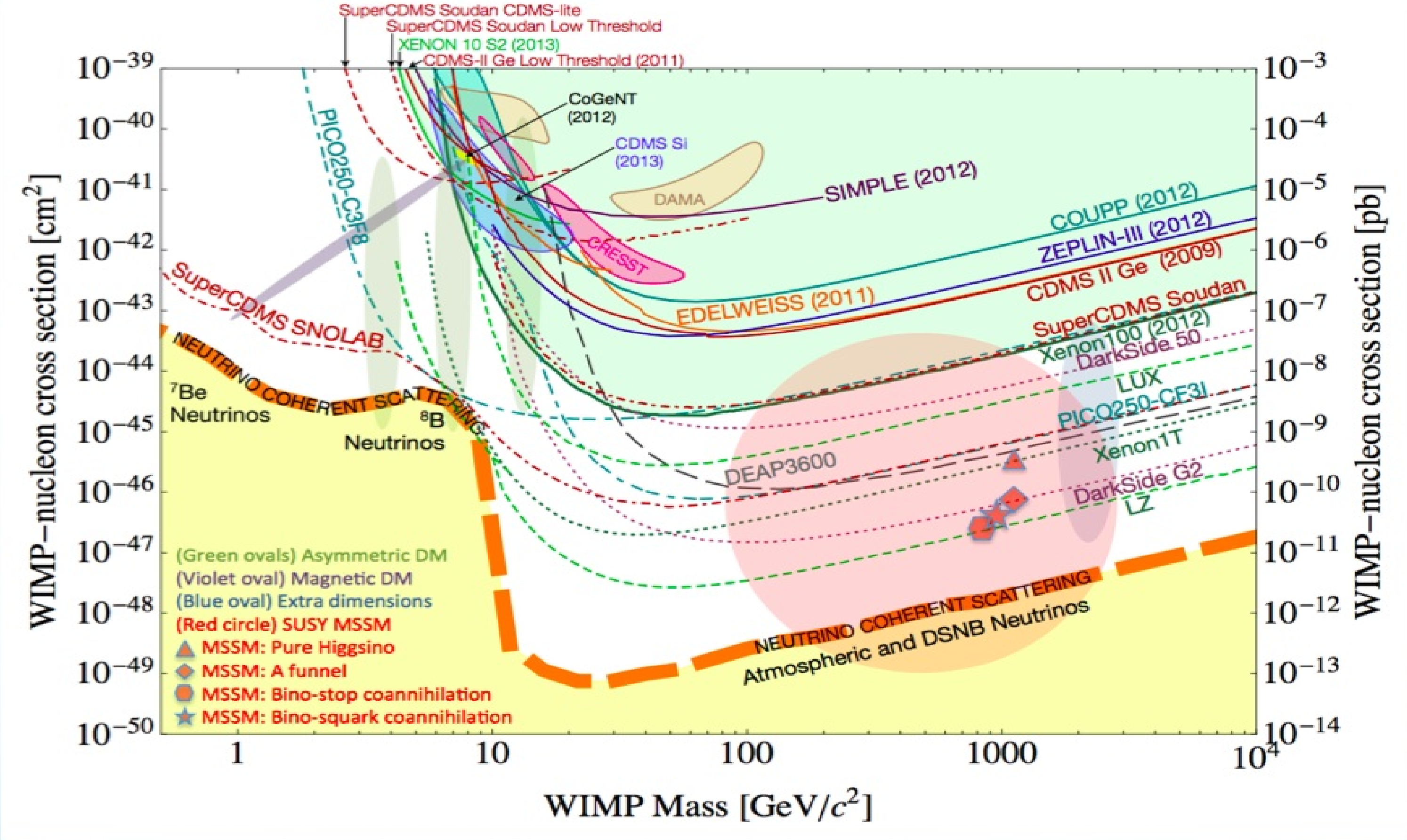
is challenging (for example) the 'hierarchy' folklore or 'fine tuning' folklore!

DM: Dark Matter

DM : the direct detection experiments and astrophysics both are challenging usual DM folklores just as much as LHC 'paradox' is challenging the 'hierarchy' folklore or 'fine tuning' folklore!

DM at the colliders is throwing out results that too we do not seem to understand! Are the results from direct detection and colliders compatible?

Does the DM have ANYTHING to do with particle physics?



1310.8327v2

Older result. Limits now pushed further down ☹

Are we at a cusp? Some people are asking the question whether it is time for a paradigm shift!

What is the way forward?

Important thing to note:

If the 'hypothetical particles' have masses much larger than the energies available, then one can not produce them directly but they can leave their footprints on the properties of known particles like Z/H, the t or the B-mesons.

That is one way forward!

Precision measurements provide a telescope to us in energy being probed.

Before taking this line further let us ask how did we reach here?

One way ahead has to be through a precision study of the the Higgs and the heavy flavour fermions t,b that the nature has provided us!

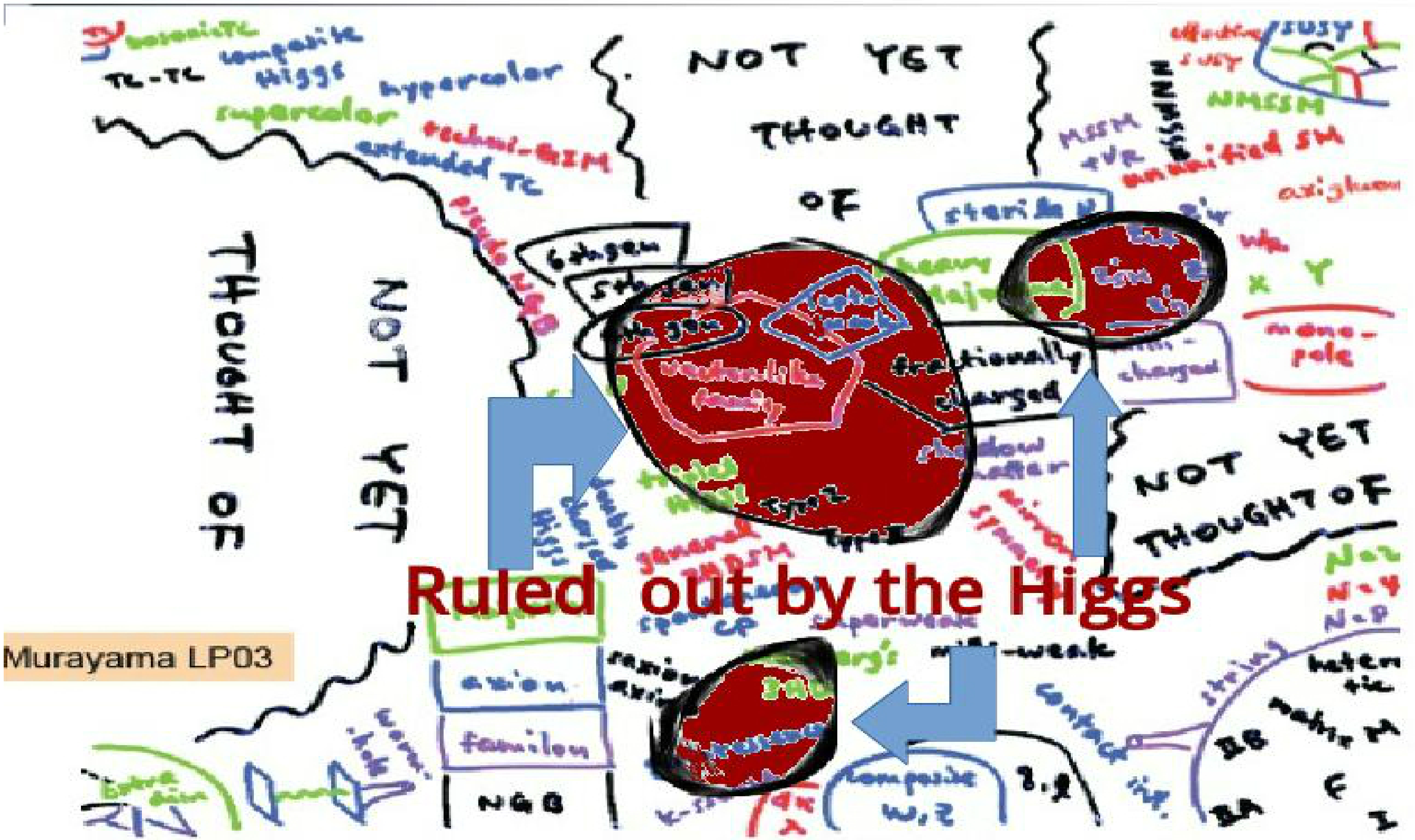
The mass and the couplings of this light state and top as well as physics of the B mesons, might be the window through which we can get a view of BSM at present!

Model independent analyses the best story of the day! (Data driven!)

Remember the SM started its life as an effective theory: Fermi's theory of β decay!

Peeping through the Higgs and the top/B-meson window!


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
6th gen
5th gen
4th gen
lepto quark
sterile ν
heavy Majorana
vector-like family
fractionally charged
milli-charged
mono-pole
S,T,U
NMSSM
MSSM
unified SM
effective SUSY
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
general 2HDSM
Type I
Type II
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
quintessence
composite W,Z
contact int.
string
matrix M
Extra dim
Murayama LP03


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
Ruled out by the Higgs
Murayama LP03
SUSY
NMSSM
hypercolor
supercolor
composite Higgs
extended TC
fractionally charged
axion
NGB
composite W, Z

Till now the path was theory drvien!

'Anticipating' the scale of BSM physics is a bit like anticipating the Higgs mass in the SM. We had no prediction for the Higgs mass, but then there were constraints from precision measurements which were given by comparison with predictions of established theory.

There was almost always a No-lose theorem!

Can we probe BSM like this: through the mass of the Higgs and through the Higgs couplings, through vacuum stability?

The 'Big Ideas' are many! Ideas like SUSY had (have) a lot of appeal! BUT NO DIRECT OBSERVATION SO FAR!

May be time has come for a new paradigm for collider physics!

To quote Michelangelo Mangano

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

BSM will appear ,most likely, as anomaly, as a 'blip' over SM processes!

Precision measurements require precision calculations!

Active and strong interaction between theorists and experimentalists essential!

"What principles determine its effects on other particles?"

(We almost know the answer!)

"How does it interact with neutrinos or with dark matter?"

"Is there one Higgs particle or many?"

"Is the Higgs really fundamental, or is it composed of others?" (We think we know the answer!)

At present we do not quite know the answer to the question 'Whither next'?

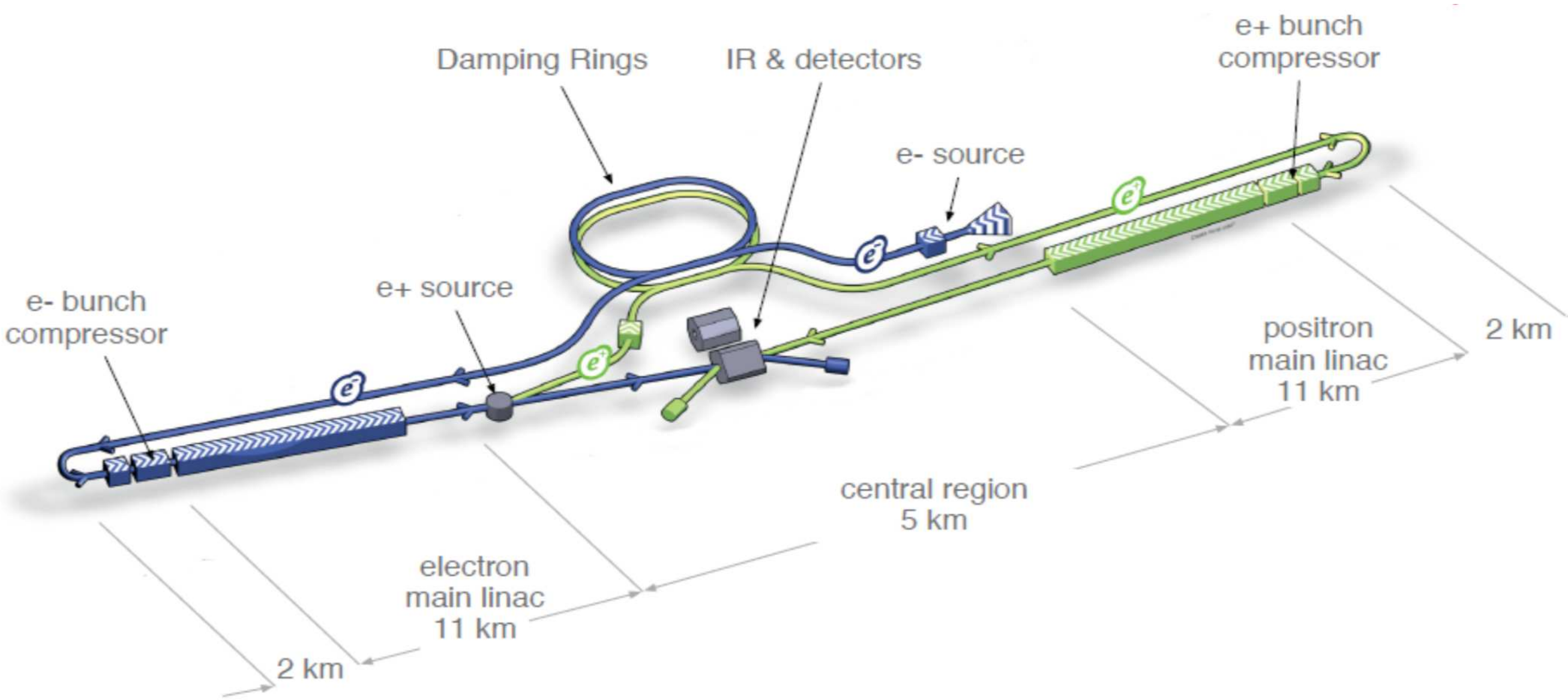
Following the 'discovery ' of the Higgs at the LHC, next logical step is to make precision studies of the properties of the Higgs.

Just like precision study of all the other particles in the SM gave information on the missing piece the Higgs, now one can learn about Beyond the SM(BSM) physics.

Can LHC offer high enough precision in the studies of the properties (mass, spin, parity) of the Higgs.

The energy scale for BSM seems to be high (initial LHC results) ☹

Historically baton has passed from hadronic to leptonic colliders and vice versa. So then may be it is the turn of high energy e^+e^- colliders.

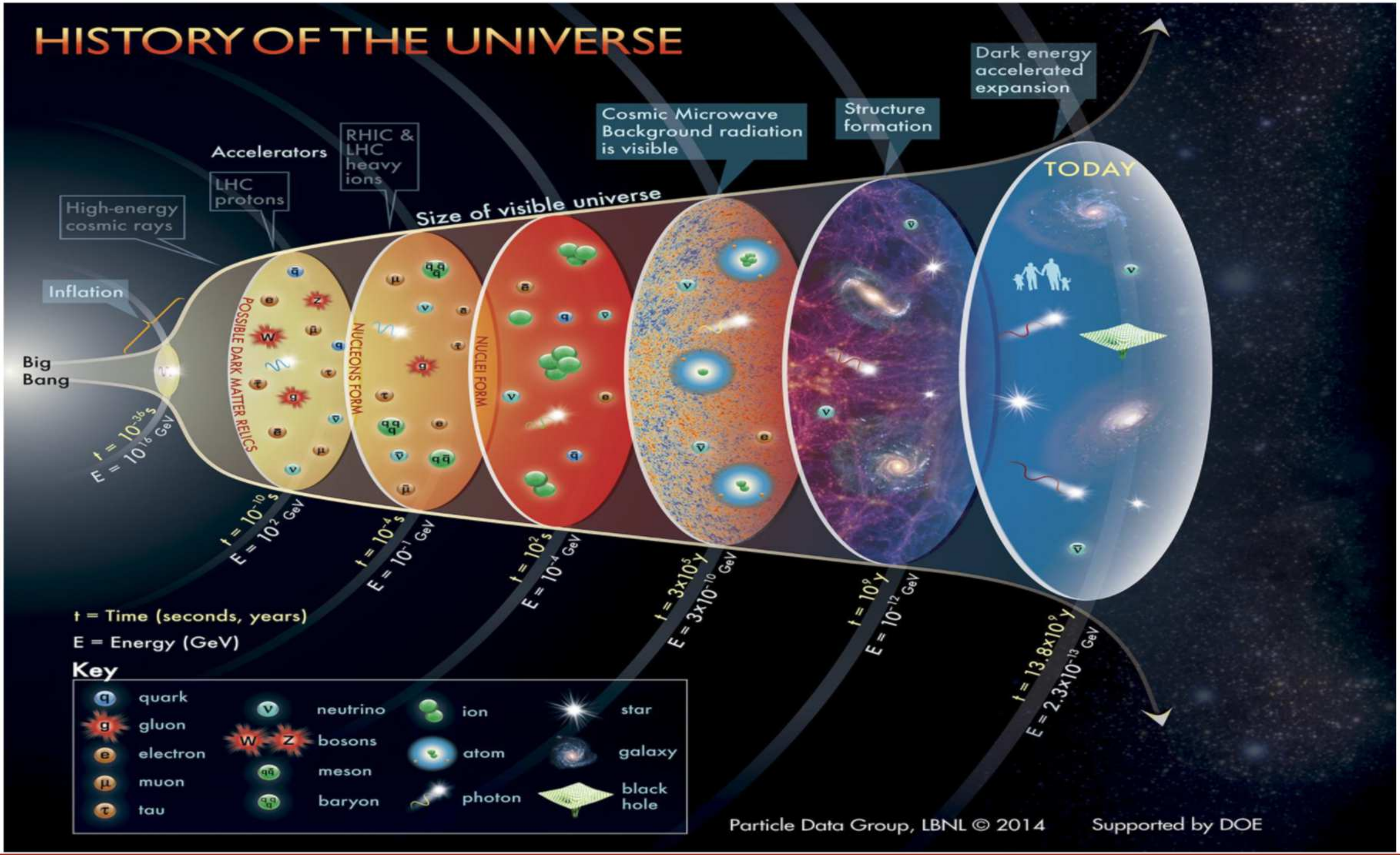


The International Linear Collide ILC : Higgs Factory (project being considered by the community)

Of course we can probe and study BSM on many fronts at the high intensity frontier!

Neutrino experiments, low energy but high precision experiments..that is a different road and a road which holds many promises!

India Based Neutrino Observatory: INO is one effort in that direction!


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

Connections with Cosmology : Some can be tested through precision measurements at the Colliders! for example the **Invisible branching ratio** of the Higgs.

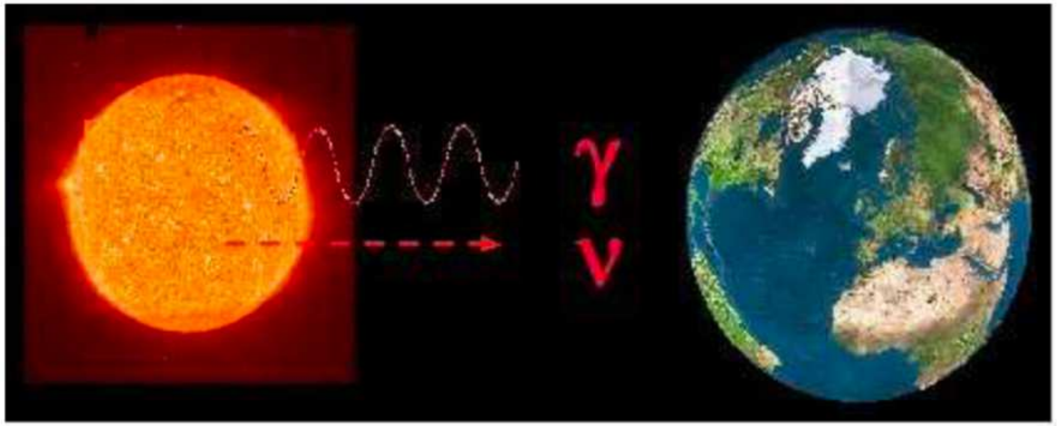
The Higgs mass and (in)stability of the Vacuum may say something about high scale physics and *MAY* have connections to some Planck Scale physics ideas!

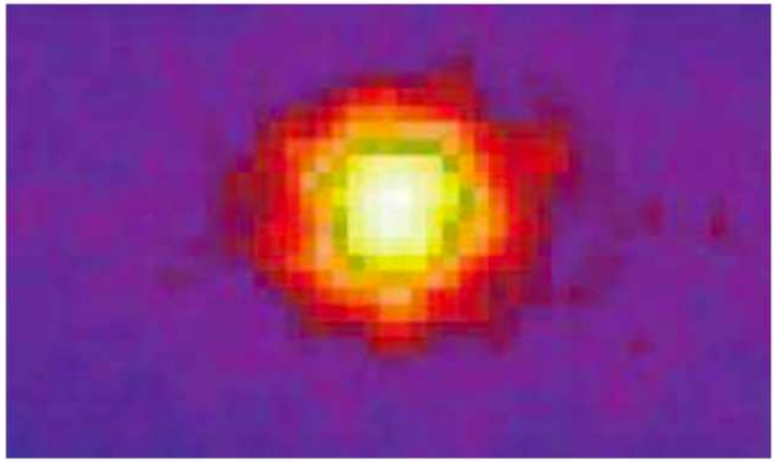
Gravitational Wave expts can probe physics in the early universe ! **LIGO India is important therein, so is GMRT**

The progress has to come through the joint investigations on the earth and in the sky!

We will probe the universe through difft. probes: the optical (Hanley), the radio (GMRT,SKA), Gravitational (LIGO),Neutrinos (Icecube, DUNE,INO) and colliders (LHC,ILC).

Example: Picture of sun through photons and through ν's:



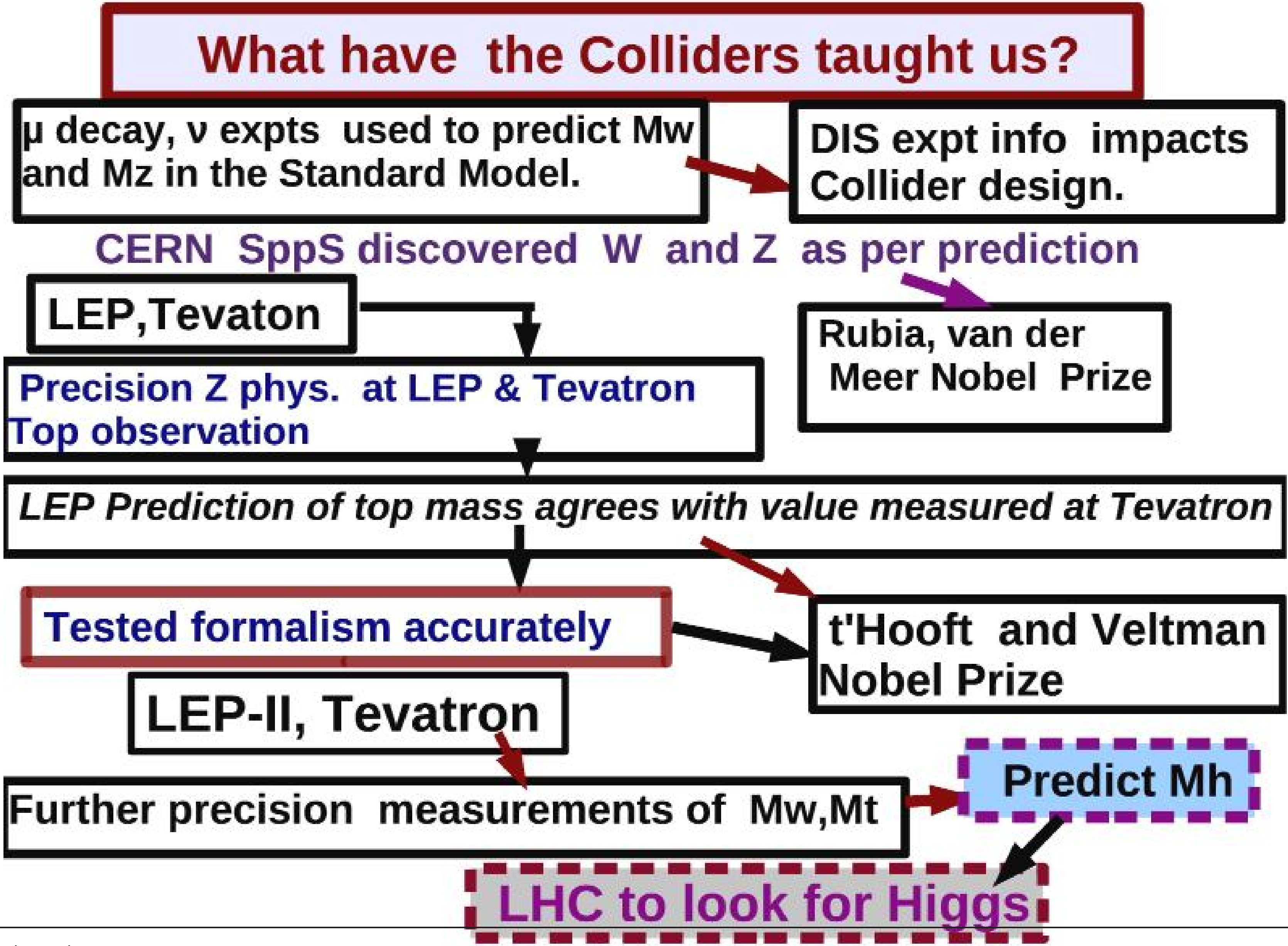


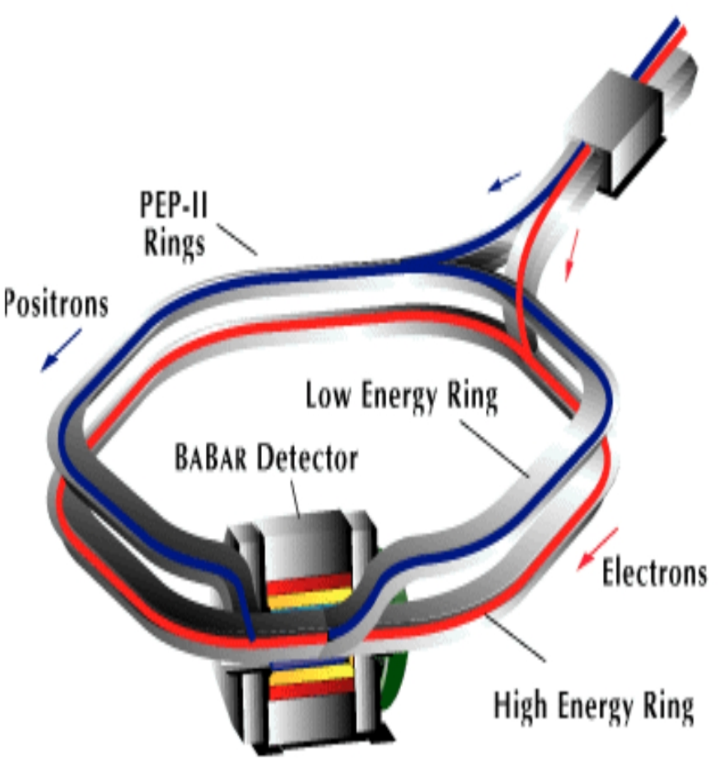
Particle physics will have to move on many fronts:

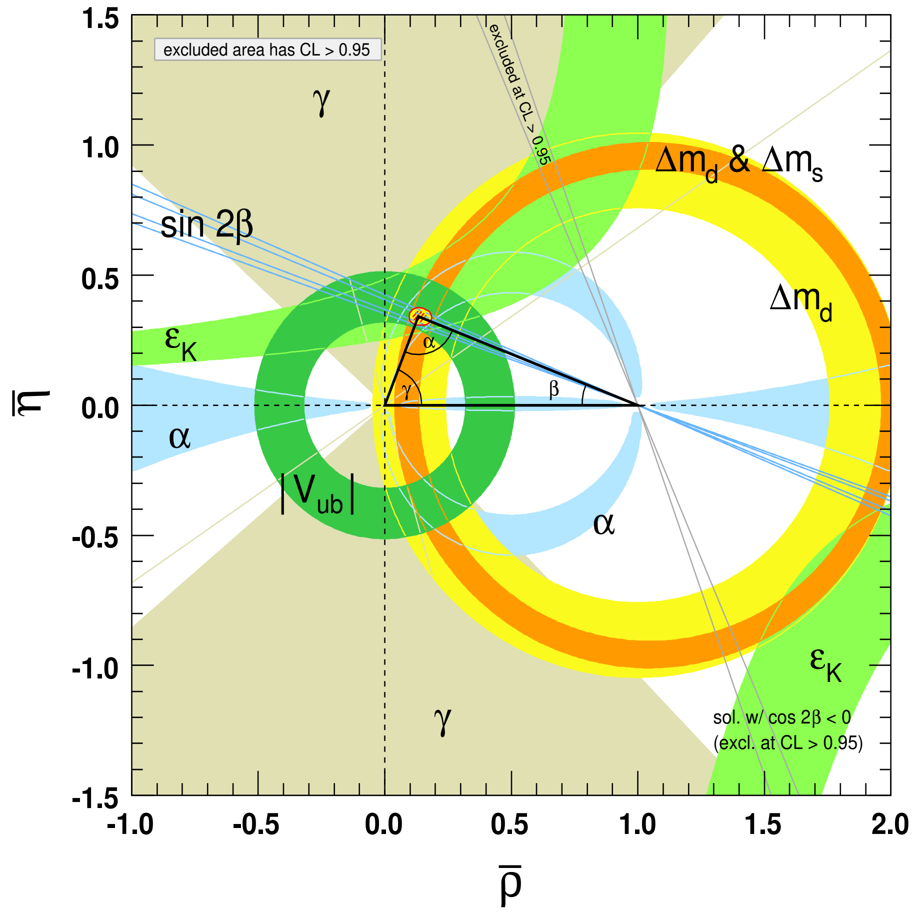
Colliders, Dark Matter detection, Neutrino experiments, Multiwave-length Astronomy.......

Path may be long but it leads to-wards light!

BACKUP!

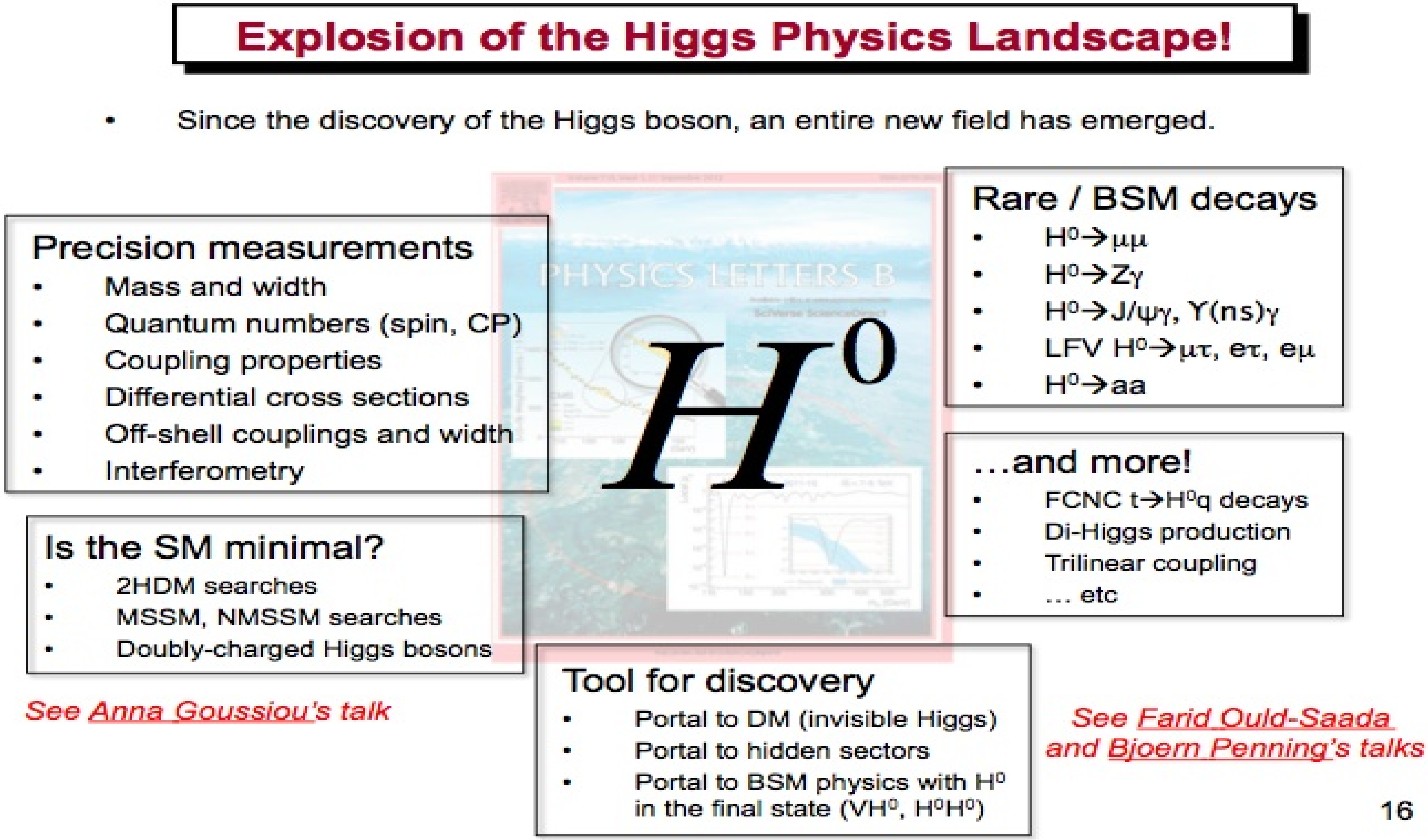

What have the Colliders taught us?
μ decay, ν expts used to predict Mw and Mz in the Standard Model.
DIS expt info impacts Collider design.
CERN SppS discovered W and Z as per prediction
LEP,Tevaton
Rubia, van der Meer Nobel Prize
Precision Z phys. at LEP & Tevatron
Top observation
LEP Prediction of top mass agrees with value measured at Tevatron
Tested formalism accurately
t'Hooft and Veltman Nobel Prize
LEP-II, Tevatron
Predict Mh
Further precision measurements of Mw,Mt
LHC to look for Higgs

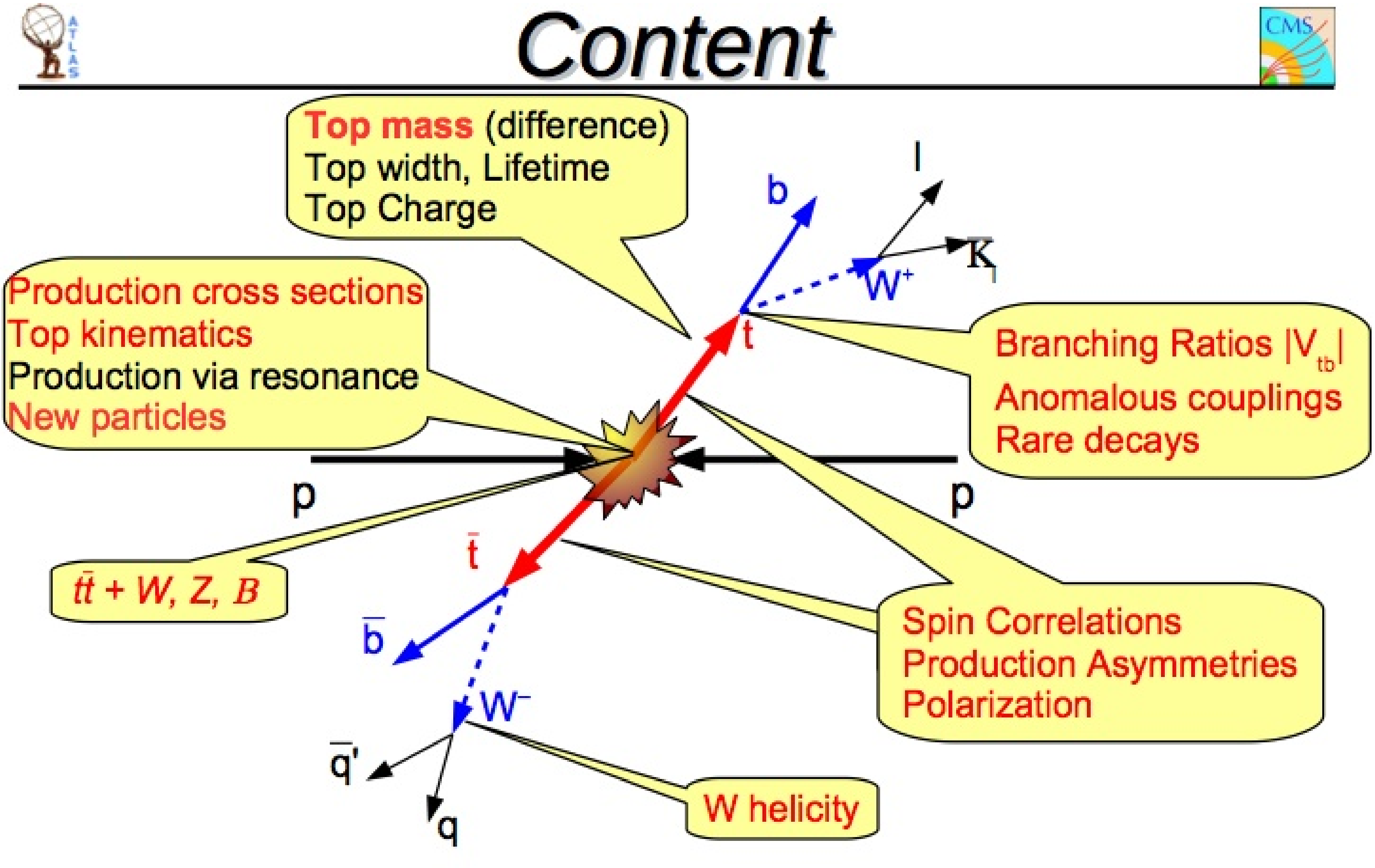




BABAR/BELLE/LHCb helped us get here!

Theory driven paths!


Explosion of the Higgs Physics Landscape!
• Since the discovery of the Higgs boson, an entire new field has emerged.
PHYSICS LETTERS B
H^0
Precision measurements
• Mass and width
• Quantum numbers (spin, CP)
• Coupling properties
• Differential cross sections
• Off-shell couplings and width
• Interferometry
Is the SM minimal?
• 2HDM searches
• MSSM, NMSSM searches
• Doubly-charged Higgs bosons
See Anna Goussiou's talk
Rare / BSM decays
• $H^0 \to \mu\mu$
• $H^0 \to Z\gamma$
• $H^0 \to J/\psi\gamma$, $\Upsilon(ns)\gamma$
• LFV $H^0 \to \mu\tau$, $e\tau$, $e\mu$
• $H^0 \to aa$
…and more!
• FCNC $t \to H^0 q$ decays
• Di-Higgs production
• Trilinear coupling
• … etc
Tool for discovery
• Portal to DM (invisible Higgs)
• Portal to hidden sectors
• Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)
See Farid Ould-Saada and Bjoern Penning's talks
16


Content
Top mass (difference)
Top width, Lifetime
Top Charge
Production cross sections
Top kinematics
Production via resonance
New particles
Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays
$t\bar{t}$ + W, Z, B
Spin Correlations
Production Asymmetries
Polarization
W helicity
b
l
W^+
t
p
p
$\bar{t}$
$\bar{b}$
W^-
$\bar{q}'$
q