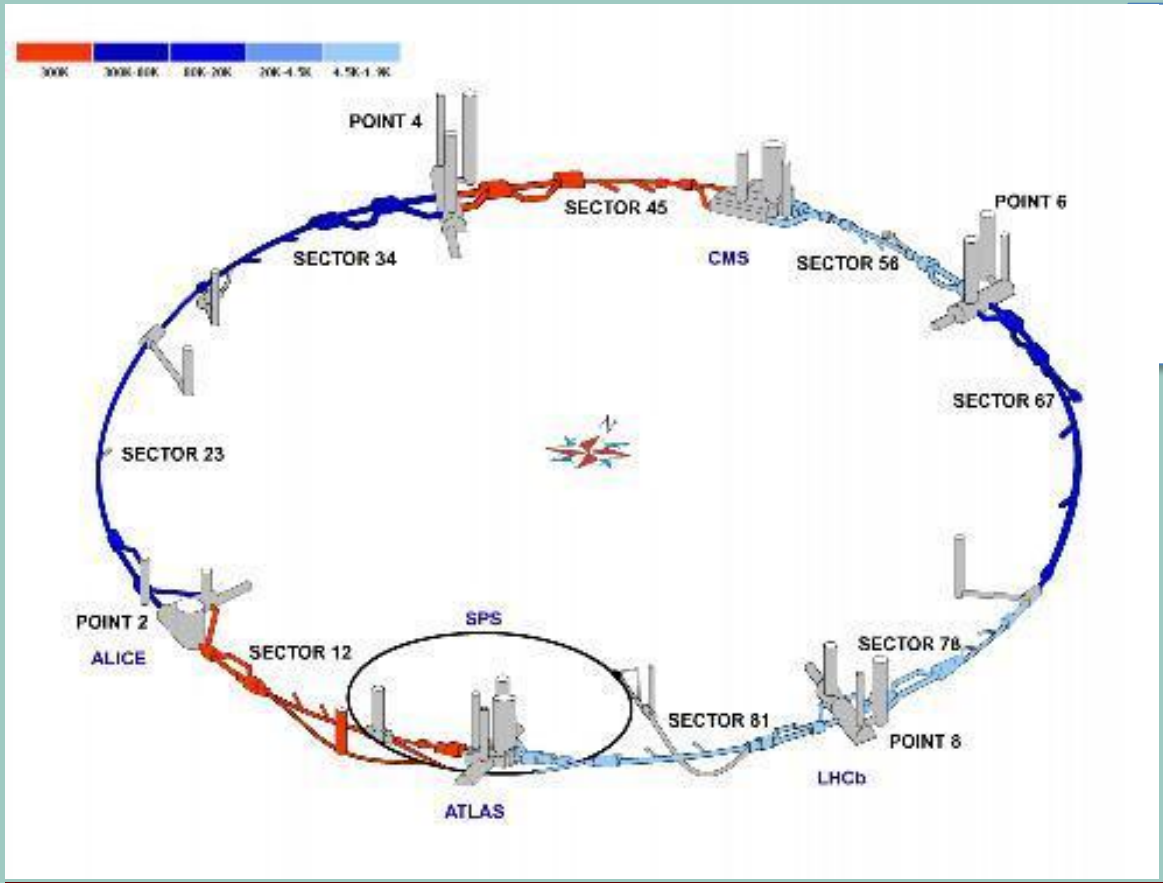

Physics Utrecht

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KAVLI IPMU

The Large Hadron Collider, and New Avenues in Elementary Particle Physics

Gerard 't Hooft,

Public Lecture,

IPMU Tokyo, April 16, 2015

CERN

European Center for Nuclear Research

LHC

Large Hadron Collider

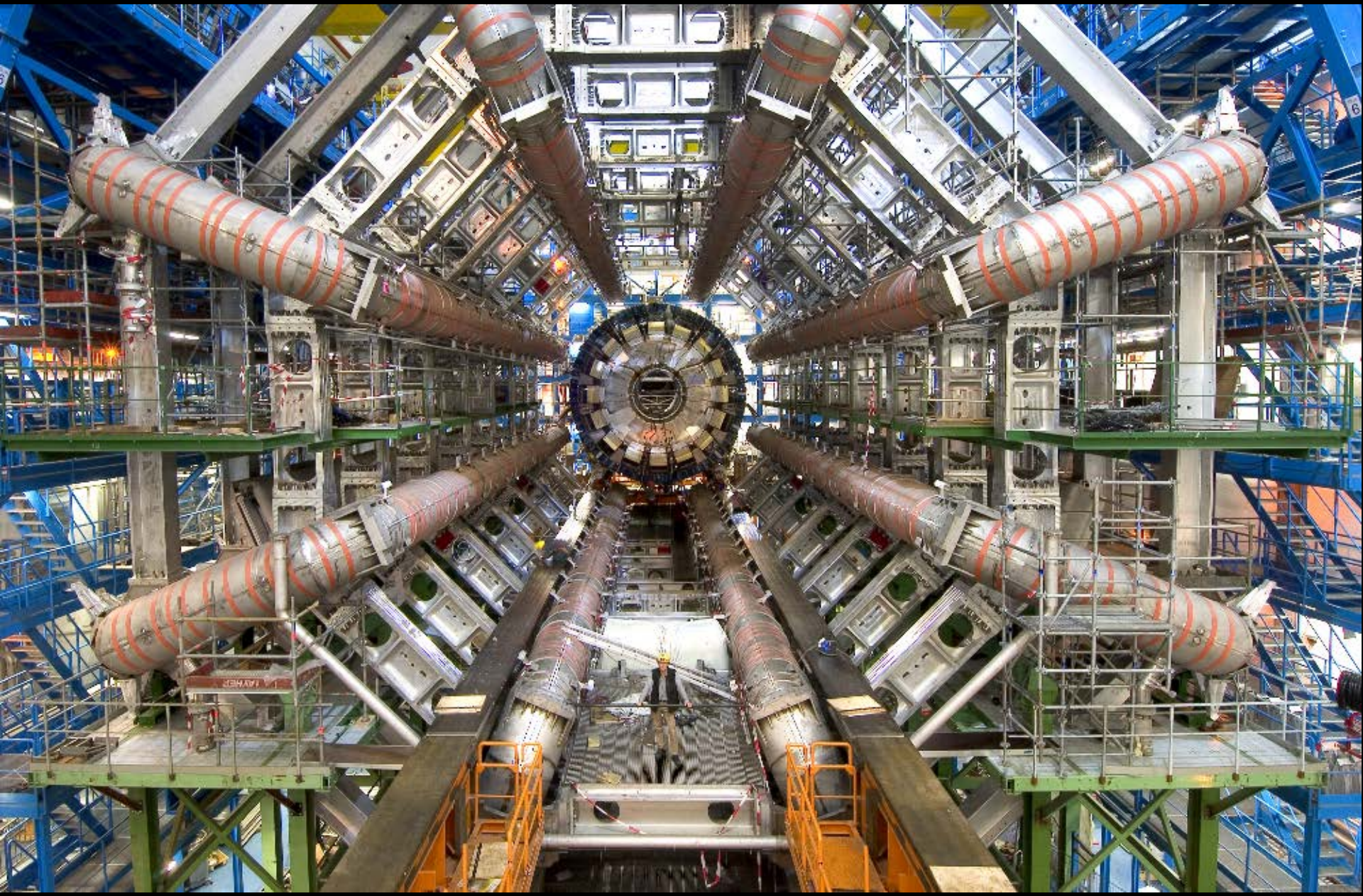
This machine
MICROSCOPE

is the strongest
in the world

Large Hadron Collider, Geneva: 7 + 7 TeV collisions

$p + p$

The Atlas Detector



- The accelerator has nearly 10,000 superconducting magnets; main dipoles weigh 35 tons, 15 meters long.

- The magnets are cooled by 130 tons of helium held at 1.9 and 4.2 K

- The accelerator contains about 15,000 MegaJoules of magnetic energy

- 1200 tons of Nb-Ti superconducting cables were used to wind the magnets

- There is a 0.01% variation in field quality among the 1232 main dipole magnets

One of the first assignments for this machine:

"Find the ***Higgs*** *particle*"

Why do we want such a particle?
What does it have to do with the masses of the other particles?

Why is it called "God Particle" ?

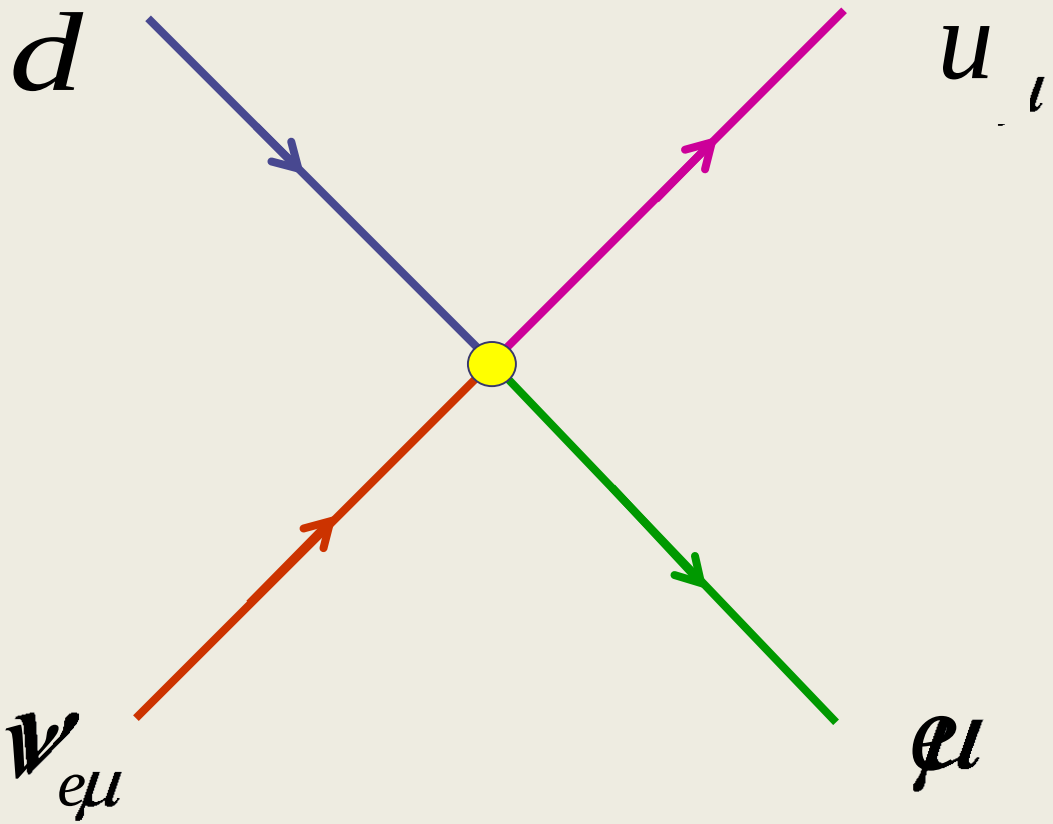
The story is more complicated
– and much more interesting ! – than the religious story

The Higgs particle is a product of ***theory*** !

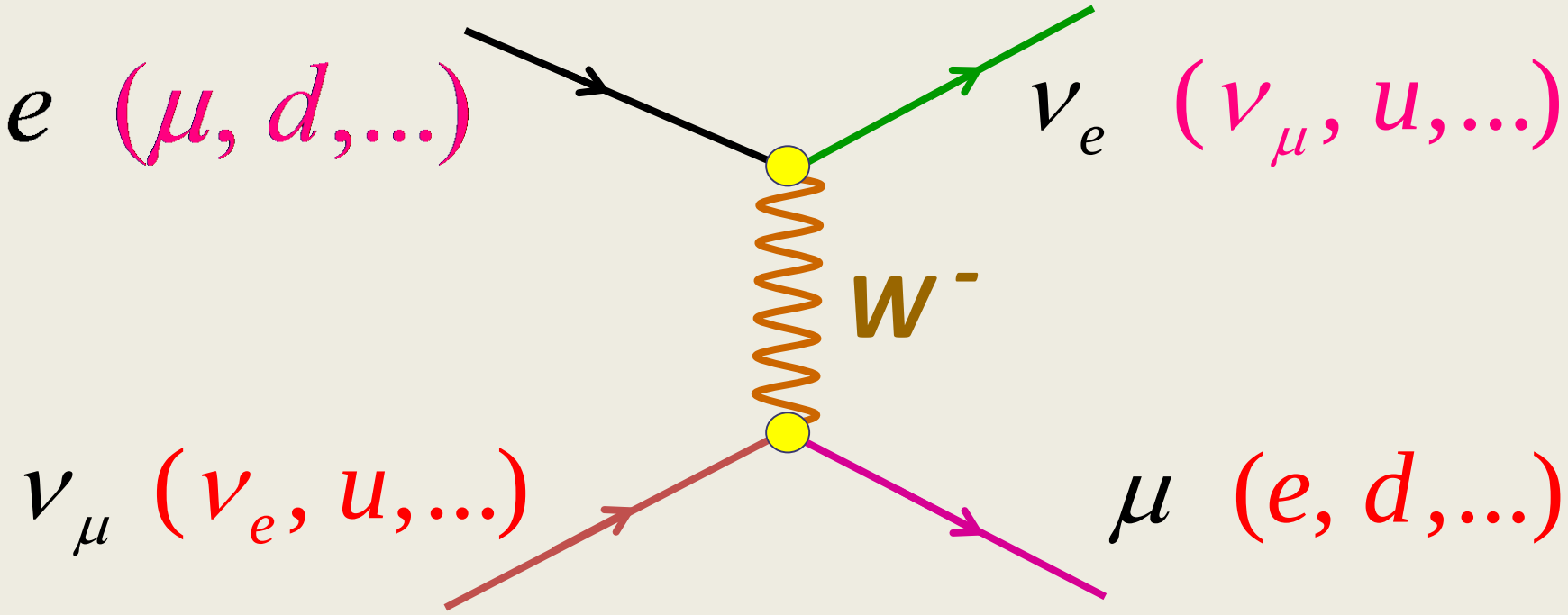
A brief history

The Weak Force

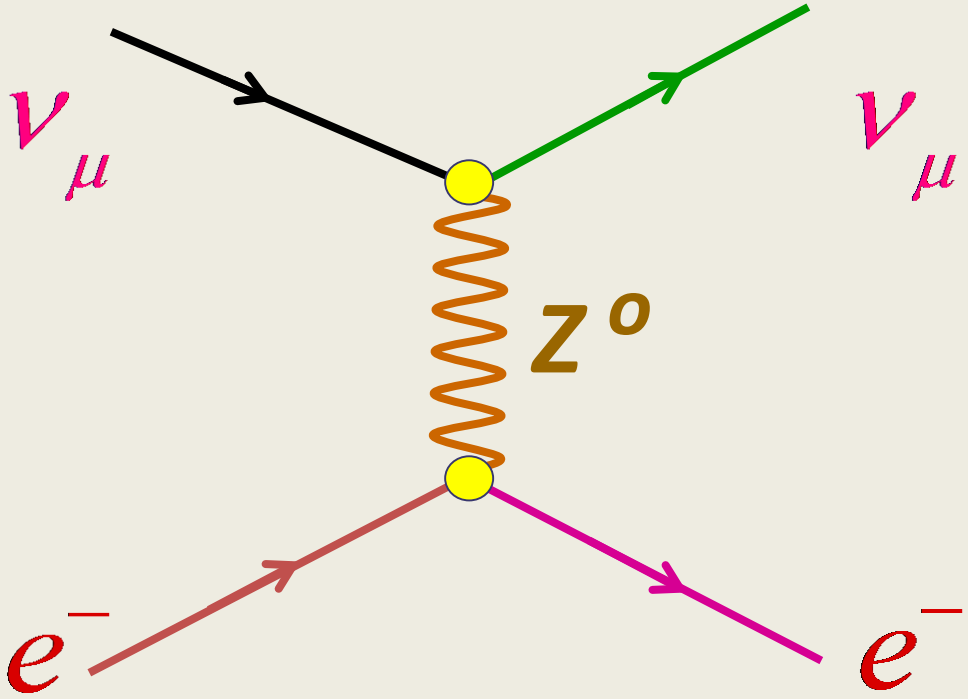
the fundamental FERMI interaction:



The
INTERMEDIATE VECTOR BOSON

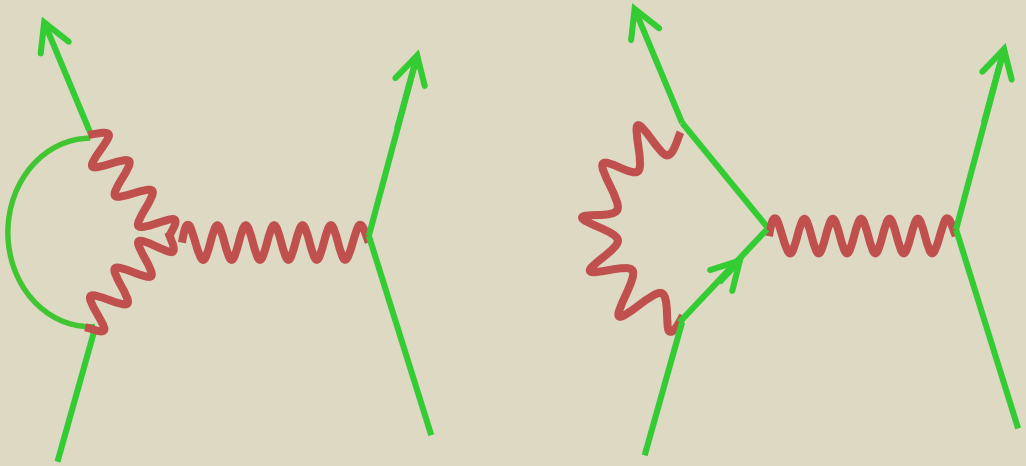


The
NEUTRAL COMPONENT



1968: attempts to calculate more subtle effects failed.

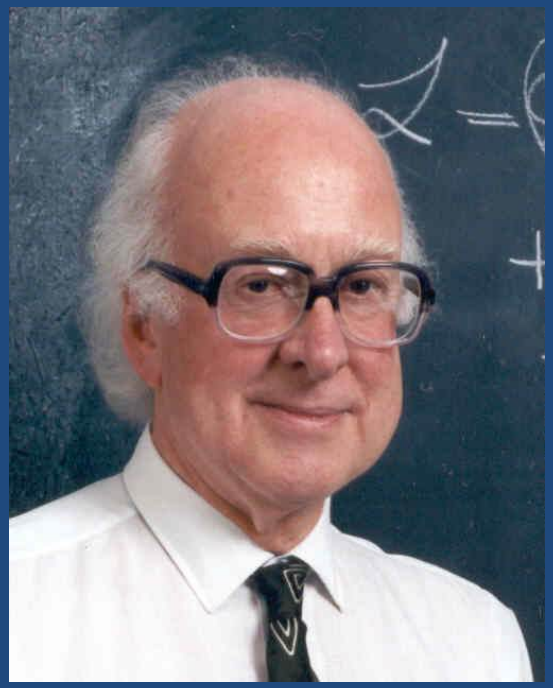
The theory was not yet right …



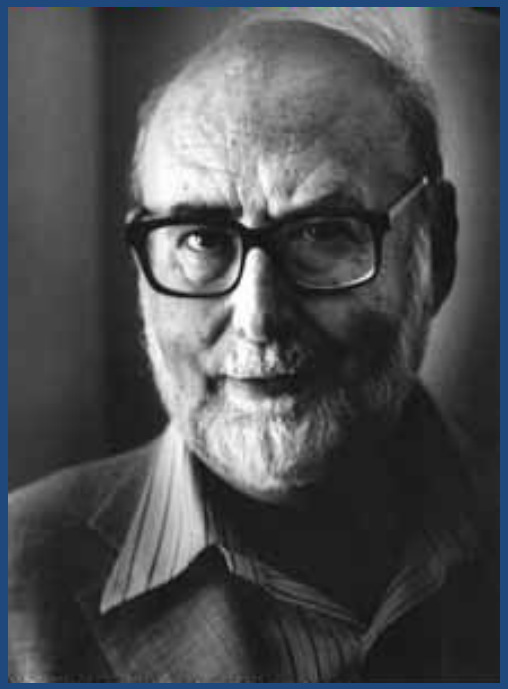
M. Veltman

These interactions seemed to be infinitely strong!

To do it right, more was needed. We had to understand how to accommodate for particles with mass, and how to break the *Left – right symmetry*



Peter Higgs



Fr. Englert

Robert Brout

proposed *Spontaneous Symmetry Breaking*

Complete symmetry ➔ particles without mass

Spontaneous symmetry breaking gives mass.

The "vacuum" is saturated with 'Higgs particles' ….

But they must also appear as *detectable* particles …

The Standard Model

leptons quarks gluons

τ-neutrino top

III

tau bottom

μ-neutrino charm

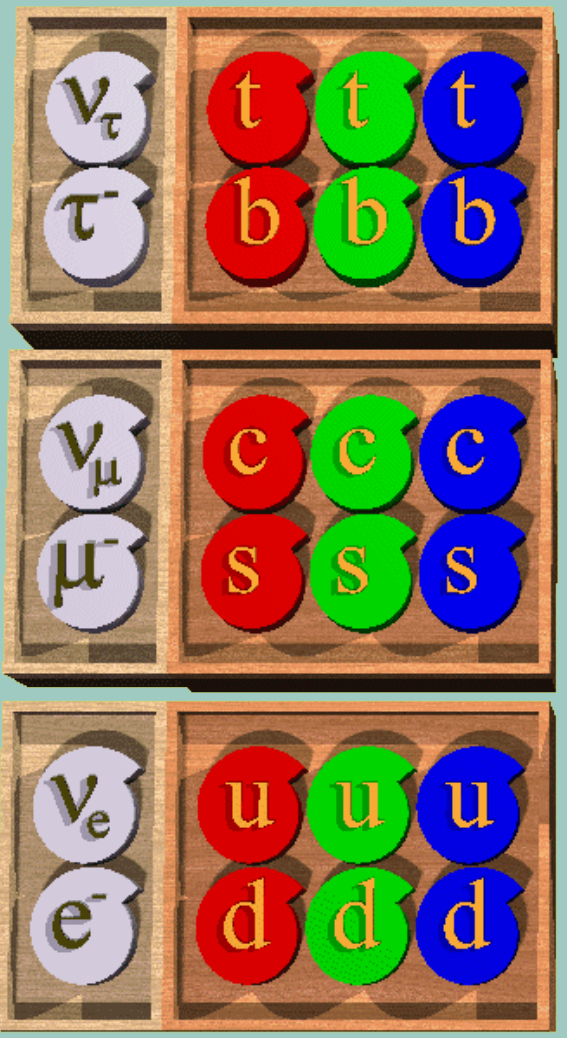
II

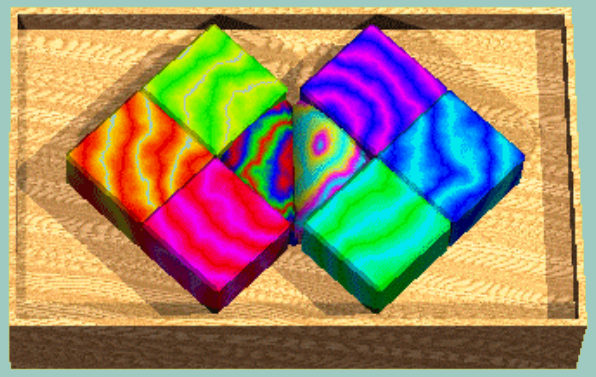
tau strange

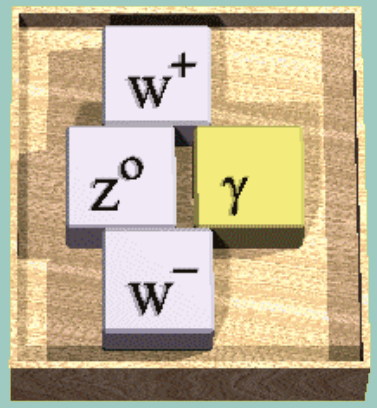
e-neutrino up

I

electron down



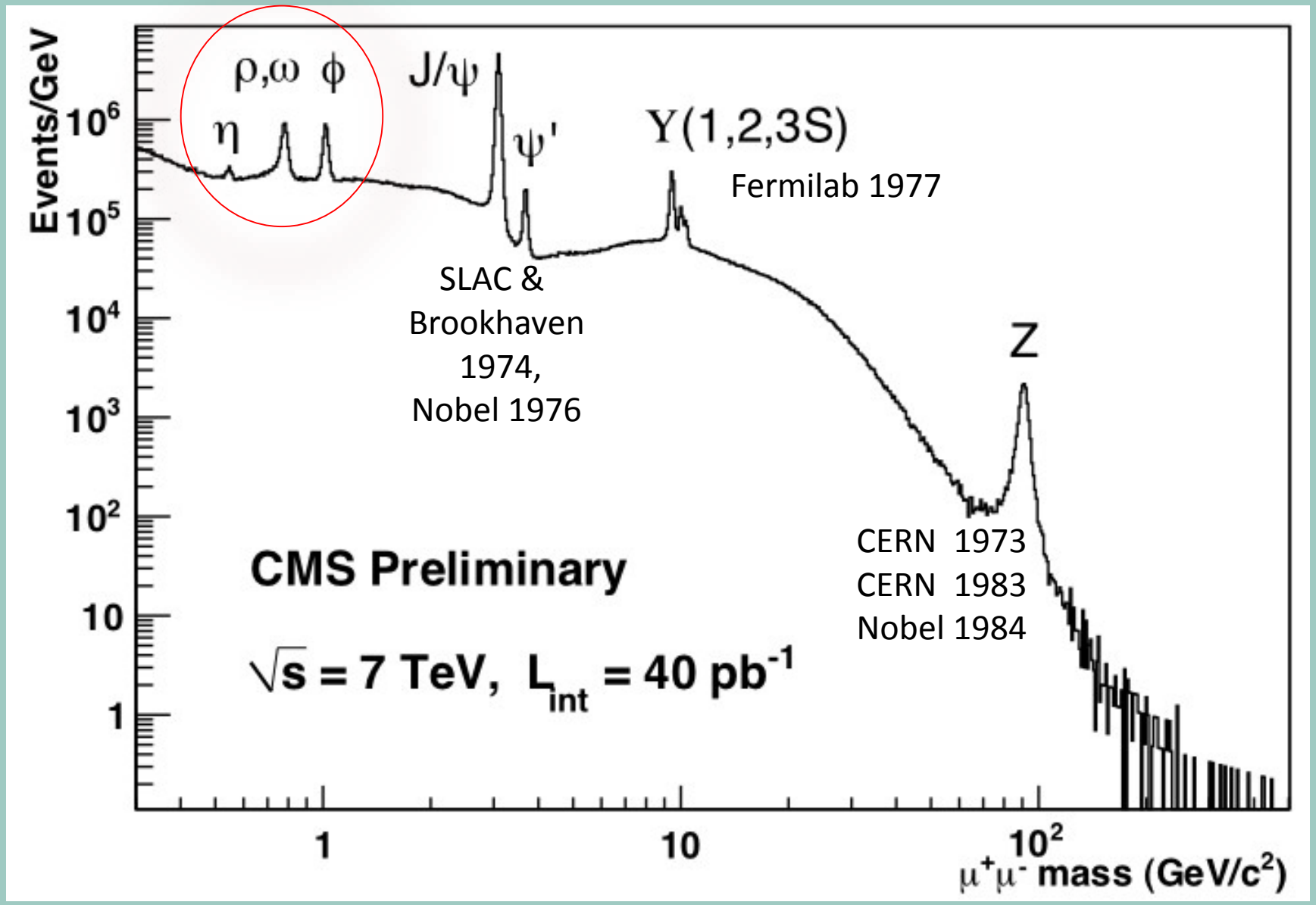


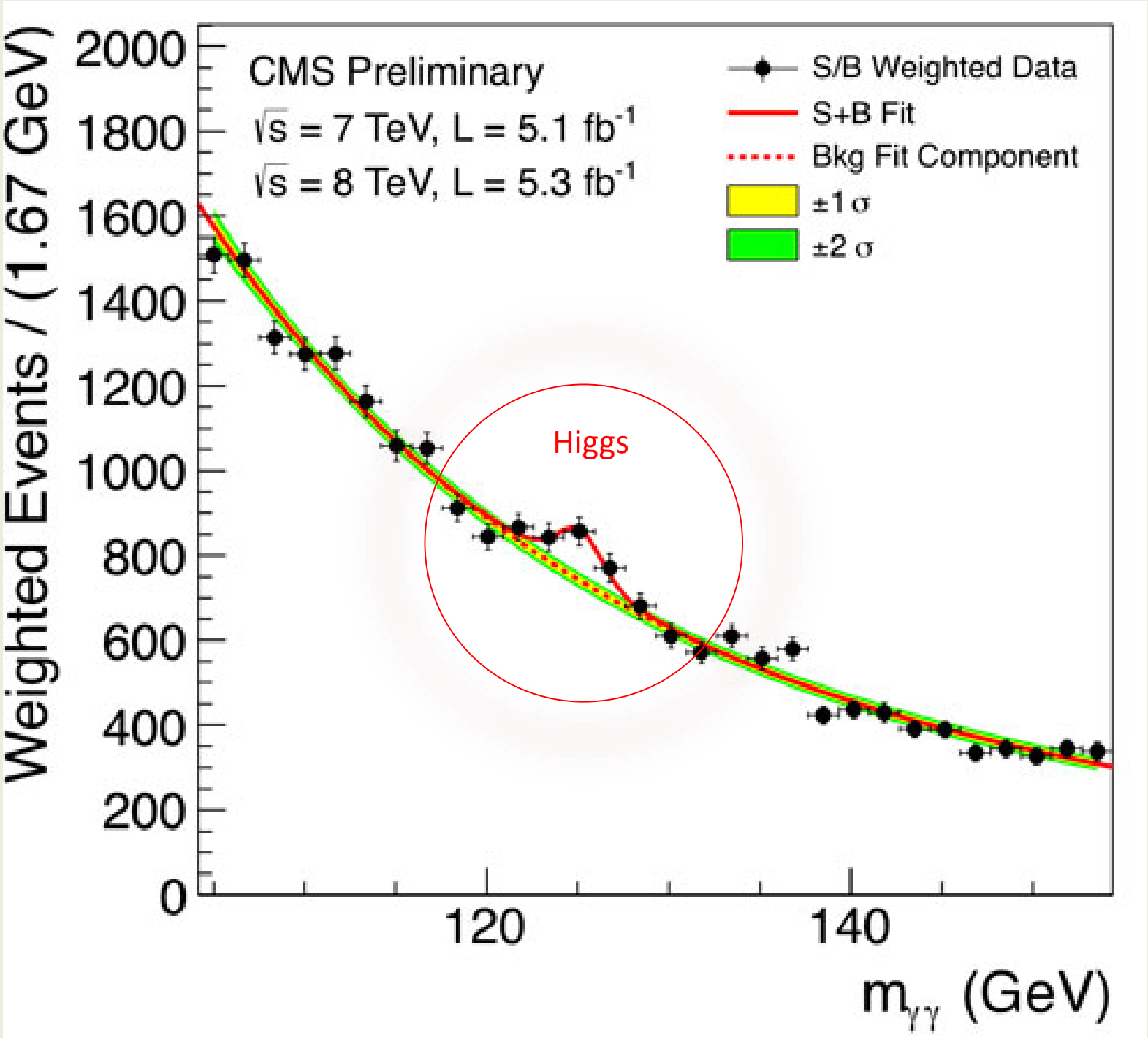


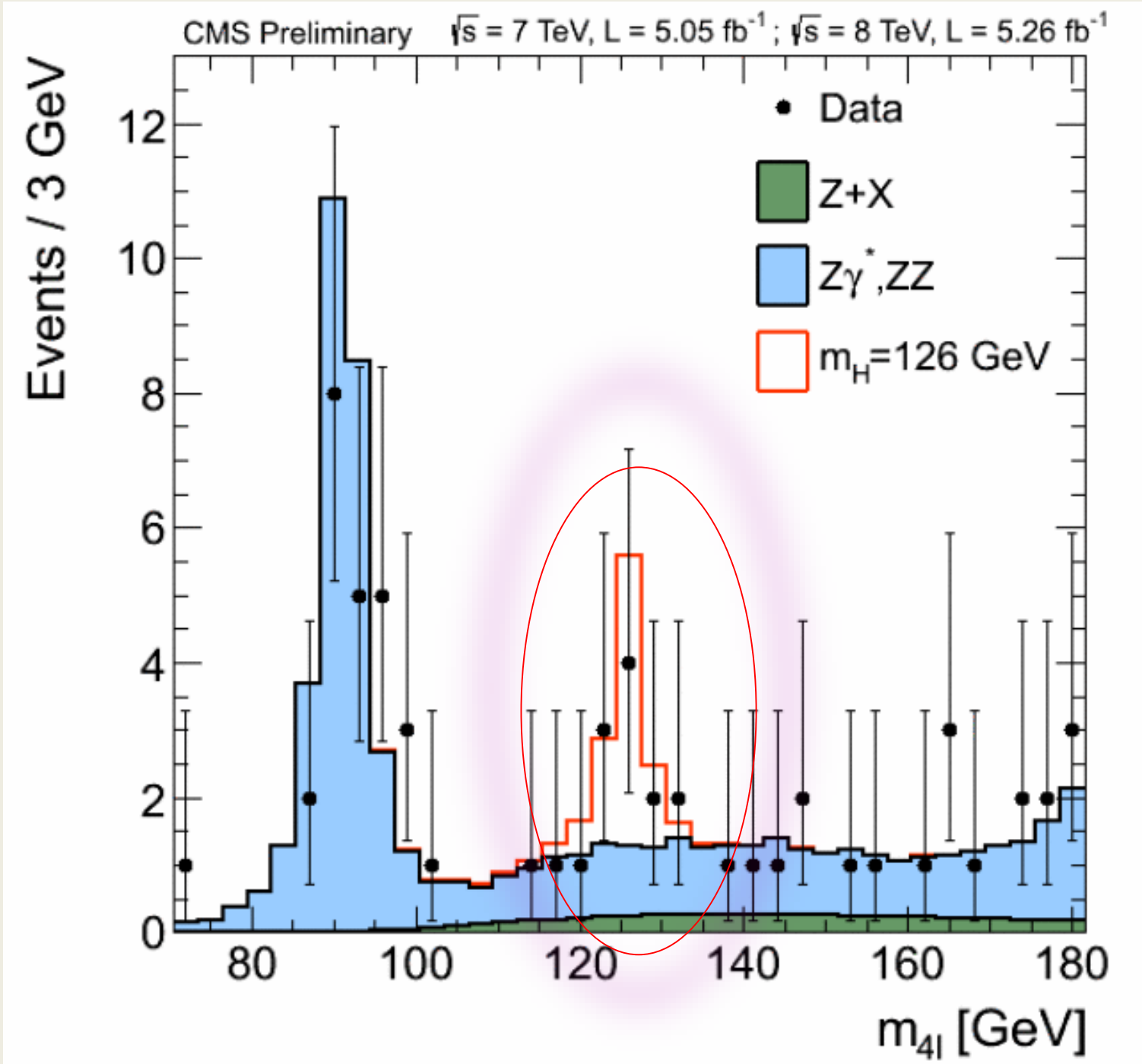
Higgs

Weak and electro-magnetic

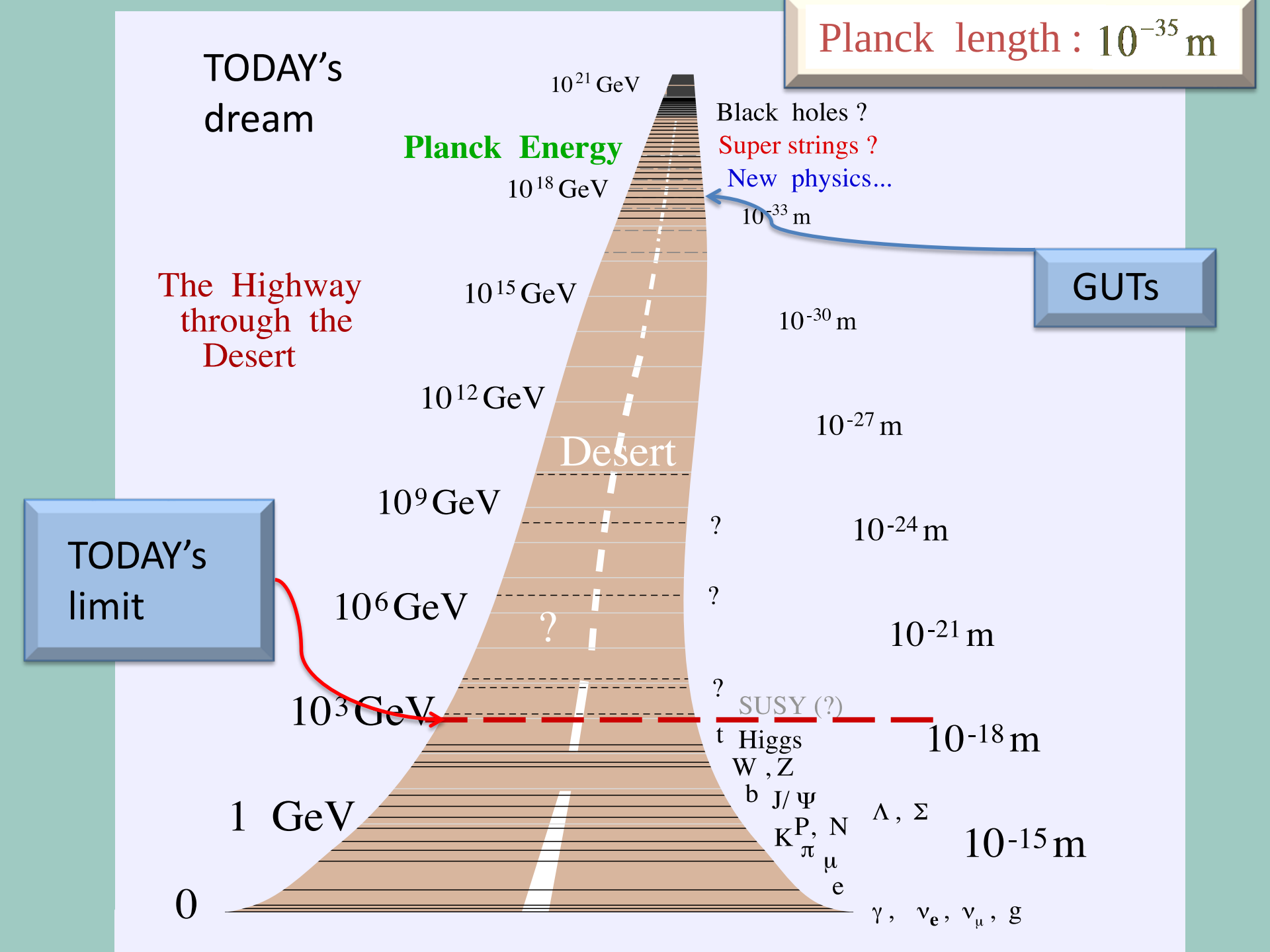
LHC (2012) reproduces past history of discoveries:



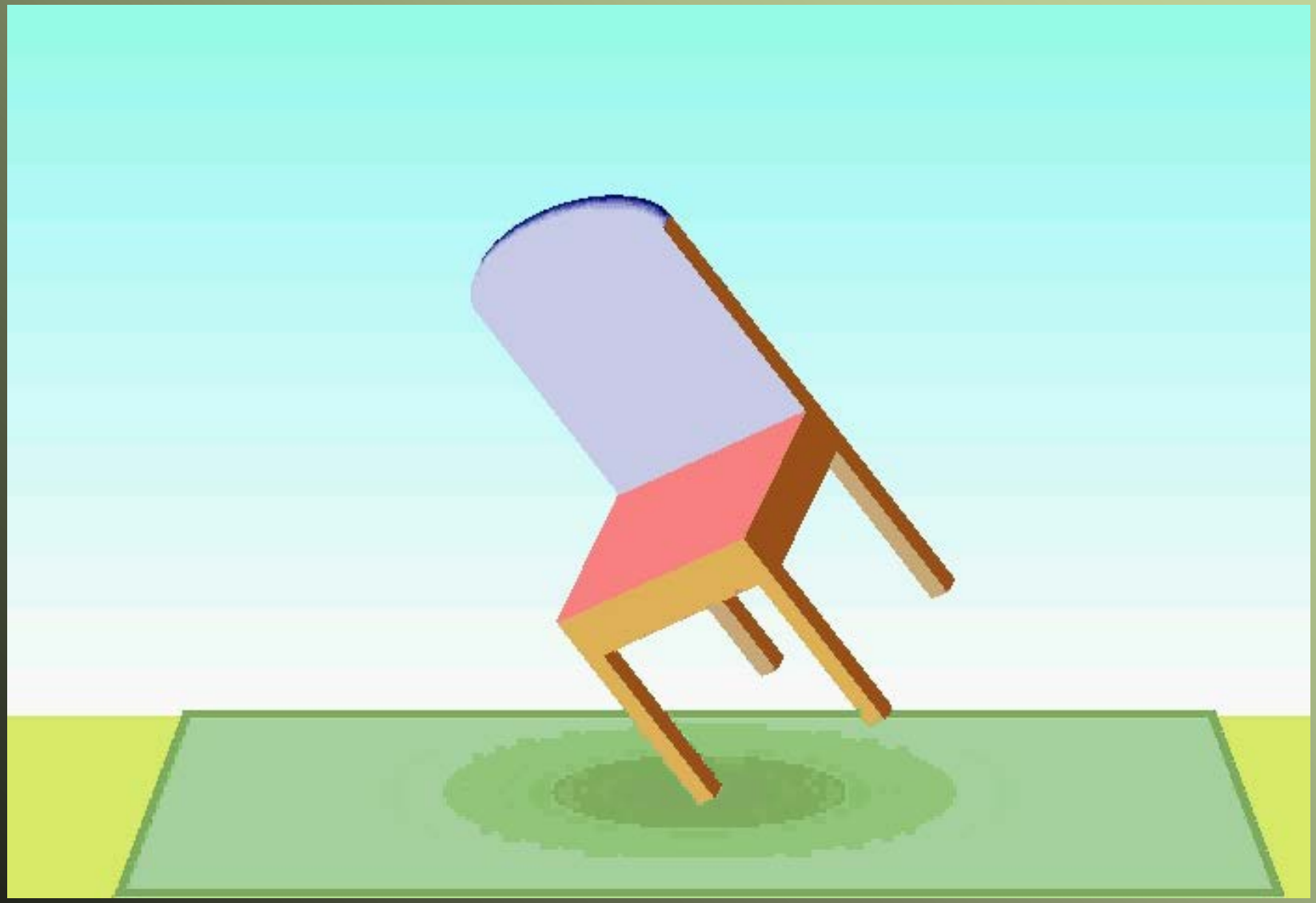

CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Higgs
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)


CMS Preliminary
√s = 7 TeV, L = 5.05 fb-1 ; √s = 8 TeV, L = 5.26 fb-1
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
0
2
4
6
8
10
12
80
100
120
140
160
180
m4l [GeV]

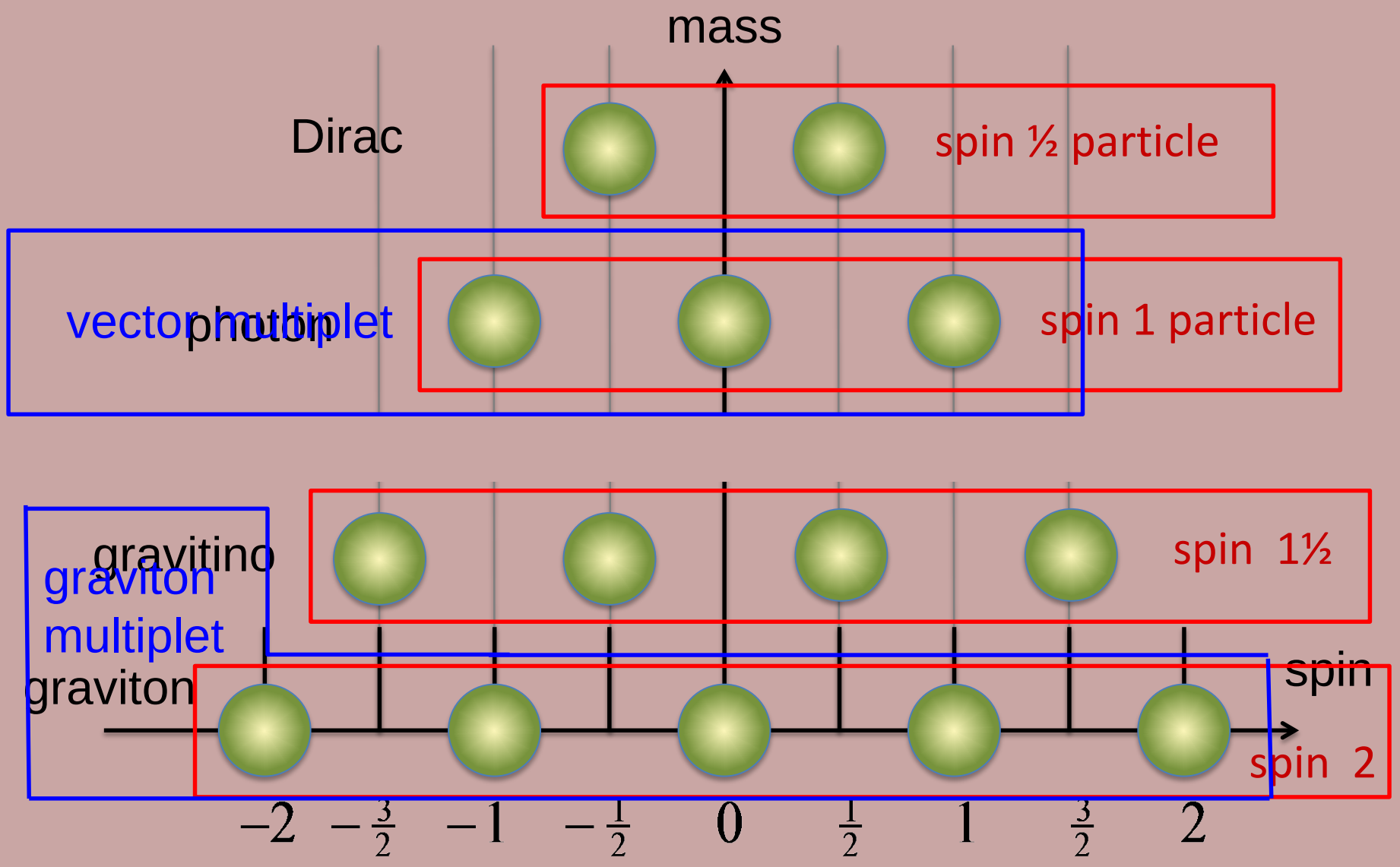
July 4 2012 Higgs discovery


Planck length : 10^{-35} m
TODAY's dream
10^{21} GeV
Planck Energy
Black holes ?
Super strings ?
New physics...
10^{18} GeV
10^{-33} m
GUTs
The Highway through the Desert
10^{15} GeV
10^{-30} m
10^{12} GeV
10^{-27} m
Desert
10^{9} GeV
?
10^{-24} m
TODAY's limit
10^{6} GeV
?
?
10^{-21} m
?
10^{3} GeV
SUSY (?)
t
Higgs
W , Z
10^{-18} m
b
J/ Ψ
1 GeV
Λ , Σ
K
P, N
π
μ
10^{-15} m
e
0
γ , ν_e , ν_μ , g

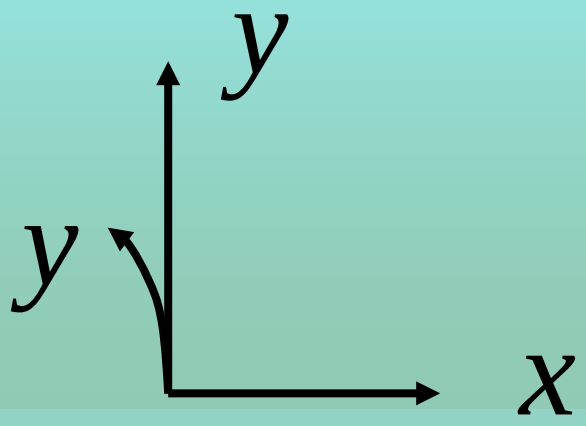
When applied to the smallest particles,
the Standard Model becomes **unnatural**



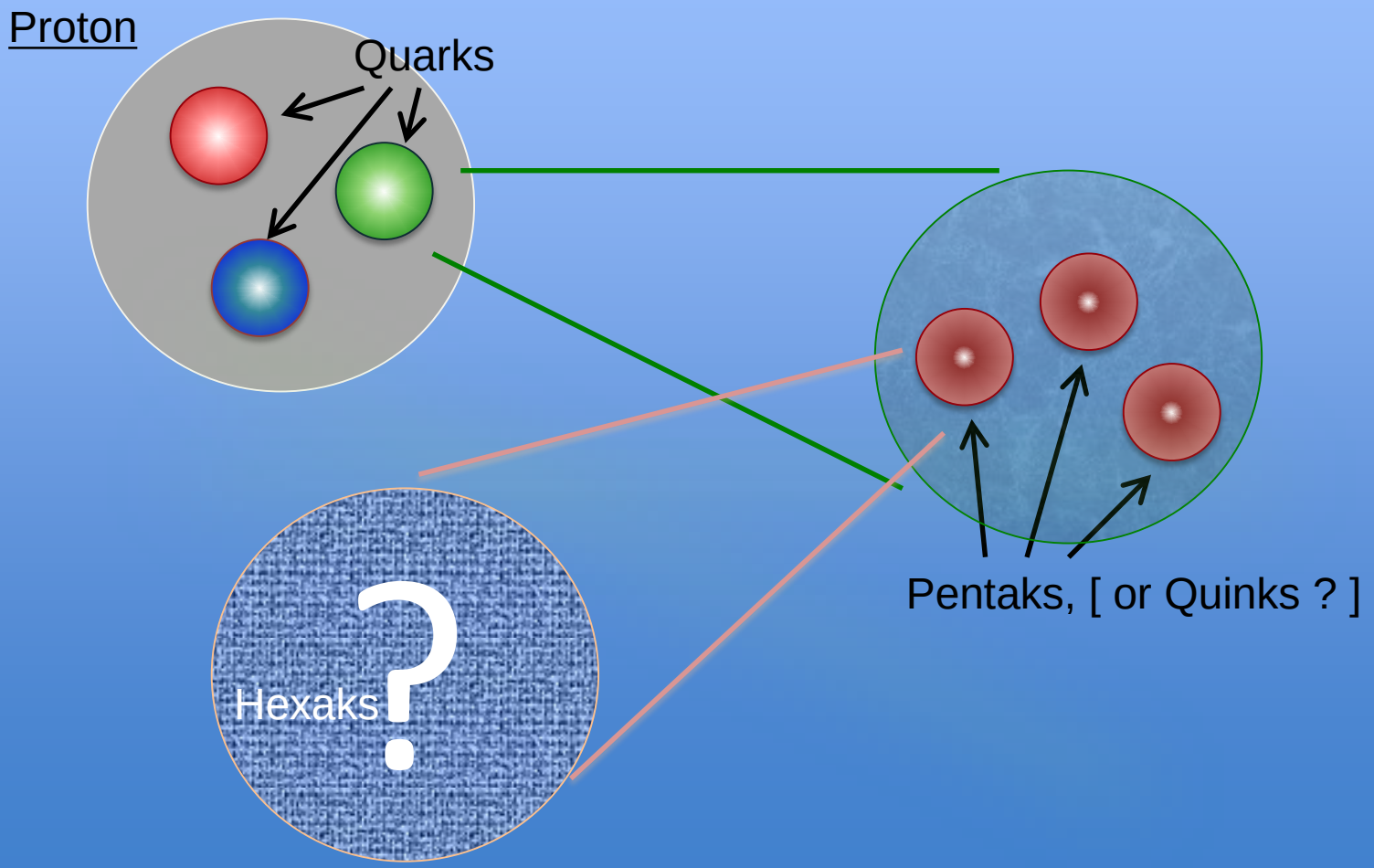
Supersymmetry: an entirely new view on space and time would be the biggest modification since Einstein 1916



Extra Dimensions



“New smaller bulding blocks ? Compositeness ?



Problems with the compositeness idea:

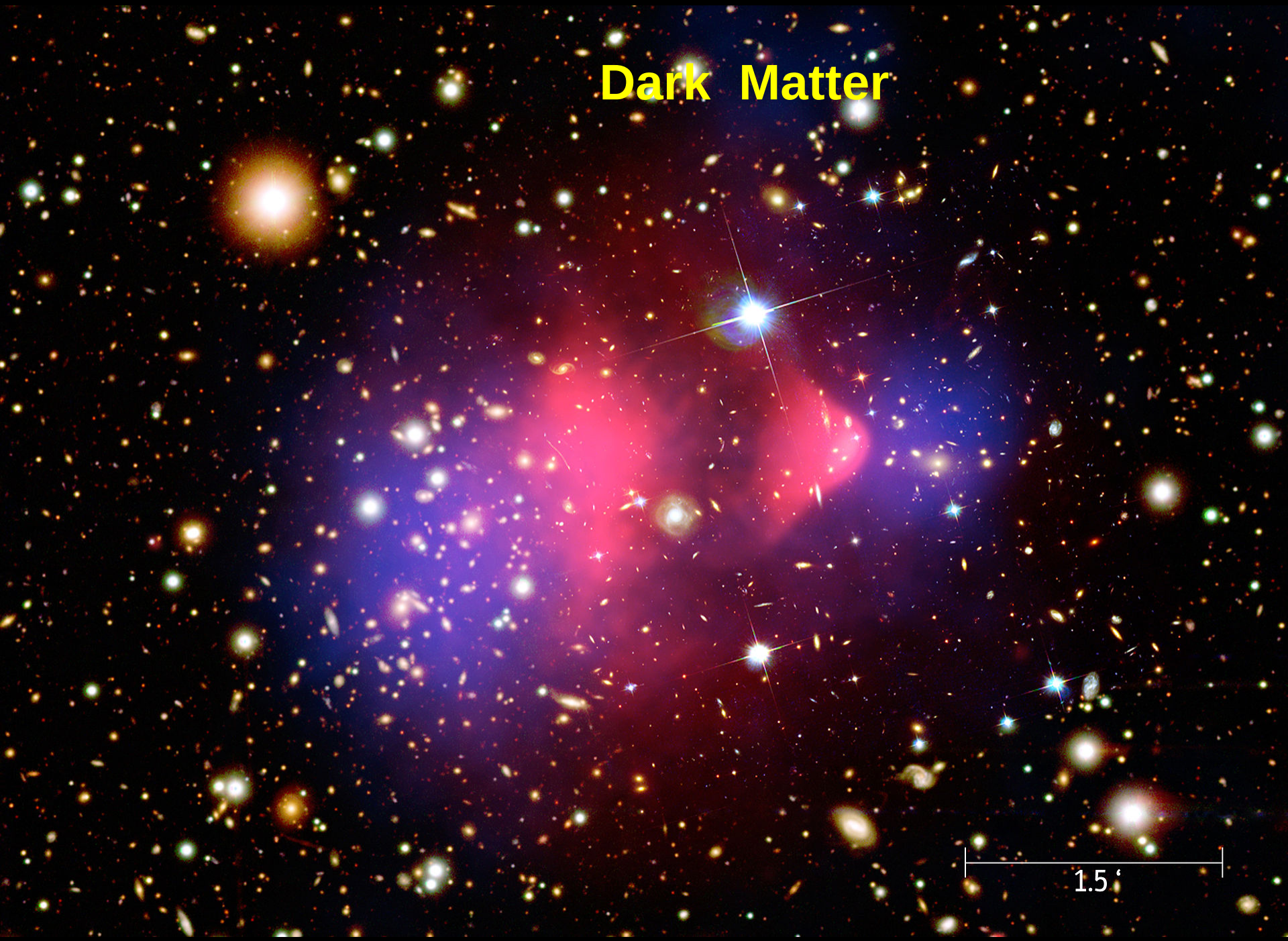
Quarks and leptons are *light*; but their constituents must be *very pointlike* (invisible below a TeV).

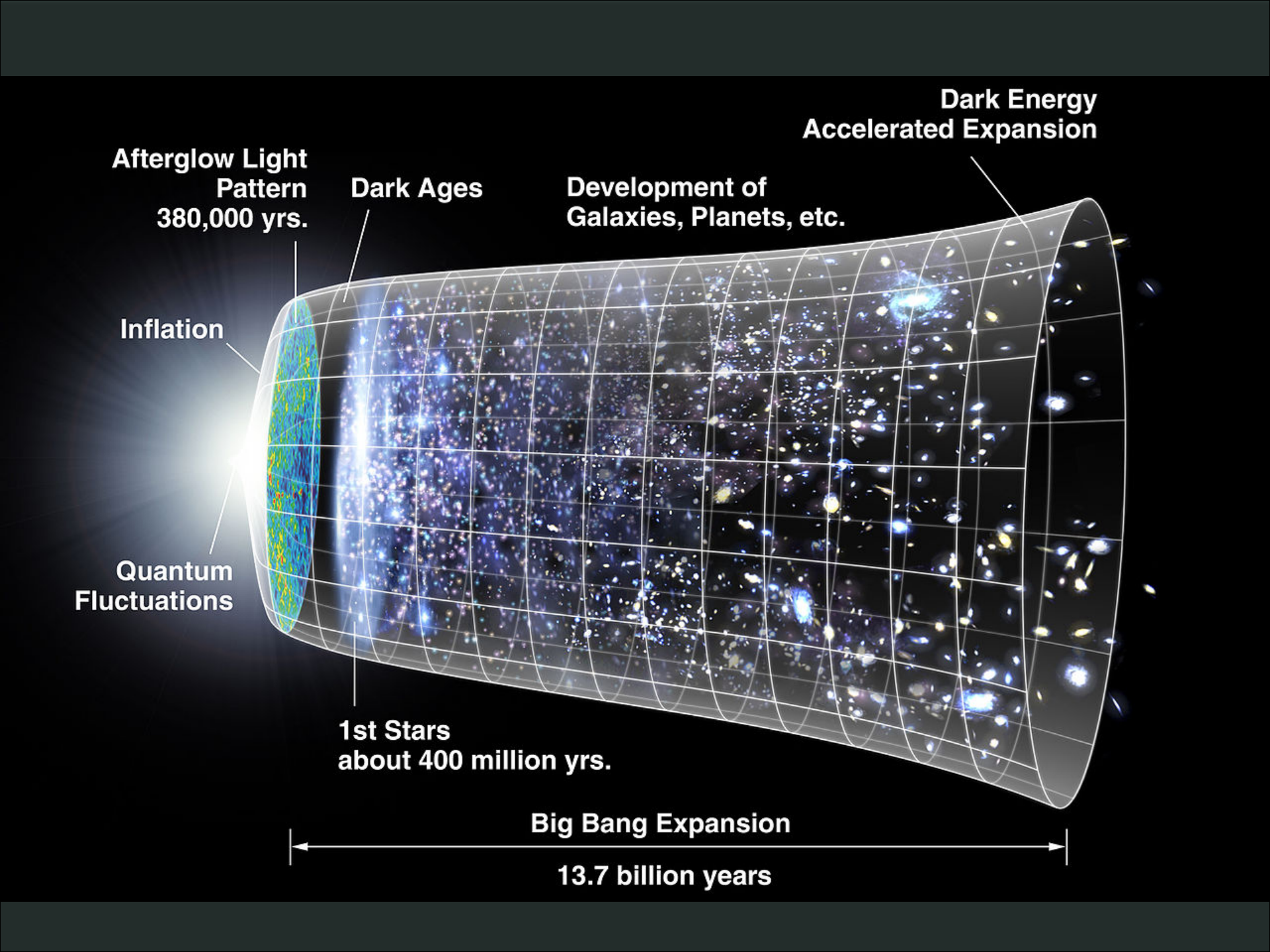
Compare: pions are light, yet quarks are pointlike
Pions are *protected* by the conservation of the chiral current (PCAC)

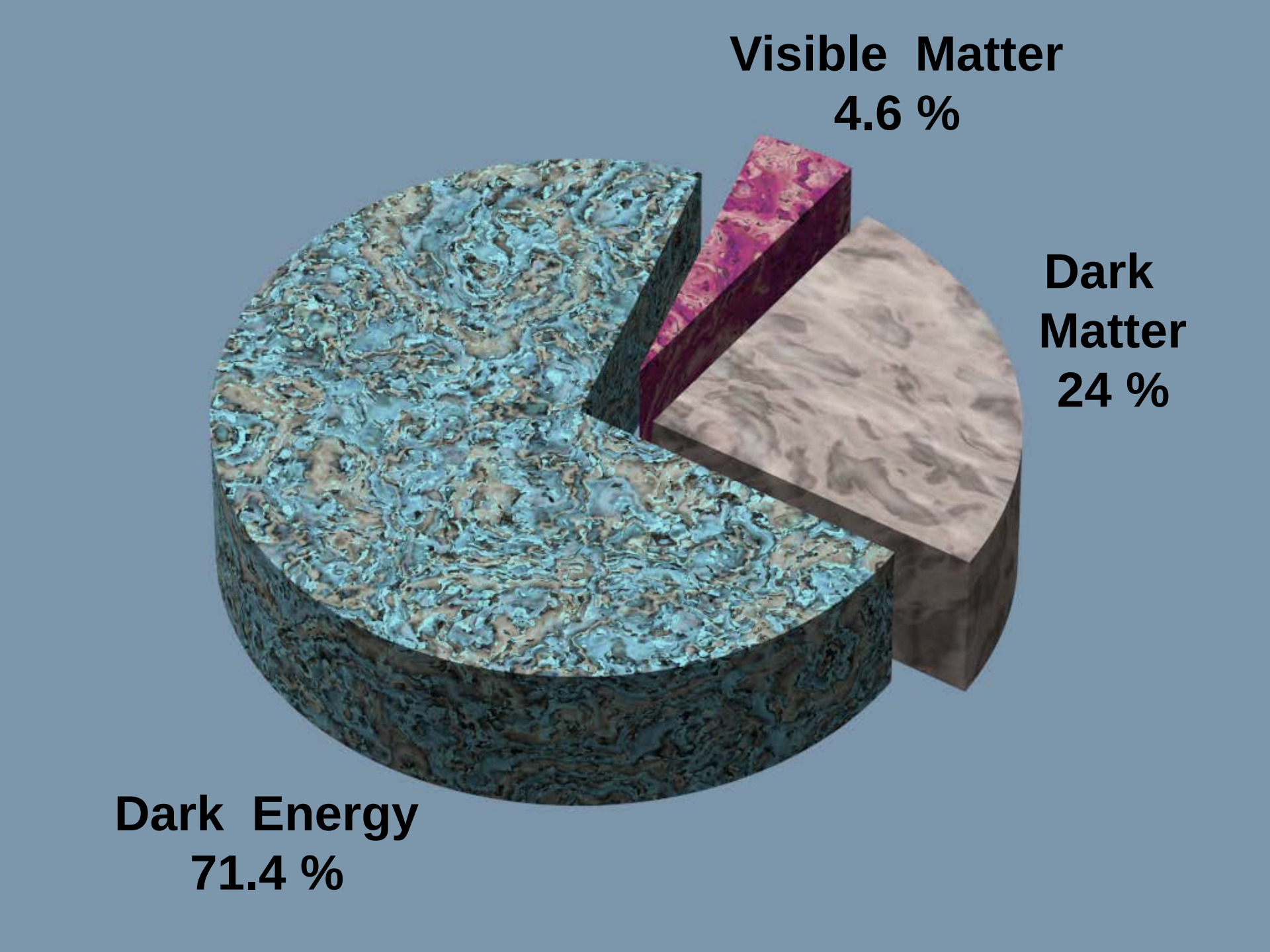
We need such a protection mechanism for the quarks and the leptons.

These are complicated mathematical conditions for the pentaks; no realistic solutions found.

Theory does not work well mathematically

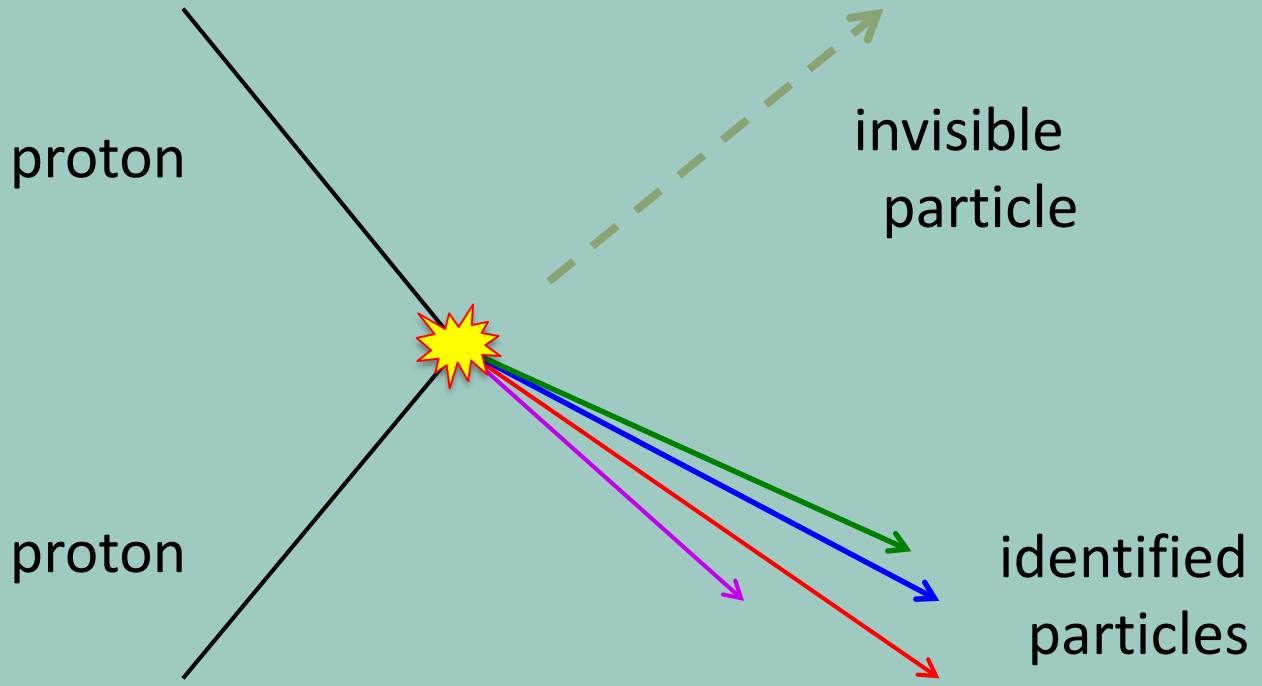

Dark Matter
1.5 ‘

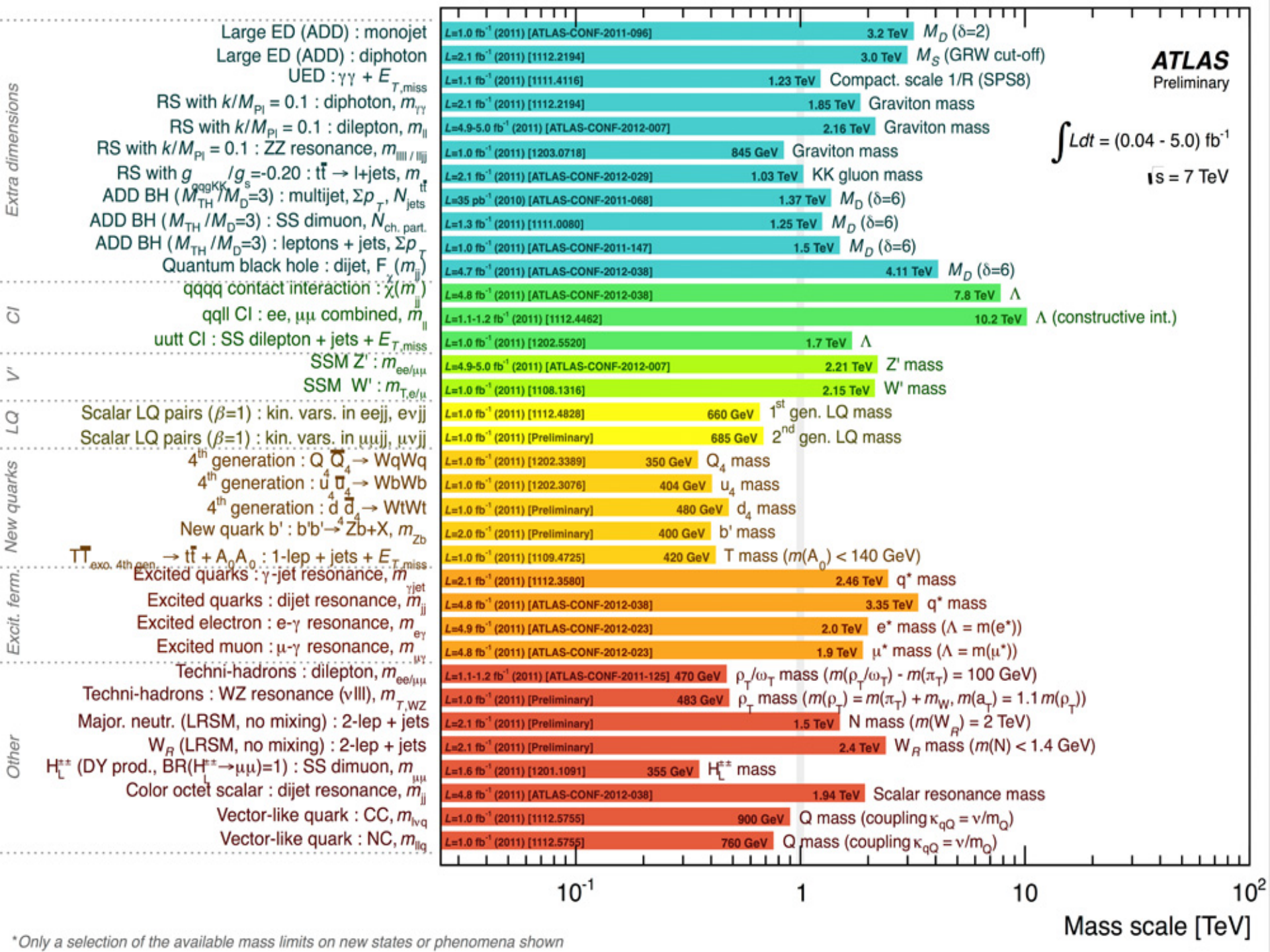

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


Visible Matter
4.6 %
Dark
Matter
24 %
Dark Energy
71.4 %

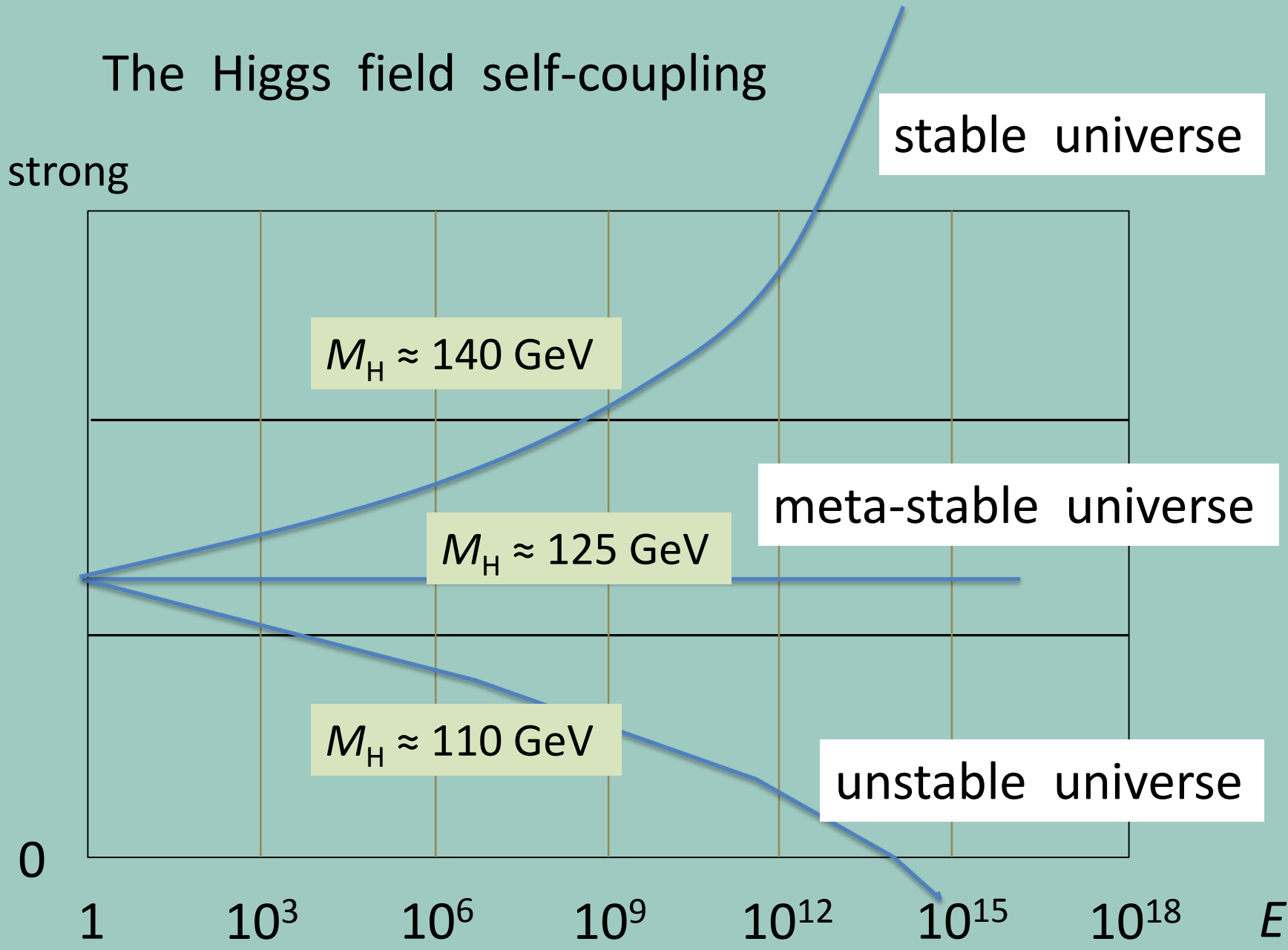
What are these dark matter particles?

Perhaps LHC will show interactions with "missing mass/energy"





*Only a selection of the available mass limits on new states or phenomena shown

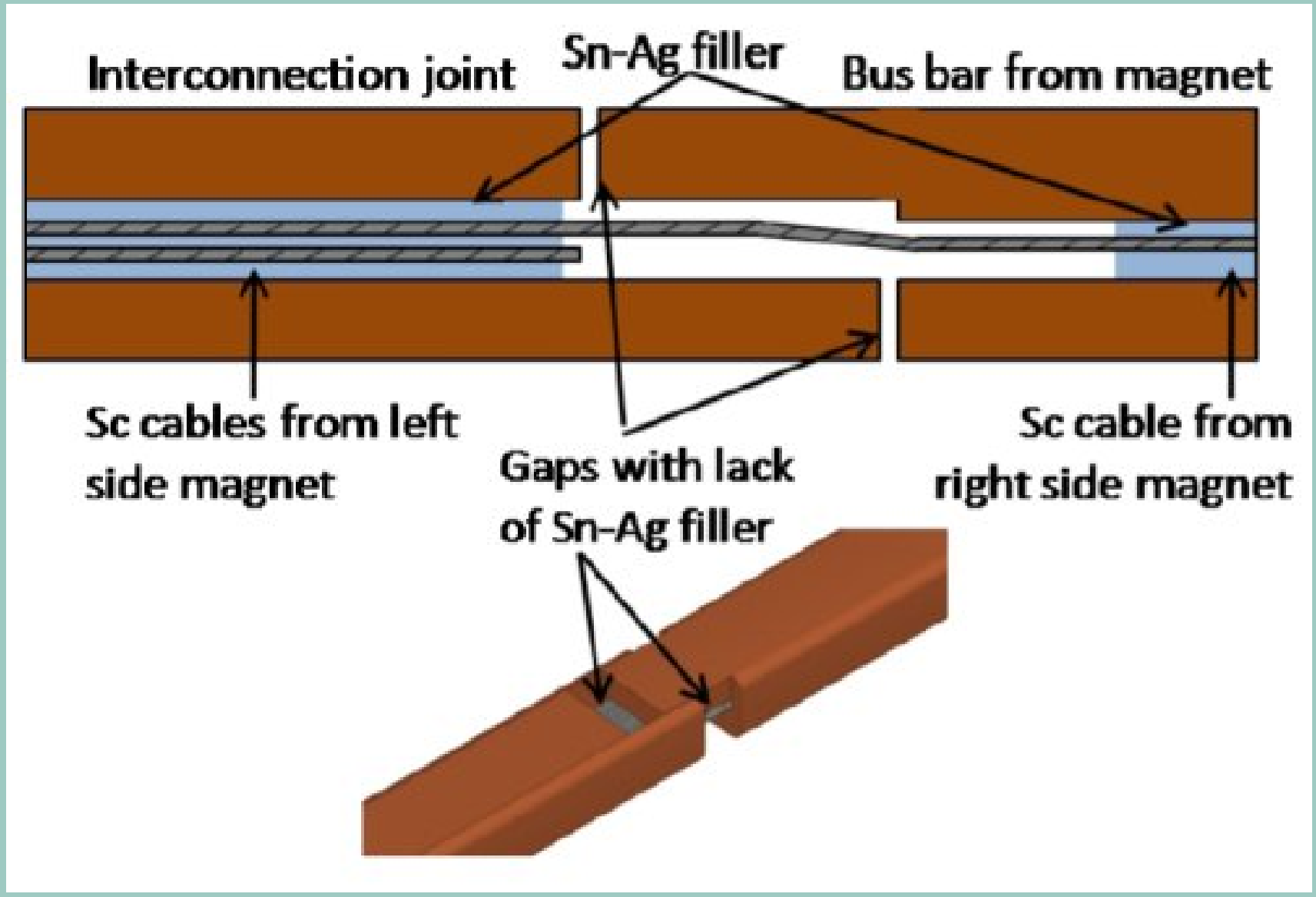

The Higgs field self-coupling
strong
stable universe
$M_H \approx 140$ GeV
meta-stable universe
$M_H \approx 125$ GeV
$M_H \approx 110$ GeV
unstable universe
0
1
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
E

This may already be the sign of "new physics" from the LHC …

?

THE END

Sept. 19, 2008


Interconnection joint
Sn-Ag filler
Bus bar from magnet
Sc cables from left side magnet
Gaps with lack of Sn-Ag filler
Sc cable from right side magnet