The Nobel Prize in Physics 2013: to Francois Englert and Peter Higgs

Talk by: Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc), Chennai

150th Science Club Meet
CLRI
15 March 2014

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert

Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François 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"*

A Note on Units

- Natural Units: Velocity of light $c = 1$
  - $E = mc^2 \quad \Rightarrow$ Measure Energy (E) & Mass (m) in GeV

    Eg: Proton mass $m_p \approx 1$ GeV

A Note on Units

- Natural Units: Velocity of light $c = 1$
    - $E = mc^2 \quad \Rightarrow$ Measure Energy (E) & Mass (m) in GeV

      Eg: Proton mass $m_p \approx 1$ GeV

Standard Model (SM) of Particle Physics

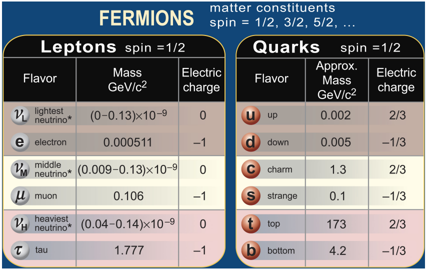
Physics operating at $\lambda \approx 10^{-17} m$ distance scale

How did we construct the SM?

- Low energy precision experiments
- High energy particle accelerators
    - Create new particles ($E = mc^2$)

The Building Blocks

[particleadventure.org]



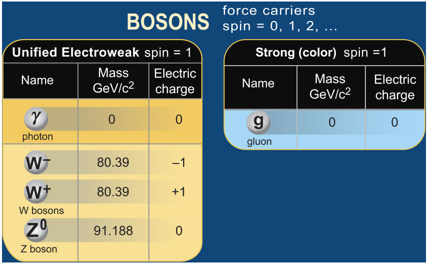
FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

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



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

Unified Electroweak spin = 1

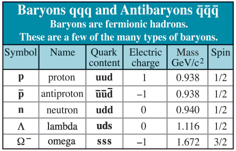
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.39	−1
W$^+$ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

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

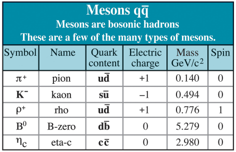
Added Higgs in 2012

Composites:



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2



Mesons $q\bar{q}$
Mesons are bosonic hadrons
These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries
  - Gauge Symmetry

Implies

Lorentz Invariance

- 4-dimensional Space-Time
- $E = mc^2$

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries
    - Gauge Symmetry

Implies

Uncertainty Principle

$$\Delta p\, \Delta x \geq \hbar$$

$$\Delta E\, \Delta t \geq \hbar$$

Virtual Particles

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries
  - Gauge Symmetry

Implies

Examples:

- Translation symmetry ⇒ Momentum Conserved
- Rotation symmetry ⇒ Angular Momentum Conserved

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries
  - Gauge Symmetry

Implies

Eg: Electromagnetism : U(1) Invariance

- Charge Conserved

Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics
- Space-Time Symmetries
- Internal Symmetries
    - Gauge Symmetry

Implies

Dirac: Matter ↔ Anti-matter

- electron ↔ positron
- proton ↔ antiproton

Form of the Theory

- Specified by the Lagrangian $L = T - V$
  (T is Kinetic Energy, V is Potential Energy)
  - Eg: Harmonic Oscillator : $L(x, \dot{x}) = T - V = \frac{1}{2} m\dot{x}^2 - \frac{1}{2} kx^2$
- Relativistic Quantum Field Theory formulation
  - Symmetries dictate form of L : Group Theory
    Demand invariance under Group Transformations:
    Eg: Lorentz Group $SO(1,3)$, Unitary Group $U(N)$, Special Unitary Group $SU(N)$, ...
- Eg: Quantum ElectroDynamics (QED) is a Gauge Theory
  - $\mathcal{L} = \bar{\psi} i\gamma^\mu(\partial_\mu - ieA_\mu)\psi - m_e\bar{\psi}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$; $F_{\mu\nu} \equiv (\partial_\mu A_\nu - \partial_\nu A_\mu)$
    Invariant under U(1) transformation:
    $\psi \to e^{ie\alpha}\psi$; $A_\mu \to A_\mu - i\partial_\mu\alpha$ for some $\alpha(t, \vec{x})$
    If α is a function of $x = (t, \vec{x})$ it is Gauge Invariance
    If α is a constant, it is Global Invariance

Standard Model (SM) theoretical structure

- Gauge Theory, Relativistic Quantum Field Theory (QFT)
  - $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge group (Internal Symmetry)
    - Strong, Weak, Electromagnetic Interactions

Eg: EM (QED) is $U(1)$ gauge symmetry

Standard Model (SM) theoretical structure

- Gauge Theory, Relativistic Quantum Field Theory (QFT)
    - $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge group (Internal Symmetry)
        - Strong, Weak, Electromagnetic Interactions

Eg: EM (QED) is $U(1)$ gauge symmetry

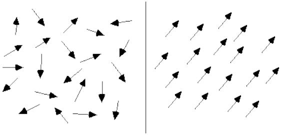
Some Gauge Symmetries Spontaneously broken ⇒ Massive Weak gauge bosons

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

Spontaneous Symmetry Breaking (SSB)

SSB : Microscopic laws symmetric, but ground state is NOT

- Analogy: Spontaneous Magnetization in Condensed Matter Systems



[Fig by F. Heylighen]

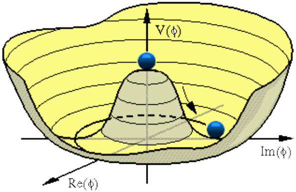
- Higgs Mechanism in QFT
    - $\mathcal{L}$ is invariant under Gauge Symmetry, but nonzero Vacuum Expectation Value (VEV) of Higgs field breaks EW symmetry

The Higgs Mechanism in the SM

$$\mathcal{L} \supset (D_\mu H)^\dagger D^\mu H + \mu^2 H^\dagger H - \frac{\lambda}{4!} (H^\dagger H)^2$$

Spontaneous Breaking of Electroweak Symmetry

$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$ (The E-B-Higgs-G-H-K Mechanism)



- Give masses to $W^\pm$, Z (γ massless)
- Generates fermion masses

$$\mathcal{L}_{Yuk} \supset -\lambda_u \overline{Q} \tilde{H} u_R - \lambda_d \overline{Q} H d_R - \lambda_e \overline{L} H e_R + h.c.$$

Under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

$H \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = (1, 2)_{1/2}$

$Q \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2)_{1/6}$; $u_R = (3, 1)_{2/3}$

$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}$; $e_R = (1, 1)_{-1}$

- Complex Yukawa couplings $\lambda \implies$ CP violation
- Unitarize WW scattering

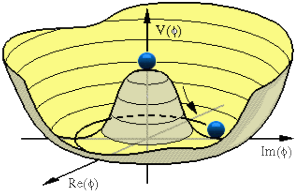
[Lee, Quigg, Thacker, 1977]

The Higgs Mechanism in the SM

$$\mathcal{L} \supset (D_\mu H)^\dagger D^\mu H + \mu^2 H^\dagger H - \frac{\lambda}{4!} (H^\dagger H)^2$$

Spontaneous Breaking of Electroweak Symmetry

$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$ (The E-B-Higgs-G-H-K Mechanism)



- Give masses to $W^\pm$, Z (γ massless)
- Generates fermion masses

$$\mathcal{L}_{Yuk} \supset -\lambda_u \overline{Q} \tilde{H} u_R - \lambda_d \overline{Q} H d_R - \lambda_e \overline{L} H e_R + h.c.$$

Under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

$H \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = (1,2)_{1/2}$

$Q \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}$; $u_R = (3,1)_{2/3}$

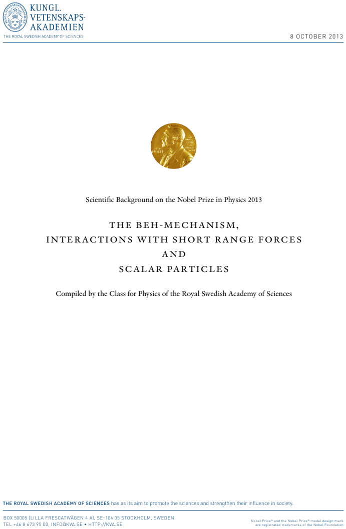
$L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}$; $e_R = (1,1)_{-1}$

- Complex Yukawa couplings $\lambda \implies$ CP violation
- Unitarize WW scattering

[Lee, Quigg, Thacker, 1977]

But, mass of a fundamental scalar is not protected against getting large quantum correction. A hint for Physics Beyond the SM

The road to the Prize



KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

8 OCTOBER 2013

Scientific Background on the Nobel Prize in Physics 2013

THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

Compiled by the Class for Physics of the Royal Swedish Academy of Sciences

THE ROYAL SWEDISH ACADEMY OF SCIENCES has as its aim to promote the sciences and strengthen their influence in society.

BOX 50005 (LILLA FRESCATIVÄGEN 4 A), SE-104 05 STOCKHOLM, SWEDEN
TEL +46 8 673 95 00, INFO@KVA.SE • HTTP://KVA.SE

Nobel Prize® and the Nobel Prize® medal design mark
are registrated trademarks of the Nobel Foundation

The Beginnings

- Fermi (1934): Theory for β-decay
- C.N.Yang, T.D.Lee (1956) : Parity Violation in Weak Decays
- Marshak, Sudarshan (1957); Feynman, Gell-Mann (1958) : V-A theory
- Schwinger (1957): SU(2) gauge field theory

  But gauge theory has massless W_μ. Contradicts experiment!

- Glashow (1961); Salam, Ward (1964): SU(2)×U(1) electroweak gauge theory

  Short range of weak interactions by adding $m_W^2 W_\mu W^\mu$

  Theory Non-renormalizable

Any way to keep gauge invariance, while making W_μ massive?

Spontaneous Symmetry Breaking & Goldstone Theorem

- Y.Nambu 1960 : BCS theory of Superconductors

  Non-relativistic gauge theory formulation of attempts by Anderson (1958) and others
  Chiral fermions global symm; Vacuum Expectation Value (VEV) to fermion condensate

  spontaneous symmetry breaking (SSB) $\Longrightarrow$ massive A_μ (short-range force)
  SSB: Heisenberg (1928) theory of magnetism

  Took it to particle physics, fermion bound state → Massless pion (massive due to explicit breaking)

- J.Goldstone (1961) : Scalar field $\phi = \phi_1 + i\phi_2$ with VEV $\langle\phi\rangle \neq 0$

  Massless mode ϕ_2 (Nambu-Goldstone Boson) appears
  Massive mode ϕ_1 initially not investigated (until Higgs)

- Goldstone, Salam, Weinberg (1962) Theorem

  SSB $\Longrightarrow$ Massless Nambu-Goldstone Boson!

Massless Mode! Abandon Theory?

- Anderson (1963) : Schwinger's problem in a model of charged plasma

  SSB Non-relativistic gauge theory, argued that there is NO massless mode!
  Hinted that in a relativistic theory the longitudinal mode is the third component of the massive vector boson.
  "*We conclude, then, that the Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang-Mills zero-mass problem*"

- A.Klein, B.W.Lee (1964) : In relativistic case, argued that Goldstone theorem can be evaded

  criticized by Walter Gilbert 1964 (1980 Chemistry Nobel!)

Clarity, ... finally!

- Francois Englert, Robert Brout (1964)

  motivated by Schwinger's work; but took specific model of gauge theory with complex scalar field
  Gauge invariance dictates $W_\mu \partial^\mu \phi_2$ term after SSB
  Massive W_μ in Gauge invariant way, so renormalizable
  Massless ϕ_2 not physical, becomes longitudinal W !

  Resolution of the puzzle!

- Higgs (1964)

  In a gauge theory massless ϕ_2 problem not there
  Same model as Englert, Brout, shows ϕ_1 is massive, studies its properties; So, called the Higgs Boson
  In $SU(3)$ gauge theory incorporates massive W_μ and massless A_μ

More Clarity

- Migdal, Polyakov (1966) : In the Soviet Union, in a strongly coupled theory shows that the massless mode is not physical
- Guralnik, Hagen, Kibble (1964); Higgs (1966); Kibble (1967): further clarify SSB in NonAbelian gauge theories
- Weinberg (1967) : puts everything together and proposes the SM (leptons)
- ’t Hooft (1971); ’t Hooft, Veltman (1972) : shows that above construction is Renormalizable

HIGGS BOSON EXPERIMENTAL DISCOVERY

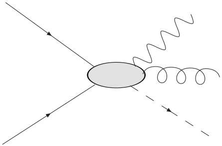
Accelerators as microscopes

Optical Microscope ($\lambda \approx 0.6\,\mu m$)

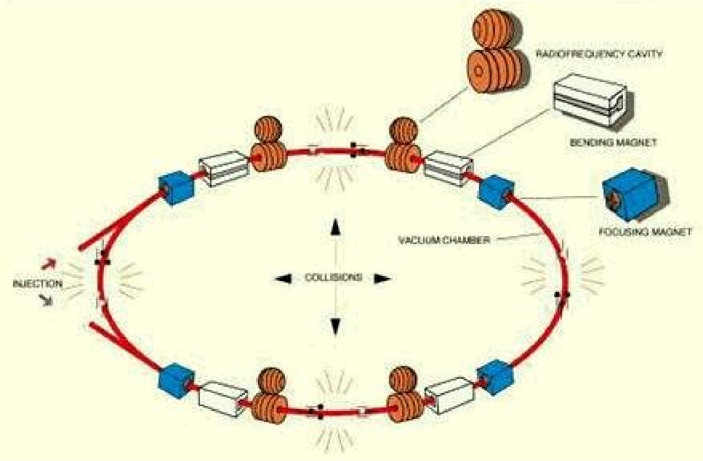
Electron Microsope ($\lambda \approx 0.2\,nm$)

Particle Accelerator ($\lambda \approx 1/E$) (E is Beam Energy)

- LEP (CERN, Europe), Tevatron (Fermilab, USA): $E \approx 100$ GeV , $\lambda \approx 10^{-17} m$
- Large Hadron Collider (LHC - CERN, Europe): $E = 14000$ GeV , $\lambda \approx 10^{-19} m$

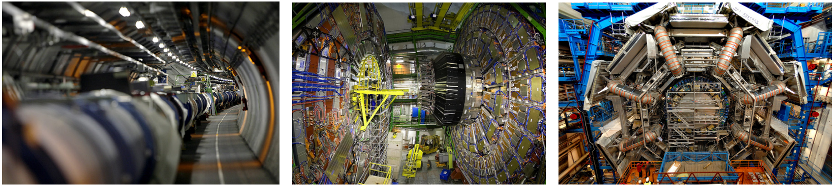


Accelerator schematic



Accelerator Animation

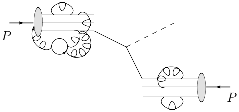
The Large Hadron Collider (LHC)



Discovered the Higgs. Continue searching for more ...

Higgs Production @ LHC

LHC is a $p-p$ collider



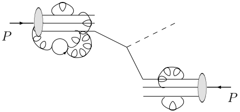
p contains partons: $g, u, d, \bar{u}, \bar{d}, \ldots$

$$x \equiv \frac{\sqrt{\hat{s}}}{\sqrt{S}{=}14\ TeV}$$

Parton momentum is fraction of $\sqrt{S}$:
parton distribution function (pdf)

Higgs Production @ LHC

LHC is a $p-p$ collider



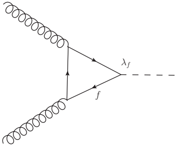
p contains partons: $g, u, d, \bar{u}, \bar{d}, \ldots$

$$x \equiv \frac{\sqrt{\hat{s}}}{\sqrt{S}{=}14\ TeV}$$

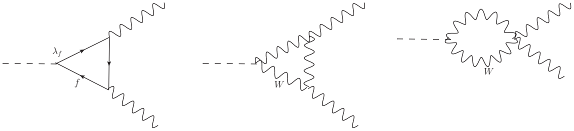
Parton momentum is fraction of $\sqrt{S}$:
parton distribution function (pdf)

$pp \to h \to \gamma\gamma$ @ LHC

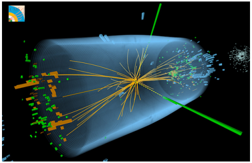
$\sigma(gg \to h)$

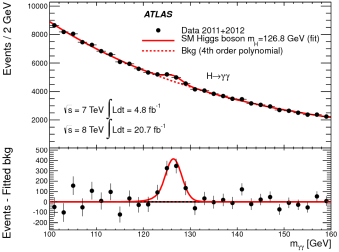


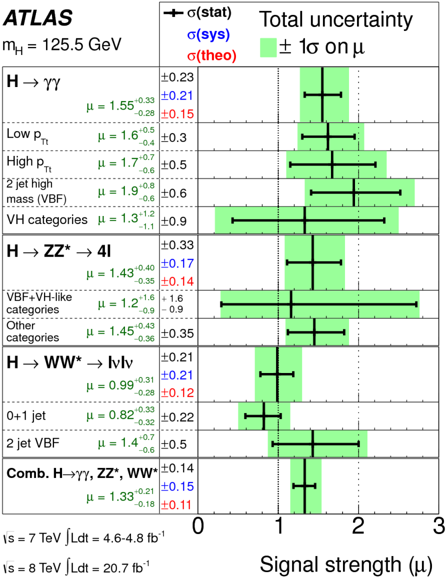
$\Gamma(h \to \gamma\gamma)$



LHC Higgs Measurements







Now that all the SM particles have been discovered, are we done?

Now that all the SM particles have been discovered, are we done?

I don't think so ...

Motivation for Physics Beyond the Standard Model (BSM)

Questions left unanswered by the SM

Observational

- What is the observed Dark Matter?
- What generates the Baryon Asymmetry of the Universe (BAU)?
- What generates the neutrino masses?

Theoretical

- SM hierarchy problem (Higgs sector): $M_{EW} \ll M_{Pl}$
- SM flavor problem: $m_e \ll m_t$
- Explained by new dynamics?
    - Extra dimensions (Warped (AdS), Flat)
    - Supersymmetry
    - Strong dynamics
    - Little Higgs

Summary

- The Higgs Mechanism : “Origin of Mass”
    - Gives masses to Electroweak Gauge Bosons, Quarks and Leptons
    - Gauge invariance intact, renormalizable
- Discovery of the Higgs Boson completes the verification of the SM!
- But SM has shortcomings : BSM resolve these?
    - Observational: DM, BAU, ν mass
    - Theoretical: Gauge (& flavor) hierarchy problem
- **Upcoming 14 TeV LHC run may tell us more**
    - Stay Tuned!

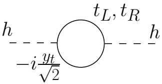
BACKUP SLIDES

BACKUP SLIDES

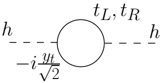
Hierarchy problem in detail

LHC (and LEP) tell us that the Higgs boson is light $m_h = 126$ GeV

$\mathcal{L} \supset \frac{1}{2}\mu^2\, H^\dagger H - \frac{\lambda}{4!}\left(H^\dagger H\right)^2$ No symmetry protecting the Higgs mass!



$$\delta m_h^2 = -\frac{3y_t^2}{16\pi^2}\Lambda^2$$



(Λ is momentum cut-off, say M_{pl})

Quadratic divergence in the Higgs sector

New physics possibilities

- Belief that some new physics cures these problems
- Look for these at the LHC

New physics possibilities

- Belief that some new physics cures these problems
- Look for these at the LHC

Supersymmetry

[SG,Yuan,2004]

Extra-dimensions : (Warped or Flat)
[Mandal, Mitra, Moreau, SG, Tibrewala 2011, 13][Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni,, 2007, 08, 10] [Cao, SG, Yuan, 2003]

Strong dynamics (Note AdS-CFT correspondence)

Little Higgs

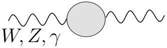
Neutrino mass connection and lepton number violation
[EDM with Triplet Higgs: de Gouvea, SG, 2005]

Dark Matter candidates

[SG, Jung, Lee, Wells, 2008, 09]

Precision Probes of BSM

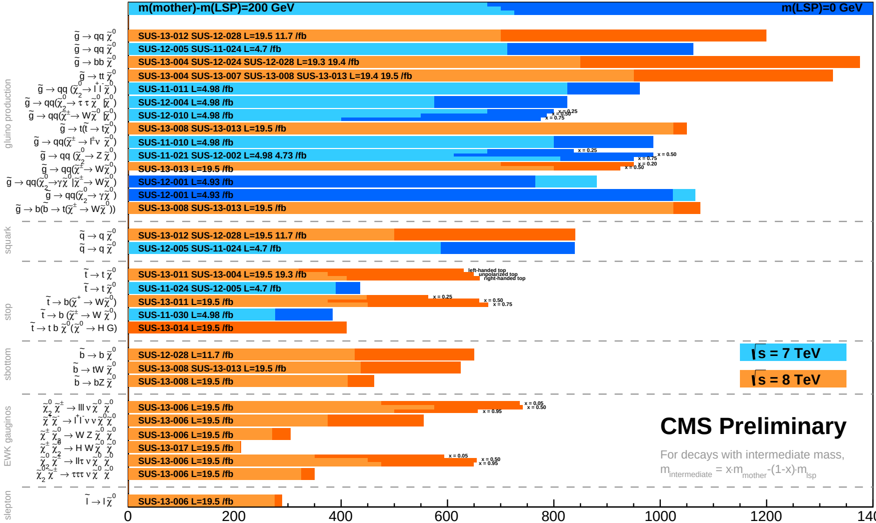
In addition to Collider probes, New Physics can also be probed in:



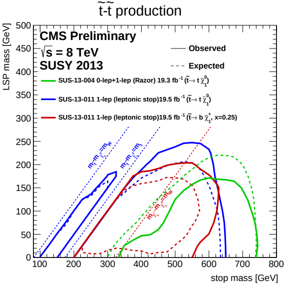
- Precision Electroweak Probes (S, T, $Zb\bar{b}$)
- Flavor Changing Neutral Currents (FCNC)
    - $K^0 \bar{K}^0$ mixing, $b \to s\gamma$, $b \to s\,\ell^+\ell^-$, $b \to s\,s\,\bar{s}$, $K \to \pi\nu\bar{\nu}$, $b \to \tau\nu X$, ...
    - Relaxed with flavor alignment : MFV, flavor symmetries
- $(g-2)_\mu$, EDM, ...

Generally result in bound : $M_{BSM} \gtrsim few - 100$ TeV

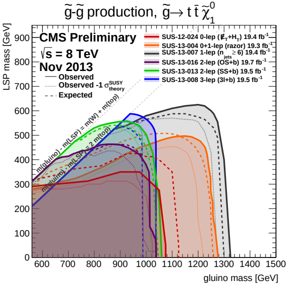
Summary of CMS SUSY Results* in SMS framework   SUSY 2013



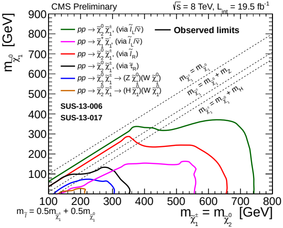
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit



t̃-t̃ production
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Expected
SUS-13-004 0-lep+1-lep (Razor) 19.3 fb⁻¹ (t̃→ t χ̃⁰₁)
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ (t̃→ t χ̃⁰₁)
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ (t̃→ b χ̃⁺₁, x=0.25)
m_t̃-m_χ̃⁰₁=m_W
m_t̃-m_χ̃⁰₁=m_t
m_χ̃±-m_χ̃⁰₁=m_W
LSP mass [GeV]
stop mass [GeV]
0
50
100
150
200
250
300
350
400
450
500
100
200
300
400
500
600
700
800

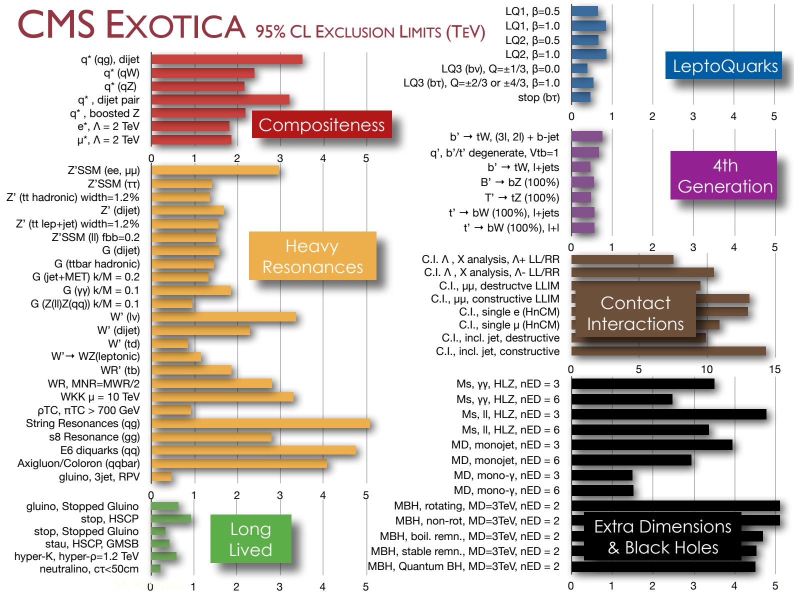


g̃-g̃ production, g̃→ t t̄ χ̃⁰₁
CMS Preliminary
√s = 8 TeV
Nov 2013
Observed
Observed -1 σ^SUSY_theory
Expected
SUS-12-024 0-lep (E̸_T+H_T) 19.4 fb⁻¹
SUS-13-004 0+1-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep (n_jets ≥ 6) 19.4 fb⁻¹
SUS-13-016 2-lep (OS+b) 19.7 fb⁻¹
SUS-13-013 2-lep (SS+b) 19.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
m(gluino) - m(LSP) = m(W) + m(top)
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500

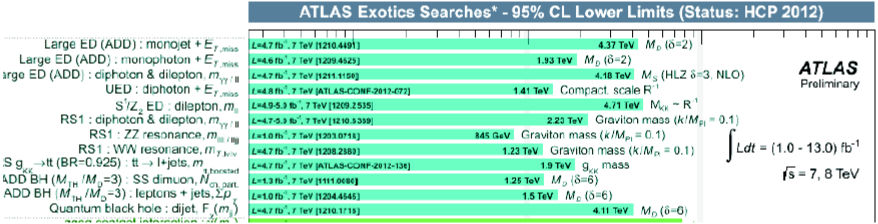


CMS Preliminary
√s = 8 TeV, L_int = 19.5 fb⁻¹
pp → χ̃⁰₂ χ̃±₁, (via l̃_L/ν̃)
pp → χ̃⁺₁ χ̃⁻₁, (via l̃_L/ν̃)
pp → χ̃⁰₂ χ̃±₁, (via l̃_R)
pp → χ̃⁰₂ χ̃±₁, (via τ̃_R)
pp → χ̃⁰₂ χ̃±₁ → (Z χ̃⁰₁)(W χ̃⁰₁)
pp → χ̃⁰₂ χ̃±₁ → (H χ̃⁰₁)(W χ̃⁰₁)
Observed limits
SUS-13-006
SUS-13-017
m_χ̃±₁ = m_χ̃⁰₁
m_χ̃±₁ = m_χ̃⁰₁ + m_Z
m_χ̃±₁ = m_χ̃⁰₁ + m_H
m_χ̃⁰₁ [GeV]
m_χ̃±₁ = m_χ̃⁰₂ [GeV]
m_l̃ = 0.5m_χ̃±₁ + 0.5m_χ̃⁰₁
100
200
300
400
500
600
700
800
900
100
200
300
400
500
600
700
800

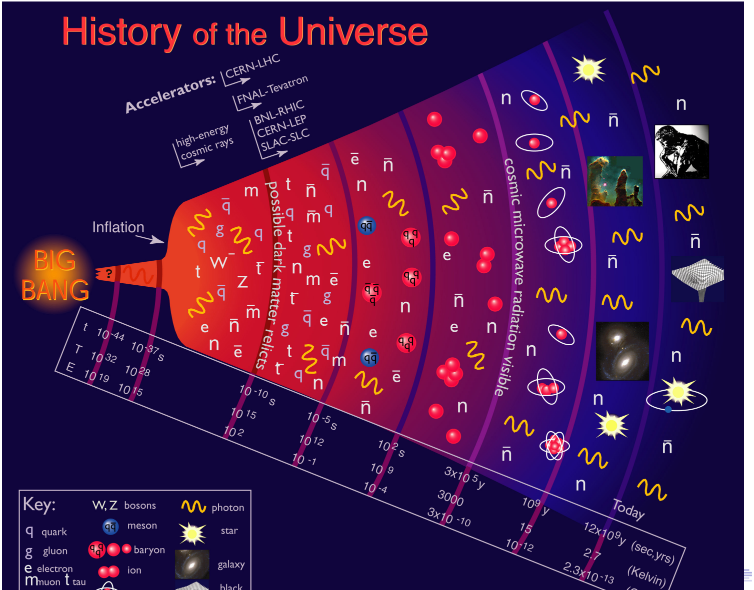
CMS Exotica 95% CL Exclusion Limits (TeV)



ATLAS Extra Dimensions Limits (Moriond 2013)



Particle Physics and the Universe



CMS Resonances Limits (Moriond 2013)