Particle Physics

at the Energy and Intensity Frontiers

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Particle Physics

Quest to understand fundamental aspects of Nature

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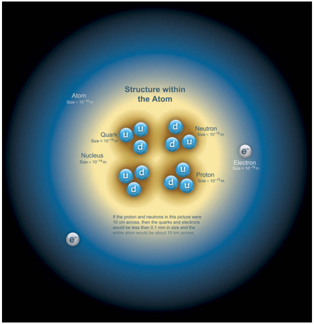

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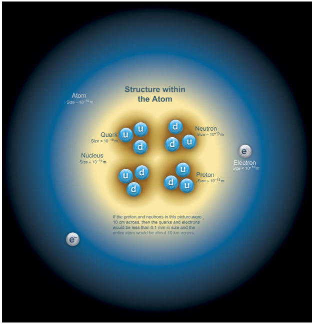

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Standard Model (SM) of Particle Physics

Physics at $\lambda \approx 10^{-18} m$ distance scale $\Leftrightarrow$ $E \approx 100$ GeV energy scale

Natural units

- Natural Units
  (velocity of light $c = 1$, Plancks constant $\hbar = 1$)
  - $E = mc^2 \quad \Rightarrow$ measure Energy (E) & Mass (m) in **Giga-electron-Volts** (GeV)

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Examples

proton rest-mass $m_p \approx 1$ GeV

LHC energy is 13000 GeV $=$ 13 Tera-eV (TeV)

The Building Blocks

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)×10^{-9}	0
e electron	0.000511	–1
ν_M middle neutrino*	(0.009–0.13)×10^{-9}	0
μ muon	0.106	–1
ν_H heaviest neutrino*	(0.04–0.14)×10^{-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

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

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- Quarks, Leptons (spin 1/2): matter particles
- Vector bosons (spin 1): strong, weak, electromagnetic force carriers
- Higgs boson (spin 0): gives masses to particles
- Gravity (spin 2): *not* part of the quantum description yet

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Unstable particles

If not forbidden by conservation laws, particle will **decay**.

Eg. muon decay: $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

Standard Model Interactions

Electromagnetism (Quantum Electro Dynamics)

... binds p^+,e^- to form (neutral) atom(s)

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... binds quarks to form mesons & baryons; also binds p, n to form nuclei

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

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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

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... causes radioactive decay: eg. $^{60}_{27}Co \rightarrow ^{60}_{28}Ni + e^- + 2\gamma$

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Gravity

... causes us to fall and break our bones

Probes and Experiments

- *Energy Frontier* (High energy particle accelerators)
  - Produce particles *directly* at an accelerator ($E = mc^2$) and detect it's decay products (in detector)
    - reconstruct a "bump"

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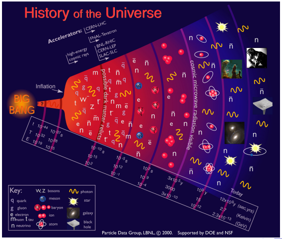
- *Cosmic Frontier* (Astrophysics/Cosmology)



Particle Physics Theory framework

- Special Relativity
- Quantum Mechanics

Symmetries:

- Space-time or Internal
- Discrete or Continuous
- Global or Local

4 space-time: $x^\mu = (t, \vec{x})$

Lorentz invariance (rotations, boosts)
Translation invariance

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Uncertainty Principle

- $\Delta p \, \Delta x \geq \hbar$
- $\Delta E \, \Delta t \geq \hbar$

$\Longrightarrow$ Virtual Particles

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Dirac theory

Matter $\leftrightarrow$ Anti-matter

electron $\leftrightarrow$ positron

proton $\leftrightarrow$ antiproton

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Example

Charge conjugation ($\mathcal{C}$): $e^- \leftrightarrow e^+$

Parity ($\mathcal{P}$): $\vec{x} \rightarrow -\vec{x}$

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Eg: gauge invariance

Electromagnetism:
U(1) Invariance: $\psi \to e^{i\alpha(x)}\psi$

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
- 3 generations of quarks and leptons + 1 Higgs-doublet
  - Complex $H\bar{\psi}\psi$ couplings imply violation of $\mathcal{CP}$-symmetry!

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Some Gauge Symmetries Spontaneously broken $\Rightarrow$ Massive Weak gauge bosons

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

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SM is spectacularly successful!

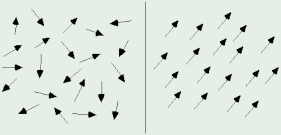
Eg. $(g-2)_\mu$: SM calculation and experiment agree to 10 decimal places!
Huge number of tests of SM, 2 or 3 inconclusive discrepancies.

Spontaneous Symmetry Breaking (SSB)

Microscopic laws symmetric, but ground state is NOT

Analogy

Spontaneous Magnetization in Condensed Matter Systems



[Fig by F. Heylighen]

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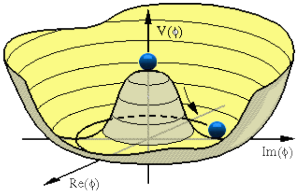
The B-E-G-H-Higgs-K mechanism in the SM: Equations of motion are invariant under Gauge Symmetry, but nonzero Vacuum Expectation Value (VEV) of Higgs field breaks EW symmetry (spontaneous Breaking of Electroweak Symmetry

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



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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Photo: A. Mahmoud
François Englert

Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs

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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"*

Are we done?

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

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I don't think so ...

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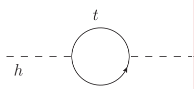
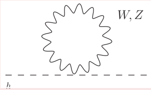
Stability problem

The mass of a fundamental scalar is not protected against large quantum corrections and is corrected to large values ("hierarchy problem"). But we have observed a 125 GeV Higgs boson. A hint for physics beyond the SM

δm_h^2 



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A nagging possibility

... that there is no dynamical explanation. Our vacuum could be just one in a vast **landscape** of vacuua. Similar to the **Anthropic** principle!

Are we done?

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

I don't think so ...

Keep looking ...

... who knows what lurks beyond what's measured?

Motivation for Physics Beyond the Standard Model (BSM)

Questions left unanswered by the SM

Observational indications for BSM

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

Theoretical arguments for BSM

- Hierarchy problem (Higgs sector): $M_{EW} \ll M_{Pl}$
- Flavor problem: $m_e \ll m_t$
- Strong CP problem
- Cosmological constant problem

Some new physics possibilities

Belief that something may cure the gauge hierarchy problem. But what?

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- Thermal relic or Non-thermal relic?
- Direct, Indirect, Collider searches underway

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- $\mathcal{CP}$ violation & Leptogenesis

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Baryon Number (B) appears to be conserved - is it really?

- Grand-unified Theories (GUT) predict Proton Decay (B violation)
  experimental limit $\tau_p \gtrsim 10^{32}$ years
- neutrino detectors (eg. SuperK) searching for it...

Summary

- The Higgs Mechanism : "Origin of Mass"
  - Gives masses to Electroweak Gauge Bosons, Quarks and Leptons
  - Discovery of the Higgs Boson completes the verification of the SM!
- But Standard Model has shortcomings : New physics resolves these?
  - Observational: Dark Matter, Baryon Asymmetry of Universe, ν mass
  - Theoretical: Gauge (& flavor) hierarchy problem
- **Ongoing and future experiments will tell us more**
  - 13 TeV LHC run ongoing
  - Stay tuned!

BACKUP SLIDES

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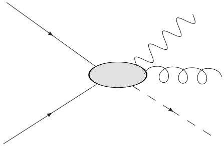
Accelerators as microscopes

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 , $\lambda \approx 10^{-18} m$
- Large Hadron Collider (LHC - CERN, Europe): $E = 13000$ GeV , $\lambda \approx 10^{-19} m$
    - Since LHC is a proton-proton machine, pdf suppression takes us to this



Searching for (new) Physics at the LHC

Quantum Mechanics is probabilistic

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- Compare to LHC event rate observed and see if devation from SM
  - LHC is a counting experiment - Statistical Evidence!

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Analogy: Coin Toss to ascertain fairness

Toss the coin many times : plot probability distribution
Smaller the deviation from fairness, larger the number of tosses required

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Similarly, if LHC results agree with new theory

- Theory established!

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Disagree?

- Consider alternate theory

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Eg: Higgs in $\gamma\gamma$ channel

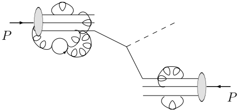
Theoretically compute the cross-section (probability) σ

- "signal" cross-section $\sigma(pp \to h \to \gamma\gamma)$
  - "background" cross-section $\sigma(pp \to \gamma\gamma)$

At LHC establish signal over background to discover Higgs

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)

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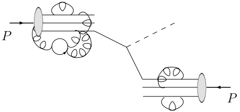

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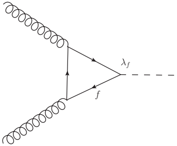
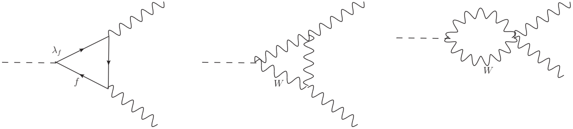
$pp \to h \to \gamma\gamma$ @ LHC

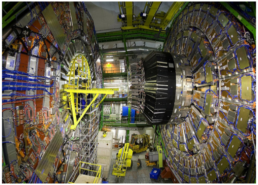
$\sigma(gg \to h)$

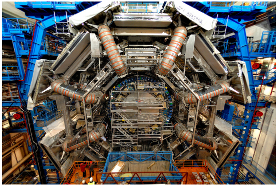


$\Gamma(h \to \gamma\gamma)$



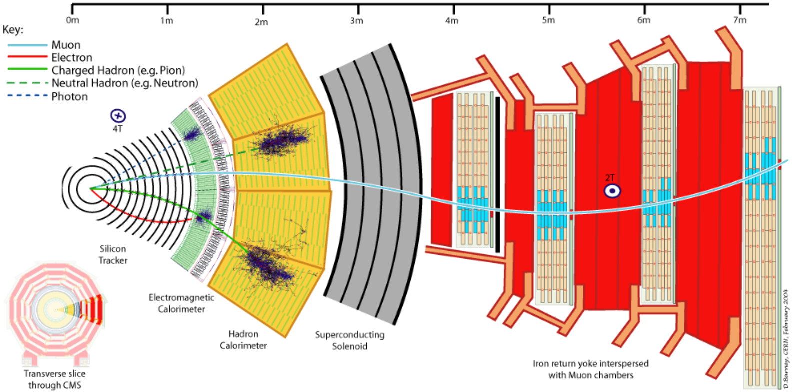
The Large Hadron Collider (LHC)



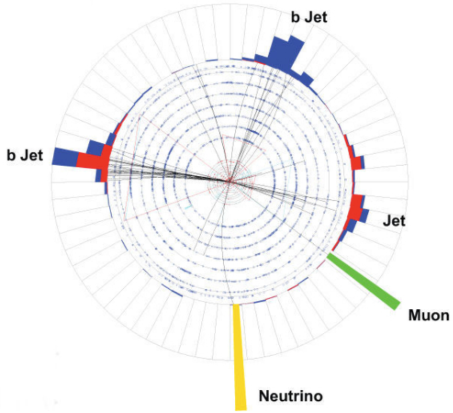


Discovered the Higgs. Continue searching for more ...

Particle Detectors

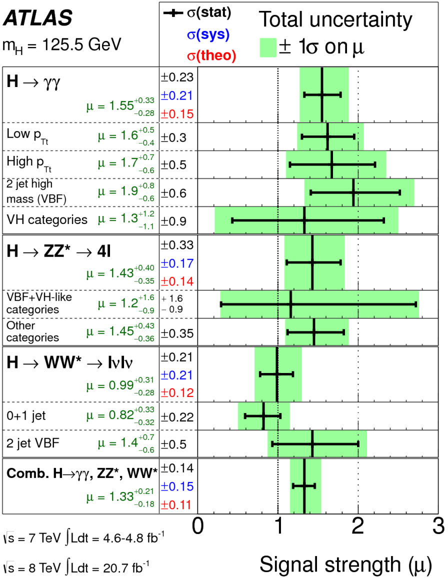


Event reconstruction



D0 Single Top Event (Tevatron)

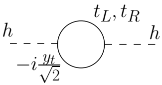
LHC Higgs Measurements



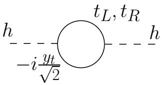
Hierarchy problem in detail

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!

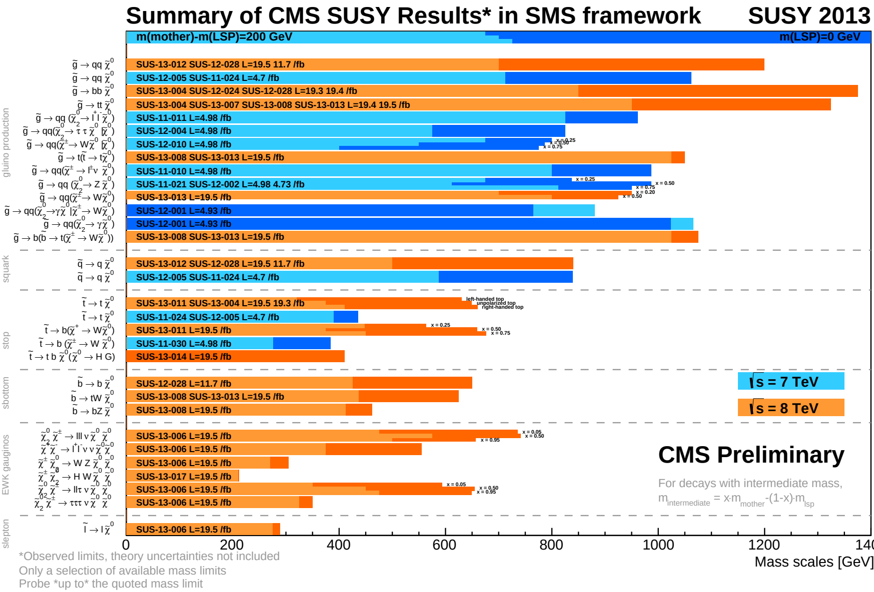


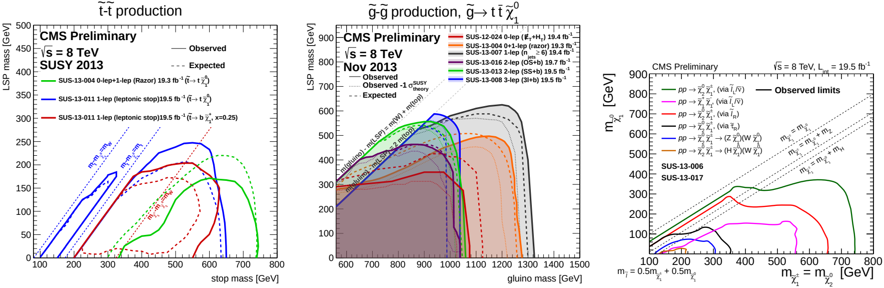
$$\delta m_h^2 = -\frac{3y_t^2}{16\pi^2}\Lambda^2$$



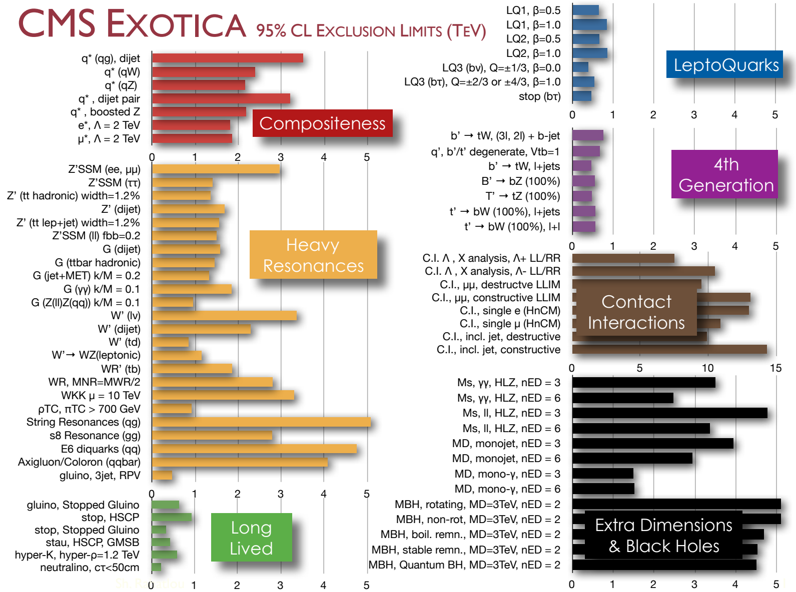
(Λ is momentum cut-off, say M_{pl})

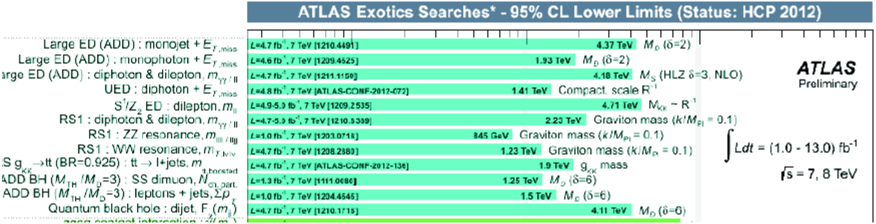
Quadratic divergence in the Higgs sector


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
gluino production
squark
stop
sbottom
EWK gauginos
slepton
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

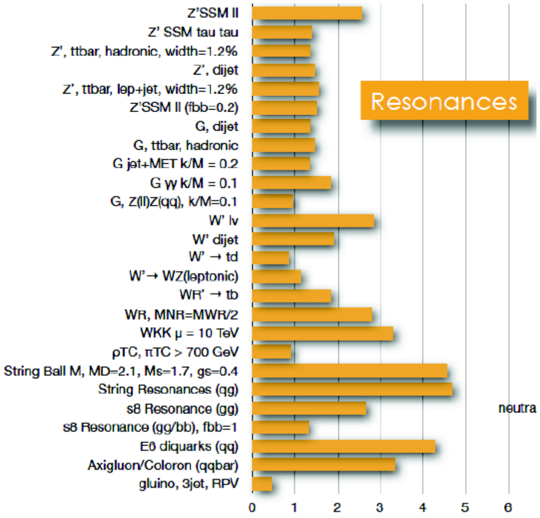


t̃-t̃ production
CMS Preliminary
√s = 8 TeV
SUSY 2013
Observed
Expected
SUS-13-004 0-lep+1-lep (Razor) 19.3 fb⁻¹
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹
SUS-13-011 1-lep (leptonic stop)19.5 fb⁻¹ x=0.25
LSP mass [GeV]
stop mass [GeV]
g̃-g̃ production, g̃→ t t̄ χ̃⁰₁
CMS Preliminary
√s = 8 TeV
Nov 2013
Observed
Expected
SUS-12-024 0-lep 19.4 fb⁻¹
SUS-13-004 0+1-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep 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]
CMS Preliminary
Observed limits
SUS-13-006
SUS-13-017

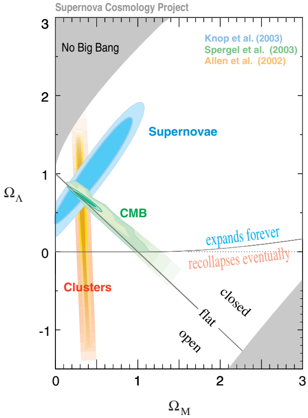

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lv)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
0 1 2 3 4 5
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
0 1 2 3 4 5
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
0 1 2 3 4 5
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
0 5 10 15
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5

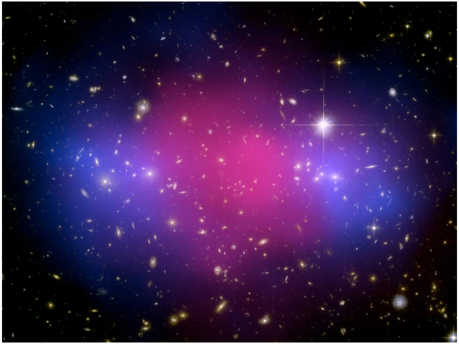

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)
Large ED (ADD) : monojet + E_T,miss
Large ED (ADD) : monophoton + E_T,miss
arge ED (ADD) : diphoton & dilepton, m_γγ / ll
UED : diphoton + E_T,miss
S1/Z2 ED : dilepton, m_ll
RS1 : diphoton & dilepton, m_γγ / ll
RS1 : ZZ resonance, m_llll / lljj
RS1 : WW resonance, m_T,lνlν
S g_KK→tt (BR=0.925) : tt → l+jets, m_tt,boosted
ADD BH (M_TH /M_D=3) : SS dimuon, N_ch. part.
ADD BH (M_TH /M_D=3) : leptons + jets, Σp_T
Quantum black hole : dijet, F_χ(m_jj)
L=4.7 fb-1, 7 TeV [1210.4491]
4.37 TeV
M_D (δ=2)
L=4.6 fb-1, 7 TeV [1209.4625]
1.93 TeV
M_D (δ=2)
L=4.7 fb-1, 7 TeV [1211.1150]
4.18 TeV
M_S (HLZ δ=3, NLO)
L=4.8 fb-1, 7 TeV [ATLAS-CONF-2012-072]
1.41 TeV
Compact. scale R-1
L=4.9-5.0 fb-1, 7 TeV [1209.2535]
4.71 TeV
M_KK ~ R-1
L=4.7-5.0 fb-1, 7 TeV [1210.8389]
2.23 TeV
Graviton mass (k/M_Pl = 0.1)
L=1.0 fb-1, 7 TeV [1203.0718]
845 GeV
Graviton mass (k/M_Pl = 0.1)
L=4.7 fb-1, 7 TeV [1208.2880]
1.23 TeV
Graviton mass (k/M_Pl = 0.1)
L=4.7 fb-1, 7 TeV [ATLAS-CONF-2012-136]
1.9 TeV
g_KK mass
L=1.3 fb-1, 7 TeV [1111.0080]
1.25 TeV
M_D (δ=6)
L=1.0 fb-1, 7 TeV [1204.4646]
1.5 TeV
M_D (δ=6)
L=4.7 fb-1, 7 TeV [1210.1718]
4.11 TeV
M_D (δ=6)
ATLAS
Preliminary
∫Ldt = (1.0 - 13.0) fb-1
√s = 7, 8 TeV

CMS Resonances Limits (Moriond 2013)



Evidence for Dark Matter (DM)



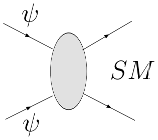


Bullet Cluster [Hubble+Chandra, NASA, ESA, CXC, M. Bradac (UCSB), and S. Allen (Stanford)]

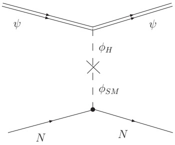
$\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

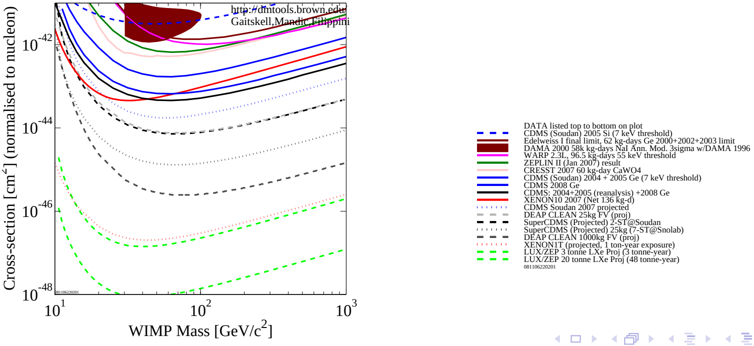
Particle Dark Matter (DM)

Self-Annihilation cross-section gives present DM Relic density



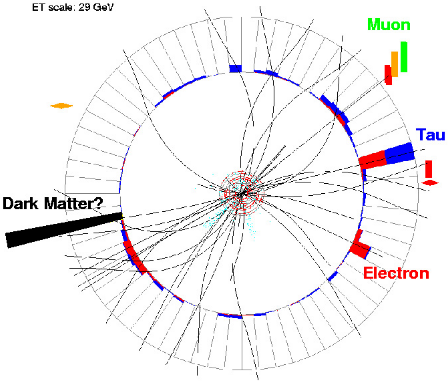
Direct Detection





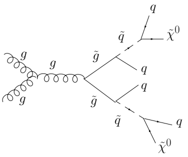
Dark Matter at the LHC?

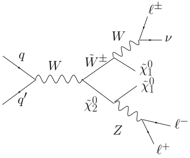
Missing momentum!

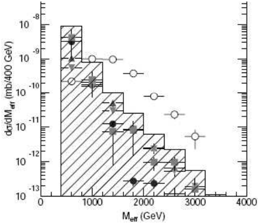


Supersymmetry (SUSY) at LHC

- Cascade decays
- Missing energy signals







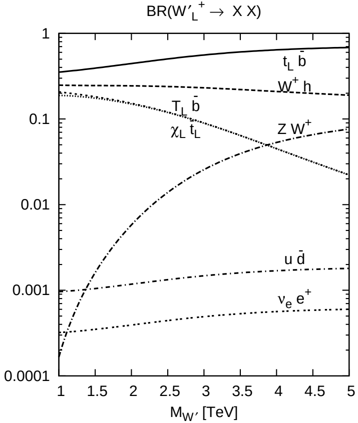
[ATLAS Physics TDR]

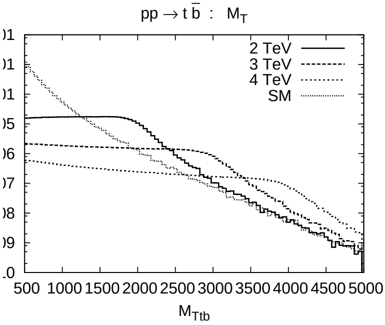
- Can we determine the spin and couplings to show SUSY?
  - Angular distributions

Composite Higgs/Warped Ex-Dim at LHC

Look for heavy Resonances/Kaluza-Klein states (Heavy Gluon, Graviton, W, Z)
LEP precision electroweak constraints $\Rightarrow V' \gtrsim 2\ TeV$

Example: $W' \to XX$ $\qquad pp \to W' \to t\bar{b} \to Wb\bar{b} \to \ell\nu b\bar{b}$





[Agashe, SG, Han, Huang, Soni, 2008]