



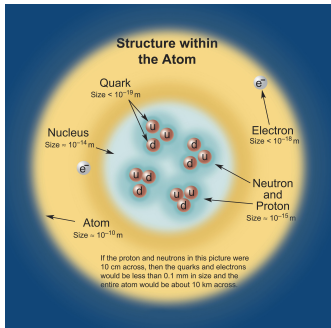
# Particle Physics

Quest to understand fundamental aspects of Nature



# Particle Physics

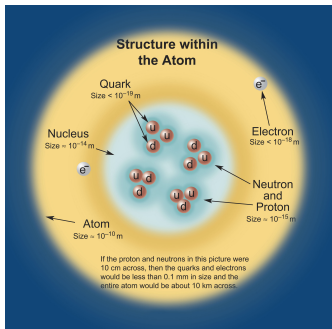
## Quest to understand fundamental aspects of Nature



[particleadventure.org]

# Particle Physics

Quest to understand fundamental aspects of Nature



[particleadventure.org]

## Standard Model (SM) of Particle Physics

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



# Natural units

- Natural Units

(velocity of light  $c = 1$ , Plancks constant  $\hbar = 1$ )

- $E = mc^2 \Rightarrow$  measure Energy ( $E$ ) & Mass ( $m$ )  
in **Giga-electron-Volts (GeV)**

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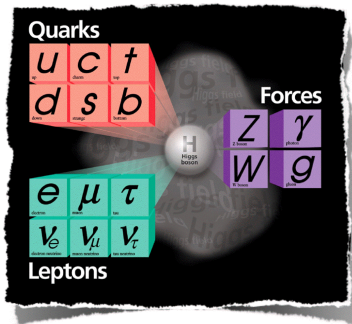
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## Examples

proton rest-mass  $m_p \approx 1$  GeV

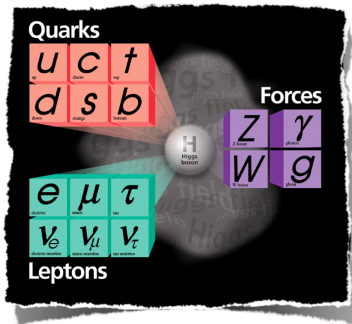
LHC energy is 13000 GeV = 13 Tera-eV (**TeV**)

# The Standard Model (SM) Particles



[Fermilab Visual Media]

# The Standard Model (SM) Particles



[Fermilab Visual Media]

## Unstable particles

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

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

# Experiments ↔ Quantum Field Theory (QFT)

- *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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- *Intensity Frontier* (Lower energy precision experiments)
  - Measure rare processes to high precision : reveal tiny effects of interesting physics; Rare effects due to
    - Tiny quantum effects of particle with  $M > E$
    - Suppressed couplings



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    - Suppressed couplings
- *Cosmic Frontier* (Astrophysics/Cosmology)
  - Known SM particles in thermal bath in the early Universe
  - Any new BSM particles?



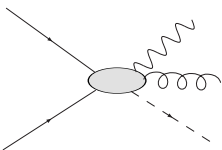
# Accelerators as microscopes

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

Electron Microscope ( $\lambda \approx 0.2 nm$ )

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

- LEP (CERN, Europe), Tevatron (Fermilab, USA):  $E \approx 100 \text{ GeV}$ ,  $\lambda \approx 10^{-18} m$
- **Large Hadron Collider** (LHC - CERN, Europe):  $E = 13000 \text{ GeV}$ ,  $\lambda \approx 10^{-19} m$   
(Since LHC is a proton-proton machine, pdf suppression)



Rules obeyed at these large  $E$ :

- Tiny particles, so **quantum mechanics**  
Boson (spin 0,1,2,...), Fermion (spin 1/2, 3/2, ...)
- $v \rightarrow c$ , so **special relativity**
- $E \gg m$ , so can **create/destroy particles**:  
but respect **conservation laws** (symmetries)

Combination is a relativistic **Quantum Field Theory (QFT)**



# Physics at a Collider

## Quantum Mechanics is probabilistic

- In given theory, predict probability of particle production and decay
- Compare to event rate observed at a collider - tests the theory
  - 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

# Physics at a Collider

## Quantum Mechanics is probabilistic

- In given theory, predict probability of particle production and decay
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  - Counting experiment - **Statistical Evidence!**

Similarly, if expt. results agree with new theory

- Theory established!



# Physics at a Collider

## Quantum Mechanics is probabilistic

- In given theory, predict probability of particle production and decay
- Compare to event rate observed at a collider - tests the theory
  - Counting experiment - **Statistical Evidence!**

## Disagree?

- Consider alternate theory

# Physics at a Collider

## Quantum Mechanics is probabilistic

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  - Counting experiment - **Statistical Evidence!**

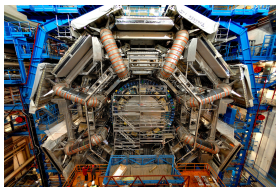
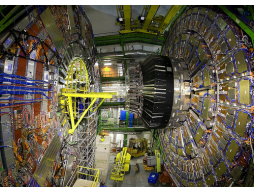
### Eg: Higgs in $\gamma\gamma$ channel

Theoretically compute the cross-section (probability)  $\sigma$

- “signal” cross-section  $\sigma(pp \rightarrow h \rightarrow \gamma\gamma)$ 
  - “background” cross-section  $\sigma(pp \rightarrow \gamma\gamma)$

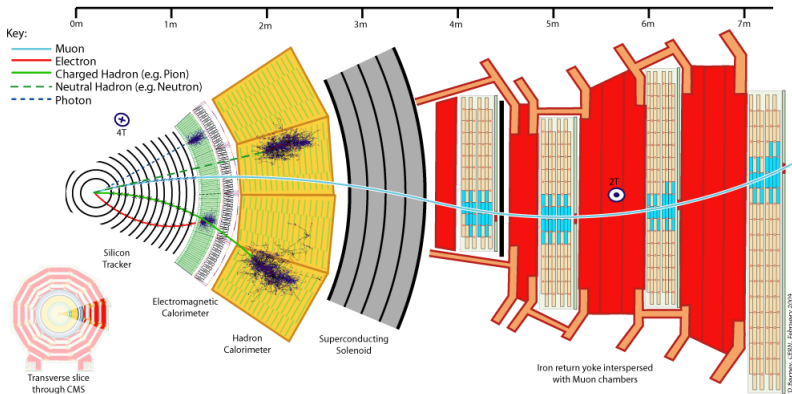
At LHC establish signal over background to discover Higgs

# The Large Hadron Collider (LHC)

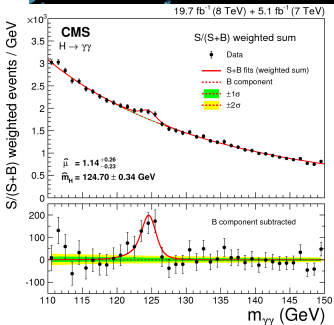
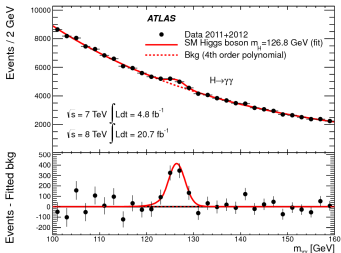
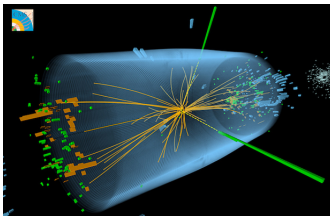
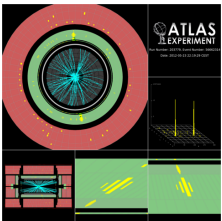


LHC discovered the Higgs. Continue searching for more ...

# Particle Detectors



# Higgs discovery @ LHC



# The expanding universe



Vesto Slipher : measured **Red-shift** (Doppler shift) of galaxies (1917) :  $z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$

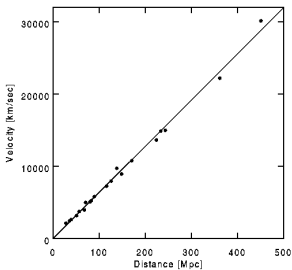
Georges Lemaître : Universe is expanding (1927)  
origin is *Big-bang*:  $t \rightarrow 0$ ,  $T \rightarrow \infty$ ,  $a \rightarrow 0$

Edwin Hubble:  $v = H_0 d$  ( $H_0$  : Hubble constant) (1929)  
 $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [Planck 2018]  
 $H_0 = 74 \pm 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [Local] **Hubble tension!**

**Friedman-Lemaître-Robertson-Walker (FLRW) metric:**

$$ds^2 = dt^2 - a^2(t) \left( \frac{1}{1-kr^2} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right)$$

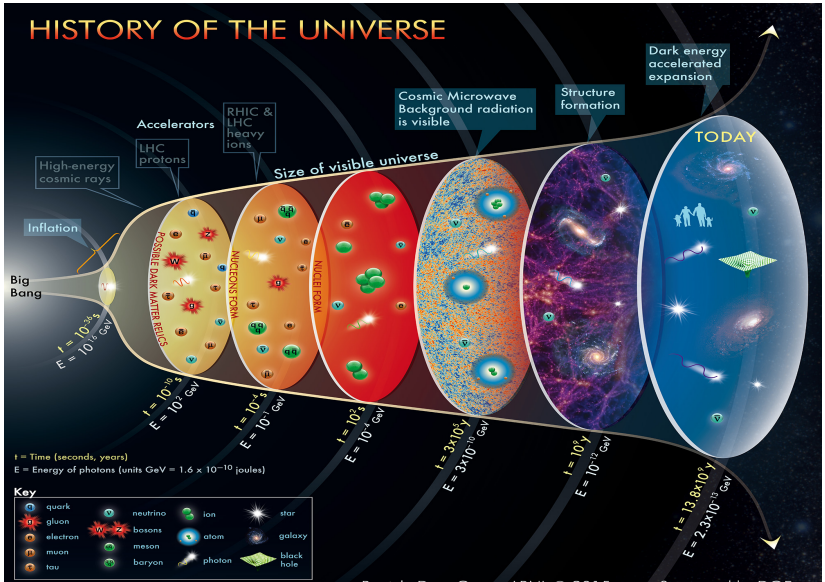
- Universe expanding and cooling  $T \sim 1/a$ ,  $z = \frac{1-a}{a}$
- **particle physics: scattering, decay rates**
  - particle of mass  $m$  in the thermal bath at  $T > m$



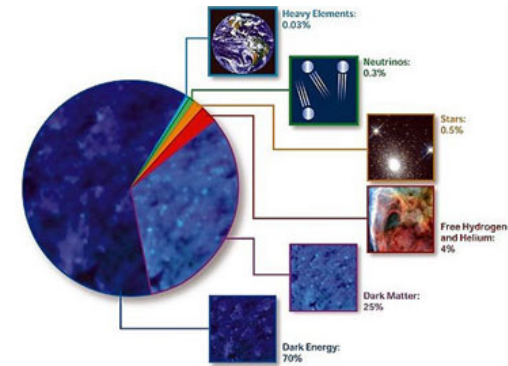
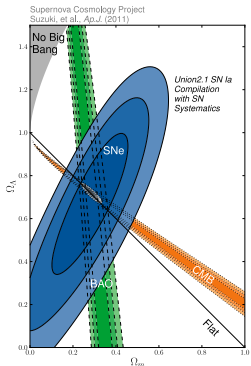
[Riess, Press and Kirshner (1996)]



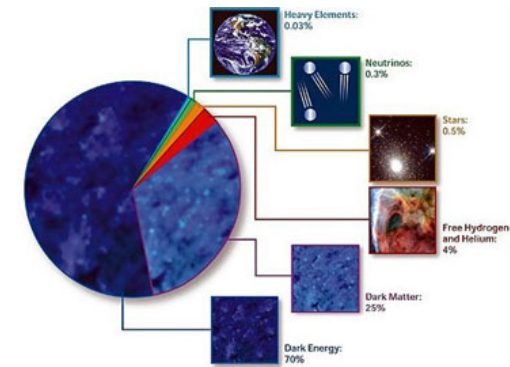
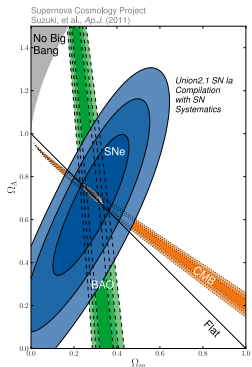
# Particle Physics in the Hot Early Universe



# Inference

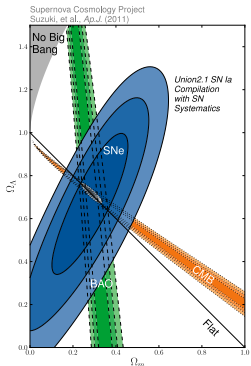


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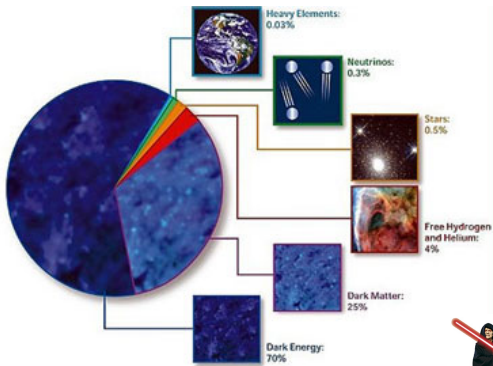


- Flat on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter** + **dark energy**
  - What is it? Evidence for **BSM Physics**?

# Inference



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The **DARK SIDE** rules!

# Quantum Field Theory (QFT) framework

- **Special Relativity**
- Quantum Mechanics
- Create/destroy particles

Symmetries:

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

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

4-momentum:  $p^\mu = (E, \vec{p})$

Lorentz invariance (rotations, boosts)

Translation invariance



# Quantum Field Theory (QFT) framework

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## Uncertainty Principle

- $\Delta p \Delta x \geq \hbar$

- $\Delta E \Delta t \geq \hbar$

⇒ Virtual Particles



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## Dirac theory

Matter ↔ Anti-matter

- electron ↔ positron
- proton ↔ 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:

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

# 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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$SU(2)_L \otimes U(1)_Y$  Spontaneously broken to  $U(1)_{EM} \Rightarrow$  **Massive Weak gauge bosons**  
The Brout-Englert-Guralnik-Hagen-Higgs-Kibble Mechanism



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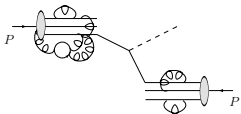
**SM is spectacularly successful!**

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



# Higgs Production @ LHC

LHC is a  $p - p$  collider



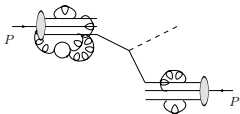
$p$  contains partons:  $g, u, d, \bar{u}, \bar{d}, \dots$

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

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

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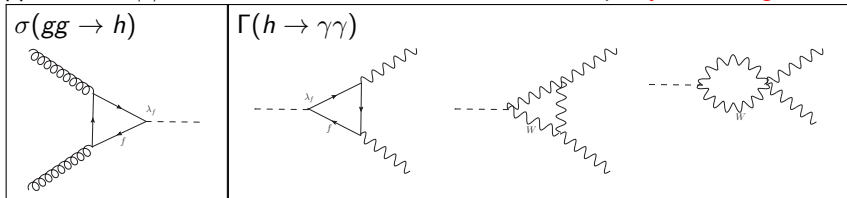
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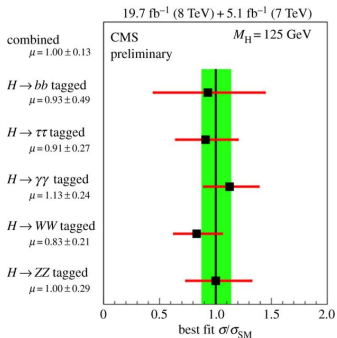
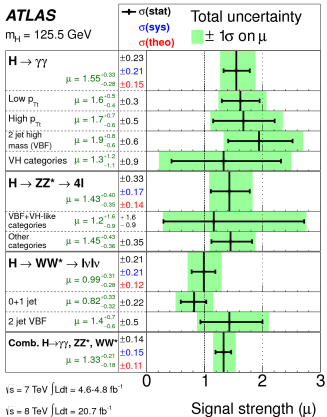
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$pp \rightarrow h \rightarrow \gamma\gamma$  @ LHC

Loop Feynman Diagrams



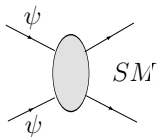
# LHC Higgs Measurements



# Particle Dark Matter (DM)

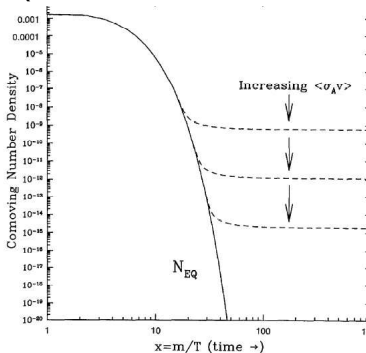
Early Universe: incomplete self-annihilation leaves relic  $\rightarrow$  DM

**Freeze-out** rate computed in QFT to find the relic number density



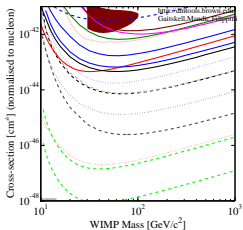
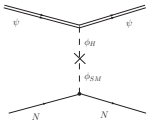
$$\Omega_0 h^2 = 10^{-29} x_f \left( \frac{eV^{-2}}{\langle \sigma v \rangle} \right)$$

$$x_f \equiv M_\psi / T_f \approx 21$$

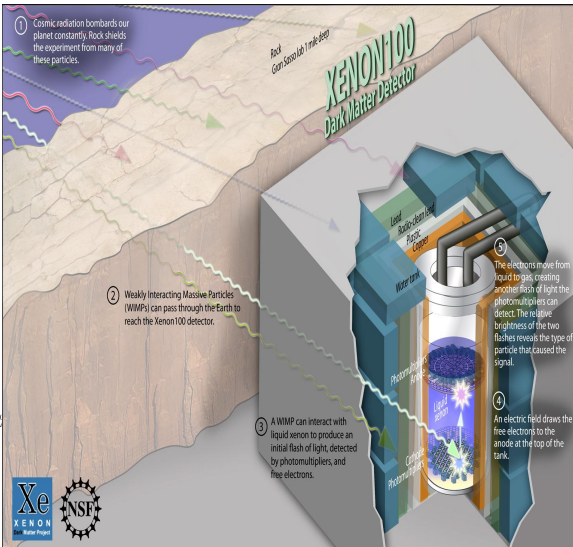


[Kolb & Turner]

## Direct Detection

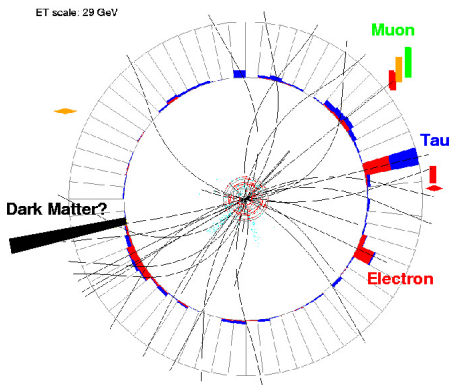


- DATA listed top to bottom on plot
- CDMS (Soudan) 2005 Si (7 keV threshold)
- Edelweiss I final limit, 62 kg-days Ge 2000+2002+2003
- DAMA 2000 58kg kg-days NaI Ann. Mod. 3sigma w/D.
- WARP 2.3L 96.5 kg-days 55 keV threshold
- ZEPLIN II (Jan 2007) result
- CRESST 2007 60 kg-days CaWO4
- CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
- CDMS 2008 Ge
- CDMS: 2004+2005 (reanalysis) +2008 Ge
- XENON10 2007 (Net 136 kg-d)
- CDMS Soudan 2007 projected
- DEAP-CLEAN 25kg FV (proj)
- SuperCDMS (Projected) 2-ST @Soudan
- SuperCDMS (Projected) 25kg (7-ST @Snolab)
- DEAP-CLEAN 1000kg FV (proj)
- XENON1T (projected, 1 ton-year exposure)
- LUX-ZEP 3 tonne L-Xe Proj (3 tonne-year)
- LUX-ZEP 20 tonne L-Xe Proj (48 tonne-year)



# Dark Matter at the LHC?

## Missing momentum!



# Summary

- The Standard Model of Particle Physics is spectacularly successful
  - $SU(3)_c \times SU(2)_L \times U(1)_Y$  gauge theory: Quantum Field Theory (QFT)
  - Electroweak Symmetry Breaking by the Higgs mechanism
- The Standard Model of Cosmology is spectacularly successful
  - FLRW metric, cosmological principle
    - small perturbations for structure
- Standard Model has shortcomings : BSM new physics resolves these?
  - Observational: Dark Matter, Baryon Asymmetry of Universe,  $\nu$  mass
  - Theoretical: Gauge & flavor hierarchy problems, strong  $CP$  problem
  - Hubble tension?
- **Ongoing and future experiments should reveal more insights**
  - LHC high luminosity run
  - Precision experiments
  - Cosmology/Astrophysics experiments



# BACKUP SLIDES

BACKUP SLIDES



# The Building Blocks

FERMIONS			matter constituents spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino*	$(0-0.13)\times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_\mu$ middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
<b>W<sup>-</sup></b>	80.39	-1	<b>Higgs Boson spin = 0</b>		
<b>W<sup>+</sup></b>	80.39	+1	Name	Mass GeV/c <sup>2</sup>	Electric charge
W bosons			<b>H</b> Higgs	126	0
<b>Z<sup>0</sup></b>	91.188	0			
Z boson					

[particleadventure.org]

- 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



# The Building Blocks

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## Unstable particles

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

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

# Standard Model Interactions

Electromagnetism (Quantum Electro Dynamics)

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



# Standard Model Interactions

## Electromagnetism (Quantum Electro Dynamics)

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

## Strong interactions (Quantum Chromo Dynamics)

... 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 <sup>2</sup>	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
$\Lambda$	lambda	<b>uds</b>	0	1.116	1/2
$\Omega^-$	omega	<b>sss</b>	-1	1.672	3/2

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$\rho^+$	rho	<b>u</b> $\bar{\mathbf{d}}$	+1	0.776	1
$\mathbf{B}^0$	B-zero	<b>d</b> $\bar{\mathbf{s}}$	0	5.279	0
$\eta_c$	eta-c	<b>c</b> $\bar{\mathbf{c}}$	0	2.980	0

[particleadventure.org]

# Standard Model Interactions

## Electromagnetism (Quantum Electro Dynamics)

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

## Strong interactions (Quantum Chromo Dynamics)

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

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## Weak interactions

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



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[particleadventure.org]

## Weak interactions

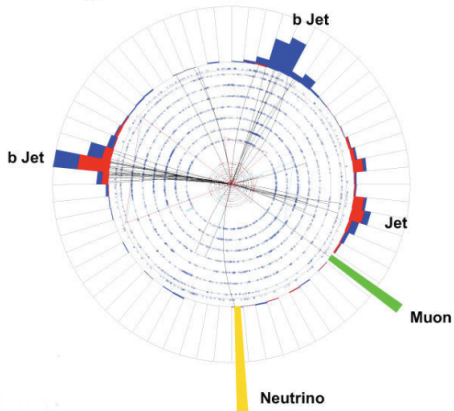
... causes radioactive decay: eg.  ${}_{27}^{60}\text{Co} \rightarrow {}_{28}^{60}\text{Ni} + e^- + 2\gamma$

## Gravity

... causes us to fall and break our bones



# Event reconstruction

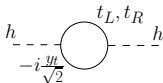


D0 Single Top Event (Tevatron)

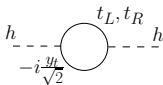
# Hierarchy problem in detail

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

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



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



( $\Lambda$  is momentum cut-off, say  $M_{pl}$ )

Quadratic divergence in the Higgs sector

# Spontaneous Symmetry Breaking (SSB)

Microscopic laws symmetric, but ground state is NOT

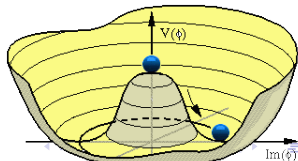
## Analogy

Spontaneous Magnetization in Condensed Matter Systems

[Fig by F. Heylighen]

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  $W^\pm$ ,  $Z$  ( $\gamma$  massless)
- Generates fermion masses



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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"*

# Are we done?

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

I don't think so ...



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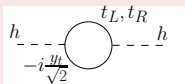
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## Stability problem

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


 $\delta m_h^2$ 


# Are we done?

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## A nagging possibility

... that there is no dynamical explanation. Our vacuum could be just one in a vast **landscape** of vacua. 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 instability):  $M_{EW} \ll M_{Pl}$
- Flavor problem:  $m_e \ll m_t$
- Strong CP problem
- Cosmological constant problem

We are intensely searching for physics Beyond the Standard Model (BSM)  
... Stay Tuned!



# Some new physics possibilities

Belief that something may cure the gauge hierarchy problem. [But what?](#)



# Some new physics possibilities

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

- Supersymmetry
- Extra-dimensions
- Strong dynamics
- Little Higgs



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Neutrino mass generation and lepton number violation

- $\mathcal{CP}$  violation & Leptogenesis



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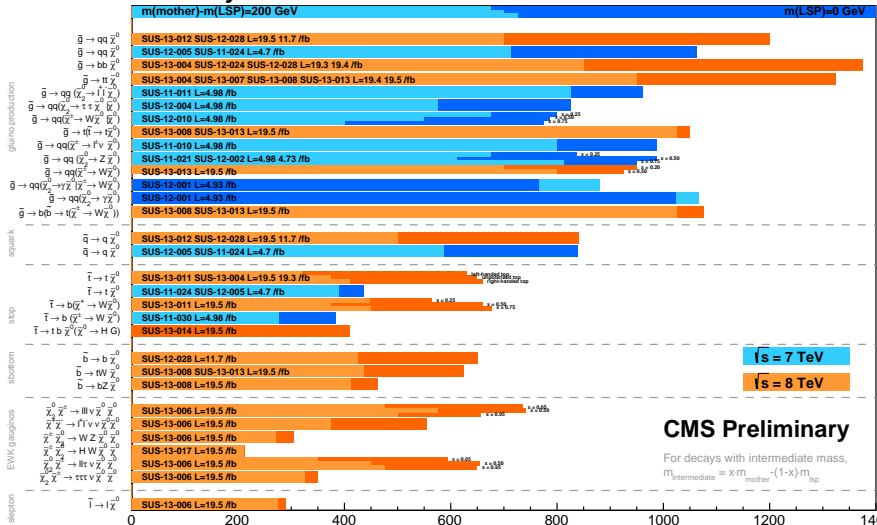
Baryon Number ( $B$ ) appears to be conserved - is it really?

- 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 of CMS SUSY Results\* in SMS framework

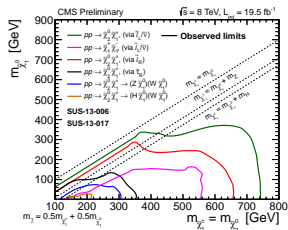
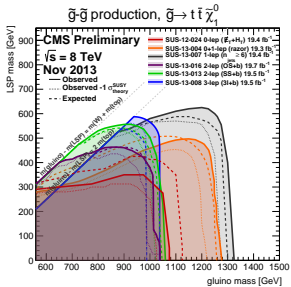
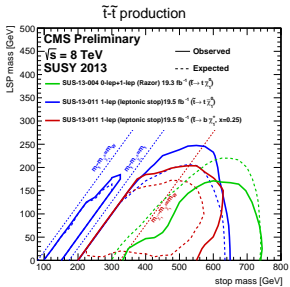
SUSY 2013



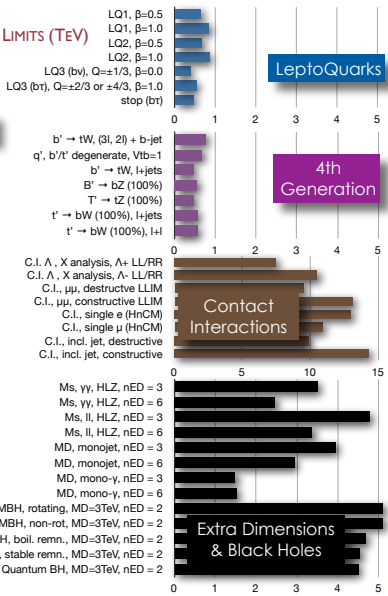
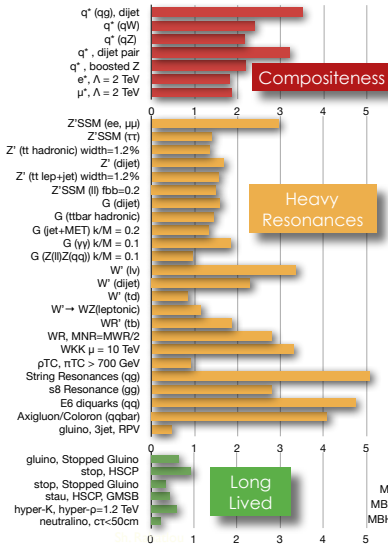
**CMS Preliminary**

For decays with intermediate mass,  
 $m_{\text{intermediate}} = x m_{\text{mother}} - (1-x) m_{\text{LSP}}$

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



# CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



## ATLAS Exotics Searches\* - 95% CL Lower Limits (Status: HCP 2012)

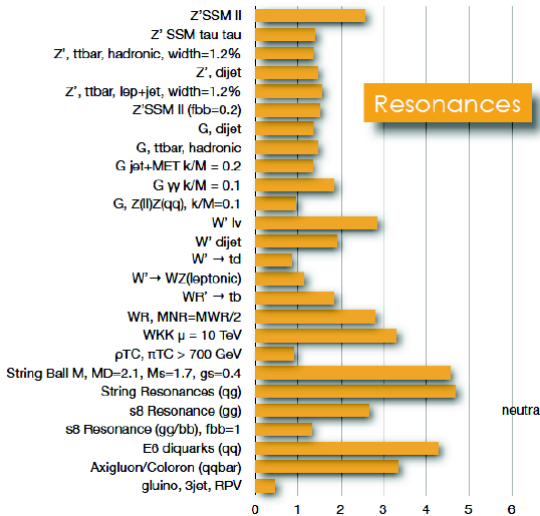
Large ED (ADD) : monojet + $E_{T,miss}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1210.4491]	4.37 TeV	$M_D (\delta=2)$
Large ED (ADD) : monophoton + $E_{T,miss}$	$L=4.6 \text{ fb}^{-1}, 7 \text{ TeV}$ [1209.4525]	1.93 TeV	$M_D (\delta=2)$
Large ED (ADD) : diphoton & dilepton, $m_{\gamma\gamma}/ll$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1211.1150]	4.18 TeV	$M_S$ (HLZ $\delta=3$ , NLO)
UED : diphoton + $E_{T,miss}$	$L=4.8 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CORF-2012-072]	1.41 TeV	Compact scale $R^{-1}$
$S/Z$ , ED : dilepton, $m_{ll}$	$L=4.9-5.3 \text{ fb}^{-1}, 7 \text{ TeV}$ [1209.2535]	4.71 TeV	$M_{KK} - R^{-1}$
RS1 : diphoton & dilepton, $m_{\gamma\gamma}/ll$	$L=4.7-5.3 \text{ fb}^{-1}, 7 \text{ TeV}$ [1210.3330]	2.23 TeV	Graviton mass ( $k/M_{pl} = 0.1$ )
RS1 : ZZ resonance, $m_{ll}/ll\gamma$	$L=1.0 \text{ fb}^{-1}, 7 \text{ TeV}$ [1203.0718]	845 GeV	Graviton mass ( $k/M_{pl} = 0.1$ )
RS1 : WW resonance, $m_{ll}/ll\gamma$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1208.2383]	1.23 TeV	Graviton mass ( $k/M_{pl} = 0.1$ )
RS $g_{KK} \rightarrow tt$ (BR=0.925) : $tt \rightarrow l+jets$ , $m_{jj,boosted}$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [ATLAS-CORF-2012-136]	1.9 TeV	$g_{KK}$ mass
ADD BH ( $M_{TH}/M_D=3$ ) : SS dimuon, $N_{obs,part}$	$L=1.3 \text{ fb}^{-1}, 7 \text{ TeV}$ [1111.0680]	1.25 TeV	$M_S (\delta=6)$
ADD BH ( $M_{TH}/M_D=3$ ) : leptons + jets, $\Sigma p_T$	$L=1.0 \text{ fb}^{-1}, 7 \text{ TeV}$ [1204.4545]	1.5 TeV	$M_D (\delta=6)$
Quantum black hole : dijet, $F(m_j)$	$L=4.7 \text{ fb}^{-1}, 7 \text{ TeV}$ [1210.1718]	4.11 TeV	$M_D (\delta=6)$

ATLAS  
Preliminary

$$\int L dt = (1.0 - 13.0) \text{ fb}^{-1}$$

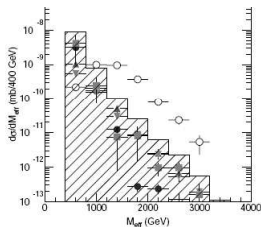
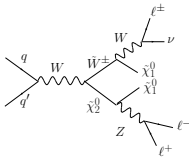
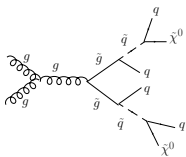
$$\sqrt{s} = 7, 8 \text{ TeV}$$

# CMS Resonances Limits (Moriond 2013)



# Supersymmetry (SUSY) at LHC

- Cascade decays
- Missing energy signals



[ATLAS Physics TDR]

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

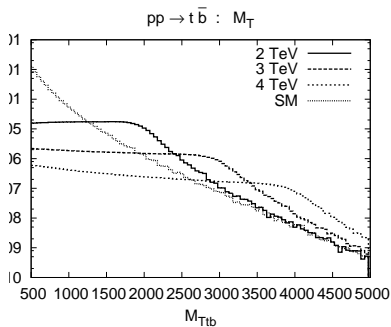
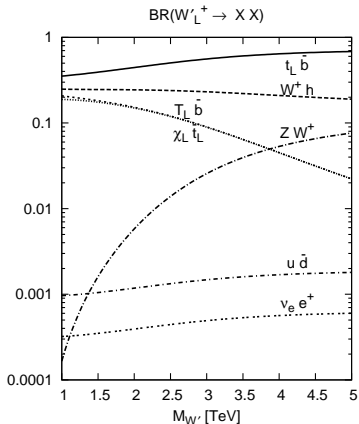
# Composite Higgs/Warped Ex-Dim at LHC

Look for heavy Resonances/Kaluza-Klein states (Heavy Gluon, Graviton, W, Z)

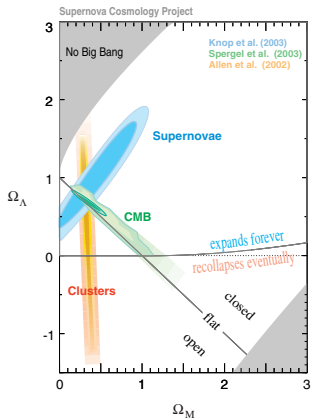
LEP precision electroweak constraints  $\Rightarrow V' \gtrsim 2 \text{ TeV}$

Example:  $W' \rightarrow XX$

$pp \rightarrow W' \rightarrow t\bar{b} \rightarrow Wb\bar{b} \rightarrow \ell\nu b\bar{b}$



# Evidence for Dark Matter (DM) → BSM physics?



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

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

