What is Theory Driving Experiment to Do? - Discussion -

Ray Volkas & Tony Williams
University of Melbourne
University of Adelaide

CoEPP Tropical Workshop, Cairns, July 12, 2013

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Contents

Key Theory Drivers

- **In scope for this discussion:**
  - Is the "Higgs resonance" the SM Higgs? - (scalar? just one? correct branching ratios? self-couplings?)
  - Do we understand EWSB now?
  - Can we resolve the Higgs mass hierarchy problem?
  - Can we find a "natural" BSM framework consistent with experiment? (e.g., light Higgs, EW Prec Tests)
  - Where are the "new physics" (i.e., BSM) particles?
  - How many neutrinos are there? Sterile neutrinos? Majorana or Dirac?
  - What are the neutrino masses and mixing angles?
  - Why is strong (QCD) CP violation so small?
  - What is the origin of the cosmological matter-antimatter asymmetry? Where is the extra CP violation?
  - Can we find viable GUT theories?

Key Theory Drivers

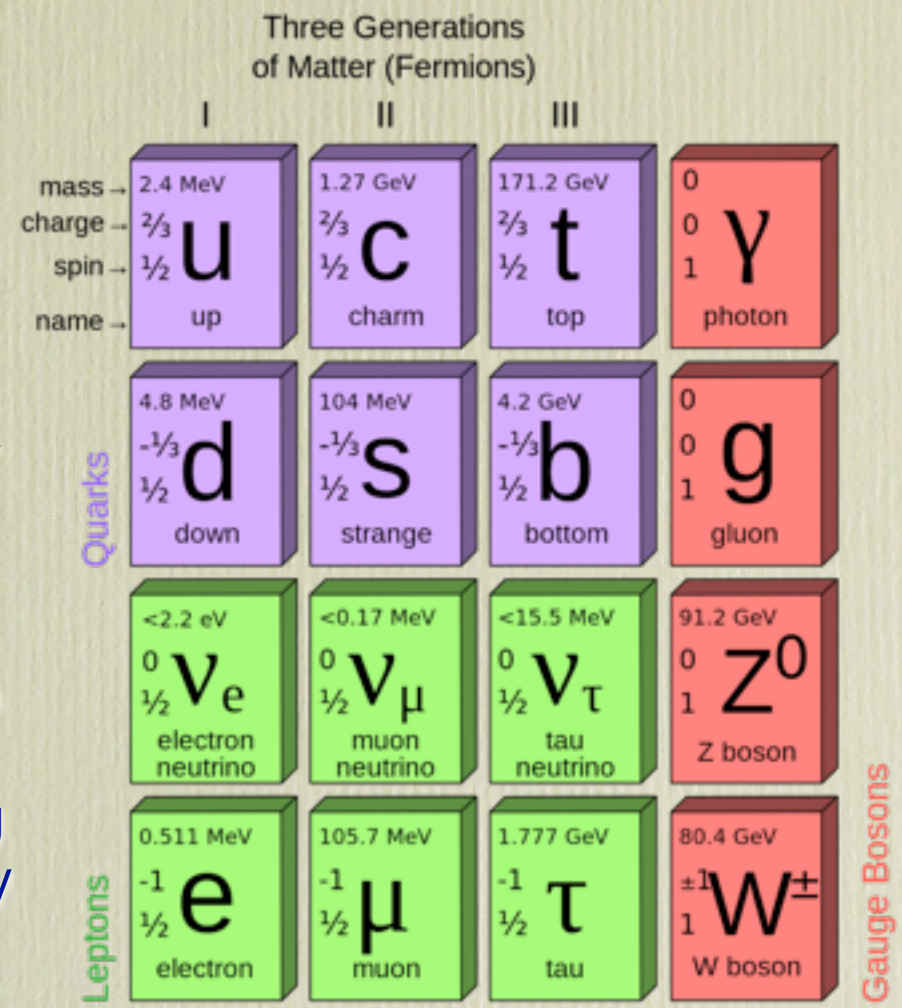
- **In scope for this discussion (continued):**
  - What is Dark Matter? Does it feel the weak force? Other forces?
  - How to detect DM and learn about its properties?
  - Are surviving global symmetries absolute? - baryon and lepton number
- **... and perhaps**
  - Is Lorentz invariance/CPT violated?

Key Theory Drivers

- **Out of scope for this discussion:**
  - Why is the expansion of the universe accelerating?
  - What is Dark Energy?
  - Is Dark Energy the cosmological constant Λ?
  - Why is Λ a tiny $\simeq 10^{-47}\text{GeV}^4$, i.e., why is it
    - approx 10^{120} times smaller than its natural size of $(\Lambda_{\text{Planck}})^4 \simeq (10^{19}\text{GeV})^4 \simeq 10^{76}\text{GeV}^4$?
    - approx 10^{46} times smaller than the contribution arising from the quark condensate of QCD?
  - Should zero-point energies and condensates of QFTs be interpreted as contributing to the cosmological constant?
  - How can we include gravity with GUTS & progress to a TOE?

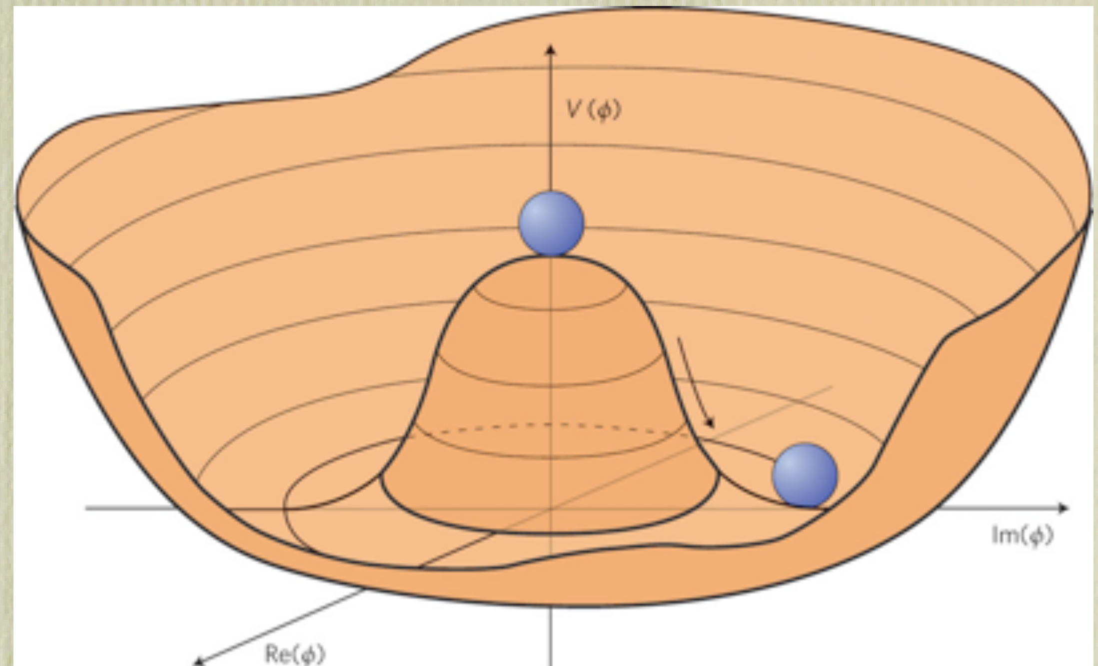
What the Standard Model is

- Combines strong, e.m and weak interactions into a single framework
- Based on flat spacetime and Poincare invariance (Lorentz + translational inv)
- Built on massless gauge theories - color $SU(3)_C$, weak left isospin $SU(2)_L$ and weak hypercharge $U(1)_Y$:
  - Gauge structure: $SU(3)_C x SU(2)_L x U(1)_Y$
  - Electroweak (EW) sector: $SU(2)_L x U(1)_Y$
  - Strong/QCD sector: $SU(3)_C$
- **PLUS** Higgs particle - a complex *scalar* spinor of $SU(2)_L$ that couples to:
  - Gauge bosons in EW sector, but not to strong sector gauge bosons
  - All fermions through a Yukawa coupling (except neutrinos since they are only left-handed)
- **PLUS** spontaneous breaking of the EW gauge symmetry - Higgs mechanism



Higgs mechanism

$$
\begin{aligned}
\mathcal{L} = &-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&+ i\bar{\Psi}\not{D}\Psi + h.c. \\
&+ \Psi_i y_{ij}\Psi_j\Phi + h.c. \\
&+ |D_\mu\Phi|^2 - V(\Phi)
\end{aligned}
$$



- The SM lagrangian density depends on 19 parameters in total:
  - Line 1: KE term for all gauge bosons
  - Line 2: KE term for all fermions + fermion-gauge boson coupling
  - Line 3: Yukawa coupling of Higgs to fermions
  - Line 4:
    - First term: KE term for Higgs + Higgs-gauge boson coupling
    - Second term: Higgs potential that causes spontaneous EW symmetry breaking (EWSB) + fermion, W^+, W^- and Z^0 masses.

Standard Model Parameters

- 19 SM Parameters:
  - 3 lepton masses
  - 6 quark masses
  - 4 CKM parameters
  - 3 gauge couplings
  - 1 QCD CP angle
  - 1 Higgs VEV
  - 1 Higgs mass
- Photon and gluons stay massless after EWSB
- In the SM the neutrinos are also massless

Parameters of the Standard Model

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV (tentative)

EW Precision Tests

- Precision Measurements from the Large Electron-Positron (LEP) Collider at CERN
  - Excellent agreement with the SM
  - Any variation to the SM must be consistent with these - a strong constraint!

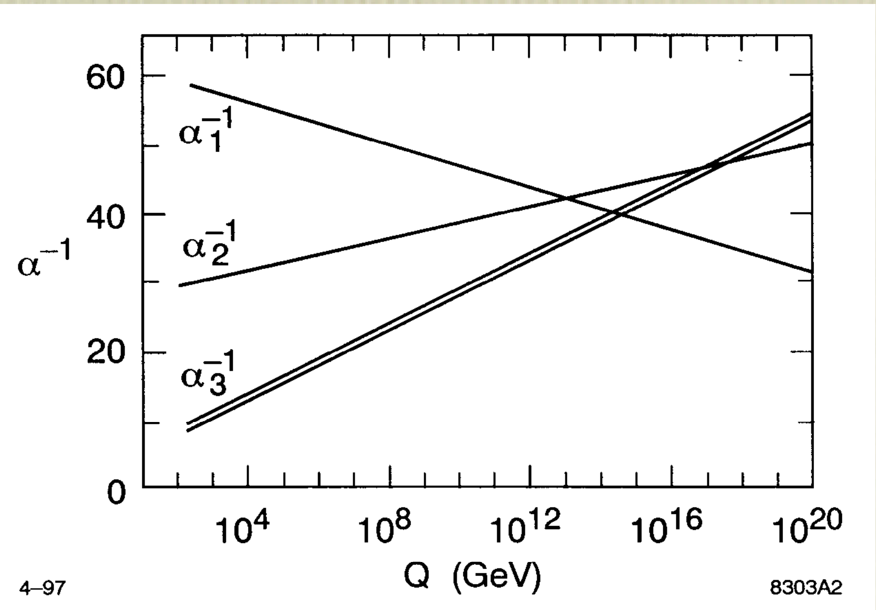
Abstract: Electroweak measurements performed with data taken at the electron-positron collider LEP at CERN from 1995 to 2000 are reported. The combined data set considered in this report corresponds to a total luminosity of about 3 fb^{-1} collected by the four LEP experiments ALEPH, DELPHI, L3 and OPAL, at centre-of-mass energies ranging from 130 GeV to 209 GeV.

From: CERN-PH-EP/2013-022 arXiv: 1302.3415 [hep-ex] February 14th, 2013 Submitted to Physics Reports

		Measurement with Total Error	Systematic Error	Standard-Model fit	Pull
	$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$ [321]	0.02750 ± 0.00033		0.02759	-0.3
a)	LEP-I				
	line-shape and				
	lepton asymmetries:				
	m_Z [GeV]	91.1875 ± 0.0021	$^{(a)}0.0017$	91.1874	0.0
	Γ_Z [GeV]	2.4952 ± 0.0023	$^{(a)}0.0012$	2.4959	-0.3
	$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	$^{(b)}0.028$	41.478	1.7
	R^0_ℓ	20.767 ± 0.025	$^{(b)}0.007$	20.742	1.0
	$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	$^{(b)}0.0003$	0.0164	0.7
	+ correlation matrix [4]				
	τ polarisation:				
	$\mathcal{A}_\ell$ ($\mathcal{P}_\tau$)	0.1465 ± 0.0033	0.0016	0.1481	-0.5
	$q\overline{q}$ charge asymmetry:				
	$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.0010	0.231439	0.8
b)	SLD				
	$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0010	0.1481	1.6
c)	LEP-I/SLD Heavy Flavour				
	R^0_b	0.21629 ± 0.00066	0.00050	0.21579	0.8
	R^0_c	0.1721 ± 0.0030	0.0019	0.1723	-0.1
	$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	0.0007	0.1038	-2.9
	$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.0017	0.0742	-1.0
	$\mathcal{A}_b$	0.923 ± 0.020	0.013	0.935	-0.6
	$\mathcal{A}_c$	0.670 ± 0.027	0.015	0.668	0.1
	+ correlation matrix [4]				
d)	LEP-II and Tevatron				
	m_W [GeV] (LEP-II, Tevatron)	80.385 ± 0.015		80.377	0.5
	Γ_W [GeV] (LEP-II, Tevatron)	2.085 ± 0.042		2.092	-0.2
	m_t [GeV] (Tevatron [307])	173.2 ± 0.9		173.3	-0.1

SM Incomplete ⇒ BSM Physics

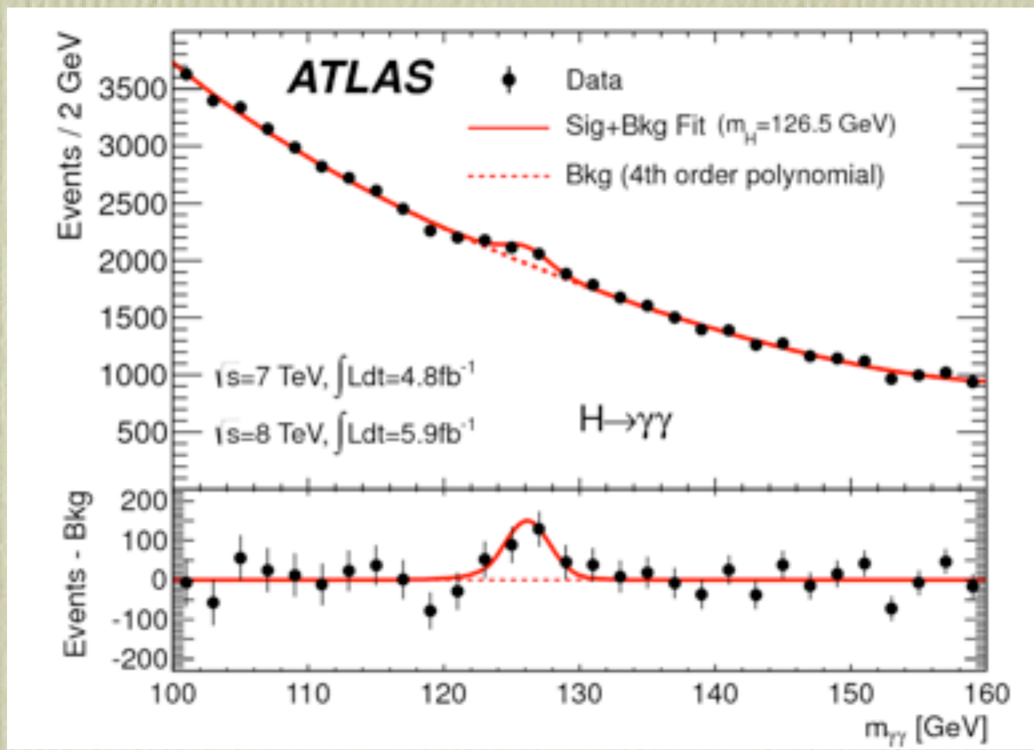
- SM is incomplete, since e.g.
  - No ν mass ⟹ can't explain ν mixing, but SM easily extended
  - No Dark Matter
  - Unsuccessful baryogenesis
  - No gravity
  - No Dark Energy
  - No explanation of Higgs mass hierarchy problem
  - Not a GUT - convergence of Weak, EM, Strong couplings at $\Lambda_{GUT} \simeq 10^{16}$GeV ⟹ expect single GUT gauge group
    - e.g., SO(10) ⊃ SU(5) ⊃ SU(3)xSU(2)xU(1)

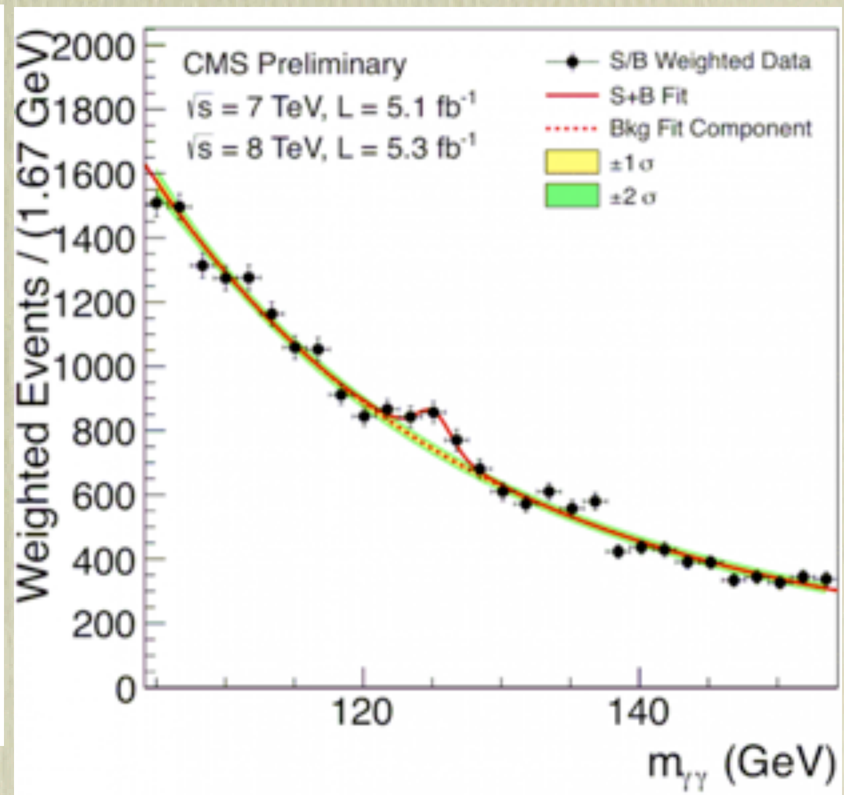


Renormalization causes SM couplings to approach each other at the GUT scale, $\Lambda_{GUT} \simeq 10^{16}$GeV
(from Peskin, SLAC-PUB-7479 - one loop result)

- *... but where is **direct** expt evidence of BSM physics?*

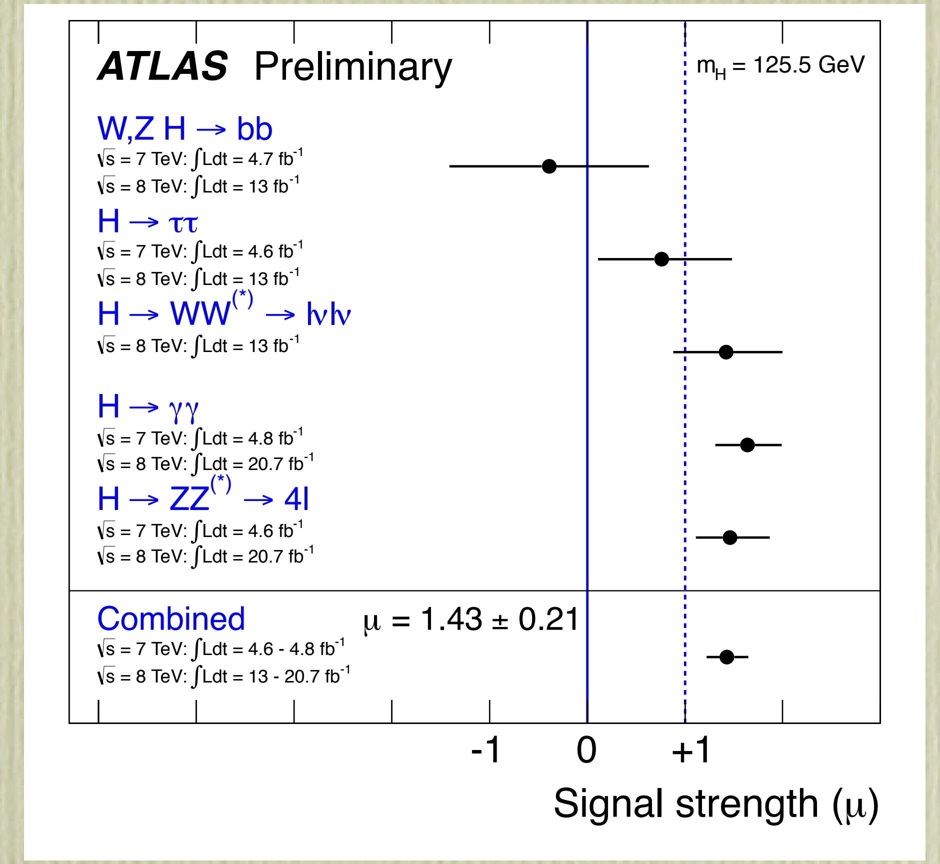
LHC: Higgs resonance

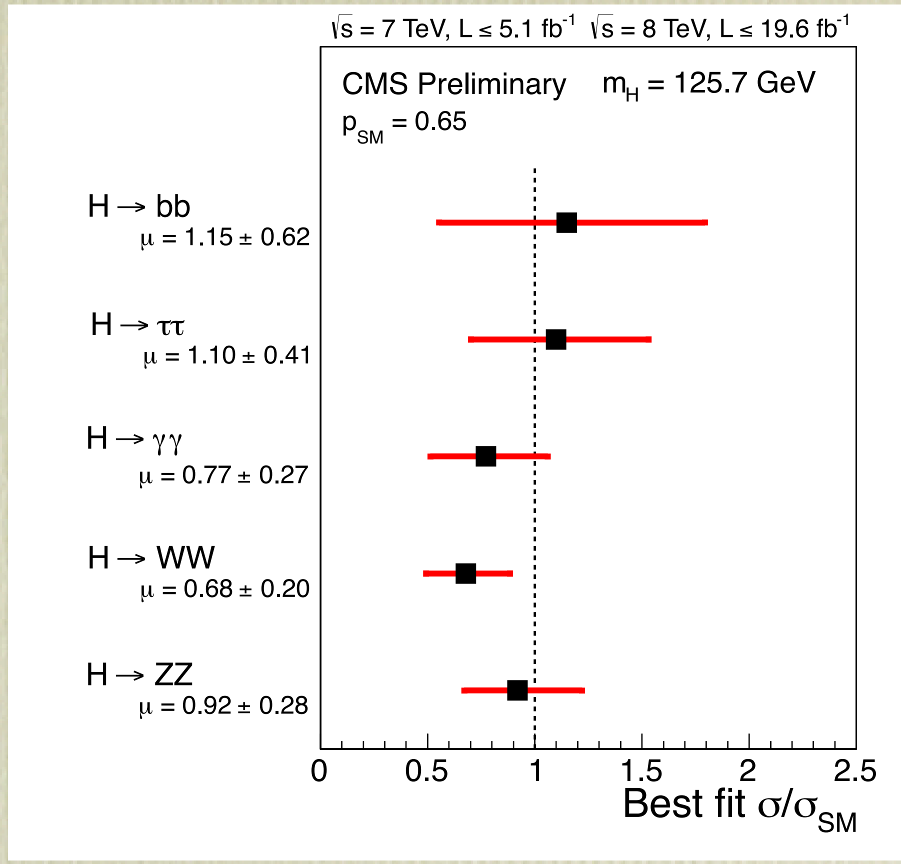




- The *"obvious"*:
  - Need increased precision to constrain Higgs parameters
  - Need to establish if spin and parity is that of a scalar
  - Need to explore if there is only one "Higgs resonance"

LHC: Higgs Branching Ratios



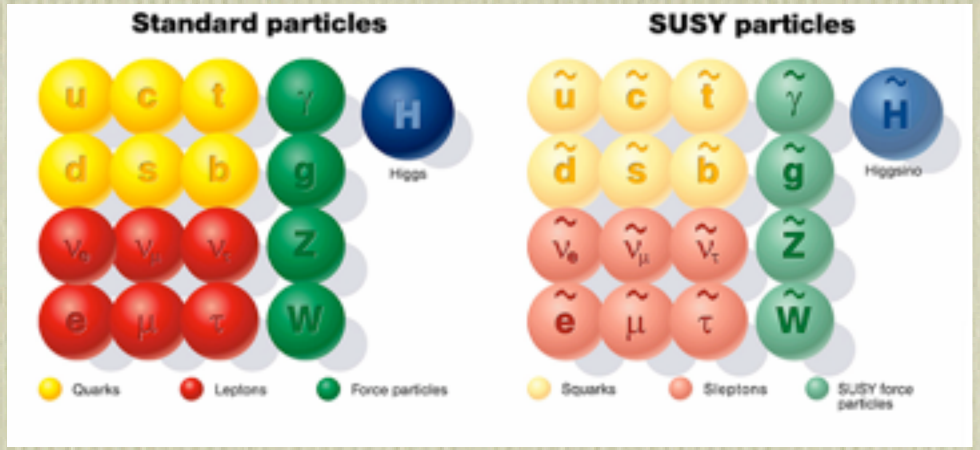


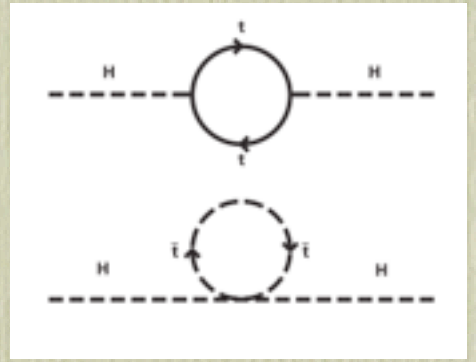
- Resonance at 125-126 GeV in multiple channels in ATLAS & CMS
  - Production rates *c.f.* SM consistent within errors (< 1.5 std dev)
  - *Also obvious:* need highest possible precision measurements, since deviations from SM signal strength ⟹ BSM physics

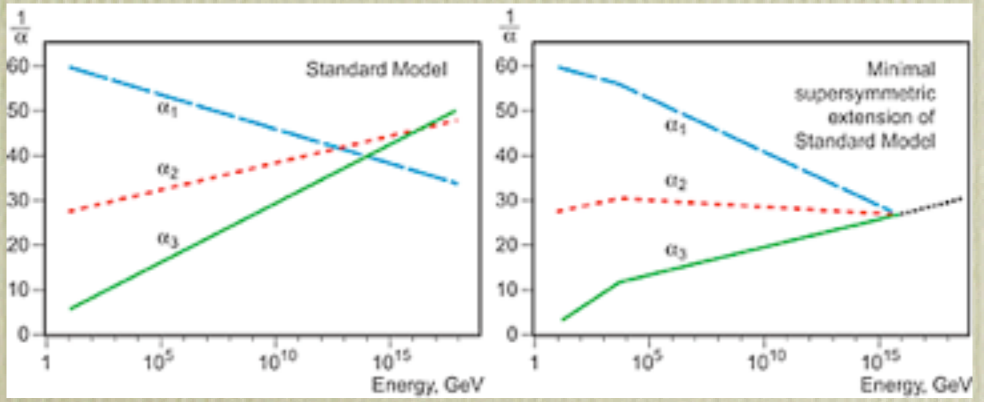
Naturalness and Fine-Tuning

- *Theoretical prejudices:*
  - *Naturalness:* A theory is unnatural if it must use a parameter space relation or region (e.g. hierarchy) that is unstable under radiative corrections.
  - *Fine-tuning:* Protecting a tree-level relation or region from large radiative corrections requires a contrived fine-tuning in unnatural theories.
- Special relations or regions OK if symmetry increased there
- Incomplete theories: Lack of naturalness and/or presence of fine-tuning $\Longrightarrow$ expect there is some missing symmetry or principle
- Principles invoked to choose between different theories - they extend the concept of "Occam's razor"
- Anthropic principle: Sometimes invoked to explain fine-tuning (e.g., 10^{120} cosmological constant problem)

LHC: Search for SUSY





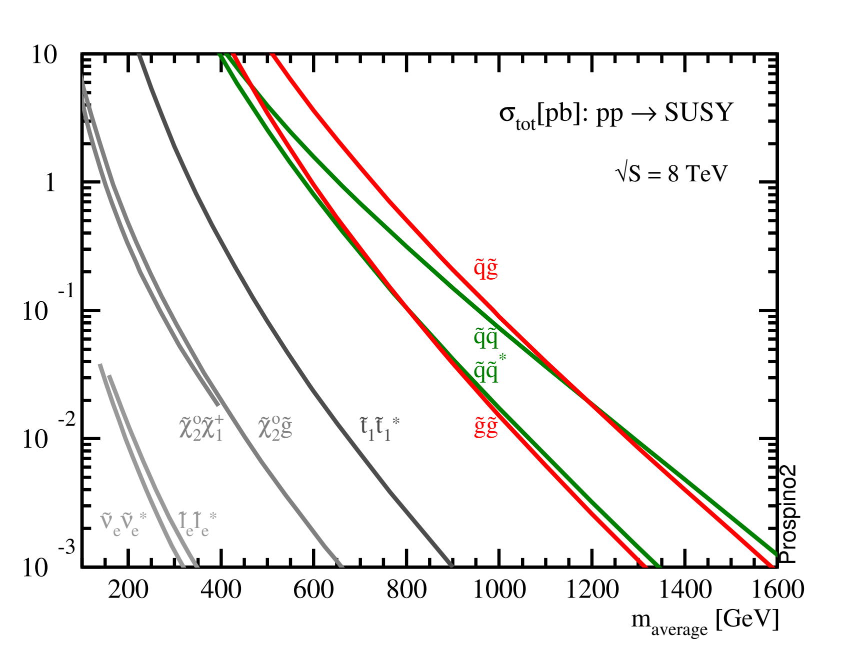


- *Many theorists have a strong prejudice for SUSY*
  - Extends Poincare group
  - Solves the Higgs mass hierarchy problem
  - Improves the convergence of forces at $\Lambda_{GUT} \simeq 10^{16}$GeV
  - Lightest SUSY Particle (LSP) is a DM candidate
- SUSY is a *class* of theories, not a single theory:
  - mSUGRA/CMSSM (fewest params)
  - MSSM & pMSSM
  - NMSSM
  - R-parity violation

LHC: Search for SUSY

- SUSY partners not yet seen $\Longrightarrow$ SUSY must be broken
  - Add soft SUSY breaking terms to parameterize effects of new SUSY-breaking sector, e.g., mSUGRA
  - Typically gives SUSY particles TeV scale masses
- SUSY models need to be consistent with: low-energy physics; EW precision tests; $M_{Higgs} \simeq 126$ GeV, etc.
- Search status constraints are model-dependent
  - Constraints often expressed for mSUGRA/CMSSM model with R-parity conservation
  - CMSSM and MSSM are being pushed by data into regions of parameter-space that are "fine-tuned"
  - NMSSM has more parameters and flexibility - degree of fine-tuning needed is a subject of considerable current interest

LHC: Search for SUSY



- *Experimentalists must continue the search for SUSY giving either:*
  - SUSY particle discovery; or
  - greater constraints on SUSY models
- Ability to simply relate constraints for a general NMSSM model (with/without R-parity violation) would be helpful
- Key issue: how unnatural/fine-tuned must MSSM/NMSSM parameters be for consistency with experiment?
- *Obviously need to:*
  - Continue inclusive squark and gluino searches
  - Continue natural/3rd generation searches

LHC: Search for SUSY

- *Discussion:* What more might experimentalists do in order to further test and constrain SUSY models?

Composite Higgs Models

- Another approach to the mass hierarchy problem is to treat the Higgs as a composite particle:
  - Challenge (as for SUSY) is to have a Higgs mass of ≃126GeV without introducing physics contradicting EW precision tests and other experimental data
  - In Composite Higgs and Little Higgs models the Higgs boson is a pseudo-Goldsone boson (like the pion) which is light because of a spontaneously broken symmetry (analogous to chiral symmetry)
  - A different but related approach is Walking Technicolor which introduces new gauge interactions

Composite Higgs Models

- *Discussion:* What level of attention should be given to such models by experimentalists?

LHC: Searches for Exotics

- *Theory inspired searches* include:
  - WIMPS
  - Extra Space-time (Extra Dimensions)
  - New gauge groups, either GUT-related or not
  - Electroweak symmetry breaking mechanisms, e.g.,Technicolor, composite Higgs, little Higgs, ...
  - New fermions/neutrinos - 4th generation, Majorana neutrinos, sterile neutrinos, leptoquarks, excited quarks/leptons, ...
  - Axions

Lambda-CDM Model

- *Theoretical prejudice:* The ΛCDM model parameterizes the Big Bang model where:
  - General relativity assumed correct for cosmological scales
  - There is a cosmological constant “Λ”
  - Dark Matter included and is cold at onset of structure formation (CDM)
    - Cold: most Dark Matter particles moving slowly c.f. speed of light
    - Dark: does not interact via e.m.
    - Matter: physical substance, clusters and interacts gravitationally
- ΛCDM is the simplest model that appears consistent with:
  - Galaxy rotational velocity curves, gravitational lensing, etc
  - The Cosmic Microwave Background
  - Large scale structure of galaxy distribution
  - H, Deuterium, He, Li abundances
  - Dark energy - Accelerating expansion of the universe as determined from distant galaxies and supernovae
- Hot DM smears out large scale structure - not viable

Dark Matter and WIMPs

- *Theoretical prejudice/hope:* DM particles are Weakly Interacting Massive Particles (WIMPs):
  - Interact through gravity and weak or weak-scale interaction - WIMP "miracle" gives right DM density for thermal WIMPs.
  - Do not interact through e.m. or the strong interaction $\Longrightarrow$ not visible, do not feel electric charge or photons and do not interact strongly with atomic nuclei
  - Are like a heavy active neutrino in many ways, i.e., difficult to detect
- If DM does not experience weak-scale interaction $\Longrightarrow$ only observable gravitationally $\Longrightarrow$ hard to study
- *Theory prejudice/hope* $\Longrightarrow$ Vigorous experimental efforts in direct, indirect and collider searches for Dark Matter WIMPs are underway (crossing sym.)

Dark Matter: Direct Searches

- Many WIMPs crossing a sufficiently large detector can lead to a few weak force interactions per year
- Construct very sensitive systems, control backgrounds and scale up to very large volumes - this worked for detecting ν's!
- Current WIMP/DM direct detection technologies:
  - Cryogenic detectors: (T<100mK) and detect heat from collision of a WIMP with crystal atom. Experiments include:
    - CDMS, CRESST, EDELWEISS, EURECA
  - Scintillation detectors: detect flash of scintillation light produced by a particle collision in liquid Xe, Ar or in NaI. Experiments include:
    - ZEPLIN, XENON, DEAP, ArDM, WARP, LUX, DAMA/LIBRA
  - Superheated Droplet Detectors (SDDs): each drop is a miniature bubble chamber. Experiments include:
    - SIMPLE, PICASSO mass
  - Time Projection Chamber: Detect recoiling tracks $\Longrightarrow$ direction info + allows reduction of isotropic background. Experiments include:
    - DMTPC, DRIFT, Newage, MIMAC
- Initial positive results reported by DAMA/LIBRA, CoGeNT, CDMS and CRESST - awaiting confirmation and cross verification

Dark Matter: Indirect Searches

- Assume WIMP annihilation and/or WIMP decay can occur via WI:
  - if ν's, γ rays, antiprotons or positrons are produced then can search for anomalous features of the spectra of these particles reaching detectors $\Longrightarrow$ must understand *in detail* the "normal" (non-WIMP) production of such particles
  - Solar or earth scenario: as WIMPS pass through the sun or earth some weakly interact and slow $\Longrightarrow$ trapped gravitationally $\Longrightarrow$ examine spectra from sun or earth for anomalies
  - Can do same by looking at any possible source of high WIMP/ Dark Matter density such as galactic center of the Milky Way
  - Experiments include:
    - Fermi γ Ray Telescope: as above, possible anomalous 130GeV line from center of Milky Way - some doubt still
    - HESS II air-Cherenkov γ ray telescope - test 130 GeV line
    - PAMELA: reported excess positrons but not clearly from DM, no evidence for excess antiprotons
    - AMANDA, IceCube and Antares searching for excess high energy ν's

Non-WIMP DM Candidates

- Asymmetric Dark Matter (ADM).
  - motivated by: DM density = 5 x baryon density - DM density determined by particle-antiparticle asymmetry just like baryons - unified picture
  - annihilation interaction > WIMP
  - few GeV mass scale - fit with DAMA/CoGeNT/CRESST/CDMS-Si?
  - can be self-interacting - good for subgalactic structure problems?
  - no conventional indirect detection signal
  - accumulation in stars

Non-WIMP DM Candidates

- keV-scale sterile neutrinos
  - connected to neutrino mass generation
  - minimal SM extension
  - warm DM - solves subgalactic structure problems
  - X-ray line astro signature
  - one version does baryogenesis as well
- Axions
  - strong CP problem
  - expect them to exist at some level - not necessary to be all of the DM or even dominant component

WIMP and non-WIMP DM

- *Discussion:* What is a sensible spectrum of experiments to search for all “reasonable” dark matter candidates?
- *Discussion:* How should we collaborate with astrophysicists? Have annual CoEPP/CAASTRO workshop? Something more concrete? DAMA/CoGeNT in the southern hemisphere? X-ray line search?

Neutrino Oscillations

- Neutrinos of one lepton flavor (ν_e, ν_μ, ν_τ) observed to propagate and "oscillate" into a different flavor
  - Solar neutrino oscillation first evidence in 1960's by Ray Davis and confirmed in 2001at Sudbury Neutrino Observatory (SNO)
  - Atmospheric neutrino oscillation seen at Super Kamiokande in 1998
  - Reactor and beam neutrino experiments also underway
- Can only be possible if neutrinos have mass $\Longrightarrow$ BSM physics
- ... *but* not difficult to extend SM to include neutrino masses and mixings - introduce unitary PMNS matrix into SM

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) mixing matrix for the three neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Neutrino Oscillations

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Neutrinos can be in an Inverted (IH) or Normal (NH) Hierarchy

$$\mathbf{U}_{\mathrm{NH}} = \begin{bmatrix} 0.822 & 0.547 & -0.150 + 0.0381\mathrm{i} \\ -0.356 + 0.0198\mathrm{i} & 0.704 + 0.0131\mathrm{i} & 0.614 \\ 0.442 + 0.0248\mathrm{i} & -0.452 + 0.0166\mathrm{i} & 0.774 \end{bmatrix}$$

$$\mathbf{U}_{\mathrm{IH}} = \begin{bmatrix} 0.822 & 0.547 & -0.150 + 0.0429\mathrm{i} \\ -0.354 + 0.0224\mathrm{i} & 0.701 + 0.0149\mathrm{i} & 0.618 \\ 0.444 + 0.0278\mathrm{i} & -0.456 + 0.0186\mathrm{i} & 0.770 \end{bmatrix}.$$

Fogli et al: Global analysis of neutrino masses, mixings and phases. 2012 http://arxiv.org/abs/1205.5254v3

Neutrino Physics

- *Theory drivers:*
  - Majorana mass for neutrinos possible and theoretically favored
  - What IS the origin of neutrino mass? How is it different from other fermions, if at all?
  - CP violation in lepton sector would encourage people who like leptogenesis
  - Precision tests of oscillation parameters - to test flavor symmetry models and begin to understand the origin of quark-lepton families

Neutrino physics

- *Discussion:* Australia used to be involved in experimental neutrino oscillation physics but is not at the moment. Should we get involved again? How to we build capacity to do that? Encourage departments that are currently non-HEP?

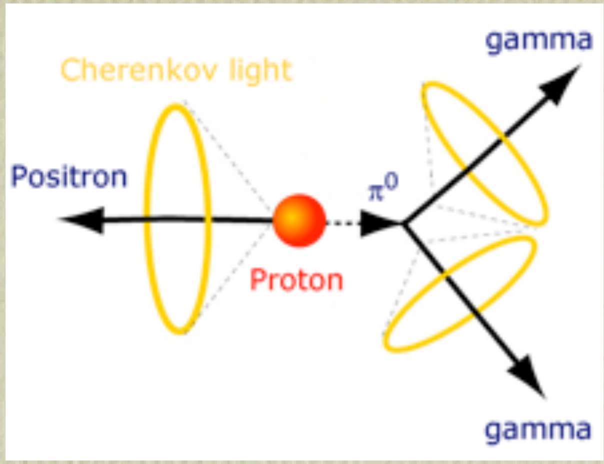
Flavor Physics

- *Theory driver - insufficient CP violation:* Need precision tests of CKM model of CP violation
- *Theory driver - predicted by many BSM theories:* Search for rare, flavor-changing processes such as:
  - $b \rightarrow s\gamma$
  - $\mu \rightarrow e\gamma$
  - $\mu \rightarrow 3e$

Flavor Physics

- *Discussion:* How should we organize the Australian community to permit us to play important roles in both ATLAS and BELLE II?

High Precision tests



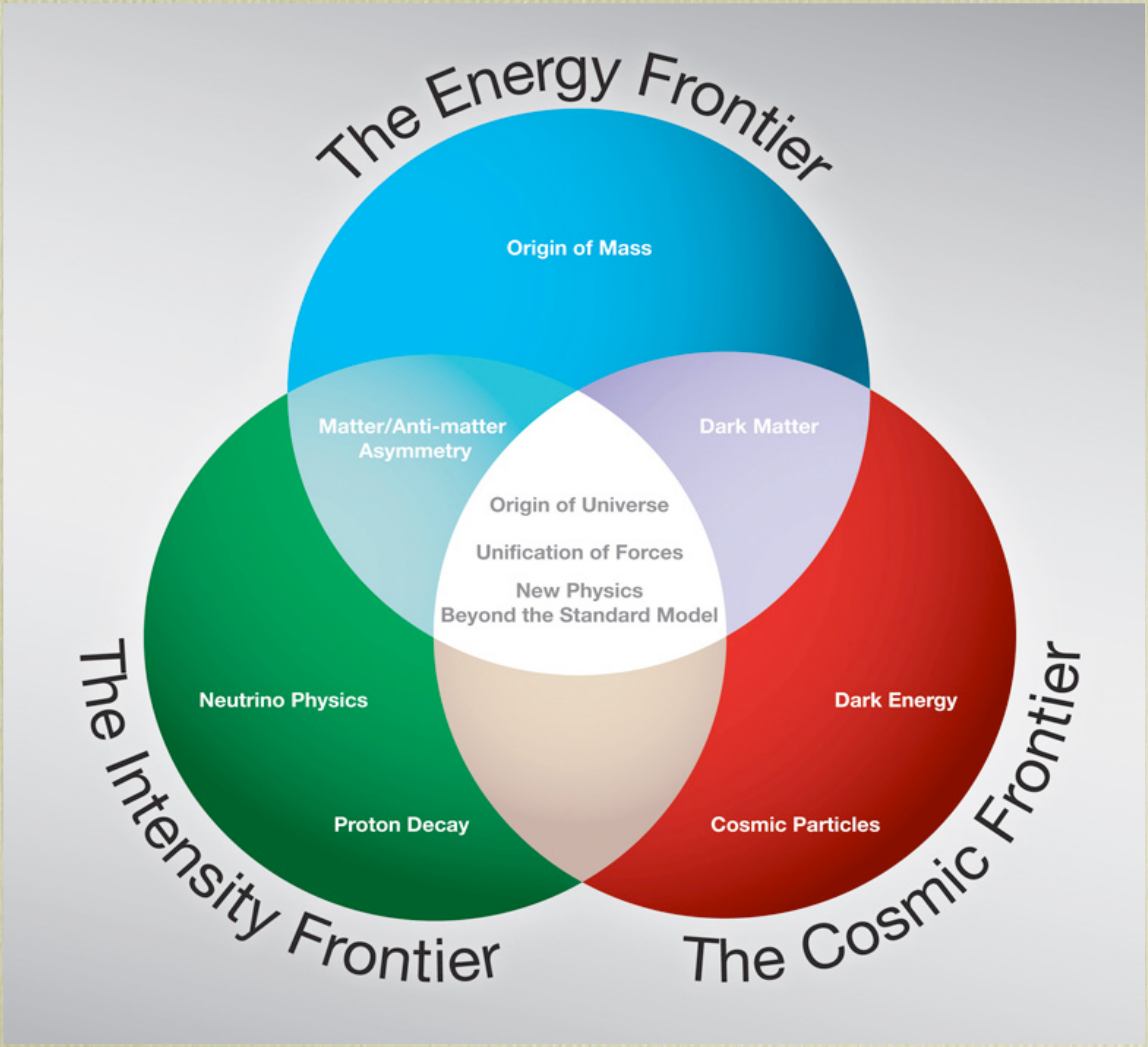
- Baryon and lepton number violation: *Theory driver* - Many GUT theories predict both baryon and lepton number violation
- Proton decay - none has been observed to date
  - Super-Kamiokande: at 90% CL gave $\tau > 6.6 \times 10^{33}$ years via antimuon decay ($p \rightarrow \mu^+ \pi^0$) and $\tau > 8.2 \times 10^{33}$ years via positron decay ($p \rightarrow e^+ \pi^0$)
- Tests of lepton flavor violation (LFV) and lepton number violation (LNV) are also of great interest - none yet seen

High Precision tests

- *Theory driver:* Is Lorentz/CPT invariance exact?
  - Greenberg: *"An interacting theory that violates CPT invariance necessarily violates Lorentz invariance. On the other hand, CPT invariance is not sufficient for out-of-cone Lorentz invariance. Theories that violate CPT by having different particle and antiparticle masses must be nonlocal."* Phys Rev Lett 89 231602 (2002)
  - Experimental limits from various tests:
    - Isotropy of speed of light
    - Lorentz violating vacuum dispersion relations
    - Vacuum birefringence (e.g., rotation of polarization plane)
    - Threshold effects (e.g., decay of energetic photons)
    - Time dilation
    - Clock comparison (e.g., preferred frame)
    - Direct CPT and matter-antimatter asymmetry tests
    - Neutrino speed (e.g., OPERA saga)

Conclusions

- Neutrino oscillations, Dark Matter, Baryogenesis, Inflation, Dark Energy $\Longrightarrow$ BSM physics
- The expectation of a Grand Unified Theory and/or a Theory of Everything $\Longrightarrow$ BSM physics
- Issues with naturalness, fine-tuning and hierarchy problems $\Longrightarrow$ BSM physics
- BSM models addressing naturalness include:
  - SUSY: MSSM and more elaborate versions
  - Composite Higgs/Technicolor/Little Higgs
- All of these BSM models expect natural occurrence of new BSM particles at around 1 TeV - but none seen yet!
- Beginning to need fine-tuning in our BSM models to push new BSM particle masses to 2TeV and above - current BSM models have a tension with experimental results
- Eagerly await 2015 for the LHC restart to continue the search for new physics
- Precision frontier: flavor physics, DM direct/indirect detection


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

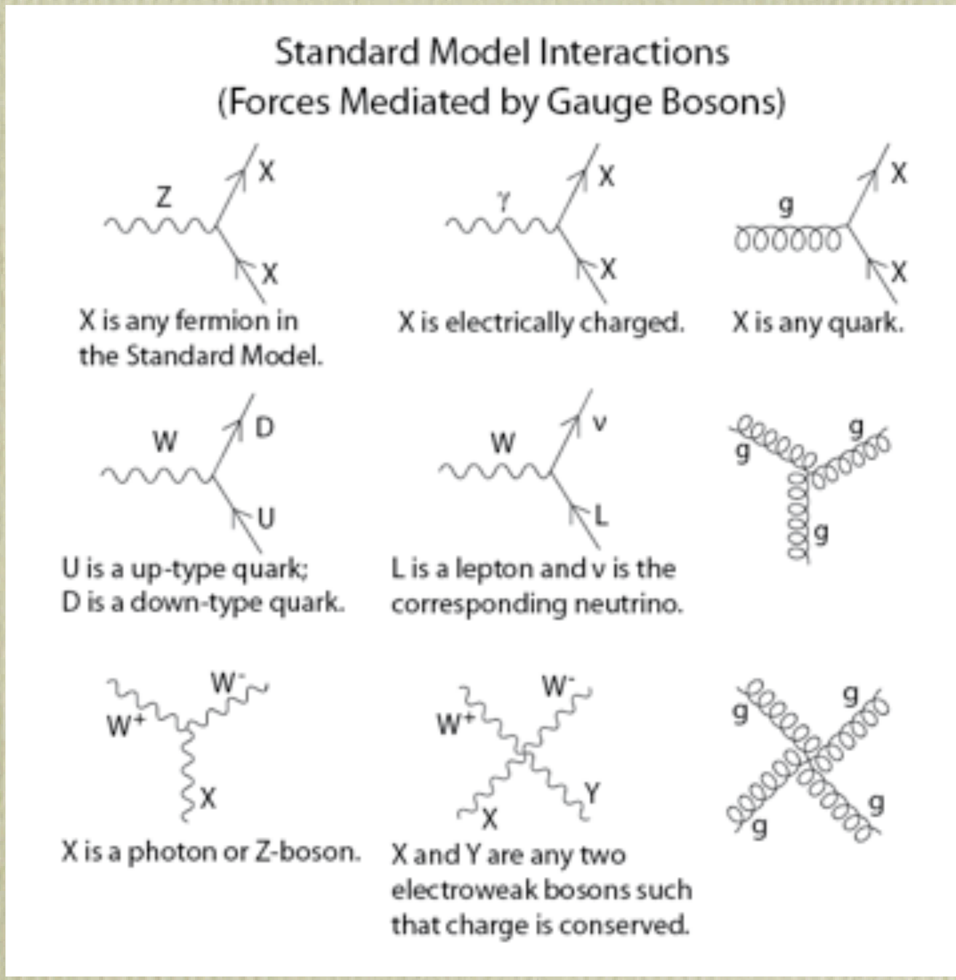
Discussion points

- What more might experimentalists do in order to further test and constrain SUSY models?
- What level of attention should be given to such models by experimentalists?
- What is a sensible spectrum of experiments to search for all “reasonable” dark matter candidates?
- How should we collaborate with astrophysicists? Have annual CoEPP/CAASTRO workshop? Something more concrete? DAMA/CoGeNT in the southern hemisphere? X-ray line search?
- Australia used to be involved in experimental neutrino oscillation physics but is not at the moment. Should we get involved again? How to we build capacity to do that? Encourage departments that are currently non-HEP?
- How should we organize the Australian community to permit us to play important roles in both ATLAS and BELLE II?

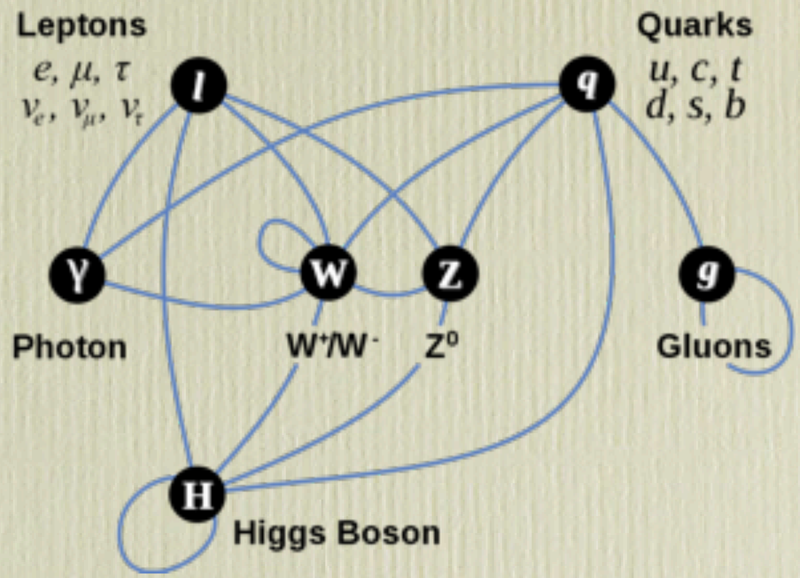
Hierarchy Problem

- Hierarchy Problem: When the parameters of a theory at high scale (e.g., $\Lambda_{GUT} \simeq 10^{16}$GeV) are many orders of magnitude different from what is measured at a low scale experimentally - related to renormalization
- Related to both naturalness and fine-tuning
- Renormalization tells how a theory changes with scale
- SM Hierarchy Problem: Why is the Higgs boson mass (125-126GeV) so much smaller than $\Lambda_{GUT} \simeq 10^{16}$GeV or $\Lambda_{Planck} \simeq 10^{19}$GeV?
  - $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ are gauge theories and change only logarithmically with scale
  - Higgs is a scalar and changes quadratically with scale $\Longrightarrow$ Higgs mass enormous at unification scale $\Longrightarrow$ extreme fine tuning of order 10^{25} to be so small at our scale

SM Interactions (after EWSB)

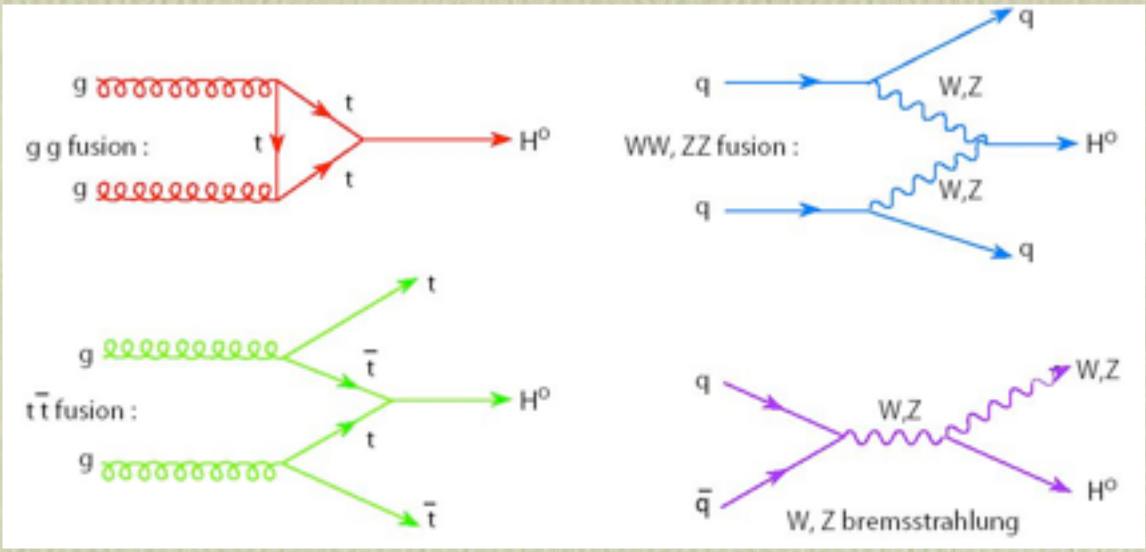


The many Higgs interactions not shown above

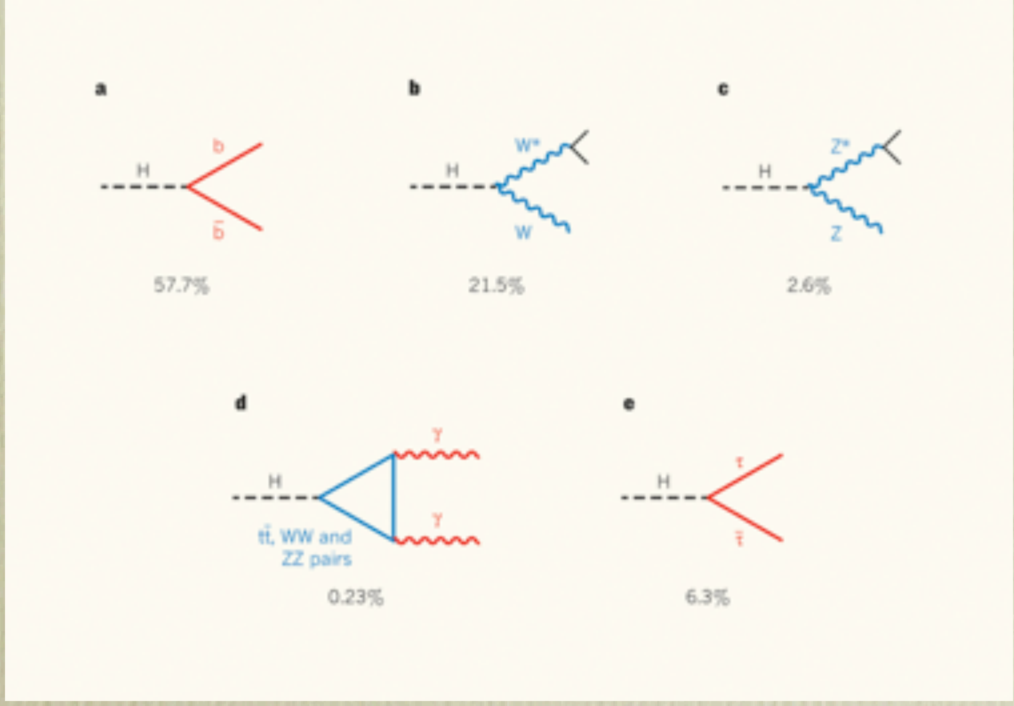


- Interactions in the SM

Interactions of the Higgs



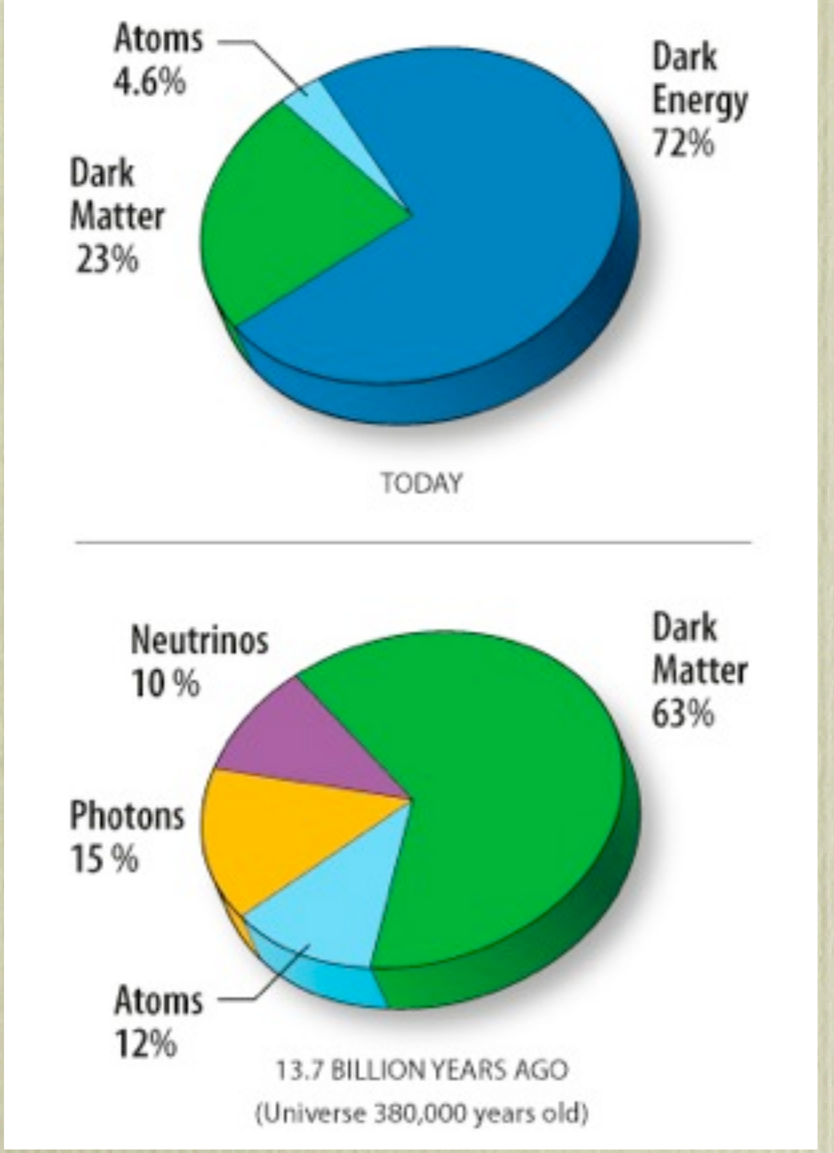
- Important Higgs production channels in p-p collisions



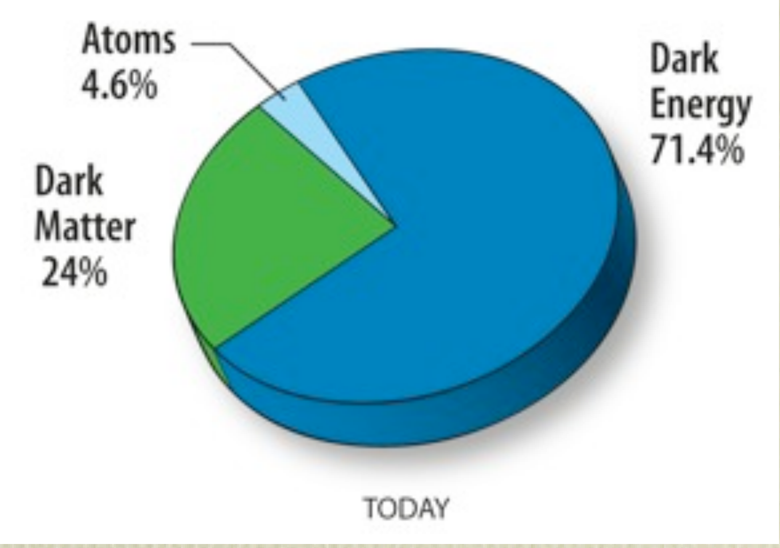
- Important Higgs decay channels
- Final states involve further decays such as:
  - $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ (4l)
  - $H \rightarrow WW \rightarrow l^+\nu l^-\nu$

Content of the Universe

5 years of WMAP data



9 years of WMAP data



- Dark Energy dominates over time