Introduction to physics beyond the Standard Model

IDPASC, 9^{th} February 2015

Mark D. Goodsell

LPTHE

Introduction to my lectures

- Introduction to physics beyond the Standard Model (BSM) (this lecture)
- Supersymmetry and its breaking (Tuesday)
- The strong CP problem (Wednedsay)
- WISPs: axions and extra $U(1)s$ (Wednedsay)

Introduction

- Deficiencies of the Standard Model.
- Hints for what lies beyond.
- The WIMP miracle from a BSM theorist's perspective.
- How far must we look? Restrictions on new physics.
- Overview of current ideas.

Why do we need BSM?

It is legitimate to ask: why do we need physics beyond the Standard Model?

The long-term and time-independent answers are:

♣ It is incomplete:

- It cannot reconcile quantum physics and gravity.
- It provides no explanation for dark matter.
- Dark energy remains a mystery.
- CP violation and electroweak baryogenesis in the Standard Model do not explain the matter/antimatter asymmetry of the universe.

♢ There are also puzzles:

- Extrapolating to high energies (beyond $\sim 10^{11}$ GeV) we find that the Standard Model is at best metastable (c.f. Pietro Slavich's talk).
- Coupling to a higher energy theory generically leads to the hierarchy problem: what protects the electroweak scale?
- Measurements of neutron dipole moments are tiny, whereas in the SM we would expect them to be several orders of magnitude larger (although it doesn't make an actual prediction). This is the Strong CP problem – see Wednesday's lecture.
- The Standard Model has many parameters with no obvious origin yet the generations fall into patterns with similar repeated properties. We have no explanation for flavour.
- The tiny values of neutrino masses and their oscillations suggest new physics at high energies.

LPTHE PARIS

However, as ever more data and experiments are performed, there are more reasons to be excited:

♠ Some hints:

- The measured muon magnetic moment is 3.4 standard deviations from its predicted value. This points at relatively light electroweak-charged new particles (which enter in loops).
- Hints from LHCb, e.g. 3.7σ discrepancy in $B^0 \to K^* \mu^+ \mu^-$.
- Several dark matter detection experiments (DAMA, CoGeNT, CRESST) reported signals.
- Excess of multi-lepton events from CMS.
- Observation of $h \to \mu\tau$ in CMS.

♡ Many anomalous astrophysical observations:

- Transparency of the universe to gamma rays.
- White dwarf cooling.
- PeV-neutrinos at IceCUBE.
- 3.5 keV and 130-GeV gamma-ray lines.
- The 'Hooperon'
- Positron flux in Pamela/AMS.
- ...

SM + gravity

The famous problem of quantum gravity:

- We have a candidate in string theory which can connect particle and gravitational physics.
- There is still much work to be done, but it is possible to connect string models with low energy physics, astrophysics and cosmology, e.g. through WISPs (see Wednesday's lecture).

The "dark problems":

- Dark energy → cosmological constant problem, can be made sense of in supersymmetric theories but remains a puzzle.
- Dark matter → what is it made of? I will talk about WIMPs and WISPs as candidates, but there are many more possibilities.

These will be more fully discussed in the "physics in the universe" lectures.

Muon $g-2$ see e.g. 1311.2198, hep-ph/0609136

Recall that a magnetic moment is a vector interaction with the magnetic field:

$$\Delta E = -\boldsymbol{\mu} \cdot \mathbf{B}$$

For a spin in quantum mechanics we write

$$\boldsymbol{\mu} = g \left(\frac{e}{2m} \right) \mathbf{S}$$

In QED, can calculate as the scattering of a lepton with an external field, i.e. a vertex correction:

$$i\mathcal{M} = -\frac{ie}{2m} \left[\overline{\psi}(p\prime) \left([p^\mu + p'^{\,\mu}] F_1(q^2) - \gamma^{\mu\nu} q_\nu [F_1(q^2) + F_2(q^2)] \right) \psi(p) \right] A_\mu$$

$$\rightarrow V_{eff} = -\frac{e}{m} [F_1(0) + F_2(0)] \mathbf{S} \cdot \mathbf{B}$$

We can define the gauge coupling e via $F_1(0) \equiv 1$ and so

$$g = 2 + 2F_2(0) \rightarrow \text{define } a_\mu \equiv \frac{g_\mu - 2}{2} = F_2(0) = \frac{\alpha}{2\pi} + \ldots$$

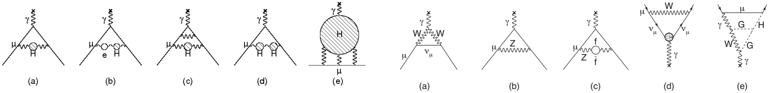
$g-2$ in the Standard Model

The calculation of the muon $g-2$ in the Standard Model is an industry; the QED contributions

have been calculated to five loops!

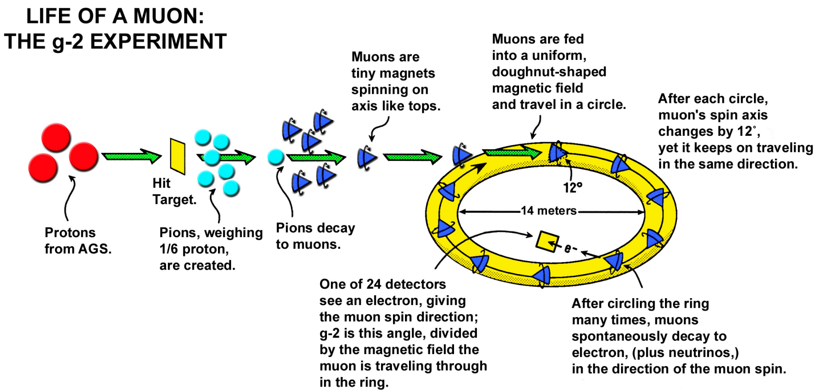
$$a_\mu^{QED} = 116\ 584\ 718.951 \times 10^{-11}$$

There are also electroweak and (subtle) hadronic contributions:



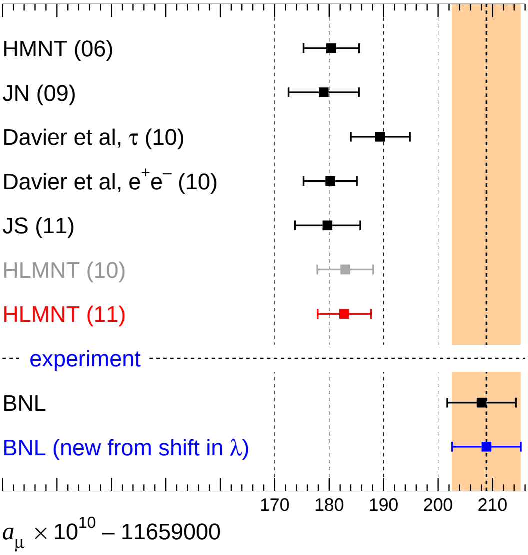
$$a_\mu^{EW} = 153.6 \pm 1.0 \times 10^{-11} \propto \frac{G_F}{\sqrt{2}} \frac{m_\mu^2}{8\pi^2}, \qquad a_\mu^{had} \approx 6\ 900 \times 10^{-11}$$

Muon $g-2$: experiment



From the E821 $g-2$ homepage, `http://www.g-2.bnl.gov/`

Discrepancy

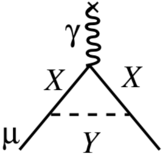


Muon $g-2$ beyond the Standard Model

The present discrepancy between theory and experiment is [1010.4180]:

$$\delta(a_\mu^{EXP} - a_\mu^{SM}) = 287 \pm \underbrace{49}_{\text{theory}} \pm \underbrace{63}_{\text{expt}} \times 10^{-11}$$

We can calculate the energy scale associated:



$$\delta a_\mu \sim \frac{1}{16\pi^2}\left(\frac{m_\mu}{m_{XY}}\right)^2$$

This implies that for $\delta a_\mu \sim 300 \times 10^{-11}$ we need

$$m_{XY} \sim 150 \text{ GeV !}$$

This represents perhaps our best hint of physics beyond the standard model <u>at low energies</u>!

Other aspects of lepton flavour

On the other hand, fermions can also have *electric* dipole moments: we can have

$$\mathcal{L}_{eff} \supset \frac{1}{2} d_\psi \overline{\psi} \gamma^{\mu\nu} \gamma_5 \psi F_{\mu\nu}.$$

However, this coupling violates CP so is absent at leading order. Alternatively we can have decays mediated by e.g.

$$\mathcal{L}_{eff} \supset \frac{1}{2} \overline{\psi}_i \gamma^{\mu\nu} (c^L_{ij} P_L + c^R_{ij} P_R) \psi F_{\mu\nu}.$$

There are tight constraints, e.g.

$$\begin{aligned} \mathrm{Br}(\mu \to e\gamma) <& 5.7 \times 10^{-13} \text{ (from MEG)} \qquad (c.f. \mathrm{Br}_{SM}(\mu \to e\gamma) \lesssim 10^{-52}! \\ d_e <& e \times 4.5 \times 10^{-15} \text{ GeV}^{-1} \text{ (from ACME)} \\ \mathrm{Br}(\mu \to 3e) <& 1.0 \times 10^{-12} \text{ (from Mu3e)} \\ & \vdots \end{aligned}$$

These hint that new light physics should conserve CP and have little flavour violation.

Flavour

One of the big puzzles of the Standard Model is the flavour structure:
Masses for quarks (from PDG):

$$\overline{m_u}(2\text{ GeV}) = 2.15(15)\text{ MeV},\quad \overline{m_c}(m_c) = 1.275 \pm 0.025\text{ GeV},\quad m_t(\text{pole}) = 173.34 \pm 0.27 \pm 0.71\text{GeV}$$

$$\overline{m_d}(2\text{ GeV}) = 4.70(20)\text{ MeV},\quad \overline{m_s}(2\text{ GeV}) = 93.5 \pm 2.5\text{ MeV},\quad \overline{m_b}(\overline{m_b}) = 4.18(0.03)\text{ GeV}$$

Masses of the leptons:

$$m_e = 0.510998928(11)\text{ MeV},\quad m_\mu = 105.6583715(35)\text{ MeV},\quad m_\tau = 1776.82 \pm 0.16\text{ MeV}$$

Why do we have such hierarchies of the Yukawa couplings? Is there something that gives it this structure?

Flavour in the SM

In the SM, the quark mass matrices are of the form

$$\mathcal{L} \supset -\overline{U}_i \mathcal{M}^{\mathcal{U}}{}_{ij} P_R U_j - \overline{D}_i \mathcal{M}^{\mathcal{D}}{}_{ij} P_R D_j + h.c.$$

In the gauge eigenstate basis, these matrices are not diagonal and they should be diagonalised by matrices

$$\begin{aligned} U_R =& T^\dagger_{U,R} U'_R, \quad U_L = T^\dagger_{U,L} U'_L \\ D_R =& T^\dagger_{D,R} D'_R, \quad D_L = T^\dagger_{D,L} D'_L \end{aligned}$$

This leaves the <u>neutral</u> currents unchanged (the GIM mechanism):

$$\begin{aligned} j^\mu_Z =& \overline{\Psi}\gamma^\mu(-s^2_W Q^2 + T_3) P_L \Psi - s^2_W \overline{\Psi}\gamma^\mu Q^2 P_R \Psi \\ \to& \overline{\Psi}' T_{\Psi,L} \gamma^\mu (-s^2_W Q^2 + T_3) P_L T^\dagger_{\Psi,L} \Psi' - s^2_W \overline{\Psi}' T_{\Psi,R} \gamma^\mu Q^2 P_R T^\dagger_{\Psi,L} \Psi' \end{aligned}$$

(n.b. if there are extra heavy vector-like fermions this will be violated)
whereas the charged currents are famously not the same in the mass eigenstate basis:

$$j^\mu_W = \overline{\Psi}\gamma^\mu T^+ P_L \Psi \to \overline{U}' T_{U,L} \gamma^\mu P_L T^\dagger_{D,L} D'$$

So we define the CKM matrix to be

$$\boldsymbol{V} \equiv T_{U,L} T^\dagger_{D,L}$$

Models of flavour

- Many models have been proposed to explain the flavour structure of the SM.
- Typically follow the philosophy of generalising Froggat-Nielsen models:
- Suppose we have some symmetry under which SM quarks are charged, forbidding the Yukawa couplings.
- We need new fields ϕ charged under this symmetry to have allowed couplings:

$$\mathcal{L} \supset \left(\frac{\phi}{M}\right)^{Q_{ij}} H\overline{\psi}_i P_L \psi_j$$

- When the symmetry is spontaneously broken ϕ obtains a vev and we define $\epsilon \equiv \frac{\phi}{M}$.
- Explain flavour structure of the Standard Model by e.g. $U(1)$ models $Y_U^{ij} \sim \epsilon^{q_i+u_j+h}, \epsilon^{q_i+d_j-h}$
- Can extend this to non-abelian symmetries, particularly discrete symmetries.
- Approach also appears in string theory models.

CP phases in CKM

- Since $T_{U,L}, T_{D,L}$ are unitary, so is $\boldsymbol{V} \rightarrow$ it consists of n^2 real numbers for n generations.
- We can remove $2n-1$ phases by $U(1)$ rotations of the $2n$ quarks $\rightarrow (n-1)^2$ physical parameters.
- An orthogonal matrix has $\frac{1}{2}n(n-1)$ real parameters; hence the number of complex phases that we need augmment $\boldsymbol{V}$ from orthogonal is

$$(n-1)^2 - \frac{1}{2}n(n-1) = \frac{1}{2}(n-1)(n-2)$$

- Hence we need $n \geq 3$ to have CP violation!
- Note that this implies we need all of the quarks to have non-zero masses $\rightarrow$ otherwise the phase is not physical and can be removed.
- In the standard model, have a small amount of CP violation from the one phase.

LPTHE PARIS

Neutral Kaons

see e.g. **CP Violation by Bigi and Sanda**

Recall:

- Define $K^0, \overline{K}^0$ as the flavour eigenstates $d\bar{s}, \bar{d}s$.
- Under CP, $CP|K^0\rangle = |\overline{K}^0\rangle$.
- They mix via processes such as $K^0 \to \pi\pi \to \overline{K}^0$
- If CP is conserved, we can then write

$$|K_1\rangle = \frac{1}{2}(|K^0\rangle + |\overline{K}^0\rangle), \qquad |K_1\rangle = \frac{1}{2}(|K^0\rangle - |\overline{K}^0\rangle)$$

- Since the Kaon is spinless and $CP|\pi^0\rangle = -|\pi^0\rangle$ then we should expect only K_1 to decay to $2\pi^0$.
- Note that since the mass of the neutral Kaons is 497.614 ± 0.024 MeV and pions have mass $134.9766(6)$ MeV, the decay to four pions is forbidden and K_2 has phase-space suppressed decays to predominantly three pions (or one pion plus two leptons) with

$$\tau_S = (8.954 \pm 0.004) \times 10^{-11}\,\mathrm{s}, \quad \tau_L = (5.116 \pm 0.021) \times 10^{-8}\,\mathrm{s}$$

CP violation in Kaons

CP violation was first reported in 1964 (what a year for physics!) by Christenson, Cronin, Fitch (R.I.P. 5.2.15) and Turley in the decay of neutral Kaons to two pions:

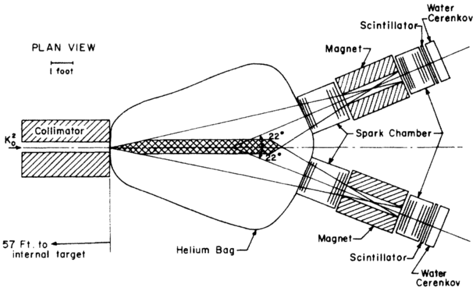


FIG. 1. Plan view of the detector arrangement.

They found $\mathrm{Br}(K_L \to 2\pi) = (2.0 \pm 0.4) \times 10^{-3}$, explained by

$$|K_L\rangle \simeq |K_2\rangle + \bar{\epsilon}|K_1\rangle, \qquad |K_S\rangle \simeq |K_1\rangle - \bar{\epsilon}|K_2\rangle$$

Now we know

$$|\epsilon| \simeq \frac{\langle \pi\pi|H|K_L\rangle}{\langle \pi\pi|H|K_S\rangle} \simeq (2.228 \pm 0.011) \times 10^{-3}$$

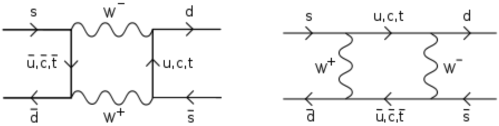
(n.b. almost same for neutral and charged pions $\to$ no direct CP in $\Delta S = 1$, $\epsilon' \sim 10^{-4}\epsilon$).

Kaons in the SM

The weak interactions generate the mass difference between the neutral Kaons as well as the mixing; we find

$$\Delta m_K = (3.484 \pm 0.006) \times 10^{-12}\ \mathrm{MeV}$$
$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3} \simeq \left| \frac{\mathrm{Re}\langle K^0 | H | \overline{K}^0 \rangle}{\sqrt{2}\Delta m_K} \right|$$

The mass shift is hard to calculate in the Standard model, but ϵ can be determined from the box diagrams:



$$\mathcal{H}(\Delta S = 2) \simeq \frac{G_F^2 M_W^2}{16\pi^2} [\bar{d}\gamma^\mu (1-\gamma_5) s]^2 \times \sum_{i,j=c,t} \eta_{ij} \boldsymbol{V}_{is} \boldsymbol{V}_{id}^* \boldsymbol{V}_{js} \boldsymbol{V}_{jd}^*$$
$$|\epsilon_{SM}| = (2.04 \pm 0.19) \times 10^{-3}$$

Leaves little room for new physics!

Flavour constraints on new physics

In the Kaon system, new physics can generate contributions to additional operators:

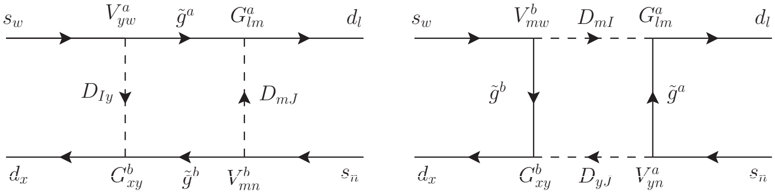
$$\mathcal{H}_K = \sum_{i=1}^{5} C_i Q_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i$$

$$Q_1 = \bar{d}_x \gamma^\mu P_L s_x \, \bar{d}_n \gamma_\mu P_L s_n \,, \quad Q_2 = \bar{d}_x P_L s_x \, \bar{d}_n P_L s_n \,,$$

$$Q_3 = \bar{d}_x P_L s_n \, \bar{d}_n P_L s_x \,, \quad Q_4 = \bar{d}_x P_L s_x \, \bar{d}_n P_R s_n \,,$$

$$Q_5 = \bar{d}_x P_L s_n \, \bar{d}_n P_R s_x \,.$$

These can come from new fermions and scalars in the loops, e.g. (see SUSY talk):



For new strongly-coupled particles with "generic" masses and phases, we have

$$\frac{|\delta\epsilon_K|}{|\epsilon_K(\exp)|} \sim \left(\frac{100 - 1000 \text{ TeV}}{M_{\text{NewPhysics}}}\right)^2$$

Other flavour constraints

There are a wealth of other quark flavour constraints:

- Similar mixing in neutral B and D mesons (typically provide weaker constraints than the Kaons because they are heavier and therefore messier!).

$\Delta F = 1$ processes are very important and can be generated at one-loop level, such as

- $b \to s\gamma$
- $b \to s l^+ l^-$
- $B^+ \to K^+ l^+ l^-$
- $B \to l^+ l^-$

The general message: new physics must have some flavour structure if it is light rather than being anarchic.
The good news for model builders: there now exist many tools to calculate all of these quantities in your favourite models (e.g. `Susy Flavor` for the MSSM, or `SARAH FlavorKit` for generic models); or operator-level analyses if you want to calculate the quantities yourself.

Neutrinos

- The masses and mixings of neutrinos are a particular puzzle in the standard model
- We know $\Delta m_{32} \approx 0.05$ eV and $\Delta m_{12} \approx 0.009$ eV but don't know the scale of the masses or the ordering: we could have $m_3 \gg m_1, m_2$ (normal hierarchy) or $m_1, m_2 \gg m_3$ (inverted hierarchy).

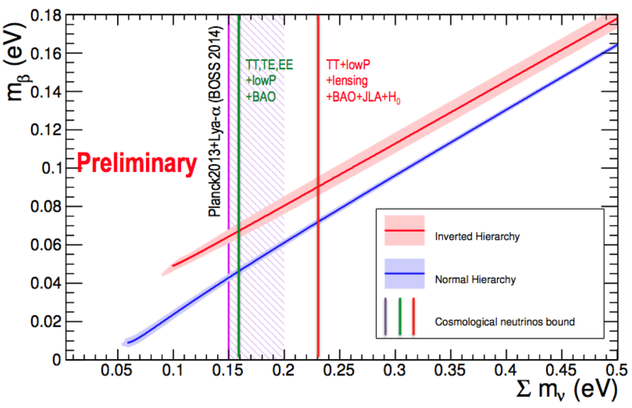
Are neutrinos Majorana or Dirac?

- The right-handed neutrino is not charged under any gauge group so its mass is not protected from large quantum corrections; we can write $-\frac{1}{2} M_N \overline{N}_R N_R$ in the Lagrangian where M_N should be the scale of some new physics.
- On the other hand, neutrinos are charged under lepton number and thus $B - L$.
- $L, B - L$ are thus explicitly broken by a right-handed Majorana neutrino mass.
- Since all global symmetries must be broken, we must have some Majorana mass for the neutrinos, the question is how large it is compared to the Dirac masses.
- If $B - L$ is unbroken until very low energies – or if it is gauged – we will therefore have "Dirac" neutrinos.
- If they are Majorana, then we can have neutrinoless double beta decay where $d + d \underbrace{\longrightarrow}_{2W\ exchange} 2u + 2e$ in the nucleus.
- The rate of double beta decay is proportional to an effective mass squared – $\Gamma \propto m_\beta^2$ – and so for very light neutrinos is hard to measure; we still have not observed it.

LPTHE PARIS

Planck constraints

Constraints on the sum of the neutrino masses from Planck:



Neutrinos BSM

- As I mentioned, if neutrinos are Majorana – which is a very reasonable assumption – then the right-handed neutrino mass ought to be associated with some new physics (although in principle it could just be another parameter).
- We then have the famous neutrino see-saw, where

$$m_\nu = \frac{m_{\rm Dirac}^2}{M_N}$$

- If the largest Dirac mass is between $1 - 100$ GeV, this means new physics between 10^{10} and 10^{14} GeV – which is very appealing when we consider that this is where the Standard Model starts to become unstable.
- On the other hand, the heavy neutrinos could have much smaller masses (so the Dirac masses would also be small) with interesting phenomenological consequences

Dark matter from a particle physicist's perspective

see e.g. **Kolb and Turner**

- I will not present evidence for dark matter or a discussion of the thermal history of the universe $\rightarrow$ see lectures on both of these topics.
- Accept for now that there is compelling evidence for dark matter, but very little for what form it should take!

From a particle physicists perspective, the WIMP paradigm is very attractive because

- Of the "WIMP miracle".
- ΛCDM seems to fit pretty well with the cosmological data (modulo some concerns, e.g. WDM may be better)
- It is a motivation for new physics at low energies.
- We could find it in direct detection experiments!

In addition, cosmology/astroparticle physics is vital to for BSM physics due to the number of observations, energy scales probed, and the number of anomalies!

DM recap

- We solve the Boltzman equation, e.g. for one species

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{EQ}^2)$$

- Freezeout when rate is about Hubble time, so $n\langle\sigma v\rangle \sim H$ at about $x \equiv m/T \sim 20$: $n(x_f) \simeq H/\langle\sigma v\rangle$
- Relic density is then roughly

$$\Omega h^2 = \frac{mn(x_f)}{\rho_{\mathrm{today}}/h^2} \times \frac{s_{\mathrm{today}}}{s_{\mathrm{freezeout}}}$$

$$\simeq 0.11 \times \frac{1.8 \times 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma v\rangle}$$

$$\simeq 0.11 \times \frac{1.5 \times 10^{-9}(\mathrm{GeV})^{-2}}{\langle\sigma\beta\rangle}$$

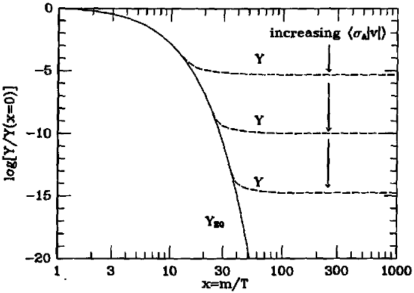


Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance.

The WIMP miracle

Note that for typical weak processes in the s-channel we have for $m \ll m_W$:

$$\begin{aligned} \langle \sigma\beta \rangle \simeq & \frac{G_F^2 m^2}{\pi} \\ & \sim 10^{-9} (\mathrm{GeV})^{-2} \left(\frac{m}{10\ \mathrm{GeV}} \right)^2 \end{aligned}$$

(this leads to the Lee-Weinberg bound of ~ 2 GeV as the lightest normal WIMP) and for $m \gg m_W$ we have

$$\begin{aligned} \langle \sigma\beta \rangle \simeq & \frac{\alpha^2}{m^2} \\ & \sim 10^{-9} (\mathrm{GeV})^{-2} \left(\frac{230\ \mathrm{GeV}}{m} \right)^2 \end{aligned}$$

This is the WIMP miracle – the coincidence that weak interactions of particles having weak-scale masses give the correct relic abundance! This is clearly encouraging for BSM and colliders.

Limits on WIMPs

see e.g. [Griest and Kamionkowski, '90]

- WIMPs should have masses greater than ~ 2 GeV or they will not annihilate quickly enough $\rightarrow$ overproduction.
- If we change the strength of the interactions by introducing new mediators or forces then this can be changed
- However, there is a limit given by unitarity:

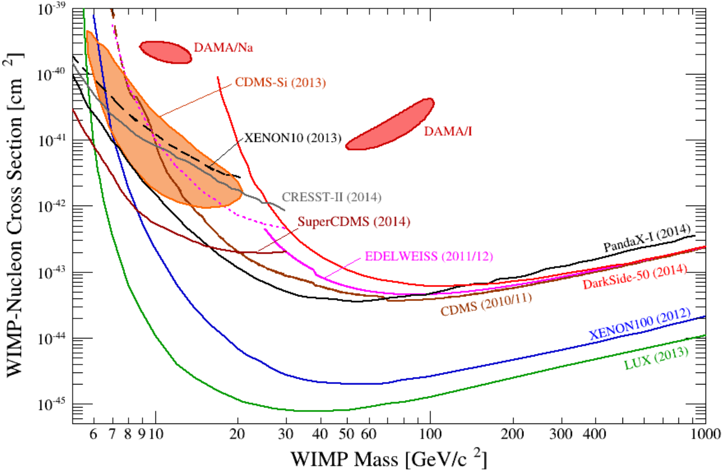
$$\sigma_J v \leq \pi(2J+1)/p_i^2$$

- In the early universe, $p_i^2 \simeq \frac{m_i^2 v_{rel}^2}{4}$ and $\langle v_{rel}^{-1} \rangle \sim \sqrt{x_f/\pi}$, so then

$$\langle \sigma v \rangle \lesssim \frac{8\pi(2J+1)}{m_i^2}$$

- This implies $m_i < \mathcal{O}(100 \text{ TeV})$.

No WIMPs yet ...



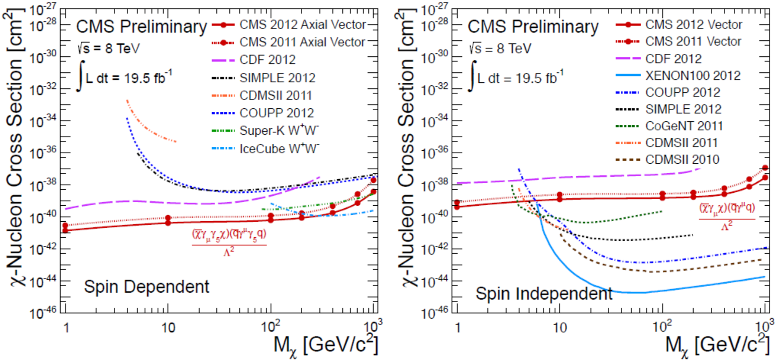
DAMA/Na
CDMS-Si (2013)
XENON10 (2013)
DAMA/I
CRESST-II (2014)
SuperCDMS (2014)
EDELWEISS (2011/12)
PandaX-I (2014)
DarkSide-50 (2014)
CDMS (2010/11)
XENON100 (2012)
LUX (2013)
WIMP-Nucleon Cross Section [cm 2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
6 7 8 9 10 20 30 40 50 60 100 200 300 400 1000
WIMP Mass [GeV/c 2]

WIMPs at the LHC

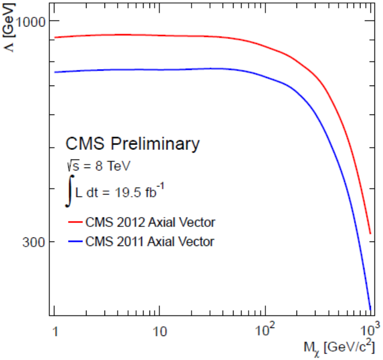
- Can compare LHC cross-sections with direct-detection cross-sections via effective operators on quarks:

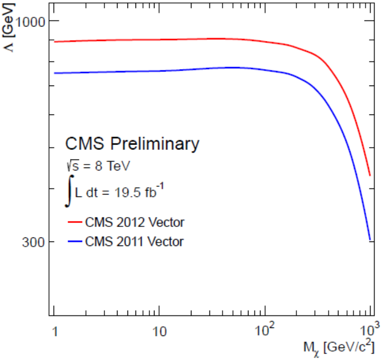
$$\mathcal{L} \supset \frac{1}{\Lambda_V^2} \overline{\Psi} \gamma_\mu \Psi \overline{q} \gamma^\mu q + \frac{1}{\Lambda_A^2} \overline{\Psi} \gamma_\mu \gamma_5 \Psi \overline{q} \gamma^\mu \gamma_5 q$$

- One advantage for the LHC is that these are not necessarily related to the dark matter density (only in the case of a vanilla WIMP).
- Another advantage is that the direct dectection experiments do not probe co-annihilations etc.



Comparison





- These give a better handle; if $\Lambda \sim m_{\mathrm{mediator}}/g^2$ we have $m_{\mathrm{mediator}} \gtrsim 400$ GeV for $M_\chi <$ TeV, so maybe dark matter is not a vanilla WIMP coupled to Z, W bosons.
- On the other hand, in SUSY the particles can have weak-scale couplings $\rightarrow$ sparticle mediators would be preferred.

Some other dark matter ideas

There are a wealth of other ideas about cold dark matter, e.g.

- WIMPZillas!
- FIMPs
- WISPs (see Wednesday's lecture)
- Dark atoms

⋮

On the other hand, there may be good evidence that dark matter should be light and warm.

Baryogenesis

The observed amount of antimatter in the universe is much lower than the amount of matter; we parameterise this by

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 6 \times 10^{-10} (\text{during BBN}).$$

This can not be produced through thermal freeze-out, which would give $\frac{n_B}{n_\gamma} = \frac{n_{\overline{B}}}{n_\gamma} \sim 10^{-20}$. It must therefore be produced through some "baryogenesis".

The famous Sakharov conditions state that for this we need:

1. B violation (clearly!)
2. Processes out of equilibrium
3. C and CP violation

Baryogenesis cont'd

Briefly, to understand these:

2. is obvious: $\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$ in thermal and chemical equilibrium.
3. is mostly the statement that there must be a difference between matter and antimatter, but note: CPT requires $\tau_X = \tau_{\overline{X}}$ so we need competing processes $X \to Y + B, X \to Z$ if X and $\overline{X}$ are produced equally:

$$\Gamma(X \to Y + B) + \Gamma(X \to Z) \stackrel{CPT}{=} \Gamma(\overline{X} \to \overline{Y} + \overline{B}) + \Gamma(\overline{X} \to \overline{Z})$$

but

$$\frac{dB}{dt} = \Gamma(X \to Y + B) - \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

and since

$$C\Big[\Gamma(X \to Y + B)\Big] = \Gamma(\overline{X} \to \overline{Y} + \overline{B}) \qquad (1)$$

we must violate C; the same applies for CP when we consider that if $PX = \pm X$ then

$$\Gamma(X \to \text{everything}) = \Gamma(PX \to \text{everything})$$

so we can average over P (the canonical example is to consider $X \to q_L q_L + q_R q_R$).

Baryogenesis in the SM

- In the standard model, baryon number is violated nonperturbatively since it is an anomalous symmetry; only $B - L$ is possibly conserved (except see later).
- Therefore the current of $B + L$ has a divergence:

$$\partial_\mu J^\mu_{B+L} = \frac{3g^2}{16\pi^2} W_{a\mu\nu} \tilde{W}^{\mu\nu}_a$$

- The RHS is a topological quantity, so it is associated with non-trivial field configurations only – such as instantons and sphalerons
- For instantons, the tunnelling rate is $\sim e^{-\frac{8\pi^2}{g^2}} \sim 10^{-173}$ so negligible (in fact, electroweak instantons of energy could be probed at a 100 TeV collider).
- For sphalerons, the energy of these configurations is $\sim \frac{8\pi v}{g} \sim 5$ TeV.
- In the early universe with $T >$ few TeV, B and L will therefore be abundantly violated – the sphaleron tunneling rate is $\propto e^{-E_{sphaleron}/T}$.

So we can generate baryon number, but unfortunately the standard model cannot account for baryogenesis:

- The CP violation is <u>too small</u>:

$$A \sim \frac{\det[M_U^2, M_D^2]}{E^{12}_{sphaleron}} \sim 10^{-20} \ll \eta \sim 10^{-10}$$

- Sphaleron processes occur in thermal equilibrium.
- One possible exception to avoid this, would be for bubble formation at the electroweak phase transition $\rightarrow$ first order phase transition
- In the standard model with a 125 GeV Higgs, the transition is second order $\rightarrow$ too smooth.

Baryogenesis beyond the standard model

- All approaches add additional CP violation.
- One approach is to harden the electroweak phase transition by extending the Higgs sector and adding new fields/couplings; this can happen in SUSY (although in the MSSM it apparently requires too light stops).
- Another involves heavy particles that decay, e.g. GUT baryogenesis (since heavy particles in GUT multiplets violate B and L).
- Although the sphalerons cannot generate a sufficient asymmetry, they can convert a lepton number excess into baryon number $\rightarrow$ leptogenesis from decay of heavy neutrinos.
- N.b. models of leptogenesis can be very predictive, e.g. if the RH neutrinos are hierarchical, Davidson-Ibarra bound gives $M_N > 10^9$ GeV, $T_{reh} > 10^{10}$ GeV.

The νMSM

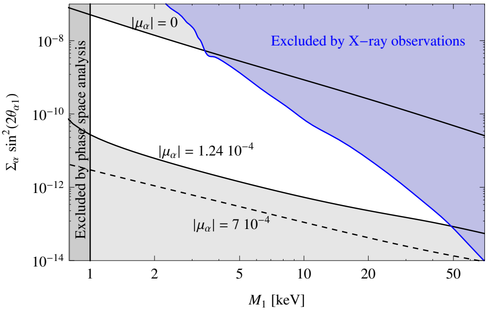
see e.g. 1208.4607

One economical model is the νMSM: add three right-handed neutrinos to the Standard Model

- Two with mass $100 \text{ MeV} < m_{N_{2,3}} < M_W$, the other light and long lived. The two heavy sterile neutrinos should be degenerate to the order of 10^{-3} to allow resonant amplification of oscillations.
- Since the masses are below M_W, the neutrinos are relativistic until after the electroweak phase transition.
- The neutrinos $N_{2,3}$ interact strongly enough to be abundant $\rightarrow$ there is a net lepton number.
- During the EWPT sphalerons transform L into B and CP-violation among the sterile neutrinos is sufficient for baryogenesis; the out-of-equilibrium decays of $N_{2,3}$

Searches for the νMSM

- These can be searched for in low-energy collider experiments (such as SHIP, for $m_{N_{2,3}} \lesssim$ GeV) in decays of charm mesons.
- The lightest sterile neutrino is a warm dark matter candidate:



This caused a great deal of excitement last year ...

LPTHE PARIS

The Higgs as a probe of new physics

- The discovery of the Higgs (or BEH) boson was a triumph for theory and experiment
- Prior to its discovery, there were a few exotic Higgsless theories: classicalons, technicolor, ...
- Now we seem to have a weakly coupled light boson
- – but by examining its properties precisely we can hope to find hints of new physics beyond a vanilla Higgs.

Higgs properties in 2012

There was some inital excitement about the digamma rate ...

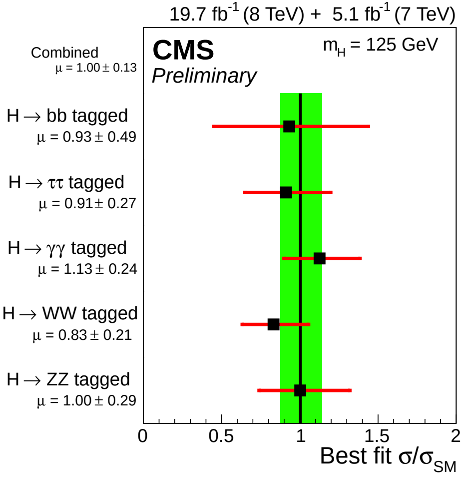
$$m_H = 125.8 \pm 0.4 \pm 0.5 \text{ GeV (CMS)}, 126.0 \pm 0.4 \pm 0.4 \text{ GeV (ATLAS)}$$

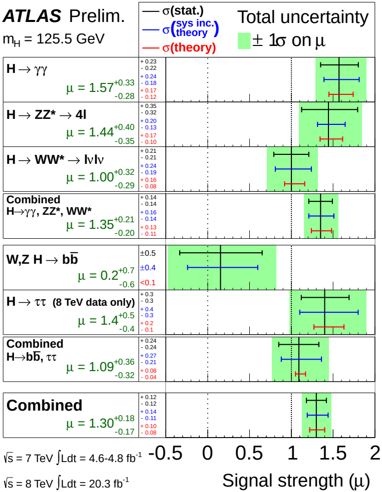
$$\mu_{ii} \equiv \frac{\sigma(pp \to h) BR(h \to ii)}{\sigma_{SM}(pp \to h) BR_{SM}(h \to ii)}$$

	CMS	ATLAS	Tevatron
$\mu_{\gamma\gamma}$	1.6 ± 0.4	1.8 ± 0.5	$3.62^{+2.96}_{-2.54}$
μ_{ZZ}	0.64 ± 0.57(7 TeV)	1.7 ± 1.1(7 TeV)	
	0.79 ± 0.56(8 TeV)	1.3 ± 0.8 (8 TeV)	
	$0.8^{+0.35}_{-0.28}$(combined, HCP)	1.4 ± 0.6 (combined, HCP)	
μ_{WW}	0.38 ± 0.56 (7 TeV)	0.5 ± 0.6 (7 TeV)	$0.32^{+1.13}_{-0.32}$
	0.98 ± 0.71 (8 TeV)	1.9 ± 0.7 (8 TeV)	
	0.74 ± 0.25(combined, HCP)	1.5 ± 0.6 (combined, HCP)	
μ_{bb}	0.59 ± 1.17 (7 TeV	0.46 ± 2.18 (7 TeV)	$1.97^{+0.74}_{-0.68}$
	0.41 ± 0.94 (8 TeV)		
	$1.3^{+0.7}_{-0.6}$(combined, HCP)	$-0.4 \pm 0.4 \pm 0.4$ (combined, HCP)	$1.56^{+0.72}_{-0.73}$(HCP)
$\mu_{\tau\tau}$	0.62 ± 1.17 (7 TeV)	0.45 ± 1.8 (7 TeV)	
	-0.72 ± 0.97 (8 TeV)		
	0.72 ± 0.52(combined, HCP)	0.7 ± 0.7 (combined, HCP)	

Results were consistent with enhancement in $\gamma\gamma$ channel and possibly suppression in $bb, \tau\tau$ channels.

Latest measurements





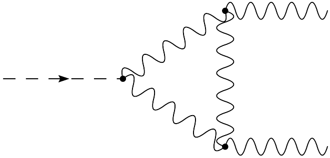
Results are consistent with the SM and the precision will not improve much; this leaves room for future disoveries at an ILC ...

$\mu_{\gamma\gamma}$ in the SM

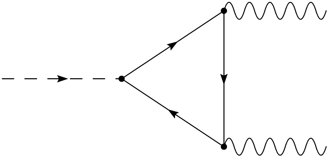
Couplings of Higgs to photons is at loop level, via top and W loops in standard model:

$$R_\gamma \equiv \frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} = \left| \frac{A_{\gamma\gamma}}{A_{\gamma\gamma}^{SM}} \right|^2$$

$$A_{\gamma\gamma} \equiv \frac{v}{2} \left[\frac{g_{hVV}}{m_V^2} Q_V^2 A_1(\tau_V) + \frac{2 g_{hff} N_C Q_f^2}{m_f} A_{1/2}(\tau_f) + \frac{g_{hSS} N_C Q_S^2}{m_S^2} A_0(\tau_S) \right]$$



$$A_1^\gamma(\tau_W) = -8.32(\approx -7)$$



$$N_c Q_t^2 A_{1/2}^\gamma(\tau_t) = 1.84(\approx \tfrac{4}{3} \times 3 \times \tfrac{4}{9})$$

New physics in $\mu_{\gamma\gamma}$

- Diphoton rate is a good probe of new physics – since new particles will enter in the loop (e.g. staus, charginos or stops)
- E.g. if we have light charged particles to enhance muon $g-2$
- SM fermions couple to higgs via their mass so $g_{hff} = \frac{m_f}{v}$
- New heavy fermions need not – we expect them to have other sources of mass, so their coupling could have either sign
- $\rightarrow$ typically easier to *suppress* $\mu_{\gamma\gamma}$ with new fields, but they can also enhance it.

Higgs production

Since no significant excess in W or Z production, expect Higgs production to not be much enhanced. Higgs production is almost entirely by gluon fusion at 8 TeV and 125.0 GeV Higgs:

$$
\begin{aligned}
\sigma_{SM}(pp \to h) = & 19.5^{+14.7\%}_{-14.7\%}\text{pb} \qquad \text{gluon fusion} \\
& + 1.578^{+2.8\%}_{-3\%}\text{pb} \qquad \text{vector boson fusion} \\
& + 0.6966^{+3.7\%}_{-4.1\%}\text{pb} \qquad \text{WH process} \\
& + 0.3943^{+5.0\%}_{-5.1\%}\text{pb} \qquad \text{ZH process} \\
& + 0.1302^{+11.6\%}_{-17.1\%}\text{pb} \qquad \text{ttH process}
\end{aligned}
$$

- Gluon fusion dominates $\rightarrow$ the coupling is generated at loop level.
- Therefore new light coloured states either increase or decrease the gluon fusion rate depending on the sign of the coupling.
- But we have not observed light coloured states at the LHC! (n.b. light stops or sgluons could still be hiding)
- Alternatively, if the Higgs mixes with other neutral scalars, we could decrease or enhance it's coupling to tops $\rightarrow$ and thus affect the total production rate $\rightarrow$ could lead to some differences.

Future of BSM from the Higgs

- The search will continue for heavy neutral scalars (heavy Higgses) – particularly in the context of SUSY, but also 2HDM etc.
- The LHC will confirm that it is a 0^+ scalar, and narrow down the Higgs self couplings (c.f. Pietro Slavich's lectures).
- It may also turn up some surprises from interference between amplitudes in e.g. the *golden channel*.
- Constraints on new particles may limit BSM models more – e.g. top partners for SUSY and composite models.
- For now, its mass is already a useful observable! (vacuum stability, heavy particle spectrum, etc)

Summary

- The Standard Model may work very well, but it is still incomplete
- There are many hints of new physics, and some that suggest that new physics is just around the corner.
- In order go beyond the Standard Model it is important to look everywhere we can: low and high energy experiments, dark matter direct detection, astrophysics, ... and try to tie them together.
- I have mentioned a few ideas, but I have not even scratched the surface of work on BSM theories.
- Tomorrow I will focus on my preferred candidate: supersymmetry.