Searches for Extended Higgs Sectors, Flavour Physics Anomalies and Dark Matter at the LHC

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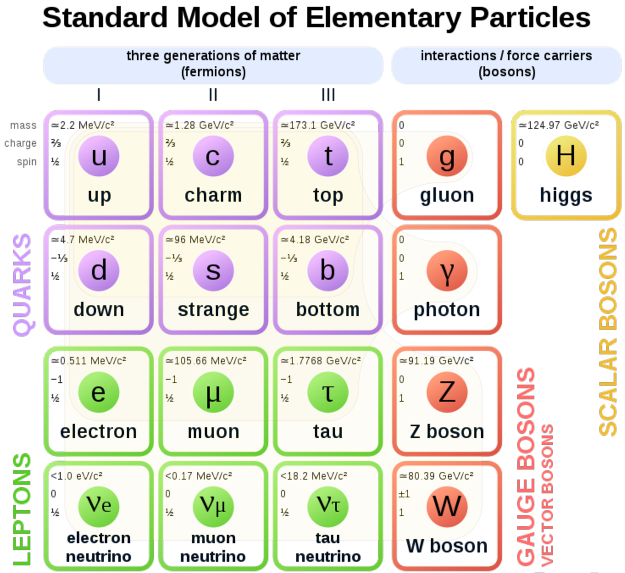
- Does many wonderful things, makes remarkably precise predictions, however it leaves some very important questions unanswered

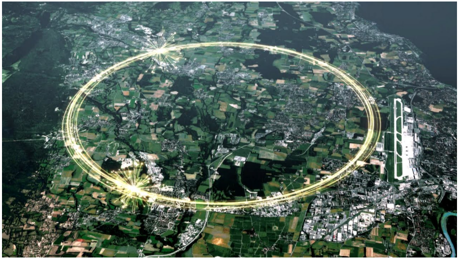
- What is dark matter, dark energy, why is there more matter than anti-matter in the universe, how does gravity fit in, where do neutrinos get their mass etc.

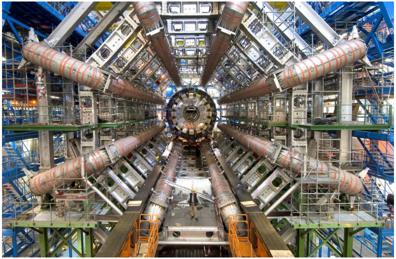
The SM continued...

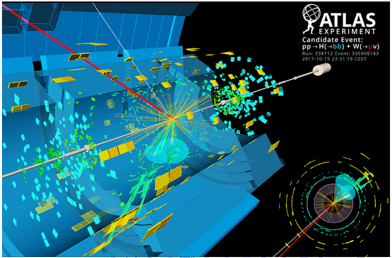


The LHC and the ATLAS experiment

- The Large Hadron Collider (LHC) is the largest particle physics experiment in the world



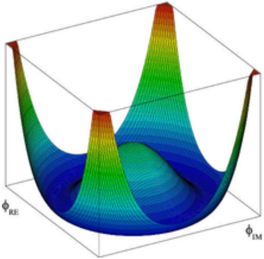


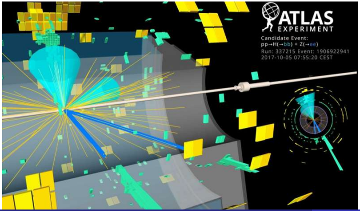


The Higgs boson explained

- The Higgs field is a fundamental field of crucial importance to particle physics theory
- The Higgs field takes the same non-zero value almost everywhere
- Explains why some fields have massive particles and others don't

$$
\begin{aligned}
\mathcal{L}_{SM} = {} & \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\
& + \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
& + \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm}, Z, \gamma \text{ and Higgs masses and couplings}} \\
& + \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}
\end{aligned}
$$





Extended Higgs Sectors and the $A \to ZH$ search

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- Search for the $A \to ZH \to \ell\ell b\bar{b}$ process

Machine learning and event selection

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- Most are standard model processes
- New physics is rare, this is because the particles produced are very heavy
- Event selection should maximise the purity of new physics events
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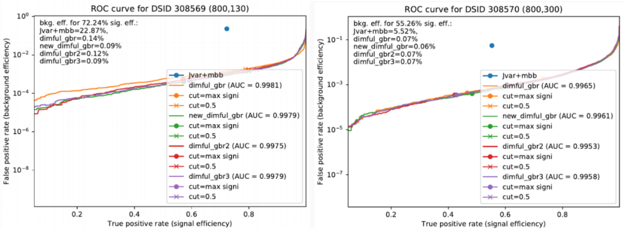
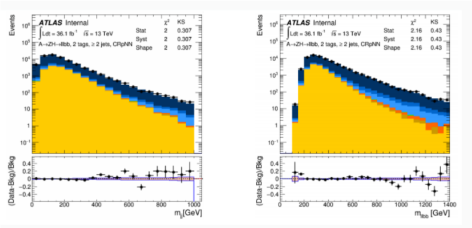
- A neural network is an artificial intelligence algorithm that mimicks the human brain

Parametric Neural Network Results





- The machine learning approach far out-performs standard cut-based approach, and the modelling in the background region is as expected, this is very promising not just for this analysis, but for many others

Higgs portal dark matter effective field theory (arXiv:1812.10914)

- We hypothesise a DM Dirac fermion, χ, of mass m_χ. It carries no Standard Model (SM) gauged charges and, thus, the lowest order "effective" operator that describes DM interactions with the SM particles is

$$\begin{aligned}\mathcal{L} &= \frac{1}{\Lambda} H^\dagger H \bar{\chi}(\cos\xi + i\gamma_5 sin\xi)\chi \\ &= \frac{1}{\Lambda}\left(vh + \frac{1}{2}h^2\right)\bar{\chi}(\cos\xi + i\gamma_5 \sin\xi)\chi \ ,\end{aligned} \tag{1}$$

where Λ is the EFT cut-off scale parameter and ξ is the CP-violating phase.

- In the second line, we expanded the EW Higgs doublet H around its expectation value $v \approx 246$ GeV in the unitary gauge, $H = \frac{1}{\sqrt{2}}(0, v + h)^{\mathrm{T}}$

Unitarity Considerations

- At low energy $E << \Lambda$, the Higgs-dark matter portal Eq. (1) is dominated by the dimension-4 $h\bar{\chi}\chi$ operators. These operators are renormalisable and also perturbative, provided $v \lesssim \Lambda$
- However, at high energy, the Higgs-DM interactions are dominated by non-renormalisable dimension-5 $h^2\bar{\chi}\chi$ interactions. In fact, for $E \gtrsim \Lambda$ the scattering amplitudes described by $h^2\bar{\chi}\chi$ operators grow as E/Λ, signalling violation of perturbative unitarity.
- This violation of unitarity is actually fictitious and reflects inapplicability of perturbative treatment to the EFT

Unitarity Violating T-matrix Elements

$$T_{0\ \chi_{L,R}\bar{\chi}_{L,R}\to hh} = \pm\frac{((s-4m_h^2)(s-4m_\chi^2))^{\frac{1}{4}}(\sqrt{s-4m_\chi^2}\cos\xi \mp i\sqrt{s}\sin\xi)}{8\pi\sqrt{s}\Lambda} \longrightarrow \propto \frac{\sqrt{s}}{8\pi\Lambda}\ , \qquad (2)$$

- can compute for the time-reversed processes. Similarly, for the longitudinal EW gauge bosons ($V \equiv W^\pm, Z^0$)

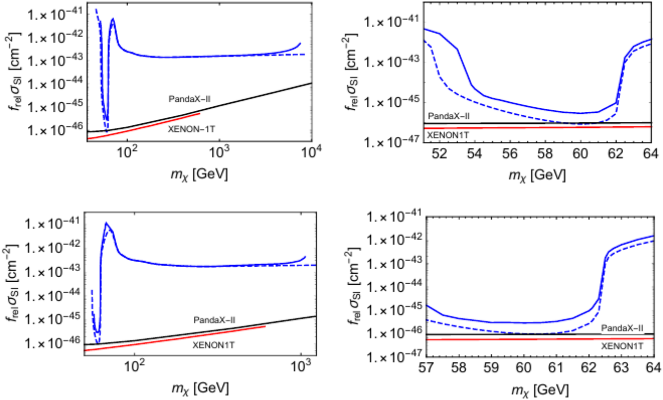
$$T_{0\ \chi_{L,R}\bar{\chi}_{L,R}\to VV} = \mp\frac{(2m_V^2-s)((s-4m_V^2)(s-4m_\chi^2))^{\frac{1}{4}}\left(\sqrt{s-4m_\chi^2}\cos\xi \mp i\sqrt{s}\sin\xi\right)}{8\pi\sqrt{s}\Lambda(s-m_h^2+im_h\Gamma_h)} \longrightarrow \propto \frac{\sqrt{s}}{8\pi\Lambda}\ , \qquad (3)$$

- Solution, use a unitarisation prescription or introduce a UV completion

$$T^U = \frac{T_0}{1-iT_0^\dagger}\ , \qquad (4)$$

Direct Detection and Relic Density Results

- For the *CP*-even case where $\xi = 0$



- Top panels are for 100% dark matter and bottom panels are for 10% dark matter, unitarised theory (solid blue), original theory (dashed blue)
- Our analysis found that this very popular model is now excluded fully

Flavour physics anomalies (PhysRevD.99.015029, PhysRevD.101.015026)

- There is mounting evidence for a violation of lepton flavour universality (LFU) in flavour-changing neutral current processes $b \to s\bar{\mu}\mu$ and b$\to c\tau\nu$ in recent measurements of B decays. The theoretically cleanest probes are the LFU ratios

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)} \quad \text{and} \quad R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})} \tag{5}$$

	observed	SM	q^2 $[\mathrm{GeV}^2]$ range
R_K	$0.846^{+0.060+0.016}_{-0.054-0.014}$	1.0003 ± 0.0001	$1 < q^2 < 6$
R_{K^*}	$0.685^{+0.113}_{-0.069} \pm 0.047$	1.00 ± 0.01	$1.1 < q^2 < 6$
R_D	$0.340 \pm 0.027 \pm 0.013$	0.299 ± 0.011	Full
R_{D^*}	$0.295 \pm 0.012 \pm 0.008$	0.252 ± 0.003	Full

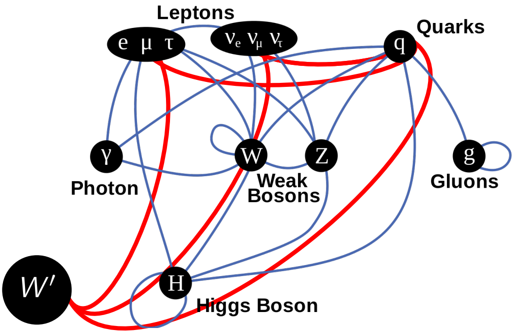
Table: LFU ratios $R_{K^{(*)}}$ and $R_{D^{(*)}}$ where we first list the statistical error and then the systematic.

Grand Unified Theories and Leptoquarks

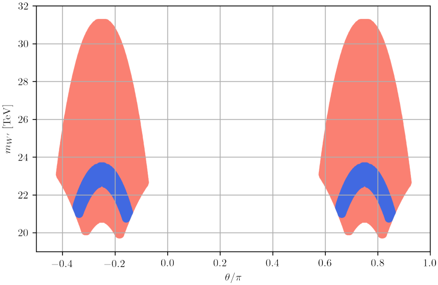
- Suggest a $SU(4)_C \times SU(2)_L \times U(1)_{Y'}$ "grand unified theory"
- This model introduces new "force carrying" gauge bosons, we call W'

$$\mathcal{L} = \frac{g_s}{\sqrt{2}} K_{ij} W'_\mu \bar{d}_i \gamma^\mu P_L \ell_j + \frac{g_s}{\sqrt{2}} K^*_{ji} W'^*_\mu \bar{\ell}_i \gamma^\mu P_L d_j - m^2_{W'} W'^*_\mu W'^\mu \quad (6)$$

- The presence of these W' bosons interferes with the SM processes $b \to s\bar{\mu}\mu$ and therefore can explain the $R_{K^{(*)}}$ measurements



Allowable Parameter Region for $R_{K^{(*)}}$ Anomalies



- The model has only two relevant free parameters θ which determines how each generation of down-type quark mixes with each lepton and the mass of the new particle $m_{W'}$

- Suggest a $SU(4)_C \times SU(2)_L \times SU(2)_R$ "grand unified theory"
- This model has the same charged gauge boson W' as before, but now has a charged scalar $\tilde{\chi}$ with interactions

$$\mathcal{L} = -\left(Y_{d4}\bar{\mathbf{d}}'_R n_4 + Y_4\bar{\mathbf{u}}'_R\mathbf{e}'^c_R\right)\tilde{\chi} + h.c. \tag{7}$$

- The $\tilde{\chi}$ scalar mediates $b \to c\tau\mathbf{n_4}$ enhancing the SM processes $b \to c\tau\nu$ and therefore can explain the $R_{D^{(*)}}$ measurements
- A minimal texture requires 3 new Yukawa couplings within Y_{d4} called y_3, $Y_{c\tau}$ and $Y_{t\mu}$.

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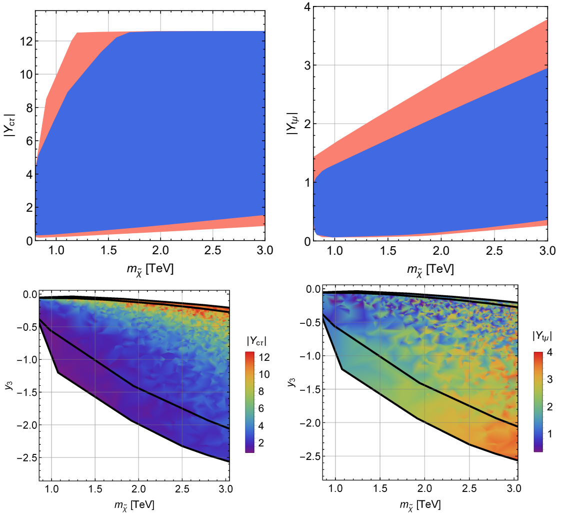


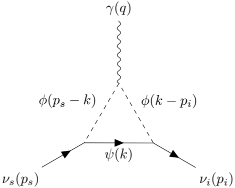
- The model also makes a number of predictions for rare processes which will be tested by the LHCb experiment

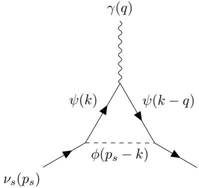
CP-violation in Radiative Neutrino Decay (arXiv:1910.08558)

- We introduce two new particles, one fermion ψ and one scalar ϕ with opposite electric charges Q and $-Q$ respectively. Their couplings with neutrinos and the sterile neutrino are described by the following Yukawa interaction

$$-\mathcal{L}_{\rm NP} \supset \sum_{m=1,2,3,s} \lambda_m \bar{\psi} \phi^* P_{\rm L} \nu_m + \lambda_m^* \bar{\nu}_m \phi P_{\rm R} \psi \,, \tag{8}$$

  where λ_m, with $m = i, s$ (for $i = 1, 2, 3$), are complex coefficients to ν_i and ν_s, which are the active and sterile neutrino mass eigenstates





CP-violation in Radiative Neutrino Decay

- Can write an $\mathcal{O}(1)$ parameter $I_{\phi\psi}$ that parametrizes the CP-violation

$$I_{\phi\psi} = \frac{\mu^2(m_s^2 + m_\psi^2 - m_\phi^2)}{m_s^4} + \frac{m_\phi^2 - m_\psi^2}{m_s^2} \log\left(\frac{m_s^2 + m_\phi^2 - m_\psi^2 - \mu^2}{m_s^2 + m_\phi^2 - m_\psi^2 + \mu^2}\right) + \frac{m_\psi^2}{m_s^2} \log\left(\frac{m_s^2 + m_\psi^2 - m_\phi^2 - \mu^2}{m_s^2 + m_\psi^2 - m_\phi^2 + \mu^2}\right) . \quad (9)$$

and μ^2 is defined as

$$\mu^2 = \sqrt{m_s^4 + m_\phi^4 + m_\psi^4 - 2m_s^2 m_\phi^2 - 2m_s^2 m_\psi^2 - 2m_\phi^2 m_\psi^2} . \quad (10)$$

The requirement $m_s > m_\phi + m_\psi$ leads to a positive μ^2

Observable Signature with Polarised photons

- Due to kinematics, the CP-violation in this process will produce an asymmetry in the number density of photons observed with a given polarisation, hence can probe properties of neutrinos indirectly
- Process is loop suppressed but observable in theory!
- Rich phenomenology, keV neutrinos as dark matter, seesaw mechanism and leptogensis, heavy dark matter and IceCube
- Problem remains, how do we actually experimentally measure polarisation of high energy photons coming from space, technology doesn't exist yet

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- Finally, showed that radiative neutrino decay can have *CP* violation induced at loop level and this produces an asymmetry in the circularly polarised photon signal

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