Top Flavoured Dark Matter in Dark Minimal Flavour Violation

GK Plenary Workshop, Freudenstadt

Monika Blanke, Simon Kast | September 26, 2016
1 Introduction
   - Simplified Models
   - Dark Minimal Flavour Violation

2 Phenomenology
   - Detector Constraints
   - Flavour Constraints
   - Relic Abundance Constraints
   - Direct Detection Constraints
   - Combined Analysis

3 Summary and Outlook
Simplified Models

- Presence of dark matter ($\Omega_{DM} \approx 27\%$) demands extension of Standard Model (SM).
  → What can we do to find the right extension?

- One extreme: full theory extension of SM (e.g. SUSY).

- Other extreme: effective field theory (EFT) approach.

- The middle way: simplified models.

- Advantage of simplified models: study specific interactions with limited number of parameters.
The Flavour Gate to Dark Matter

Assume an analogy to the SM fermions → dark flavour triplet $\chi_i$. 

Heavy scalar mediator $\phi$, carrying colour and hypercharge. 

Lagrangian has unbroken $Z_3$ symmetry and hence yields stability of $\chi$ (for $m_\phi > m_\chi$).
The Flavour Gate to Dark Matter

Assume an analogy to the SM fermions → dark flavour triplet $\chi_i$.

Flavoured dark matter coupling to SM right-handed up quark triplet:

$$\mathcal{L}_{NP,\text{int}} = -\lambda_{ij} \bar{u}_{Ri} \chi_j \phi + \text{h.c.}$$

- DM flavour triplet $\chi_j$, Dirac fermion, SM gauge singlet.
- Heavy scalar mediator $\phi$, carrying colour and hypercharge.
- Lagrangian has unbroken $\mathbb{Z}_3$ symmetry and hence yields stability of DM $\chi$ (for $m_\phi > m_\chi$).
Flavour symmetry

\[ U(3)_u \times U(3)_d \times U(3)_q \times U(3)_{\chi} \]

is only broken by SM Yukawa couplings and the DM-quark coupling \( \lambda_{ij} \) (Dark Minimal Flavour Violation).

⇒ only DM mass splitting originates from RG running:

\[ m_{ij} = m_\chi (1 + \eta \lambda^\dagger \lambda + ...)_{ij}. \]

- \( \eta \) depends on the full theory \( \rightarrow \) has to be a parameter of the simplified model.

- Flavour with lowest mass is our DM candidate.
  \( \rightarrow \) we choose the “top-flavour”. [Kilic, Klimek, Yu ’15]
After using all the symmetries at our disposal, $\lambda$ has 9 parameters left and can be parametrized as:

$$\lambda = U_2^\lambda U_1^\lambda U_{12}^\lambda D_\lambda$$

- $D_\lambda$ is a real diagonal matrix $D_\lambda = \text{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})$.
- $U_{ij}^\lambda$ are unitary matrices with mixing angles $\Theta_{ij}$ and phases $\delta_{ij}$.

$\Rightarrow$ new source of flavour and CP violation
Constraints from SUSY Searches at LHC

Constraints from SUSY searches ($t\bar{t}$ or dijet final states)
[ATLAS collaboration ’14]

Study $pp \rightarrow \phi \bar{\phi} \rightarrow q\bar{q}\chi\bar{\chi}$

- Production either through $g\phi\bar{\phi}$ or NP interaction (coupling-dependent).
- Decay either to top or jet ($+\not{E}_T$).

**Figure**: NP interaction production channel.

**Figure**: Cross section for $t\bar{t}$ final state, mixing angles set to zero.
The phenomenologically interesting region is $m_\chi \leq 1$ TeV.

- Too large couplings $D_{\lambda,ii}$ would exclude nearly all of parameter space.
- Most serious constraints are given by searches for dijet final state.

$\Rightarrow$ Safe parameter space:

$$m_\phi \geq 850 \text{ GeV}$$

$$2.0 \geq D_{\lambda,33} > D_{\lambda,22}, D_{\lambda,11}$$

$\Rightarrow$ Also save with mixings allowed.

**Figure** : Exclusion plot for dijet final state, mixing angles set to zero.
No mesons with top quark are possible, the only constraints come from D mesons.
⇒ not too strong

The NP contribution has to be smaller than experimental bounds.
⇒ constraints on mixing angles, mostly $\Theta_{12}$

**Figure**: NP contribution to neutral D meson mixing.

**Figure**: Valid mixing angles for different coupling splittings. $m_\phi = 850$ GeV, $m_\chi = 250$ GeV.
DM Constraints from Observed Relic Abundance
[Steigman, Dasgupta, Beacom ’12]

- Assume DM abundance as a thermal relic.
- Depending on mass splitting several freeze out scenarios are possible.
- If DM mass is below top mass several channels drop out.
  ⇒ different impact on parameters
- Co-annihilation has to be just as large as to produce the correct relic density.
  ⇒ cuts out valid area for $D_{\chi, ii}$ depending on $m_\phi$ and $m_\chi$
- Lower bounds on DM mass depending on mediator mass.
- Depending on $\eta$ an upper DM bound arises in single flavour freeze out scenarios.

Figure: Coannihilation of DM flavours.

Figure: Valid points in quasi degenerate freeze out scenario.
DM Bounds from Direct Detection Experiments

[LUX collaboration ’16]

- Many contributions to total WIMP-nucleon cross section, only Z-penguin with neutron is negative. ⇒ saves the day
- Tree level and neutron Z-penguin have to nearly cancel each other. ⇒ serious constraints on $\Theta_{13}$
- For too large couplings the cancellation is no longer possible → excluded.
- Top flavoured DM is the natural choice.

Figure: Cancellation of tree level and neutron Z-penguin contributions (symbolic).

Figure: Valid mixing angle $\Theta_{13}$ vs $D_{\lambda,33}$. 
Combined Analysis of Constraints

- A combination of relic abundance and direct detection constraints confine $\Theta_{13}$ to a narrow interval around the “perfect” cancellation point.
- The lower and upper bounds on the DM mass become more serious, since the parameters do not only have to fulfill relic abundance constraints.
- The combined analysis clearly prefers top flavoured DM.

**Figure:** Valid points in $\Theta_{13}$-$D_{\lambda,33}$-plane (QDF).

**Figure:** Valid points for $m_\phi = 850$ GeV and $m_\chi = 250$ GeV (QDF).
Recap

- A simplified model of flavoured DM coupled to SM right-handed up quark triplet. Coupling is general following the concept of DMFV.

- Assuming \( m_\chi < 1 \) TeV (phenomenologically interesting area).

- With this mass the RA constraints demand high \( D_{\lambda,ii} \) for high mediator mass \( m_\phi \).

- High couplings prevent the necessary cancellation in WIMP-nucleon cross section. \( \Rightarrow \) Mediator mass can not be too large if \( m_\chi < 1 \) TeV.

- Collider constraints limit couplings for a reasonable \( m_\phi \) (NP production).

- Constraints from dijet searches prefer \( D_{\lambda,33} \geq D_{\lambda,22}, D_{\lambda,11} \).

- Direct detection constraints prefer top flavoured DM.

- In combination with the limits on couplings, the RA constraints produce a lower bound for the DM mass (depending on \( m_\phi \)).

- In SFF the splitting conditions in combination with RA constraints also establishes an upper bound on \( m_\chi \) (depending on \( m_\phi \) and \( \eta \)).
Conclusion and Outlook

- All kinds of different constraints → multitude of effects and interesting interplay.
- Especially interesting effect on mixing angle $\theta_{13}$ due to DD and RA constraints.
  ⇒ Future measurements of direct detection experiments can potentially exclude a large class of models.
- Simplified models are powerful tool to study diversity of constraints.
- Going beyond Minimal Flavour Violation is worth the effort.
  → Dark Minimal Flavour Violation as guidance.
The End

Thank you!
The End

Thank you!

Questions?
Georges Aad et al. “Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton–proton collision data”. In: *JHEP* 09 (2014), p. 176. DOI: 10.1007/JHEP09(2014)176. arXiv: 1405.7875 [hep-ex].

Georges Aad et al. “Search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV $pp$ collisions with the ATLAS detector”. In: *JHEP* 11 (2014), p. 118. DOI: 10.1007/JHEP11(2014)118. arXiv: 1407.0583 [hep-ex].

R Aaij et al. “Precision measurement of D meson mass differences”. In: *JHEP* 1306 (2013), p. 065. DOI: 10.1007/JHEP06(2013)065. arXiv: 1304.6865 [hep-ex].
References II

Prateek Agrawal, Monika Blanke, and Katrin Gemmler. “Flavored dark matter beyond Minimal Flavor Violation”. In: JHEP 1410 (2014), p. 72. DOI: 10.1007/JHEP10(2014)072. arXiv: 1405.6709 [hep-ph].

D. S. Akerib et al. “Improved WIMP scattering limits from the LUX experiment”. In: (2015). arXiv: 1512.03506 [astro-ph.CO].

Sinya Aoki et al. “Review of lattice results concerning low-energy particle physics”. In: Eur.Phys.J. C74 (2014), p. 2890. DOI: 10.1140/epjc/s10052-014-2890-7. arXiv: 1310.8555 [hep-lat].

A.J. Bevan et al. “The UTfit collaboration average of D meson mixing data: Winter 2014”. In: JHEP 1403 (2014), p. 123. DOI: 10.1007/JHEP03(2014)123. arXiv: 1402.1664 [hep-ph].
Monika Blanke et al. “FCNC Processes in the Littlest Higgs Model with T-Parity: a 2009 Look”. In: Acta Phys.Polon. B41 (2010), pp. 657–683. arXiv: 0906.5454 [hep-ph].

N. Carrasco et al. “$D^0 - \bar{D}^0$ mixing in the standard model and beyond from $N_f = 2$ twisted mass QCD”. In: Phys.Rev. D90.1 (2014), p. 014502. DOI: 10.1103/PhysRevD.90.014502. arXiv: 1403.7302 [hep-lat].

Carlos A. Chavez, Ray F. Cowan, and W.S. Lockman. “Charm meson mixing: An experimental review”. In: Int.J.Mod.Phys. A27 (2012), p. 1230019. DOI: 10.1142/S0217751X12300190. arXiv: 1209.5806 [hep-ex].
Csaba Csaki, Adam Falkowski, and Andreas Weiler. “The Flavor of the Composite Pseudo-Goldstone Higgs”. In: JHEP 0809 (2008), p. 008. DOI: 10.1088/1126-6708/2008/09/008. arXiv: 0804.1954 [hep-ph].

Yuval Grossman, Yosef Nir, and Gilad Perez. “Testing New Indirect CP Violation”. In: Phys.Rev.Lett. 103 (2009), p. 071602. DOI: 10.1103/PhysRevLett.103.071602. arXiv: 0904.0305 [hep-ph].

Alexander L. Kagan and Michael D. Sokoloff. “On Indirect CP Violation and Implications for D0 - anti-D0 and B(s) - anti-B(s) mixing”. In: Phys.Rev. D80 (2009), p. 076008. DOI: 10.1103/PhysRevD.80.076008. arXiv: 0907.3917 [hep-ph].
Can Kilic, Matthew D. Klimek, and Jiang-Hao Yu. “Signatures of Top Flavored Dark Matter”. In: *Phys.Rev.* D91.5 (2015), p. 054036. DOI: 10.1103/PhysRevD.91.054036. arXiv: 1501.02202 [hep-ph].

Alexey A Petrov. “Long-distance effects in charm mixing”. In: (2013). arXiv: 1312.5304 [hep-ph].

Gary Steigman, Basudeb Dasgupta, and John F. Beacom. “Precise Relic WIMP Abundance and its Impact on Searches for Dark Matter Annihilation”. In: *Phys.Rev.* D86 (2012), p. 023506. DOI: 10.1103/PhysRevD.86.023506. arXiv: 1204.3622 [hep-ph].

James D. Wells. “Annihilation cross-sections for relic densities in the low velocity limit”. In: (1994). arXiv: hep-ph/9404219 [hep-ph].
Constraints from SUSY Searches at LHC

[ATLAS collaboration '14]

- Study the process $pp \rightarrow \phi \bar{\phi} \rightarrow q\bar{q}\chi\bar{\chi}$.
- Depending on decay product of $\phi$ we detect either a top signature or a jet ($+\vec{E}_T$).
- Inspiration from SUSY searches at LHC
  $\Rightarrow$ Upper bounds on CS of both $t\bar{t}$ and dijet signals.

**Figure**: Studied LHC DM production processes.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Constraints from SUSY Searches at LHC

Involved QCD processes

Involved NP processes

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Constraints from $\bar{t}t + \not{E}_T$ Searches at LHC

- $D_{\lambda,33}$ increased
  $\rightarrow$ BR of decay goes up.

- $D_{\lambda,11}, D_{\lambda,22}$ increased
  $\rightarrow$ BR of decay goes down.

- **BUT**: For high $D_{\lambda,11} = D_{\lambda,22}$ we observe increasing excluded areas.

Figure: Exclusion plot for $\bar{t}t$ final state, mixing angles set to zero.
Constraints from SUSY Searches at LHC

**Explanation**: NP production

- Major contribution to total production (for high $D_{\lambda,11}$, $D_{\lambda,22}$)
- This effect can make up for drop in BR
- $D_{\lambda,33}$ not relevant, since the protons do not contain top
- Very high couplings can lead to serious exclusion areas.

**Figure**: Cross section of $t\bar{t}$ final state for $m_\phi = 850$ GeV and $m_\chi = 50$ GeV, mixing angles set to zero.
Constraints from dijet + $E_T$ Searches at LHC

- Stronger exclusion bounds on model.
- The phenomenologically interesting region is $m_\chi \leq 1$ TeV.
- Too large couplings $D_{\lambda,ii}$ would exclude nearly all of parameter space.
- Most serious constraints come from dijet final state.

⇒ Safe parameter space:

$$m_\phi \geq 850 \text{ GeV}$$

$$2.0 \geq D_{\lambda,33} \geq D_{\lambda,22}, D_{\lambda,11}$$

**Figure**: Exclusion plot for dijet final state, mixing angles set to zero.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Influence of Mixing Angles on LHC production

- Mixing angles shift influences between couplings $D_{\lambda,ij}$.
  $\Rightarrow$ For big splitting in the couplings, mixing angles can cause big shifts in cross sections.

- For our choice of $m_\phi$ bounds from $t\bar{t}$ final state cause no constraints.

- Worst allowed case for dijet final state, in our safe parameter space, is $D_{\lambda,11} = D_{\lambda,22} = D_{\lambda,33} = 2.0$
  $\Rightarrow$ Unchanged by mixing angles.

  $\Rightarrow$ Mixing angles can cause no problem with this choice of safe parameter space.
Flavour Constraints from Neutral Meson Mixing

[UTfit collaboration ’14]

- No mesons with top quark are possible, the only constraints come from D mesons.
  ⇒ not too strong

- The NP contribution has to be smaller than experimental bounds.

\[ M_{12,\text{NP}}^D = \frac{1}{2m_D} \langle \bar{D}^0 | \mathcal{H}_{\text{eff}}^{\Delta C=2,\text{new}} | D^0 \rangle^* \]

\[ = \frac{1}{384\pi^2m^2} \sum_{i,j} \lambda_{uj}^* \lambda_{cj} \lambda_{ui}^* \lambda_{ci} \cdot L(x_i, x_j) \cdot \eta_D \cdot m_D f_D^2 \hat{B}_D. \]

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Flavour Constraints from Neutral Meson Mixing

\((\lambda \lambda^\dagger)_{cu}^2 = (U_{\lambda} D_{\lambda} D_{\lambda}^\dagger U_{\lambda}^\dagger)_{cu}^2\)

- For degeneracy, \(D_{\lambda,11} = D_{\lambda,22} = D_{\lambda,33}\) the mixing matrices \(U_{\lambda}^\dagger\) will drop out.

- The higher the splitting \(\Delta_{ij} = D_{\lambda,ii} - D_{\lambda,jj}\), the more we will see the constraints on the mixing angle \(\theta_{ij}\).

\[\Rightarrow\] Most significant constraints on \(\theta_{12}\), other mixings nearly unconstrained.

\(\text{Figure: Valid mixing angles for different coupling splittings. } m_\phi = 850 \text{ GeV and } m_\chi = 250 \text{ GeV.}\)
DM Constraints from Observed Relic Abundance

[Steigman, Dasgupta, Beacom ’12]

- Assume DM abundance as a thermal relic, \( T_f \propto \frac{m_\chi}{20} \)
- Coannihilation CS has to be just large enough to produce the correct relic density (we allow for a 10% tolerance interval):

\[
\langle \sigma v \rangle_{\text{eff,exp}} = 2.2 \times 10^{-26} \text{cm}^3/\text{s}.
\]

\[\Rightarrow \] cuts out valid area for \( D_{\lambda,ii} \)
depending on \( m_\phi \) and \( m_\chi \)

\[
\langle \sigma v \rangle_{\text{eff}} = \frac{1}{9} \times \frac{3}{256\pi} \sum_{i,j=1,2,3} \sum_{k,l=u,c,t} \lambda_{ki}^* \lambda_{kj} \lambda_{lj}^* \lambda_{lj} \sqrt{(4m_\chi^2 - (m_k - m_l)^2) (4m_\chi^2 - (m_k + m_l)^2)} \left( m_\phi^2 + m_\chi^2 - \frac{m_k^2}{2} - \frac{m_l^2}{2} \right)^2.
\]

Figure: Coannihilation of DM flavours.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
DM Constraints from Observed Relic Abundance

- Depending on the mass splitting of the different DM flavours several freeze out scenarios are possible.

\[ m_{ij} = m_\chi (1 + \eta (D_{\lambda,ii})^2 + \ldots) \delta_{ij}. \]

- For a DM mass below the top quark mass this decay channel drops out.

  \[ \Rightarrow \text{CS formula and hence impact on parameters can be quite different} \]

- Extreme example: only \( \chi_t \) present at freeze out with DM mass below top mass threshold:

\[
\langle \sigma v \rangle_{\text{eff}} = \frac{3}{256 \pi} \sum_{k,l=u,c} \lambda_{k3} \lambda^*_{k3} \lambda_{l3} \lambda^*_{l3} \frac{4m^2_\chi}{(m^2_\phi + m^2_\chi)^2} .
\]

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Quasi Degenerate Freeze Out (QDF) Szenario

- All DM flavours are present at the freeze out.
- We require the mass splitting to be less than 1% (significantly smaller than $T_f$) for this to happen.
- $\eta$ is free parameter $\rightarrow$ choose it favourable: -0.01.
- This guarantees top flavoured DM (see direct detection section for motivation).
- Constraint cuts out valid area for $D_{\lambda,ii}$ depending on $m_\phi$ and $m_\chi$.
- Lower bound on $m_\chi$ due to upper limits for $D_{\lambda,ii}$, depending on $m_\phi$.

Figure: Valid points in quasi degenerate freeze out scenario.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Single Flavour Freeze Out (SFF) Scenario

- Only $m_\chi$ present at freeze out.
- We require the mass splitting to be more than 10% (significantly bigger than $T_f$) for this to happen.
- $\eta$ is free parameter $\rightarrow$ choose it favourable: -0.075.
- This guarantees top flavoured DM (see direct detection section for motivation).
- Constraint cuts out valid area of parameters depending on $m_\phi$ and $m_\chi$, with significant effect on mixing angles.
- In addition to lower bound, we also find an upper bound on $m_\chi$ due to upper and lower (from mass splitting condition) limits for $D_{\lambda,ii}$, depending on $m_\phi$.

**Figure:** Valid points in single flavour freeze out scenario for $m_\phi = 850$ GeV and $m_\chi = 210$ GeV.

**Figure:** Mass bounds in single flavour freeze out scenario.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV September 26, 2016 32/15
DM Bounds from Direct Detection Experiments

Many contributions to total WIMP-nucleon cross section:

$$\sigma_{n}^{SI} = \frac{\mu_{n}^{2}}{\pi A^{2}}|Zf_{p} + (A - Z)f_{n}|^{2}.$$
All contributions have to combine to a WIMP-nucleon cross section below the LUX bounds.

- All contributions are positive, only the Z-penguin with the neutron is negative \( \Rightarrow \) saves the day.
- Largest contribution comes from tree level process. Largest negative term is hence interference term of tree level and neutron Z-penguin.
- Most important terms, have to nearly cancel each other:

\[
A_{\mathcal{I}} \cdot D_{\lambda,33}^4 \cdot \sin(\theta_{13})^4 - A_{\mathcal{II}} \cdot D_{\lambda,33}^4 \cdot \sin(\theta_{13})^2 \cdot \cos(\theta_{13})^2 \cdot \cos(\theta_{23})^2
\]

![Diagram](image)

**Figure:** Cancellation of tree level and neutron Z-penguin contributions (symbolic).
DM Bounds from Direct Detection Experiments

- Tree level and neutron Z-penguin have to nearly cancel each other. ⇒ serious constraints on $\theta_{13}$

- For higher couplings the cancellation gets more complicated.

- For too large couplings the cancellation is no longer possible at all → excluded.

- Top-flavoured DM is the natural choice: ⇒ Tree level contribution small ⇒ Neutron Z-penguin contribution large.

Figure: Valid mixing angle $\Theta_{13}$ vs $D_{\lambda,33}$.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Combined Analysis of Constraints (QDF)

Combined application of both flavour, relic abundance and direct detection constraint in quasi degenerate freeze out scenario.

**Figure** : Valid points for $m_\phi = 850$ GeV and $m_\chi = 150$ GeV (QDF).

**Figure** : Valid points for $m_\phi = 850$ GeV and $m_\chi = 250$ GeV (QDF).

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
A combination of relic abundance and direct detection constraints confine $\theta_{13}$ to a narrow interval.

The bounds on the DM mass become more serious, since the parameters do not only have to fulfill relic abundance constraints.

The combined analysis clearly prefers top flavoured DM.

**Figure**: Valid points in $\theta_{13}$-$D_{\lambda,33}$-plane (QDF).
Combined Analysis of Constraints (SFF)

Combined application of both flavour, relic abundance and direct detection constraint in single flavour freeze out scenario.

Figure : Valid points for $m_\phi = 850$ GeV and $m_\chi = 225$ GeV (SFF).

Figure : Valid points for $m_\phi = 850$ GeV and $m_\chi = 250$ GeV (SFF).

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Combined Analysis of Constraints (SFF)

- A combination of relic abundance and direct detection constraints confine $\theta_{13}$ to a narrow interval (even more serious than in QDF).
- Especially in SFF the combination of all constraints extremely limits the chance of finding a valid configuration of all parameters for $m_{\chi_t} \leq m_{\text{top}}$.
- The combined analysis clearly prefers top flavoured DM.

Figure: Valid points in mass plot for combined constraints (SFF).
Figure: Exclusion plots for dijet final state for various couplings, mixing angles set to zero.
Figure: Exclusion plots for dijet final state for various couplings, mixing angles set to zero.
**Figure**: Exclusion plots for dijet final state for various couplings, mixing angles set to zero.
Figure: Exclusion plots for $\bar{t}t$ final state for various couplings, mixing angles set to zero.
Figure: Cross section for $t\bar{t}$ final state, mixing angles set to zero.

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Figure: Impact of flavour constraints on $\Theta_{12}$. 

References

Monika Blanke, Simon Kast – Top Flavoured DM in DMFV
Figure: Valid mixing angles for different coupling splittings. $m_\phi = 850$ GeV and $m_\chi = 250$ GeV.
Figure: Valid points in quasi degenerate freeze out scenario in $D_{\lambda,11} - D_{\lambda,22}$-plane for various DM masses.
Figure: Valid points in quasi degenerate freeze out scenario in $D_{\lambda,11} - D_{\lambda,33}$-plane for various DM masses.
Figure: Valid points in quasi degenerate freeze out scenario in $D_{\lambda,22} - D_{\lambda,33}$-plane for various DM masses.
Figure: Valid points in single flavour freeze out scenario in $D_{\lambda,33} - \sin(\Theta_{ij})$-plane for $m_\phi = 850$ GeV and $m_\chi = 150$ GeV.
Figure: Valid points in single flavour freeze out scenario in $D_{\lambda,33} - \sin(\Theta_{ij})$-plane for $m_\phi = 850 \text{ GeV}$ and $m_\chi = 210 \text{ GeV}$. 

References
**Figure**: Valid points in single flavour freeze out scenario in $D_{\lambda,33} - \sin(\Theta_{ij})$-plane for $m_\phi = 850$ GeV and $m_\chi = 230$ GeV.
Figure: Valid points for LUX bounds in $D_{\lambda,33} - \sin(\Theta_{13})$ plane.
**Figure**: Valid points for LUX bounds in $D_{\lambda,33} - \sin(\Theta_{13})$–plane.

References

Monika Blanke, **Simon Kast** – Top Flavoured DM in DMFV
Figure: Valid points for LUX bounds in $D_{\lambda,33} - \sin(\Theta_{13})$ plane, with SFF splitting applied.
Figure: Valid points of combined analysis for quasi degenerate freeze out scenario in $D_{\lambda,33} - \sin(\Theta_{13})$ plane for different DM masses.
Figure: Valid mixing angles for different coupling splittings for quasi degenerate freeze out scenario. \( m_\phi = 850 \text{ GeV} \) and \( m_\chi = 150 \text{ GeV} \).
**Figure**: Valid mixing angles for different coupling splittings for quasi degenerate freeze out scenario. $m_\phi = 850 \text{ GeV}$ and $m_\chi = 250 \text{ GeV}$. 

References

Monika Blanke, **Simon Kast** – Top Flavoured DM in DMFV
Figure: Valid mixing angles for different coupling splittings for single flavour freeze out scenario. $m_\phi = 850$ GeV and $m_\chi = 225$ GeV.
Figure: Valid mixing angles for different coupling splittings for single flavour freeze out scenario. $m_\phi = 850$ GeV and $m_\chi = 250$ GeV.