Inert doublet model assisted by Peccei-Quinn symmetry

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Can WIMPs and axions coexist as dark matter particles?

- WIMP and Axion are both compelling DM candidates
- To stabilize WIMPs, a discrete ad hoc $\mathbb{Z}_2$ symmetry is needed
- Pseudo-Goldstone boson of the breakdown of the $U(1)_{PQ}$

arXiv: 2407.01415 [hep-ph]

Can WIMPs and axions coexist as dark matter particles?

SSB of PQ → $$\eta = \frac{1}{\sqrt{2}}\left(f_a + \sigma(x)\right) e^{\frac{ia(x)}{f_a}}$$

→ **Vector-like quark**

Portal bet. the dark sector and the SM fields

arxiv 2207.00487 , 2305.08662 [hep-ph]

⇒ Solves dark matter problem

⇒ Solves strong CP problem

⇒ Residual $\mathbb{Z}_2$ stabilizes WIMP

Inert Higgs Doublet Model

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + i A^0}{\sqrt{2}} \end{pmatrix}$$

Lightest neutral component is WIMP

$$V = \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4(\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2\right]$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$M_{A^0}^2 = \mu_2^2 + \frac{1}{2}\lambda_c v^2,$$

$$M_{H^0}^2 = \mu_2^2 + \frac{1}{2}\lambda_L v^2$$

λ_2 has no effect on scalar masses and their phenomenology

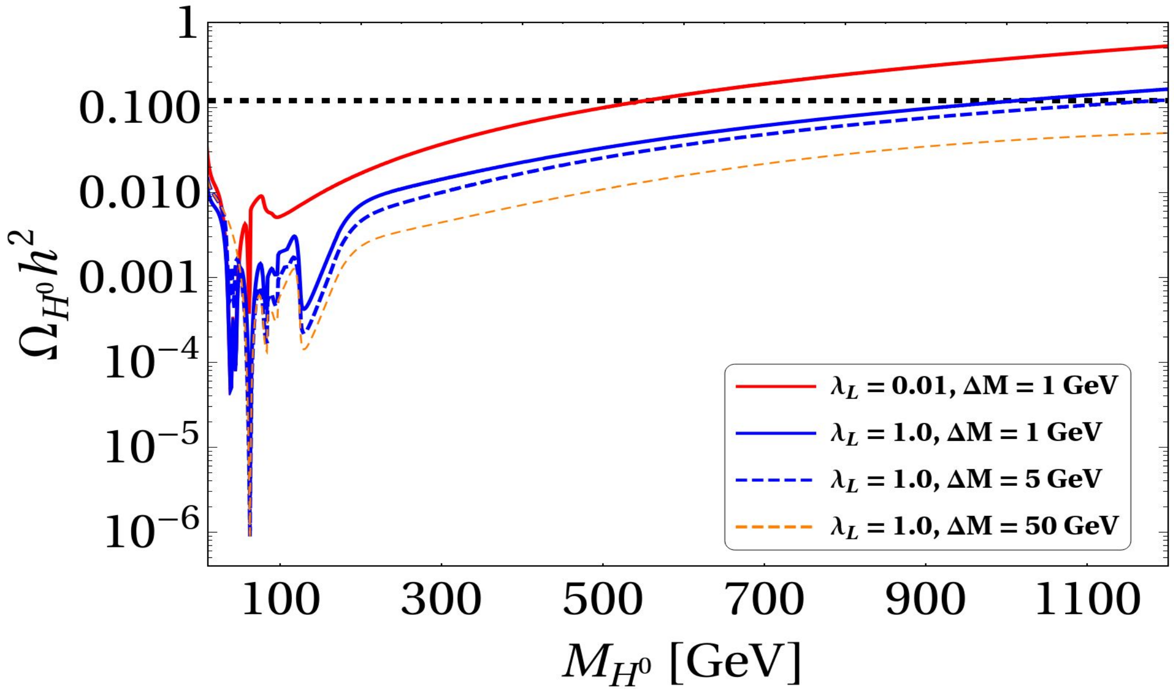
- ❖ Perturbativity & unitarity
- ❖ EW bound
- ❖ LEP & LHC
- ❖ S, T, U parameters

VLQ interaction with axion: $f_\Psi \, \eta^* \, \overline{\Psi}_L \Psi_R + h.c.$

	η	Ψ_L	Ψ_R	Φ_2
$SU(3)_C$	1	3	3	1
$SU(2)_L$	1	1	1	2
$U(1)_{PQ}$	2	-1	1	-1

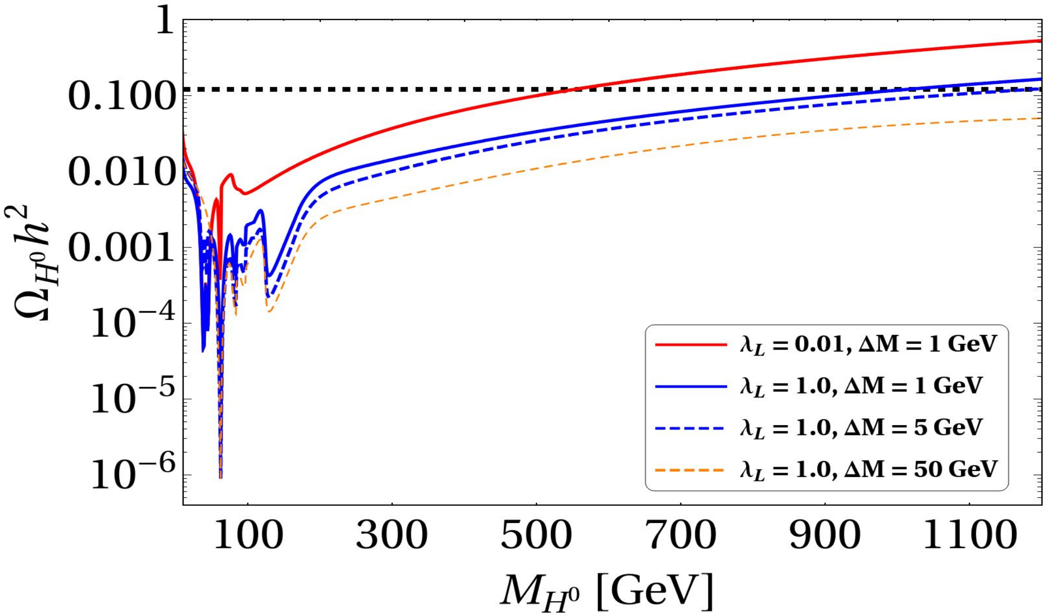
$$\mathcal{L} \supset f \, \bar{q}_L \, \Phi_2 \, \Psi_R + h.c.$$

- We consider interaction predominantly with 3rd-generation SM quarks



arxiv 2111.15236 [hep-ph]

$$\Omega_{H^0} h^2 + \Omega_a h^2 = \Omega_{\rm total} h^2 = 0.120 \pm 0.001$$



Axion relic density:
coherent oscillations

$$\Omega_a h^2 \simeq 0.18\,\theta^2 \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{1.19}$$

$$f_a = \left(\frac{\Omega_{\text{total}}h^2 - \Omega_{H^0}h^2}{0.18}\right)^{1/1.19} 10^{12}\ \text{GeV}$$

Multicomponent WIMP-axion reopens
phenomenologically attractive

$$100\ \text{GeV} < M_{H^0} < 550\ \text{GeV}$$

Searches at the LHC

- Monojet or multijet with MET are traditional searches for dark matter at LHC
- In degenerate mass spectrum, traditional searches are displaced vertex searches

To search degenerate spectrum of IDM, our consideration

An isolated, energetic lepton (electron or muon) accompanied by two jets (one identified as a b-jet) and significant missing transverse momentum

Our collider searches are model-independent

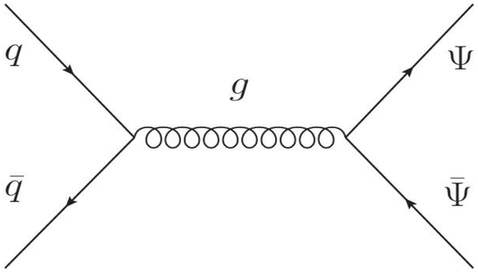
Signal Topology

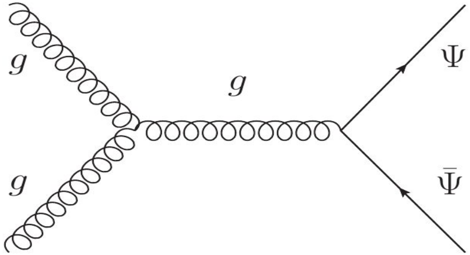
Topology-1 $$pp \to \Psi\bar{\Psi} \to (t\,H^-)(\bar{t}H^+) = t\bar{t} + H^+H^-$$

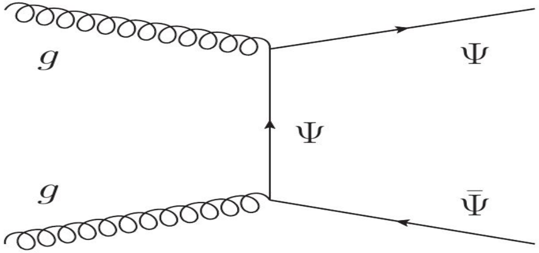
Topology-2 $$pp \to \Psi\bar{\Psi} \to (t\,H^-)(\bar{b}H^0/\bar{b}A^0) = t\bar{b}(\text{or }\bar{t}b) + H^\pm H^0/H^\pm A^0$$

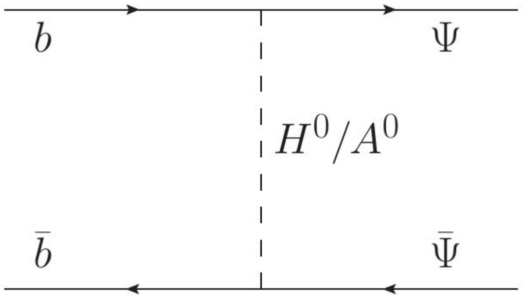
Topology-3 $$pp \to \Psi\bar{\Psi} \to (bH^0/bA^0)(\bar{b}H^0/\bar{b}A^0) = b\bar{b} + H^0H^0/H^0A^0/A^0A^0$$

At least one of the top quark decay leptonically

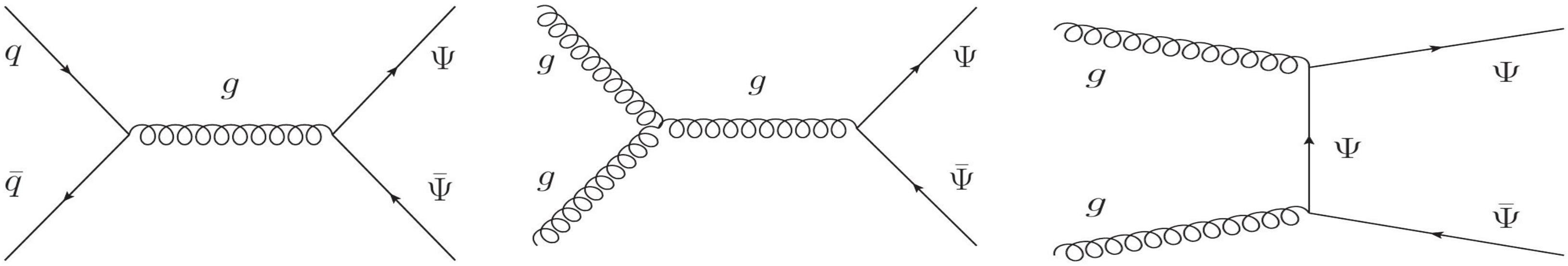








- Two b-quarks $\sigma \sim$ negligibly small
- Cross-section depends on the mass of VLQ and QCD coupling strength
- We also consider one-loop QCD correction of VLQs pair production


q
q̄
g
Ψ
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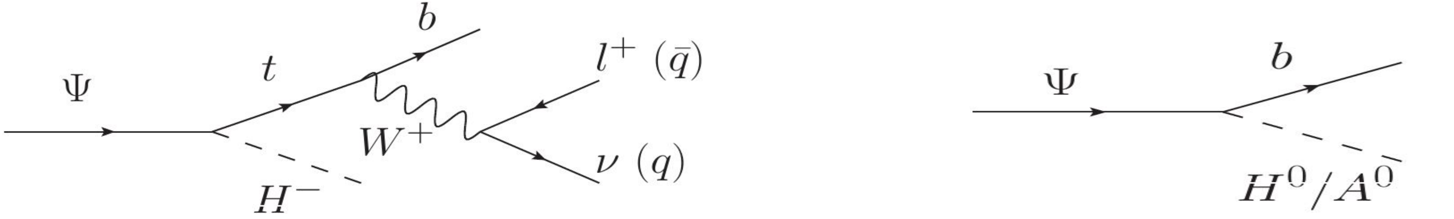

Ψ
t
b
W^+
l^+ ($\bar{q}$)
ν (q)
H^-
Ψ
b
H^0/A^0

	M_{H^0} GeV	M_Ψ GeV	$BR(\Psi \to tH^-)$	LO (fb) $\mathcal{O}(\alpha_S^2)$	NLO (fb) $\mathcal{O}(\alpha_S^3)$
BP2	445	750	0.40	$191.7^{+28.6\%}_{-20.8\%}$	$287.2^{+9.1\%}_{-10.7\%}$
BP5	700	1500	0.496	$1.79^{+29.2\%}_{-21.3\%}$	$2.47^{+11.6\%}_{-12.2\%}$

$$\mu_{F,R} = \zeta\sqrt{\hat{s}}$$

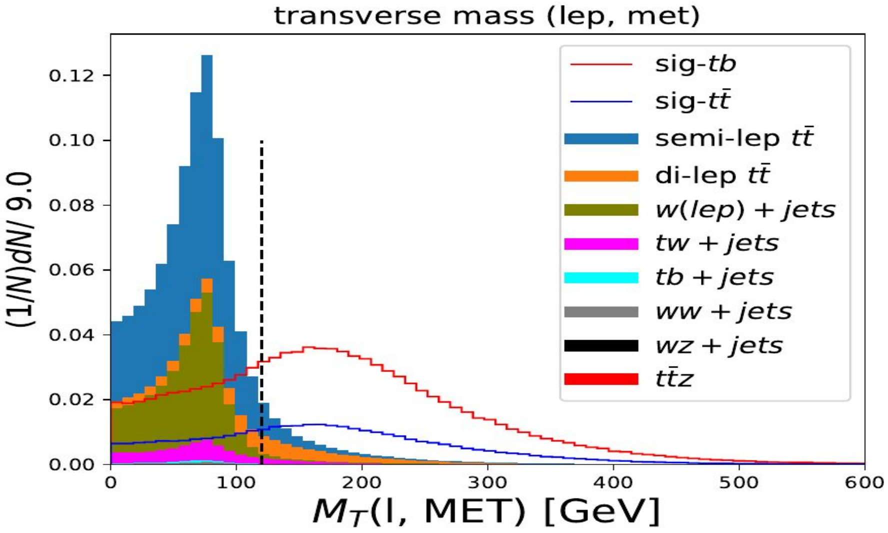
$$\{1/2, 1, 2\}$$

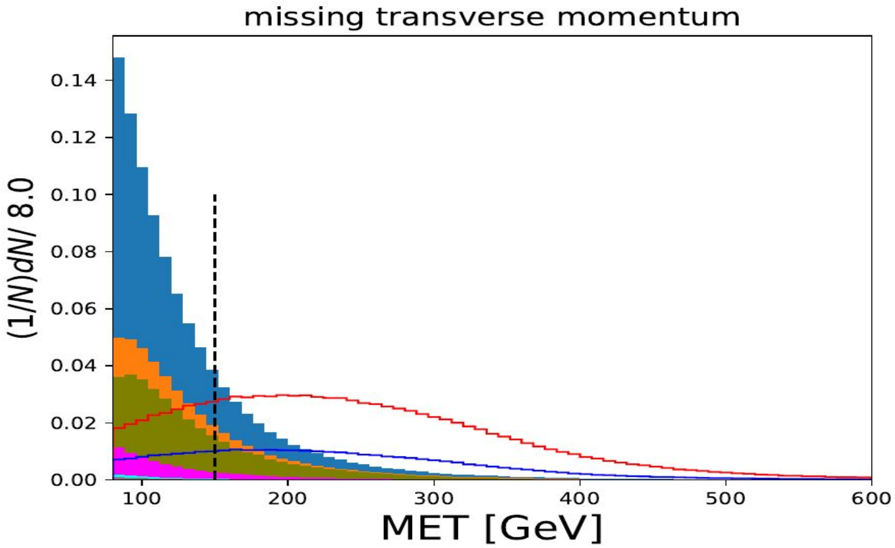
Backgrounds that mimic the signal

1. **Semileptonic** $t\bar{t} + \text{jets}$
2. **Dileptonic** $t\bar{t} + \text{jets}$ (Lost-lepton background)
3. **Single top-quark:** → $tW + \text{jets}$ $tb + \text{jets}$
4. $W + \text{jets}$
5. **Di-boson+jets** → W(lep) Z (invi or had), Z invi decay contributes most because of large MET
   W W (lep-had)
6. $t\bar{t}V$

Event reconstruction

- Electron or muon, $P_T(l) > 30 \quad |\eta| \leq 2.4$
- Reject if electrons and positrons fall within $1.44 < |\eta| < 1.57$
- Lepton Isolation:
- Lepton veto: In case the event contains more than one lepton $P_T(l) > 5\ \mathrm{GeV}$
- two AK4 jets with one of them is b-tagged
- Separation between all isolated objects (lepton, jets) from MET should be greater than 0.4





$$M_T(l, \mathrm{MET}) = \sqrt{2P_T(l)|MET|(1 - \cos\Delta\Phi)}$$

- Lepton's transverse mass > 120 GeV
- MET > 150 GeV
- Di-leptonic $t\bar{t}$ becomes leading BG

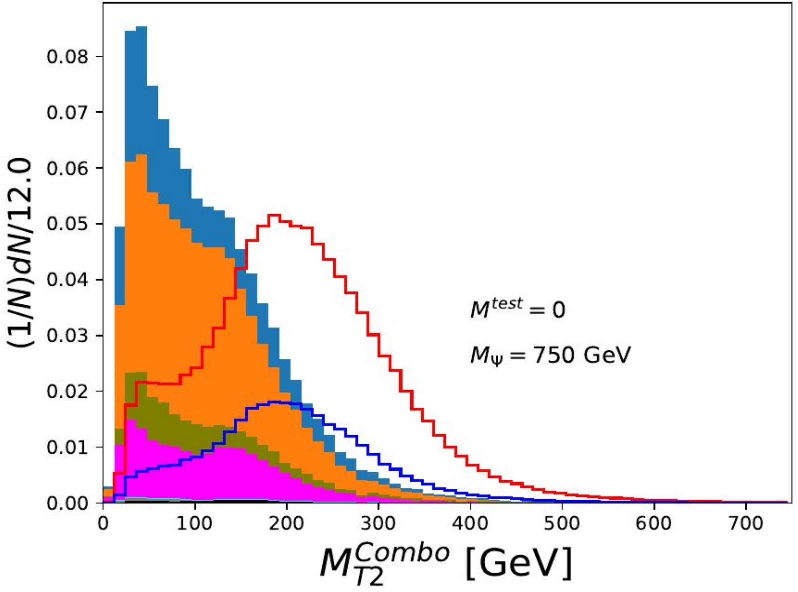
$$M_{T2}(\vec{P}_T^{\,1}, \vec{P}_T^{\,2}, \vec{E}_T) = \min_{\vec{q}_T^{\,1}+\vec{q}_T^{\,2}=\vec{E}_T}\left[\ \max\{\ M_T(\vec{P}_T^{\,1}, \vec{q}_T^{\,1}),\ M_T(\vec{P}_T^{\,2}, \vec{q}_T^{\,2})\ \}\right]$$

arXiv:hep-ph/9906349
arXiv:0910.3679

we propose:

$$M_{T2}^{Combo} = \min[\ M_{T2}(j_1 + l,\ j_2,\ \vec{E}_T),\ M_{T2}(j_1,\ j_2 + l,\ \vec{E}_T)]$$

- ➔ endpoint is expected to be around the top quark mass for the dileptonic $t\bar{t}$ events
- ➔ Signal has a larger value

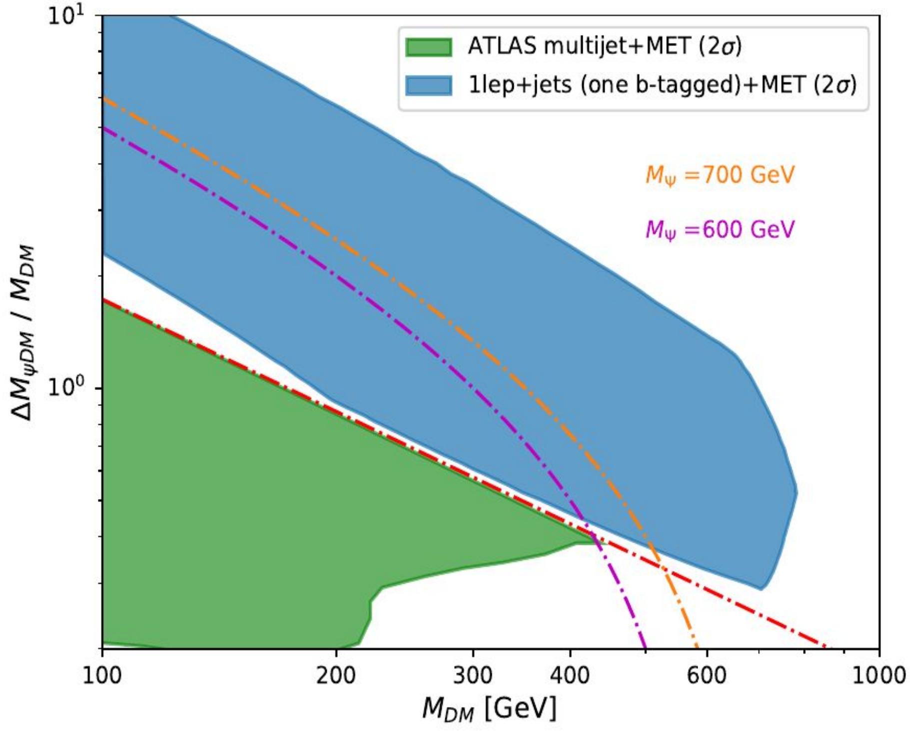


Multivariate analysis

The full set of BDT input variables

$$N_{\text{jets}},\ \text{MET}, P_T(j_{1,2}, l),\ \Delta\Phi(i, \text{MET}),\ \Delta R(i, \text{MET}),\ \Delta R(b, l)$$

$$m(l, b),\ M_T(l, \text{MET}),\ M_T(b, \text{MET}),\ \sqrt{\hat{s}_{\min}},\ M_{T2}^{Combo}$$



- This contour is plotted for 300 fb^{-1} assuming VLQ primarily interacts with 3rd-gen quarks
- reinterpreted analysis for interaction with first two gen of SM quarks

  arXiv:1511.04452 [hep-ph]
- A vast parameter space that gives correct relic density and is allowed from DD and other constraints can be explored at the 14 TeV LHC

Summary and conclusion

- Multicomponent WIMP-axion dark matter model is discussed; solves dark matter and strong CP problem
- Residual $\mathbb{Z}_2$ stabilizes WIMP
- Reopen desert region of IDM
- A compelling final state is considered for searching dark matter and dark sector particles at the LHC
- NLO-QCD corrections of VLQ pair production processes are considered
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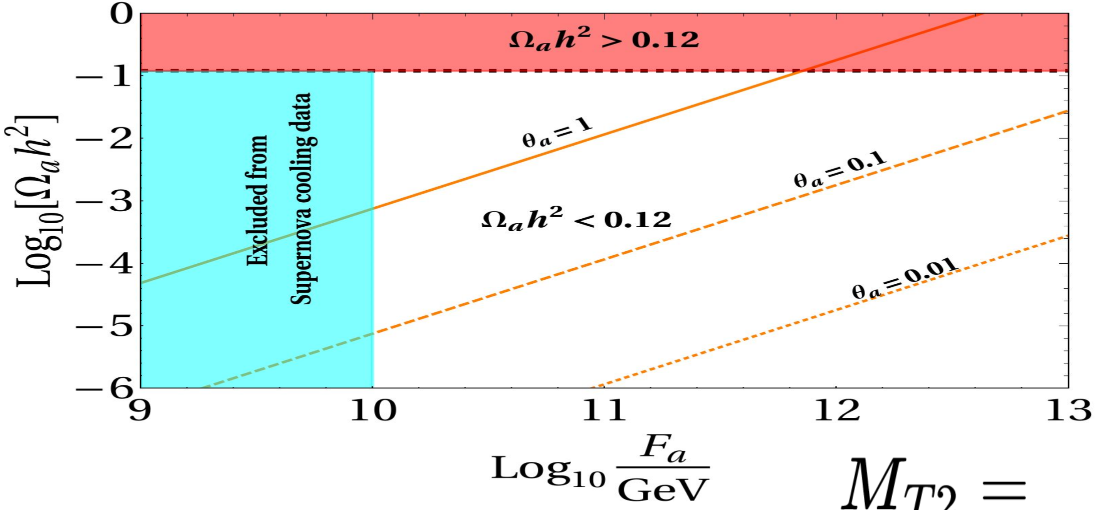
Thank You

Backup

KSVZ top-philic

Axion relic density is obtained from the misalignment mechanism $\Omega_a h^2 \simeq 0.18\theta_a^2 \left(\frac{F_a}{10^{12}\text{GeV}}\right)^{1.19}$



$$M_{T2} = \min_{\overrightarrow{p_{1T}}^{\text{invi}} + \overrightarrow{p_{2T}}^{\text{invi}} = MET} [\max\{M_T^{(1)}, M_T^{(2)}\}]$$

$$(M_T^{(i)})^2 = m_i^2 + M_{\text{invi}}^2 + 2(E_{iT}E_{iT}^{\text{invi}} - \overrightarrow{p_{iT}} \cdot \overrightarrow{p_{iT}}^{\text{invi}}), \ \{i = 1, 2\}$$

Strong CP problem

$$SU(3)_c \qquad \theta \frac{g_s^2}{32\pi^2} \tilde{G}_{a,\mu\nu} G^{a,\mu\nu} \qquad \theta = [0, 2\pi]$$

$$\tilde{G}_{a,\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^{a,\alpha\beta}$$

- It violates discrete symmetries P and CP
- No CP violation is observed in the QCD sector
- The neutron's electric dipole moment is an observable consequence of CP violation in QCD

nED measurement $\Rightarrow \bar{\theta} \leq 10^{-10}$

$$\bar{\theta} = \theta + Arg\, det M$$