Probing Dark sector at the LHC with precision

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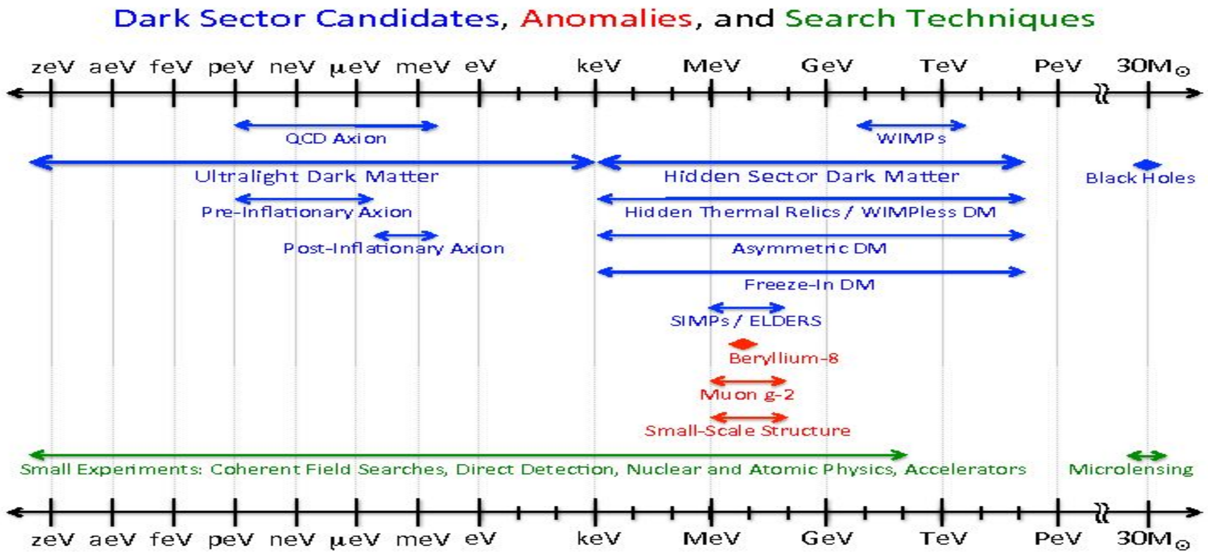
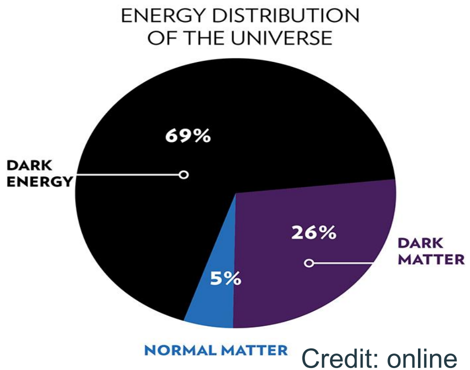
Higgs Hunting 2024

Orsay, Paris, 23-25 September 2024

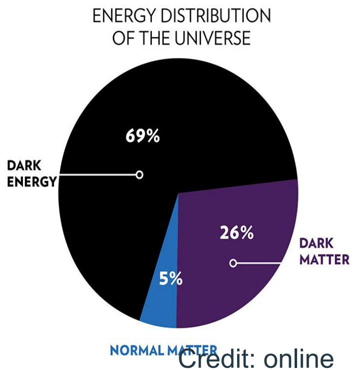


Credit: Cern



Credit: online

- A **richer dark sector** can exist or can involve **Multicomponent DM** candidates
- Low-energy experiments aim to detect DM candidates and require various inputs from cosmology, lattice-QCD, particle physics models and experimental inputs.
- LHC searches target not only dark matter but entire dark sectors without requiring any external inputs
- Searches at LHC can be either model-dependent or **model-independent**
- **Higher order corrections** for more precise probing and constraining the model



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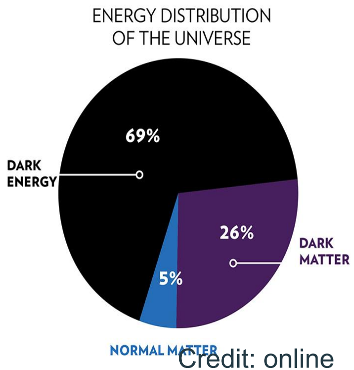

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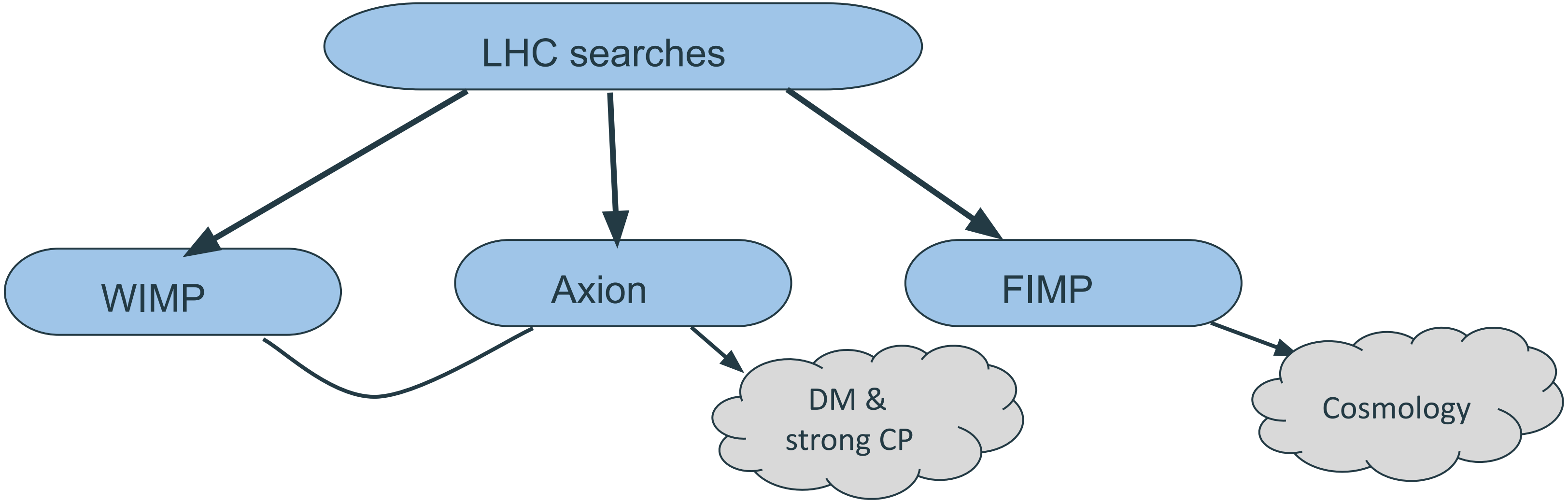
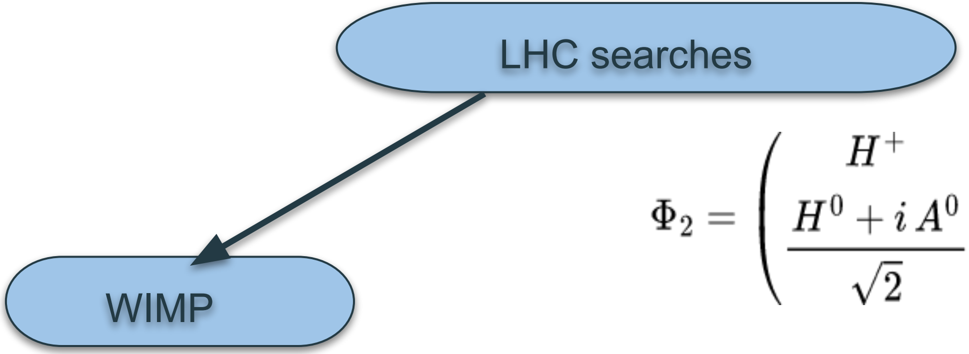


Inert Higgs Doublet Model



$$\Phi_2 = \begin{pmatrix} H^+ \\ \dfrac{H^0 + i\,A^0}{\sqrt{2}} \end{pmatrix} \qquad \mathbb{Z}_2 \text{ odd}$$

- IDM – Simple extension of the SM
- Provides viable DM (Higgs portal)
- We can perform a model-independent (depends only on mass) search at the LHC and constrain this model.

Precise probing of the inert Higgs-doublet model at the LHC

Phys. Rev. D 105 115038

AG, Partha Konar, Satyajit Seth

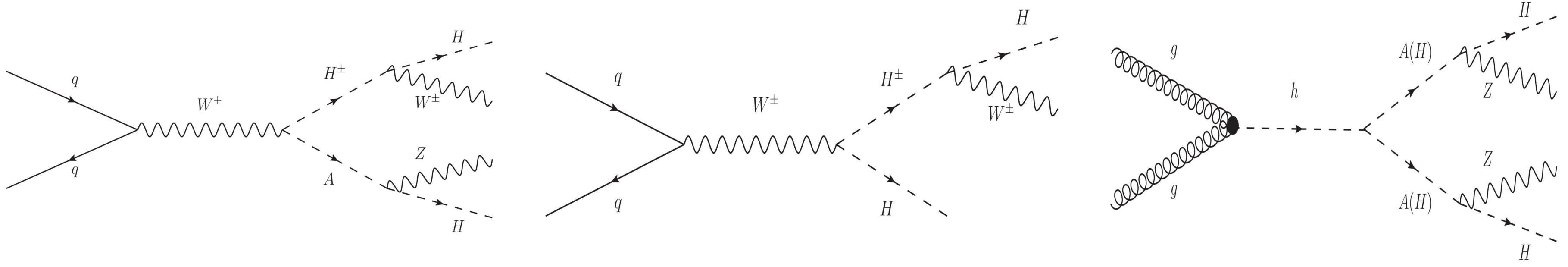
- NLO-QCD corrections are significant
- advanced MVA with BDT of di-fatjet plus MET signal

$pp \to H^{\pm}H, AH$ [QCD] K-fac = 1.33-1.37

$pp \to H^{\pm}A, H^{+}H^{-}, AA$

K-fac = 1.35-1.56, 1.7-1.9

2 fatjets + MET

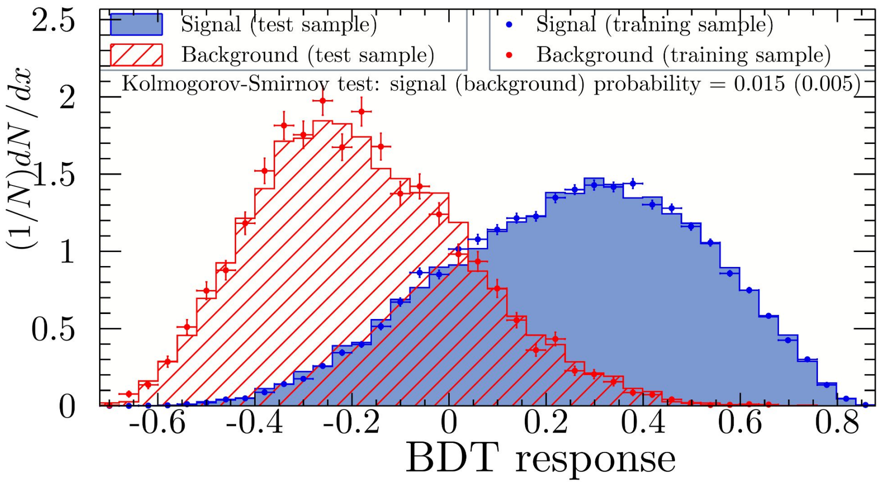


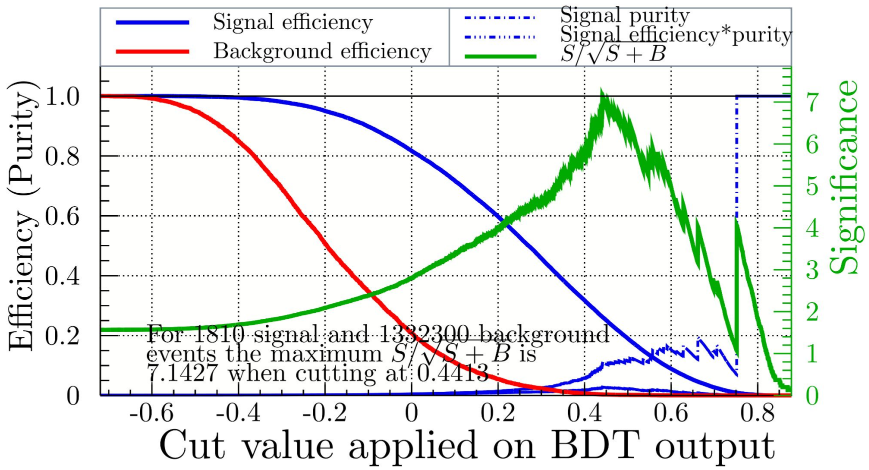
Background: Z+jets (10^4 pb), W+jets, $t\bar{t}$ +jets, tW+jets, VV+jets [signal cross section ~ 100 fb]

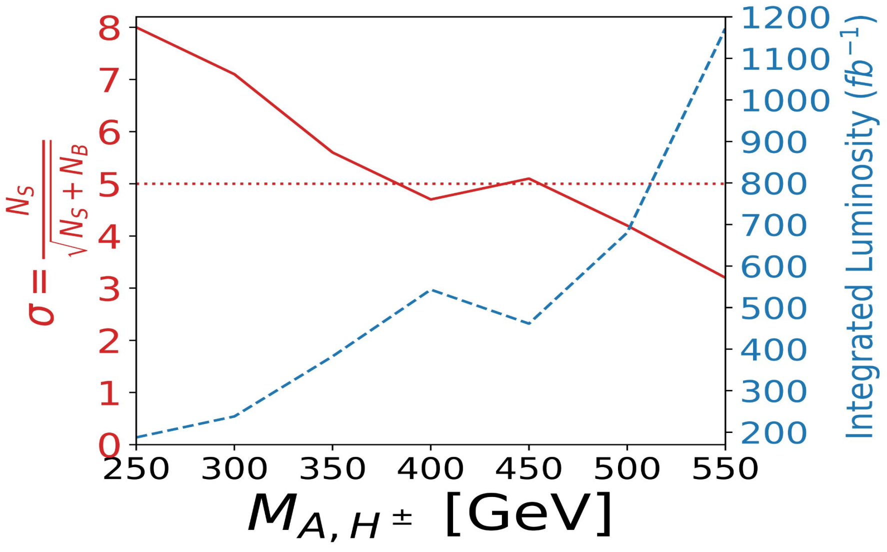
- NLO+PS signal
- Jet-substructure variables
- Advanced Multivariate analysis with BDT

Event selection:

- at least two Fatjets (CA), R = 0.8
- MET > 100 GeV, lepton and b-veto
- M_{J_0}, M_{J_1} > 40 GeV

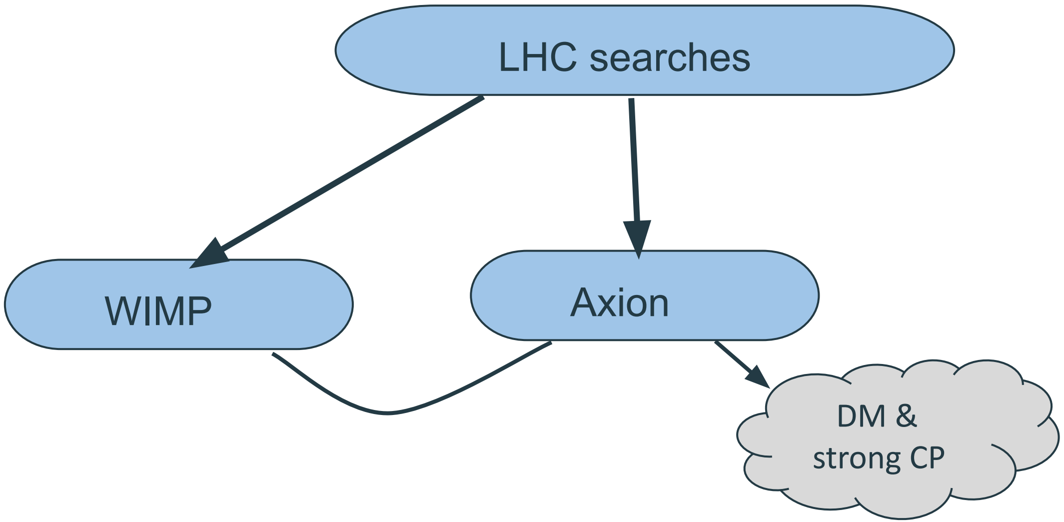






Conclusions:

- In search of the hierarchical mass region of IDM, we propose di fatjets + MET signal
- BSM scalar mass falling in the range of 250–550 GeV can be excluded with 1200 fb^{-1} integrated luminosity at 14 TeV LHC



★ Multicomponent WIMP and axion dark matter model at the LHC

Unveiling desert region in inert doublet model assisted by Peccei-Quinn symmetry

JHEP09(2024)104
(arxiv:2407.01415)
AG, Partha Konar

WIMP and axion coexist as dark matter particles

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

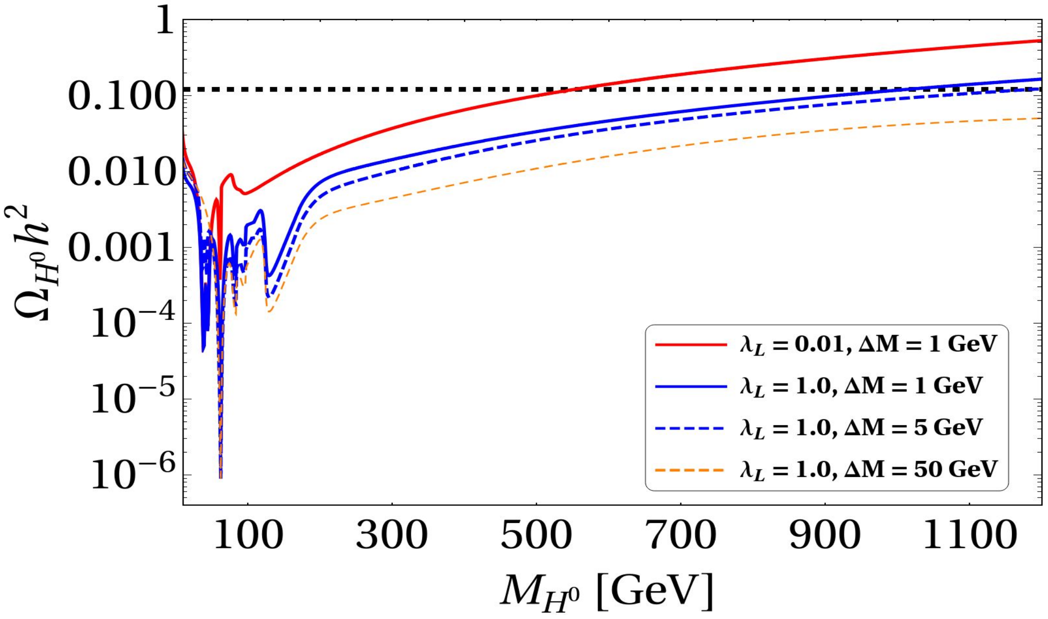
→ **Vector-like quark**

Portal bet. the dark sector and the SM fields

- Solves dark matter problem
- Solves strong CP problem
- Residual $\mathbb{Z}_2$ stabilizes WIMP

arxiv: 2207.00487 ,2305.08662 [hep-ph]

WIMP+Axion: The real SM singlet WIMP interacts with up-type quarks via VLQ, with detailed DM phenomenology and collider searches.



- Small and large λ_L is allowed from DD because of the multicomponent
- Multicomponent WIMP-axion model reopens phenomenologically attractive

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

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

We consider interaction predominantly with 3rd-generation SM quarks

Signal Topology

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

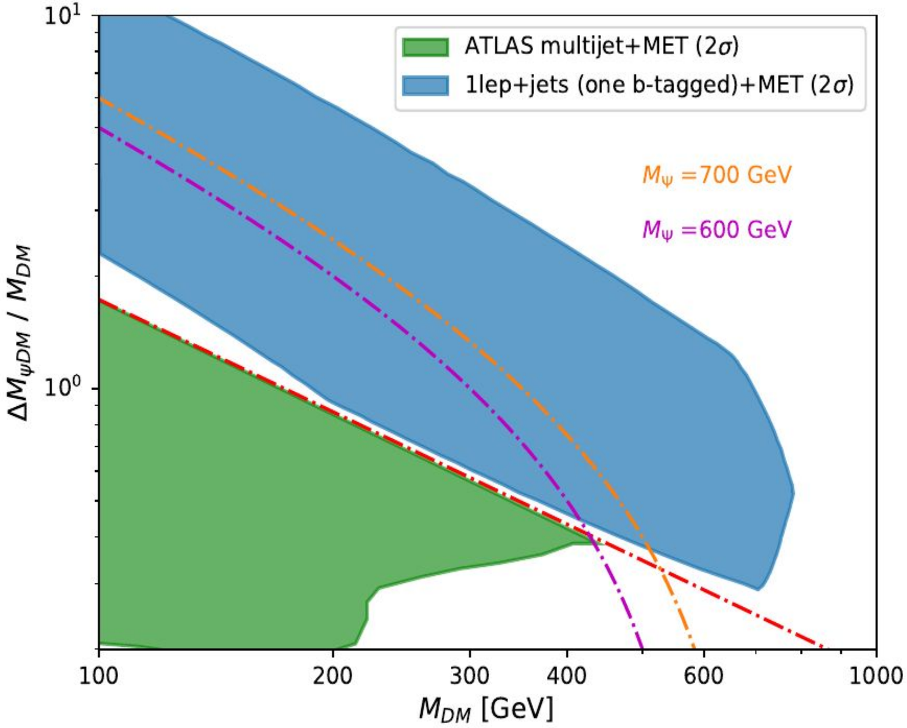
Topology-2 $$pp \to \Psi\bar{\Psi} \to (t\,H^-)(\bar{b}H^0/\bar{b}A^0) = t\bar{b}(\text{or }\bar{t}b) + H^\pm H^0/H^\pm A^0$$

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

To search degenerate spectrum of IDM:

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



- This contour is plotted for $300\ \mathrm{fb}^{-1}$
- one-loop QCD correction of VLQs pair production
- reinterpreted analysis for interaction with first two gen of SM quarks

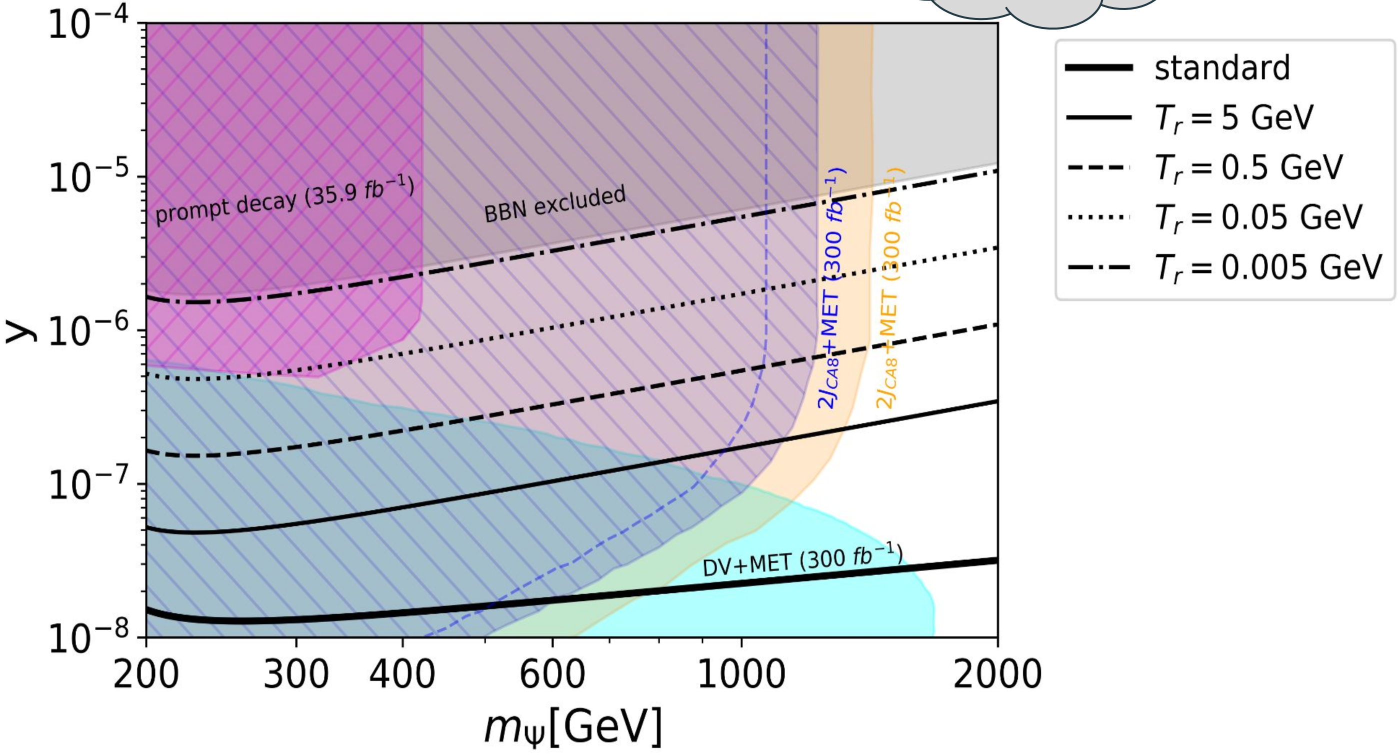
  arXiv:1511.04452 [hep-ph]

- 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

Probing FIMP at the LHC

AG, Partha Konar, Sudipta Show
(e-Print: 2409.xxxxx)

Cosmology



Summary and conclusion

- LHC can explore the entire dark sector, including dark matter
- Searches at LHC can be either model-dependent or model-independent
- Most of our searches are model-independent and account for NLO-QCD corrections to the partonic cross-section
- WIMP and mixed Axion-WIMP multicomponent models are discussed
- Prompt decay of FIMP and its searches is possible at the LHC due to alternative cosmological scenarios

Thank You

Backups

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

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- NLO-QCD corrections are significant
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→ 2 fatjets + MET

$$\mathcal{L}_{SM} + (\mathcal{D}_\mu \Phi_2)^\dagger (\mathcal{D}^\mu \Phi_2) + V_{IDM} + \mathcal{L}_{HEFT}$$

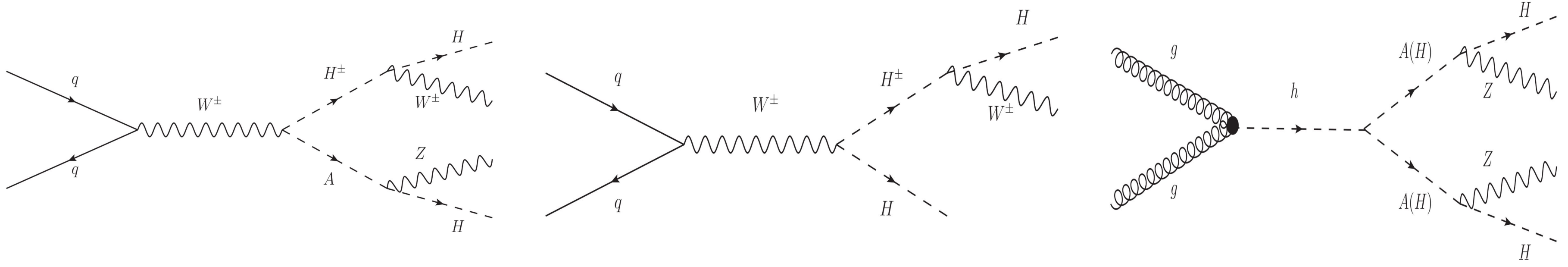
$pp \to H^\pm H, AH$ [QCD] K-fac = 1.33-1.37

$$\mathcal{L}_{HEFT} = -\frac{1}{4} C_{eff} h G^a_{\mu\nu} G^{a\mu\nu}$$

$pp \to H^\pm A, H^+ H^-, AA$

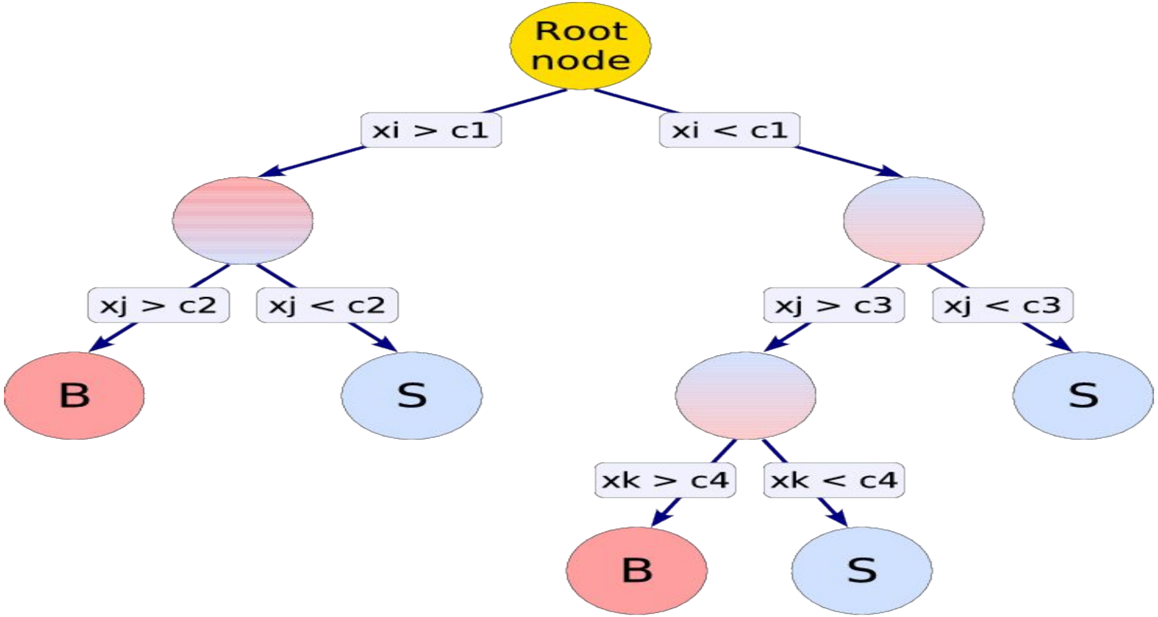
K-fac = 1.35-1.56, 1.7-1.9

$$C_{eff} = \frac{\alpha_s}{3\pi v}(1 + \frac{11}{4}\frac{\alpha_s}{\pi})$$



Arxiv 1805.09795

Boosted Decision tree



- Binary classifier
- Split the phase space into many hypercubes
- Weight of misclassified events increased (boosting)
- Many trees are constructed, and their outputs are combined
- Very powerful classifier

https://cds.cern.ch/record/1019880/plot

Top-philic Dark Matter in a Hybrid KSVZ axion framework

JHEP 12 (2022) 167

AG, Partha Konar, Rishav Roshan

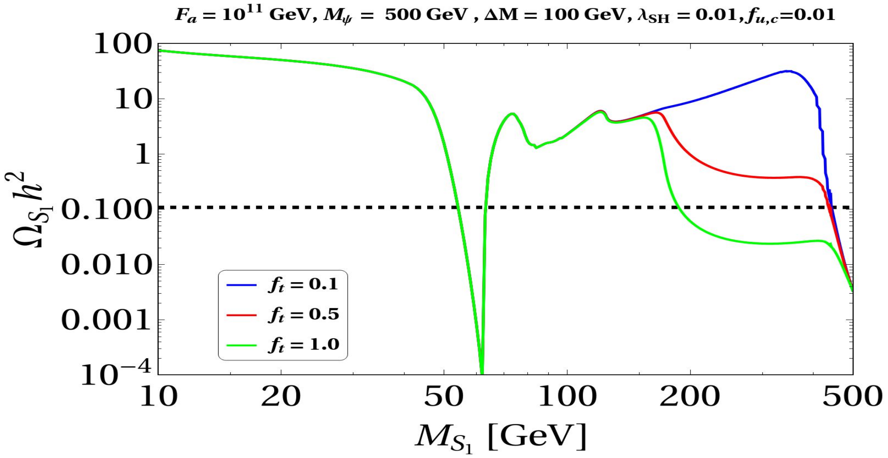
KSVZ model

- Extend SM by $U(1)_{PQ}$ symmetry
- Color vector-like quark
- Complex scalar singlet that breaks PQ symmetry

$$\eta = \frac{1}{\sqrt{2}}(F_a + \sigma_0)\ \exp\left(i\frac{\mathbf{a(x)}}{F_a}\right)$$

Extended KSVZ model

$$S = \frac{S_1 + iS_2}{\sqrt{2}}$$



- solves strong CP problem
- multi-component dark matter scenario
- After the breaking of PQ, a remnant $\mathbb{Z}_2$ symmetry stabilises the scalar DM
- The presence of color VLQ has a significant role in DM and collider phenomenology
- Two top-fatjets plus MET signal is analyzed using BDT

$$f_i S \overline{\Psi}_L u_{iR} + h.c \qquad (i = u, c, t)$$

Relevant para for DM pheno. $\{M_\Psi, M_{S_1}, \Delta M, f_i\}$

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

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

VLQ interaction with axion addresses the strong CP problem

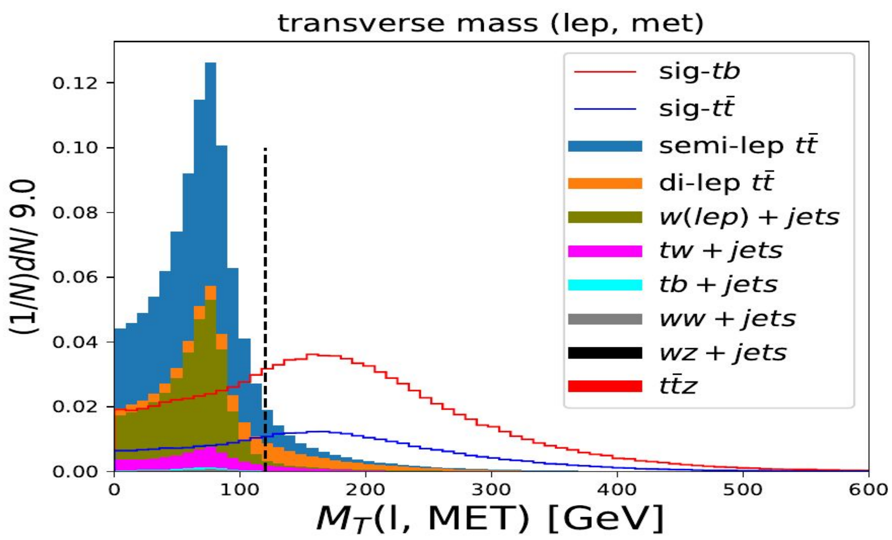
$$f_\Psi \, \eta^* \, \overline{\Psi}_L \Psi_R + h.c.$$

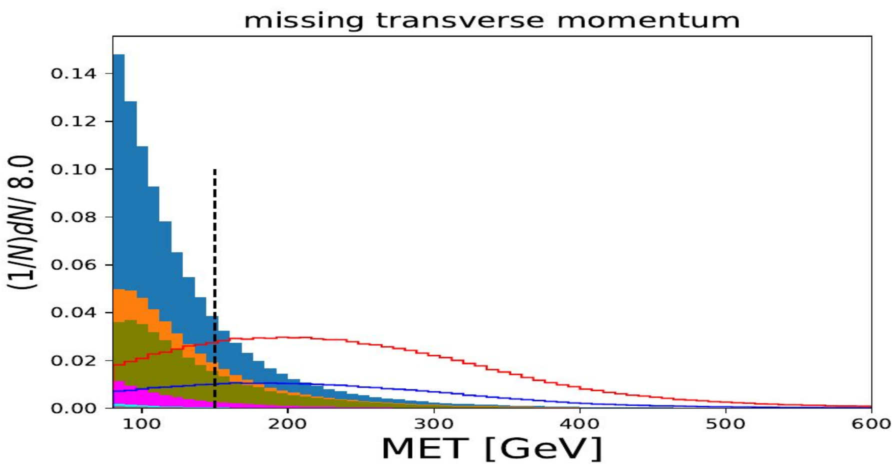
	η	Ψ_L	Ψ_R	Φ_2
$SU(3)_C$	1	3	3	1
$SU(2)_L$	1	1	1	2
$U(1)_{PQ}$	2	-1	1	-1

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

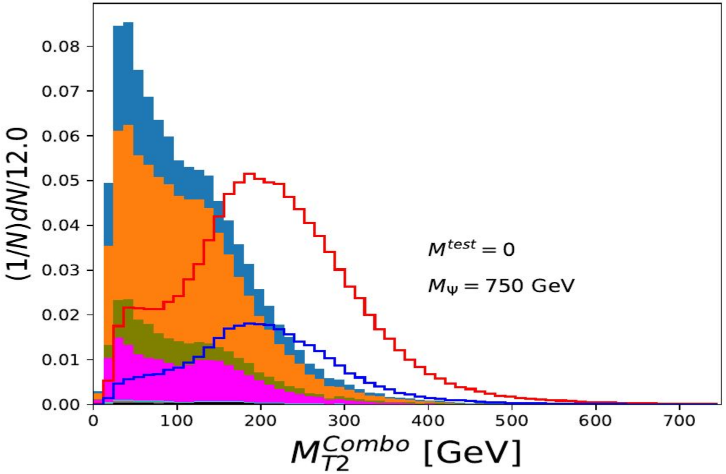
$$\mathcal{L} \supset f \, \bar{q}_L \, \Phi_2 \, \Psi_R + h.c.$$

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





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



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

arXiv:hep-ph/9906349
arXiv:0910.3679

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

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