Muon-jet Phenomenology

Detecting multimuon-jets from the Higgs exotic decays in the Higgs portal framework

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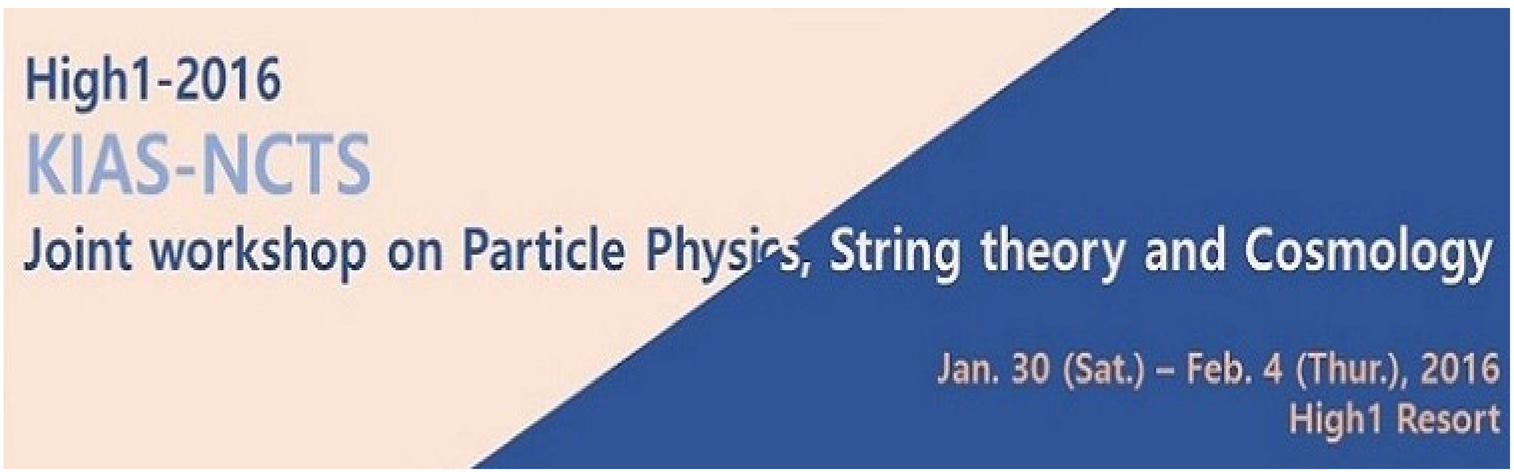


Outline

1. Motivation
2. Introduction of lepton-jets
3. Toy models & Constraints
4. Benchmark points & Kinematical distributions
5. Conclusions

Motivation

- **May the Higgs boson have decay channels that are not predicted by the Standard Model ?**
- One of the global fits to all the SM Higgs boson signal strength has constrained the non-standard decay width of the Higgs boson to be less than 0.94 MeV (branching ratio about 19%) at 95% C.L.-“Higgcision Updates 2014” (Phys. Rev. D 90, 095009 (2014), arXiv:1407.8236v2)

Motivation

- Both ATLAS and CMS Collaborations also published the searching for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson.
- ATLAS : The branching ratio for Invisible Decays is about 75% at 95% C.L. (Phys. Rev. Lett. 112, 201802 (2014), arXiv: 1402.3244)
- CMS : The branching ratio for Invisible Decays is about 58% at 95% C.L. (Eur. Phys. J. C 74 (2014) 2980, arXiv: 1404.1344)

Motivation

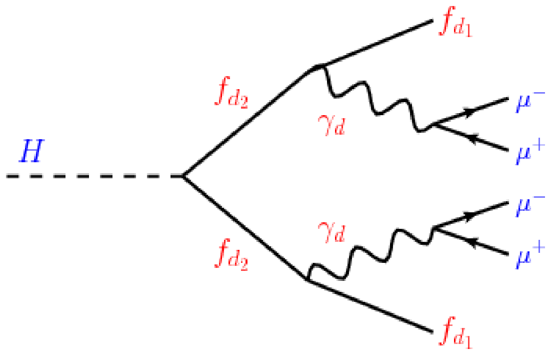
- In some hidden-sector models, the Higgs boson can be connected the hidden sector via Higgs-portal type interaction: $(\Phi^\dagger \Phi)(S^\dagger S)$, where Φ is the standard model (SM) Higgs field and S is the scalar field in the hidden sector. When both the Higgs field and S develops vacuum expectation values, the Φ and S mix to form mass eigenstates, and the Higgs boson can decay into a pair of the scalar bosons if kinematically allowed.
- In some models, the dark sector can also be connected with the SM particles via $Z - Z'$ (dark photon or dark Z) mixing.

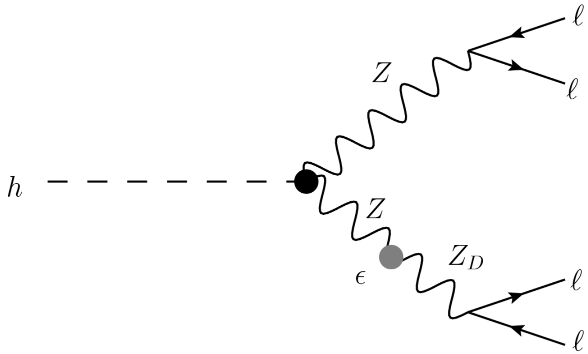
Motivation

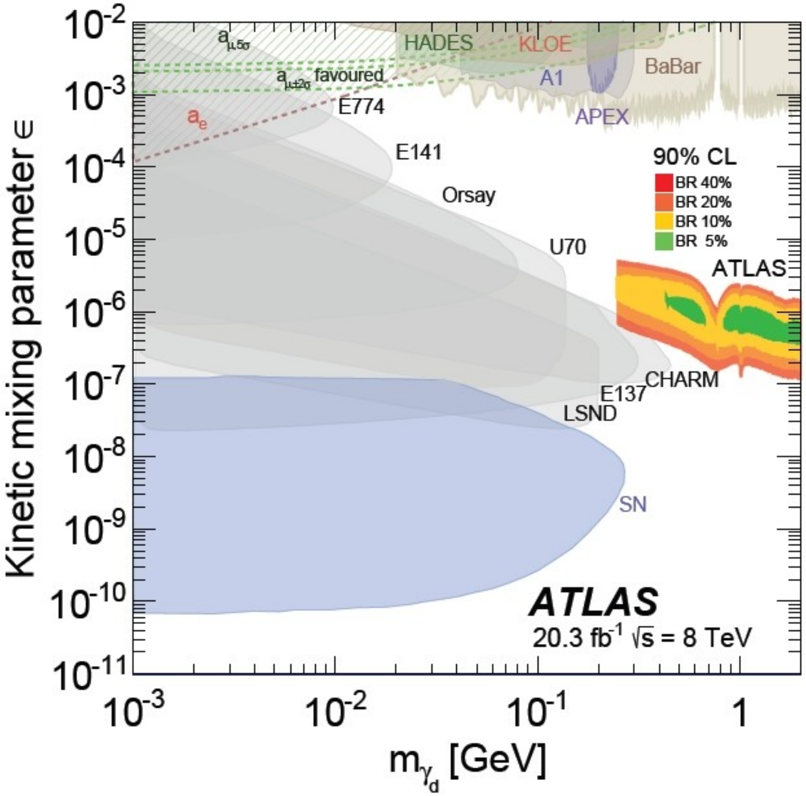
- When the hidden gauge bosons or scalar bosons are very light, say below 1 GeV, they will decay into the heaviest SM particles if kinematically allowed.
- For example, a 500 MeV scalar boson decays, via the mixing with the SM Higgs boson, can decay into a pair of muons, pions, electrons, or photons. The dominant modes would be pions and muons.

Motivation

- ***We will use the muon-jet feature to search for very light particles from the decay of the Higgs boson !!***







G. Aad *et al.* [ATLAS Collaboration], JHEP **1411**, 088 (2014)

Introduction of lepton-jets

- A lepton jet is a cluster of highly collimated particles: electrons, muons and possibly pions
- These arise if light unstable particles with masses in the MeV to GeV range (for example dark photons) reside in the hidden sector and decay predominantly to SM particles. At the LHC, hidden sector particles may be produced with large boosts, causing the visible decay products to form jet-like structures.

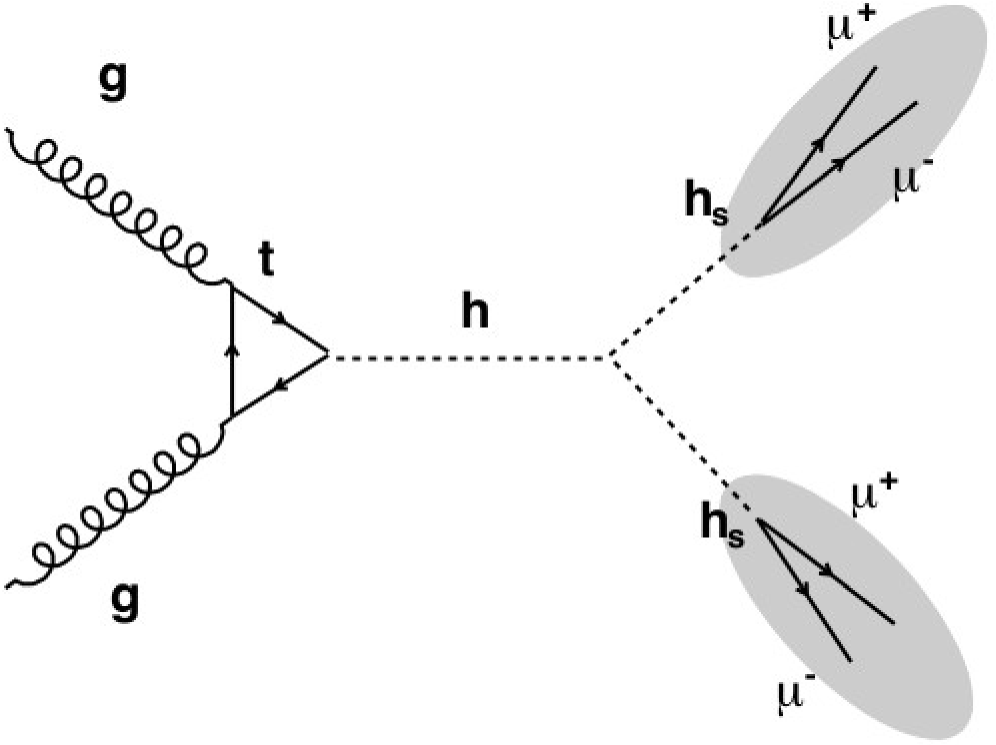
Introduction of lepton-jets

- The opening angle of two partons coming from a parent particle X can be roughly estimated
- $$\Delta R \simeq 2\mathrm{m}_X / p_{T,X}$$
- We can estimate pT,X = 50 GeV, for a particle X coming from the decay of a 125 GeV Higgs produced at rest. Partons from the X decay are then typically separated by R < 0.2 when mX < 5 GeV. Therefore, we expect to have a Higgs decaying into collimated leptons if the parent particle X has a mass of the order of 10 GeV or less.

Toy models & Constraints

- Toy model-1 : Only one light scalar : h_s
- Toy model-2 : Two light scalars : h_D1, h_D2
- Constraint from the global fits to all the SM Higgs boson signal strength
- Constraint from bounds of meson decays

Toy model-1 : Only one light scalar : h_s



Constraints of toy model-1

- **The global fits to all the SM Higgs boson signal strength**
- One of the global fits to all the SM Higgs boson signal strength has constrained the nonstandard decay width of the Higgs boson to be less than 0.94 MeV (branching ratio about 19%) at 95% C.L.

$$\Gamma(h \to h_s h_s) \approx \frac{\mu_f^2}{32\pi m_h} = \frac{<\phi>^2}{32\pi m_h}(\frac{\mu_f}{<\phi>})^2$$

$$\Gamma(h \to h_s h_s) < 0.94 MeV \Rightarrow \frac{\mu_f}{<\phi>} \leq 0.014$$

Bounds from meson decays

- J. D. Clarke, R. Foot and R. R. Volkas, JHEP **1402**, 123 (2014) [arXiv:1310.8042 [hep-ph]].

case 1 : For $100MeV < m_{h_s} < 210MeV$,
fixed target experiments and $B \to K + invisible$ decays
$\to \sin^2\theta \leq 10^{-8}$

case 2 : For $210MeV < m_{h_s} < 280MeV$,
$B \to K\mu^+\mu^-$ decays and fixed target experiments
$\to \sin^2\theta \leq 10^{-10}$

case 3 : For $280MeV < m_{h_s} < 360MeV$,
the same experiments constrain $\sin^2\theta \leq 10^{-10}$ expect for a window between $10^{-8} \leq \sin^2\theta \leq 10^{-5}$ which is still allowed.

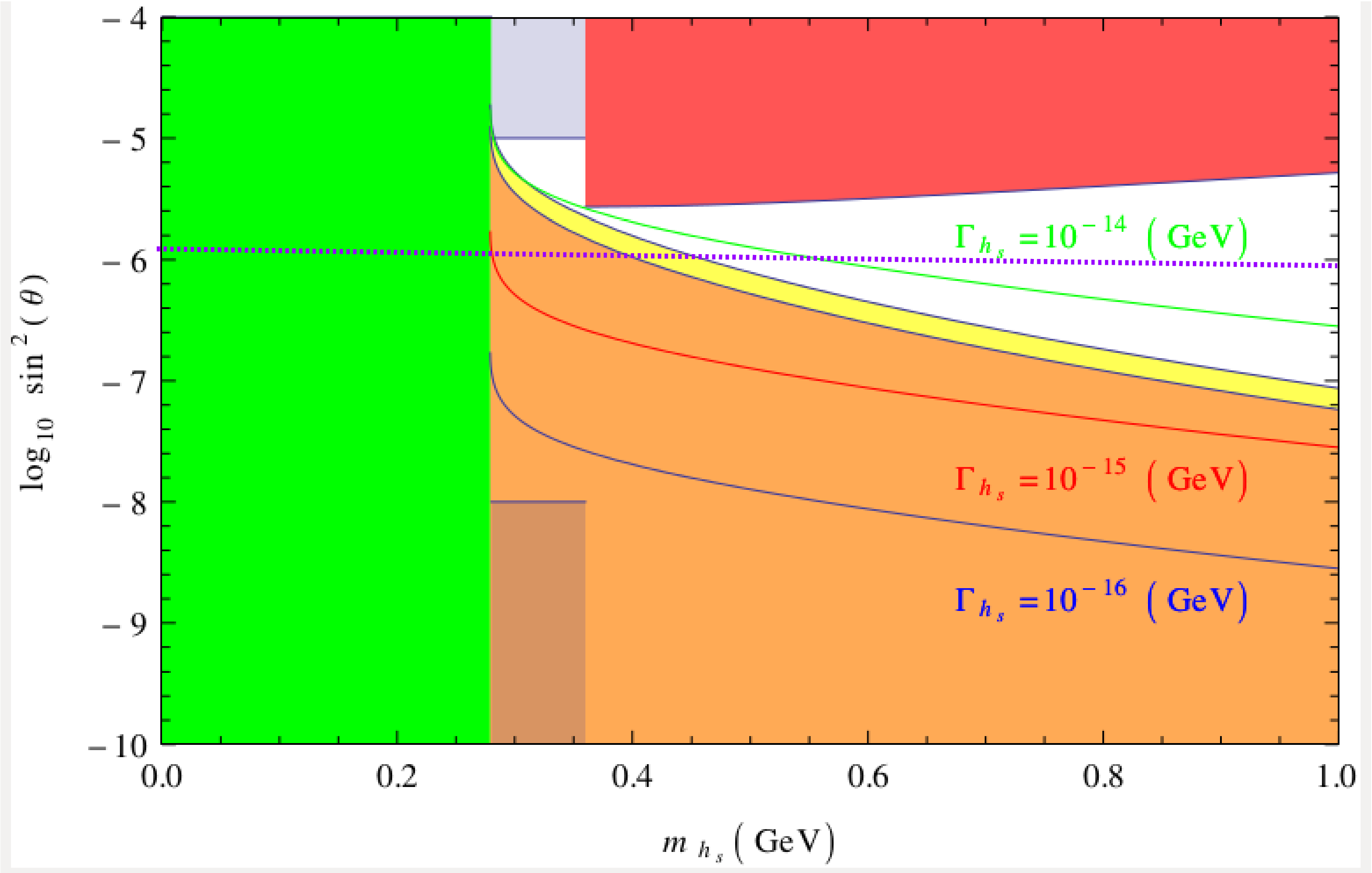
case4 : For $360MeV < m_{h_s} < 4.8GeV$,
$B \to K\mu^+\mu^-$ decays limit $sin^2\theta \times Br(s \to \mu^+\mu^-) \leq 10^{-6}$

$$\Longrightarrow sin^2\theta \times \left(\frac{\Gamma(h_s \to l^+l^-)}{\Gamma(h_s \to l^+l^-) + \Gamma(h_s \to \pi\pi)}\right) < 10^{-6}$$

case 5 : For $4.8GeV < m_{h_s} < 10GeV$,
searches for the Bjorken process $Z \to Z^* h_s \to Z^* + hadrons$ at LEP1 give the best limit
$\to sin^2\theta \leq 10^{-2}$.

Bounds from meson decays

- J. D. Clarke, R. Foot and R. R. Volkas, JHEP **1402**, 123 (2014) [arXiv:1310.8042 [hep-ph]].



Benchmark points for Toy Model-1

TABLE I. Total decay width ,signal cross section and decay length for the process $pp \to h \to 2h_s \to 4\mu$ for various benchmark points for Toy Model-1 at LHC-14. We fix $\mu_f = 5 \times 10^{-2}$ GeV, $sin\theta = 10^{-3}$, and $m_{h_s} = 0.3 - 1$ GeV.

m_{h_s} (GeV)	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Γ_{h_s} (10^{-15} GeV)	2.068	4.839	7.760	11.29	15.60	20.97	27.45	35.24
σ_{14TeV} (fb)	0.335	0.319	0.287	0.237	0.187	0.146	0.113	0.0875
$\gamma c\tau$ (cm)	1989	637	318	182	113	74	50	35

Kinematical distributions

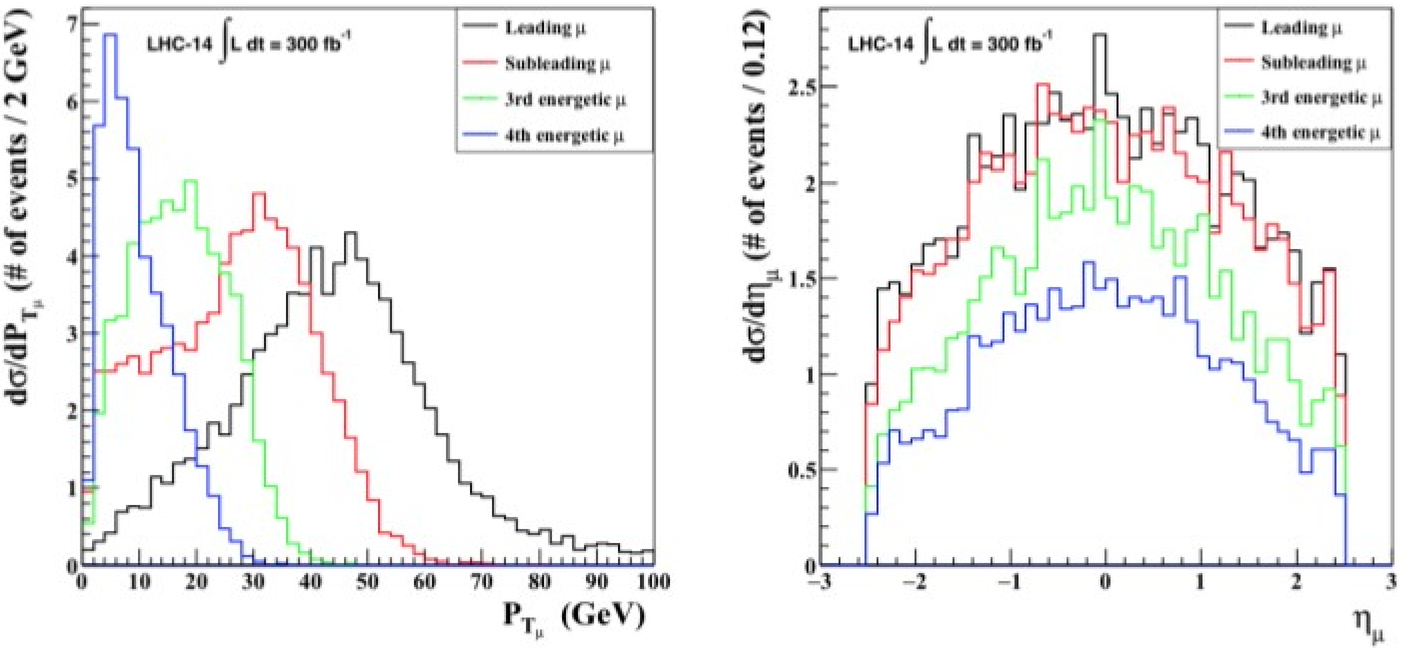
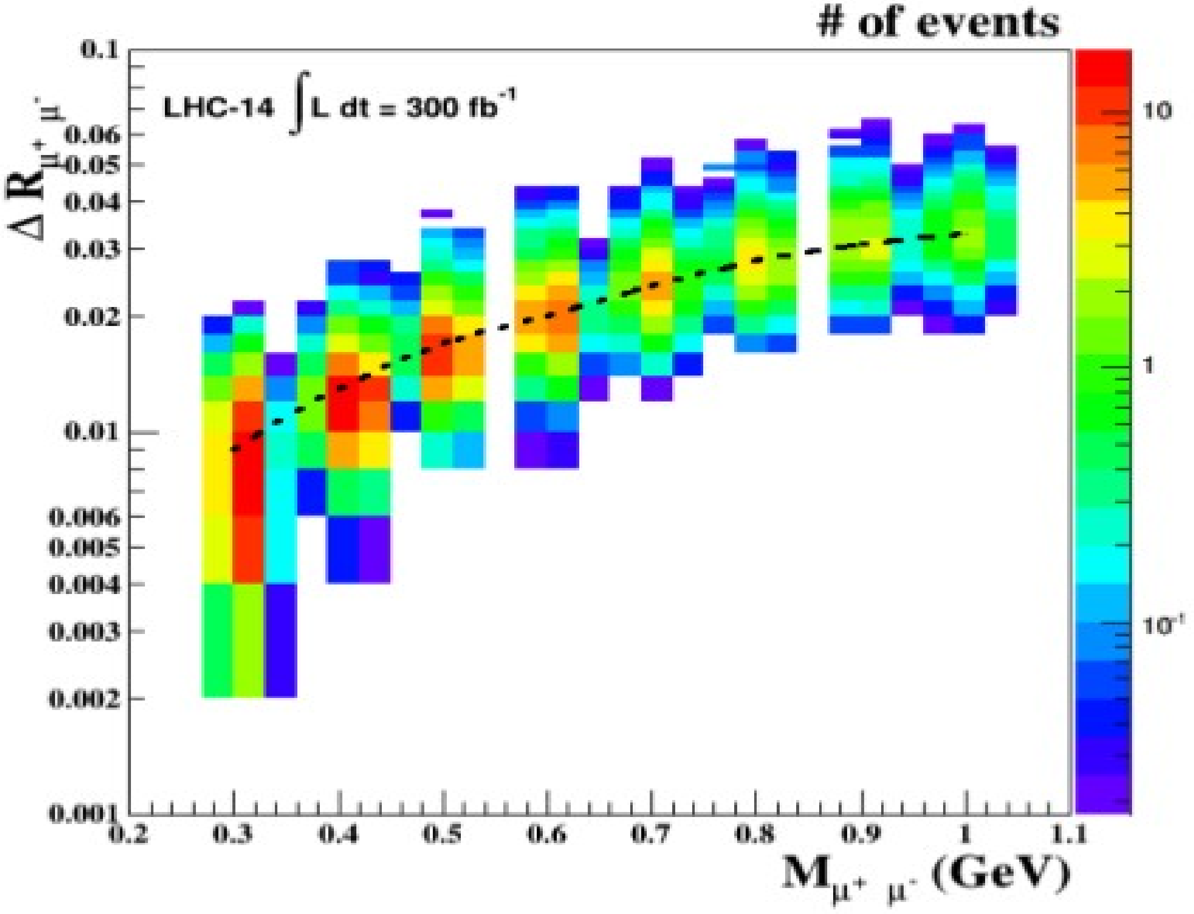
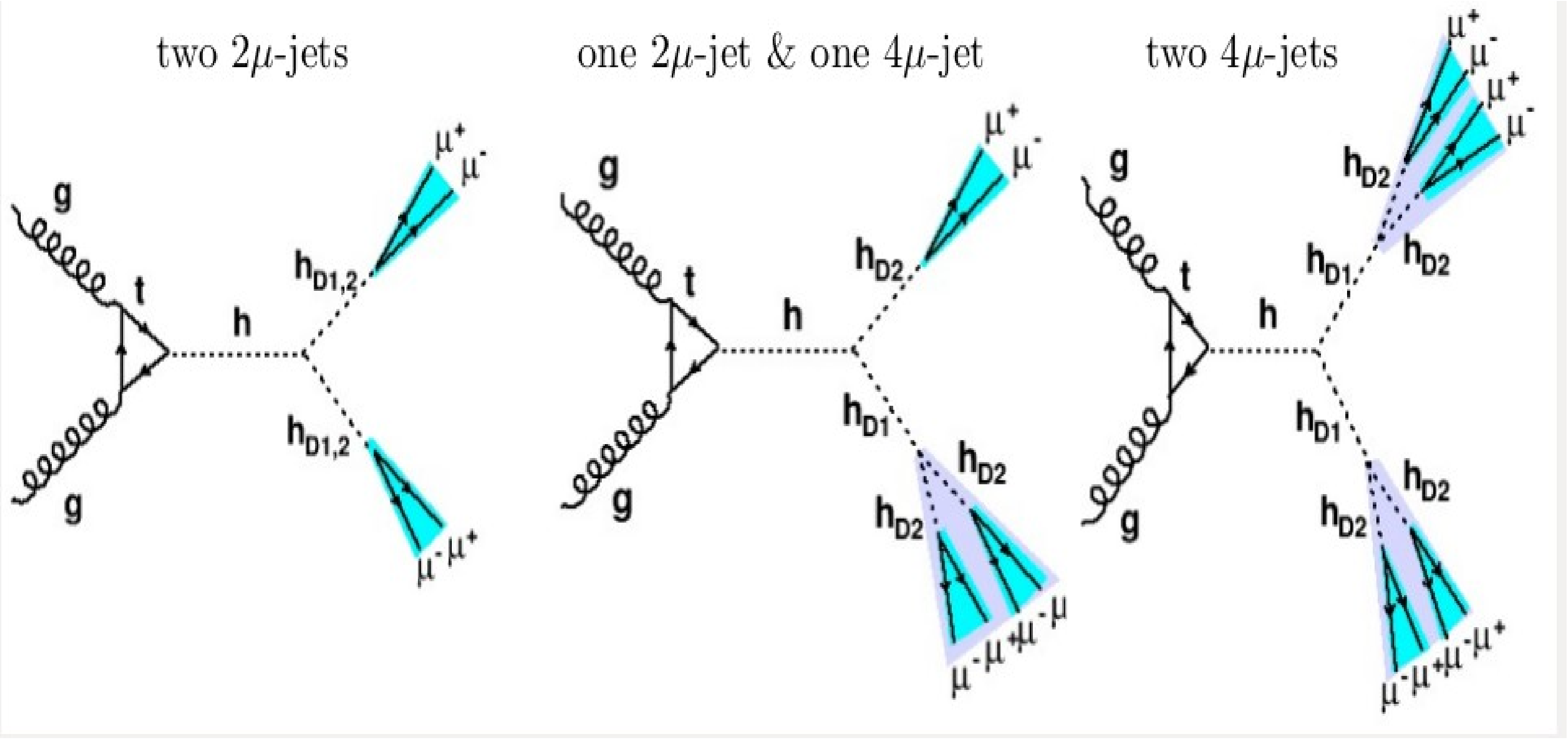


FIG. 5. Transverse momentum p_{T_μ} (left panels) and rapidity η_μ (right panels) distributions for the four final state muons arranged in p_T in toy model-1 with $m_{h_s} = 0.5$ GeV.

Kinematical distributions



Toy model-2 : Two light scalars : h_D1, h_D2



Constraints of toy model-2

- **The global fits to all the SM Higgs boson signal strength**
- One of the global fits to all the SM Higgs boson signal strength has constrained the nonstandard decay width of the Higgs boson to be less than 0.94 MeV (branching ratio about 19%) at 95% C.L.

$$\Gamma(h \to h_{D1}h_{D1}) \approx \frac{\mu_h^2}{32\pi m_h} = \frac{<\phi>^2}{32\pi m_h}(\frac{\mu_h}{<\phi>})^2$$

$$\Gamma(h \to h_{D1}h_{D1}) < 0.94MeV \Rightarrow \frac{\mu_h}{<\phi>} \leq 0.014$$

$$\Gamma(h \to h_{D2}h_{D2}) \approx \frac{\mu_k^2}{32\pi m_h} = \frac{<\phi>^2}{32\pi m_h}(\frac{\mu_k}{<\phi>})^2$$

$$\Gamma(h \to h_{D2}h_{D2}) < 0.94MeV \Rightarrow \frac{\mu_k}{<\phi>} \leq 0.014$$

$$\Gamma(h \to h_{D1}h_{D2}) \approx \frac{\mu_p^2}{16\pi m_h} = \frac{<\phi>^2}{16\pi m_h}(\frac{\mu_p}{<\phi>})^2$$

$$\Gamma(h \to h_{D1}h_{D2}) < 0.94MeV \Rightarrow \frac{\mu_p}{<\phi>} \leq 9.9 \times 10^{-3}$$

Constraint from bounds of meson decays of h_D2 is similar to h_s in toy model-1, but it does not restrict to h_D1 !

Benchmark points for Toy Model-2

TABLE II. Benchmark point for case 1, 2, and 3 for the toy model-2.

	case 1	case 2	case 3
$\mu_h\ (GeV)$	0	3.5	2.5
$\mu_p\ (GeV)$	3.5	0	2.5
$\mu_{HD}\ (10^{-4} GeV)$	5.5	5.5	5.5
$m_{h_{D_1}}$ (GeV)	2.0	2.0	2.0
$m_{h_{D_2}}$ (GeV)	0.5	0.5	0.5
$\Gamma_{h_{D_1}}\ (10^{-9}$ GeV)	1.30	1.30	1.30
$\Gamma_{h_{D_2}}\ (10^{-15}$ GeV)	7.76	7.76	7.76

- case 1 : $\lambda_{hh_{D_1}h_{D_1}} = 0$

  $\lambda_{hh_{D_1}h_{D_2}} = 3.5$ and $B(h \to h_{D_1}h_{D_2}) = 0.185$

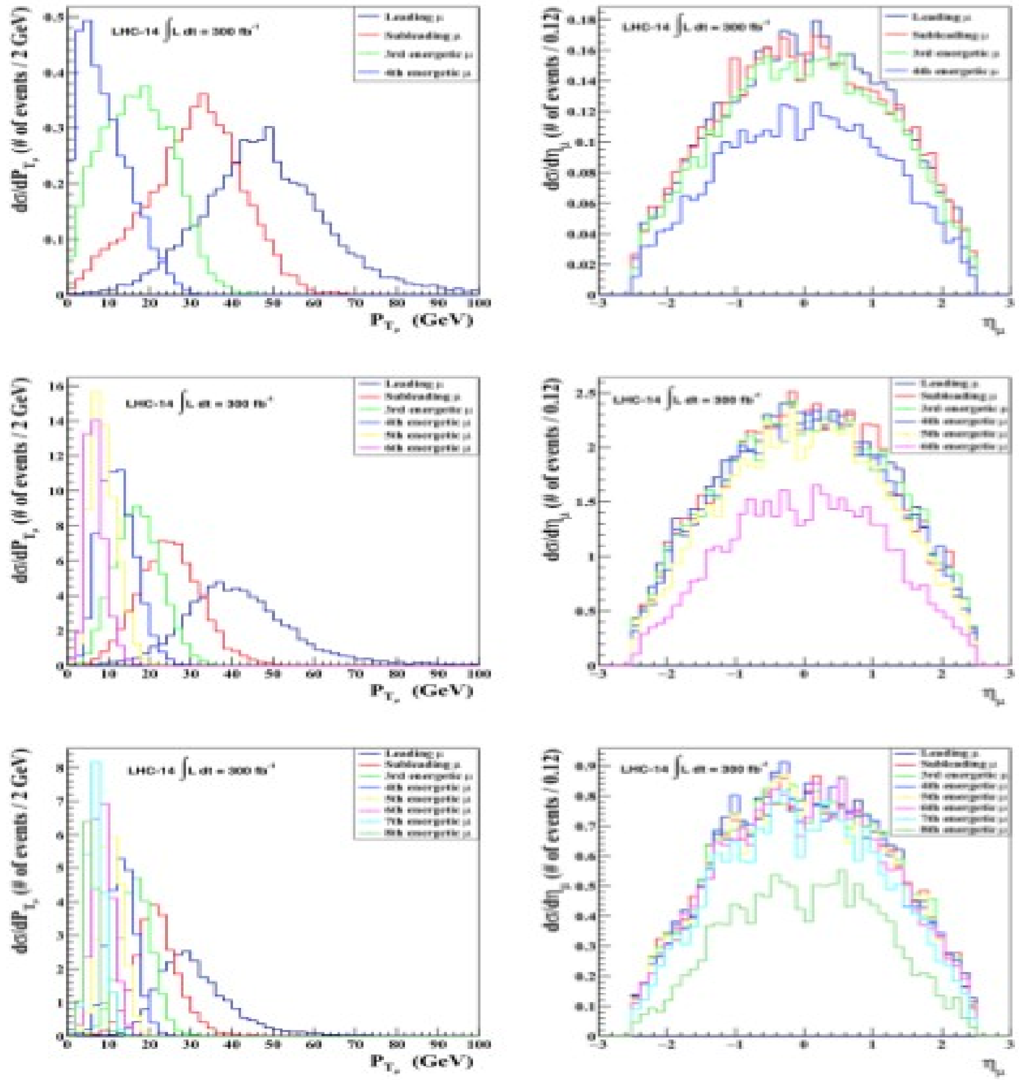
- case 2 : $\lambda_{hh_{D_1}h_{D_2}} = 0$

  $\lambda_{hh_{D_1}h_{D_1}} = 3.5$ and $B(h \to h_{D_1}h_{D_1}) = 0.185$

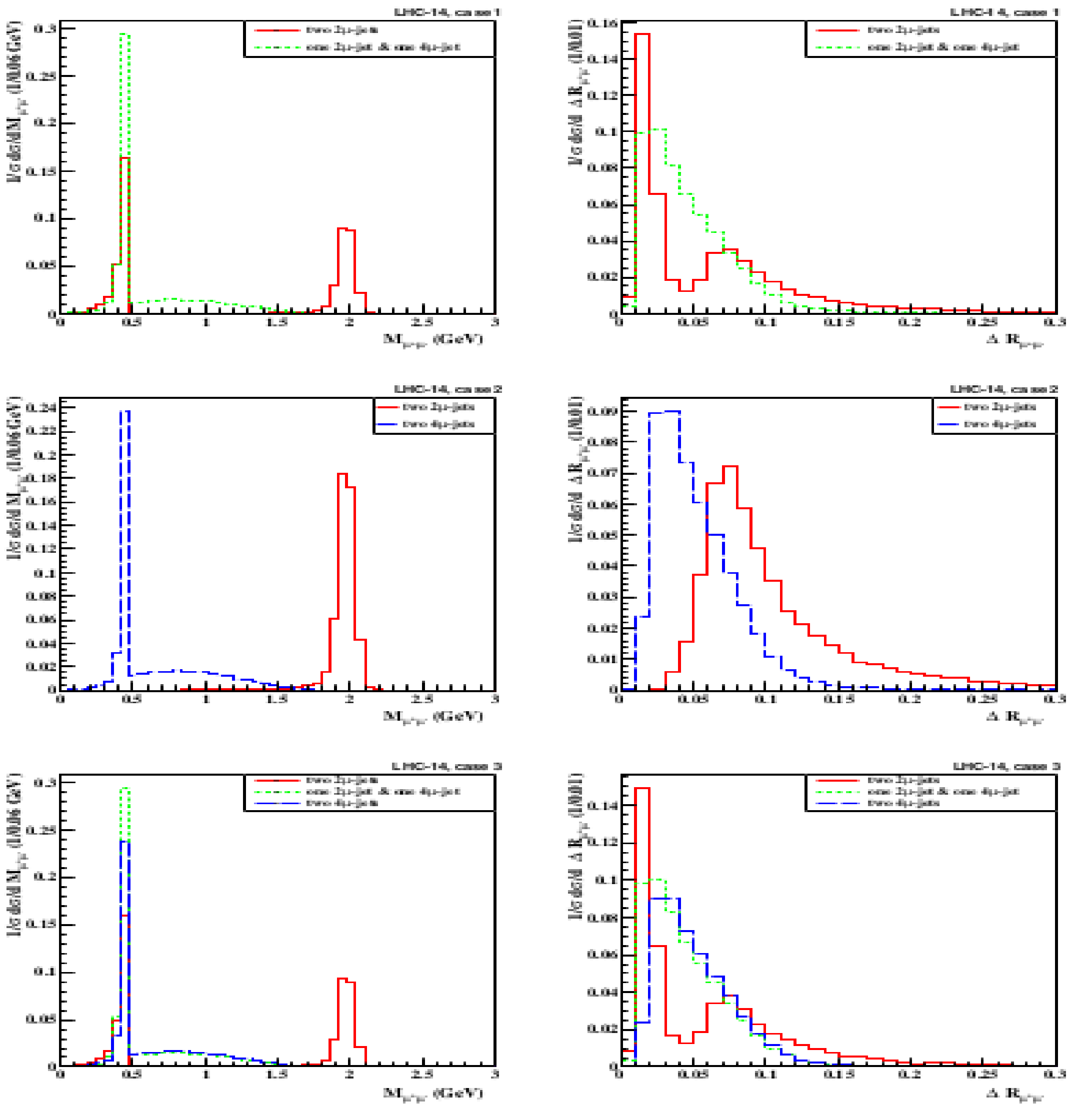
- case 3 : $\lambda_{hh_{D_1}h_{D_2}} = \lambda_{hh_{D_1}h_{D_1}}$

  $\lambda_{hh_{D_1}h_{D_2}} = \lambda_{hh_{D_1}h_{D_1}} = 2.5$ and $B(h \to h_{D_1}h_{D_2}) = B(h \to h_{D_1}h_{D_1}) = 0.0939$

Kinematical distributions



Kinematical distributions



Conclusions

- Muon-jets are interesting and clean signatures at the collider, provided the angular resolution of muons are fine enough. The current designs of the ATLAS and CMS have such capabilities of probing angular separation as small as 10^−3 .
- In general, muon-jets arise from the decay of fast-moving light particles. In this work, we have demonstrated a couple of dark-sector models, in which there are a number of very light scalar bosons, which can be accessed via the Higgs boson decays. We have investigated the signatures of 2μ-jets and 4μ-jets, which consist of, respectively, one and two pairs of oppositely-charged muons in a very narrow cone defined by $\Delta R < 0.01$.

Thank you for your listening ! !