Search for Low Mass Dark Photons in the CMS Hadronic Calorimeter in Proton-Proton Collisions at $\sqrt{s}$= 13 TeV

Yao Yao, Devin Taylor, Mani Tripathi

UC Davis Physics

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Outline

- Introduction to $p\,p \rightarrow \mu^{+}\mu^{-}\gamma_{D}$ signal and its reconstruction in CMS detector.
- Signal Region selections.
- Dark photon showering in the Hadronic Calorimeter (HCal) leads to a jet that has high neutral energy fraction.
- Distinguishing Signal from Background with BDT method.
- A Brief look into Control Region.

Dark Photon

- Dark photon (DP):

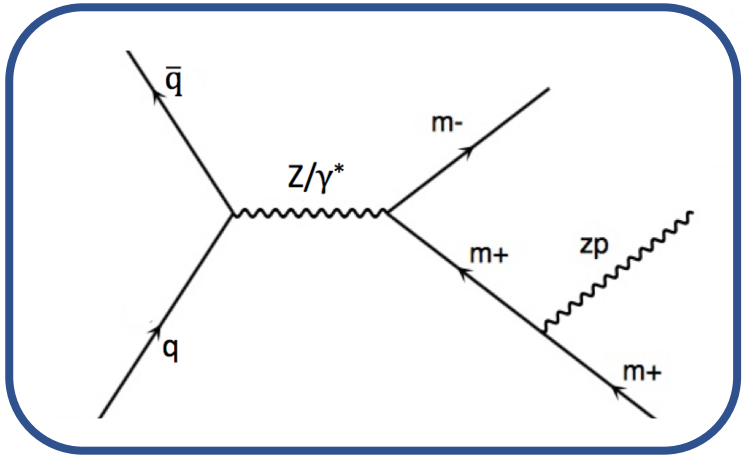
  $SU(3) \otimes SU(2) \otimes U(1) \otimes U(1)'$

  Dark photon can recoil from a charged particle.

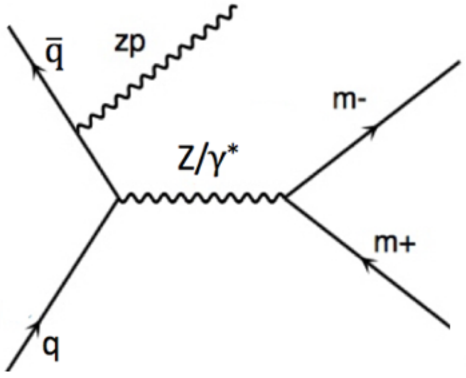
  Compared to the SM photon, the dark photon has a much smaller electromagnetic coupling constant:

  $$\alpha_D = \alpha_{EM} * f_D \qquad f_D\text{: Dark factor}$$

- Feynman Diagram:



Final State Radiation



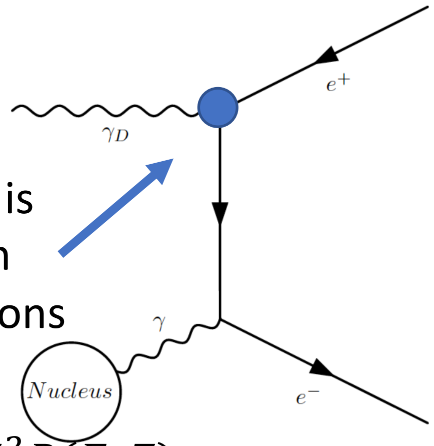
Initial State Radiation

Note: Dark photon mass is set to be smaller than 1MeV, thus it can't decay as e+ e- pair.

Final states:

- $\mu^+ \mu^-$ + X
- signal can appear as MET or Jet
- depends on how *dark photon interacts with detector material*.

The cross section of this process is affected by the coupling strength between dark photon and electrons



$$\sigma_{\gamma_D \to ee} = f_D \, \sigma_{\gamma_{SM} \to ee} = \alpha_D r_e^2 Z^2 P(E, Z)$$

This process is implemented in GEANT4 in signal simulation.

Dark Photon searching limits

Dark photon has two free parameters: Mass and Dark factor

- We analyze DP signals with f_D from 0.001 to 0.1.
- The limits on f_D largely depends on the radius of HCal.
- We expect to set an upper limit on DP mass at 1MeV. There is no lower limit on DP mass.

Signal simulation and Signal Region

Process $p\,p \rightarrow \mu^{+}\mu^{-}\gamma_D$ is simulated using HAHM (Hidden Abelian Higgs model) through Madgraph.

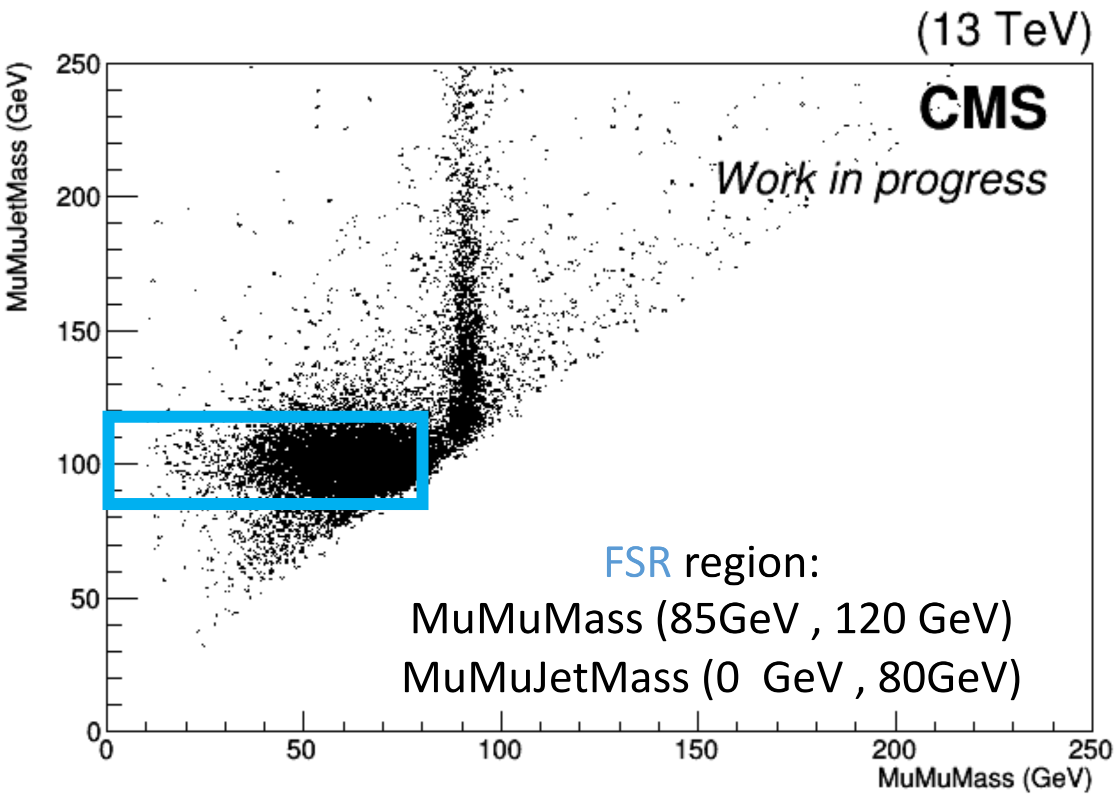
Simulation requirements:

Mass(DP)	= 0.5 MeV
$\Delta R(muon, DP)$	> 0.4
pT(muons)	> 10 GeV
pT(DP)	> 10 GeV
InvMass(muons)	> 10 GeV

Dark factor	Cross section (pb)
0.001	0.01136
0.005	0.05697
0.01	0.11353
0.05	0.5431
0.1	1.266

Jet is the reco jet that goes to the same direction as GenDp. (deltaR(genDp, jet) < 0.2)

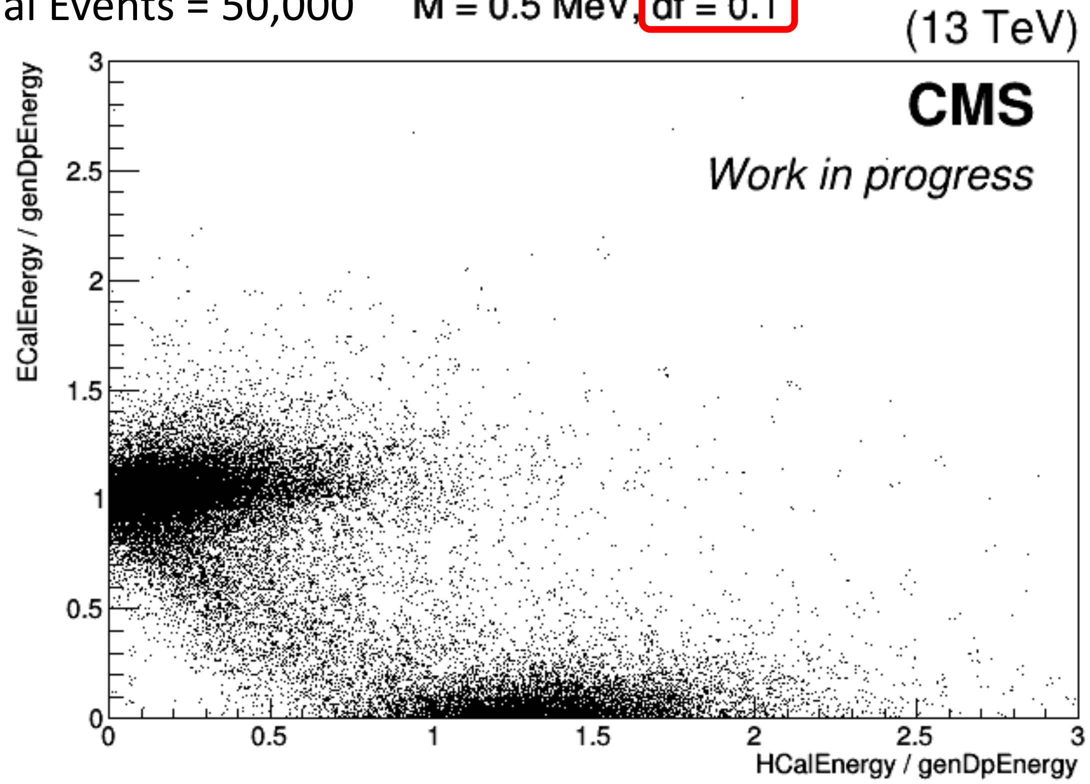
(M = 0.5MeV, df = 0.01) #Signal Events = 50,000

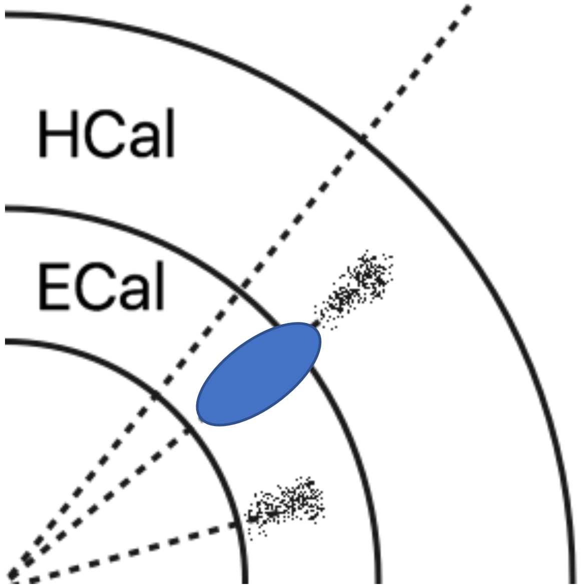


Dark photon reconstruction

- We are expecting dark photon to be reconstructed as a jet.
  - Within certain range of dark factor, the jet deposits most of its energy in HCAL.
  - The jet is dominated by neutral energies.

#Signal Events = 50,000   M = 0.5 MeV, df = 0.1





Dark photon reconstruction

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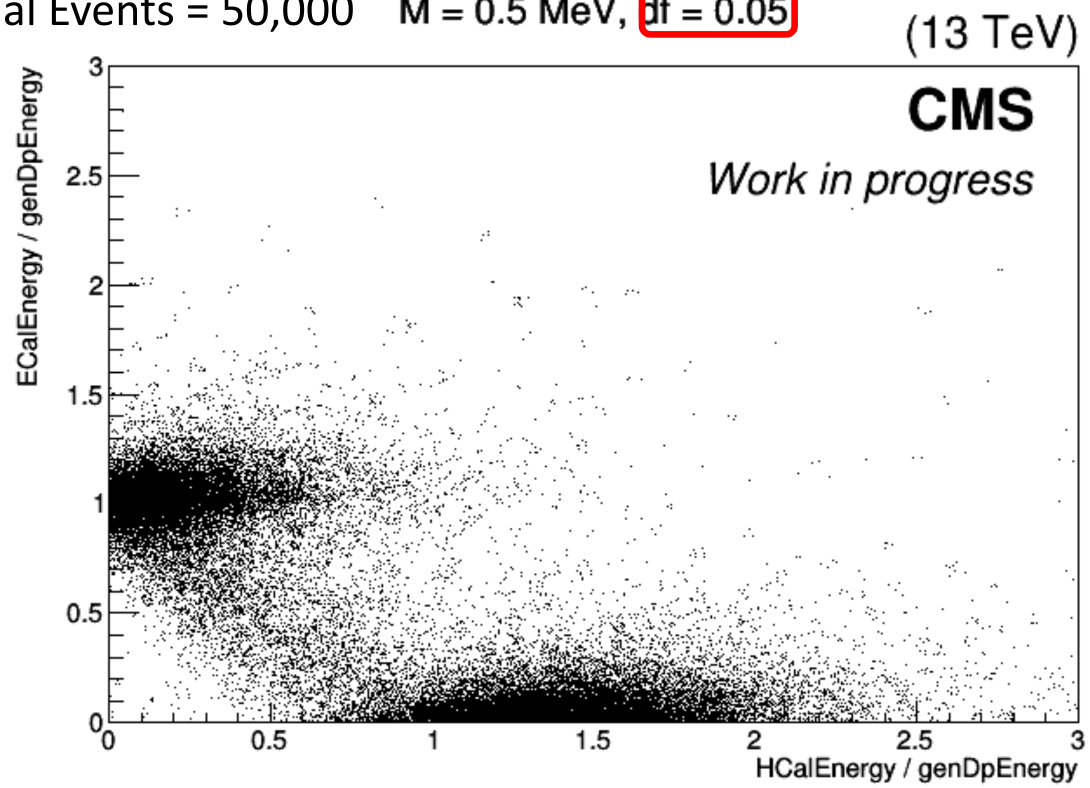
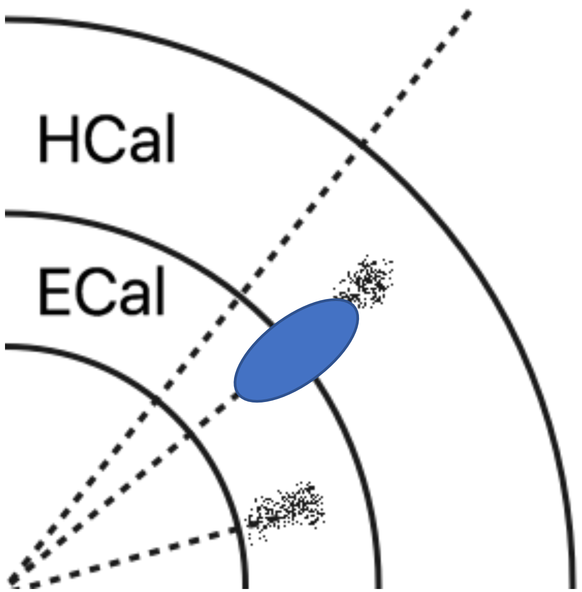
#Signal Events = 50,000   M = 0.5 MeV, df = 0.05





Dark photon reconstruction

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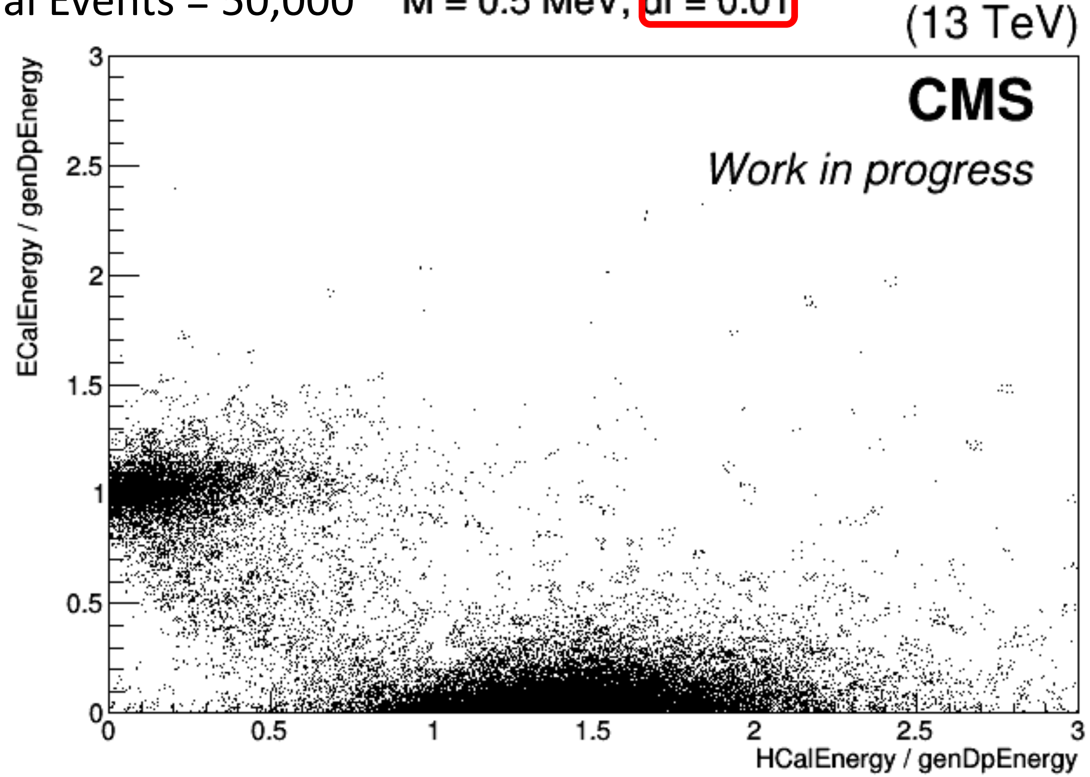
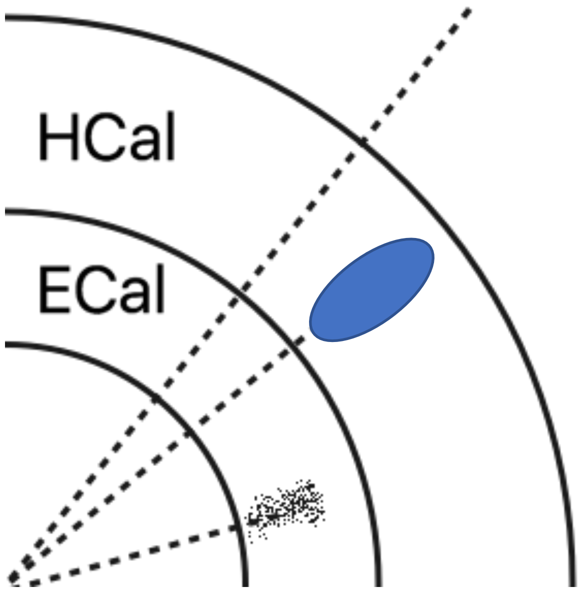
#Signal Events = 50,000 M = 0.5 MeV, df = 0.01

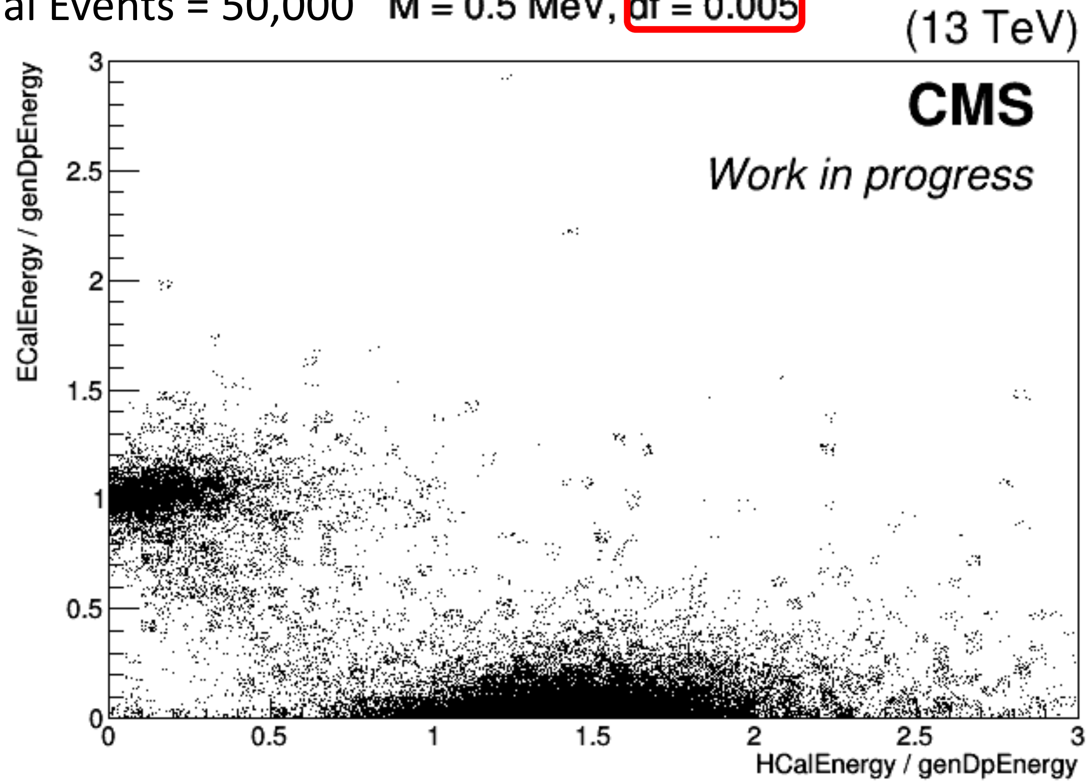


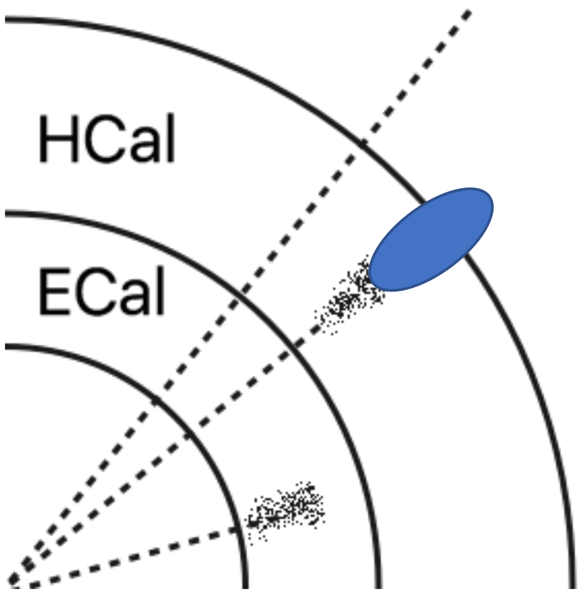


Dark photon reconstruction

- We are expecting dark photon to be reconstructed as a jet.
  - Within certain range of dark factor, the jet deposits most of its energy in HCAL.
  - The jet is dominated by neutral energies.

#Signal Events = 50,000 M = 0.5 MeV, df = 0.005

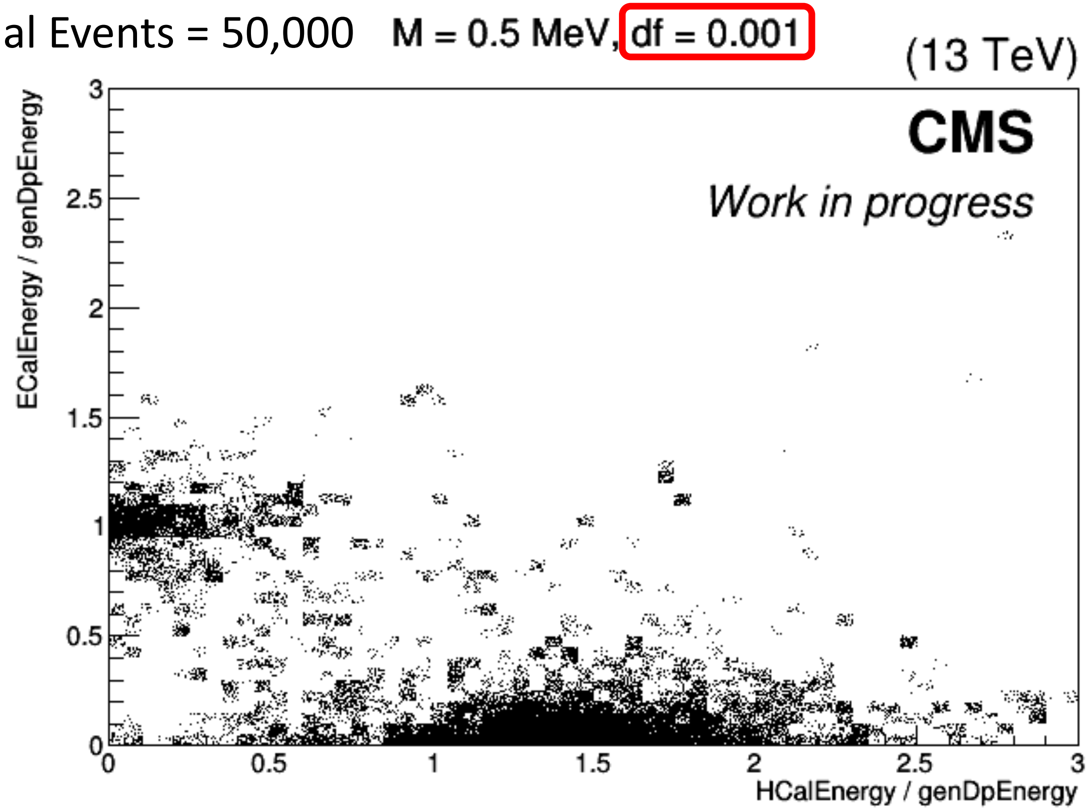


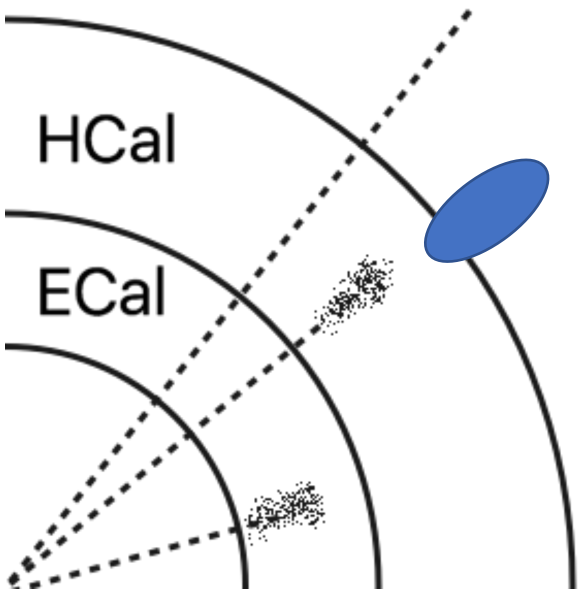


Dark photon reconstruction

- We are expecting dark photon to be reconstructed as a jet.
  - Within certain range of dark factor, the jet deposits most of its energy in HCAL.
  - The jet is dominated by neutral energies.

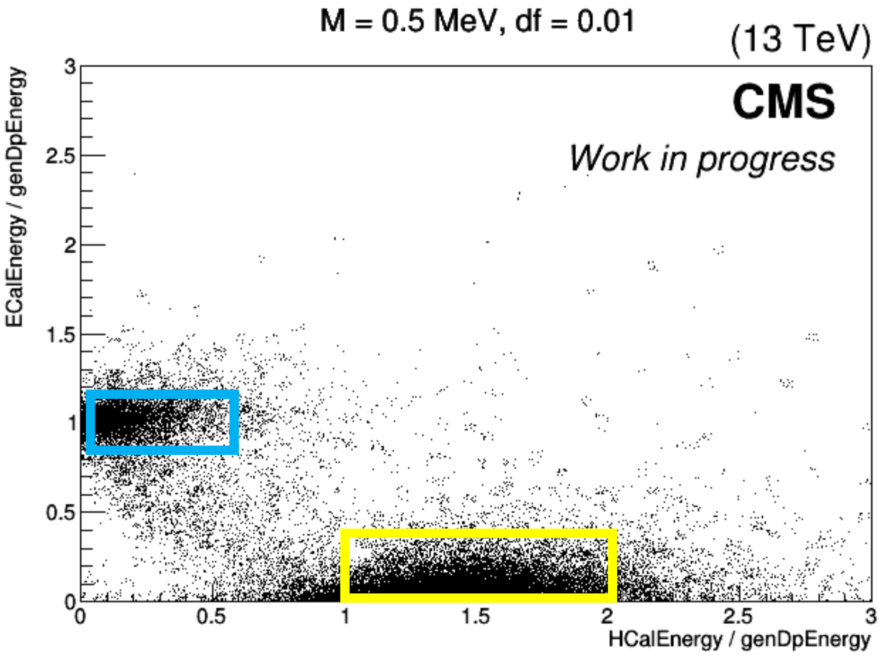
#Signal Events = 50,000

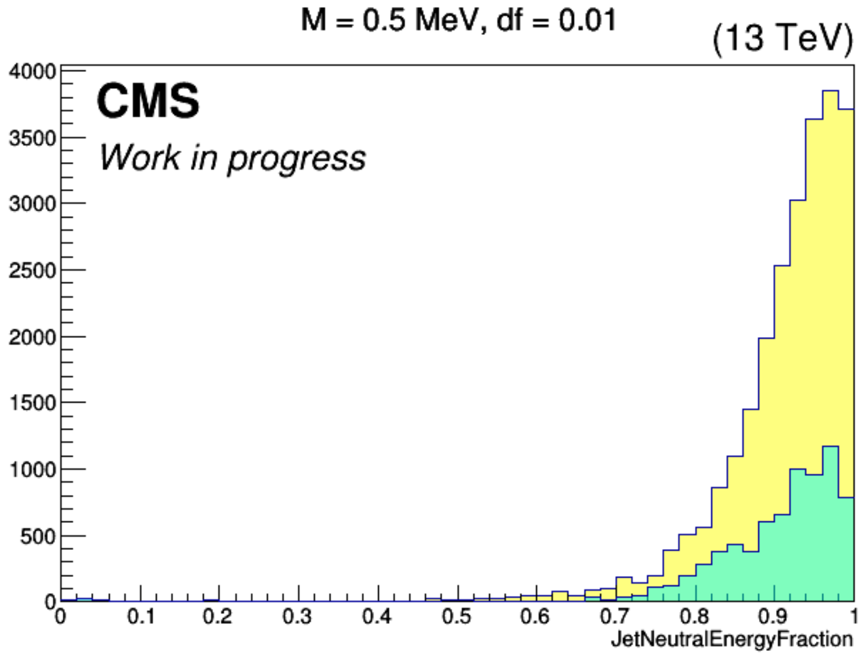




Dark photon reconstruction

- We are expecting dark photon to be reconstructed as a jet.
  - Within certain range of dark factor, the jet deposits most of its energy in HCAL.
  - The jet consists mostly of reconstructed neutral hadrons





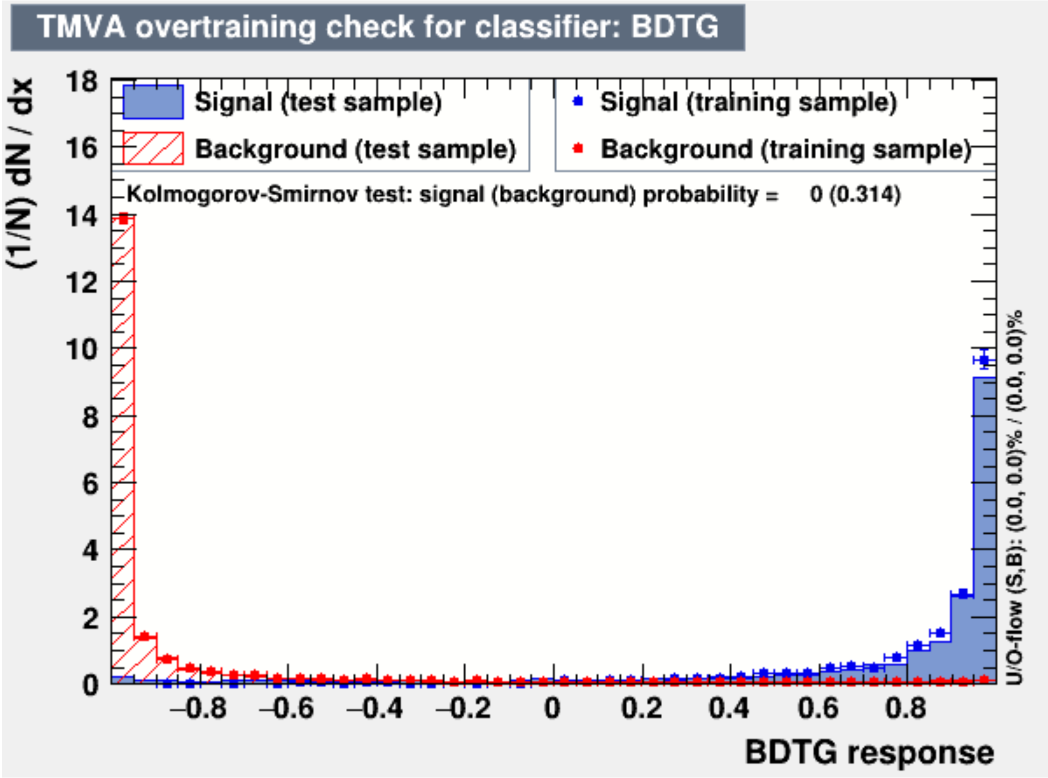
ECal: x∈(0, 0.5), y ∈ (0.8, 1.2)
HCal: x∈(1, 2), y ∈ (0.0, 0.25)

BDT training

- We use BDT Gradient method to optimize Signal vs Background classification with TMVA package in ROOT.
- Dominating backgrounds: TTJets and DYJetsToLL.

- Training variables:
  - We use 36 variables including the information about muons, jet, and jet's leading neutral and charged constituents.
  - The top ranked jet variables are mainly about jet's leading neutral constituent, jet's neutralEnergyFraction, etc.

- Training results:
  - An example of signals with df = 0.01
    - BDT score distribution for Signal and Background
    - ROC integral 0.973



Event selection and backgrounds (2016)

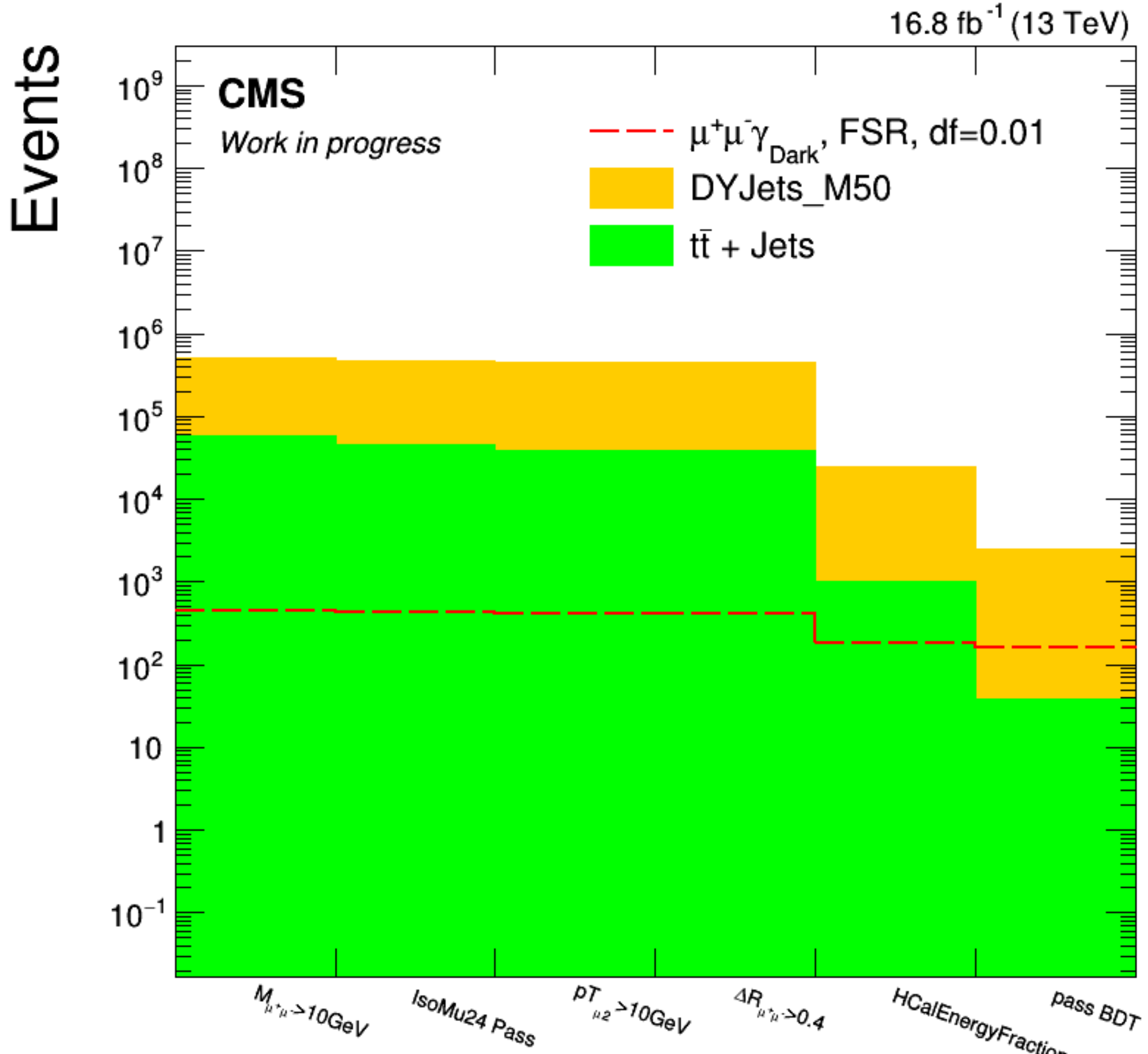
The following cuts focus on looking for FSR dark photon jets and showers mostly in Hcal.

For both signal and backgrounds:

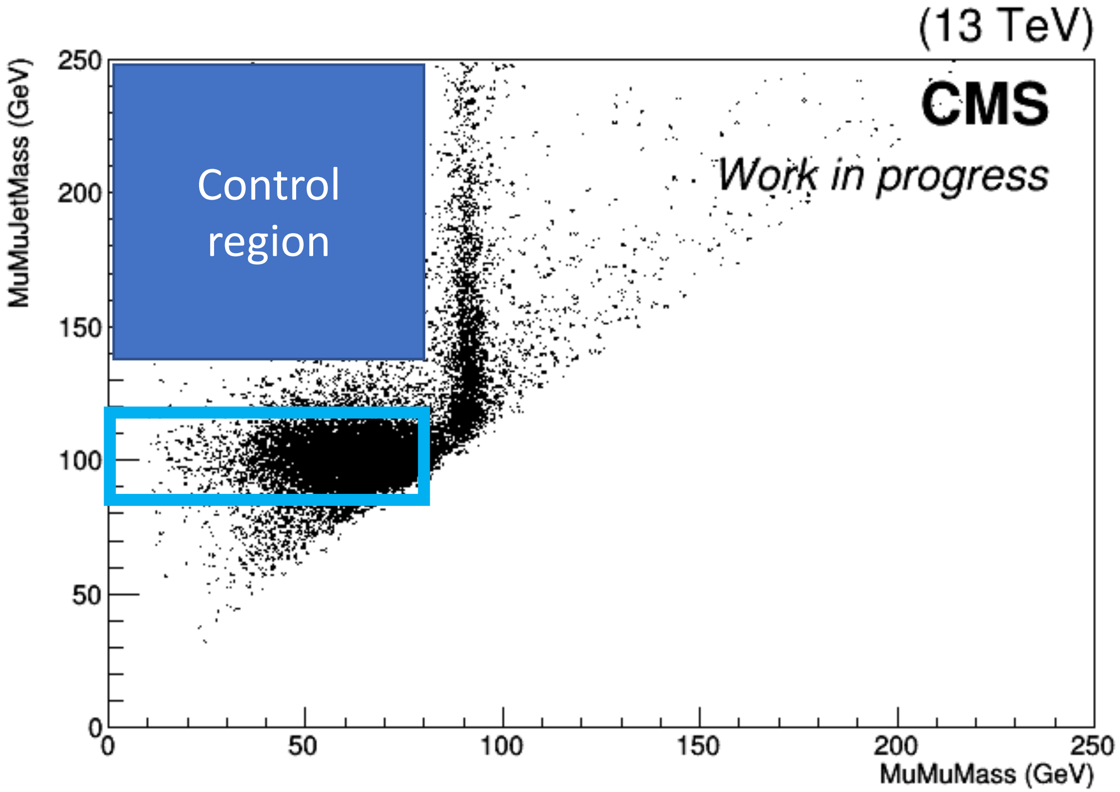
Pre-select: FSR jet satisfies

- M(mu1,mu2,jet) (85GeV , 120 GeV)
- M(mu1,mu2) (0 GeV , 80 GeV)
- deltaR(mu, jet) > 0.4
- Jet pT > 15 GeV, |eta| < 1.5, pass HBHENoiseIsoFilter

1. Require 2 tight muons coming from primary vertex and oppositely charged , dimuon mass > 60 GeV
2. Trigger: IsoMu24 or IsoMuTk24
3. Leading muon pT > 26 GeV and Second muon pT > 10 GeV
4. Muon separation deltaR > 0.4
5. The FSR jet satisfies
   - Jet_neutralHadronEnergyFraction > 0.6
   - Jet_neutralEmEnergyFraction < 0.2
6. Train the signal over backgrounds using BDTG.



Control region



Control region requirement:

1) There is no such a jet in the event that is identified as a Signal FSR jet (it satisfies

   i) 10 < MuMuMass < 80

   ii) 85 < MuMuJetMass < 120

2) There exist a jet in the event that is identified as a Control Region jet (it satisfies

   i) 10 < MuMuMass < 80

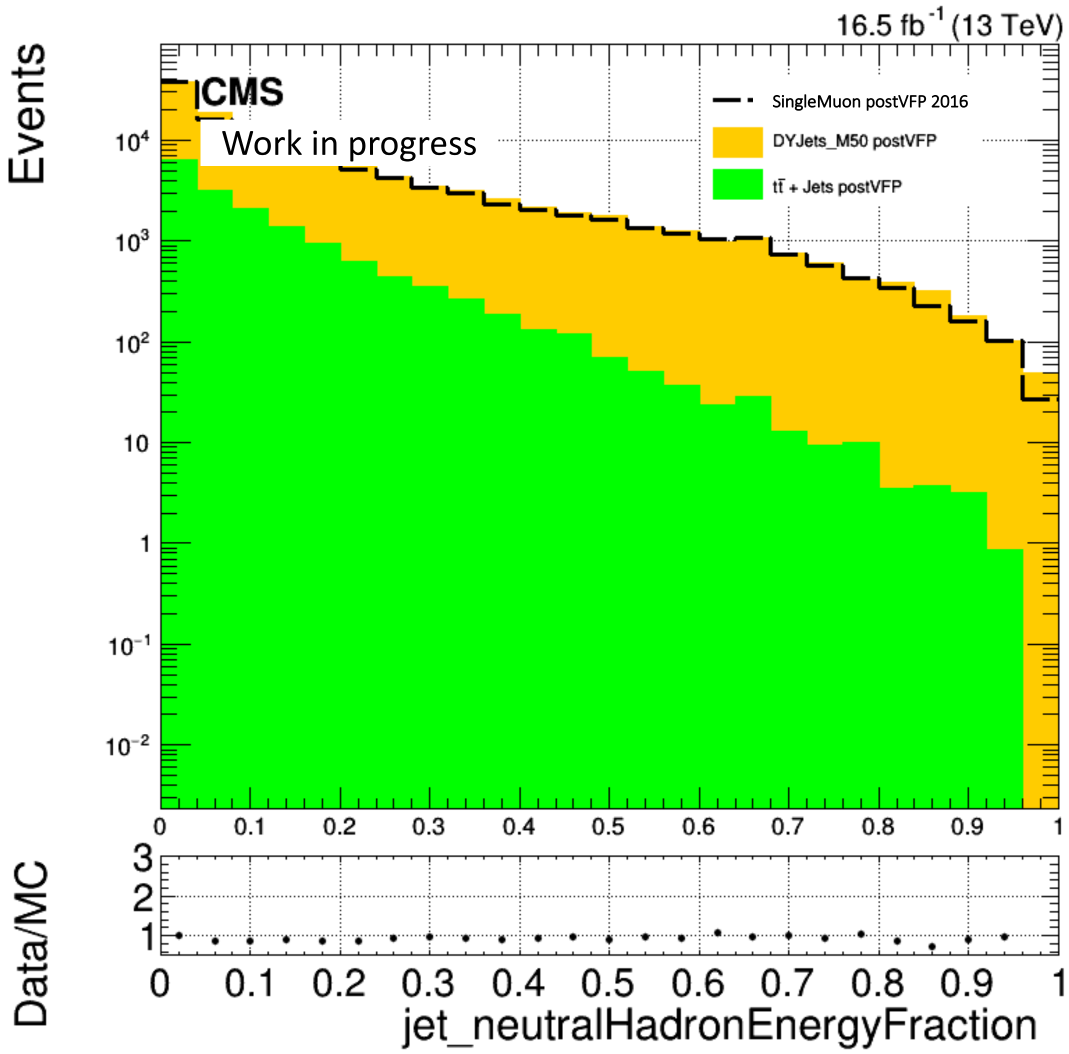
   ii) 140 < MuMuJetMass

Control region 2016

Data: Single Muon Triggered dataset
MC : DYJetsToLL_M50,
TTJets

Pre-request: there exists a CR jet in the event and no FSR jet.

Other selections are the same as signal region's selections, without applying jet's energy fraction cuts and BDT training results.



Summary

- We present a preliminary search for dark photons reconstructed as jets in the CMS detector using 2016 MC and data.
- For dark photons with dark factor >=0.01, they can be distinguished from backgrounds more easily than those with smaller dark factor.
- The current stage is optimizing the selections for the dark photons with small dark factor.
- BDT will be validated using k-fold cross validation method. BDT's hyper parameters will be optimized after we pin down the inputs for BDT training.
- We expect to have results in fall for the full Run II data.

Back up

- BDT Training variables

Rank	Variable	Variable Importance
1	jet_KtFractionNeutralHadron1JetAxis	5.521e-02
2	jet_KtNeutralHadron1JetAxis	5.034e-02
3	deltaR_leadingMu_jet	4.329e-02
4	MuMuJetMass	4.250e-02
5	jet_eta	4.168e-02
6	deltaR_MuMu	4.044e-02
7	deltaR_subleadingMu_jet	3.763e-02
8	MuMuMass	3.598e-02
9	leadingMuPhi	3.535e-02
10	jet_neutralEmEnergyFraction	3.515e-02
11	subleadingMuPt	3.490e-02
12	jet_phi	3.454e-02
13	subleadingMuEta	3.445e-02
14	leadingMuEta	3.283e-02
15	subleadingMuPhi	3.197e-02
16	jet_PtFractionOfNeutralHadrons	3.056e-02
17	leadingMuPt	2.982e-02
18	jet_et	2.785e-02
19	jet_pt	2.716e-02
20	jet_neutralHadronEnergyFraction	2.636e-02
21	jet_PtSumOfNeutralHadrons	2.619e-02
22	jet_chargedHadronEnergyFraction	2.607e-02
23	jet_neutralHadronMultiplicity	2.510e-02
24	jet_neutralMultiplicity	2.355e-02
25	jet_n60	2.354e-02
26	jet_PtSumOfChargedHadrons	2.339e-02
27	jet_nConstituents	2.270e-02
28	jet_PtFractionOfChargedHadrons	2.071e-02
29	jet_chargedHadronMultiplicity	1.970e-02
30	jet_n90	1.904e-02
31	jet_KtFractionChargedHadron1JetAxis	1.662e-02
32	jet_chargedMultiplicity	1.410e-02
33	jet_KtChargedHadron1JetAxis	1.127e-02
34	jet_electronEnergyFraction	0.000e+00
35	jet_muonEnergyFraction	0.000e+00
36	jet_chargedEmEnergyFraction	0.000e+00

Rank	Variable	Separation
1	jet_KtNeutralHadron1JetAxis	5.338e-01
2	jet_KtFractionNeutralHadron1JetAxis	5.158e-01
3	jet_PtSumOfNeutralHadrons	3.561e-01
4	jet_PtFractionOfNeutralHadrons	3.368e-01
5	jet_neutralHadronEnergyFraction	3.260e-01
6	jet_PtFractionOfChargedHadrons	2.517e-01
7	jet_chargedHadronEnergyFraction	2.410e-01
8	jet_pt	2.394e-01
9	jet_et	2.251e-01
10	jet_neutralHadronMultiplicity	2.163e-01
11	jet_KtFractionChargedHadron1JetAxis	2.151e-01
12	deltaR_subleadingMu_jet	2.057e-01
13	jet_n90	1.864e-01
14	deltaR_MuMu	1.807e-01
15	leadingMuPt	1.803e-01
16	deltaR_leadingMu_jet	1.778e-01
17	jet_nConstituents	1.494e-01
18	jet_PtSumOfChargedHadrons	1.395e-01
19	MuMuJetMass	1.332e-01
20	jet_n60	1.212e-01
21	jet_neutralMultiplicity	1.198e-01
22	jet_neutralEmEnergyFraction	1.026e-01
23	jet_chargedMultiplicity	7.775e-02
24	jet_chargedHadronMultiplicity	7.345e-02
25	jet_KtChargedHadron1JetAxis	5.919e-02
26	jet_eta	5.413e-02
27	subleadingMuPt	5.336e-02
28	MuMuMass	1.789e-02
29	leadingMuEta	7.684e-03
30	subleadingMuEta	7.366e-03
31	jet_muonEnergyFraction	7.319e-03
32	subleadingMuPhi	7.254e-03
33	jet_phi	6.334e-03
34	leadingMuPhi	4.411e-03
35	jet_electronEnergyFraction	2.775e-03
36	jet_chargedEmEnergyFraction	2.775e-03