Feasibility Study of Measuring the Higgs Self-coupling Using the Muon Collider

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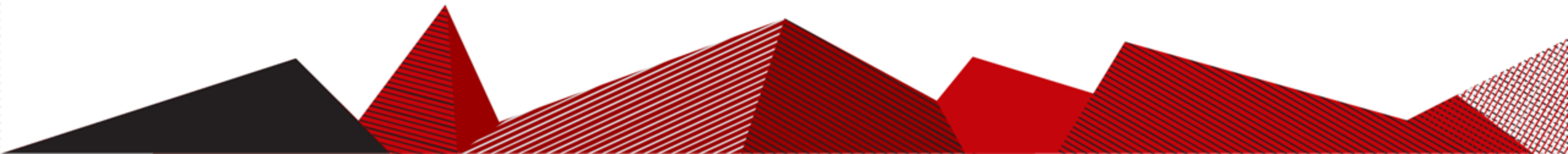
- Signal: $\mu^- + \mu^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + H + H$
- Background:
  - $\mu^- + \mu^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + b + \bar{b} + Z$
  - $\mu^- + \mu^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + b + \bar{b} + H$
  - $\mu^- + \mu^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + b + \bar{b} + b + \bar{b}$

Muon Collider Detector card workflow

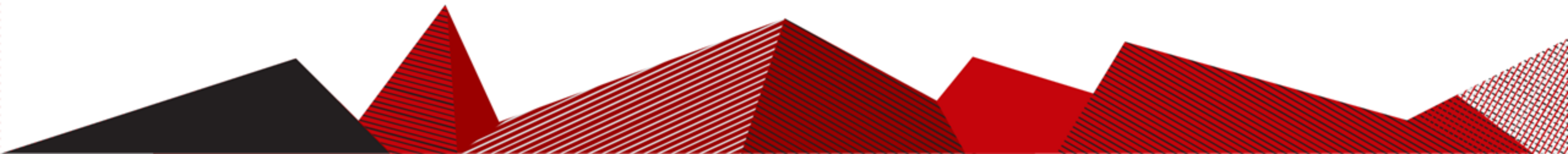


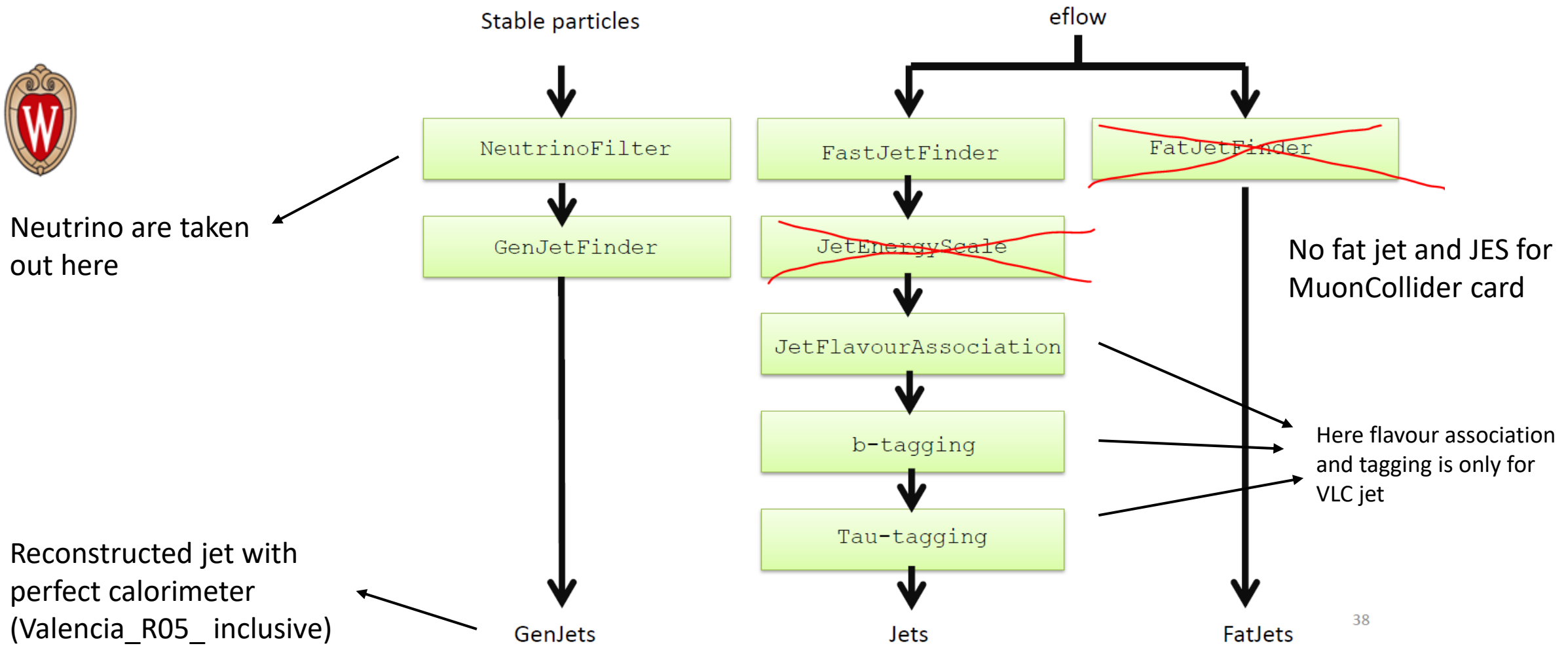
```
##################
# Neutrino Filter
##################

module PdgCodeFilter NeutrinoFilter {

    set InputArray Delphes/stableParticles
    set OutputArray filteredParticles

    set PTMin 0.0

    add PdgCode {12}
    add PdgCode {14}
    add PdgCode {16}
    add PdgCode {-12}
    add PdgCode {-14}
    add PdgCode {-16}

}
```

```
######################
# MC truth jet finder
######################

module FastJetFinder GenJetFinder {
    set InputArray NeutrinoFilter/filteredParticles

    set OutputArray jets

    # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt, 5 Cambridge/Aachen, 6
antikt, 7 anti-kt with winner-take-all axis (for N-subjettiness), 8 N-jettiness,
9 Valencia
    set JetAlgorithm 9
    set ParameterR 0.5

    set JetPTMin 20.0
}
```

muon is not included in GenJet

```
#################################
# Propagate particles in cylinder
#################################

module ParticlePropagator ParticlePropagator {
    set InputArray Delphes/stableParticles

    set OutputArray stableParticles
    set ChargedHadronOutputArray chargedHadrons
    set ElectronOutputArray electrons
    set MuonOutputArray muons

    # radius of the magnetic field coverage in the calorimeter, in m
    set Radius 1.5
    # half-length of the magnetic field coverage in the calorimeter, in m
    set HalfLength 2.31

    # magnetic field, in T
    set Bz 4.0
}
```




Stable particles
eflow
NeutrinoFilter
GenJetFinder
FastJetFinder
FatJetFinder
JetEnergyScale
JetFlavourAssociation
b-tagging
Tau-tagging
Neutrino are taken out here
No fat jet and JES for MuonCollider card
Here flavour association and tagging is only for VLC jet
Reconstructed jet with perfect calorimeter (Valencia_R05_ inclusive)
GenJets
Jets
FatJets

```
###############
# Jet finder AKT
###############

module FastJetFinder FastJetFinderAKt {
    #  set InputArray Calorimeter/towers
    set InputArray EFlowMerger/eflow

    set OutputArray AKTjets

    # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt, 5 Cambridge/Aachen, 6
antikt, 7 anti-kt with winner-take-all axis (for N-subjettiness), 8 N-jettiness,
9 Valencia
    set JetAlgorithm 6
    set ParameterR 0.5

    set JetPTMin 20.0
}
```

```
####################
# Energy flow merger
####################

module Merger EFlowMerger {
    # add InputArray InputArray
    add InputArray HCal/eflowTracks
    add InputArray ECal/eflowPhotons
    add InputArray HCal/eflowNeutralHadrons
    set OutputArray eflow
}
```

```
#########################################################
# Tower Merger (in case not using e-flow algorithm)
#########################################################

module Merger Calorimeter {
    # add InputArray InputArray
    add InputArray ECal/ecalTowers
    add InputArray HCal/hcalTowers
    add InputArray MuonMomentumSmearing/muons
    set OutputArray towers
}
```

```
##############
#   HCAL
##############

module SimpleCalorimeter HCal {
    set ParticleInputArray ParticlePropagator/stableParticles
    set TrackInputArray ECal/eflowTracks

    set TowerOutputArray hcalTowers
    set EFlowTrackOutputArray eflowTracks
    set EFlowTowerOutputArray eflowNeutralHadrons

    set IsEcal false

    set EnergyMin 1.0
    set EnergySignificanceMin 1.0

    set SmearTowerCenter true

    set pi [expr {acos(-1)}]
```

```
    # default energy fractions {abs(PDG code)} {Fecal Fhcal}
    add EnergyFraction {0} {1.0}
    # energy fractions for e, gamma and pi0
    add EnergyFraction {11} {0.0}
    add EnergyFraction {22} {0.0}
    add EnergyFraction {111} {0.0}
    # energy fractions for muon, neutrinos and neutralinos
    add EnergyFraction {12} {0.0}
    add EnergyFraction {13} {0.0}
    add EnergyFraction {14} {0.0}
    add EnergyFraction {16} {0.0}
    add EnergyFraction {1000022} {0.0}
    add EnergyFraction {1000023} {0.0}
    add EnergyFraction {1000025} {0.0}
    add EnergyFraction {1000035} {0.0}
    add EnergyFraction {1000045} {0.0}
    # energy fractions for K0short and Lambda
    add EnergyFraction {310} {0.7}
    add EnergyFraction {3122} {0.7}
```

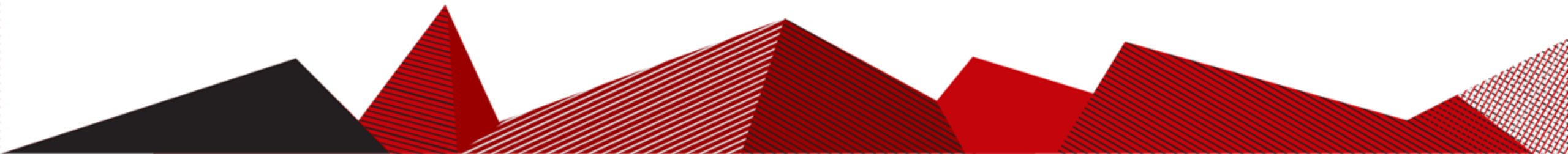
```
##############
#   ECAL
##############

module SimpleCalorimeter ECal {
    set ParticleInputArray ParticlePropagator/stableParticles
    set TrackInputArray TrackMerger/tracks

    set TowerOutputArray ecalTowers
    set EFlowTrackOutputArray eflowTracks
    set EFlowTowerOutputArray eflowPhotons

    set IsEcal true

    set EnergyMin 0.5
    set EnergySignificanceMin 1.0

    set SmearTowerCenter true

    set pi [expr {acos(-1)}]
```

```
  # default energy fractions {abs(PDG code)} {fraction of energy deposited in ECAL}

  add EnergyFraction {0} {0.0}
  # energy fractions for e, gamma and pi0
  add EnergyFraction {11} {1.0}
  add EnergyFraction {22} {1.0}
  add EnergyFraction {111} {1.0}
  # energy fractions for muon, neutrinos and neutralinos
  add EnergyFraction {12} {0.0}
  add EnergyFraction {13} {0.0}
  add EnergyFraction {14} {0.0}
  add EnergyFraction {16} {0.0}
  add EnergyFraction {1000022} {0.0}
  add EnergyFraction {1000023} {0.0}
  add EnergyFraction {1000025} {0.0}
  add EnergyFraction {1000035} {0.0}
  add EnergyFraction {1000045} {0.0}
  # energy fractions for K0short and Lambda
  add EnergyFraction {310} {0.3}
  add EnergyFraction {3122} {0.3}
```

Conclusion of observation on the workflow

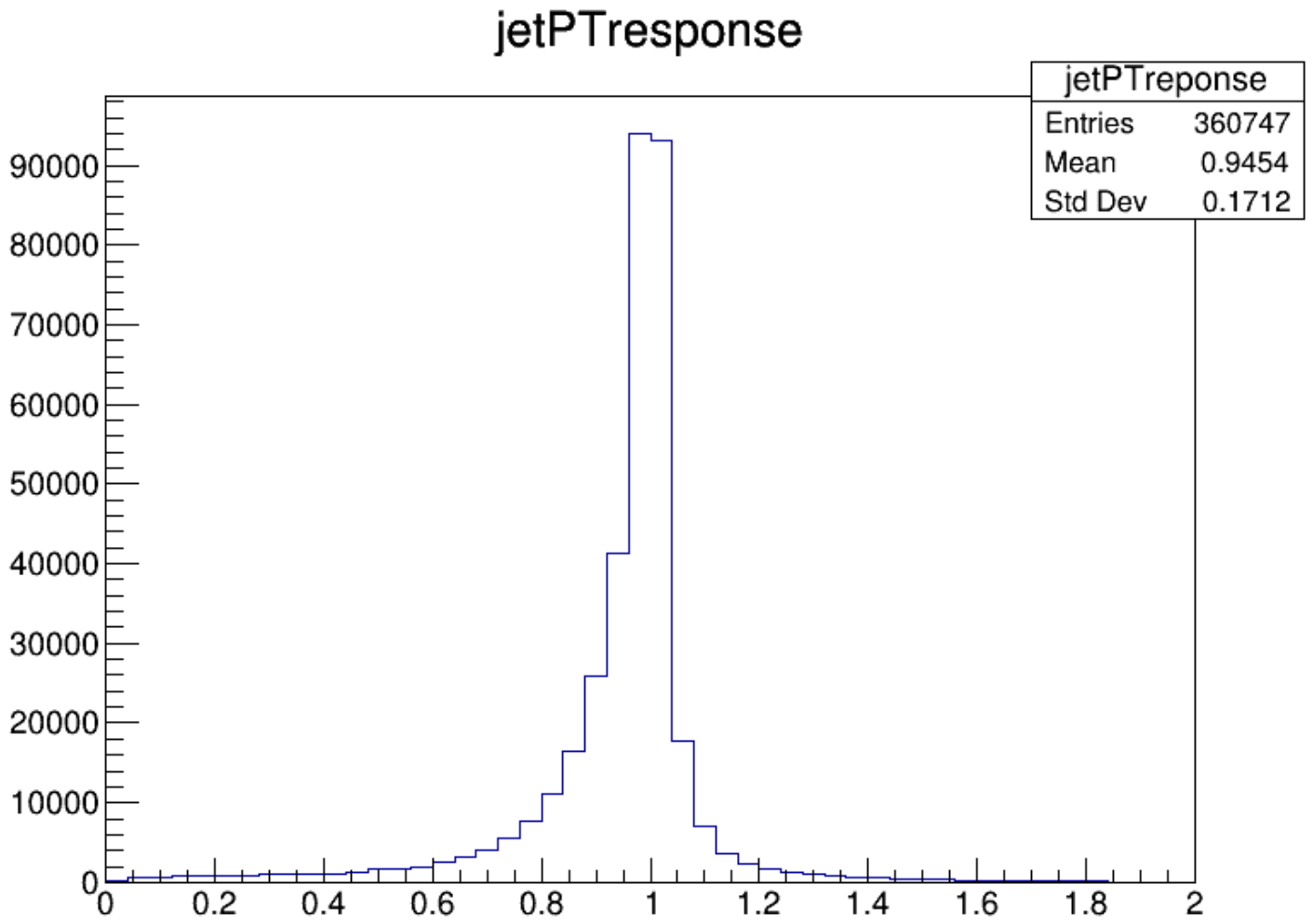
- Both Gen jet and reco jet doesn’t include neutrino.
  - Should add neutrino four-momentum to gen jet in order to get the truth jet
- Gen jet have muon but reco don’t ?
  - It is possible to change from using energy track to use calorimeter towers which does include muon.
- Gen jet is using VLCR05_inclusive
- These leave some questions for jets calibration.

Jets Calibration



JES

- 100k events of $\mu^- + \mu^+ \rightarrow t + \bar{t}$


jetPTresponse
jetPTreponse
Entries 360747
Mean 0.9454
Std Dev 0.1712
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Muon-in-jet situation

1. Create Muon-tagging:
   - Matching reco muon with reco jet
2. Checked distributions of energy response for jets w/ and w/o muon-tagging in different regions.
3. Muon-in-jet correction

Percent of jet's been tagged

Jet P_T Response as function of θ and P_T

jet P_T [GeV]	θ = 0	0.5	1	1.5	2	2.5	3
500	N/A	5%	7%	8%	8%	8%	8%	8%	6%	5%
450	0%	7%	14%	14%	12%	10%	11%	14%	13%	5%
400	4%	8%	13%	11%	10%	7%	10%	12%	9%	5%
350	3%	6%	10%	8%	7%	5%	7%	10%	10%	6%
300	3%	8%	8%	6%	7%	5%	5%	8%	9%	5%
250	5%	6%	7%	3%	4%	3%	5%	6%	6%	5%
200	5%	6%	6%	3%	3%	3%	3%	5%	7%	5%
150	5%	6%	4%	3%	2%	2%	2%	3%	5%	6%
100	5%	5%	4%	3%	2%	2%	2%	3%	4%	5%
50	5%	5%	4%	2%	3%	2%	3%	3%	4%	4%
0										

Muon-tagging = true

Jet P_T Response as function of θ and P_T

jet P_T [GeV]	θ = 0	0.5	1	1.5	2	2.5	3
500	1	1.01	0.99	0.98	0.98	0.98	0.97	0.98	0.99	1.03
450	1	1.01	1.03	1	0.98	0.98	0.96	0.99	0.99	1.02
400	1.06	1	1	0.98	0.99	1.03	0.97	1.02	1.01	1.02
350	1	0.97	0.98	1.01	0.92	0.96	1	0.99	0.98	0.97
300	1.01	0.97	0.99	1	0.98	0.99	1.02	0.96	0.96	0.95
250	0.95	0.91	0.97	0.94	0.93	0.97	0.97	0.98	0.97	0.93
200	0.97	0.97	0.96	0.99	0.92	0.9	0.98	0.9	0.93	0.97
150	0.98	0.95	0.88	0.85	0.9	0.95	0.83	0.89	0.91	0.96
100	0.95	0.94	0.92	0.9	0.84	0.91	0.87	0.92	0.93	0.95
50	0.93	0.94	0.92	0.94	0.91	0.97	0.94	0.93	0.93	0.93
0										

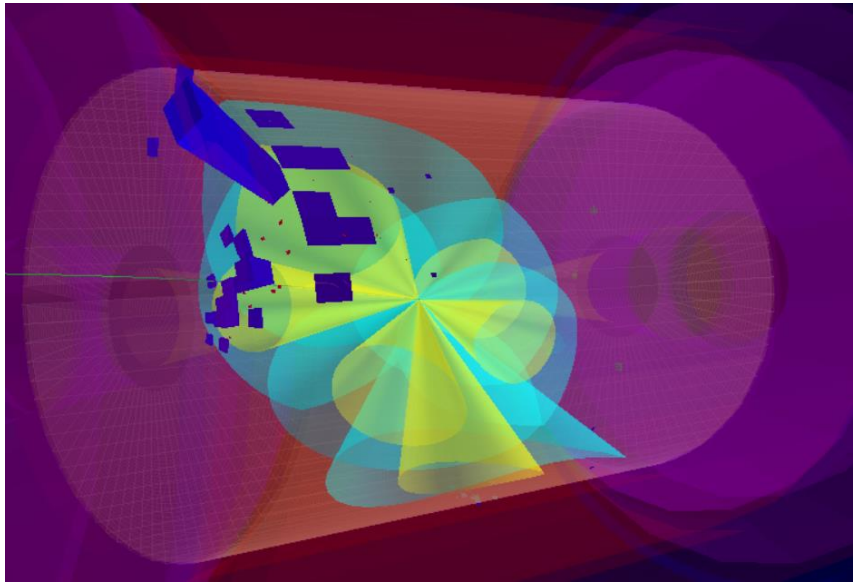
θ

Muon-tagging = false

Jet P_T Response as function of θ and P_T

jet P_T [GeV] \ θ	0	0.5	1	1.5	2	2.5	3
500	1	0.99	0.96	0.96	0.95	0.95	0.95	0.96	0.97	1.01
450	1.02	0.98	0.96	0.97	0.96	0.96	0.96	0.95	0.95	1.01
400	1.04	0.97	0.96	0.97	0.96	0.96	0.96	0.97	0.95	0.99
350	1.02	0.94	0.98	0.96	0.97	0.97	0.96	0.97	0.95	0.97
300	0.97	0.92	0.93	0.95	0.97	0.97	0.96	0.96	0.93	0.94
250	0.93	0.91	0.93	0.94	0.96	0.95	0.95	0.95	0.9	0.92
200	0.92	0.9	0.89	0.94	0.96	0.97	0.95	0.91	0.88	0.92
150	0.91	0.89	0.87	0.94	0.96	0.97	0.95	0.9	0.88	0.91
100	0.9	0.91	0.91	0.95	0.97	0.97	0.96	0.92	0.91	0.89
50	0.84	0.9	0.91	0.94	0.95	0.95	0.94	0.92	0.9	0.85
0										

Observations



1. Only a few (<10%) are reco_muon-tagged, about half of the gen_muon-tagging：
   - Some gen muon are not reconstructed.
2. For those muon-tagged jets , the JES is already pretty good, which seems like muons are included?
   - Here it’s really confusing 🤔 as the detector card does set both energy fraction of muon to 0 for both HCAL and ECAL, but what my result of JES is not consistent with that, any ideas?

Next step:

1. Changing the Gen Jet algorithm to anti-kt or changing reco jet algorithm to VLCR05_inclusive?
2. neutrino-in-jet correction:
   - $\mathrm{JES} = \frac{P_{T_{reco}}}{P_{T_{gen+\nu}}}$
3. Still consider Muon-in-jet situation?