Jet substructure study with new Hidden Valley Pythia module

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(On behalf of Jet Substructure Team)

Dark Showers Meeting - 24/02/2022

Outline

1

Introduction

JSS observables

Motivations

2

Consistency Checks

Old HV vs new HV

Vector mesons production 0.5 vs 0.75

3

IRC Safety Checks

IRC safety

Evolution of JSS in the process

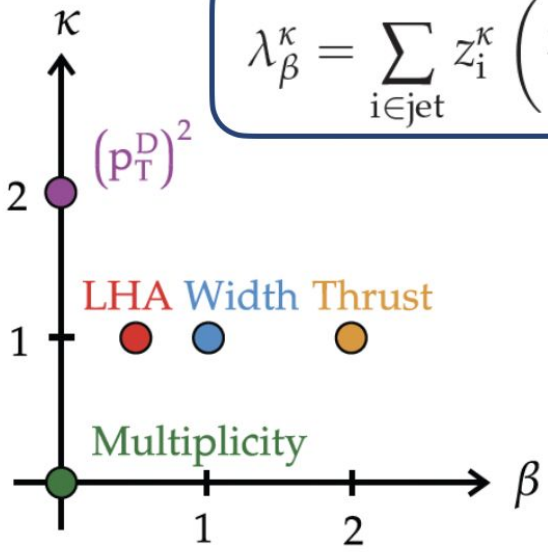
Looking inside jets

arXiv:1901.10342

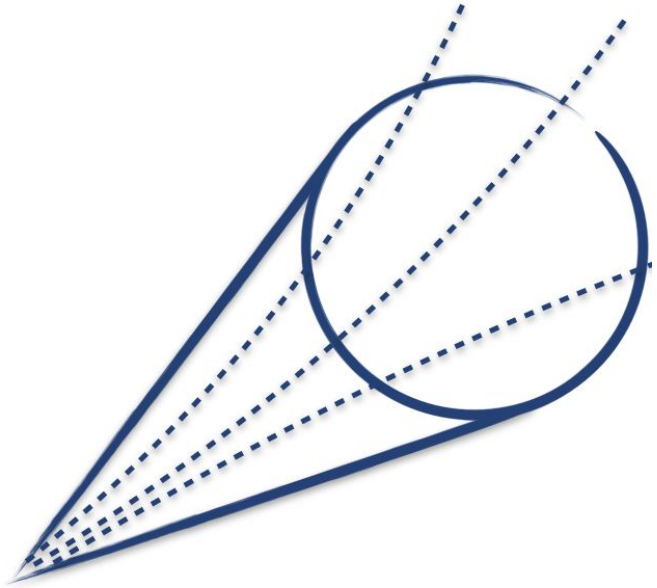
arXiv:1712.07124

Map of generalized angularities (*)

$$\lambda_\beta^\kappa = \sum_{i \in jet} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$



Infer radiation pattern



(*) NOT ALL ARE IRC SAFE

Motivations for the study

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch 2021/08/22

Search for resonant production of strongly-coupled dark matter in proton-proton collisions at 13 TeV

The CMS Collaboration

The first collider search for da… tor is presented, using a data sample … CMS detector at the CERN LHC at a center-of… sector is hypothesized to couple to the standard model … Z′ mediator. The resonant production and decay of such a media… collisions would result in two "semi-visible" jets, which contain both … and invisible dark matter. This would lead to moderate missing energy aligned … one of the jets, a signature ignored by most dark matter searches. The observed dijet transverse mass spectrum is smoothly falling, as expected from the SM; no structure compatible with the signal is observed. Assuming the same couplings as the SM Z boson, mediator masses up to 3.9 TeV are excluded at 95% confidence level, depending on the other signal model parameters. To enhance the sensitivity of the search for this particular class of models, a boosted decision tree (BDT) is trained using jet substructure variables to distinguish between semi-visible jets and standard model jets from background processes. When the BDT is employed to select events with jets identified as semi-visible, the mediator mass exclusion increases to 5.1 TeV, for wider ranges of the other signal model parameters.

ANALYSIS WANTS TO EXPLOIT JSS

Autoencoders for Semivisible Jet Detection

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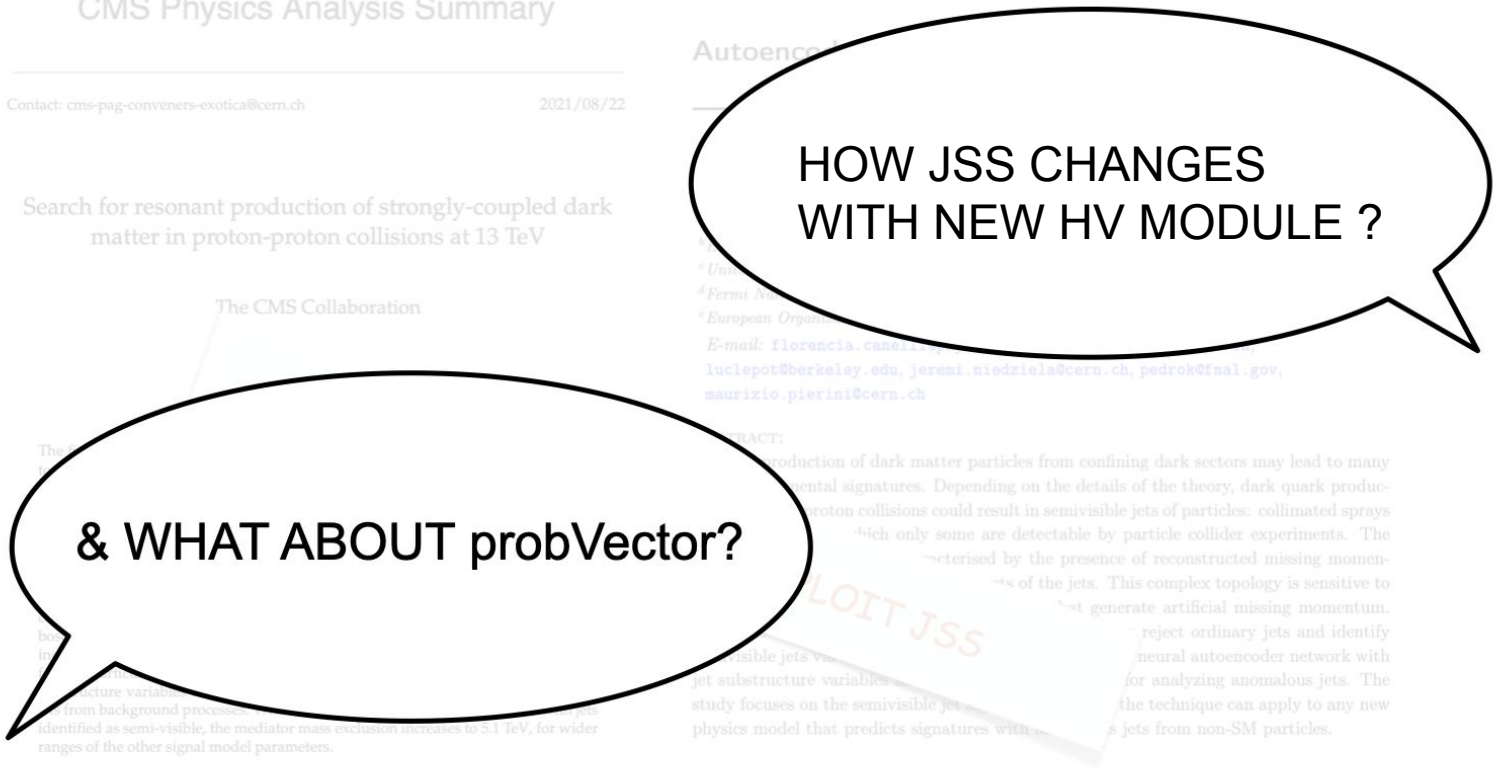
ABSTRACT:

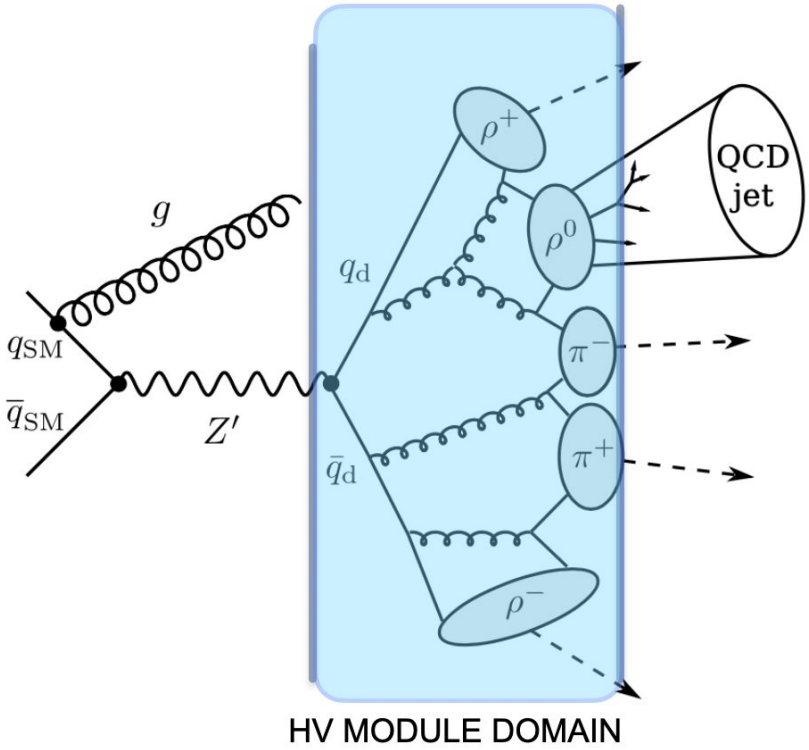
The production of dark matter particles from confining dark sectors may lead to many … experimental signatures. Depending on the details of the theory, dark quark produc… …-proton collisions could result in semivisible jets of particles: collimated sprays … which only some are detectable by particle collider experiments. The … acterised by the presence of reconstructed missing momen… …ts of the jets. This complex topology is sensitive to … …at generate artificial missing momentum. With th… reject ordinary jets and identify semivisible jets vi… neural autoencoder network with jet substructure variables … for analyzing anomalous jets. The study focuses on the semivisible jet … the technique can apply to any new physics model that predicts signatures with … jets from non-SM particles.

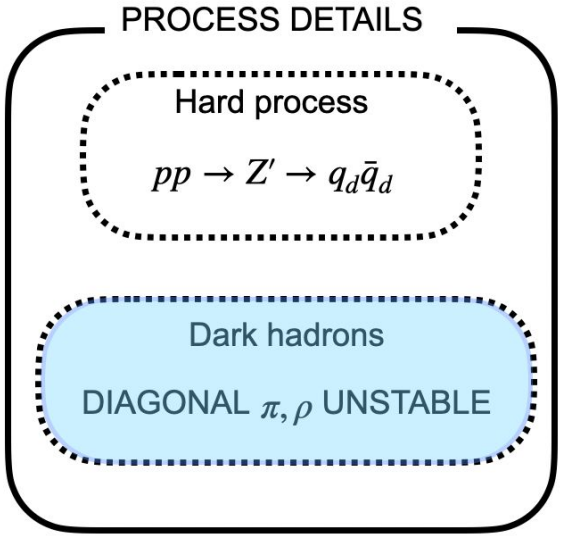
Motivations for the study



(*) probVector is the probability to produce a vector meson from HV

Process

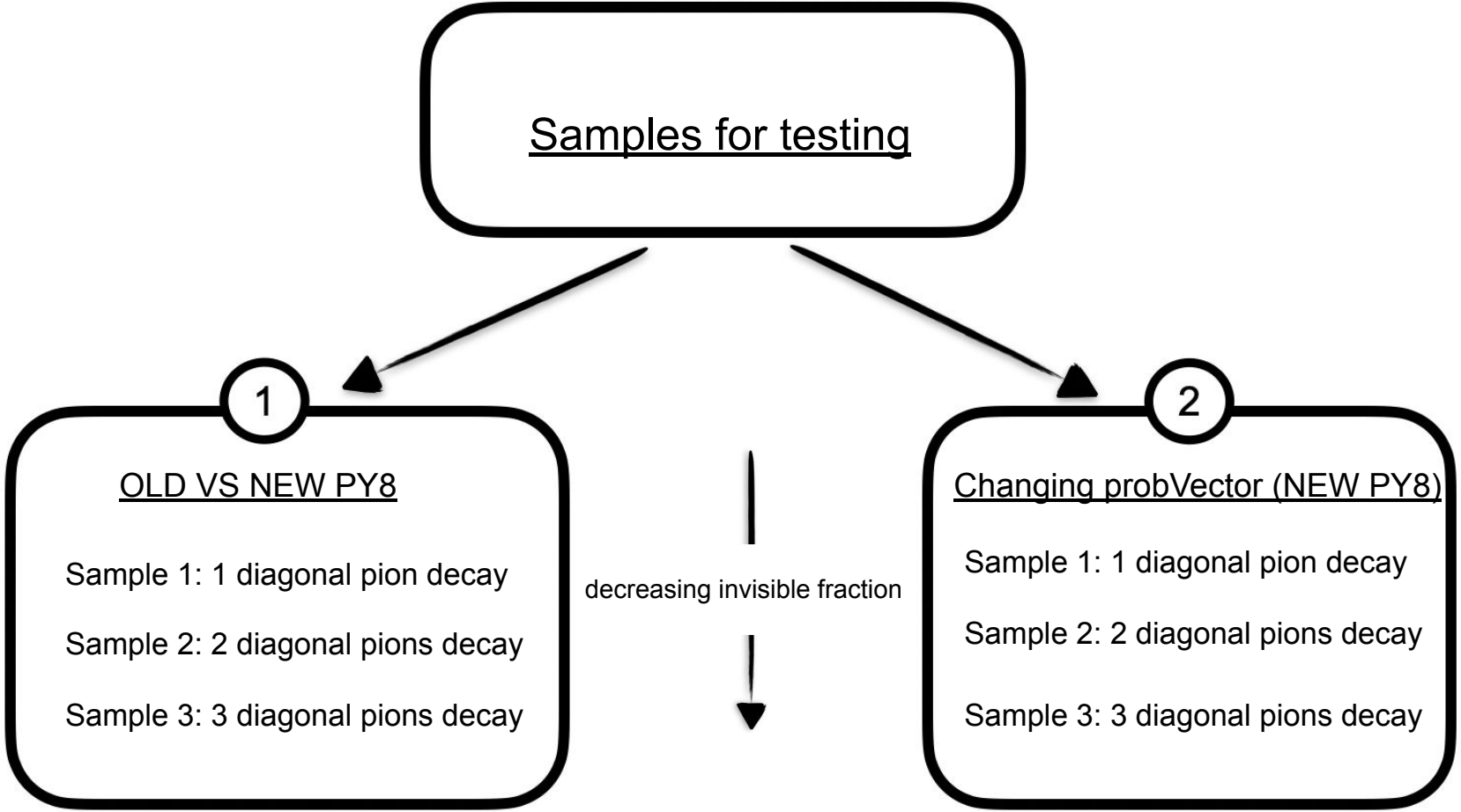




(*) Image adapted from E. Bernreuther paper [arXiv:1907.04346v2]

(*) vector meson is taken to decay to dark pions

Testing JSS observables



Samples

1

Nc = 3, Nf =3 (50k events X 3)

PARAMETERS SETTING

$\Lambda_{dark} = 10\ GeV$

$m_{q_d} = 10.2\ GeV$ (*)

$m_\pi = 6\ GeV\ , m_\rho = 26\ GeV$

probVector = 0.75

2

Nc = 3, Nf =3 (50k events X 3)

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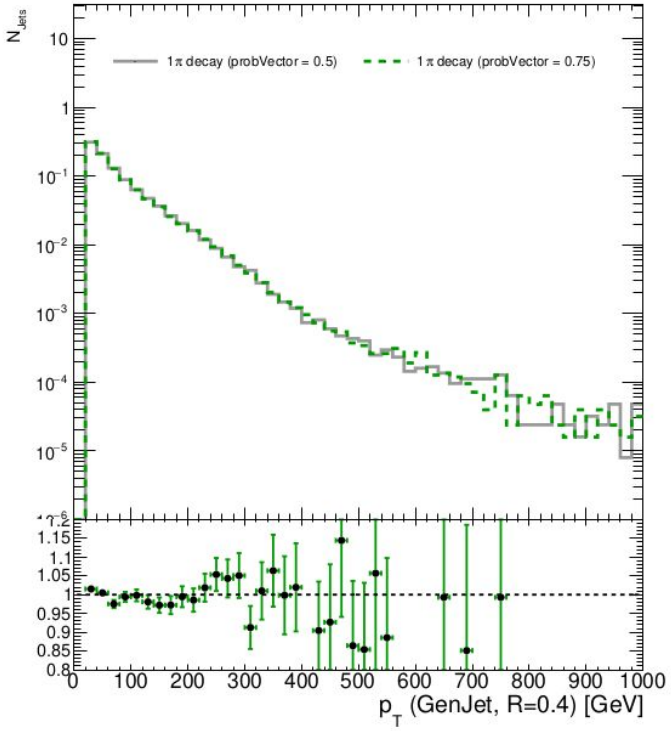
$m_{q_d} = 10.2\ GeV$ (*)

$m_\pi = 6\ GeV\ , m_\rho = 26\ GeV$

probVector = 0.5 / 0.75

(*) constituent quark mass: $m_{q_d} = \bar{m}_{q_d} + \#\Lambda$

Jets & constituents

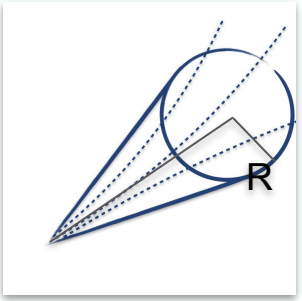


Gen-level jets and constituents in Delphes

AK4 jets : R = 0.4

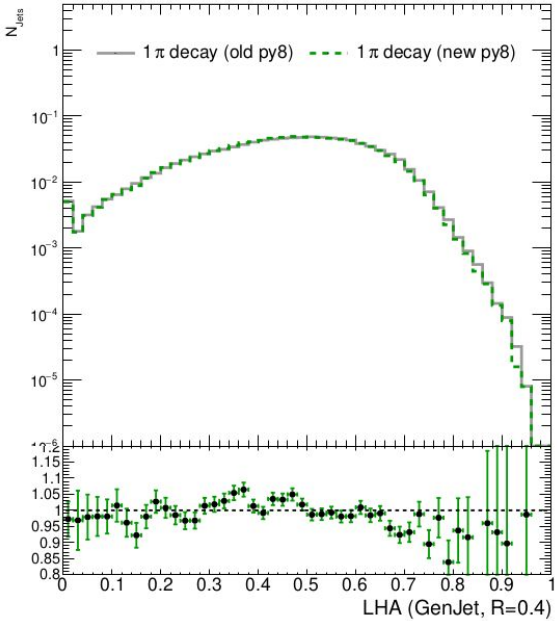
Minimum pt : 25 GeV

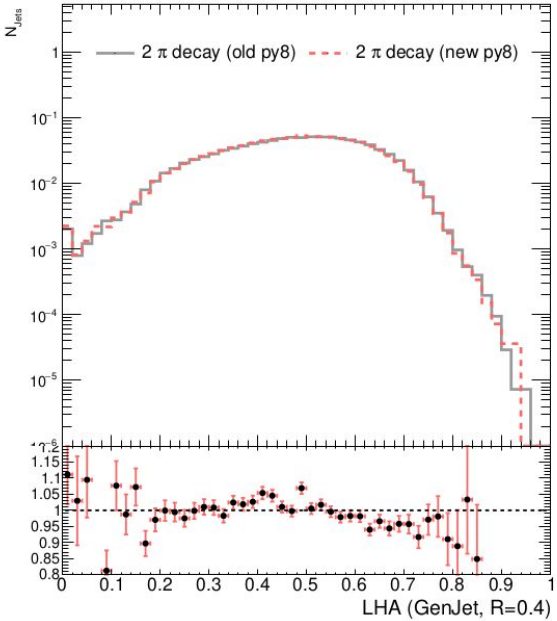
Constituents: status 1 SM particles within jet cone

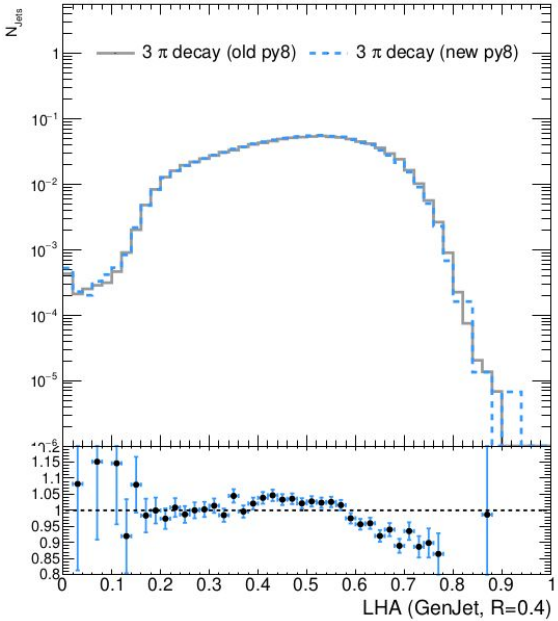


Comparing old & new HV module

Generalized angularities

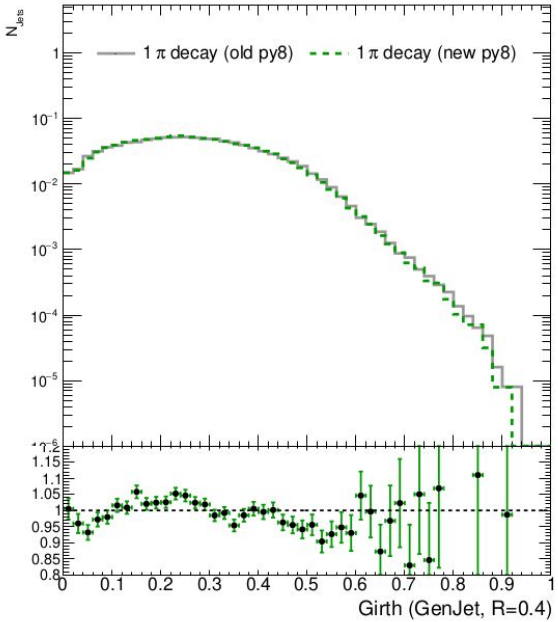


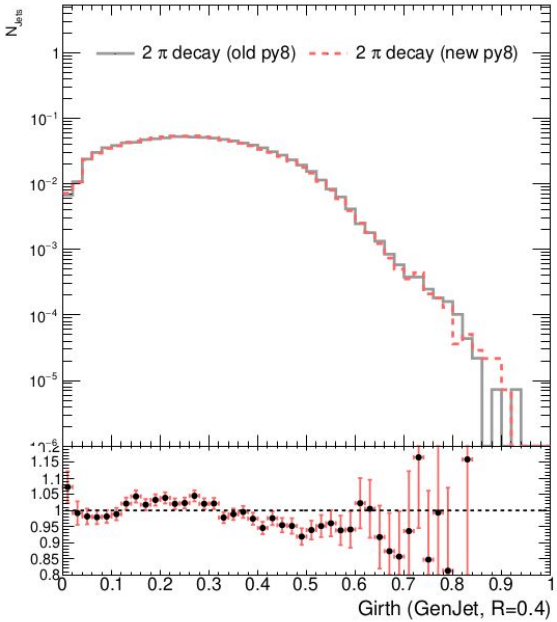


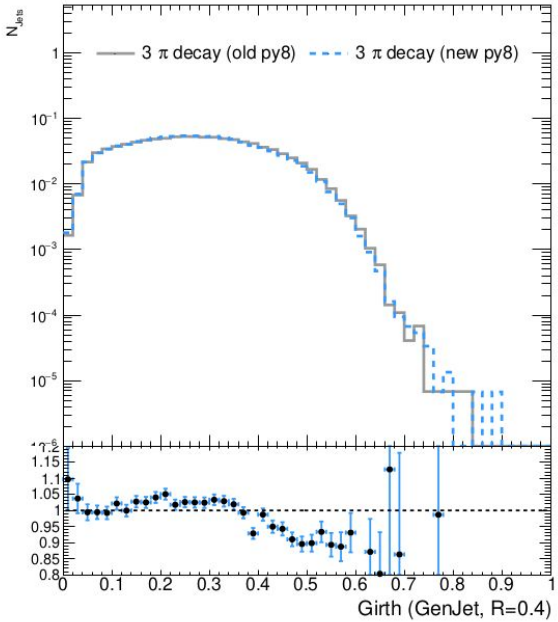


- Some systematic discrepancies for LHA > 0.35
- Higher discrepancies for 3 pions decay (smaller invisible fraction)
- Discrepancies also observed in AK8 gen jets (could not confirm for p_T>200 GeV due to limited statistics, see backup)

Generalized angularities







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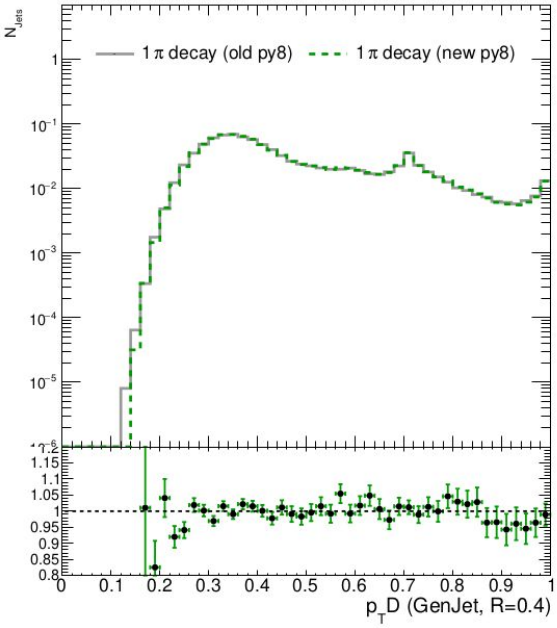
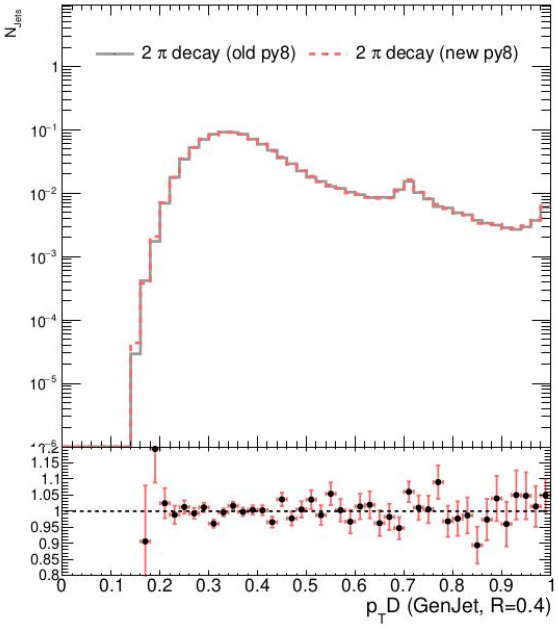
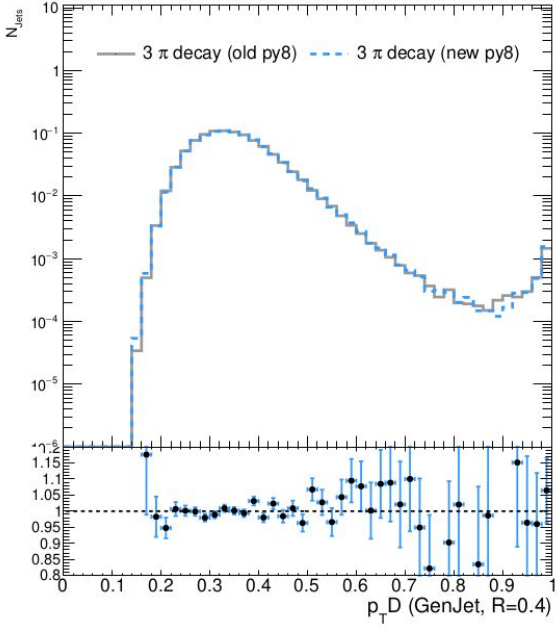
Generalized angularities

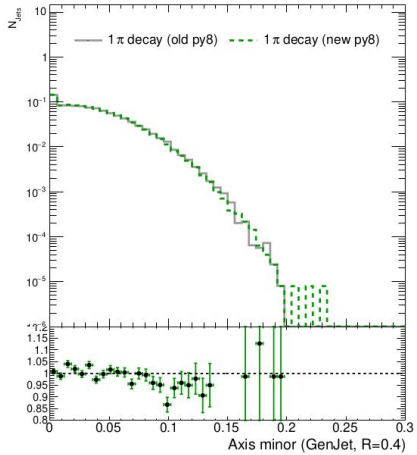


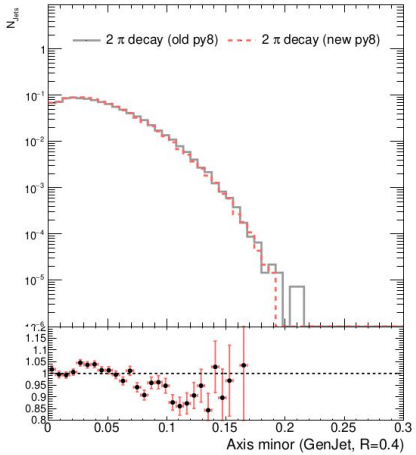


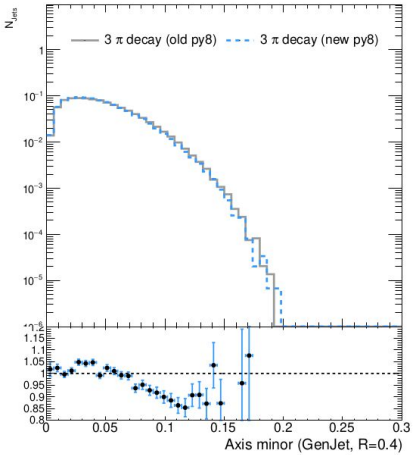


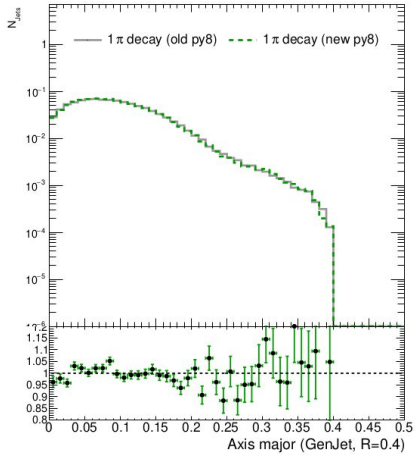
- No obvious discrepancies
- Peak at 0.7 is certainly due to jets with 2 high p_T SM pions with equal p_T: $1/\sqrt{2} \approx 0.7$

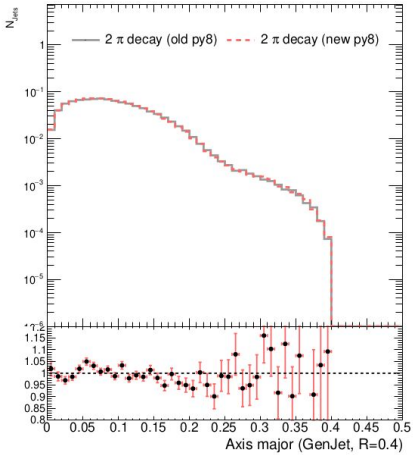
Axis minor and major

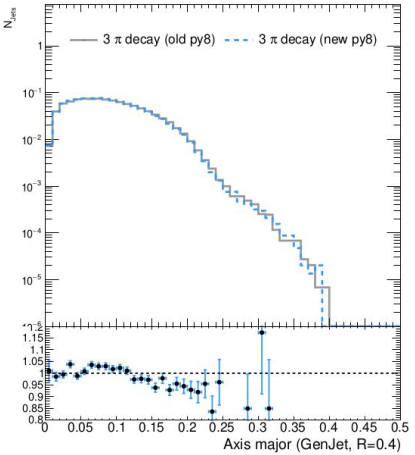








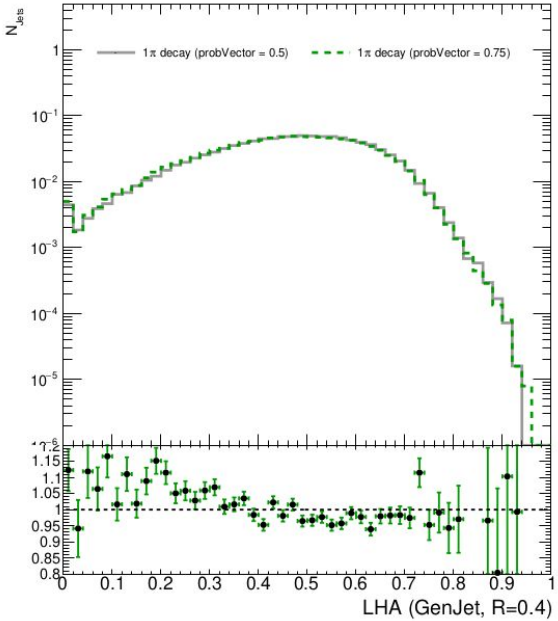


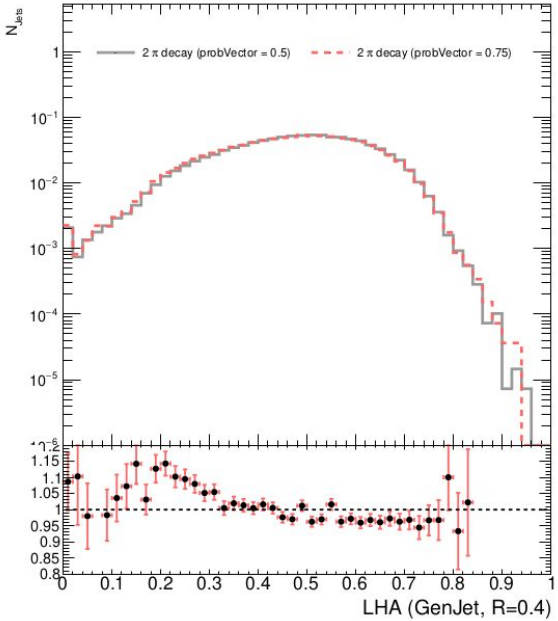


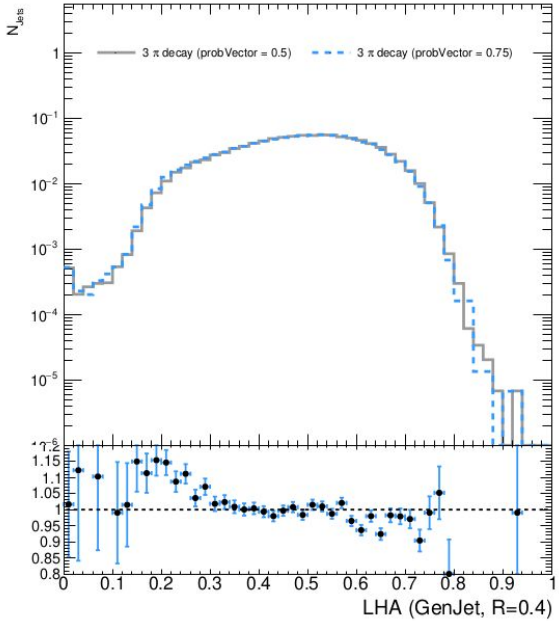
- Narrower jets with new HV Pythia version
- Seems consistent with jet angularities (lower angularities)
- Same differences observed for AK8 gen jets (see backup)

Comparing probVector = 0.5 & probVector = 0.75

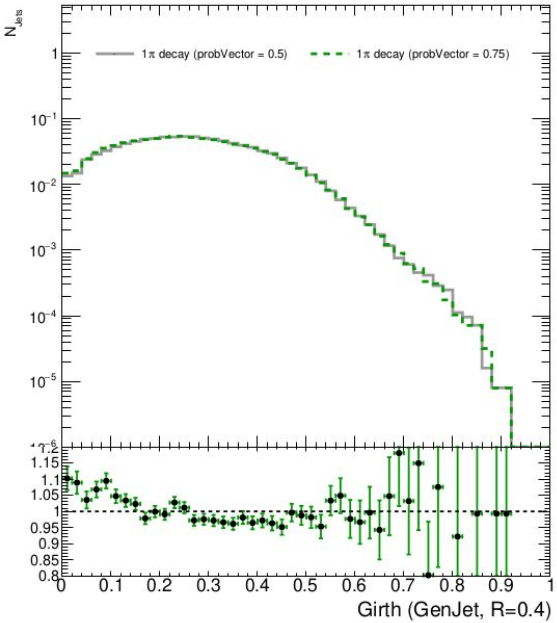
Comparing probVector=0.5 and probVector=0.75 (new Pythia)

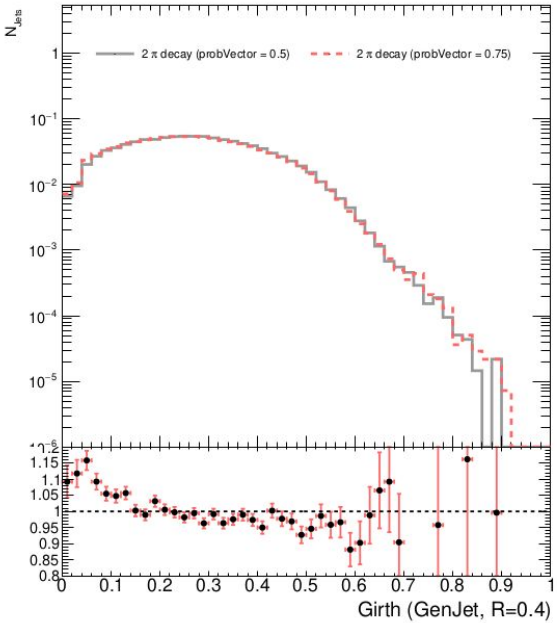


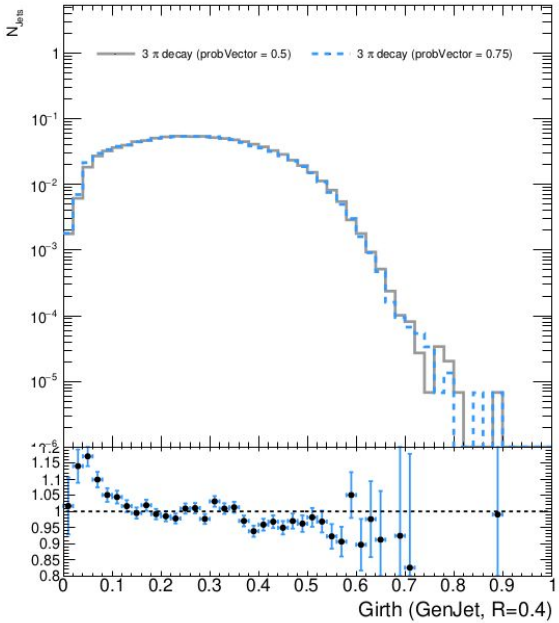




Comparing probVector=0.5 and probVector=0.75 (new Pythia)







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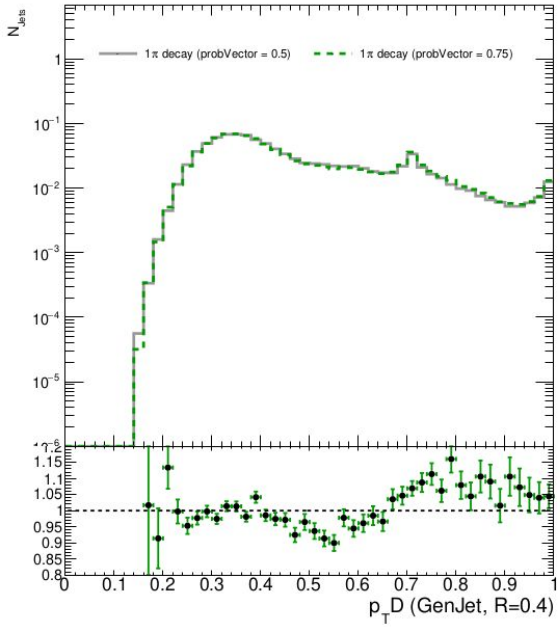
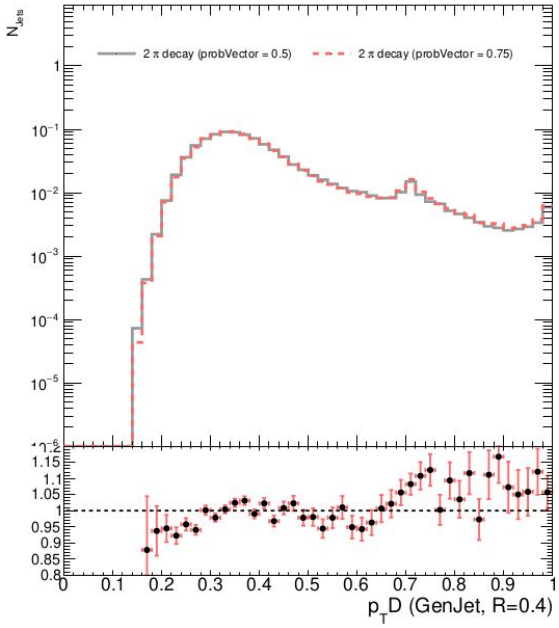
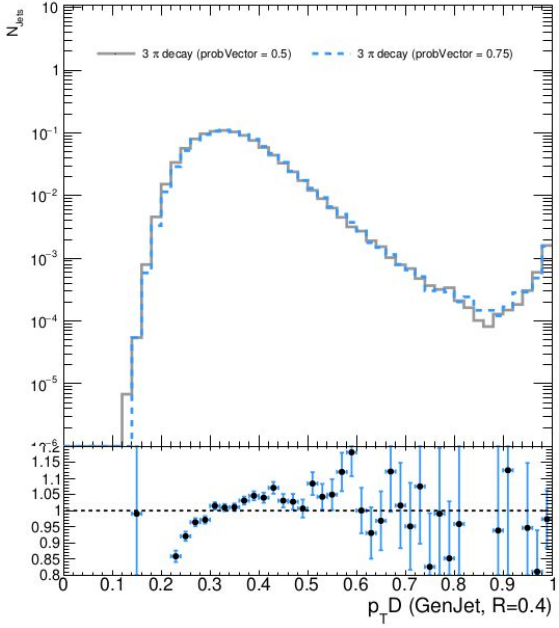
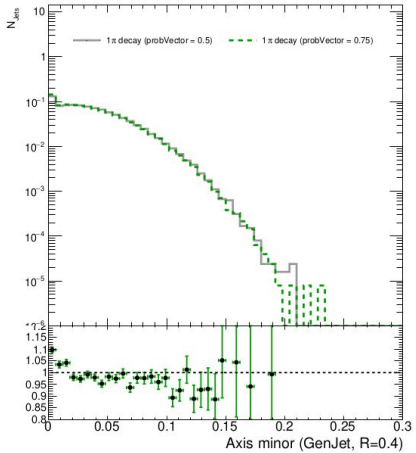
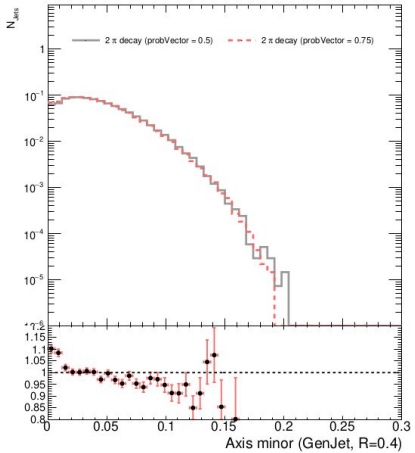


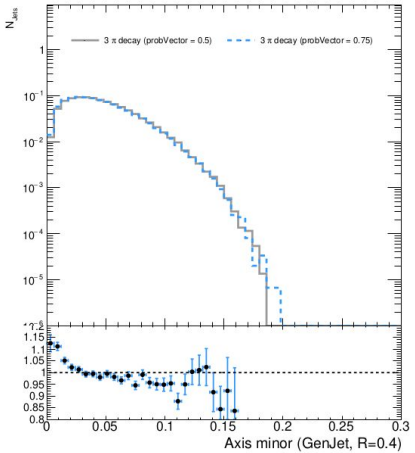


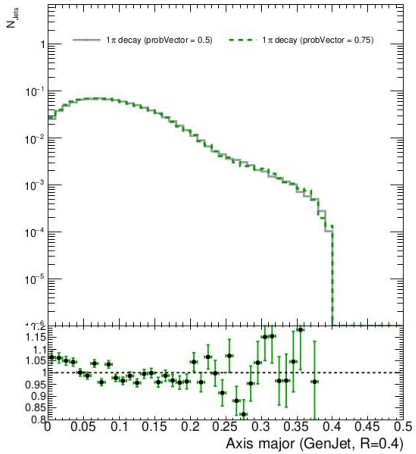


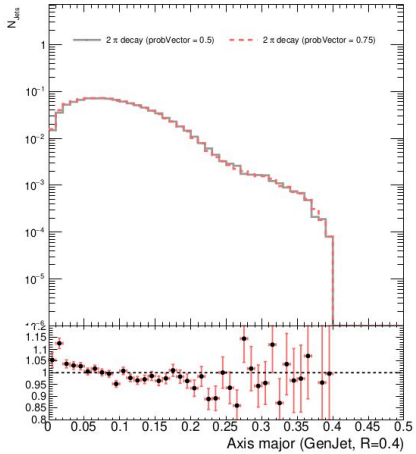
Axis minor and major

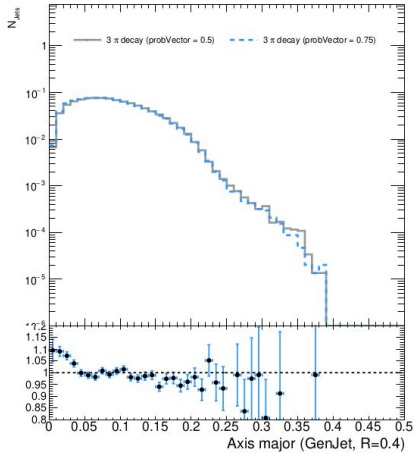








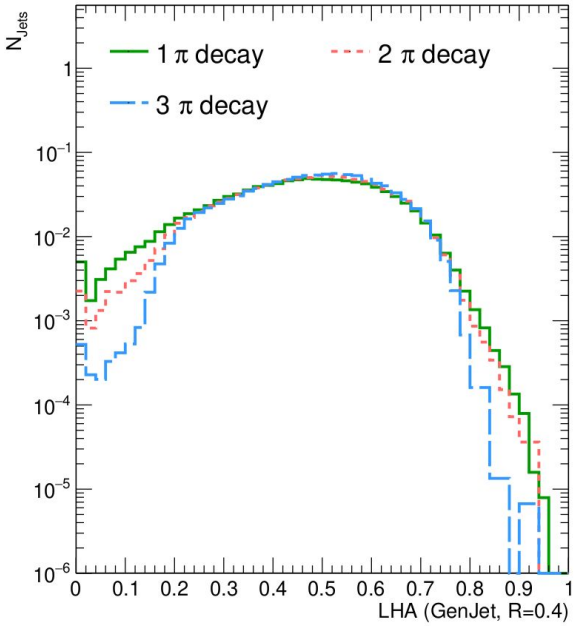


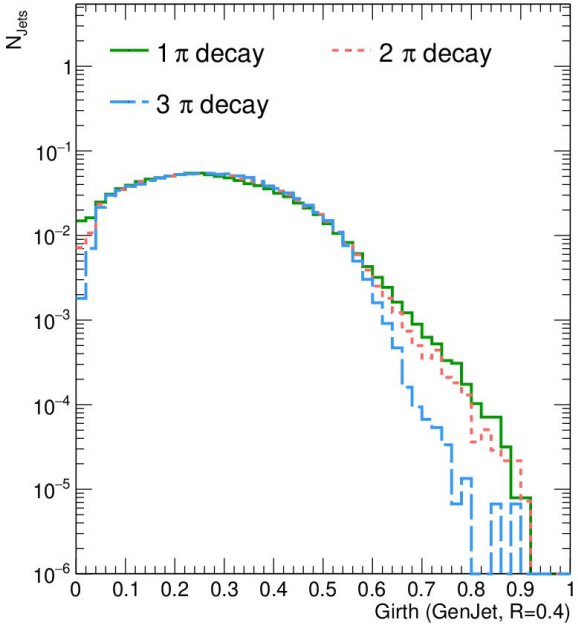


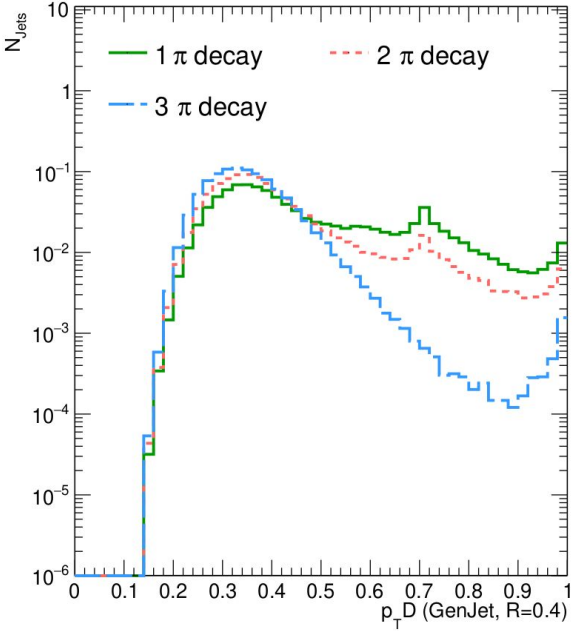
- Narrower jets with higher probVector

Comparing 1, 2 & 3 dark pions decays

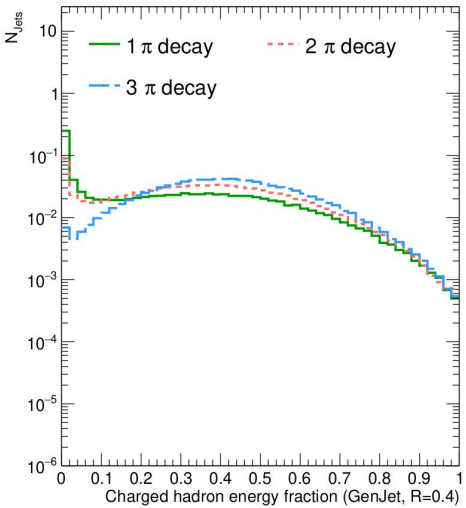
Comparing 1, 2 and 3 dark pions decays

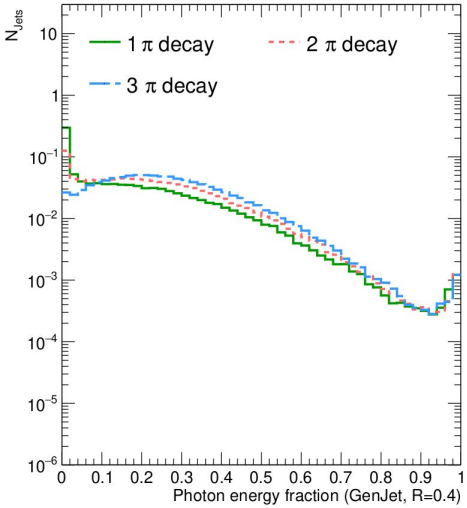


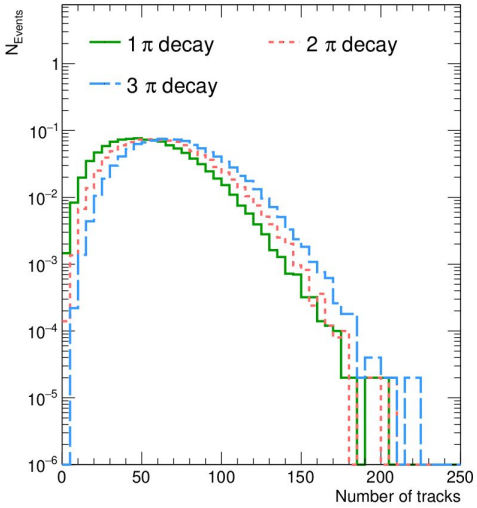


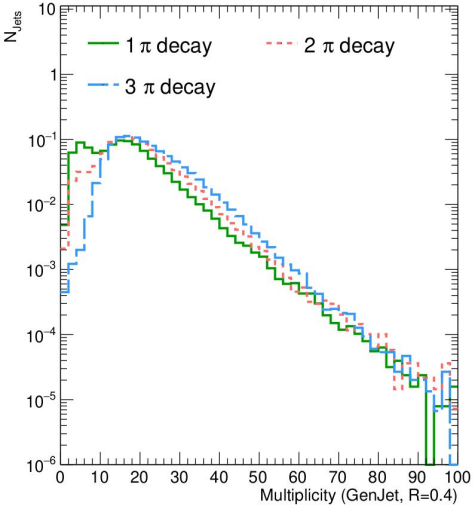


Comparing 1, 2 and 3 dark pions decays







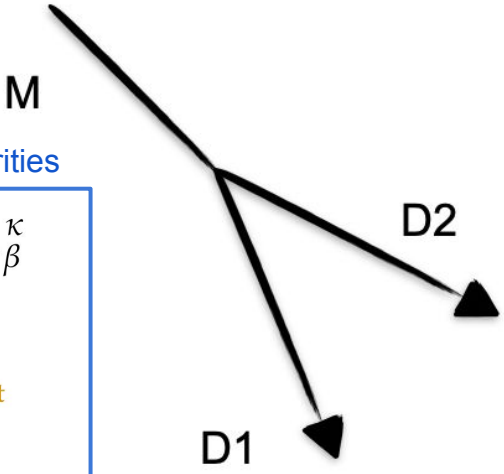


- Energy fractions, number of tracks / constituents change significantly as the number of unstable dark pions changes

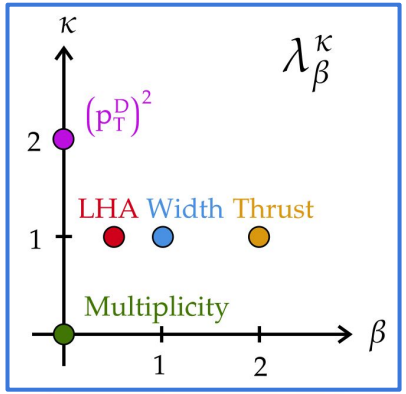
Test of IRC safety

IRC safety

Phys. Rev. D **17**, 2773
Phys. Rev. D **17**, 2789
Phys. Rev. Lett. **111**, 102002



Generalized angularities



$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$

IRC for JSS observables

Take a generalized angularity V: only for κ = 1 the collinear splitting of M1 into D1 and D2 must not change the value of V

We expect large fluctuations for IRC unsafe observables looking at the evolution of the shower from dark sector to SM

Some IRC unsafe observables which were used in standard quark-gluon discriminant can introduce large model dependence if used in dark sector analysis

collinear safety: $V_{m+1}(\ldots, k_i, k_j, \ldots) \longrightarrow V_m(\ldots, k_i + k_j, \ldots) \quad \text{if } k_i \parallel k_j$

Test of IRC safety

Strategy: Check how substructure variables evolve with showering from dark sector to SM

Procedure

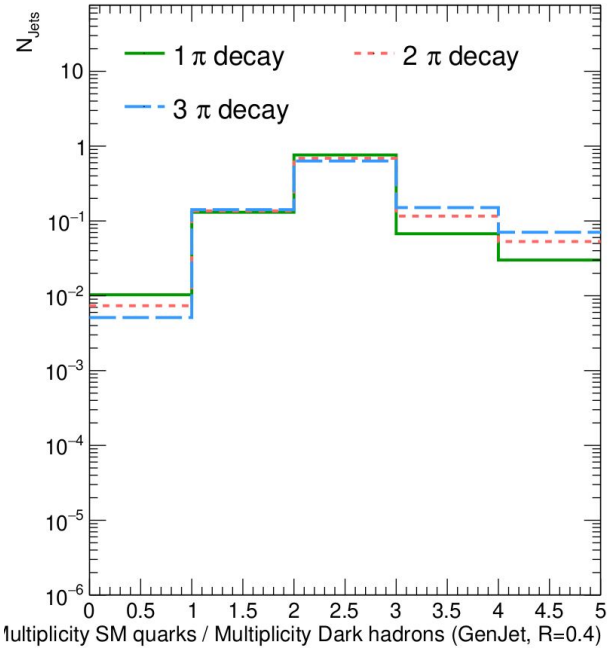
- Compute JSS at 3 levels:
  - **(1)** Unstable dark hadrons decaying to SM quarks (multiplicity N_1)
  - **(2)** SM quarks from dark hadrons (multiplicity N_2)
  - **(3)** SM hadrons from hadronization of the SM quarks

- Plot ratios **(1)/(2)**, **(2)/(3)** and **(1)/(3)**

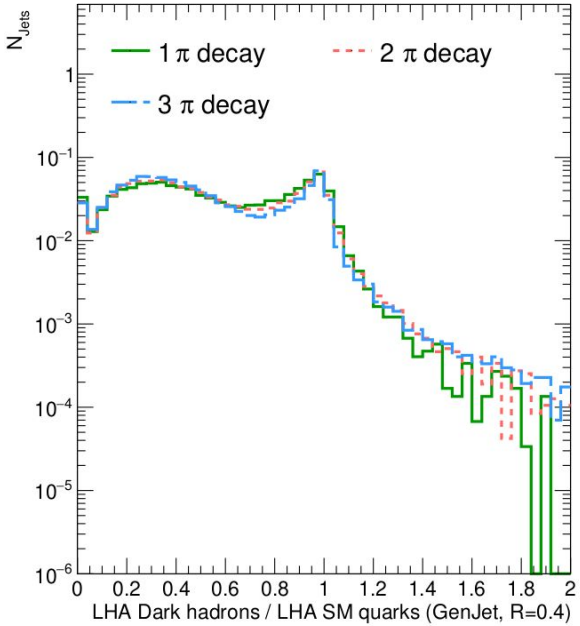
- Levels defined based on Pythia particle status and PDG ID of daughters or mothers

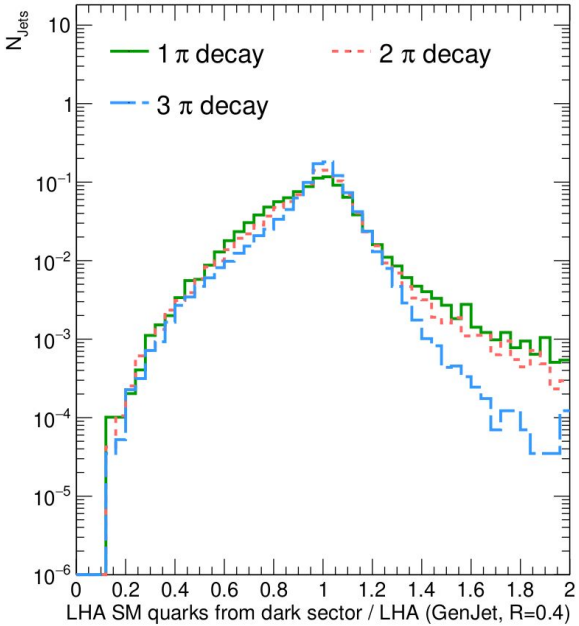
- To make the comparison fair between each level, looked only at jets for which $N_2 = 2N_1$
  - So that there is no bias from not taking all SM quarks from unstable dark hadrons
  - Most jets have $N_2 = 2N_1$

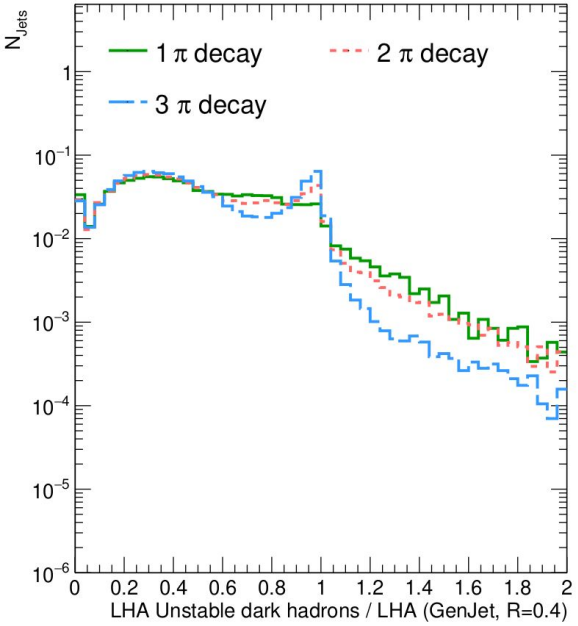
- Used new Pythia 8 version with probVector = 0.75



Test of IRC safety - LHA

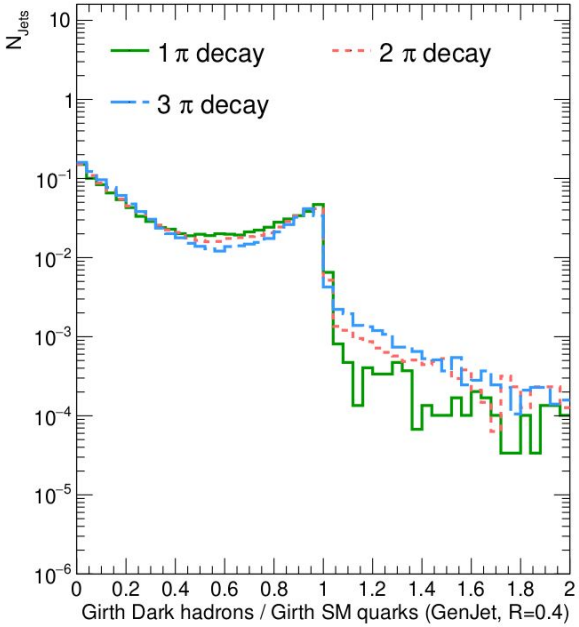


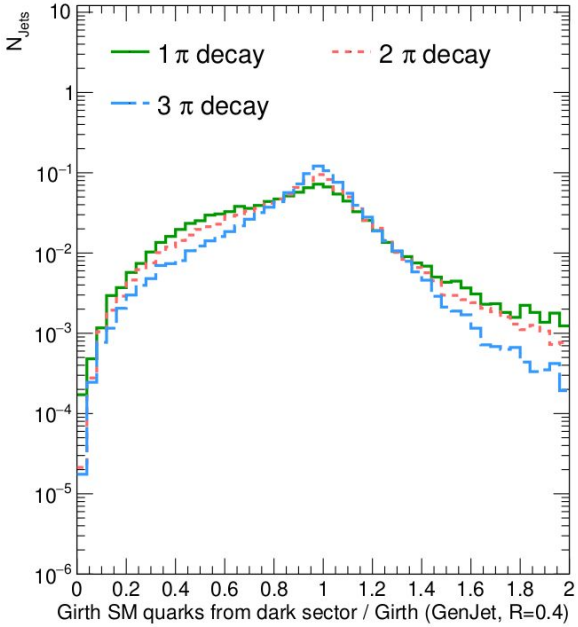


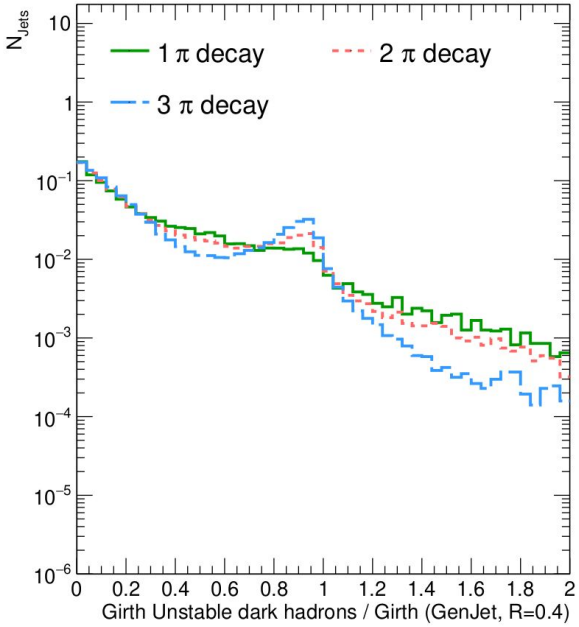


- Peak at 1 in all ratios
  ➜ LHA is IRC safe (as expected)

Test of IRC safety - Girth



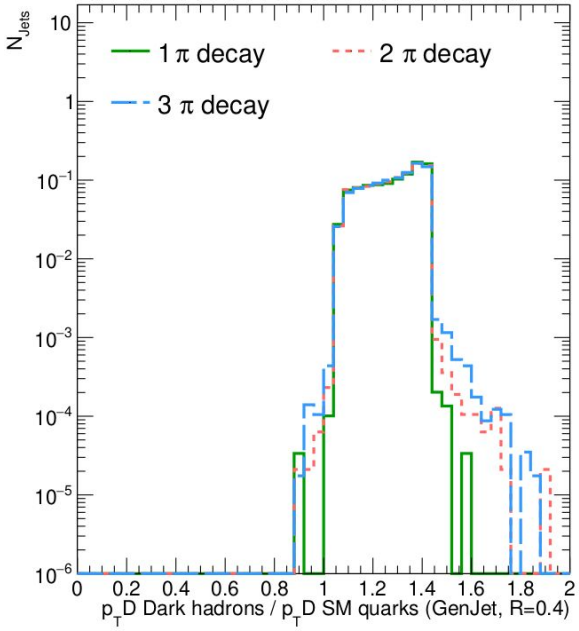


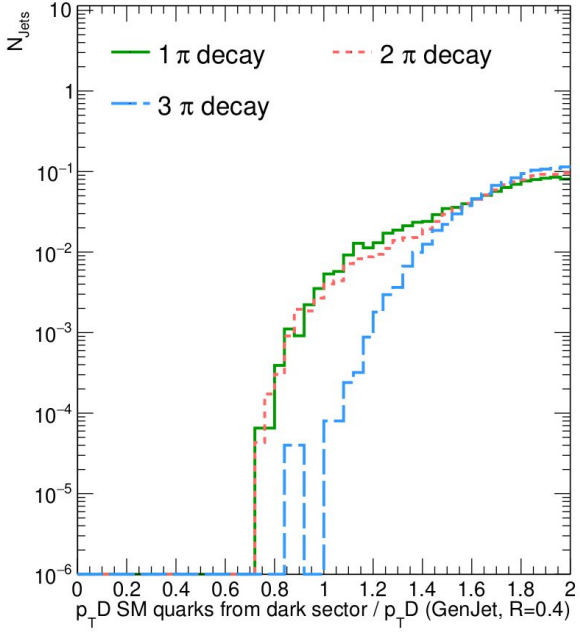


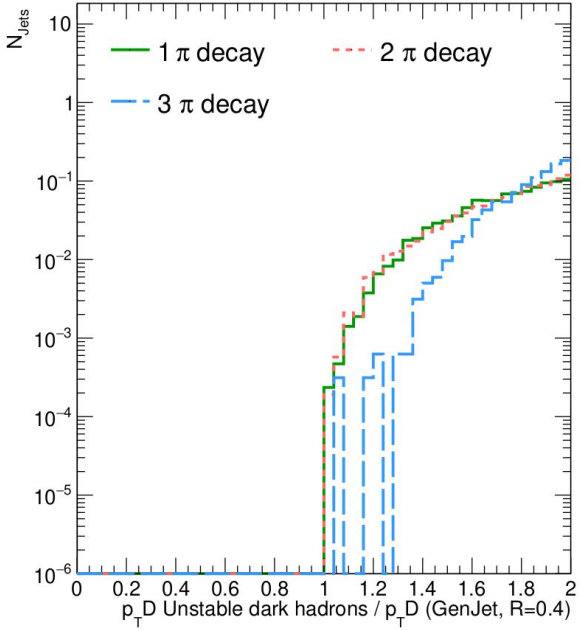
- Peak at 1 in all ratios
  ➜ Girth is IRC safe (as expected)

- Values close to 0 certainly due to jets with 1 unstable dark hadron (ΔR≈0)

Test of IRC safety - $p_T D$







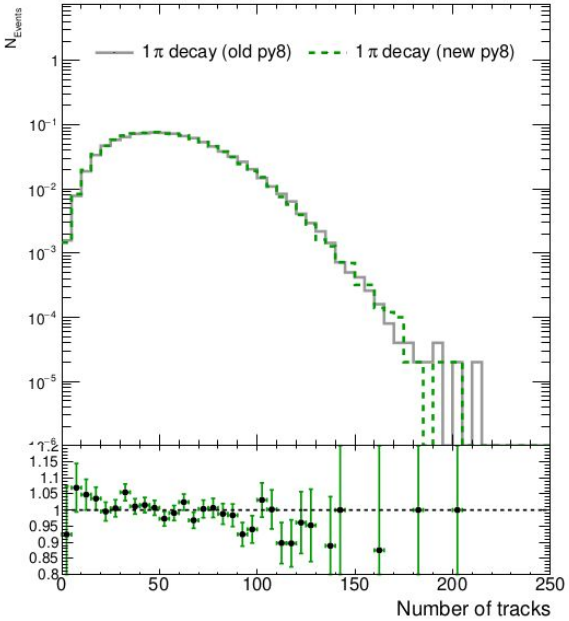
- Ratios not consistent with
  - ➜ $p_T D$ varies at different stages during the showering
  - ➜ $p_T D$ is not IRC safe (as expected)

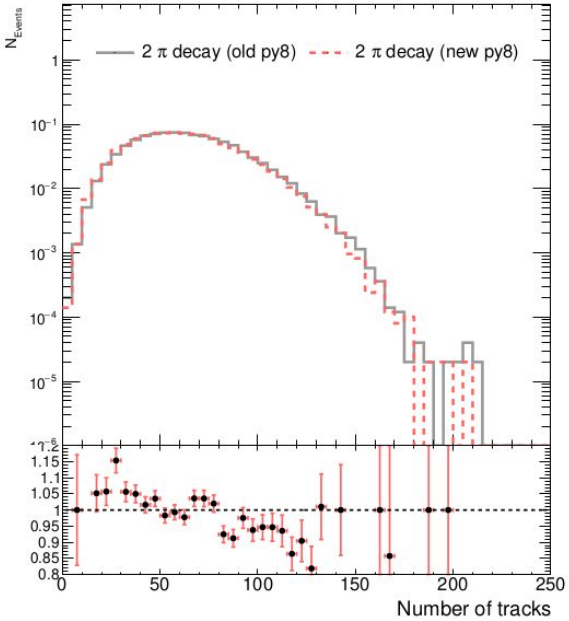
Conclusions

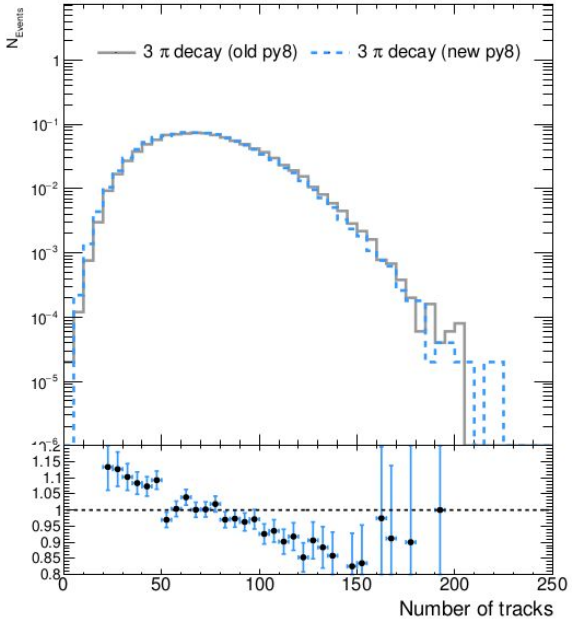
- Some differences observed for JSS observables between old and new Hidden Valley Pythia module
  - Enhanced discrepancies for smaller invisible fraction
  - Observed for both AK4 and AK8 gen jets with low p_T cut (25 GeV)
- Jets seems narrower with higher probVector and with new HV Pythia version
- Some substructure observables (energy fractions, number of constituents) can show large variations for different values of probVector
- Could check IRC safety of some JSS observables (generalized angularities): $p_T D$ shows large variations - is it safe to use it in analysis? [originally used for the limited purpose of quark-gluon discrimination]

Backup

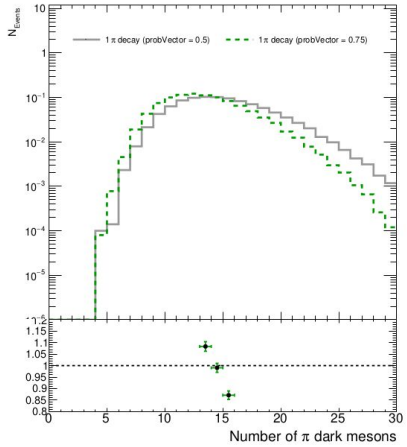
Number of tracks

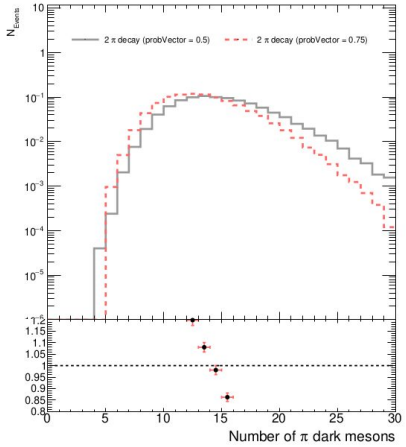


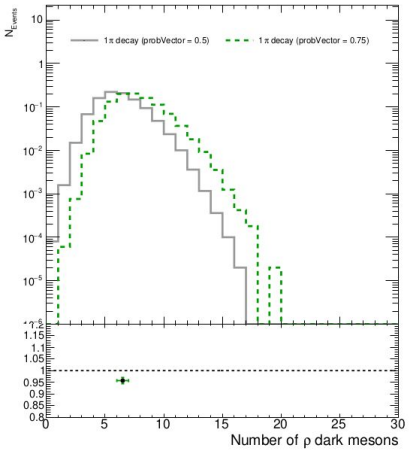


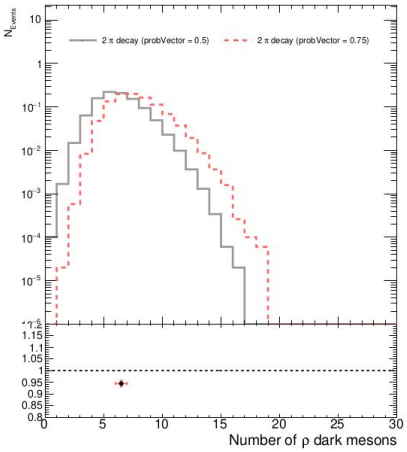


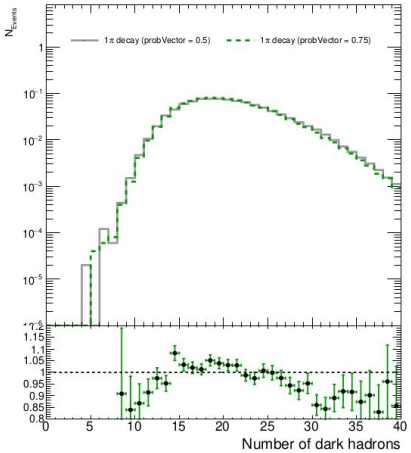
Number of dark hadrons

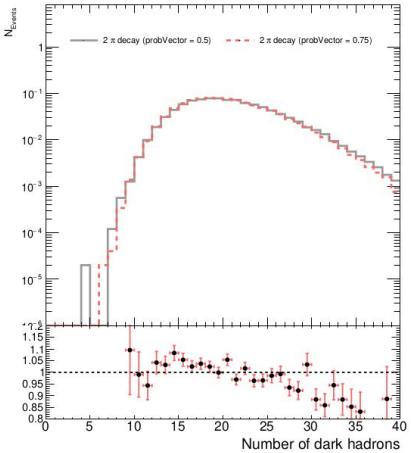






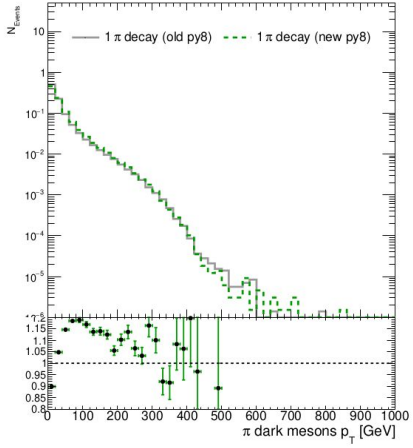


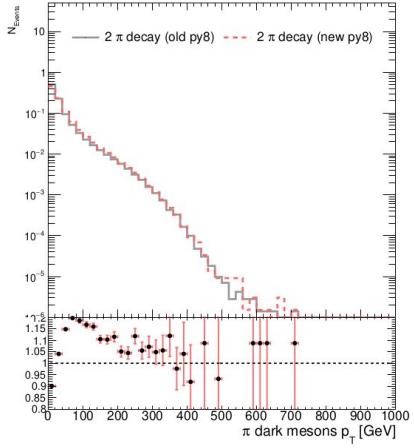


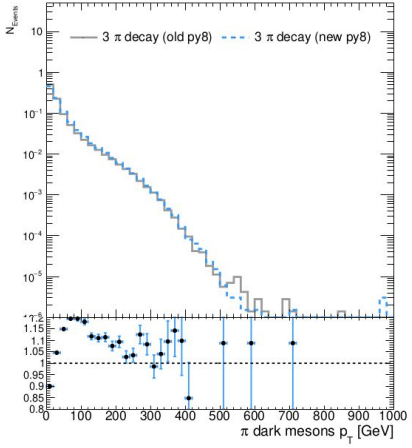


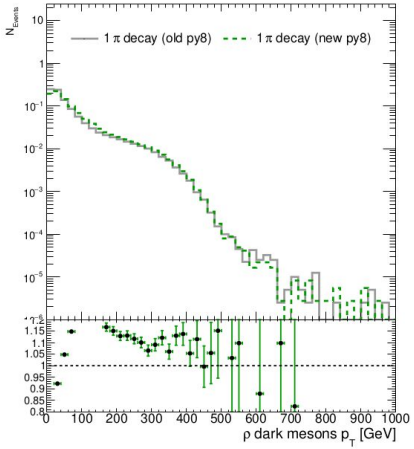
- When changing probVector, the total number of dark hadrons does not change, but ratio of dark pions to dark rhos changes, as expected.

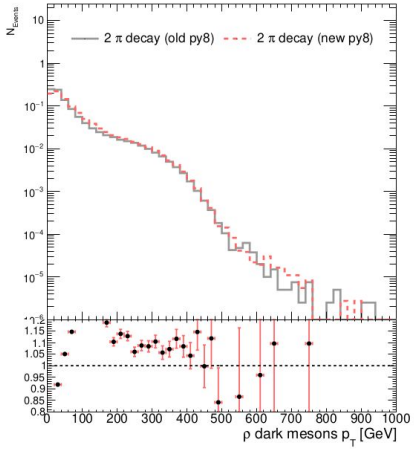
Dark pions and rhos p_T

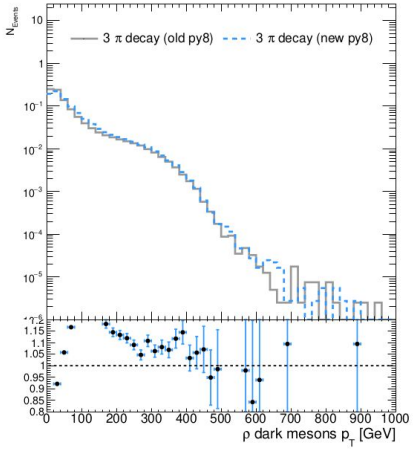






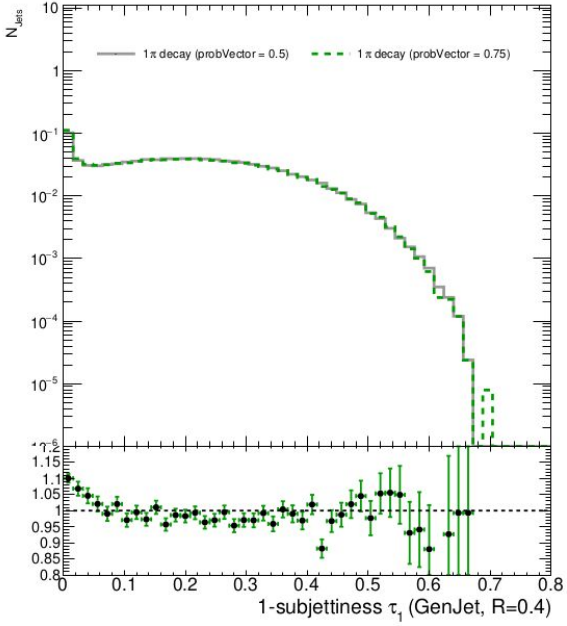


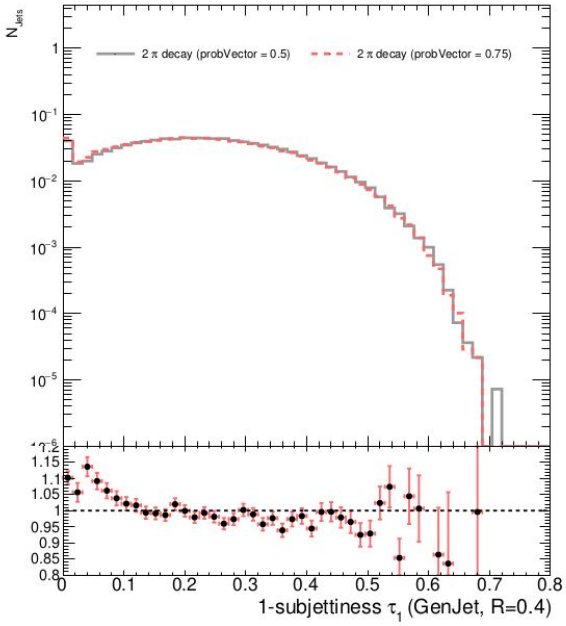


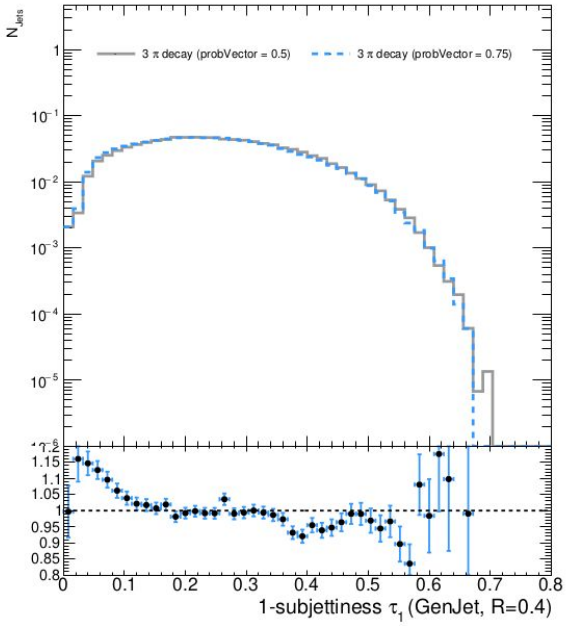


Supplementary material for GenJet with R=0.4

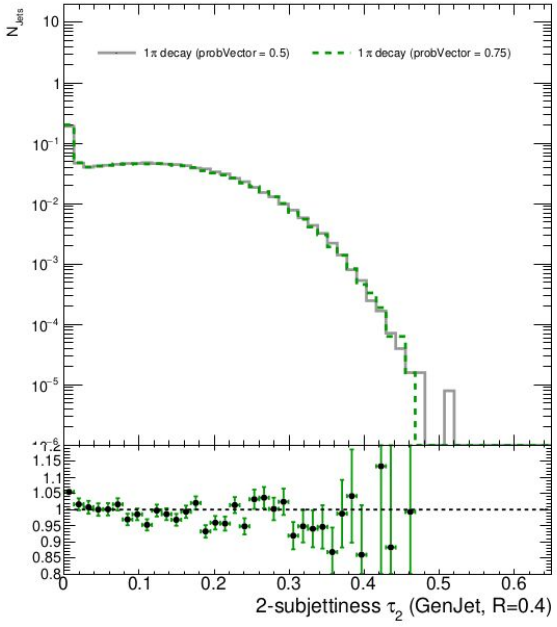
Comparing probVector=0.5 and probVector=0.75 (new Pythia)

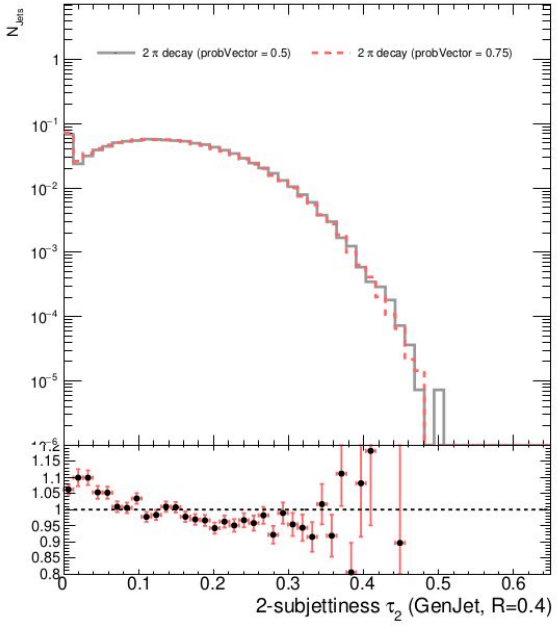


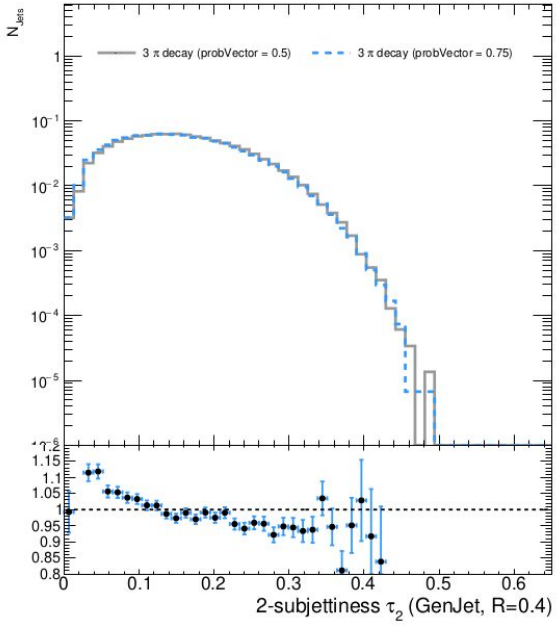




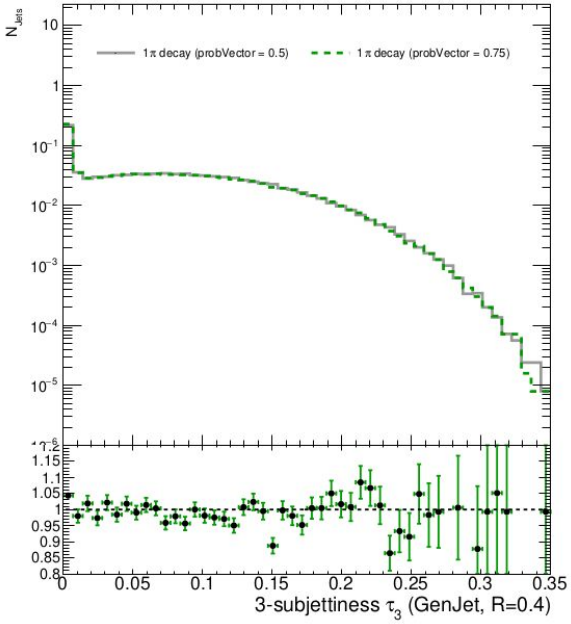
Comparing probVector=0.5 and probVector=0.75 (new Pythia)

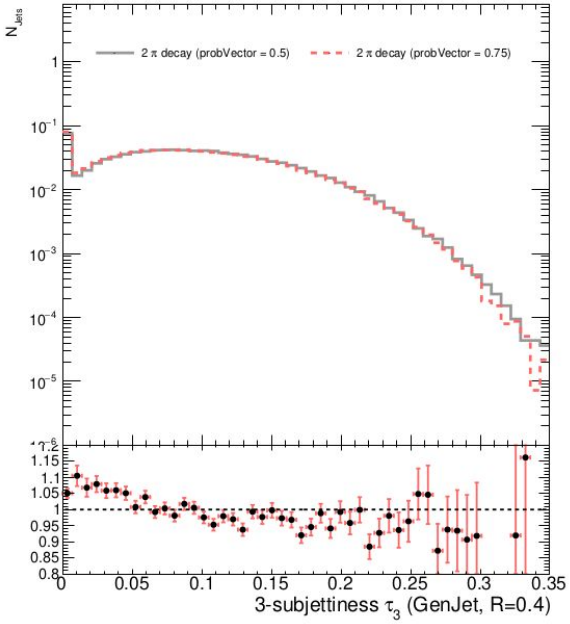


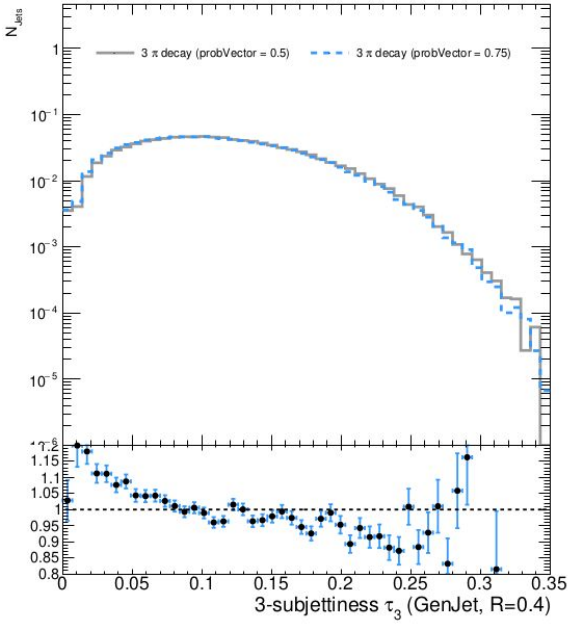




Comparing probVector=0.5 and probVector=0.75 (new Pythia)

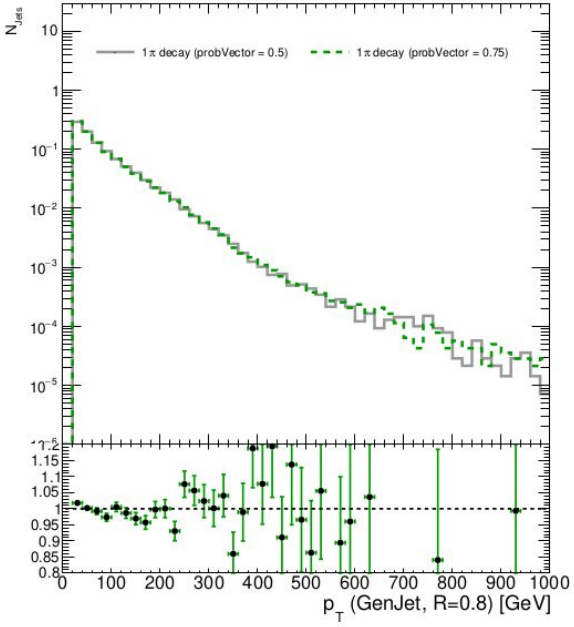


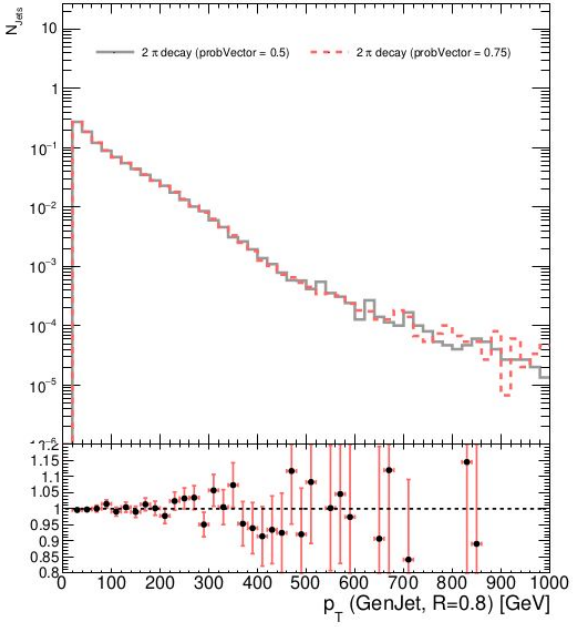


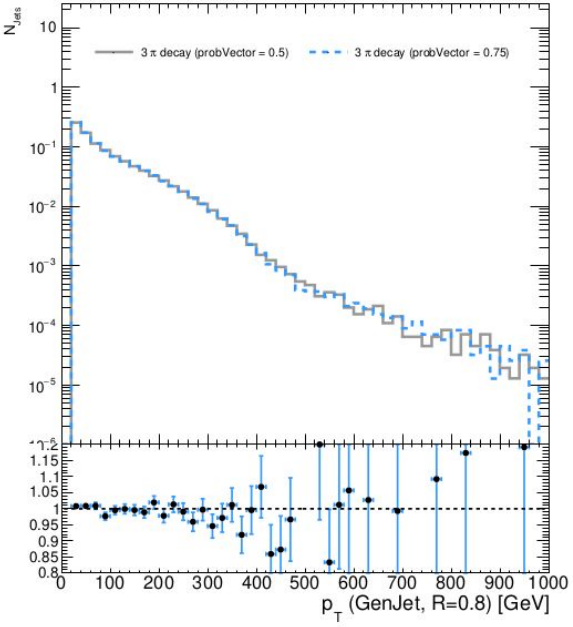


GenJet with R=0.8 study

Comparing old and new Pythia Hidden Valley module

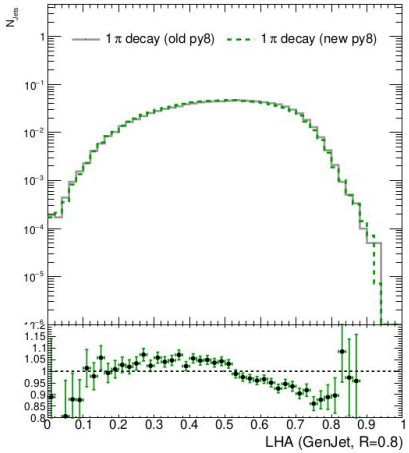


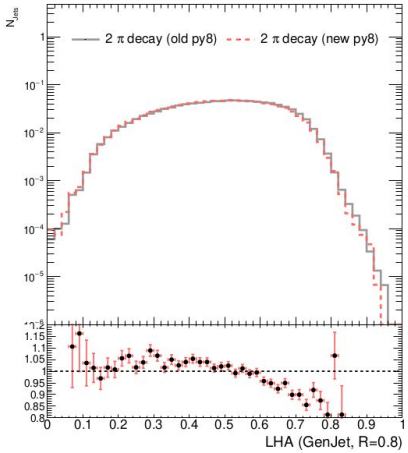


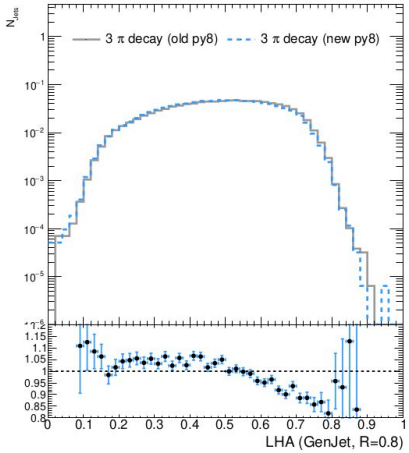


Generalized angularities for AK8 GenJets

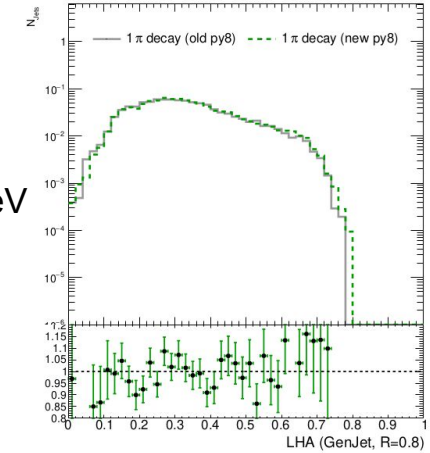
No jet p_T cut

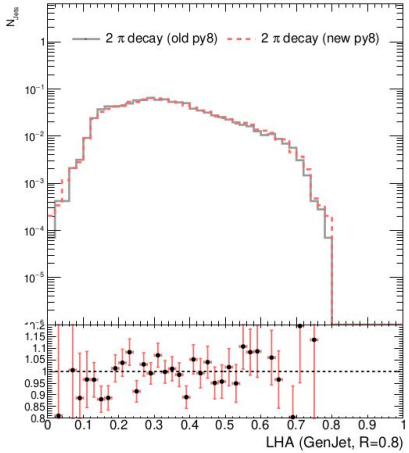


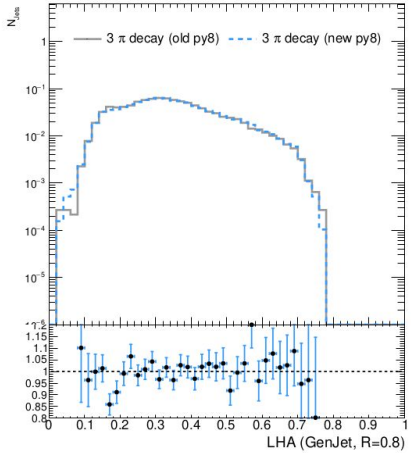




p_T > 200 GeV

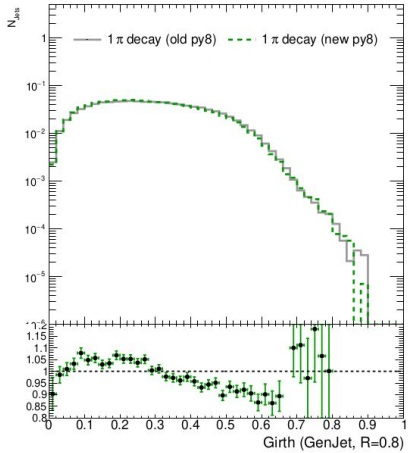


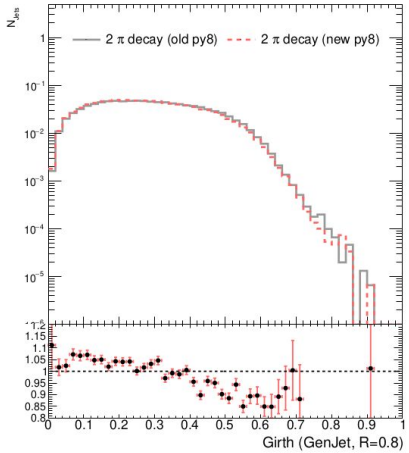


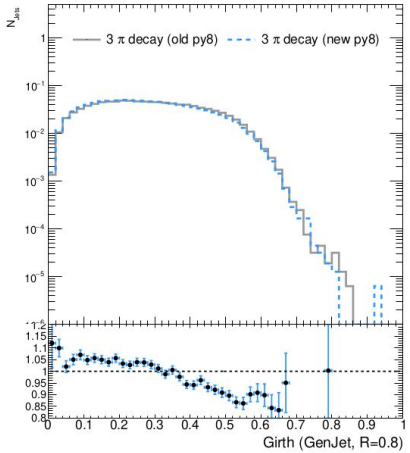


Generalized angularities for AK8 GenJets

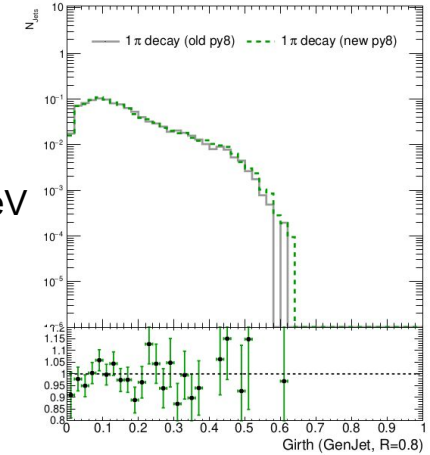
No jet p_T cut

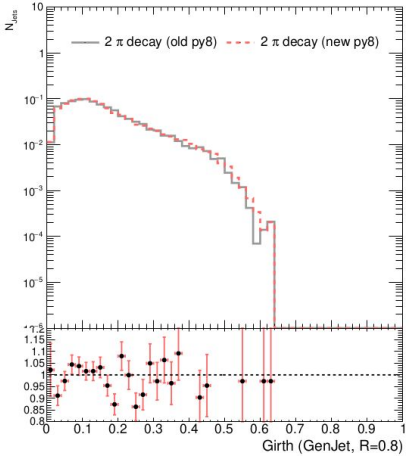


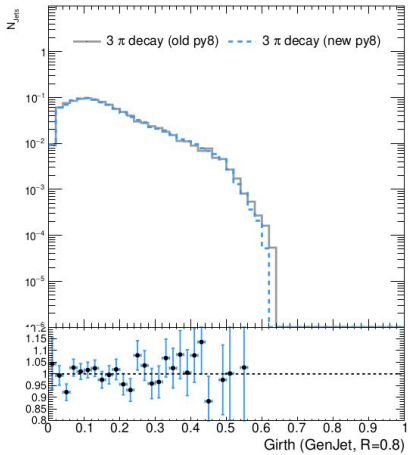




p_T > 200 GeV

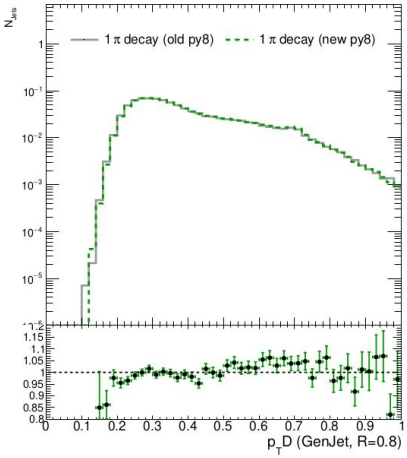


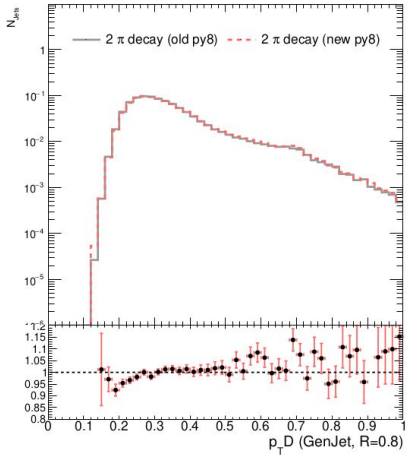


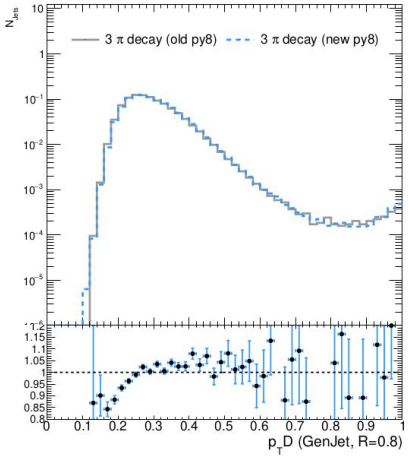


Generalized angularities for AK8 GenJets

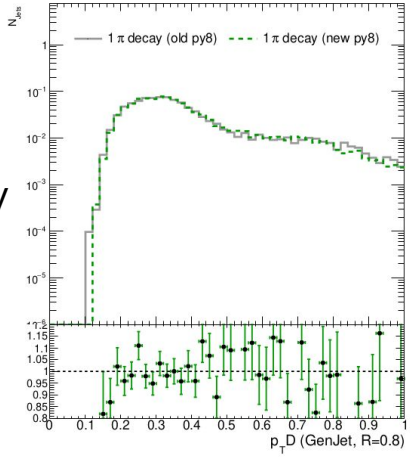
No jet p_T cut

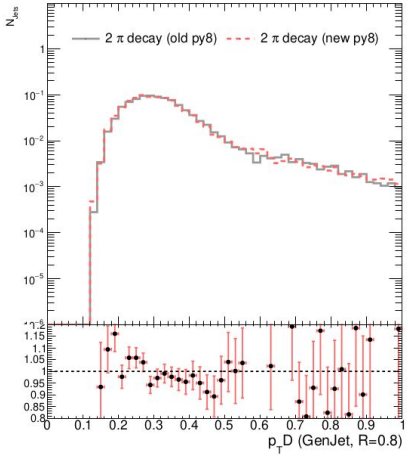


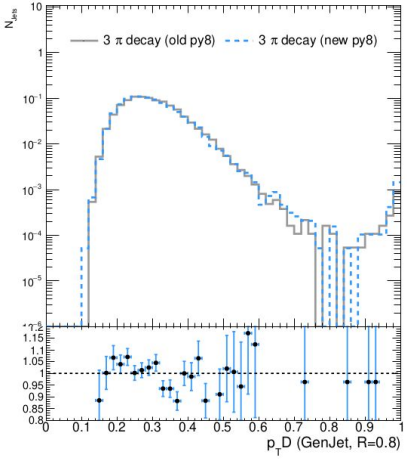




p_T > 200 GeV

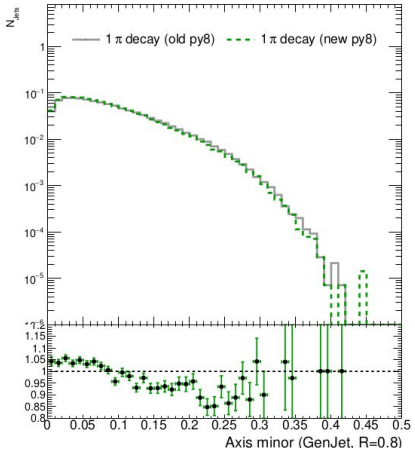


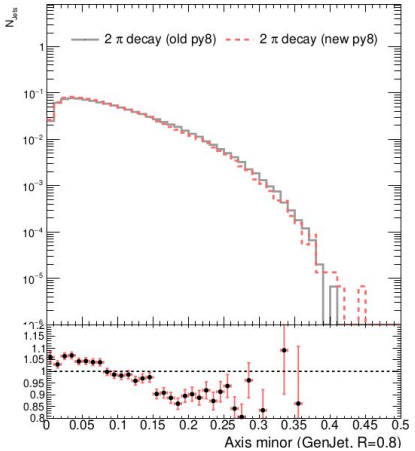


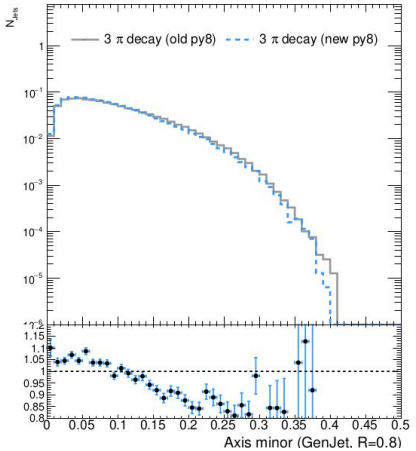


Axis minor for AK8 GenJets

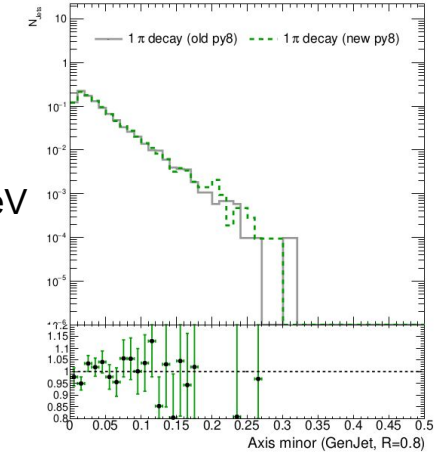
No jet p_T cut

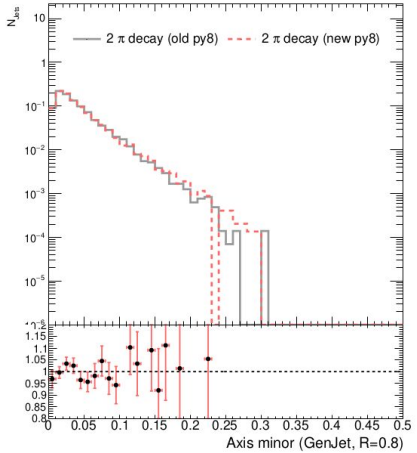


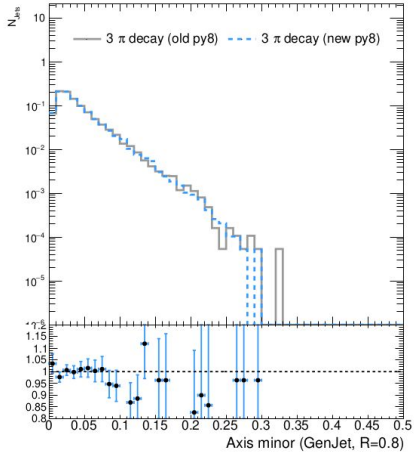




p_T > 200 GeV

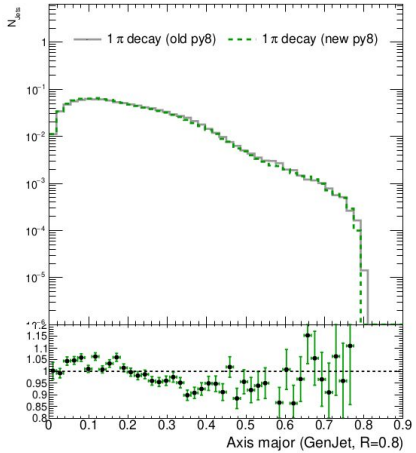


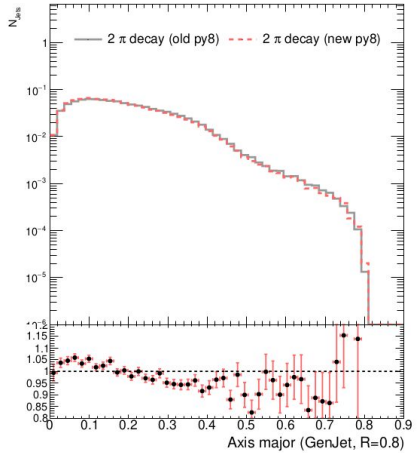


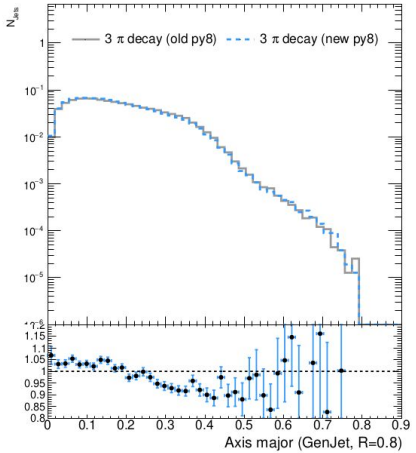


Axis major for AK8 GenJets

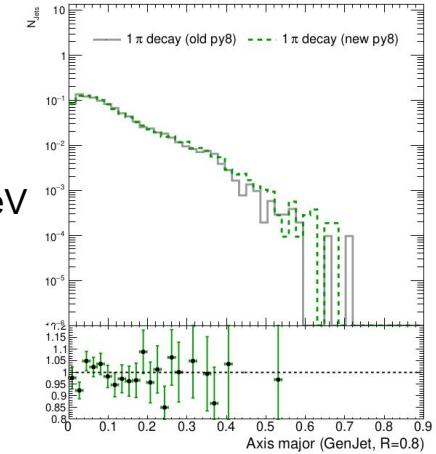
No jet p_T cut

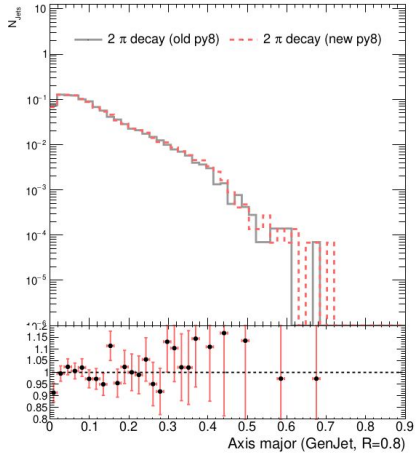


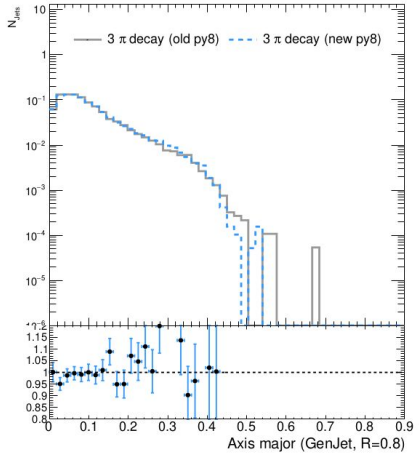




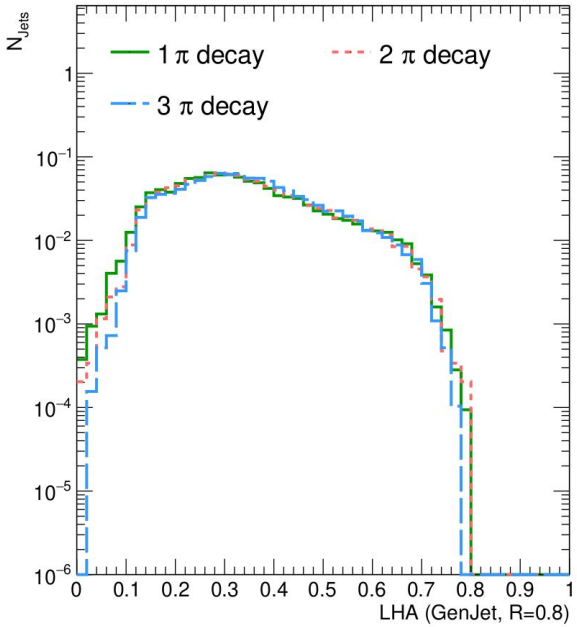
p_T > 200 GeV

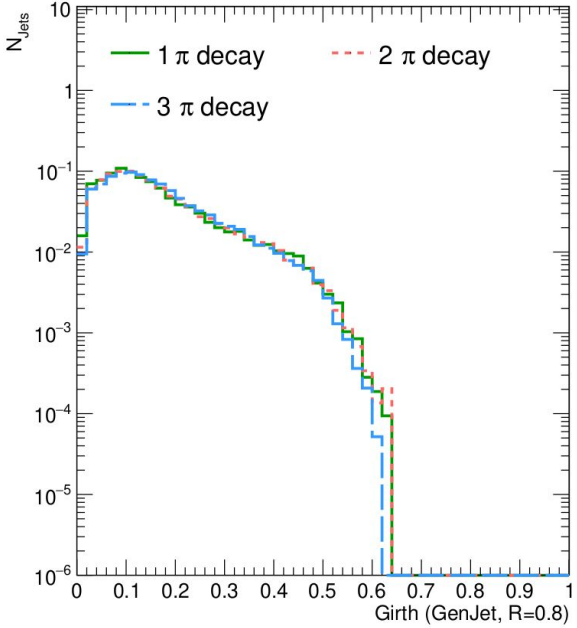


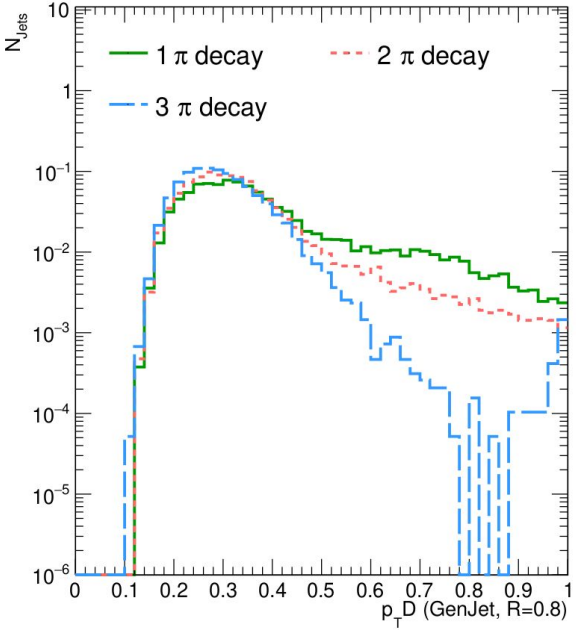




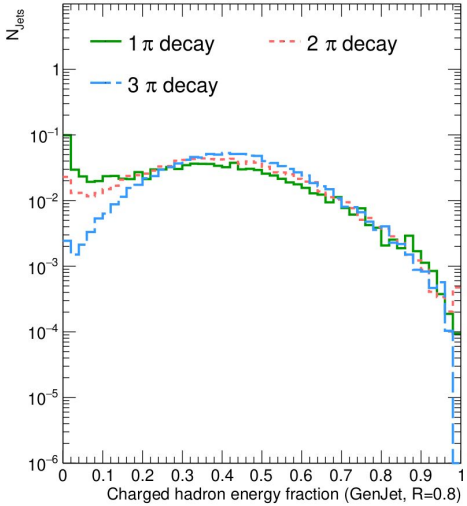
Comparing 1, 2 and 3 dark pions decays

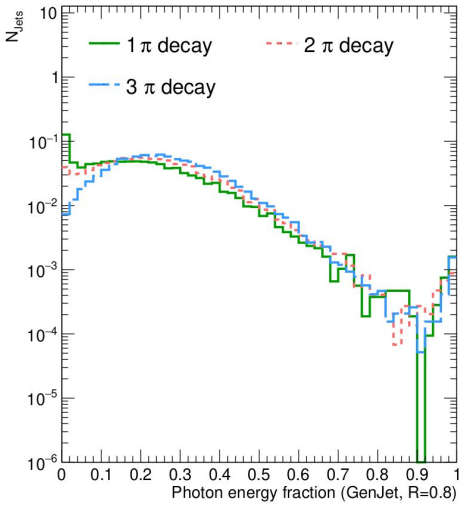


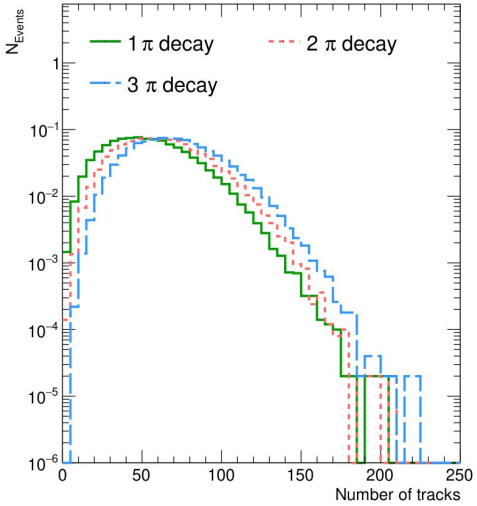


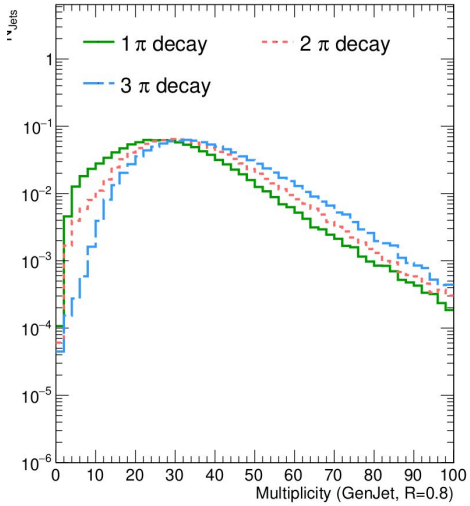


Comparing 1, 2 and 3 dark pions decays

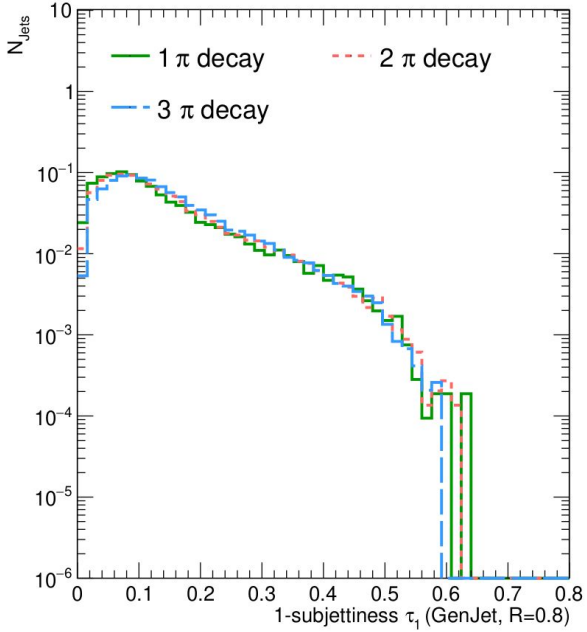


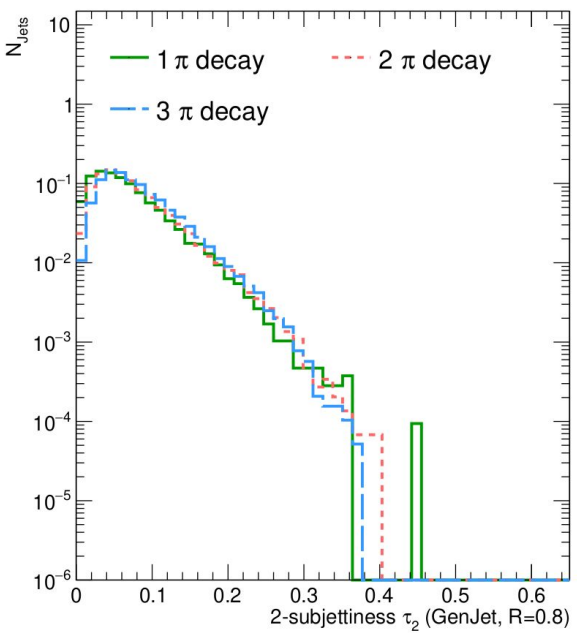


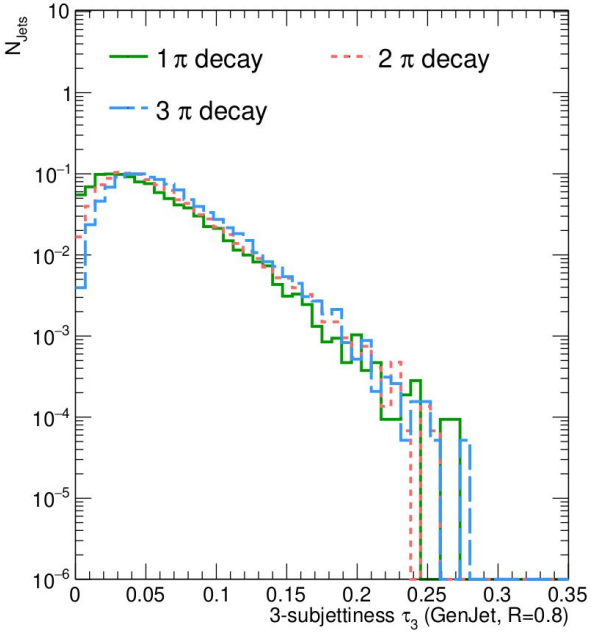




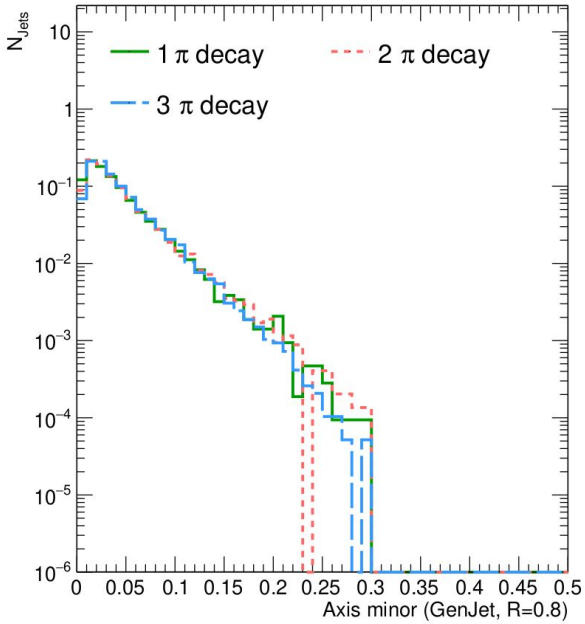
Comparing 1, 2 and 3 dark pions decays

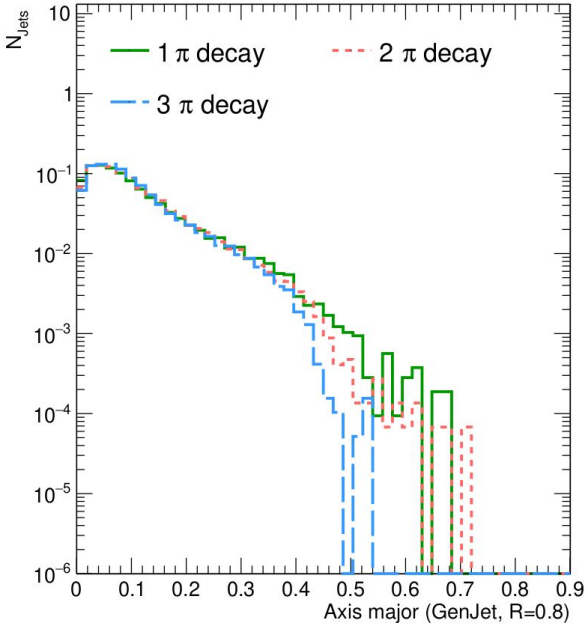




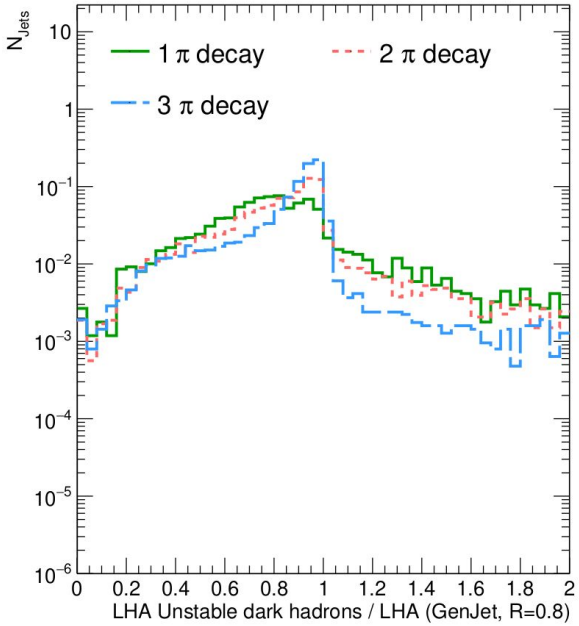


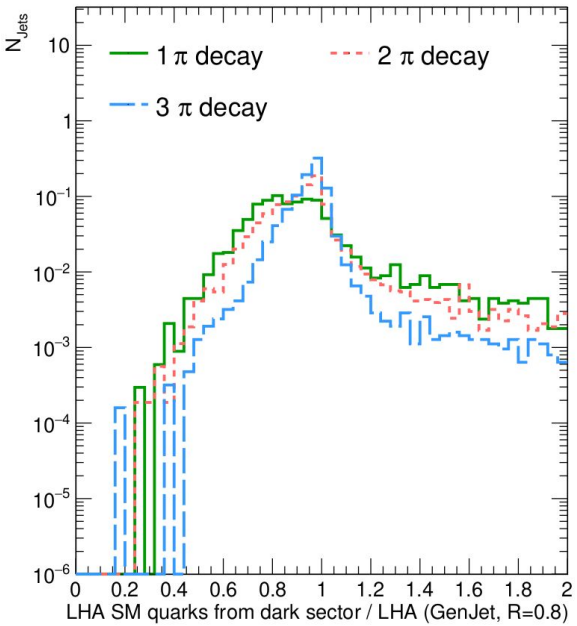
Comparing 1, 2 and 3 dark pions decays

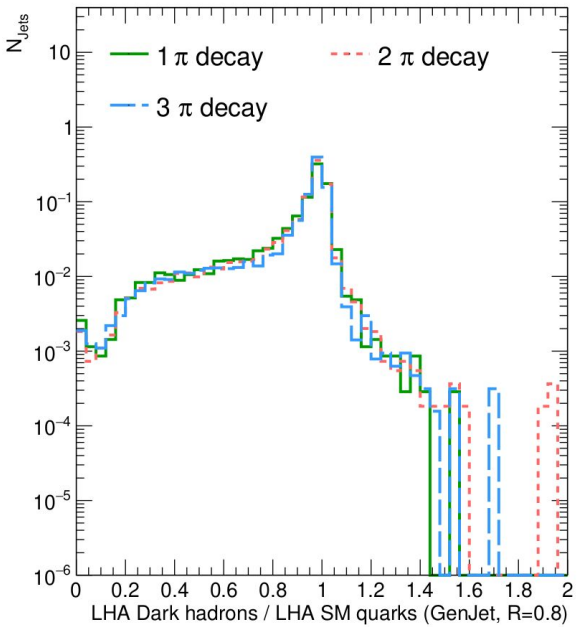




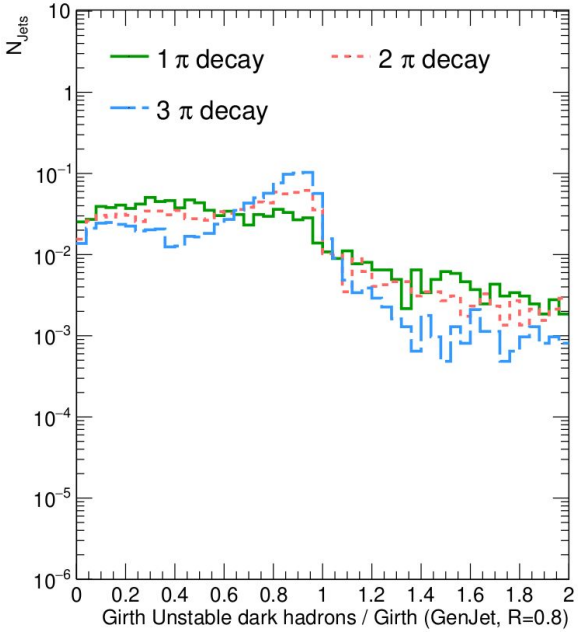
Test of IRC safety - LHA

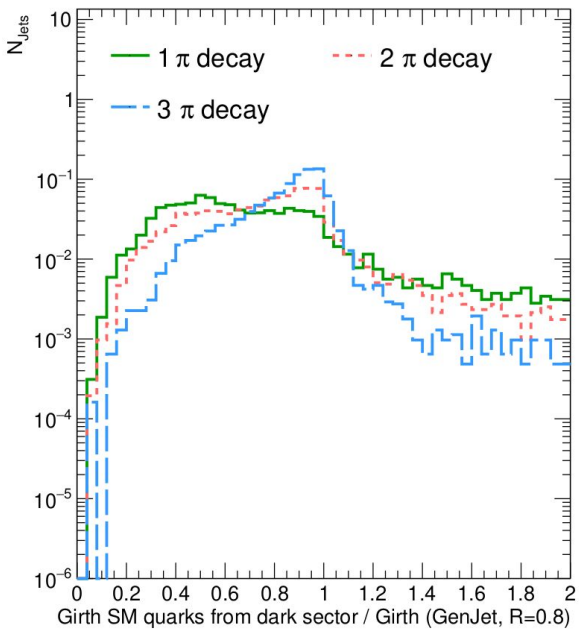


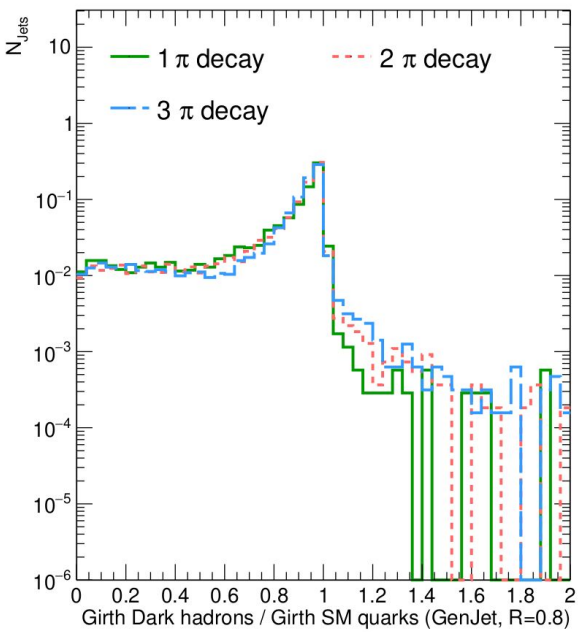




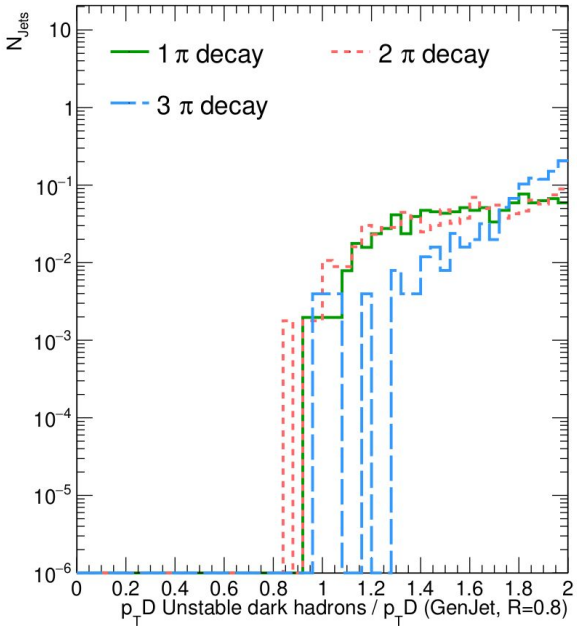
Test of IRC safety - Girth

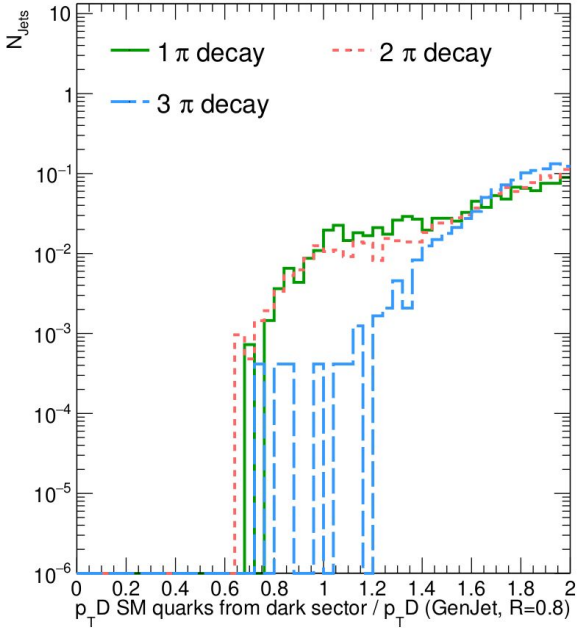


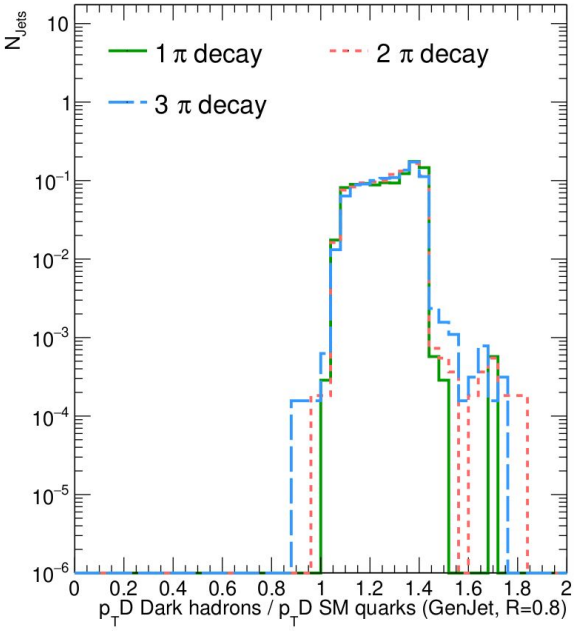




Test of IRC safety - $p_T D$

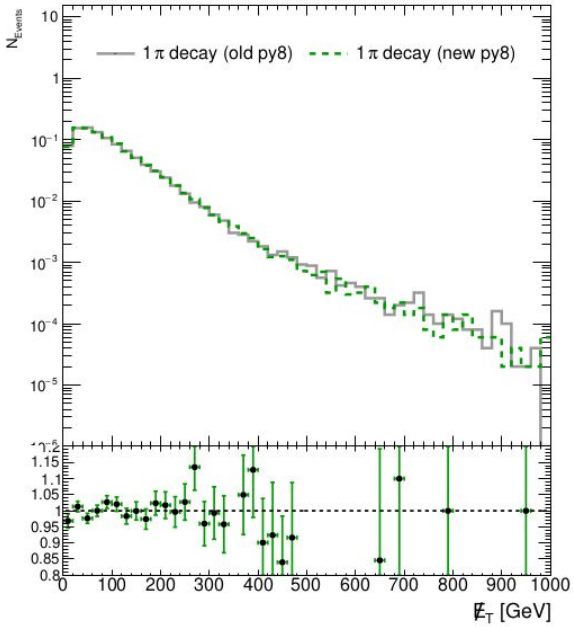


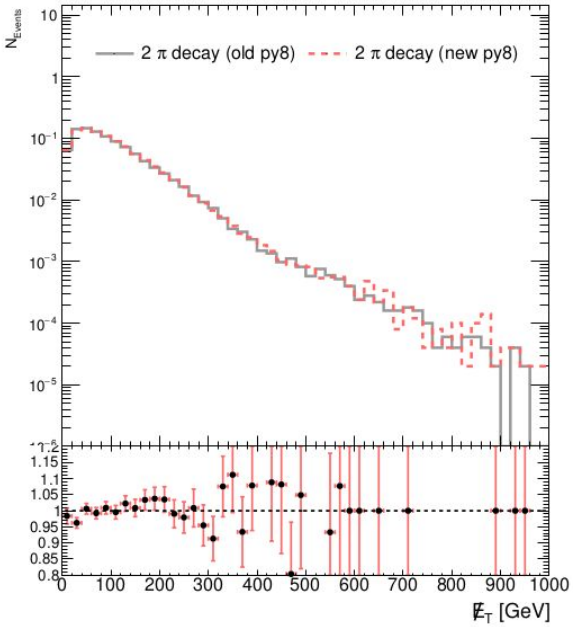


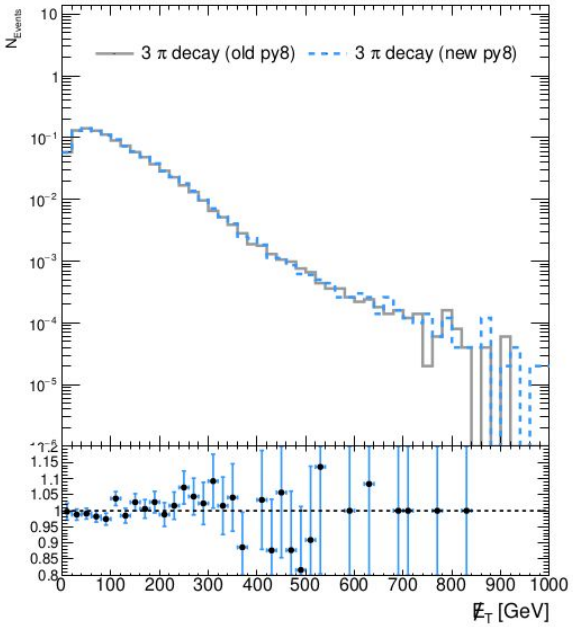


Kinematic variables

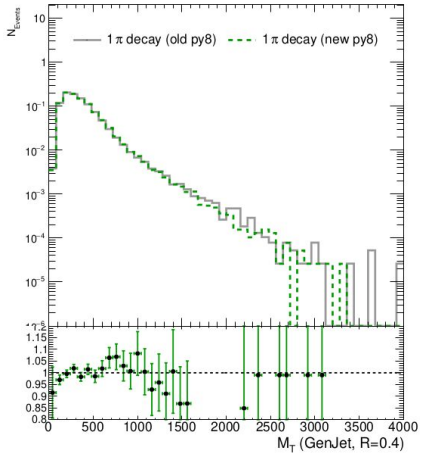
MET

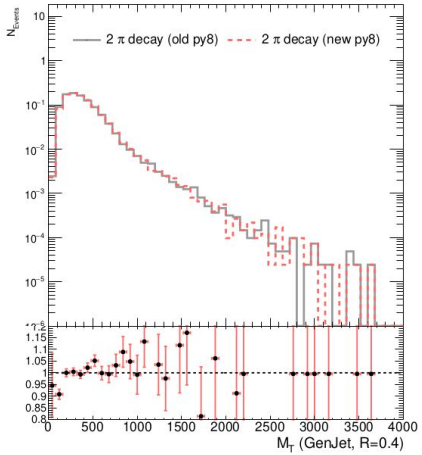

1 π decay (old py8)
1 π decay (new py8)
N_Events
E_T [GeV]

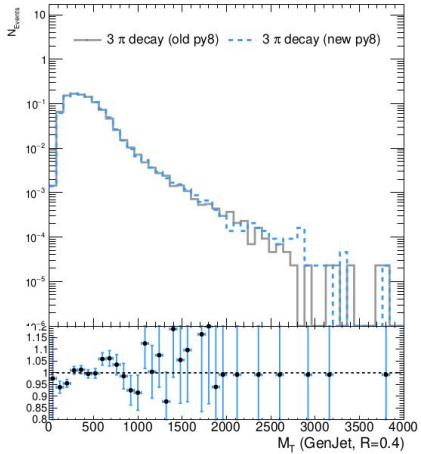

2 π decay (old py8)
2 π decay (new py8)
N_Events
E_T [GeV]

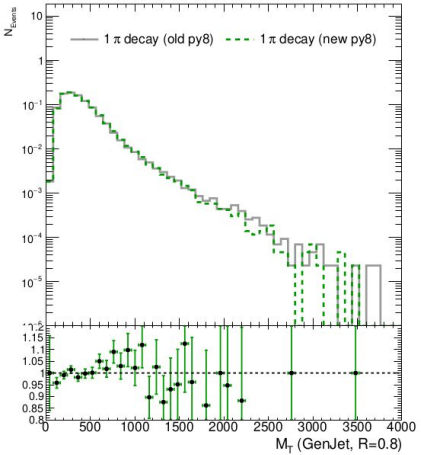

3 π decay (old py8)
3 π decay (new py8)
N_Events
E_T [GeV]

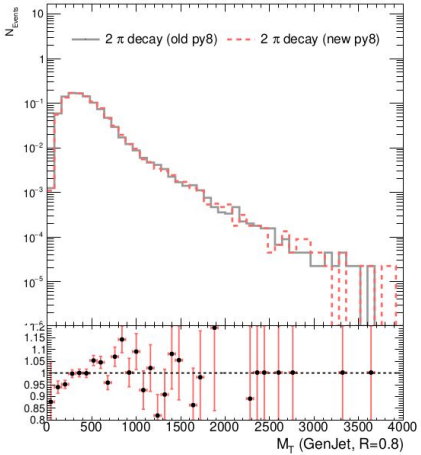
Transverse mass

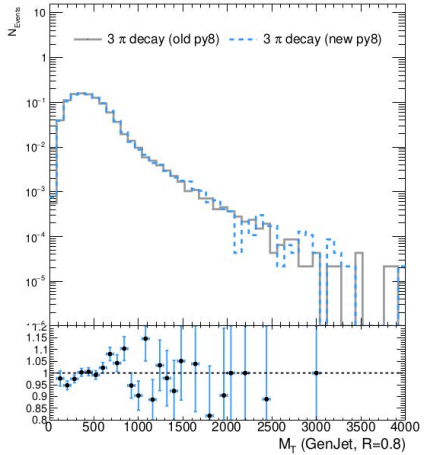












Min azimuthal angle between jets and MET