University of Massachusetts Amherst

LOOP INDUCED $\mathrm{ggZZ} \to 4\ell$ WITH UP TO 2 JETS USING MADGRAPH AND PYTHIA

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INTRODUCTION

- The production of 2j final state using ME calculations is very challenging for several reasons:
  - The LO process is a *loop induced* one.
  - It has a large number of Feynman diagrams, all of them with a loop.
  - Separation between qqZZ and ggZZ at higher multiplicities needs to be done correctly and carefully.

- This presentation aims to outline a practical method to generate $gg \rightarrow (H*) \rightarrow ZZ + 0,1,2j$ using MadGraph.
- A detailed study is then presented, for the matching of the three samples with showers, using Pythia.
- Most of the study focuses on SBI processes, but we will also show some preliminary results for Background only generation.

OUTLINE OF THE STRATEGY

- We can produce 0+1j sample in the standard way and using a strategy similar to the available Sherpa sample, including with the full gg, gq and qq initial state spectrum in the 1 jet process.
- The 2 jet events can only be generated with the help of MadSpin to decay the Z boson final states, and thus are produced without spin correlations, at least for the SBI and B type processes.
- We can then use the independently generated 0+1 and 2 jet final state samples and run Pythia matching to form an inclusive sample.
- This way we preserve the spin correlations and full off-shell Z boson effects for the 0,1 jet sample unlike for the 2 jet sample.

- In the next few slides, I elaborate on the details of generating each of these samples.

ZZ + 0 jet Production

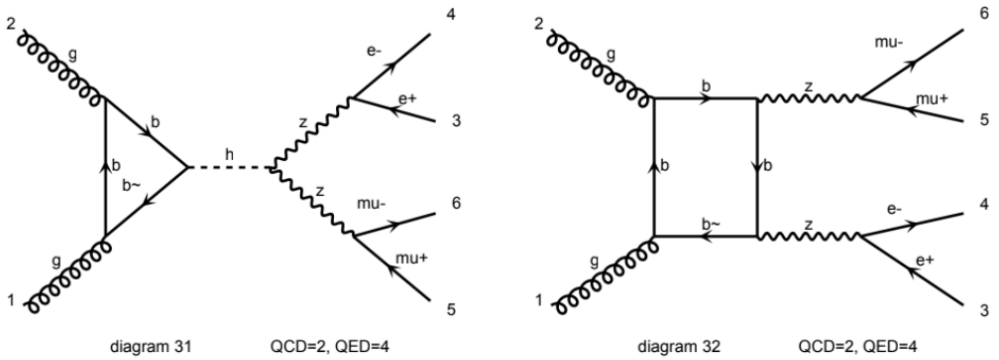
MadGraph Syntax

↓

generate p p > l+ l- l+ l- [noborn=QCD]

→ Works well!
Same as g g > l+ l- l+ l- [noborn=QCD]

To generate the Background-only processes, we simply add $/h$ at the end of the above command to remove the Higgs mediated diagrams



ZZ + 1 jet Production

generate p p > l+ l- l+ l- j [noborn=QCD]

Contains two type of diagrams:

- NNLO real corrections to qqZZ
- NLO real corrections to SBI ggZZ

Need to weed out the qqZZ diagrams and keep only the corrections to the ggZZ process.

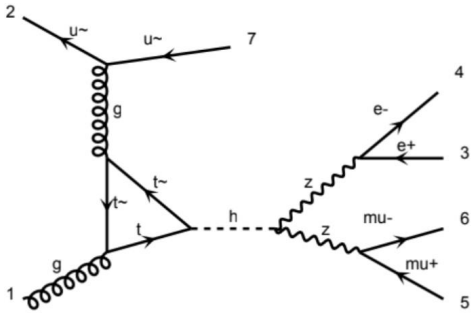


diagram 73 QCD=3, QED=4

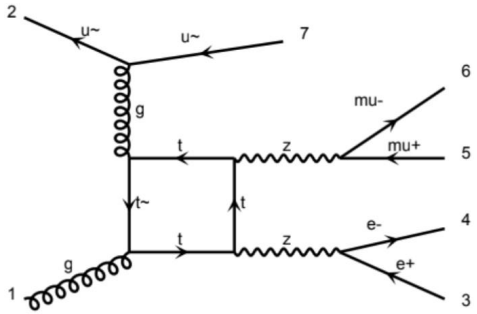


diagram 74 QCD=3, QED=4

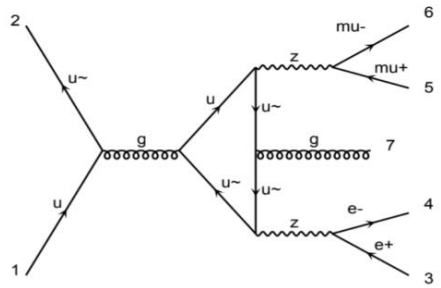


diagram 29 QCD=3, QED=4

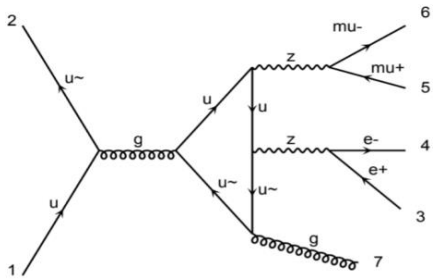


diagram 30 QCD=3, QED=4

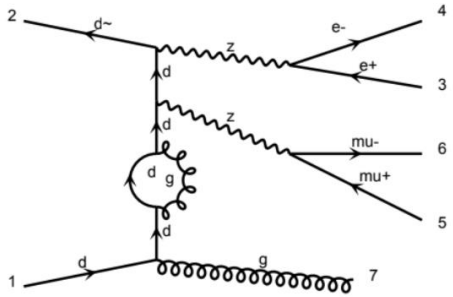


diagram 101 QCD=3, QED=4

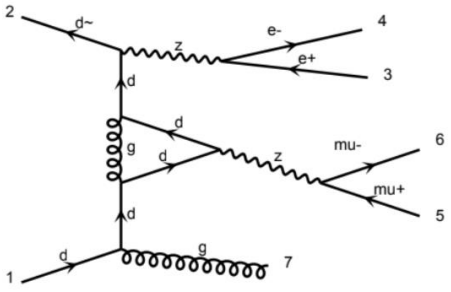


diagram 102 QCD=3, QED=4

ZZ + 2 jet Production

generate p p > l+ l- l+ l- j j [noborn=QCD]

Not feasible with current computing power. Not possible to generate directly using MadGraph.

Can be generated with Z boson final state, instead of the 4 lepton final state, and then using MadSpin to decay the Z bosons to lepton pairs.

generate p p > z z j j [noborn=QCD]

decay z > l+ l-

When using MadSpin:

- Spin correlations can be restored for signal (S) gg-H-ZZ+2j events, but not for SBI and B.
- Z/γ^* off-shell effects not present. Sample is limited to $m_{4\ell} > 180$ GeV.

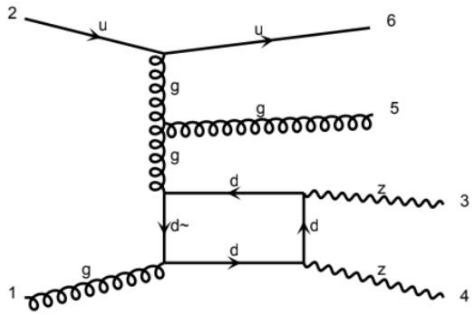
ZZ + 2 jet Production

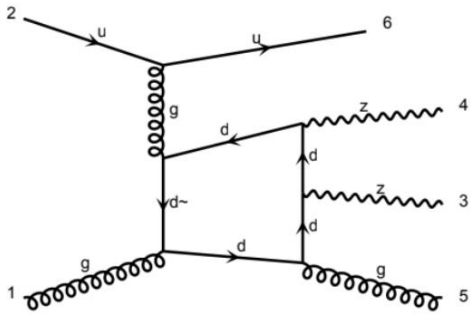
generate p p > z z j j QED=2 [noborn=QCD]

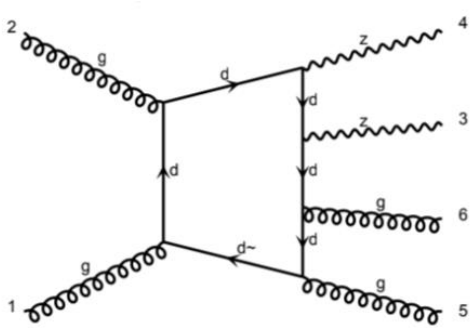
Again, 2-jet events will include:

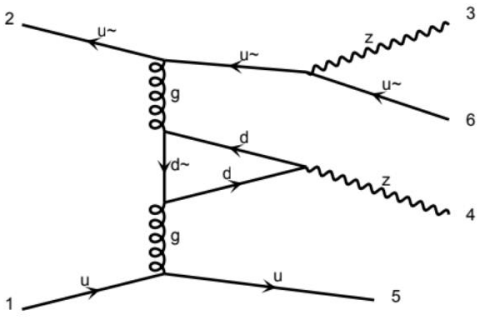
- NNNLO real corrections to qqZZ
- NNLO real corrections to SBI ggZZ

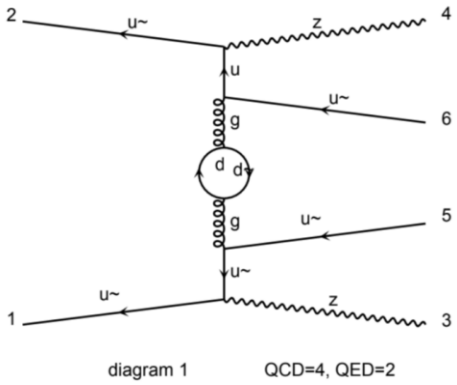
We need to keep only the second.

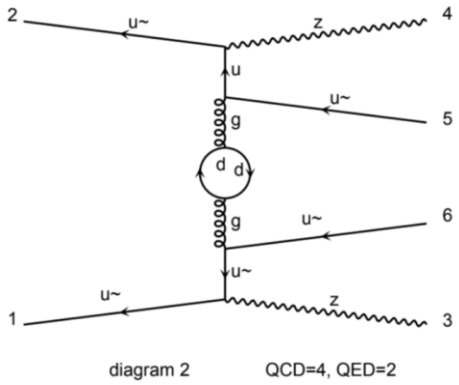






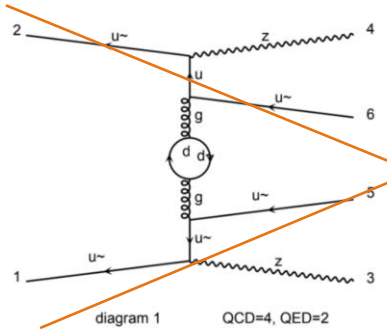


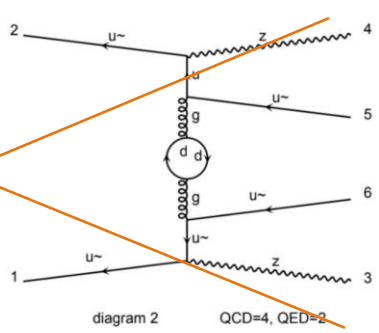


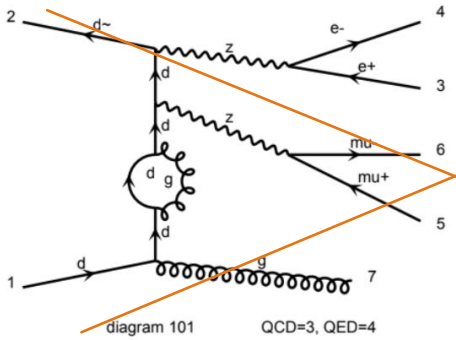


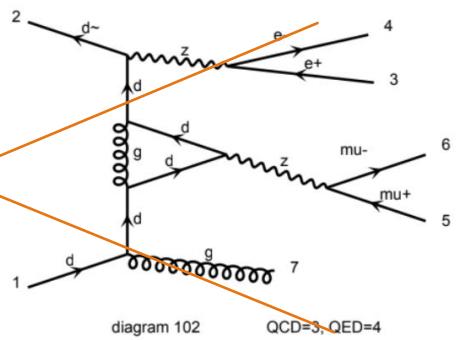
LOOP DIAGRAM FILTER

- Types of diagrams to be filtered out:









- We are using a standard MadGraph tool that allows us to create loop diagram filters.
- Remove diagrams if:
  - Gluons are present in the loop
  - There is no Z boson, photon, or Higgs boson connected to the loop

LOOP DIAGRAM FILTER

- These conditions will also ensure that all the relevant diagrams like the following are included:

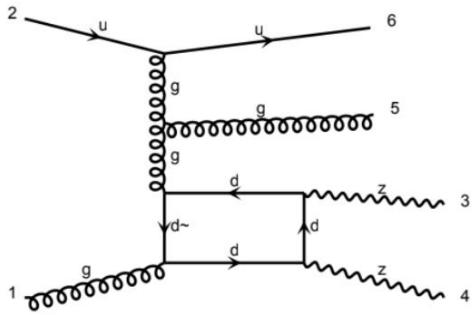


diagram 118 QCD=4, QED=2

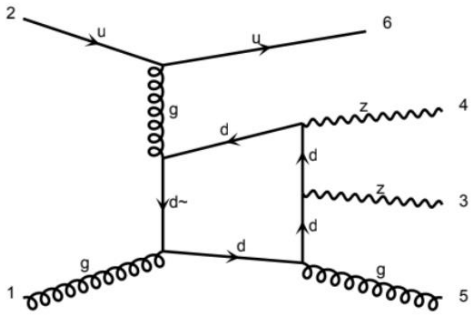


diagram 119 QCD=4, QED=2

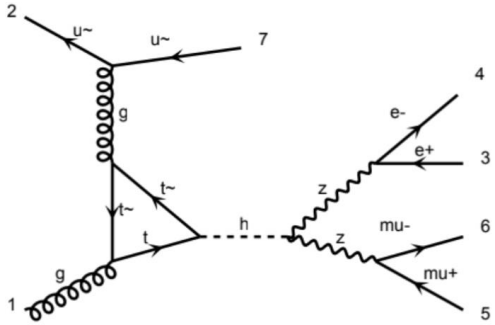


diagram 73 QCD=3, QED=4

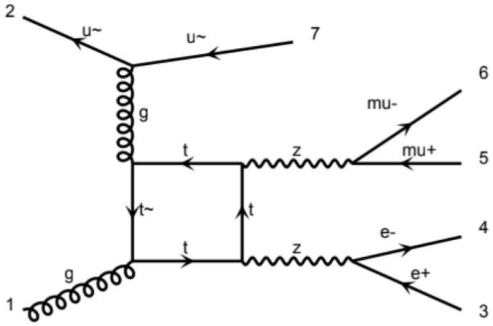


diagram 74 QCD=3, QED=4

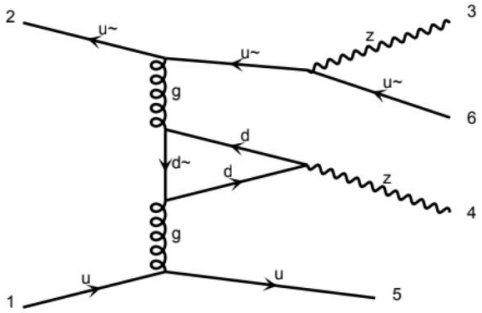


diagram 61 QCD=4, QED=2

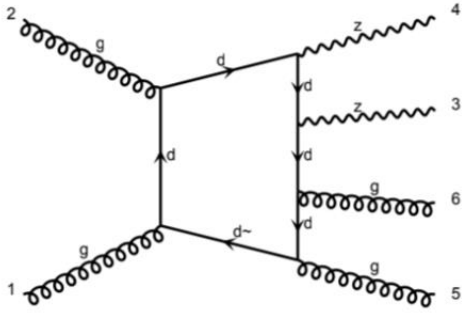


diagram 202 QCD=4, QED=2

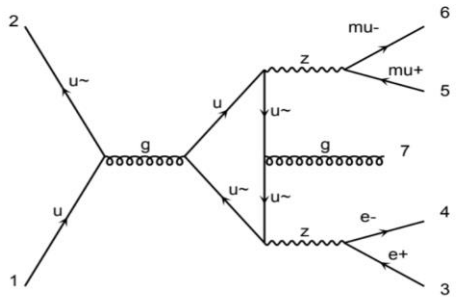


diagram 29 QCD=3, QED=4

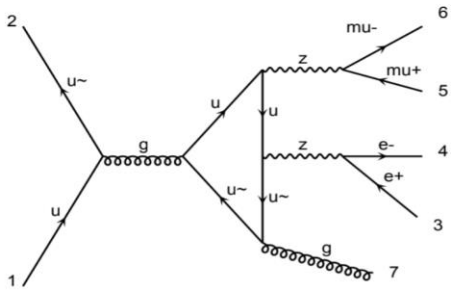


diagram 30 QCD=3, QED=4

QED RESTRICTION

- The QED <= 2 restriction further restricts unnecessary diagrams like the ones below, which could potentially lead to double counting with ZZZ processes,
- This could as well cause complications in merging because of the presence of non-QCD jets.
- The contribution due to these diagrams is likely small anyway, but is yet to be tested by me.

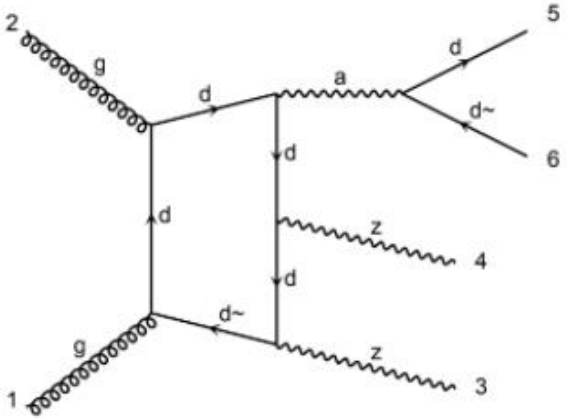


diagram 25 QCD=2, QED=4

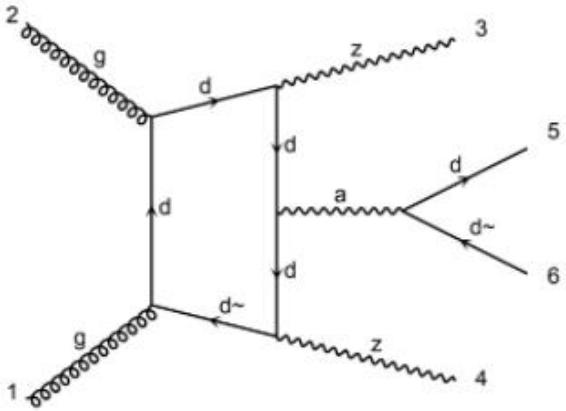


diagram 26 QCD=2, QED=4

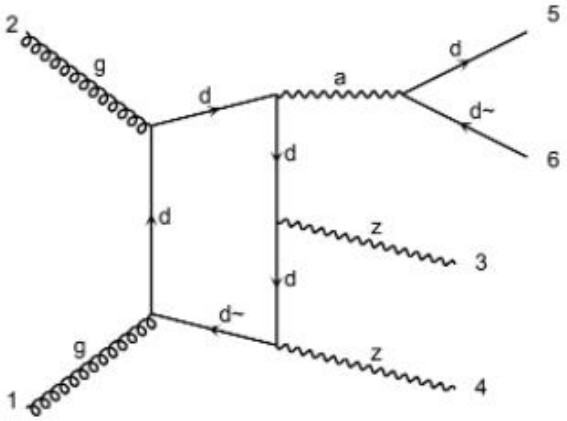


diagram 27 QCD=2, QED=4

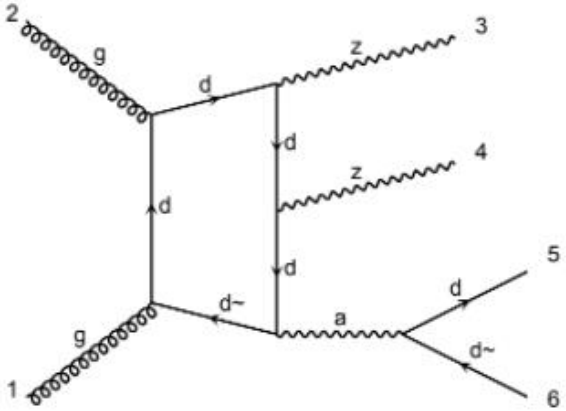


diagram 28 QCD=2, QED=4

MERGING

- It turns out that performing CKKW-L merging on loop induced process produces incorrect and non-physical results.
- As such, we followed the lead of other papers and used MLM merging instead.
- ggZZ with 0+1+2 jets at ME and using MLM matching successfully generated!

DJR CHECK STRATEGY

- We study the DJR($0 \rightarrow 1$) distribution using the 0+1 jet sample with different matching scales.
- A good matching scale should give a smooth DJR distribution
- qCut (shower scale) is scanned to find an accurate matching scheme.
- These checks are done in the space with $m4l > 220\ GeV$ cut, and using the default 4F scheme.

- Then we validate the qCut choice by looking at the DJR($1 \rightarrow 2$) distribution using the 0+1+2 jet sample.
- The same qCut should yield a smooth distribution.

- **Note**: The following plots have been generated using "generate <..> /a" for quick computation. In the $m4l > 220\ GeV$ space, the photon contribution is anyway negligible.

DJR(0 → 1) PLOTS

- We do a DJR check for the following configuration:

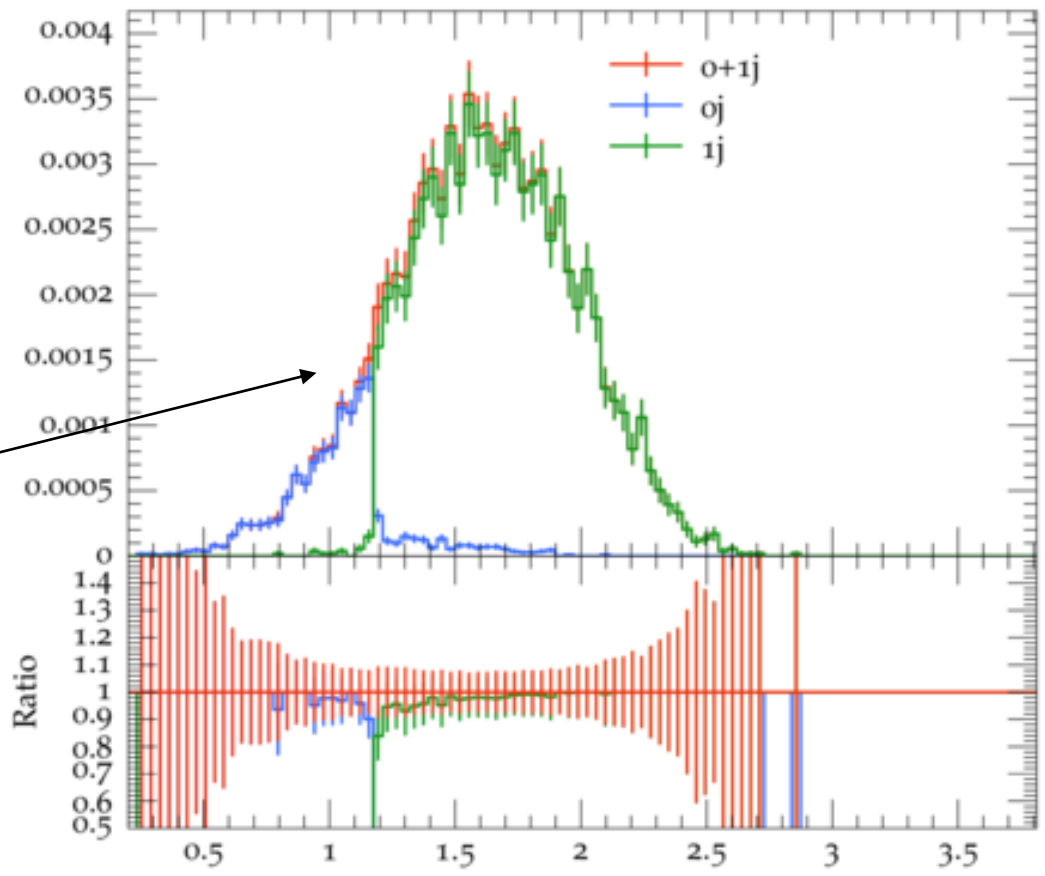
  xqcut = 5.0 GeV

  qCut = 15.0 GeV

- **Very smooth transition!**
- Matching efficiency:

  14% for 0 jet

  20% for 1 jet



DJR(0 → 1) PLOTS

- We do a DJR check for the following configuration:

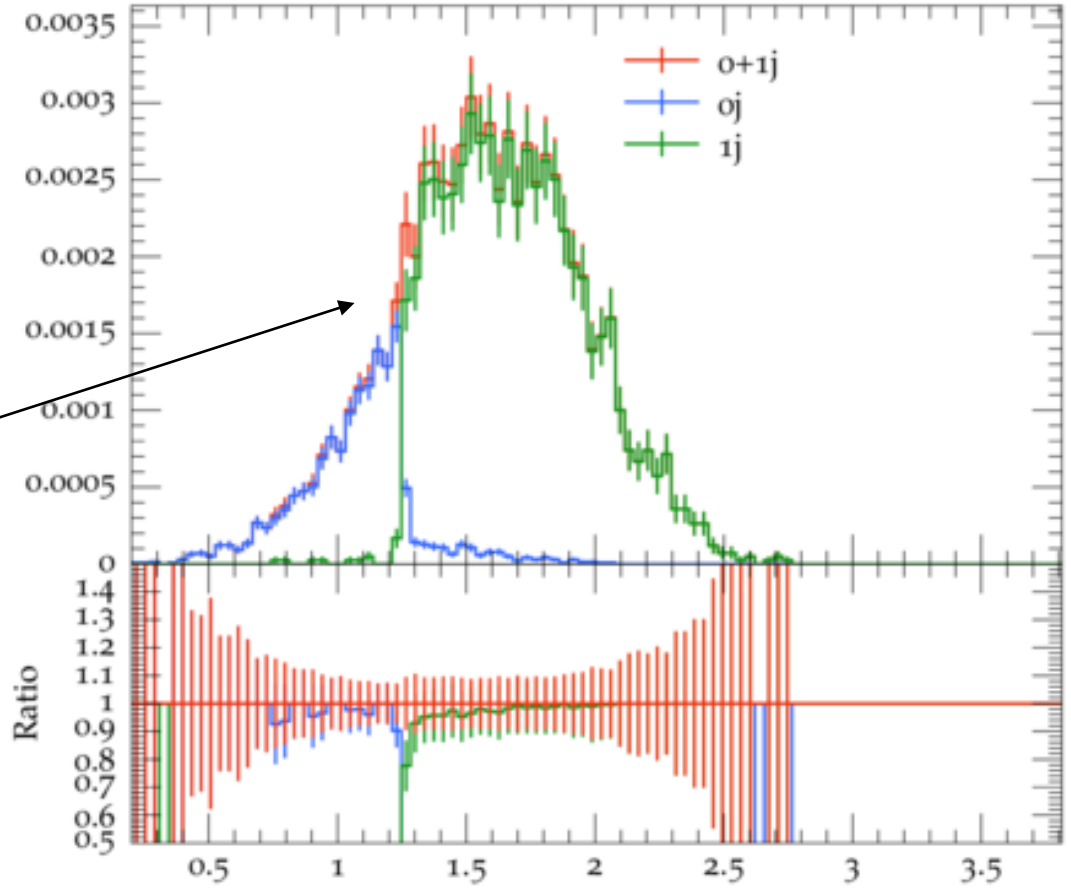
  xqcut = 8.0 GeV

  qCut = 18.0 GeV

- **Smooth transition!**
- Matching efficiency:

  18% for 0 jet

  24% for 1 jet



DJR(0 → 1)

DJR(0 → 1) PLOTS

- We do a DJR check for the following configuration:

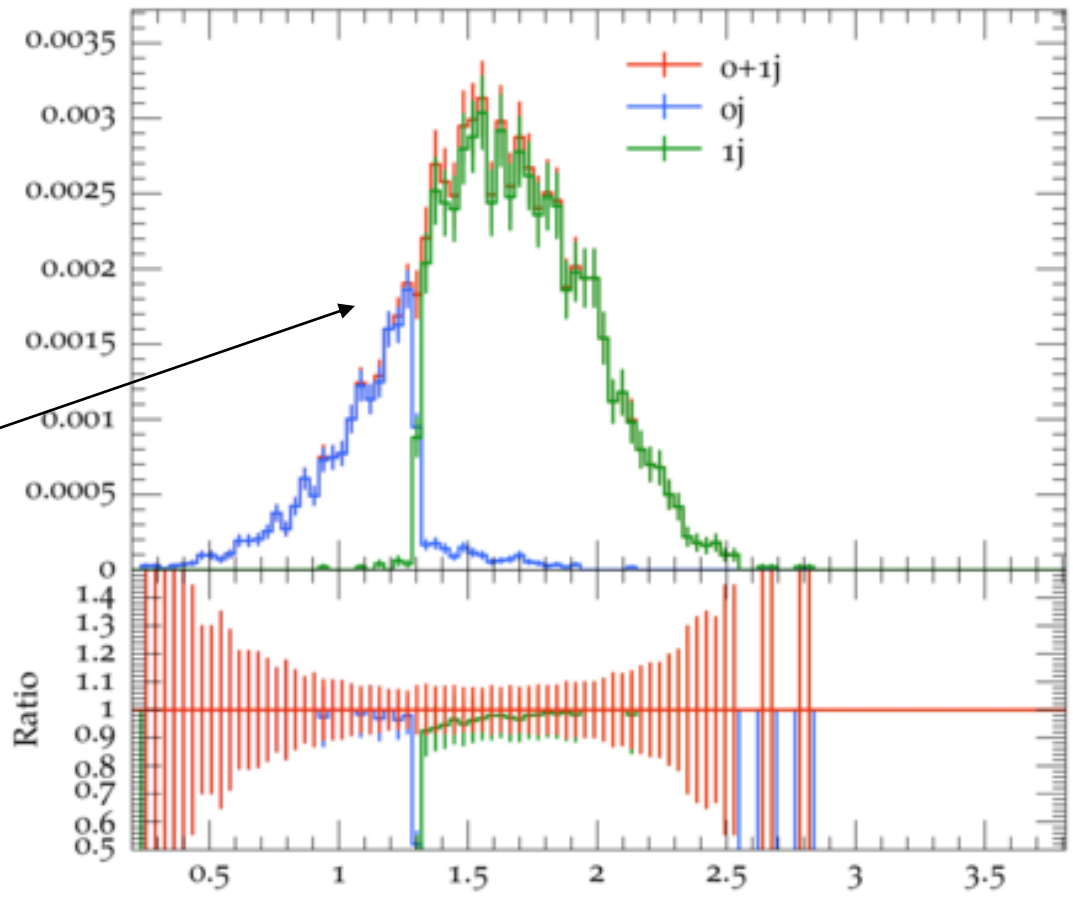
  xqcut = 10.0 GeV

  qCut = 20.0 GeV

- **Very smooth transition!**
- Matching efficiency:

  20% for 0 jet

  26% for 1 jet



DJR(0 → 1) PLOTS

- We do a DJR check for the following configuration:

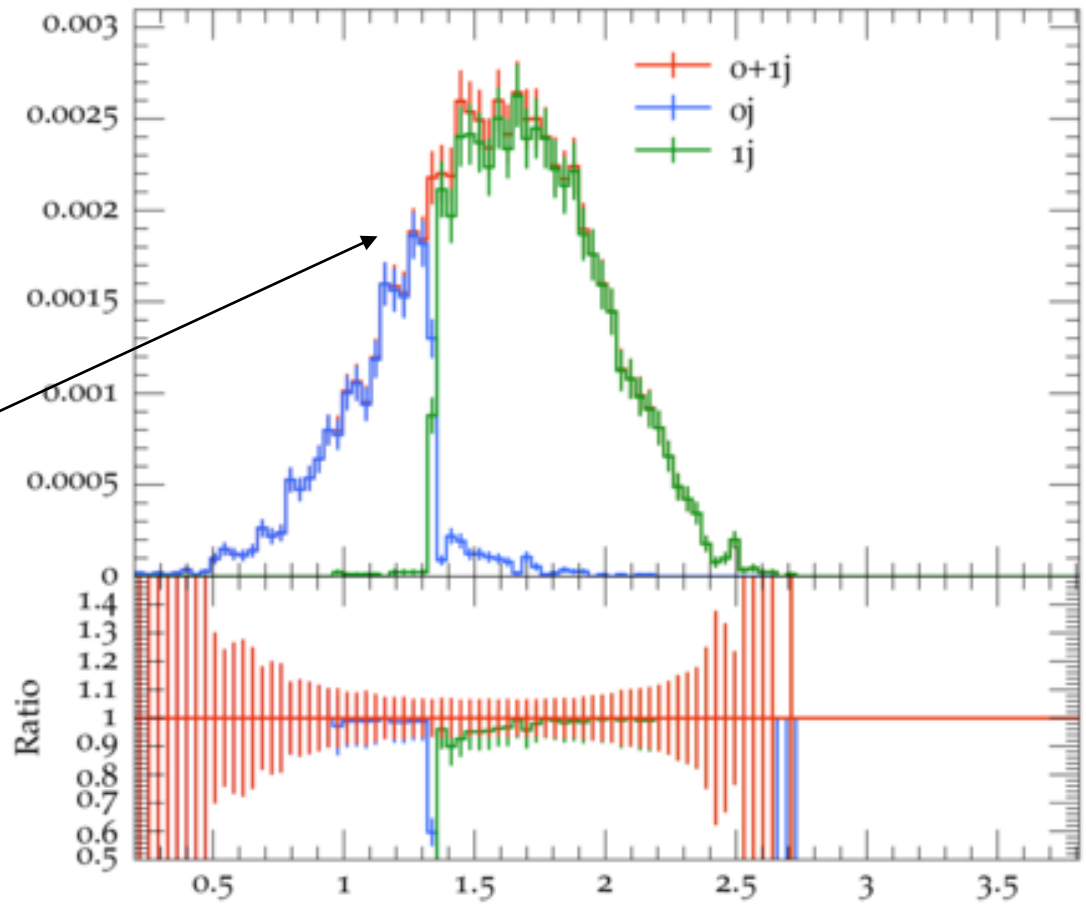
  xqcut = 12.0 GeV

  qCut = 22.0 GeV

- **Smooth transition!**
- Matching efficiency:

  23% for 0 jet

  30% for 1 jet



DJR(0 → 1)

DJR $(0 \rightarrow 1)$ TEST CONCLUSIONS

- Based on the plots, we can safely estimate the validity range for the matching to be between 15 GeV and 22 GeV qCut values.

- Within this ranges, the cross-section agreement between the 0 jet showered and the matched cross sections was within 20% (with 15 qCut giving the best match ~0.7%)

- For a good qCut, we must also obtain smooth transitions for DJR$(1 \rightarrow 2)$. We decide to probe these two qCut values - 15 GeV and 20 GeV which give the best results in $(0 \rightarrow 1)$ region and are sort of boundaries of the validity range- for the full 0,1,2 jet matching production.

DJR(1 → 2) PLOTS

- We check the DJR plot for:

  xqcut = 5.0 GeV

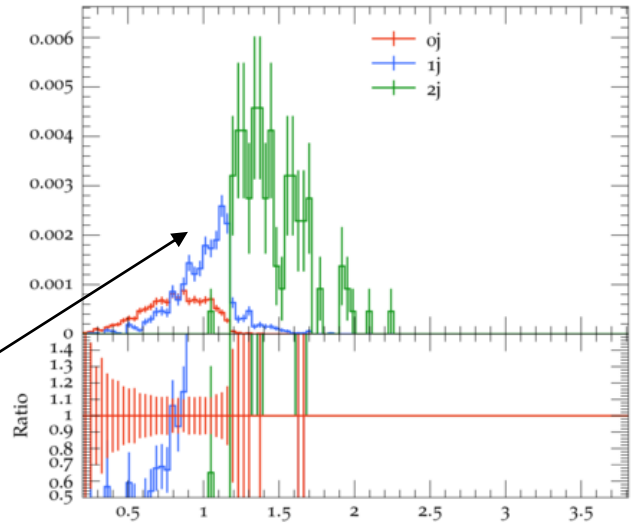
  qCut = 15.0 GeV

- Limited statistics due to low matching efficiency
- **But smooth transition and smooth looking 0+1+2j plot.**
- Matching efficiency:

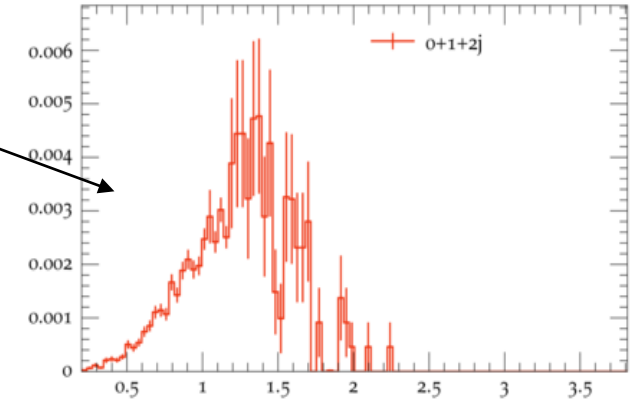
  14% for 0 jet

  6% for 1 jet

  5% for 2 jet



DJR(1→ 2)



DJR(1→ 2)

DJR(1 → 2) PLOTS

- We check the DJR plot for:

  xqcut = *10.0 GeV*

  qCut = *20.0 GeV*

- **Simulation is still running.**

DJR(0 → 1) PLOTS

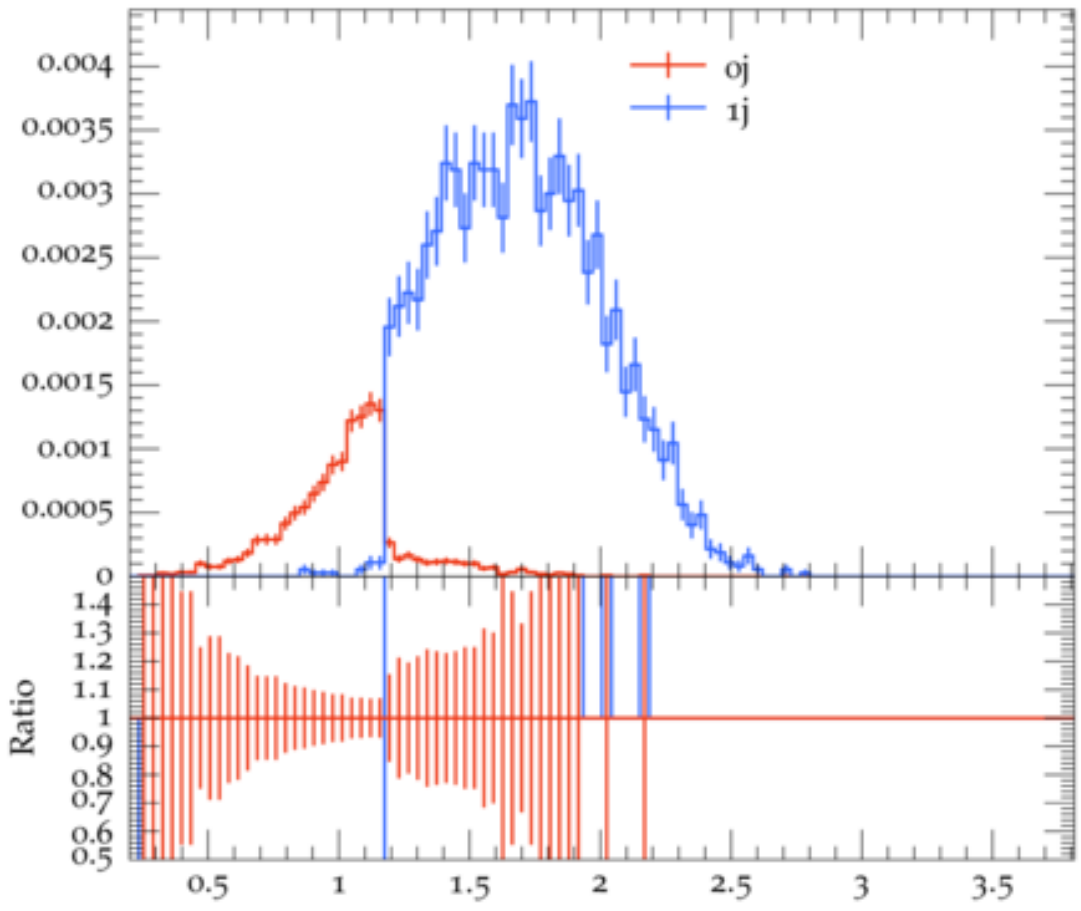
- We also tried to do a DJR check for the *Background only* processes using following configuration:

  xqcut = 5.0 GeV

  qCut = 15.0 GeV

- **Unphysical transition**

Background only



DJR(0 → 1)

DJR(0 → 1) PLOTS

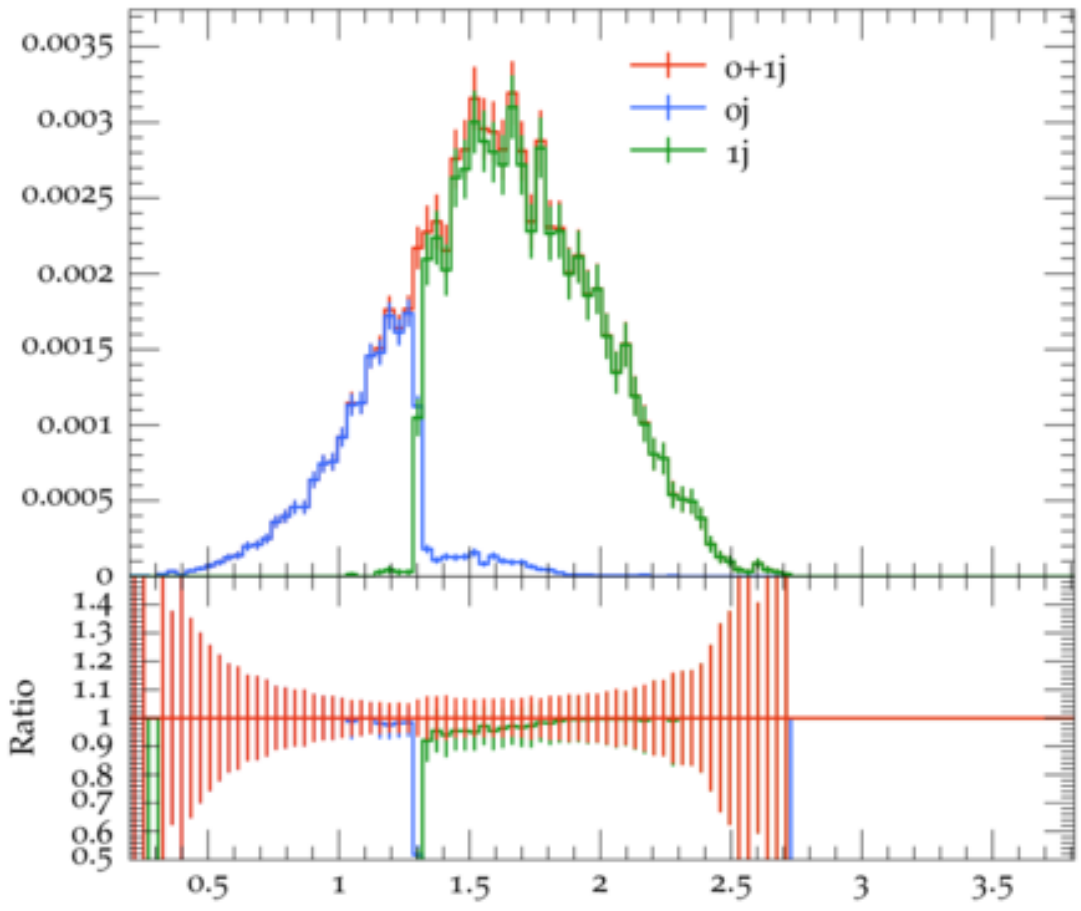
- We also tried to do a DJR check for the *Background only* processes using following configuration:

  xqcut = 10.0 GeV

  qCut = 20.0 GeV

- **Better transition!**

Background only



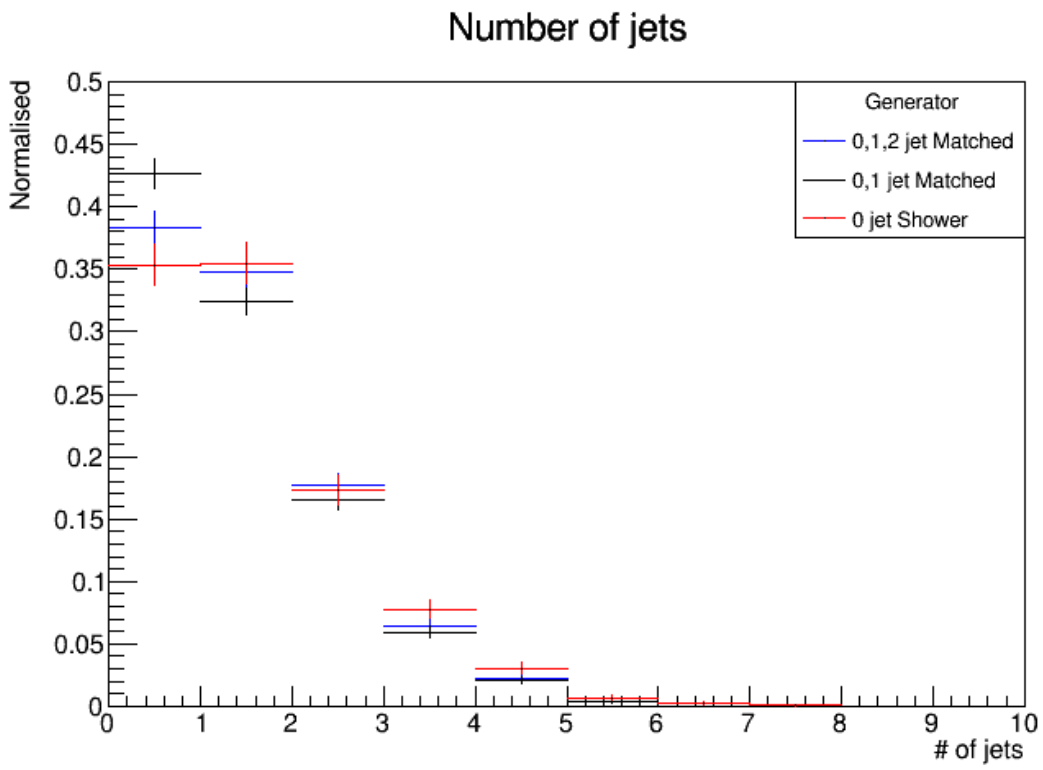
DJR(0 → 1)

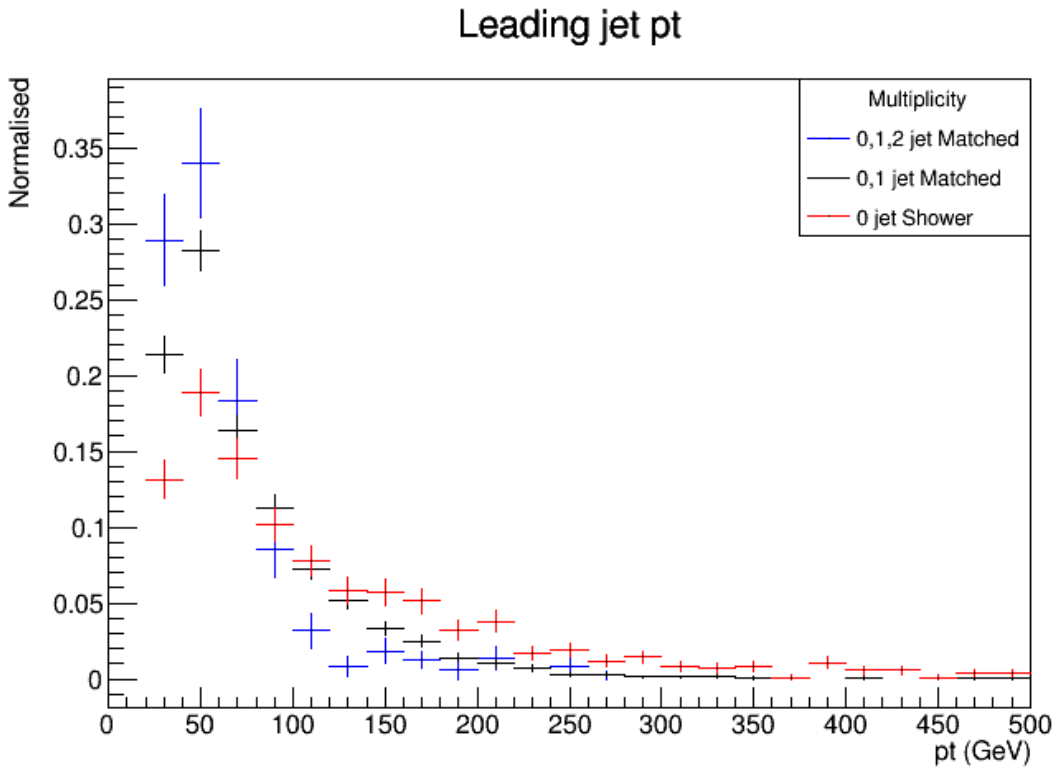
DJR ($1 \rightarrow 2$) TEST CONCLUSIONS

- For DJR($1 \rightarrow 2$) distribution in SBI in the qCut = 15 GeV sample, more statistics is needed to determine if we have a good matching, but preliminary results seem to show promise!
- A xqcut = 5 GeV yields a matching efficiency of ~5-20%
  - Challenging to obtain good sample size with 2j sample.
- A xqcut = 10 GeV would yield a better matching efficiency
  - The event generation for this is underway.

- We will show some comparisons in a fiducial phase-space close to the off-shell analysis ($p_T^{\ell} > 5\ \mathrm{GeV}$, $m_{4\ell} > 220\ \mathrm{GeV}$, $p_T^{\mathrm{jet}} > 30\ \mathrm{GeV}$, $|\eta^{\mathrm{jet}}| < 4.5$)

MADGRAPH 0+1+2J VALIDATION PLOTS





xqcut = 5 GeV
qCut = 15 GeV

CONCLUSIONS

- We have developed and implemented the diagram filters to filter out diagrams that are correction to the qqZZ process.
- We performed a careful evaluation of the matching accuracy in consultation with MadGraph authors, implementing patches to the code that allow for the 2j generation without crashing.
- We have presented the 0,1 jet matched results to one of the Pythia authors who validated the strategy we use.
- We studied the DJR distribution to determine the physical range for the matching scale. We determine that qCut = 15.0 GeV to qCut = 22.0 GeV seem to yield physical results for the $(0 \rightarrow 1)$ transition in the SBI process.
- For B only and S only process, a detailed study is still underway.
- We are still trying to determine the validity range and ideal qCut values using the DJR$(1 \rightarrow 2)$ plots.