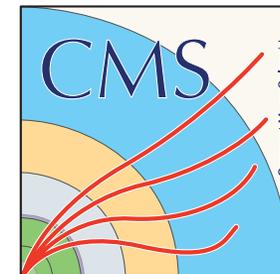


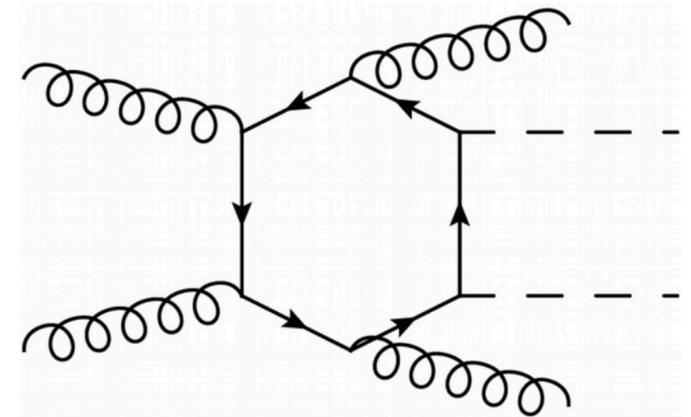
Sherpa hhjj Studies

Siewyan Hoh (CMS), Rachel Hyneman (ATLAS)



Introduction

- Parallel efforts within ATLAS and CMS to produce+study hhjj production using run cards from Jonas Lindert
 - Using Sherpa 2.2.10 with OpenLoops 2.1.1 (ATLAS)/OpenLoops 2.1.0 (CMS)
 - Using ppjjhh2 OpenLoops process library
 - “VBF-Like” Selector in run card:
 - FastjetSelector Mass(p[4]+p[5])>100. antikt 2 40. 0. 0.5
 - (≥ 2 anti-kt jets with $p_T > 40$ GeV, $m_{jj} > 100$ GeV, no minimum η_j , and $\Delta R_{jj} > 0.5$)
 - Two step generation; using libraries from HEFT model.
 - Exclusive 2-jet, NLO process
- Goal: understand how much this sample may contaminate VBF analyses
 - Already essentially covered by existing ggF HH samples?



Notes

- Studies shown today are work-in-progress
 - Almost entirely shape comparisons (arbitrary y scale)
- Somewhat limited statistics
 - ATLAS studies use 10,000 hhjj events; CMS studies use 5,000 hhjj events
- Cross-section integration of hhjj sample is computationally expensive – makes generating this sample challenging
- No Higgs boson decay implemented in Sherpa hhjj sample (to-do)

Sherpa hhjj Cross Section:

Rachel: $0.00229441 \text{ pb} \pm (1.1037\text{e-}05 \text{ pb} = 0.481038 \%)$

Siewyan: $0.00256453 \text{ pb} \pm (0.000730388 \text{ pb} = 28.48 \%)$

Overview

1. Comparisons of quark-initiated versus gluon-initiated jets in Sherpa hhjj sample
2. Comparisons of quark/gluon-initiated versus parton shower jets in Sherpa hhjj sample
3. Comparisons of Sherpa hhjj sample versus MadGraph5+Pythia8 hhjj sample
4. Comparisons of hhjj jets versus “VBF” jets in Madgraph+Herwig7 VBF HH sample

Comparisons of Quark/Gluon Jets in Sherpa hhjj Sample

Technical Details

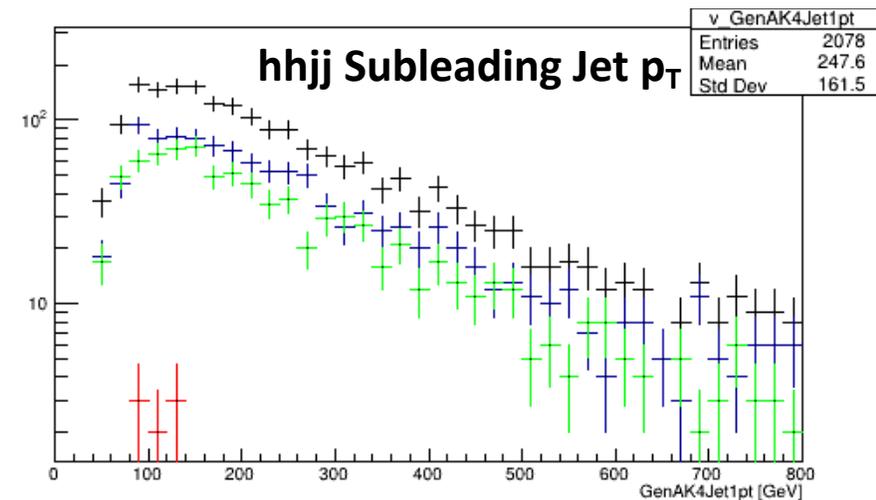
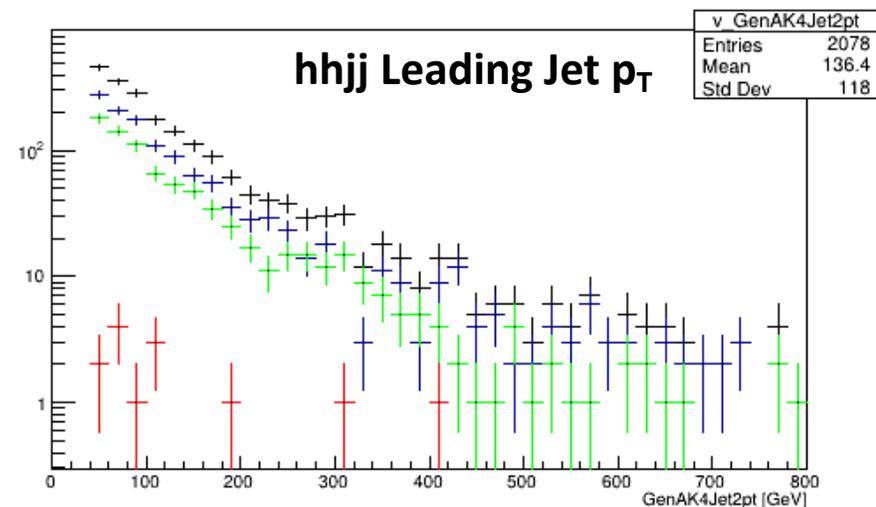
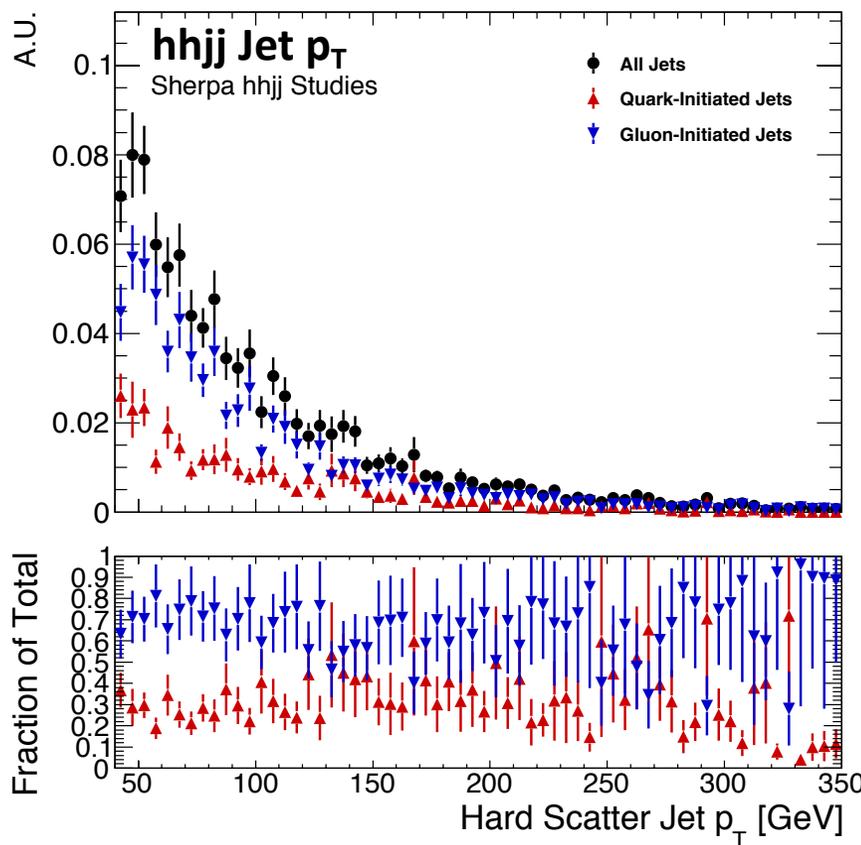
- Selecting “hard scatter jets” as those matched to two quarks/gluons from hard scatter process (status code 3) based on proximity ($\Delta R_{j,q} < 0.4$)
 - When multiple jets are matched to the same quark/gluon, take the jet with the minimum ΔR
- Separating Sherpa hhjj events based on whether the two jets are quark or gluon initiated
- Plots are normalized to show relative fraction of each event type

Hard Scatter Jets (Quark- vs. Gluon-Initiated)

Jet p_T

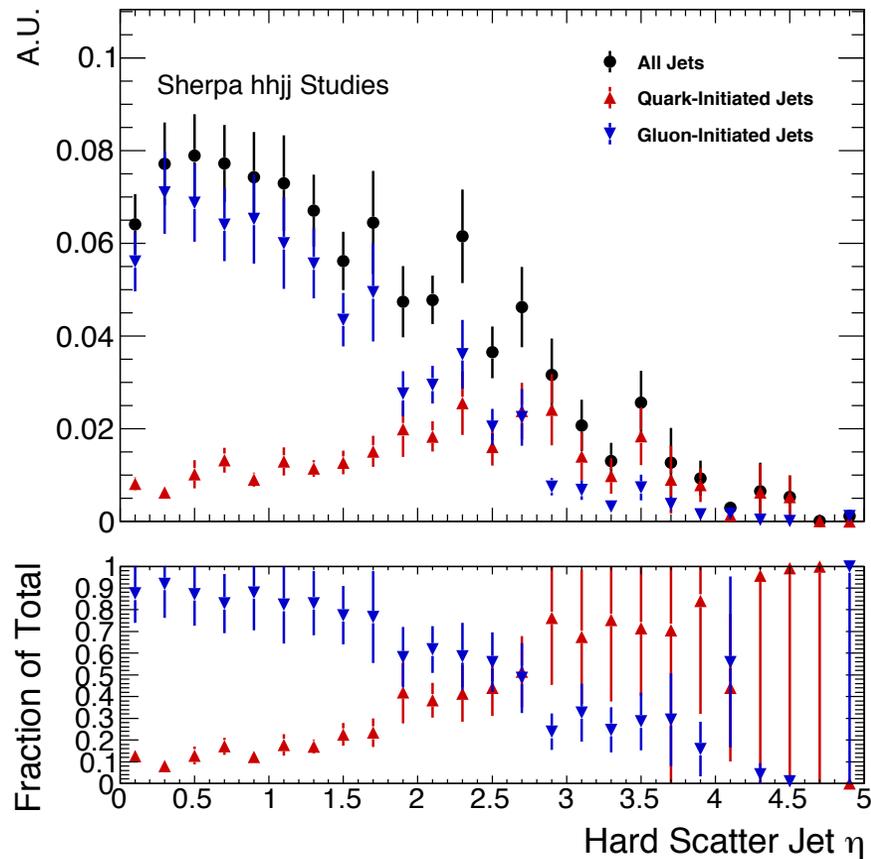
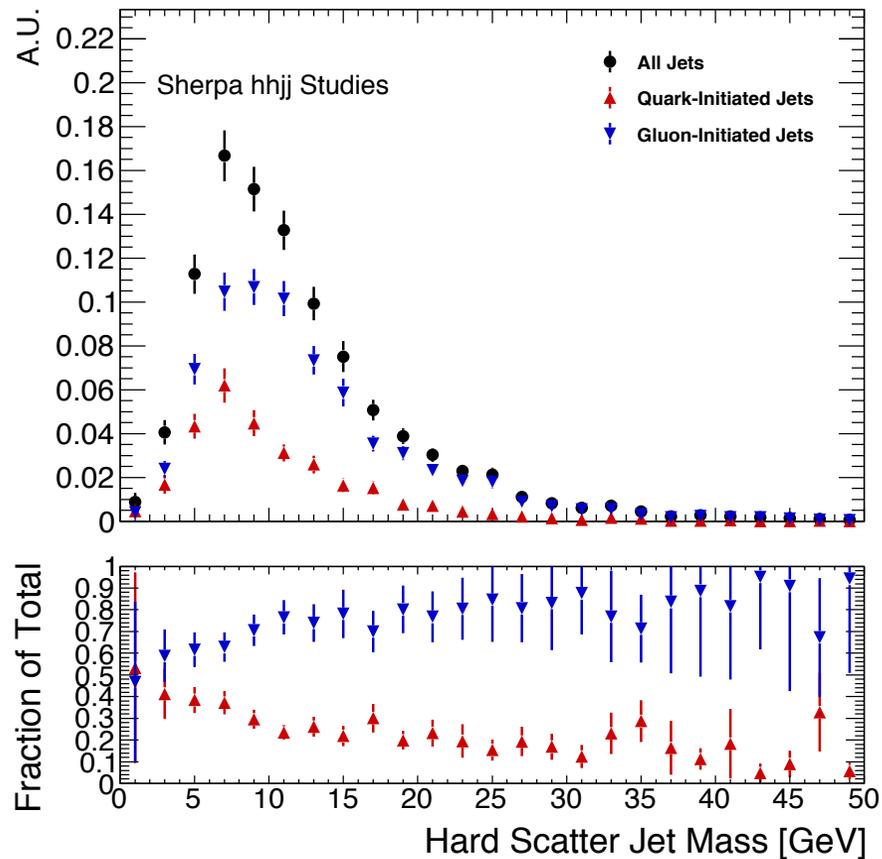
- Significantly more gluon-initiated jets than quark-initiated
- Similar p_T spectra for gluon/quark-initiated jets
- Consistent observations from both CMS/ATLAS studies

Black: total
Blue: gluon-initiated
Green: light quark
Red: heavy quark



Hard Scatter Jets (Quark- vs. Gluon-Initiated)

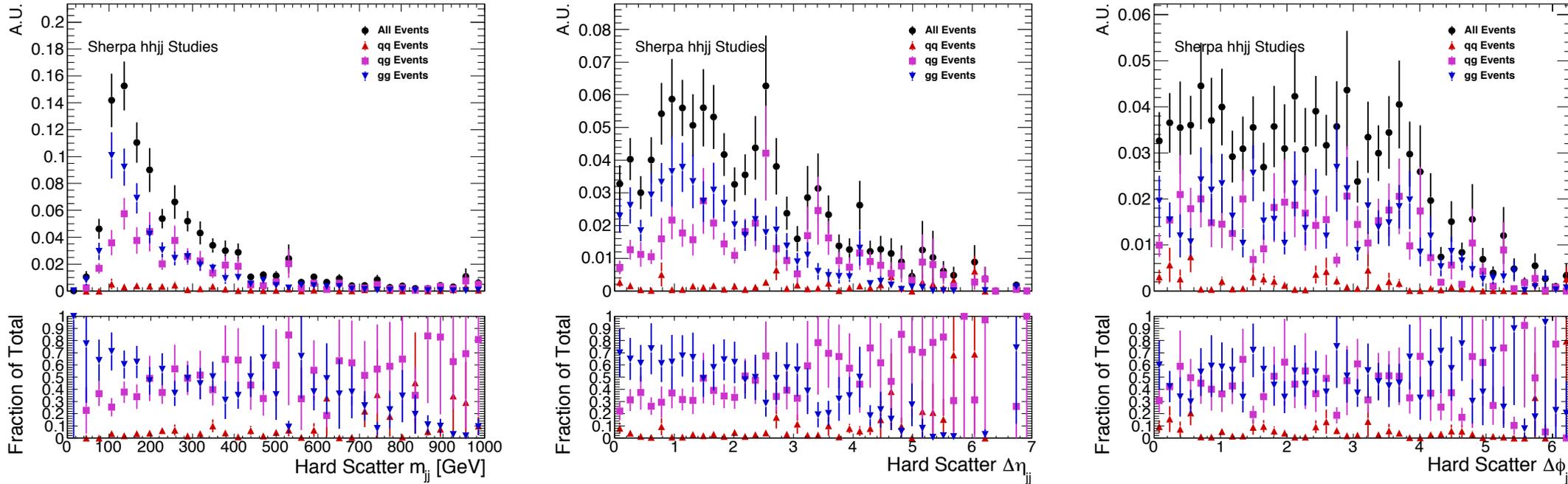
mass and η



- Quark jets significantly more forward than gluon jets (more VBF-like)
- Quark jets also less massive

Hard Scatter Jets (Quark- vs. Gluon-Initiated)

Dijet Variables: m_{jj} , $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$

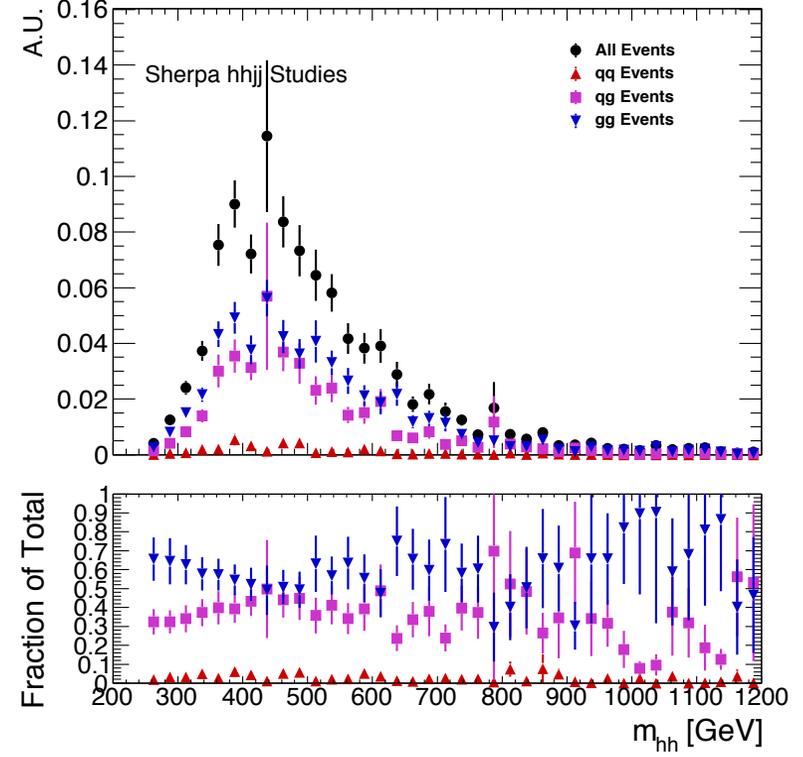
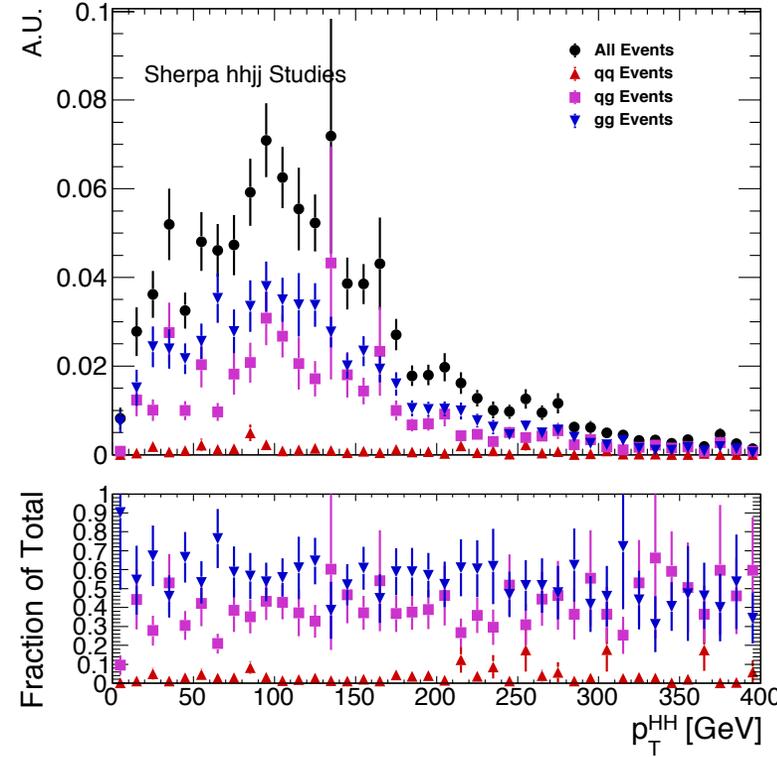
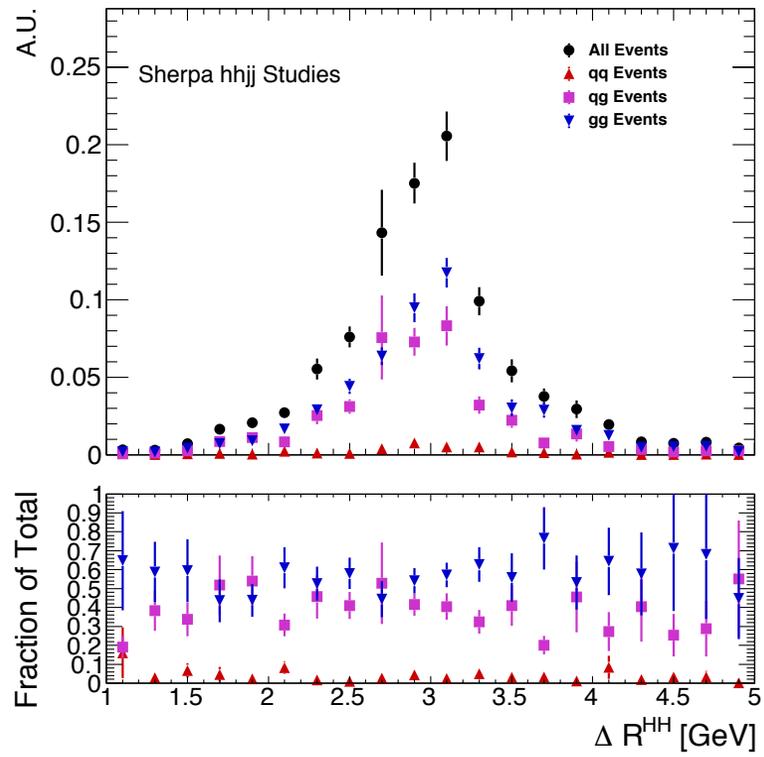


- Few qq events – consistent with observation of more gluon-initiated jets
- Gluon-gluon events tend to have lower m_{jj} and $\Delta\eta_{jj}$ (less “VBF-like”)
- Hard to draw conclusions about quark-quark events due to limited statistics, but expect to be more like “VBF-like”

Red = quark+quark
 Purple = quark+gluon
 Blue = gluon+gluon
 Black = all

Hard Scatter Jets (Quark- vs. Gluon-Initiated)

Higgs Kinematics: ΔR_{HH} , p_T^{HH} and m_{HH}



- Looks like quark-gluon events are slightly more broadly peaked in ΔR_{HH} , but hard to make strong conclusions
- Significant difference in m_{hh} spectra – proportionally more gg events at low m_{hh}

Red = quark+quark
Purple = quark+gluon
Blue = gluon+gluon
Black = all

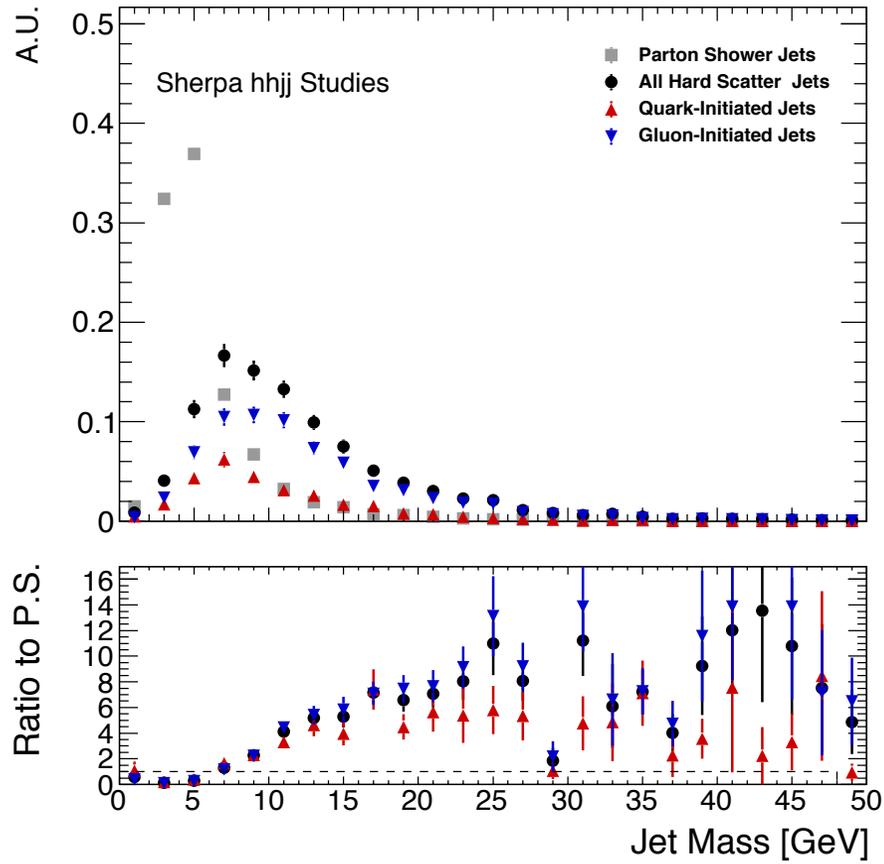
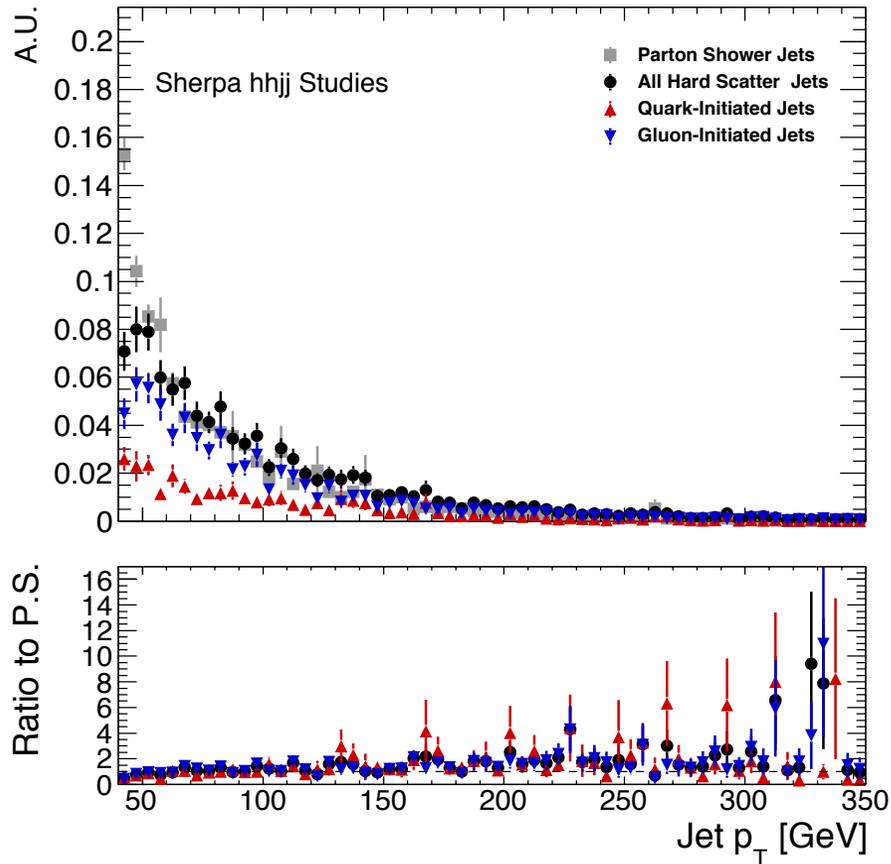
Comparisons of Quark/Gluon vs. Parton Shower Jets in Sherpa hhjj Sample

Technical Details

- Parton showering done by Sherpa
 - Parton shower jets = jets not ΔR -matched to a hard scatter quark/gluon
- Same separation of Sherpa hhjj events based on whether the two jets are quark- or gluon-initiated

Hard Scatter vs. Parton Shower Jets

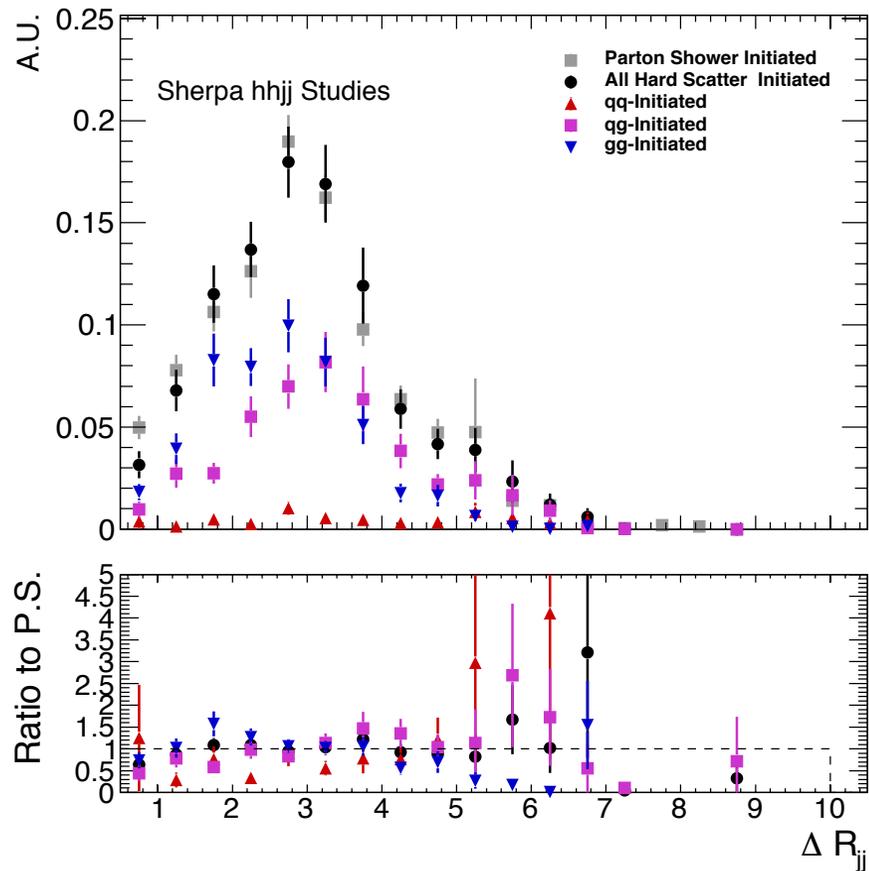
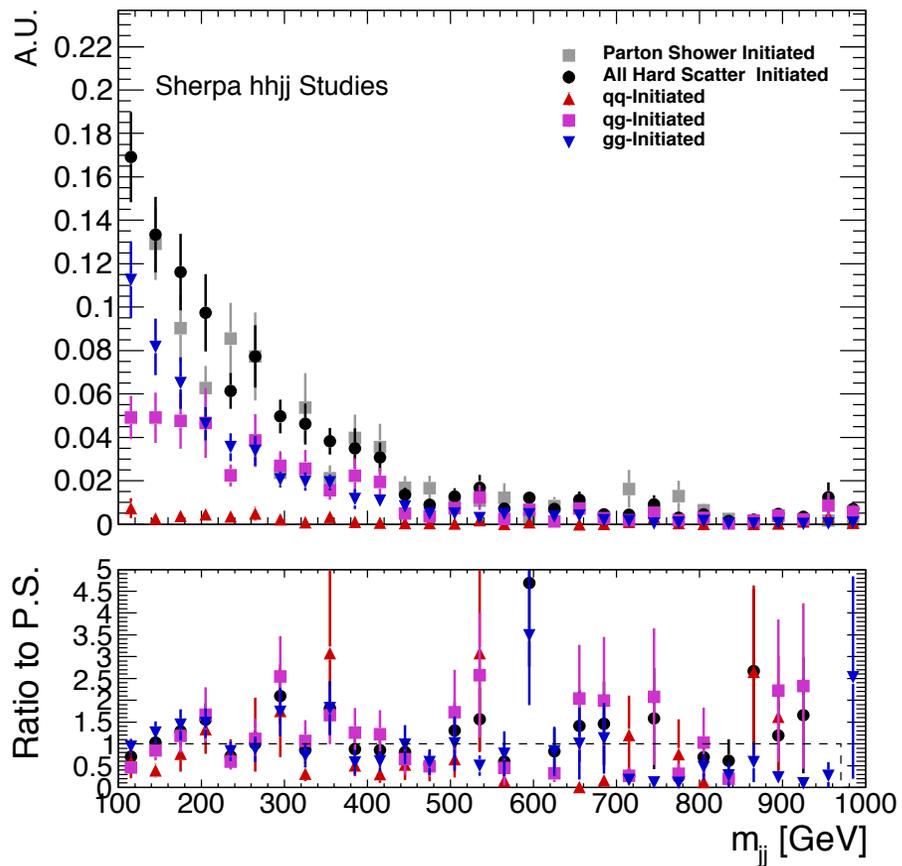
p_T and m



- Grey shows Parton Shower jets
- Bottom panel shows ratio of HS (all, **quark**, and **gluon**) to PS jets
- More soft PS jets
 - Restricting range of p_T^j plot to avoid region cut out by generator filter ($p_T^j > 40$)
- Mass difference driven by generator filter

Hard Scatter vs. Parton Shower Jets

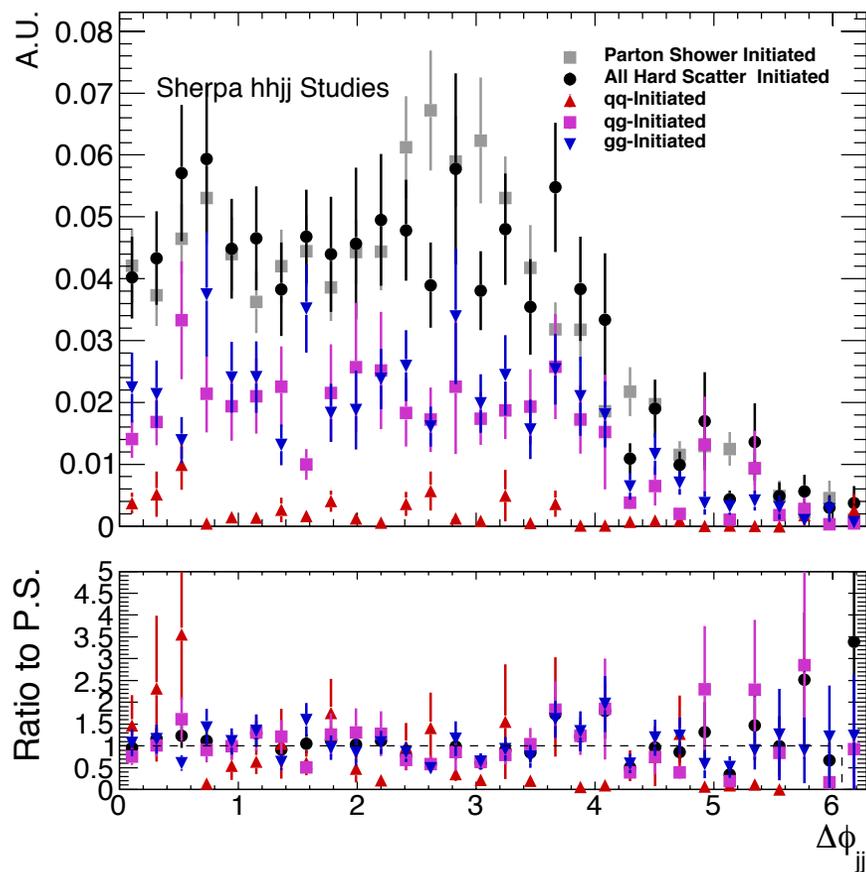
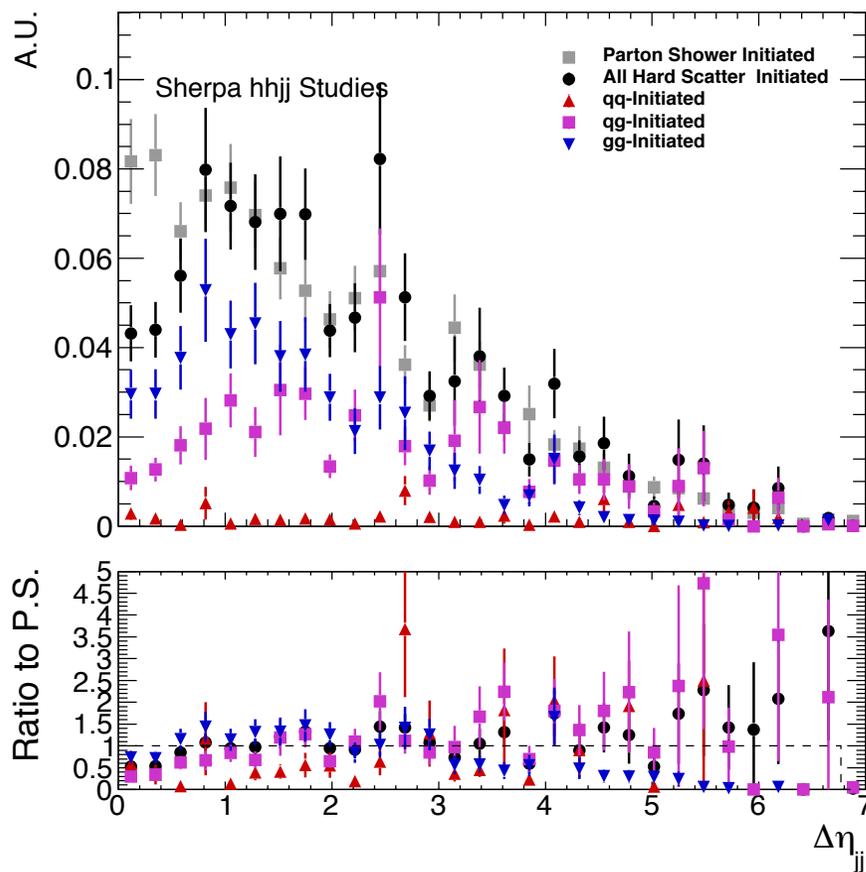
m_{jj} and ΔR_{jj}



- Relatively consistent distributions when comparing PS to all HS
- Restricting ranges of both plots to avoid region cut out by generator filter ($m_{jj} > 100$ and $\Delta R_{jj} > 0.5$)

Hard Scatter vs. Parton Shower Jets

$\Delta\eta_{jj}$ and $\Delta\phi_{jj}$



- Differences at low end of spectrum likely driven mostly by ΔR_{jj} cut in generator filter
- Generally similar distributions beyond very small $\Delta\eta/\phi$ region

Generator Comparison

Sherpa vs MadGraph5 hhjj

Technical Details

- Generated 5000 Madgraph5 hhjj events to perform comparison
 - No parton-level filter applied to MG5 sample
 - Applying an “analysis” level filter to both hhjj samples to obtain better comparison
 - ≥ 2 jets with $p_T > 40$ GeV, $m_{jj} > 100$ GeV, and $\Delta R_{jj} > 0.5$
- Generator-level Jet definition:
 - Define as GenJet (anti- k_T 0.4) matched to partons with status code 23(3); using last copy before decay
 - Excluding partons decaying from Higgs (and jets matched to these partons)
- Jet-Particle matching assumes parton closest to the jet in ΔR
- Gen-level Higgs definition:
 - Looking at status code 62(3) and last copy before decays

Sherpa hhjj Cross Section:

Total XS is 0.00256453 pb +- (0.000730388 pb = 28.48 %)

aMC@NLO hhjj Cross Section:

```
xsec_match [pb]          accepted [%]
4.576e-02 +/- 6.652e-04  100.0 +/- 0.0
-----
4.576e-02 +/- 6.652e-04  100.0 +/- 0.0
```

Comparison of Filter Effects

N_i

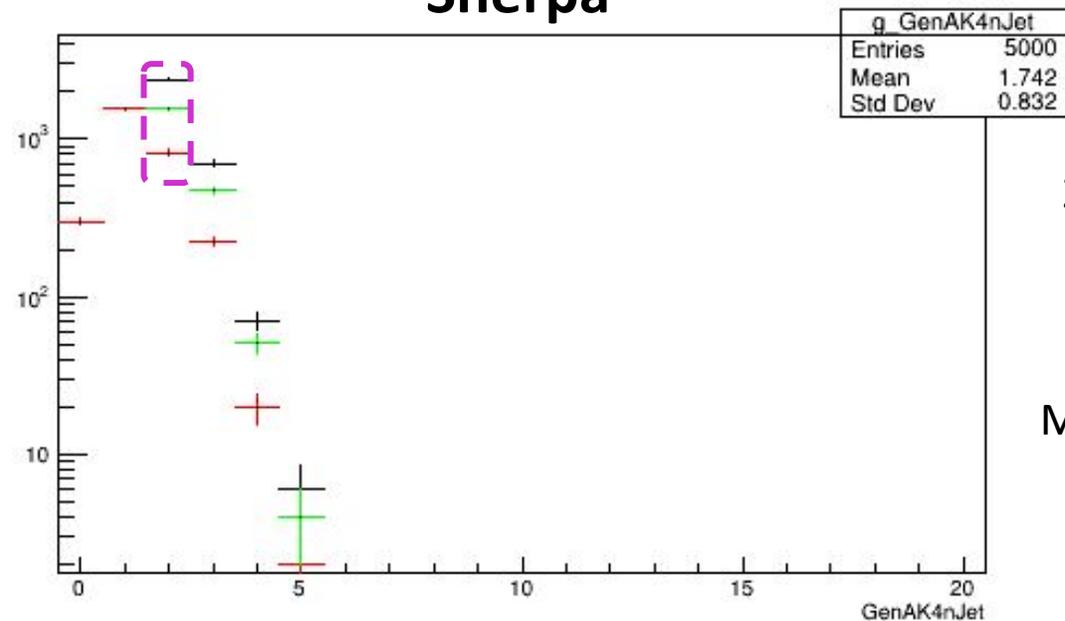
- “VBF-like” = passing analysis-filter; “ggF-like” defined as orthogonal to VBF-like phase space
- Caveat: Sherpa inherently favors VBF-like, while MG5 does not (so take comparisons with a grain of salt)
- Expect higher yield of ggF-like in Madgraph, and vice-versa

Black: Before filter

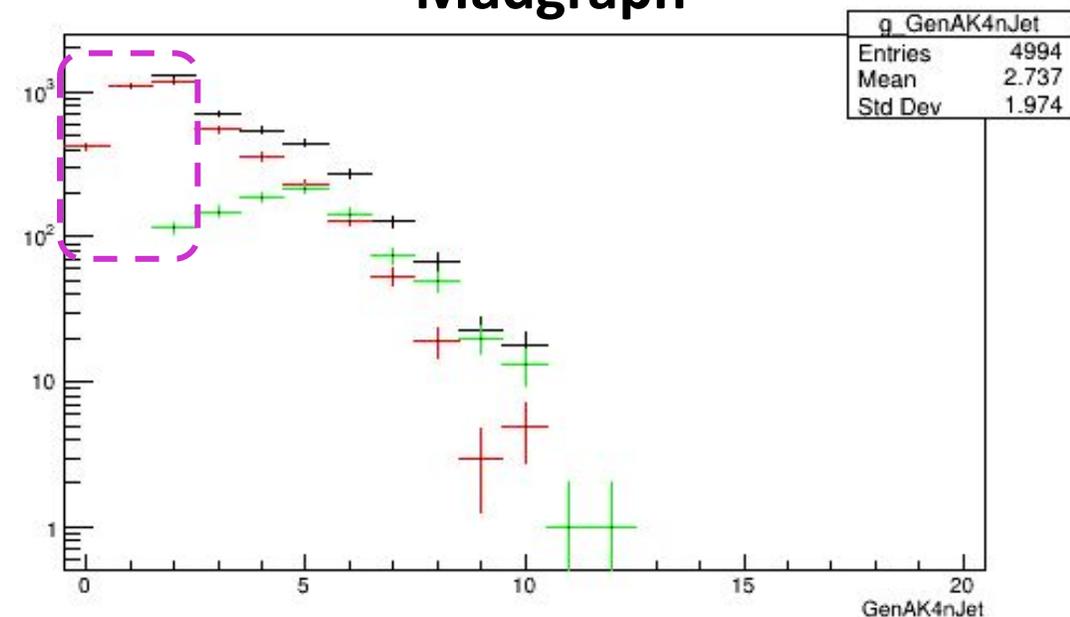
Red: ggF-like

Green: vbf-like

Sherpa



Madgraph



Comparison of Filter Effects

m_{jj}

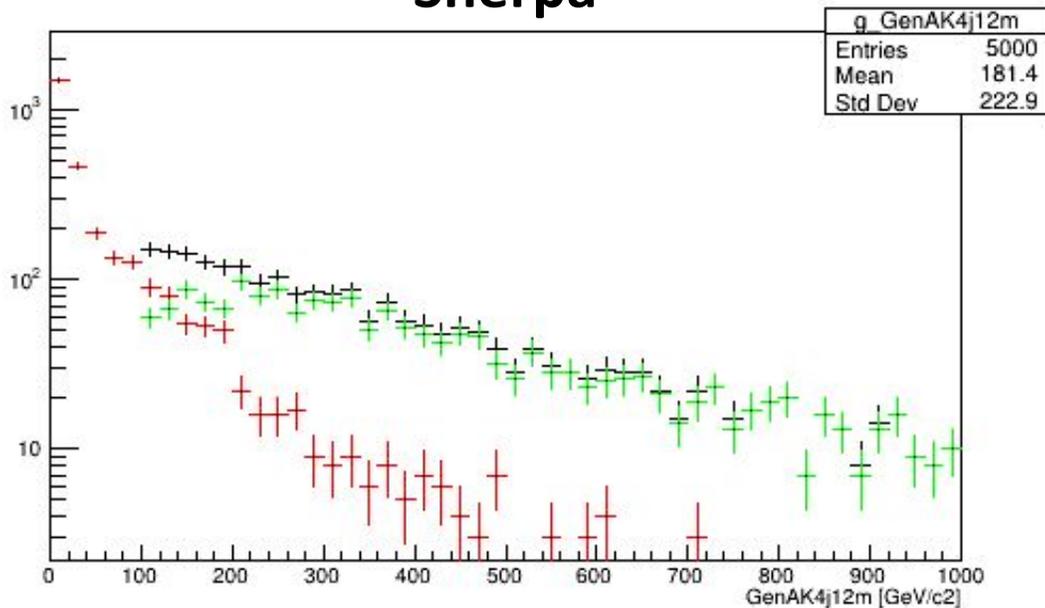
- More “ggF-like” events in MG5 sample at low m_{jj}
- Caveat: Sherpa inherently favors VBF-like, while MG5 does not (so take comparisons with a grain of salt)

Black: Before filter

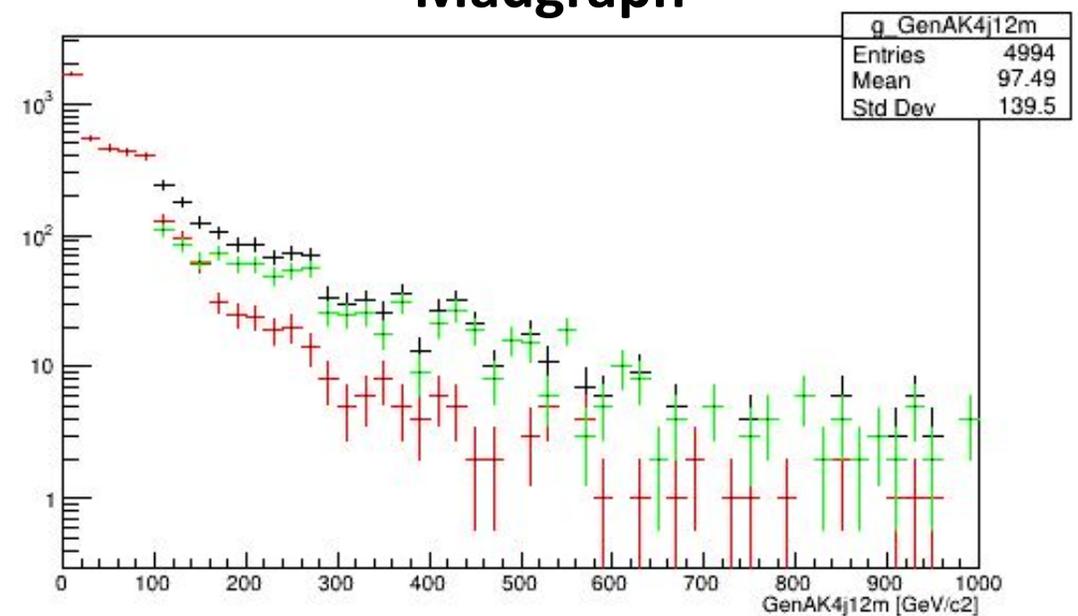
Red: ggF-like

Green: vbf-like

Sherpa



Madgraph

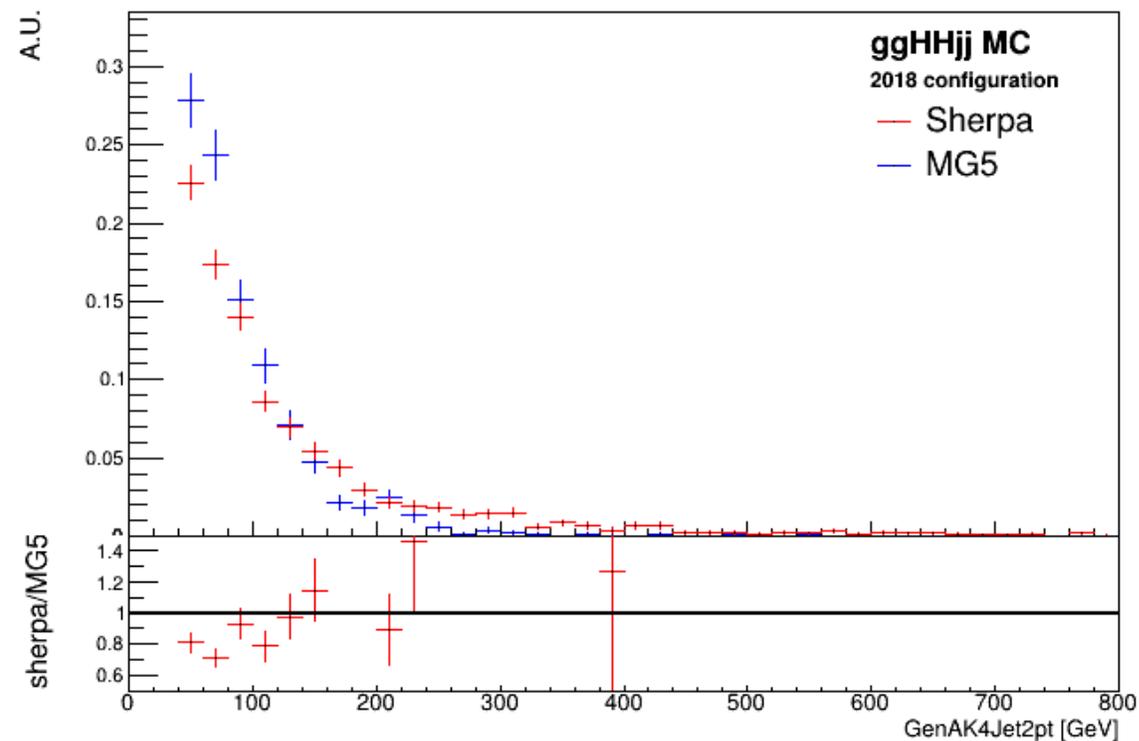
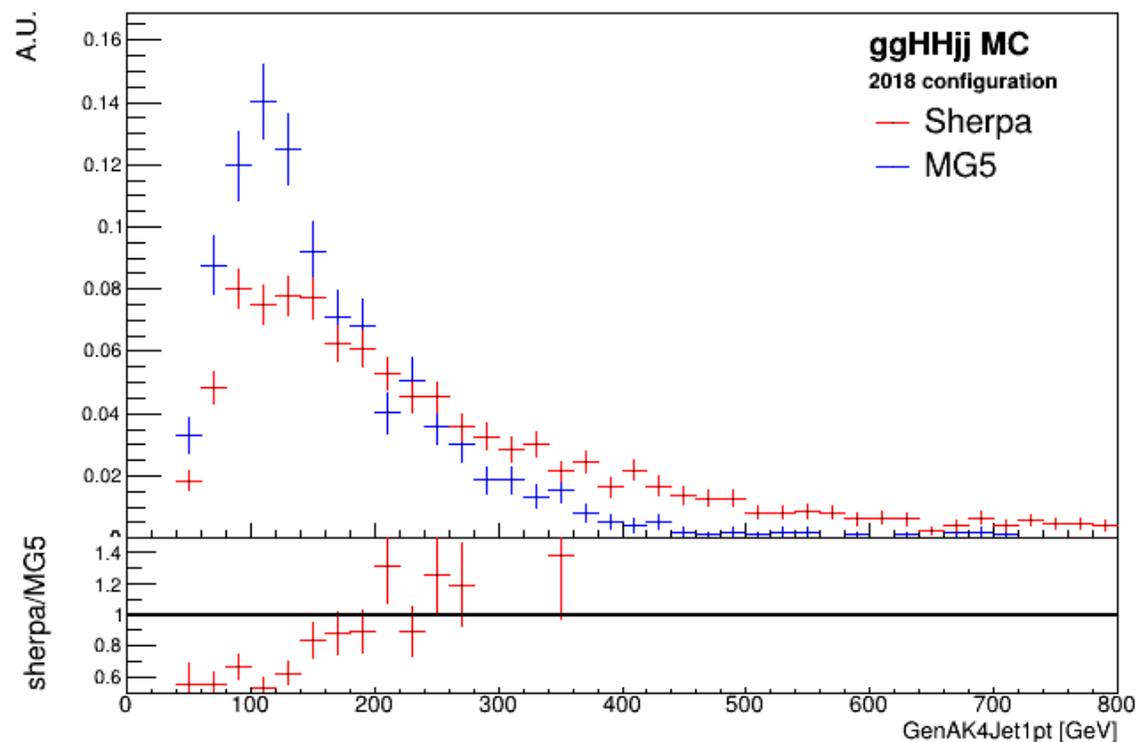


Generator Comparison

Leading and Subleading Jet p_T

- Applying “VBF-like” analysis-level filter to both samples
- Can see harder Sherpa jet p_T distributions

Red: Sherpa
Blue: MG5



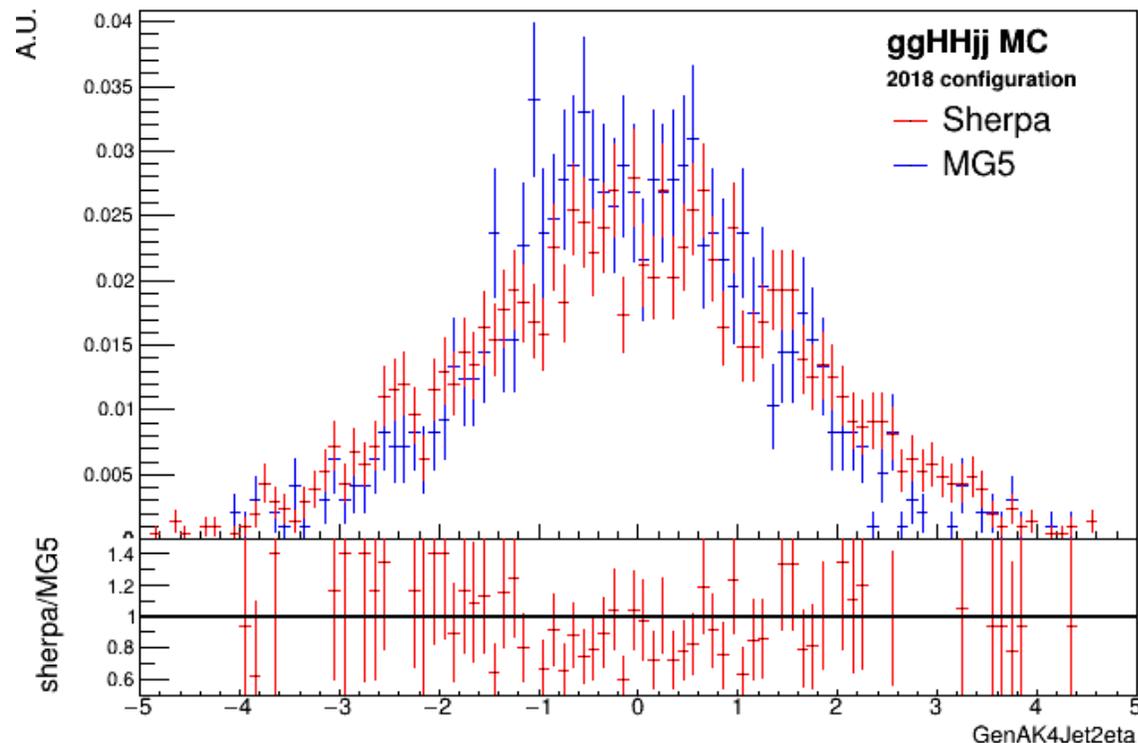
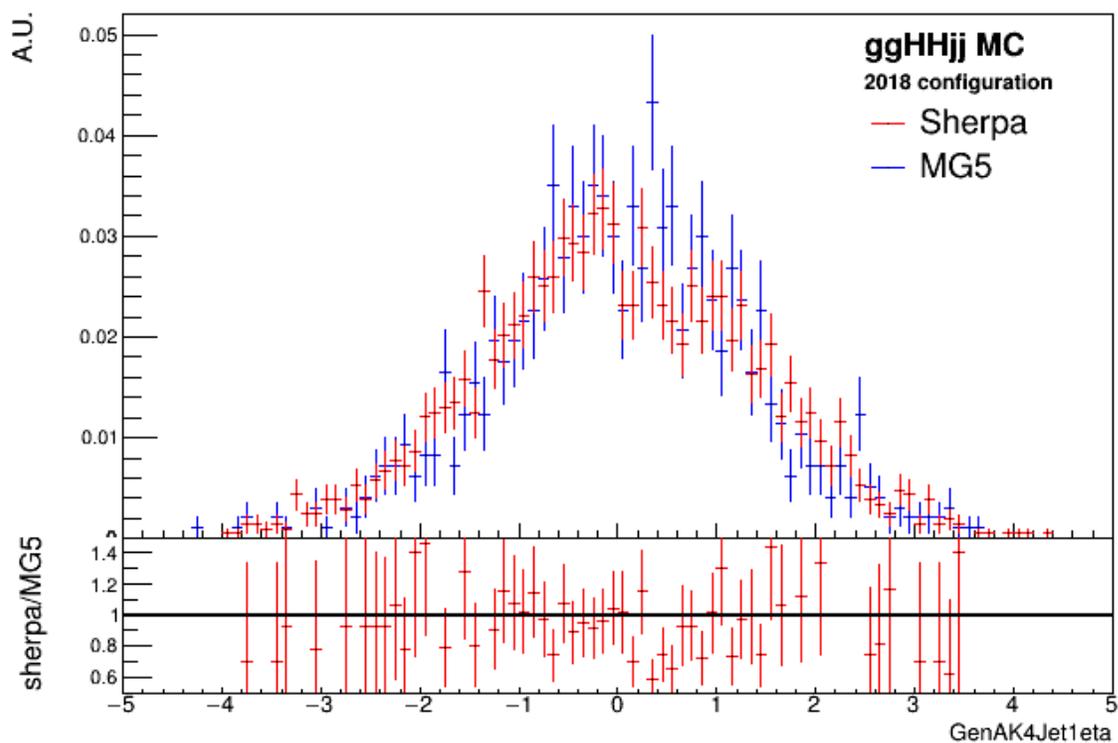
Generator Comparison

Leading and Subleading Jet η

- Applying “VBF-like” analysis-level filter to both samples
- Relatively similar shapes, though large statistical uncertainty in MG5 sample (due to VBF-like filter)

Red: Sherpa

Blue: MG5

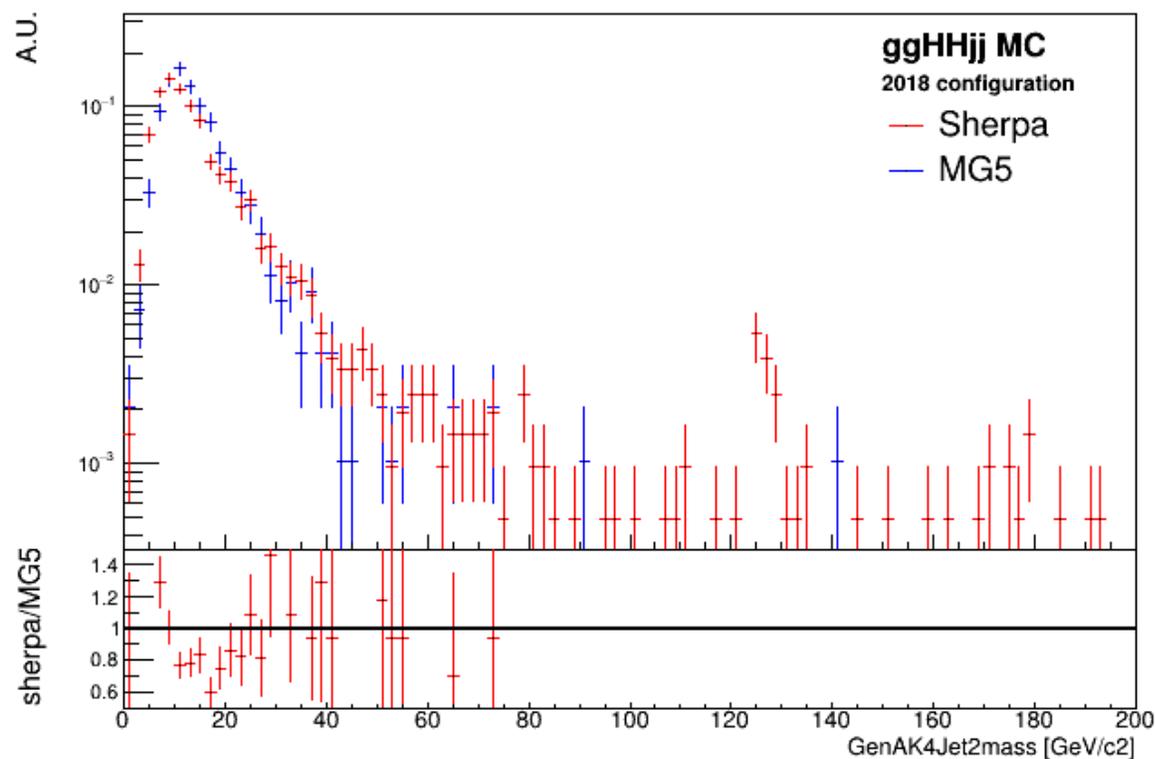
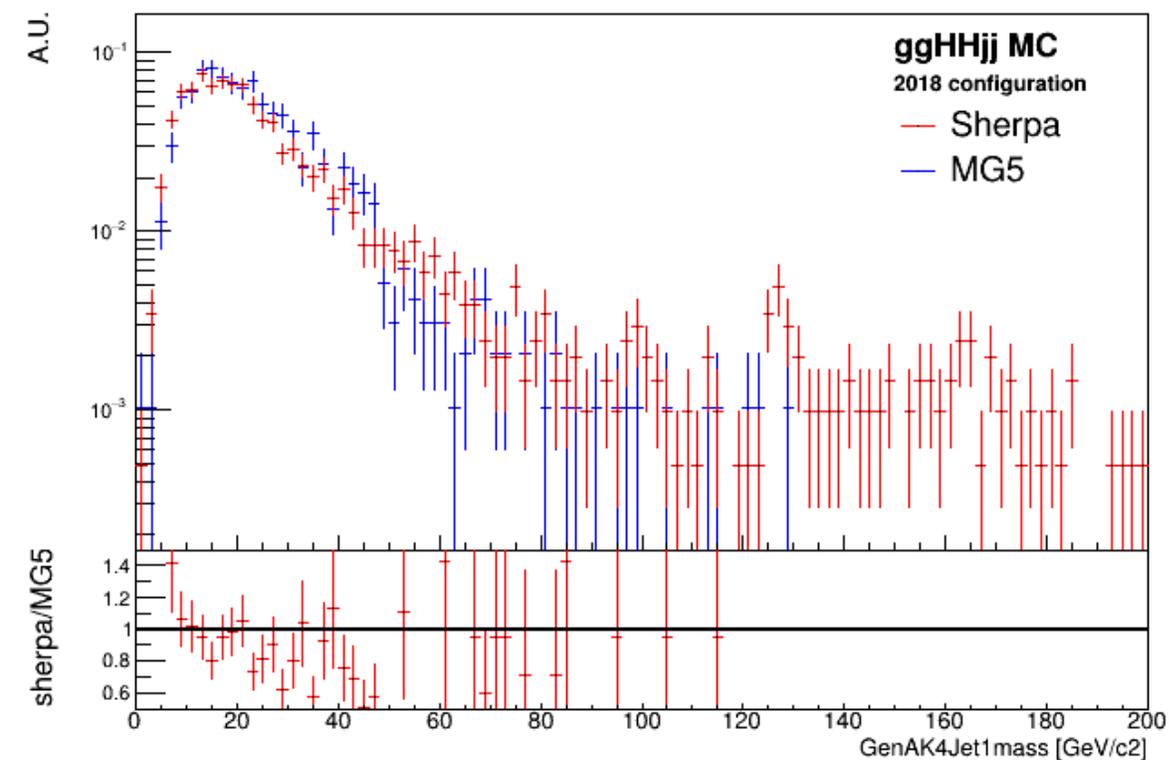


Generator Comparison

Leading and Subleading Jet Mass

- Applying “VBF-like” analysis-level filter to both samples
- Relatively larger jet masses from Sherpa

Red: Sherpa
Blue: MG5



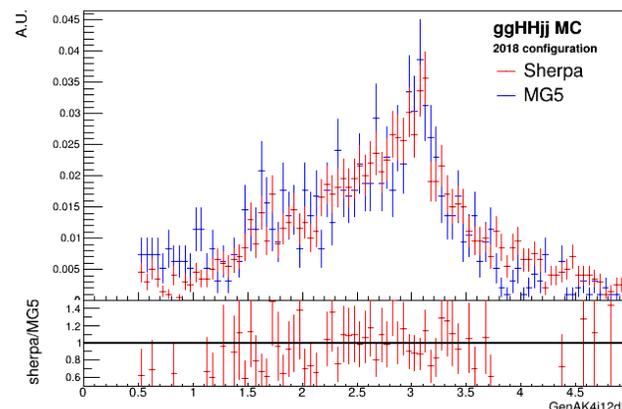
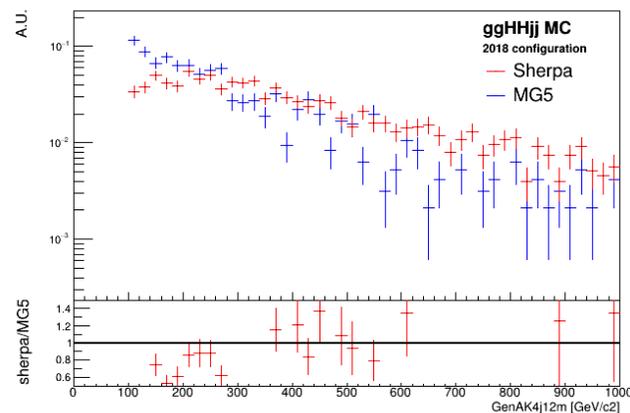
Generator Comparison

Dijet Kinematics

Red: Sherpa
Blue: MG5

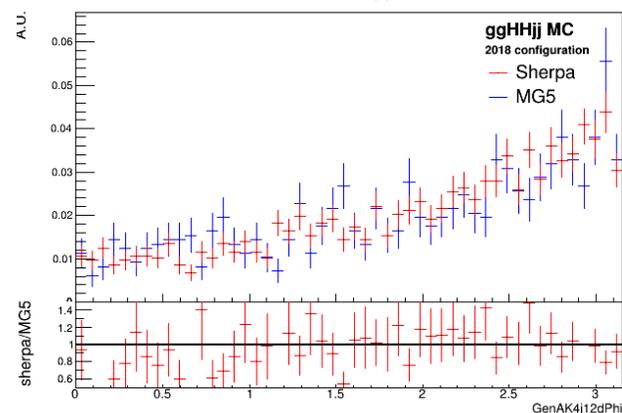
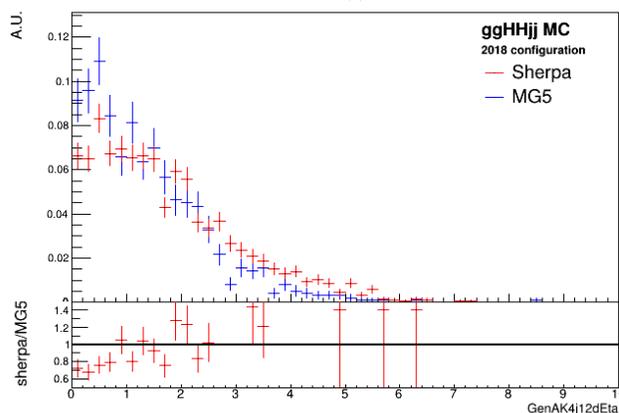
m_{jj}

ΔR_{jj}



$\Delta\eta_{jj}$

$\Delta\phi_{jj}$

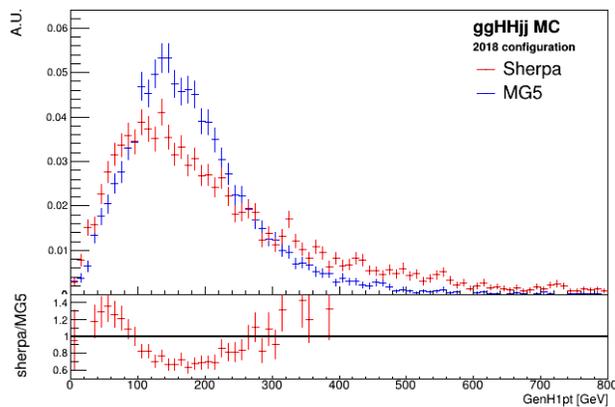


- Significant differences in m_{jj} and $\Delta\eta_{jj}$; important for VBF analyses
 - Differences observed in m_{jj} (below 100 GeV) are expected due to Sherpa sample generator filter
 - Above ~ 150 GeV, m_{jj} distributions agree decently well
 - $\Delta\eta_{jj}$ discrepancies also likely driven by Sherpa generator filter

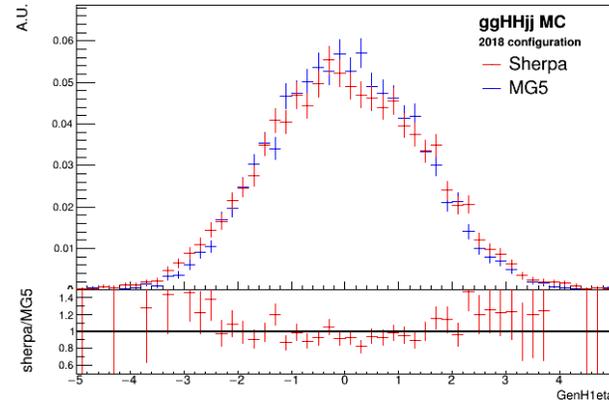
Generator Comparison Higgs Kinematics

Red: Sherpa
Blue: MG5

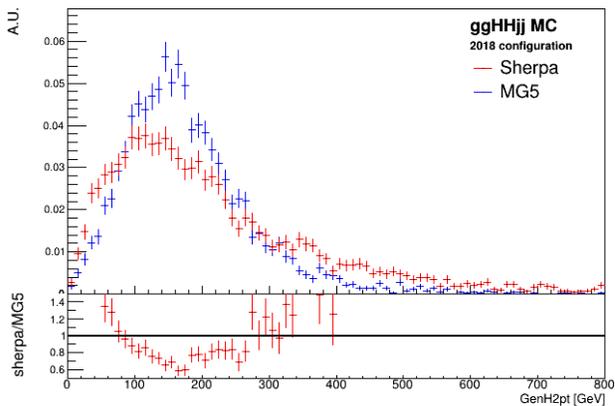
Leading Higgs p_T



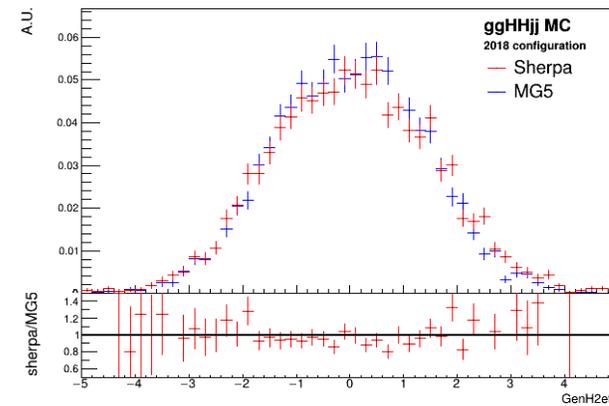
Subleading Higgs η



Subleading Higgs p_T



Subleading Higgs η

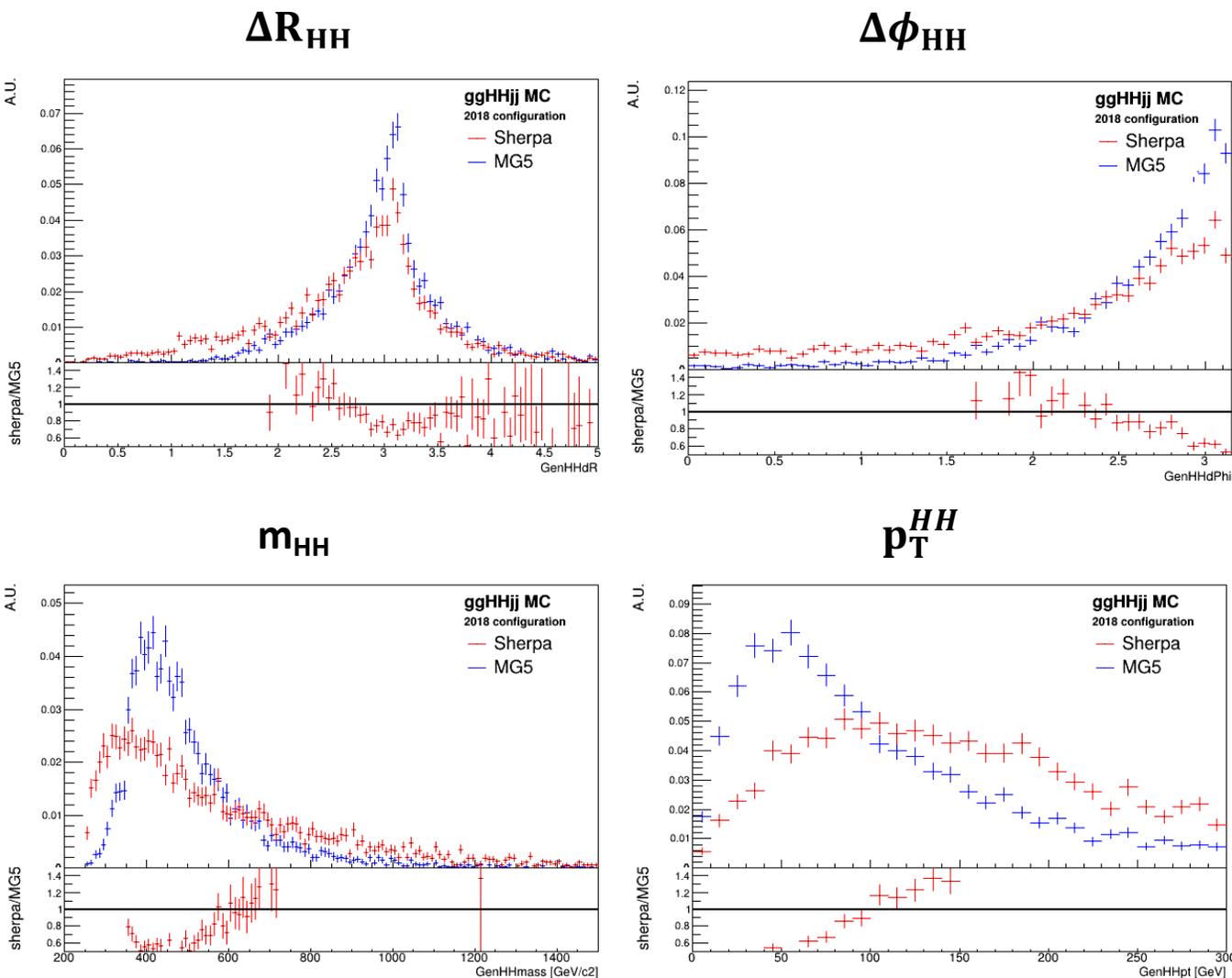


- Significant difference in Higgs p_T spectra
- In Sherpa, the parton-level cut affects the coupling to Higgs
 - Sherpa tends to produce low momentum Higgs pair
- Angular variables largely agree decently well between two generators

Generator Comparison

Di-Higgs Kinematics

Red: Sherpa
Blue: MG5



- DiHiggs p_T/m_{HH} modeling quite different from Sherpa vs MG5; consistent w/ previous slide
- Sherpa VBF parton-level filter affects the Higgs coupling, as a result producing softer momentum Higgs
 - ΔR_{HH} smaller, as Higgs are closer to each other
 - $\Delta\phi_{HH}$ smaller, as Higgs are less separated

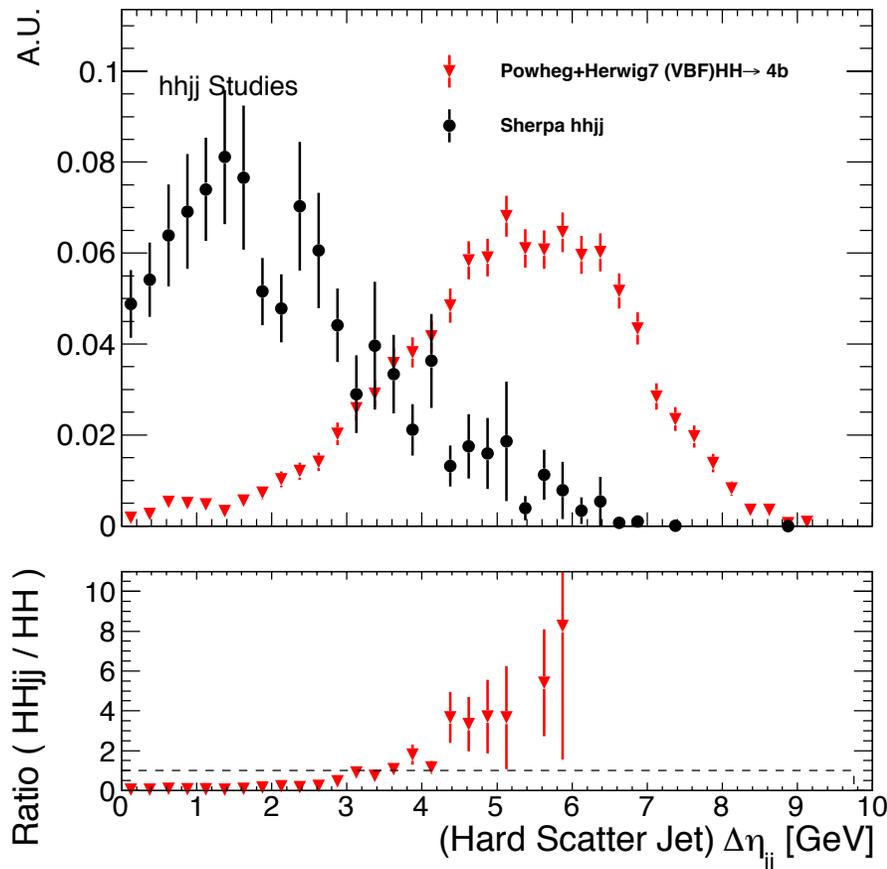
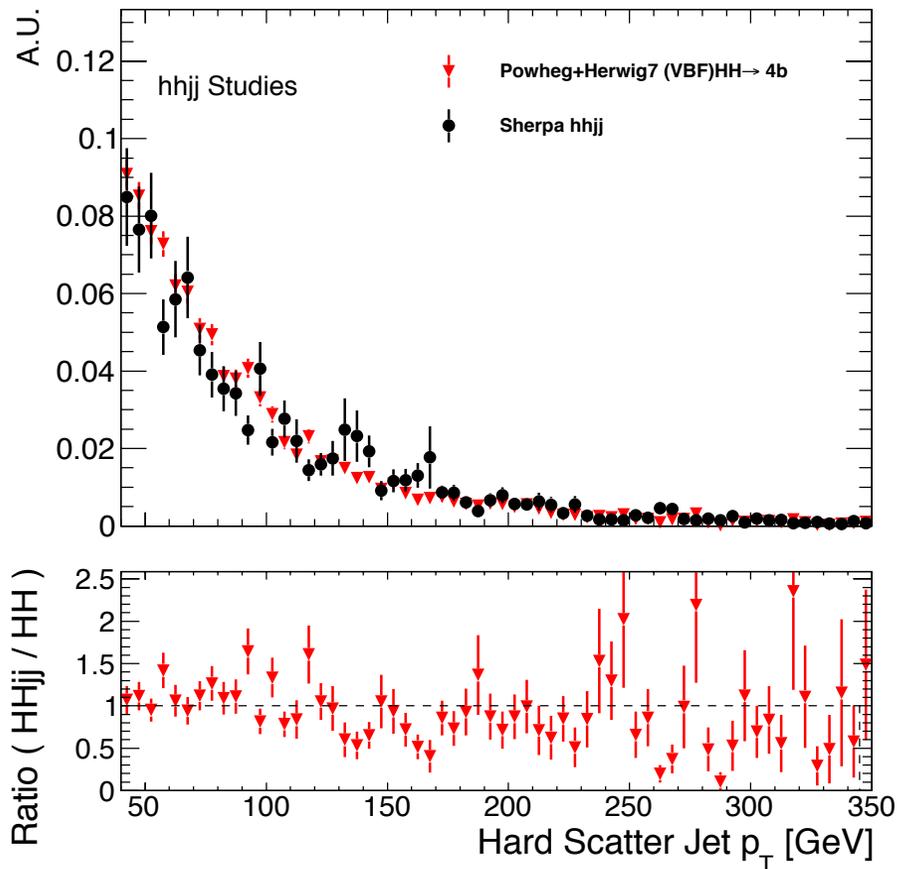
Comparison with Madgraph+HW7 VBF HH Sample

Technical Details

- Comparing hhjj “hard scatter jets” against “VBF” jets from Madgraph+Herwig7 VBF HH(4b) sample
 - Using 8161 events (10k, removing VHH events)
 - Ignoring jets matched to Higgs b-decay products ($\Delta R_{j,b} < 0.4$)
 - Tagging “VBF” jets based on proximity to truth quark ($\Delta R_{j,q} < 0.4$)
- Applying “analysis level” filter to both samples to mitigate differences from hhjj selector
 - ≥ 2 jets with $p_T > 40$ GeV, $m_{jj} > 100$ GeV, and $\Delta R_{jj} > 0.5$
 - Also requiring $\eta_j < 5$

Hard Scatter vs. VBF Jets

p_T and $\Delta\eta_{jj}$

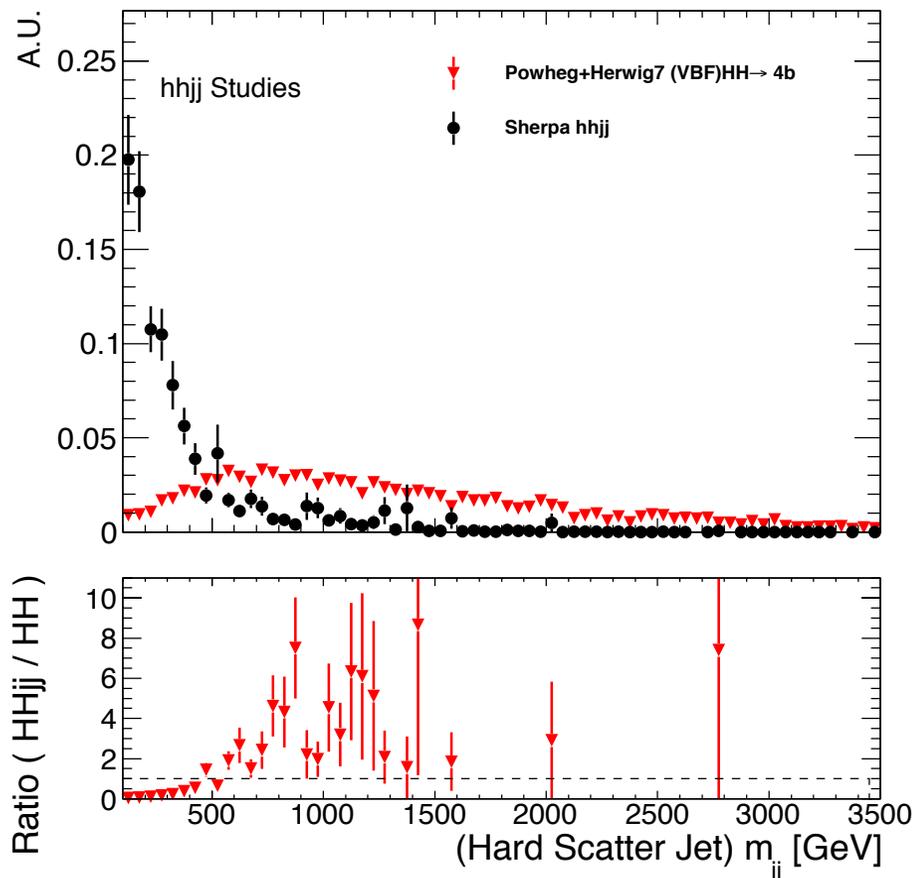
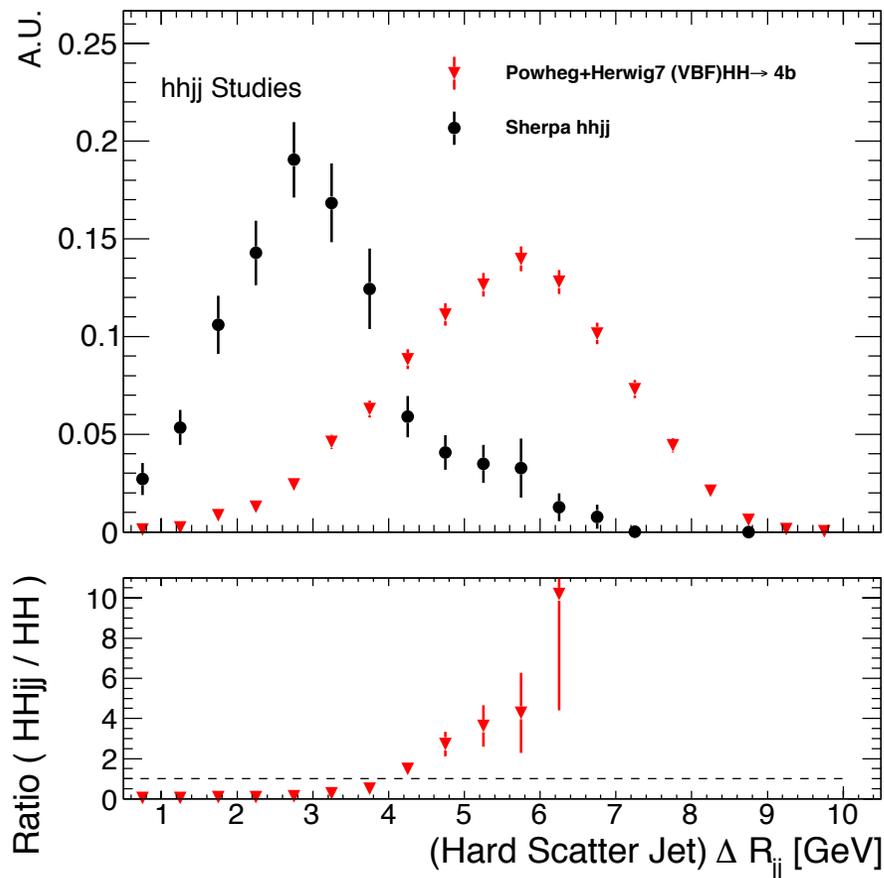


- Similar jet p_T distributions
- Sherpa hhjj events have significantly smaller $\Delta\eta_{jj}$
 - $\Delta\eta_{jj}$ commonly used in VBF analyses, so may expect less hhjj contamination

Black = Sherpa hhjj
Red = VBF HH4b

Hard Scatter vs. VBF Jets

ΔR_{jj} and m_{jj}

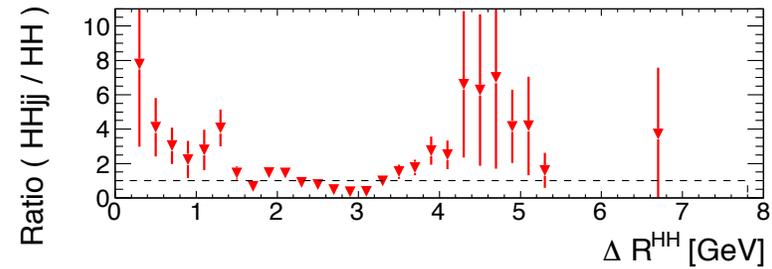
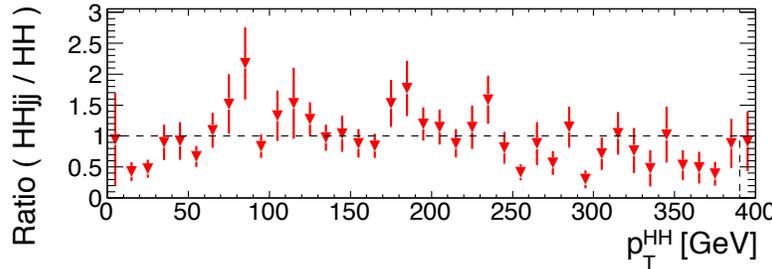
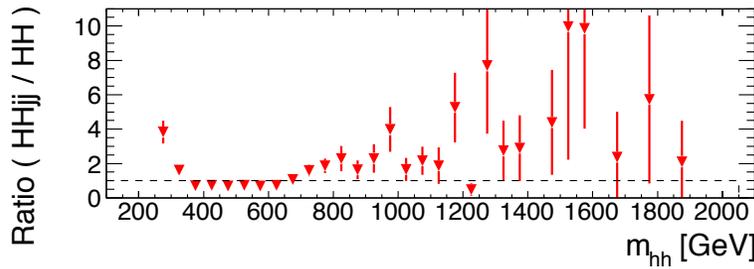
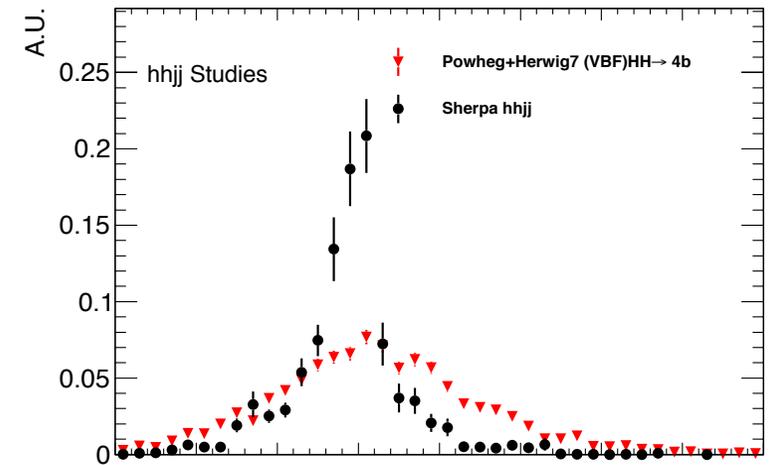
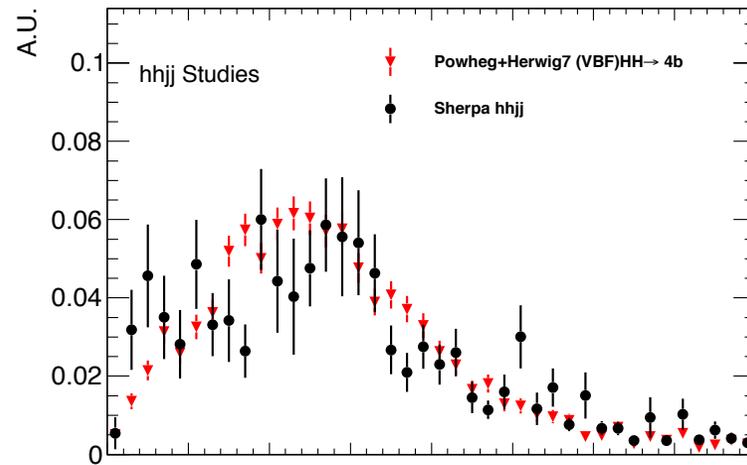
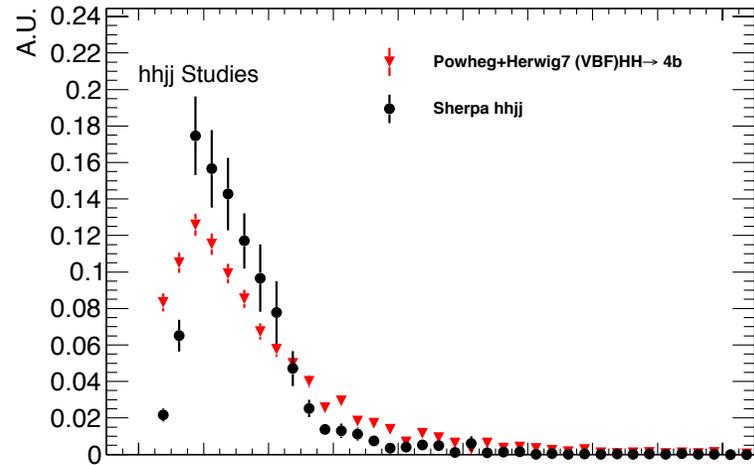


- Sherpa hhjj events have significantly smaller ΔR_{jj} and m_{jj}
 - Both of these variables are commonly used in VBF analyses

Black = Sherpa hhjj
Red = VBF HH4b

Higgs Boson Kinematics

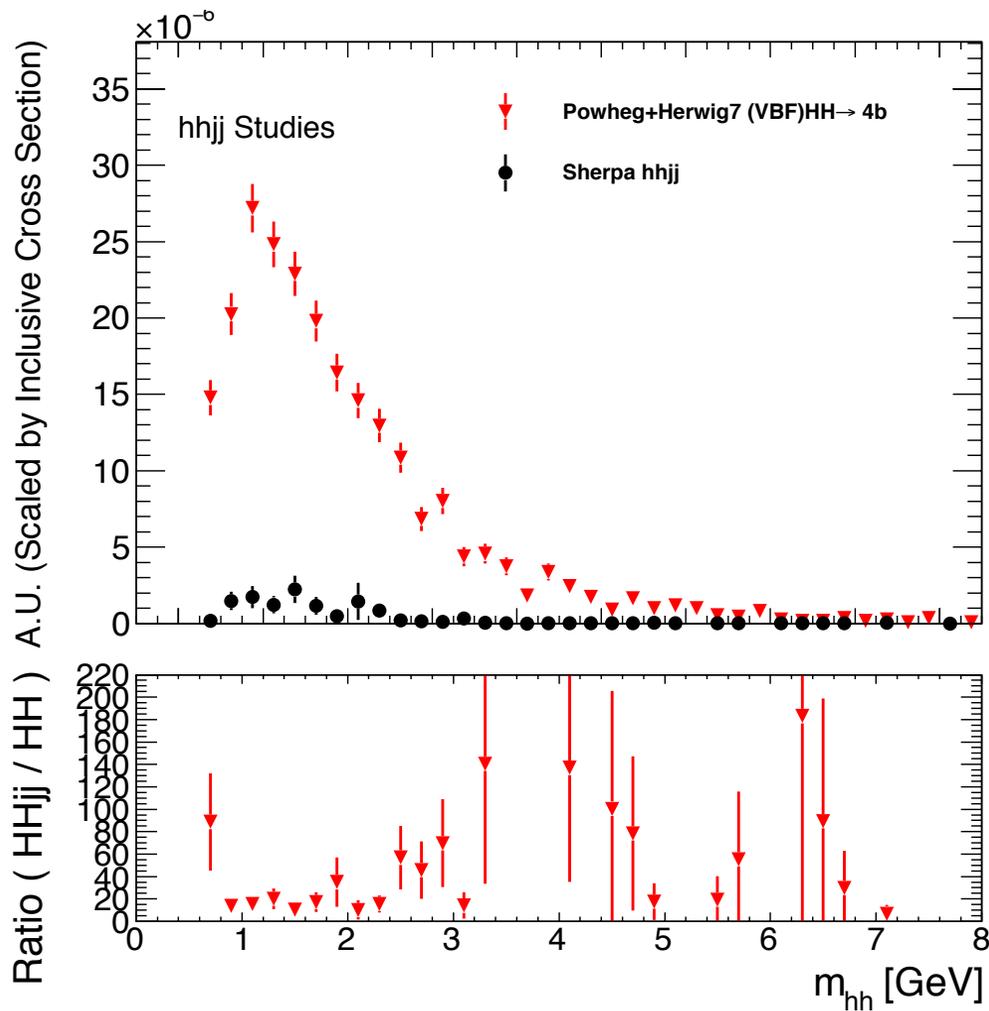
$$m_{HH}, p_T^{HH}, \Delta R_{HH}$$



- m_{hh} distribution more strongly peaked in Sherpa hhjj sample than in VBF sample
- Similar p_T^{hh} distributions
- Much “peakier” ΔR_{HH} distribution in Sherpa hhjj sample
- Different production modes, so do expect real Higgs kinematics differences

Black = Sherpa hhjj
Red = VBF HH4b

“Back of the Envelope” Estimation hhjj Contamination in VBF Analyses



- Normalize each sample to:
 - $\frac{\sigma}{N_{evt}} * \frac{(\sum w_{post-cuts})}{(\sum w_{pre-cuts})}$
 - $\sigma_{VBF} = 1.72 \text{ fb}$
 - $\sigma_{hhjj} = 2.29 \text{ fb}$
- Apply loose “VBF analysis” cuts
 - $m_{jj} > 700 \text{ GeV}$
 - $\Delta R_{jj} > 3$
 - $\Delta \eta_{jj} > 3$
- Ratio of hhjj/VBF: ~ 0.0508

Conclusions

- Have presented many parallel studies of Sherpa hhjj sample from both CMS and ATLAS
- Comparing quark- vs. gluon-initiated jets, can see that Sherpa hhjj sample contains significantly more gluon jets
 - MG5 sample contains relatively more light quark jets
- “Hard scatter” jet kinematics relatively similar to parton shower jets, but softer, when applying cuts to mimic selector
- Comparing against MG5 generator, the two-step generation in Sherpa gives reasonable result in term of angular variable shape
- “Hard scatter” jets from Sherpa hhjj sample do not appear to behave strongly like “VBF” jets – implies many hhjj events will be removed from VBF HH analyses
 - Rough estimation: order(few %) of hhjj events will contaminate VBF HH analysis phase space

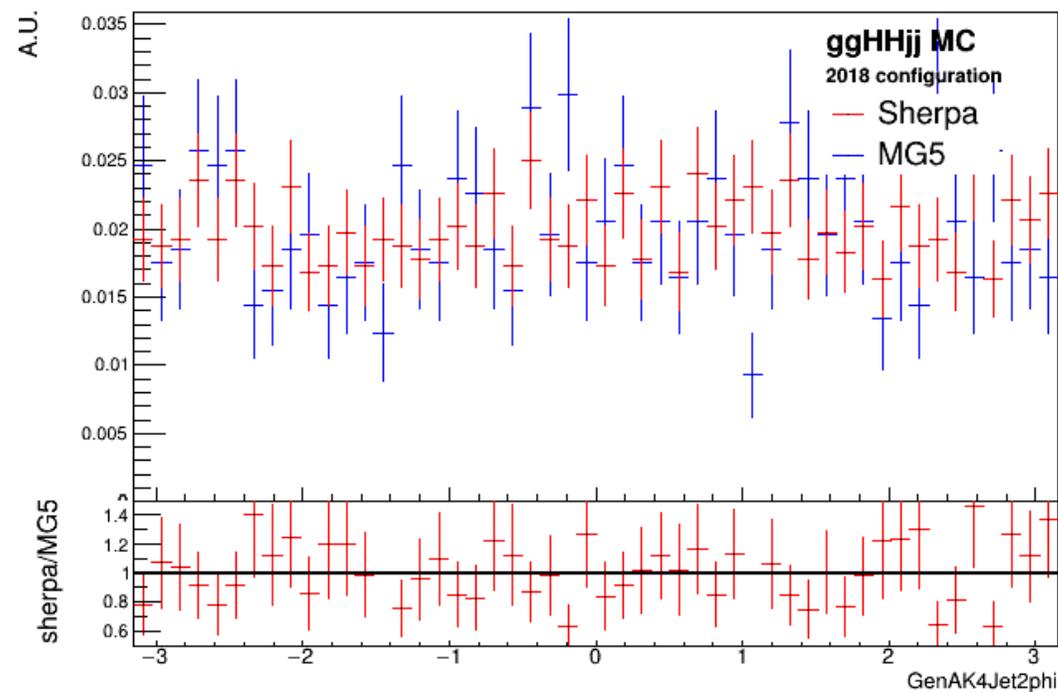
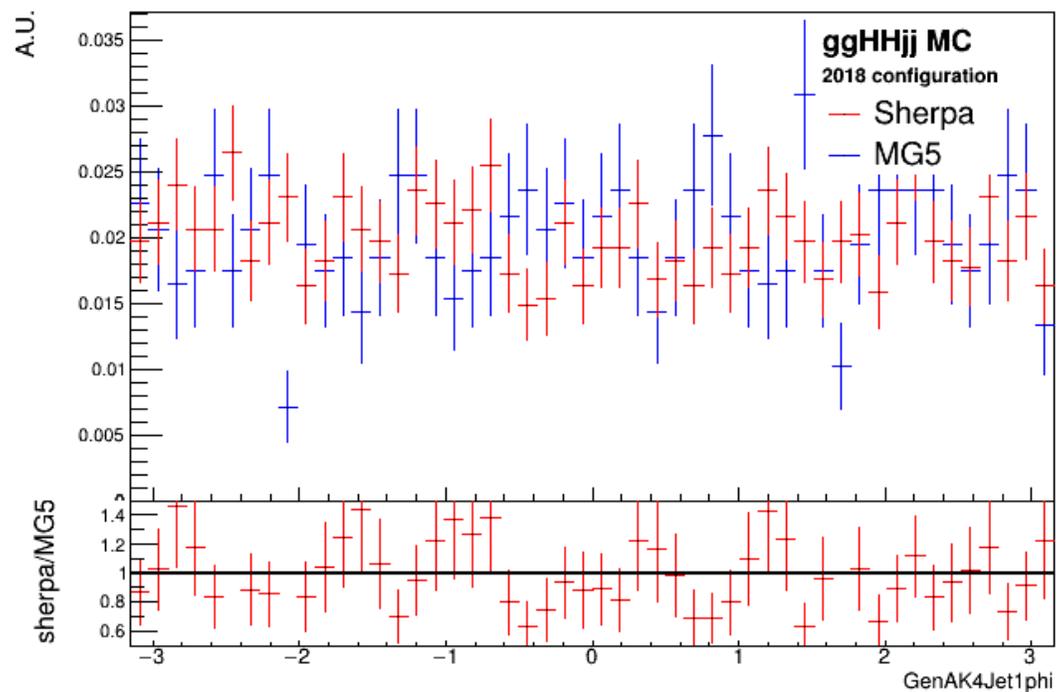
Backup Slides

Generator Comparison

Leading and Subleading Jet ϕ

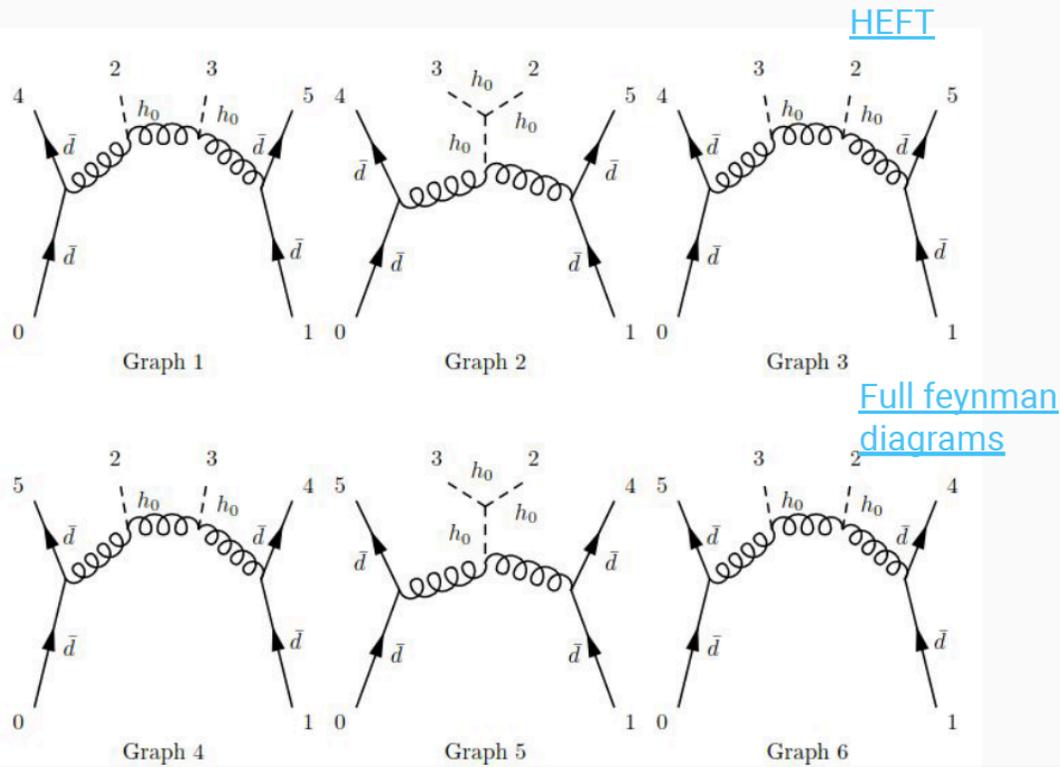
- Shapes compatible (sanity check)

Red: Sherpa
Blue: MG5

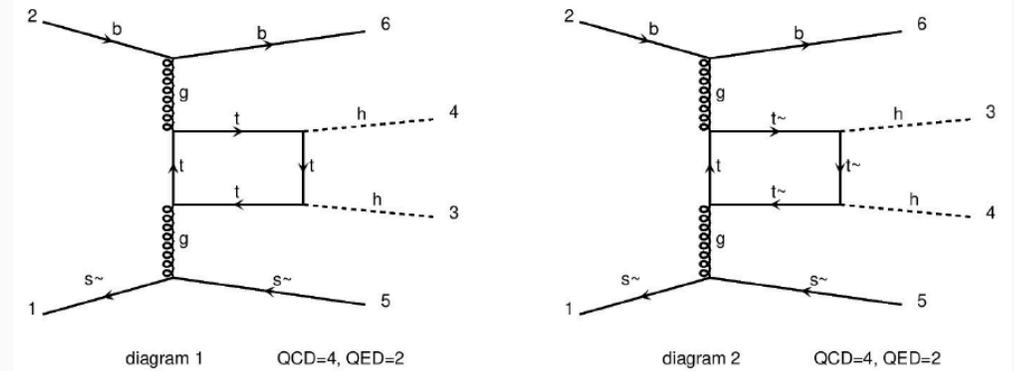


Note on HEFT Model

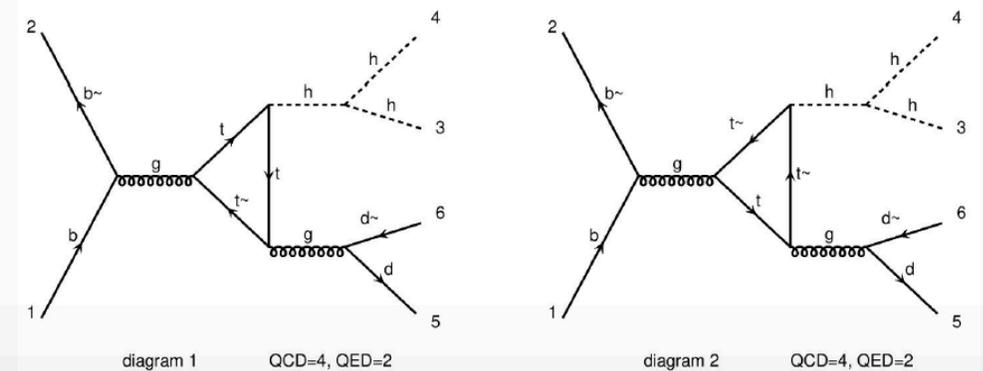
- What we learnt so far, **Sherpa** does not automatically generate loop-induced phase space; [using external libraries](#) from HEFT model.



VBF

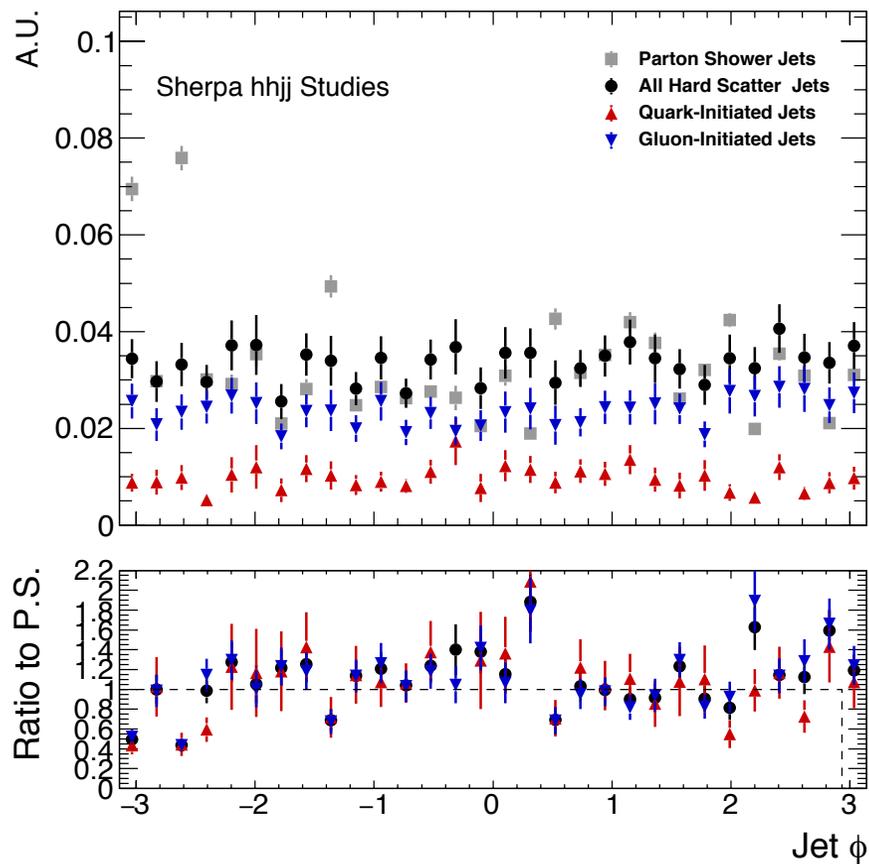
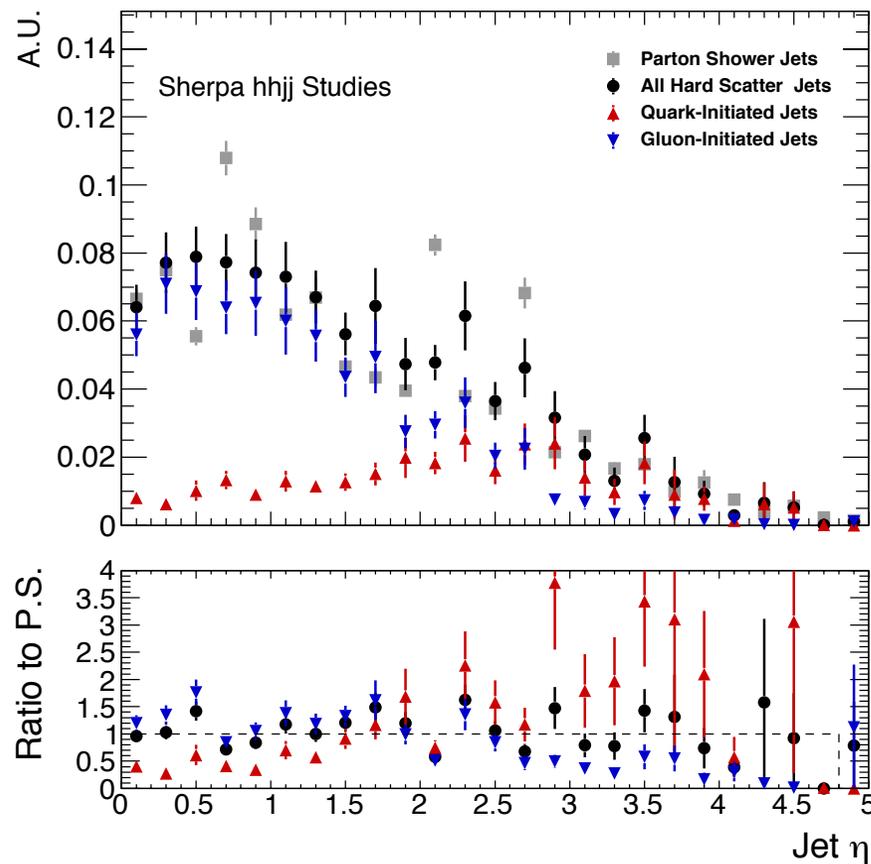


ggF



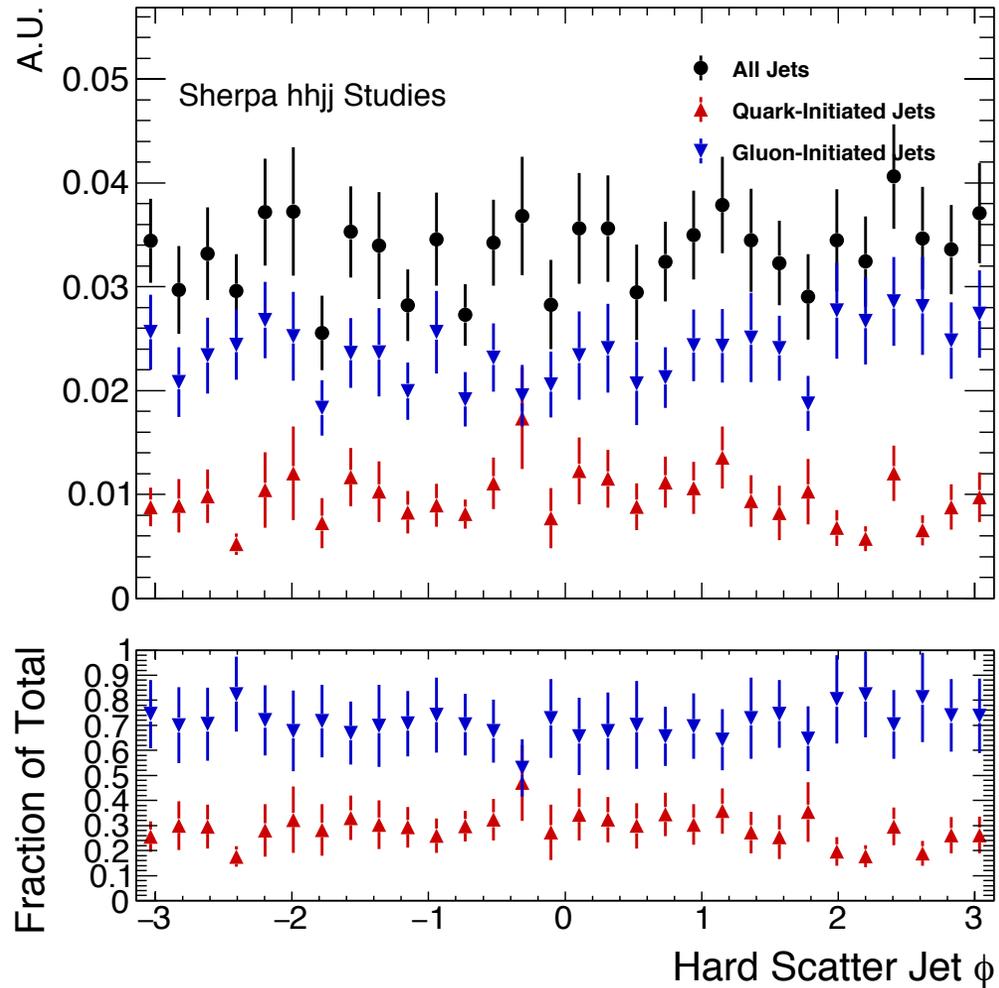
Hard Scatter vs. Parton Shower Jets

η and ϕ



- Some very strange behavior in the PS distributions
- More investigation needed before drawing conclusions

Sanity Check: Quark/Gluon Jet ϕ



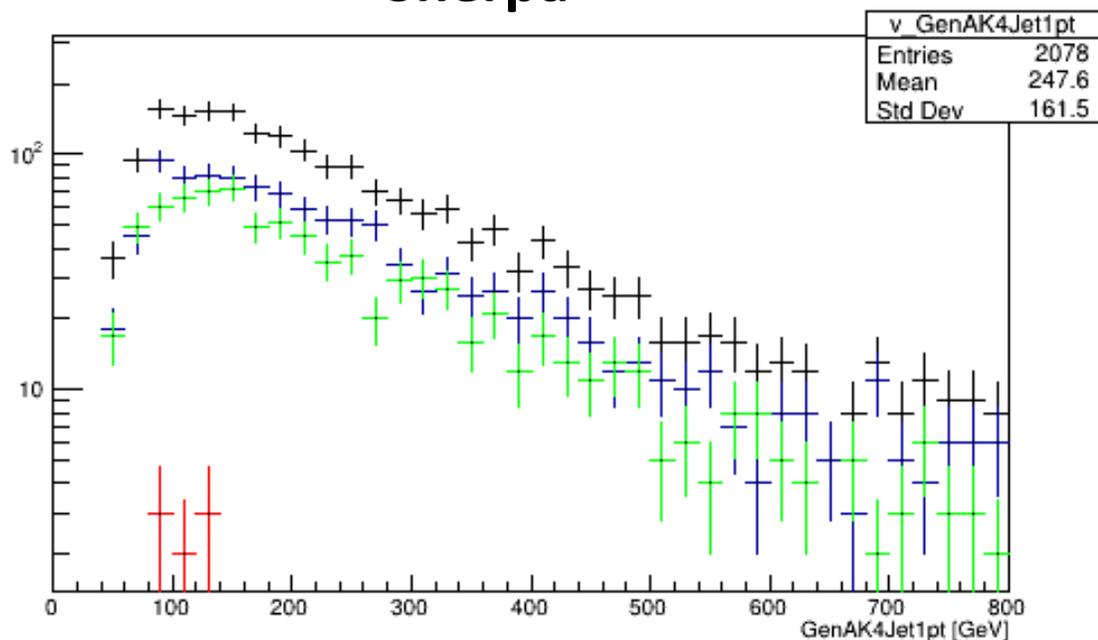
Jet Flavor Content Comparison

Leading Jet p_T

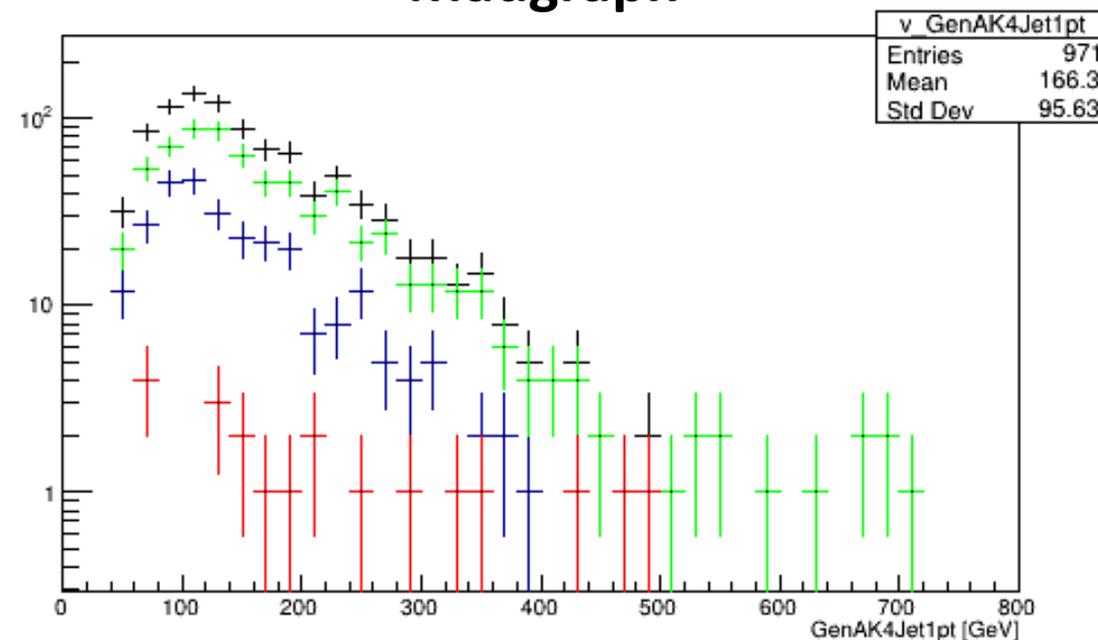
- Significantly more gluon-initiated jets in Sherpa than in Madgraph
- Very few heavy quark jets
- Harder jets from Sherpa sample

Black: total distribution
Blue: gluon-initiated
Green: light quark
Red: heavy quark

Sherpa



Madgraph

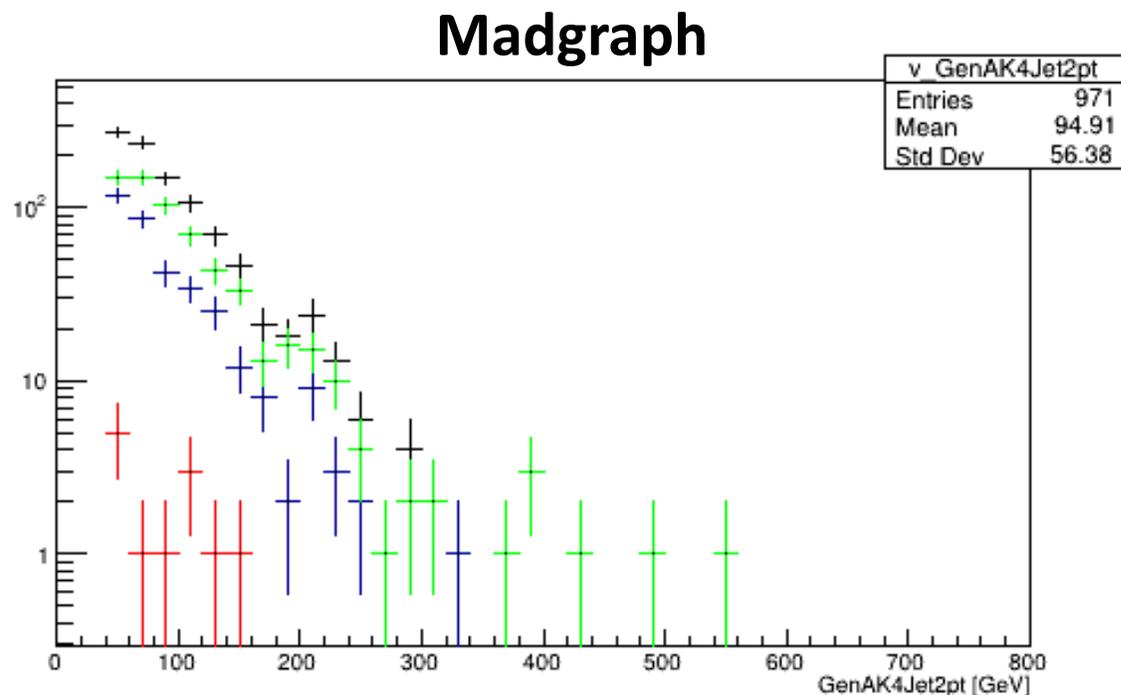
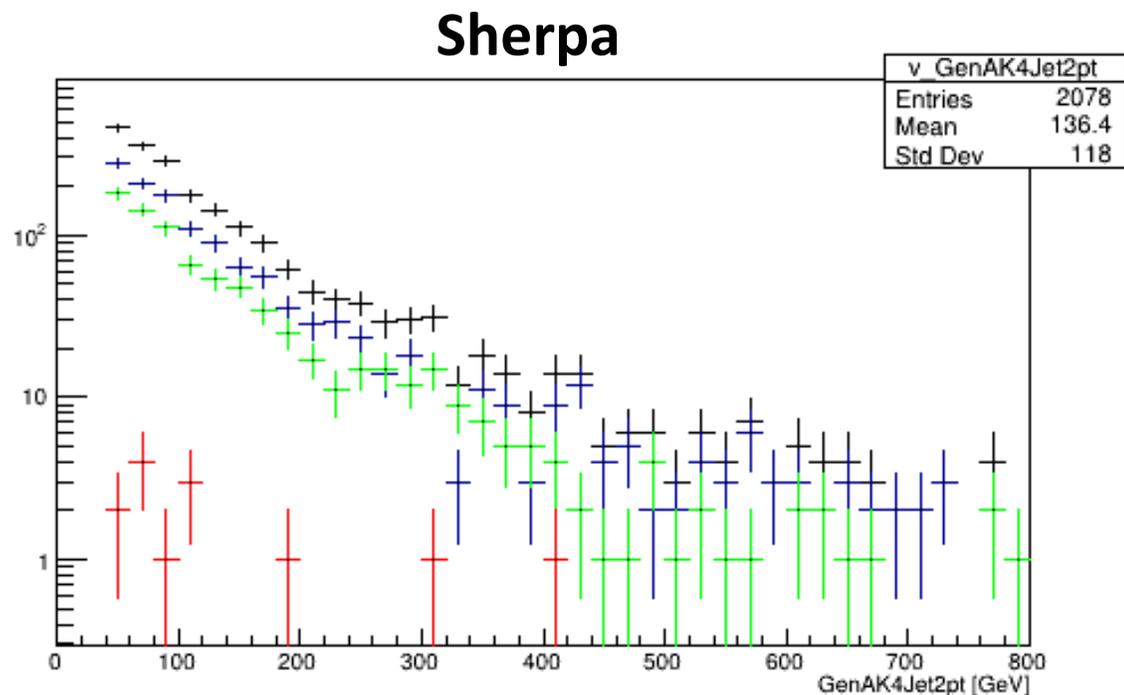


Jet Flavor Content Comparison

Subleading Jet p_T

- Also see harder subleading jets from Sherpa
- Hard to get a strong sense of difference in jet p_T depending on jet type

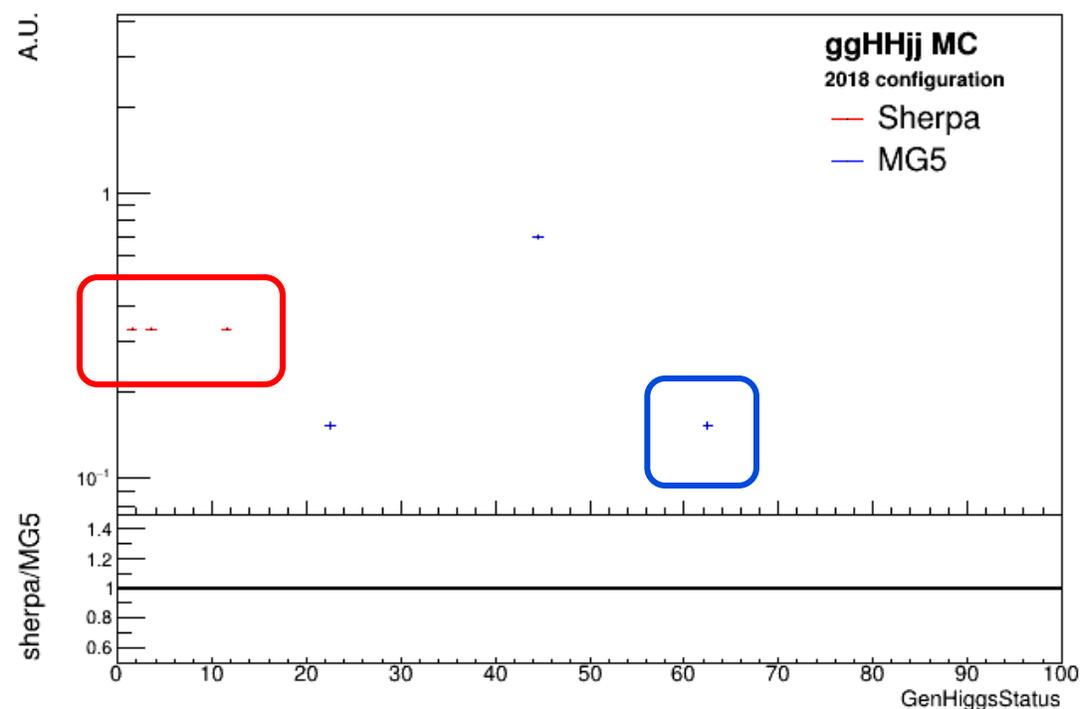
Black: total distribution
Blue: gluon-initiated
Green: light quark
Red: heavy quark



Generator Comparison

Di-Higgs Kinematics

Red: Sherpa
Blue: MG5

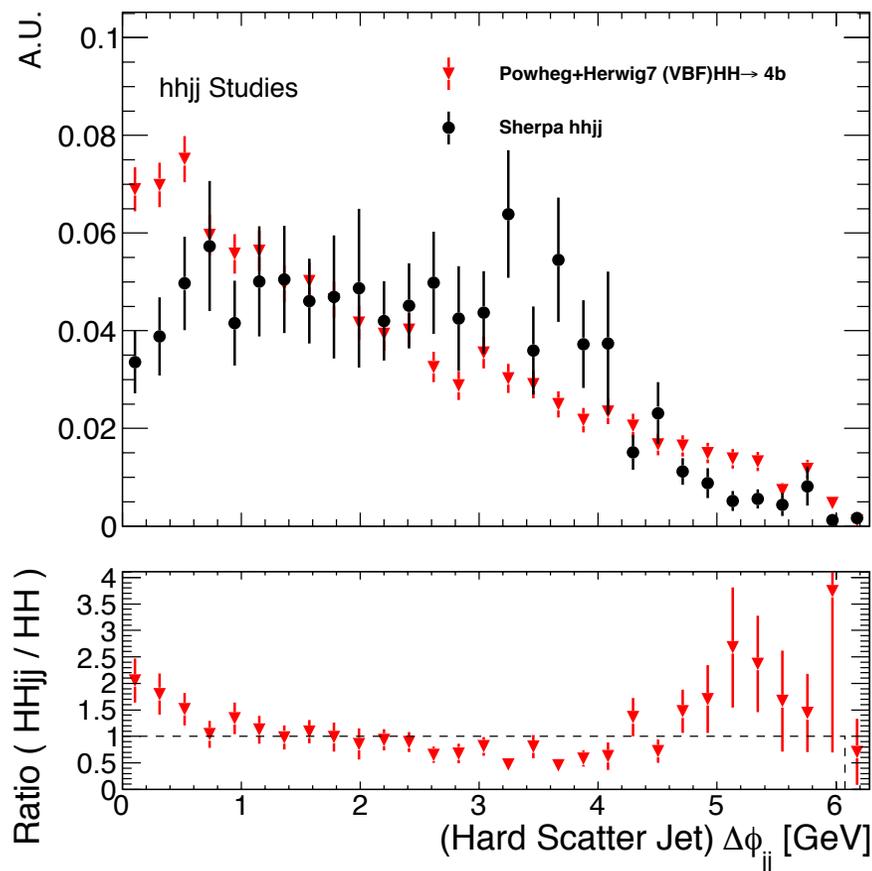
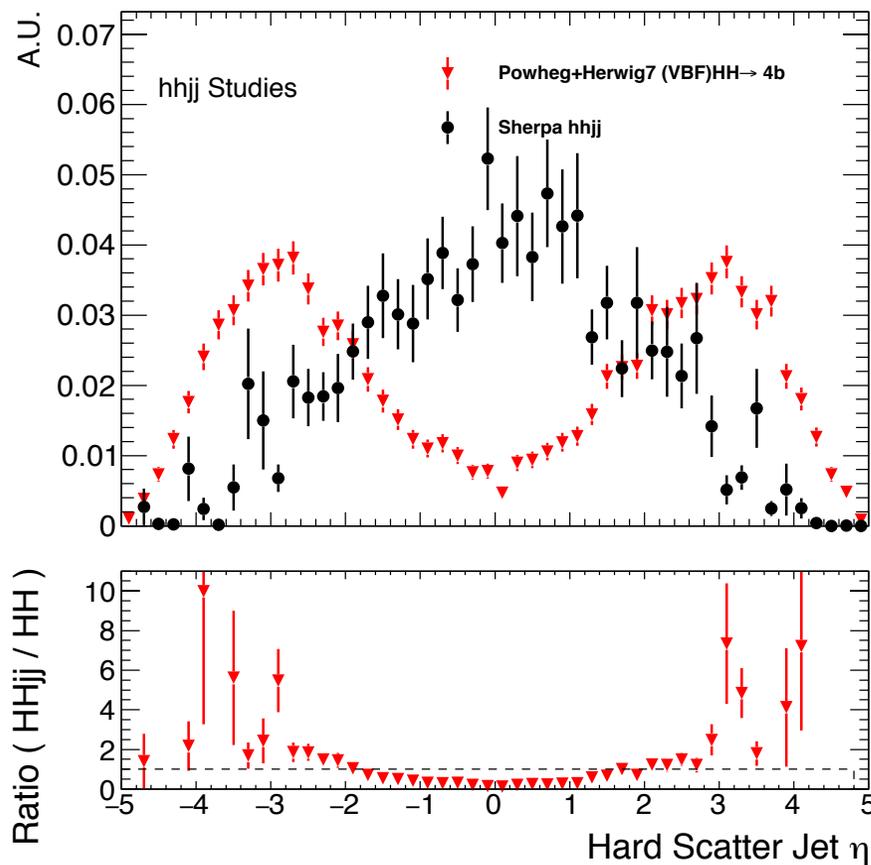


- Sherpa tends to produce low momentum Higgs compared to MG5, consistent with the observation on angular difference between two Higgs
- Maybe taking the wrong Higgs in the decay chain (Sherpa)?

0	null entry
1	particle not decayed or fragmented, represents the final state as given by the generator
2	decayed or fragmented entry (i.e. decayed particle or parton produced in shower.)
3	identifies the "hard part" of the interaction, i.e. the partons that are used in the matrix element calculation, including immediate decays of resonances. (documentation entry, defined separately from the event history. "This includes the two incoming colliding particles and partons produced in hard interaction." [*])
4-10	undefined, reserved for future standards
11-200	at the disposal of each model builder equivalent to a null line
201-...	at the disposal of the user, in particular for event tracking in the detector

Hard Scatter vs. VBF Jets

Jet η and $\Delta\phi_{jj}$



Black = Sherpa hhjj

Red = VBF HH4b