Using Jet Substructure to Probe Exotic Higgs Decays

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based on work in collaboration with Adam Falkowski (Rutgers), David Krohn (Princeton), Jessie Shelton (Yale) and Lian-Tao Wang (Princeton).

Takeaway points

- The higgs boson may be light, below LEP bounds, with exotic decays such as
- Traditionally very hard. Will be swamped by QCD backgrounds.
- Can we use Jet substructure to "resurrect" the higgs ?
- The answer seems to be "Yes".

$$h \rightarrow \eta\eta \rightarrow gggg$$

"Buried Higgs"

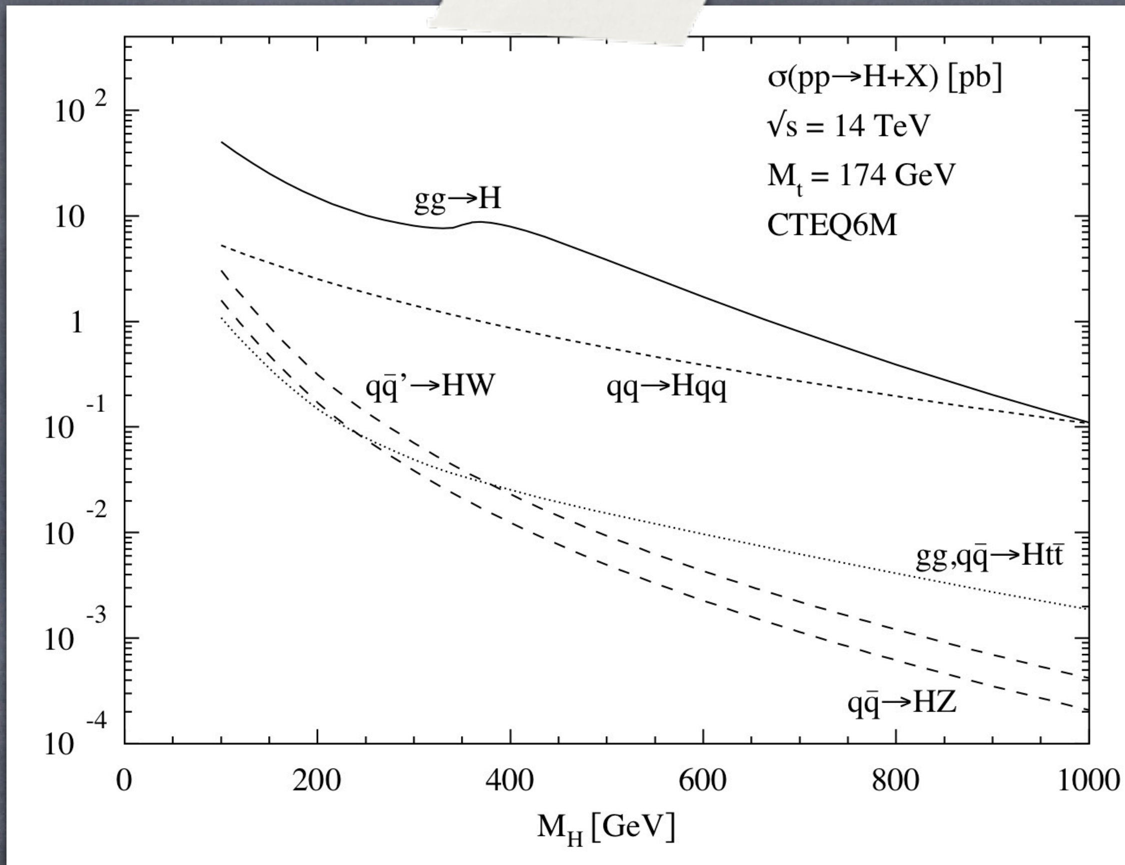
$$h \rightarrow \eta\eta \rightarrow cccc$$

"Charming Higgs"

B. Bellazzini, C. Csaki, A. Falkowski and A. Weiler (2009)

Introduction

- Discovery of the higgs boson is a key aim of the LHC.
- The higgs boson discovery will probably rely on a combination of channels like gluon fusion, vector boson fusion, associated production with tops and associated production with vector bosons.
- One of the problems that will be encountered are the large QCD backgrounds.



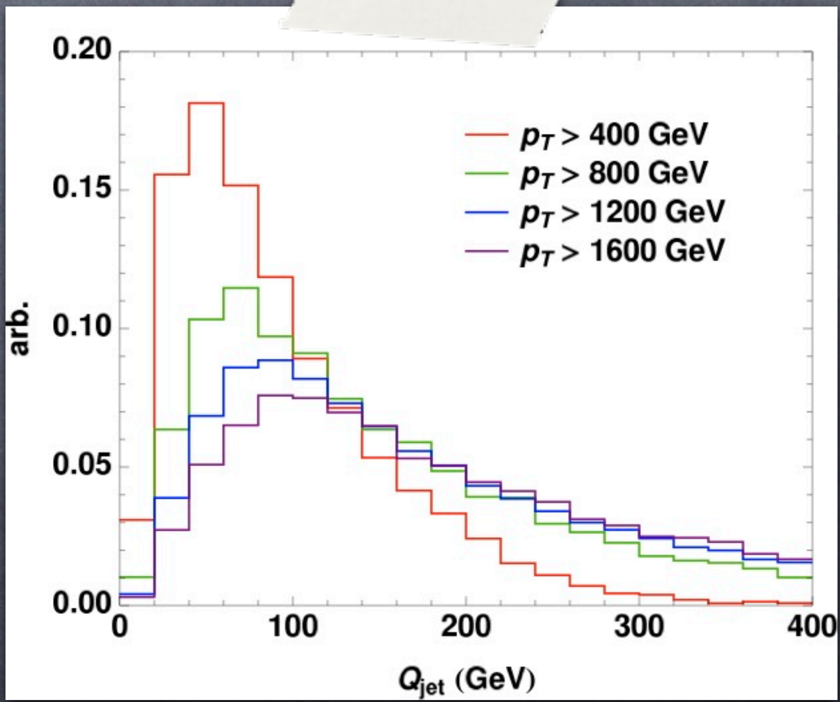
M. Spira, QCD effects in Higgs Physics (1998)

- The backgrounds may have intrinsic scales very close to the higgs mass. For instance a top pair event with a leptonically decaying W can give a b-quark with an energy very close to 65 GeV. If the other W decays along beam pipe this will look like a W+H event. (Butterworth,Davison,Rubin and Salam (2008)

$$t\bar{t} \to (bl\nu)(bl\nu)$$

- QCD dijet events can fake an expected jet invariant mass since

$$m_{jet} \sim \alpha_s P_T$$



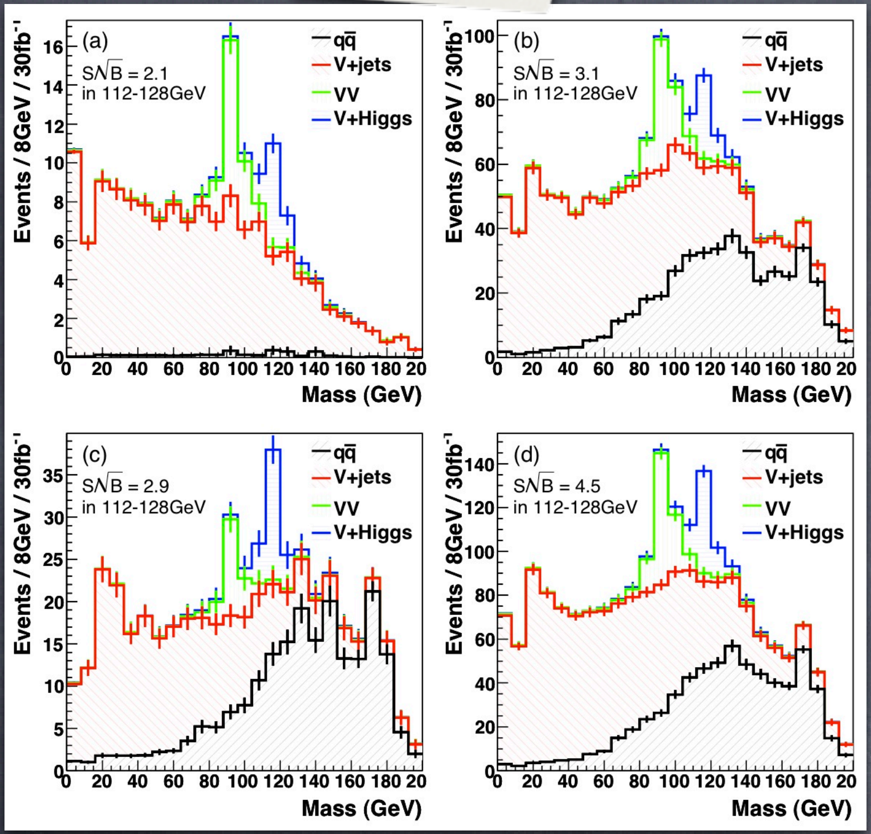
Jessie Thaler and Lian-Tao Wang (2008)

One strategy.

- Look at events in a boosted regime.
    - A boosted particle decay leads to large transverse momenta. Restrict backgrounds to a narrow region of phase space.
    - The cross-section may correspond only to a small fraction of the total cross-section though.
    - Due to the large transverse momenta the decay products will appear as a single jet ("fat jet").

- We can try to distinguish the fat jets from signal events and fat jets from background (QCD) events by looking at their Jet Substructure.
    - An observable that is a smooth functional of the energy flow distribution among the cells can define an IR-safe jet shape. (G. Sterman, 1979)
    - The "jet mass" is a simple example.
    - Another example in the parton shower approximation is the "energy sharing" variable

$$z_X = \min(E_A, E_B)/E_X$$

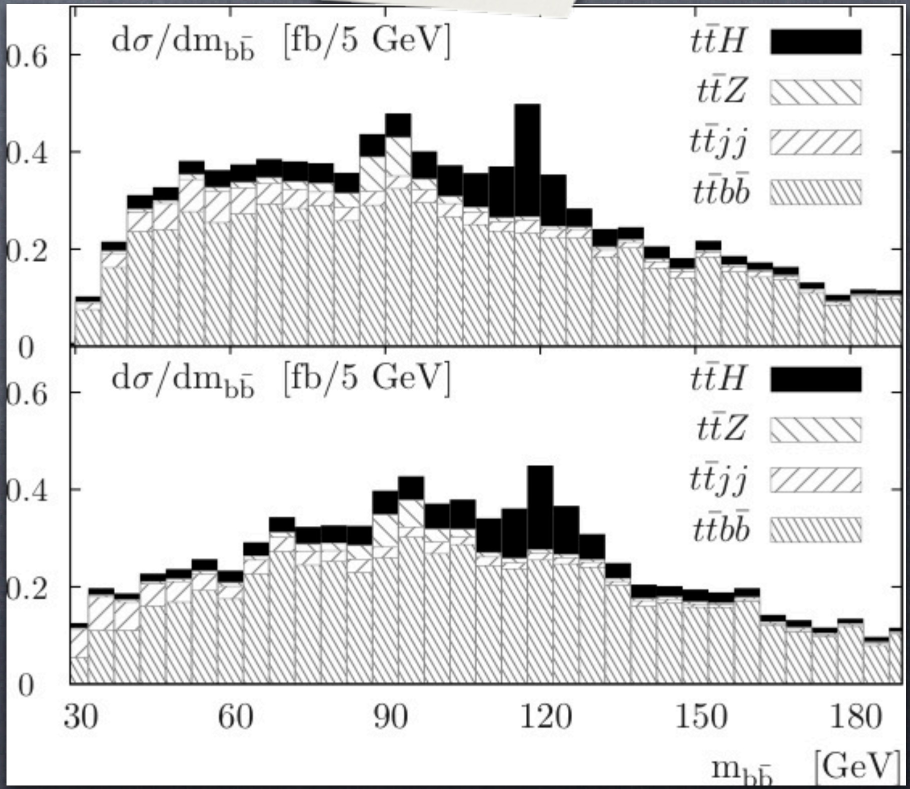


$$V + H \rightarrow (ll/l\nu)\,(b\bar{b})$$

Butterworth,Davison,Rubin and Salam (2008)

$$pp \rightarrow t\bar{t}H \rightarrow t\bar{t}\; b\bar{b}$$

Plehn, Salam and Spannowsky (2009)



What about more exotic decay channels ?

- It is not necessary for the Higgs to be as heavy as 114 GeV if it decays in a non standard way. (Dermisek and Gunion (2005))
  (B.A.Dobrescu and K.T.Matchev (2000))
- This may happen if the higgs decays into a pair of light singlet pseudo scalars.
- Assuming SM production cross sections, for the 4 tau decay channel the LEP bound can be as low as about 86 GeV or as much as 110 GeV for the 4 b quark final state. (S. Schael (2006))
  (S. Chang, R. Dermisek, J.F. Gunion and N. Weiner (2008))
- The above ideas can be naturally realized in "double-protection" or "super-little higgs" models.

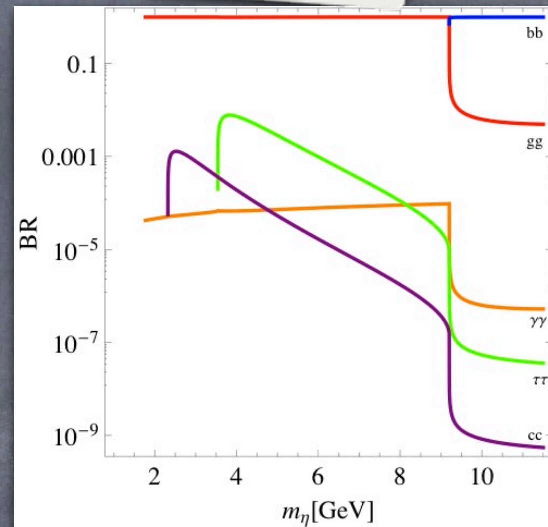
(A. Birdel, Z. Chacko, M.K. Gillard (2004); P.H. Chankoski, A. Falkowski, S. Pokorski, J. Wagner (2004); T.S.Roy, M. Schmaltz (2006); C. Csaki, G. Marandella, Y. Shirman, A. Strumia (2006); B. Bellazzini, C. Csaki, A. Delgado , A. Weiler (2009))

"Buried" Higgs and "Charming" Higgs

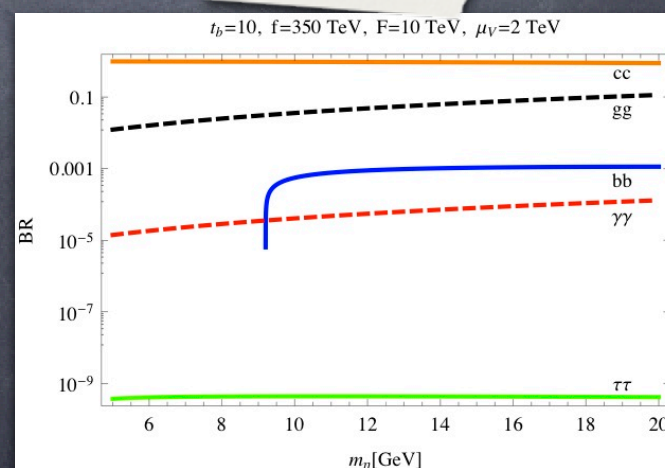
$h \to \eta\eta \to gggg$ "Buried Higgs"

B. Bellazzini, C. Csaki, A. Falkowski and A. Weiler (2009)

$h \to \eta\eta \to cccc$ "Charming Higgs"



- With the higgs decaying to 4 jets the higgs could be as light as 78 GeV without being detected at LEP.
- The true higgs would be deeply buried in the QCD background. Would have been missed at LEP and would be hard to see at the Tevatron or LHC.
- Hard channels. But can we use the techniques of jet substructure to "unbury" the higgs ?



- Let us look specifically at W+H with four gluon final states
  - The kinematic cuts :

$$
\begin{aligned}
P_T^{\text{jet}} &> 200\,\text{GeV} \\
P_T^{\text{l}} &> 30\,\text{GeV} \\
y_l &< 2.5 \\
|m_{\text{jet}} - m_h| &< 10\,\text{GeV}
\end{aligned}
$$

  - We need something to replace b-tagging
    - We expect to see two smaller subjets inside the fat jet of equal masses.
    - Since these pseudoscalar subjets are color singlets we expect minimal color dipole stretching across the jet and inter-subjet radiation should be less compared to a QCD fat jet.

- To this end we define two variables to quantify
  - The subjet mass equality
  - Radiation outside the subjets

$$\alpha = \min\left[\frac{m(j_1)}{m(j_2)}, \frac{m(j_2)}{m(j_1)}\right],$$

$$\beta = \frac{p_T(j_3)}{p_T(j)}.$$

- Generate cell events to include detector coarse graining.

- Cluster events with R=1.0 (for 80 GeV & 100 GeV higgs case) and R=1.2 (120 GeV higgs case) cone sizes using the Kt algorithm.

  M. Cacciari, G.P. Salam, G. Soyez , (FastJet)

- Define subjets for jet substructure analysis using anti-Kt algorithm and R=0.3 cone size.

- Generate backgrounds in Pythia 6.403. T. Sjostrand, S. Mrenna and P. Skands (1996)

- Include effects due to pile-ups and multiple interactions.
- Partially optimize the cuts.
- Use a filtering procedure to clean the jet of ISR/MI/pile-up contamination. We have used "jet-trimming" with Rs=0.2 and fc=0.03. But a procedure such as "jet-pruning" should also work.

  D. Krohn, J. Thaler and Lian-Tao Wang (2009)
  S.D.Ellis, C.K.Vermilion and J.R. Walsh (2009)

- One caveat is that any filtering procedure should be applied after a cut on the radiation outside the subjets variable.

Results

Cut	Range	S [fb]	B[fb]	S/B	$S/\sqrt{B}$ @ 100 fb^{-1}
p_T	> 200 GeV	$1.9 \cdot 10^1$	$3.3 \cdot 10^4$	$5.9 \cdot 10^{-4}$	1.1
m_j	$70 \leftrightarrow 90$ GeV	$1.3 \cdot 10^1$	$1.9 \cdot 10^3$	$6.9 \cdot 10^{-3}$	3.0
α	> 0.7	$6.3 \cdot 10^0$	$3.6 \cdot 10^2$	$1.7 \cdot 10^{-2}$	3.3
β	$< 5 \cdot 10^{-3}$	$9.1 \cdot 10^{-1}$	$4.9 \cdot 10^0$	$1.9 \cdot 10^{-1}$	4.1

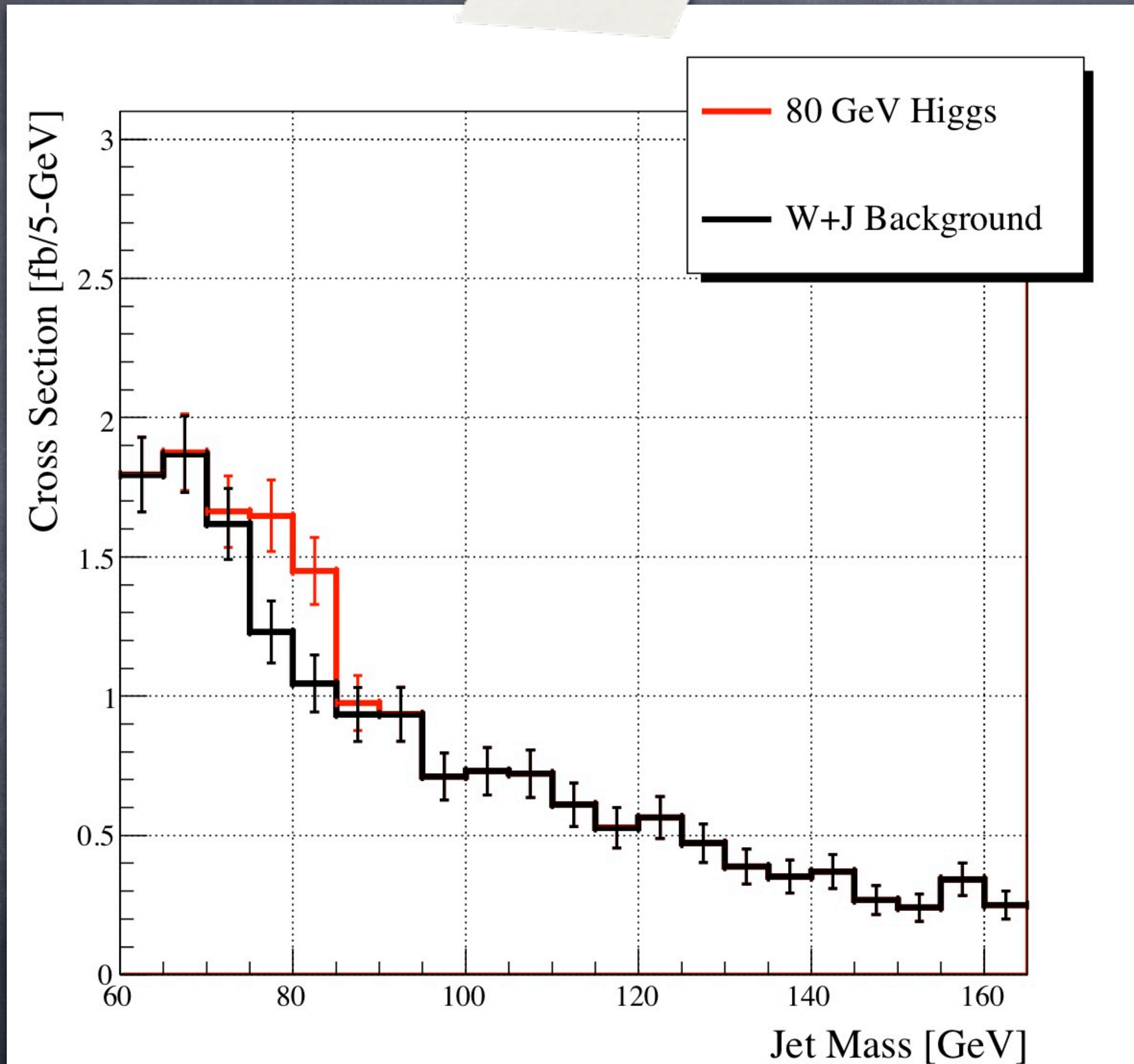
Table 1: $m_H = 80$ GeV, $R = 1.0$

Cut	Range	S [fb]	B[fb]	S/B	$S/\sqrt{B}$ @ 100 fb^{-1}
p_T	> 200 GeV	$1.7 \cdot 10^1$	$3.3 \cdot 10^4$	$5.1 \cdot 10^{-4}$	0.9
m_j	$90 \leftrightarrow 110$ GeV	$1.0 \cdot 10^1$	$1.1 \cdot 10^3$	$9.5 \cdot 10^{-3}$	3.1
α	> 0.7	$5.1 \cdot 10^0$	$2.7 \cdot 10^2$	$1.9 \cdot 10^{-2}$	3.1
β	$< 5 \cdot 10^{-3}$	$8.2 \cdot 10^{-1}$	$3.1 \cdot 10^0$	$2.7 \cdot 10^{-1}$	4.7

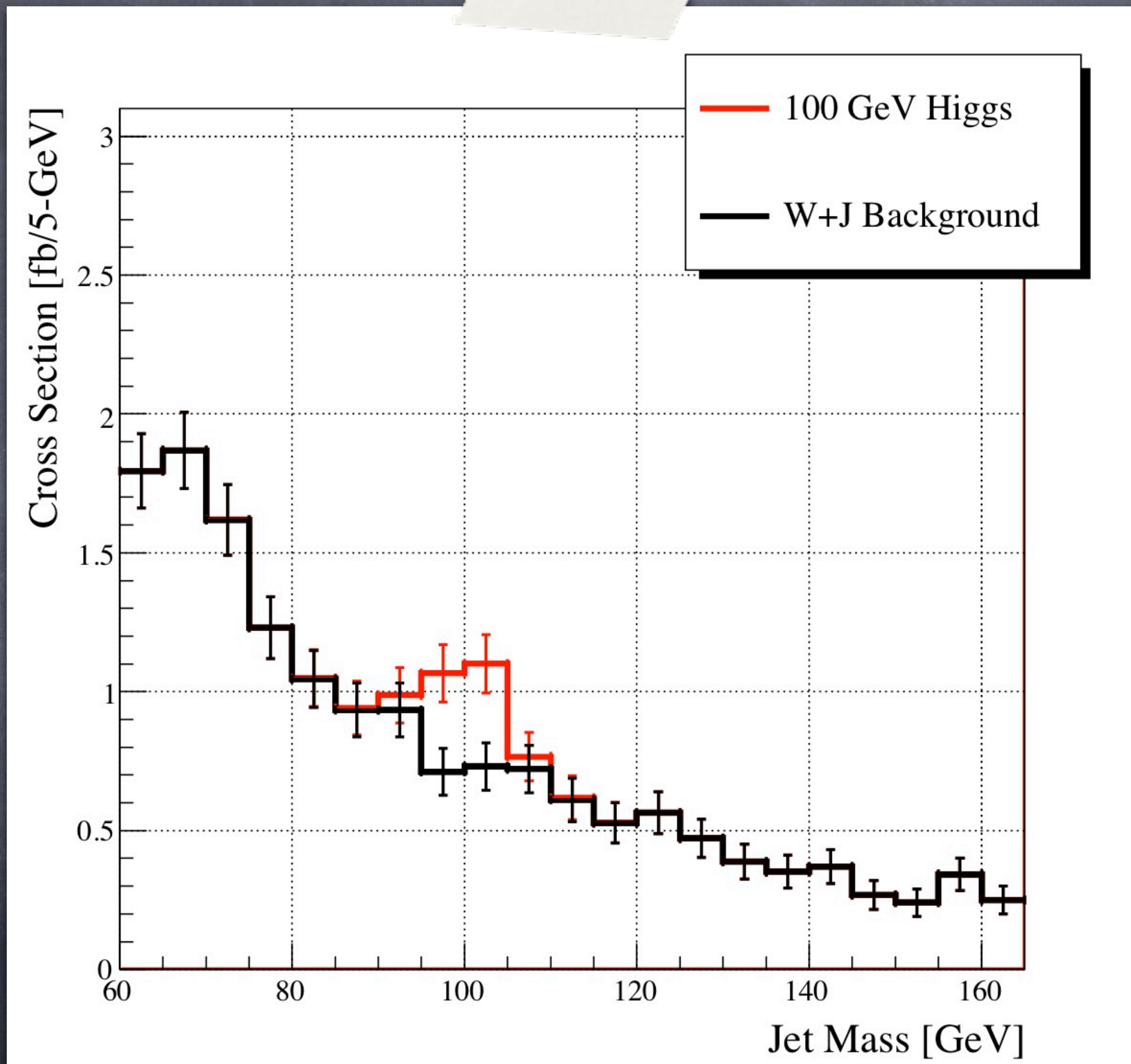
Table 2: $m_H = 100$ GeV, $R = 1.0$

Cut	Range	S [fb]	B[fb]	S/B	$S/\sqrt{B}$ @ 100 fb^{-1}
p_T	> 200 GeV	$1.3 \cdot 10^1$	$3.3 \cdot 10^4$	$4.1 \cdot 10^{-4}$	0.7
m_j	$110 \leftrightarrow 130$ GeV	$7.6 \cdot 10^0$	$5.3 \cdot 10^2$	$1.4 \cdot 10^{-2}$	3.3
α	> 0.7	$4.0 \cdot 10^0$	$1.6 \cdot 10^2$	$2.5 \cdot 10^{-2}$	3.1
β	$< 7 \cdot 10^{-3}$	$7.8 \cdot 10^{-1}$	$3.6 \cdot 10^0$	$2.2 \cdot 10^{-1}$	4.1

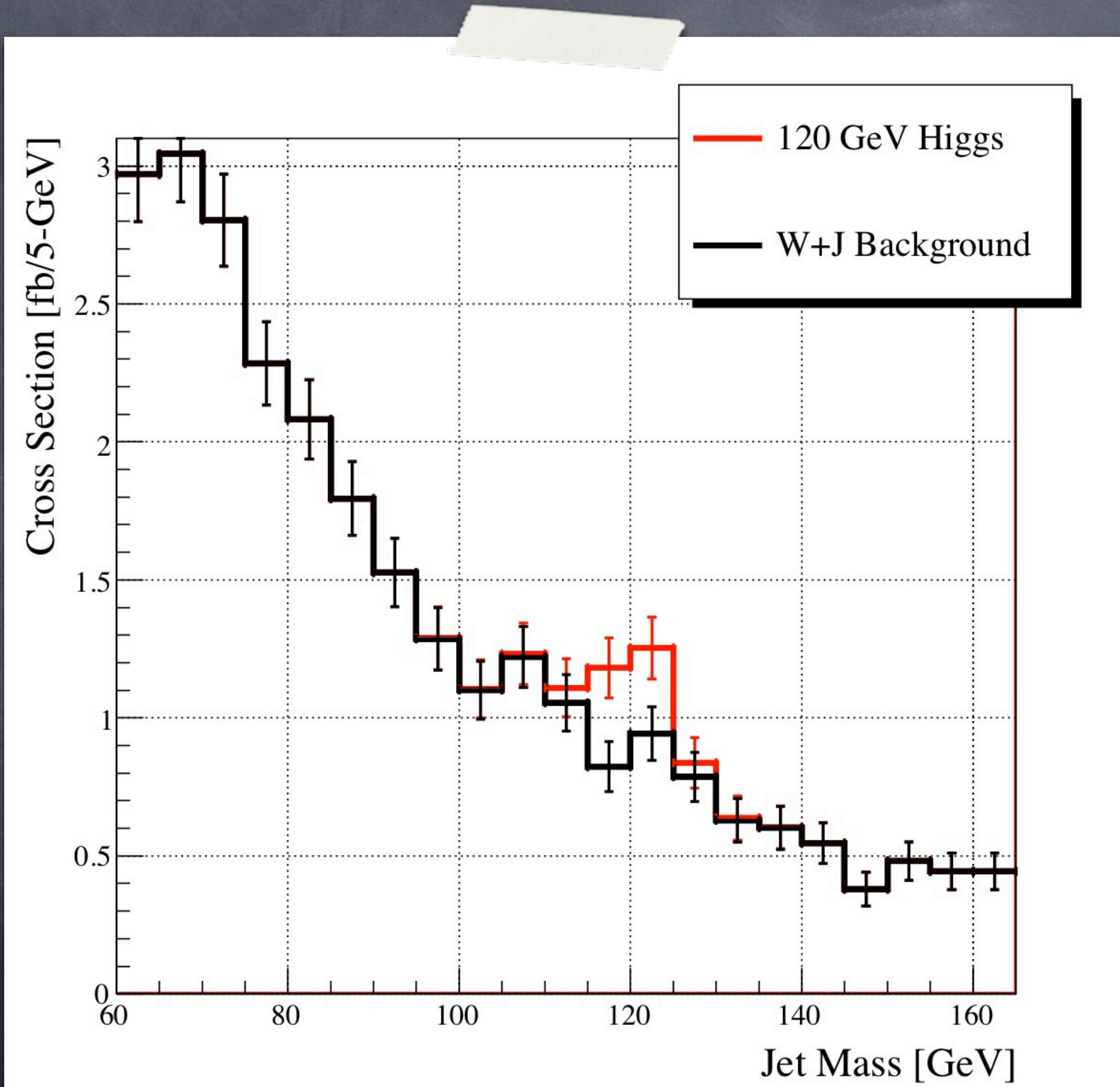
Table 3: $m_H = 120$ GeV, $R = 1.2$



80 GeV Higgs
W+J Background
Cross Section [fb/5-GeV]
3
2.5
2
1.5
1
0.5
0
60
80
100
120
140
160
Jet Mass [GeV]



100 GeV Higgs
W+J Background
Cross Section [fb/5-GeV]
0
0.5
1
1.5
2
2.5
3
60
80
100
120
140
160
Jet Mass [GeV]


120 GeV Higgs
W+J Background
Cross Section [fb/5-GeV]
3
2.5
2
1.5
1
0.5
0
60
80
100
120
140
160
Jet Mass [GeV]

Summary

- Jet Substructure is a powerful tool that can play a valuable role in higgs searches at the LHC.
- We have looked specifically at an exotic higgs decay channel in V+H and ttbar+H.
- The results look promising and reiterates the utility of jet substructure studies.

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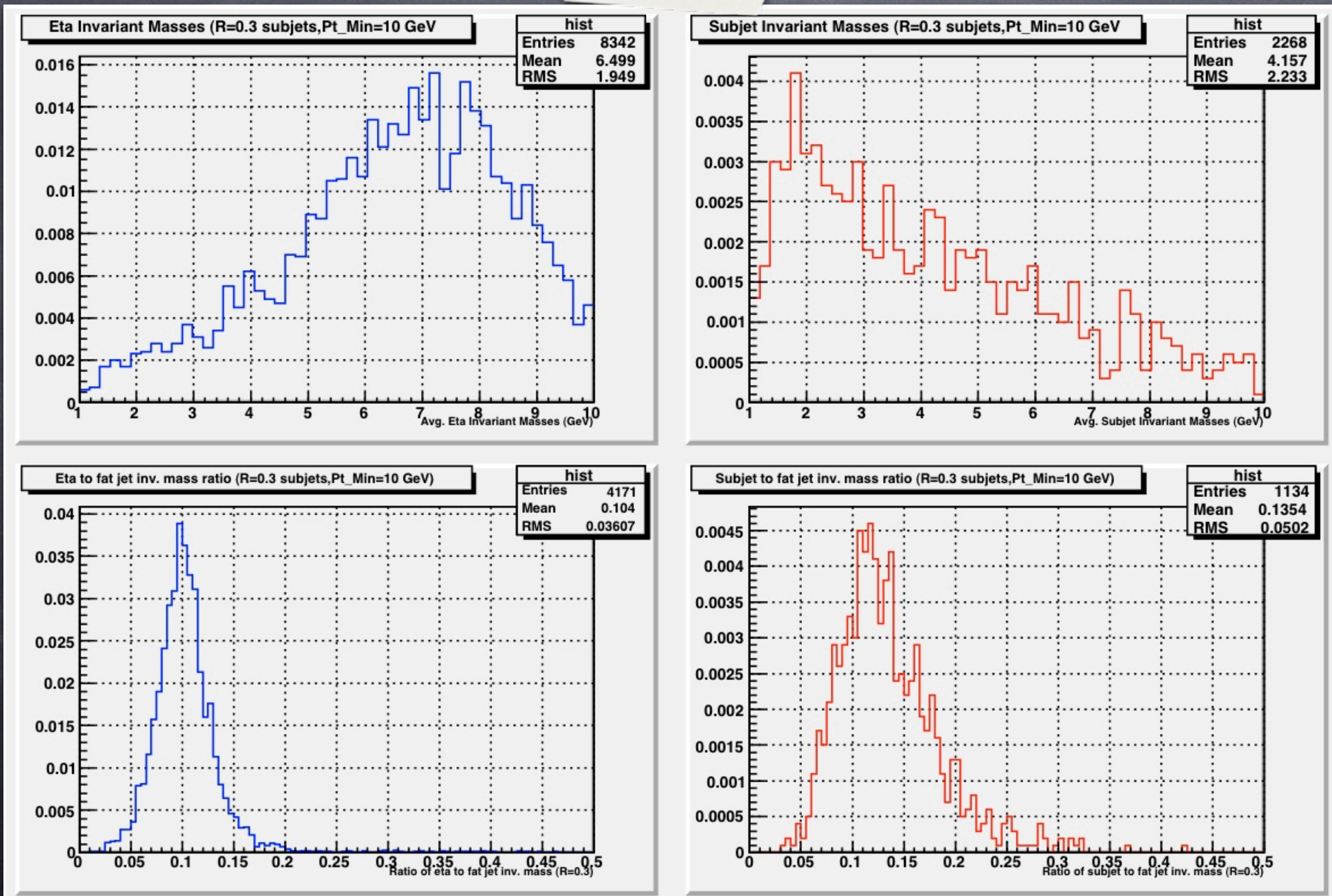
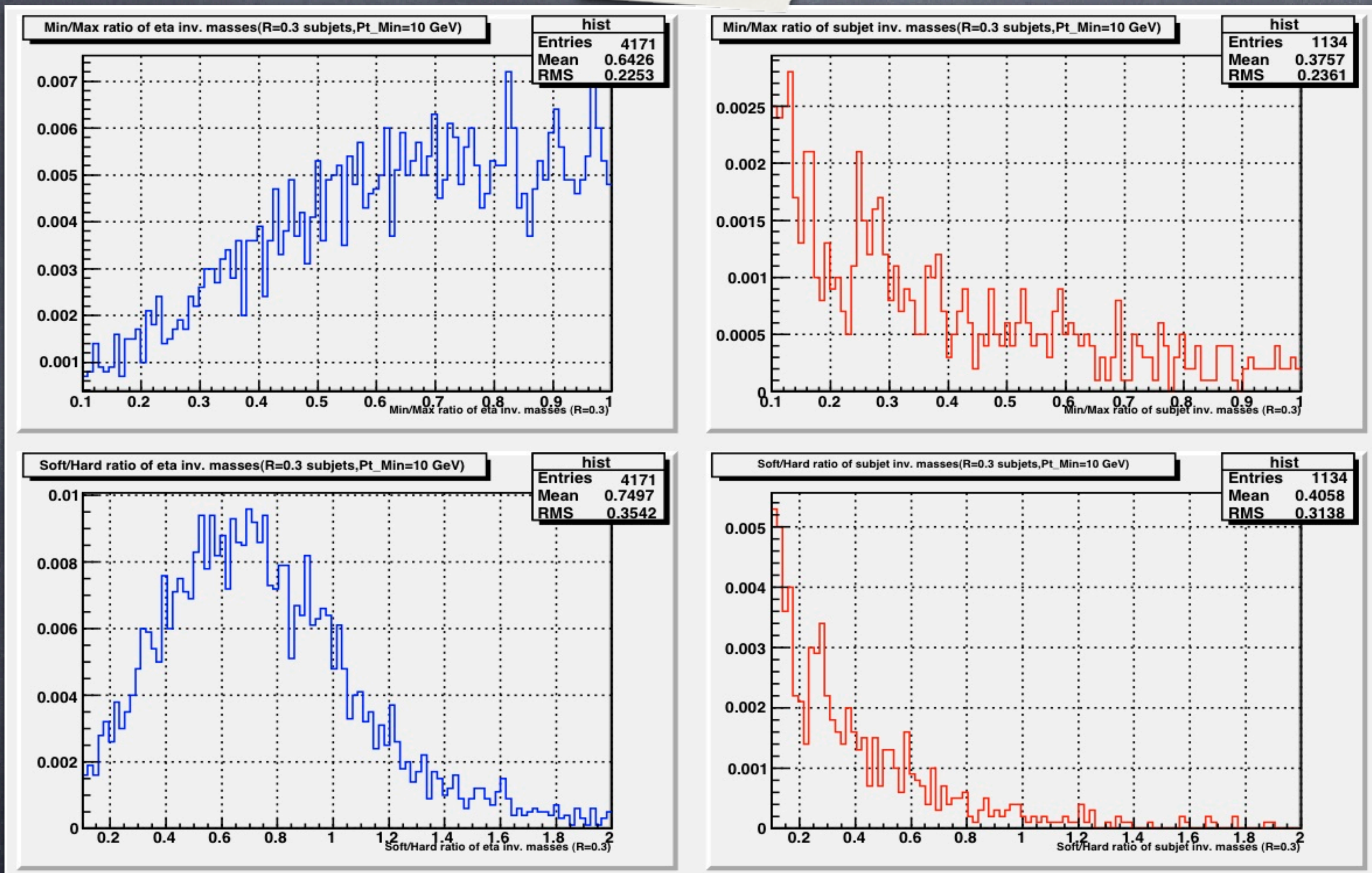
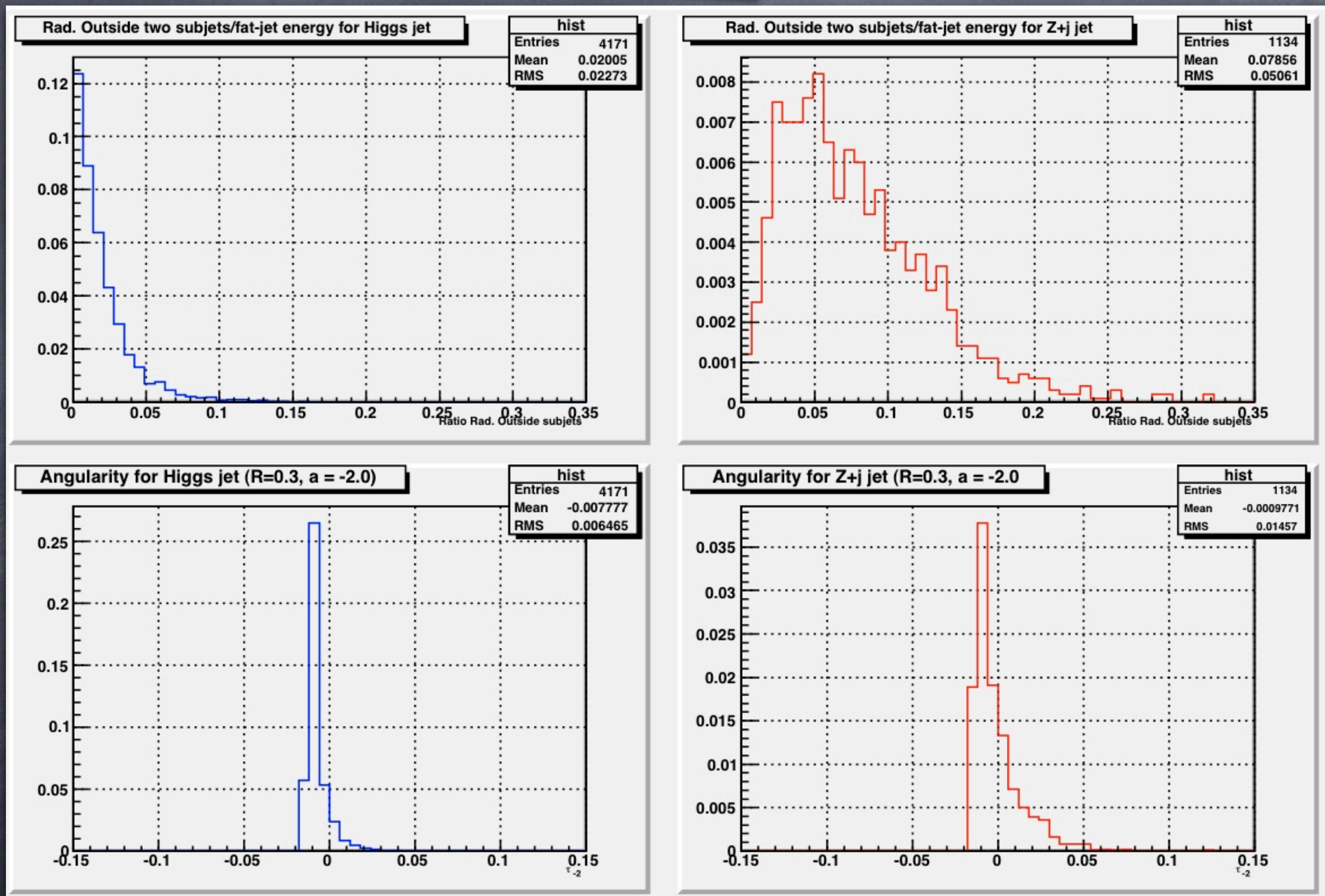
Backup slides

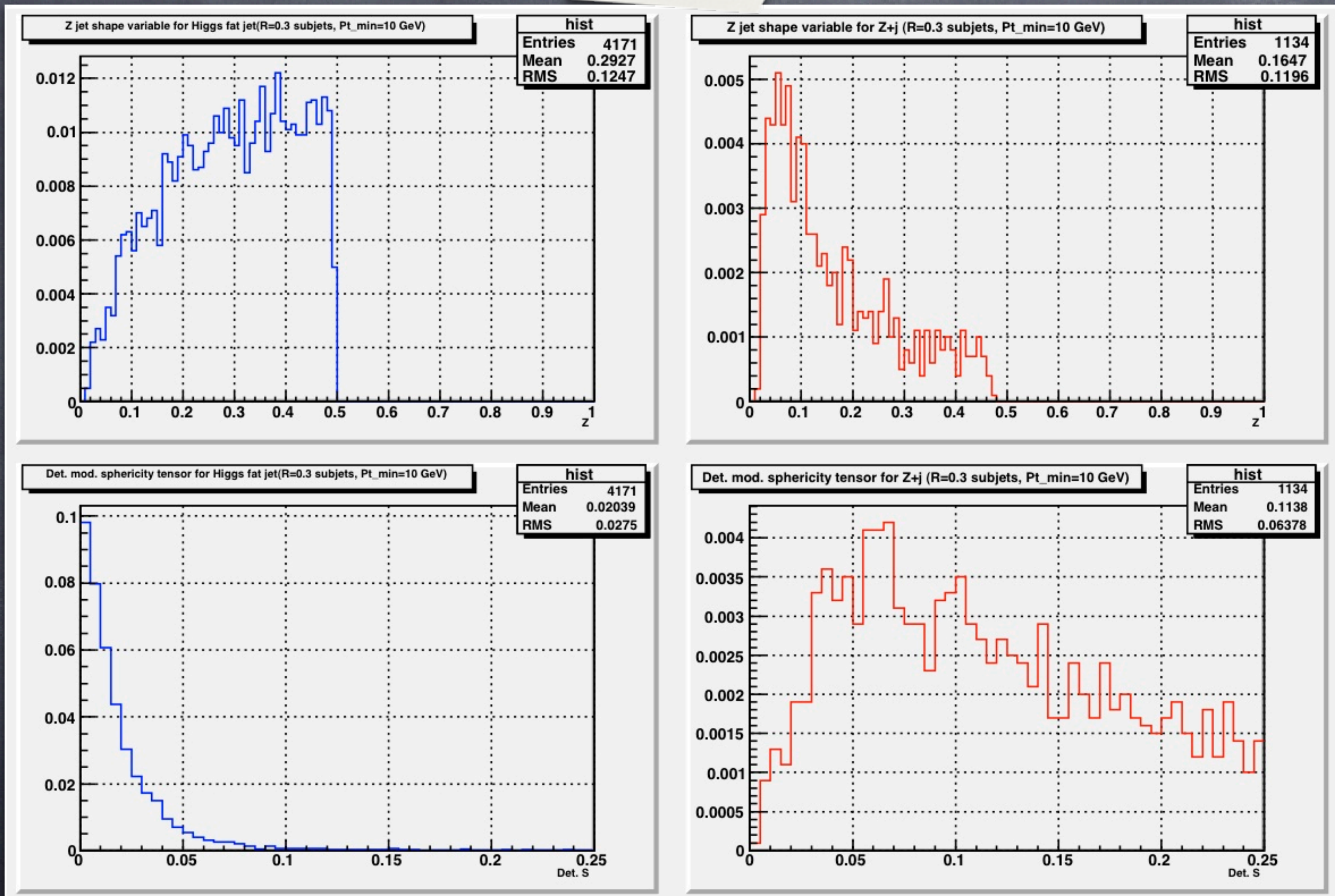




Min/Max ratio of eta inv. masses(R=0.3 subjets,Pt_Min=10 GeV)
hist
Entries 4171
Mean 0.6426
RMS 0.2253
Min/Max ratio of eta inv. masses (R=0.3)
Min/Max ratio of subjet inv. masses(R=0.3 subjets,Pt_Min=10 GeV)
hist
Entries 1134
Mean 0.3757
RMS 0.2361
Min/Max ratio of subjet inv. masses (R=0.3)
Soft/Hard ratio of eta inv. masses(R=0.3 subjets,Pt_Min=10 GeV)
hist
Entries 4171
Mean 0.7497
RMS 0.3542
Soft/Hard ratio of eta inv. masses (R=0.3)
Soft/Hard ratio of subjet inv. masses(R=0.3 subjets,Pt_Min=10 GeV)
hist
Entries 1134
Mean 0.4058
RMS 0.3138
Soft/Hard ratio of subjet inv. masses (R=0.3)



Rad. Outside two subjets/fat-jet energy for Higgs jet
hist
Entries 4171
Mean 0.02005
RMS 0.02273
Ratio Rad. Outside subjets
Rad. Outside two subjets/fat-jet energy for Z+j jet
hist
Entries 1134
Mean 0.07856
RMS 0.05061
Ratio Rad. Outside subjets
Angularity for Higgs jet (R=0.3, a = -2.0)
hist
Entries 4171
Mean -0.007777
RMS 0.006465
Angularity for Z+j jet (R=0.3, a = -2.0
hist
Entries 1134
Mean -0.0009771
RMS 0.01457


Z jet shape variable for Higgs fat jet(R=0.3 subjets, Pt_min=10 GeV)
hist
Entries 4171
Mean 0.2927
RMS 0.1247
z
Z jet shape variable for Z+j (R=0.3 subjets, Pt_min=10 GeV)
hist
Entries 1134
Mean 0.1647
RMS 0.1196
z
Det. mod. sphericity tensor for Higgs fat jet(R=0.3 subjets, Pt_min=10 GeV)
hist
Entries 4171
Mean 0.02039
RMS 0.0275
Det. S
Det. mod. sphericity tensor for Z+j (R=0.3 subjets, Pt_min=10 GeV)
hist
Entries 1134
Mean 0.1138
RMS 0.06378
Det. S

Jet-Algorithms

$$\rho_{ij} = \min\left[(p_T^i)^{2k}, (P_T^j)^{2k}\right] \frac{R_{ij}^2}{R_0^2}$$

$$\rho_i = (p_T^i)^{2k}$$