# ATLAS bHbb Analysis

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SLAC/Stanford ATLAS and Theory Joint Jamboree Session

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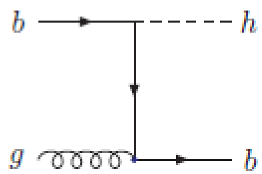
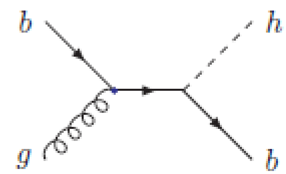
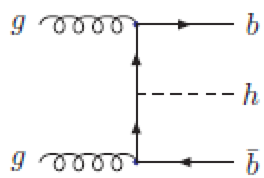
The ATLAS bHbb analysis is a search for BSM Higgs and H(125) production in association with one or two b-jets (called tag b-jets) followed by H $\rightarrow \boldsymbol{b\bar{b}}$ . QCD background is suppressed by requiring the detection of one or two tag b-jets in addition to the two b-jets from the Higgs decay. A signal event consists of Higgs decay b-jets 1 & 2 with $\boldsymbol{p}_{T1}, \boldsymbol{p}_{T2} \approx \dfrac{\boldsymbol{M}_H}{2}$, and one or two tag b-jets with 20 GeV < $\boldsymbol{p}_{T\,tag} < \min(\boldsymbol{p}_{T1}, \boldsymbol{p}_{T2})$.

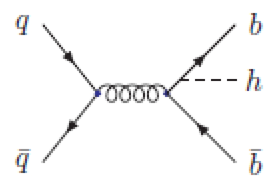
In the 5 flavor scheme (5FS) the following processes lead to $\boldsymbol{b\bar{b}}$ fusion production of Higgs in association with one or two b-jets:




3 b-jet final state if $\boldsymbol{h} \rightarrow \boldsymbol{b\bar{b}}$




4 b-jet final state if $\boldsymbol{h} \rightarrow \boldsymbol{b\bar{b}}$

# General 2HDM Couplings

Table 1 Tree-level fermion couplings of the $H$ and $A$ bosons in the 2HDM subject to symmetries that suppress FCNC. The couplings are normalized to the SM values and are given in the limit that the couplings of the light scalar boson $h$ are SM-like. Here $U$, $D$, and $E$ refer to up-type quarks, down-type quarks and charged leptons, respectively, and $\tan\beta$ is the ratio of the vacuum expectation values of the two scalar doublets.

| | $H\overline{U}U$ | $H\overline{D}D$ | $H\overline{E}E$ | $iA\overline{U}\gamma_5 U$ | $iA\overline{D}\gamma_5 D$ | $iA\overline{E}\gamma_5 E$ |
|---|---|---|---|---|---|---|
| | $\xi_H^u$ | $\xi_H^d$ | $\xi_H^e$ | $\xi_A^u$ | $\xi_A^d$ | $\xi_A^e$ |
| Type I | $-\cot\beta$ | $-\cot\beta$ | $-\cot\beta$ | $-\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| Type II (MSSM like) | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ | $-\tan\beta$ | $-\tan\beta$ |
| Type III (lepton specific) | $-\cot\beta$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\cot\beta$ | $-\tan\beta$ |
| Type IV (flipped) | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $-\cot\beta$ | $-\tan\beta$ | $\cot\beta$ |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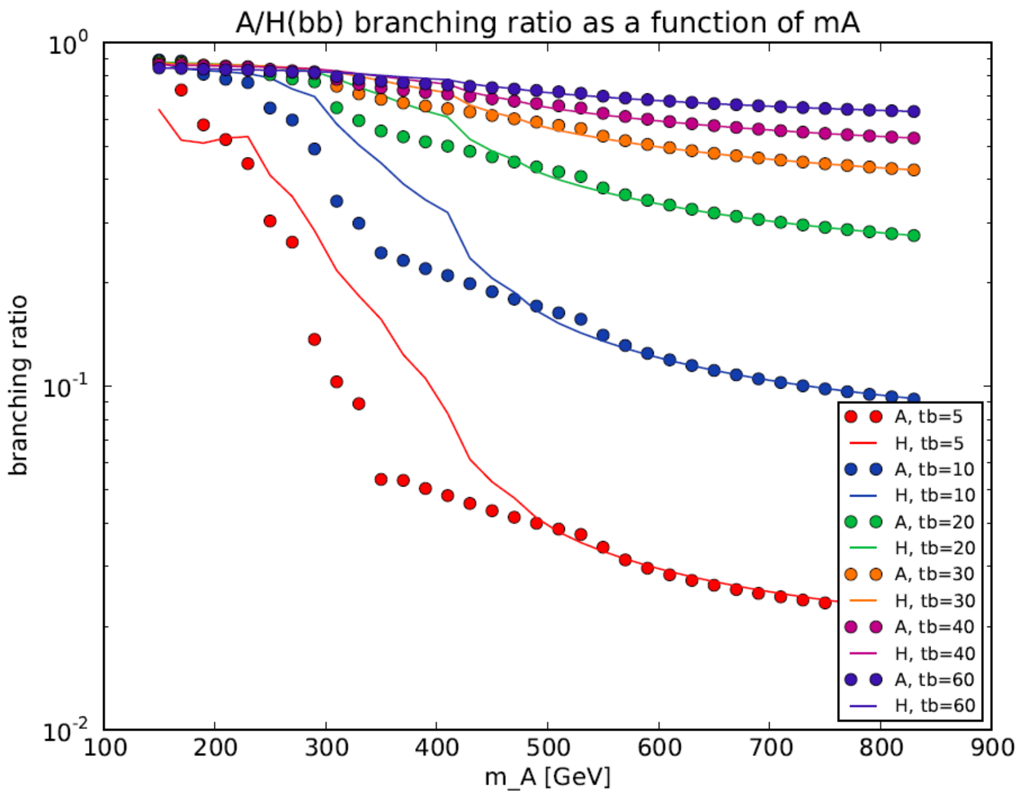
# Run 1 Analysis

*PhD thesis of Katie Malone with help from Giacinto P. , Su Dong, and T.B.*
*ATL-COM-PHYS-2014-089*

Signal MC Samples
MadgraphPythia_AUET2B_CTEQ6L1




| Dataset ID | mass (GeV) | Width (GeV) |
|---|---|---|
| 181120 | 250 | 1.68 |
| 181121 | 280 | 1.92 |
| 181122 | 310 | 2.50 |
| 181123 | 350 | 3.23 |
| 181124 | 400 | 3.93 |
| 181125 | 450 | 4.71 |
| 181126 | 500 | 5.59 |
| 181127 | 550 | 6.84 |
| 181128 | 600 | 8.11 |
| 181129 | 650 | 9.26 |
| 181130 | 700 | 10.3 |
| 181131 | 800 | 12.5 |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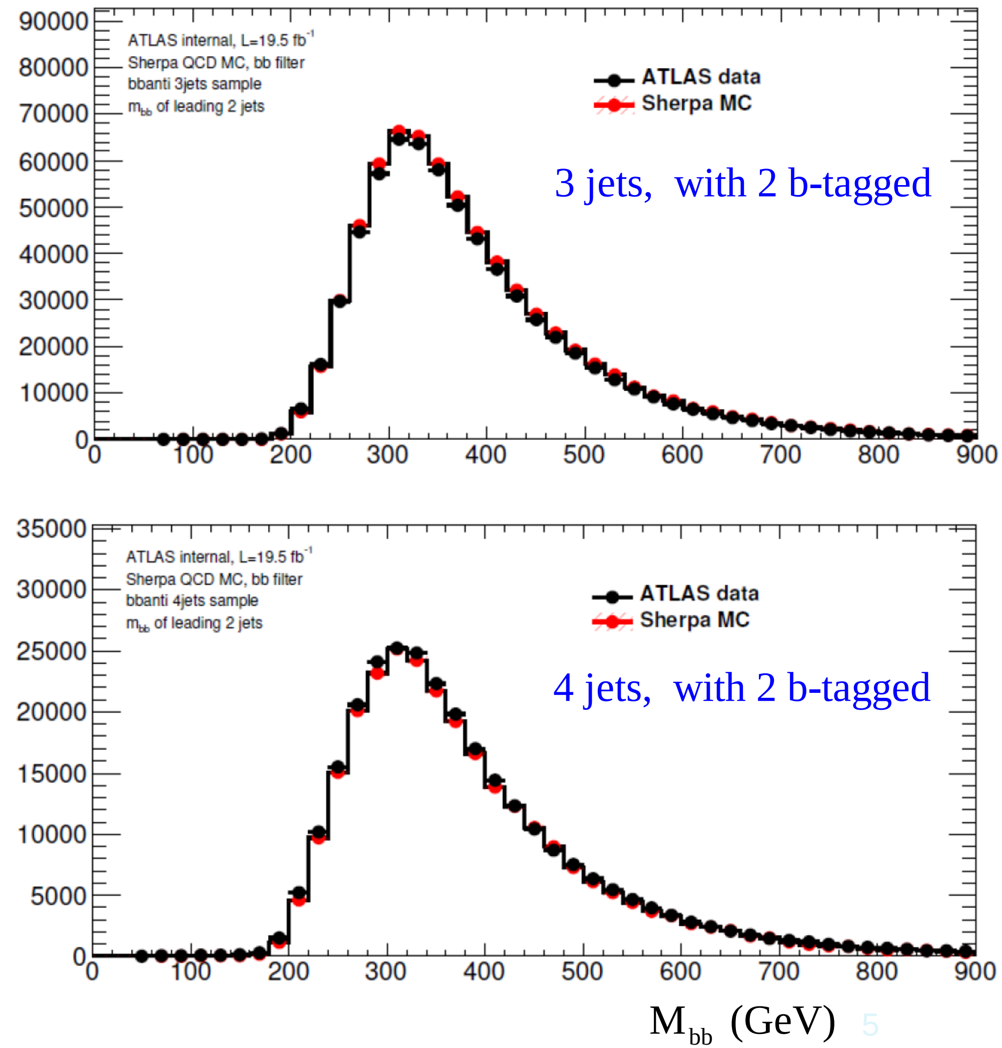
# Run 1 Analysis

Background MC Sample
189907.Sherpa_CT10_bb_MassiveCB_2Bjets

| subprocess | cross section (pb) |
|---|---|
| $jj \to b\bar{b}jj$ | 58531 |
| $jj \to b\bar{b}j$ | 33411 |
| $bj \to bjj \;+\; \bar{b}j \to \bar{b}jj$ | 22147 |
| $bj \to bjjj \;+\; \bar{b}j \to \bar{b}jjj$ | 16282 |
| $bj \to bj \;+\; \bar{b}j \to \bar{b}j$ | 12135 |
| $jj \to b\bar{b}$ | 1672 |
| $cj \to cb\bar{b}j \;+\; \bar{c}j \to \bar{c}b\bar{b}j$ | 1602 |
| $bj \to bb\bar{b}j \;+\; \bar{b}j \to \bar{b}b\bar{b}j$ | 997 |
| $jj \to b\bar{b}c\bar{c}$ | 776 |
| $cj \to cb\bar{b} \;+\; \bar{c}j \to \bar{c}b\bar{b}$ | 681 |
| $bj \to bb\bar{b} \;+\; \bar{b}j \to \bar{b}b\bar{b}$ | 387 |
| $jj \to b\bar{b}b\bar{b}$ | 376 |
| $b\bar{c} \to b\bar{c}j \;+\; \bar{b}c \to \bar{b}cj$ | 206 |
| $bc \to bcj \;+\; \bar{b}\bar{c} \to \bar{b}\bar{c}j$ | 194 |
| $b\bar{c} \to b\bar{c}jj \;+\; \bar{b}c \to \bar{b}cjj$ | 143 |
| $bc \to bcjj \;+\; \bar{b}\bar{c} \to \bar{b}\bar{c}jj$ | 136 |
| $bc \to bc \;+\; \bar{b}\bar{c} \to \bar{b}\bar{c}$ | 122 |
| $b\bar{c} \to b\bar{c} \;+\; \bar{b}c \to \bar{b}c$ | 121 |
| $b\bar{b} \to b\bar{b}j$ | 62 |
| $bb \to bbj \;+\; \bar{b}\bar{b} \to \bar{b}\bar{b}j$ | 53 |
| $b\bar{b} \to b\bar{b}jj$ | 44 |
| $bb \to bbjj \;+\; \bar{b}\bar{b} \to \bar{b}\bar{b}jj$ | 39 |
| $b\bar{b} \to b\bar{b}$ | 37 |
| $bb \to bb \;+\; \bar{b}\bar{b} \to \bar{b}\bar{b}$ | 30 |



# Run 1 Analysis

Trigger: EF_2b35_loose_j145_j35_a4tchad

- L1: At least one J75 RoI
- L2: At least two 30 GeV jets, of which one must be at least 140 GeV. Additionally, at least two jets must satisfy a medium $b$-tag
- EF: At least two 35 GeV jets, of which one must be at least 145 GeV. Additionally, at least two jets must satisfy a medium $b$-tag

Signal Trigger Efficiency, no offline selection

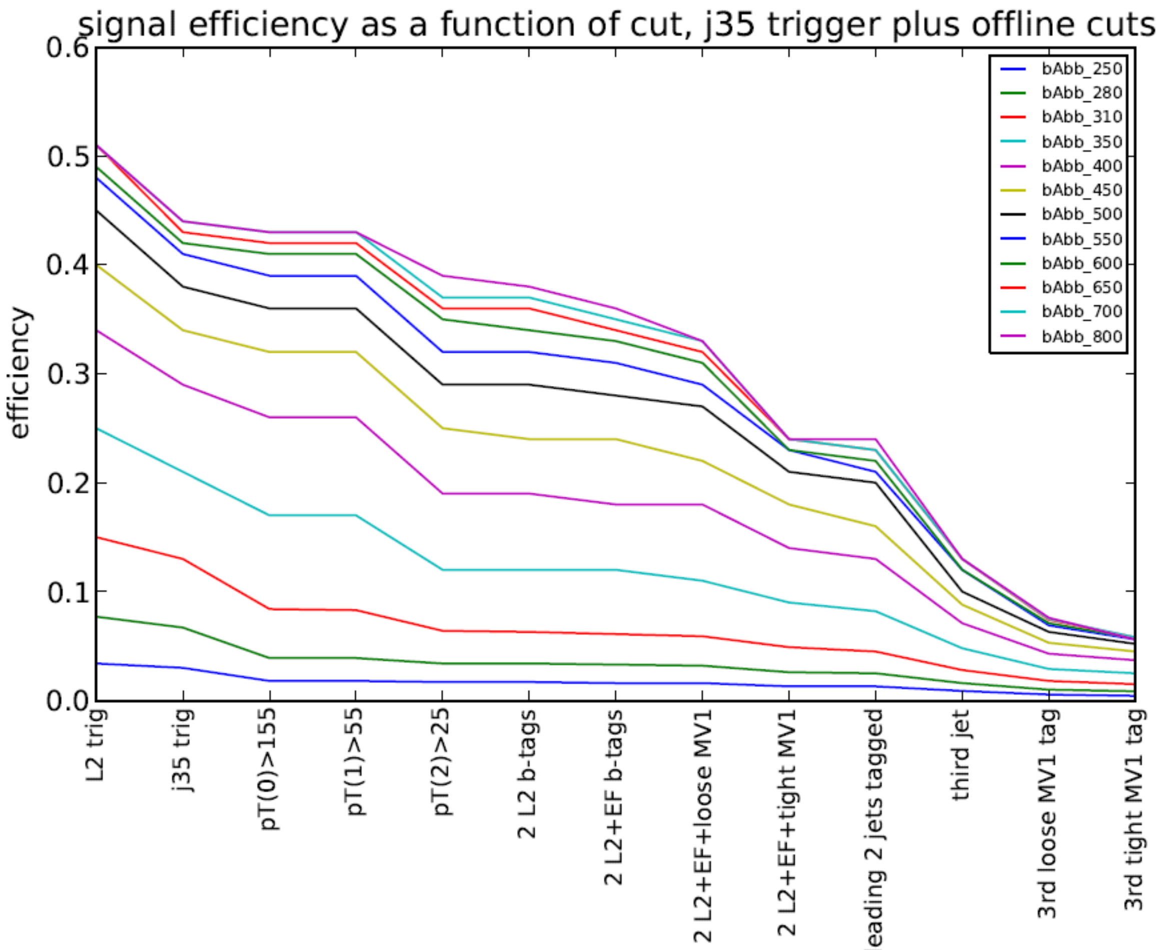
| $M_H$ (GeV): | 250 | 280 | 310 | 350 | 400 | 450 | |
|---|---|---|---|---|---|---|---|
| L1 trigger | 1 | 1 | 1 | 1 | 1 | 1 | (MC bug) |
| L2 trigger | 0.034 | 0.077 | 0.15 | 0.25 | 0.34 | 0.4 | |
| j35 trigger | 0.03 | 0.067 | 0.13 | 0.21 | 0.29 | 0.34 | |

| $M_H$ (GeV): | 500 | 550 | 600 | 650 | 700 | 800 | |
|---|---|---|---|---|---|---|---|
| L1 trigger | 1 | 1 | 1 | 1 | 1 | 1 | (MC bug) |
| L2 trigger | 0.45 | 0.48 | 0.49 | 0.51 | 0.51 | 0.51 | |
| j35 trigger | 0.38 | 0.41 | 0.42 | 0.43 | 0.44 | 0.44 | |

# Run 1 Analysis

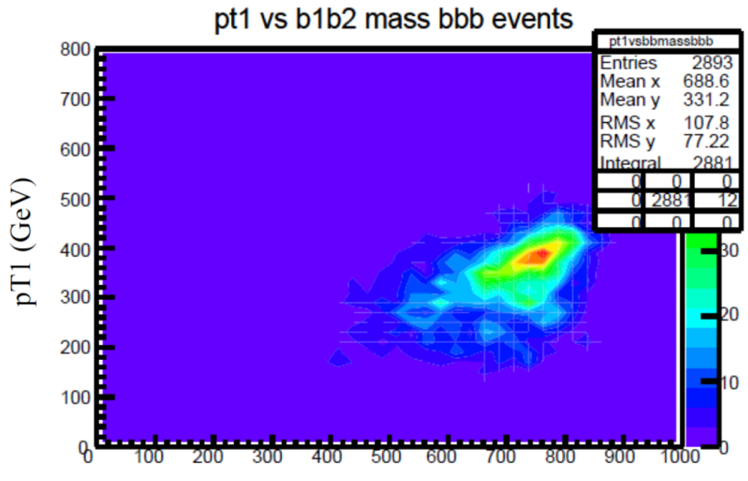
Event Selection:

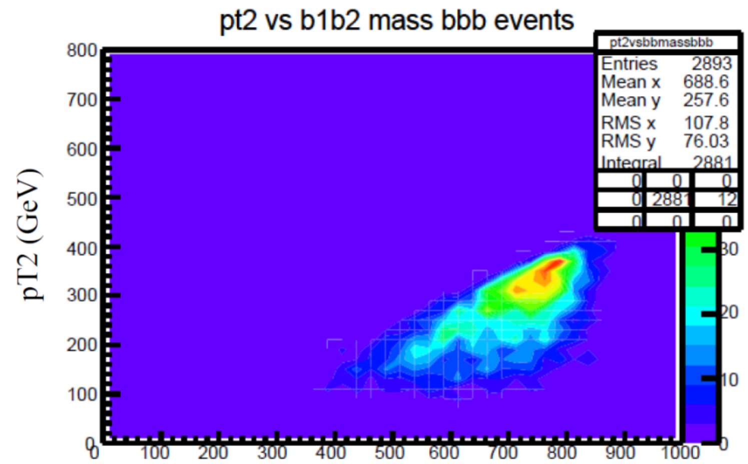
- $p_T$ **cuts of 155 and 55 GeV on leading and sub-leading jets, respectively.**
- **Two jets passing online (L2 and EF in trigger) and offline (MV1) $b$-tags**
- **Leading 2 jets must pass tight MV1 $b$-tag**
- $p_T$ **cut of 25 GeV on third jet.**
- **Third jet passing offline $b$-tag** (Tight 60% for signal; loose or anti-tag for bkgnd)



# Run 1 Analysis

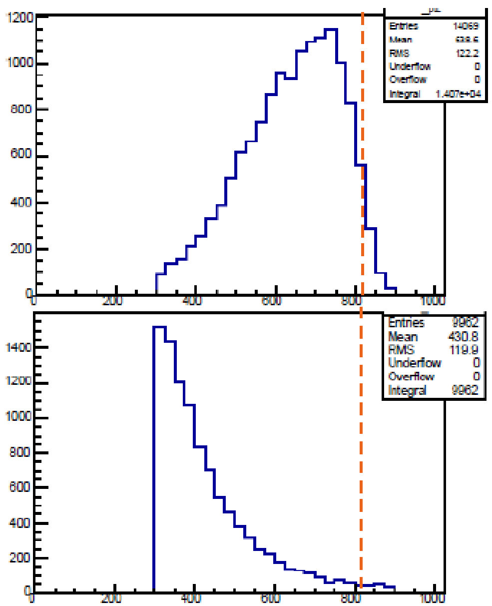
## Mass Resolution and Rotated bb Mass Variable $M_{bb}'$




mA=800 GeV

Background

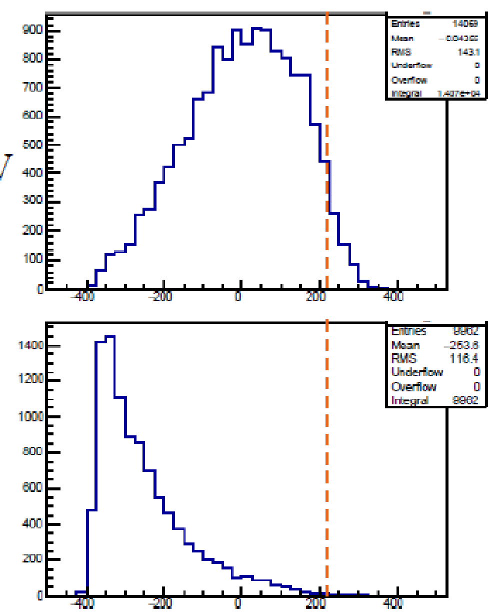



$M_{bb}$ (GeV)

$\Rightarrow$

mA=800 GeV

Background




$M_{bb}'$ (GeV)

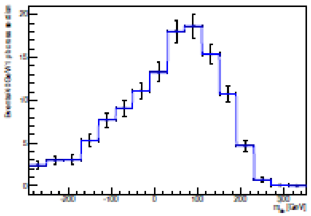
Rotate to Major Axis of $M_{bb}$ - pT1 - pT2 Tensor

# Run 1 Analysis

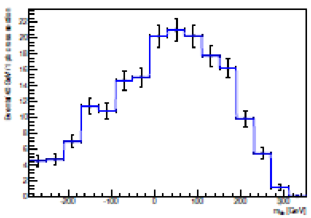
## $n_{jets}$ Categories

Every event has 2 *b*-jets

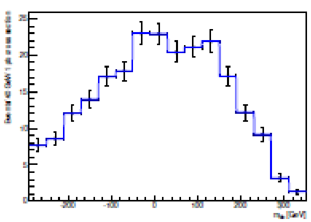
- $n_{jets}$ (3, 4, 5+ jets) categories



3 jets: best mass resolution



4 jets: FSR starts to smear out signal



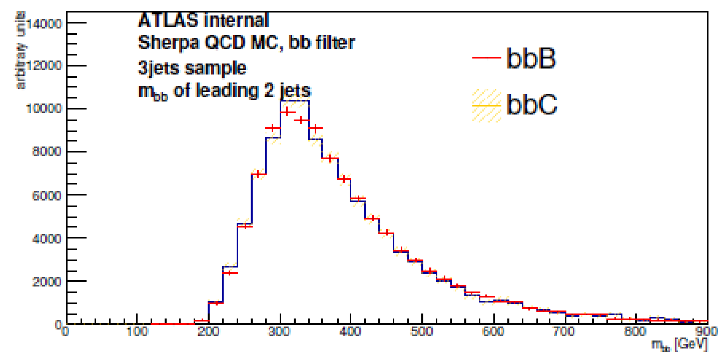
5 jets: worst resolution

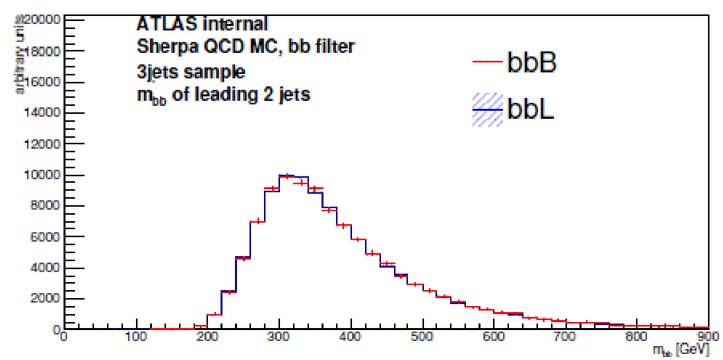
[signal MC, 800 GeV]

## *b*-tag Categories

- bbb: third jet *b*-tagged at 60% working point **[signal region]**
- bbloose: third jet *b*-tagged at 80% WP, but NOT 60%
- bbanti: veto on third *b*-tagged jet **[background control region]**

fit strategy assumes same shape for all *b*-tag regions in background



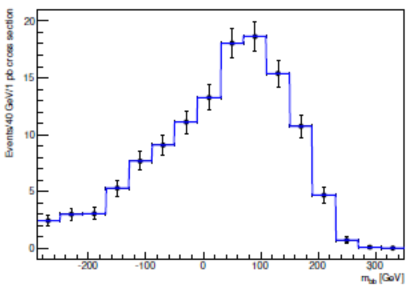



# Run 1 Analysis

binned likelihood function:

$$\text{Pois}(N|\mu S + B) \prod_{l=1}^{N_{cat}} \prod_{i=1}^{N_l} [\mu N_{S,l} PDF_{sig,l}(m_{bb,i}) + N_{B,l} PDF_{bkg}(m_{bb,i})]$$

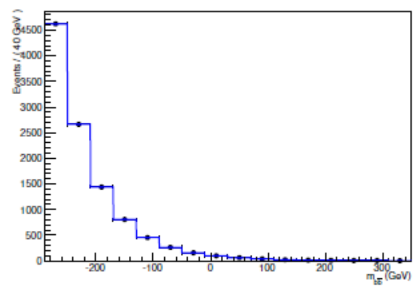
***PDF**$_{sig}$*




800 GeV, bbb 3jets

- signal PDF is parameterized histogram, fit to MC
- normalization allowed to float in final fit

***PDF**$_{bkg}$*




background, 3jets

- background shape and normalization taken from data
- assumption: shape(bbb) = shape(bbloose) = shape(bbanti) *

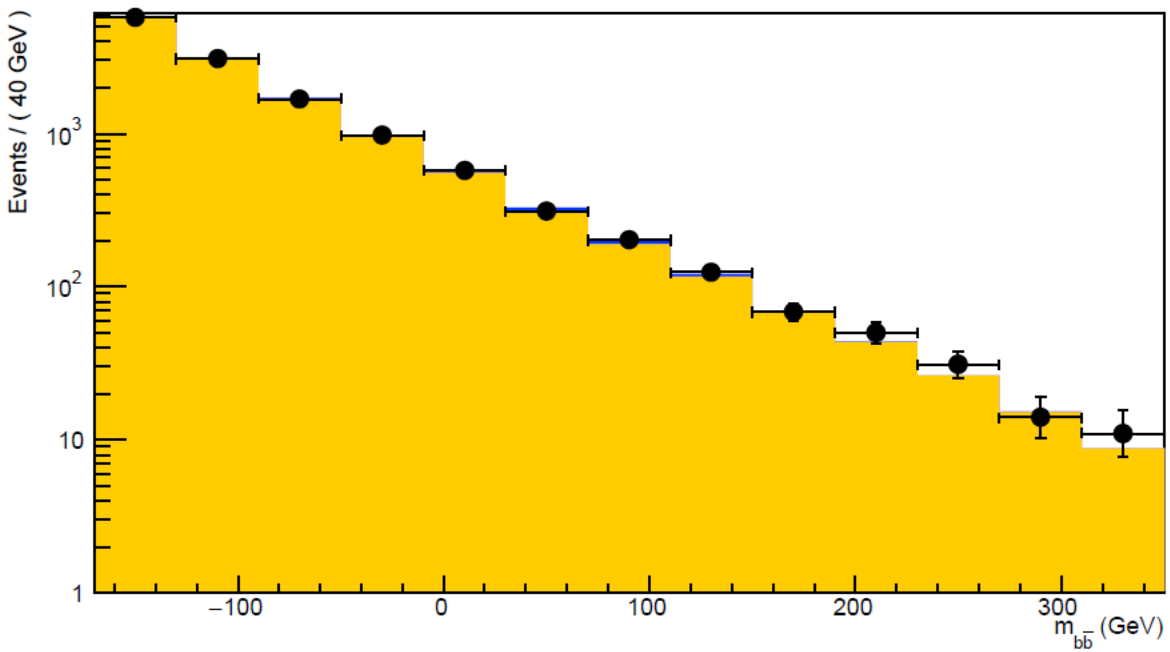
*except $PDF_{bbb}^{n\ jets} = (\alpha m'_{bb}) PDF_{bbanti}^{n\ jets}$

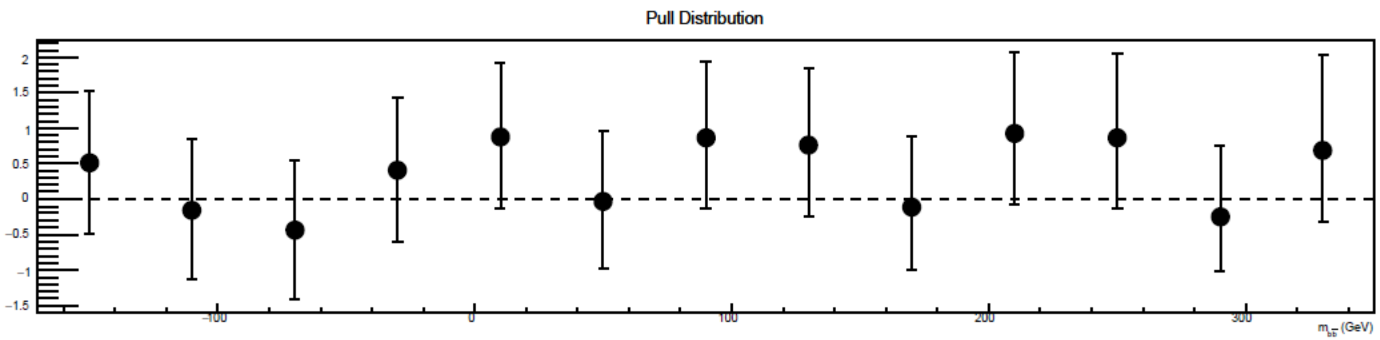
$$PDF_{bbloose}^{n\ jets} = (\beta m'_{bb}) PDF_{bbanti}^{n\ jets} \quad (2)$$

- $\alpha$, $\beta$ fit (separately in each $n_{jets}$ bin) during fit to data

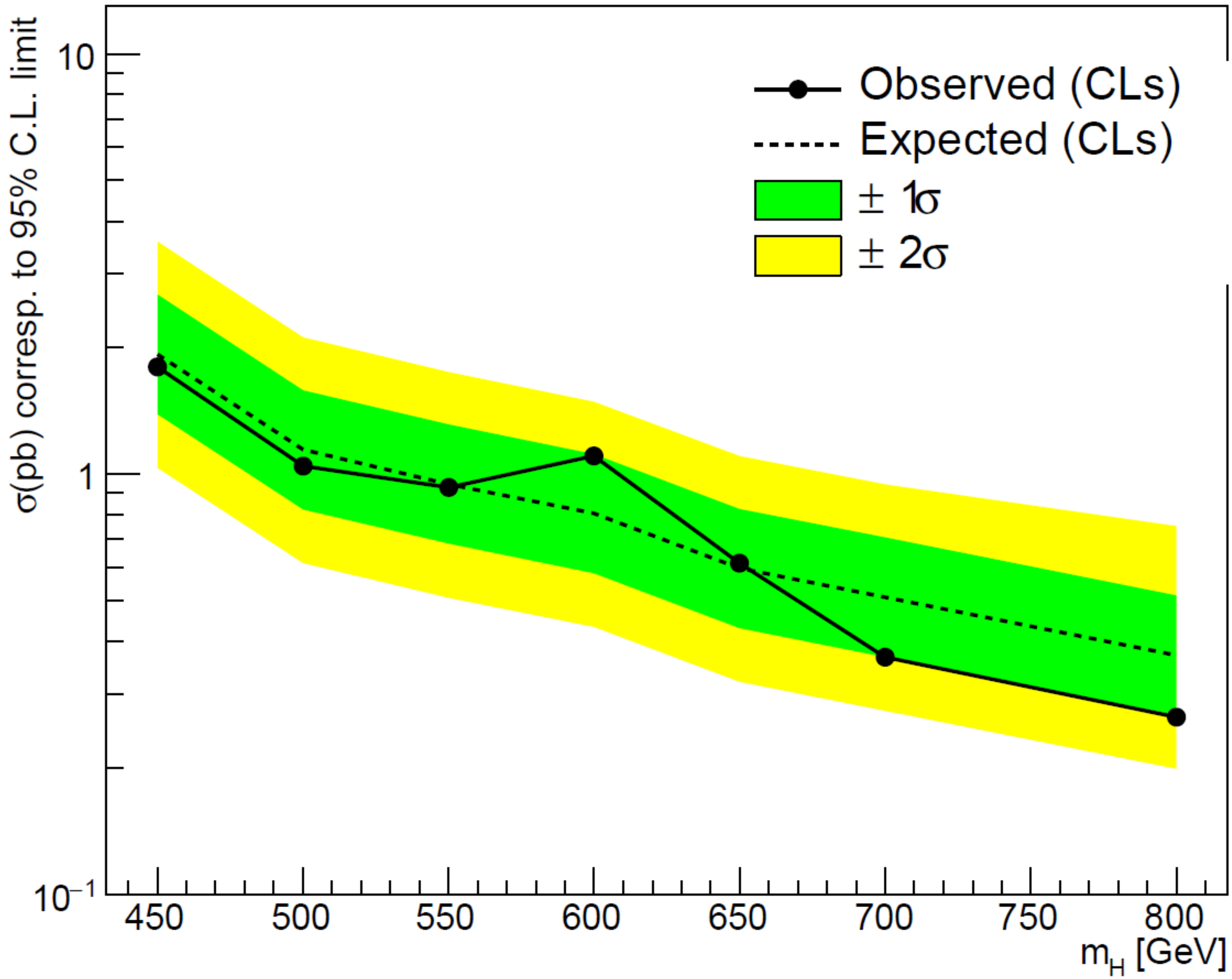
# Run 1 Analysis

## $M_A = 600$ GeV   bbb category

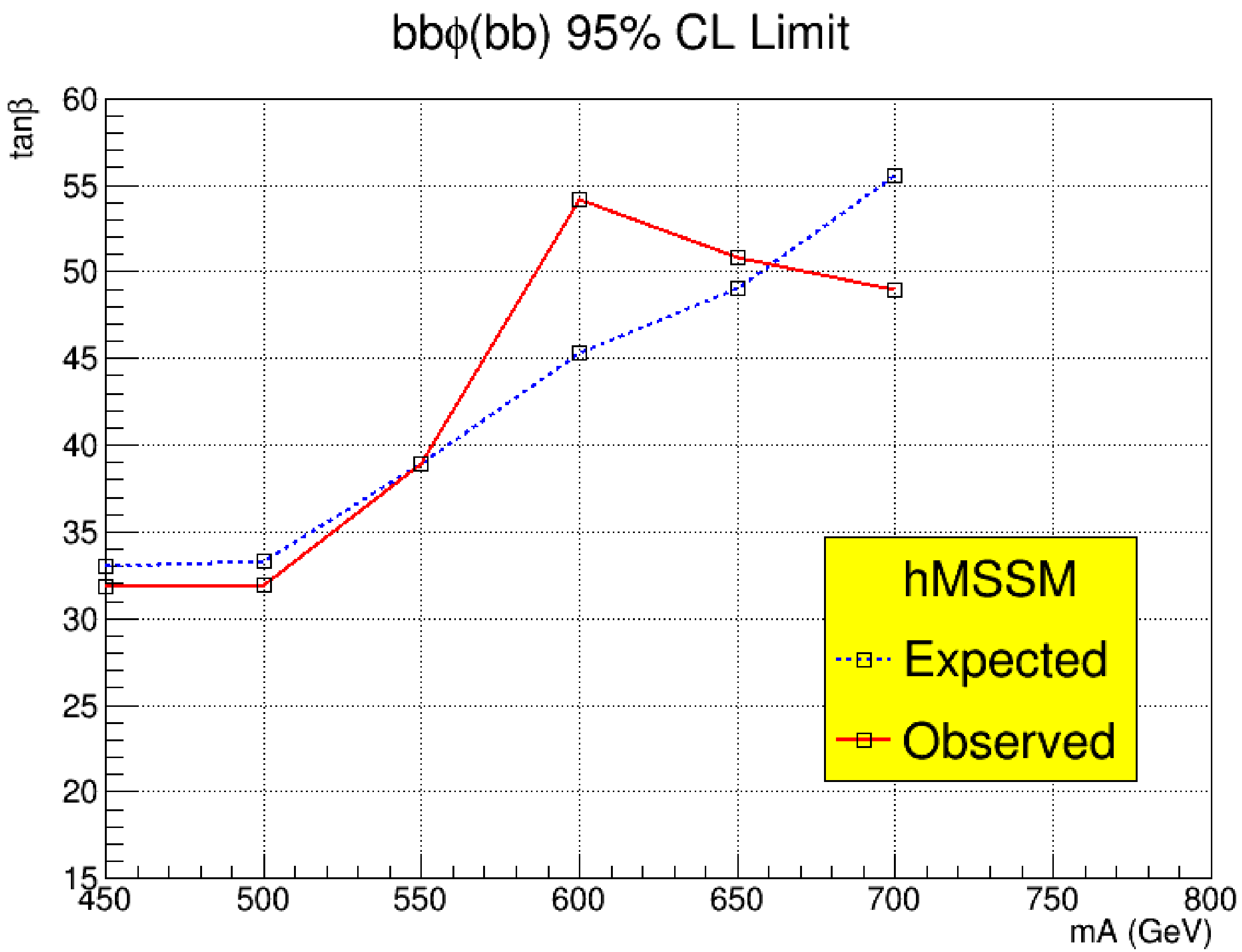


## Run 1 Analysis



# Run 1 Analysis



## Run 2 MC Signal Generation

$gg \to b\bar{b}A,\ A \to \tau^+\tau^-$ **was generated with 4FS MG5_aMC@NLO+PYTHIA8**
**( but with 5FS pdf NNPDF23LO ) & 0 total Higgs width**
$\approx 40\%$ **of the events are negative.**

**In order to avoid negative weights and to include a nonzero total Higgs width we have explored using Sherpa 2.2 to produce** $bg \to bA + 0/1$ **jet, &** $gg \to b\bar{b}A,\quad A \to b\bar{b}$

**We have compared 4FS/ 5FS production with Sherpa 2.2 and CT104F/CT10 pdf , and found little difference in b jet and Higgs pT distributions .**

**We choose the 5FS Sherpa 2.2 production of** $bg \to bA + 0/1$ **jet, &** $gg \to b\bar{b}A,\quad A \to b\bar{b}$
**with the 5FS pdf NNPDF30NNLO**

For Run 2 MC production choose $A^0$ total width based on the following MSSM model: $\tan\beta = 20$ $\mu = -800$ GeV $M_{SUSY}$=1000 GeV $A_t$=2000 GeV $M_2$=800 GeV $M_3$=1600 GeV

| DSID | $M_{A^0}$ $(GeV)$ | $\Gamma_{A^0}(total)$ $(GeV)$ | $\Gamma_{A^0}(total)$ Run 1 $(GeV)$ | $BR(A^0 \to b\bar{b})$ | $BR(A^0 \to \tau^+\tau^-)$ | $BR(A^0 \to t\bar{t})$ | $\sigma(b\bar{b}h)$ * $(fb)$ | $\sigma(b\bar{b}A^0)$ $(fb)$ |
|---|---|---|---|---|---|---|---|---|
| 344046 | 200 | 2.4 | | 0.94 | 0.06 | 0.00 | 3228.8 | 77912.1 |
| 344047 | 250 | 2.9 | 1.7 | 0.94 | 0.06 | 0.00 | 1601.4 | 34296.8 |
| 344048 | 300 | 3.3 | 2.5 | 0.93 | 0.07 | 0.00 | 1117.3 | 16786.1 |
| 344049 | 350 | 3.8 | 3.2 | 0.93 | 0.07 | 0.00 | 902.3 | 8771.1 |
| 344050 | 400 | 4.2 | 3.9 | 0.92 | 0.07 | 0.01 | 786.1 | 4811.6 |
| 344051 | 450 | 4.7 | 4.7 | 0.91 | 0.07 | 0.02 | 715.4 | 2791.6 |
| 344052 | 500 | 5.1 | 5.6 | 0.91 | 0.07 | 0.02 | 668.8 | 1693.6 |
| 344053 | 550 | 5.5 | 6.8 | 0.91 | 0.07 | 0.02 | 636.3 | 1066.4 |
| 344054 | 600 | 5.9 | 8.1 | 0.91 | 0.07 | 0.02 | 612.6 | 693.0 |
| 344055 | 650 | 6.3 | 9.3 | 0.91 | 0.07 | 0.02 | 594.8 | 462.9 |
| 344056 | 700 | 6.7 | 10.4 | 0.91 | 0.07 | 0.02 | 581.0 | 316.8 |
| 344057 | 750 | 7.1 | | 0.90 | 0.07 | 0.02 | 570.1 | 221.5 |
| 344058 | 800 | 7.5 | 12.5 | 0.90 | 0.08 | 0.02 | 561.3 | 157.9 |
| 344059 | 850 | 7.9 | | 0.90 | 0.08 | 0.02 | 554.2 | 114.6 |
| 344060 | 900 | 8.3 | | 0.90 | 0.08 | 0.02 | 548.2 | 84.5 |
| 344061 | 1000 | 9.1 | | 0.90 | 0.08 | 0.02 | 539.0 | 47.9 |
| 344062 | 1100 | 9.8 | | 0.90 | 0.08 | 0.02 | 532.3 | 28.5 |
| 344063 | 1200 | 10.7 | | 0.89 | 0.08 | 0.02 | 527.2 | 17.7 |
| 344064 | 1300 | 11.6 | | 0.87 | 0.08 | 0.02 | 523.3 | 11.5 |
| 344065 | 1400 | 12.5 | | 0.86 | 0.08 | 0.02 | 520.2 | 7.6 |

*$\sigma_{SM}(b\bar{b}h) = 500\ fb$

For Run 2 Monte Carlo Production choose $A^0$ total width based on the following MSSM model: $\tan\beta = 20$ $\mu = -800$ GeV

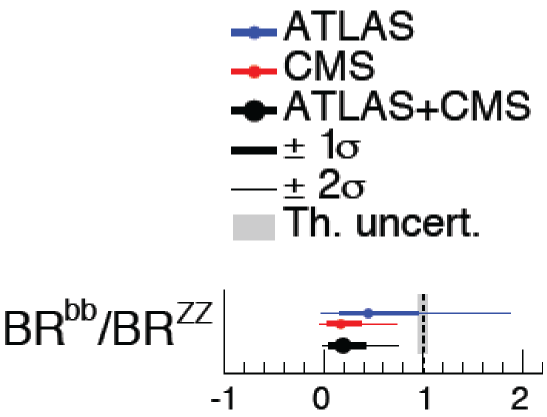
$M_{SUSY}$ =1000 GeV $A_t$=2000 GeV $M_2$=800 GeV $M_3$=1600 GeV

| DSID | $M_A$ (GeV) | $\Gamma_{A^0}(total)$ (GeV) | $\frac{BR(h\to b\bar{b})}{BR_{SM}(h\to b\bar{b})}$ | $\frac{BR(h\to ZZ)}{BR_{SM}(h\to ZZ)}$ | $\frac{\left(\frac{BR(h\to b\bar{b})}{BR_{SM}(h\to b\bar{b})}\right)}{\left(\frac{BR(h\to ZZ)}{BR_{SM}(h\to ZZ)}\right)}$ | $\sigma(b\bar{b}h)$* (fb) | $\sigma(b\bar{b}A^0)$ (fb) |
|---|---|---|---|---|---|---|---|
| 344046 | 200 | 2.4 | 1.54 | 0.24 | 6.42 | 3228.8 | 77912.1 |
| 344047 | 250 | 2.9 | 1.40 | 0.44 | 3.27 | 1601.4 | 34296.8 |
| 344048 | 300 | 3.3 | 1.30 | 0.58 | 2.24 | 1117.3 | 16786.1 |
| 344049 | 350 | 3.8 | 1.23 | 0.68 | 1.81 | 902.3 | 8771.1 |
| 344050 | 400 | 4.2 | 1.18 | 0.75 | 1.57 | 786.1 | 4811.6 |
| 344051 | 450 | 4.7 | 1.14 | 0.80 | 1.43 | 715.4 | 2791.6 |
| 344052 | 500 | 5.1 | 1.12 | 0.84 | 1.33 | 668.8 | 1693.6 |
| 344053 | 550 | 5.5 | 1.10 | 0.86 | 1.28 | 636.3 | 1066.4 |
| 344054 | 600 | 5.9 | 1.08 | 0.89 | 1.21 | 612.6 | 693.0 |
| 344055 | 650 | 6.3 | 1.07 | 0.90 | 1.19 | 594.8 | 462.9 |
| 344056 | 700 | 6.7 | 1.06 | 0.92 | 1.15 | 581.0 | 316.8 |
| 344057 | 750 | 7.1 | 1.06 | 0.93 | 1.14 | 570.1 | 221.5 |
| 344058 | 800 | 7.5 | 1.05 | 0.94 | 1.12 | 561.3 | 157.9 |
| 344059 | 850 | 7.9 | 1.04 | 0.94 | 1.11 | 554.2 | 114.6 |
| 344060 | 900 | 8.3 | 1.04 | 0.95 | 1.09 | 548.2 | 84.5 |
| 344061 | 1000 | 9.1 | 1.03 | 0.96 | 1.07 | 539.0 | 47.9 |
| 344062 | 1100 | 9.8 | 1.03 | 0.97 | 1.06 | 532.3 | 28.5 |
| 344063 | 1200 | 10.7 | 1.02 | 0.97 | 1.05 | 527.2 | 17.7 |
| 344064 | 1300 | 11.6 | 1.02 | 0.98 | 1.04 | 523.3 | 11.5 |
| 344065 | 1400 | 12.5 | 1.02 | 0.98 | 1.04 | 520.2 | 7.6 |

$*\sigma_{SM}(b\bar{b}h) = 500\ fb^{-1}$

**Excluded at 95% CL by Atlas $BR^{bb}$ / $BR^{ZZ}$**

ATLAS: ATLAS-CONF-2015-044
CMS: CMS-PAS-HIG-15-002



**PLOT TRUTH HADRON LEVEL QUANTITIES**

**Produce TRUTH3 DAOD files for** $M_h = 125$ **GeV and** $M_A = 250, 500, 700, 1000, 1400$ **GeV**

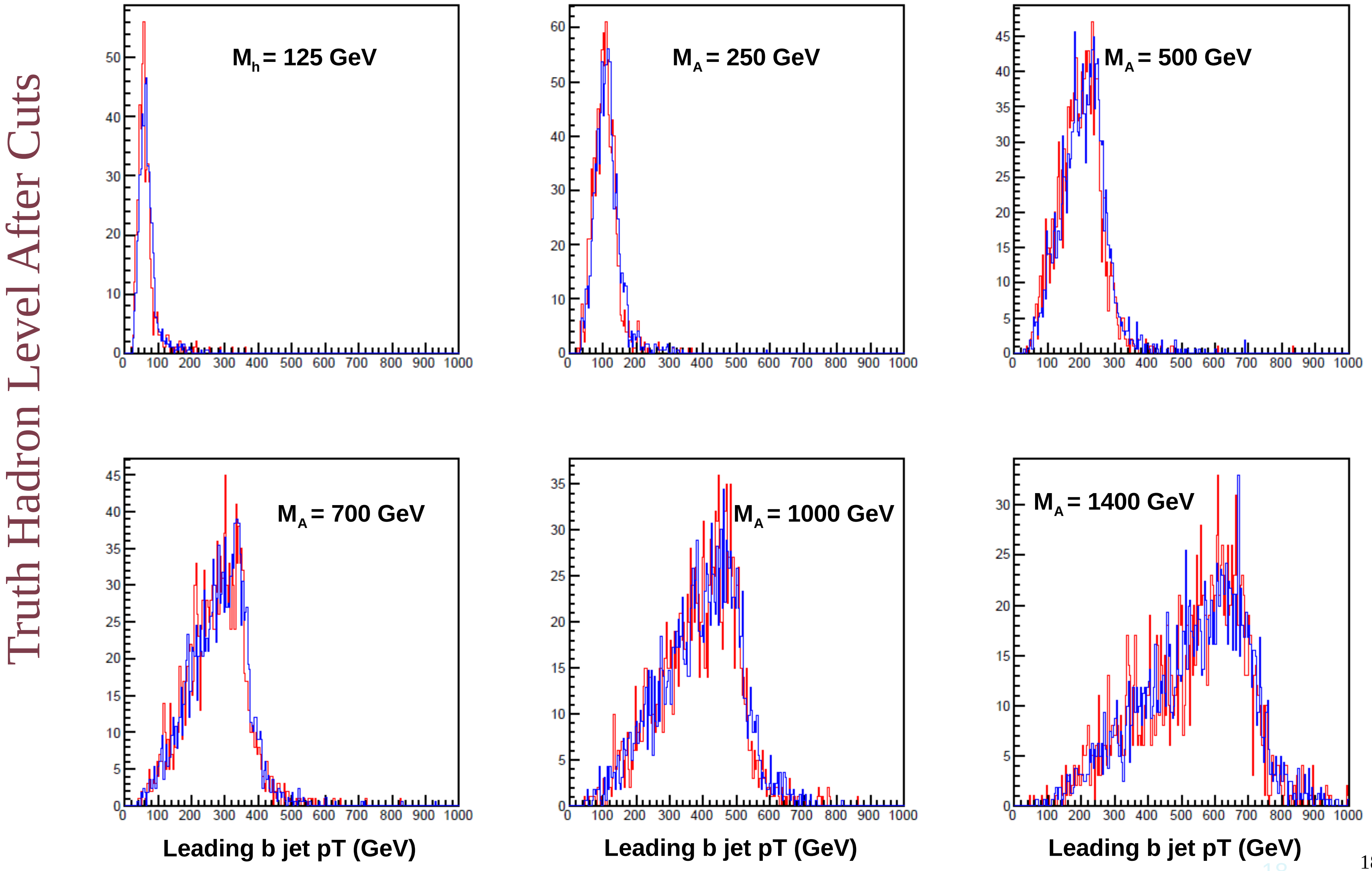
**Require at least 3 b-tagged AntiKt4TruthJets with** $|\eta| < 2.5$

**Form the Higgs from the 1st and 2nd leading** $p_T$ **b-tagged AntiKt4TruthJet with** $|\eta| < 2.5$

**Define the leading tag b-jet to be the 3rd leading** $p_T$ **b-tagged AntiKt4TruthJet with** $|\eta| < 2.5$

MG5_aMC@NLO+PYTHIA8 4FS $gg \to b\bar{b}A,\ A \to b\bar{b}$
but with 5FS pdf NNPDF23LO; 0 total width
ignore MC weight and plot using unit weight
5000 events

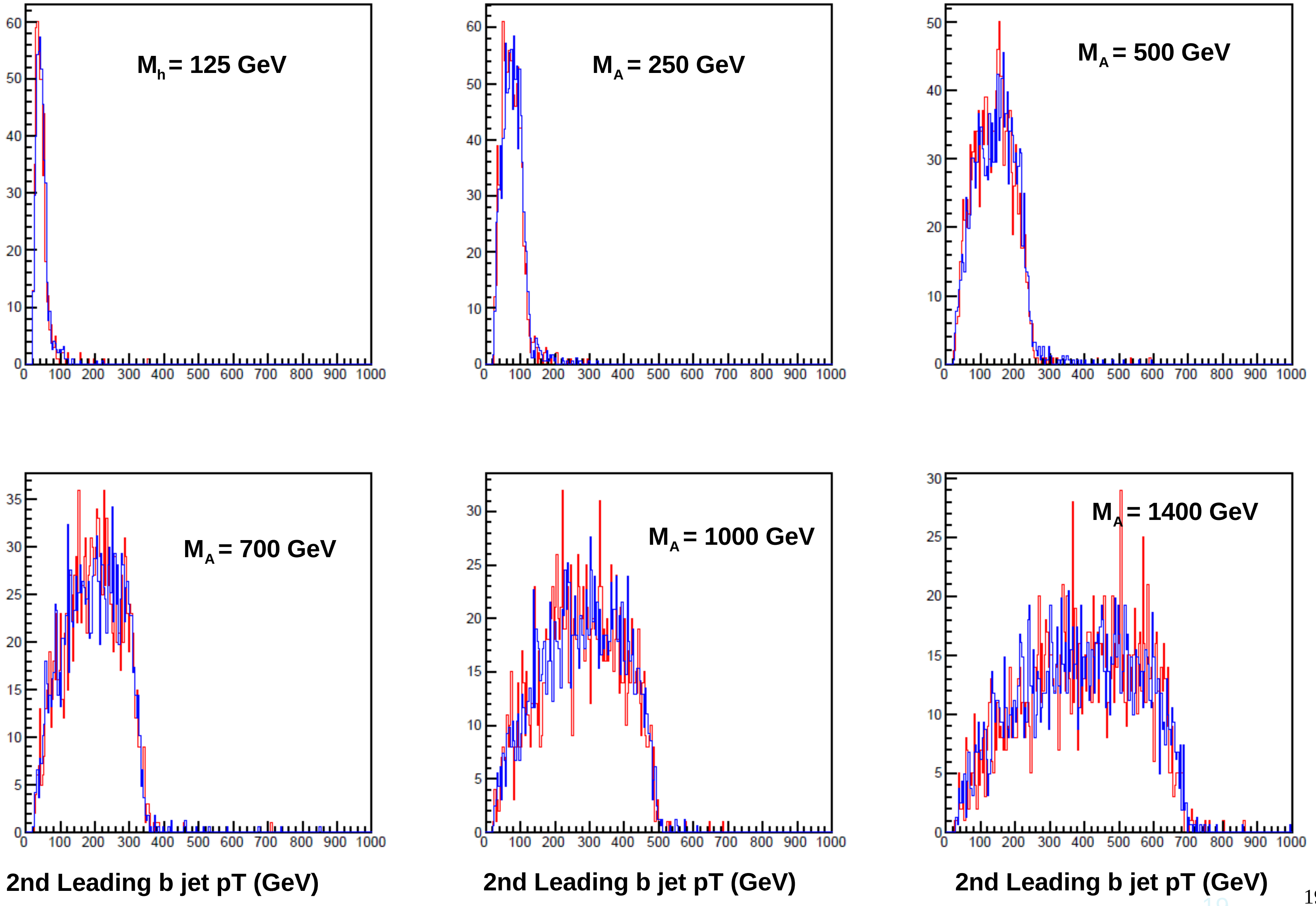
SHERPA 5FS $bg \to bA + 0/1$ jet, $A \to b\bar{b}$
with 5FS pdf NNPDF30NNLO; total width from $\tan\beta = 20$, ..
but use SM coupling of Higgs to $b\bar{b}$
5000 events



**MG5_aMC@NLO+PYTHIA8 4FS** $gg \to b\bar{b}A,\ A \to b\bar{b}$
**but with 5FS pdf NNPDF23LO; 0 total width**
**ignore MC weight and plot using unit weight**
**5000 events**

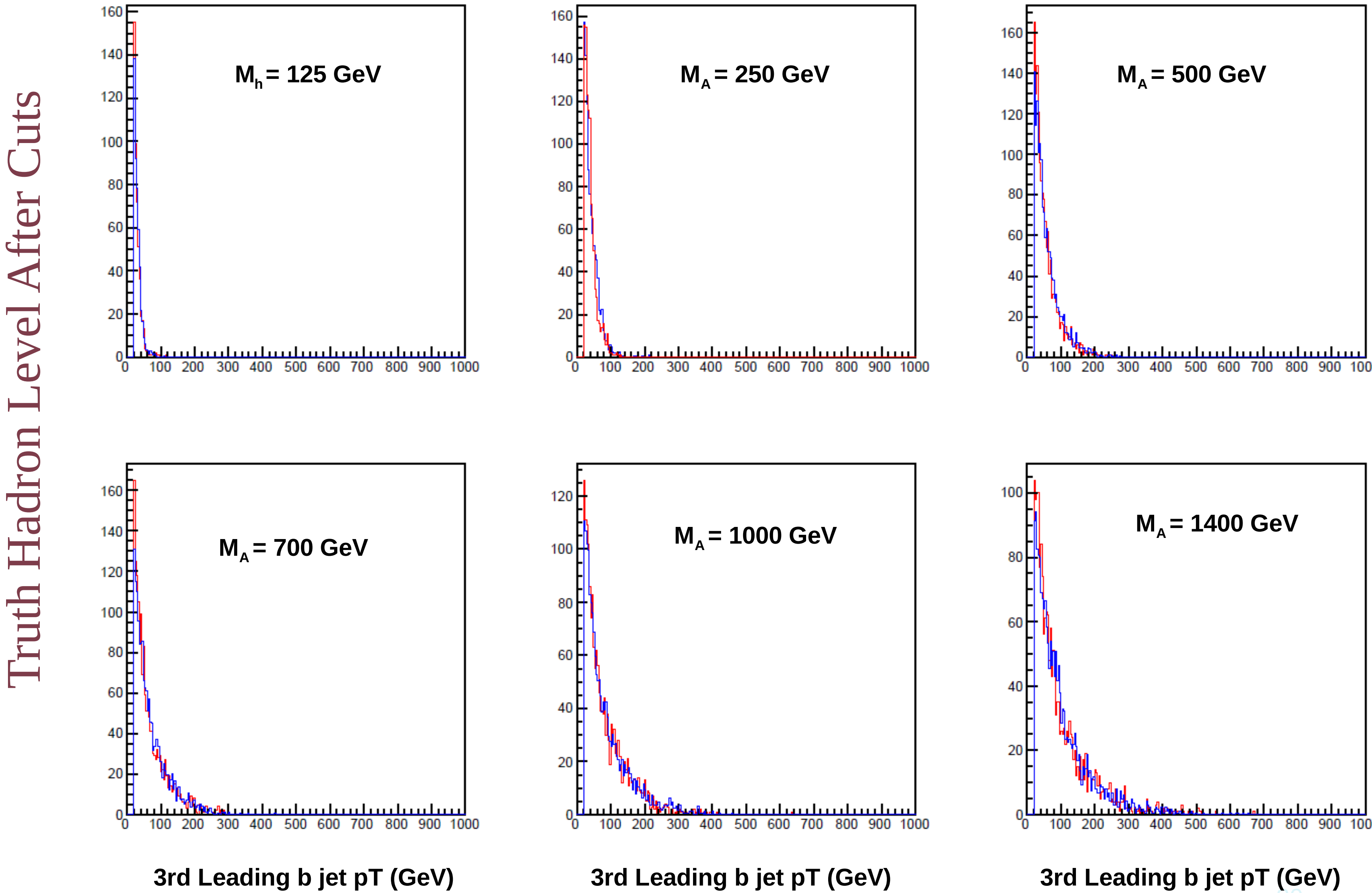
**SHERPA 5FS** $bg \to bA + 0/1$ **jet,** $A \to b\bar{b}$
**with 5FS pdf NNPDF30NNLO; total width from** $\tan\beta = 20$, **..**
**but use SM coupling of Higgs to** $b\bar{b}$
**5000 events**

Truth Hadron Level After Cuts



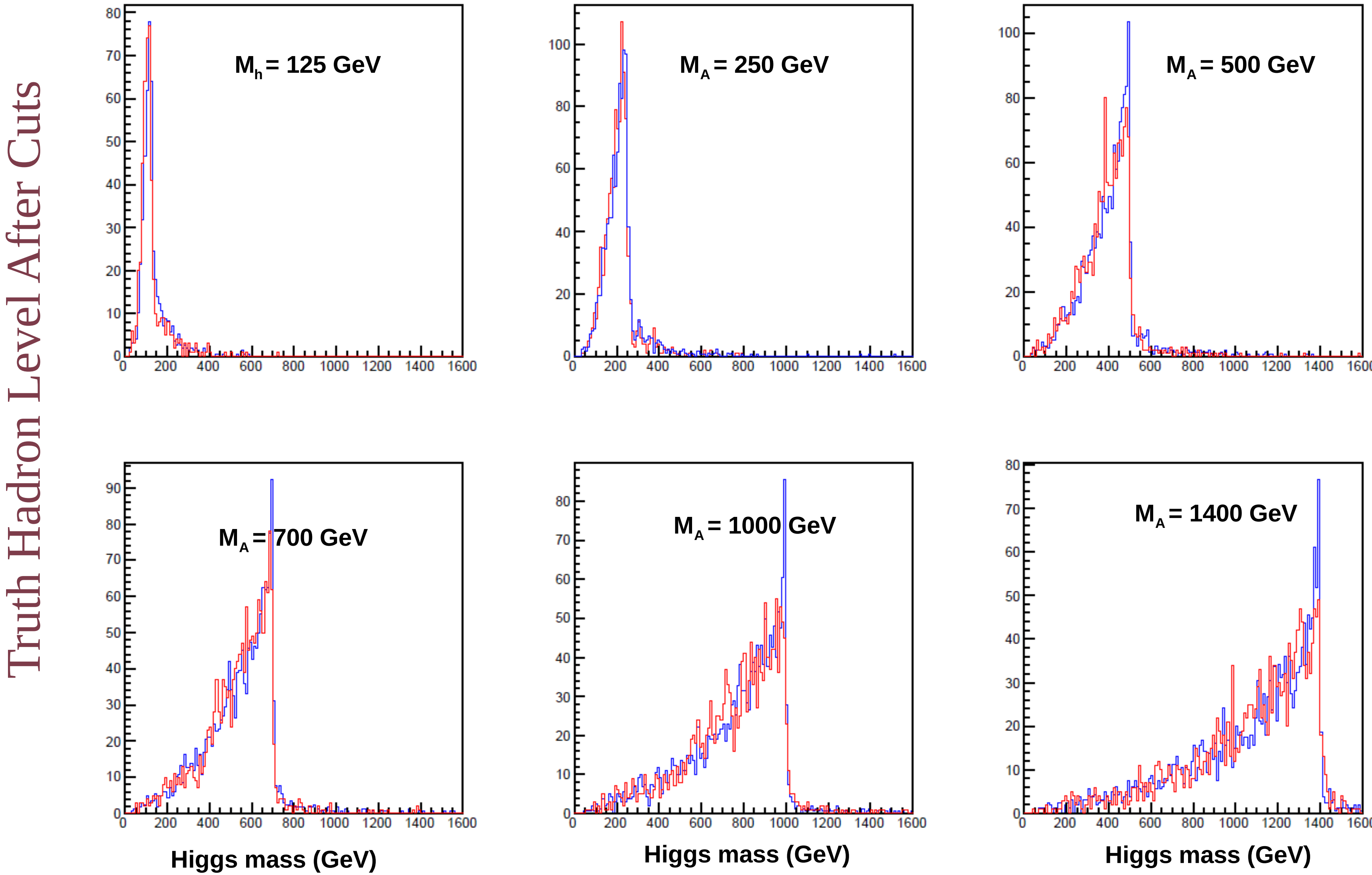
**MG5_aMC@NLO+PYTHIA8 4FS** $gg \to b\bar{b}A,\ A \to b\bar{b}$
**but with 5FS pdf NNPDF23LO; 0 total width**
**ignore MC weight and plot using unit weight**
**5000 events**

**SHERPA 5FS** $bg \to bA + 0/1$ **jet,** $A \to b\bar{b}$
**with 5FS pdf NNPDF30NNLO; total width from** $\tan\beta = 20$, **..**
**but use SM coupling of Higgs to** $b\bar{b}$
**5000 events**



**MG5_aMC@NLO+PYTHIA8 4FS $gg \to b\bar{b}A,\ A \to b\bar{b}$**
**but with 5FS pdf NNPDF23LO; 0 total width**
**ignore MC weight and plot using unit weight**
**5000 events**

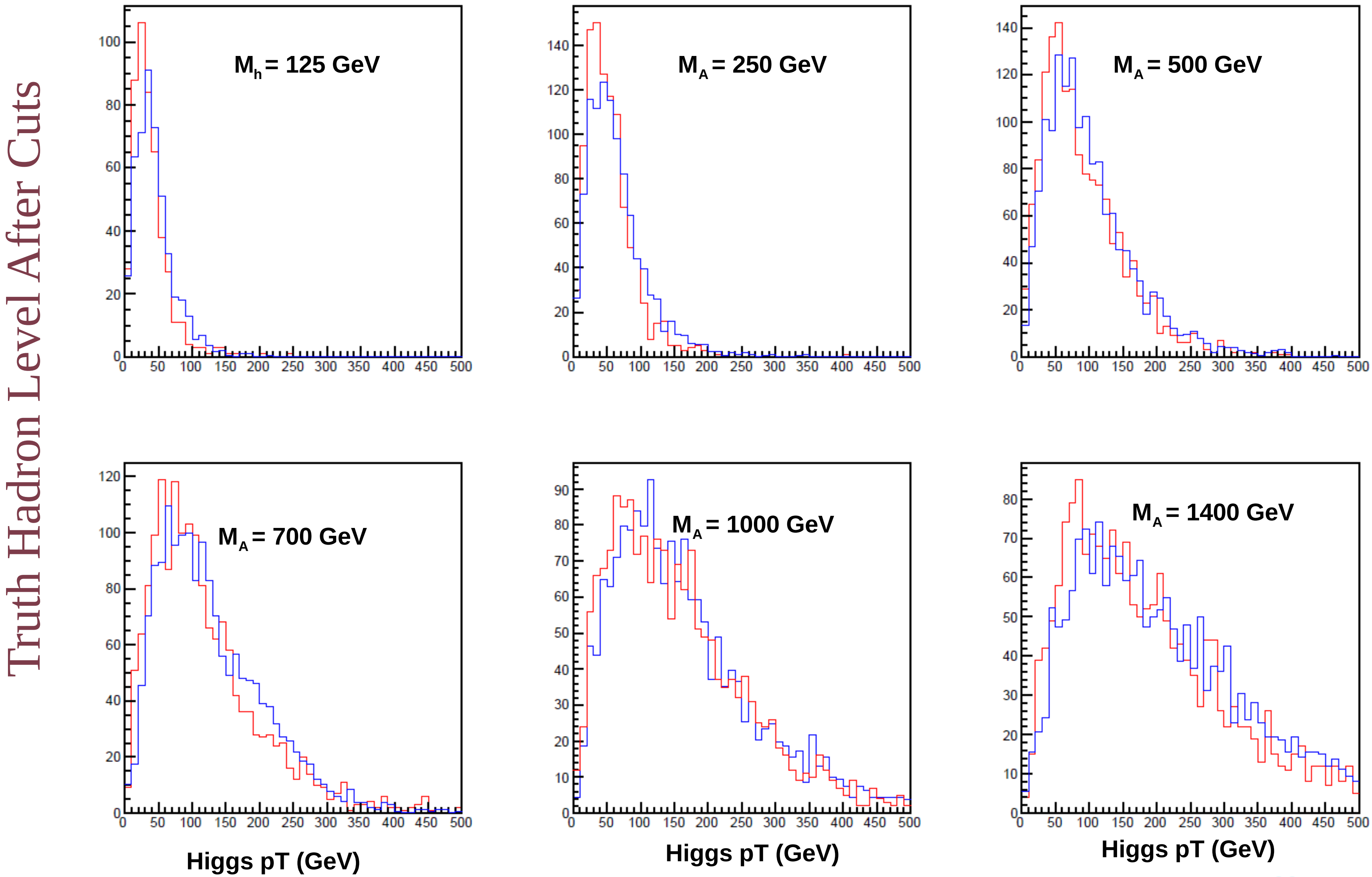
**SHERPA 5FS $bg \to bA + 0/1$ jet, $A \to b\bar{b}$**
**with 5FS pdf NNPDF30NNLO; total width from $\tan\beta = 20$, ..**
**but use SM coupling of Higgs to $b\bar{b}$**
**5000 events**




**( Discrepancy not explained by 0 width of MG5_aMC@NLO+PYTHIA8 )**

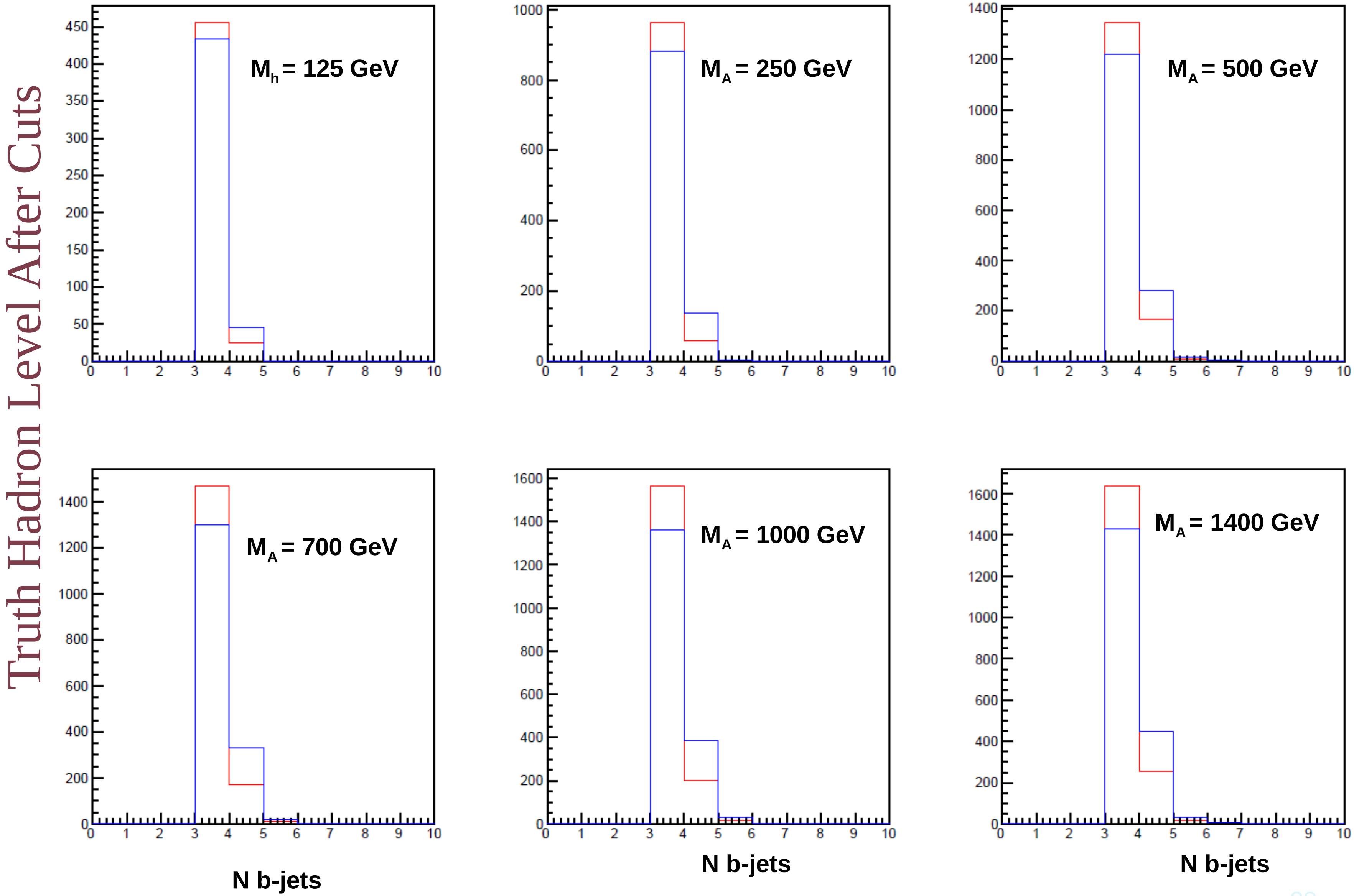
**MG5_aMC@NLO+PYTHIA8 4FS $gg \to b\bar{b}A,\ A \to b\bar{b}$**
**but with 5FS pdf NNPDF23LO; 0 total width**
**ignore MC weight and plot using unit weight**
**(with global recoil) 5000 events**

**SHERPA 5FS $bg \to bA + 0/1$ jet, $A \to b\bar{b}$**
**with 5FS pdf NNPDF30NNLO; total width from $\tan\beta = 20$, ...**
**but use SM coupling of Higgs to $b\bar{b}$**
**5000 events**

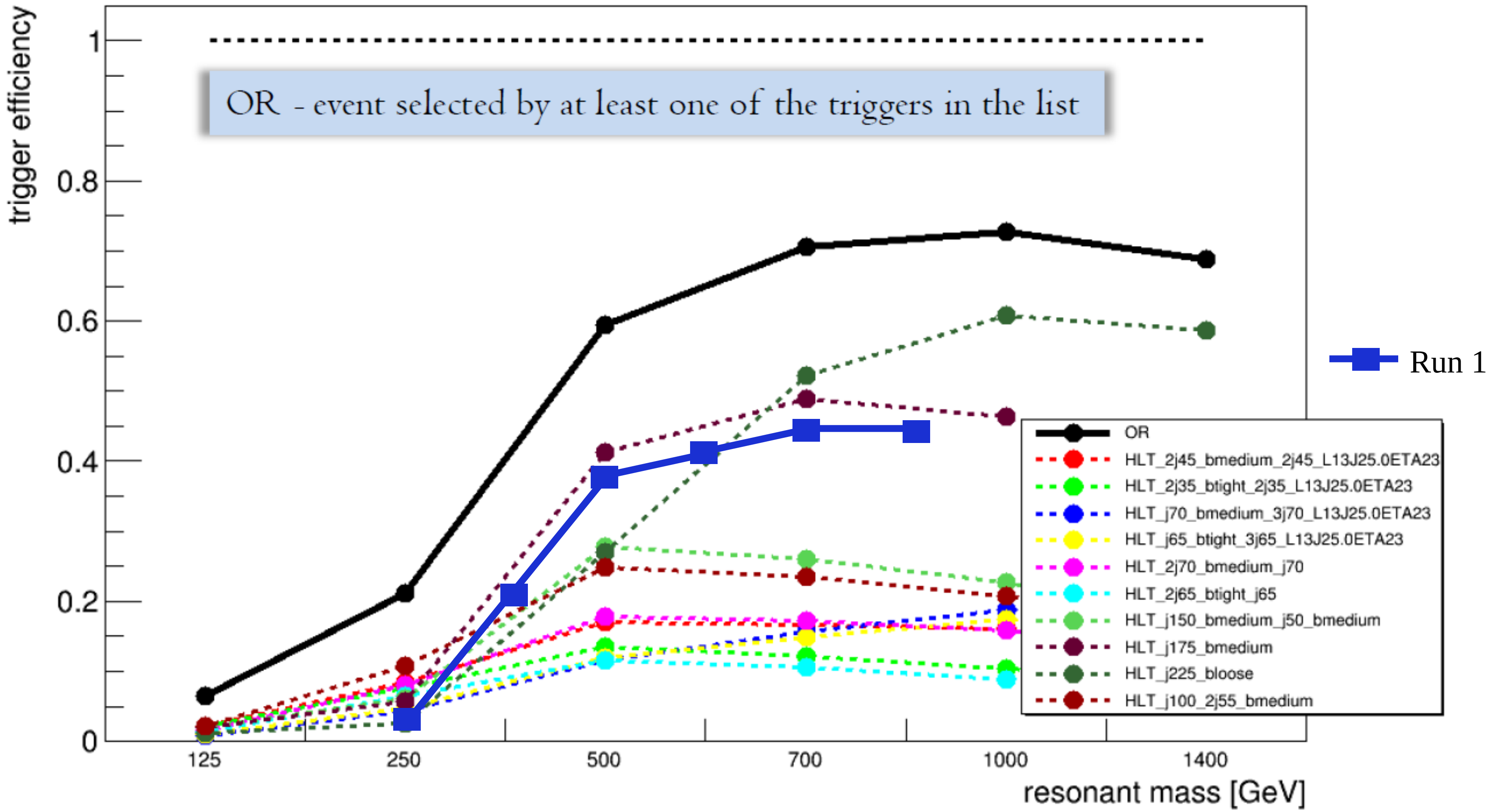


**MG5_aMC@NLO+PYTHIA8 4FS** $gg \to b\bar{b}A,\ A \to b\bar{b}$
**but with 5FS pdf NNPDF23LO; 0 total width**
**ignore MC weight and plot using unit weight**
**5000 events**

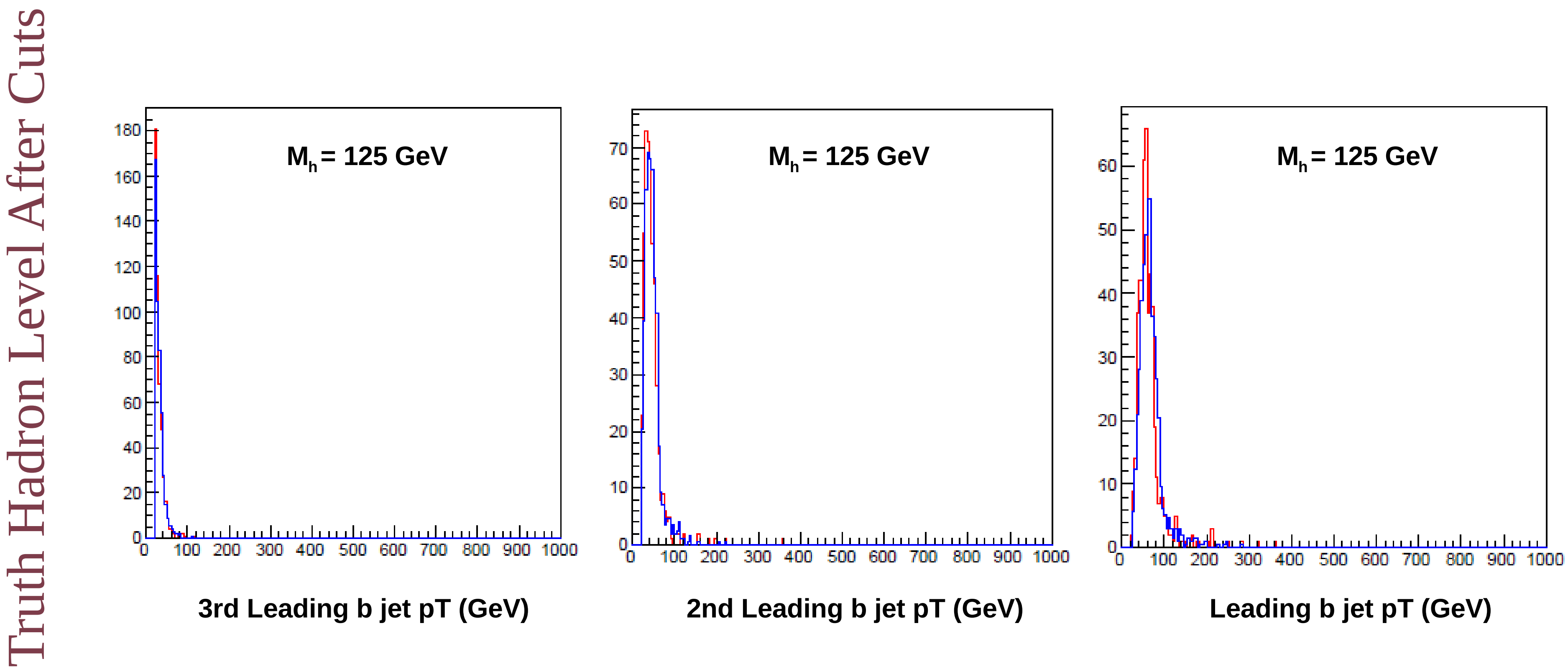
**SHERPA 5FS** $bg \to bA + 0/1$ **jet,** $A \to b\bar{b}$
**with 5FS pdf NNPDF30NNLO; total width from** $\tan\beta = 20$, ..
**but use SM coupling of Higgs to** $b\bar{b}$
**5000 events**



# Run 2 b-jet trigger efficiency for bHbb (no offline event selection)



# b–jets have very low pT when $M_H$ is low





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# Analysis Goals in the Short Term (Higgs Couplings 2016, SLAC, Nov 9-12)

- Present $M_H$>400 GeV results for 2015 and 2016 data.
- Current plan is to use the Run1 analysis for Run2 data
- If time permits include two differences w.r.t. the Run1 analysis:
  - Use MVA in place of the rotated Mbb' variable
  - Introduce a new 4 b-jet category.

# Longer Term Goals

- Improve trigger efficiency for $M_H$ < 400 GeV
  - Investigate possibility of a low Pt threshold 3 b-jet or 4 b-jet HLT
  - Investigate L1 topological trigger
- For Moriond 2017 present $M_H$ > 400 GeV results for Run 1 + Run 2
- Once low mass trigger problem is solved perform dedicated low Higgs Mass search ($M_H$< 400 GeV)