Phenomenology of boosted b-jets in di-Higgs processes at the LHC

Anna Przybyl

Max Planck Institute Presentation

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A little bit about me…

Anna Przybyl

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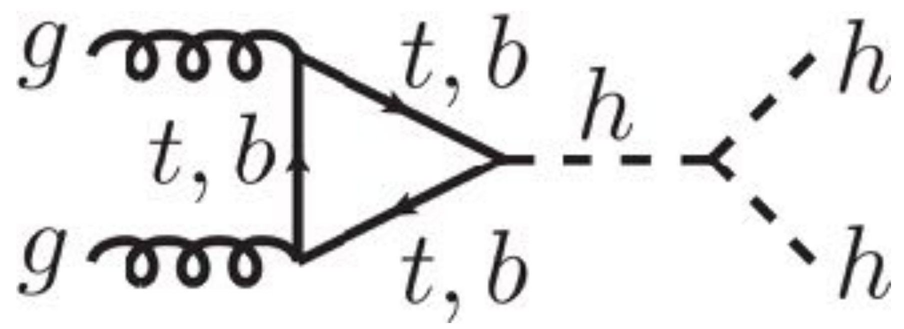
- From Naperville, IL
- Studied at UIUC
    - Researched and also worked
- Currently finishing my master's in Uppsala, Sweden
- I enjoy ceramics and bouldering

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

UPPSALA UNIVERSITET

Di-Higgs in SUSY

MSSM + NMSSM



Physical Higgses:

$h,\ H,\ A,\ H^{\pm}$

$h,\ H_1,\ H_2,\ A_1,\ A_2,\ H^{\pm}$

- SUSY is symmetry between fermions and bosons
  - Higgs sector must be extended, various scenarios with $m_h = 125$ GeV
- In di-Higgs:
  - Colored squarks enter loops
  - Extra Higgses (i.e. possible resonances)
- MSSM extends SM via additional Higgs doublet, NMSSM extends MSSM via additional Higgs singlet

The goal of the thesis

Di-Higgs in SUSY models

$gg \to hh \to b\bar{b}b\bar{b}$

most probable!

Using benchmark points within simplified models from earlier papers [1,2]:

1. Optimize jet reconstruction
   - Slimjet vs. fatjet reconstruction
   - anti-k_T (R) vs. variable R (minR, maxR, ρ)

$$R_{\text{eff}} = \frac{\rho}{p_T}$$

2. Come up with kinematic cut to distinguish signal (NP diagrams + NP diagram interferences) from background (SM di-Higgs and QCD background)

[1] Stefano Moretti et al. “Deconstructing squark contributions to di-Higgs production at the LHC”. In: Physical Review D 107.11 (June 2023). issn: 2470-0029. doi: 10.1103/physrevd.107.115010. url: http://dx.doi.org/10.1103/PhysRevD.107.115010.
[2] Stefano Moretti et al. Deconstructing resonant Higgs pair production at the LHC: effects of coloured and neutral scalars in the NMSSM test case. 2025. arXiv: 2506 . 09006 [hep-ph]. url: https://arxiv.org/abs/2506.09006.

The benchmark points

Di-Higgs in SUSY models

$gg \to hh \to b\bar{b}b\bar{b}$

most probable!

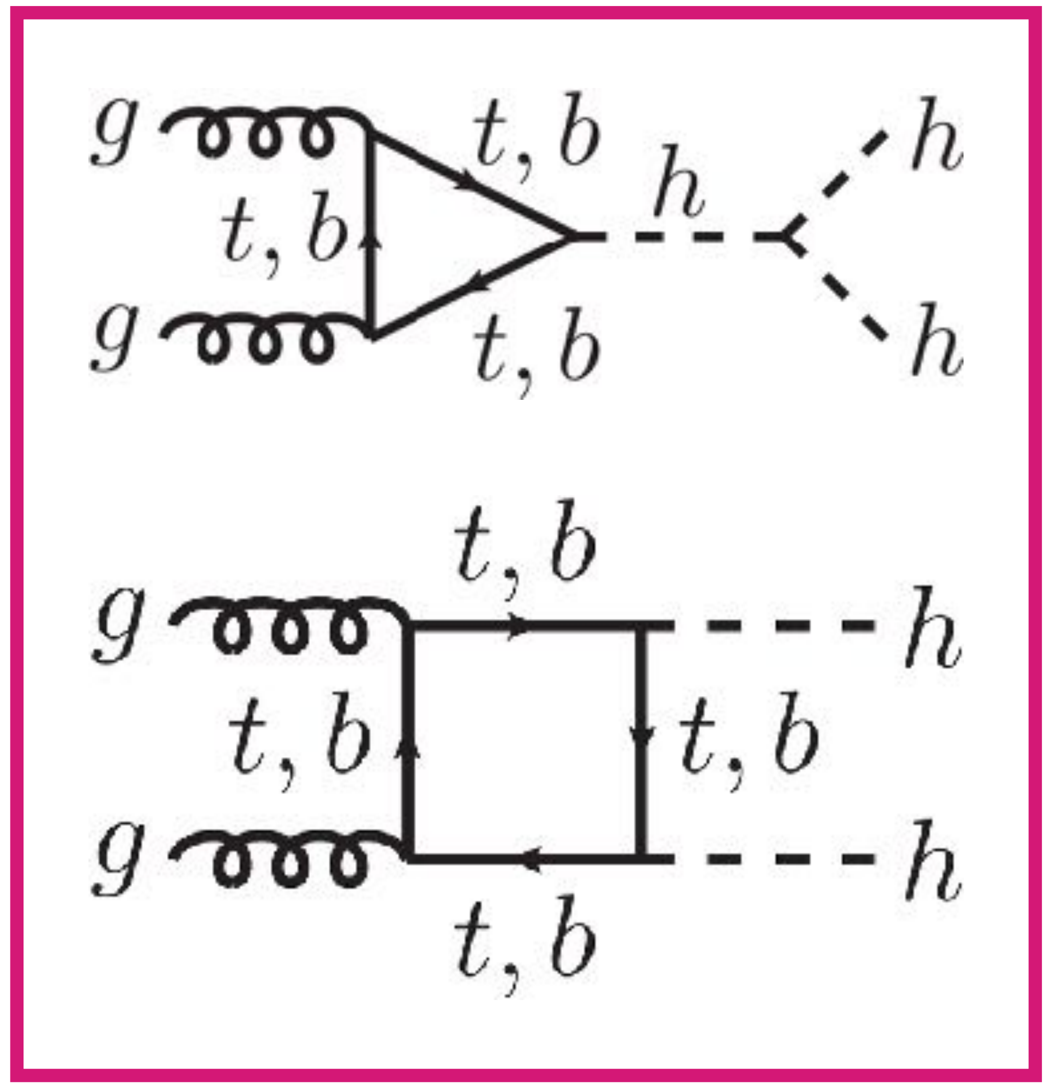
Three BPs:

- MSSM non-resonant case
- NMSSM resonant cases (350 GeV resonance and 800 GeV resonance)

Simplified SUSY models written (limited number of squarks) → appropriate parameter spaces scanned → BPs chosen

Feynman diagrams

Di-Higgs processes in SM + MSSM + NMSSM



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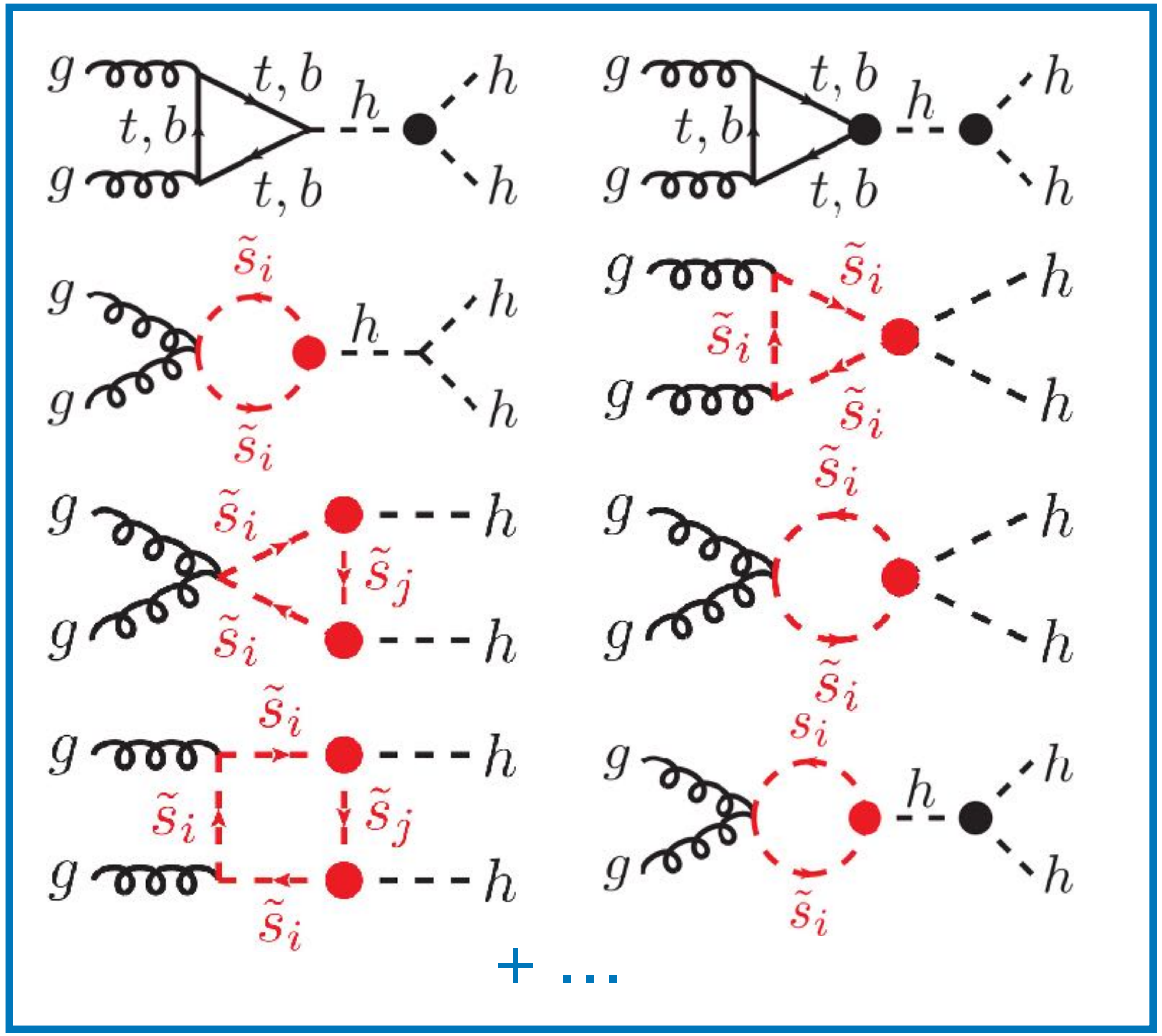

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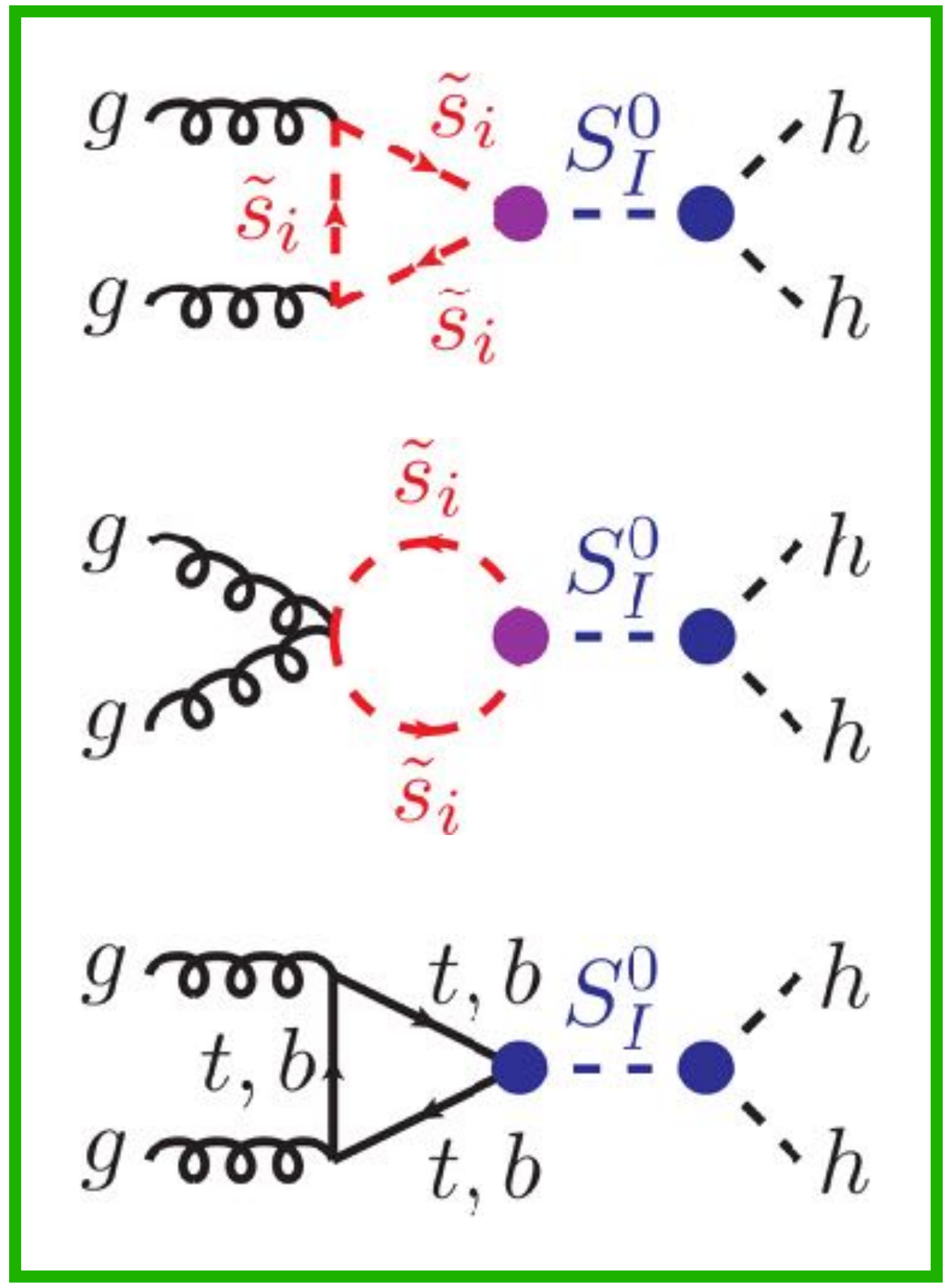
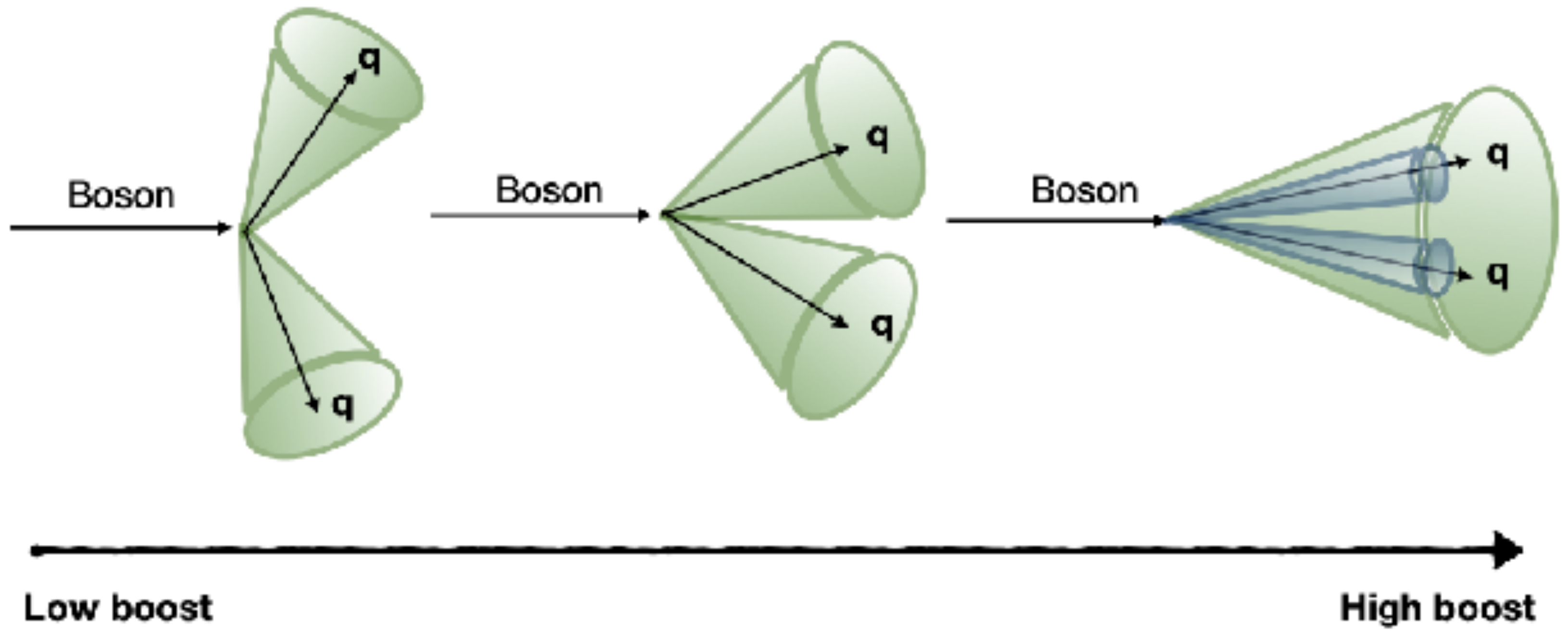
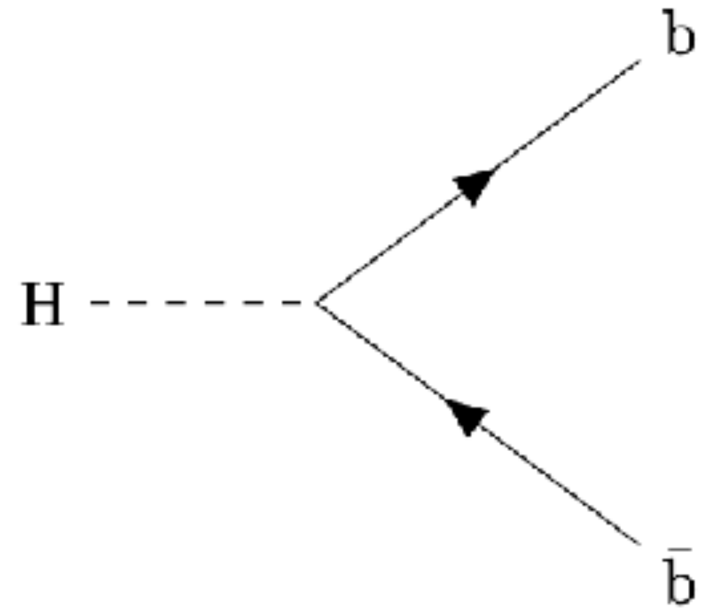


Jet reconstruction

Slimjet/fatjet analysis, jet algorithms…

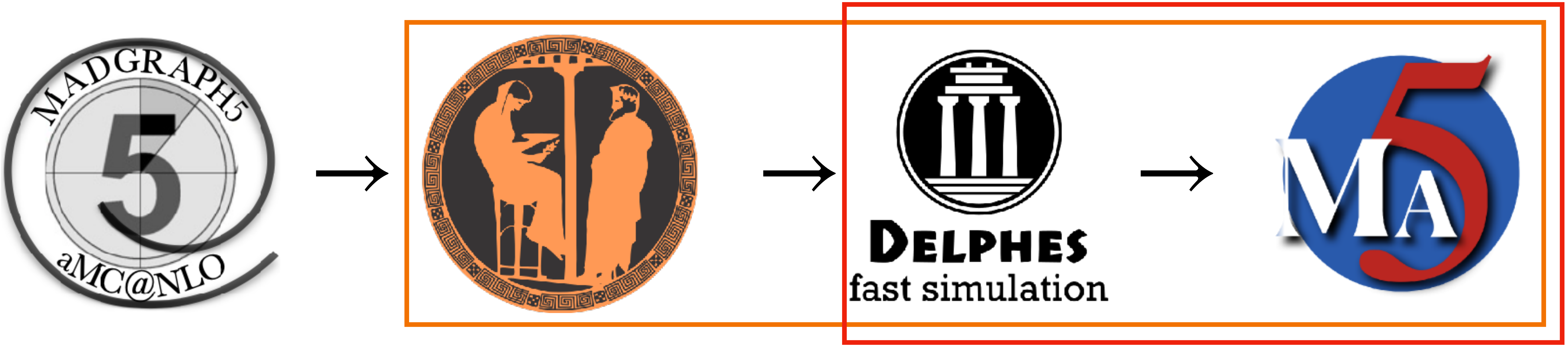


- Slimjet reconstruction:
  - Typical “resolved” case, reconstructs 4 separate b-jets with small R
- Fatjet reconstruction:
  - Boosted b-jets are collimated together, makes sense to reconstruct them together as one “fatjet” with higher R



- Jet algorithms:
  - anti-k_T and variable R work in the same way, but variable R uses an effective radius

Workflow and analysis process



1. Jet optimization (R, ρ) done using Delphes

2. Higgs tagging done (dijets/fatjets closest to Higgs mass are labeled as “1”, the next ones are labeled as “2”)

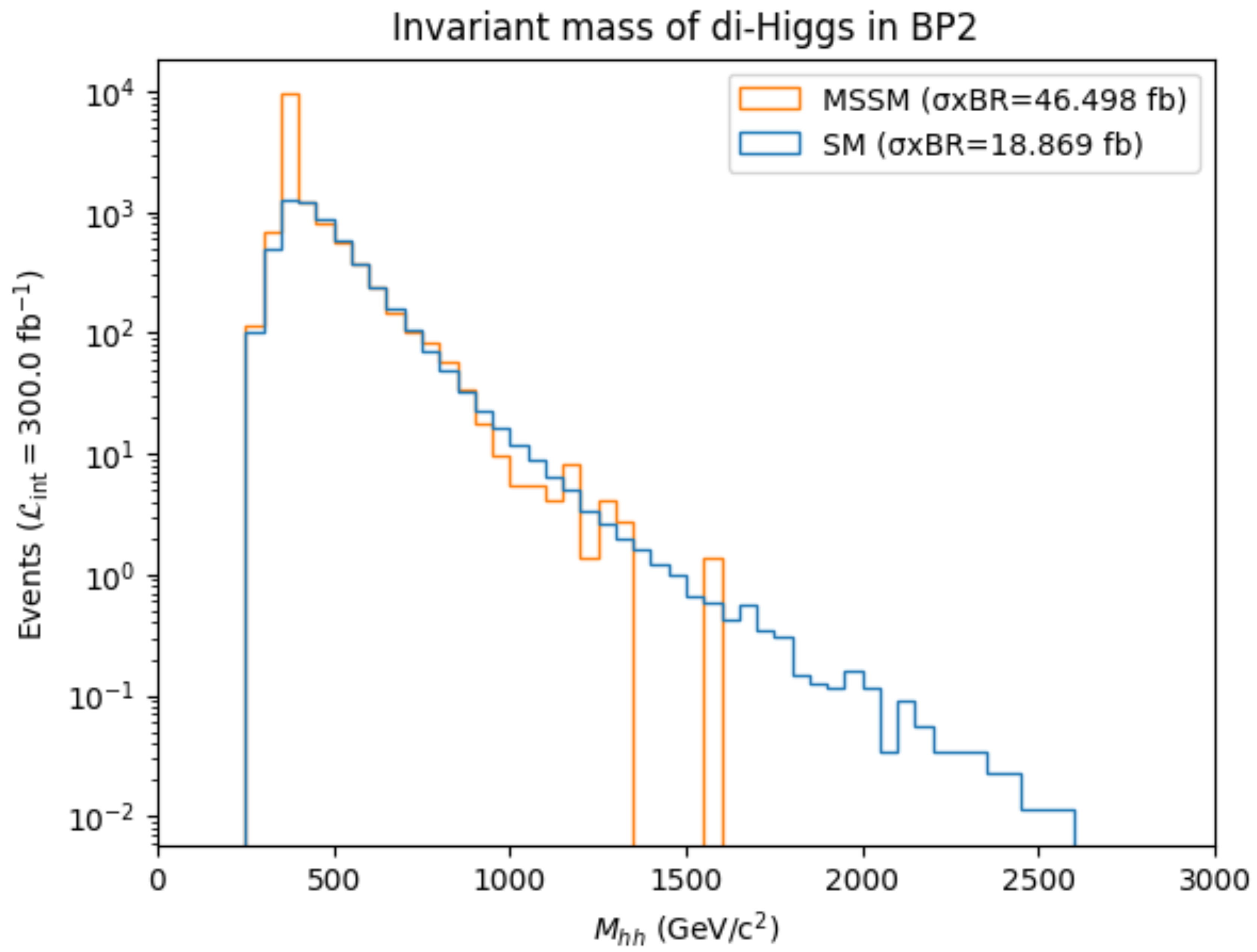
3. Kinematic cuts placed on THT, dijet/fatjet mass and p_T using MadAnalysis5

BP2 — 350 GeV resonance

Jet optimization

	$\sigma_{\text{before decay}}$ (fb)	$\sigma_{\text{after decay}}$ (fb)
SM	18.869	5.492
NMSSM	46.498	10.6

	slimjet
R	0.4
minR	0.2
maxR	0.5
ρ	10



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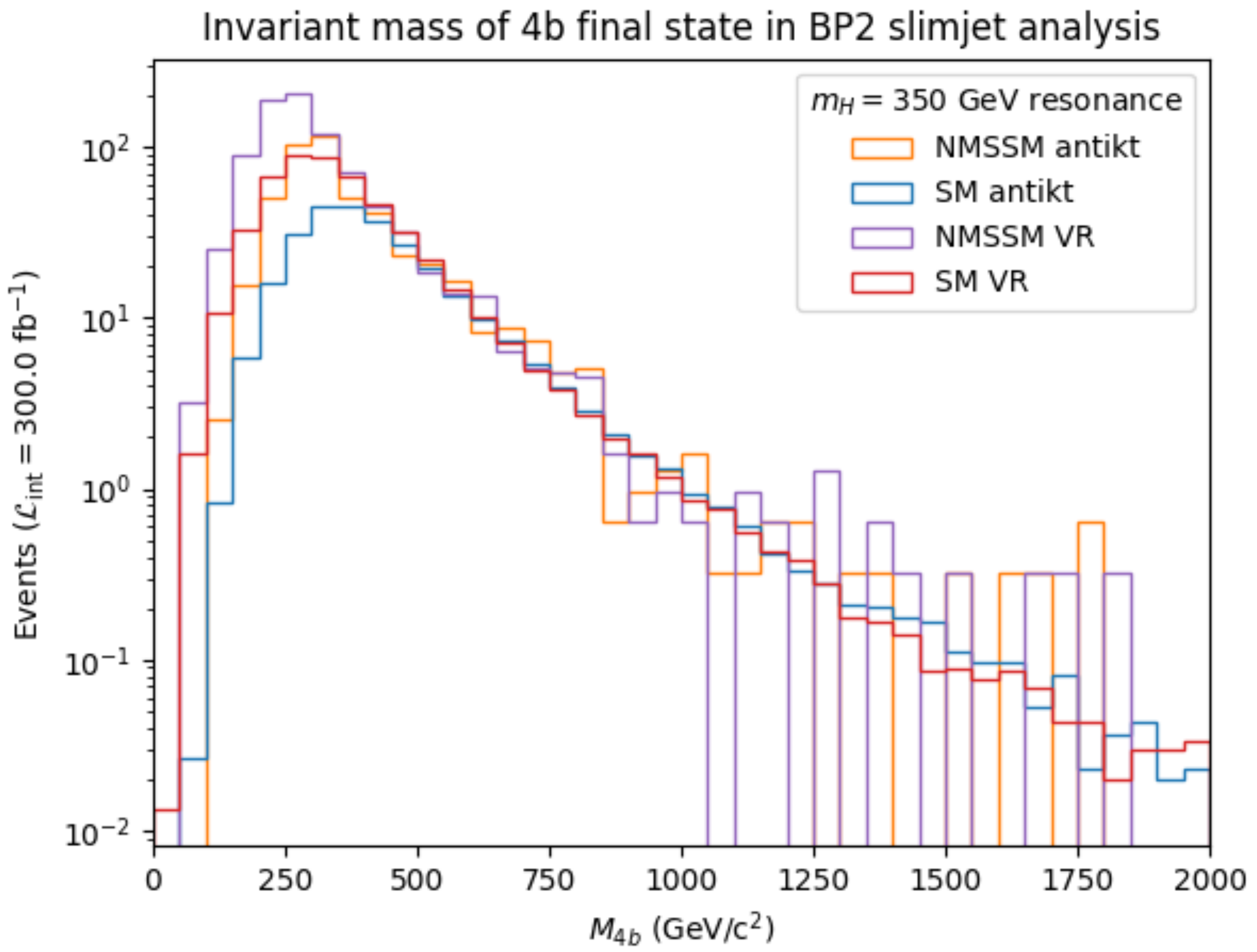
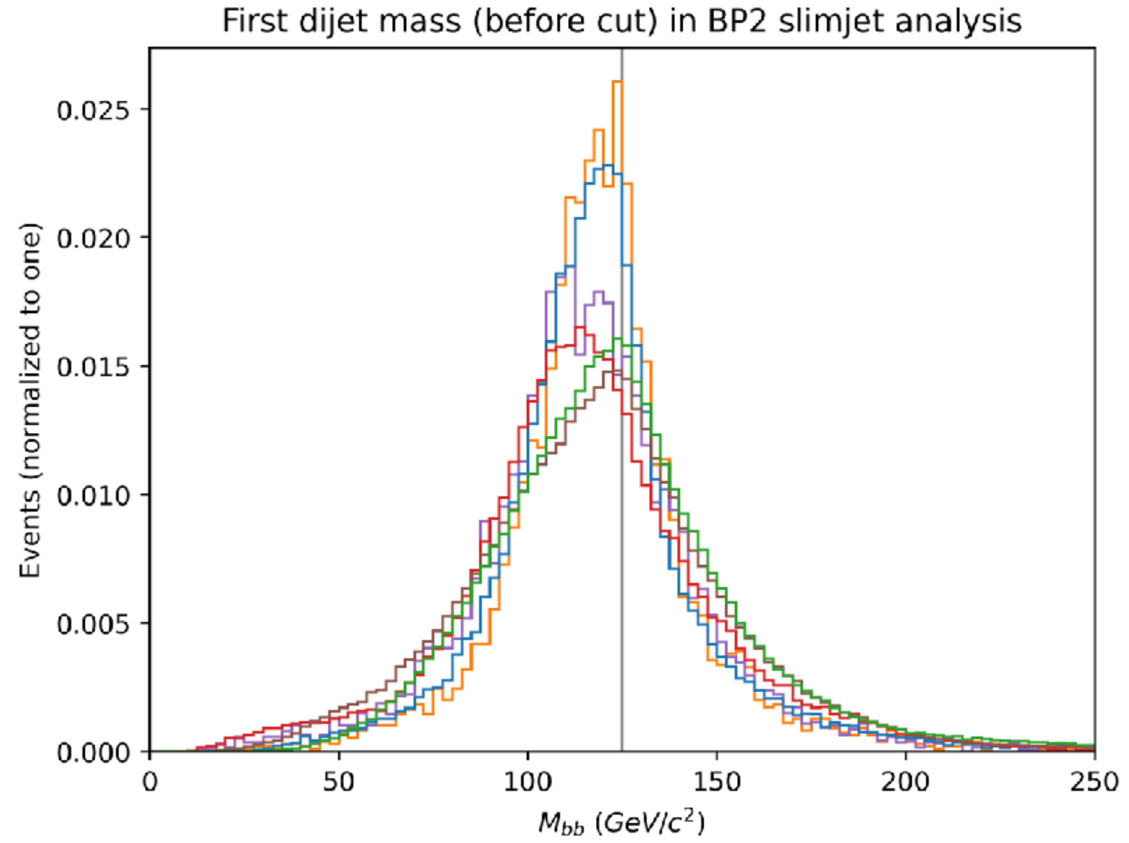
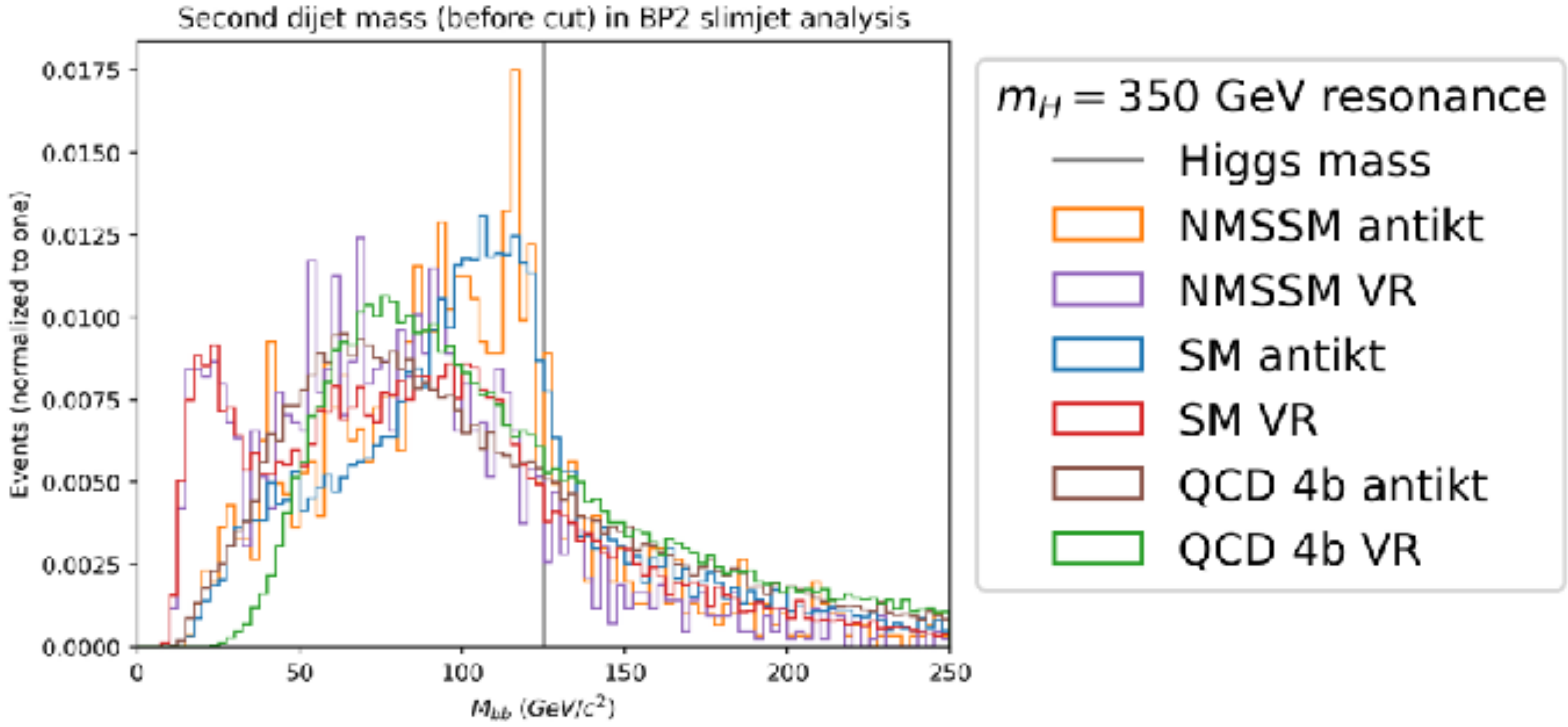


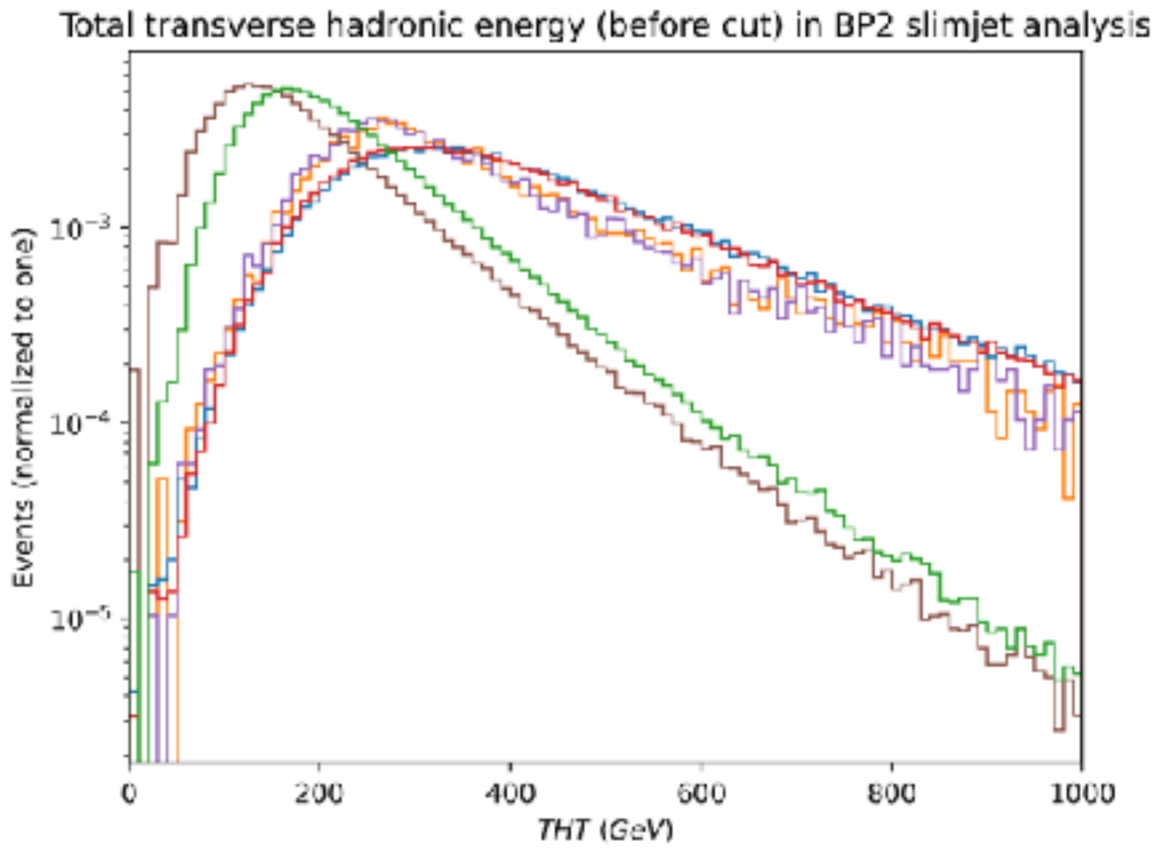
BP2 — 350 GeV resonance

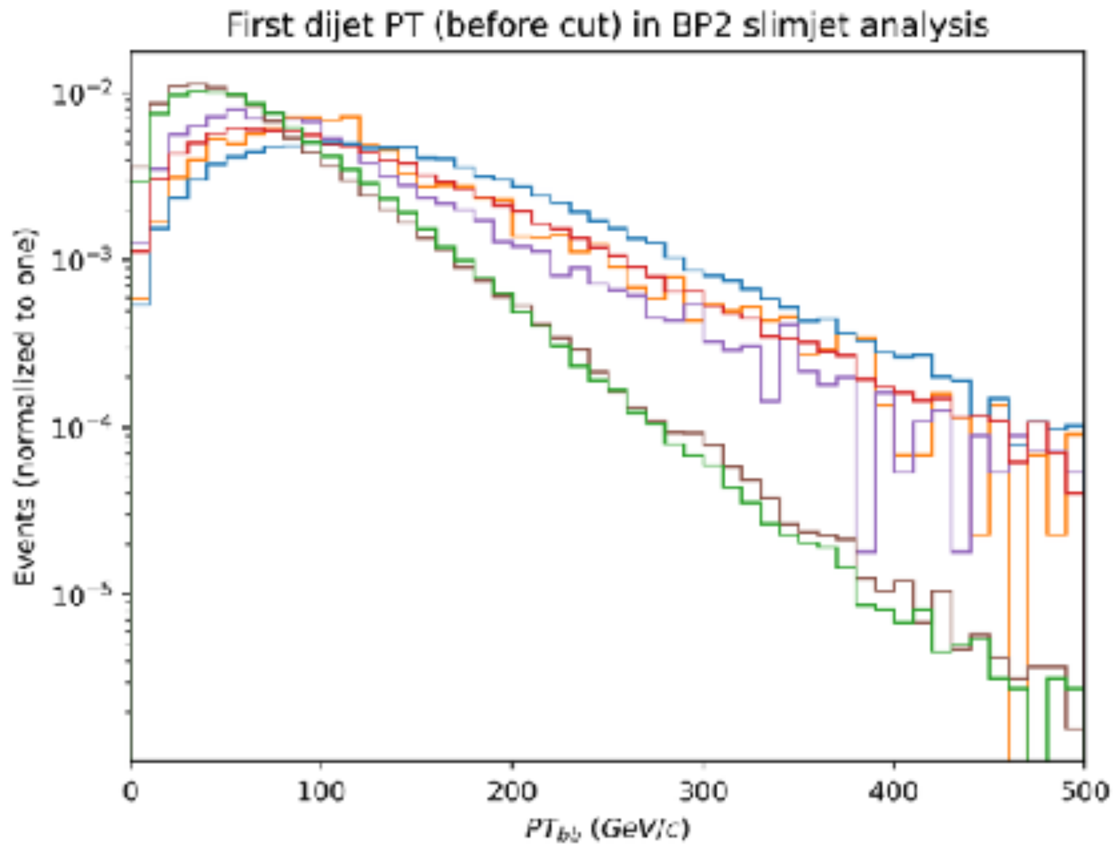
Kinematic cut

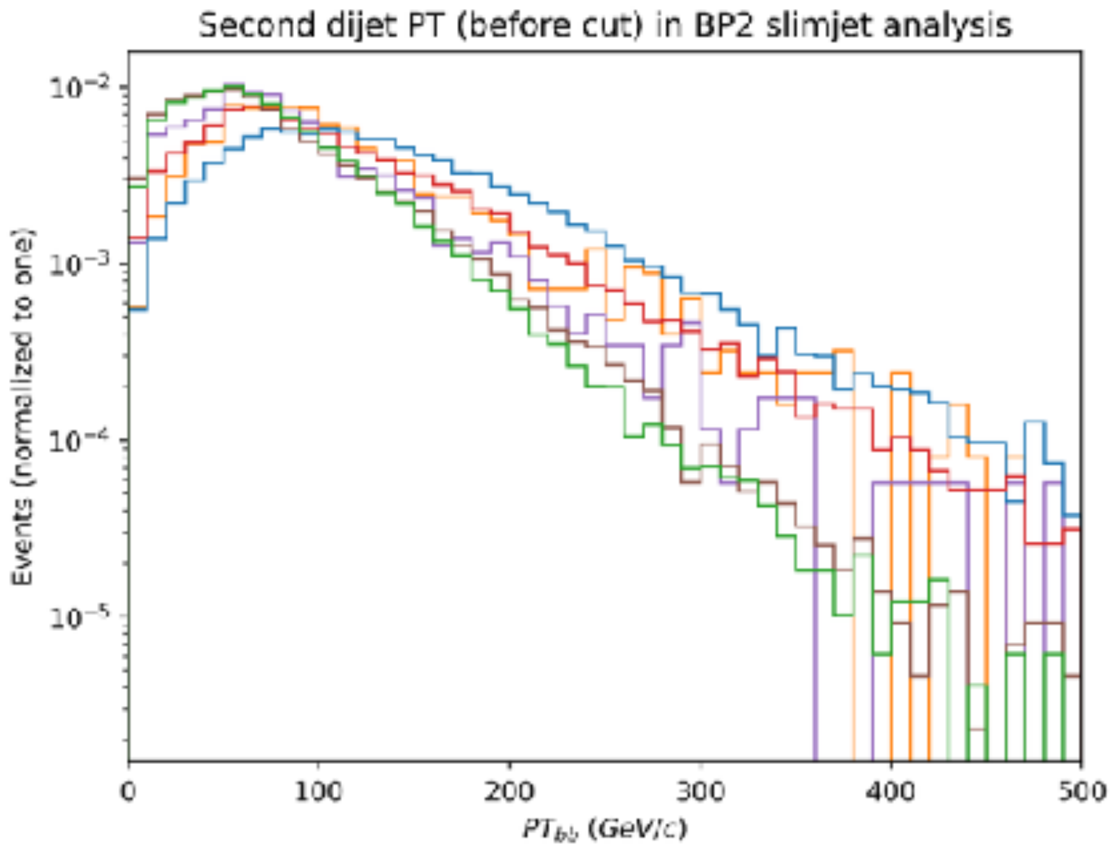
(including QCD background)











	THT	Dijet 1 mass	Dijet 1 pT	Dijet 2 mass	Dijet 2 pT
If N(b) > 2	THT>300	110<m<140	pT<175	—	—
If N(b) > 3	THT>300	110<m<140	pT<175	m<150	pT<175

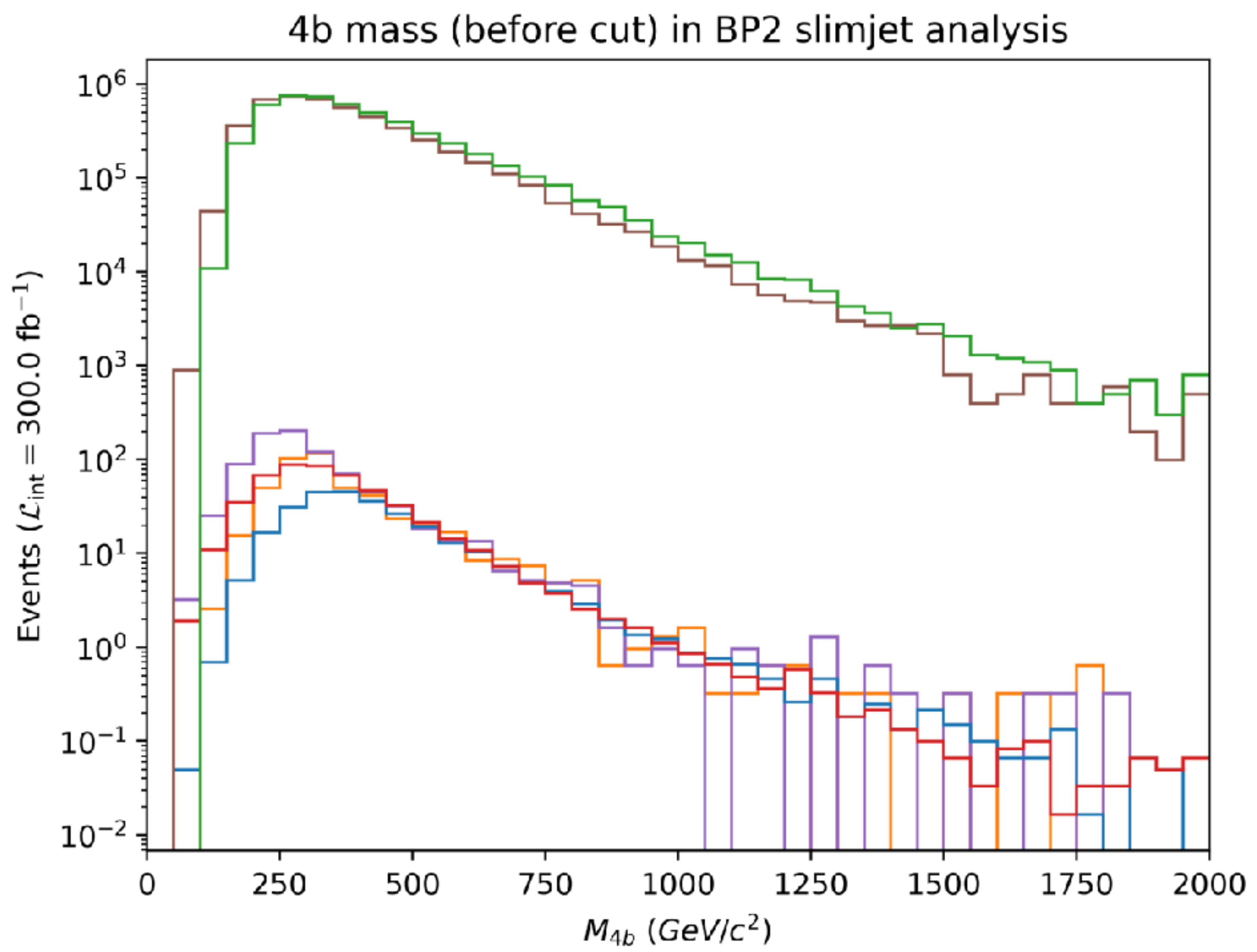
All units in GeV.

BP2 — 350 GeV resonance (4b)

Applying the cut

SR: $M_{4b} < 500$ GeV

$\sigma_{\text{QCD}} = 192$ pb



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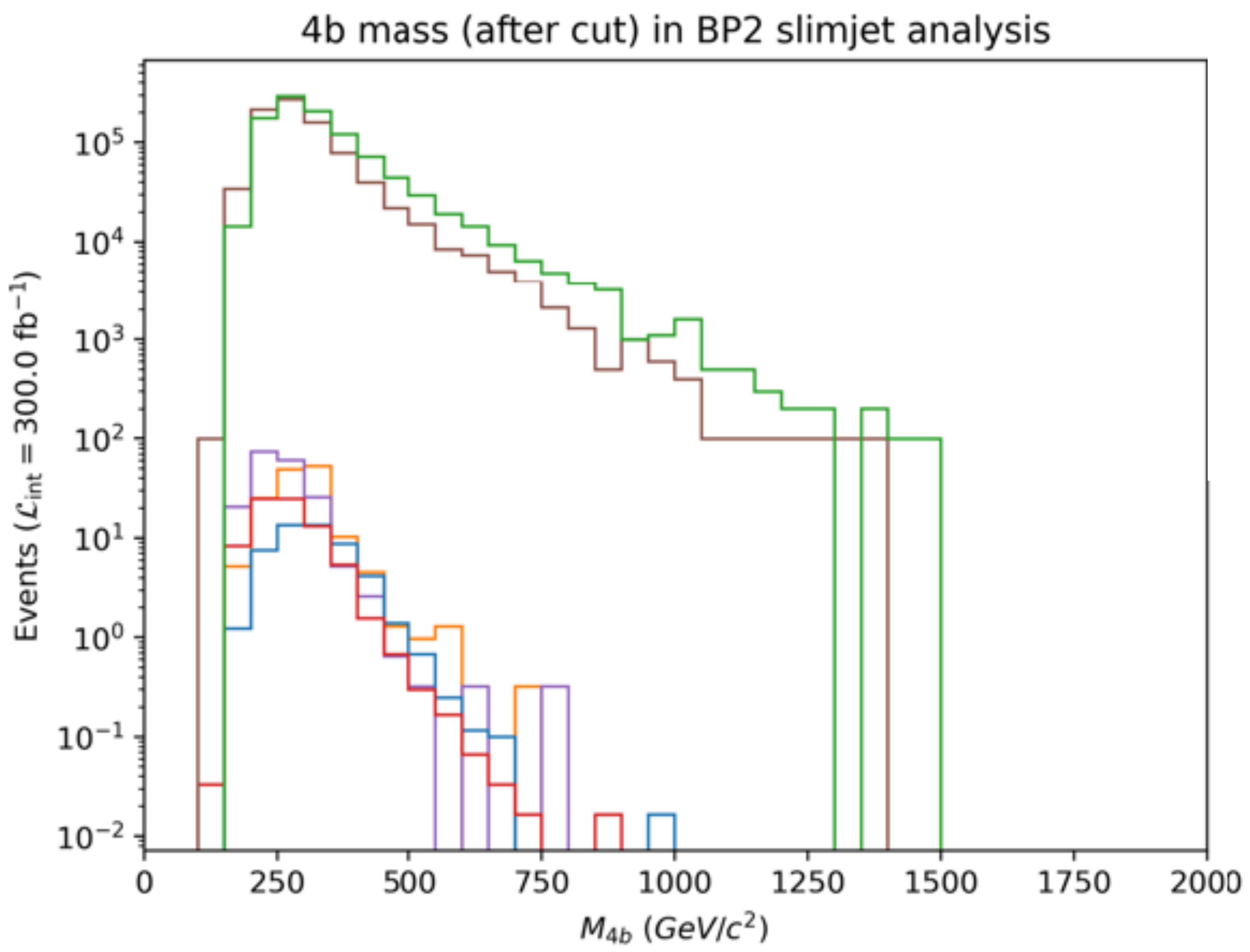
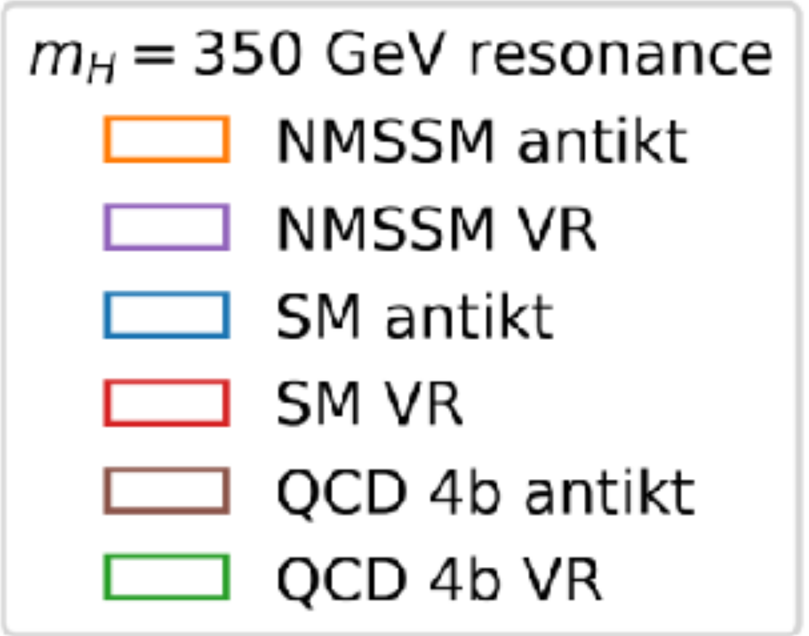




SR events before cut (4b)	anti-kT	Variable R
BSM di-Higgs	402	778
SM di-Higgs	206	435
Signal (BSM-SM)	196	343
QCD 4b	3867732	3821103
S/(√B)	0.0999	0.175

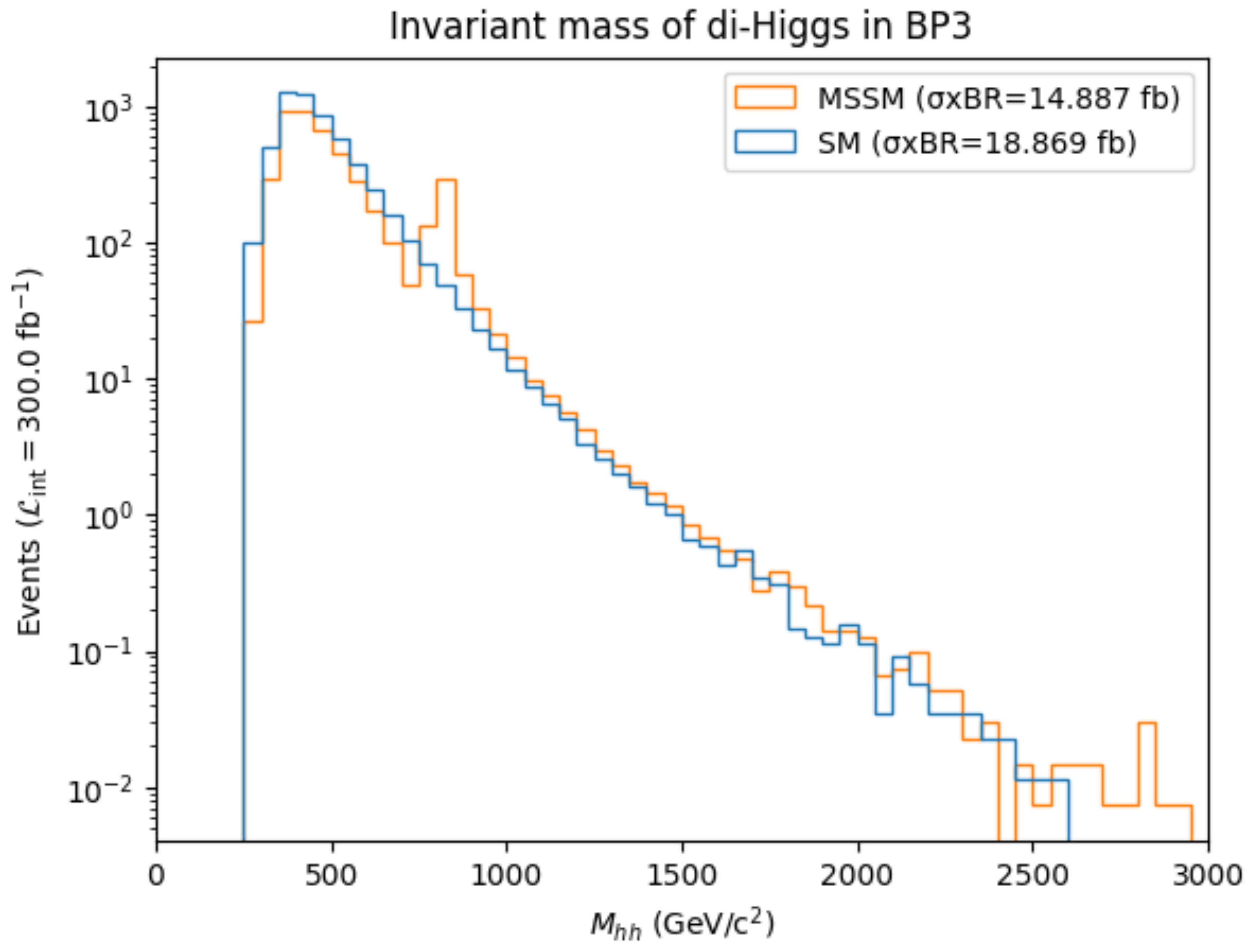
SR events after cut (4b)	anti-kT	Variable R
BSM di-Higgs	148	189
SM di-Higgs	50	78
Signal (BSM-SM)	98	111
QCD 4b	816552	924165
S/(√B)	0.109	0.115

BP3 — 800 GeV resonance

Jet optimization

	$\sigma_{\text{before decay}}$ (fb)	$\sigma_{\text{after decay}}$ (fb)
SM	18.869	5.492
NMSSM	14.887	4.84

	fatjet
R	0.8
minR	0.6
maxR	1.6
ρ	400



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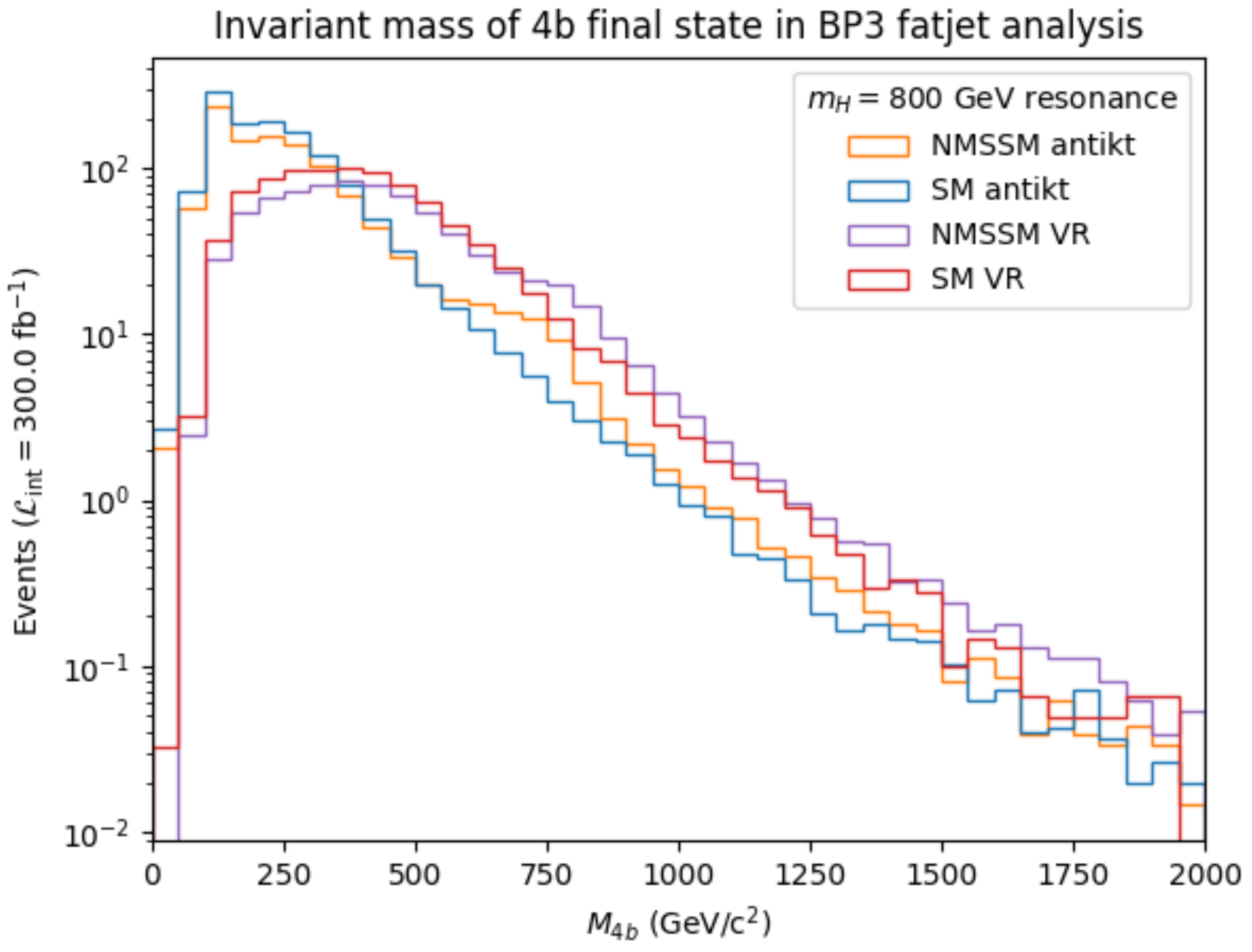
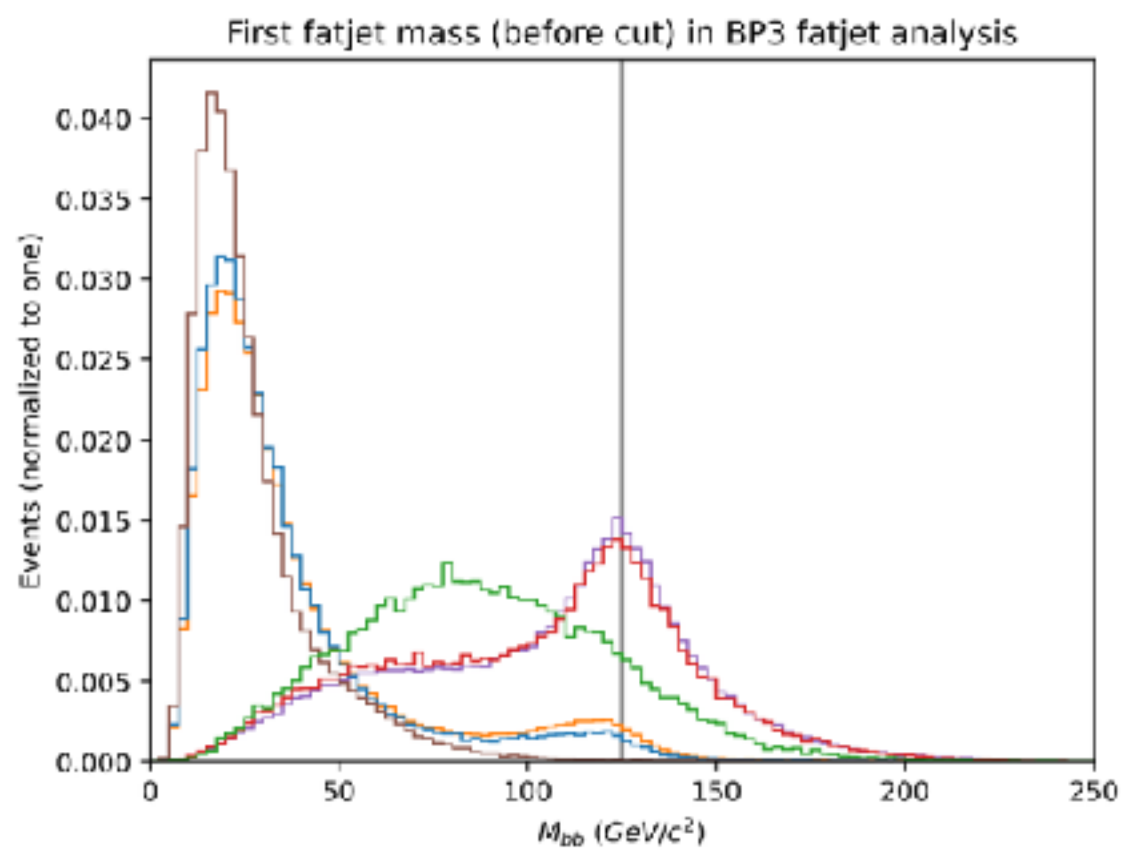
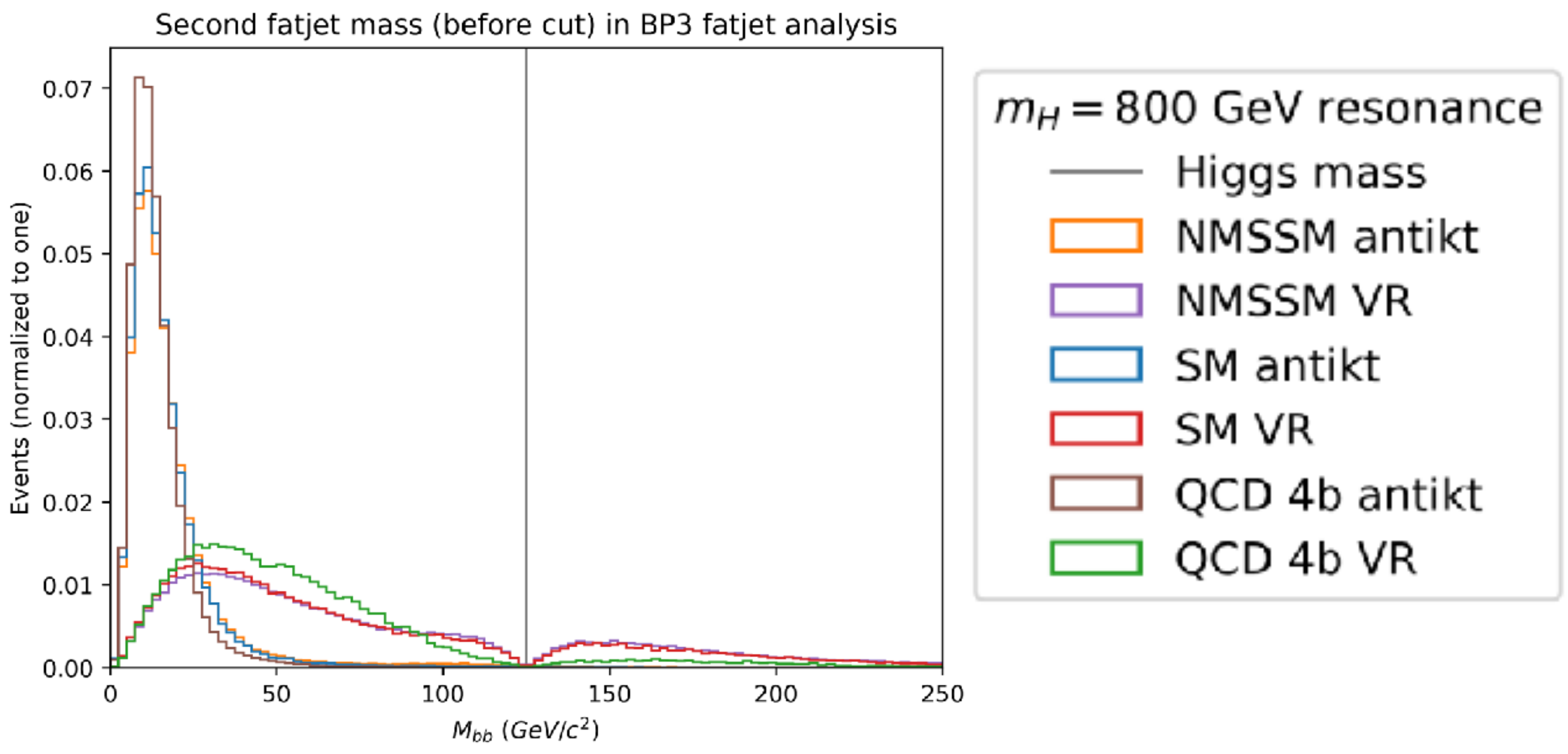


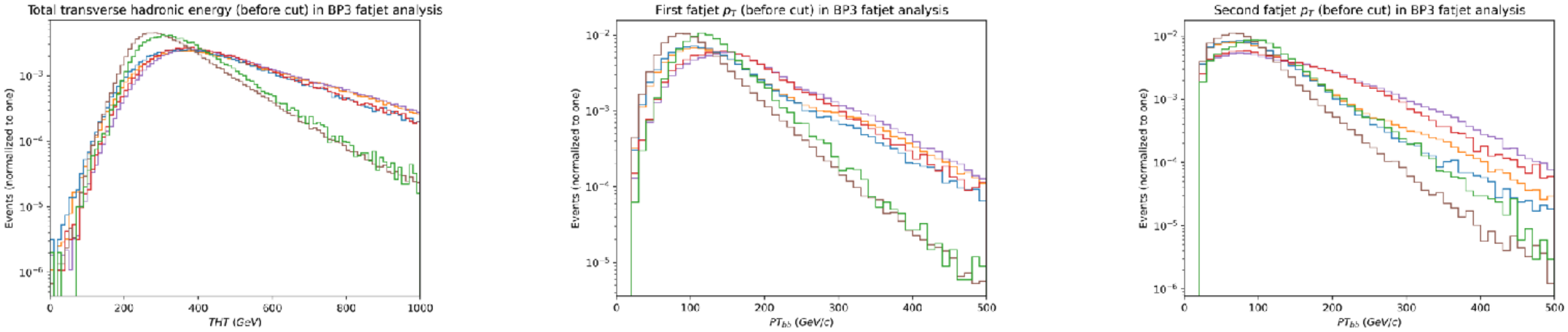
BP3 — 800 GeV resonance

Kinematic cut

(including QCD background)





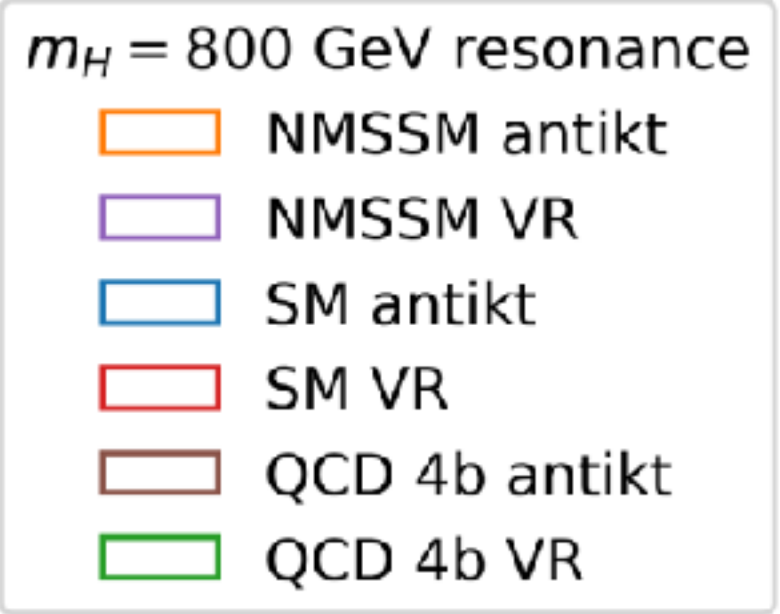


	THT	Fatjet 1 mass	Fatjet 1 pT	Fatjet 2 mass	Fatjet 2 pT
If N(b) > 1	THT>300	100<m<150	250<pT	M<150	250<pT

All units in GeV.

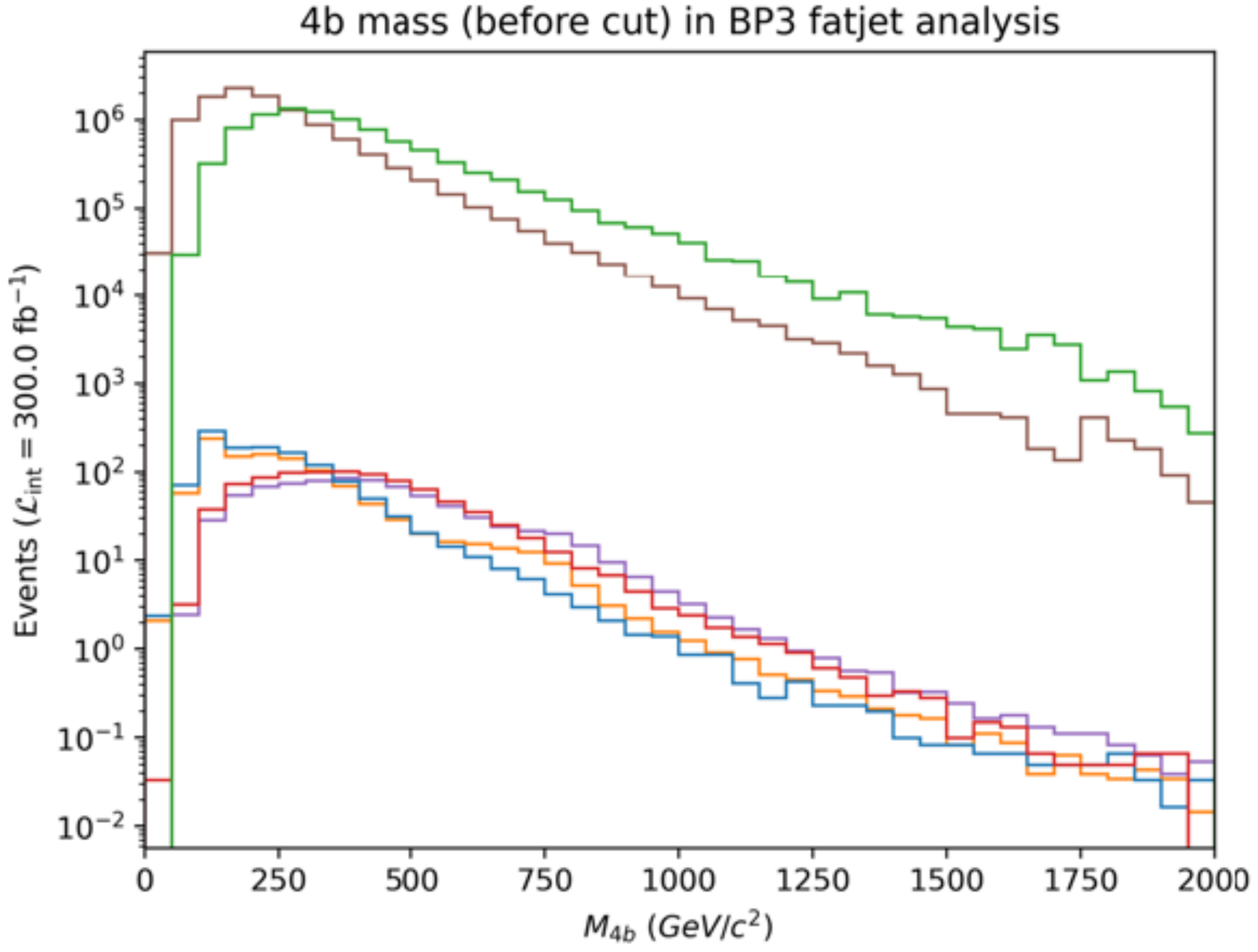
SR (in GeV): $600 < M_{4b} < 1200$

$\sigma_{\text{QCD}} = 45$ pb



BP3 — 800 GeV resonance

Applying the cut



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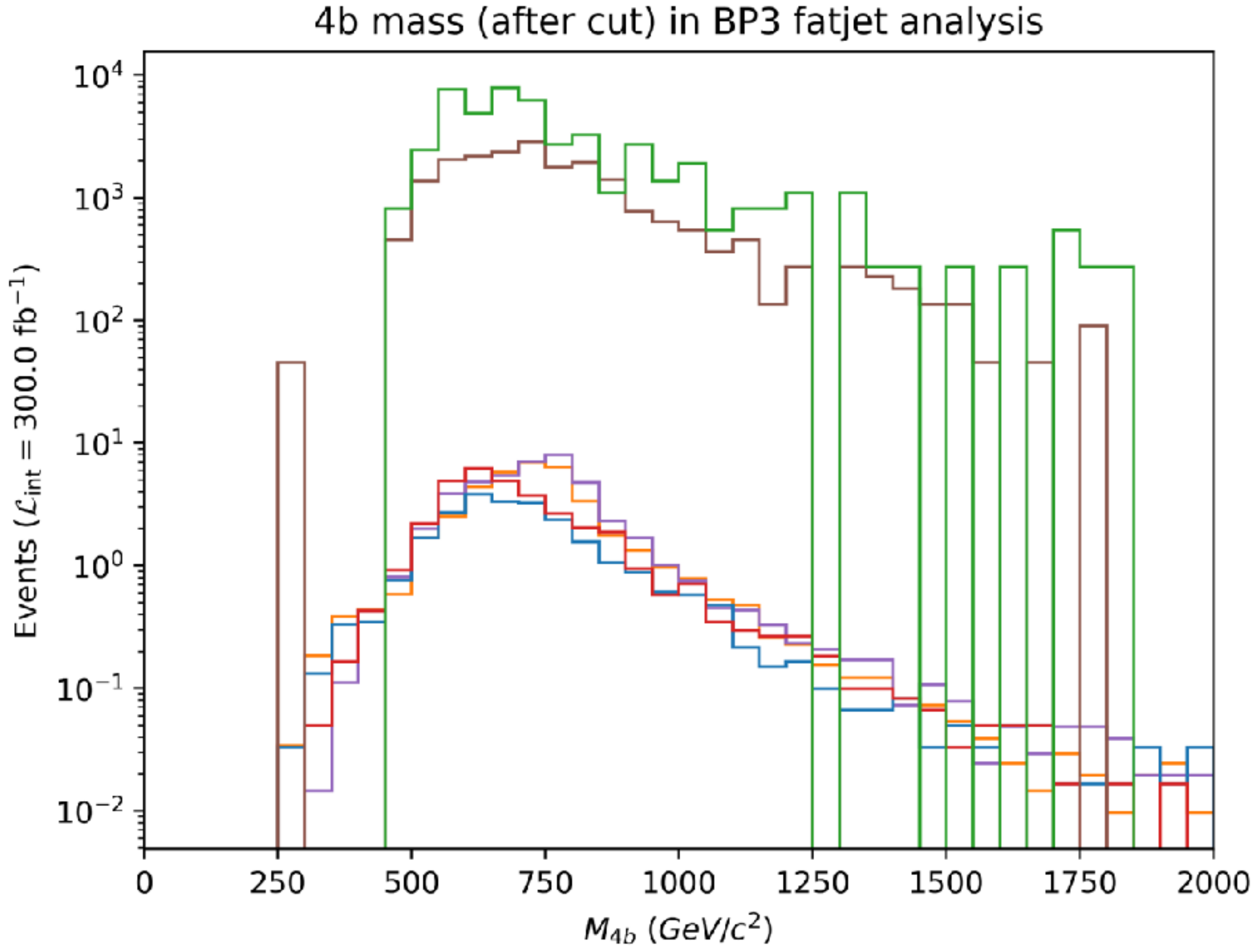

SR events before cut (4b)	anti-kT	Variable R
BSM di-Higgs	66	140
SM di-Higgs	39	120
Signal (BSM-SM)	27	20
QCD 4b	383012	1122262
S/(√B)	0.0426	0.0188

SR events after cut (4b)	anti-kT	Variable R
BSM di-Higgs	33	37
SM di-Higgs	18	24
Signal (BSM-SM)	15	13
QCD 4b	15401	34247
S/(√B)	0.118	0.0668

Conclusion

Di-Higgs in SUSY models

$$gg \to hh \to b\bar{b}b\bar{b}$$

most probable!

- Variable R (generally) reconstructs more signal events
    - But it also reconstructs more QCD events
    - Smaller R works much better in excluding random background
- Kinematic cuts on the BPs decrease QCD background by ~ an order of magnitude
    - SM di-Higgs and BSM di-Higgs have similar kinematics
- Future work: investigating/placing cuts on jet substructure would also be a good idea, cuts as selection cuts for ML study

Thank you!

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The simplified MSSM model

- Based on superpotential

$$W_{\text{MSSM}} = y_u Q H_u U^c + y_d Q H_d D^c + y_\ell L H_d E^c + \mu H_u H_d$$

- Introduces two stop squarks
- Lagrangian induced by NP:

Squark terms

$$\mathcal{L}_{\text{NP}}^{\tilde{q}} = -(\lambda^{\text{SM}} + \kappa_{hhh}) v h^3 - \frac{1}{\sqrt{2}}(y_t^{\text{SM}} + \kappa_{htt}) h \bar{t} t + v h (\tilde{s}_1^* \ \tilde{s}_2^*) \begin{pmatrix} \kappa_{h\tilde{s}\tilde{s}}^{11} & \kappa_{h\tilde{s}\tilde{s}}^{12} \\ \cdot & \kappa_{h\tilde{s}\tilde{q}}^{22} \end{pmatrix} \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix}$$
$$+ hh (\tilde{s}_1^* \ \tilde{s}_2^*) \begin{pmatrix} \kappa_{hh\tilde{s}\tilde{s}}^{11} & \kappa_{hh\tilde{s}\tilde{s}}^{12} \\ \cdot & \kappa_{hh\tilde{s}\tilde{s}}^{22} \end{pmatrix} \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix}$$

Modified couplings

Higgs masses in the MSSM

Physical CP-even states: h and H

- Upper bound on lighter Higgs:

$$m_{h,0}^2 \leq m_Z^2 \cos^2 2\beta, \text{ where } \tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

- Light Higgs must be lower than Z boson mass (91.2 GeV)
- Large loop corrections needed for $m_h = 125$ GeV
  - Can come from top-stop sector → large $\tan\beta$
- Resonant di-Higgs production is suppressed because at large $\tan\beta$, heavy Higgs mass must be higher than a TeV

The simplified NMSSM model

- Based on superpotential

$$W_{\text{NMSSM}} = y_u Q H_u U^c + y_d Q H_d D^c + y_\ell L H_d E^c + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

- Introduces two stop squarks, two sbottom squarks, one neutral scalar

- Lagrangian terms induced by NP:

Modified couplings

$$\mathcal{L}_M = -(\lambda_{\text{SM}} + \kappa_{hhh}) v h^3 - \frac{1}{\sqrt{2}}(y_f^{\text{SM}} + \kappa_{hff}) h \bar{f} f$$

Squark terms

$$\mathcal{L}_{\tilde{s}} = \sum_i \left(\kappa_{h\tilde{s}\tilde{s}}^{ii} v h \tilde{s}_i^* \tilde{s}_i + \kappa_{hh\tilde{s}\tilde{s}}^{ii} h h \tilde{s}_i^* \tilde{s}_i\right) + \left(\sum_{i>j} \kappa_{h\tilde{s}\tilde{s}}^{ij} v h \tilde{s}_i^* \tilde{s}_j + \text{h.c.}\right)$$

Scalar terms

$$\mathcal{L}_S = \sum_I \kappa_{Shh}^I v S_I^0 h h + \kappa_{Sff}^I S_I^0 \bar{f} f$$

Scalar-squark terms

$$\mathcal{L}_{\tilde{s}S} = \sum_{I,i} \kappa_{S\tilde{s}\tilde{s}}^{Ii} v S_I^0 \tilde{s}_i^* \tilde{s}_i$$

Higgs masses in the NMSSM

Physical CP-even states: h, H_1, and H_2

- Upper bound on lighter Higgs:

$$m_{h,0}^2 \leq m_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta \right)$$

- Light Higgs can be heavier than Z
- Less constraints than MSSM
- At $1 \lesssim \tan\beta \lesssim 3$ and large λ, $m_h = 125$ GeV without loop corrections

Benchmark points

Di-Higgs in SUSY models

In MSSM

- Large squark loops at large $\tan\beta$

In NMSSM

- Large resonance effects:

  Large λ and small $\tan\beta$

- Large squark effects:

  Small λ and high $\tan\beta$

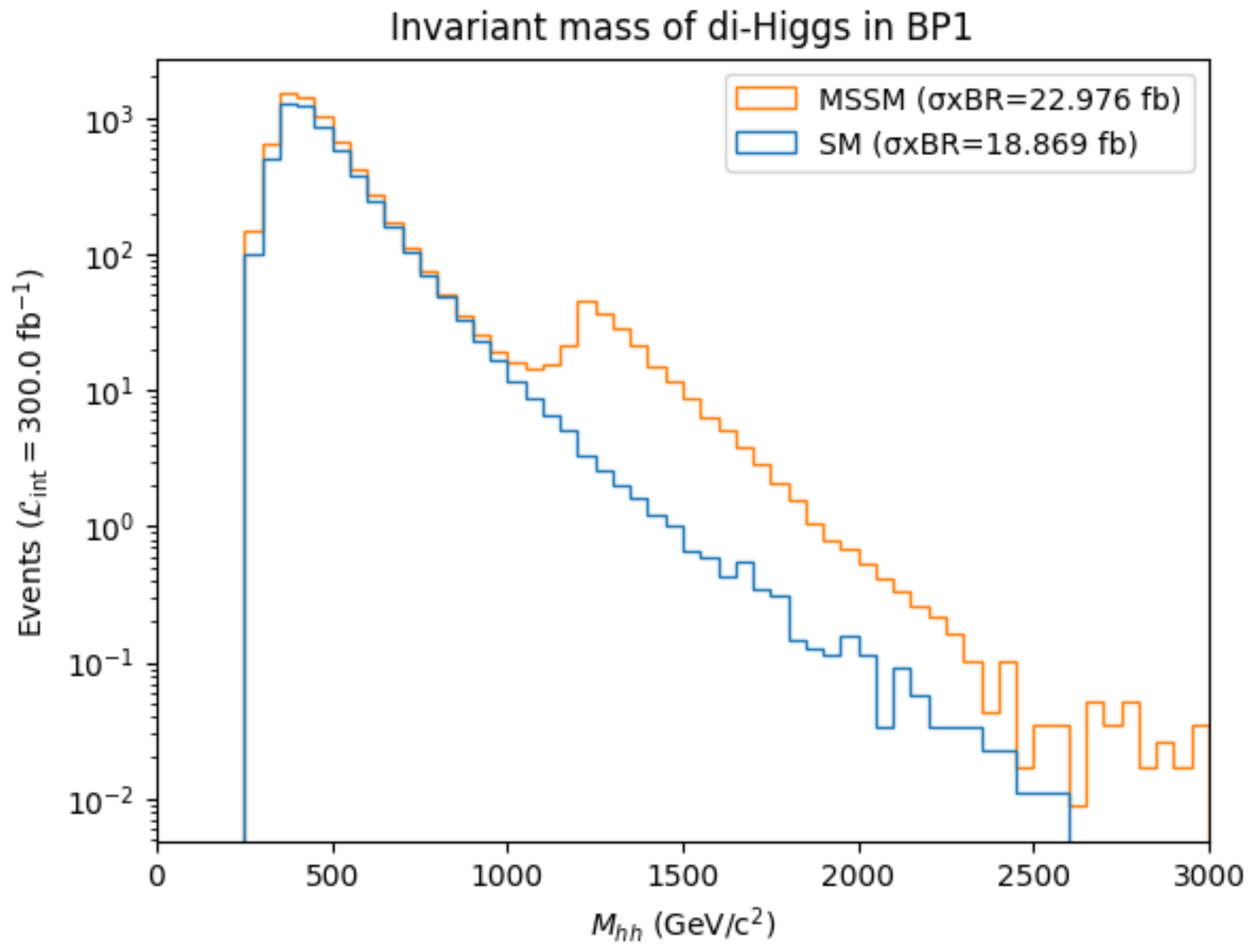
	BP1	BP2	BP3
production mode	non-resonant	resonant	resonant
$m_{\tilde{t}_1}$ (in GeV) $m_{\tilde{t}_2}$ (in GeV)	600.6 1301.0	1601.5 1951.8	602.4 1398.9
$m_{\tilde{b}_1}$ (in GeV) $m_{\tilde{b}_2}$ (in GeV)	–	1852.7 1951.8	1365.0 1623.0
$m_{S_1^0}$ (in GeV)	–	354.6	800.0
$\tan\beta$	45.4	30	2.5
λ	–	0.043	0.7
reconstruction	slimjet and fatjet	slimjet	fatjet

BP1 — non-resonant slimjet

Jet optimization

	$\sigma_{\text{before decay}}$ (fb)	$\sigma_{\text{after decay}}$ (fb)
SM	18.869	5.492
MSSM	22.976	6.697

	slimjet
R	0.4
minR	0.2
maxR	0.4
ρ	100



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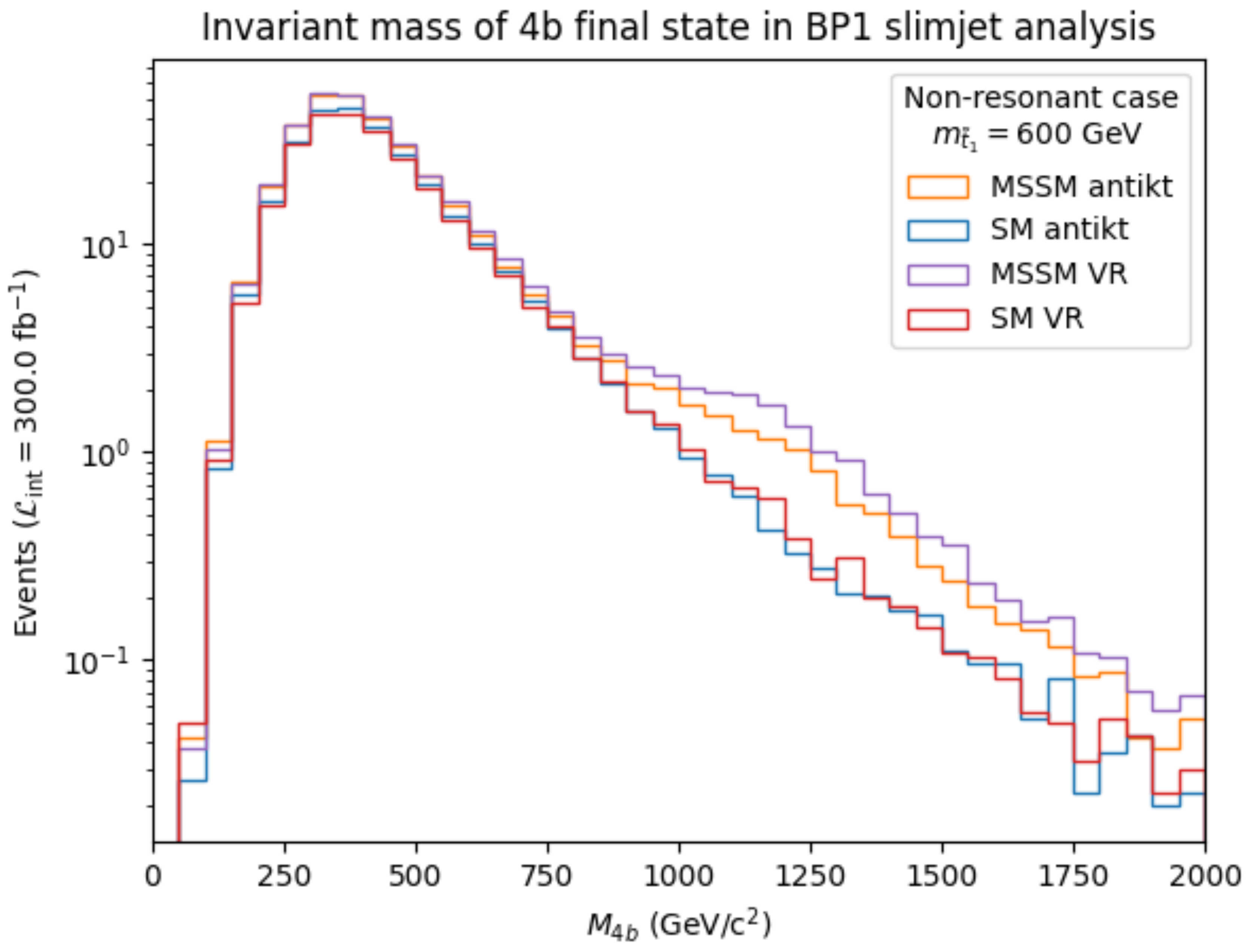
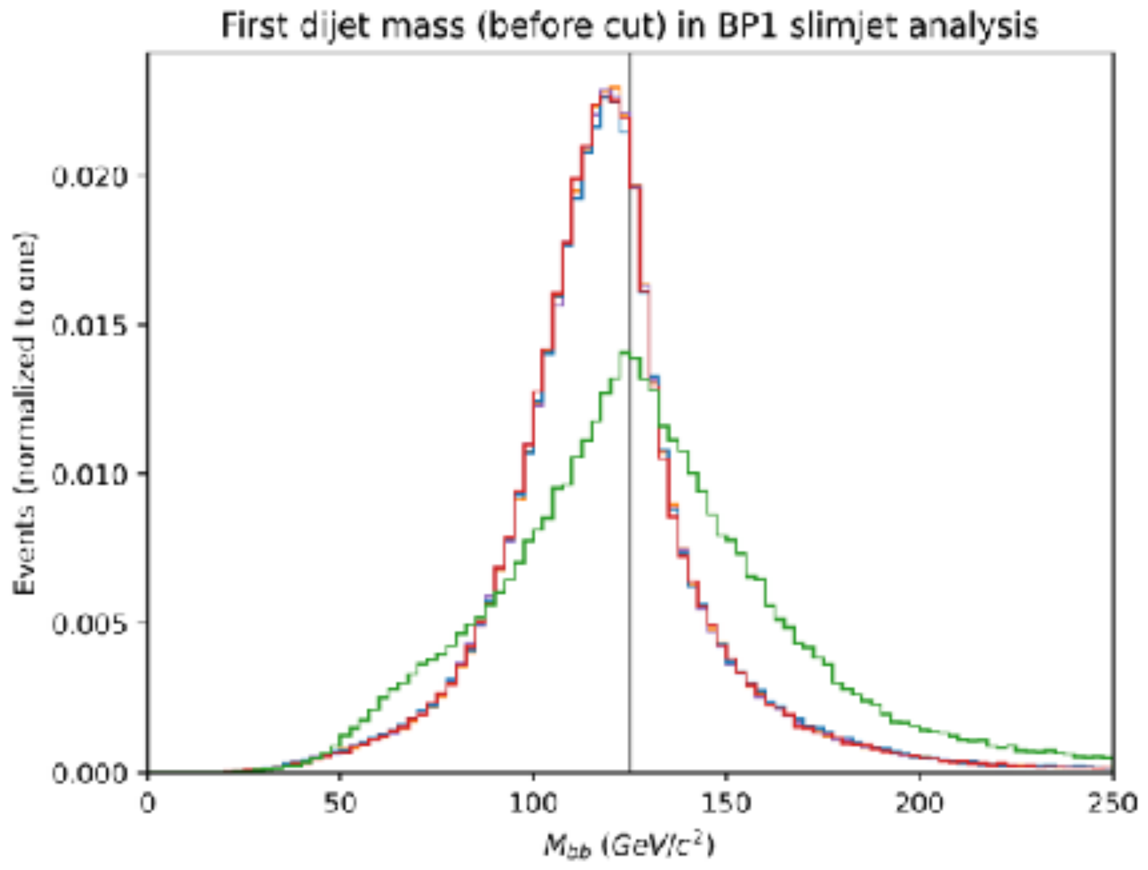
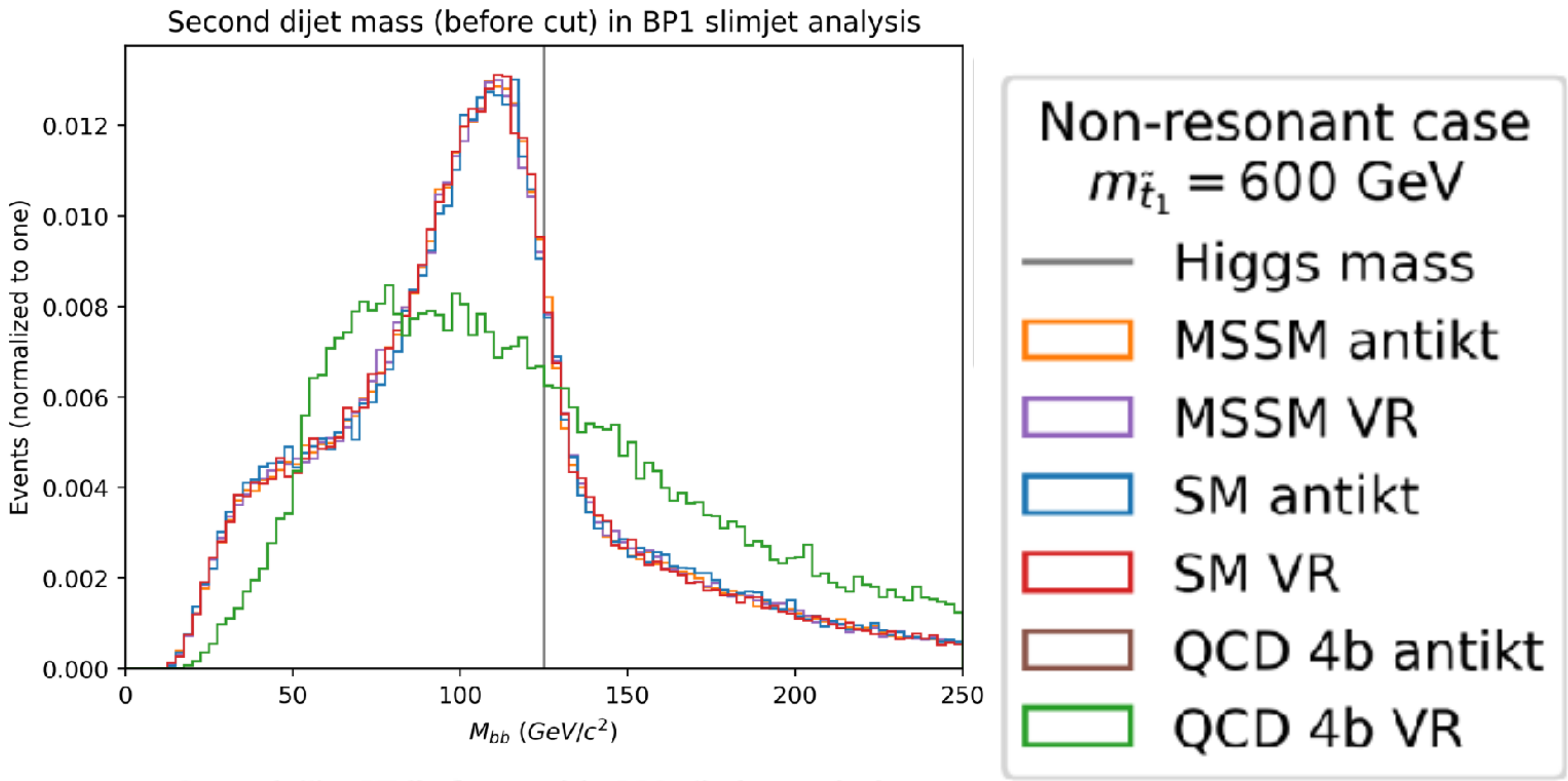


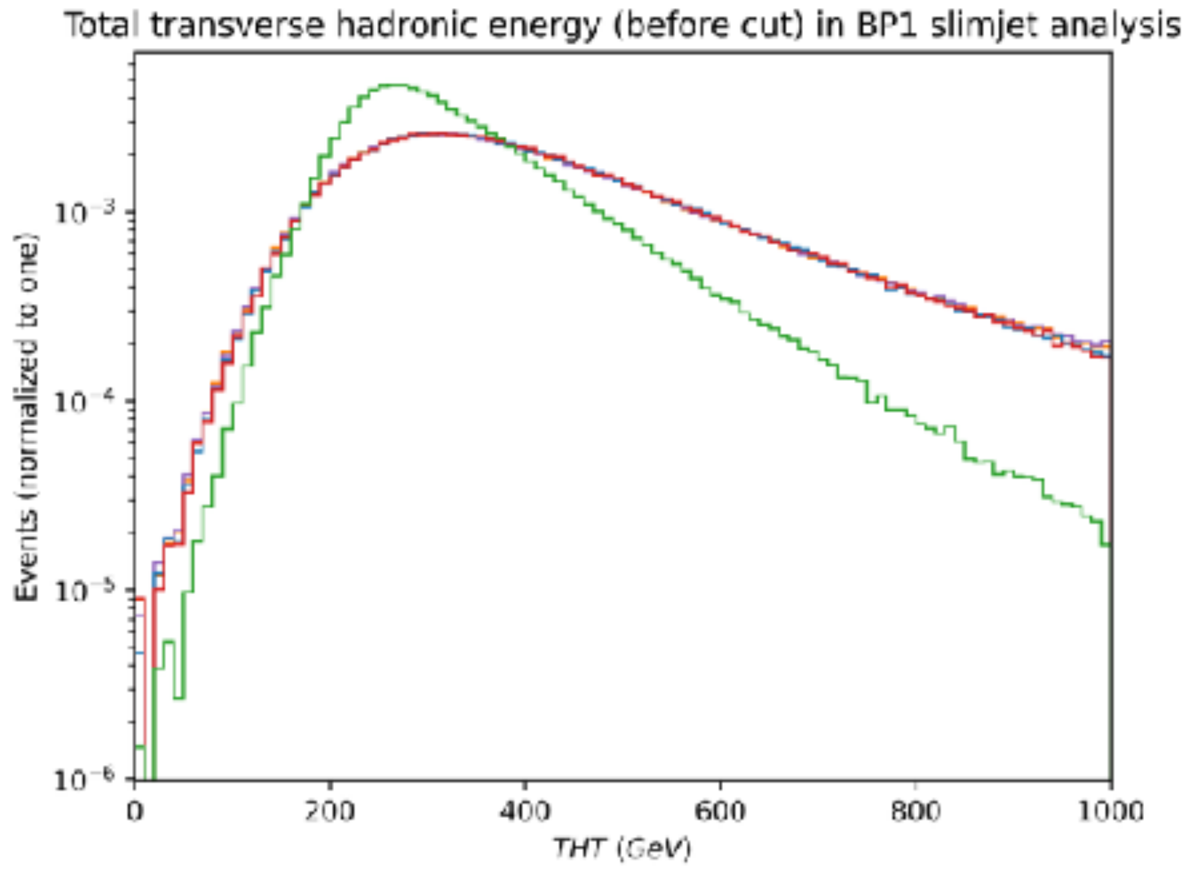
BP1 — non-resonant slimjet

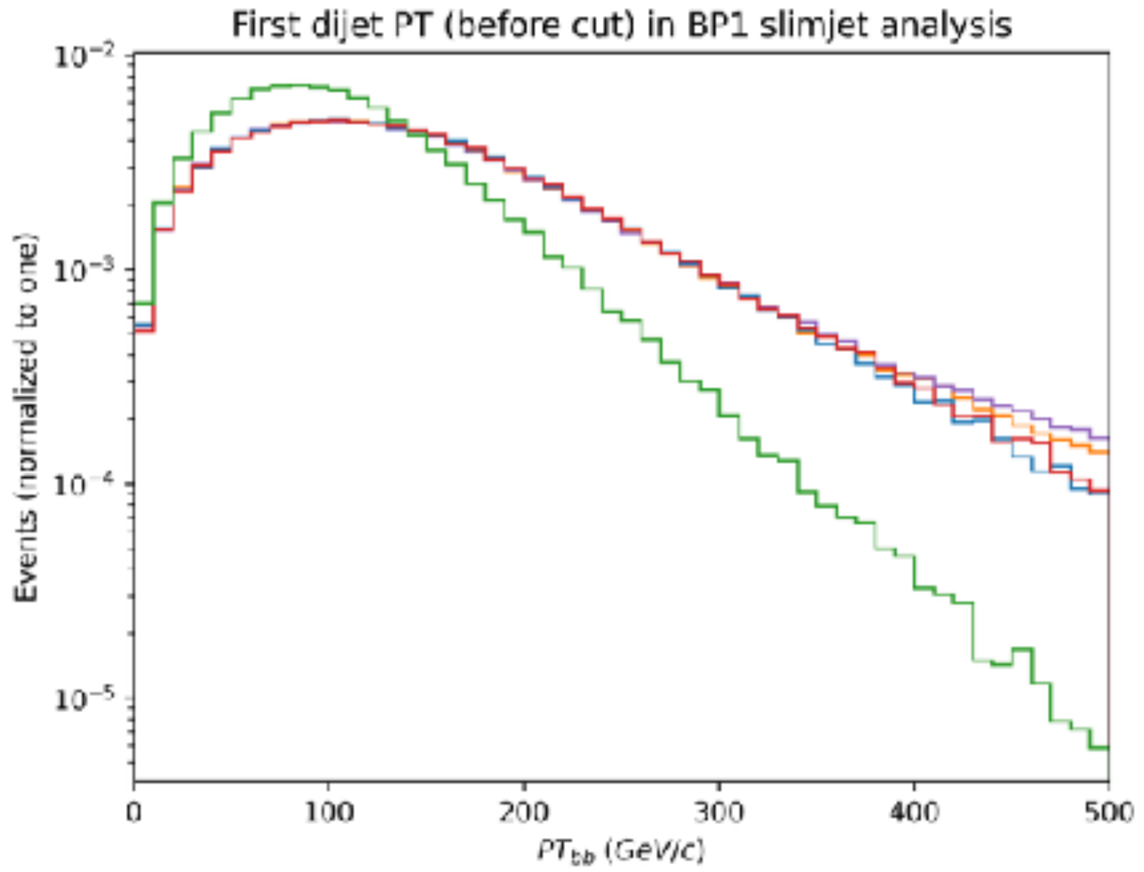
Kinematic cut

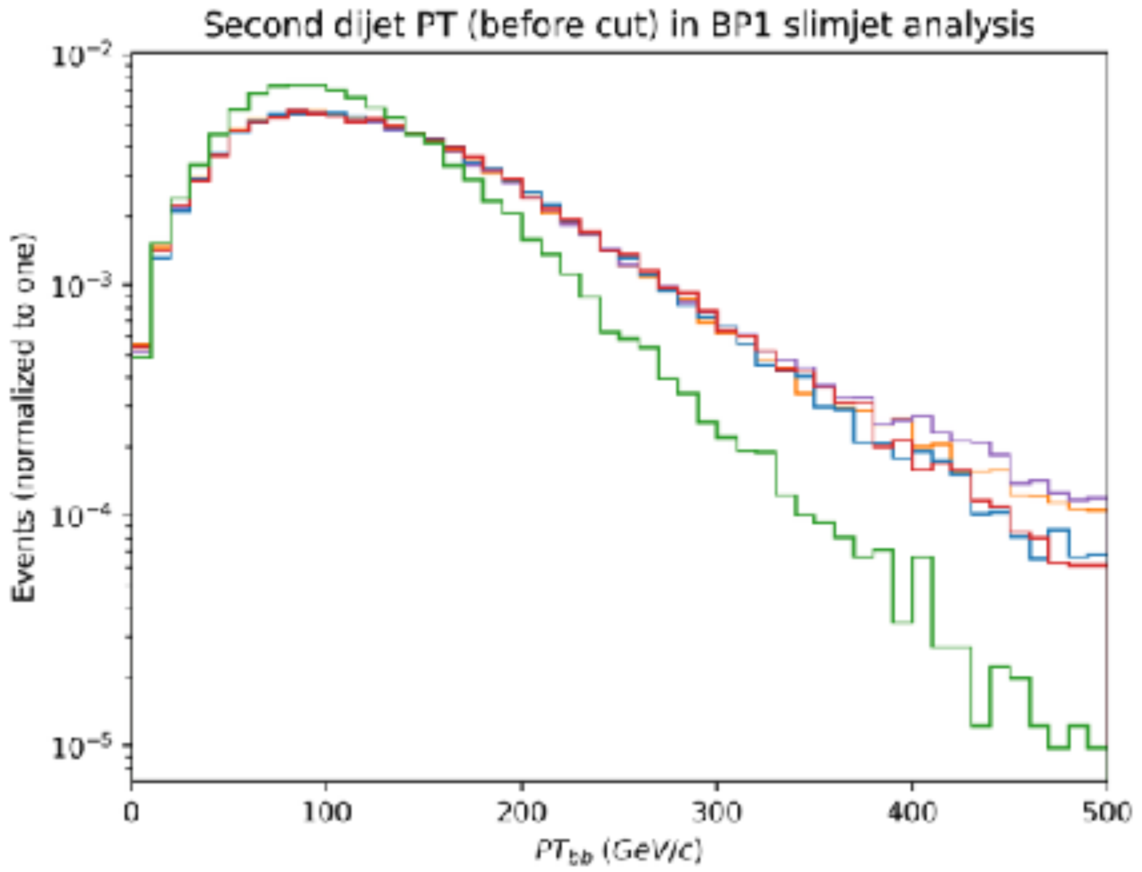
(including QCD background)











	THT	Dijet 1 mass	Dijet 1 pT	Dijet 2 mass	Dijet 2 pT
If N(b) > 2	THT>300	110<m<140	200<pT	—	—
If N(b) > 3	THT>300	110<m<140	200<pT	m<150	200<pT

All units in GeV.

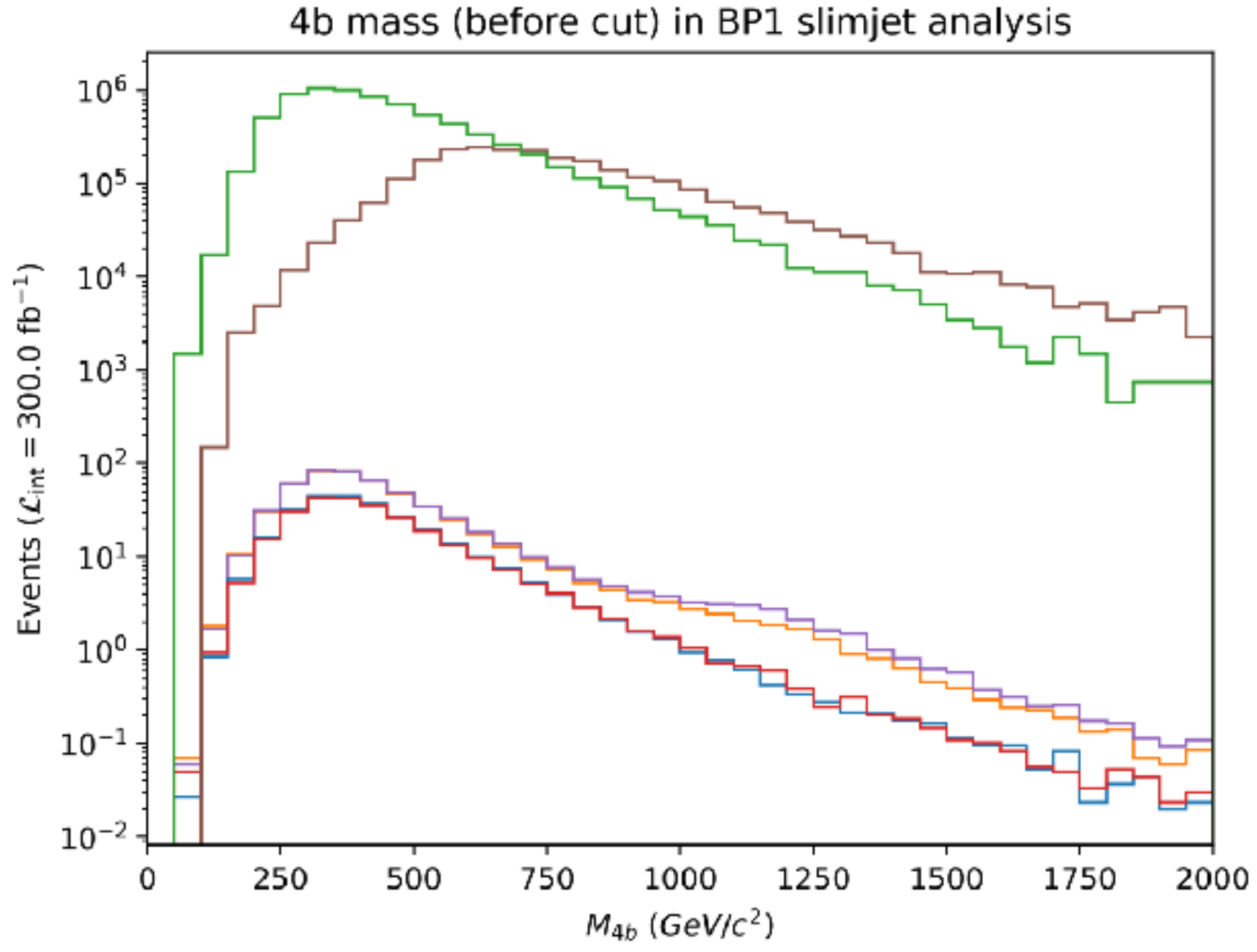
SR: $M_{4b} > 800$ GeV

$\sigma_{\text{QCD}} = 45$ pb

Non-resonant case
$m_{\tilde{t}_1} = 600$ GeV
MSSM antikt
MSSM VR
SM antikt
SM VR
QCD 4b antikt
QCD 4b VR

BP1 — non-resonant slimjet (4b)

Applying the cut



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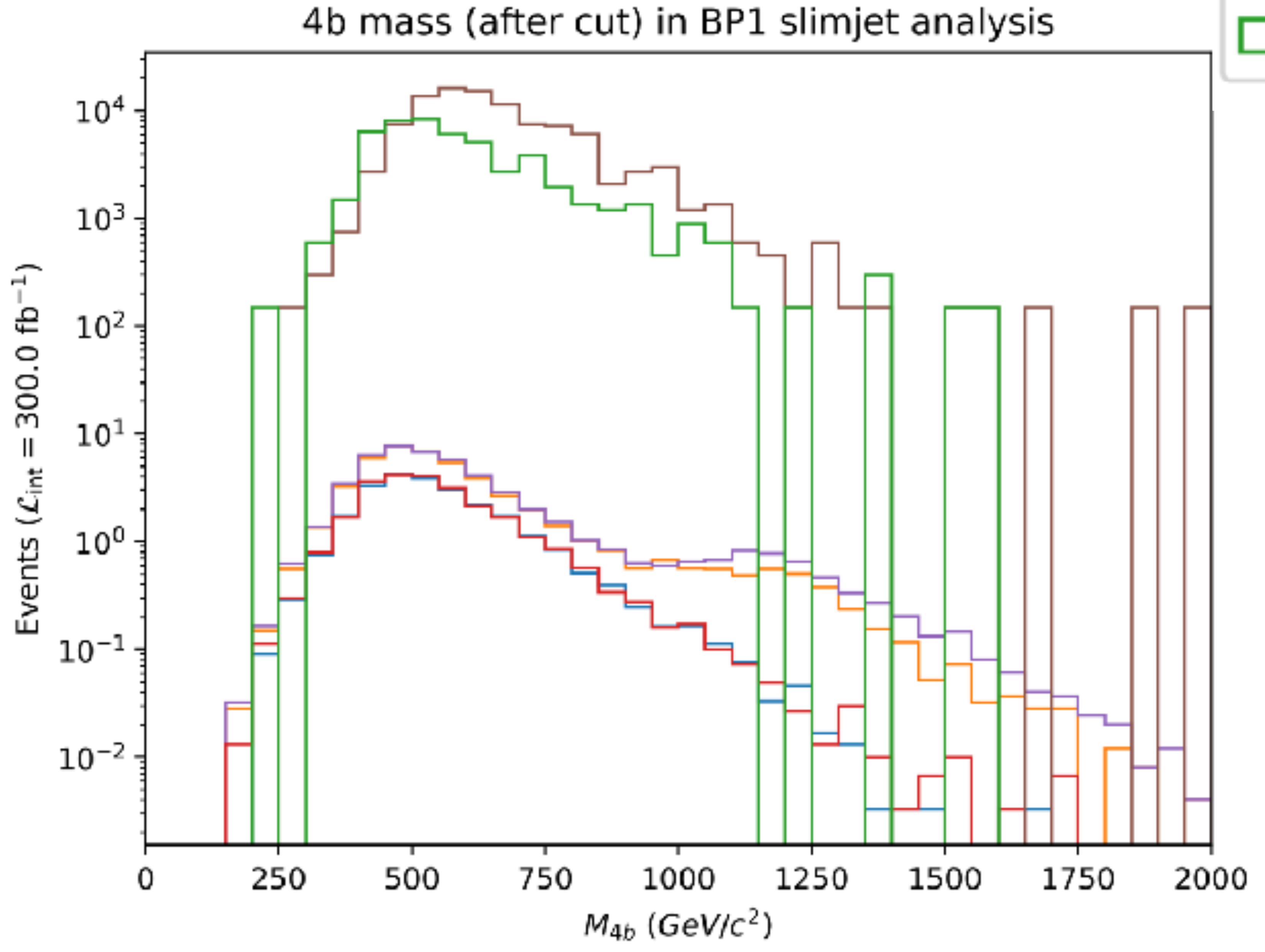


SR events before cut (4b)	anti-kT	Variable R
BSM di-Higgs	33	40
SM di-Higgs	13	13
Signal (BSM-SM)	20	27
QCD 4b	994459	519268
S/(√B)	0.0204	0.0380

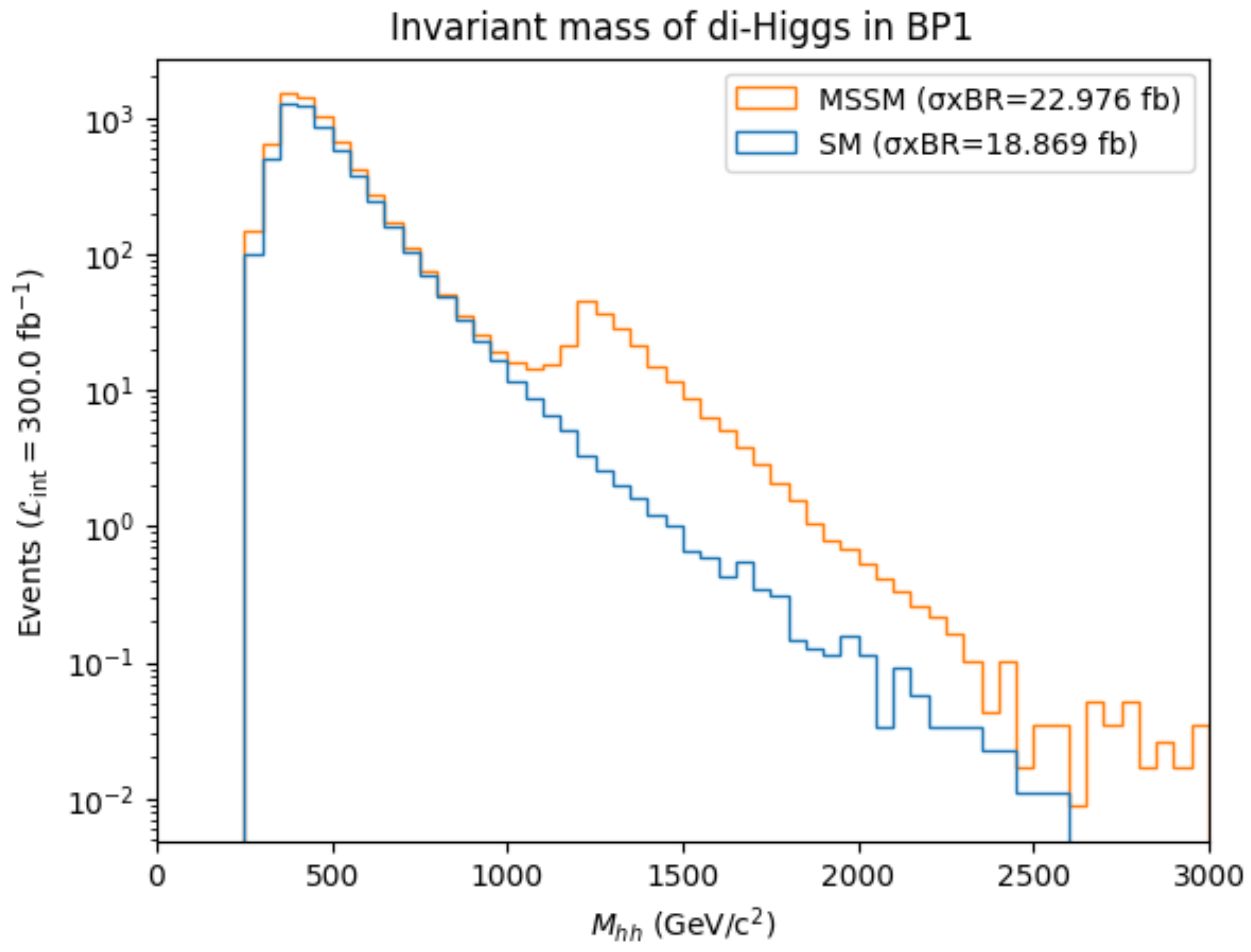
SR events after cut (4b)	anti-kT	Variable R
BSM di-Higgs	7	8
SM di-Higgs	2	2
Signal (BSM-SM)	5	6
QCD 4b	19144	51120
S/(√B)	0.0367	0.0813

BP1 — non-resonant fatjet

Jet optimization

	$\sigma_{\text{before decay}}$ (fb)	$\sigma_{\text{after decay}}$ (fb)
SM	18.869	5.492
MSSM	22.976	6.697

	fatjet
R	0.8
minR	0.6
maxR	1.4
ρ	450



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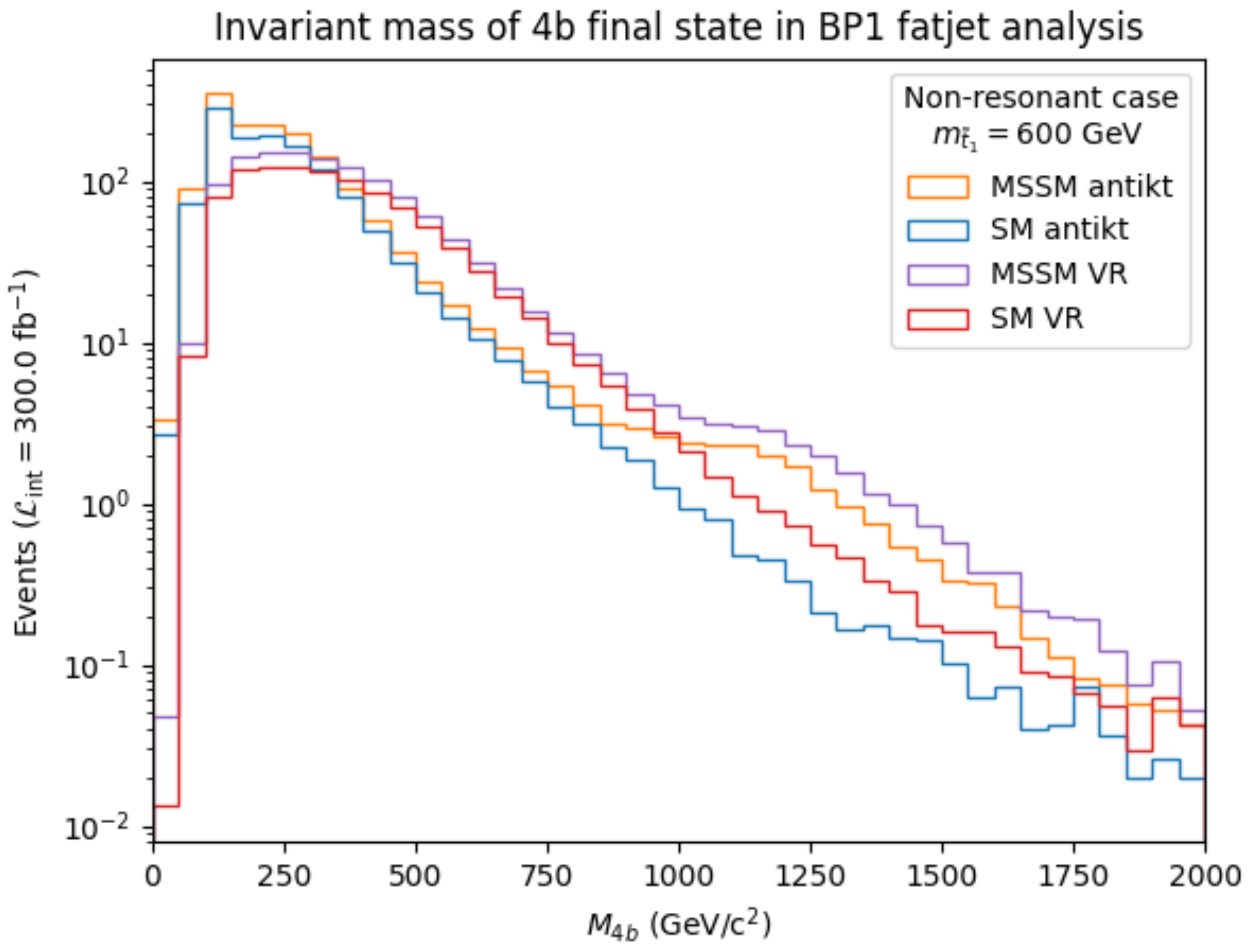
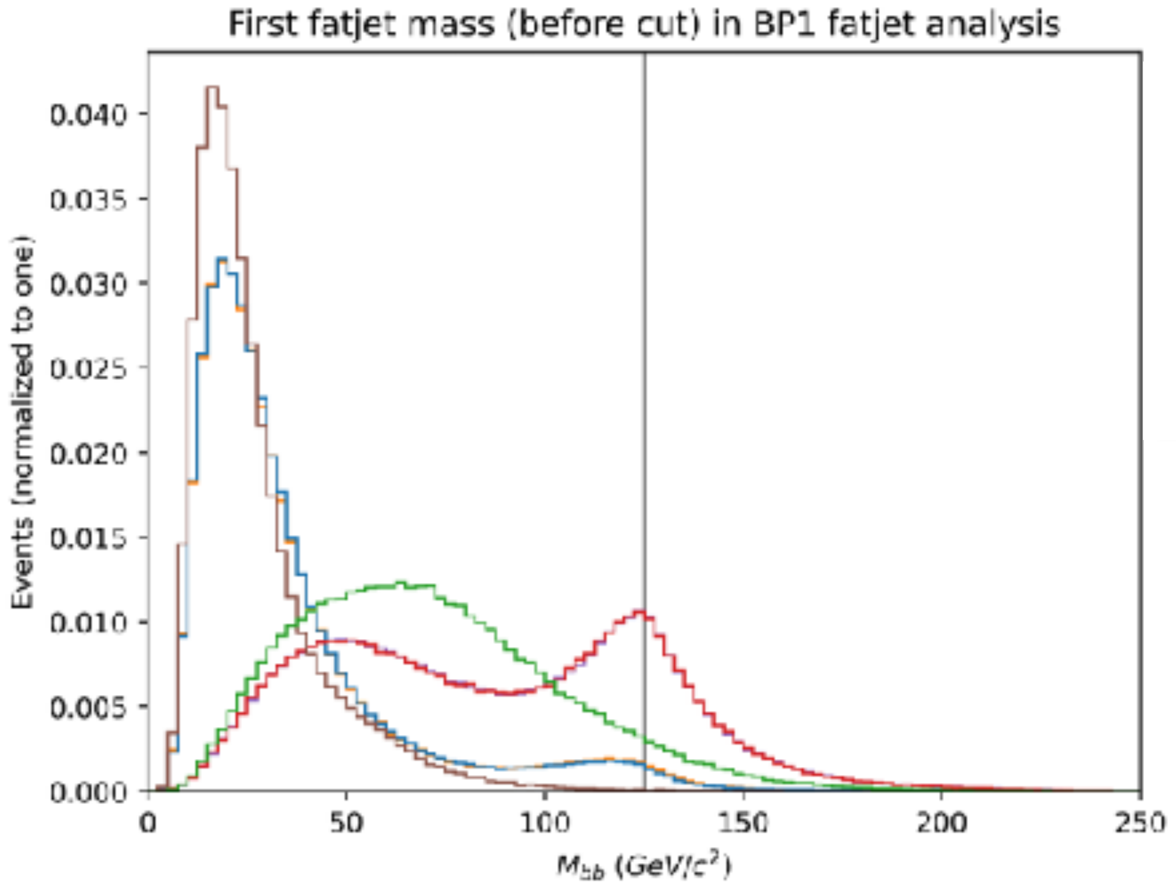
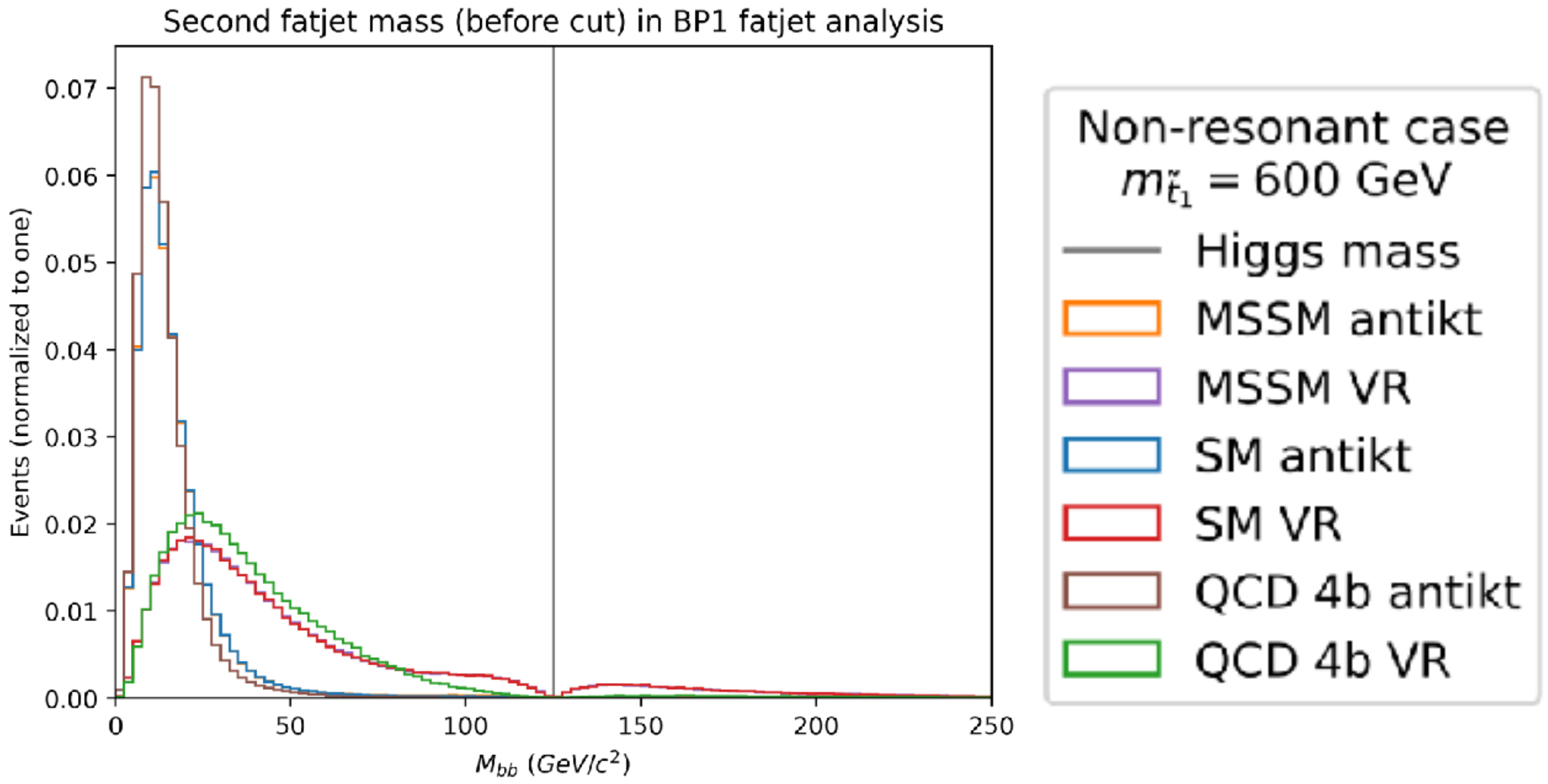


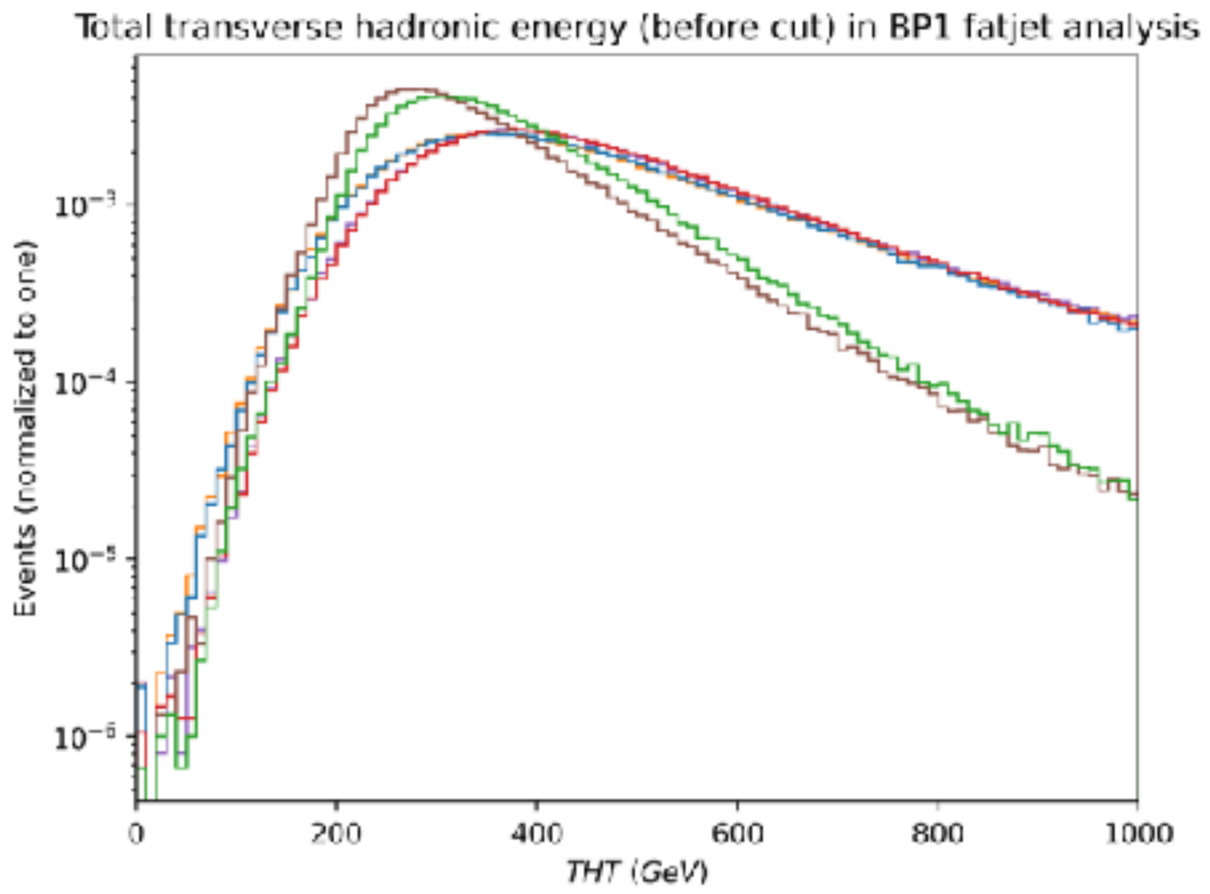
BP1 — non-resonant fatjet

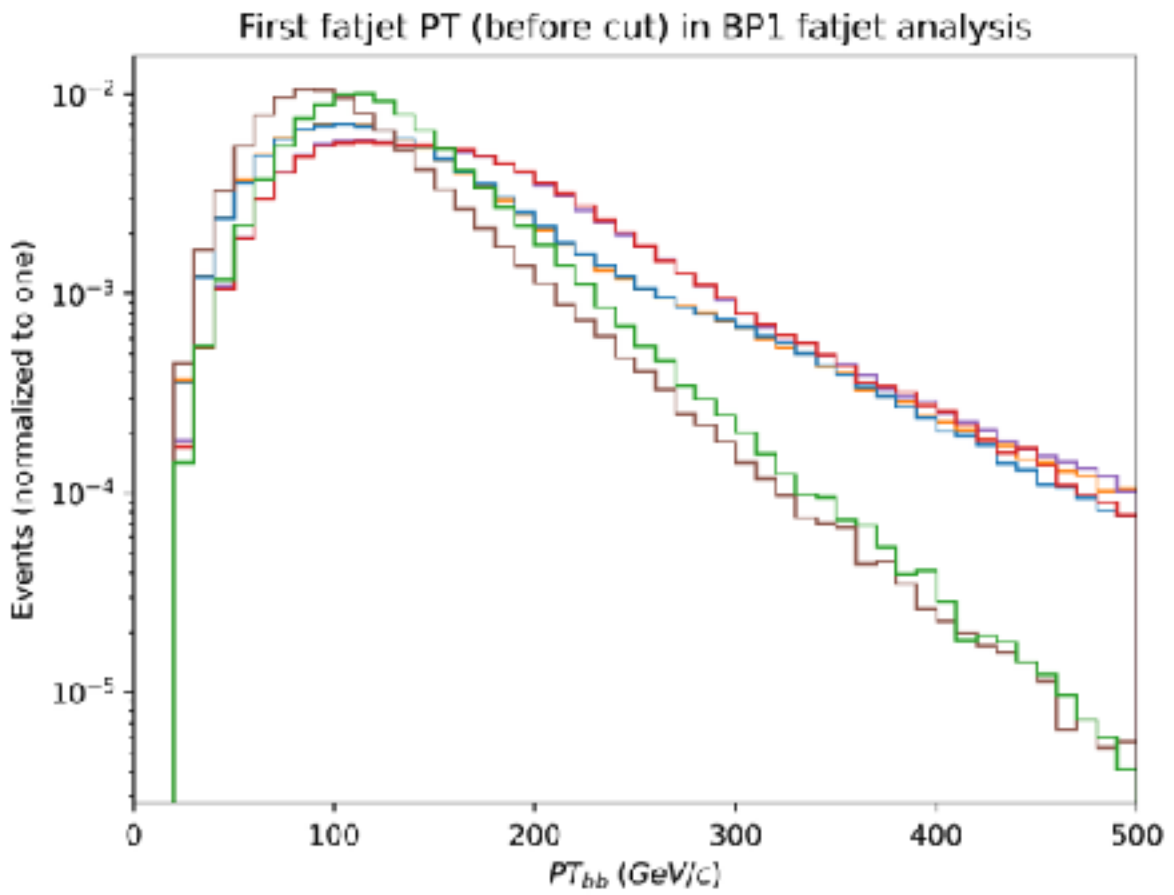
Kinematic cut

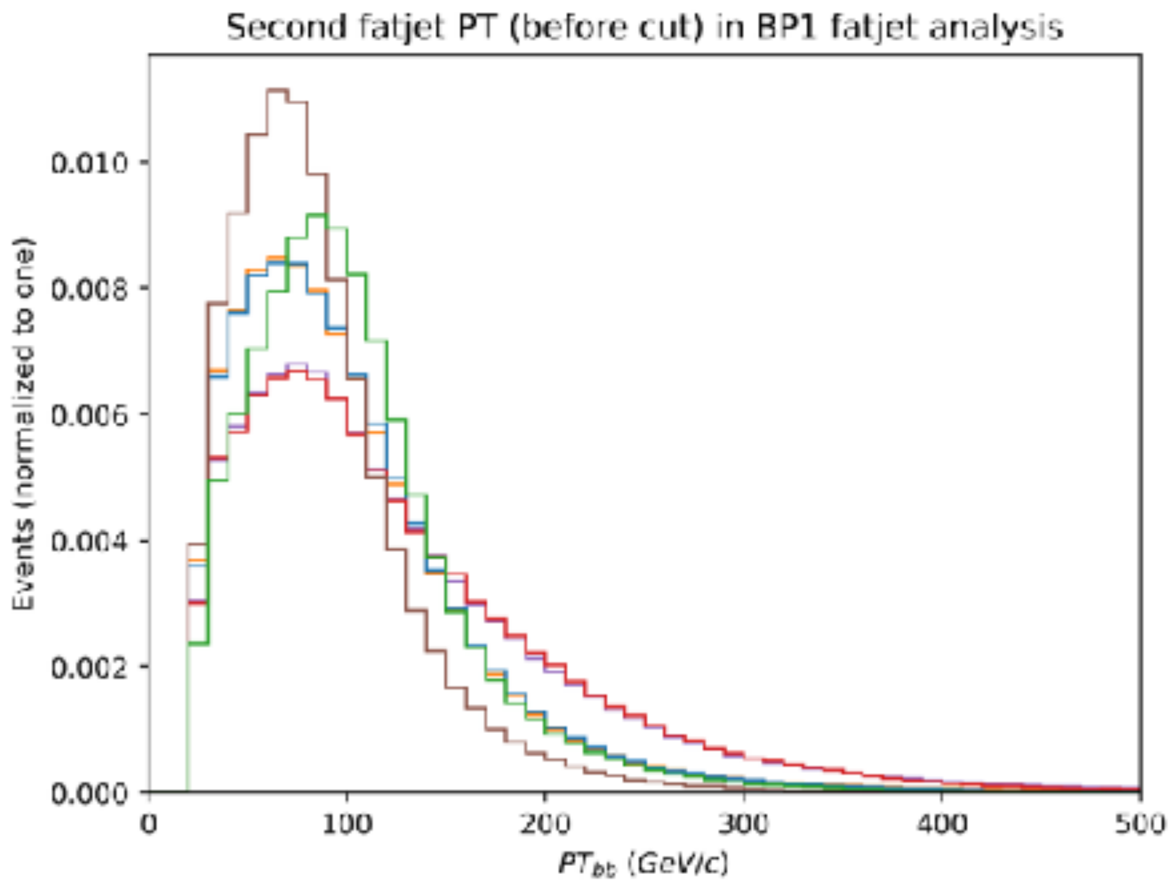
(including QCD background)











	THT	Fatjet 1 mass	Fatjet 1 pT	Fatjet 2 mass	Fatjet 2 pT
If N(b) > 1	THT>300	90<m<200	—	90<m<200	—

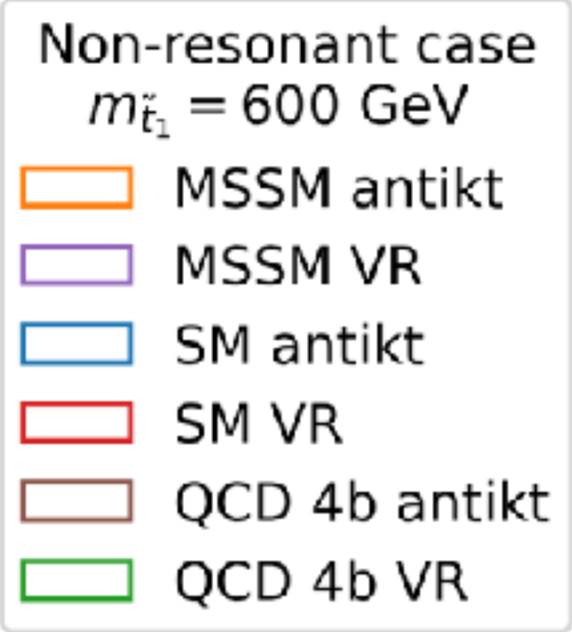
All units in GeV.

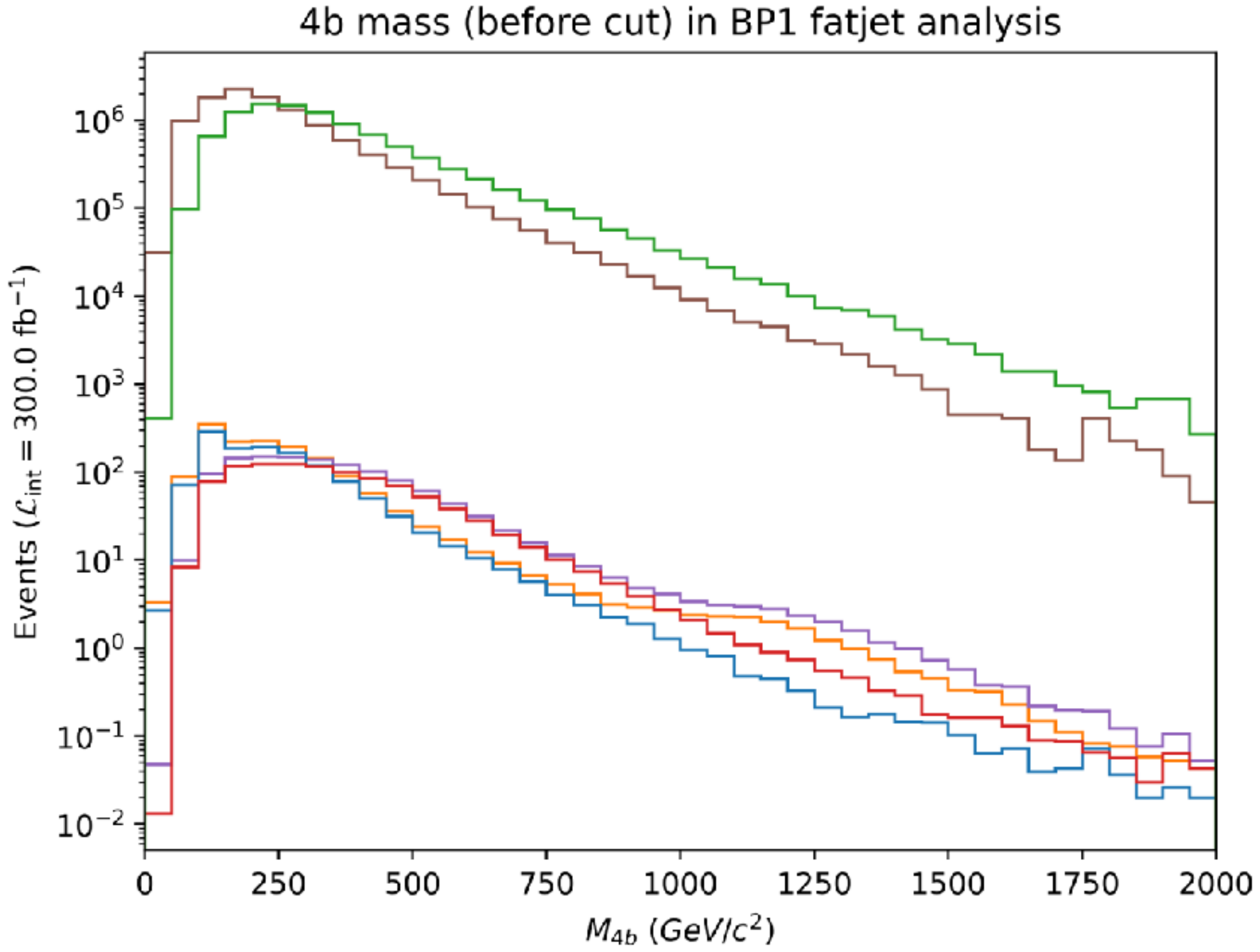
BP1 — non-resonant fatjet

Applying the cut

SR: $M_{4b} > 800$ GeV

$\sigma_{QCD} = 45$ pb





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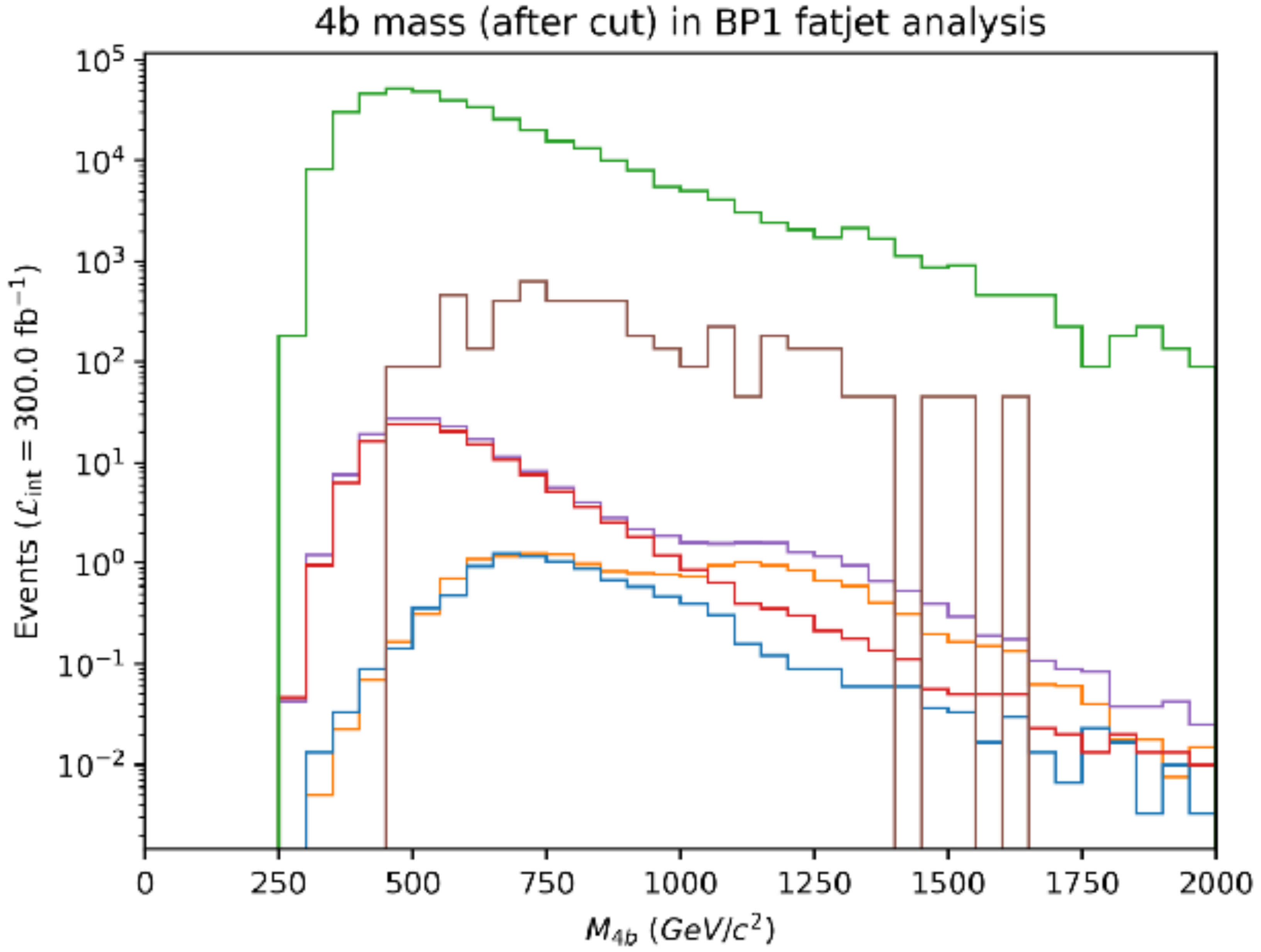

SR events before cut (4b)	anti-kT	Variable R
BSM di-Higgs	29	47
SM di-Higgs	13	28
Signal (BSM-SM)	16	19
QCD 4b	123941	337937
S/(√B)	0.0455	0.0325

SR events after cut (4b)	anti-kT	Variable R
BSM di-Higgs	11	23
SM di-Higgs	4	13
Signal (BSM-SM)	7	10
QCD 4b	2175	64371
S/(√B)	0.141	0.0421