VBS WH Updates

Background extrapolation attempts

July 22nd, 2022

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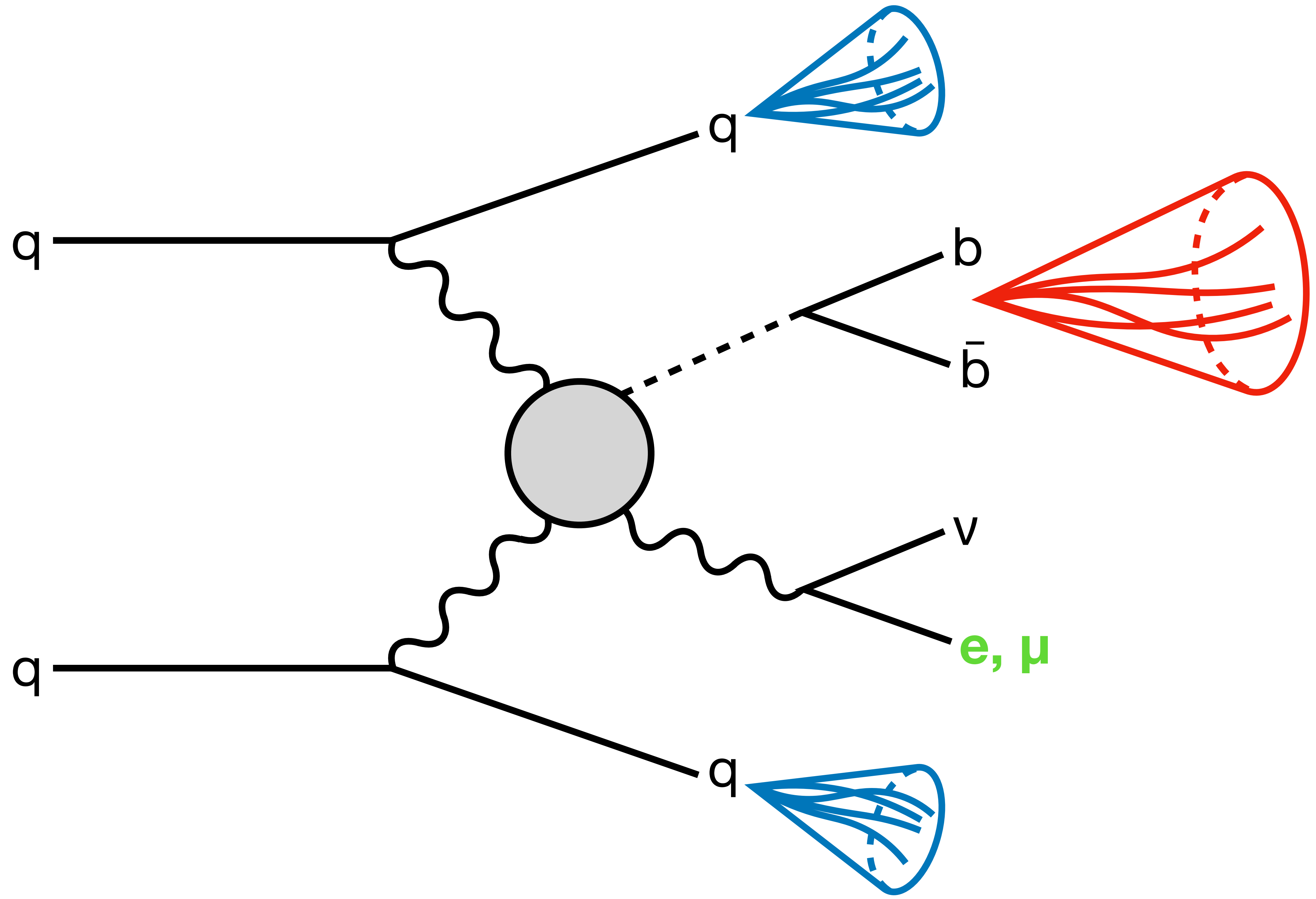
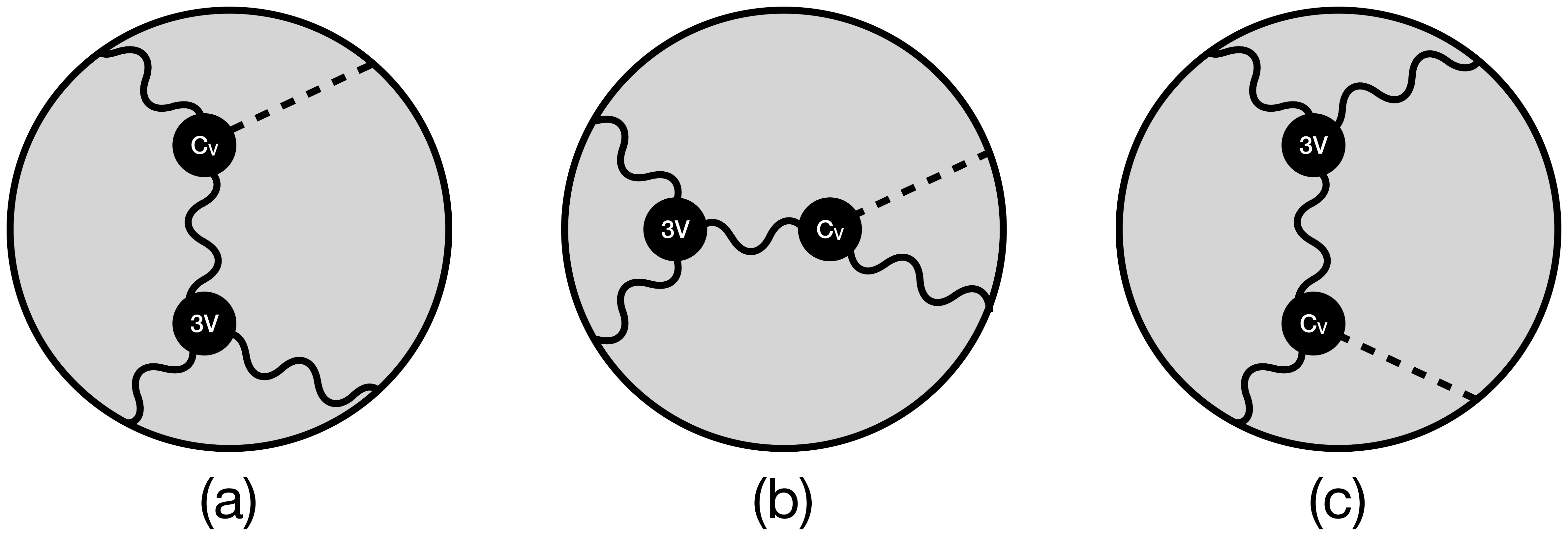
Target Final State

- Targeting **VBS** WH→**ℓ**ν**b$\bar{\text{b}}$**
- Sensitive to $\kappa_V \rightarrow \lambda_{WZ} = \kappa_Z/\kappa_W$
  - Handle for ruling out $\lambda_{WZ} = -1$ (BSM)
- VBS WH BSM kinematics:
  - High-p_T H and W (high S_T)
  - VBS jets with large $\Delta\eta_{jj}$, M_{jj}





VBS WH Skim

Cut	VH	VV/VVV/VBSWZ	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (κ_W = -1)	Eff.*
Skim AND Postskim	232	6.5K	122K	7.6K	1K	86K	10K	233K	—	2K	—

Object	Primary Skim	Postskim
Leptons (μ, e)	≥ 1 veto*	== 1 loose AND == 1 tight*
Fat Jets	≥ 1 w/ p_T > 200 GeV AND mass > 10 GeV AND M_{SD} > 10 GeV AND ΔR(fat jet, any veto lepton) > 0.8	≥ 1 w/ p_T > 250 GeV AND mass > 50 GeV AND M_{SD} > 40 GeV AND ΔR(fat jet, tight lepton) > 0.8
Jets	≥ 1 w/ p_T > 20 GeV AND ΔR(jet, any veto lepton) > 0.4	—
Other	—	S_T > 800 GeV

*Using the ttH lepton ID

Overview

	Cut	VH	VV/VVV/VBSWZ	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH ($\kappa_W = -1$)	Eff.*
	Skim AND Postskim	232	6.5K	122K	7.6K	1K	86K	10K	233K	—	2K	—
Preselection	**$p_T(\ell) > 40$ GeV**	220	5.9K	110K	6.9K	910	78K	8.8K	211K	10%	1.8K	5%
	Passes single-lepton triggers	181	5.3K	98K	6.2K	773	68K	7.6K	186K	12%	1.6K	14%
	≥ 1 AK8 jet w/ $p_T > 250$ GeV AND mass > 50 GeV AND $M_{SD} > 40$ GeV	181	5.3K	98K	6.2K	767	68K	7.4K	186K	0%	1.6K	0%
	2 VBS jets (max E)	50	2K	47K	4.4K	654	50K	6.3K	111K	40%	1.1K	30%
	$M_{jj} > 500$ GeV AND $\lvert\Delta\eta_{jj}\rvert > 3$	7	376	7.7K	994	124	10K	1.4K	21K	81%	920	17%
	No b-tagged (med.) AK4 jets	6	323	6.7K	286	28	2.5K	239	**10K**	52%	**870**	5%
SR	**$M_{jj} > 1.5$ TeV AND $\lvert\Delta\eta_{jj}\rvert > 4$**	1	38	928	47	5	428	42	**1.5K**	85%	**479**	45%
	$S_T > 1.2$ TeV	0	7	156	9	1	37	4	**215**	86%	**208**	57%
	PNet Xbb vs. QCD > 0.9 AND $M_{SD} < 150$	0	0	1	0	0	2	1	**4**	98%	**109**	48%

- Switched to ParticleNet Xbb tagger
- Added global b-veto: discard event if there are *any* b-tagged "good" AK4 jets
- Next: SR and background extrapolation proposals

*eff = 1 - after/before

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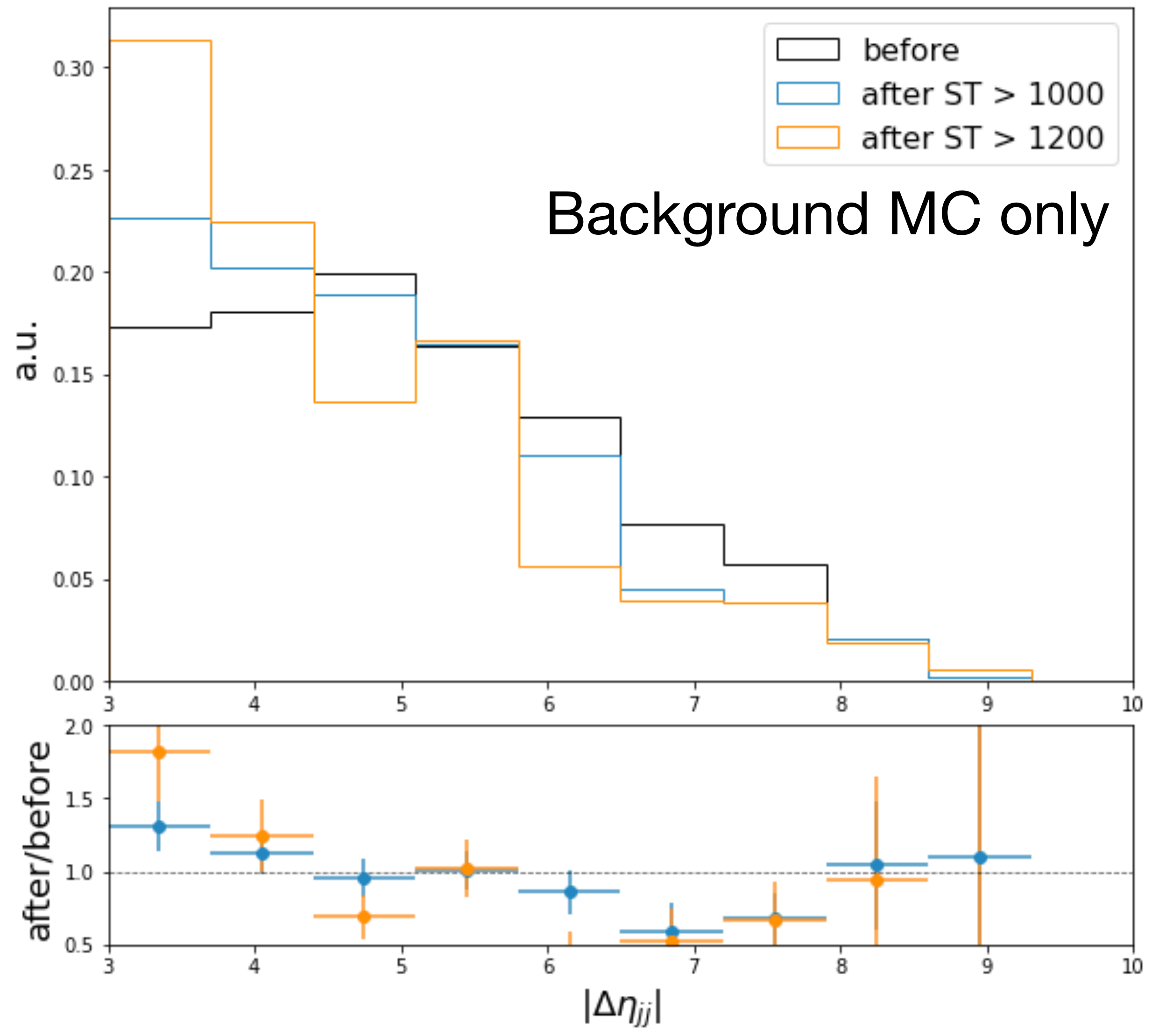
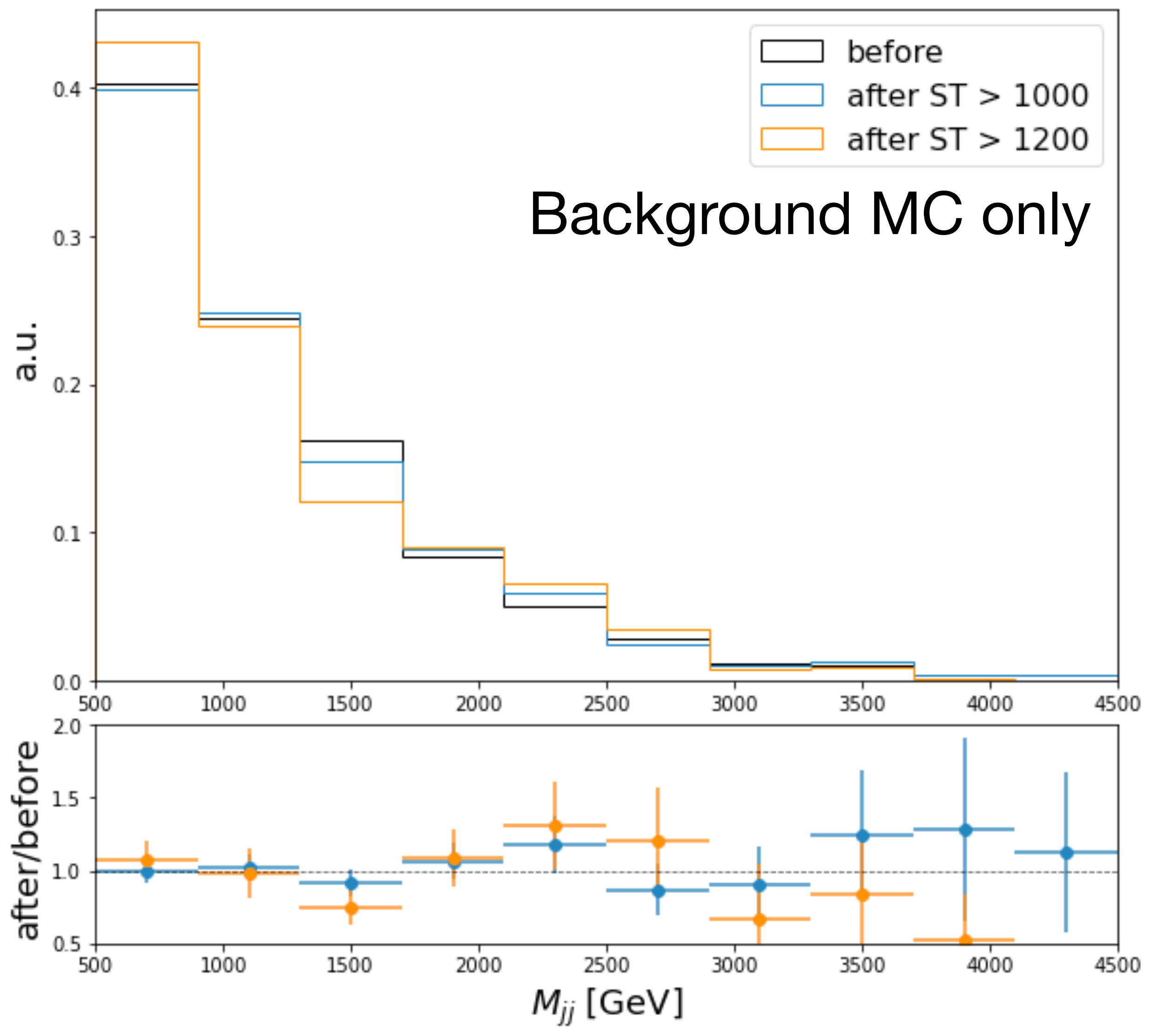
Looking for ABCD: M_{jj} and/or $|\Delta\eta_{jj}|$ vs. S_T



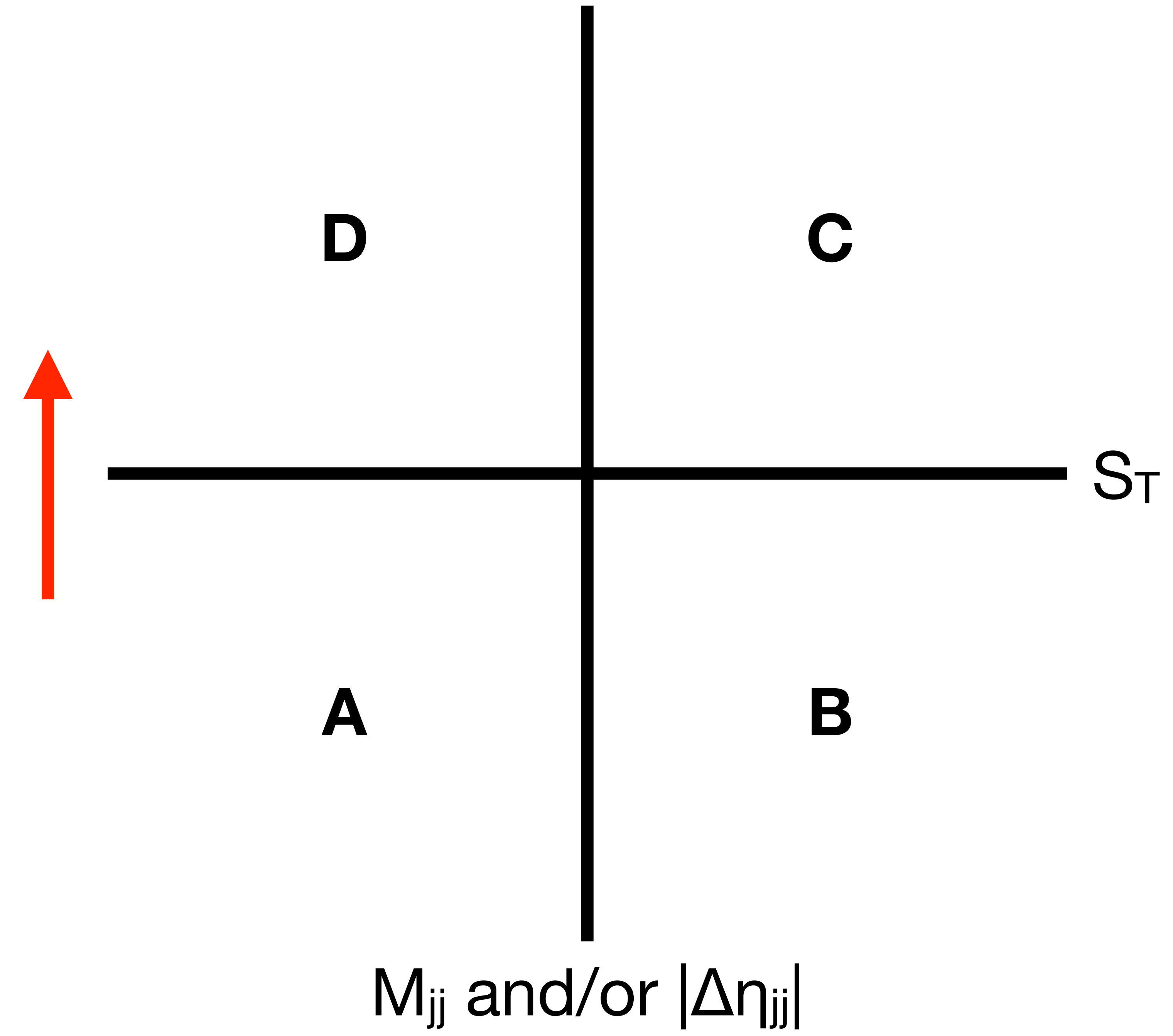
PNet Xbb Score > 0.9
AND M_{SD} < 150 GeV
AND M_{jj} > 1500 GeV

Correlated w/ S_T



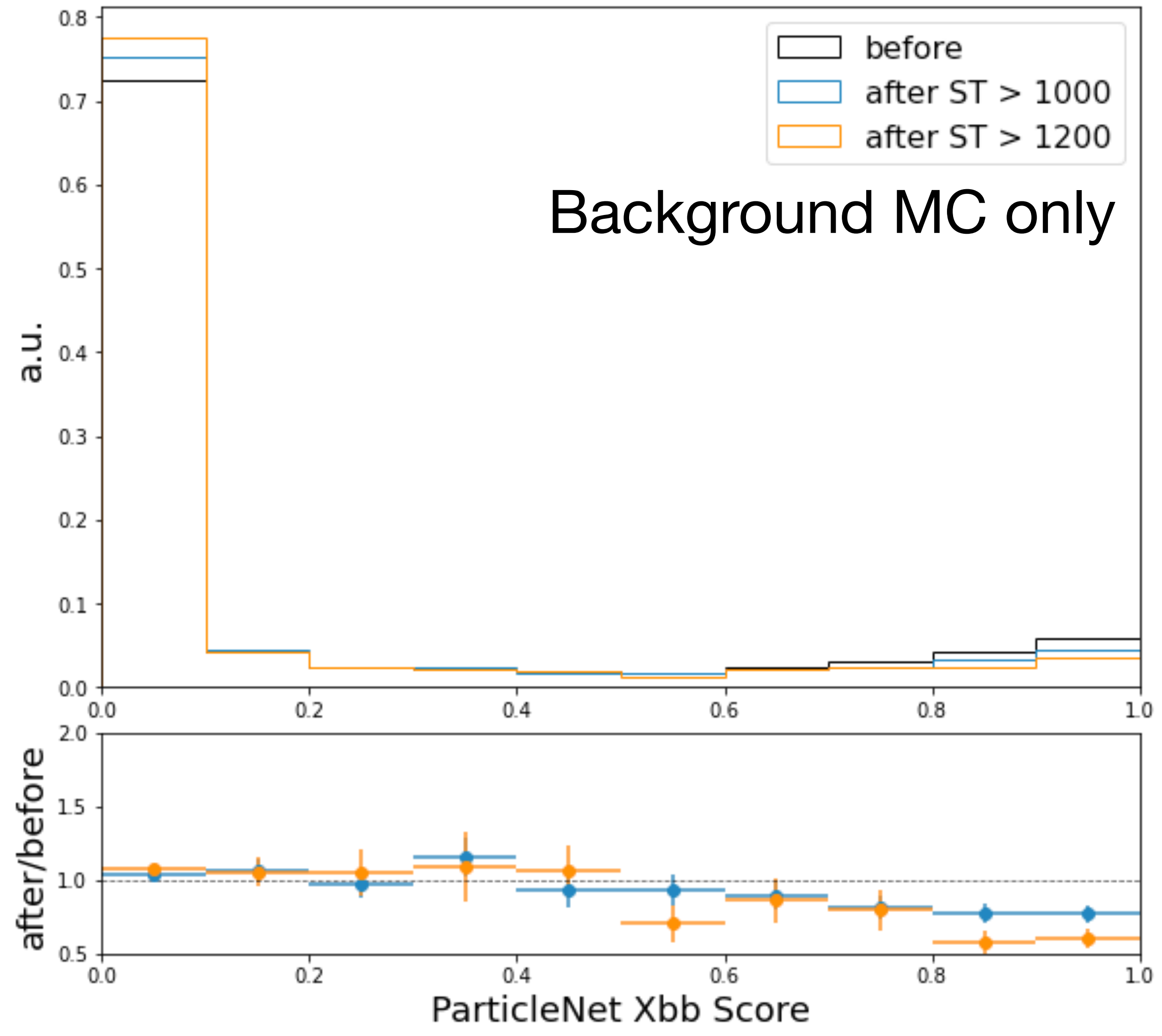
PNet Xbb Score > 0.9
AND M_{SD} < 150 GeV
AND $|\Delta\eta_{jj}|$ > 4

Correlated w/ S_T



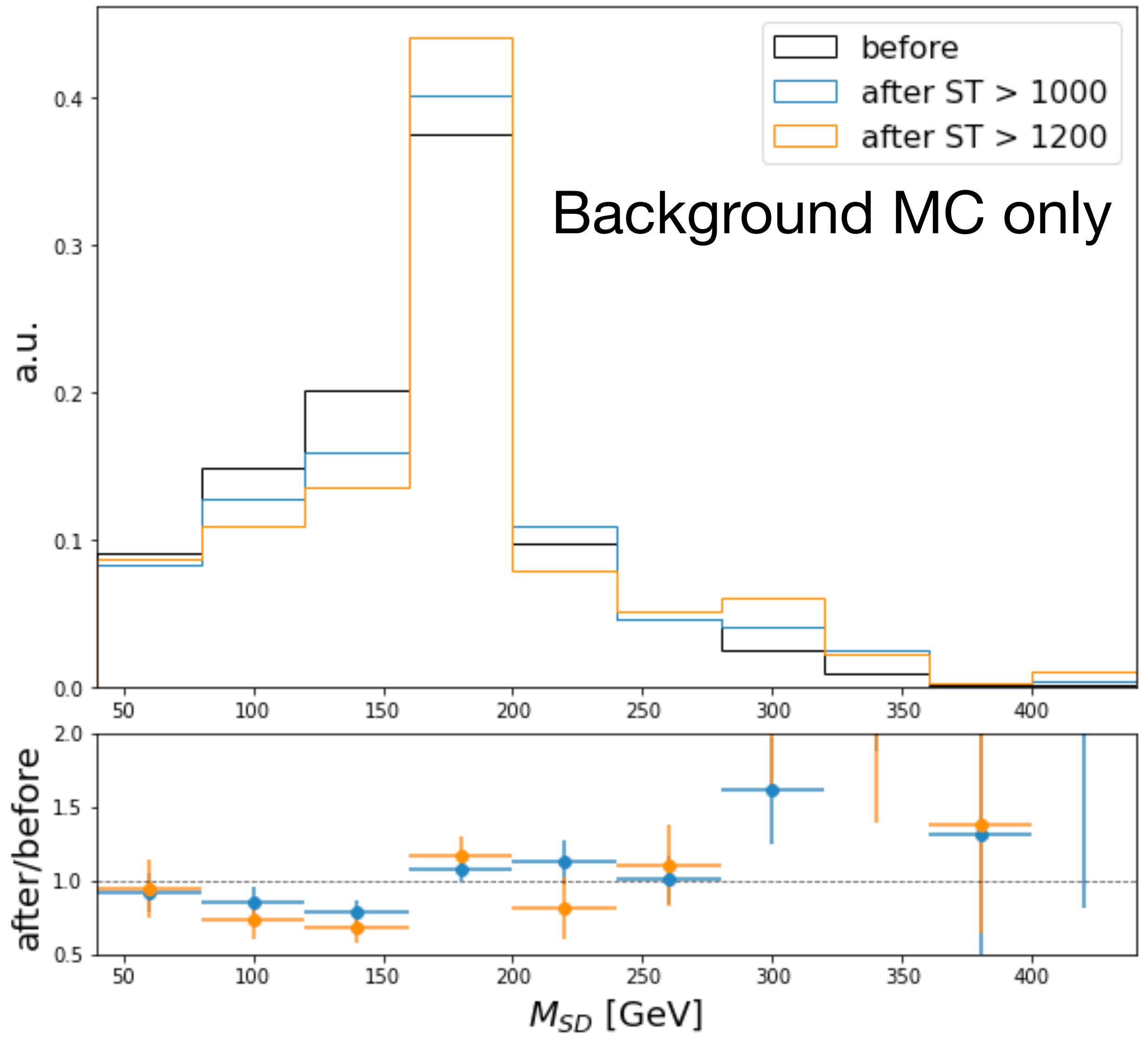
Not viable: shape changes across S_T cut (A→B ≠ C→D)

Looking for ABCD: M_{SD} and/or PNet vs. S_T



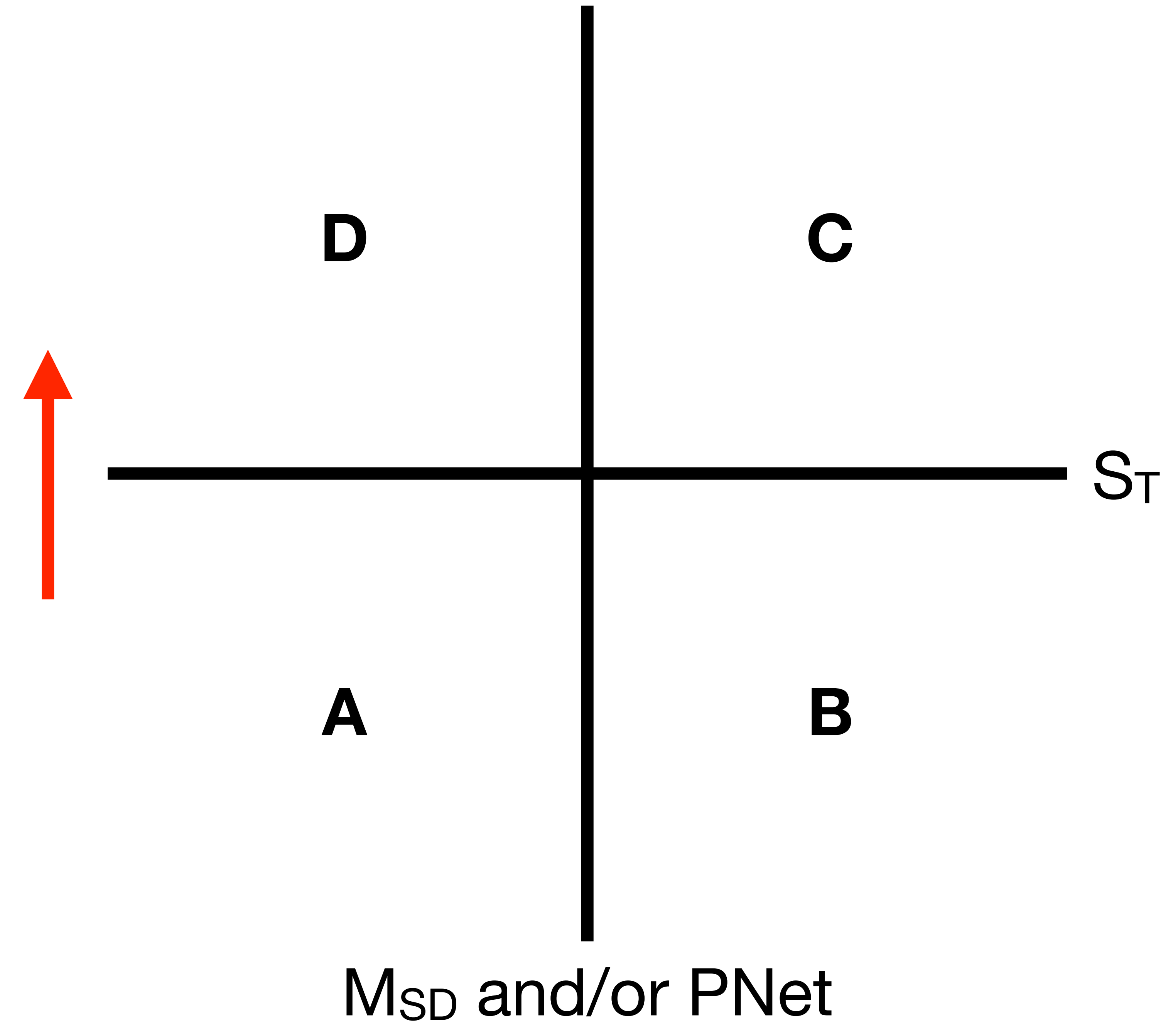
M_{SD} < 150 GeV
AND M_{jj} > 1500 GeV
AND $|\Delta\eta_{jj}|$ > 4

Correlated w/ S_T



PNet Xbb Score > 0.9
AND M_{jj} > 1500 GeV
AND $|\Delta\eta_{jj}|$ > 4

Correlated w/ S_T



Not viable: shape changes across S_T cut (A→B ≠ C→D)

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ABCD Alternative

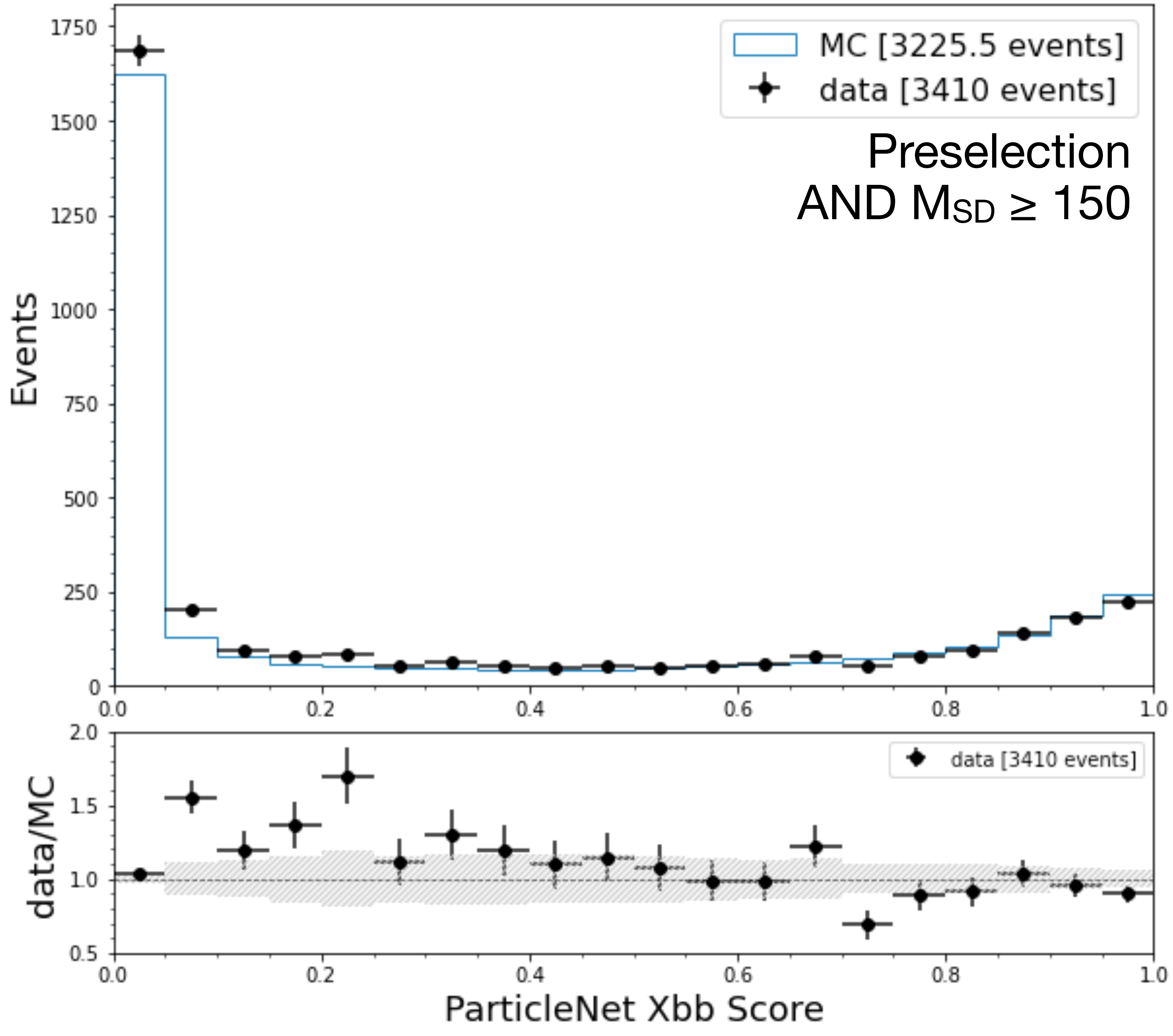
	Cut	VH	VV/VVV/VBSWZ	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH ($\kappa_W = -1$)	Eff.*
	Preselection**	6	323	6.7K	286	28	2.5K	239	**10K**	—	**870**	—
SR	**$M_{jj} > 1.5$ TeV AND $\lvert\Delta\eta_{jj}\rvert > 4$**	1	38	928	47	5	428	42	**1.5K**	85%	**479**	45%
SR	**$S_T > 1.2$ TeV**	0	7	156	9	1	37	4	**215**	86%	**208**	57%
SR	**PNet Xbb vs. QCD > 0.9 AND $M_{SD} < 150$ GeV**	0	0	1	0	0	2	1	**4**	98%	**109**	48%
CR	**PNet Xbb vs. QCD ≤ 0.9 AND $M_{SD} \geq 150$ GeV**	0	2	65	3	0	17	2	**90**	58%	**1**	100%

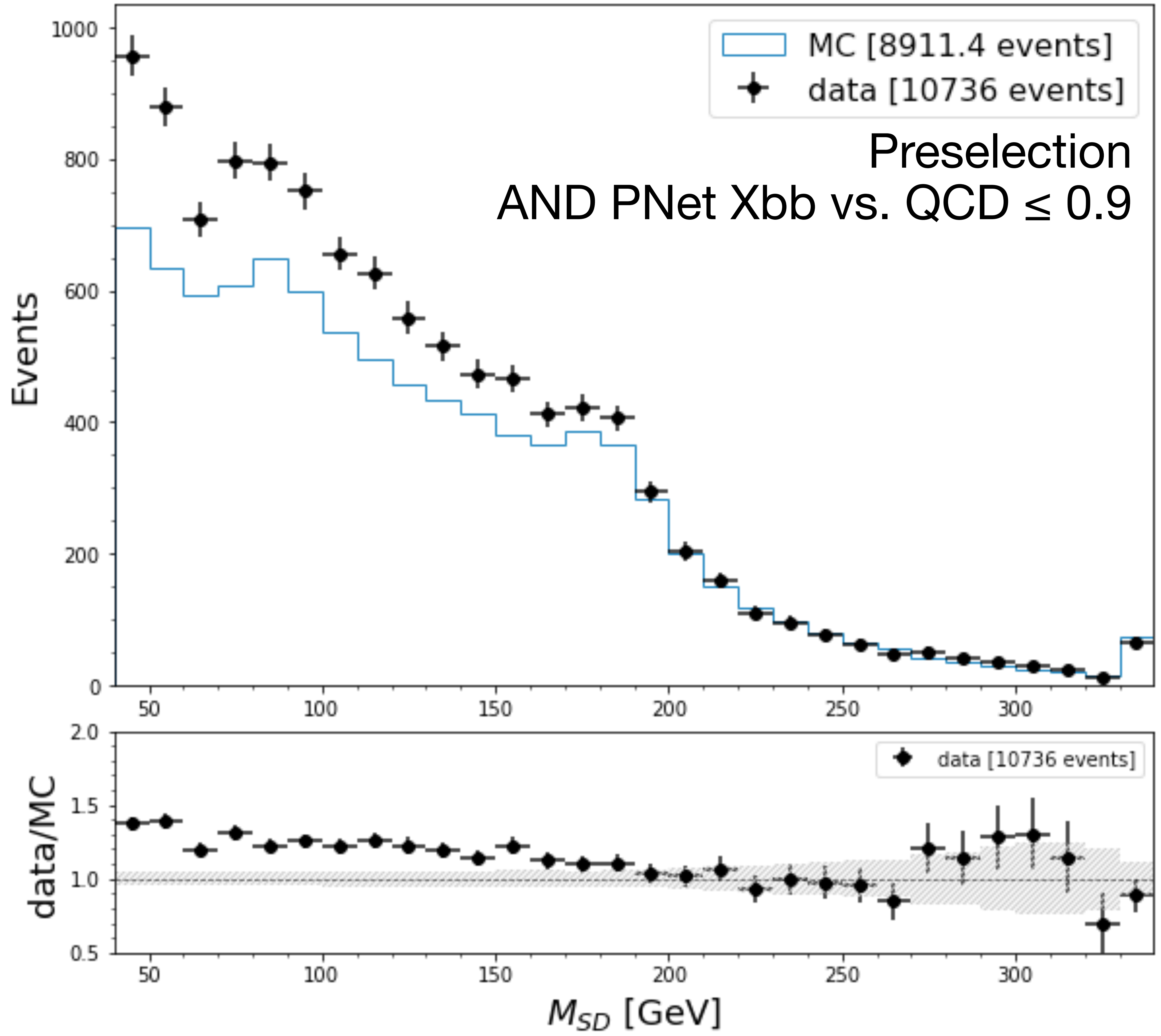
Cut	VH	VV/VVV/VBSWZ	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg		VBSWH ($\kappa_W = -1$)	S/B
Preselection**	6	323	6.7K	286	28	2.5K	239	**10K**		**870**	—
$M_{SD} \geq 150$ GeV (PNet VR)	0	55	1.8K	100	16	1.4K	58	**3.4K**		**25**	1%
PNet Xbb vs. QCD ≤ 0.9 (M_{SD} VR)	4	310	6.7K	221	22	1.9K	188	**9.3K**		**410**	4%

- Get extrapolation factor α = CR/SR from MC, apply to data in CR
- First: check PNet Xbb vs. QCD and M_{SD} are modeled well
  - i.e. check data vs. MC in validation regions (VRs) above

*eff = 1 - after/before
**Recall: includes $S_T > 800$ GeV, $M_{jj} > 500$, and $\lvert\Delta\eta_{jj}\rvert > 3$

Validation Regions

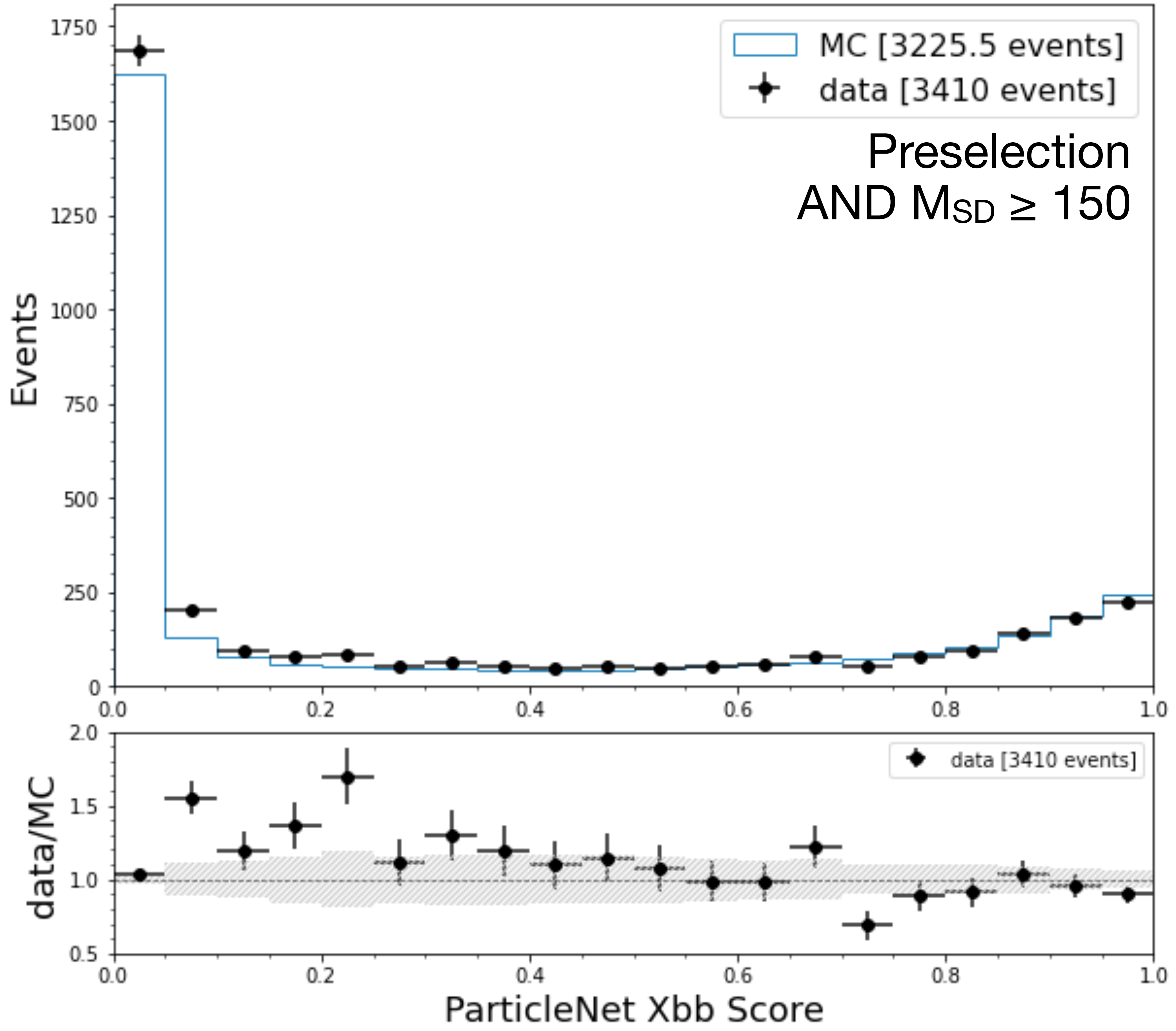


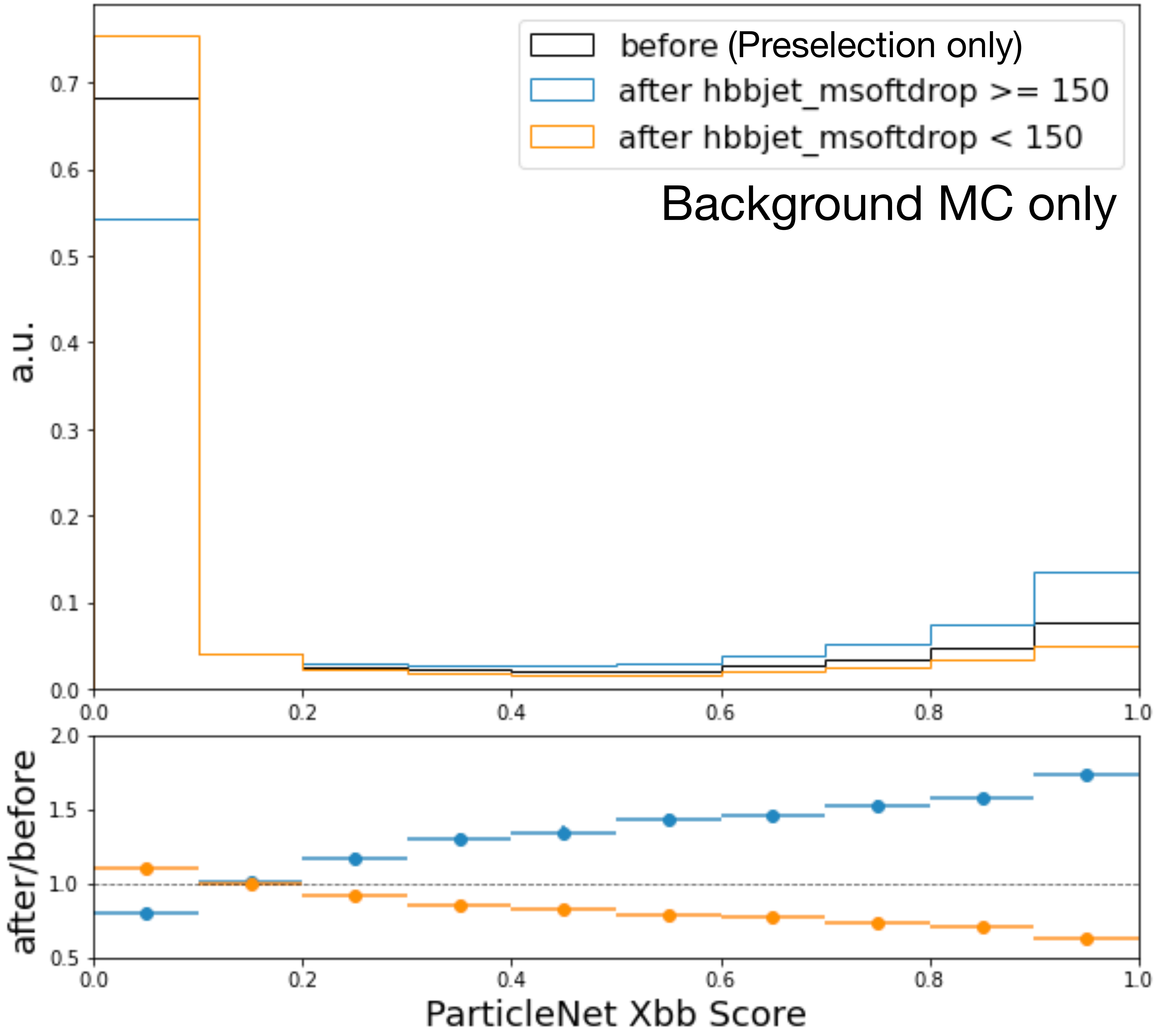


Data/MC agreement does not look good

Missing sfs for: Xbb, DeepJet (for b-veto?), triggers

Validation Regions

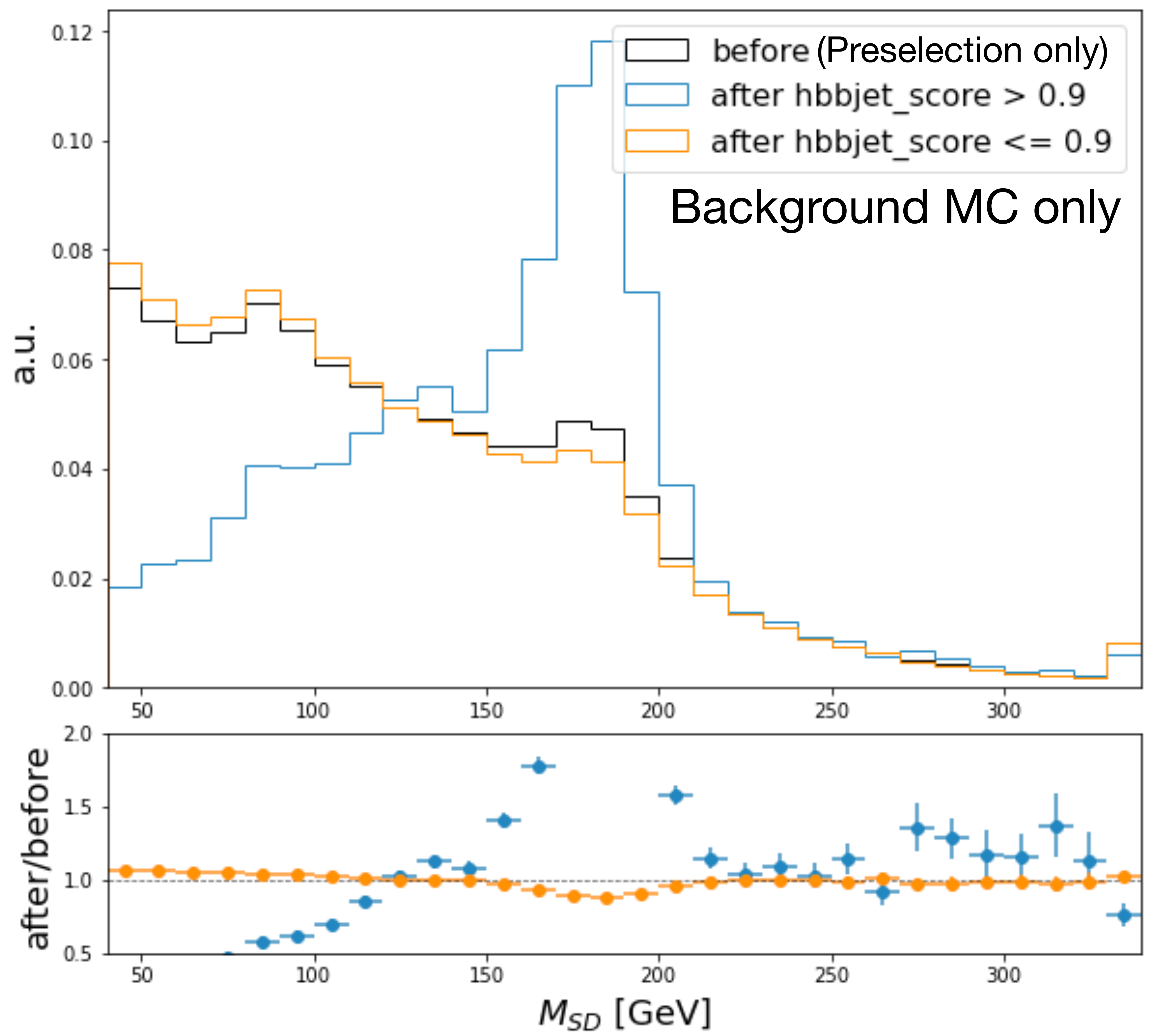


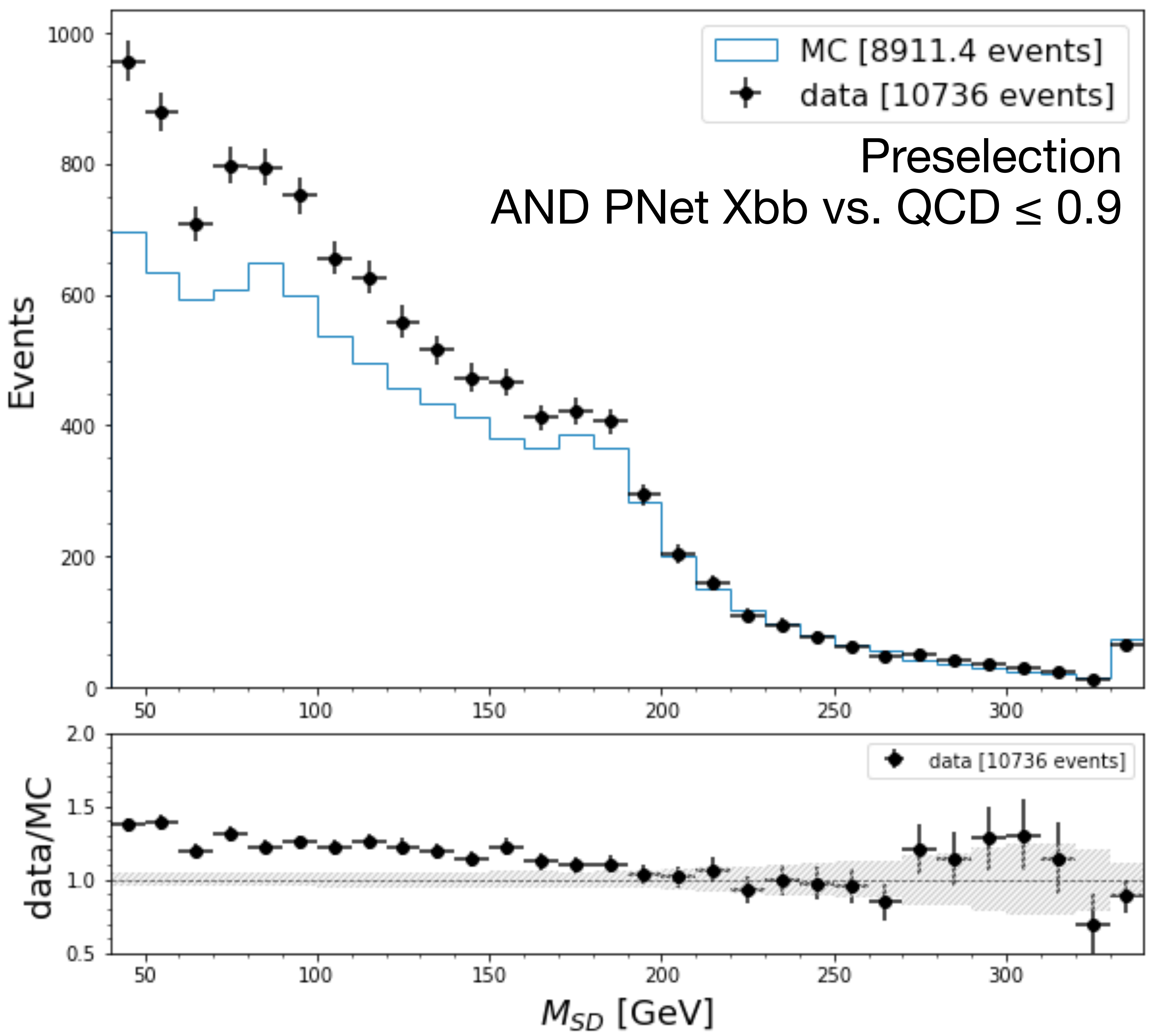


Missing sfs for: **Xbb**, DeepJet (for b-veto?), triggers

Maybe MSD cut biases MC Xbb score shape more than data?
⇒ could be fixed by scale factors

Validation Regions





Missing sfs for: Xbb, DeepJet (for b-veto?), triggers

Conclusions

- The two ABCD extrapolations shown do not seem to be viable
- Proposed another strategy: extrapolate across PNet Xbb + M_{SD} cuts, get α from MC
  - Data/MC agreement does not look good in VRs so far
  - Still missing some scale factors (maybe most importantly Xbb)

CMS

UC San Diego

Backup

*Professor
†Post-doc
‡Graduate Student
§Undergraduate Student

Who is involved?

- UC San Diego:
  A. Arora‡, P. Chang†, L. Giannini†, J. Guiang‡, F. Würthwein*, Y. Xiang‡, A. Yagil*

- U. Nebraska:
  F. Golf*

- Boston University:
  D. Spitzbart†, I. Suarez*

- UC Santa Barbara:
  C. Campagnari*

UC San Diego University of Nebraska Lincoln BOSTON UNIVERSITY UC SANTA BARBARA

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VBS WH Cross Sections

Model	σ [pb]
$\kappa_W = \kappa_Z = +1$ (SM)	0.075
$\kappa_W = -1$	0.433
$\kappa_Z = -1$	0.433

×6

- Setting $\kappa_W = -1$ or $\kappa_Z = -1$ equivalently enhances cross section by a factor of 6
- These numbers are taken from MadGraph*: `generate p p > w h j j QCD=0`
  - Includes gen-level filters (e.g. jet $p_T > 10$ GeV)
  - Generated 10,000 events for each to obtain xsec value
- **Optimizing for $\kappa_W = -1$** (kinematics are equivalent to $\kappa_Z = -1$)
  - Generated 100k UL NanoAOD events for 2016 pre-VFP, 2016 post-VFP, 2017, and 2018

*More details in backup

BSM Signal Models

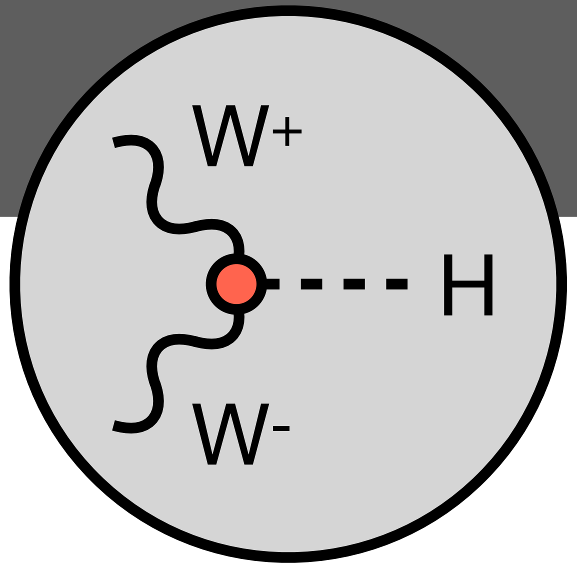
$\kappa_W = -1$

models/sm/couplings.py

```
GC_72 = Coupling(name = 'GC_72',
                 value = '(ee**2*complex(0,1)*vev)/(2.*sw**2)',
                 value = '-((ee**2*complex(0,1)*vev)/(2.*sw**2))',
                 order = {'QED':1})
```

models/sm/vertices.py

```
V_52 = Vertex(name = 'V_52',
              particles = [ P.W__minus__, P.W__plus__, P.H ],
              color = [ '1' ],
              lorentz = [ L.VVS1 ],
              couplings = {(0,0):C.GC_72})
```



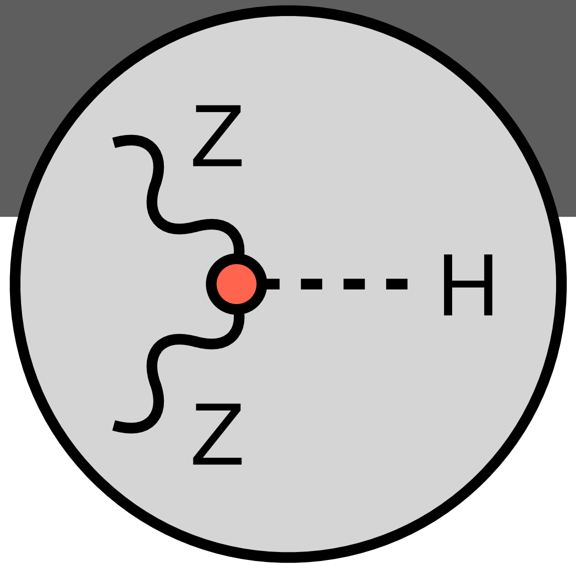
$\kappa_Z = -1$

models/sm/couplings.py

```
GC_81 = Coupling(name = 'GC_81',
                 value = 'ee**2*complex(0,1)*vev + …',
                 value = '-(ee**2*complex(0,1)*vev + … )',
                 order = {'QED':1})
```

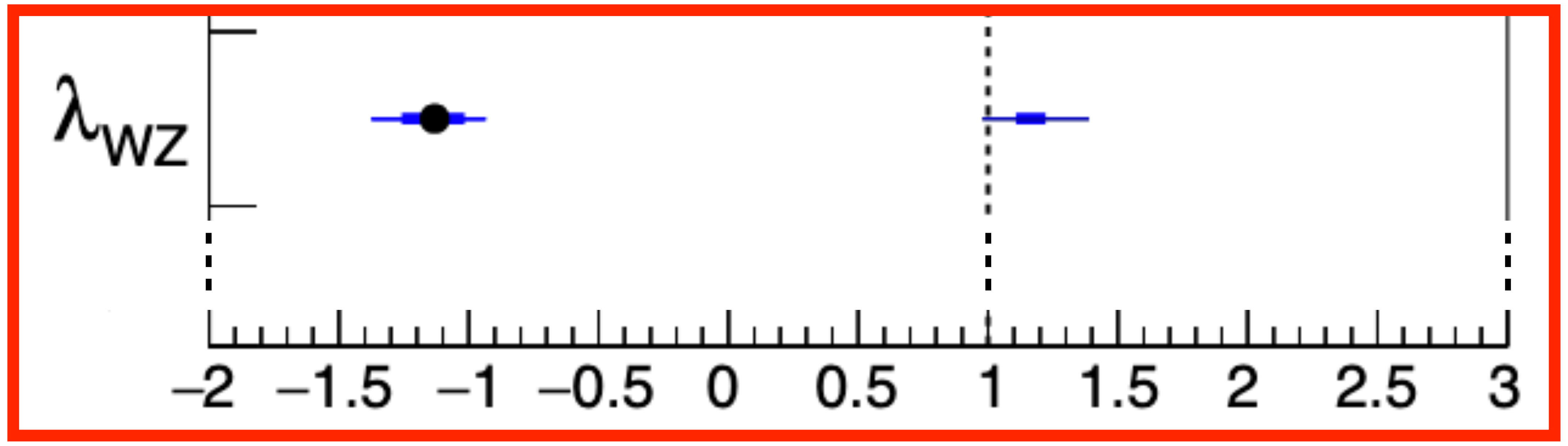
models/sm/vertices.py

```
V_69 = Vertex(name = 'V_69',
              particles = [ P.Z, P.Z, P.H ],
              color = [ '1' ],
              lorentz = [ L.VVS1 ],
              couplings = {(0,0):C.GC_81})
```



Only changed one line in SM Madgraph model!

Current CMS Result



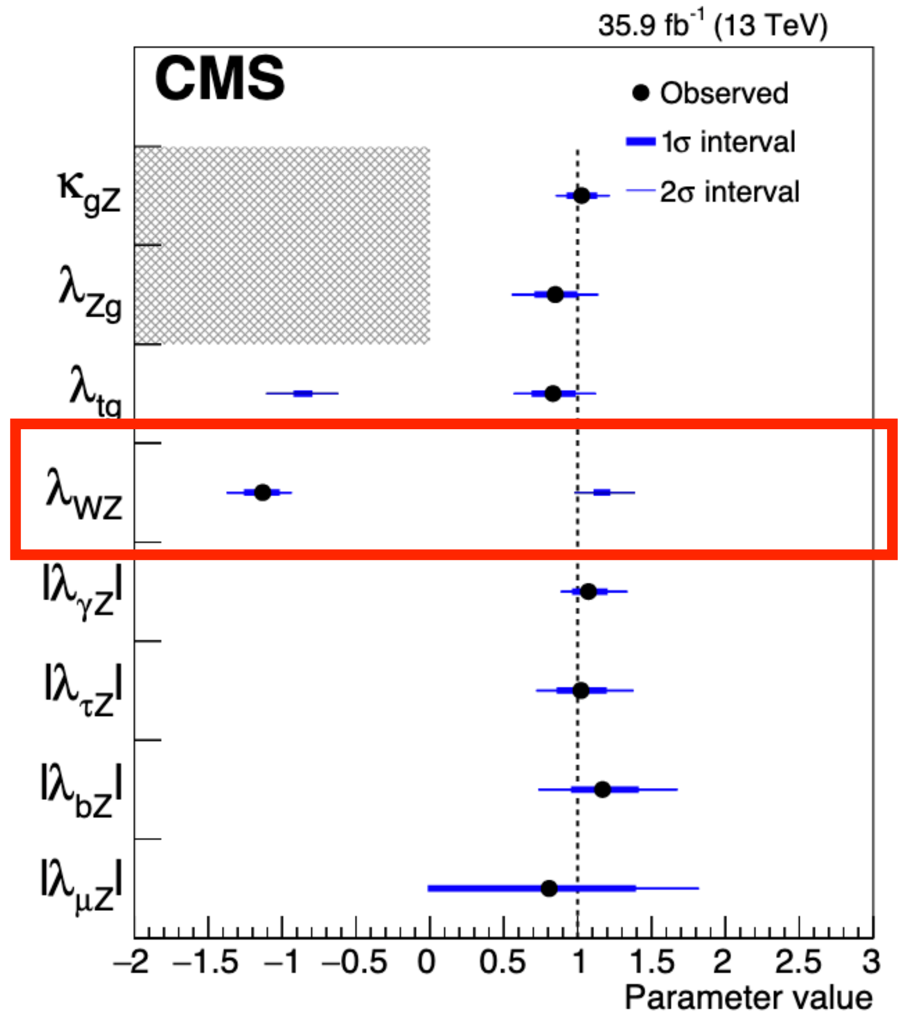
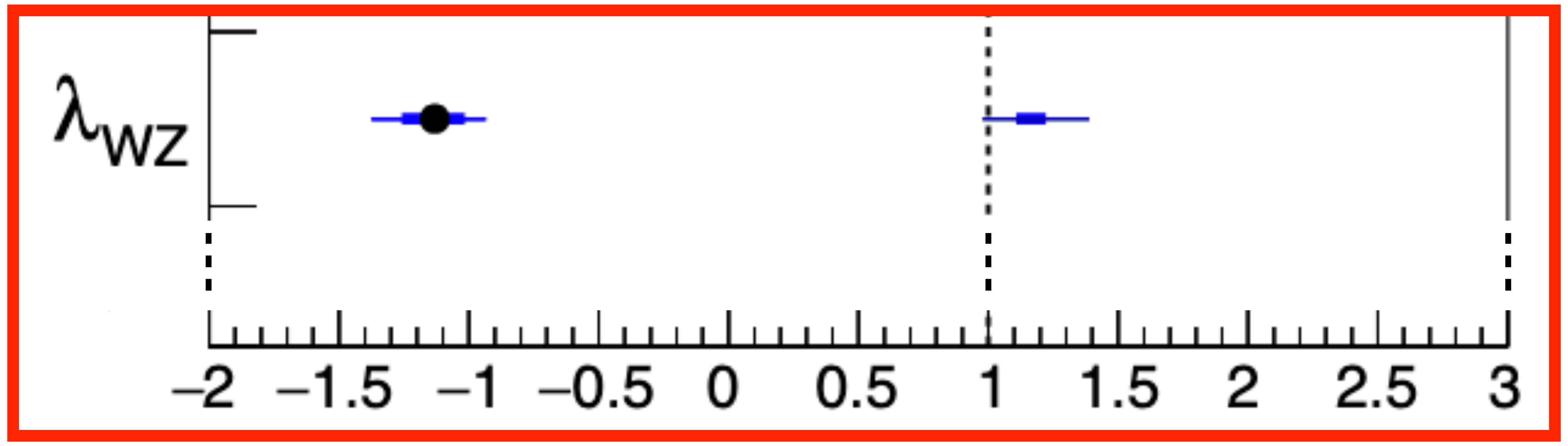


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of λ_{WZ} and λ_{tg} are considered.

- From 35.9 fb^{-1} Higgs combination: best fit hints at λ_{WZ} = -1 (BSM)
  - https://arxiv.org/pdf/1809.10733.pdf
- **With the handles we have on BSM λ_{WZ} via VBS WH, we can rigorously explore this!**

Current CMS Result



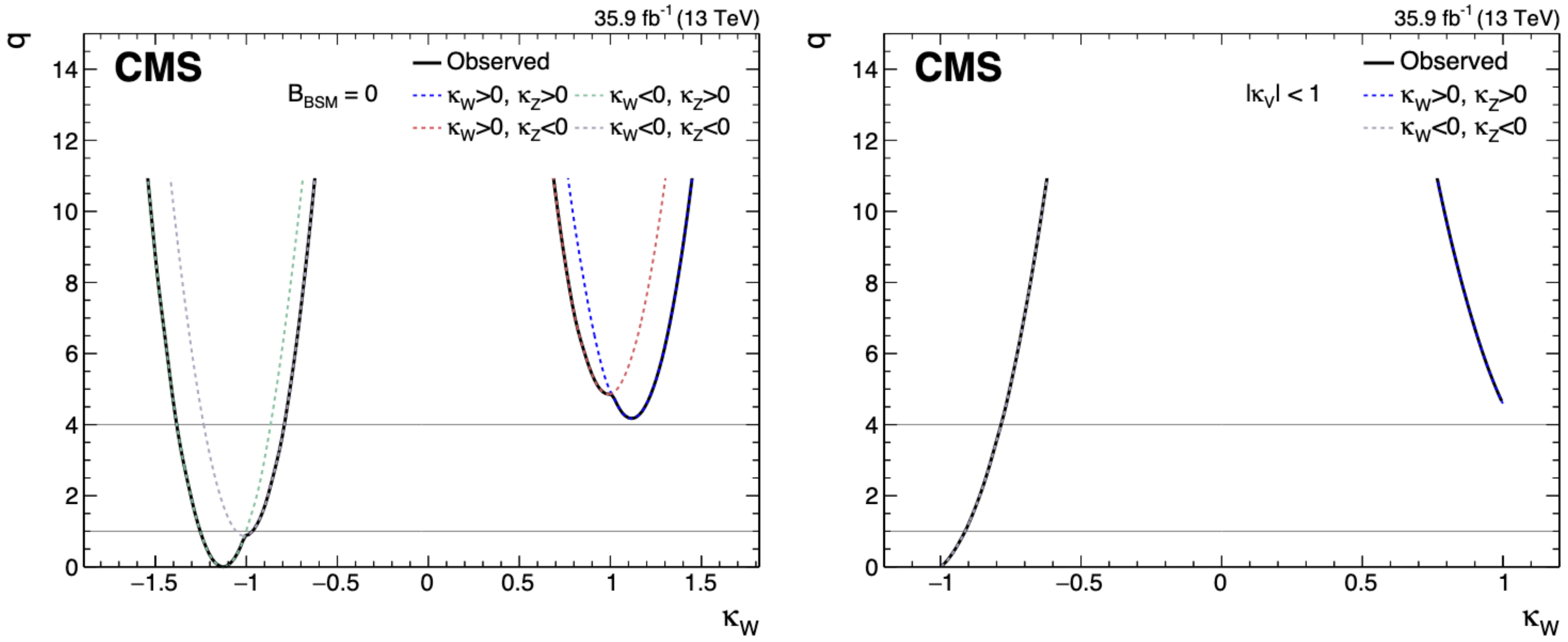


Figure 13: Scan of the test statistic q as a function of κ_W in the generic κ model assuming $\mathcal{B}_{BSM} = 0$ (left) and allowing $\mathcal{B}_{inv}$ and $\mathcal{B}_{undet}$ to float (right). The different colored lines indicate the value of q for different combinations of signs for κ_W and κ_Z. The solid black line shows the minimum value of $q(\kappa_W)$ in each case and is used to determine the best fit point and the 1σ and 2σ CL regions. The scan in the right figure is truncated because of the constraints of $|\kappa_W| \leq 1$ and $|\kappa_Z| \leq 1$, which are imposed in this model.

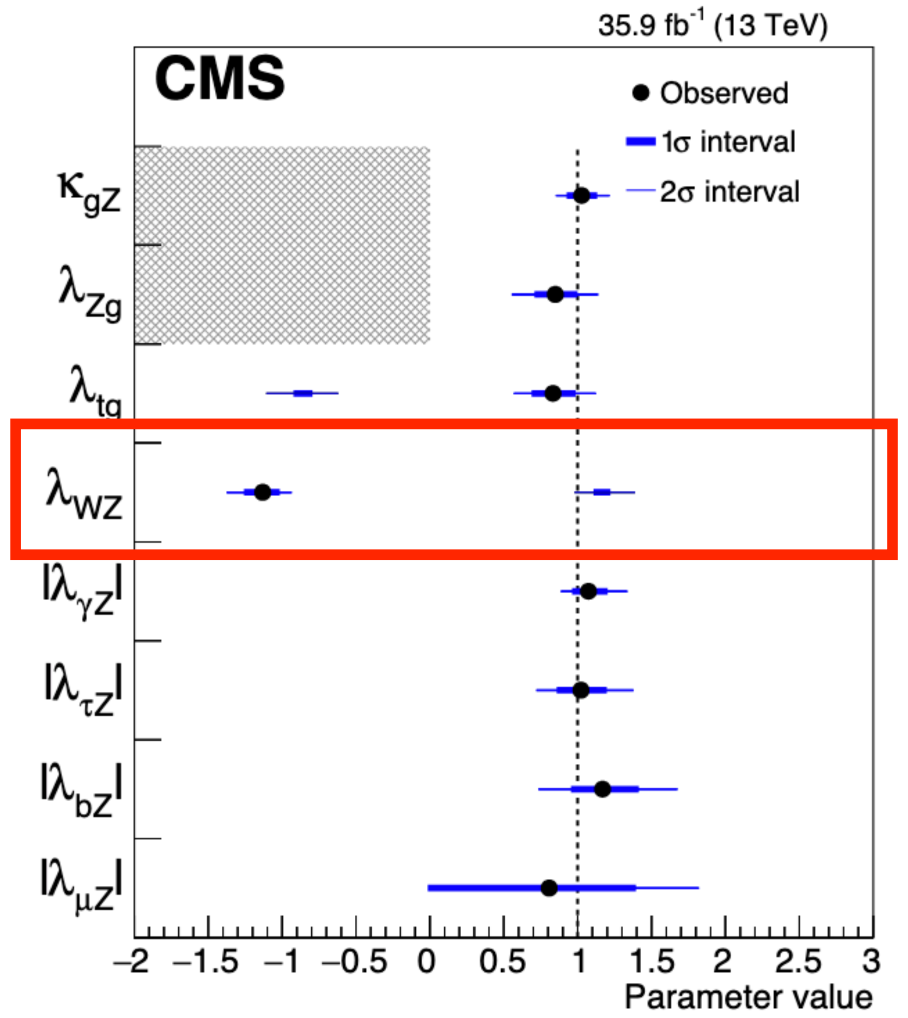
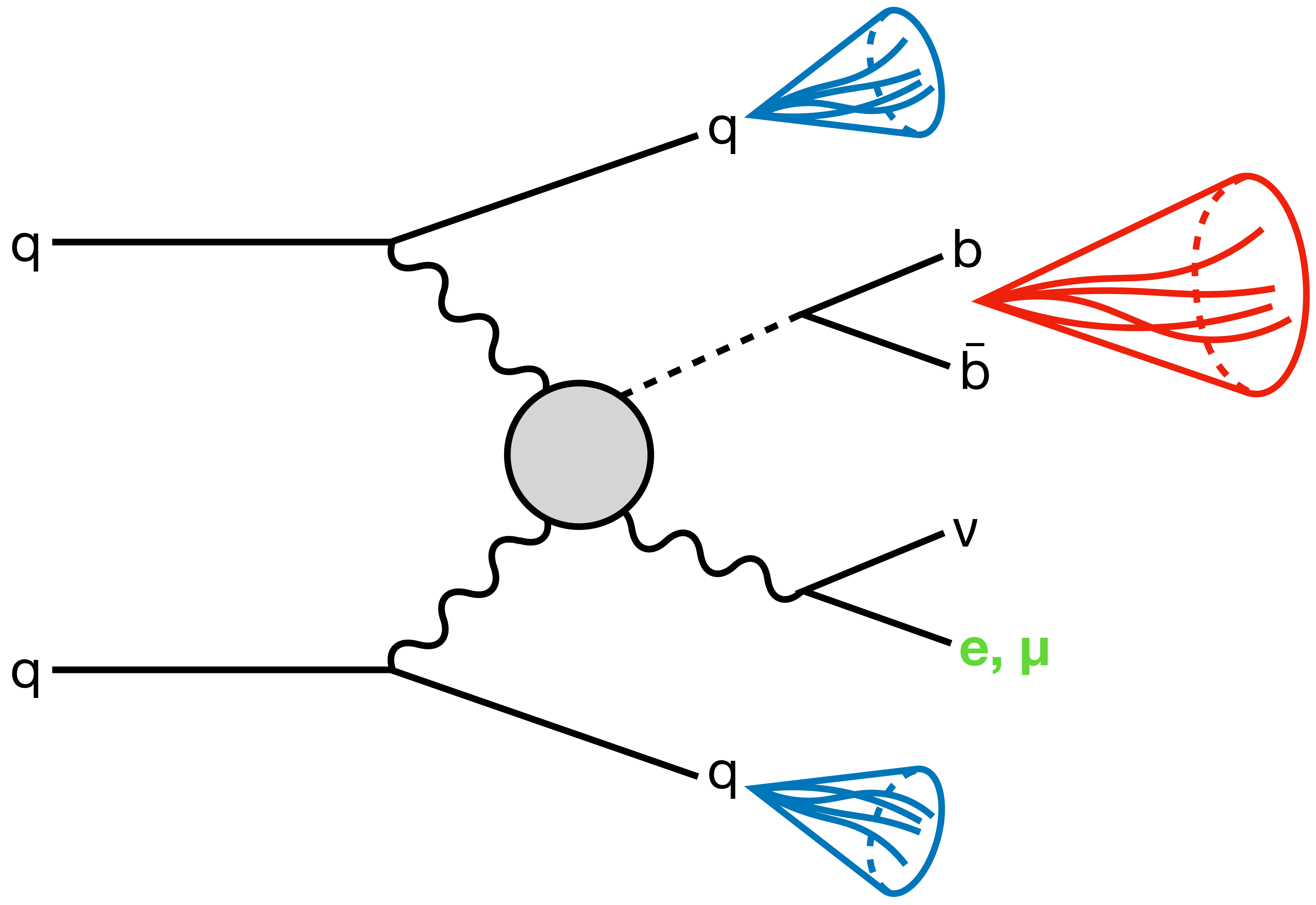


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of λ_{WZ} and λ_{tg} are considered.

https://arxiv.org/pdf/1809.10733.pdf

VBS WH Objects



Object	Selections
One **Lepton** (loose veto in postskim)	• Passes ttH tight ID • p_T > 40 GeV
One **Hbb** Ak8 Jet	• ΔR(Ak8 jet, any veto lep) > 0.8 • p_T > 250 GeV • mass > 50 GeV • M_{SD}* > 40 GeV • Has max(PNet Hbb vs. QCD score) • PNet Hbb vs. QCD score > 0.9

Two **VBS** Ak4 jets	• ΔR(Ak4 jet, any veto lep) > 0.4
	• ΔR(Ak4 jet, Hbb Ak8 jet) > 0.8
	• p_T > 30 GeV
	• For > 2 candidates**:
	  • All in same η-hemisphere: leading/trailing (in P) jets
	  • Else: leading (in P) jet from each η-hemisphere

*M_{SD} = soft drop mass
**Hereafter referred to as the "Max-E" selection

VBS WH Cutflow

Skim & Postskim already applied!

	VH		VV/VVV/VBSWZ		W+Jets		SingleTop		TTbar+X		TTbar1L		TTbar2L		TotalBkg		VBSWH (kW < 0)	
cut	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt
Bookkeeping	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	399990	59598.1
SKIM_FindLeptons	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	399990	59598.1
SKIM_Geq1VetoLep	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	129280	19148.8
SKIM_Geq2Jets	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	128653	19057.0
SKIM_Geq1FatJetNoVetoLepOverlap	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	52537	7773.7
POSTSKIM_Exactly1TightLep	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	31748	4734.4
POSTSKIM_Geq1FatJetNoTightLepOverlap	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	24525	3653.0
POSTSKIM_STgt800	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372792	233443.3	13122	1950.0
SelectLeptons	63165	231.7	484277	6482.0	4603393	121610.6	76733	7558.5	939478	1042.8	1943369	86381.3	262377	10136.4	8372792	233443.3	13122	1950.0
Has1TightLep	63165	231.7	484277	6482.0	4603393	121610.6	76733	7558.5	939478	1042.8	1943369	86381.3	262377	10136.4	8372792	233443.3	13122	1950.0
LepPtGt40	60944	220.0	435912	5900.1	3889493	109822.4	68935	6915.5	817993	910.4	1761239	78242.7	227019	8754.4	7261535	210765.4	12416	1848.4
Passes1LepTriggers	54536	180.9	386803	5342.0	3325103	97557.5	61557	6223.5	700889	772.5	1535810	68294.5	197780	7636.6	6262478	186007.5	10736	1591.5
SelectFatJets	54536	180.9	386803	5342.0	3325103	97557.5	61557	6223.5	700889	772.5	1535810	68294.5	197780	7636.6	6262478	186007.5	10736	1591.5
Geq1FatJet	54470	181.1	384920	5337.1	3323420	97531.5	61404	6201.8	695035	767.0	1534845	68250.4	190755	7367.7	6244849	185636.6	10726	1590.3
SelectHbbFatJet	54470	181.1	384920	5337.1	3323420	97531.5	61404	6201.8	695035	767.0	1534845	68250.4	190755	7367.7	6244849	185636.6	10726	1590.3
SelectJetsNoHbbOverlap	54470	181.1	384920	5337.1	3323420	97531.5	61404	6201.8	695035	767.0	1534845	68250.4	190755	7367.7	6244849	185636.6	10726	1590.3
SaveAk4GlobalBVeto	54470	181.1	384920	5337.1	3323420	97531.5	61404	6201.8	695035	767.0	1534845	68250.4	190755	7367.7	6244849	185636.6	10726	1590.3
SelectVBSJetsMaxE	17662	50.3	251204	2035.9	2399176	47338.8	43921	4372.3	593328	654.0	1126440	50406.5	161098	6253.2	4592829	111110.9	7458	1113.0
MjjGt500_detajjGt3	3039	7.2	44926	376.4	393418	7744.0	10903	994.0	111929	124.2	231383	10337.4	35368	1371.5	830966	20954.6	6167	920.1
ApplyAk4GlobalBVeto	1846	5.7	36616	323.3	324790	6747.2	2889	286.0	26727	28.4	55460	2486.0	6173	239.0	454501	10115.6	5827	870.5
MjjGt1500_detajjGt4	241	0.8	5399	38.4	65490	927.7	535	47.0	4174	4.7	9479	428.0	1084	42.1	86402	1488.6	3166	479.2
STGt1200	30	0.0	1165	7.5	25376	155.8	85	9.4	661	0.6	831	36.9	116	4.5	28264	214.7	1384	207.7
XbbScoreGt0p9_MSDLt150	23	0.0	65	0.0	217	1.3	1	0.2	44	0.0	45	2.0	13	0.5	408	4.0	729	108.8

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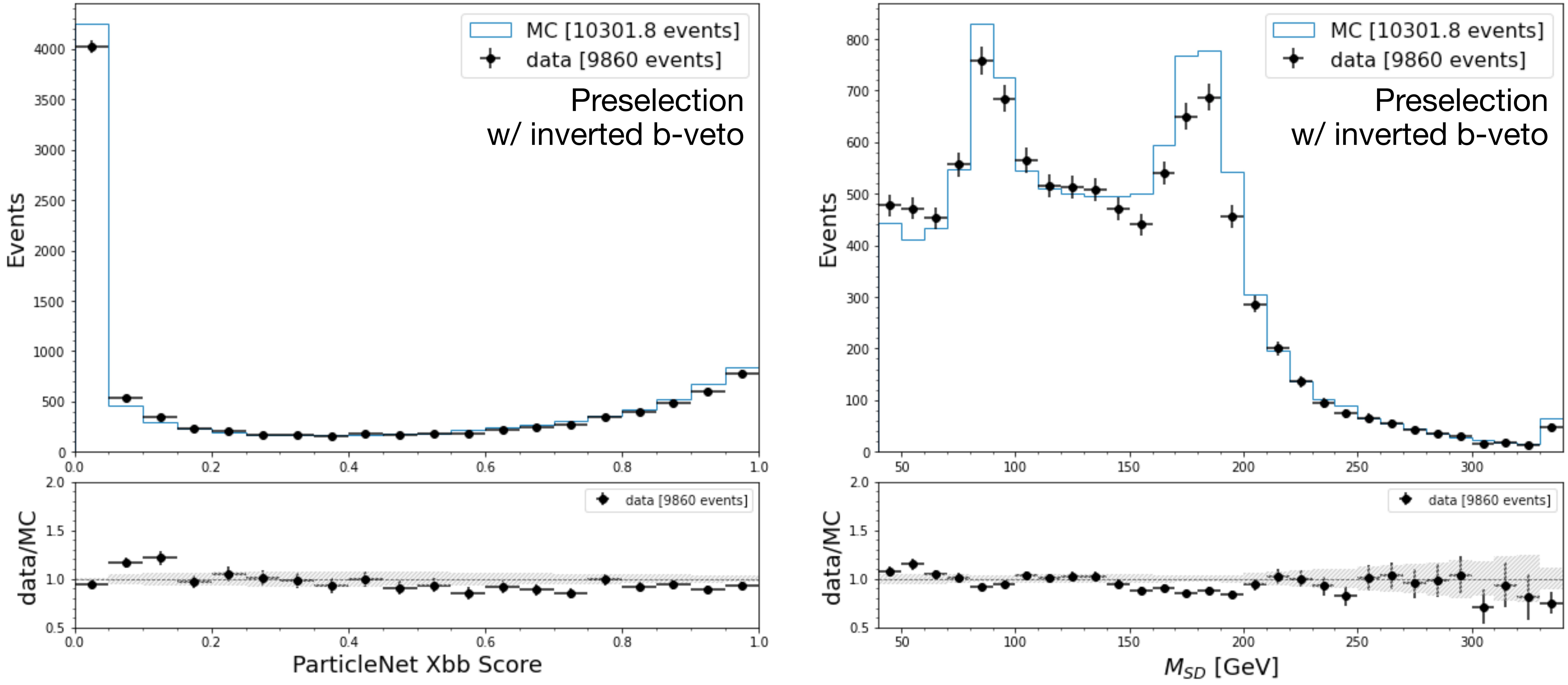
Validation Regions: Inverted b-veto



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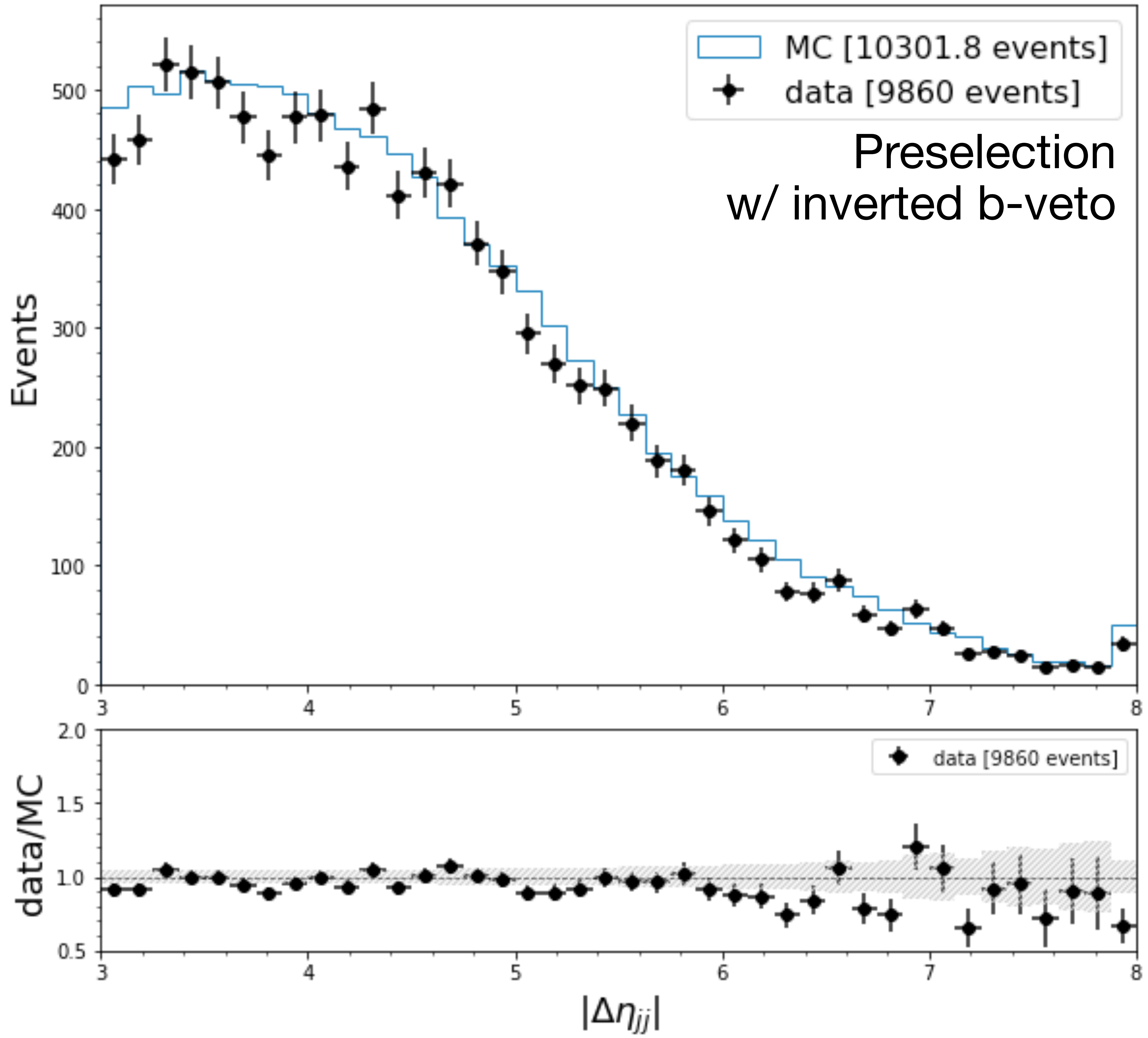
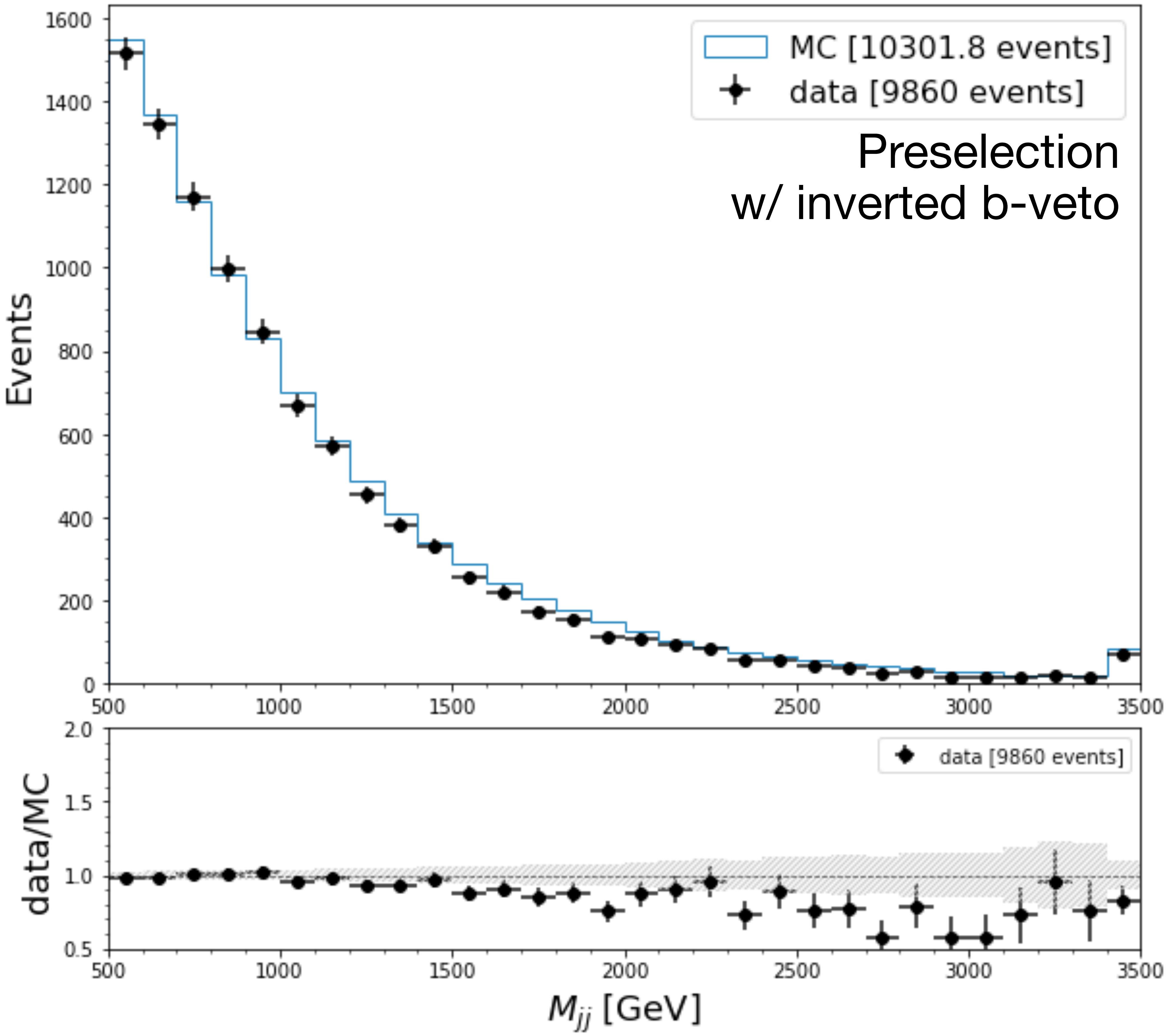
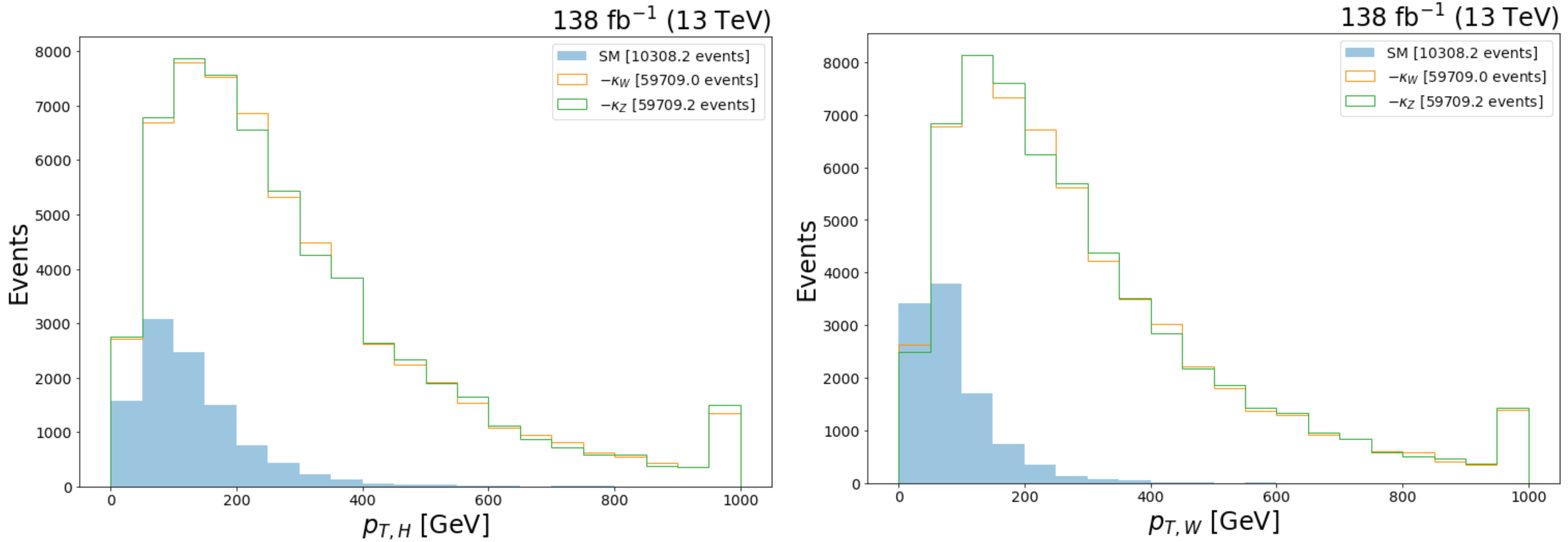


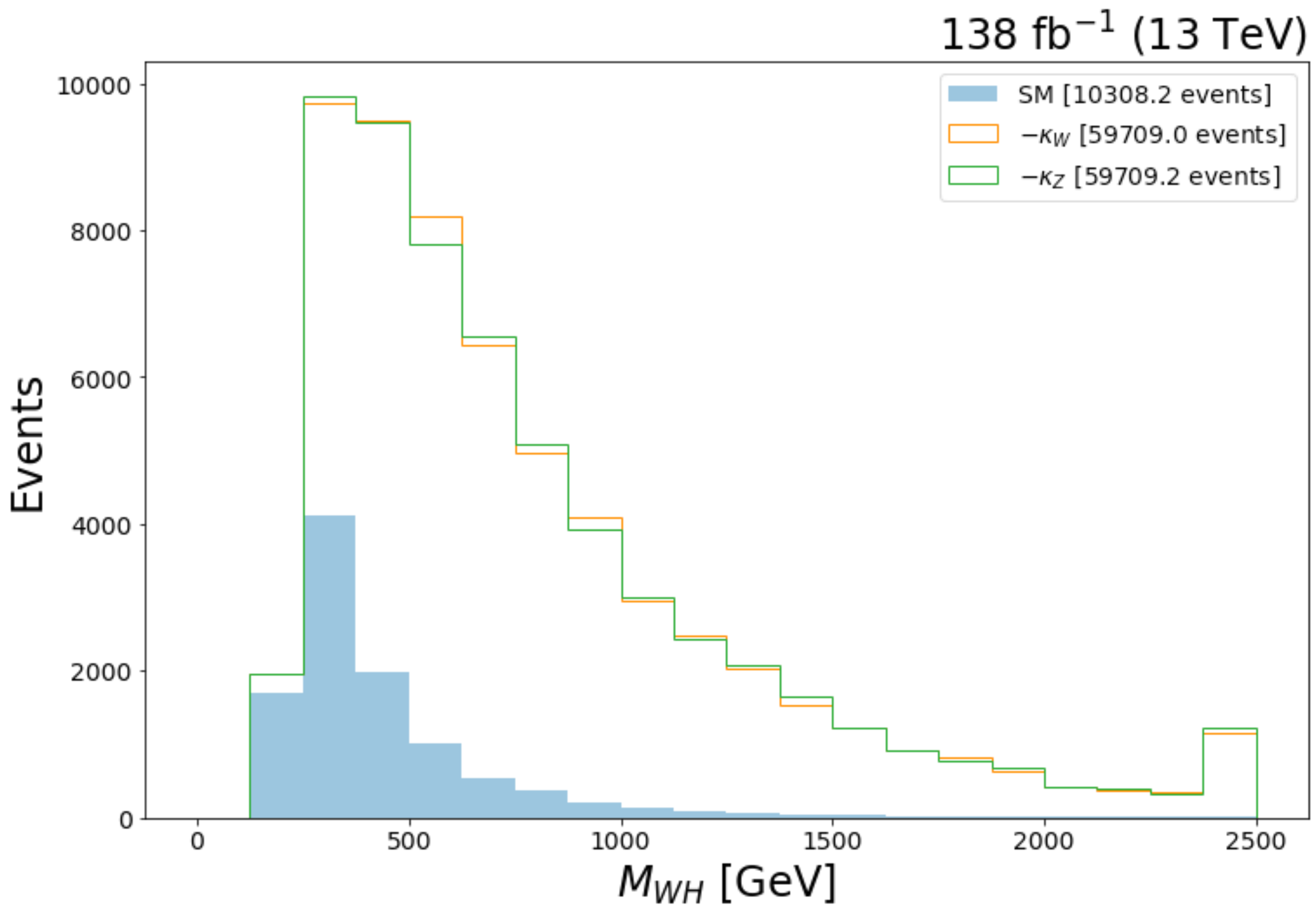


LHE W and H Kinematics



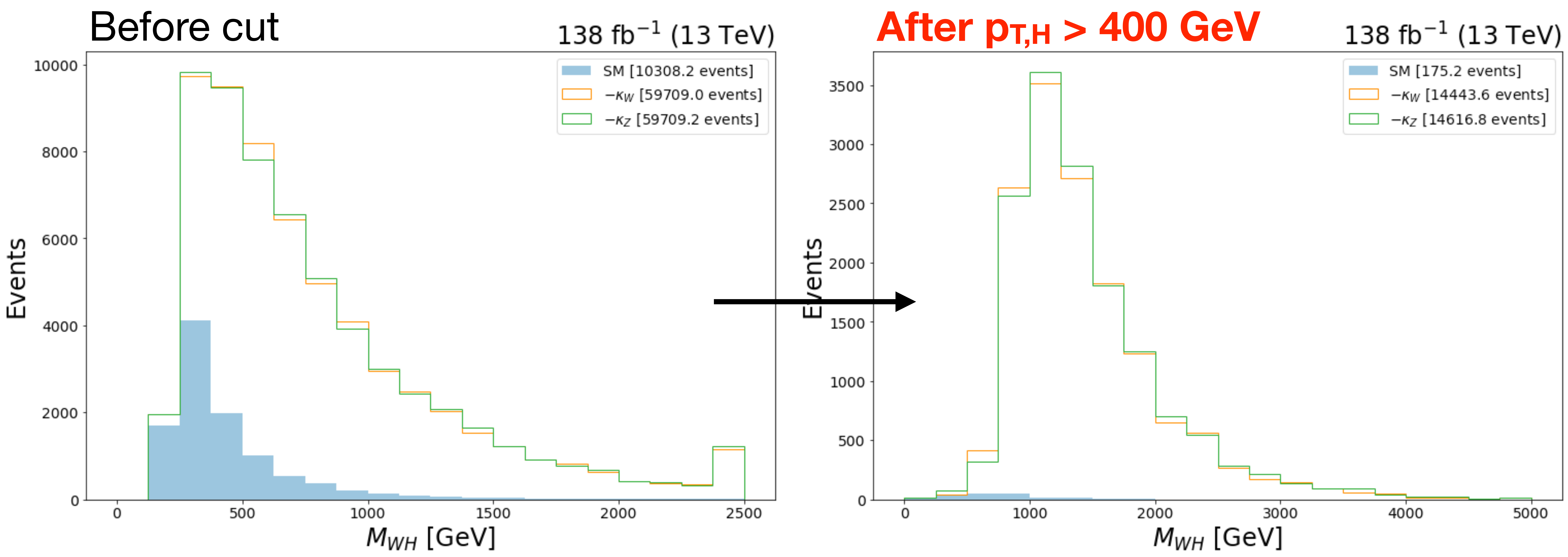
Strong boost in W and H in BSM ($-\kappa_W$ or $-\kappa_Z$) models

LHE W and H Kinematics



Strong boost in W and H in BSM (-κ_W or -κ_Z) models

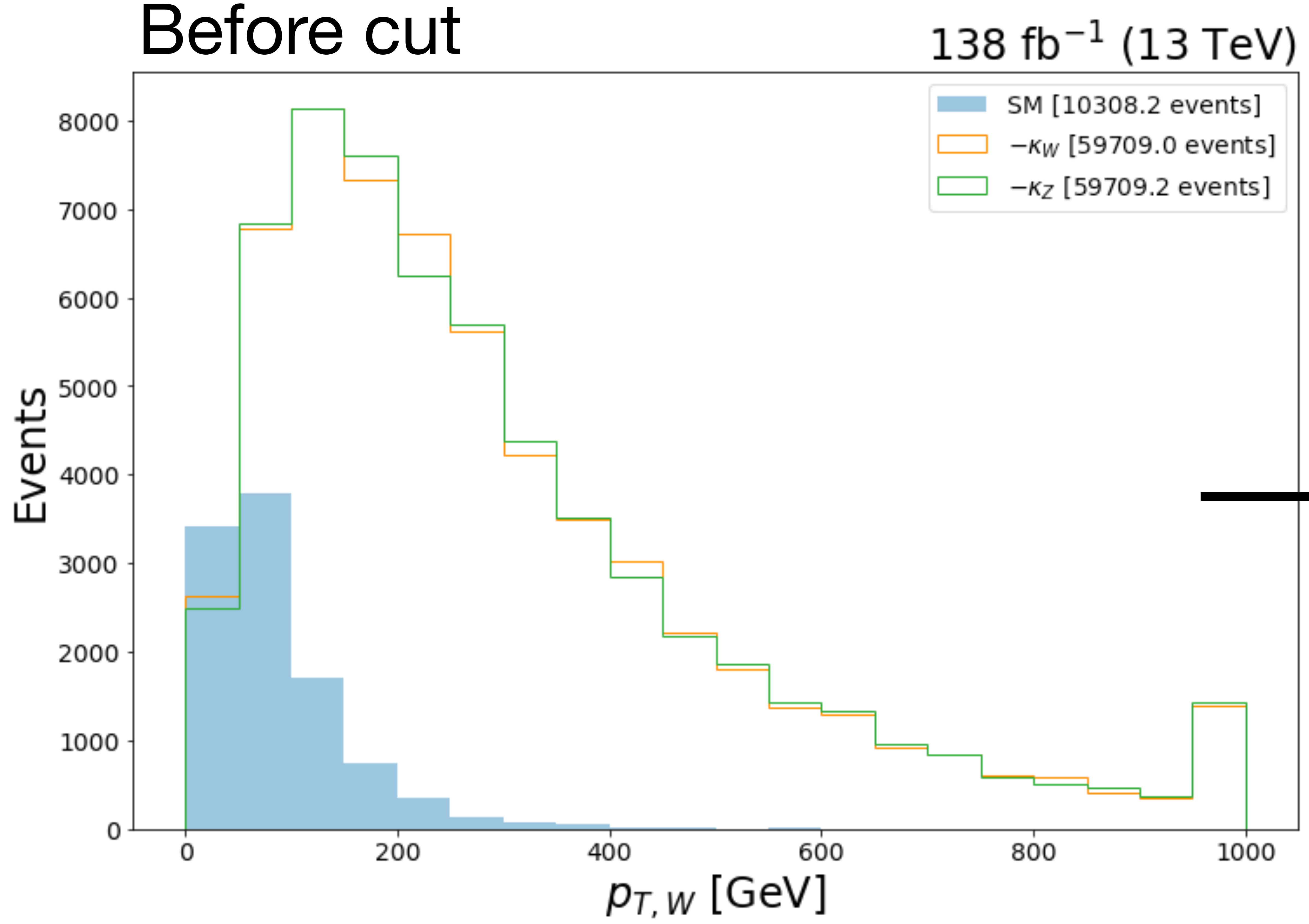
LHE W and H Kinematics



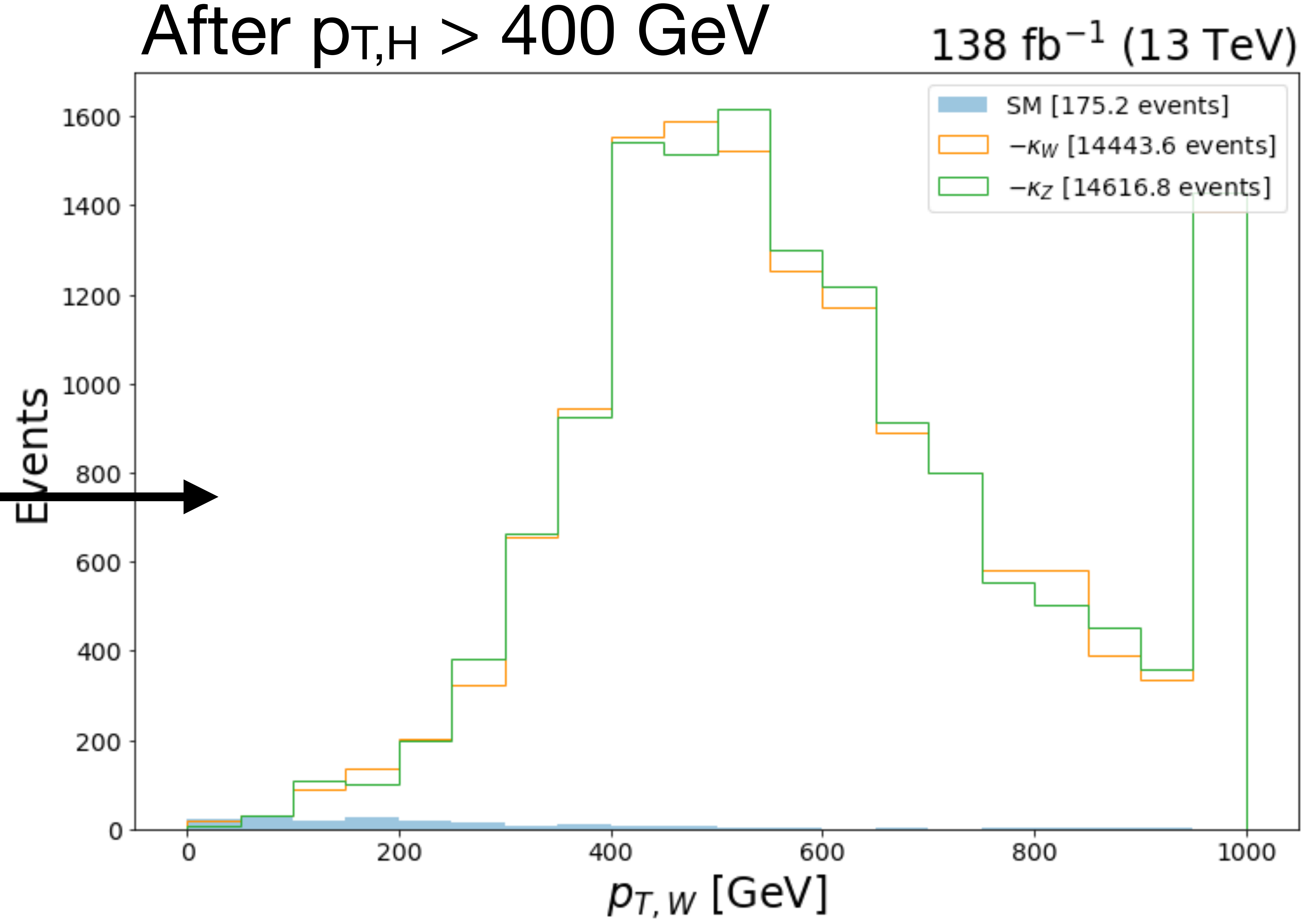
High s-hat events have large M_{WH}

LHE W and H Kinematics

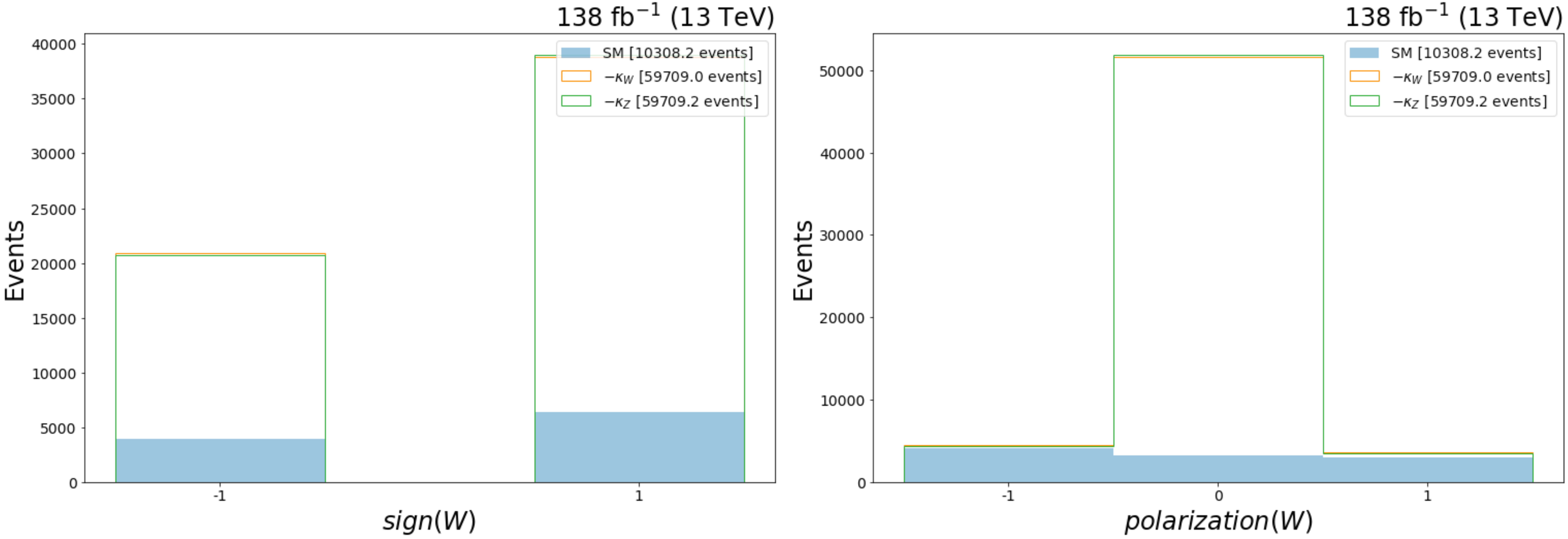
Before cut



After $p_{T,H}$ > 400 GeV

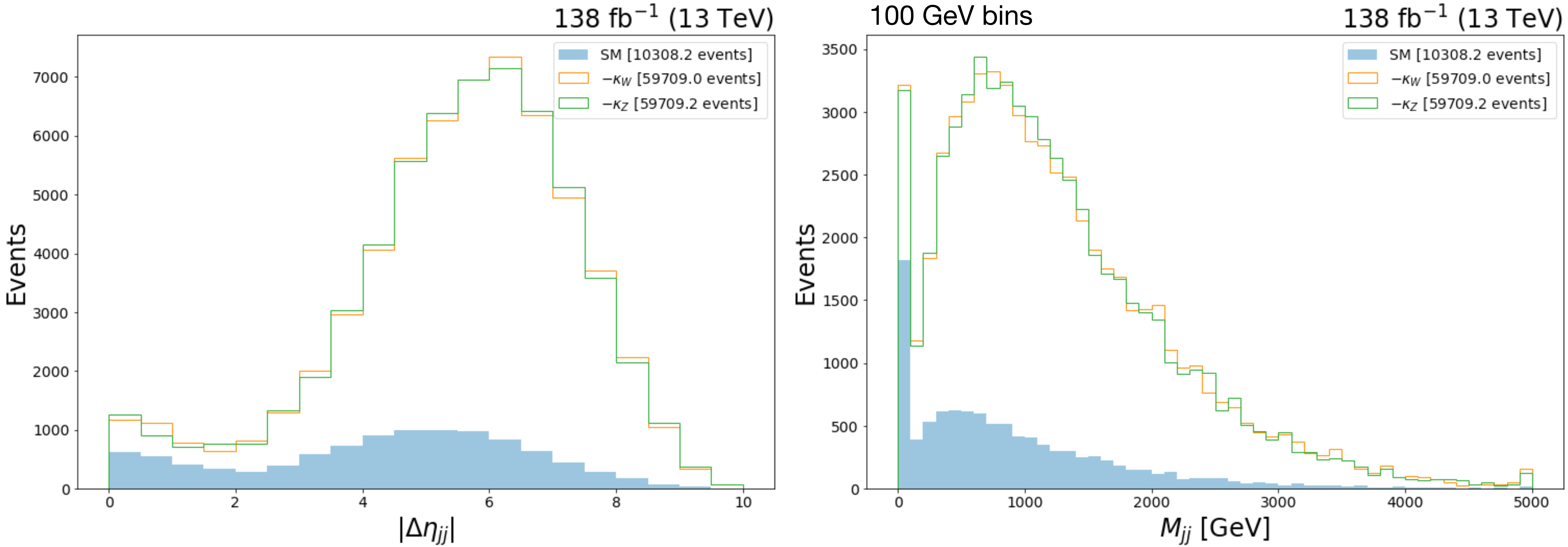


LHE W Characteristics



Some W^+/W^- asymmetry; more longitudinally polarized W's

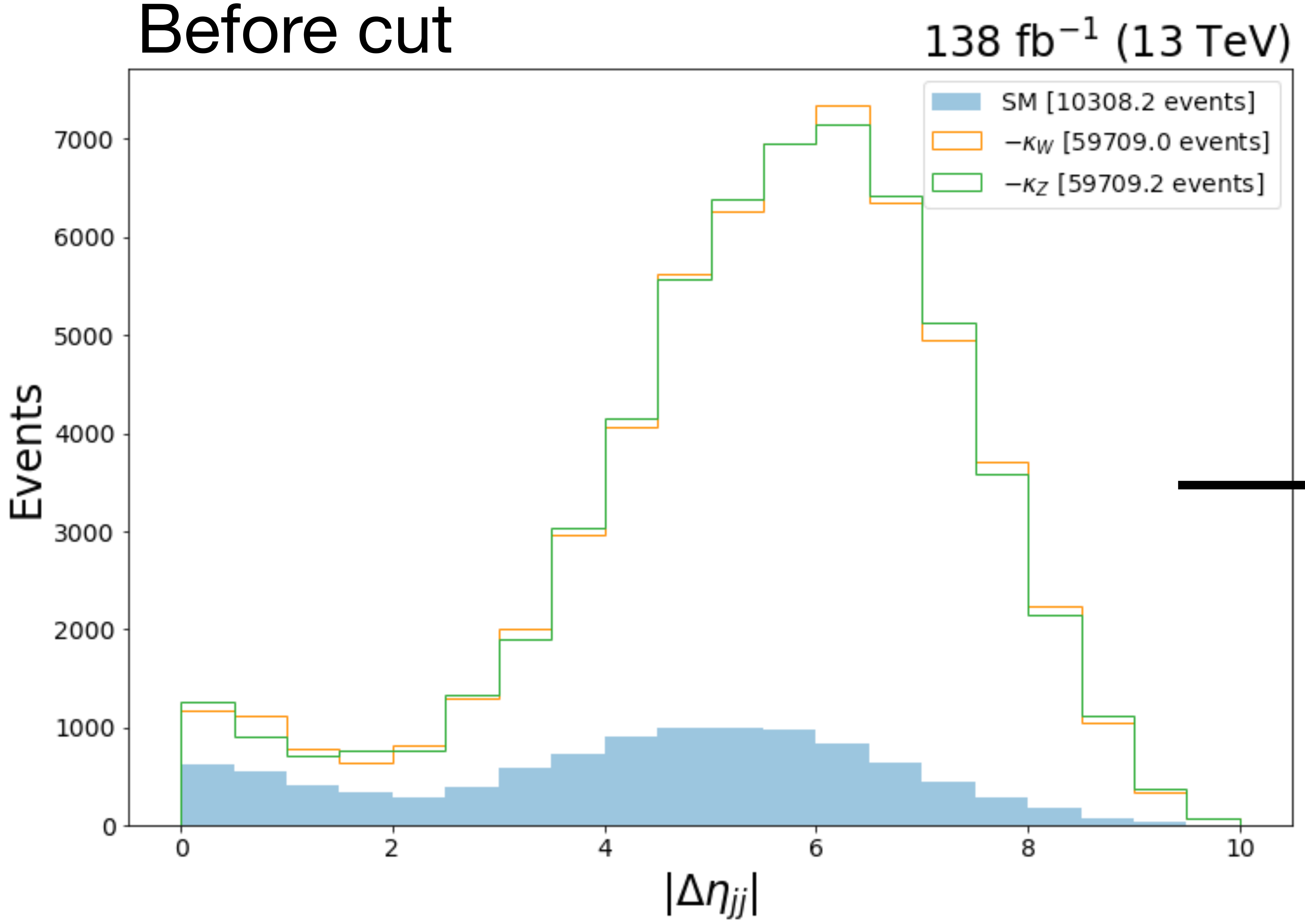
LHE VBS Kinematics



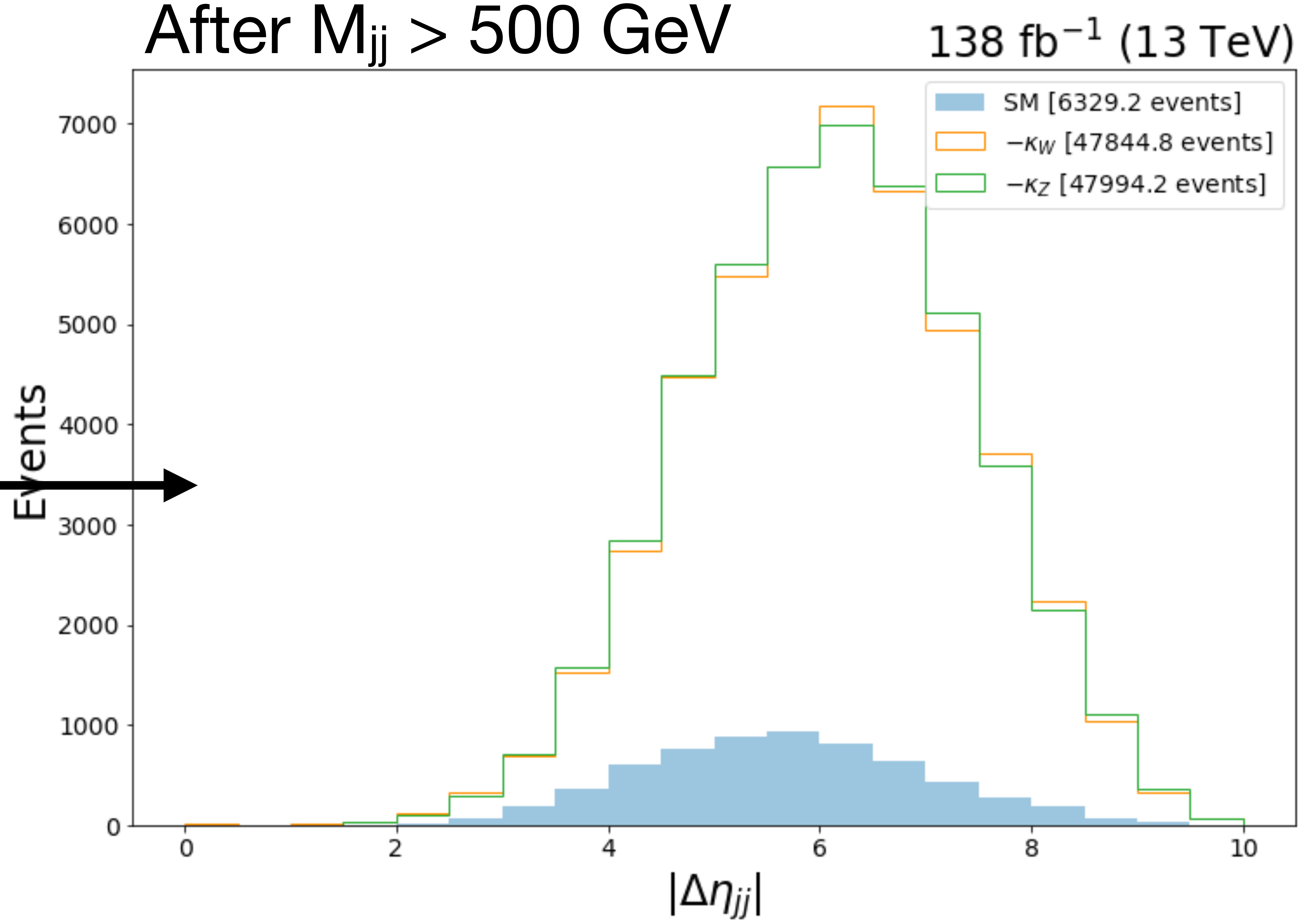
VBS-like signal: large $|\Delta\eta_{jj}|$, M_{jj}

LHE VBS Kinematics

Before cut

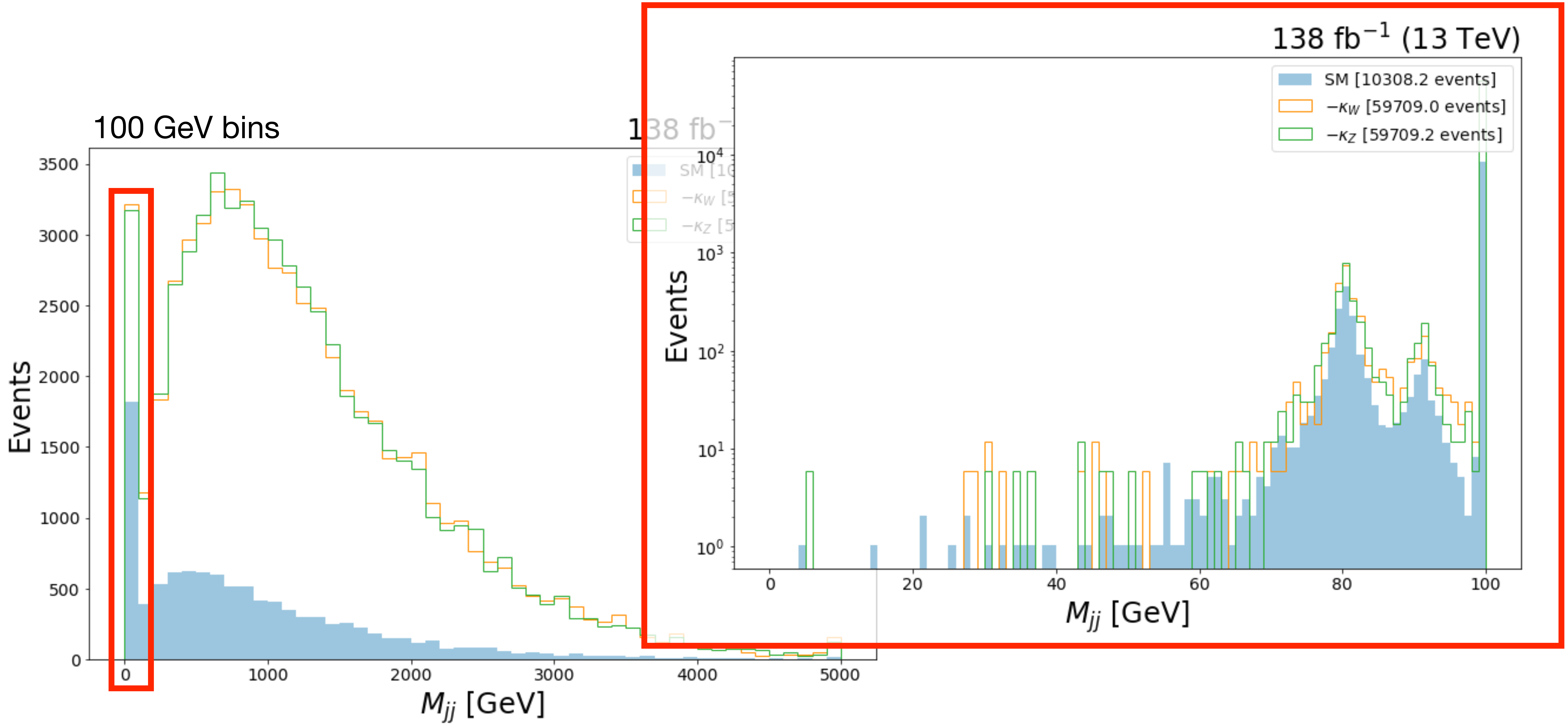


After M_{jj} > 500 GeV



VBS-like signal: large $|\Delta\eta_{jj}|$, M_{jj}

LHE VBS Kinematics



Visible W and Z peaks from pp → WHV (V→jj)