VBS WH Analysis

Issues with the EWK W/Z samples

August 15th, 2022

P. Chang, L. Giannini, ***J. Guiang****, F. Würthwein, Y. Xiang*

Overview

Yields scaled to lumi×σ, rounded for readability

	Cut	VH	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	232	6.5K	122K	7.6K	1K	86K	10K	233K	—	2K	—
	Object Selection	48	1.9K	46K	4.2K	605	48K	5.6K	106K	55%	1.1K	45%
	Preselection	2	41	466	184	19	1.6K	101	2.4K	98%	561	48%
SR1	**M_{jj} > 600 GeV AND $\|\Delta\eta_{jj}\|$ > 4**	1	19	228	115	10	921	54	1.3K	44%	528	6%
SR1	**S_T > 900 GeV**	1	13	140	75	6	483	26	744	45%	431	18%
SR1	**PNet Xbb vs. QCD > 0.9 AND M_{SD} < 150**	1	4	18	12	1	42	9	**85**	89%	**336**	22%
SR2	**S_T > 1500 GeV**	0	0	1	0	0	1	0	**2**	97%	**95**	72%

Yields scaled to lumi×σ, rounded for readability

	Cut	VH	EWK	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	232	28K	13K	122K	7.6K	1K	86K	10K	268K	—	2K	—
	Object Selection	48	8.4K	4.2K	46K	4.2K	605	48K	5.6K	117K	56%	1.1K	45%
	Preselection	2	617	74	466	184	19	1.6K	101	3K	97%	561	48%
SR1	**M_{jj} > 600 GeV AND $\|\Delta\eta_{jj}\|$ > 4**	1	477	24	228	115	10	921	54	1.8K	40%	528	6%
SR1	**S_T > 900 GeV**	1	379	18	140	75	6	483	26	1.1K	38%	431	18%
SR1	**PNet Xbb vs. QCD > 0.9 AND M_{SD} < 150**	1	76	4	18	12	1	42	9	**161**	86%	**336**	22%
SR2	**S_T > 1500 GeV**	0	12	0	1	0	0	1	0	**14**	91%	**95**	72%

Added EWK W/Z samples, they are a problem

(also added DY samples)

*eff = 1 - after/before

Overview

Yields scaled to lumi×σ, rounded for readability

	Cut	VH	EWK	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	232	28K	13K	122K	7.6K	1K	86K	10K	268K	—	2K	—
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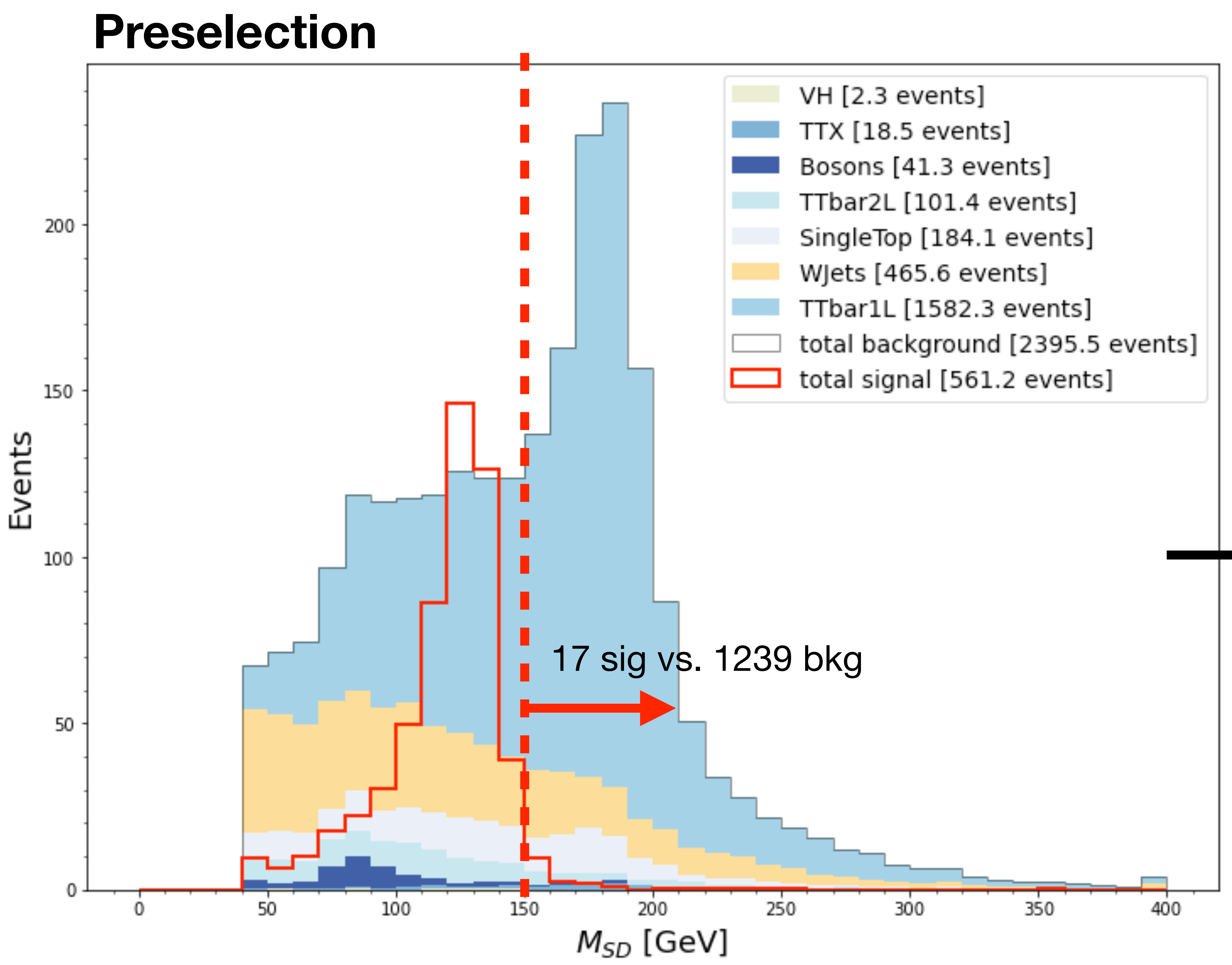
SR2	**S_T > 1500 GeV**	0	12	0	1	0	0	1	0	**14**	91%	**95**	72%

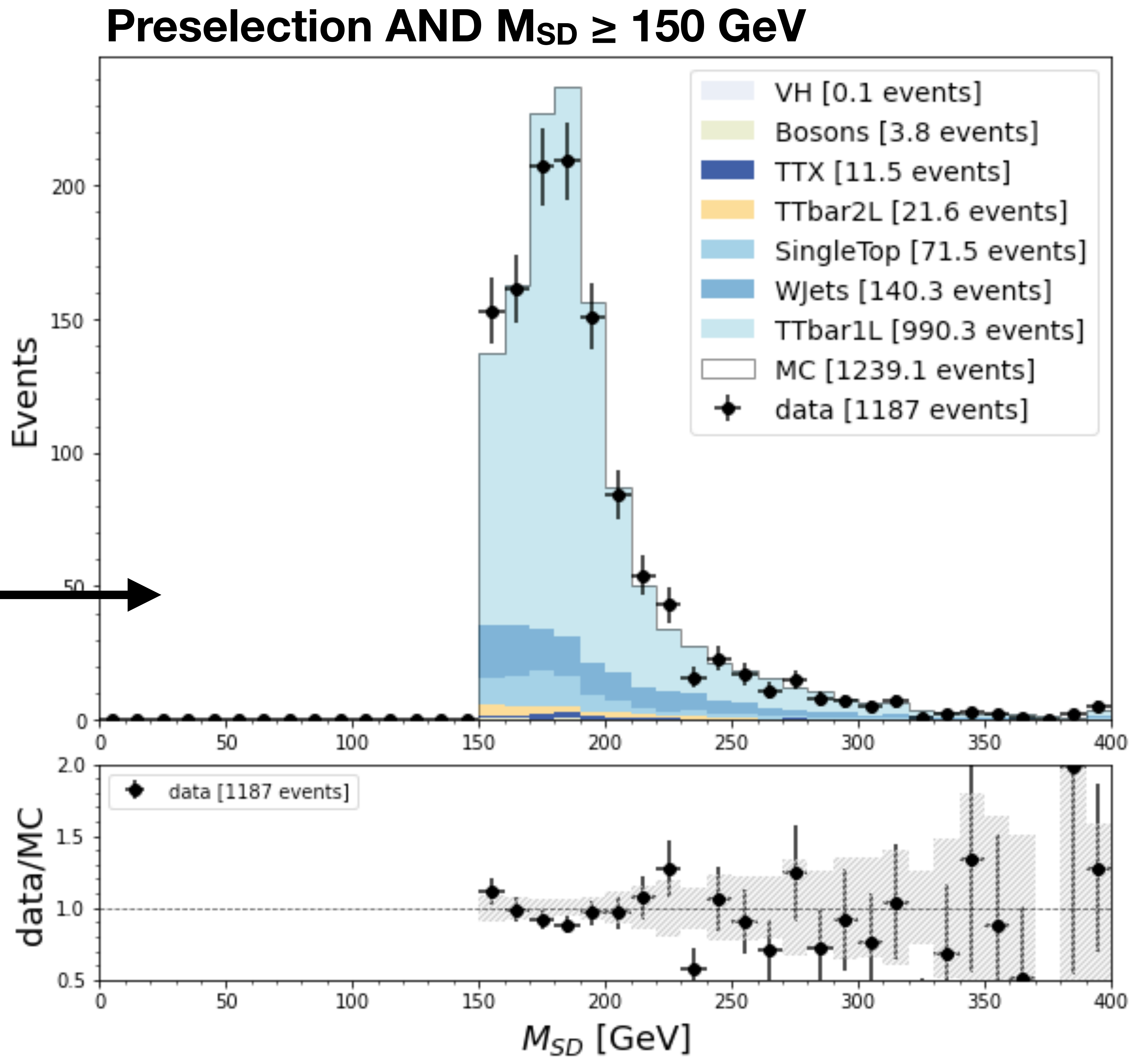
- New samples add *a lot* of background
  - Entirely from EWK $W^{\pm}$, $W\to\ell\nu$ samples
- Recall: MC was over-predicting what we see in data
  - ⇒ problem is much worse now

Sample	σ [pb]
EWK W^{+}, $W\to\ell\nu$	39.33
EWK W^{+}, $W\to qq$	10.67
EWK W^{-}, $W\to\ell\nu$	32.26
EWK W^{-}, $W\to qq$	10.67
EWK Z, $Z\to\ell\ell$	6.22
EWK Z, $Z\to\nu\nu$	10.72
EWK Z, $Z\to qq$	10.67

*eff = 1 - after/before

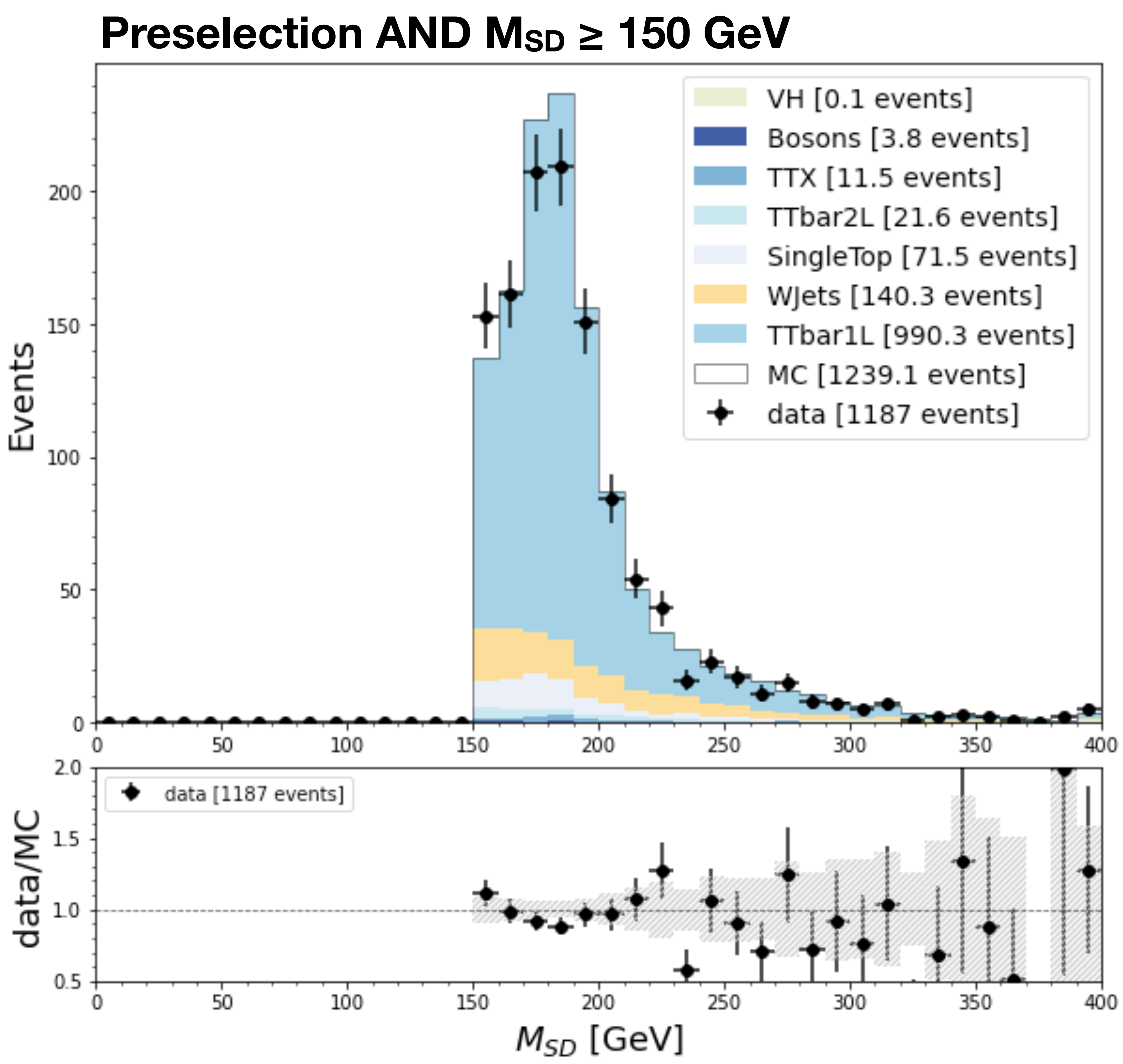
Validation: Hbb

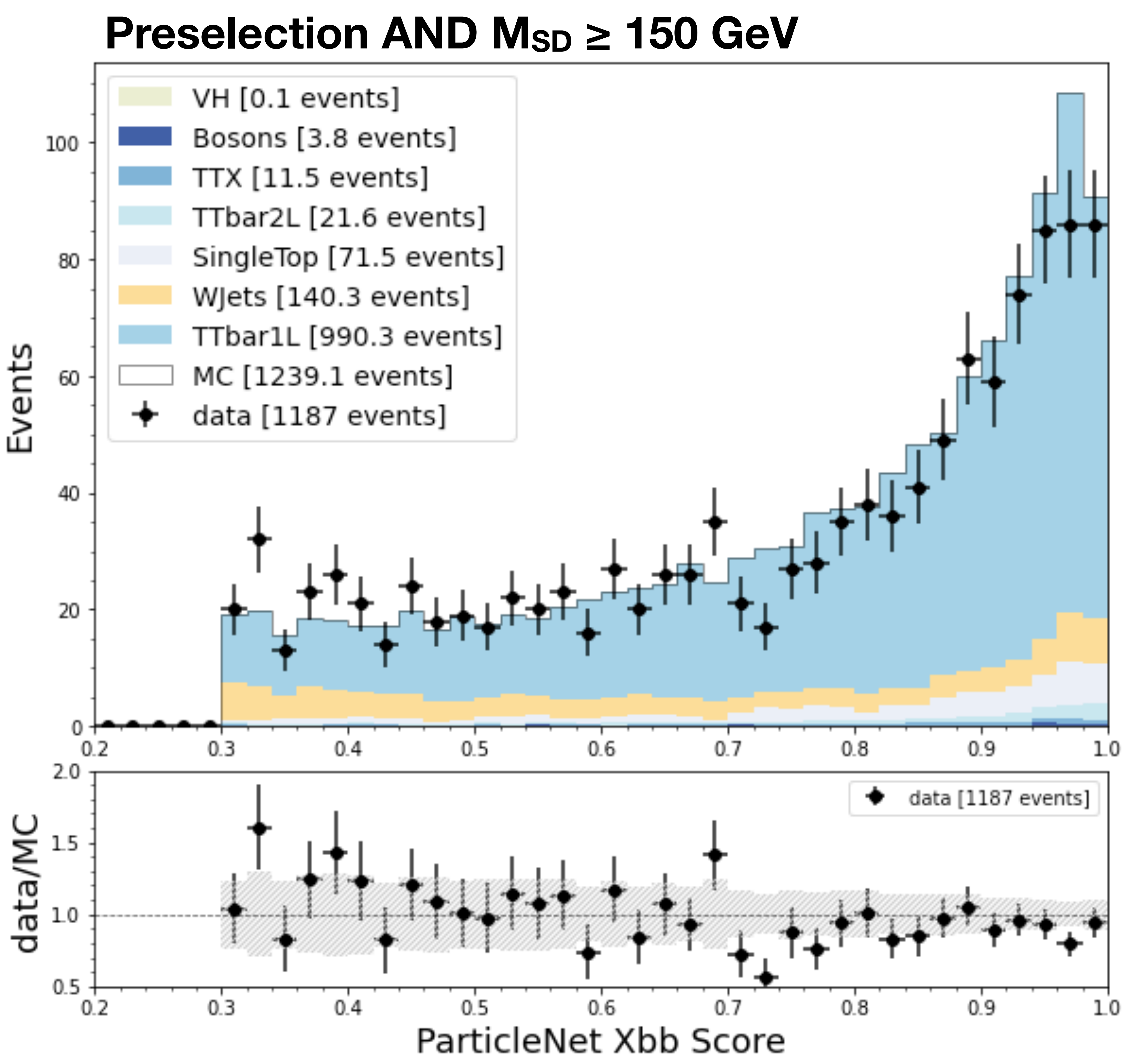




Agreement looked good

Validation: Hbb





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

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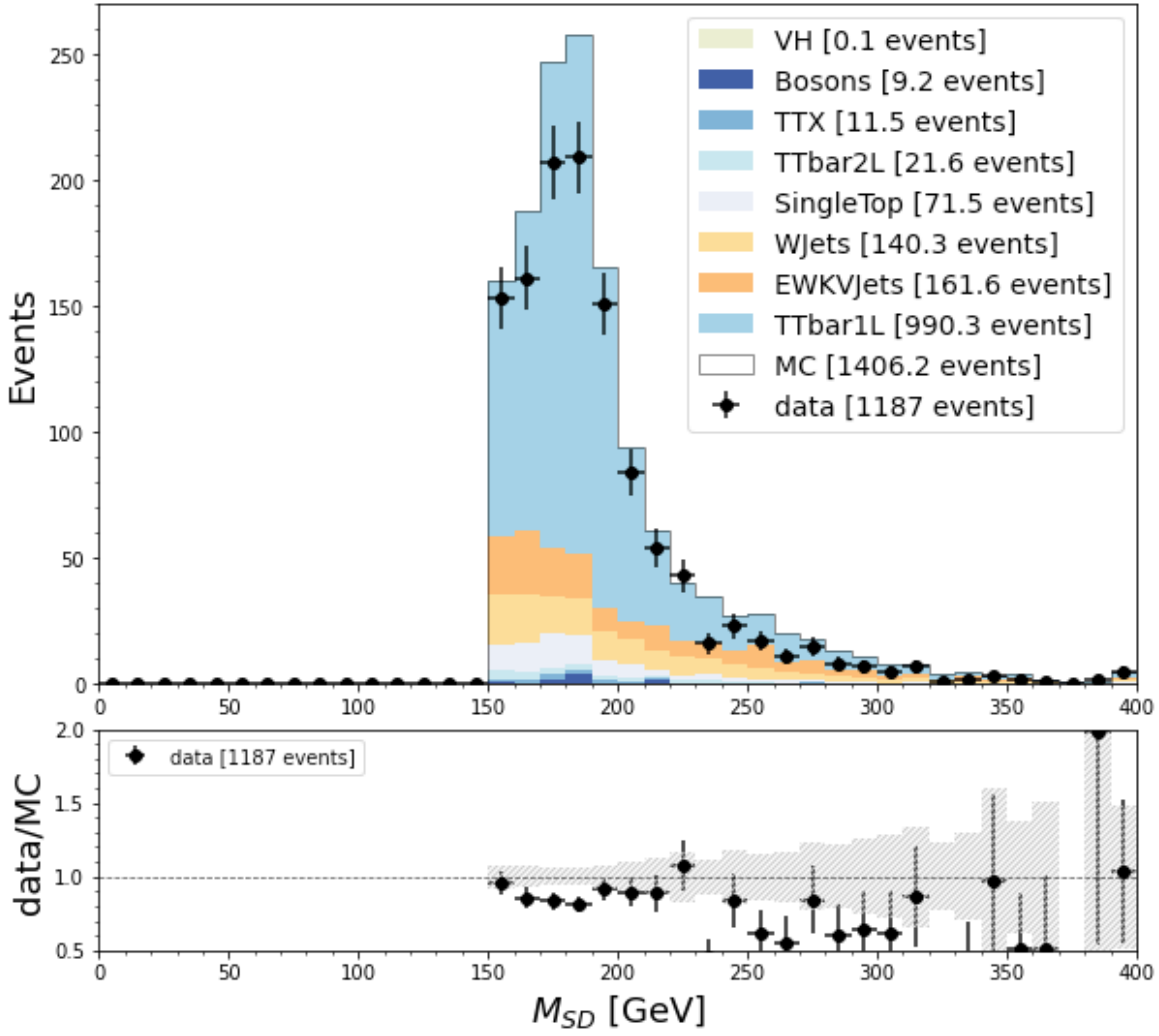
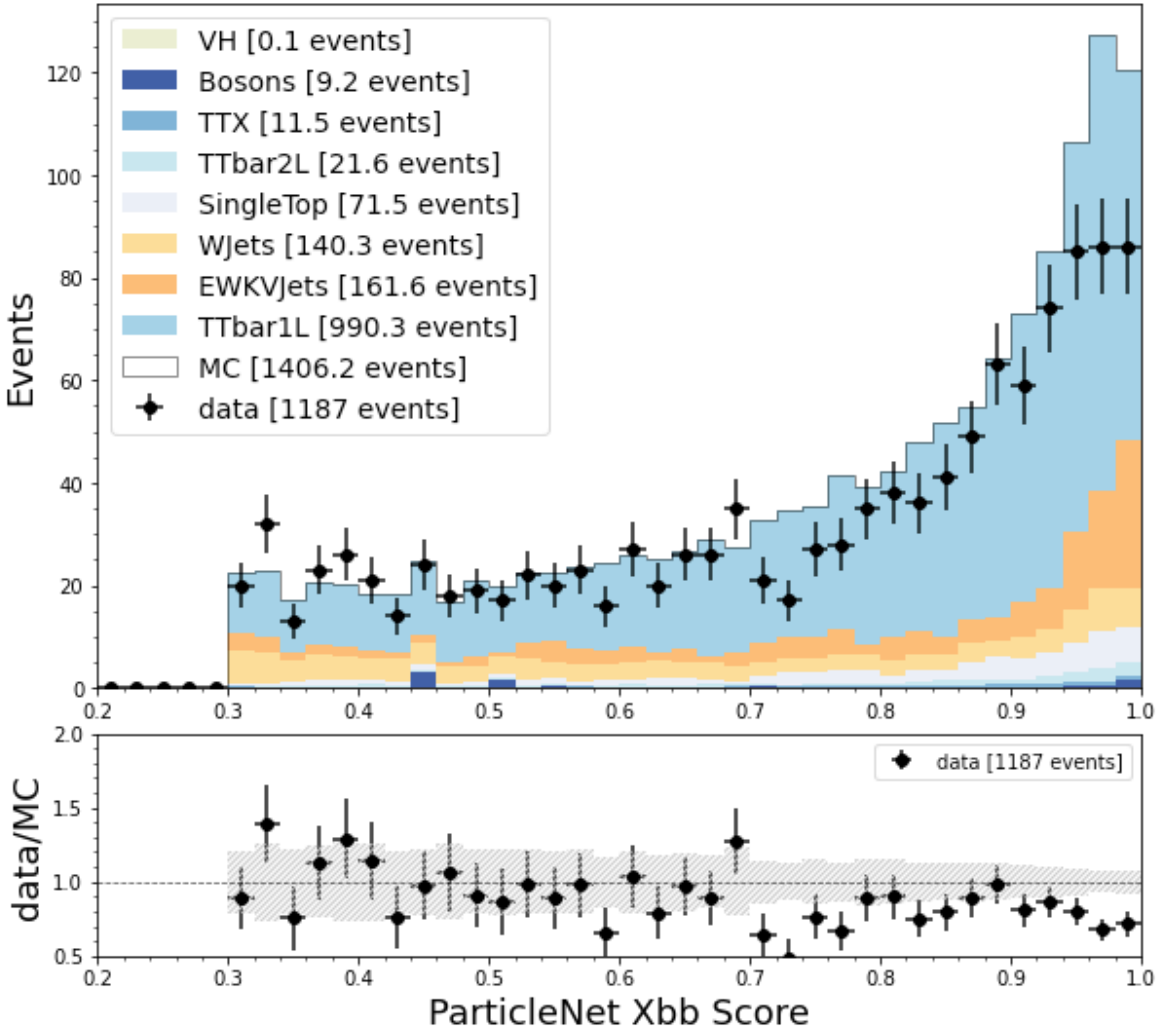
Validation: Hbb

Preselection AND M_{SD} ≥ 150 GeV



Preselection AND M_{SD} ≥ 150 GeV



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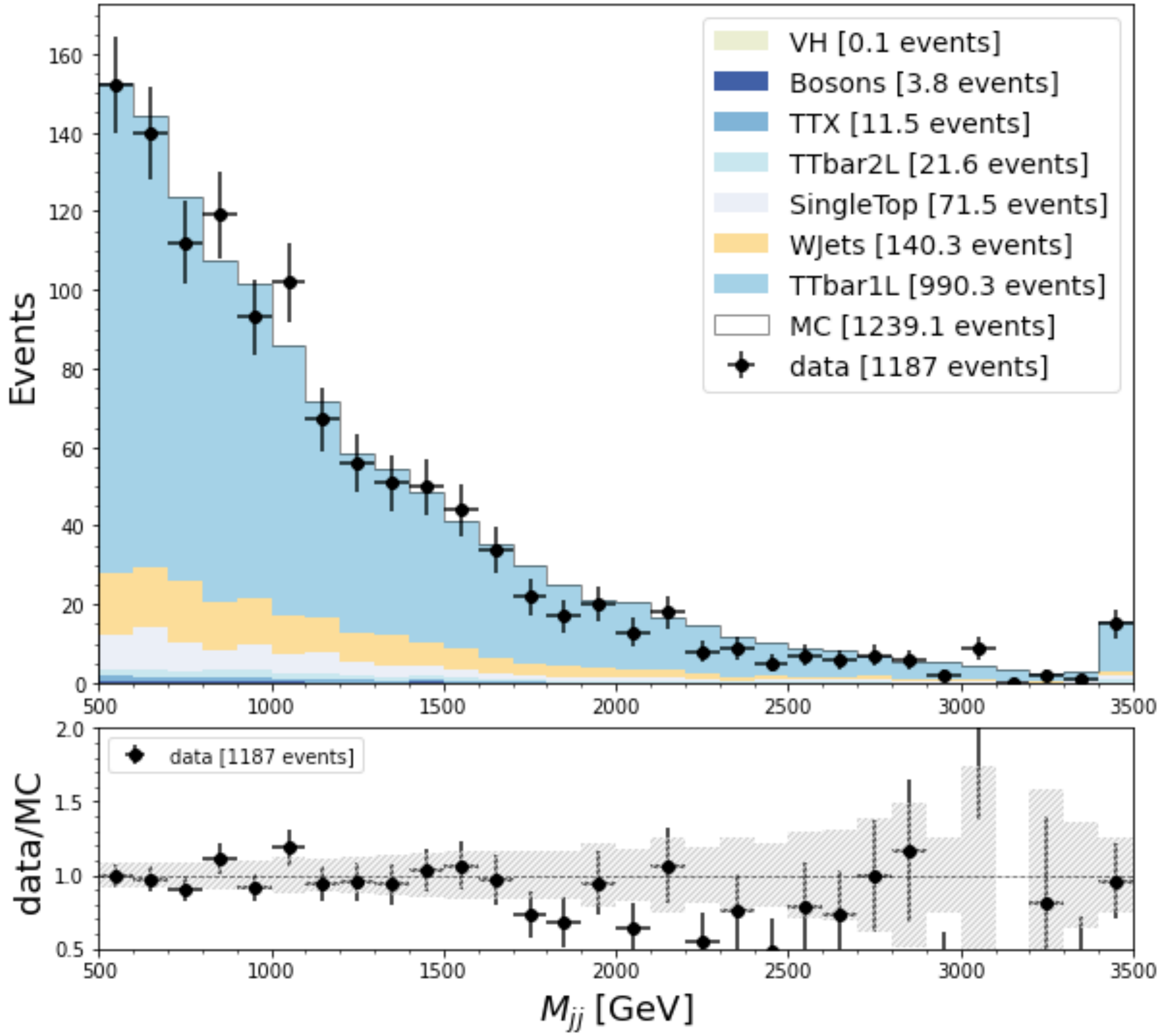
Validation: VBS

Preselection AND $M_{SD} \geq 150$ GeV



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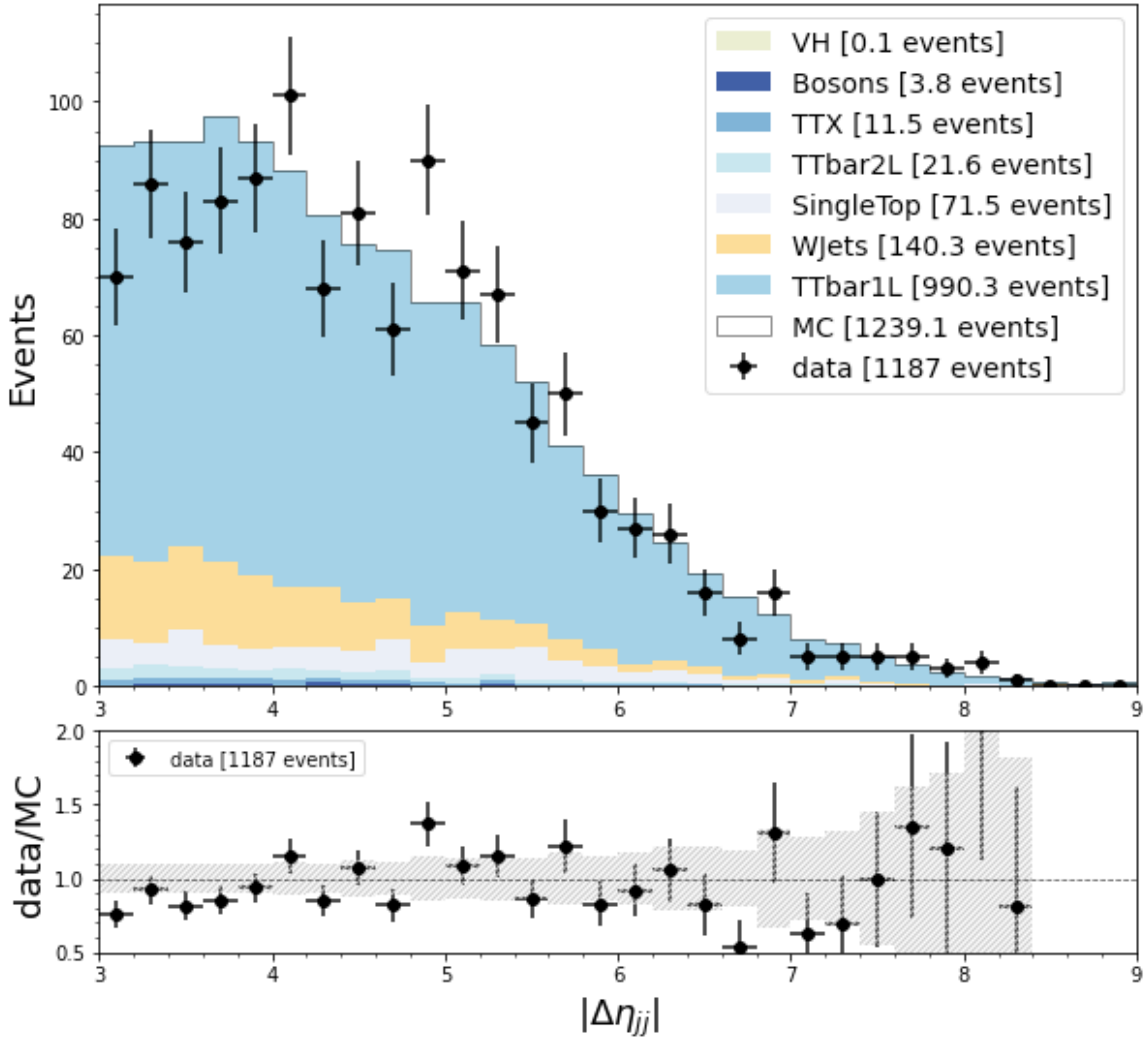

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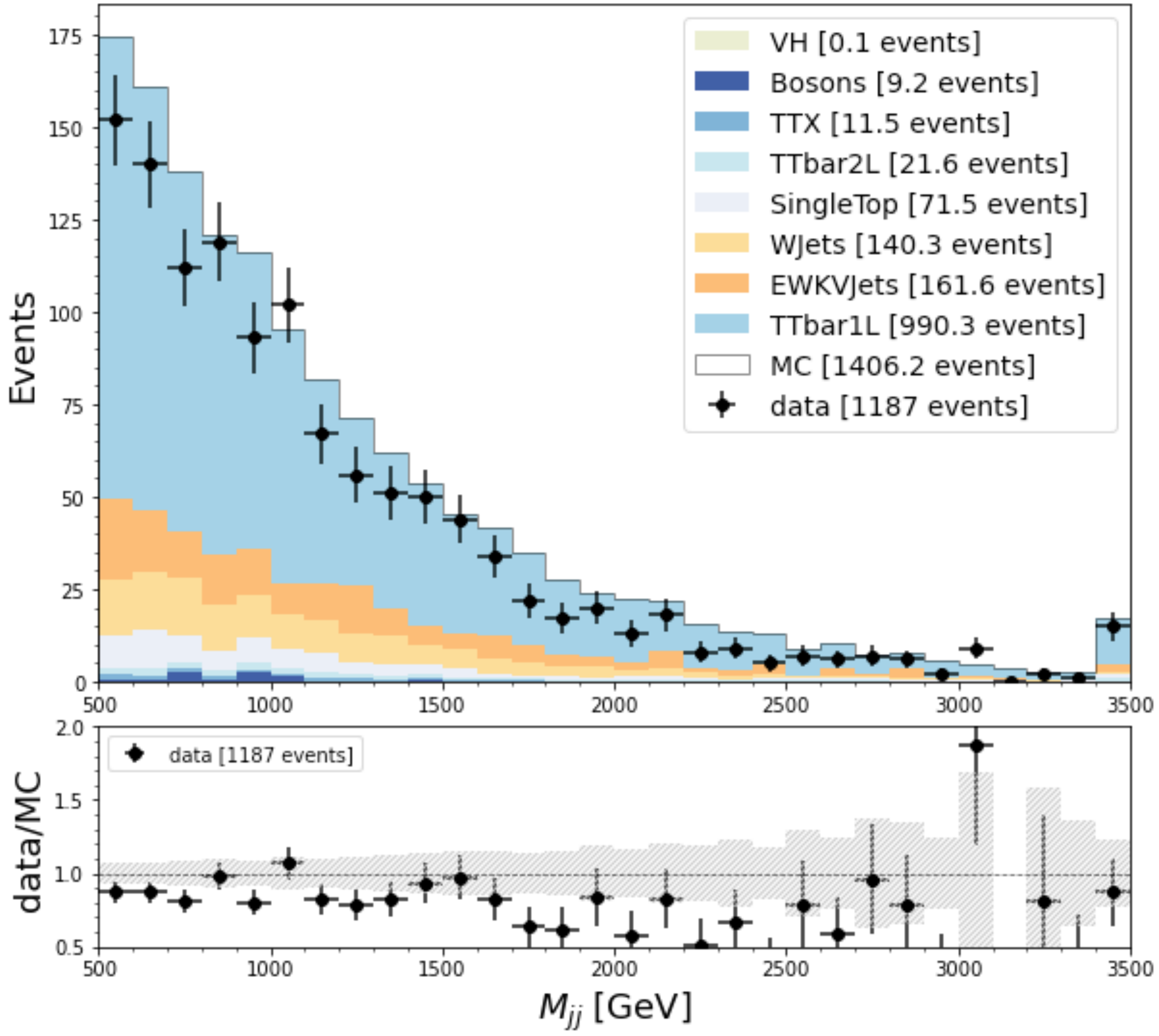
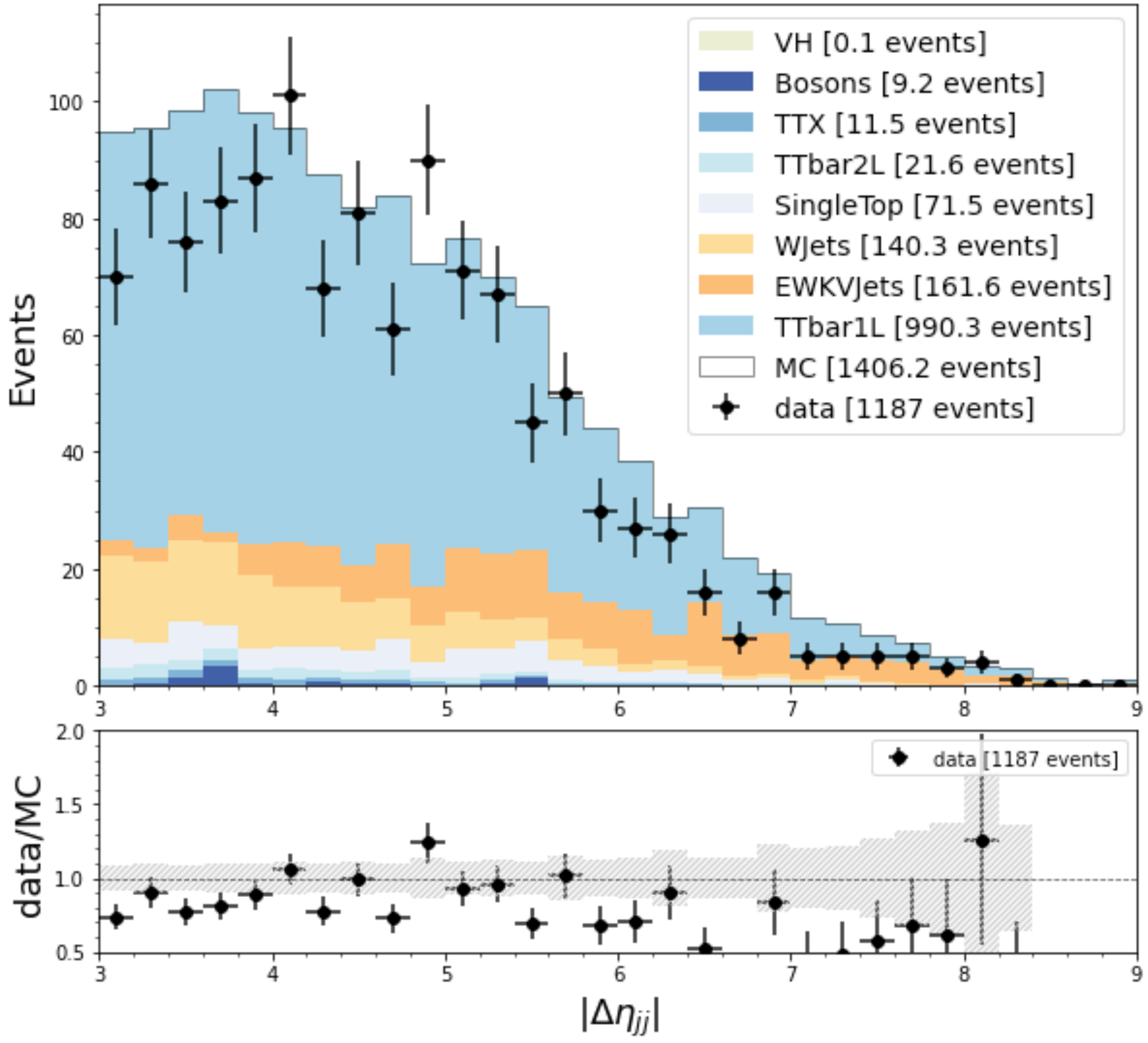


Preselection AND $M_{SD} \geq 150$ GeV



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

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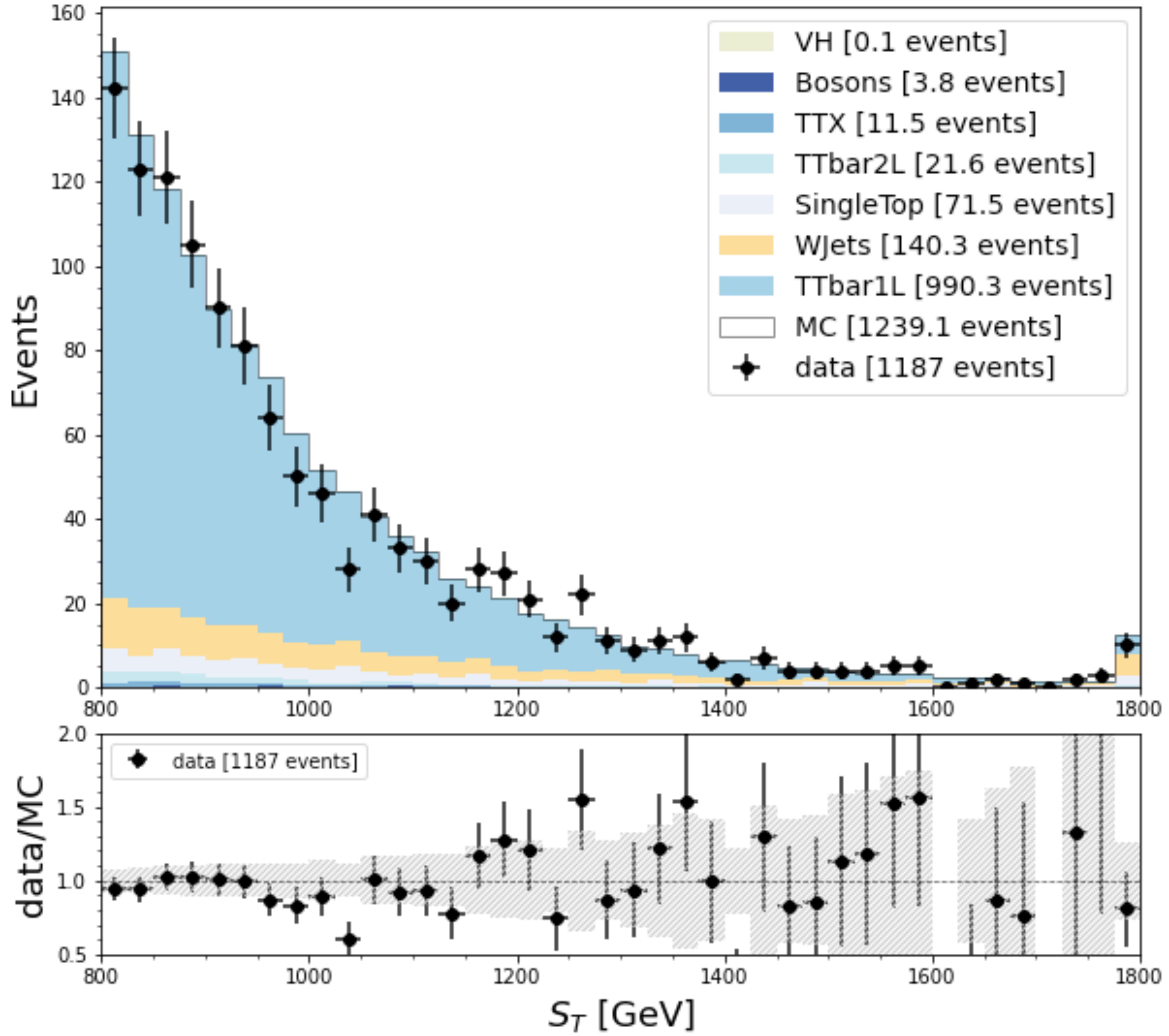
Validation: S_T

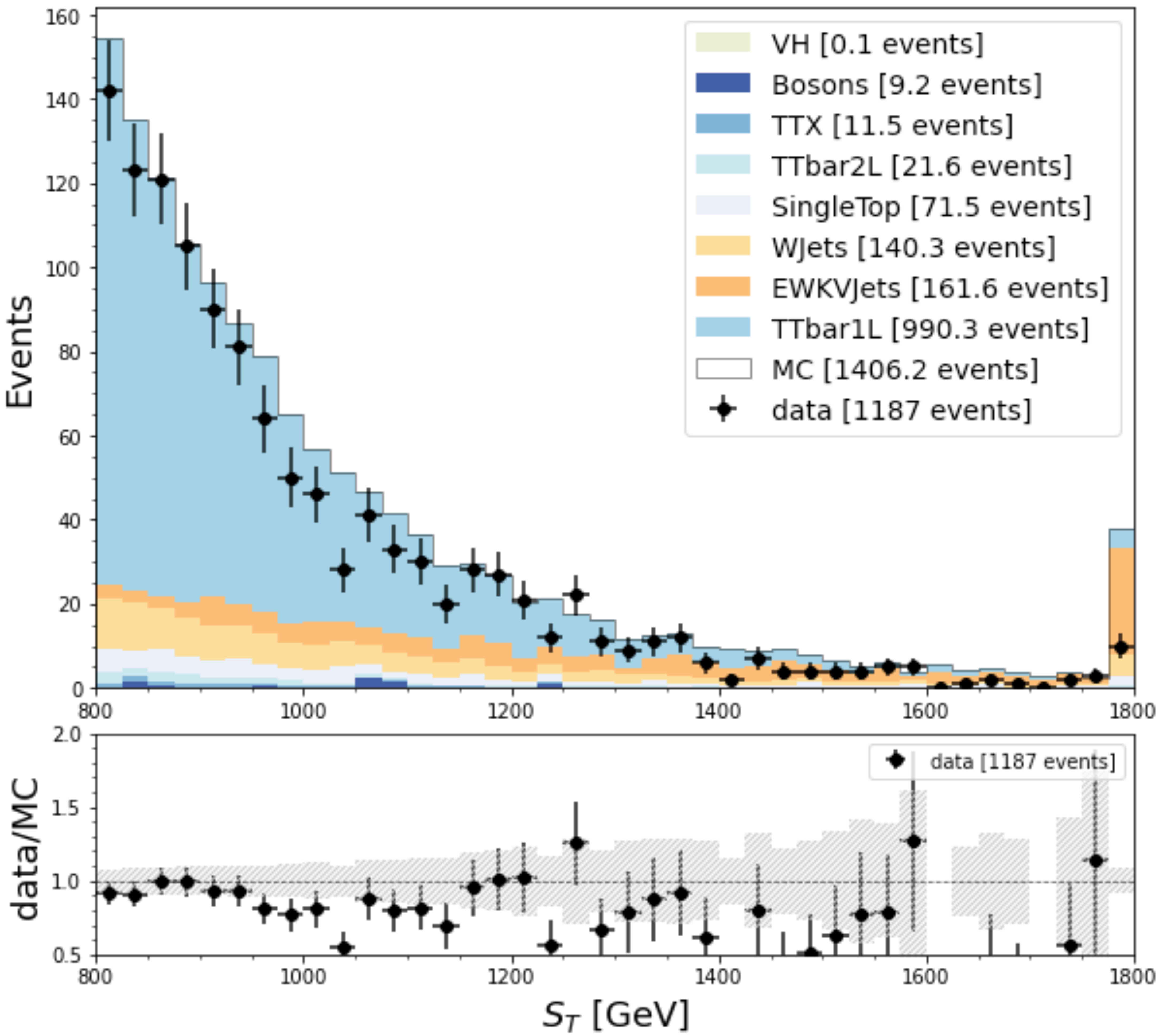
Preselection AND $M_{SD} \geq 150$ GeV



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

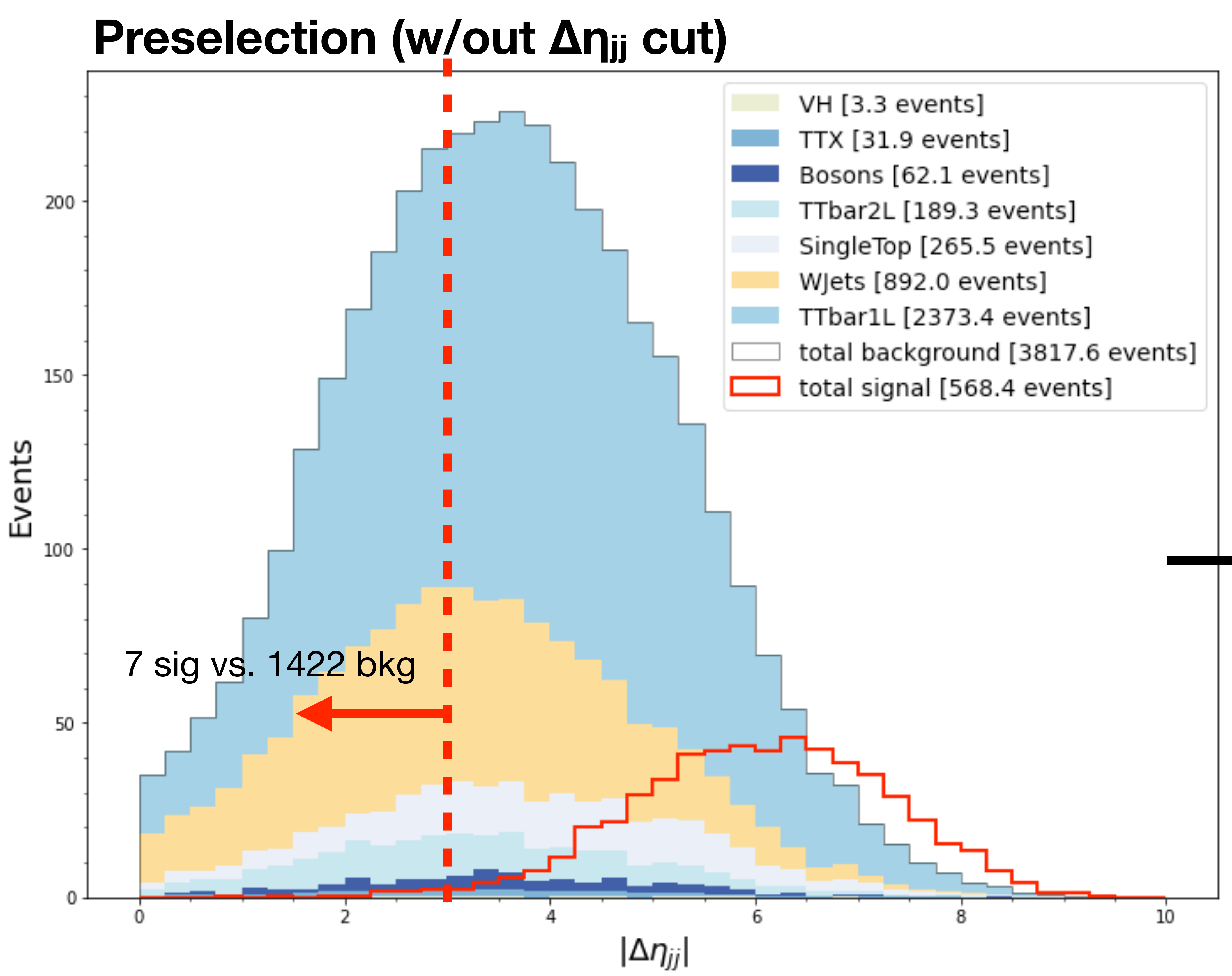
Validation: S_T

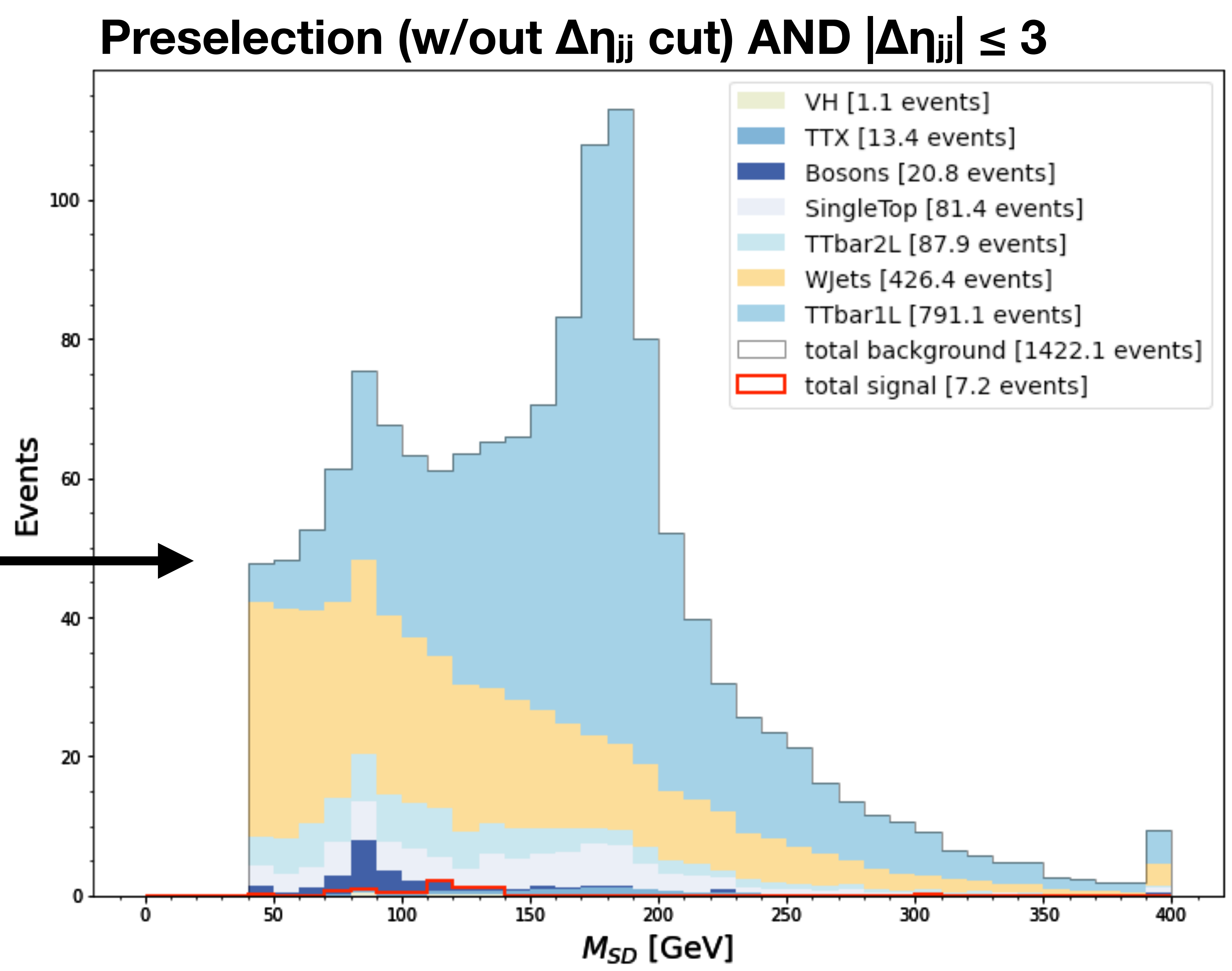
Preselection AND $M_{SD} \geq 150$ GeV



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

Validation: Hbb

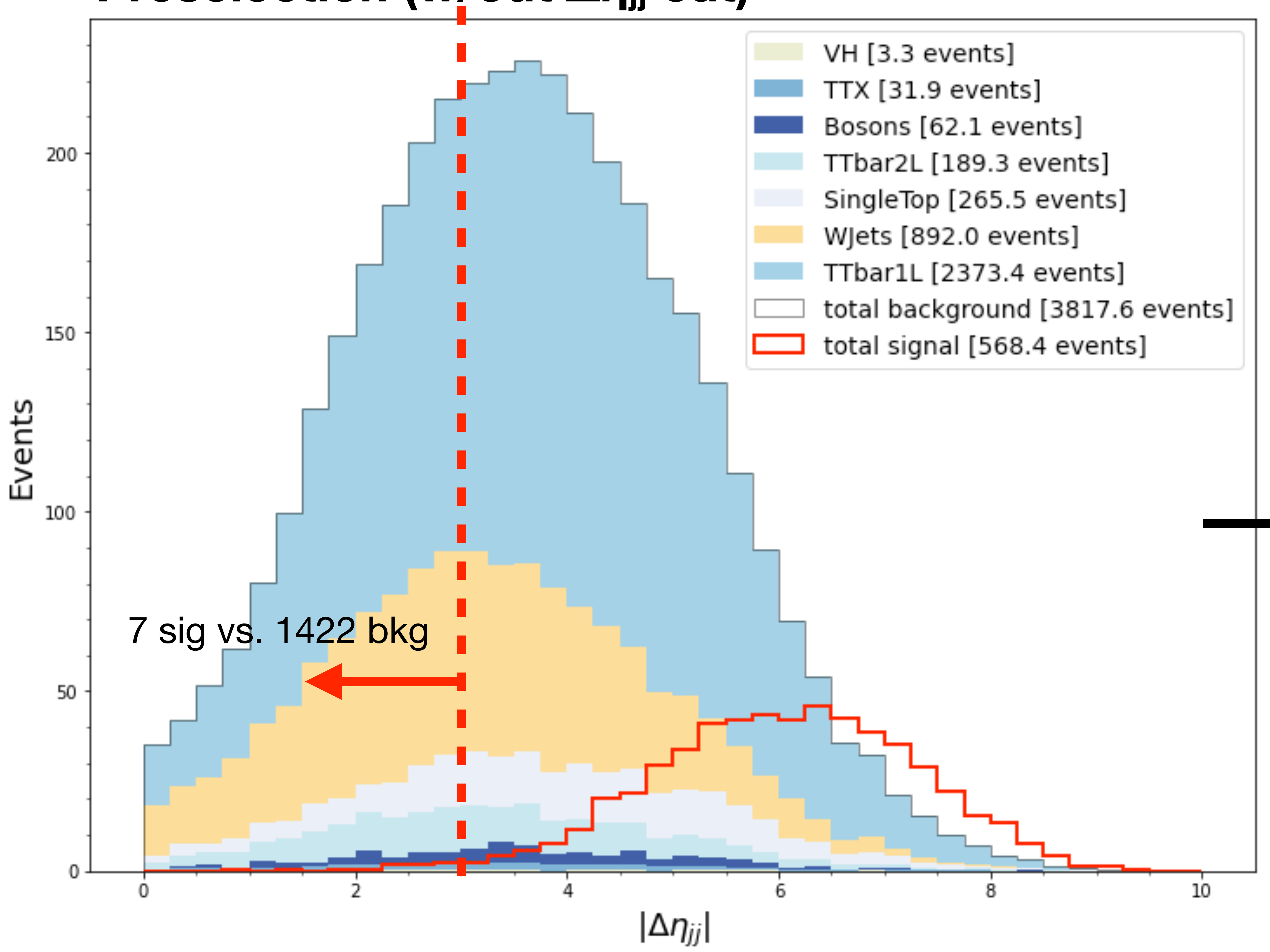




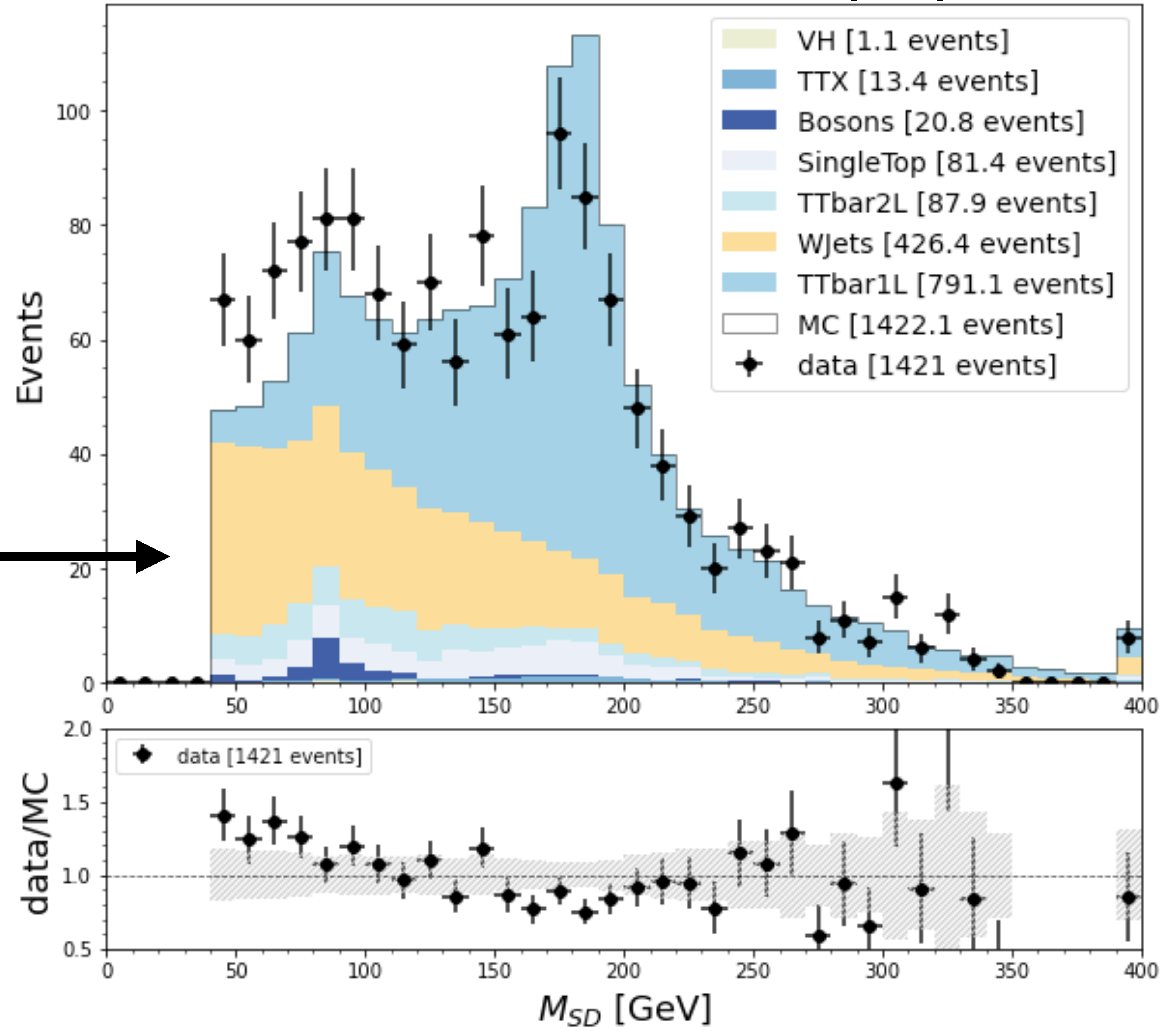
Viable validation region in Δη$_{jj}$ sideband!

Validation: Hbb

Preselection (w/out $\Delta\eta_{jj}$ cut)



Preselection (w/out $\Delta\eta_{jj}$ cut) AND $|\Delta\eta_{jj}| \leq 3$



Agreement within 50%

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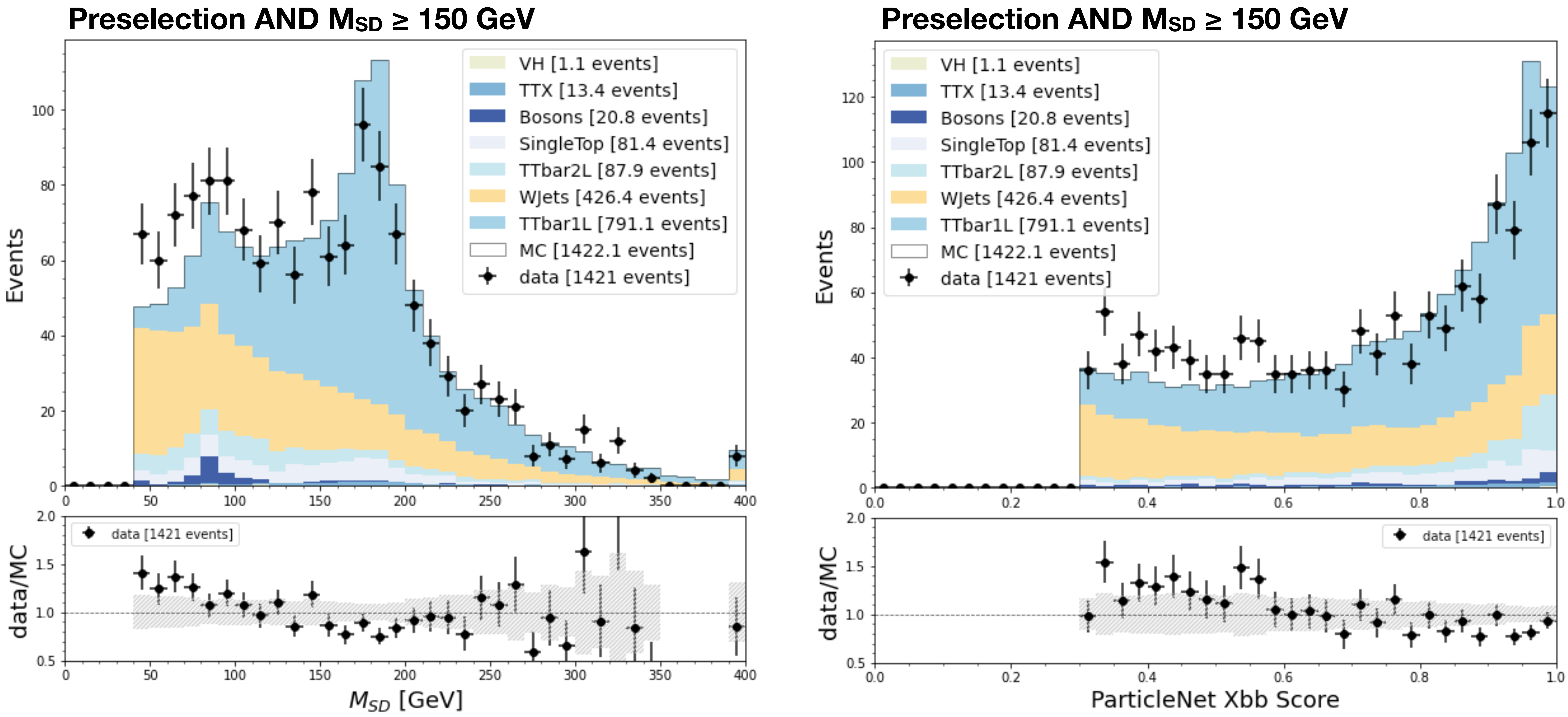
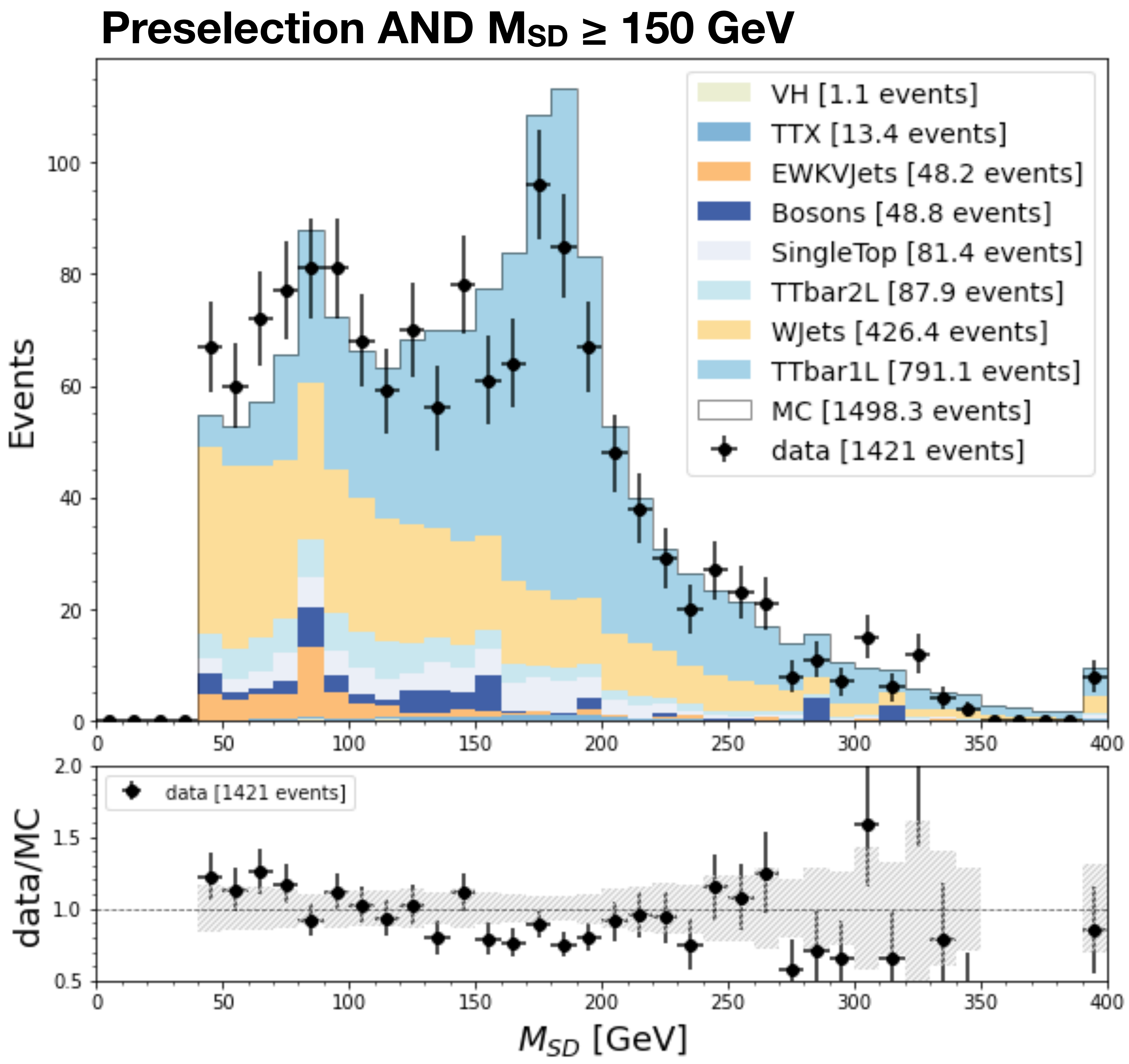
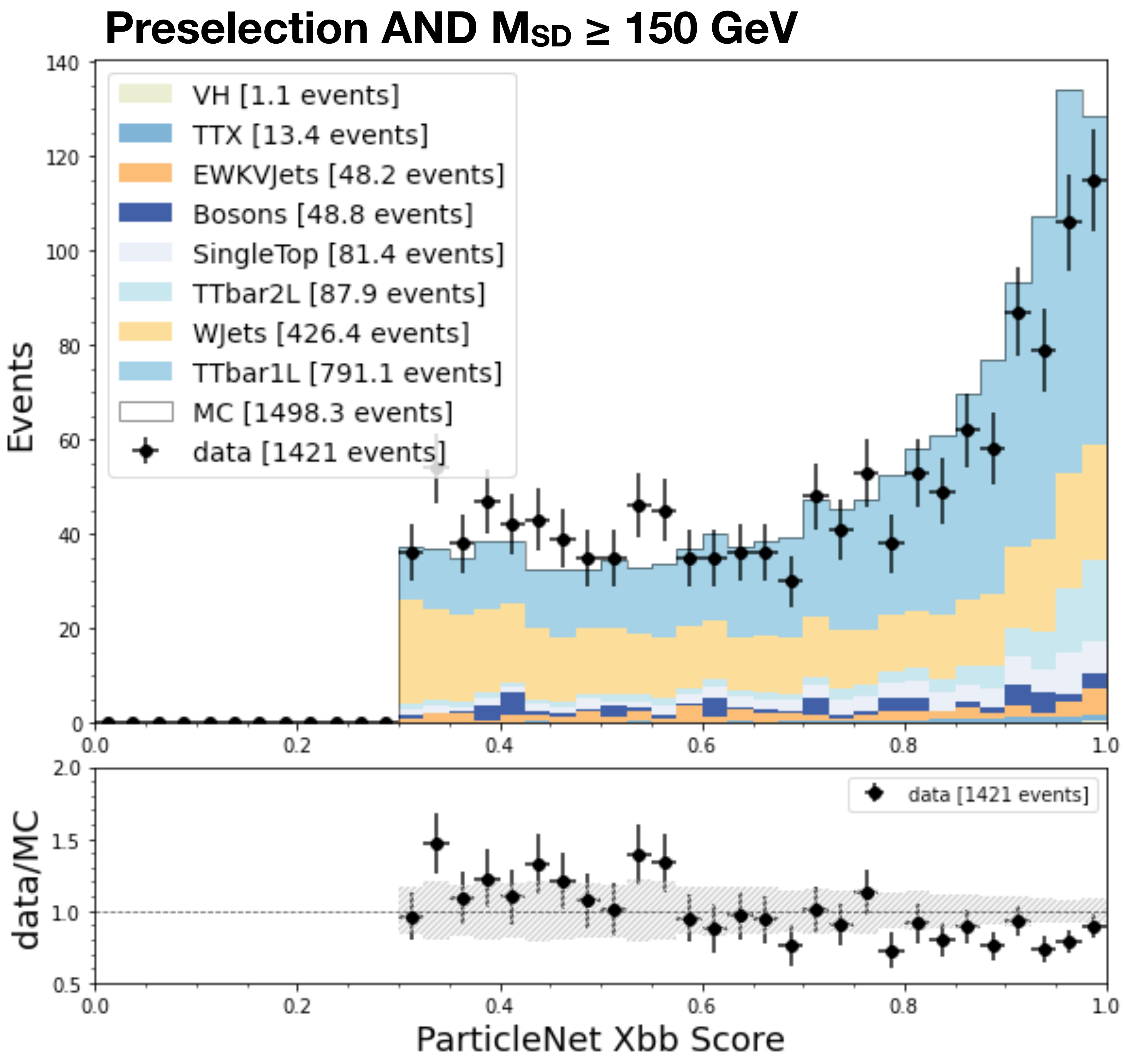
Validation: Hbb



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

Validation: Hbb





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

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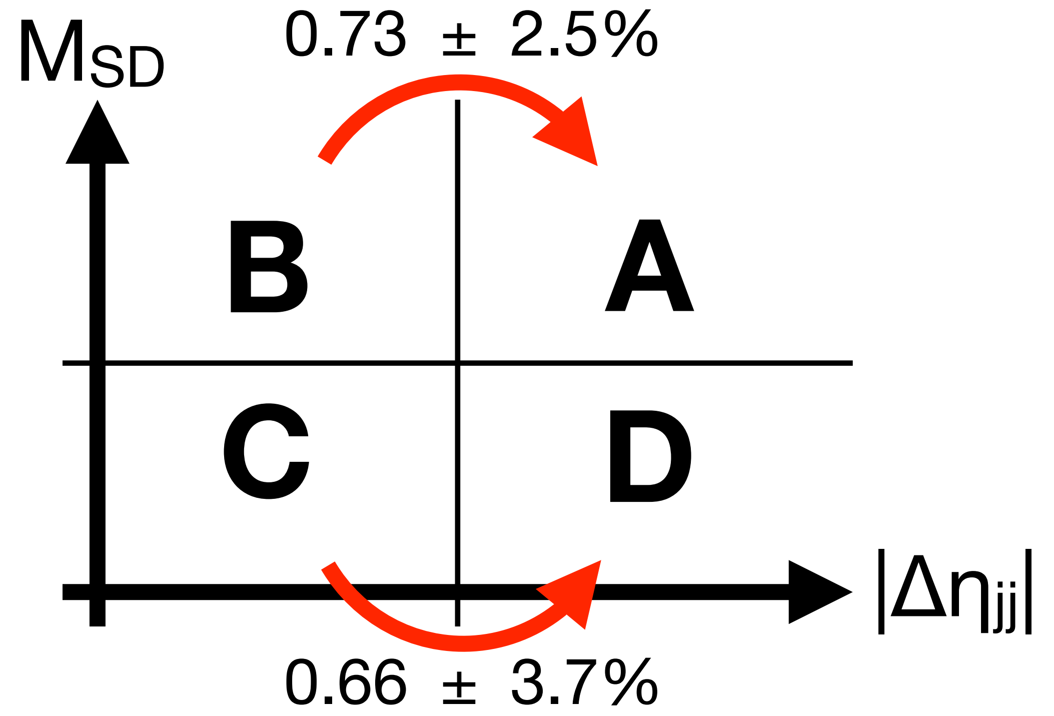
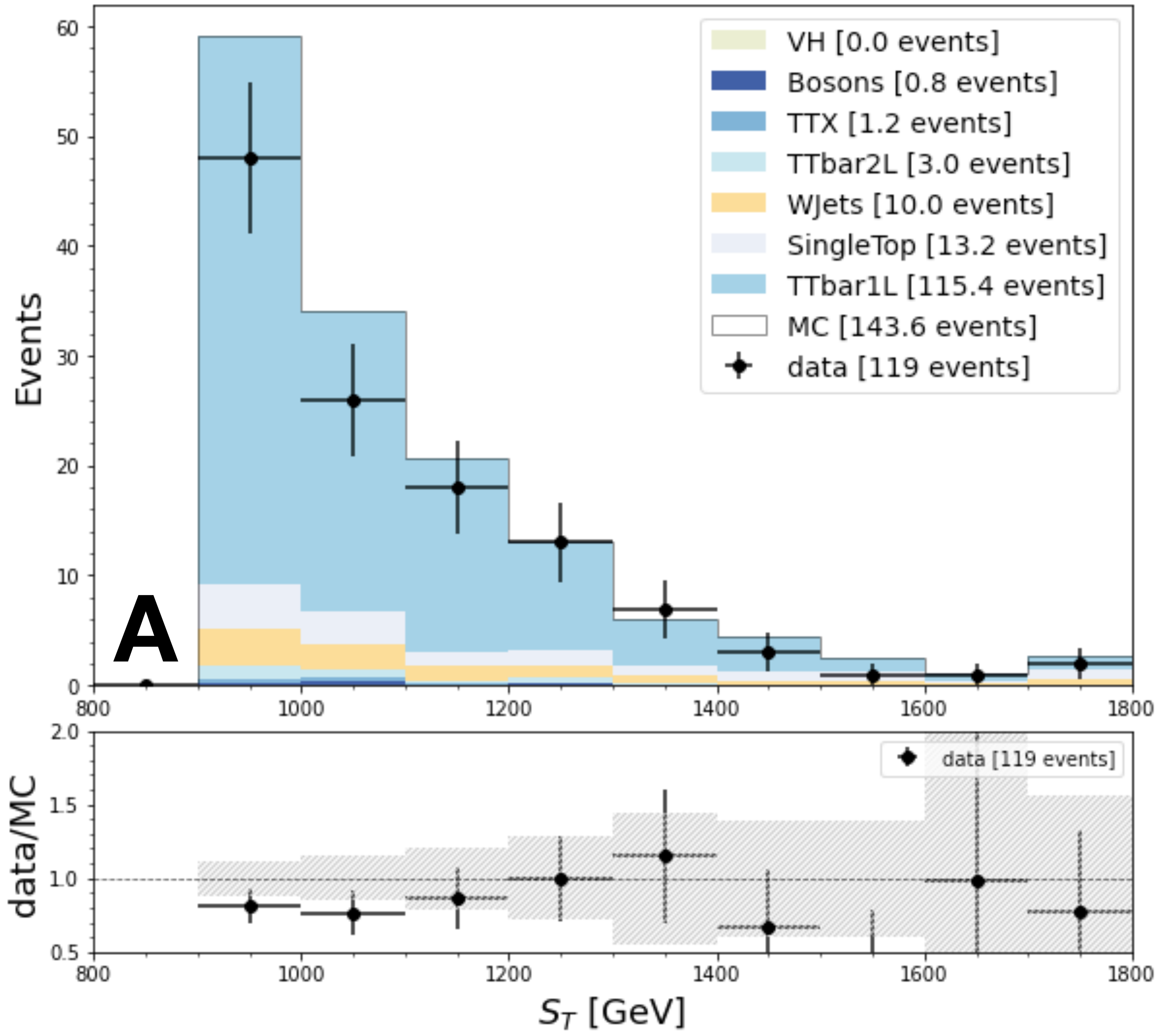
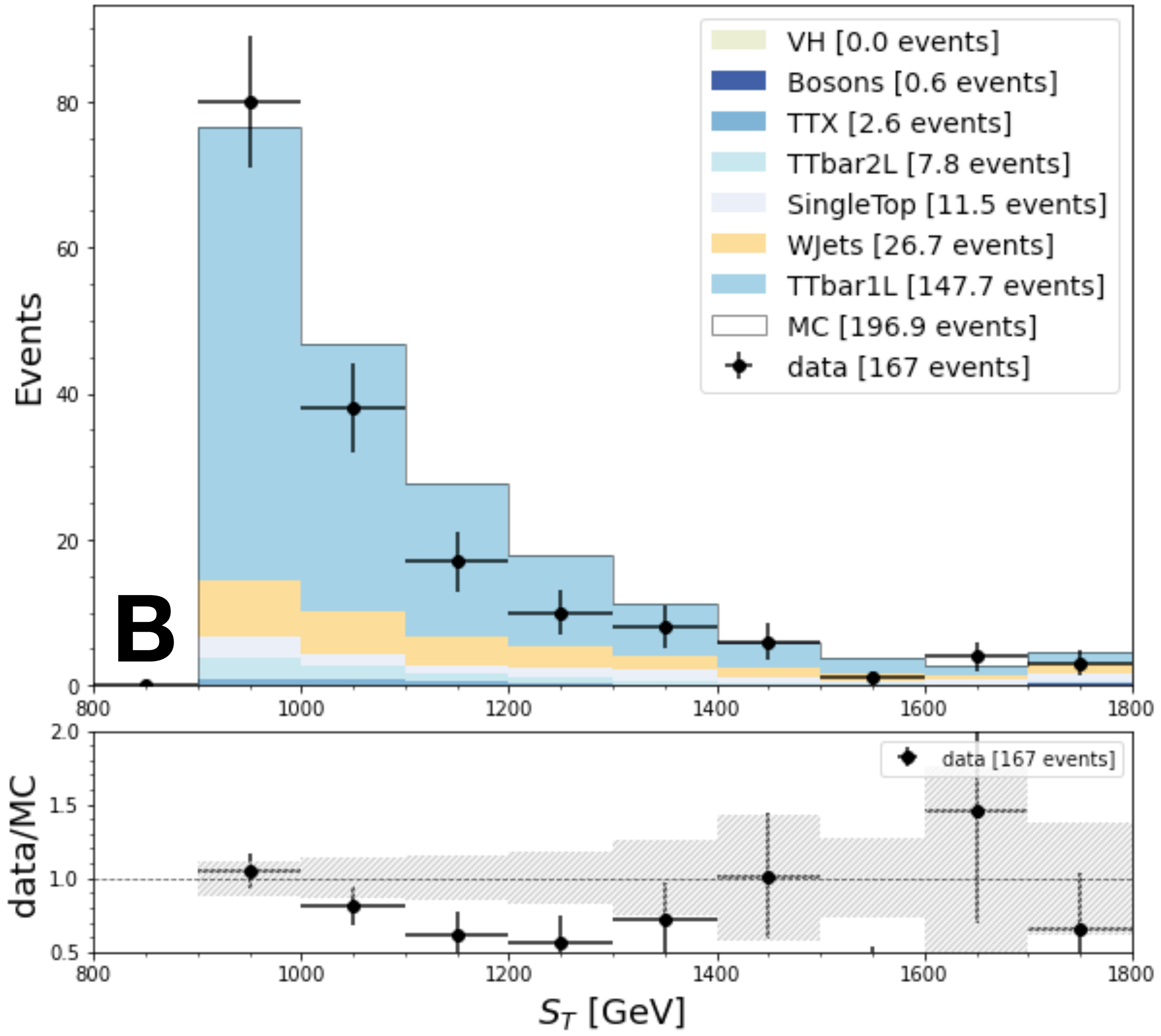
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

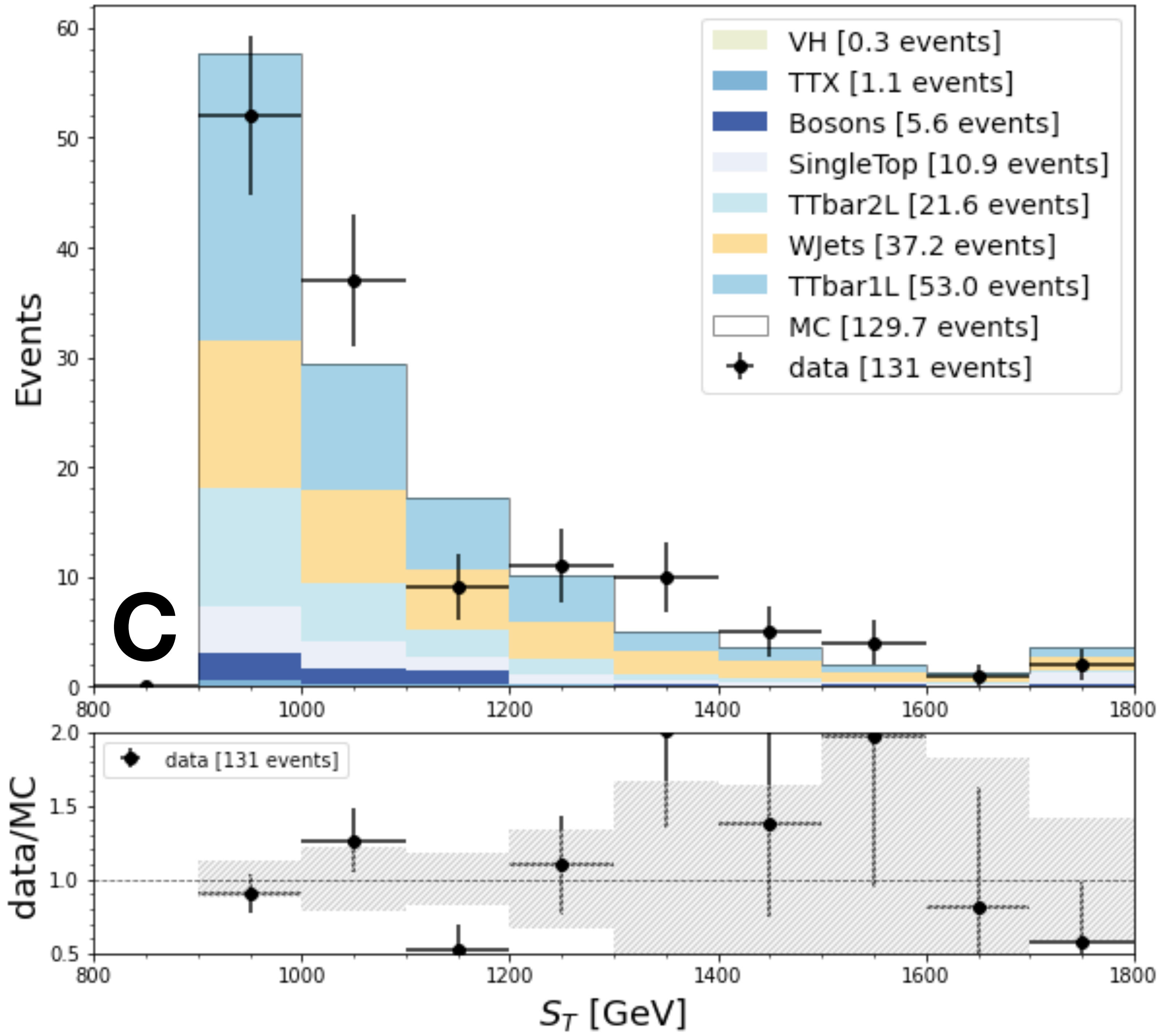
Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} ≥ 150 GeV	A	143.62	2.88	8.08	1.16	119	10.91
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	196.94	3.08	0.93	0.45	167	12.92
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} < 150 GeV	C	129.68	2.67	12.10	1.44	131	11.45
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	85.42	2.58	336.33	7.79	—	—







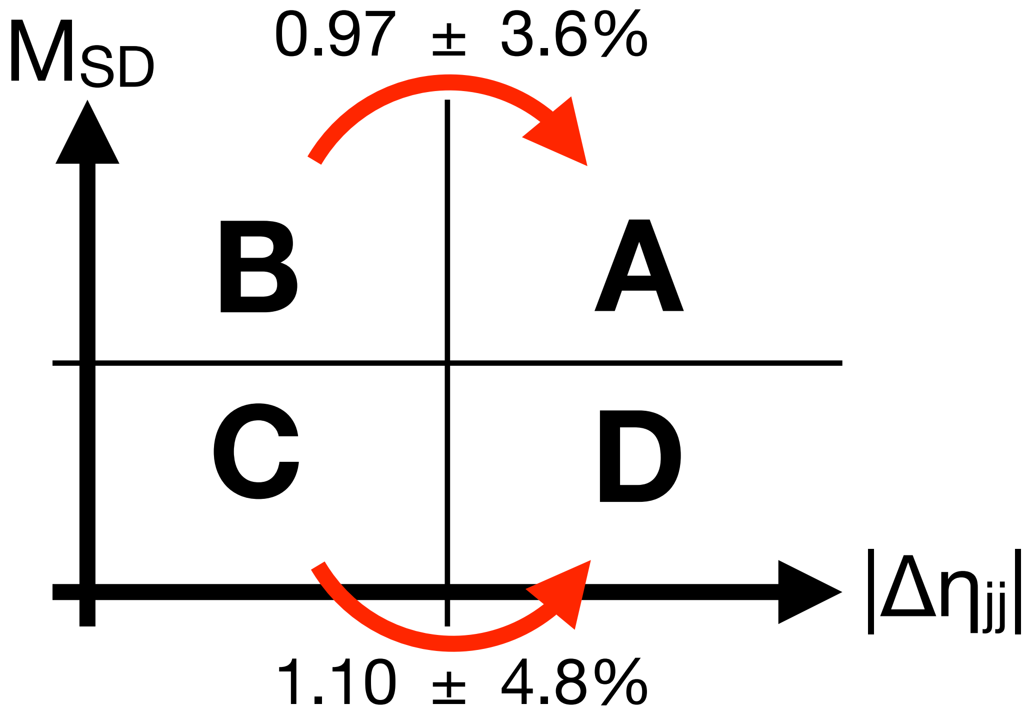


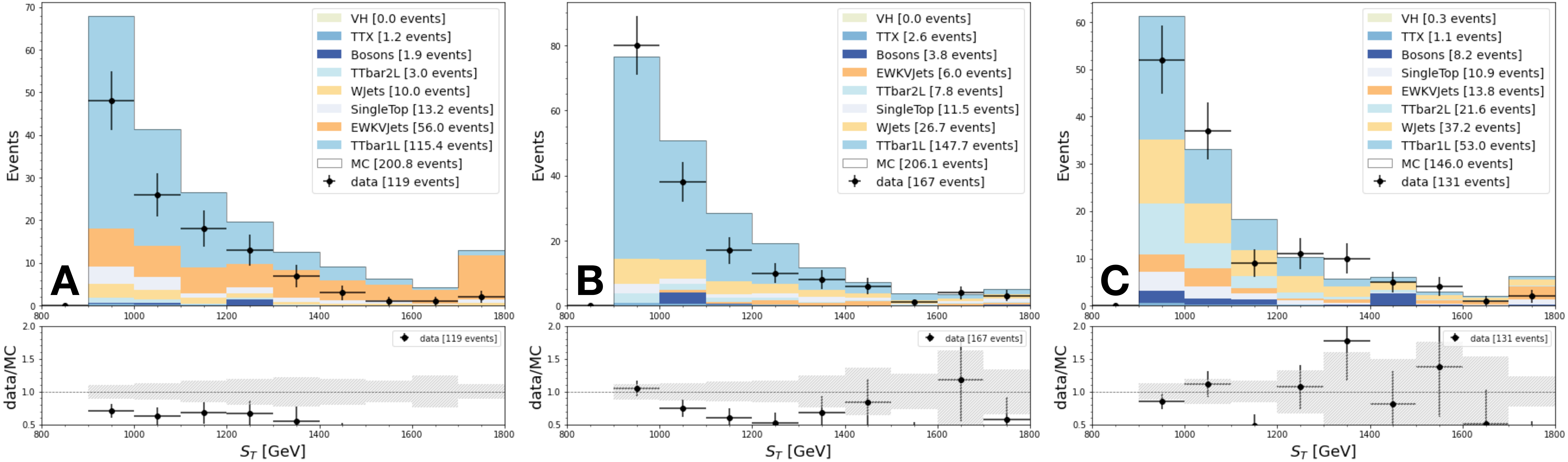
*err = $\sqrt{\Sigma_i w_i^2}$ for MC, $\sqrt{\text{count}}$ for data

SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\|\Delta\eta_{jj}\| > 4$ AND $M_{SD} \geq 150$ GeV	A	200.78	5.71	8.08	1.16	119	10.91
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} \geq 150$ GeV	B	206.14	4.70	0.93	0.45	167	12.92
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} < 150$ GeV	C	146.01	4.39	12.10	1.44	131	11.45
$\|\Delta\eta_{jj}\| > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	161.04	6.10	336.33	7.79	—	—





*err = $\sqrt{\Sigma_i w_i^2}$ for MC, $\sqrt{\text{count}}$ for data

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SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

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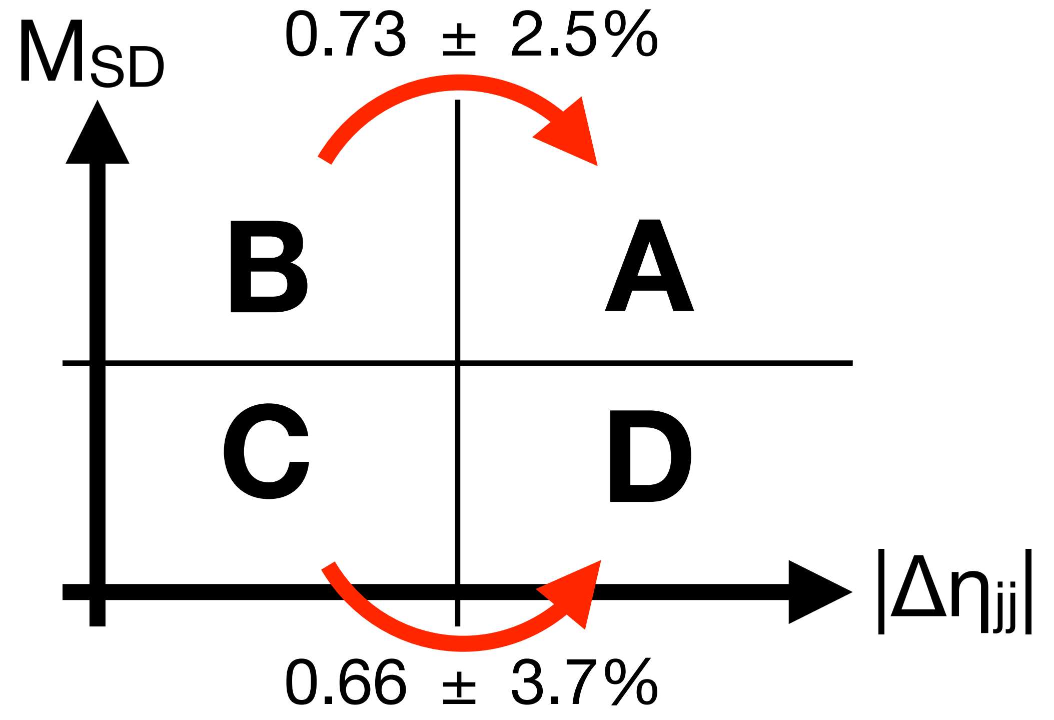

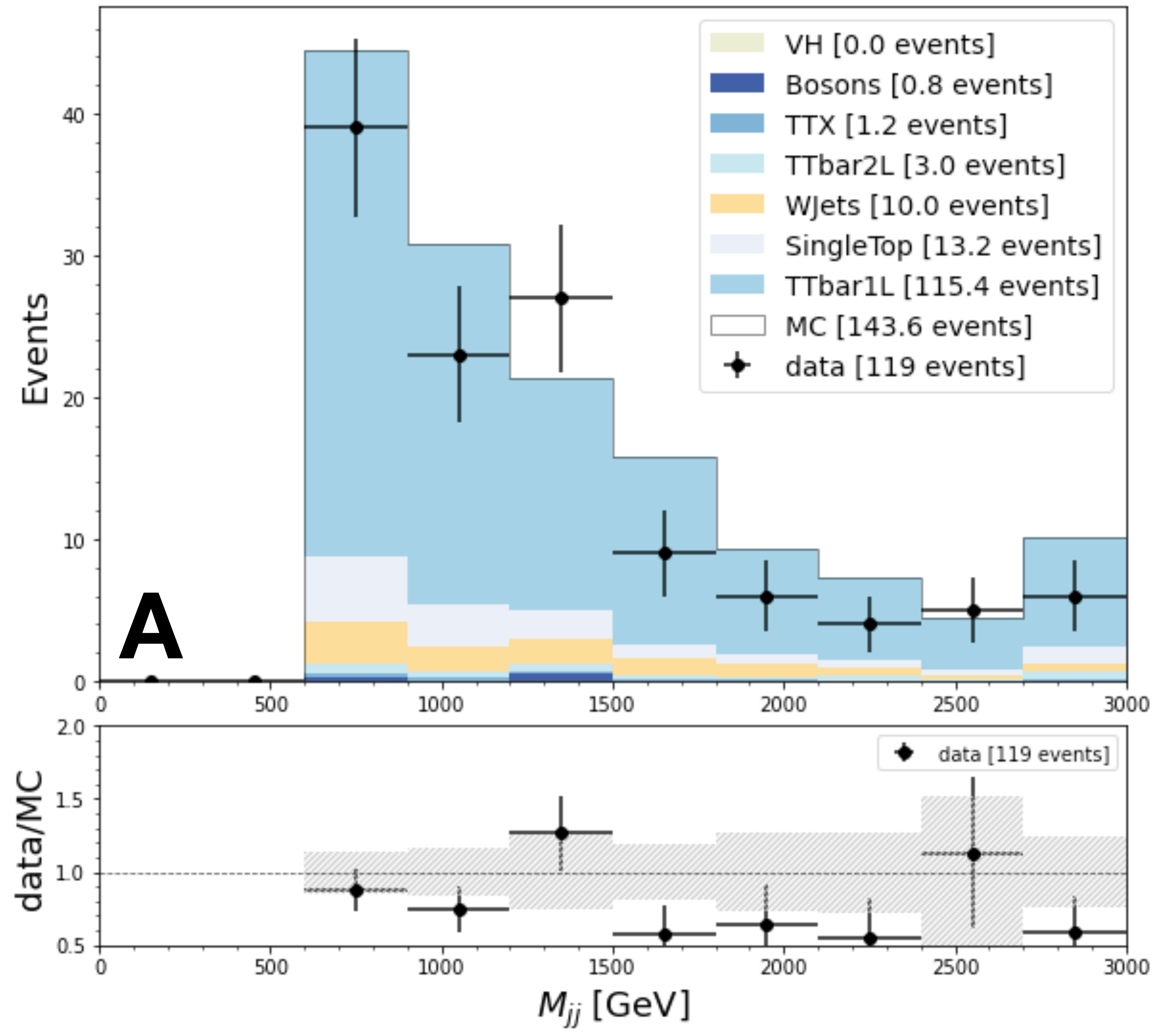

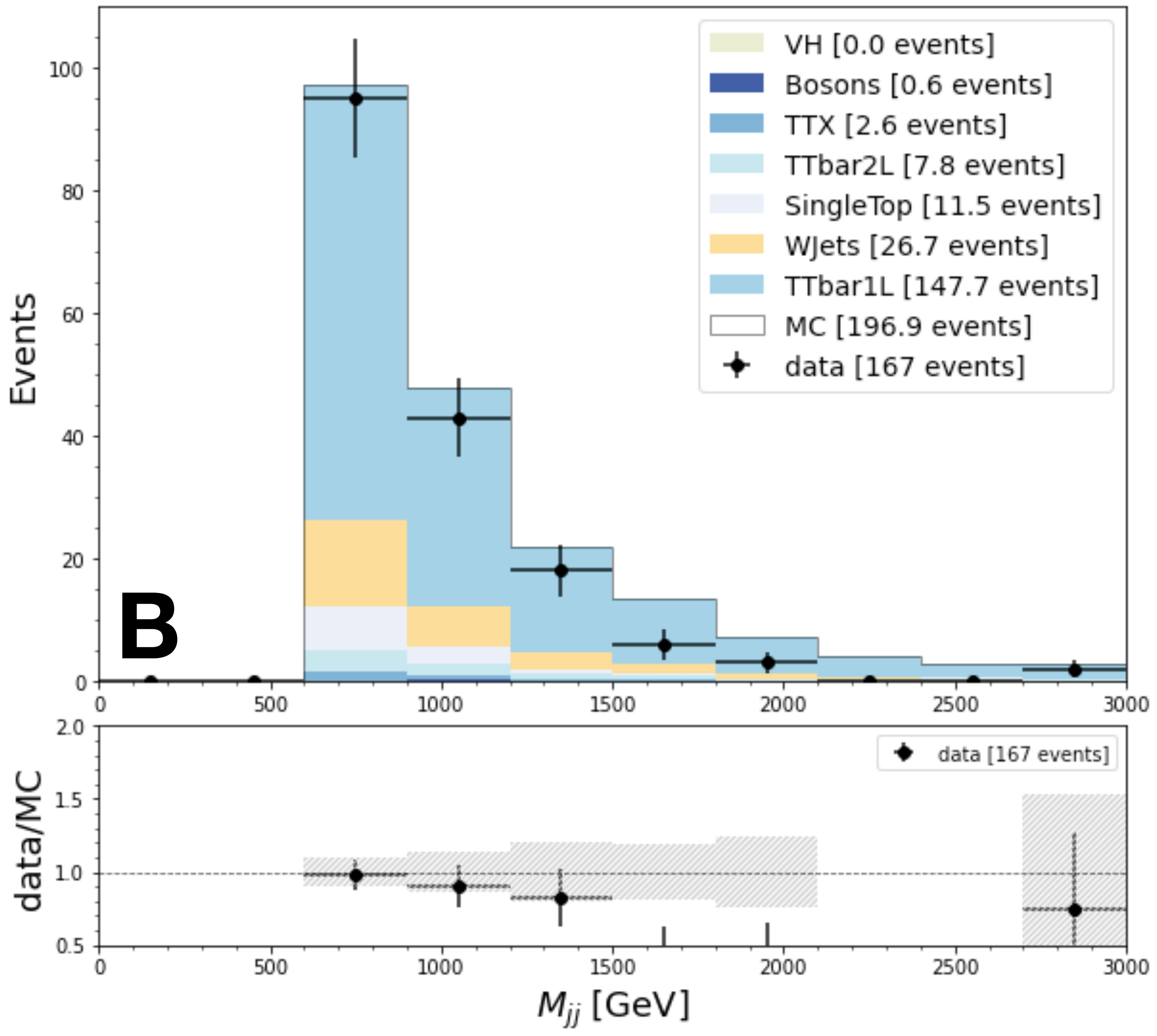

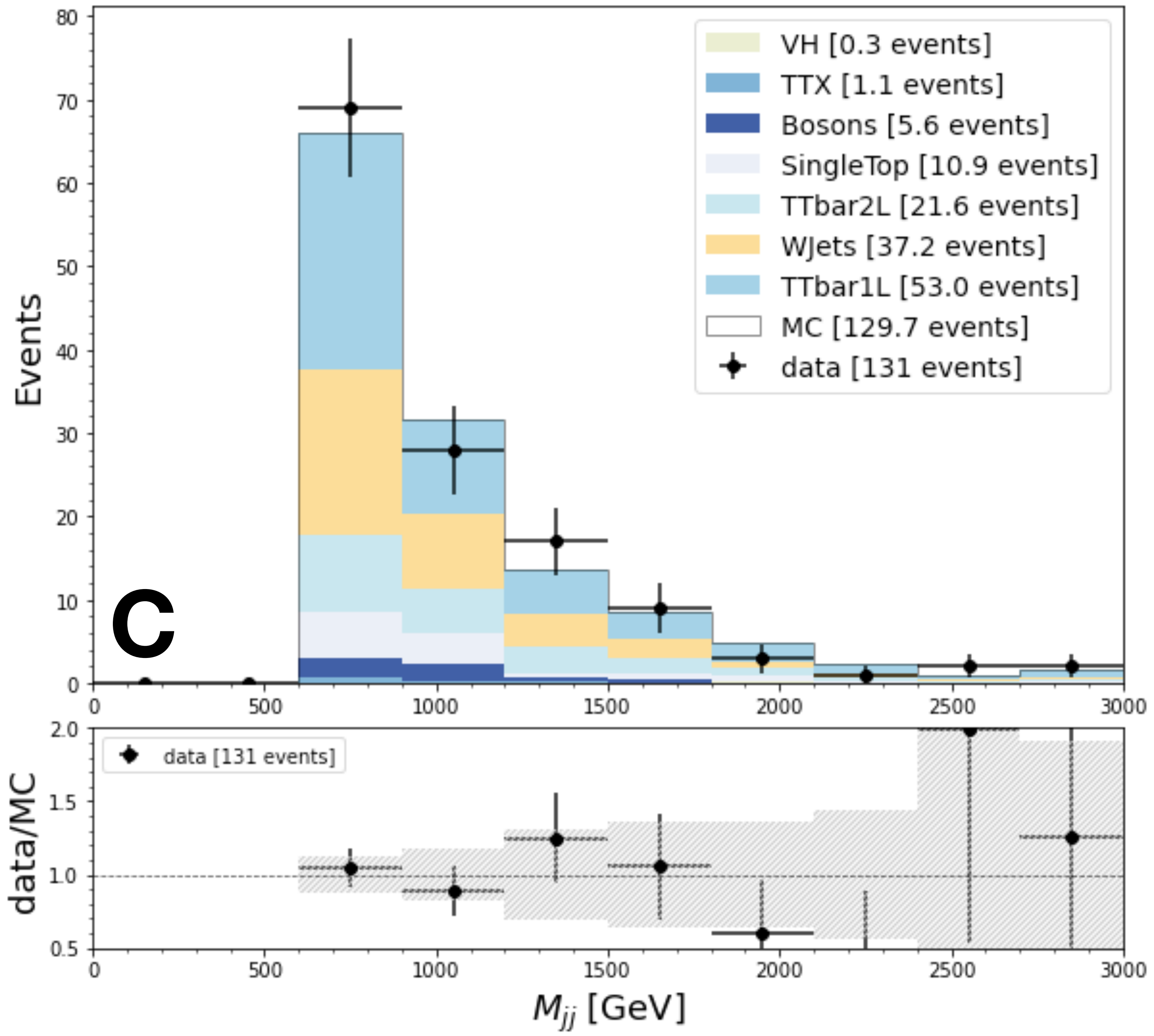

*err = $\sqrt{\Sigma_i w_i^2}$ for MC, $\sqrt{\text{count}}$ for data

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SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
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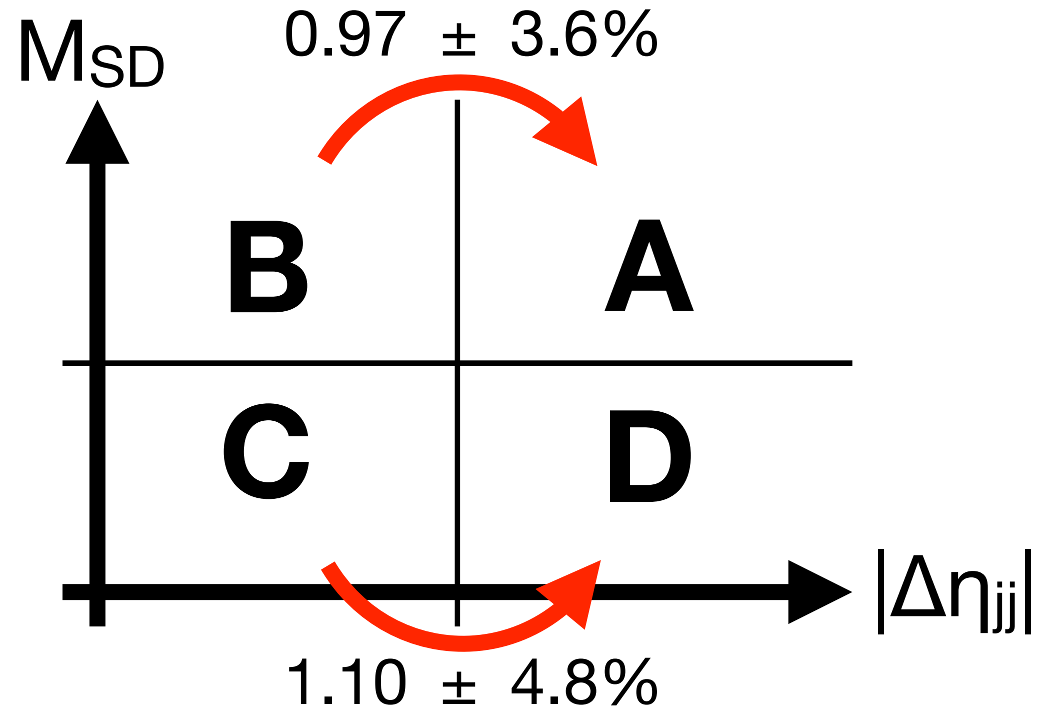

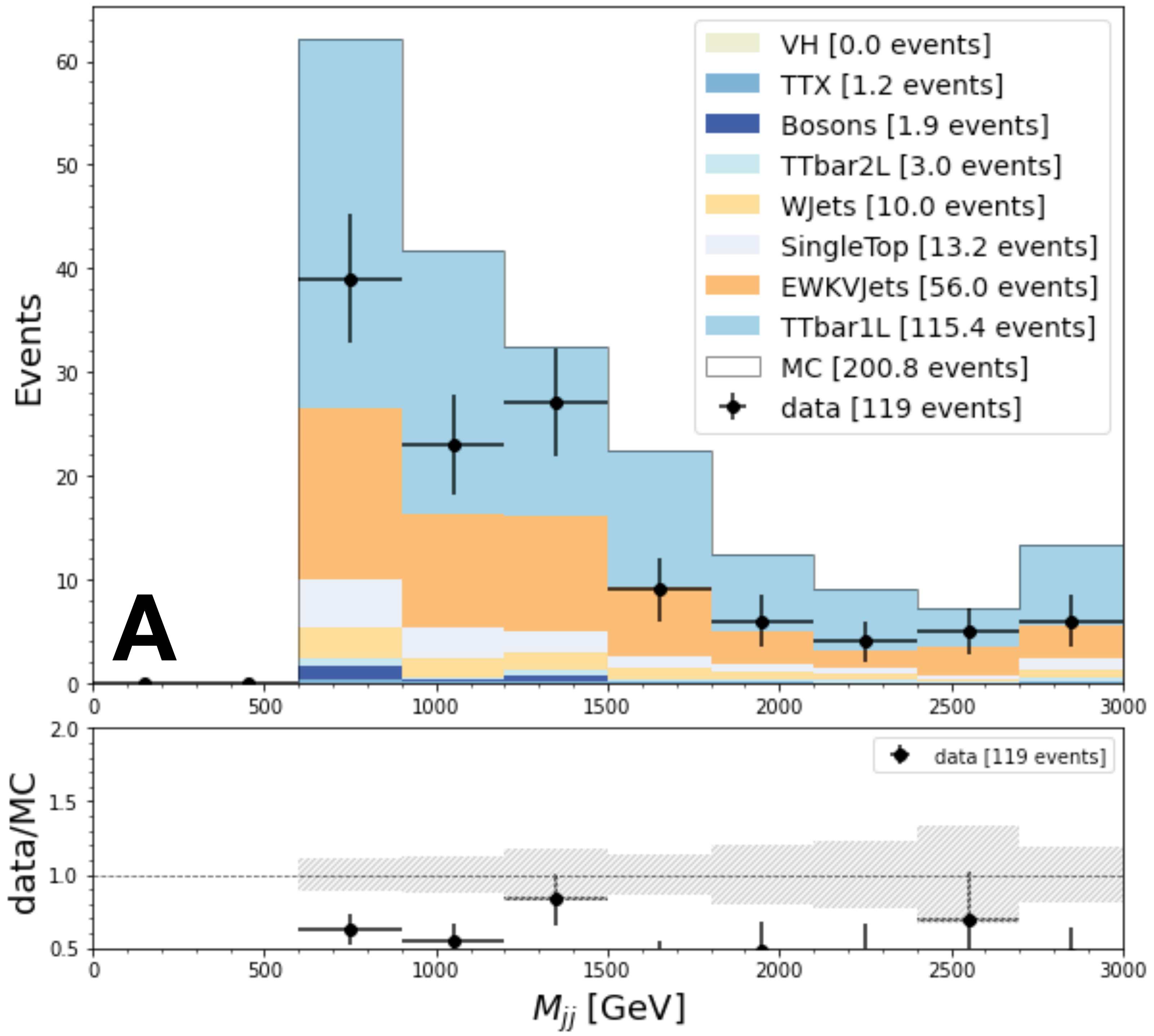

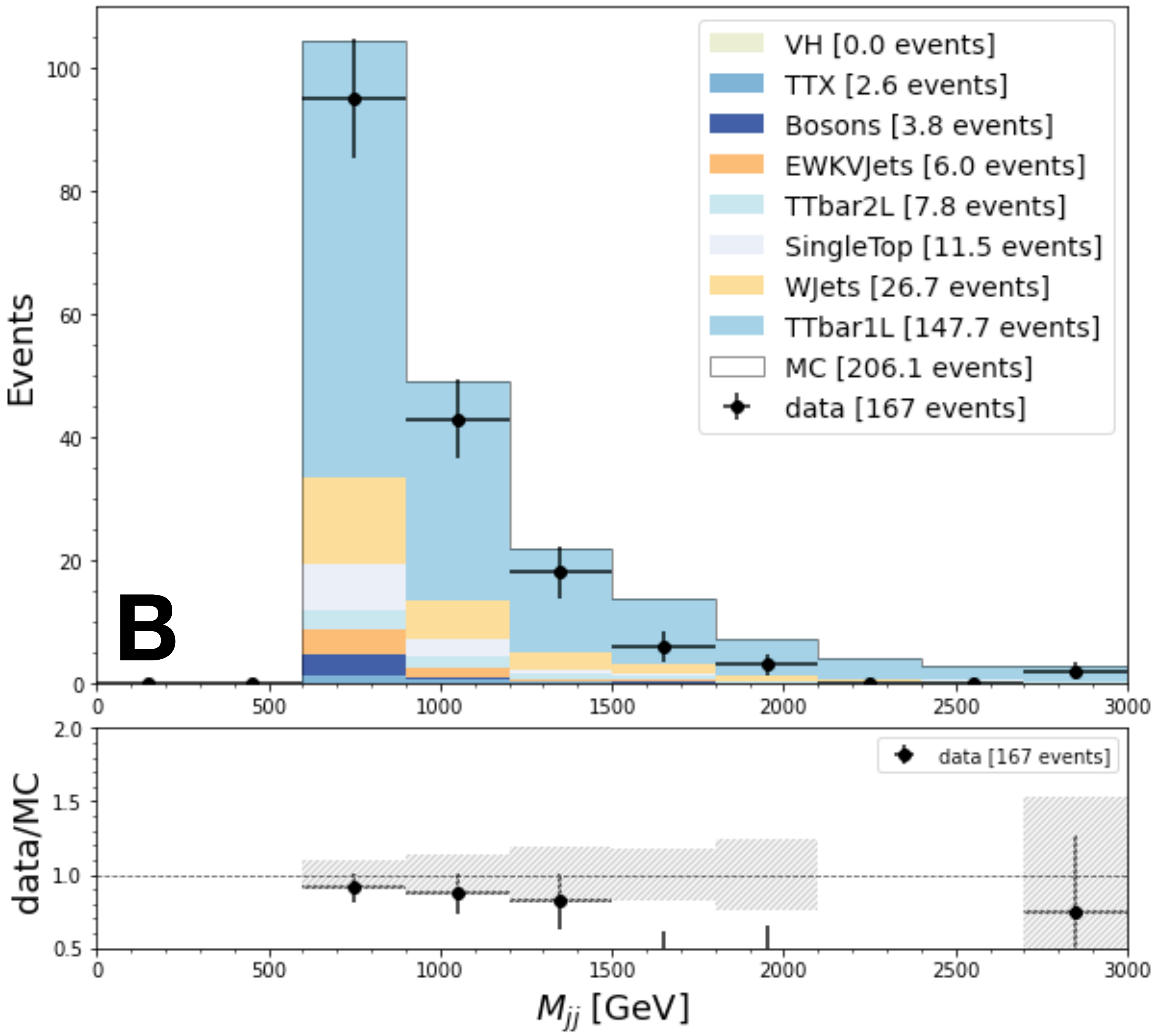

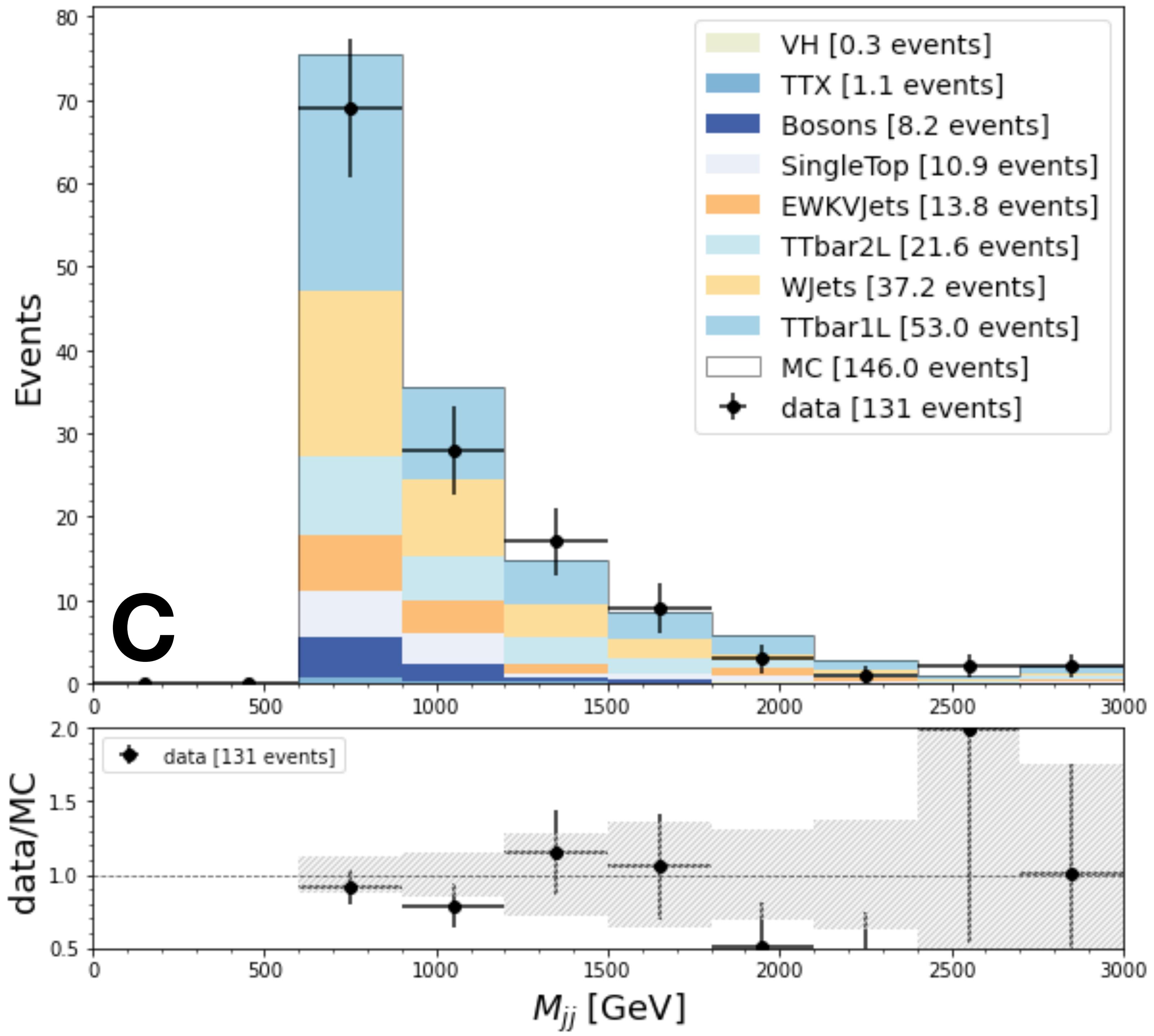

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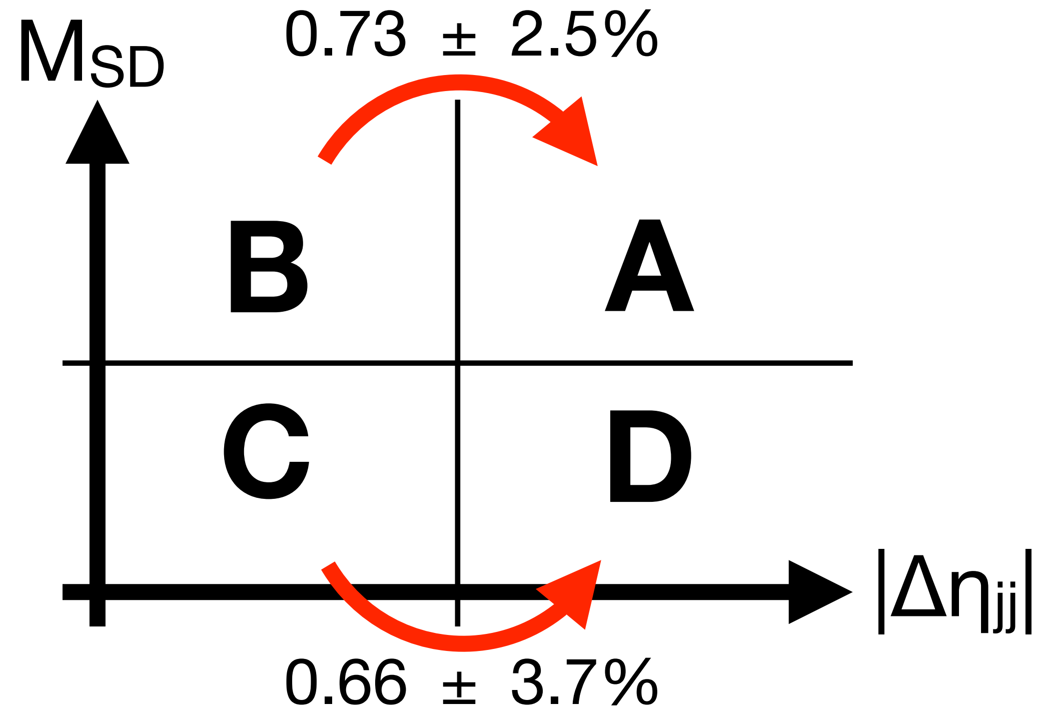

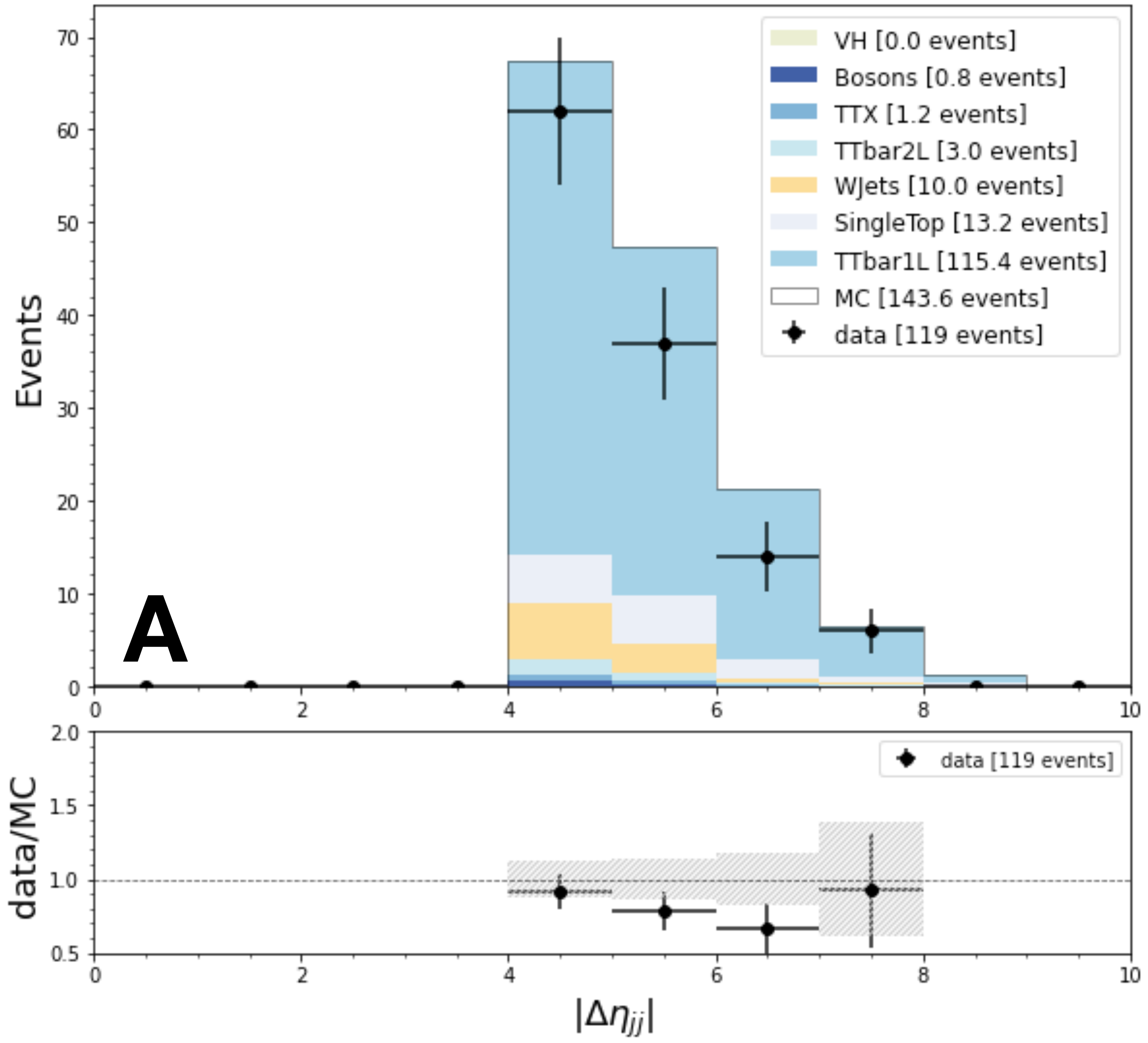

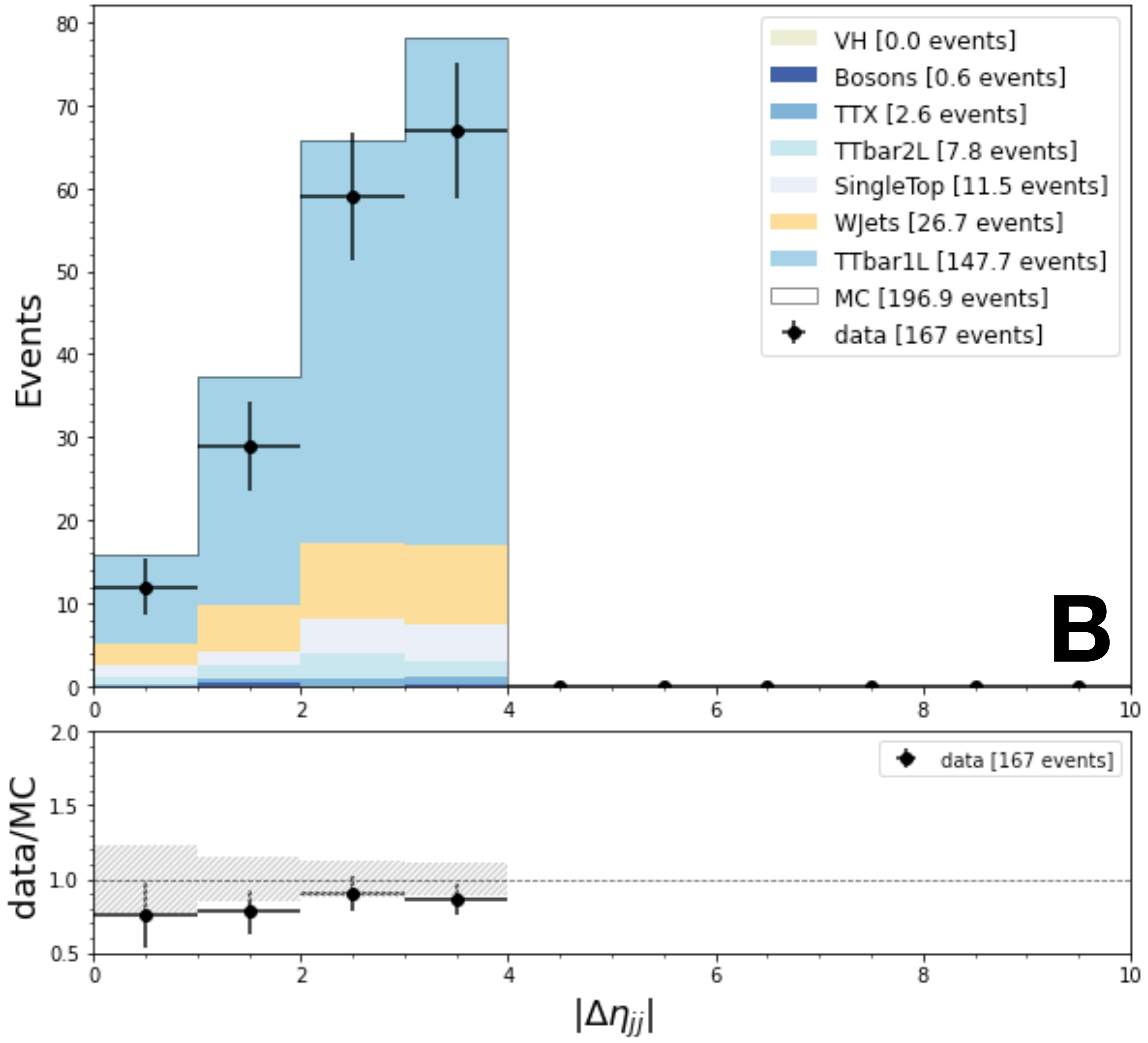

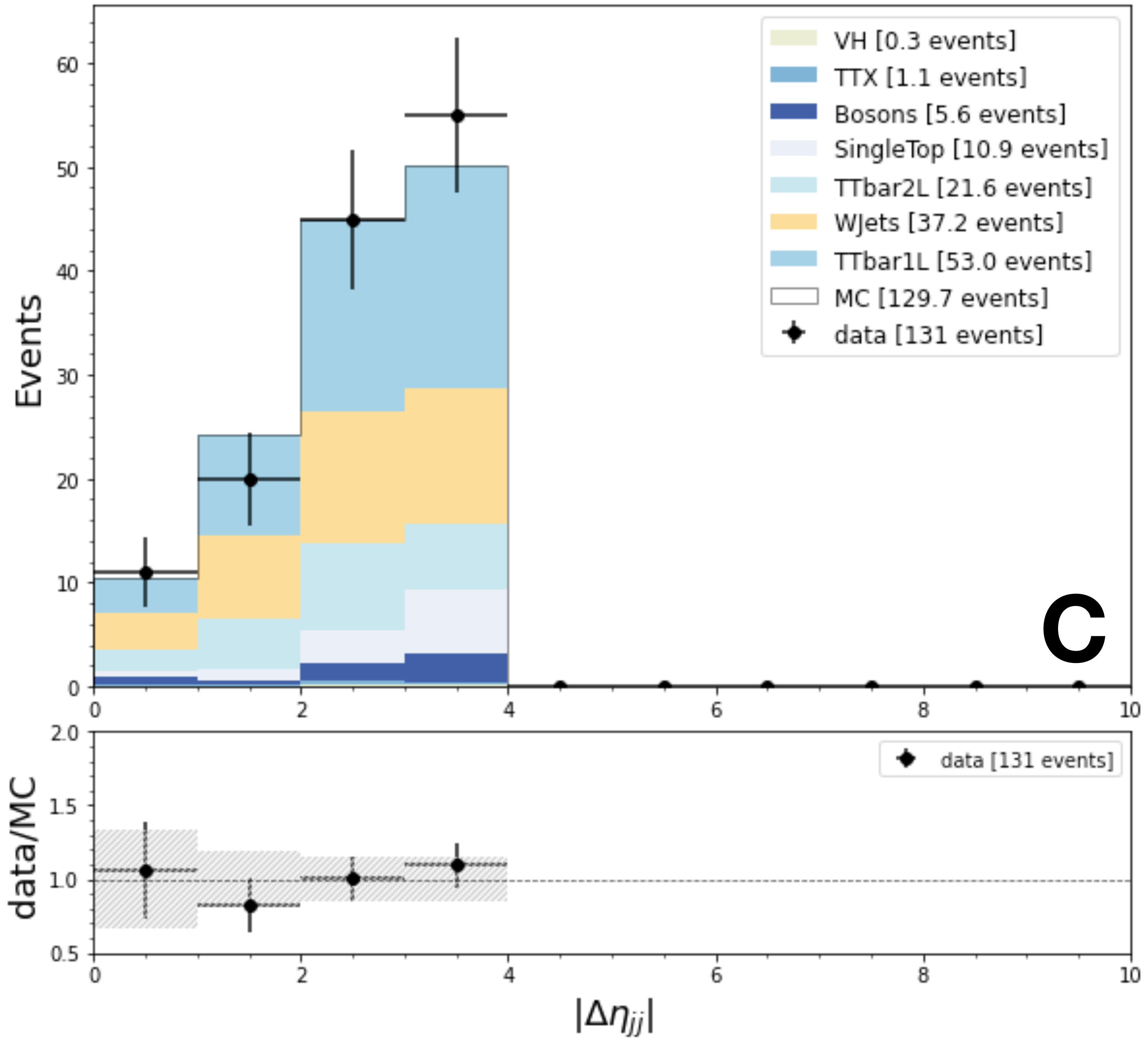

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SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

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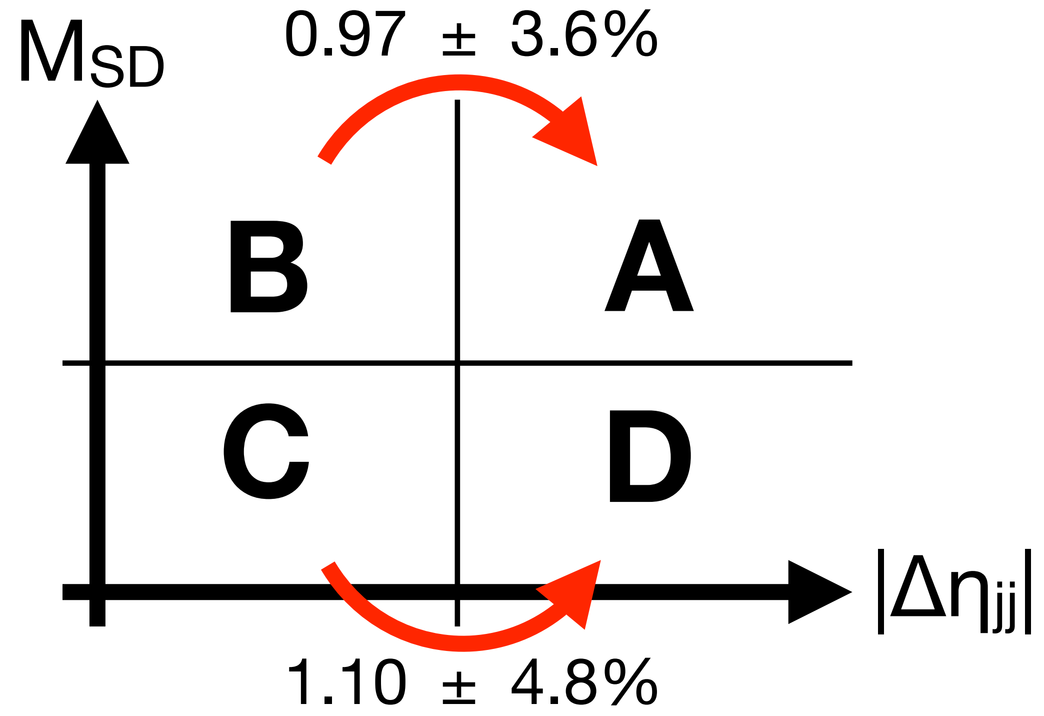

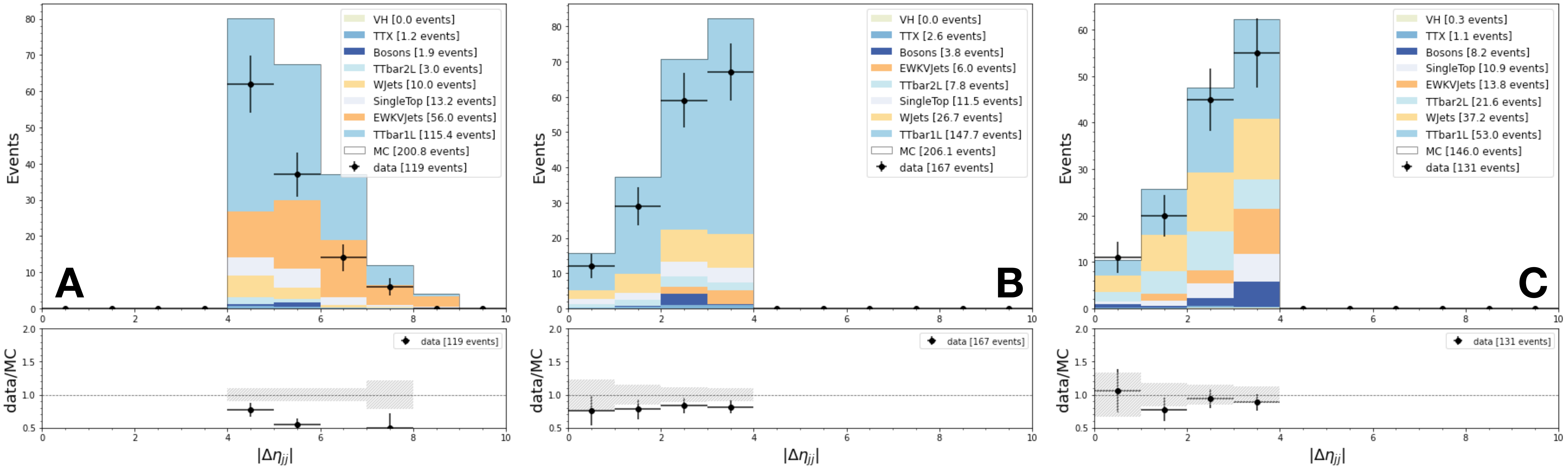

*err = $\sqrt{(\Sigma_i w_i^2)}$ for MC, $\sqrt{(\text{count})}$ for data

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Conclusions

- MC already over-predicted what we see in data, now much worse
  - Particularly bad in high $\Delta\eta_{jj}$, high S_T regions
- What do we do now?
  - Maybe cross-sections are wrong?
  - Other sanity checks to run?

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

BSM Signal Models

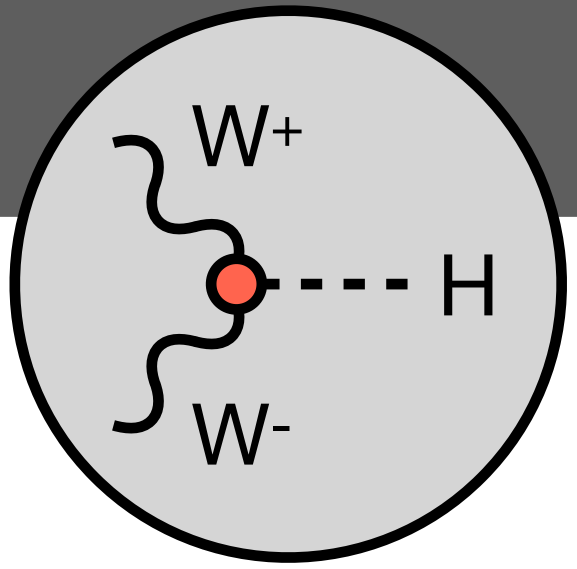
$\kappa_W = -1$

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})
```



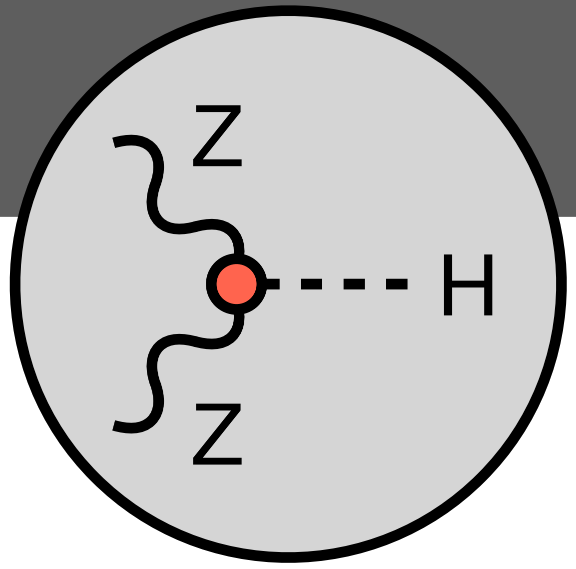
$\kappa_Z = -1$

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})
```

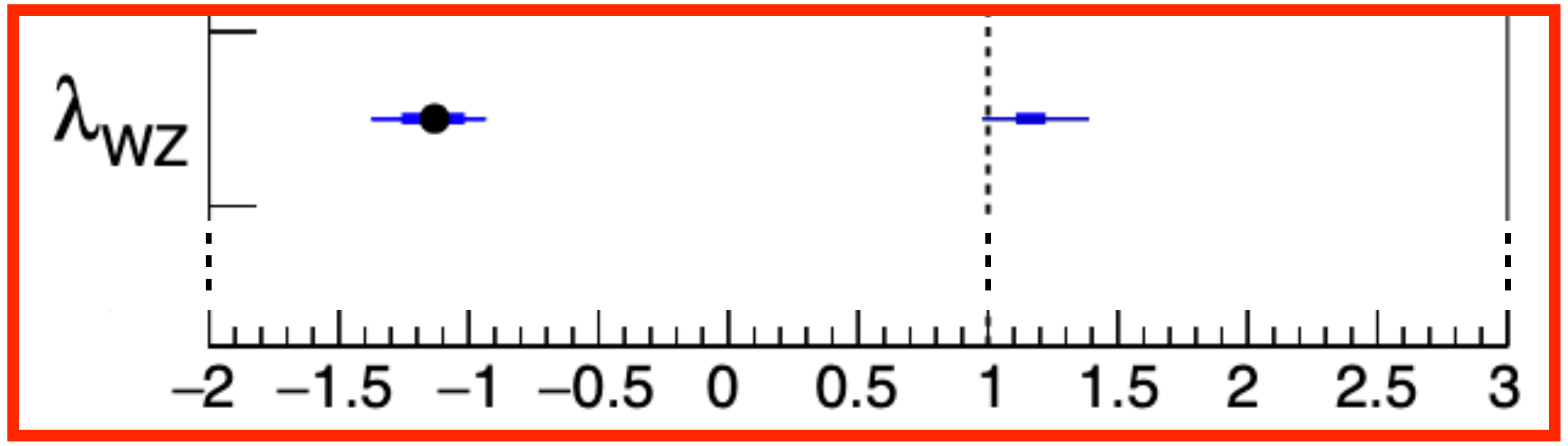
models/sm/vertices.py

```
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!

2016 CMS Result



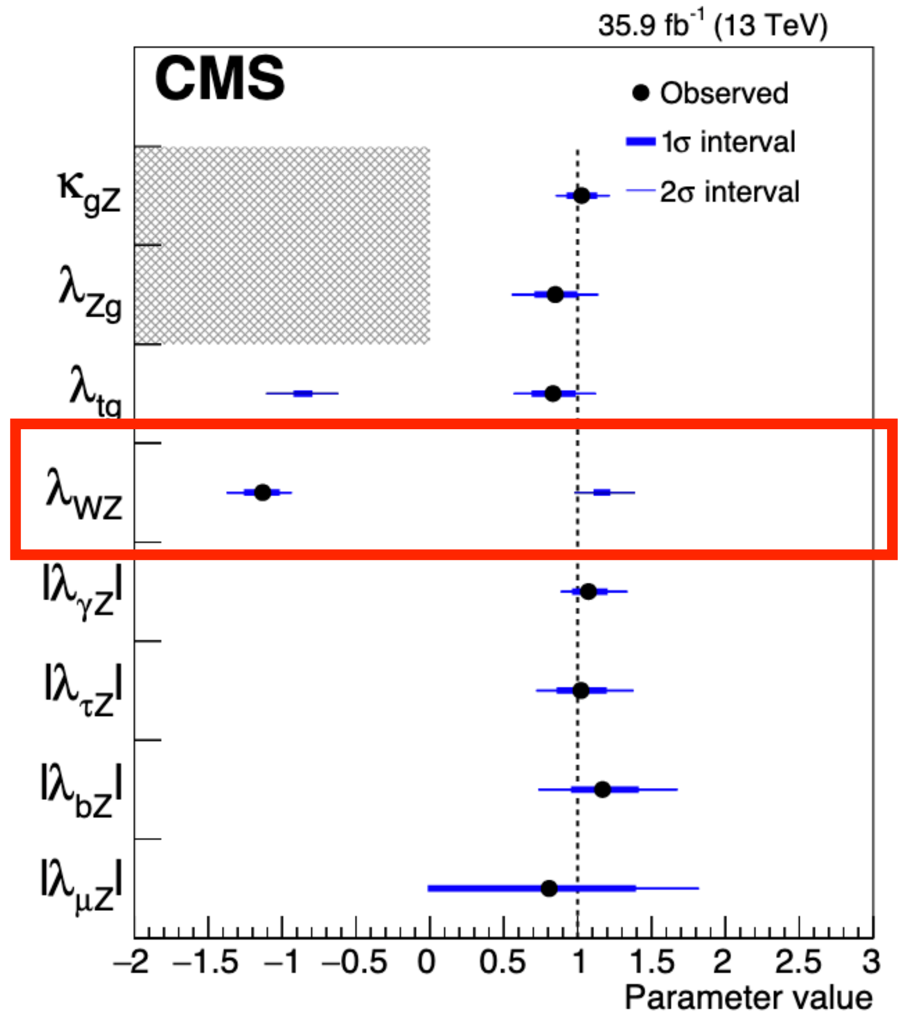
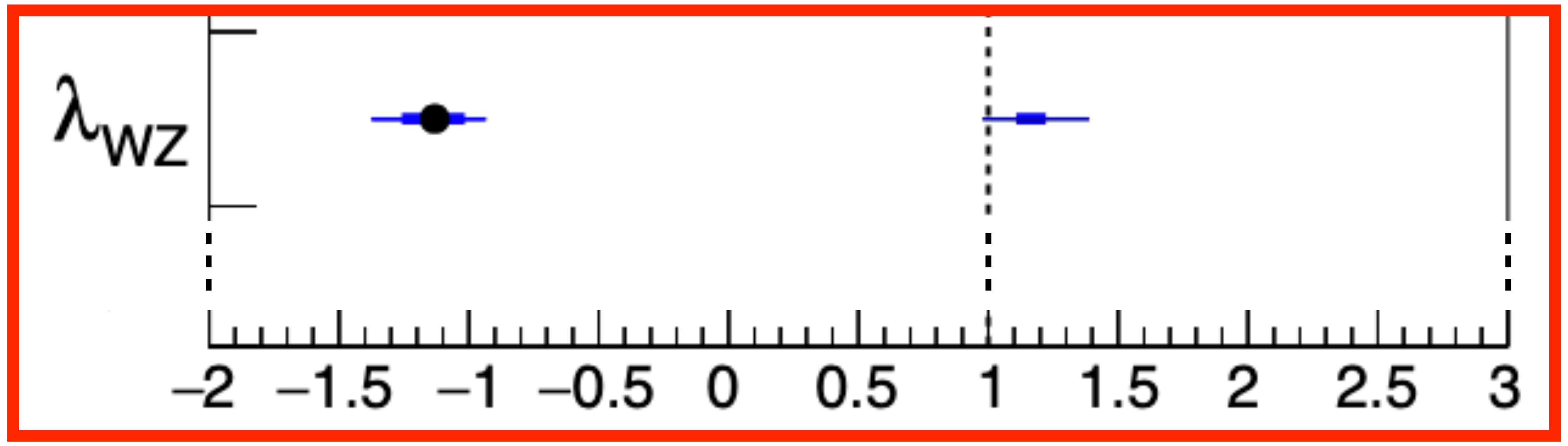


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and H $\rightarrow \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values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

2016 CMS Result



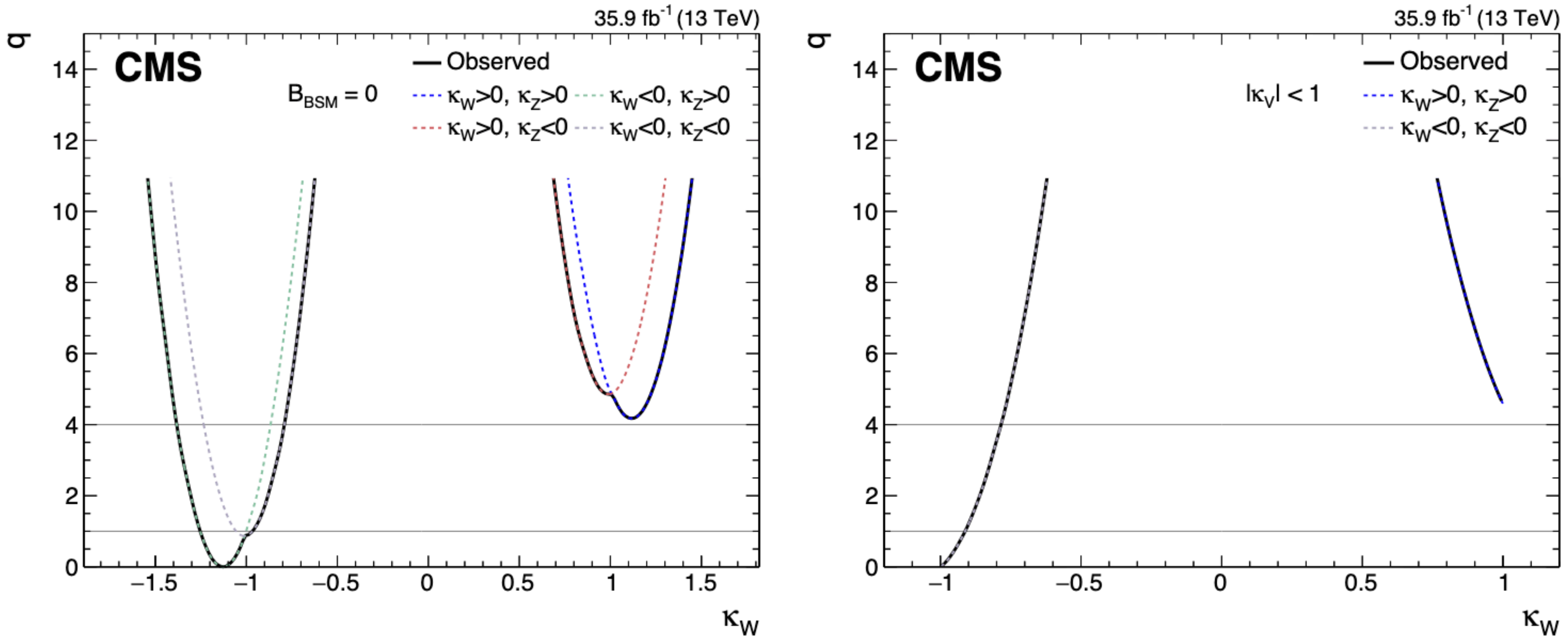


Figure 13: Scan of the test statistic q as a function of κ_W in the generic κ model assuming $\mathcal{B}_{BSM} = 0$ (left) and allowing $\mathcal{B}_{inv}$ and $\mathcal{B}_{undet}$ to float (right). The different colored lines indicate the value of q for different combinations of signs for κ_W and 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.

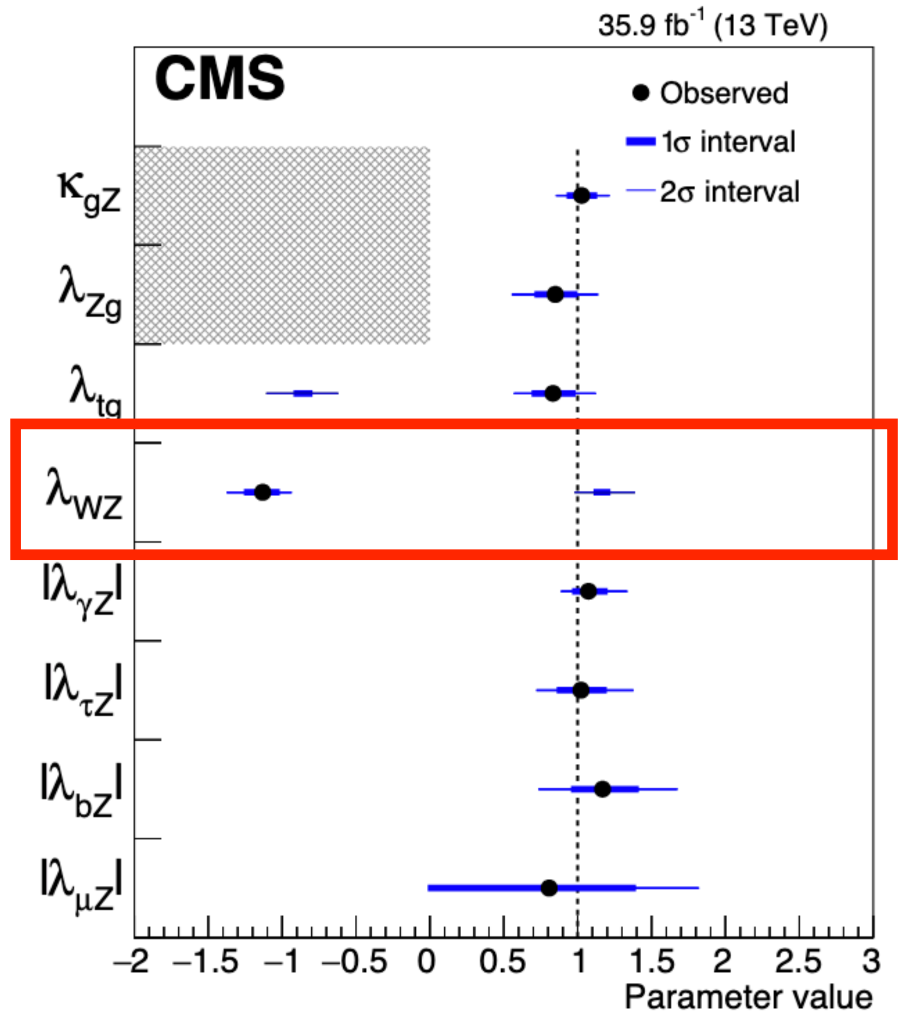


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of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

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

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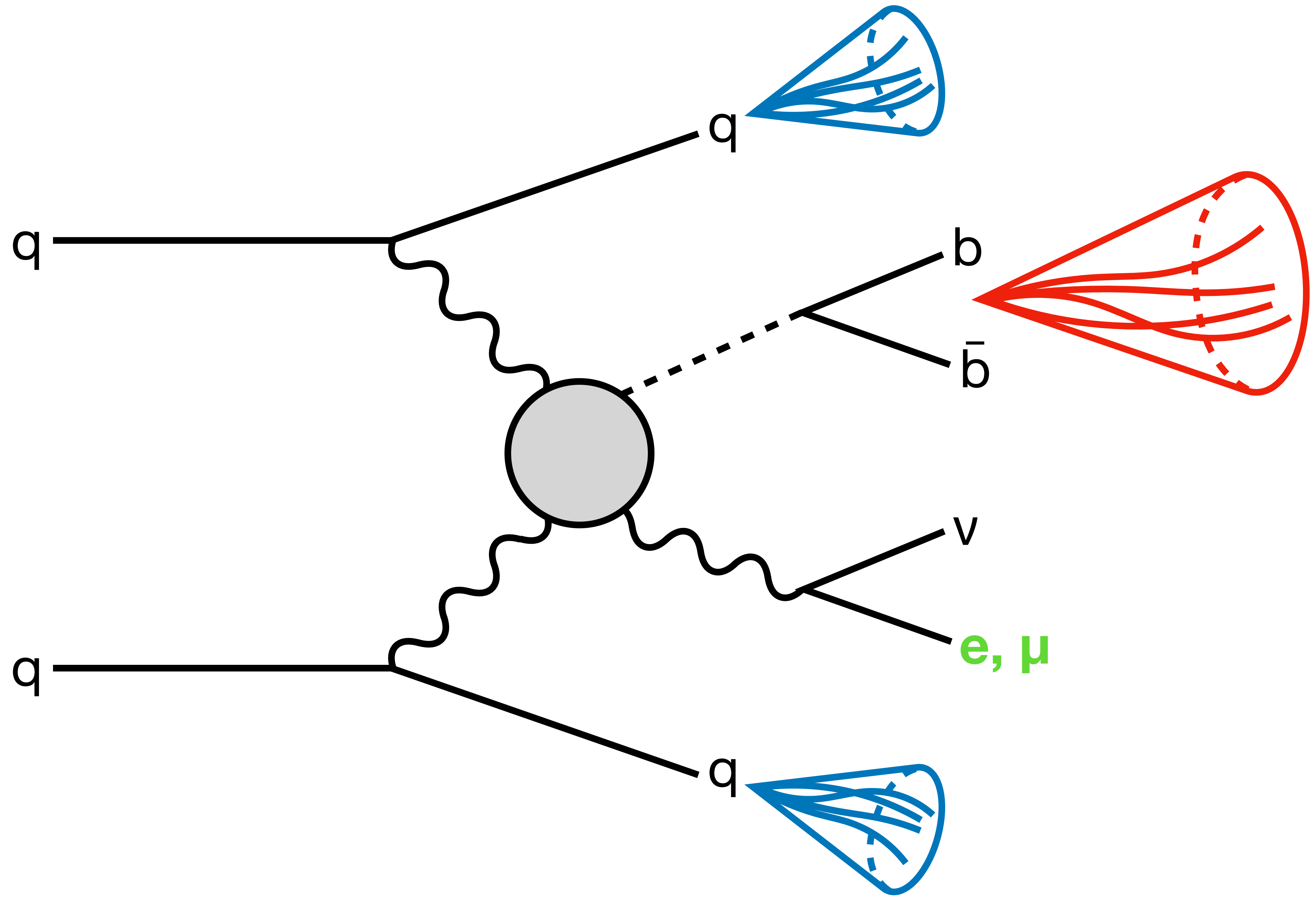
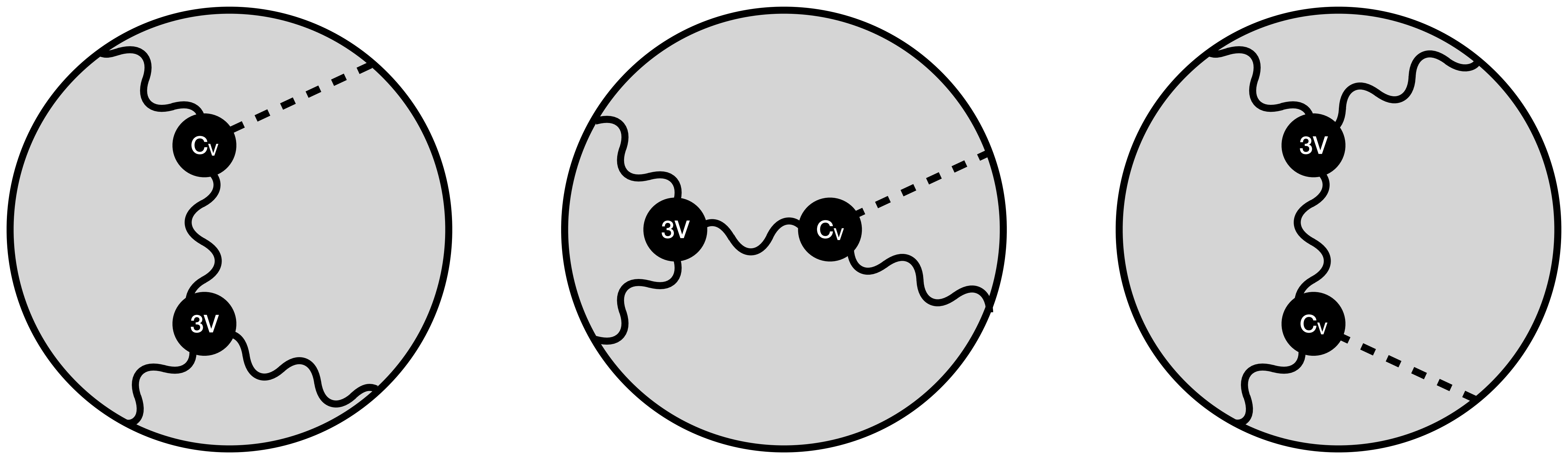
Target Final State

- Targeting **VBS** WH→$\ell\nu b\bar{b}$
- Sensitive to κ_V → $\lambda_{WZ} = \kappa_Z/\kappa_W$
  - Handle for ruling out λ_{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}





(a) (b) (c)

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VBS WH Cross Sections

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

Analysis Skim

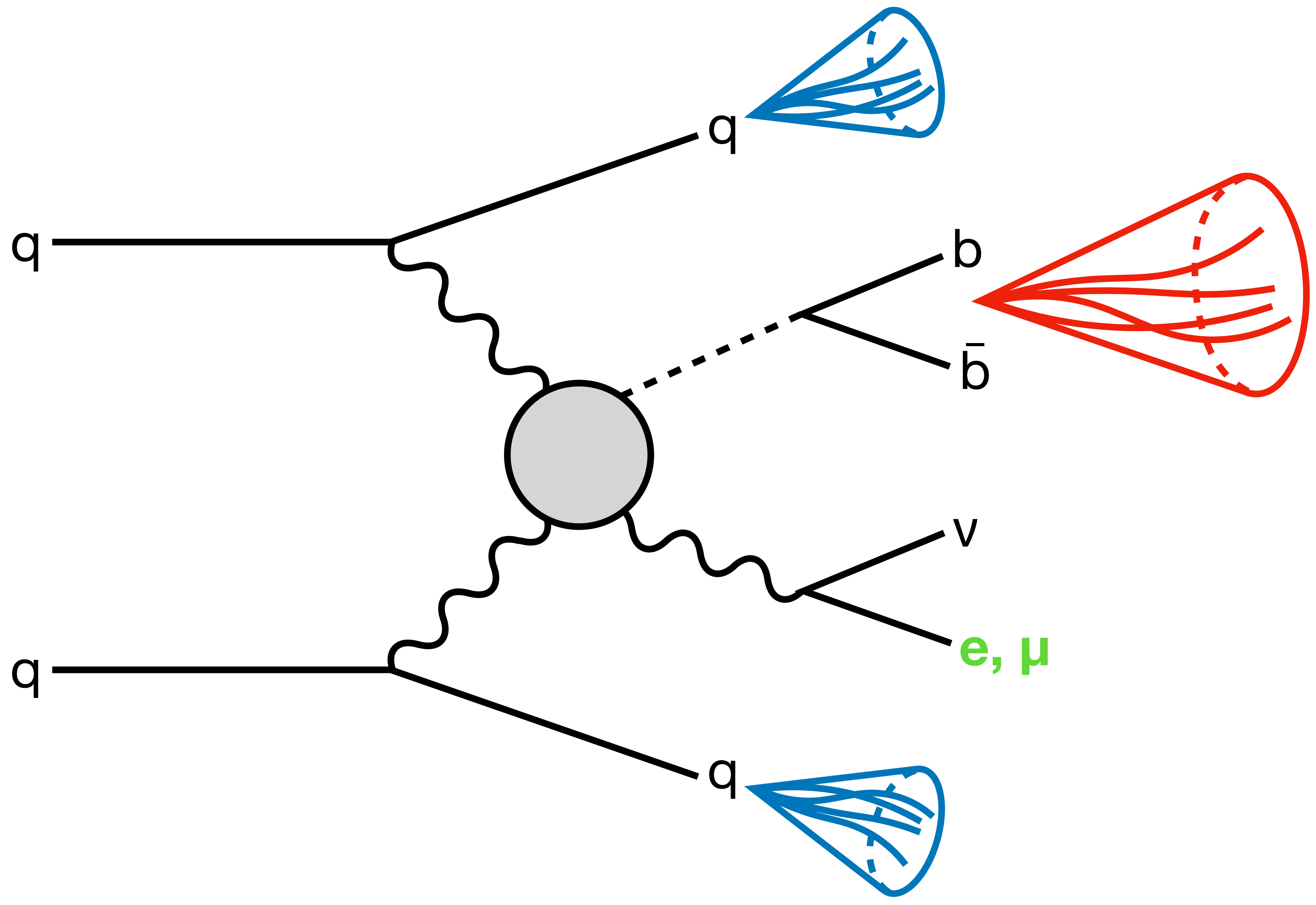
Yields scaled to lumi×σ, rounded for readability

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

Object	Selection
Leptons (μ, e)	== 1 loose AND == 1 tight*
Fat Jets	≥ 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

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 Xbb vs. QCD score) • PNet Xbb vs. QCD score > 0.3

Two **VBS** Ak4 jets	• ΔR(Ak4 jet, any veto lep) > 0.4
	• ΔR(Ak4 jet, Hbb Ak8 jet) > 0.8
	• p_T > 30 GeV
	• Passes tight jet ID
	• 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

Weighted yields ("wgt") scaled to lumi×σ

	VH		VV/VVV/VBSWZ		W+Jets		SingleTop		TTbar+X		TTbar1L		TTbar2L		TotalBkg		VBSWH (λ_{WZ} = -1)	
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
FindLeptons	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	399990	59598.1
Geq1VetoLep	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	129280	19148.8
Geq2Jets	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	128653	19057.0
Geq1FatJetNoVetoLepOverlap	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	52537	7773.7
Exactly1TightLep	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	31748	4734.4
Geq1FatJetNoTightLepOverlap	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8372794	233443.4	24525	3653.0
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	220.0	484277	6105.5	4603393	116465.8	76733	7157.0	939478	952.8	1943369	81903.7	262377	8969.2	8372792	221774.1	13122	1879.1
LepPtGt40	60944	210.2	435912	5592.1	3889493	105845.4	68935	6584.1	817993	838.2	1761239	74619.5	227019	7821.5	7261535	201511.0	12416	1785.6
Passes1LepTriggers	54536	172.7	386803	5064.1	3325103	93973.1	61557	5922.4	700889	710.8	1535810	65124.8	197780	6820.1	6262478	177788.0	10736	1536.3
SelectFatJets	54536	172.7	386803	5064.1	3325103	93973.1	61557	5922.4	700889	710.8	1535810	65124.8	197780	6820.1	6262478	177788.0	10736	1536.3
Geq1FatJet	54470	172.9	384920	5060.1	3323420	93954.1	61404	5904.0	695035	706.2	1534845	65090.1	190755	6580.2	6244849	177467.6	10726	1535.2
SelectHbbFatJet	54470	172.9	384920	5060.1	3323420	93954.1	61404	5904.0	695035	706.2	1534845	65090.1	190755	6580.2	6244849	177467.6	10726	1535.2
SelectJetsNoHbbOverlap	54470	172.9	384920	5060.1	3323420	93954.1	61404	5904.0	695035	706.2	1534845	65090.1	190755	6580.2	6244849	177467.6	10726	1535.2
SaveAk4GlobalBVeto	54470	172.9	384920	5060.1	3323420	93954.1	61404	5904.0	695035	706.2	1534845	65090.1	190755	6580.2	6244849	177467.6	10726	1535.2
SelectVBSJetsMaxE	17662	48.0	251204	1931.1	2399176	45556.4	43921	4167.3	593328	604.6	1126440	48139.3	161098	5585.1	4592829	106031.8	7458	1075.2
MjjGt500_detajjGt3	3039	7.0	44926	355.8	393418	7448.8	10903	948.2	111929	114.6	231383	9863.5	35368	1225.3	830966	19963.2	6167	889.6
XbbGt0p3	2020	2.7	8633	48.3	34602	564.2	5486	513.3	71857	71.4	131324	5552.2	10113	353.9	264035	7106.0	4084	590.1
ApplyAk4GlobalBVeto	1627	2.3	6912	41.3	26699	465.6	1848	184.1	19216	18.5	37379	1582.3	2908	101.4	96589	2395.5	3877	561.2
MjjGt1500_detajjGt4	949	1.2	3606	19.1	10804	227.8	1193	114.6	10366	9.8	21868	920.6	1559	53.5	50345	1346.5	3640	528.1
STGt900	541	0.8	2437	13.5	7935	139.6	731	74.9	6327	5.8	11599	483.1	766	25.8	30336	743.5	2979	431.4
XbbScoreGt0p9_MSDLt150	426	0.8	666	3.5	896	18.4	107	11.7	779	0.7	999	41.8	257	8.5	4130	85.4	2322	336.3
STGt1500	40	0.0	73	0.0	148	1.0	3	0.2	40	0.0	22	0.8	4	0.1	330	2.3	643	95.5

Skim already applied!