VBS WH Analysis

Hbb subgroup update

October 12th, 2022

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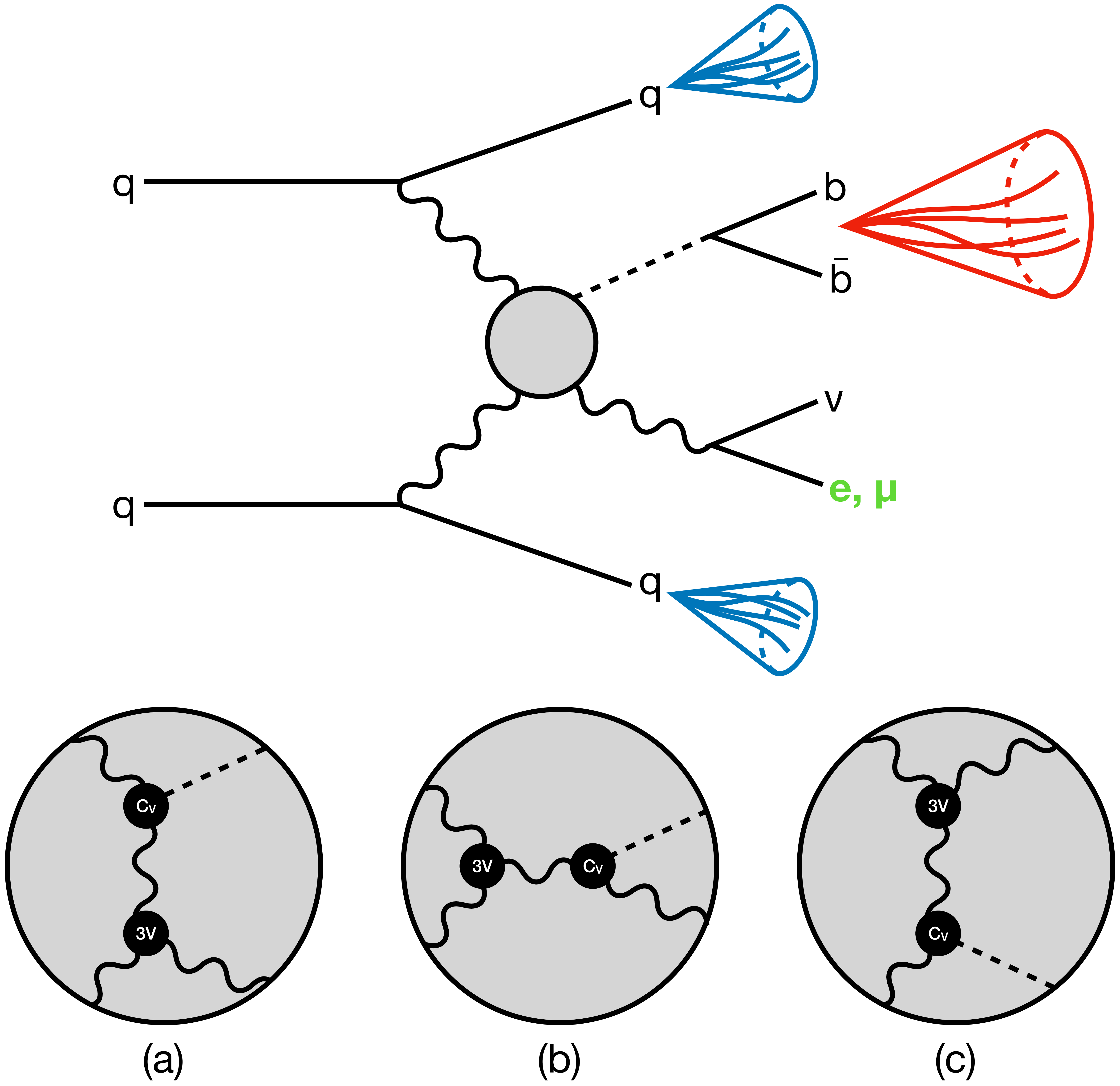
Target Final State

- Targeting **VBS** WH→**ℓ**ν**b$\bar{b}$**
- Sensitive to κ_V → $\lambda_{WZ} = \kappa_Z/\kappa_W$
  - 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}



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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	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
Skim	228	7.5K	26K	133K	8.2K	1.2K	89K	11K	277K	—	2.2K	—

Object	Selection
Leptons (μ, e)	== 1 veto 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	≥ 2 w/ p_T > 20 GeV AND ΔR(jet, any veto lepton) > 0.4
Other	S_T > 800 GeV

*Using the same ID as Peking U. (PKU) analysis team

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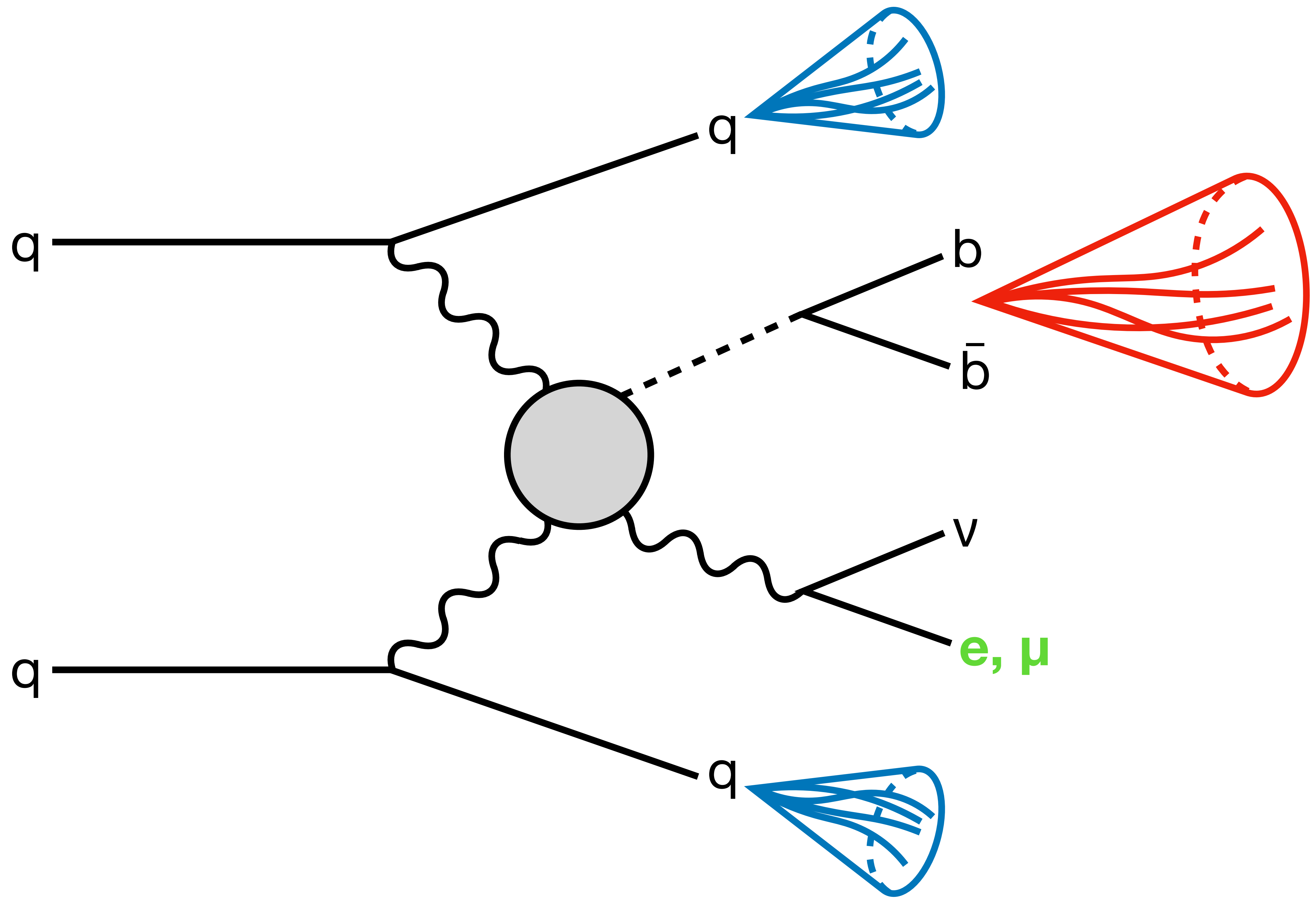
VBS WH Objects



Object	Selections
One **Lepton**	• Passes PKU tight ID + 2nd lepton veto • 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

Preselection

Yields scaled to lumi×σ, rounded for readability

	Cut	VH	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	228	7.5K	26K	133K	8.2K	1.2K	89K	11K	277K	—	2.2K	—
	Object Selection	58	3.4K	12K	55K	5K	777	56K	7.6K	140K	49%	1.3K	40%
Presel.	**Mjj > 500 GeV AND |Δηjj| > 3**	12	778	2.3K	9.6K	1.2K	150	12K	1.7K	28K	80%	1.1K	17%
Presel.	**max(PNet Xbb score) > 0.3**	5	77	259	730	640	95	6.7K	730	9.2K	67%	701	35%
Presel.	**No b-tagged (med.) AK4 jets**	4	51	211	603	241	27	2K	230	**3.4K**	63%	**666**	5%

- Using ParticleNet Xbb (mass-decorrelated) tagger
- Veto events with any b-tagged “good” jets
- Can identify key variables from here (next slides)
- Unable to use this region for validation
    - Too much signal
    - Must use a sideband

*eff = 1 - after/before

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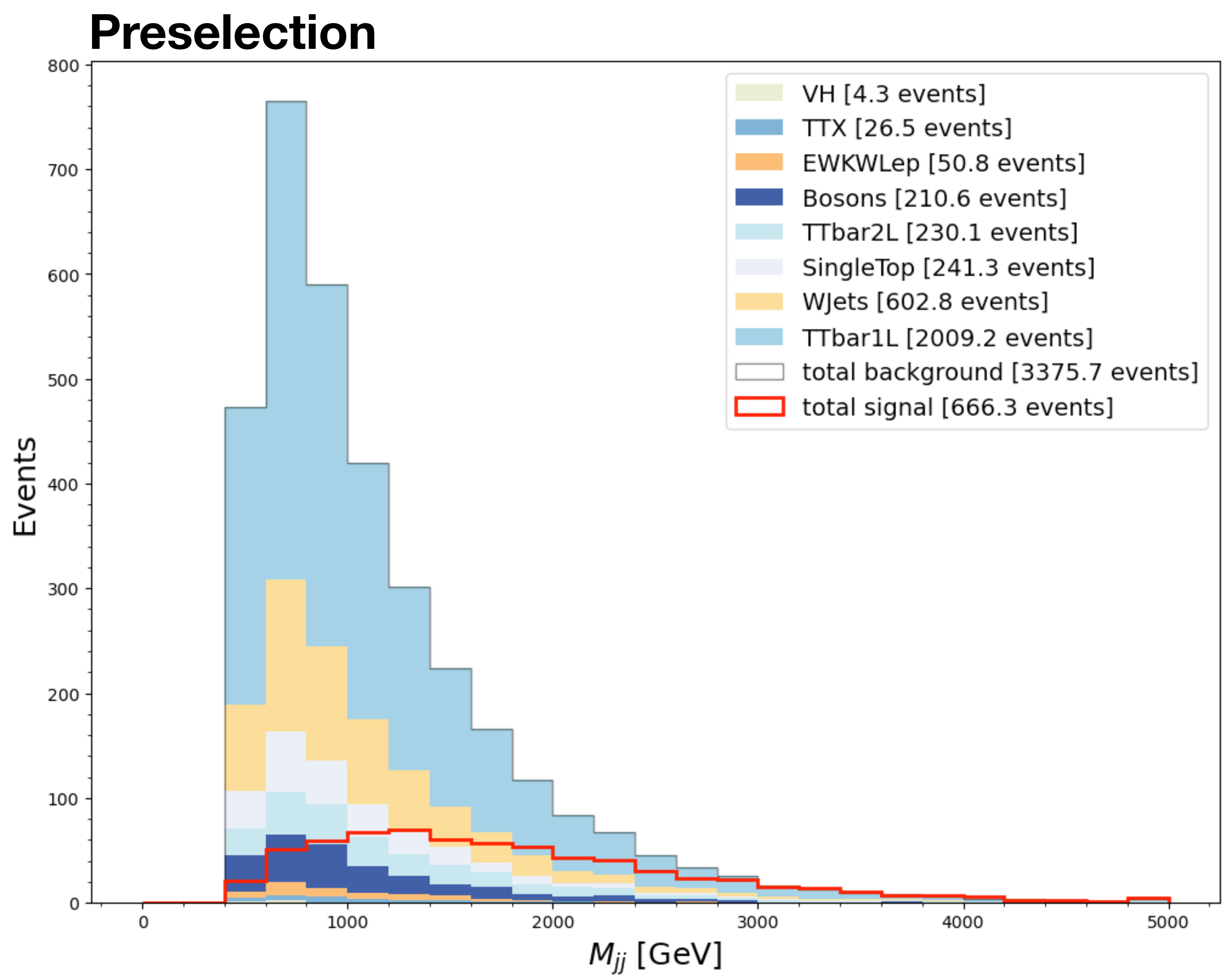
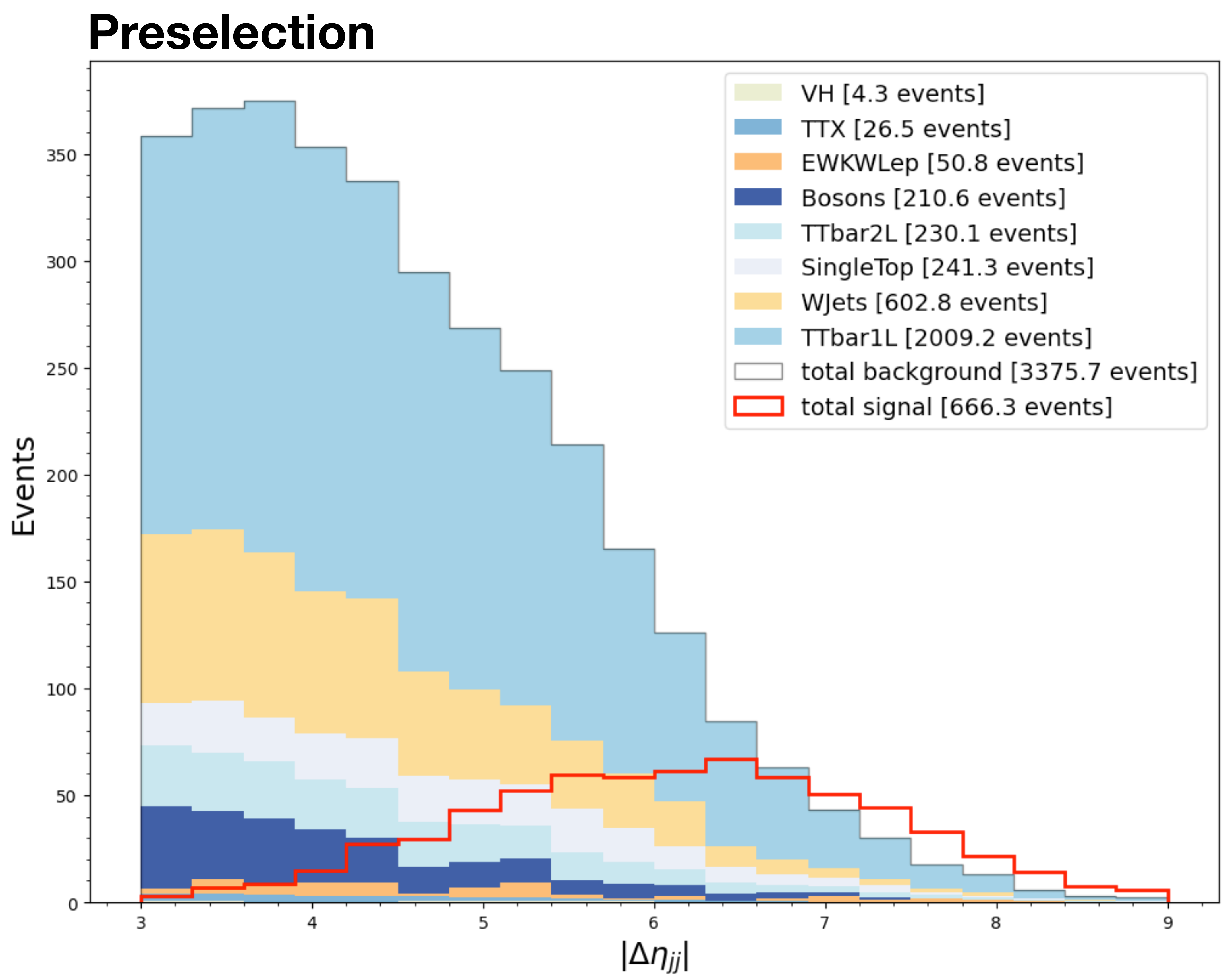
Preselection: VBS





Strong signal vs. background separation in $\Delta\eta_{jj}$

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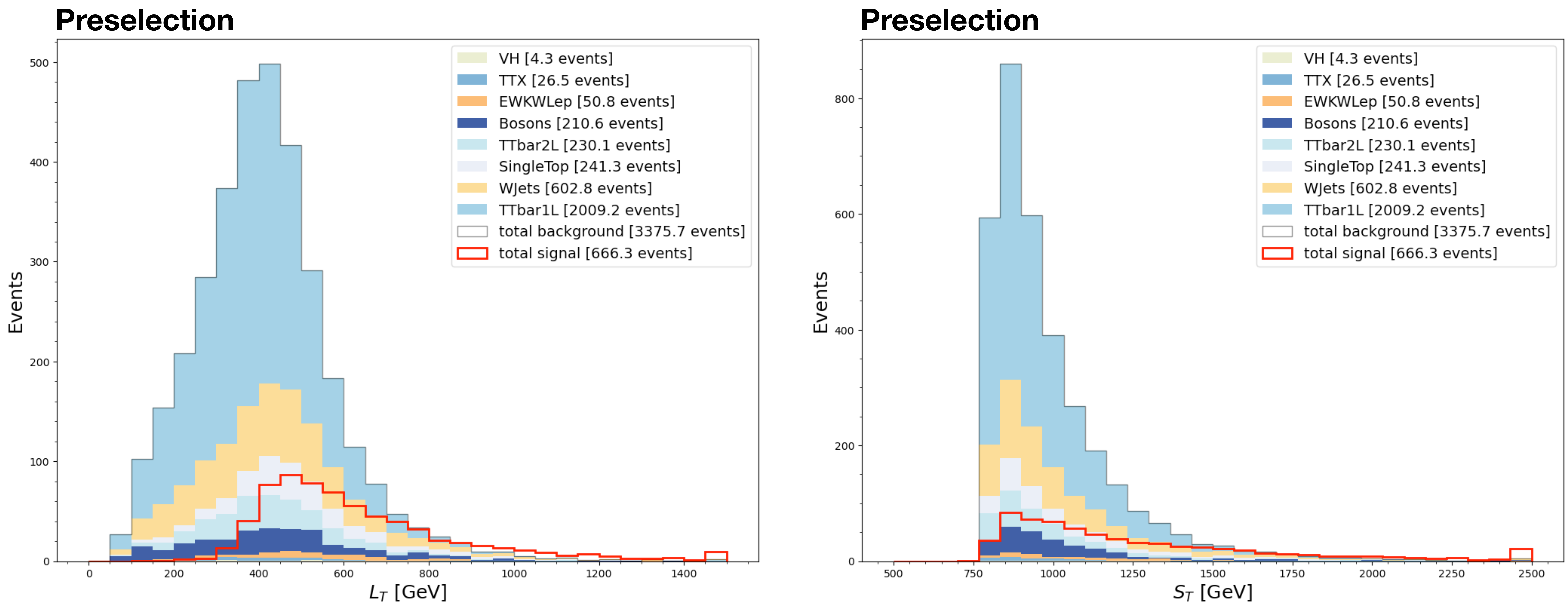
Preselection: L_T and S_T

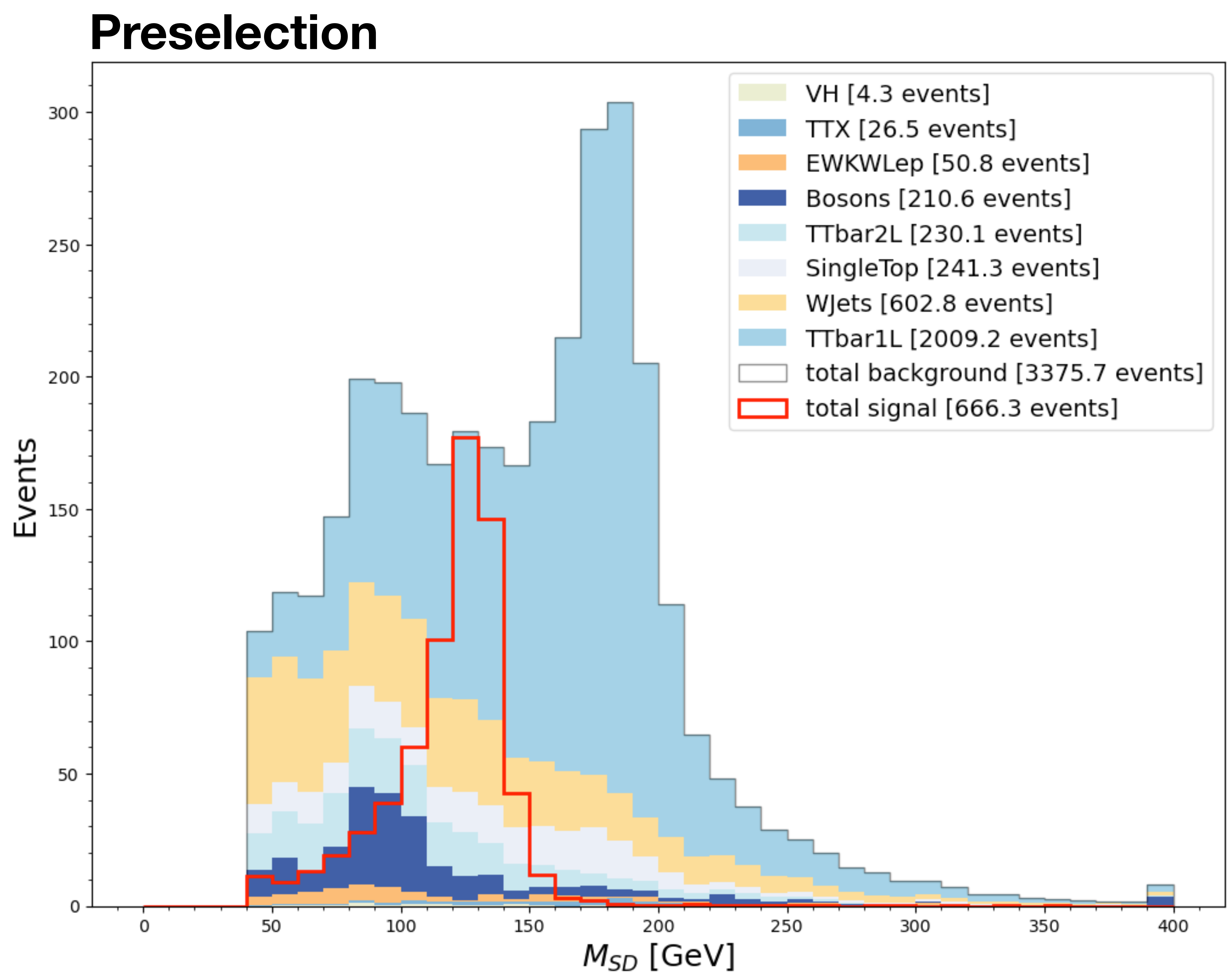


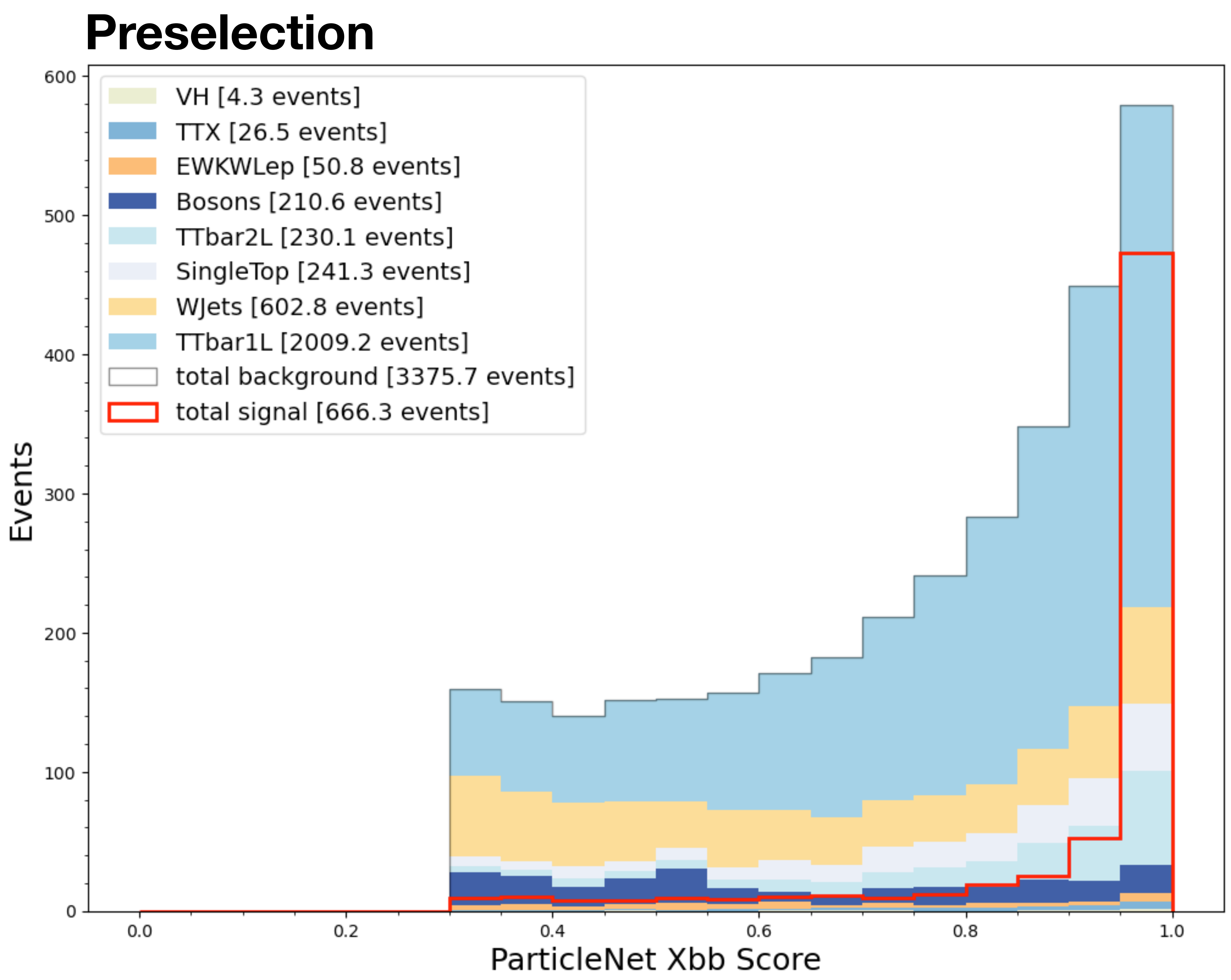
$L_T = p_T(\ell) + MET$

$S_T = L_T + p_T$(Hbb jet)

Strong signal vs. background separation in S_T

Preselection: Hbb

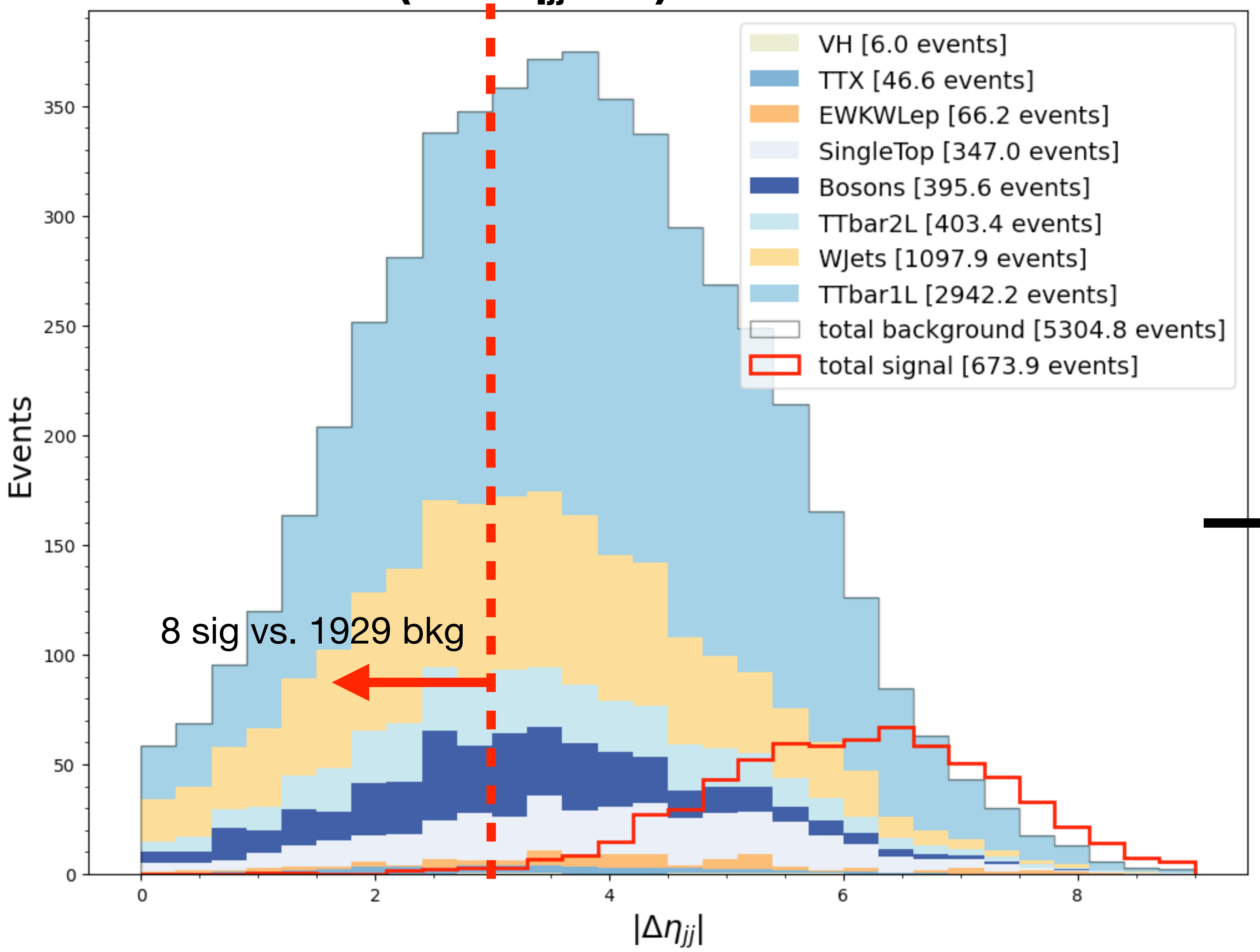




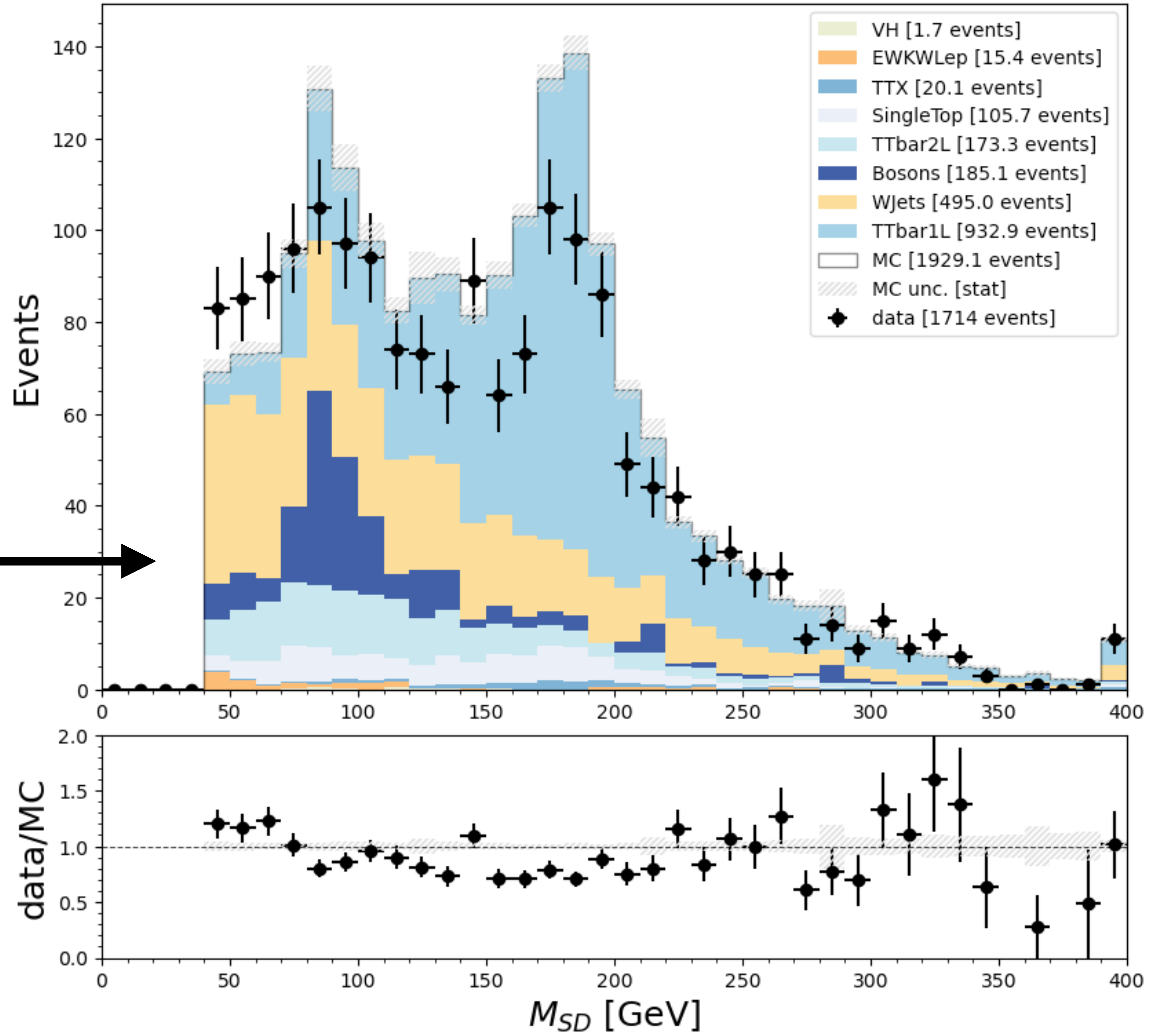
Strong separation in Hbb variables as well

Validation: Hbb

Preselection (no $\Delta\eta_{jj}$ cut)



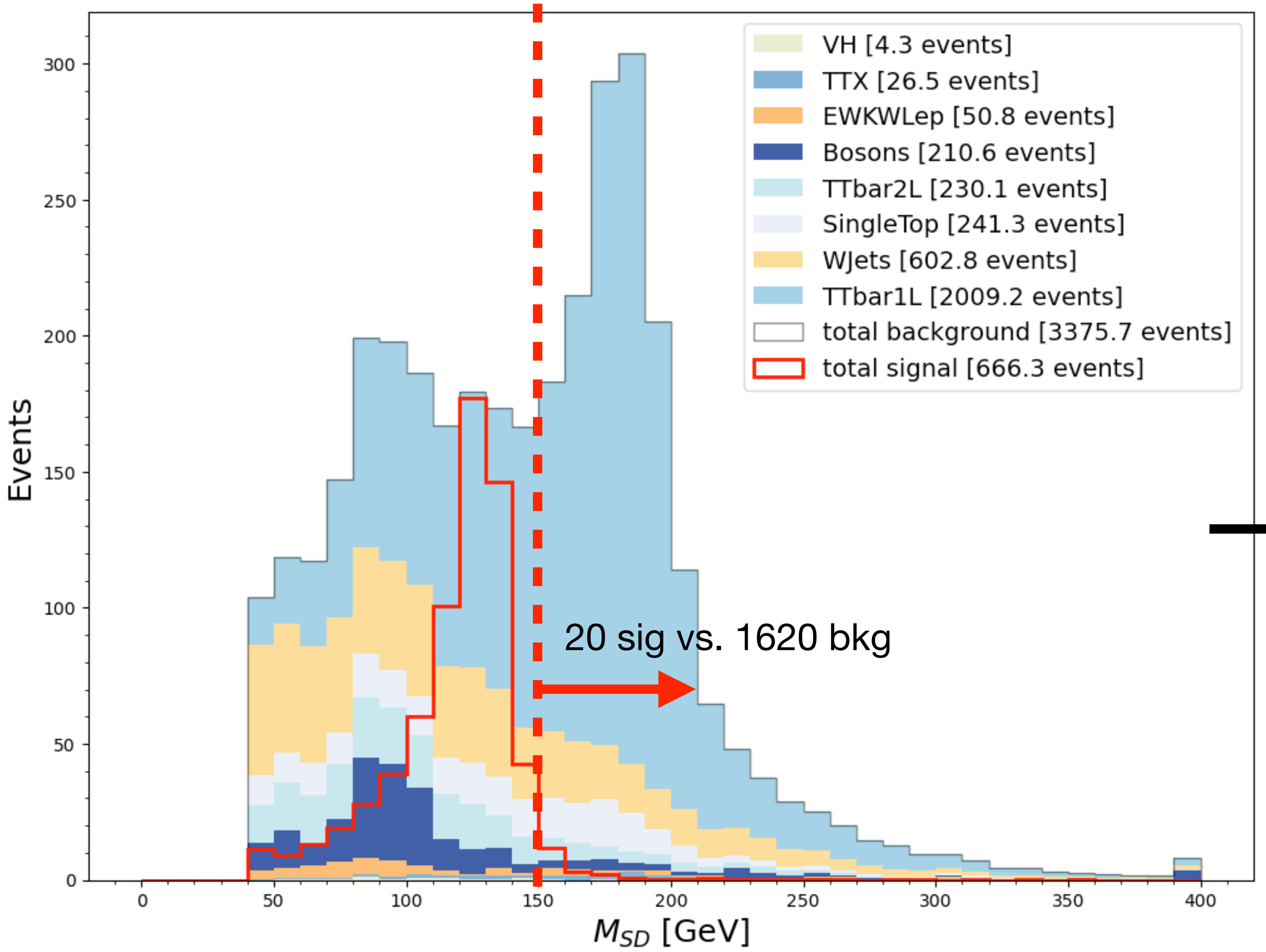
Preselection (no $\Delta\eta_{jj}$ cut) AND $|\Delta\eta_{jj}| \leq 3$



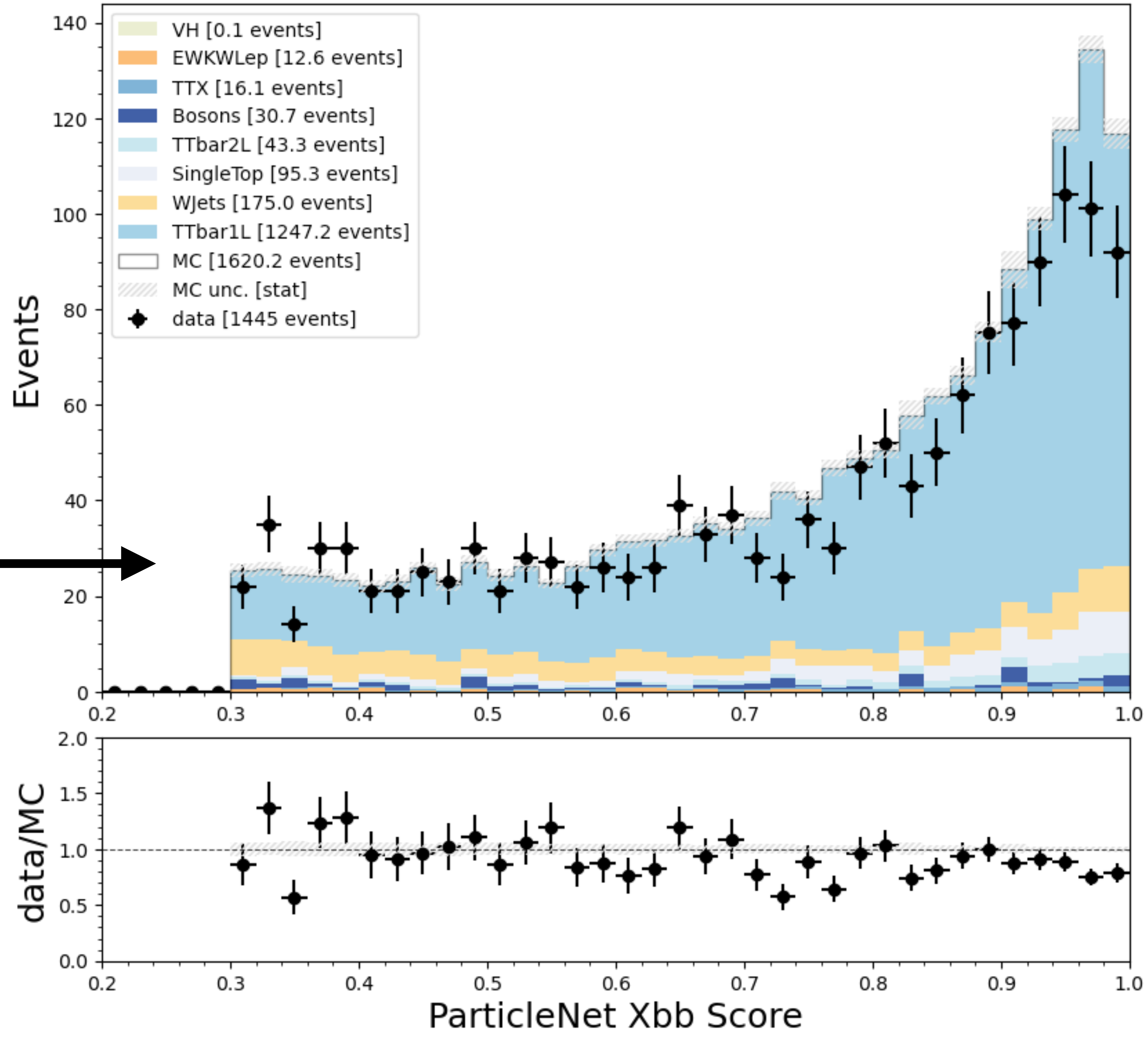
Agreement looks good, more plots in backup

Validation: Hbb

Preselection



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



Agreement looks good, more plots in backup

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Signal Regions

Yields scaled to lumi×σ, rounded for readability

Region	Cut	VH	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	228	7.5K	26K	133K	8.2K	1.2K	89K	11K	277K	—	2.2K	—
	Object Selection	58	3.4K	12K	55K	5K	777	56K	7.6K	140K		1.3K	
	Preselection	4	51	211	603	241	27	2K	230	3.4K	99%	666	69%
SR1	**M_{jj} > 600 GeV AND $\|\Delta\eta_{jj}\|$ > 4**	2	31	86	305	150	14	1.2K	127	1.9K	43%	627	6%
SR1	**S_T > 900 GeV**	2	23	54	190	97	8	630	68	1.1K	44%	515	18%
SR1	**PNet Xbb vs. QCD > 0.9 AND M_{SD} < 150**	1	2	9	25	15	1	56	26	**133**	88%	**396**	23%
SR2	**S_T > 1500 GeV**	0	0	2	1	1	0	1	1	**6**	95%	**113**	72%

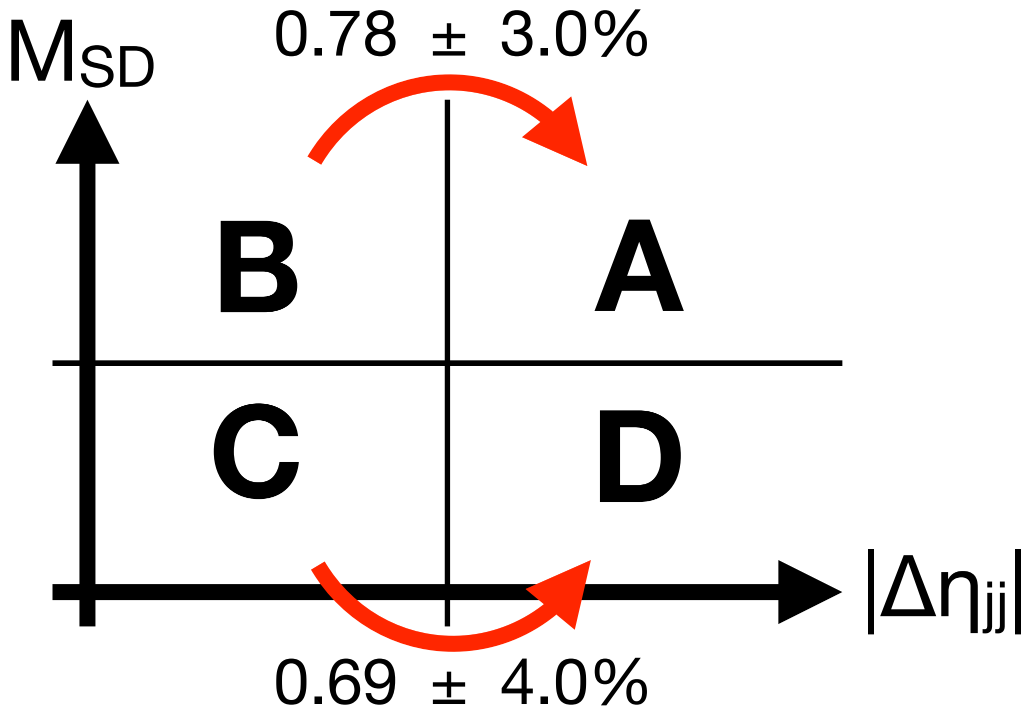
- **Signal Region 1 (SR1): 396 signal vs. 133 background**
    - Can exclude $\lambda_{WZ} = -1$
    - Background can be estimated via ABCD
- **Signal Region 2 (SR2): 113 signal vs. 6 background**
    - High purity via tighter kinematics; worth exploring in its own right
    - Most valuable if data in SR1 is not consistent with either $\lambda_{WZ} = -1$ or $\lambda_{WZ} = +1$ hypotheses

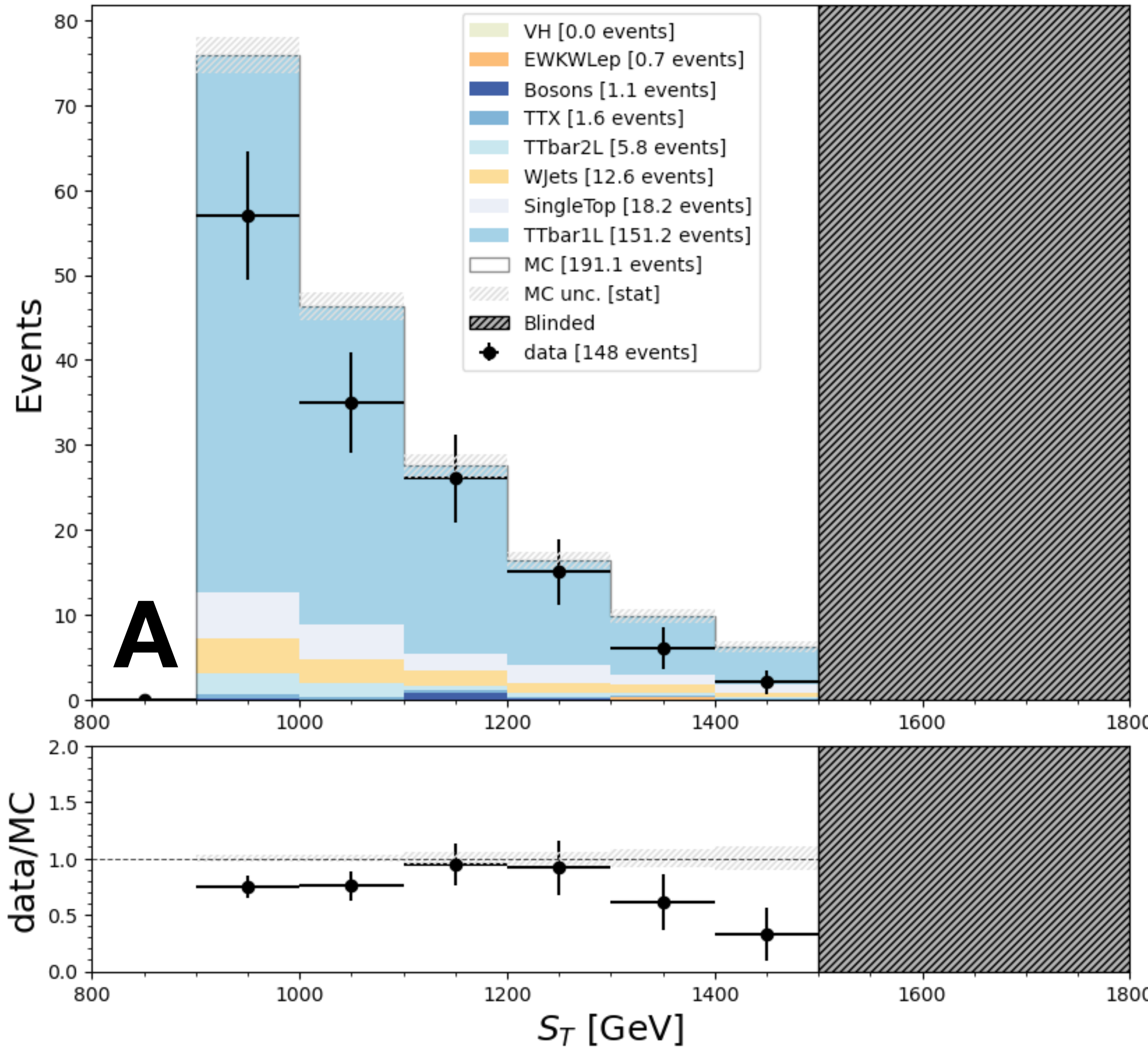
*eff = 1 - after/before

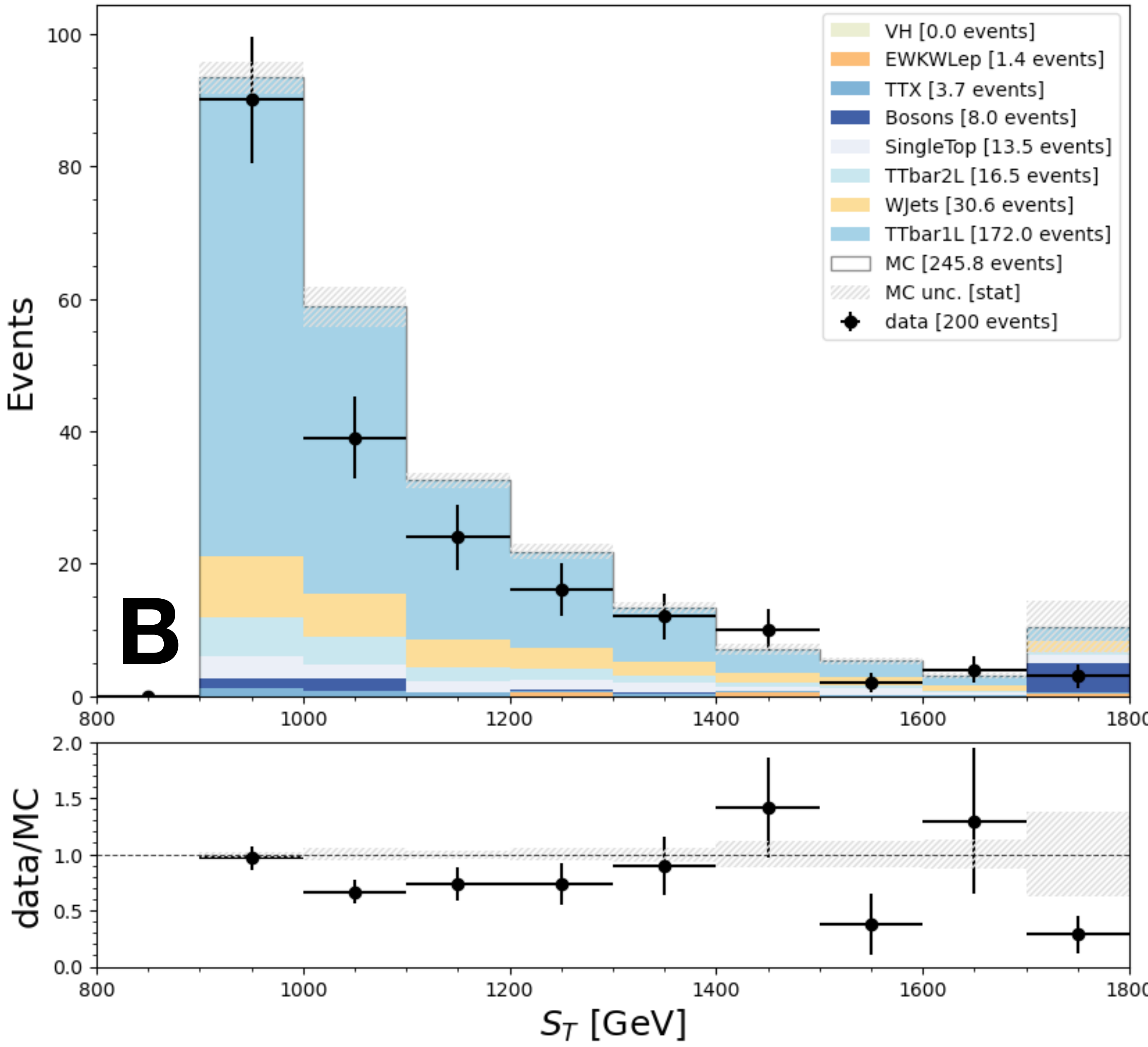
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

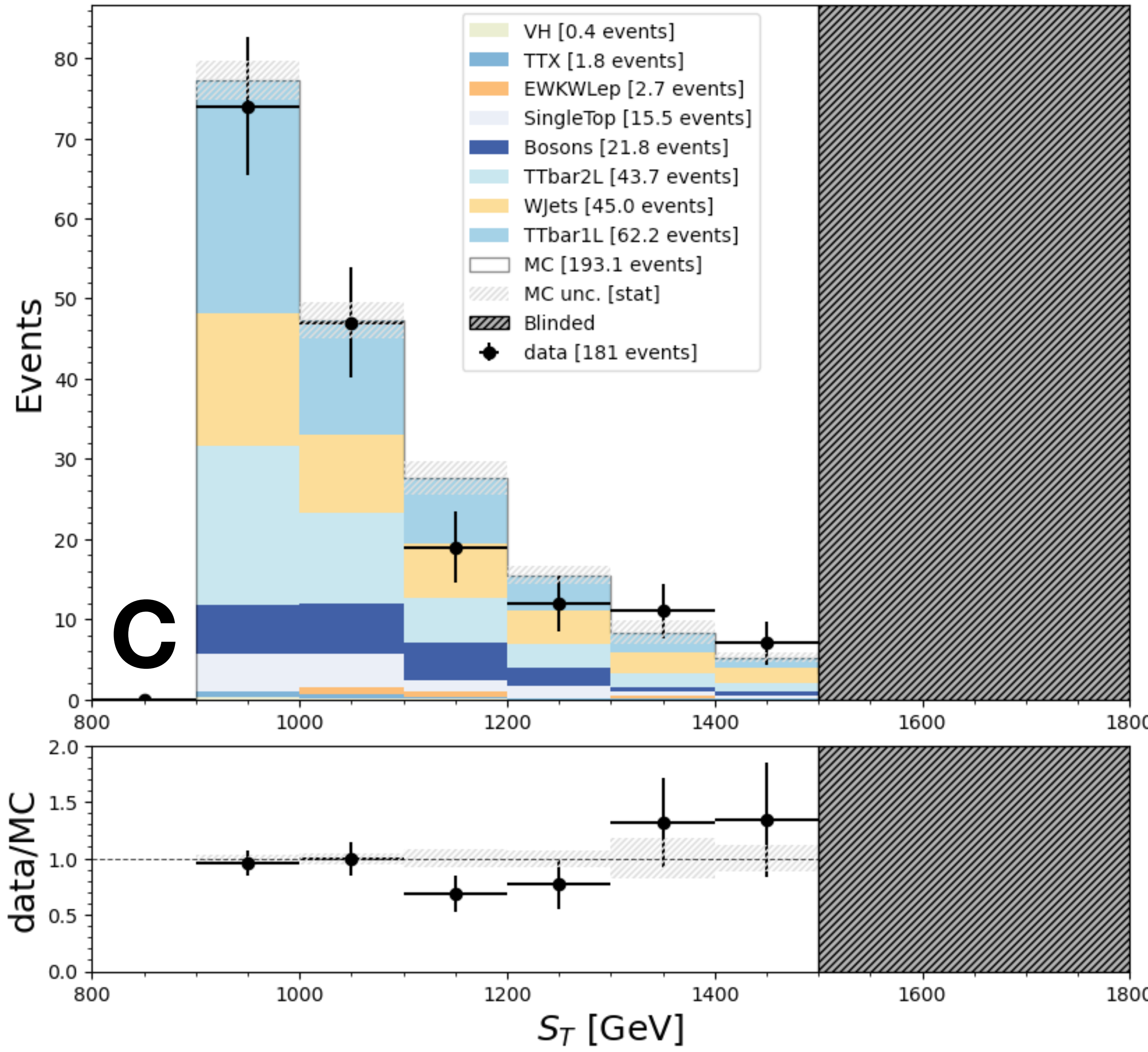
Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} \geq 150$ GeV	A	191.14	3.48	10.60	1.36	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	245.76	5.90	0.89	0.44	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	193.14	4.61	14.75	1.57	181	13.45
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	133.44	4.31	395.72	8.45	–	–









*err = $\sqrt{\sum_i w_i^2}$ 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.*
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} \geq 150$ GeV	A	191.14	3.48	10.60	1.36	148	12.17
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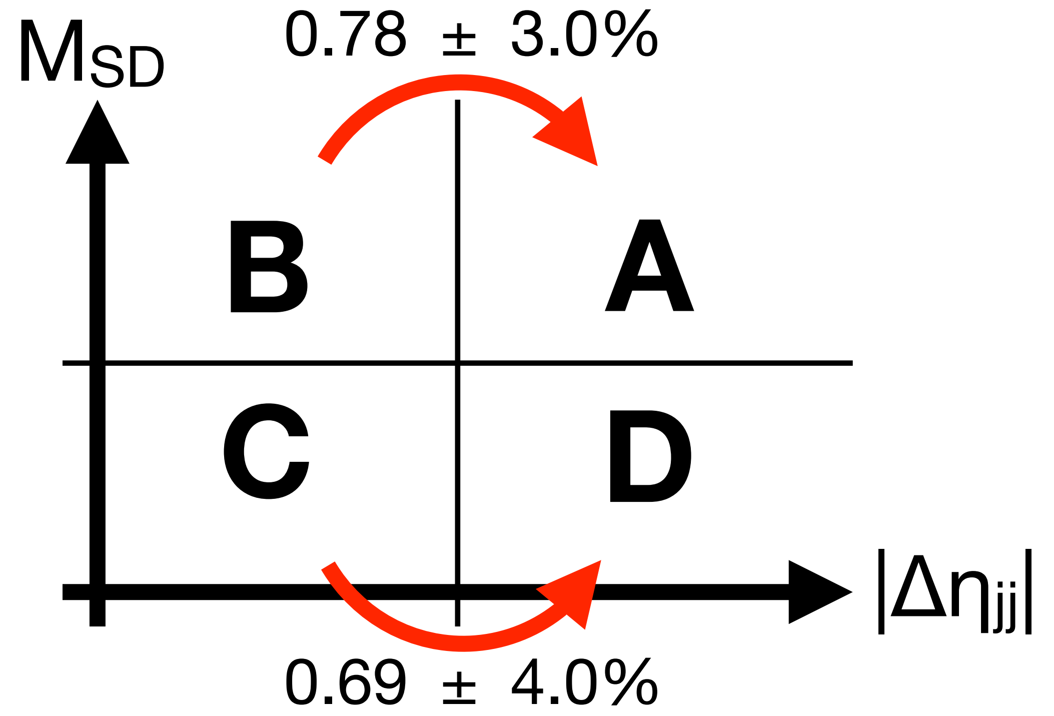

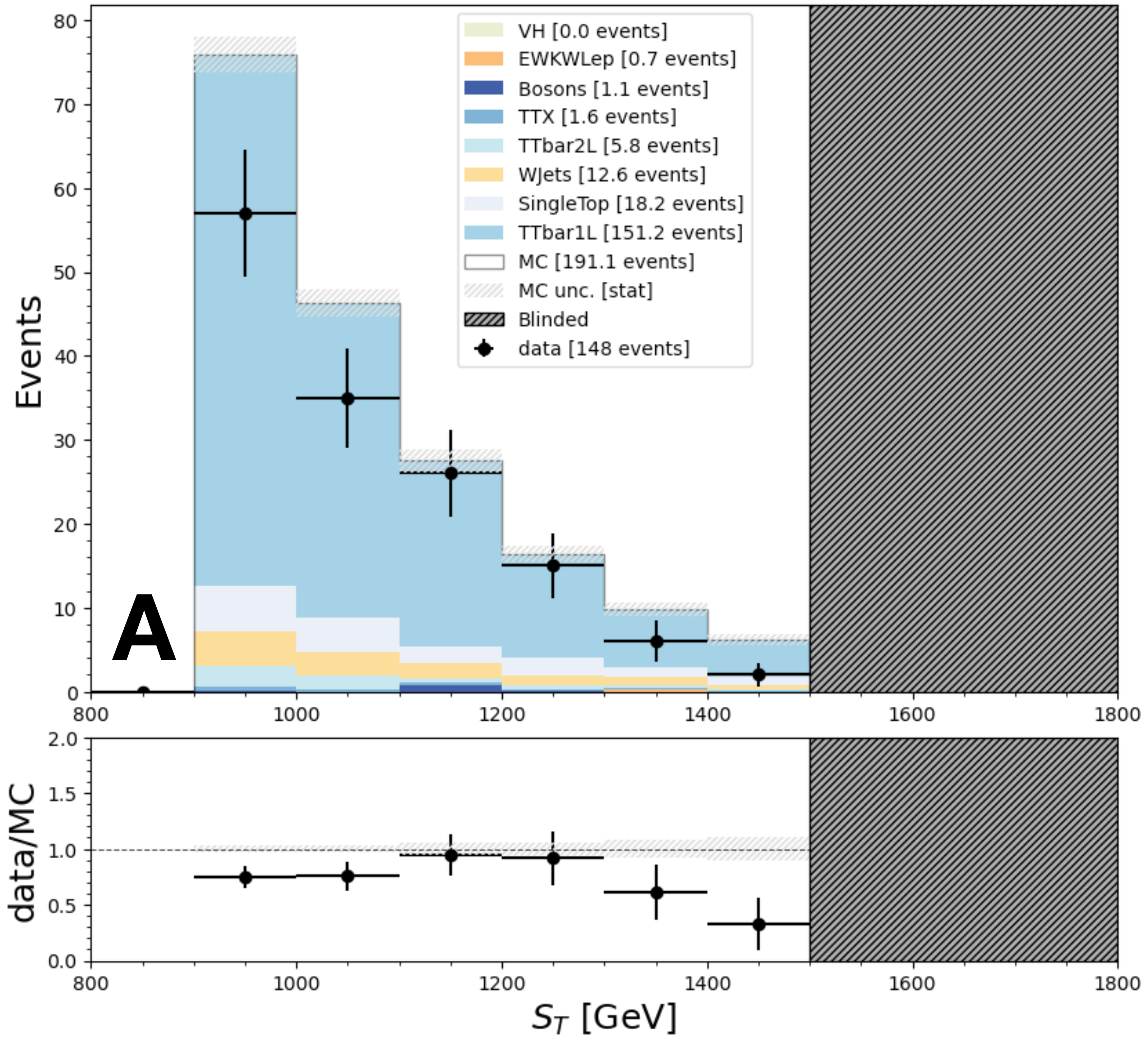

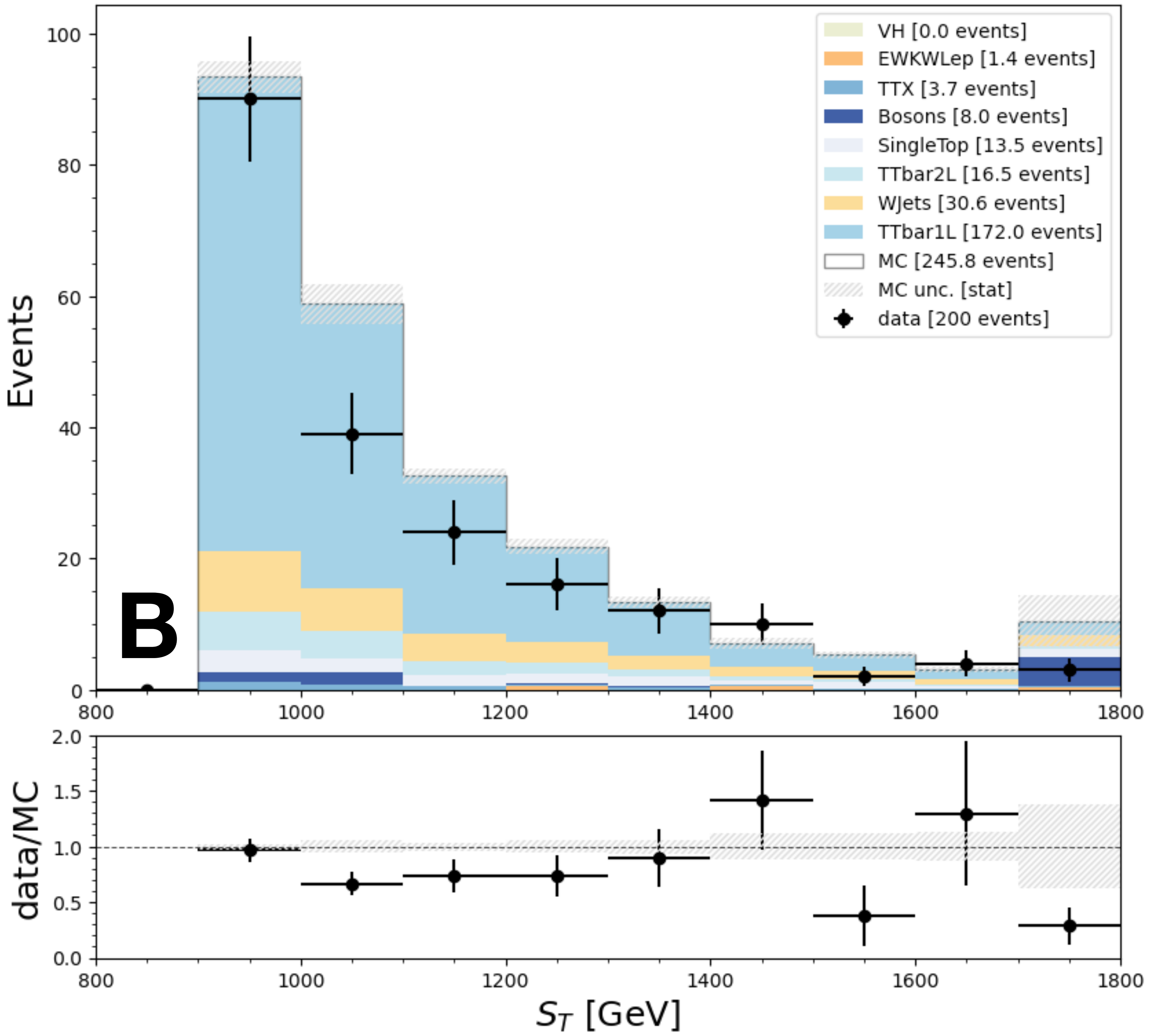

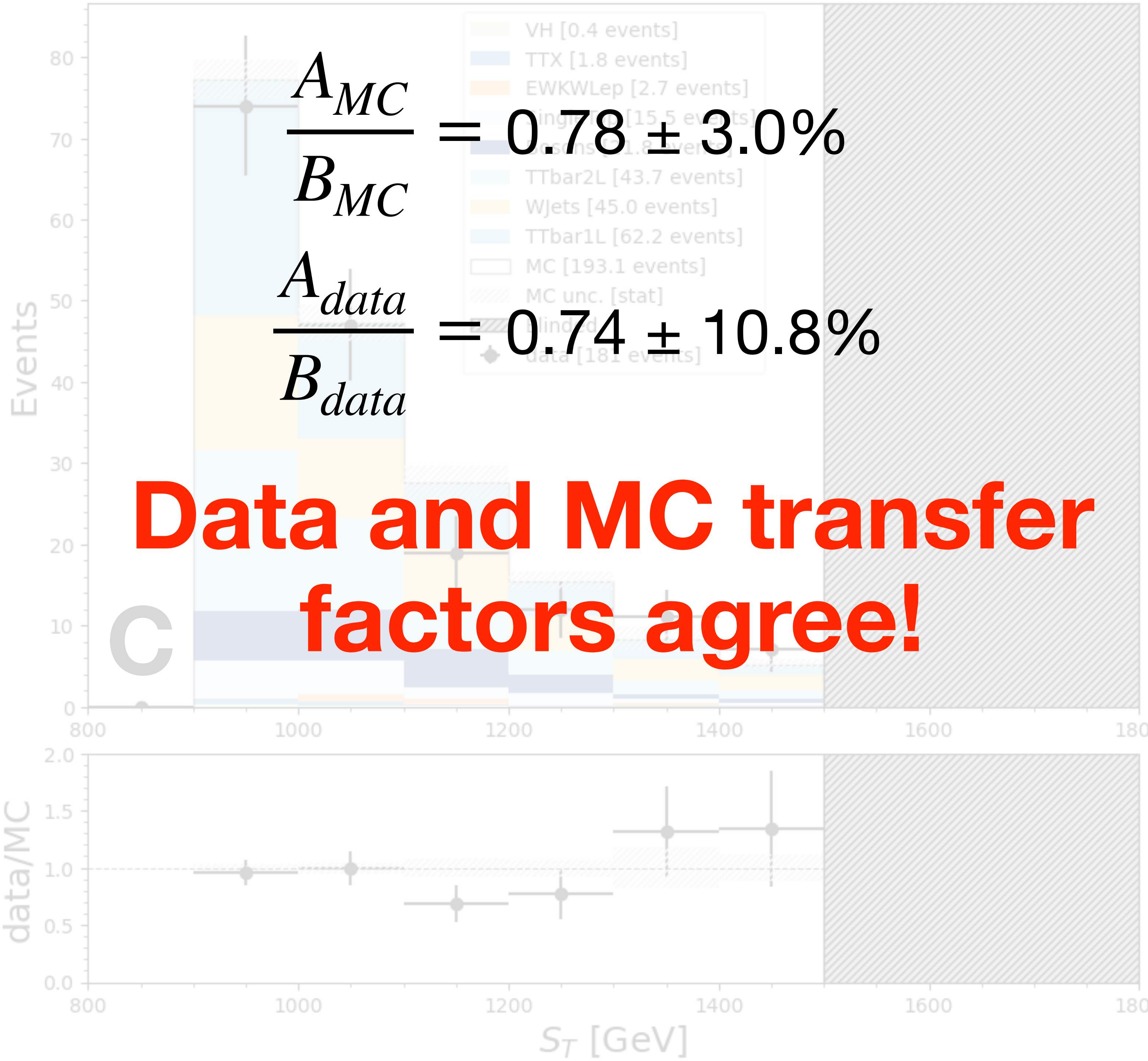

$$\frac{A_{MC}}{B_{MC}} = 0.78 \pm 3.0\%$$

$$\frac{A_{data}}{B_{data}} = 0.74 \pm 10.8\%$$

Data and MC transfer factors agree!

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

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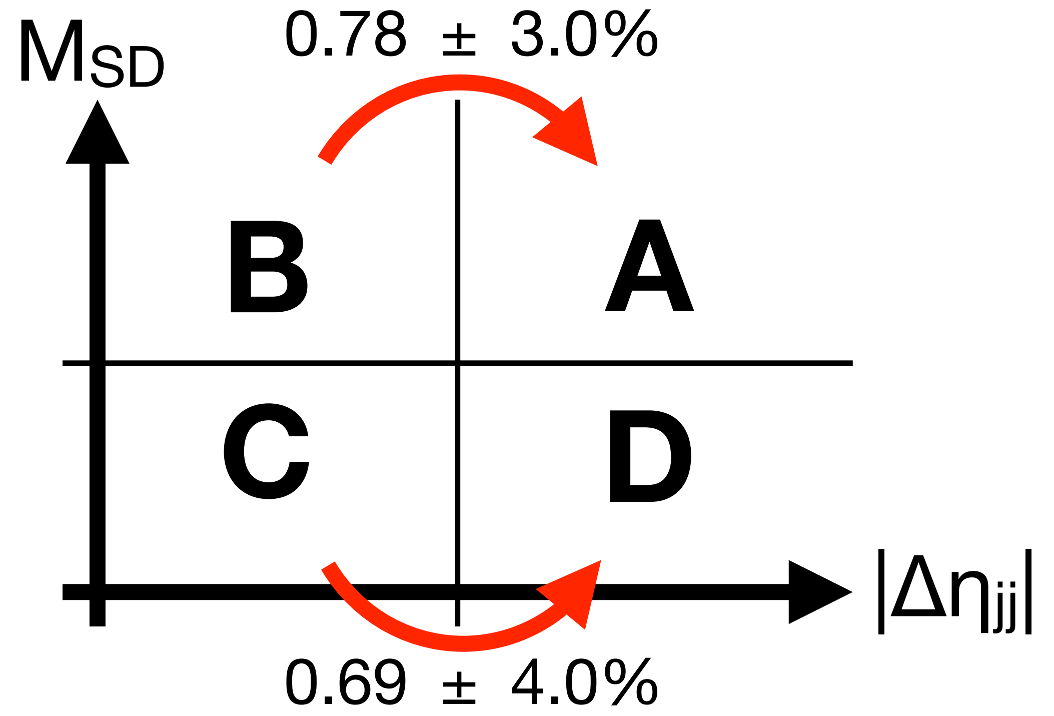
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

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.*
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} ≥ 150 GeV	A	191.14	3.48	10.60	1.36	148	12.17
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	245.76	5.90	0.89	0.44	200	14.14
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} < 150 GeV	C	193.14	4.61	14.75	1.57	181	13.45
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} < 150 GeV (SR1)	D	**133.44**	4.31	395.72	8.45	–	–



- Errors: 14% (syst.), 13% (stat.)

Over-predicted

$$D^{pred}_{MC} = \frac{A_{MC}}{B_{MC}} \times C_{MC} = 150.21$$

$$\epsilon_{syst} = \left|1 - \frac{D^{pred}_{MC}}{D_{MC}}\right| = \left|1 - \frac{150.2}{133.4}\right| = 13\% \oplus 5\% = 14\%$$

W+Jets comp. (backup)

$$D^{pred}_{data} = \frac{A_{data}}{B_{data}} \times C_{data} = 133.94$$

$$\epsilon_{stat} = \sqrt{\left(\frac{\sqrt{A_{data}}}{A_{data}}\right)^2 + \left(\frac{\sqrt{B_{data}}}{B_{data}}\right)^2 + \left(\frac{\sqrt{C_{data}}}{C_{data}}\right)^2} = \sqrt{\frac{1}{A_{data}} + \frac{1}{B_{data}} + \frac{1}{C_{data}}} = 13\%$$

Predicted SR1 Yield: 133.9 ± 17.61 ± 18.12

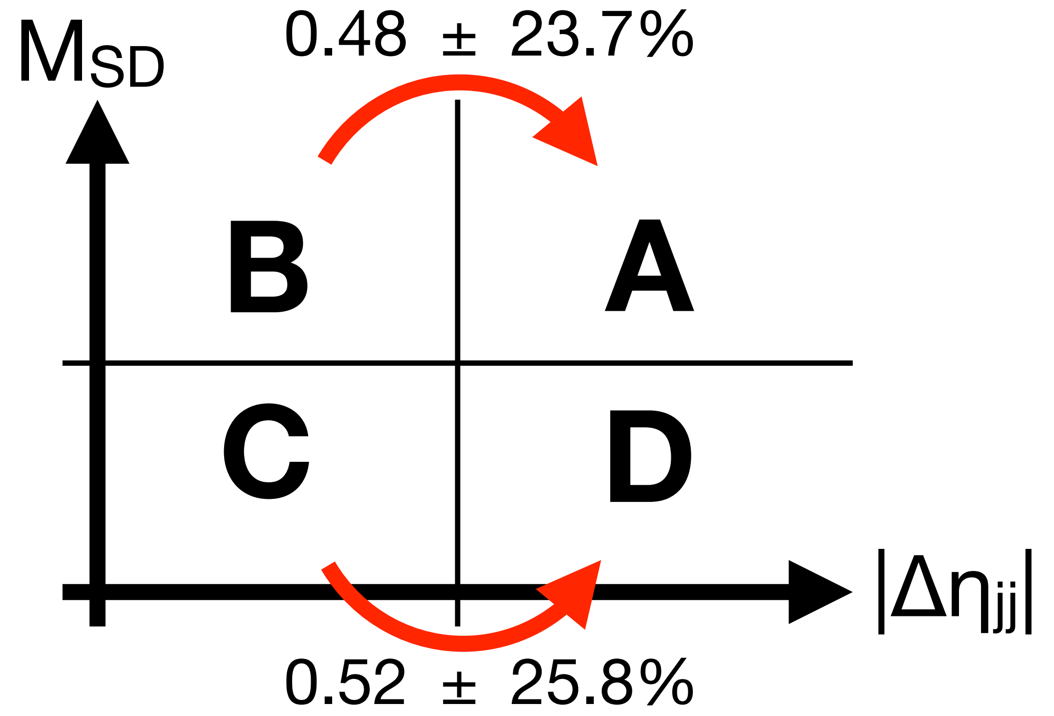
stat. *syst.*

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

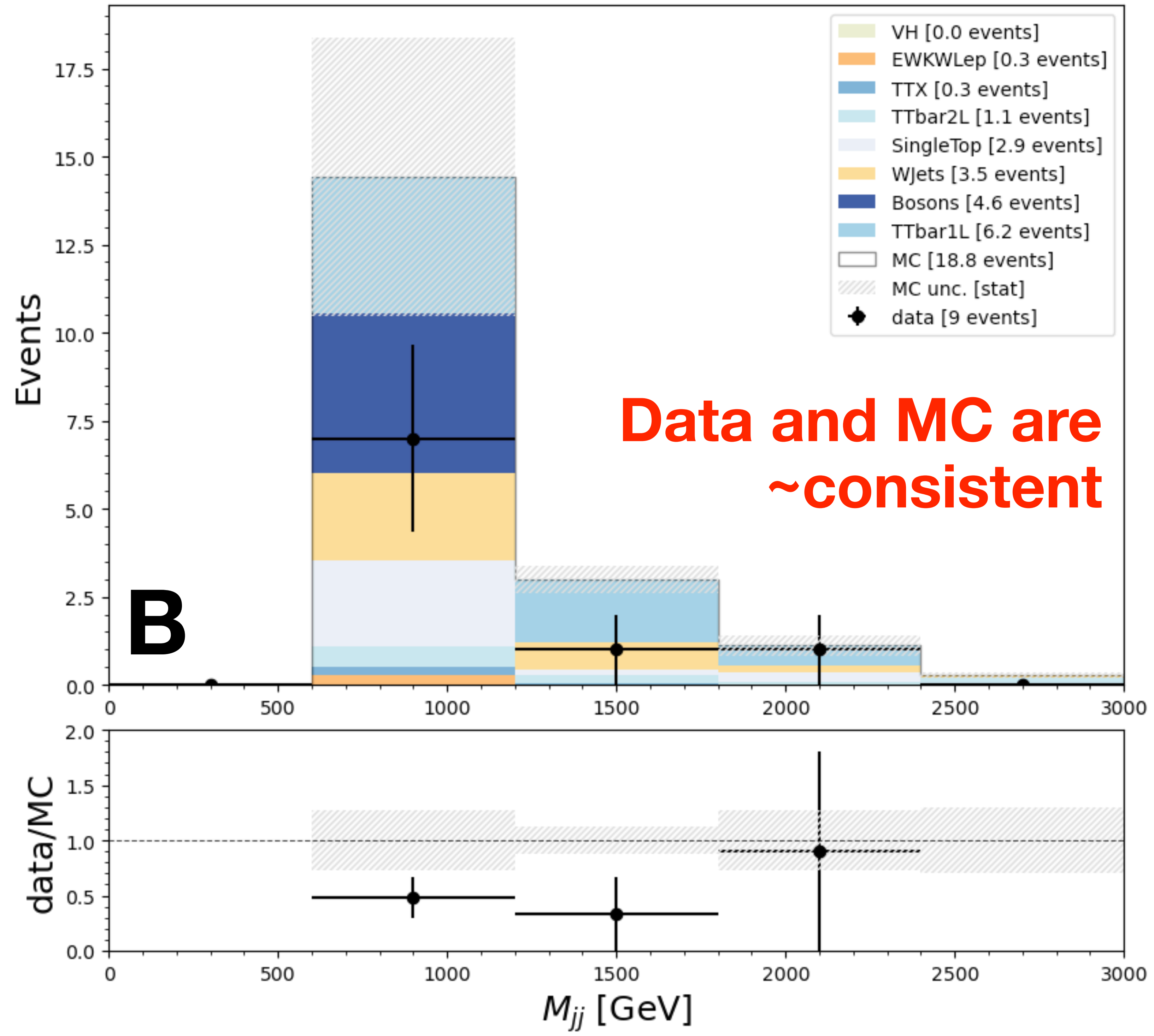
SR2 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 1500 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 $M_{SD} \geq 150$ GeV	A	9.07	0.96	2.13	0.57	—	—
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	**18.81**	3.99	0.00	0.00	**9**	3.00
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	11.96	1.34	4.02	0.83	—	—
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR2)	D	6.26	1.45	112.67	4.54	—	—



- Only region B can be unblinded (right)
  - Data vs. MC somewhat consistent within stat. error
- Strategy:
  - Validate SR1 to SR2 (S_T > 900 to S_T > 1500) efficiency is well-modeled by MC in Region B
  - If above checks out, use MC to calculate SR2/SR1
  - Apply SR2/SR1 from MC to ABCD-predicted SR1 yield



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

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SR1 to SR2: Validate in Region B

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 1500 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	9.07	0.96	2.13	0.57	—	—
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$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} < 150 GeV	C	11.96	1.34	4.02	0.83	—	—
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR2)	D	6.26	1.45	112.67	4.54	—	—

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	191.14	3.48	10.60	1.36	148	12.17
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$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} < 150 GeV	C	193.14	4.61	14.75	1.57	181	13.45
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	133.44	4.31	395.72	8.45	—	—

$$\frac{B_{data,\ SR2}}{B_{data,\ SR1}} \pm \epsilon_{stat} = \mathbf{0.0450} \pm 34.08\%$$

$$\frac{B_{MC,\ SR2}}{B_{MC,\ SR1}} \pm \epsilon_{stat} = \mathbf{0.0765} \pm 21.37\%$$

Consistent

where $\epsilon = \sqrt{\left(\frac{B^{err}_{SR2}}{B_{SR2}}\right)^2 + \left(\frac{B^{err}_{SR1}}{B_{SR1}}\right)^2}$

- To go from SR1 to SR2:
  - Multiply predicted bkg in SR1 by MC SR1/SR2 efficiency ($D_{MC,\ SR1}/D_{MC,\ SR2}$)
  - Take data stat. err. (33%) in B as systematic error

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

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SR1 to SR2: Apply Eff. Measured in MC

Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 1500 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	9.07	0.96	2.13	0.57	—	—
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$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} < 150 GeV	C	11.96	1.34	4.02	0.83	—	—
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR2)	D	**6.26**	1.45	112.67	4.54	—	—

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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$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	**133.44**	4.31	395.72	8.45	—	—

- Errors: 36% (syst.), 13% (stat.)

$$D^{pred}_{data,\ SR2} = \frac{D_{MC,\ SR2}}{D_{MC,\ SR1}} \times D^{pred}_{data,\ SR1} = 6.28$$

$$\epsilon_{syst} = \sqrt{(\epsilon_{syst,\ SR1\rightarrow SR2})^2 + (\epsilon_{syst,\ SR1})^2} = 36\%$$

$$\epsilon_{stat} = \left(\frac{D_{MC,\ SR2}}{D_{MC,\ SR1}} \times D^{pred}_{data,\ SR1} \times \epsilon_{stat,\ SR1}\right)\frac{1}{D^{pred}_{data,\ SR2}} = 13\%$$

Predicted Yield: 6.28 ± 0.83 ± 2.26

stat. syst.

*err = √(Σ$_i$w$_i^2$) for MC, √(count) for data

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Signal Systematics

- High enough statistics in SR1 that signal systematics should be carefully considered
- Planning to compute signal systematics for the following:
  - Scale factors: ParticleNet Xbb, ~~PKU lepton ID (POG)~~, ~~DeepJet (for b-veto)~~, ~~trigger efficiency~~
  - M_{SD} resolution
  - ~~JES, JER, MET~~
  - ~~Pileup reweighting~~
  - ~~Renormalization and factorization scales~~
  - ~~PDF~~
  - ~~Simulation statistics~~
  - ~~Luminosity~~ (2.5%)

Summary

- Presented an updated roadmap towards a final result with two signal regions:

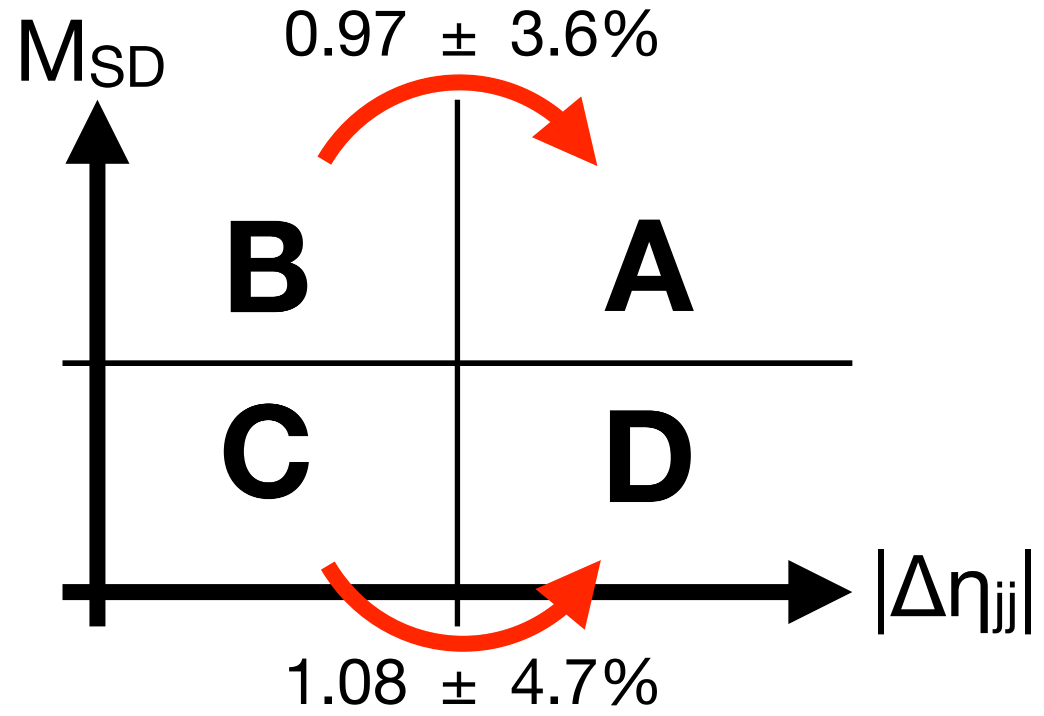
	Signal Region 1 (SR1)	Signal Region 2 (SR2)
Yields	**Expected sig: 396 ± 8.5** **Predicted bkg: 134 ± 17.6 ± 18.1** *stat. syst.*	**Expected sig: 113 ± 4.5** **Predicted bkg: 6 ± 0.8 ± 2.3** *stat. syst.*
Description	• Data-driven bkg. extrapolation • Can exclude λ_{WZ} = -1	• Semi-data-driven bkg. extrapolation • Can exclude λ_{WZ} = -1 • Most valuable if SR1 is ambiguous

- Nearly finished with computing signal systematics
- Working towards an expected result (i.e. settle statistical interpretation)
- Finally: write AN and present a final status report

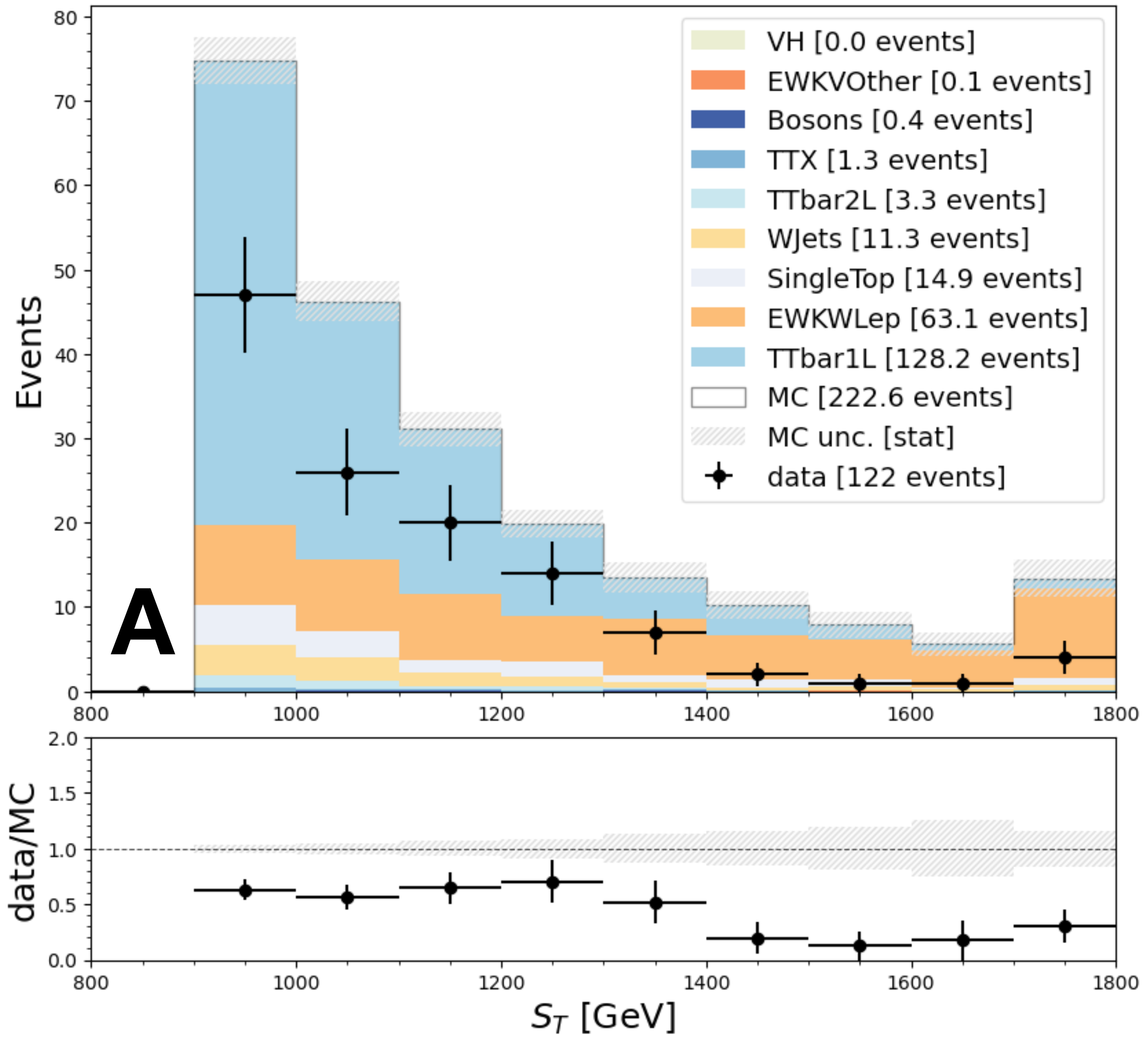
An Aside: Erroneous EWK Samples

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 $M_{SD} \geq 150$ GeV	A	222.65	5.89	9.18	1.25	122	11.05
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	230.24	5.58	1.00	0.45	179	13.38
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	171.95	4.84	14.00	1.55	142	11.92
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	185.91	6.90	370.22	8.16	–	–



- Last time: it was suggested that we add EWK samples
- EWK W ($W \rightarrow \ell\nu$) particularly problematic because it **destroys data/MC agreement** in Region A for SR1 ABCD
  - Especially bad at high $S_T = p_T(\ell) + \text{MET} + p_T(\text{Hbb jet})$
- How do they enter this analysis in the first place?
  - Focus only on relevant samples



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

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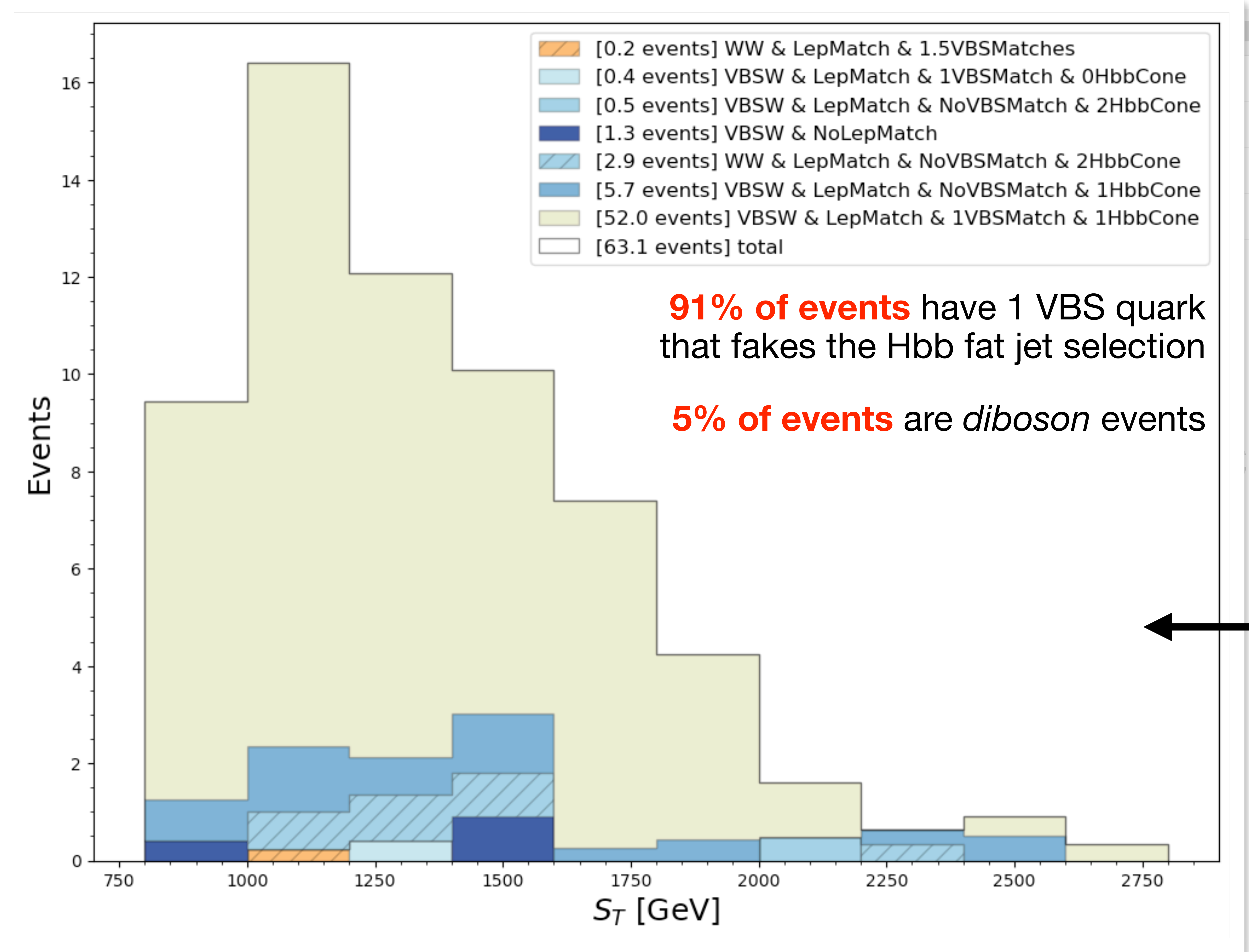
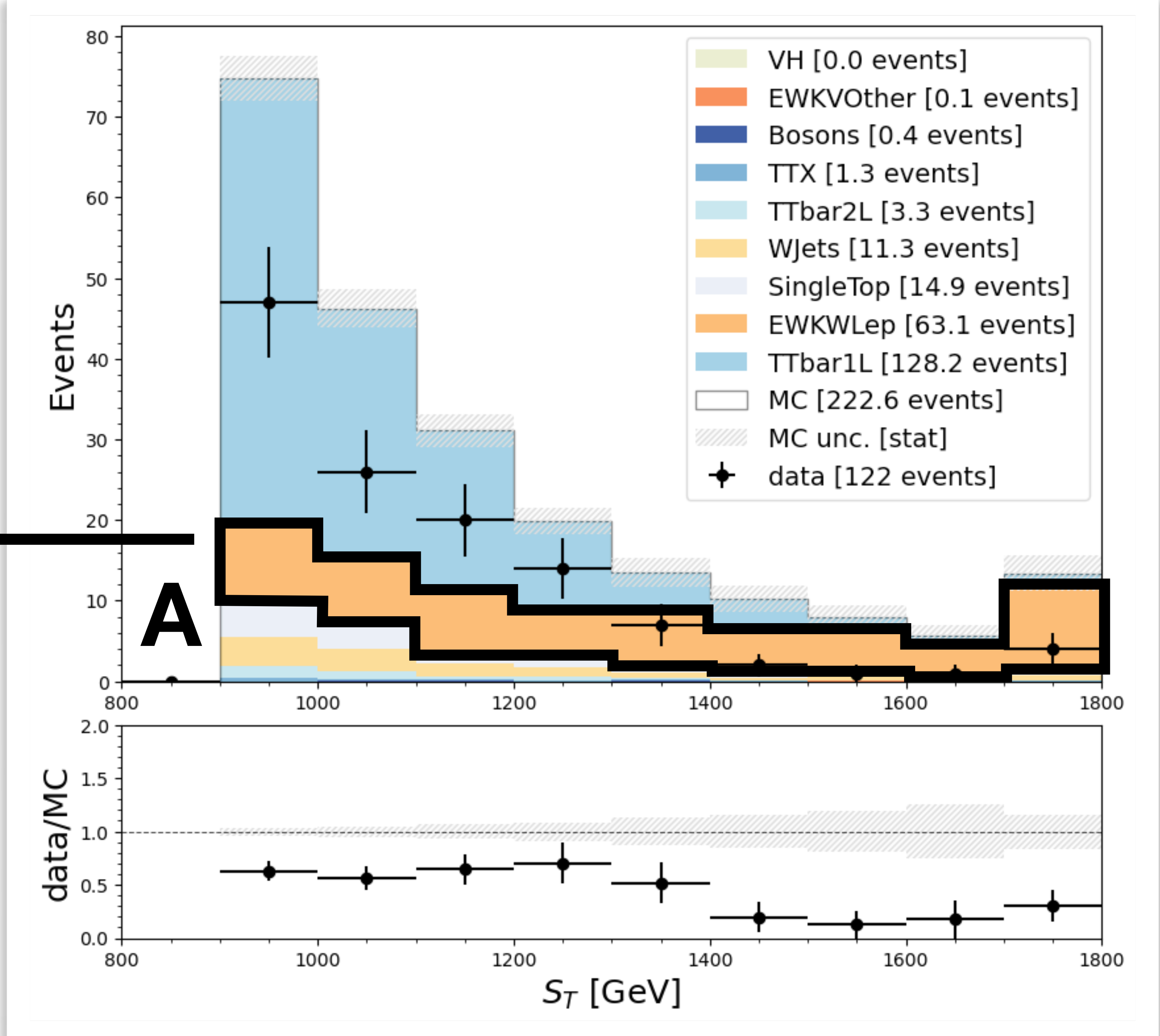
An Aside: Erroneous EWK Samples

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

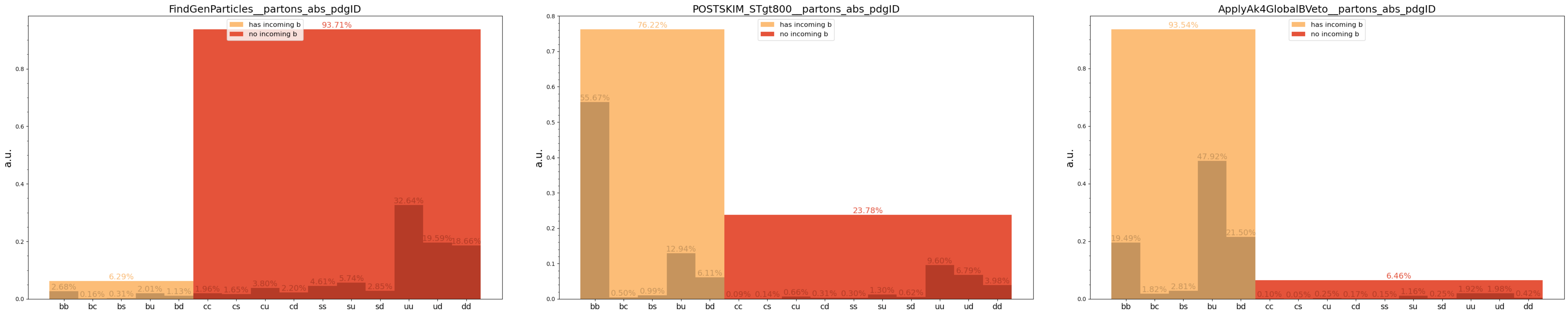
Cut	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4	122	11.05
$\lvert\Delta\eta_{jj}\rvert \leq$ 4	179	13.38
$\lvert\Delta\eta_{jj}\rvert \leq$ 4	142	11.92
$\lvert\Delta\eta_{jj}\rvert$ > 4	—	—





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

An Aside: Erroneous EWK Samples



No selection → … → Skim selections → … → Preselection

- After preselection, 93% of EWK W events are b-initiated
  - EWK W samples generated with 5-flavor scheme
- Fat jet selections + S_T cut in skim are mostly responsible
  - Outgoing VBS b quarks have higher p_T and are more central

An Aside: Erroneous EWK Samples

- EWK W samples generated as follows:

```
generate pp > l vl j j / t t~ h QCD = 0
```

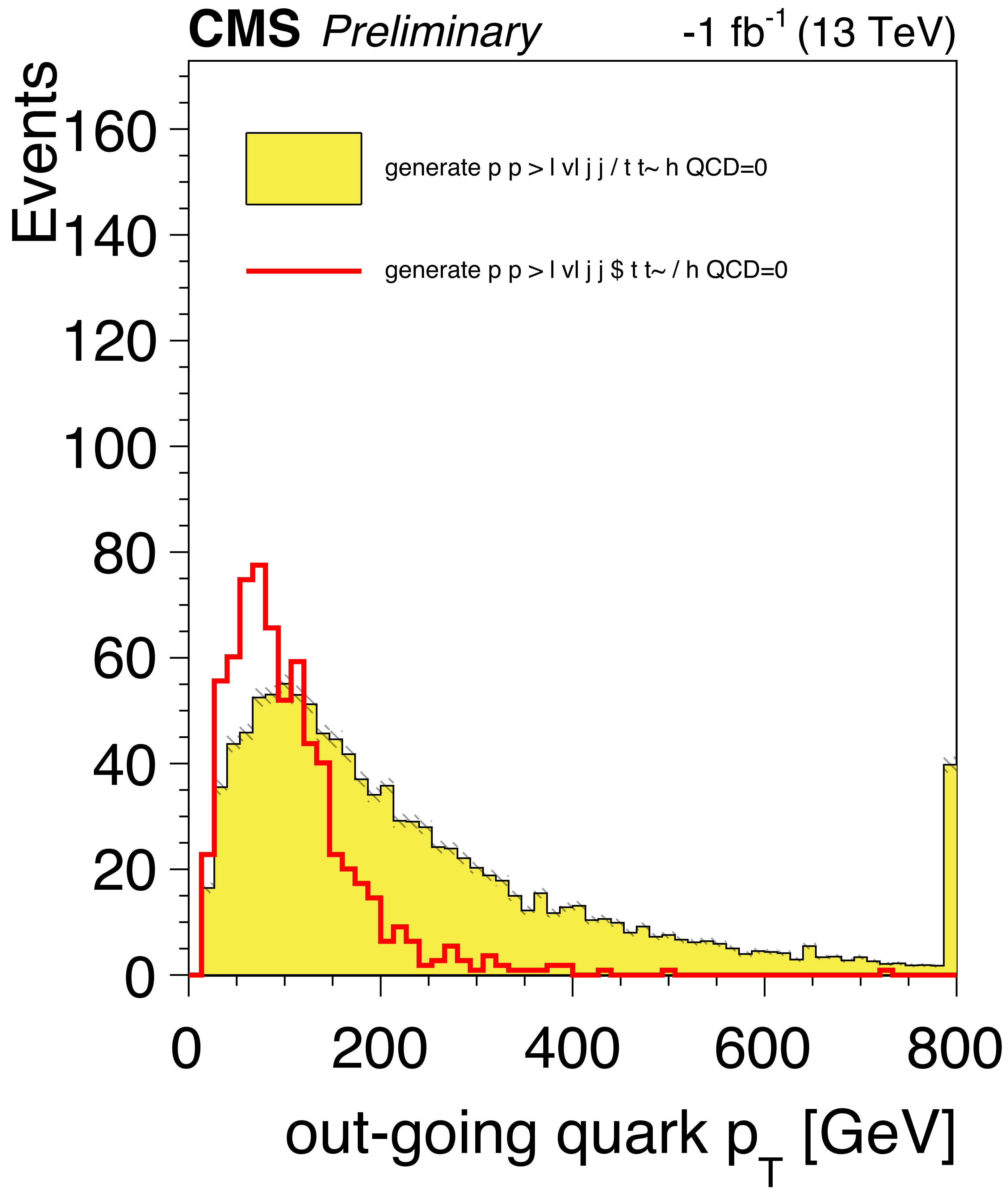
  - The **slash** notation excludes t, $\bar{t}$, and H diagrams from generation, and *ignores* any interference terms from them

- If we instead use

```
generate pp > l vl j j $ t t~ / h QCD = 0
```

  - The **dollar-sign** notation also excludes the t and $\bar{t}$ diagrams, but *includes* interference terms

  - We see high-p_T tail of outgoing b quarks disappears



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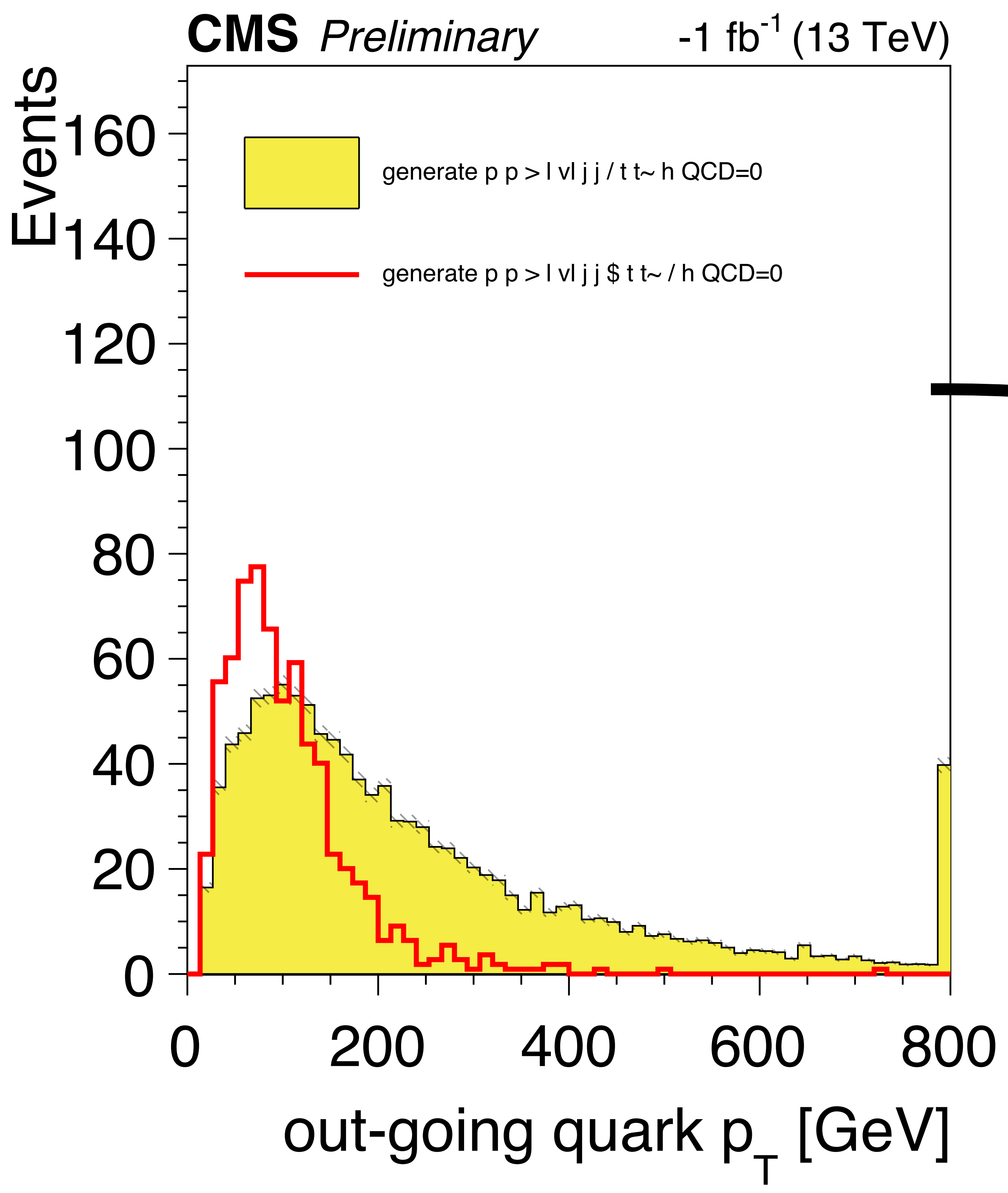
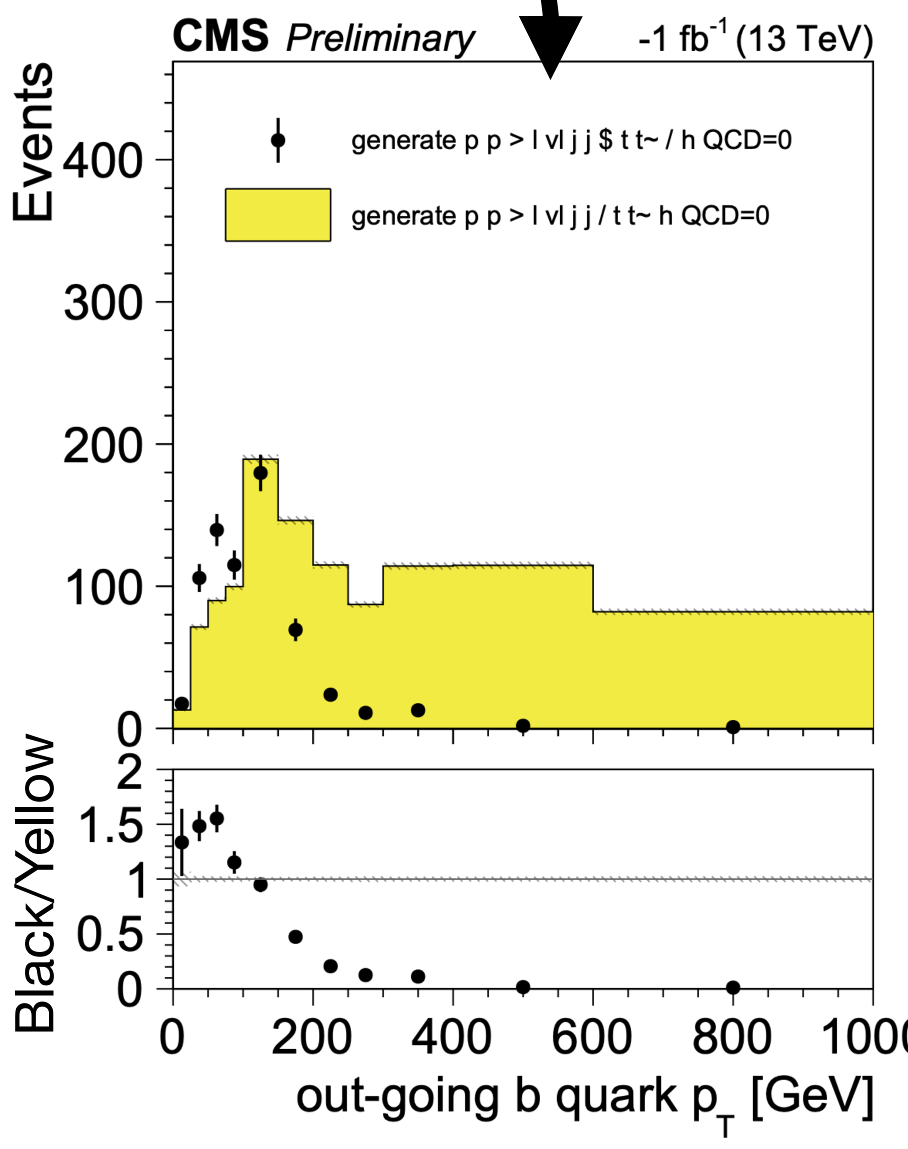
An Aside: Erroneous EWK Samples

- Implies there is significant interference from t and $\bar{t}$ diagrams that is currently ignored
- Essentially a “BSM” model where the top quark does not exist
  - Specifically affects us: fat jet selection is faked by high p_T outgoing b quarks
- Derived a scale factor to correct outgoing b quark p_T distribution
- Completely removes EWK W contribution to CRs in question → rescues data/MC



Use re-binned ratio as scale factor



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Backup

Who is involved?

- UC San Diego:
  A. Arora‡, L. Giannini†, J. Guiang‡, F. Würthwein*,
  Y. Xiang‡, A. Yagil*
- U. Florida:
  P. Chang*
- Boston University:
  D. Spitzbart†, I. Suarez*
- UC Santa Barbara:
  C. Campagnari*

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

BSM Signal Models

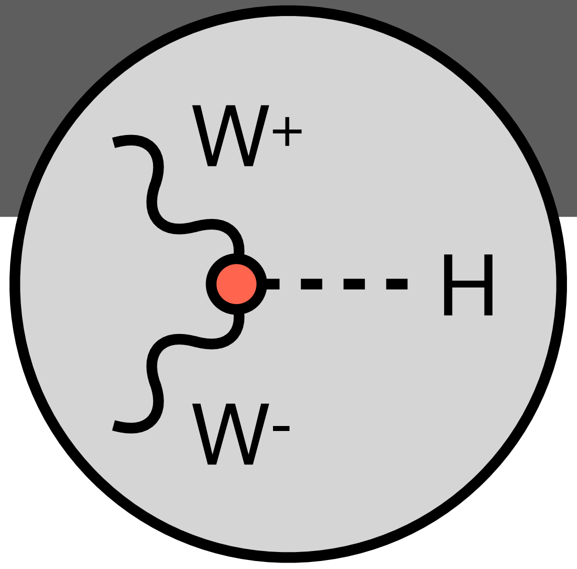
$\kappa_W = -1$

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})
```



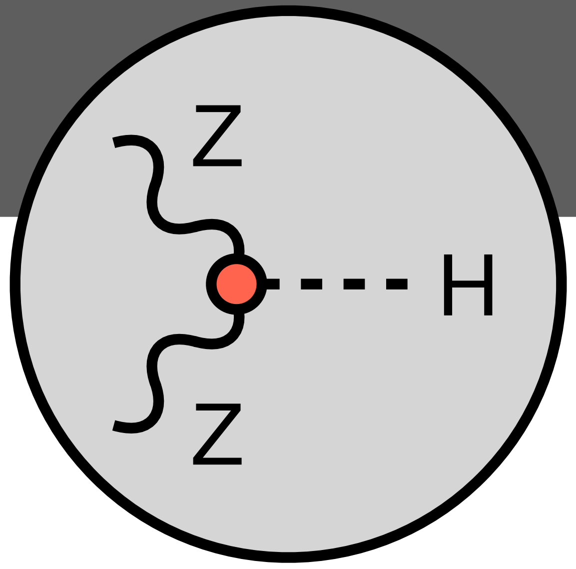
$\kappa_Z = -1$

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})
```

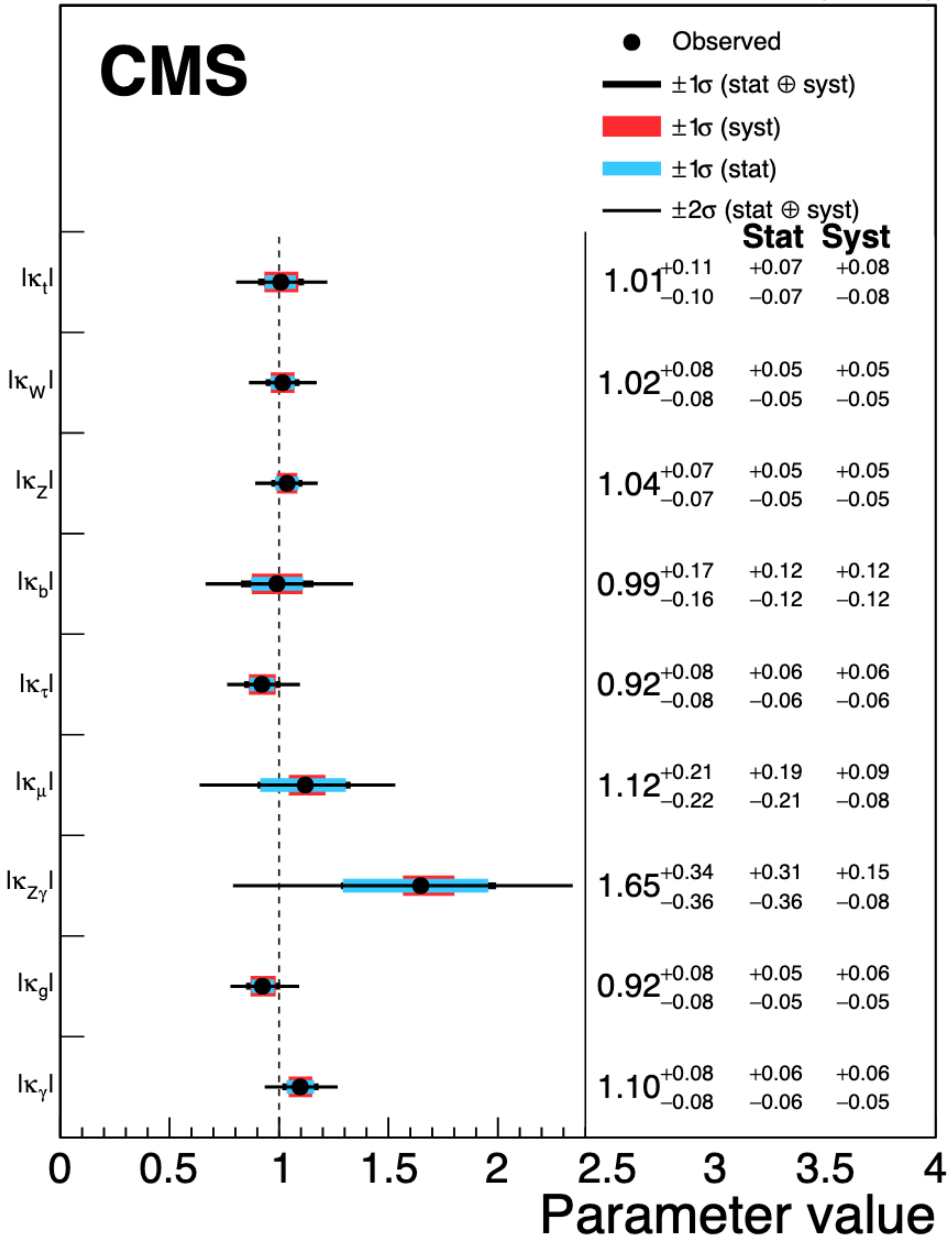


Only changed one line in SM Madgraph model!

Why only λ_{WZ} = -1?

- Other analyses have already pinned $|\kappa_W| = 1$ and $|\kappa_Z| = 1$ with less than 10% uncertainty
    - i.e. we know $|\lambda_{WZ}| = 1 \Rightarrow \lambda_{WZ} = +1$ or $\lambda_{WZ} = -1$
- If we can exclude $\lambda_{WZ} = -1$, then we are done
- This analysis can very effectively exclude $\lambda_{WZ} = -1$
- Further effort to scan the magnitude of κ_W or κ_Z does not seem worthwhile

*From AN-2021/214**



*Identical to the figure published in Nature

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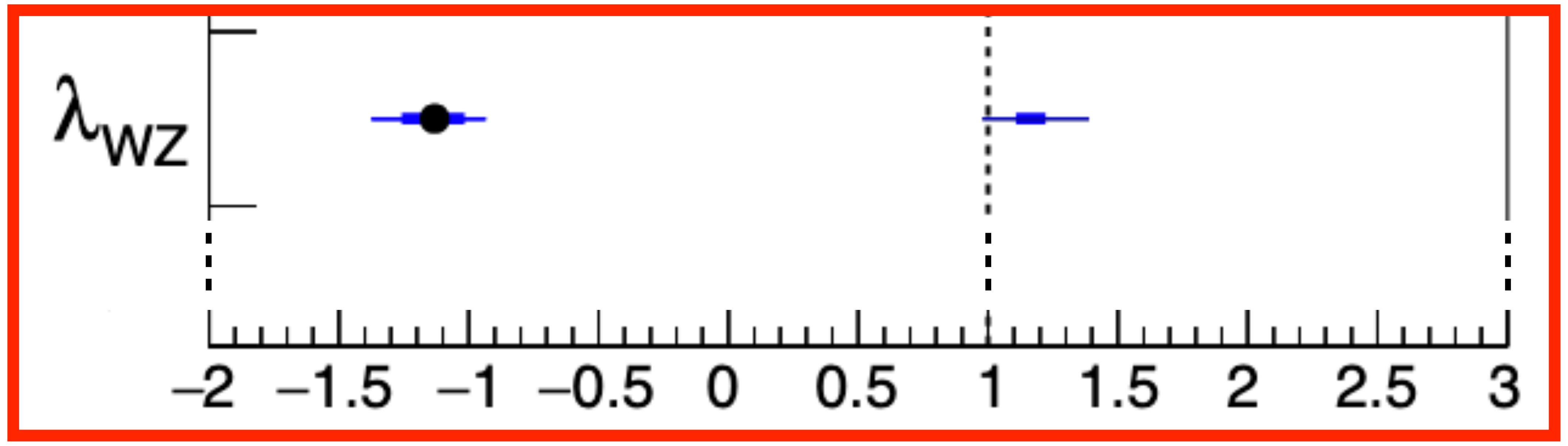
2016 CMS Result



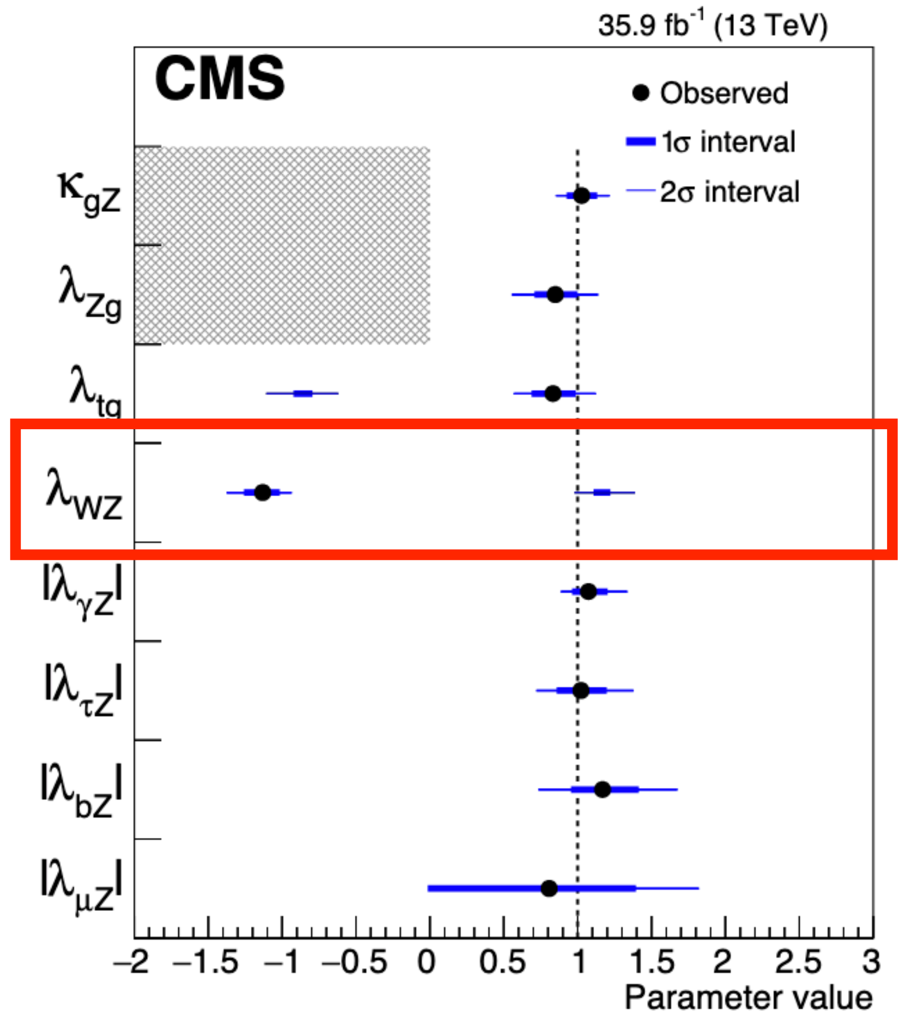
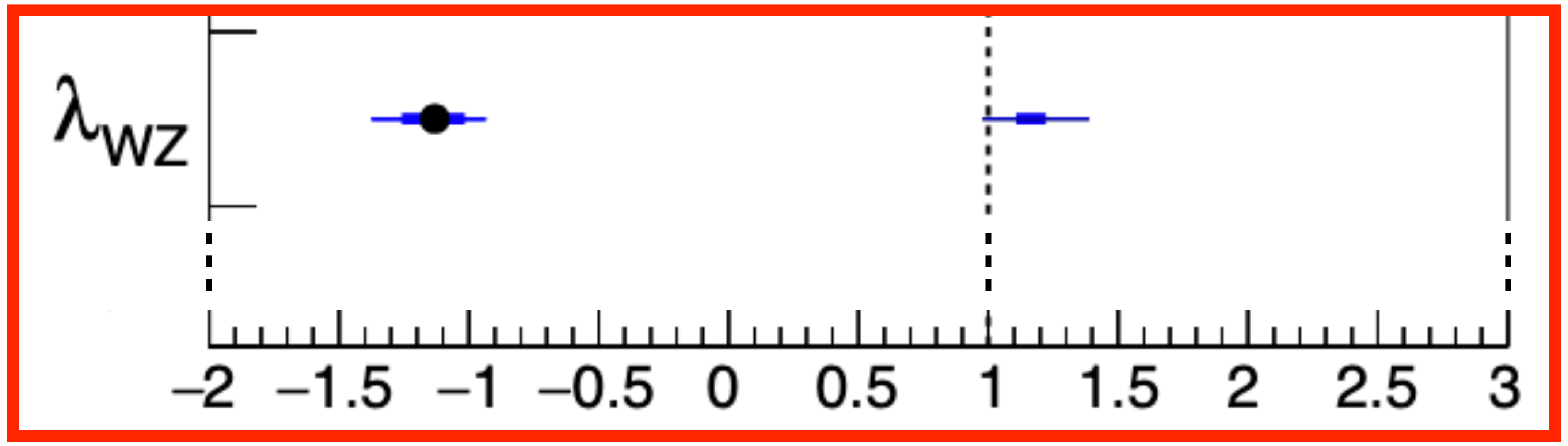


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \rightarrow \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values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



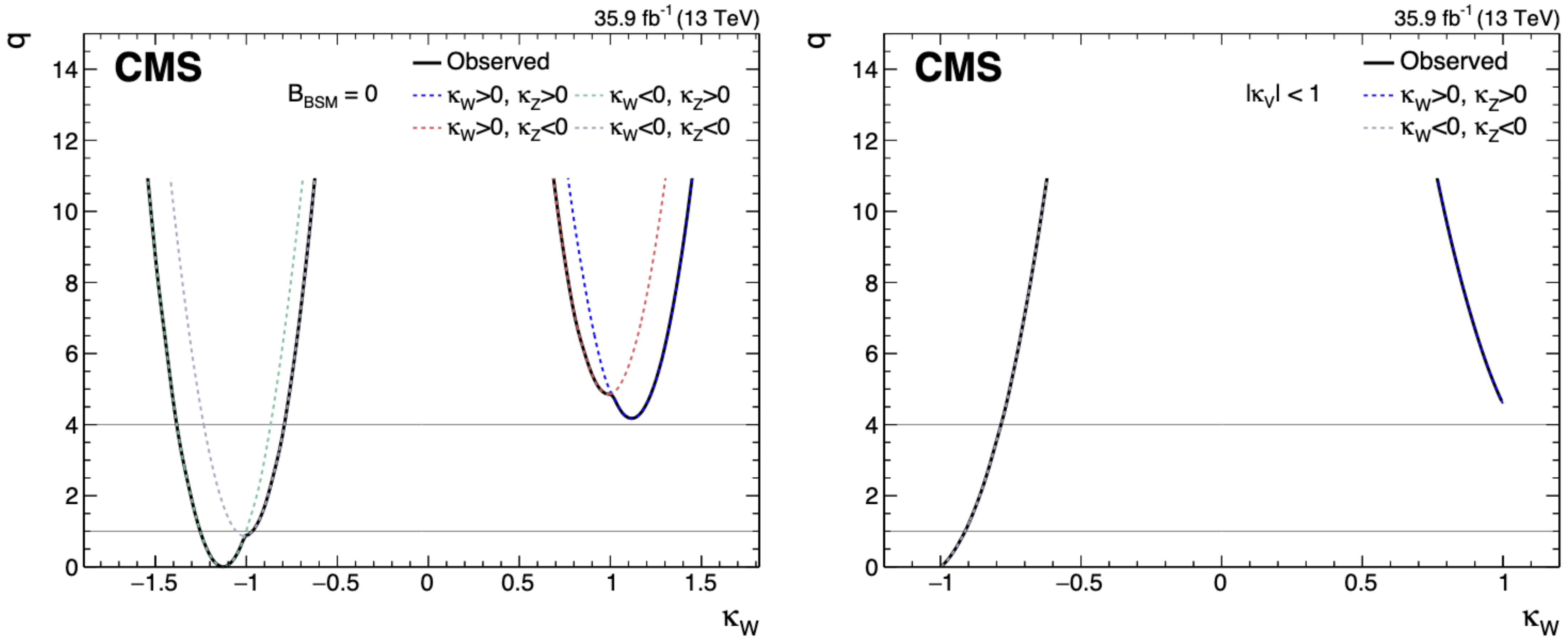


Figure 13: Scan of the test statistic q as a function of κ_W in the generic κ model assuming $\mathcal{B}_{BSM} = 0$ (left) and allowing $\mathcal{B}_{inv}$ and $\mathcal{B}_{undet}$ to float (right). The different colored lines indicate the value of q for different combinations of signs for κ_W and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

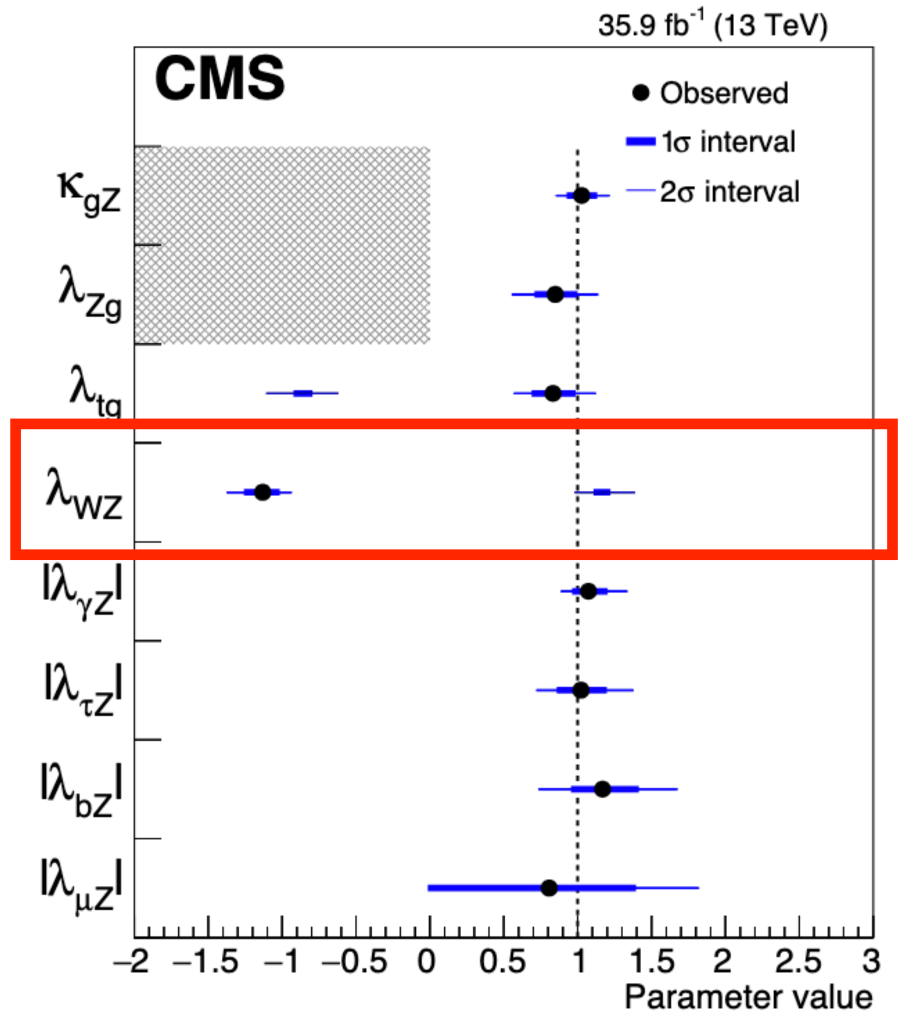


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of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

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

MC Samples: 2016

Process	Sample Name	σ [pb]
SingleTop	/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	136.02
	/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[0]	19.559
	/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[0]	19.559
	/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	80.95
TTbar1L	/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8[0]	373.9093904
TTbar2L	/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	94.936764
TTX	/TTToHadronic_TuneCP5_13TeV-powheg-pythia8[0]	367.825066
	/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8[1]	0.2043
	/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8[0]	0.2529
	/ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.1279
	/ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.215
	/TTWZ_TuneCP5_13TeV-madgraph-pythia8[0]	0.003884
	/TTWW_TuneCP5_13TeV-madgraph-pythia8[0]	0.0115
	/TTbb_4f_TTTo2L2Nu_TuneCP5-Powheg-Openloops-Pythia8[0]	0.04
	/TTbb_4f_TTToSemiLeptonic_TuneCP5-Powheg-Openloops-Pythia8[0]	0.62
WJets	/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1310.78
	/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1325.9
	/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8[0]	348.5703
	/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8[0]	47.308275
	/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8[0]	11.358487
	/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8[0]	5.2086934
	/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1.1880809
	/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8[1]	0.024098031
Bosons	/DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	20657.0
	/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	6198.0
	/EWKWplus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKWminus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKZ2Jets_ZToLL_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	6.22
	/EWKZ2Jets_ZToNuNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	10.72
	/EWKZ2Jets_ZToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WWTolnulnu_TuneCP5_13TeV-madgraph-pythia8[0]	12.178
	/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	12.178
	/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.054024
	/WZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[1]	5.6
	/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	4.42965
	/ZZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.28
	/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8[0]	0.564
	/ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg_pythia8[0]	1.256
	/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.2086
	/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.1651
	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.05565
	/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.01398
	/WWJJToLNuLNu_EWK_noTop_TuneCP5_13TeV-madgraph-pythia8[0]	0.284
	/WZJJ_EWK_InclusivePolarization_TuneCP5_13TeV_madgraph-madspin-pythia8[0]	0.01701
	/ZZJJTo4L_TuneCP5_13TeV-madgraph-pythia8[1]	0.00884
EWKWLep	/EWKWPlus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	39.33
	/EWKWMinus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	32.26
VH	/VHToNonbb_M125_TuneCP5_13TeV-amcatnloFXFX_madspin_pythia8[1]	2.207
	/WminusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.04901236122
	/WplusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.08487599411
	/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.02627486511
	/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.002461395396

[0] /RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11-v1/NANOAODSIM
[1] /RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11-v2/NANOAODSIM
[2] /RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11_ext1-v1/NANOAODSIM

Table 1: Background MC samples used in this analysis, corresponding to 2016preVFP detector conditions (UL), with their respective cross sections in picobarns.

Process	Sample Name	σ [pb]
SingleTop	/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	80.95
	/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	136.02
	/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[1]	19.559
	/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[1]	19.559
TTbar1L	/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8[0]	373.9093904
TTbar2L	/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	94.936764
TTX	/TTToHadronic_TuneCP5_13TeV-powheg-pythia8[0]	367.825066
	/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8[0]	0.2043
	/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8[0]	0.2529
	/ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.1279
	/ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.215
	/TTWZ_TuneCP5_13TeV-madgraph-pythia8[0]	0.003884
	/TTWW_TuneCP5_13TeV-madgraph-pythia8[0]	0.0115
	/TTbb_4f_TTTo2L2Nu_TuneCP5-Powheg-Openloops-Pythia8[0]	0.04
	/TTbb_4f_TTToSemiLeptonic_TuneCP5-Powheg-Openloops-Pythia8[0]	0.62
WJets	/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1283.91
	/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1303.06
	/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8[0]	341.046
	/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8[0]	45.4362
	/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8[0]	11.0051
	/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8[0]	4.94177
	/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1.15544
	/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8[1]	0.0216234
Bosons	/DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	20657.0
	/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	6198.0
	/EWKWplus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKWminus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKZ2Jets_ZToLL_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	6.22
	/EWKZ2Jets_ZToNuNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	10.72
	/EWKZ2Jets_ZToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WWTolnulnu_TuneCP5_13TeV-madgraph-pythia8[0]	12.178
	/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	12.178
	/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.054024
	/WZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[1]	5.6
	/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	4.42965
	/ZZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.28
	/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8[0]	0.564
	/ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg_pythia8[0]	1.256
	/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.2086
	/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.1651
	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.05565
	/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.01398
	/WWJJToLNuLNu_EWK_noTop_TuneCP5_13TeV-madgraph-pythia8[0]	0.284
	/WZJJ_EWK_InclusivePolarization_TuneCP5_13TeV_madgraph-madspin-pythia8[0]	0.01701
	/ZZJJTo4L_TuneCP5_13TeV-madgraph-pythia8[1]	0.00884
EWKWLep	/EWKWPlus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	39.33
	/EWKWMinus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	32.26
VH	/VHToNonbb_M125_TuneCP5_13TeV-amcatnloFXFX_madspin_pythia8[1]	2.207
	/WminusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.04901236122
	/WplusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.08487599411
	/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.02627486511
	/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.002461395396

[0] /RunIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17-v1/NANOAODSIM
[1] /RunIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17-v2/NANOAODSIM
[2] /RunIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17_ext1-v1/NANOAODSIM

Table 2: Background MC samples used in this analysis, corresponding to 2016postVFP detector conditions (UL), with their respective cross sections in picobarns.

MC Samples: 2017, 2018

Process	Sample Name	σ [pb]
SingleTop	/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	136.02
	/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[0]	80.95
	/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[1]	19.559
	/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[1]	19.559
TTbar1L	/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8[0]	373.9093904
TTbar2L	/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	94.936764
TTX	/TTToHadronic_TuneCP5_13TeV-powheg-pythia8[0]	367.825066
	/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8[0]	0.2043
	/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8[0]	0.2529
	/ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.1279
	/ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8[1]	0.215
	/TTWZ_TuneCP5_13TeV-madgraph-pythia8[0]	0.003884
	/TTWW_TuneCP5_13TeV-madgraph-pythia8[0]	0.0115
	/TTbb_4f_TTTo2L2Nu_TuneCP5-Powheg-Openloops-Pythia8[0]	0.04
	/TTbb_4f_TTToSemiLeptonic_TuneCP5-Powheg-Openloops-Pythia8[0]	0.62
WJets	/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1319.76
	/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1334.74
	/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8[0]	350.435
	/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8[0]	46.5726
	/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8[0]	11.1485
	/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8[2]	5.02246
	/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8[0]	1.183
	/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8[1]	0.0258083
Bosons	/DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	20657.0
	/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8[0]	6198.0
	/EWKWplus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKWminus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/EWKZ2Jets_ZToLL_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	6.22
	/EWKZ2Jets_ZToNuNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	10.72
	/EWKZ2Jets_ZToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[0]	10.67
	/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WWTolnulnu_TuneCP5_13TeV-madgraph-pythia8[0]	12.178
	/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[1]	12.178
	/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	49.997
	/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.054024
	/WZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[1]	5.6
	/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8[1]	4.42965
	/ZZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	3.28
	/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8[0]	0.564
	/ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg_pythia8[0]	1.256
	/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8[0]	0.1651
	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8[3]	0.05565
	/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8[3]	0.01398
	/WWJJToLNuLNu_EWK_noTop_TuneCP5_13TeV-madgraph-pythia8[0]	0.284
	/WZJJ_EWK_InclusivePolarization_TuneCP5_13TeV_madgraph-madspin-pythia8[0]	0.01701
	/ZZJJTo4L_TuneCP5_13TeV-madgraph-pythia8[1]	0.00884
	/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8[3]	0.2086
EWKWLep	/EWKWPlus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	39.33
	/EWKWMinus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[1]	32.26
VH	/VHToNonbb_M125_TuneCP5_13TeV-amcatnloFXFX_madspin_pythia8[1]	2.207
	/WminusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.04901236122
	/WplusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.08487599411
	/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.02627486511
	/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[0]	0.002461395396

[0] /RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9-v1/NANOAODSIM
[1] /RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9-v2/NANOAODSIM
[2] /RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9-v3/NANOAODSIM
[3] /RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9_ext1-v2/NANOAODSIM

Table 3: Background MC samples used in this analysis, corresponding to 2017 detector conditions (UL), with their respective cross sections in picobarns.

Process	Sample Name	σ [pb]
SingleTop	/ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[0]	19.559
	/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[2]	136.02
	/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8[2]	80.95
	/ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8[0]	19.559
TTbar1L	/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8[2]	373.9093904
TTbar2L	/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[2]	94.936764
TTX	/TTToHadronic_TuneCP5_13TeV-powheg-pythia8[2]	367.825066
	/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8[2]	0.2043
	/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8[2]	0.2529
	/ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8[0]	0.1279
	/ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8[0]	0.215
	/TTWZ_TuneCP5_13TeV-madgraph-pythia8[2]	0.003884
	/TTWW_TuneCP5_13TeV-madgraph-pythia8[2]	0.0115
	/TTbb_4f_TTTo2L2Nu_TuneCP5-Powheg-Openloops-Pythia8[2]	0.04
	/TTbb_4f_TTToSemiLeptonic_TuneCP5-Powheg-Openloops-Pythia8[2]	0.62
WJets	/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8[2]	1321.16
	/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8[2]	1335.7
	/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8[2]	351.689
	/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8[2]	47.1663
	/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8[2]	11.4196
	/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8[2]	5.12389
	/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8[2]	1.18295
	/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8[0]	0.0255202
Bosons	/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8[1]	0.2086
	/DYJetsToLL_M-10to50_TuneCP5_13TeV-madgraphMLM-pythia8[2]	20657.0
	/DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8[2]	6198.0
	/EWKWplus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[2]	10.67
	/EWKWminus2Jets_WToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[2]	10.67
	/EWKZ2Jets_ZToLL_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	6.22
	/EWKZ2Jets_ZToNuNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	10.72
	/EWKZ2Jets_ZToQQ_dipoleRecoilOn_TuneCP5_13TeV-madgraph-pythia8[2]	10.67
	/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[2]	49.997
	/WWTolnulnu_TuneCP5_13TeV-madgraph-pythia8[2]	12.178
	/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8[0]	12.178
	/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[2]	49.997
	/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8[2]	3.054024
	/WZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[2]	5.6
	/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8[0]	4.42965
	/ZZTo2Q2L_mllmin4p0_TuneCP5_13TeV-amcatnloFXFX-pythia8[2]	3.28
	/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8[2]	0.564
	/ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg_pythia8[2]	1.256
	/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8[1]	0.1651
	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8[1]	0.05565
	/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8[1]	0.01398
	/WWJJToLNuLNu_EWK_noTop_TuneCP5_13TeV-madgraph-pythia8[2]	0.284
	/WZJJ_EWK_InclusivePolarization_TuneCP5_13TeV_madgraph-madspin-pythia8[2]	0.01701
	/ZZJJTo4L_TuneCP5_13TeV-madgraph-pythia8[0]	0.00884
EWKWLep	/EWKWPlus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	39.33
	/EWKWMinus2Jets_WToLNu_M-50_TuneCP5_withDipoleRecoil_13TeV-madgraph-pythia8[0]	32.26
VH	/VHToNonbb_M125_TuneCP5_13TeV-amcatnloFXFX_madspin_pythia8[0]	2.207
	/WminusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[2]	0.04901236122
	/WplusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8[2]	0.08487599411
	/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[2]	0.02627486511
	/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8[2]	0.002461395396

[0] /RunIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1-v2/NANOAODSIM
[1] /RunIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1_ext1-v2/NANOAODSIM
[2] /RunIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1-v1/NANOAODSIM

Table 4: Background MC samples used in this analysis, corresponding to 2018 detector conditions (UL), with their respective cross sections in picobarns.

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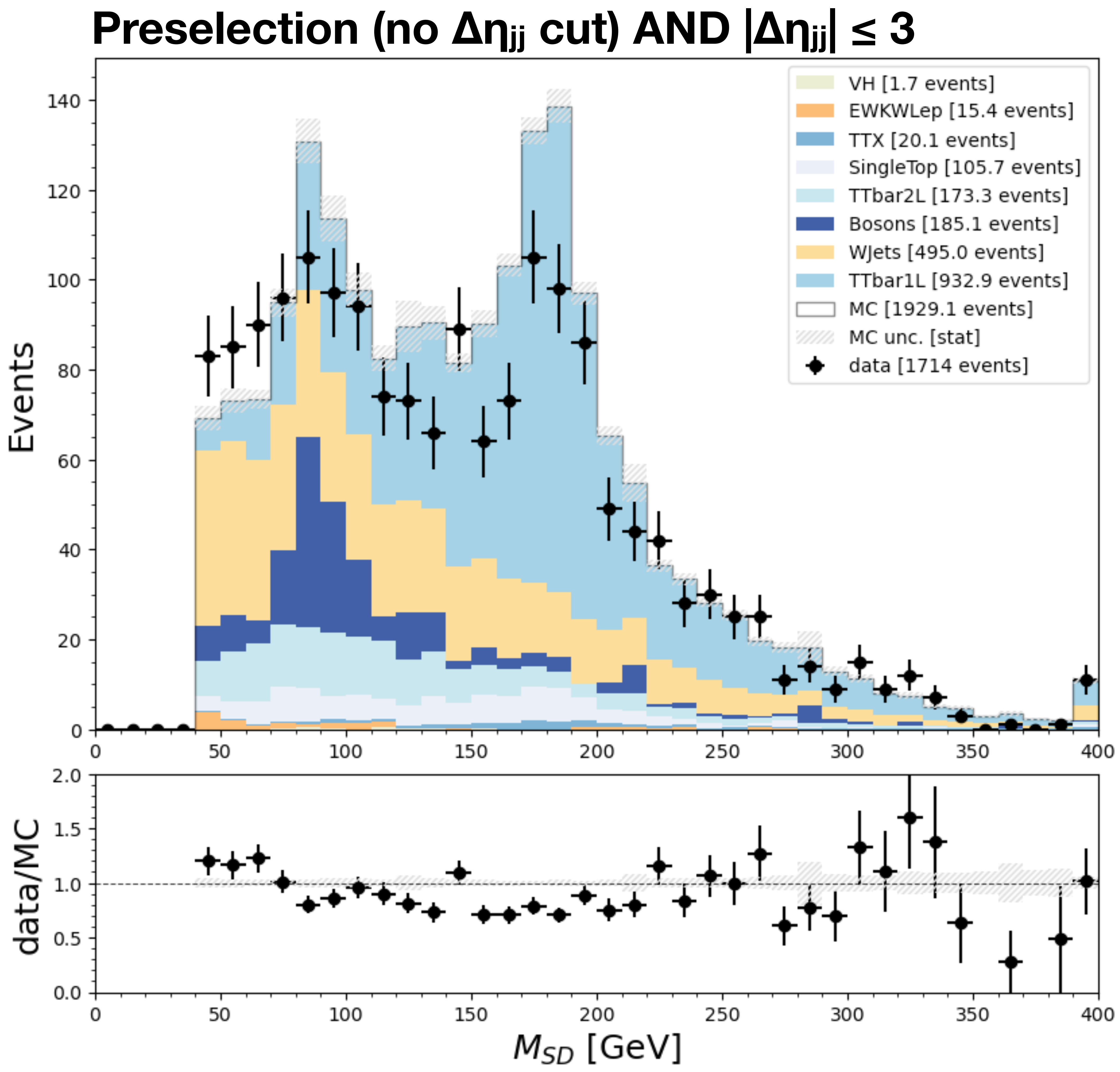
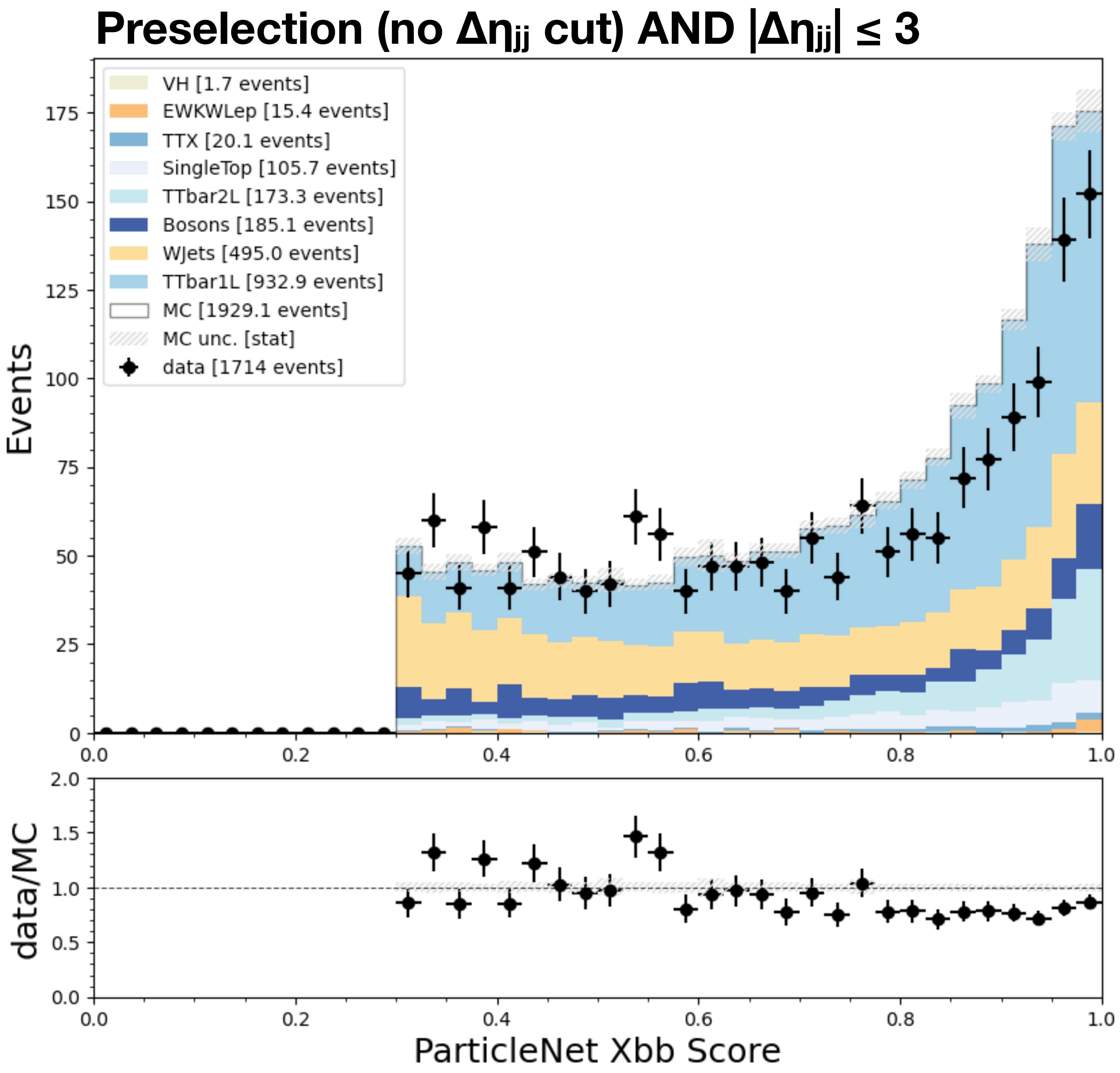
VBS WH Cutflow

Yields scaled to lumi×σ, rounded for readability

	VH		EWKWLep		Bosons		W+Jets		SingleTop		TTbar+X		TTbar1L		TTbar2L		TotalBkg		VBSWH	
cut	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt	raw	wgt
Bookkeeping	80673	228.00	83184	32017.05	886799	25828.35	4682666	133380.10	82462	8176.50	949174	1179.84	2041509	89322.90	295702	11023.32	9102169	301156.06	15189	2175.65
FixEWKSamples	80673	228.00	83184	7471.13	886799	25828.35	4682666	133380.10	82462	8176.50	949174	1179.84	2041509	89322.90	295702	11023.32	9102169	276610.14	15189	2175.65
PassesEventFilters	80296	226.80	82961	7454.95	880194	25663.45	4634787	132873.35	82139	8150.98	945345	1174.97	2036224	89088.60	294500	10978.13	9036446	275611.23	15150	2169.99
SelectLeptons	80296	226.80	82961	7475.48	880194	25663.45	4634787	132873.35	82139	8150.98	945345	1174.97	2036224	89088.60	294500	10978.13	9036446	275631.77	15150	2169.99
Has1TightLep	80296	224.07	82961	7417.81	880194	25371.46	4634787	131329.97	82139	8049.32	945345	1160.42	2036224	87885.90	294500	10817.94	9036446	272256.89	15150	2146.87
LepPtGt40	78713	216.99	81186	7168.00	846368	24292.77	4273473	125338.79	78344	7744.41	885905	1087.57	1946523	84026.60	277528	10186.53	8468040	260061.66	14750	2088.68
Passes1LepTriggers	72604	190.44	75776	6559.09	777350	21577.48	3890340	112336.78	71870	6951.19	803715	873.40	1777943	74742.78	253425	9057.30	7723023	232288.46	13637	1873.94
SelectFatJets	72604	190.44	75776	6654.84	777350	21577.48	3890340	112336.78	71870	6951.19	803715	873.40	1777943	74742.78	253425	9057.30	7723023	232384.22	13637	1873.94
Geq1FatJet	72604	190.44	75776	6800.51	777350	21577.48	3890339	112336.77	71870	6951.19	803715	873.40	1777942	74742.78	253425	9057.30	7723021	232529.87	13637	1873.94
SelectHbbFatJet	72604	190.44	75776	7022.32	777350	21577.48	3890339	112336.77	71870	6951.19	803715	873.40	1777942	74742.78	253425	9057.30	7723021	232751.68	13637	1873.94
SelectJetsNoHbbOverlap	72604	189.45	75776	7351.90	777350	21432.59	3890339	111810.51	71870	7076.68	803715	891.27	1777942	76131.76	253425	9228.99	7723021	234113.15	13637	1866.71
SelectVBSJetsMaxE	23228	57.55	27941	3372.10	451315	12111.25	2840393	54957.74	51694	5008.45	697610	777.25	1307767	56298.19	207197	7604.07	5607145	140186.60	9533	1305.90
SaveSystVariables	23228	57.55	27941	3807.02	451315	12111.25	2840393	54957.74	51694	5008.45	697610	777.25	1307767	56298.19	207197	7604.07	5607145	140621.53	9533	1305.90
SaveVariables	23228	57.55	27941	4473.76	451315	12111.25	2840393	54957.74	51694	5008.45	697610	777.25	1307767	56298.19	207197	7604.07	5607145	141288.26	9533	1305.90
MjjGt500_detajjGt3	4063	11.72	8479	778.36	85352	2314.80	498871	9631.65	13174	1162.22	136305	149.90	279281	11803.33	47457	1710.46	1072982	27562.44	7901	1079.20
XbbGt0p3	2826	5.37	3364	77.02	15256	259.30	43764	729.87	6779	639.81	89724	94.73	159687	6655.08	20855	729.97	342255	9191.15	5130	700.67
ApplyAk4GlobalBVeto	2355	4.31	2058	50.76	12418	210.56	33790	602.85	2357	241.29	23697	26.54	46218	2009.24	6372	230.12	129265	3375.66	4868	666.31
MjjGt600_detajjGt4	1415	2.33	1616	31.04	6682	86.02	13715	305.33	1523	150.41	12747	13.81	27576	1192.76	3554	126.86	68828	1908.56	4571	627.06
STGt900	852	1.72	1315	22.84	4571	54.10	10077	190.33	924	96.83	7913	7.85	14730	630.09	1921	67.70	42303	1071.46	3757	514.92
XbbGt0p9_MSDLt150	665	1.11	277	1.69	1100	8.50	1133	24.70	134	14.53	1031	1.03	1317	56.19	743	25.71	6400	133.44	2889	395.72
SavePDFWeights	665	1.11	277	1.69	1100	8.50	1133	24.70	134	14.53	1031	1.03	1317	56.19	743	25.71	6400	133.44	2889	395.72
STGt1500	68	0.05	42	0.00	137	1.90	181	1.30	6	0.61	54	0.13	30	1.34	26	0.94	544	6.26	803	112.67

Validation: Hbb





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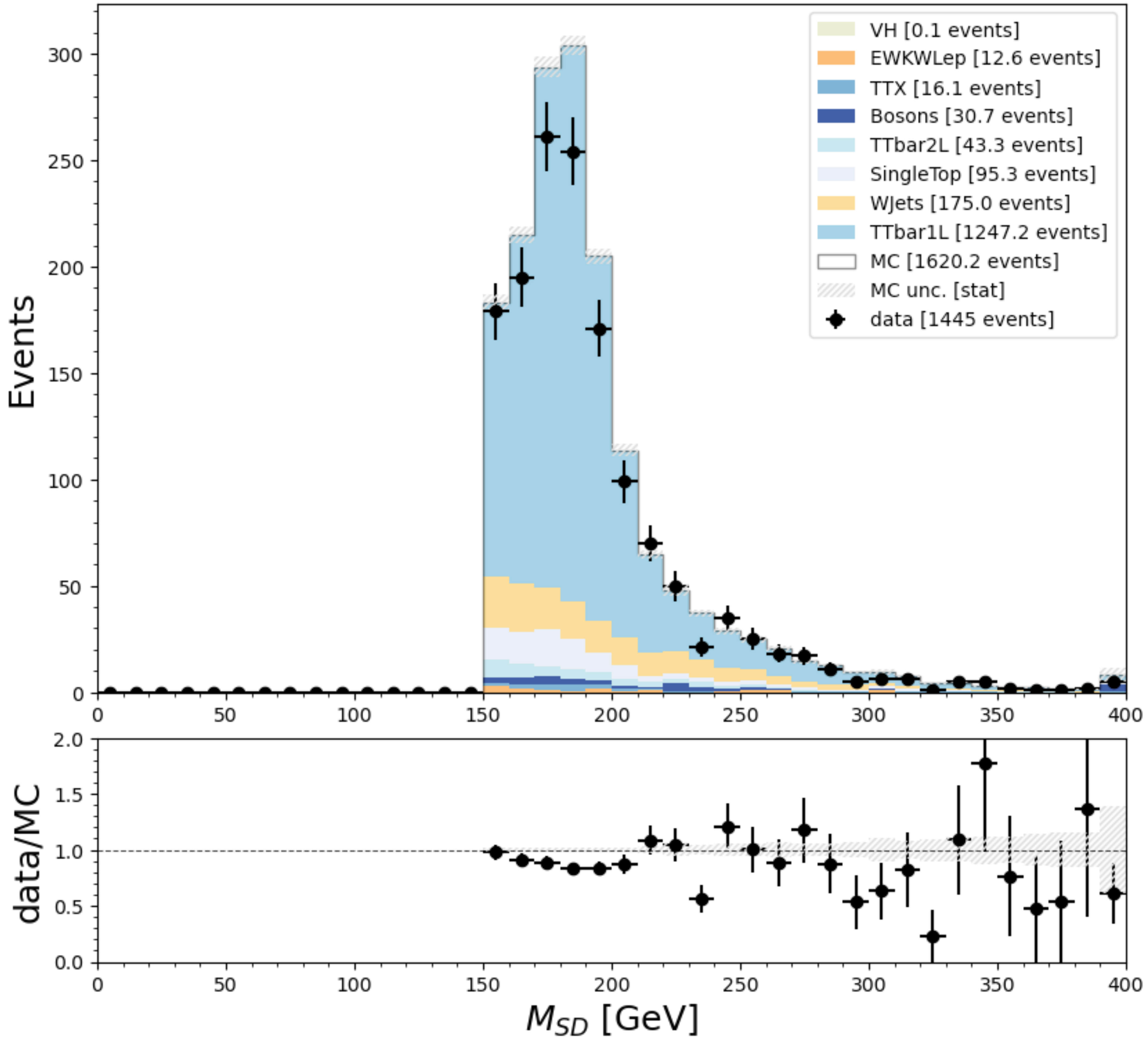
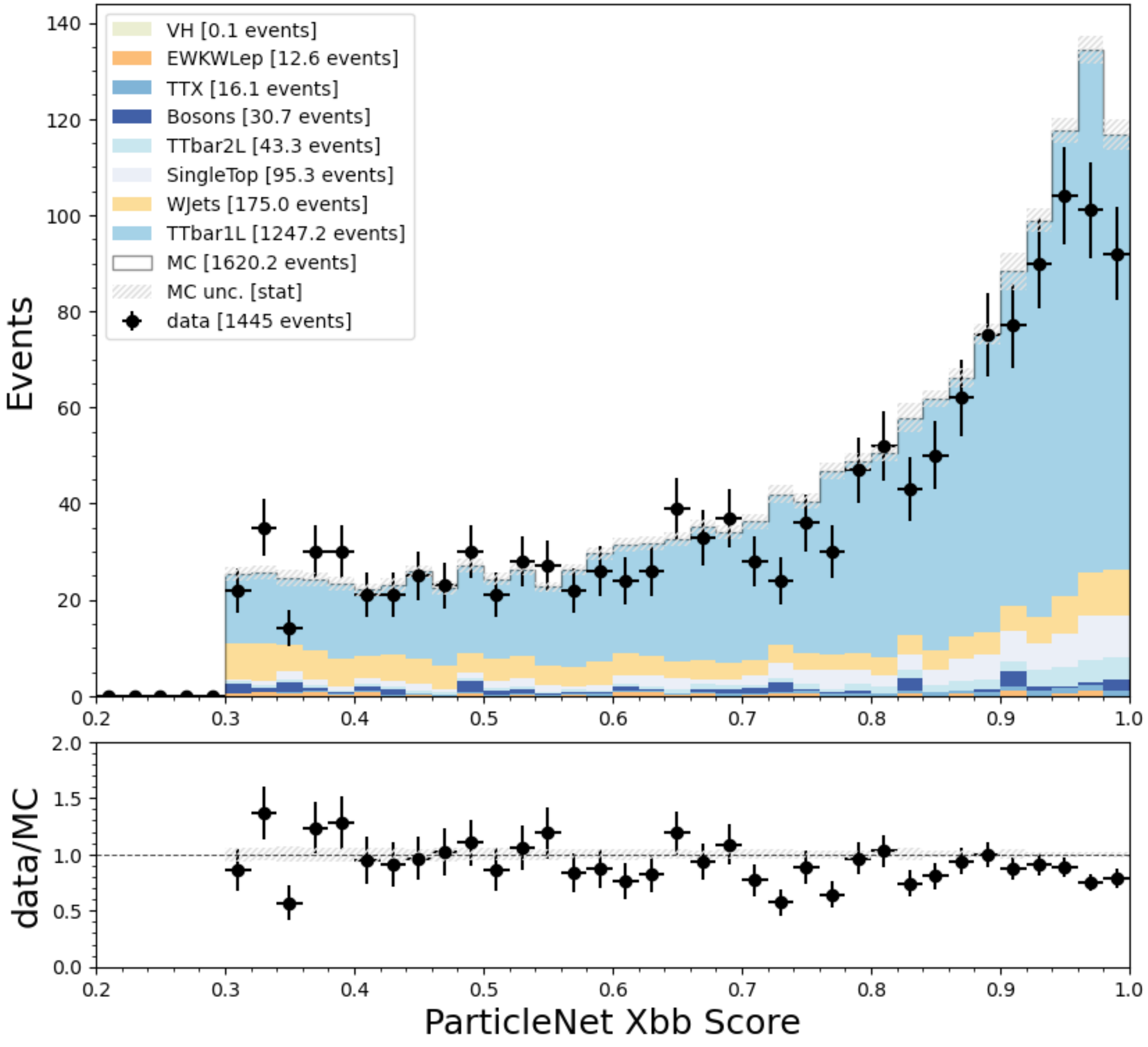
Validation: Hbb

Preselection AND M_{SD} ≥ 150 GeV



Preselection AND M_{SD} ≥ 150 GeV



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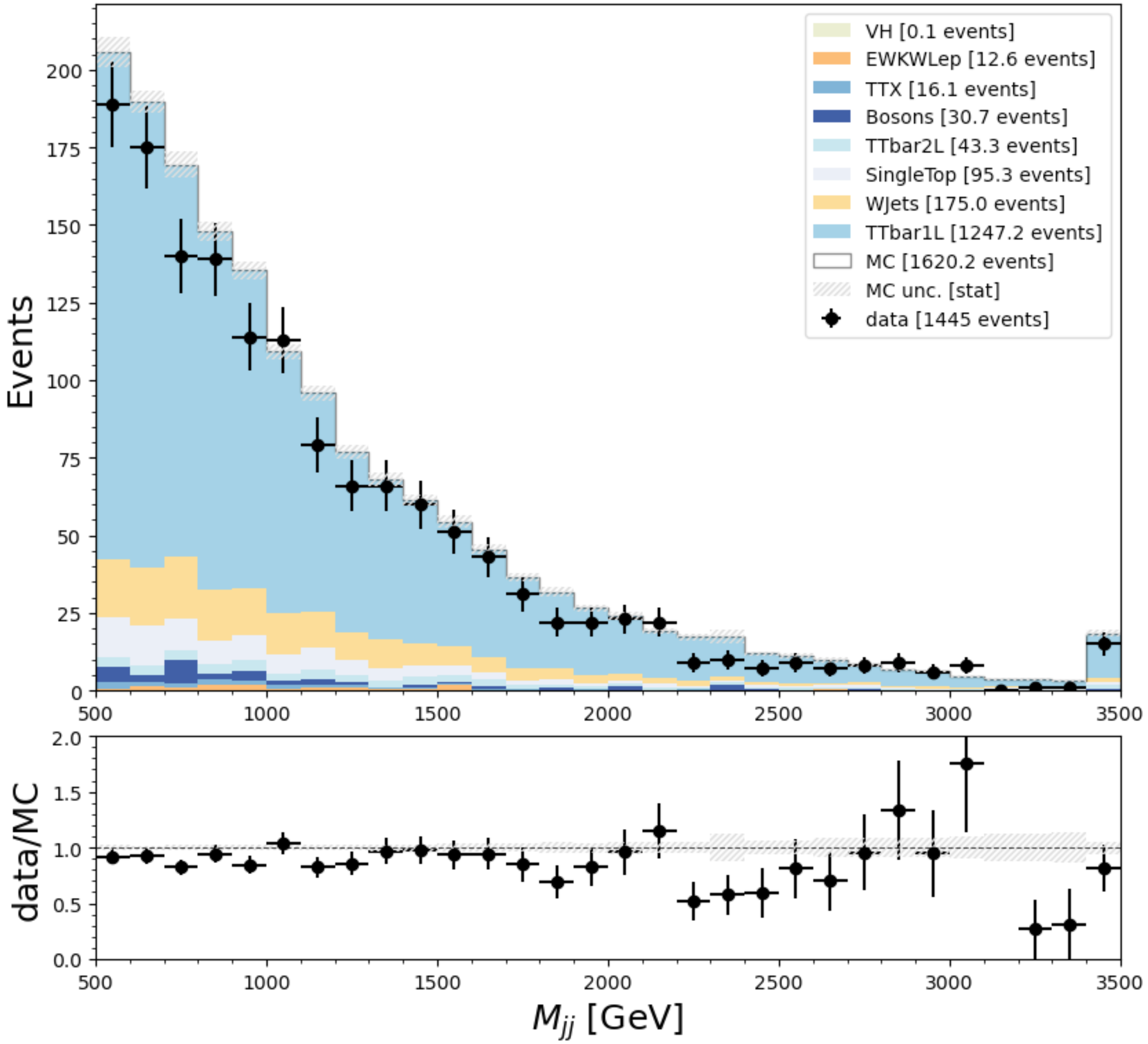
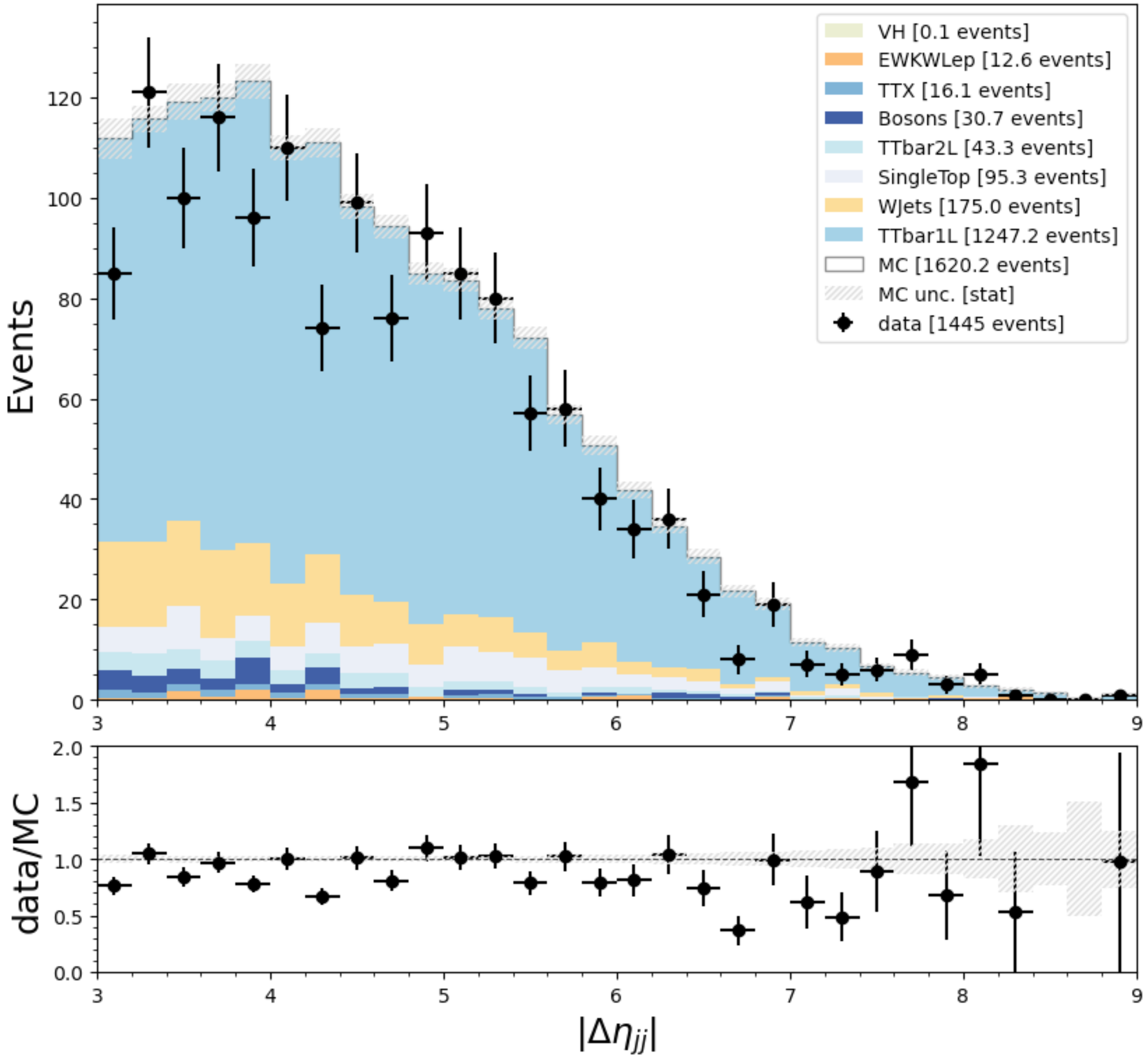
Validation: VBS

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



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



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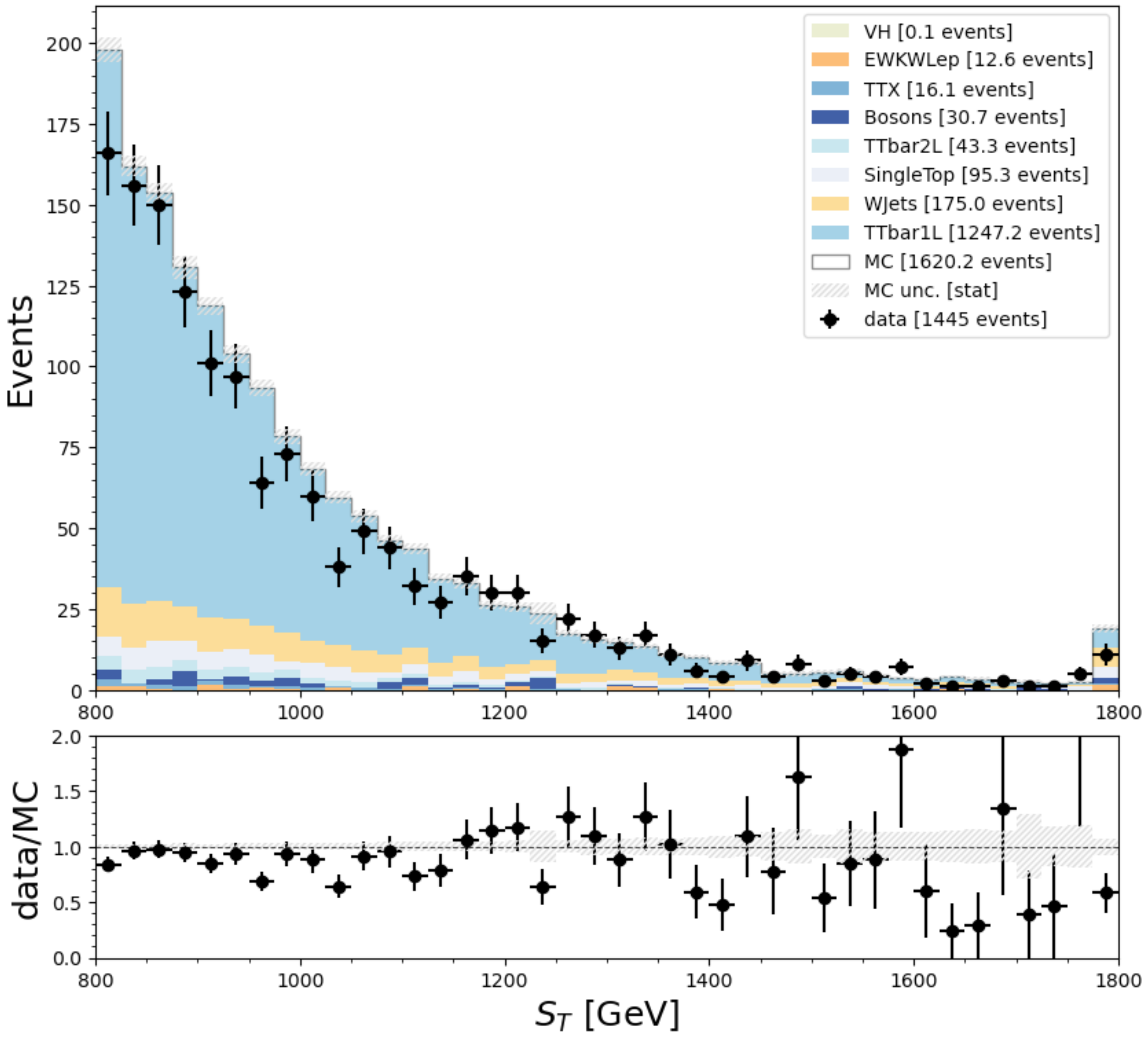
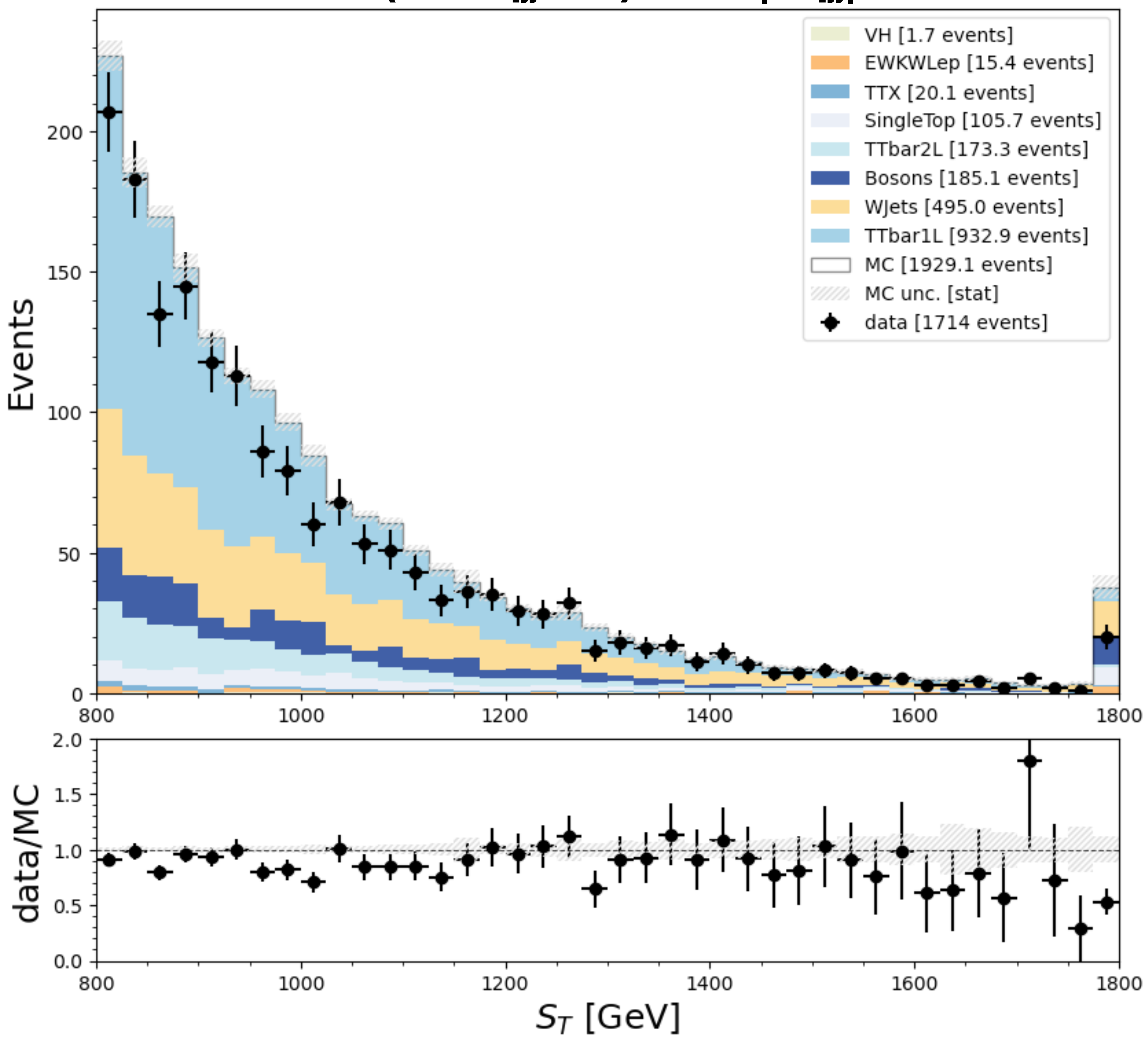
Validation: S_T

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



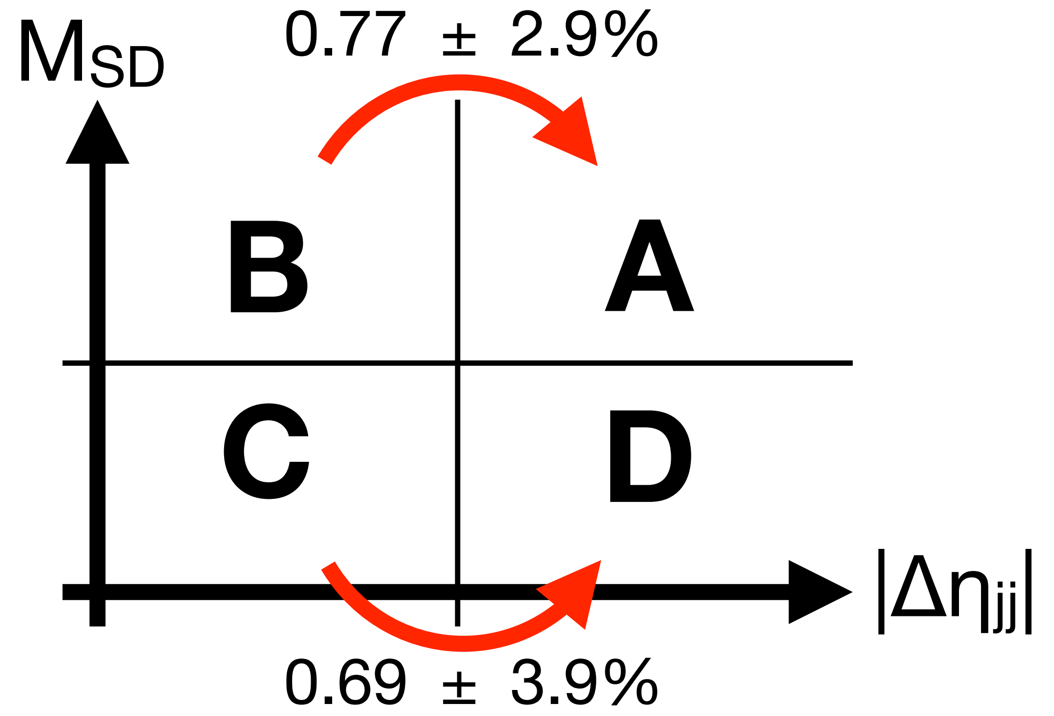
Preselection (no $\Delta\eta_{jj}$ cut) AND $|\Delta\eta_{jj}| \leq 3$

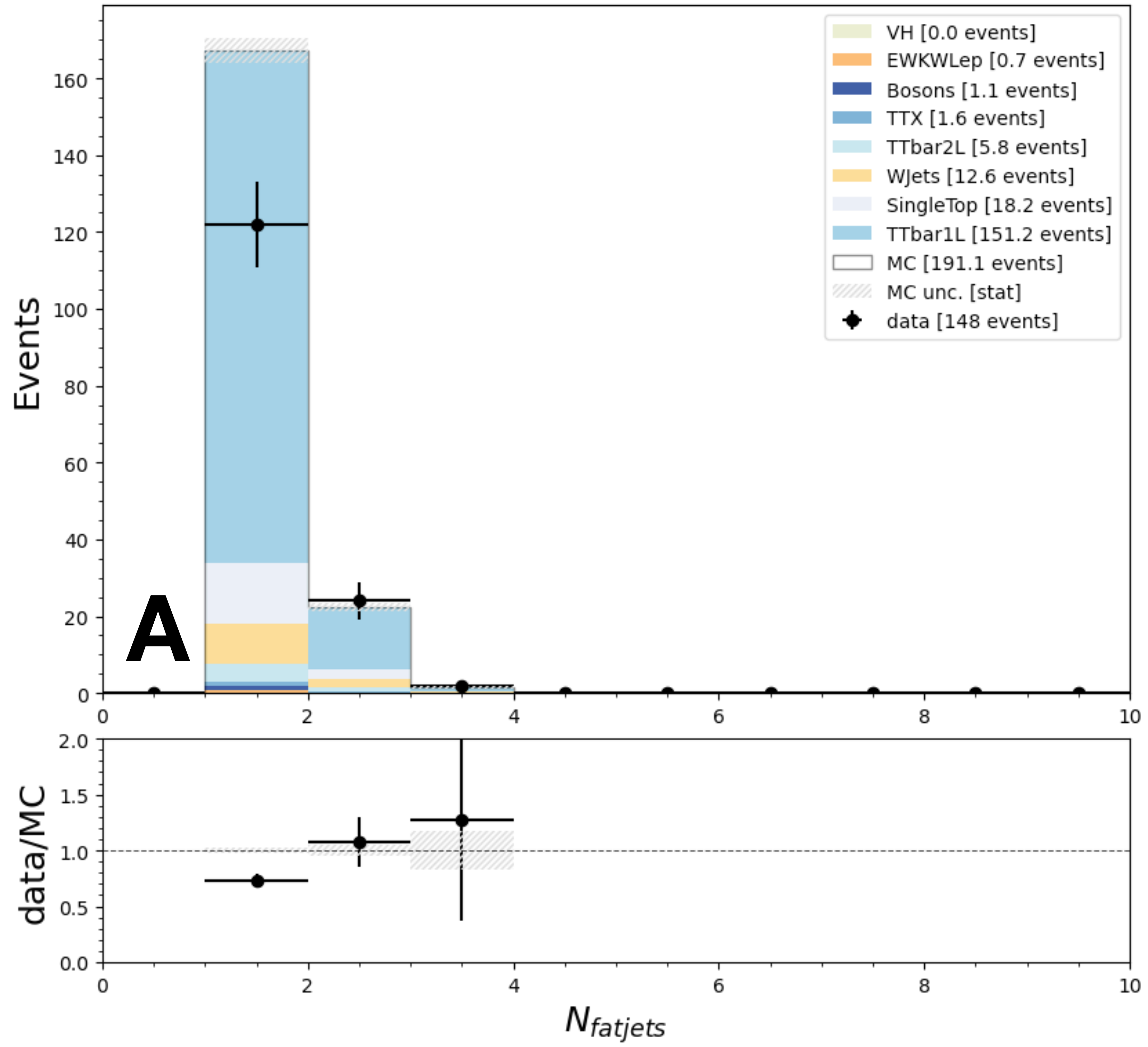


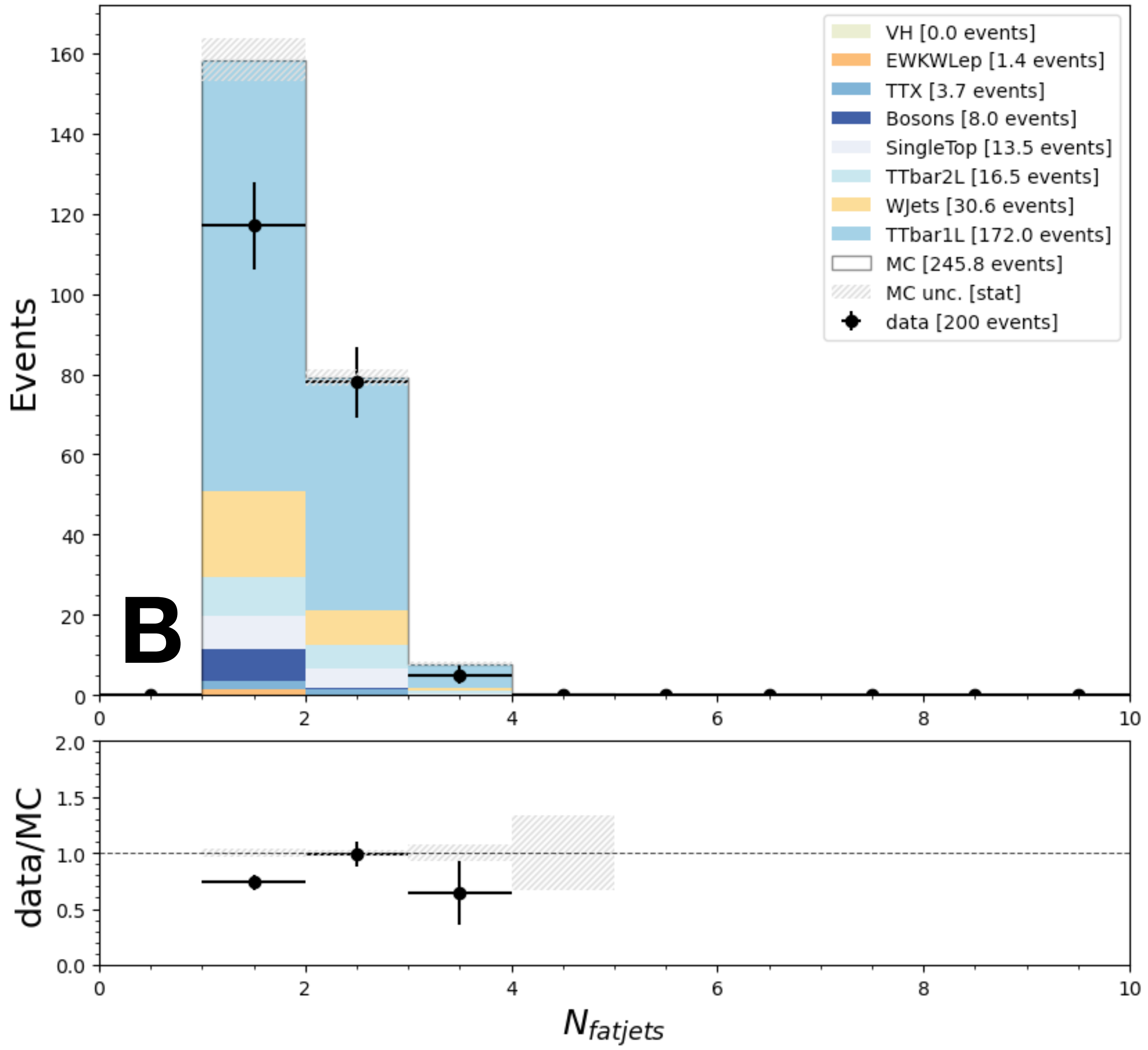
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

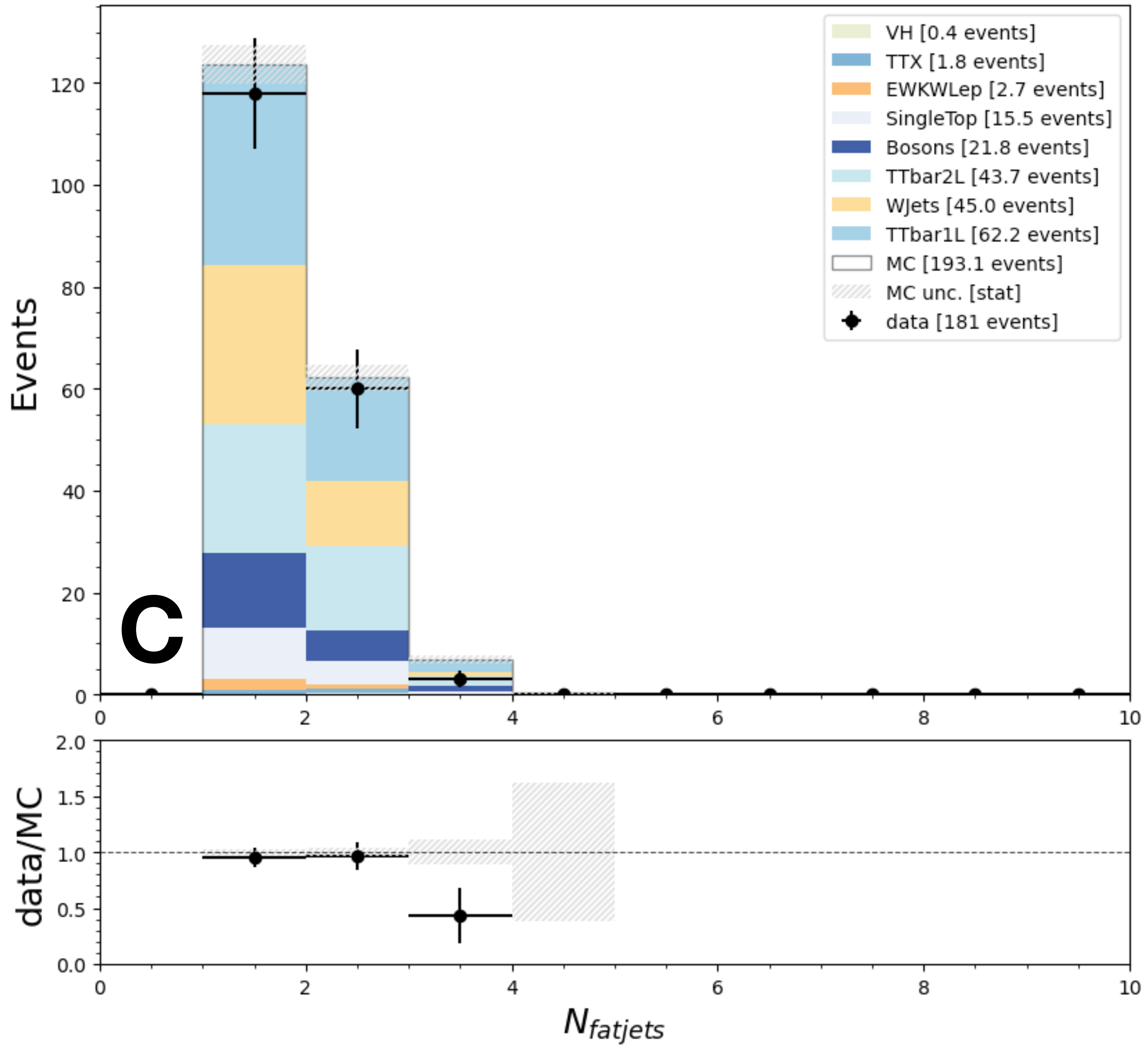
Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} \geq 150$ GeV	A	202.82	3.62	11.75	1.44	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	261.73	6.08	0.92	0.46	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	204.69	4.82	16.27	1.69	181	13.45
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	141.04	4.39	427.99	8.92	—	—









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

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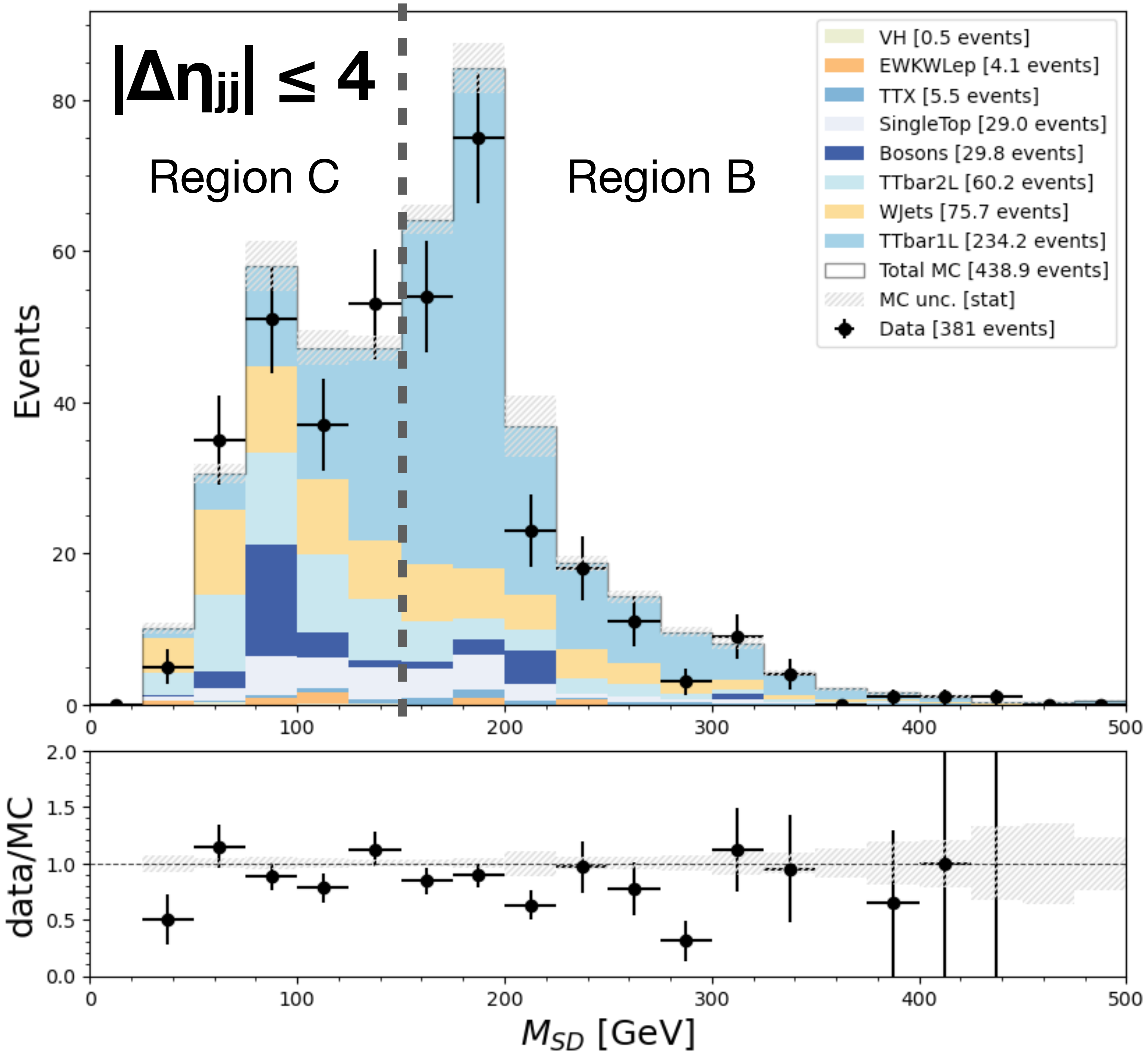
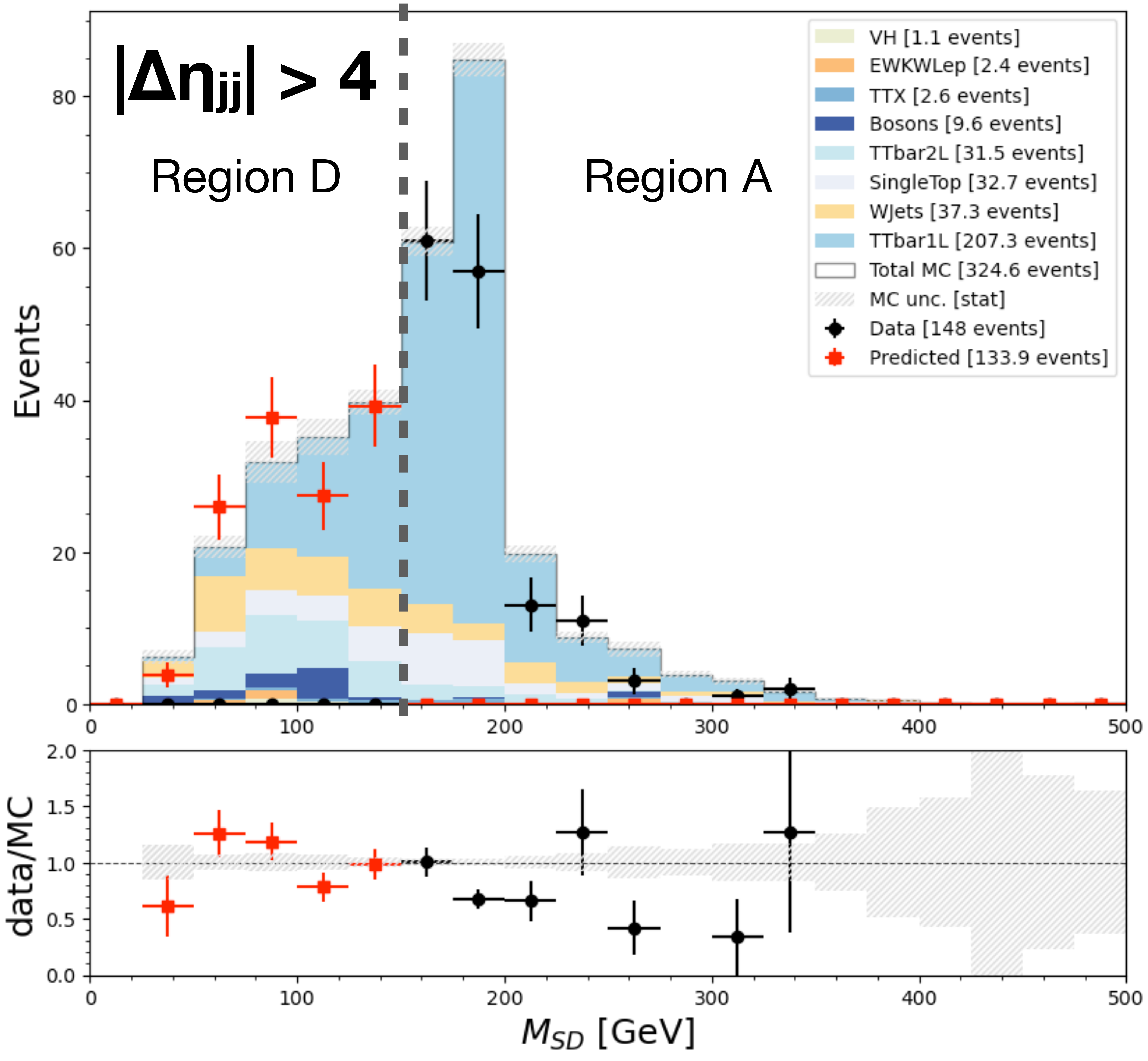
SR1 ABCD

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





Shape of data in Region D is taken from Region C directly for visualization purposes

(final fit is a single bin)

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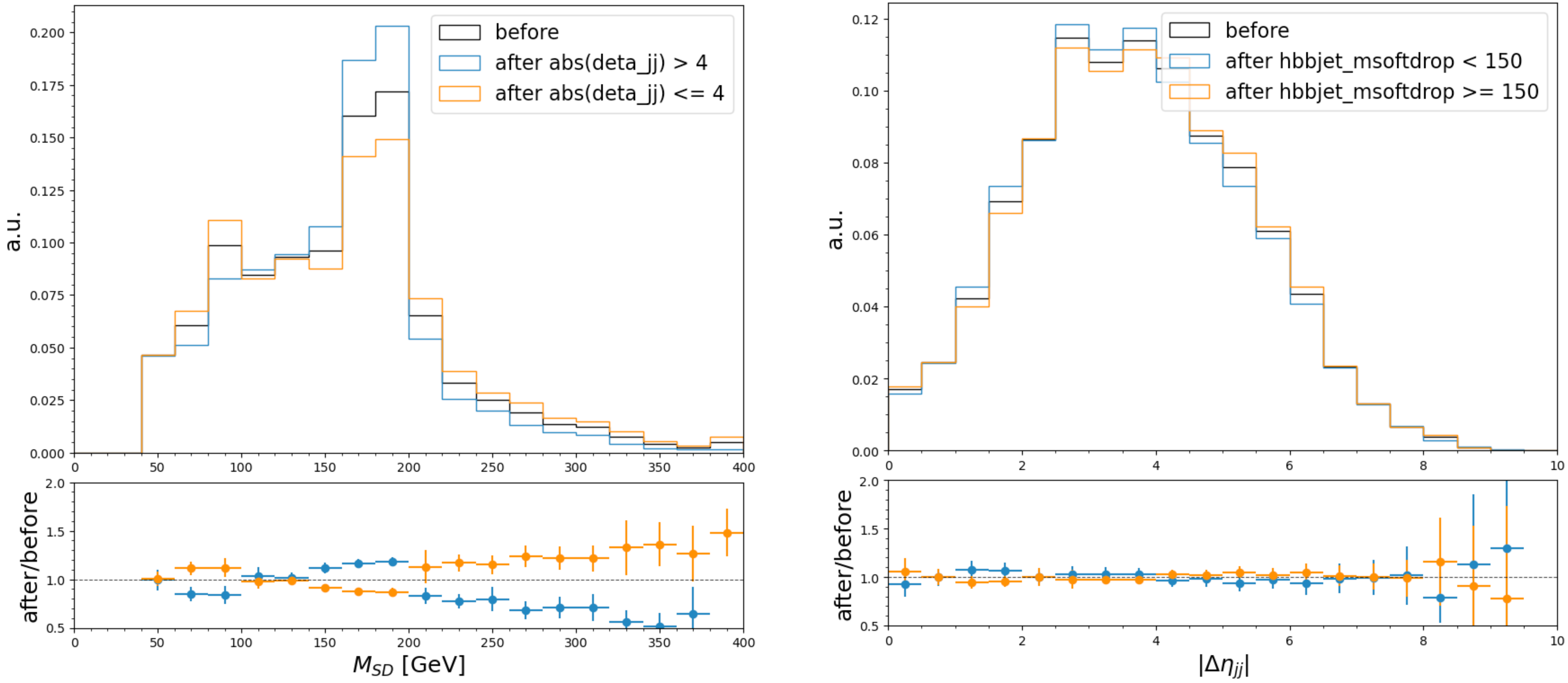
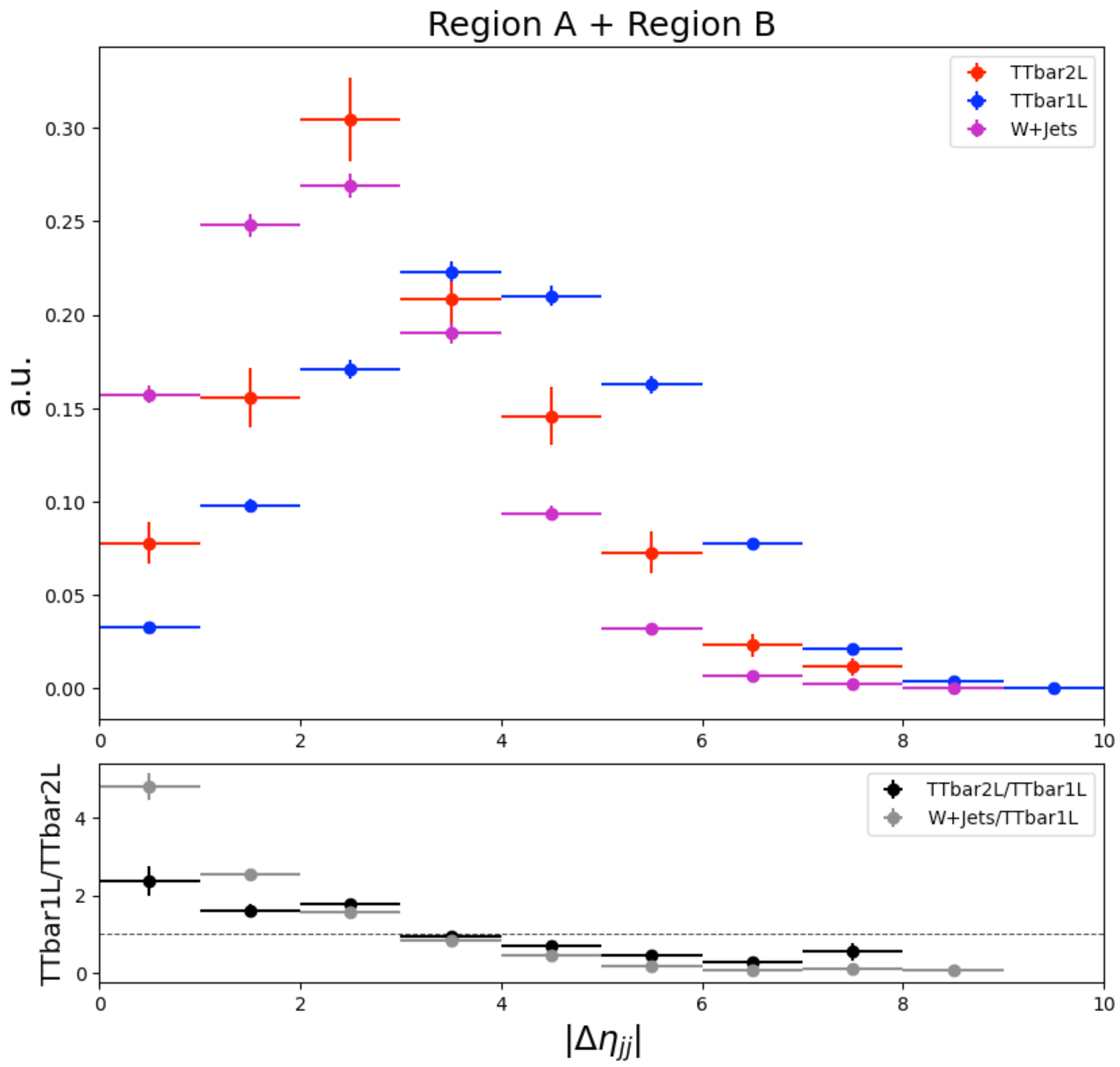
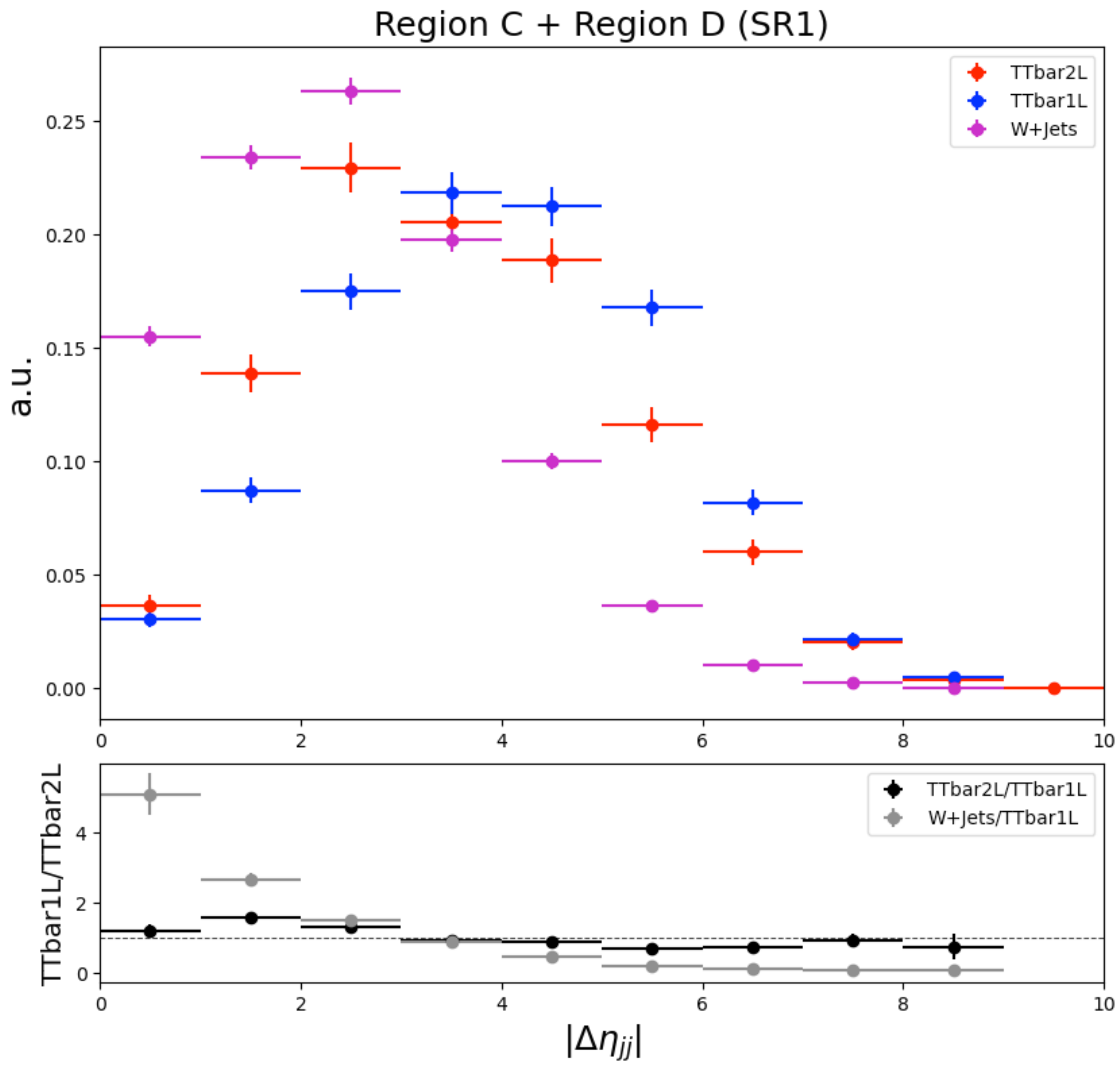
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD} Correlations

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



SR1 ABCD: Composition





TT1L & TT2L |Δη$_{jj}$| shapes roughly consistent, W+Jets is much different

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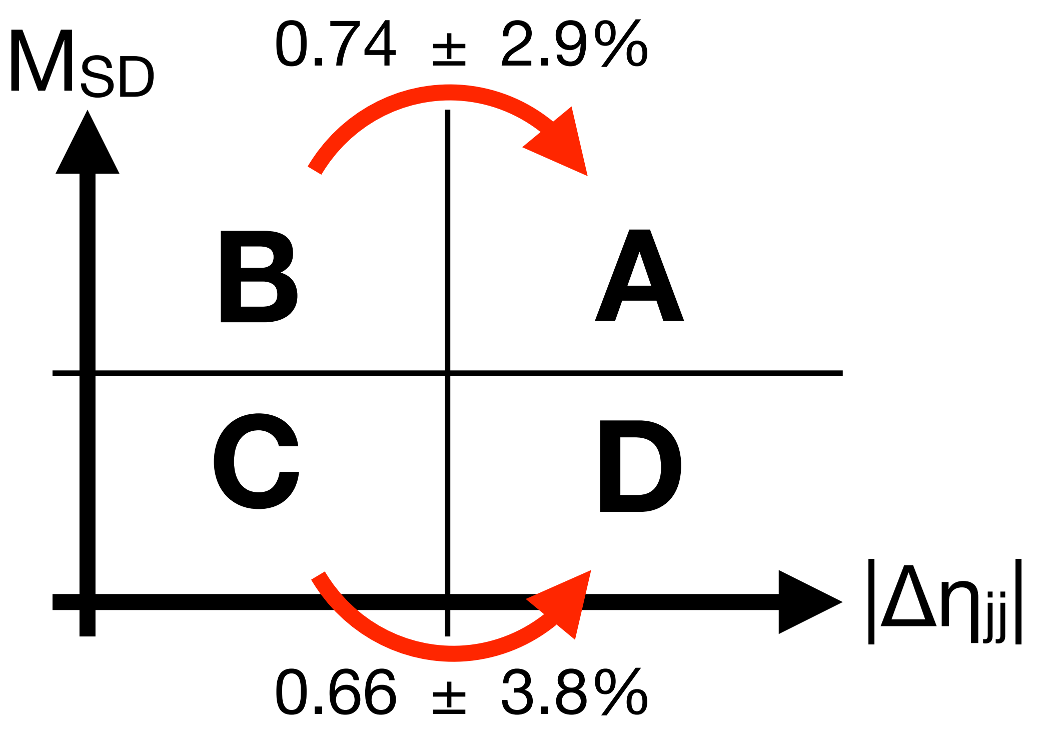
SR1 ABCD: Composition

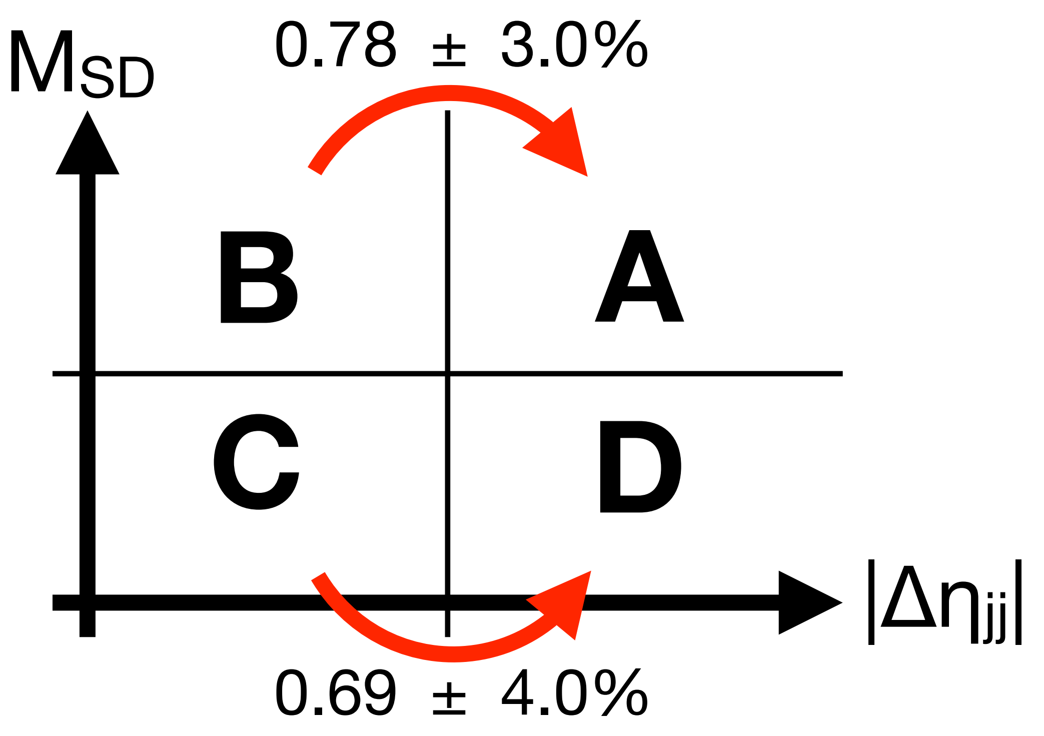
Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9 (WJets x 2)

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND $M_{SD} \geq$ 150 GeV	A	203.74	3.72	10.60	1.36	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND $M_{SD} \geq$ 150 GeV	B	276.36	6.05	0.89	0.44	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND M_{SD} < 150 GeV	C	238.18	4.94	14.75	1.57	181	13.45
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	158.13	4.98	395.72	8.45	—	—



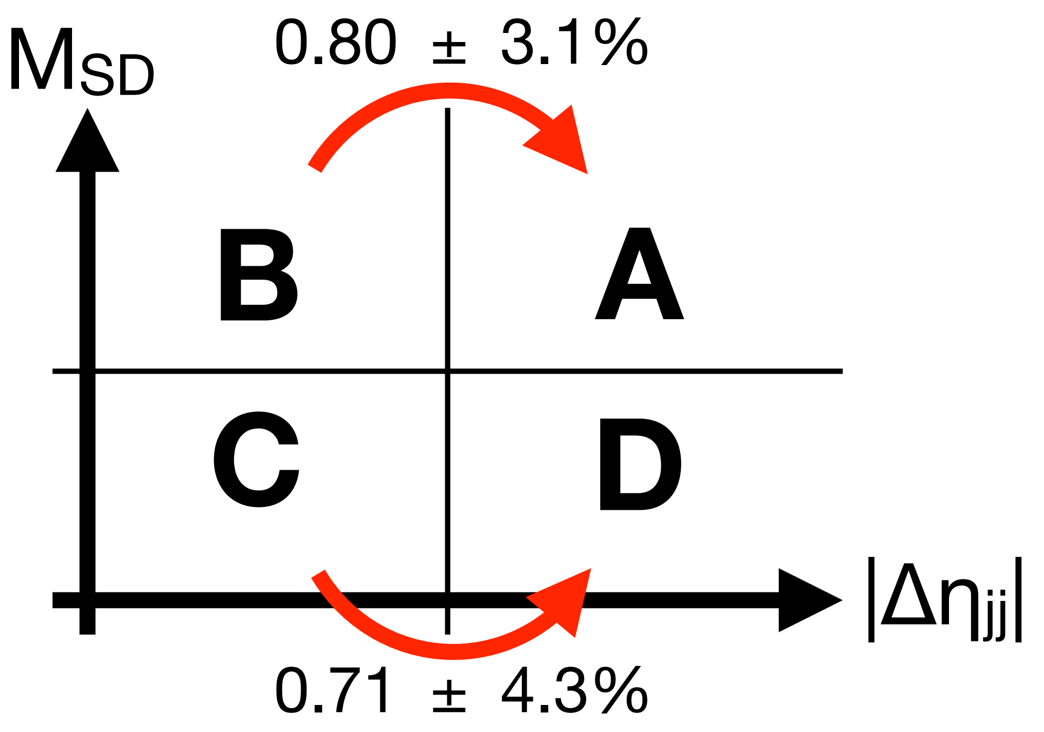
Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND $M_{SD} \geq$ 150 GeV	A	191.14	3.48	10.60	1.36	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND $M_{SD} \geq$ 150 GeV	B	245.76	5.90	0.89	0.44	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND M_{SD} < 150 GeV	C	193.14	4.61	14.75	1.57	181	13.45
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	133.44	4.31	395.72	8.45	—	—



Presel. (w/out $\Delta\eta_{jj}$ cut) AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9 (WJets x 0.5)

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND $M_{SD} \geq$ 150 GeV	A	184.84	3.42	10.60	1.36	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND $M_{SD} \geq$ 150 GeV	B	230.45	5.86	0.89	0.44	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq$ 4 AND M_{SD} < 150 GeV	C	170.61	4.52	14.75	1.57	181	13.45
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR1)	D	121.09	4.13	395.72	8.45	—	—



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

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An Aside: Erroneous EWK Samples

- EWK W samples generated as follows:

```
generate pp > l vl j j / t t~ h QCD = 0
```

  - The **slash** notation excludes t, $\bar{t}$, and H diagrams from generation, and *ignores* any interference terms from them
  - Diagram from https://arxiv.org/abs/2204.07652 (Fig. 2k)