VBS WH Analysis

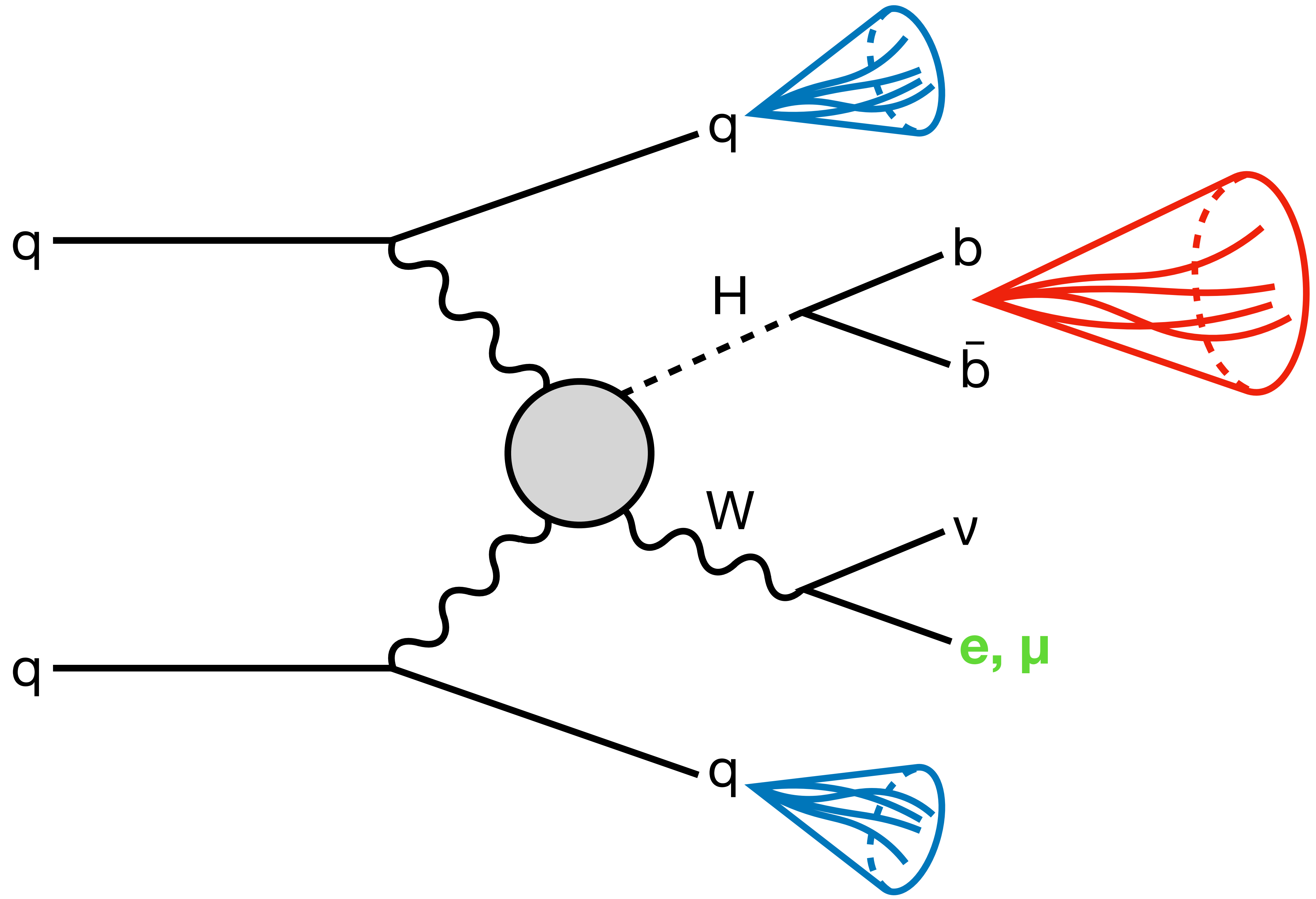
Hbb subgroup status report

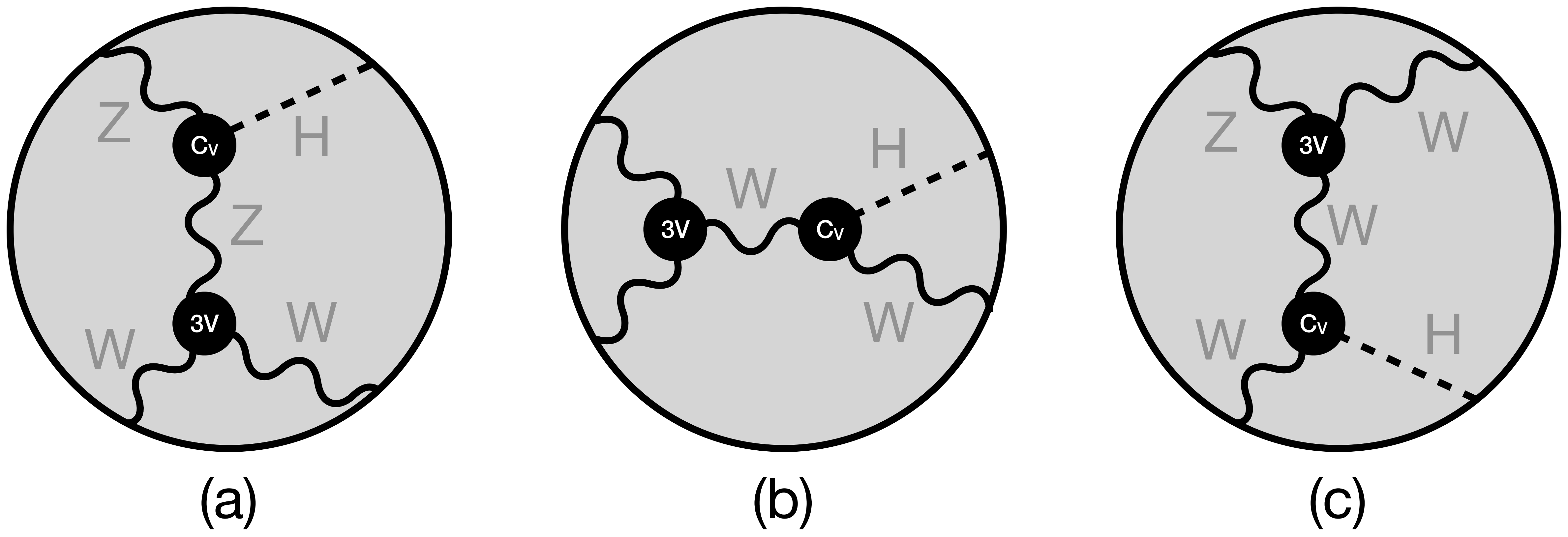
February 8th, 2023

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

Target Final State

- Targeting **VBS** WH→**ℓ**ν**b$\bar{b}$**
  - Where H→**b$\bar{b}$** reconstructed as a single AK8 jet
- 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)
    - $S_T = p_T(\ell) + \text{MET} + p_T(H\rightarrow b\bar{b}$ fat jet)
  - VBS jets with large $\Delta\eta_{jj}$, M_{jj}





Analysis Strategy

- Trigger on lepton from W
- Share HLTs and lepton ID with resolved search
- Cut-based signal region:
    - **413 signal vs. 131 background**
- Data-driven bkg. estimate (ABCD)
- Counting experiment
    - Fit the signal and bkg. yields to exclude S+B hypothesis

Name	Selections*
Object selection	• POG lepton ID • Basic jet/fat jet selections • 2 VBS jets • $H \rightarrow b\bar{b}$ fat jet = max PNet Xbb score

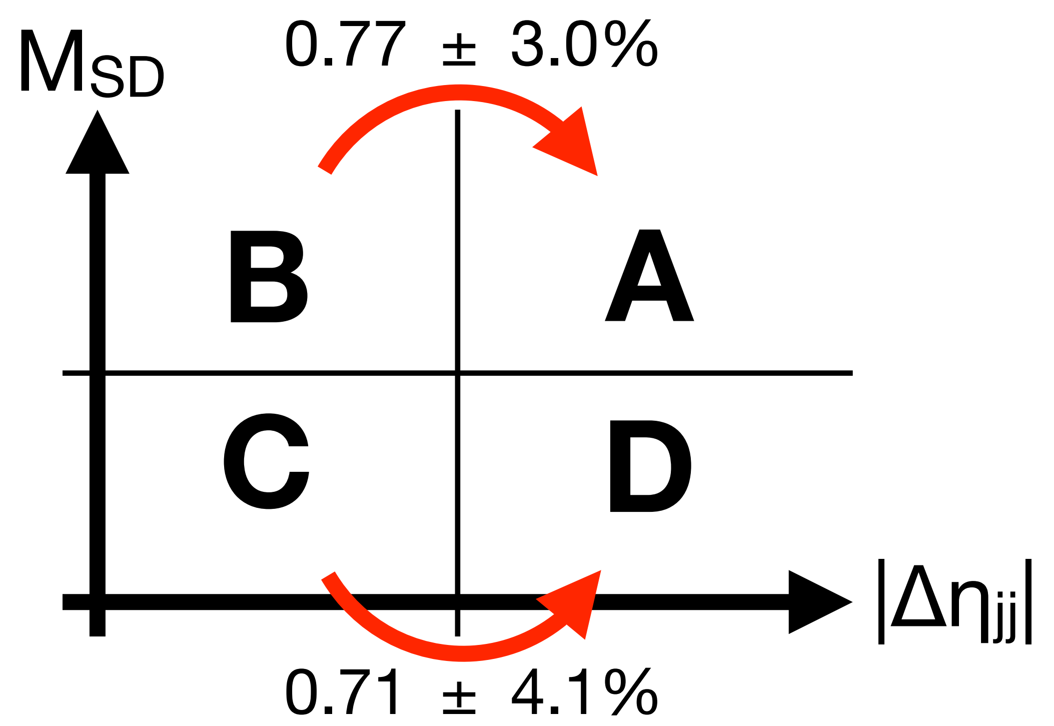
Signal Region	• VBS jets:
	  • $M_{jj} > 600$ GeV
	  • $\lvert\Delta\eta_{jj}\rvert > 4$
	• $H \rightarrow b\bar{b}$ fat jet:
	  • PNet Xbb > 0.9
	  • $M_{SD} < 150$ GeV
	• $S_T > 900$ GeV

*Detailed selections and yields provided in backup

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

Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

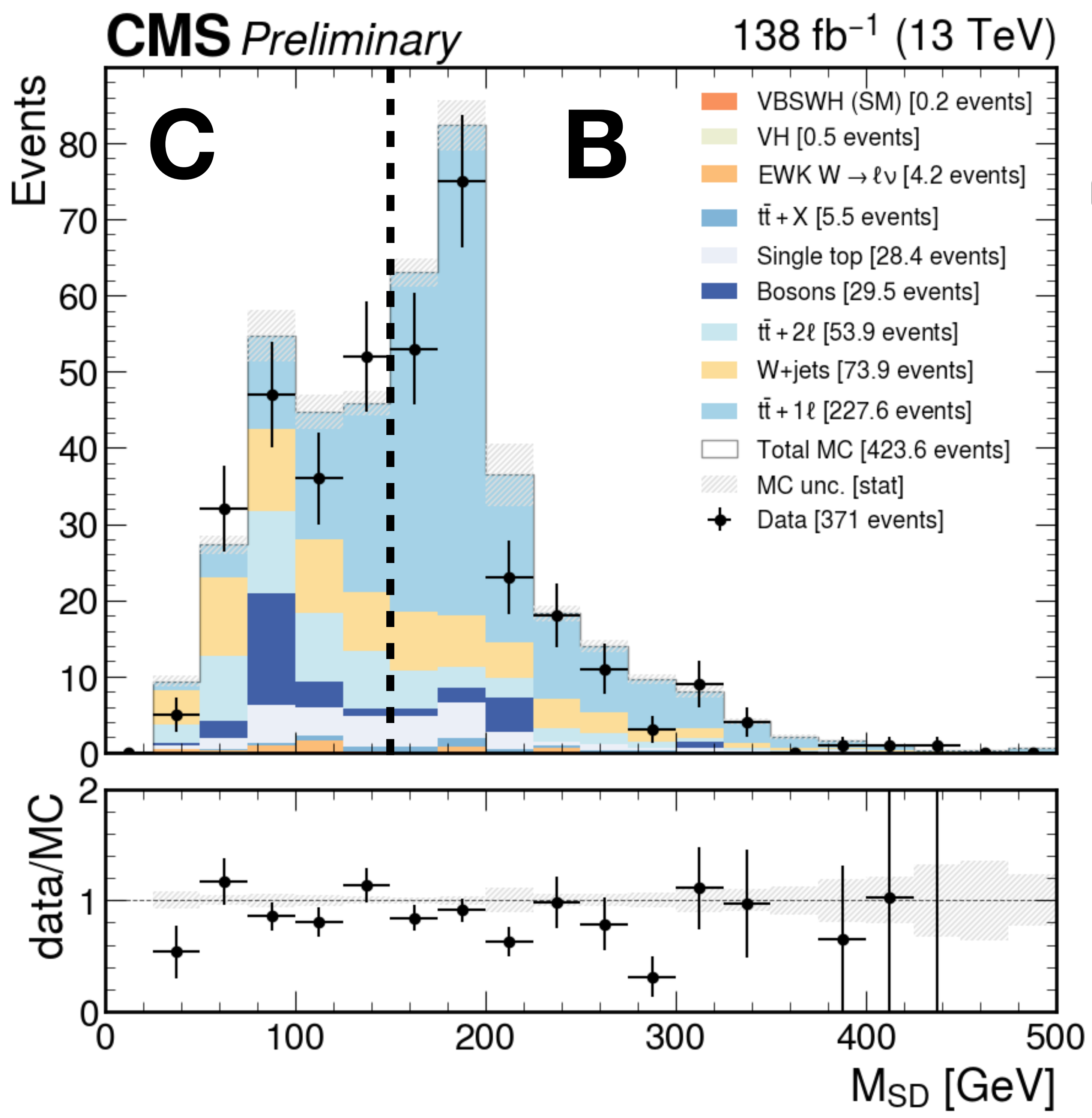
Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} ≥ 150 GeV	A	186.32	3.41	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	241.61	5.85	0.94	0.42	199	14.11
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4 AND M_{SD} < 150 GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\lvert\Delta\eta_{jj}\rvert$ > 4 AND M_{SD} < 150 GeV (SR)	D	129.61	4.23	413.34	8.91	–	–

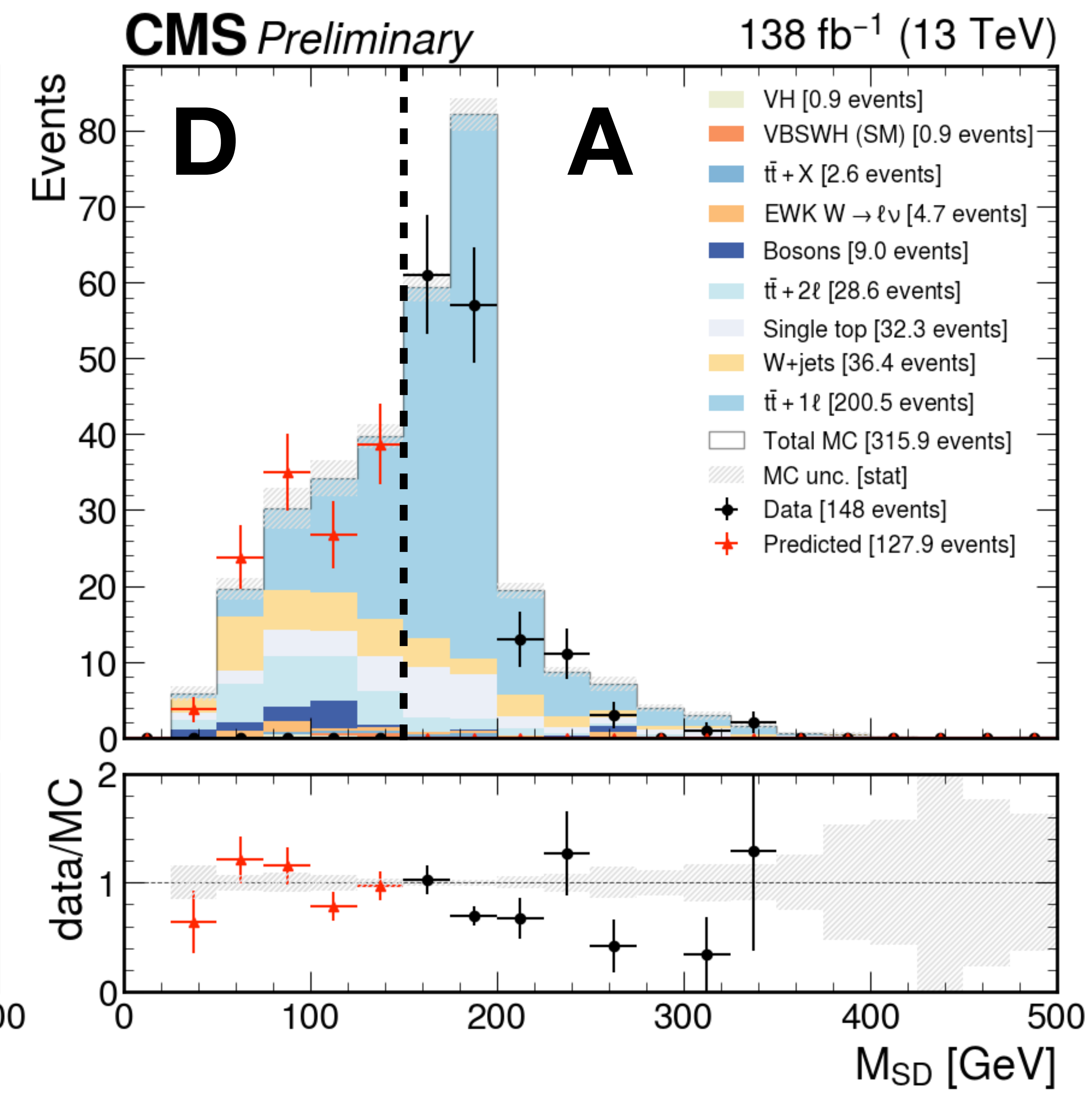


- Predicted bkg. in D = C × A/B
- Data an MC agree reasonably well in A, B, C
- Data and MC transfer factors agree:

$$\frac{A_{MC}}{B_{MC}} = 0.77 \pm 3.0\%$$

$$\frac{A_{data}}{B_{data}} = 0.74 \pm 10.9\%$$





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

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

Preselection 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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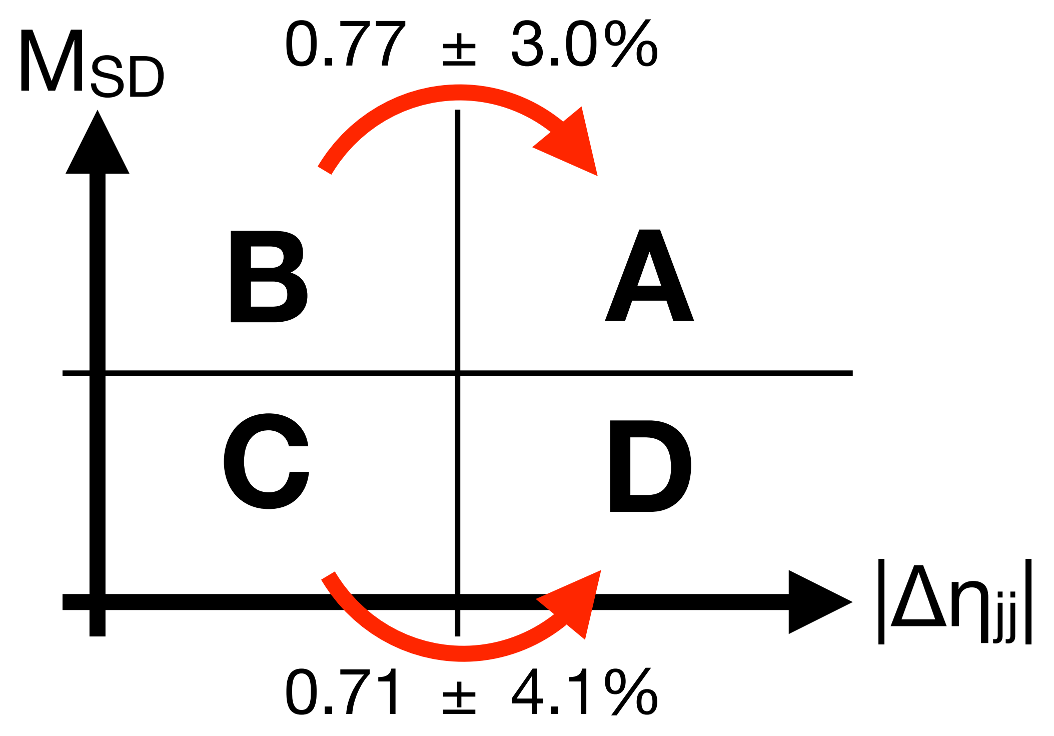

- Errors: 10% (syst.), 13% (stat.)

Over-predicted

$$D_{MC}^{pred} = \frac{A_{MC}}{B_{MC}} \times C_{MC} = \mathbf{140.34}$$

$$\epsilon_{syst} = \left|1 - \frac{D_{MC}^{pred}}{D_{MC}}\right| = \left|1 - \frac{140.3}{129.6}\right| = 8\% \oplus 6\% = 10\%$$

Bkg comp. syst. (backup)

$$D_{data}^{pred} = \frac{A_{data}}{B_{data}} \times C_{data} = 127.92$$

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

$$= \sqrt{\frac{1}{A_{data}} + \frac{1}{B_{data}} + \frac{1}{C_{data}}} = 13\%$$

Predicted SR Yield: 127.9±16.97±13.11

stat. *syst.*

*err = √(Σ_iw_i²) for MC, √(count) for data

Signal Systematics

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

Systematic	SR1
PDF variations	2.2%
μ_F scale	17.8%
Parton shower ISR weights	0.1%
Parton shower FSR weights	1.5%
Pileup reweighting	0.2%
L1 pre-fire corrections	1.0%
HLT scale factors	0.8%
Simulation stat. unc.	2.2%
Lepton scale factors	1.5%
ParticleNet Xbb scale factors	5.7%
DeepJet b-tagging scale factors	0.3%
MET unc.	0.3%
Jet energy scale	6.6%
Jet energy resolution	0.8%
Luminosity	2.5%

HiggsCombine Datacard

Systematic	SR1
PDF variations	2.2%
μ_F scale	17.8%
Parton shower ISR weights	0.1%
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→

```
imax 1 number of channels
jmax 1 number of backgrounds
kmax 19 number of nuisance parameters
------------------------------------------
bin                          bin1
observation                   128
------------------------------------------
bin                          bin1        bin1
process                 VBSWH_mkW    TotalBkg
process                         0           1
rate                       413.34      127.92
------------------------------------------
abcd_syst      lnN              -       1.101
abcd_stat      lnN              -       1.133
pdf_vars       lnN          1.022           -
muF_scale      lnN          1.178           -
isr_weights    lnN          1.001           -
fsr_weights    lnN          1.015           -
pu_rwgt        lnN          1.002           -
L1_prefire     lnN          1.010           -
hlt_sfs        lnN          1.008           -
mc_stat        lnN          1.022           -
lep_id         lnN          1.015           -
elec_reco      lnN          1.003           -
muon_iso       lnN          1.000           -
xbb_sfs        lnN          1.057           -
btag_sfs       lnN          1.003           -
met_unc        lnN          1.003           -
jes            lnN          1.066           -
jer            lnN          1.008           -
lumi           lnN          1.025           -
```

HiggsCombine datacard

HiggsCombine Settings

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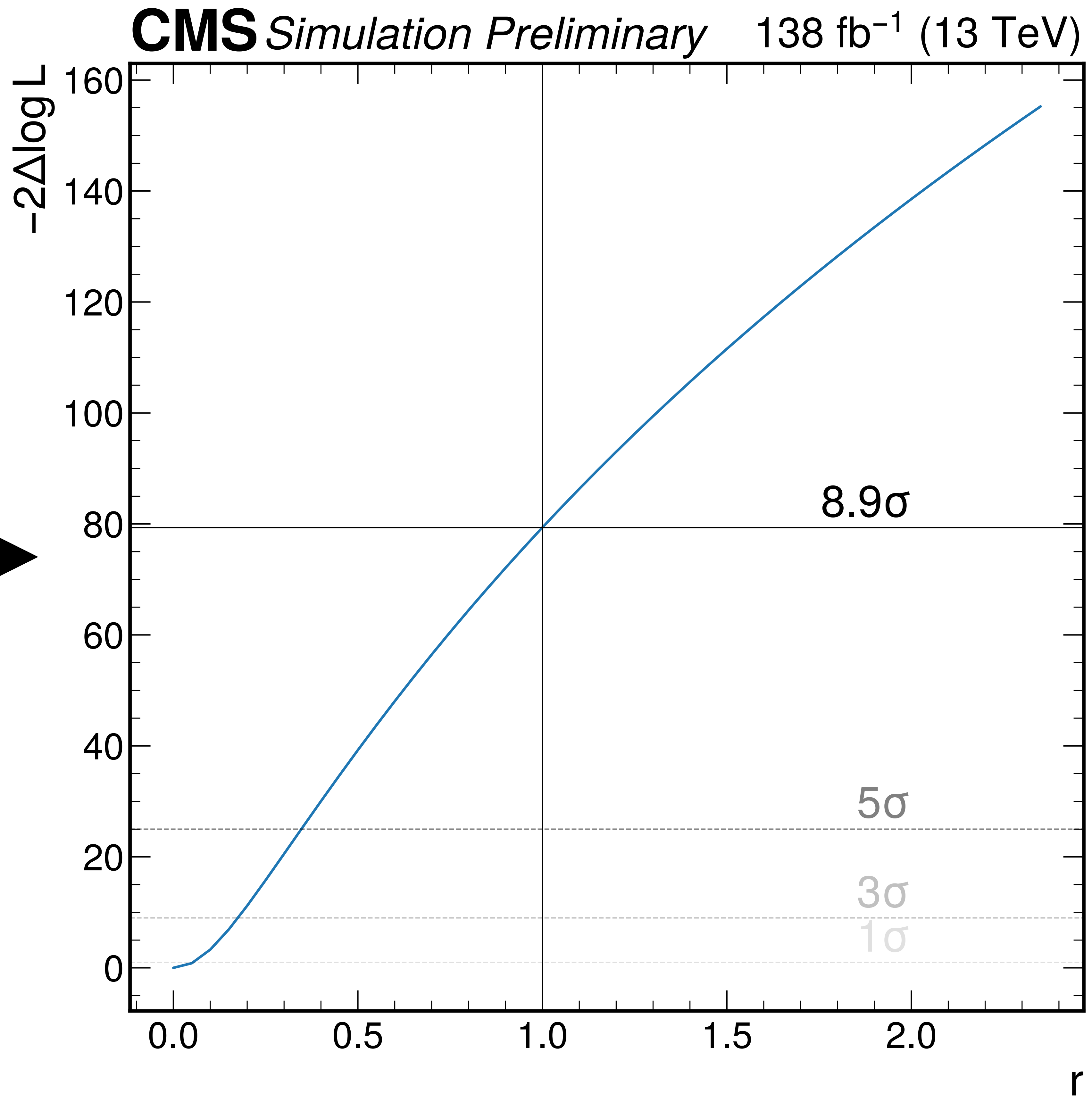
abcd_stat     lnN                -      1.133
pdf_vars      lnN            1.022          -
muF_scale     lnN            1.178          -
isr_weights   lnN            1.001          -
fsr_weights   lnN            1.015          -
pu_rwgt       lnN            1.002          -
L1_prefire    lnN            1.010          -
hlt_sfs       lnN            1.008          -
mc_stat       lnN            1.022          -
lep_id        lnN            1.015          -
elec_reco     lnN            1.003          -
muon_iso      lnN            1.000          -
xbb_sfs       lnN            1.057          -
btag_sfs      lnN            1.003          -
met_unc       lnN            1.003          -
jes           lnN            1.066          -
jer           lnN            1.008          -
lumi          lnN            1.025          -
```

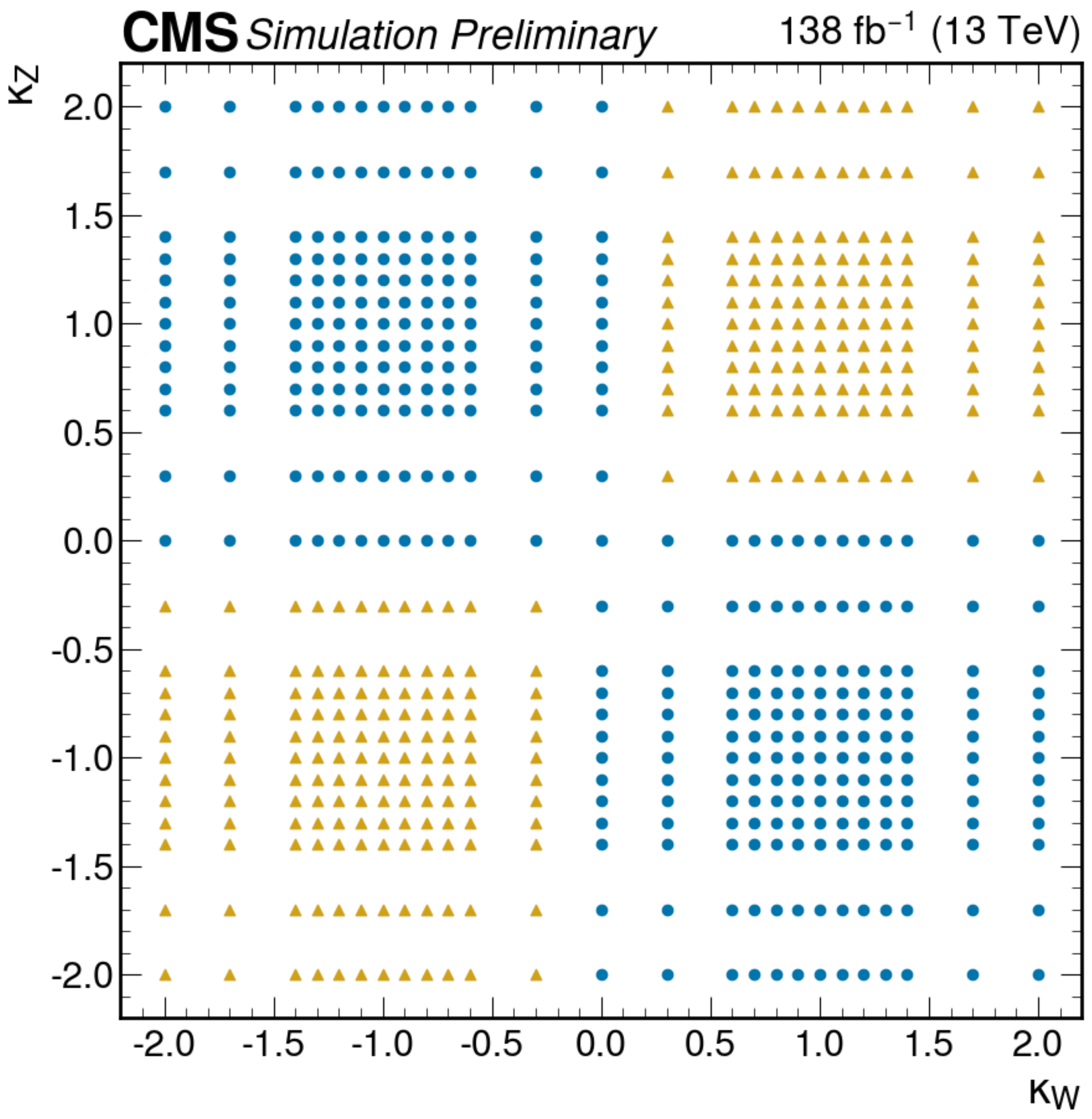
```
combine -M MultiDimFit -d vbswh.root
    -m 125 -t -1
    --expectSignal=0
    --setParameters r_VBSWH_mKW=0
    --setParameterRanges r_VBSWH_mKW=0.0,2.0
    --saveNLL
    --algo grid
    --points 101
    --rMin 0 --rMax 5
    --alignEdges 1
```



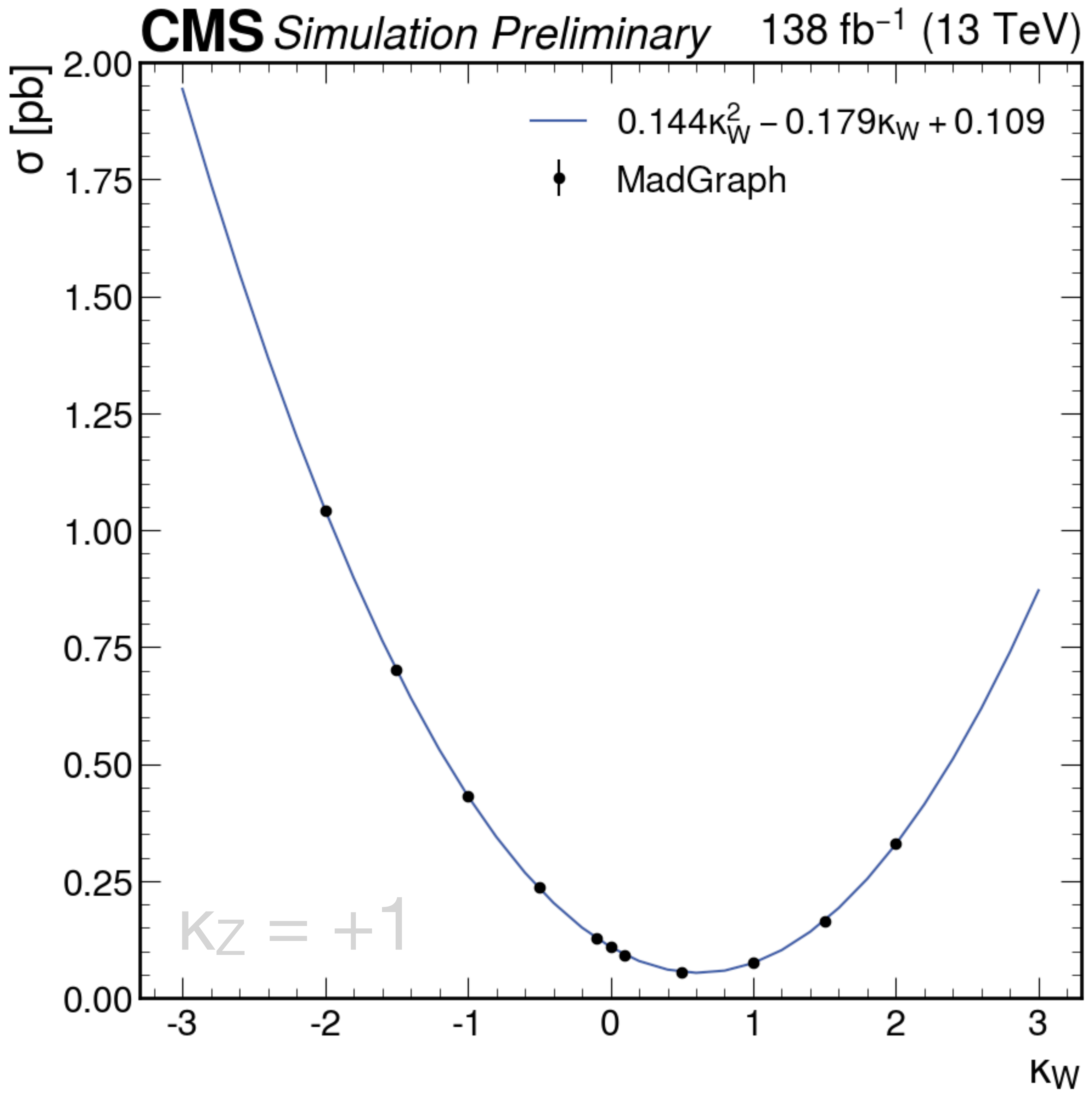
Full output here: http://uaf-10.t2.ucsd.edu/~jguiang/dump/AsymptoticLimits.txt

λ_{WZ} Scan

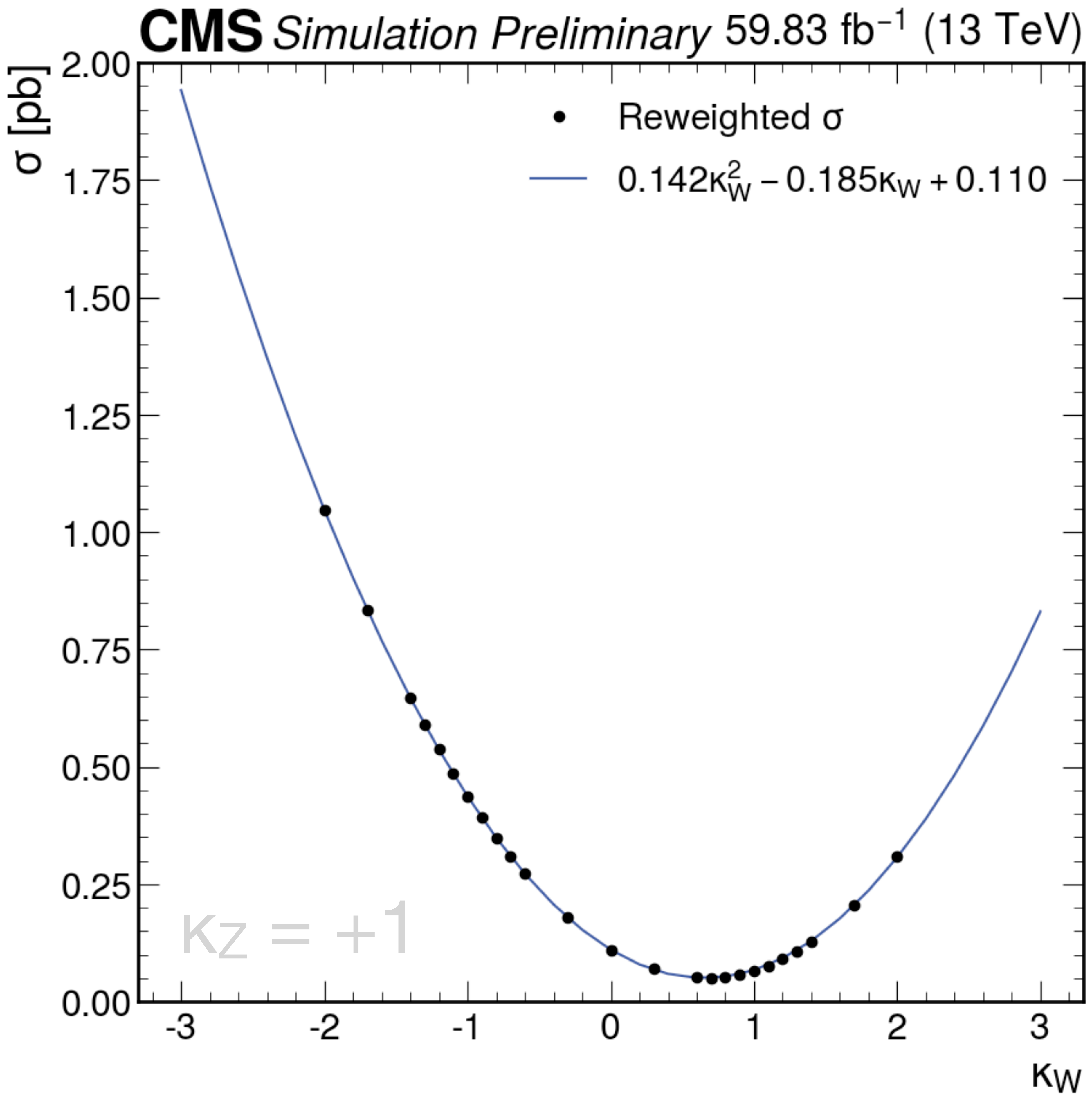
- Generated two signal samples:
  - $\lambda_{WZ} \leq 0$ sample
    - Reweighted around ($\kappa_W = -1$, $\kappa_Z = +1$)
  - $\lambda_{WZ} > 0$ sample
    - Reweighted around ($\kappa_W = +1$, $\kappa_Z = +1$)
  - Used PKU reweighting model
  - Full Run 2 samples
  - 100k events per NanoAODv9 “year”



New Signal Samples: Validation



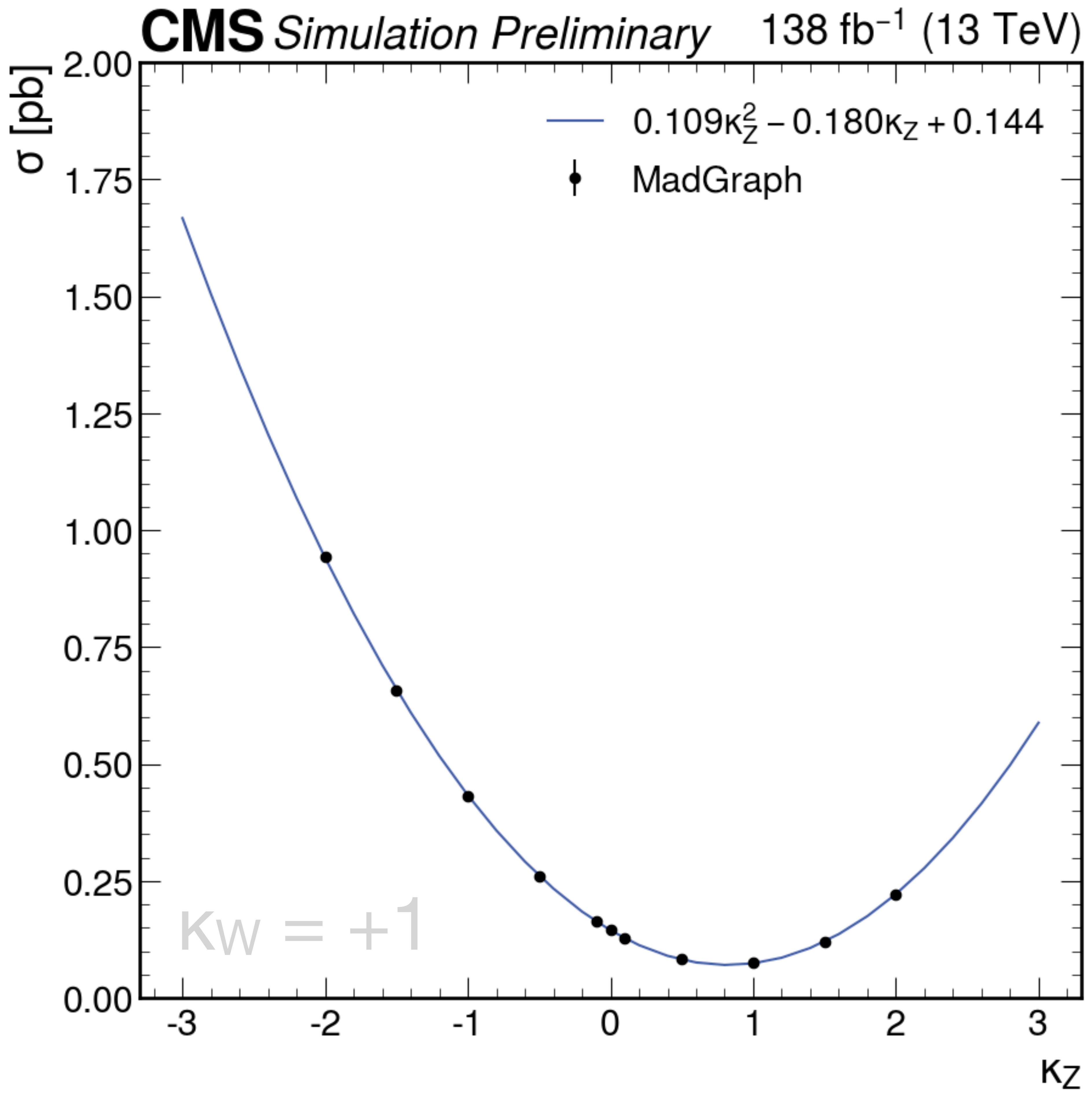
Single-points



Reweighted points

(Also checked that the acceptance for $\kappa_W = -1$, $\kappa_Z = +1$ matches)

New Signal Samples: Validation



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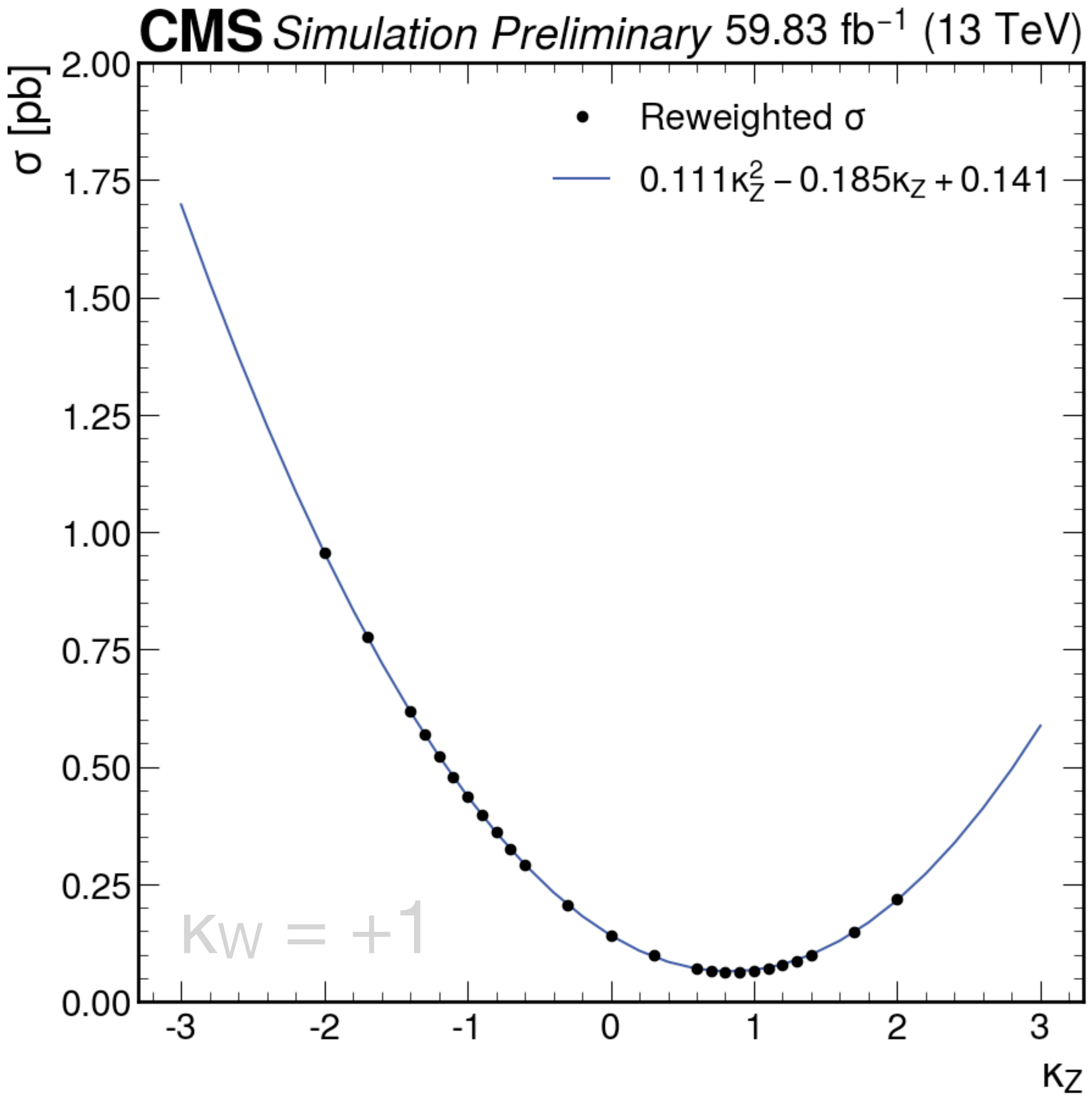

Reweighted points

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HiggsCombine Settings

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kmax 19 number of nuisance parameters
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process                         0           1
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abcd_stat      lnN              -       1.133
pdf_vars       lnN          1.022           -
muF_scale      lnN          1.178           -
isr_weights    lnN          1.001           -
fsr_weights    lnN          1.015           -
pu_rwgt        lnN          1.002           -
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btag_sfs       lnN          1.003           -
met_unc        lnN          1.003           -
jes            lnN          1.066           -
jer            lnN          1.008           -
lumi           lnN          1.025           -
```

scan_kW_X_kZ_Y.dat

```
combine -M MultiDimFit -d scan_kW_X_kZ_Y.root
    -m 125 -t -1
    --expectSignal=0
    --setParameters r_VBSWH_mKW=0
    --setParameterRanges r_VBSWH_mKW=0.0,2.0
    --saveNLL
    --algo grid
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    --rMin 0 --rMax 5
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```
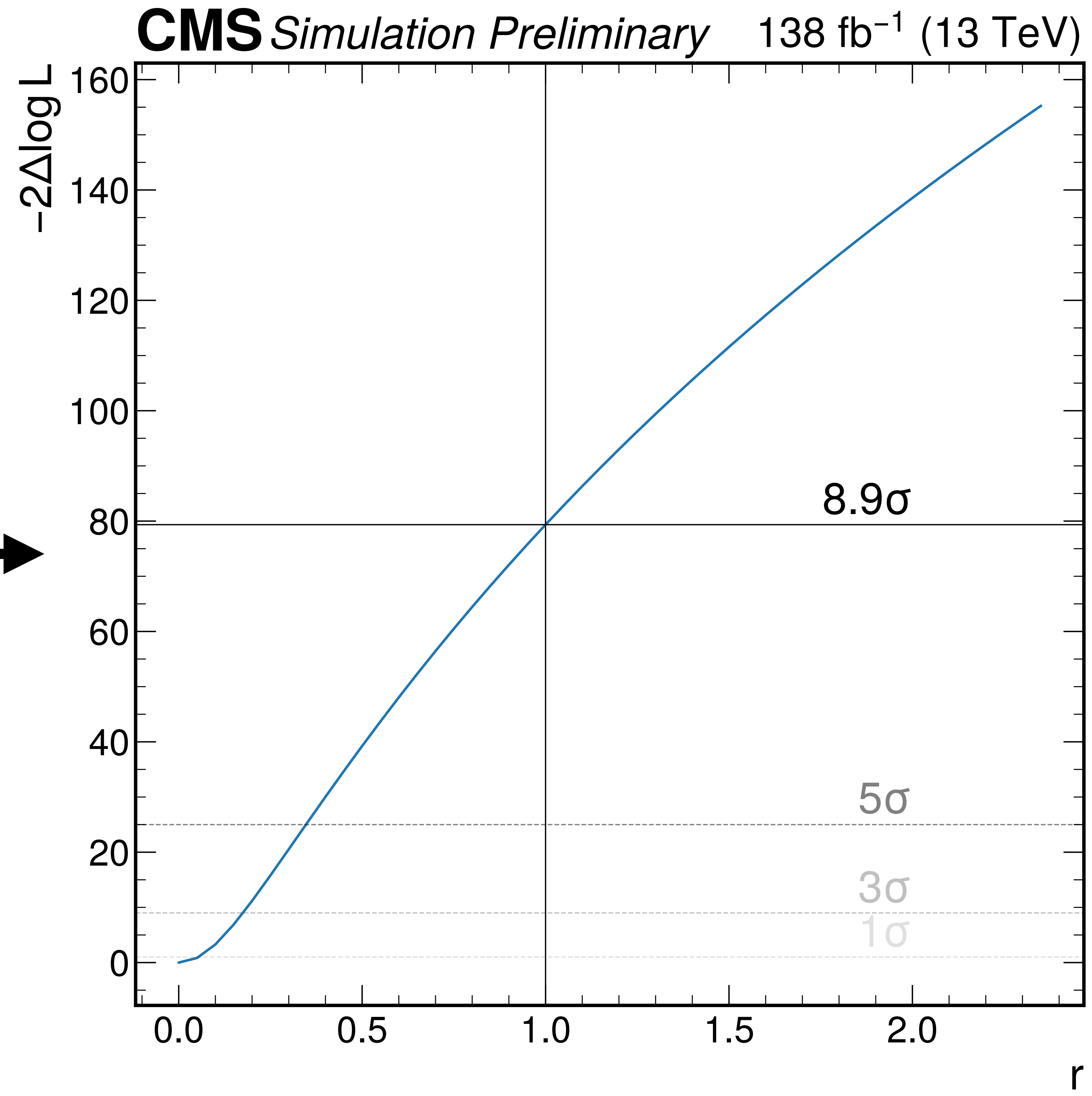
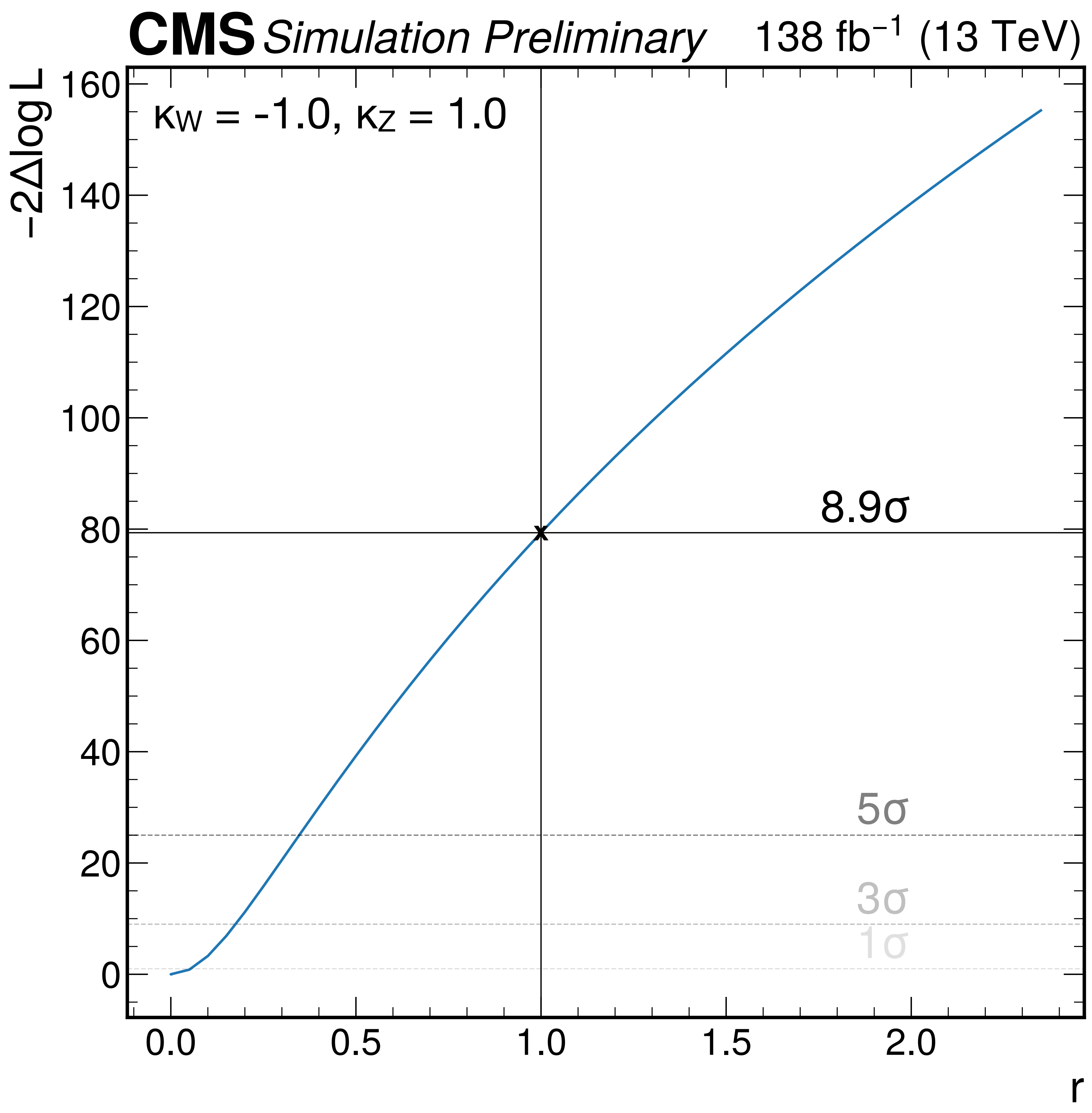
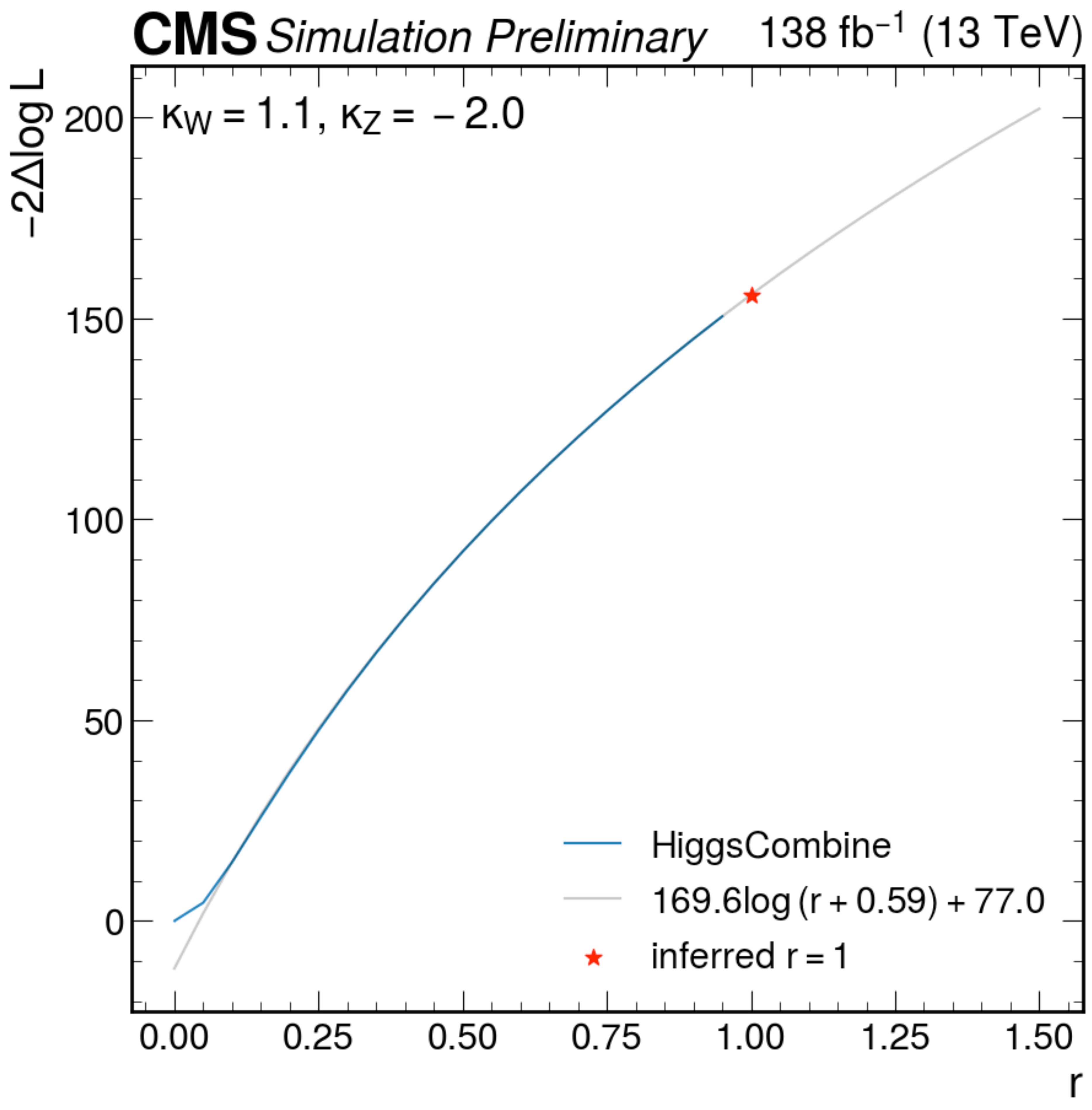



Repeat for each point κ_W = X, κ_Z = Y

Extrapolated Points



Take σ exclusion of r = 1



Infer σ exclusion of r = 1

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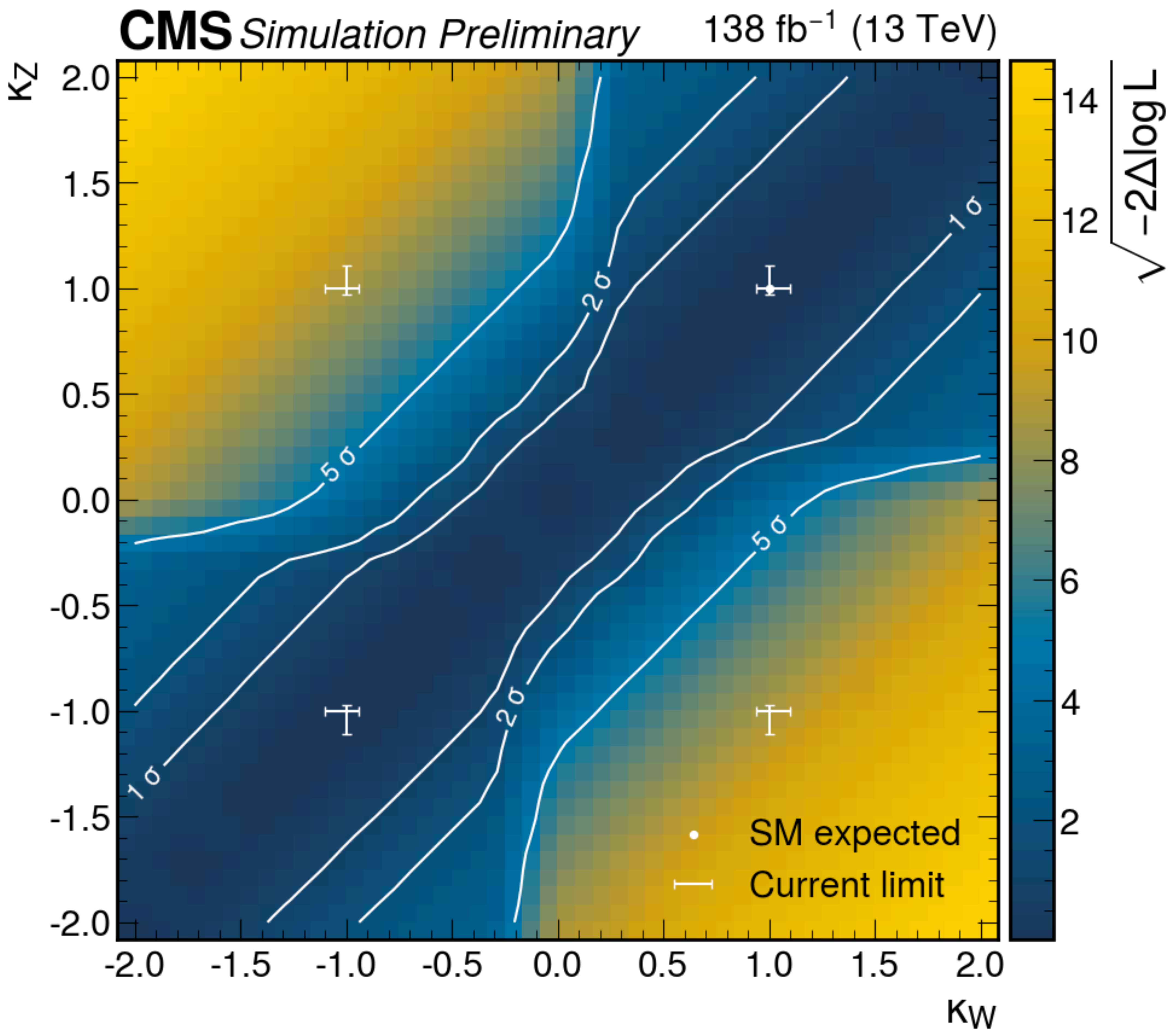
λ_{WZ} Scan Results

- Interpolated exclusion limits plotted on z-axis
- Current best limits on $|\kappa_V|$ are plotted as capped "error bars" (represent 1D limits, not 2D errors)
  - $|\kappa_W| = 1.02 \pm 0.08$
  - $|\kappa_Z| = 1.04 \pm 0.07$
- Contours show σ = 1, 2, 5 exclusion boundaries
  - This clearly shows we exclude $\lambda_{WZ} = -1$ when considered alongside current best limits



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Publication Plan Proposal


Available on the CMS information server CMS AN-XX-XXX

CMS Draft Analysis Note

The content of this note is intended for CMS internal use and distribution only

2023/01/19
Archive Hash: 52fc864-D
Archive Date: 2021/06/30

A search for electroweak $W(\rightarrow \ell\nu)H(\rightarrow b\bar{b})jj$ production

Andrew Levin, Jie Xiao, Sitian Qian, Qiang Li, and Rafia Shabbir
Peking University

DRAFT

Abstract

This analysis note contains a study of electroweak-induced $W(\rightarrow l\nu)H(\rightarrow bb)jj$ based on the 138 fb^{-1} of data collected at 13 TeV during 2016-2018. The study exploits the discriminating power of the dijet masses and the pseudo-rapidity separation between the jets, and enhances the sensitivity using a boosted decision tree. The best-fit signal strength based on a binned likelihood fit in which the signal strength is a free parameter corresponds to an observed (expected) significance of X.XX σ (0.45 σ).

This box is only visible in draft mode. Please make sure the values below make sense.

PDFAuthor: Andrew Micheal Levin, Rafia Shabbir, Jie Xiao, Sitian Qian, Qiang Li
PDFTitle: TBD
PDFSubject: CMS
PDFKeywords: CMS, Higgs, VBS

Please also verify that the abstract does not use any user defined symbols

AN-22-065

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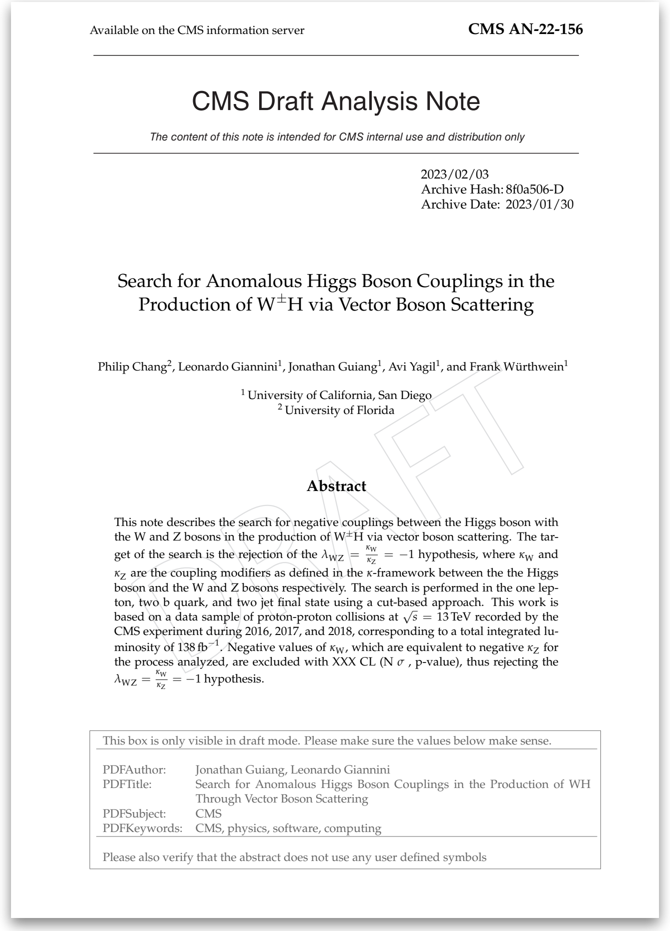
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CMS Draft Analysis Note

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2023/02/03
Archive Hash: 8f0a506-D
Archive Date: 2023/01/30

Search for Anomalous Higgs Boson Couplings in the Production of $W^{\pm}H$ via Vector Boson Scattering

Philip Chang[2], Leonardo Giannini[1], Jonathan Guiang[1], Avi Yagil[1], and Frank Würthwein[1]

[1] University of California, San Diego
[2] University of Florida

DRAFT

Abstract

This note describes the search for negative couplings between the Higgs boson with the W and Z bosons in the production of $W^{\pm}H$ via vector boson scattering. The target of the search is the rejection of the $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = -1$ hypothesis, where κ_W and κ_Z are the coupling modifiers as defined in the κ-framework between the the Higgs boson and the W and Z bosons respectively. The search is performed in the one lepton, two b quark, and two jet final state using a cut-based approach. This work is based on a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the CMS experiment during 2016, 2017, and 2018, corresponding to a total integrated luminosity of 138 fb^{-1}. Negative values of κ_W, which are equivalent to negative κ_Z for the process analyzed, are excluded with XXX CL (N σ , p-value), thus rejecting the $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = -1$ hypothesis.

This box is only visible in draft mode. Please make sure the values below make sense.

PDFAuthor: Jonathan Guiang, Leonardo Giannini
PDFTitle: Search for Anomalous Higgs Boson Couplings in the Production of WH Through Vector Boson Scattering
PDFSubject: CMS
PDFKeywords: CMS, physics, software, computing

Please also verify that the abstract does not use any user defined symbols

AN-22-156

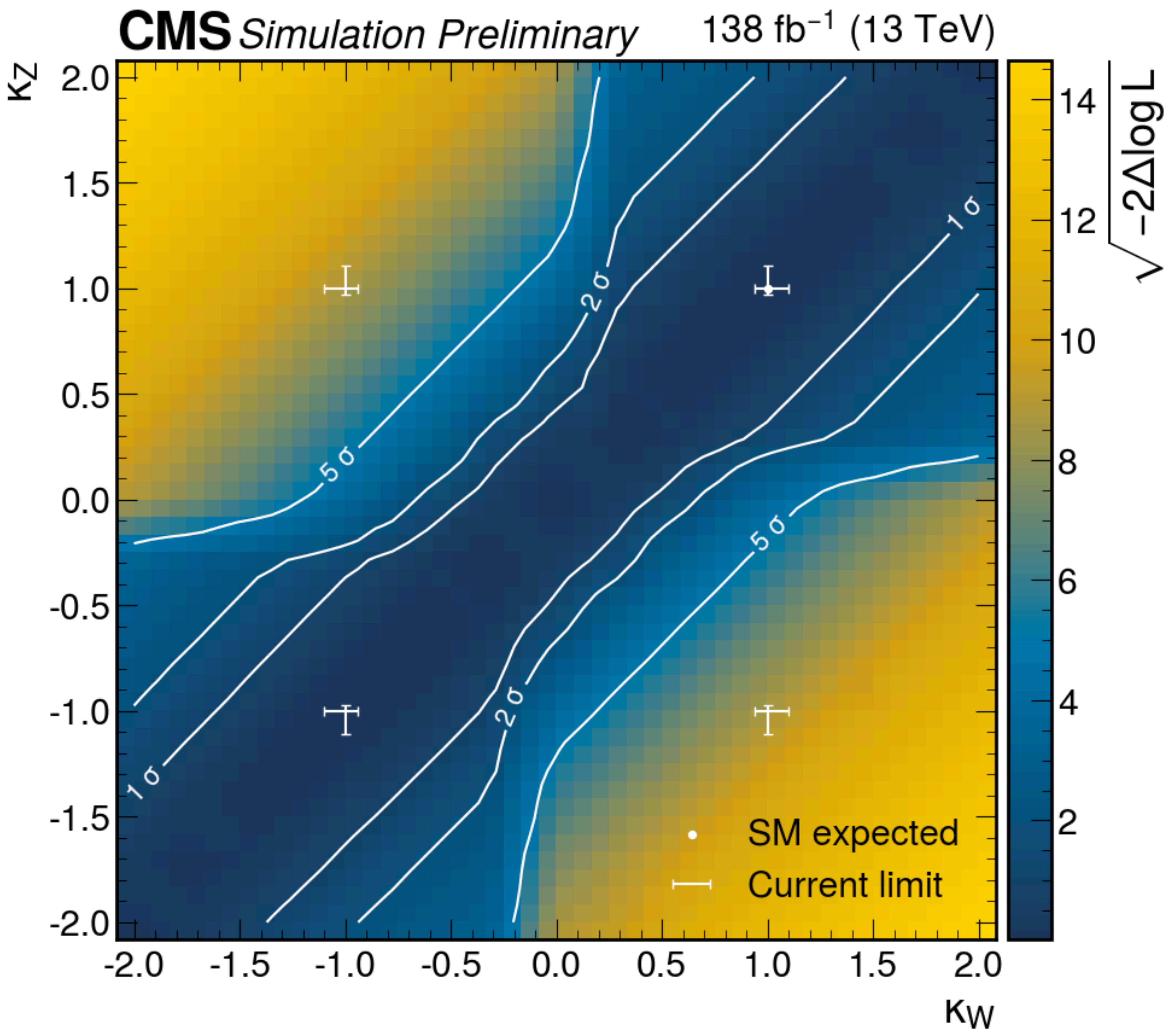
⟶ PLB (or PRL)

- Two results: SM VBS WH measurement (resolved) and λ_{WZ} = -1 exclusion (boosted)
- Neither analysis is sensitive to the other's signal model ⇒ **keep separate**
- Publish in same paper, but **do not combine results** (present "side-by-side")
- **Target journal: PLB (or PRL)**

Summary

- Presented a status update

	Signal Region
Yields	**Expected sig: 413 ± 8.9** **Predicted bkg: 128 ± 17.0 ± 13.1** *stat.* *syst.*
Description	• Data-driven bkg. extrapolation • Can exclude $\lambda_{WZ} = -1$



- Cut-based analysis w/ data-driven bkg. estimate
- Set of signal systematics completed
- VBS WH allows us to exclude $\lambda_{WZ} < 0$
  - 2D scan performed
- Wrote an AN draft + proposed publication plan
- Next: paper draft and pre-approval

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Backup

BSM Signal Models

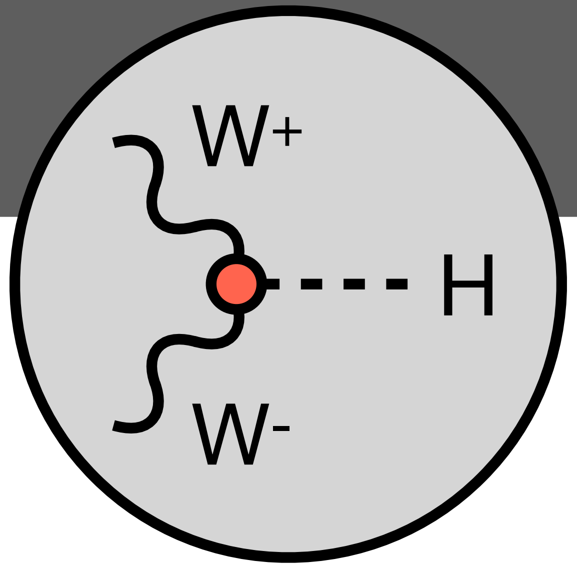
$\kappa_W = -1$

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})
```



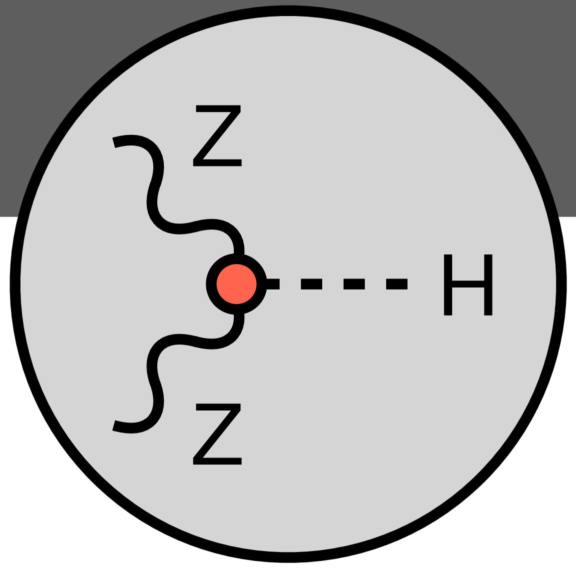
$\kappa_Z = -1$

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!

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

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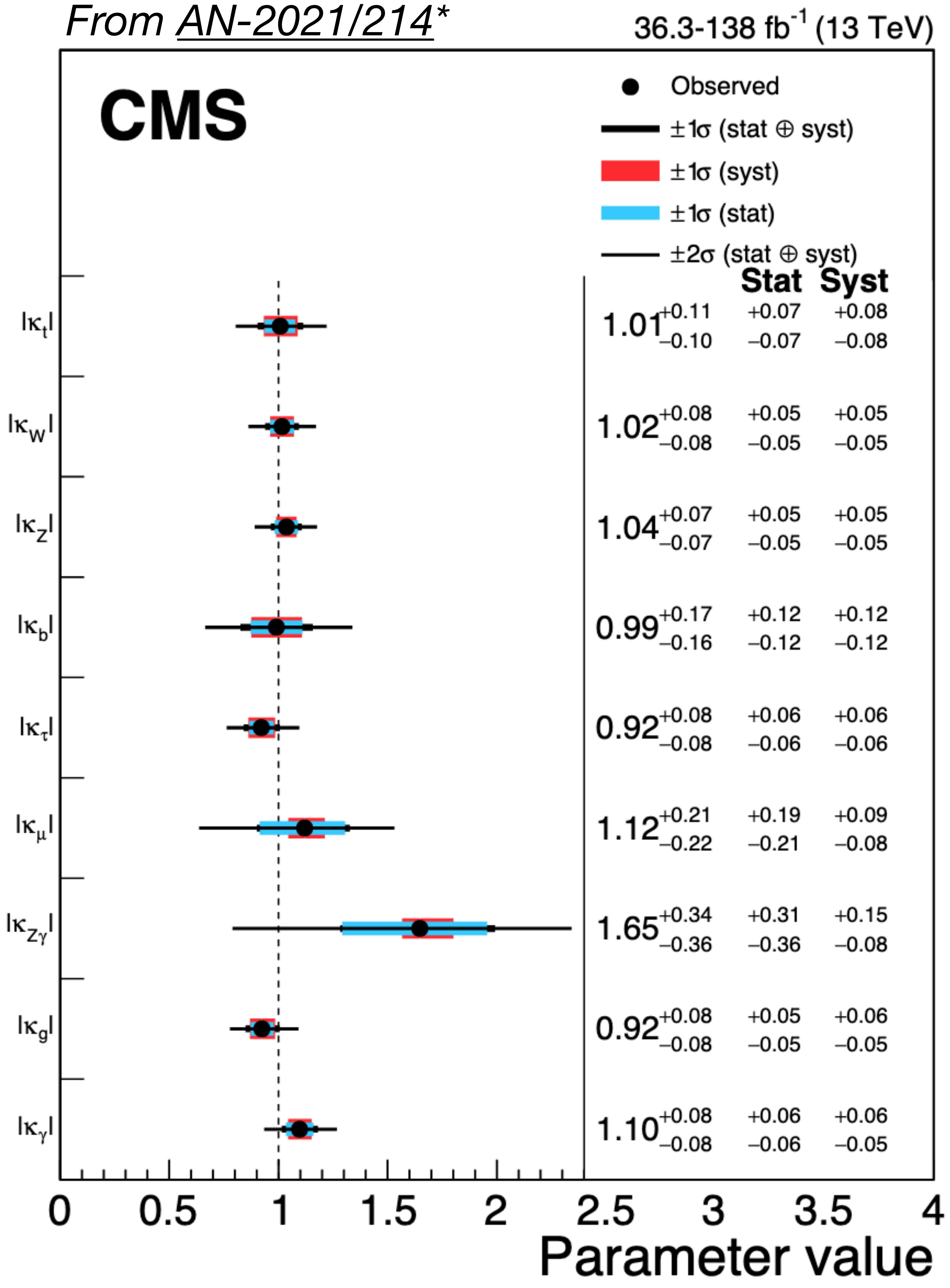
Why focus on $\lambda_{WZ} = -1$?

- 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 $\lambda_{WZ} = -1$
- A 2D scan of κ_W and κ_Z can more strongly exclude this

*From AN-2021/214**



*Identical to the figure published in Nature

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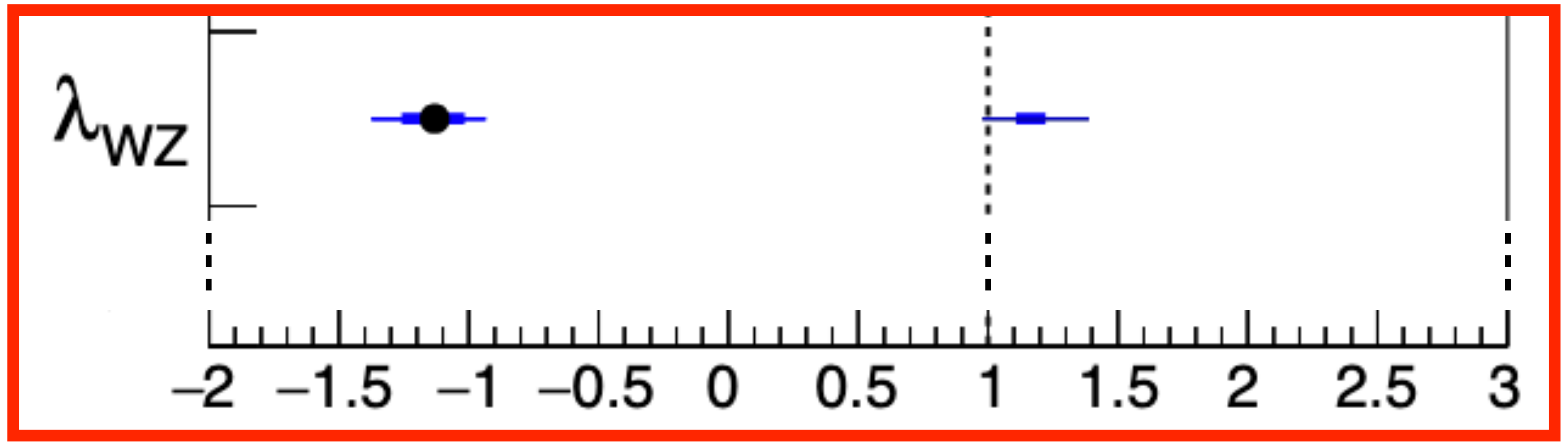
2016 CMS Result



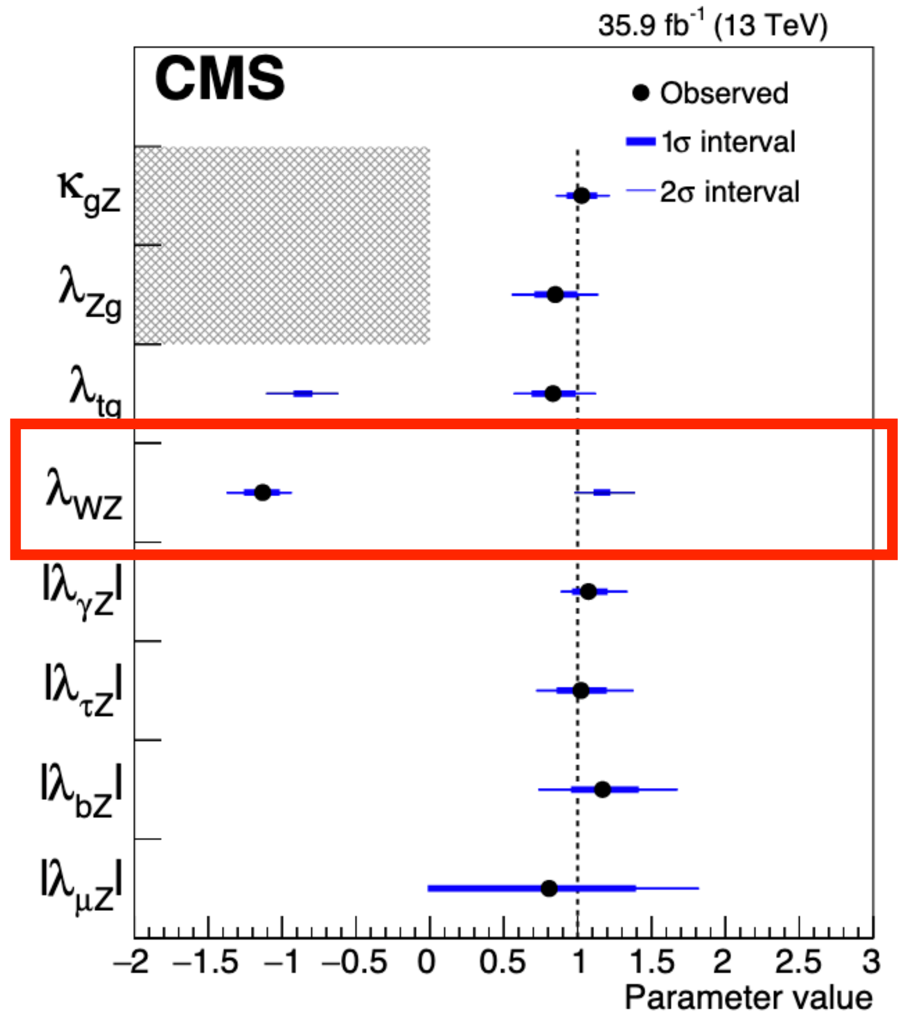
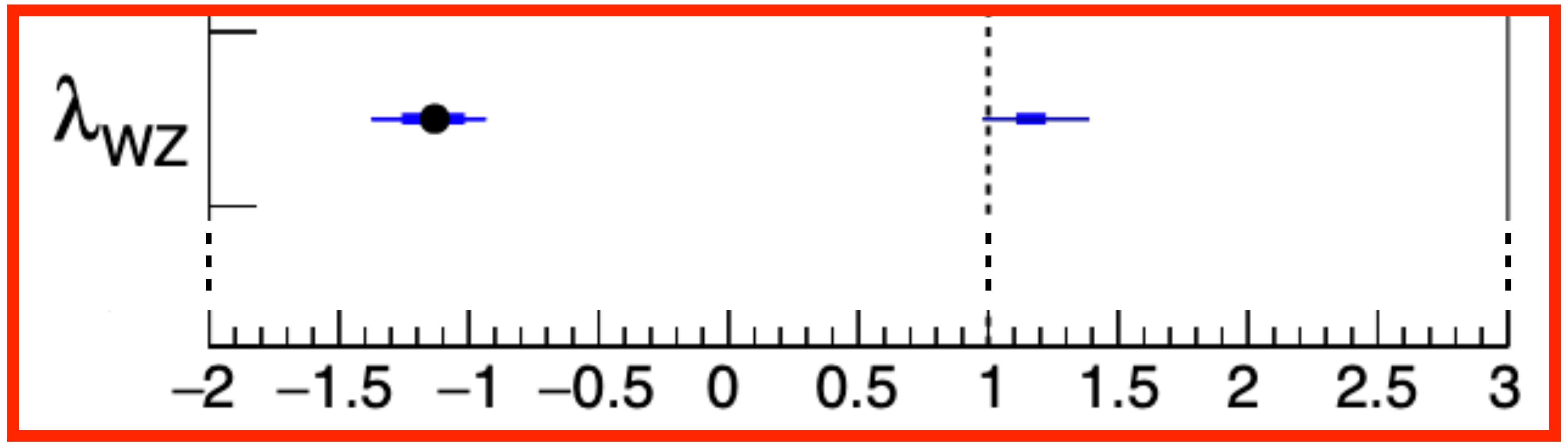


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and H $\to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of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

2016 CMS Result



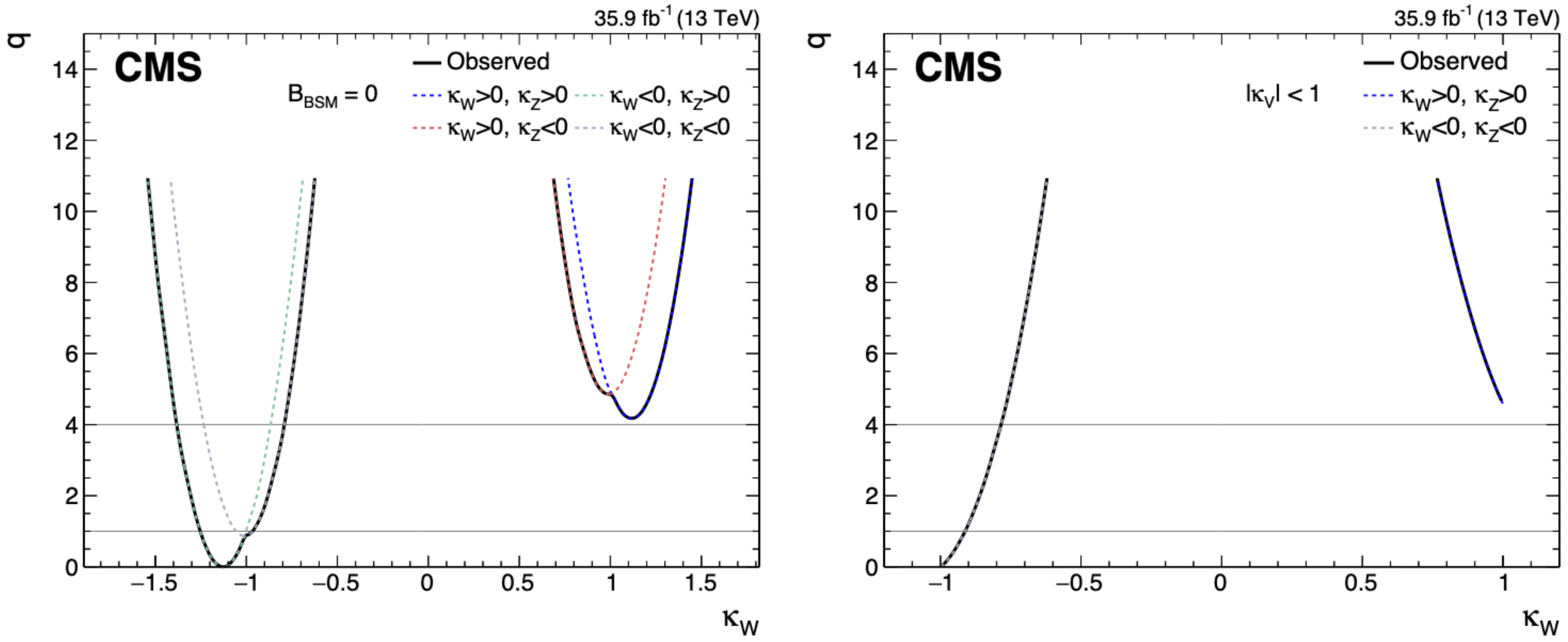


Figure 13: Scan of the test statistic q as a function of κ_W in the generic κ model assuming $\mathcal{B}_{BSM} = 0$ (left) and allowing $\mathcal{B}_{inv}$ and $\mathcal{B}_{undet}$ to float (right). The different colored lines indicate the value of q for different combinations of signs for κ_W and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

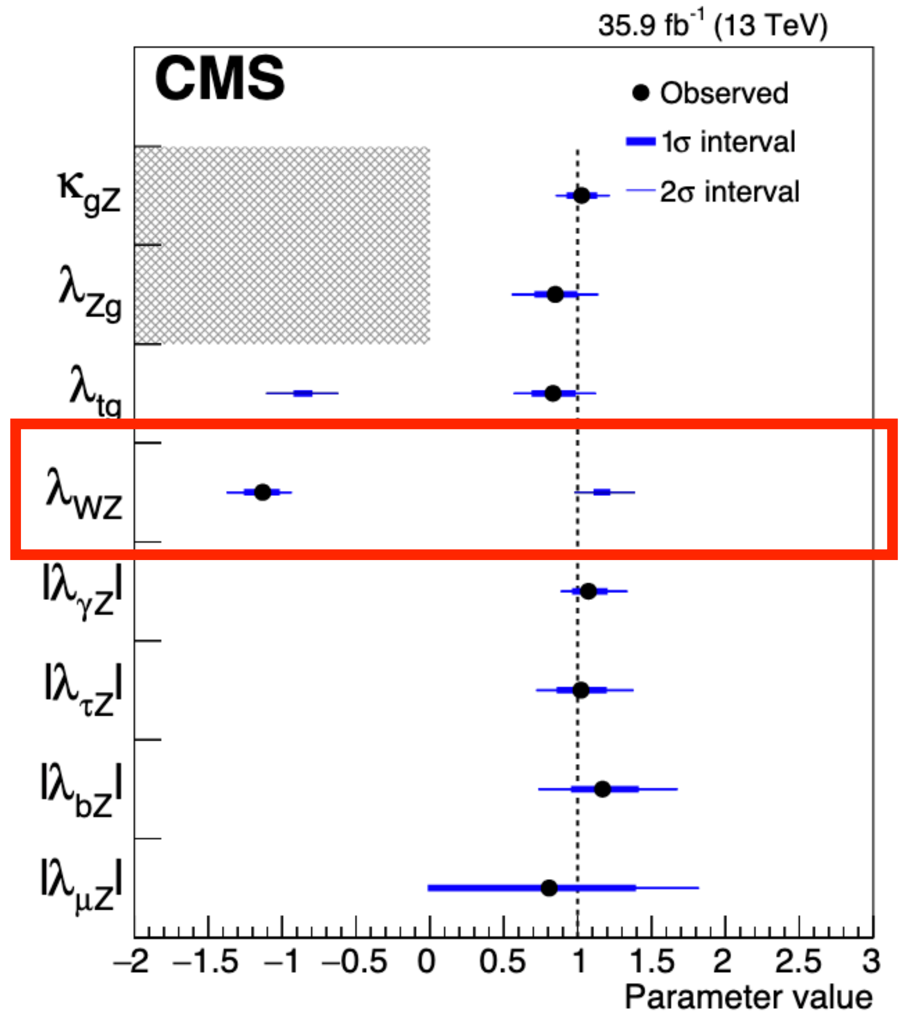


Figure 16: Summary of the model with coupling ratios and effective couplings for the ggH and $H \to \gamma\gamma$ loops. The points indicate the best fit values while the thick and thin horizontal bars show the 1σ and 2σ CL intervals, respectively. For this model, both positive and negative values of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

VBS WH Cutflow

Yields scaled to lumi×σ, rounded for readability

	VBSWH (SM)		VH		EWKWLep		Bosons		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	raw	wgt	raw	wgt
Bookkeeping	72600	8.30	80673	228.00	83184	32017.05	886799	25828.35	4682666	133380.10	82462	8176.50	949174	1185.02	2041509	87275.70	295702	10251.55	9174769	298350.58	16165	2373.05
FixEWKSamples	72600	8.30	80673	228.00	83184	7602.13	886799	25828.35	4682666	133380.10	82462	8176.50	949174	1185.02	2041509	87275.70	295702	10251.55	9174769	273935.66	16165	2373.05
PassesEventFilters	72289	8.27	80267	226.78	82941	7577.36	879897	25656.67	4633789	132855.20	82104	8147.62	945092	1179.86	2035744	87028.10	294374	10205.60	9106497	272885.46	16093	2363.40
SelectLeptons	72289	8.27	80267	226.78	82941	7577.36	879897	25656.67	4633789	132855.20	82104	8147.62	945092	1179.86	2035744	87028.10	294374	10205.60	9106497	272885.46	16093	2363.40
Has1TightLep	72289	8.17	80267	224.05	82941	7486.14	879897	25364.80	4633789	131312.03	82104	8046.03	945092	1165.30	2035744	85853.30	294374	10056.71	9106497	269516.53	16093	2337.77
LepPtGt40	69946	7.91	78685	216.97	81169	7195.91	846087	24285.81	4272556	125322.10	78315	7741.48	885669	1092.09	1946073	82083.42	277410	9469.72	8535910	257415.41	15630	2270.63
SelectFatJets	69946	7.91	78685	216.97	81169	7195.91	846087	24285.81	4272556	125322.10	78315	7741.48	885669	1092.09	1946073	82083.42	277410	9469.72	8535910	257415.41	15630	2270.63
Geq1FatJet	69556	7.87	78389	215.29	80651	7112.19	823044	23957.57	4245877	124024.48	77379	7626.84	872793	1078.63	1938832	81770.63	271936	9284.72	8458457	255078.21	15530	2255.15
SelectHbbFatJet	69556	7.87	78389	215.29	80651	7112.19	823044	23957.57	4245877	124024.48	77379	7626.84	872793	1078.63	1938832	81770.63	271936	9284.72	8458457	255078.21	15530	2255.15
SelectJetsNoHbbOverlap	69556	7.86	78389	214.08	80651	7108.21	823044	23800.86	4245877	123442.63	77379	7762.41	872793	1098.65	1938832	83283.20	271936	9461.39	8458457	256179.29	15530	2247.43
SelectVBSJetsMaxE	35522	4.00	25122	63.74	29515	2829.65	479171	13414.43	3097368	60486.63	55453	5479.73	756299	957.44	1422140	61430.97	222245	7793.68	6122835	152460.27	10268	1483.96
SaveSystWeights	35522	4.00	25122	63.74	29515	2829.65	479171	13414.43	3097368	60486.63	55453	5479.73	756299	957.44	1422140	61430.97	222245	7793.68	6122835	152460.27	10268	1483.96
SaveVariables	35522	4.00	25122	63.74	29515	2829.65	479171	13414.43	3097368	60486.63	55453	5479.73	756299	957.44	1422140	61430.97	222245	7793.68	6122835	152460.27	10268	1483.96
ObjectSelection	35522	4.00	25122	63.74	29515	2829.65	479171	13414.43	3097368	60486.63	55453	5479.73	756299	957.44	1422140	61430.97	222245	7793.68	6122835	152460.27	10268	1483.96
Passes1LepTriggers	32939	3.62	23005	56.15	27555	2560.24	439818	11890.06	2818098	54058.98	50869	4908.31	686927	768.76	1300418	54692.96	203543	6947.60	5583172	135886.67	9489	1334.59
MjjGt500	23327	2.55	6215	16.77	9729	943.60	136548	3807.54	1545452	16774.01	18829	1754.73	221499	251.50	400019	16713.74	73591	2492.10	2435209	42756.54	7934	1114.55
XbbGt0p3	20985	2.28	4146	6.77	3650	114.56	26564	471.60	142467	1337.34	9512	957.09	150845	165.23	232131	9583.88	34054	1128.27	624354	13767.02	5087	715.89
ApplyAk4GlobalBVeto	19197	2.09	3301	5.75	2169	75.15	20984	382.24	104689	1063.76	3103	337.24	39186	45.79	65876	2834.02	10507	359.48	269012	5105.53	4815	679.55
Preselection	19197	2.09	3301	5.75	2169	75.15	20984	382.24	104689	1063.76	3103	337.24	39186	45.79	65876	2834.02	10507	359.48	269012	5105.53	4815	679.55
MjjGt600_detajjGt4	15041	1.64	1385	2.30	1591	38.92	6434	82.24	13514	295.72	1496	147.45	12433	13.48	27224	1150.72	3427	113.60	82545	1846.07	4462	628.35
STGt900	9676	1.06	837	1.51	1296	27.64	4450	50.64	9993	186.12	912	95.29	7809	7.89	14576	609.39	1903	62.22	51452	1041.77	3642	512.74
XbbGt0p9_MSDLt150	8373	0.92	651	0.91	273	3.04	1061	7.90	1117	24.05	133	14.36	1008	1.01	1301	54.27	724	23.16	14641	129.62	2797	413.34
SR1	8373	0.92	651	0.91	273	3.04	1061	7.90	1117	24.05	133	14.36	1008	1.01	1301	54.27	724	23.16	14641	129.62	2797	413.34
SavePDFWeights	8373	0.92	651	0.91	273	3.04	1061	7.90	1117	24.05	133	14.36	1008	1.01	1301	54.27	724	23.16	14641	129.62	2797	413.34
STGt1500	886	0.10	69	0.05	42	0.14	132	1.89	179	1.22	6	0.62	53	0.12	30	1.31	26	0.87	1423	6.32	752	110.52
SR2	886	0.10	69	0.05	42	0.14	132	1.89	179	1.22	6	0.62	53	0.12	30	1.31	26	0.87	1423	6.32	752	110.52

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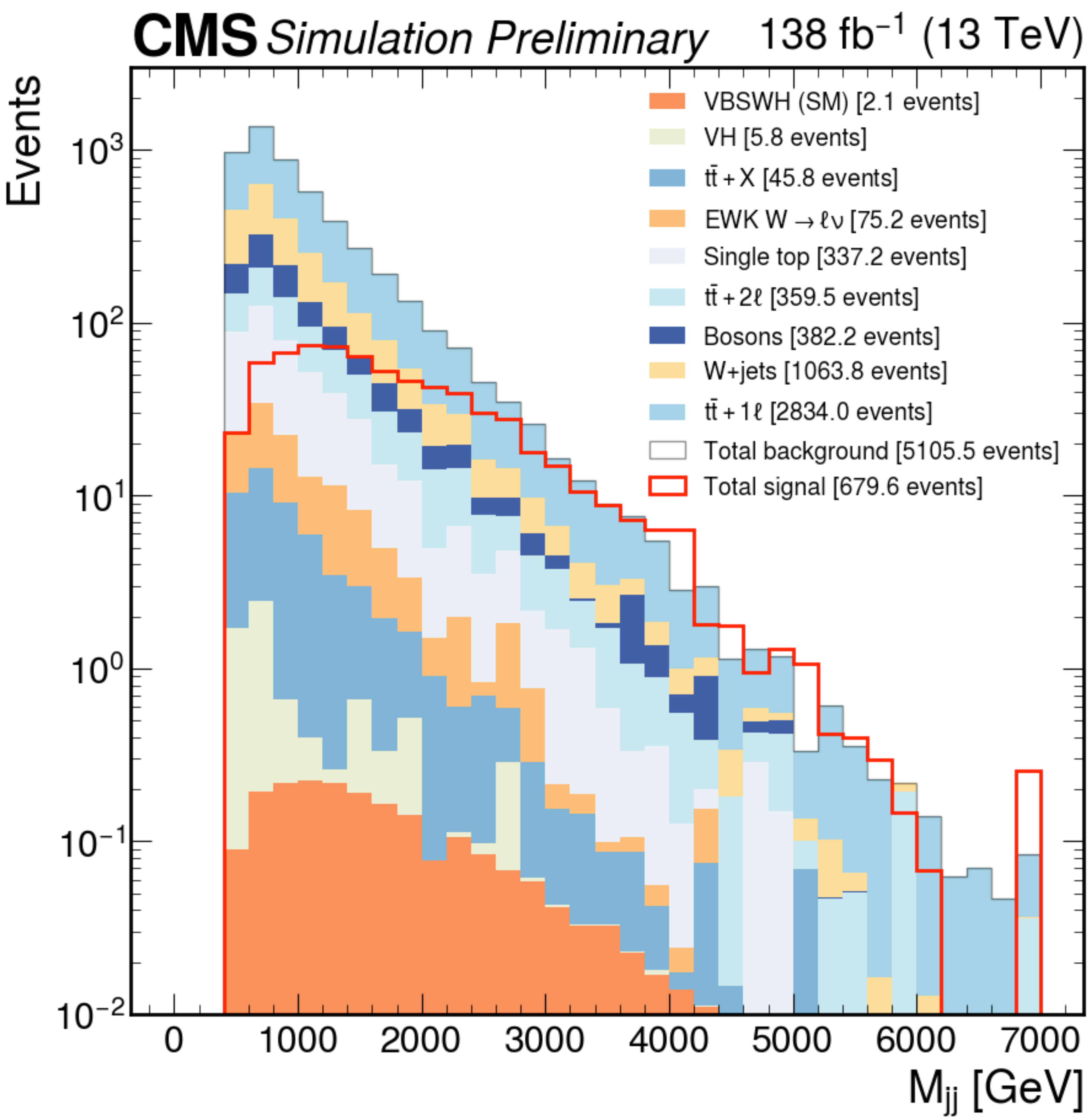
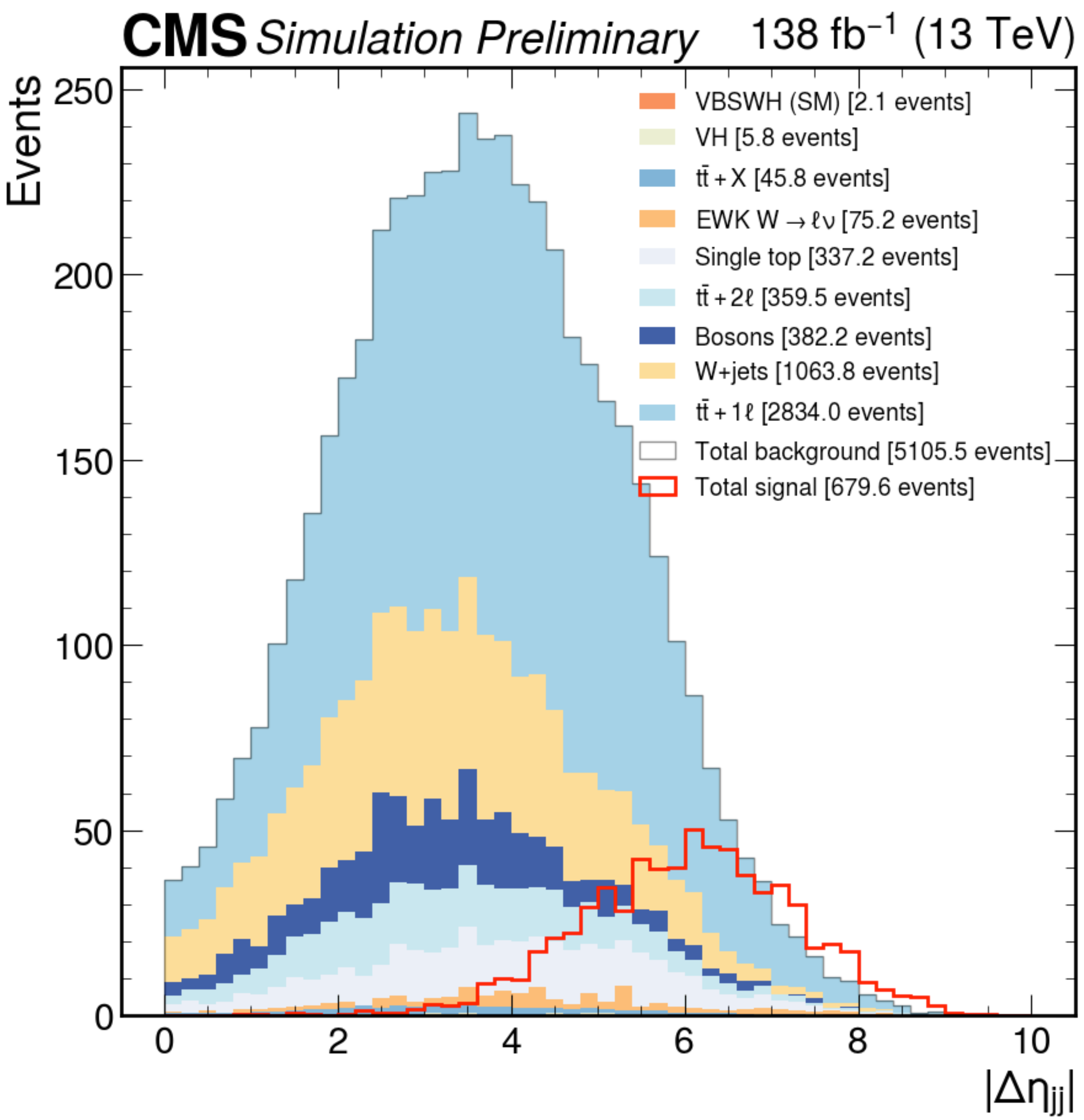
Preselection: VBS





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

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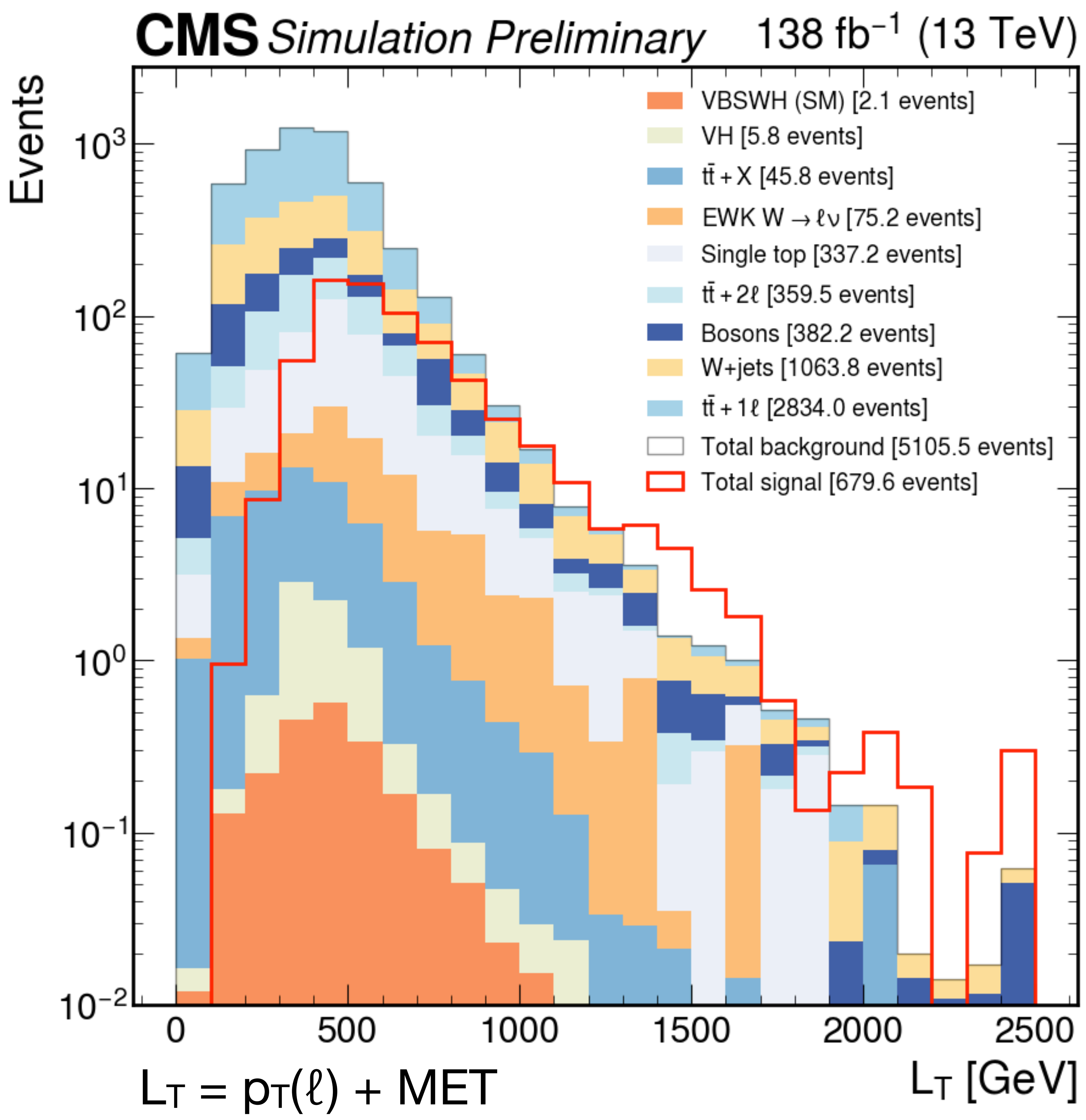
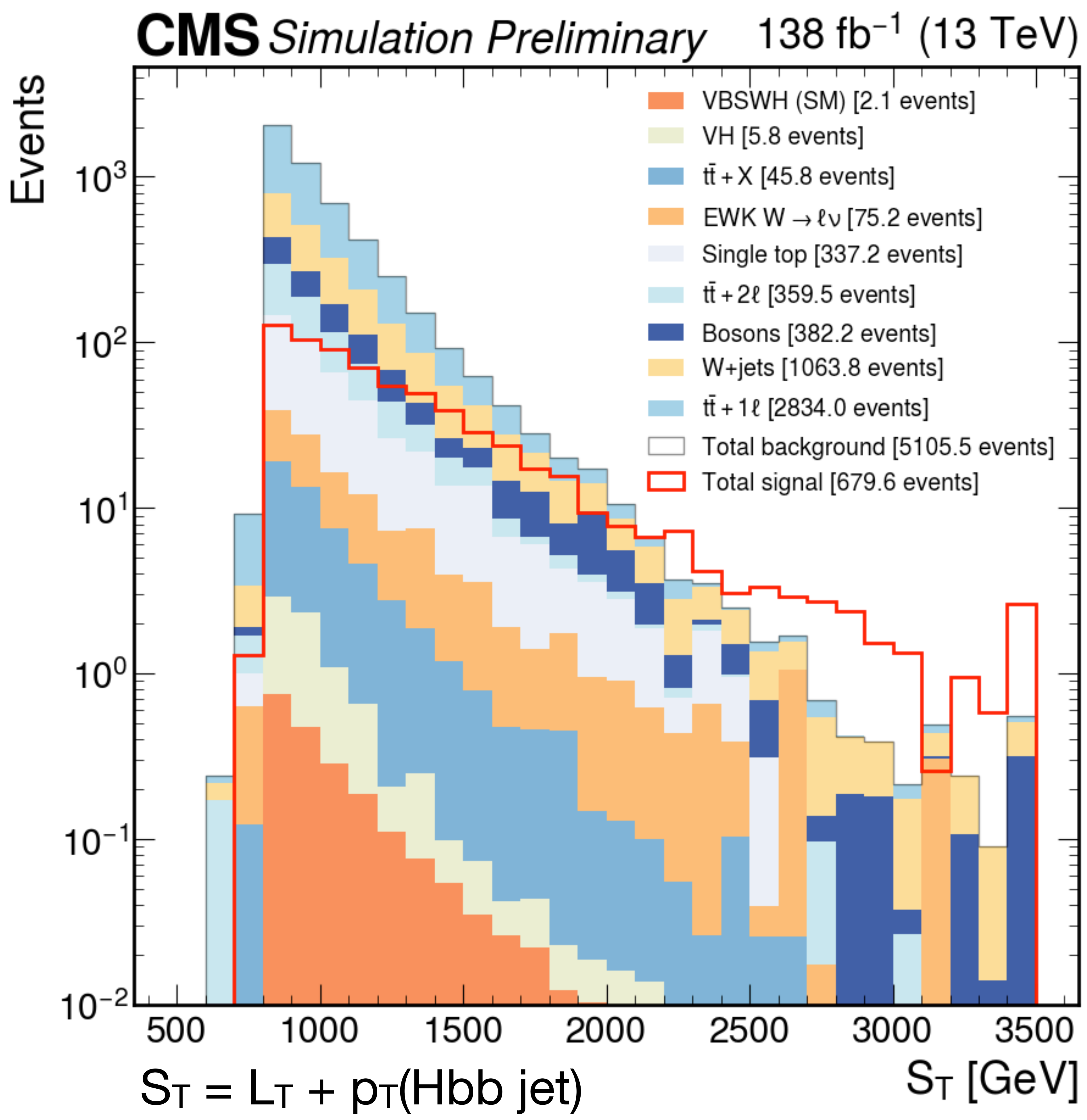
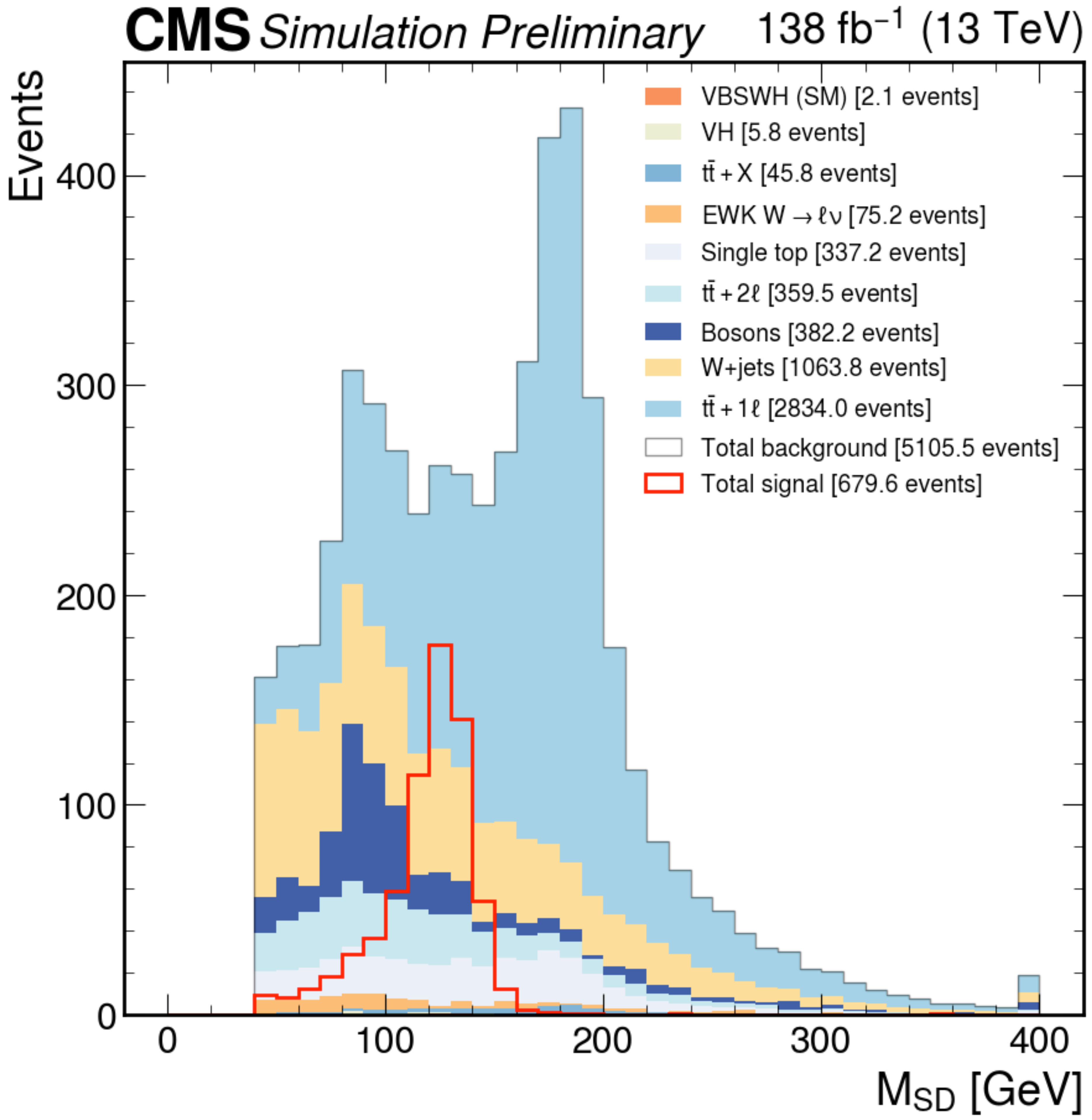
Preselection: L_T and S_T

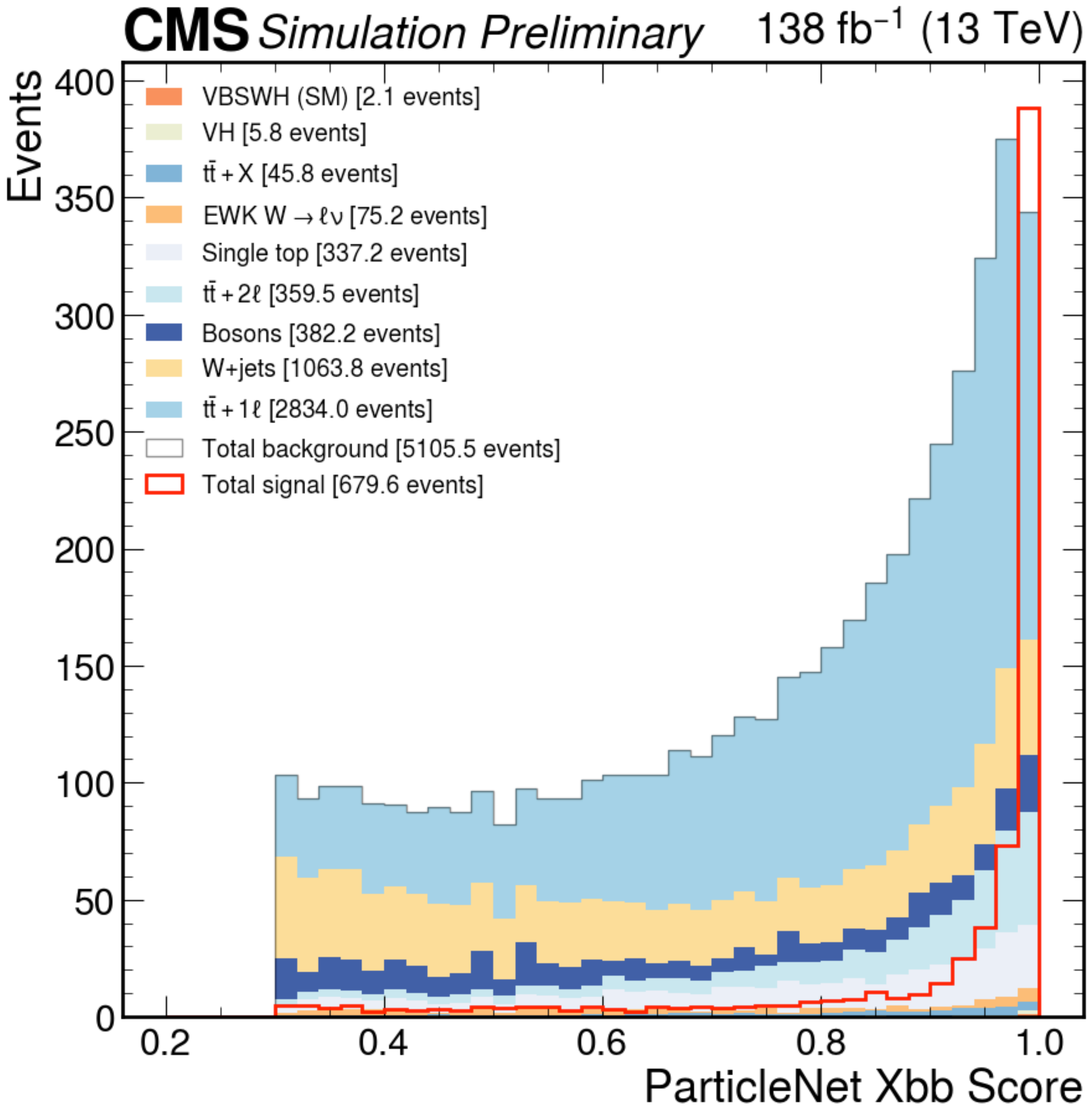




Strong signal vs. background separation in S_T

Preselection: Hbb





Strong separation in Hbb variables as well

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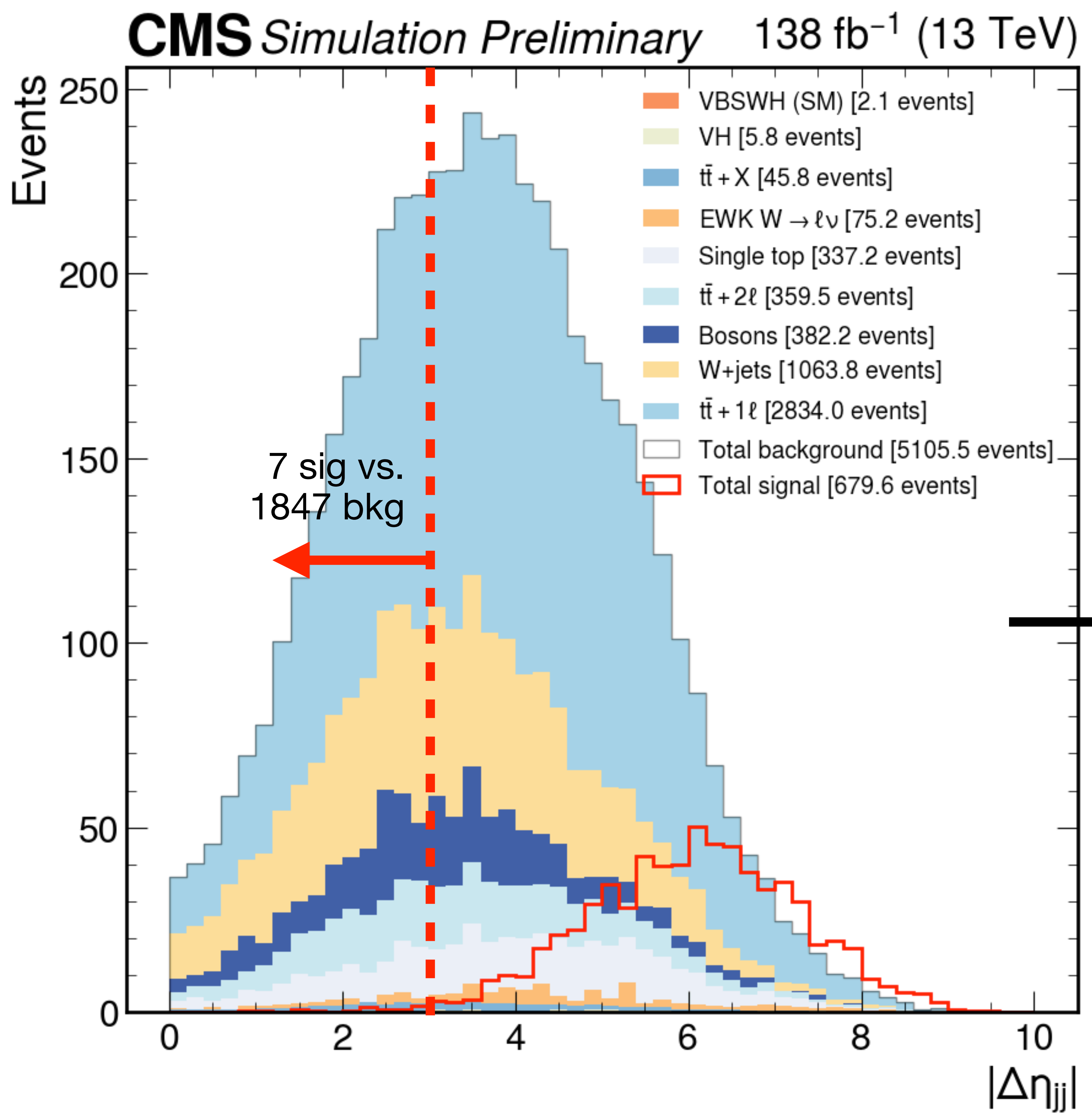
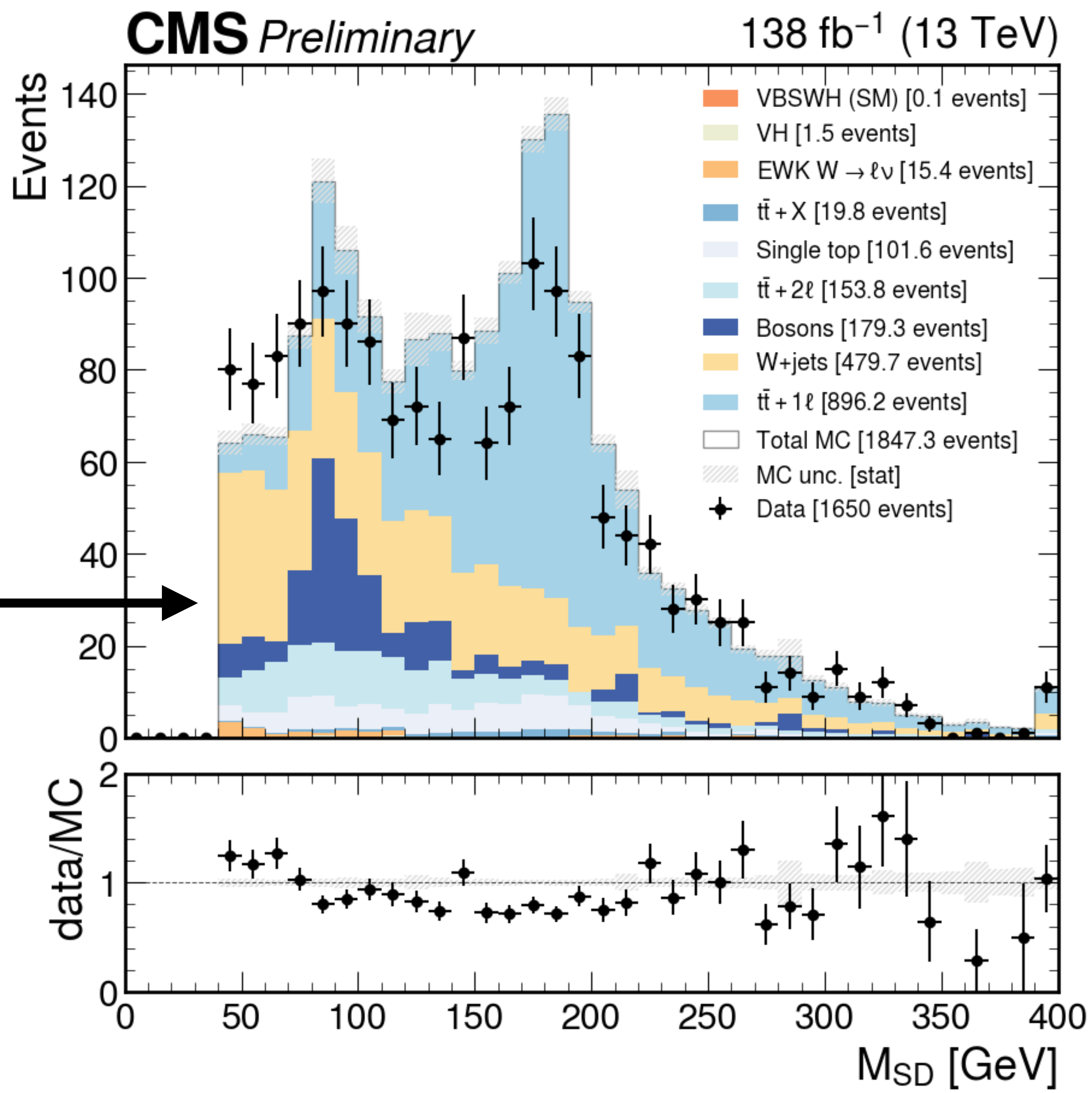
$\Delta\eta_{jj}$ Control Region





Agreement looks good, more plots in backup

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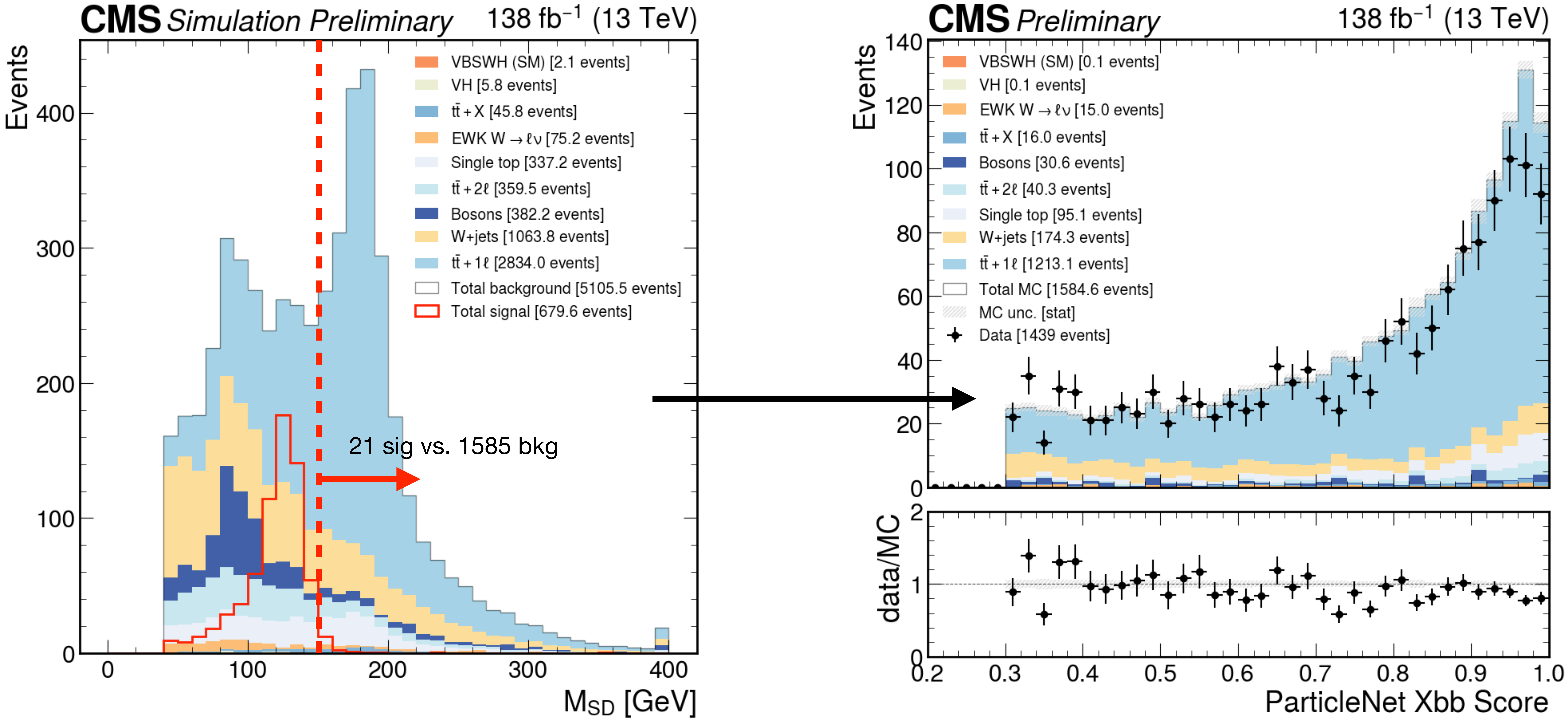
M_{SD} Control Region



Agreement looks good, more plots in backup

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Analysis Skim

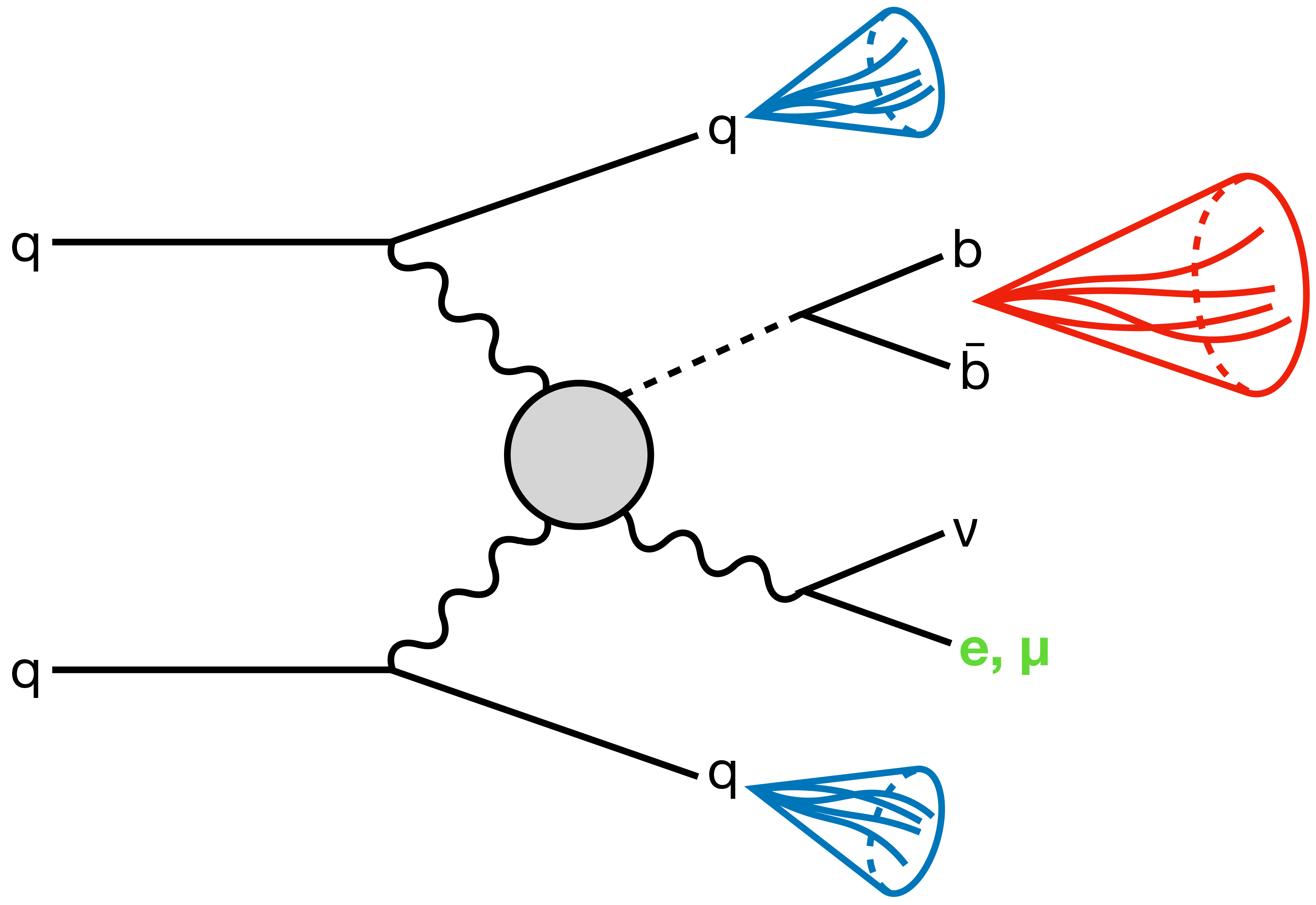
Yields scaled to lumi×σ, rounded for readability

Cut	VBSWH (SM)	VH	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
Skim	8	228	7.6K	26K	133K	8.2K	1.2K	87K	10K	274K	—	2.4K	—

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
**S_T = $p_T(\ell)$ + MET + p_T(fat jet w/ highest Xbb score)

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 > 300 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

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Preselection

Yields scaled to lumi×σ, rounded for readability

Cut	VBSWH (SM)	VH	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
Skim	8	228	7.6K	26K	133K	8.2K	1.2K	87K	10K	274K	—	2.4K	—
Object selection	4	64	2.8K	13K	60K	5.5K	957	61K	7.8K	152K	44%	1.5K	37%
Single lepton triggers	4	56	2.6K	12K	54K	4.9K	769	55K	6.9K	136K	11%	1.3K	10%
M_{jj} > 500 GeV	3	17	944	3.8K	17K	1.8K	252	17K	2.5K	43K	69%	1.1K	16%
max(PNet Xbb score) > 0.3	2	7	115	472	1.3K	957	165	9.6K	1.1K	14K	68%	716	36%
No b-tagged (med.) AK4 jets	2	6	75	382	1.1K	337	46	2.8K	359	**5.1K**	63%	**680**	5%

Presel. (last three rows, with Single lepton triggers)

- Using ParticleNet Xbb (mass-decorrelated) tagger
- Veto events with any b-tagged "good" jets
- Can identify key variables from here (next slides)

Year	HLT paths

2016	`HLT_IsoMu24`
	`HLT_IsoTkMu24`
	`HLT_Ele27_WPTight_Gsf`

2017	`HLT_IsoMu27` `HLT_Ele32_WPTight_Gsf_L1DoubleEG`
2018	`HLT_IsoMu24` `HLT_Ele32_WPTight_Gsf`

*eff = 1 - after/before

Signal Regions

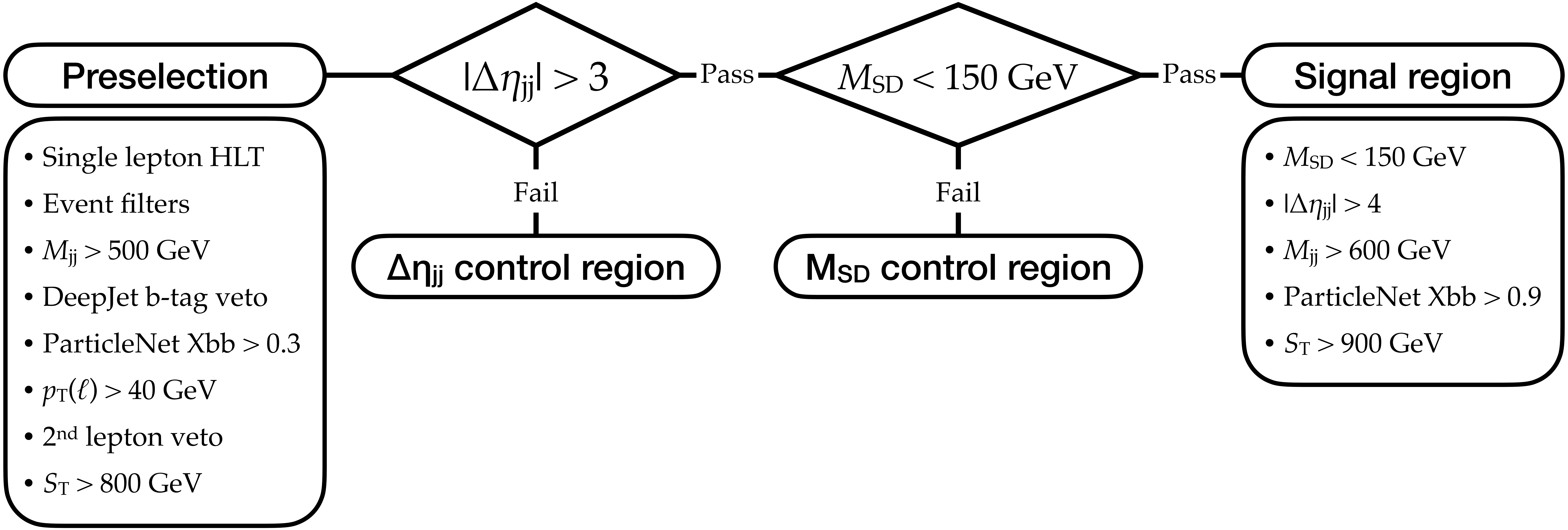
Yields scaled to lumi×σ, rounded for readability

	Cut	VBSWH (SM)	VH	EWK W	Bosons	W+Jets	SingleTop	TTbar+X	TTbar1L	TTbar2L	TotalBkg	Eff.*	VBSWH (λ_{WZ} = -1)	Eff.*
	Skim	8	228	7.6K	26K	133K	8.2K	1.2K	87K	10K	274K	—	2.4K	—
	Object selection	4	64	2.8K	13K	60K	5.5K	957	61K	7.8K	152K	44%	1.5K	37%
	Single lepton triggers	4	56	2.6K	12K	54K	4.9K	769	55K	6.9K	136K	11%	1.3K	10%
	Preselection	2	6	75	382	1.1K	337	46	2.8K	359	5.1K	96%	680	49%
SR	**M_{jj} > 600 GeV AND $\|\Delta\eta_{jj}\|$ > 4**	2	2	39	82	296	147	13	1.2K	114	1.8K	64%	628	8%
SR	**S_T > 900 GeV**	1	2	28	51	186	95	8	609	62	1K	44%	513	18%
SR	**PNet Xbb vs. QCD > 0.9 AND M_{SD} < 150**	1	1	3	8	24	14	1	54	23	**130**	88%	**413**	19%
SR2	**S_T > 1500 GeV**	0	0	0	2	1	1	0	1	1	**6**	95%	**111**	73%

- **Signal Region (SR): 413 signal vs. 131 background**
    - Can exclude λ_{WZ} = -1
    - Background can be estimated via ABCD
- **SR2** not used in analysis (backup)

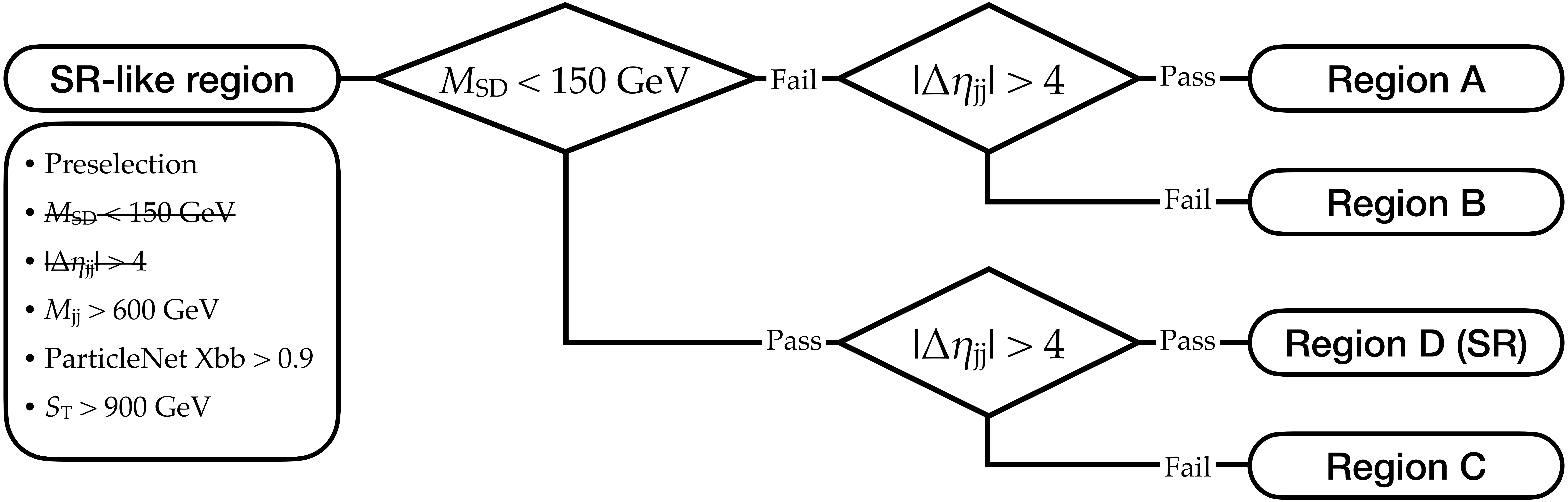
*eff = 1 - after/before

VBS WH Cutflow



UC San Diego

VBS WH Cutflow



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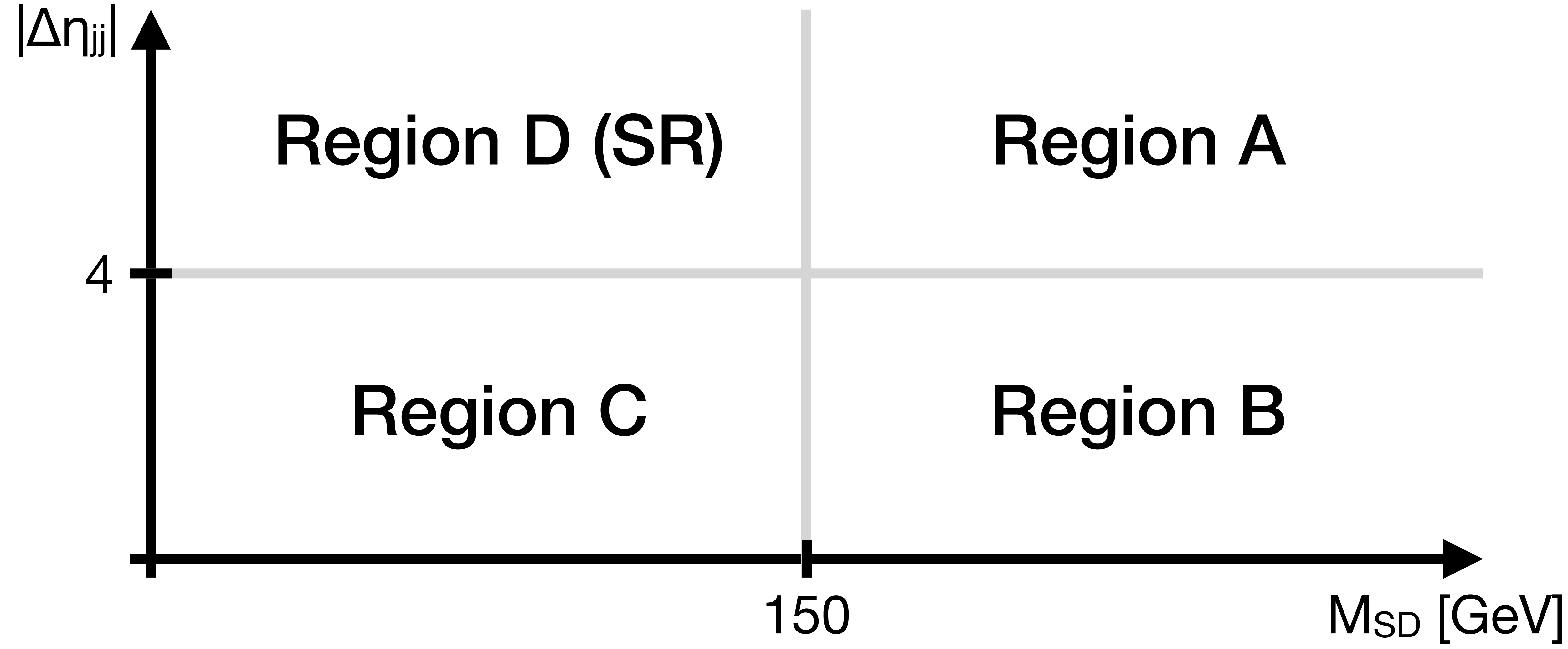
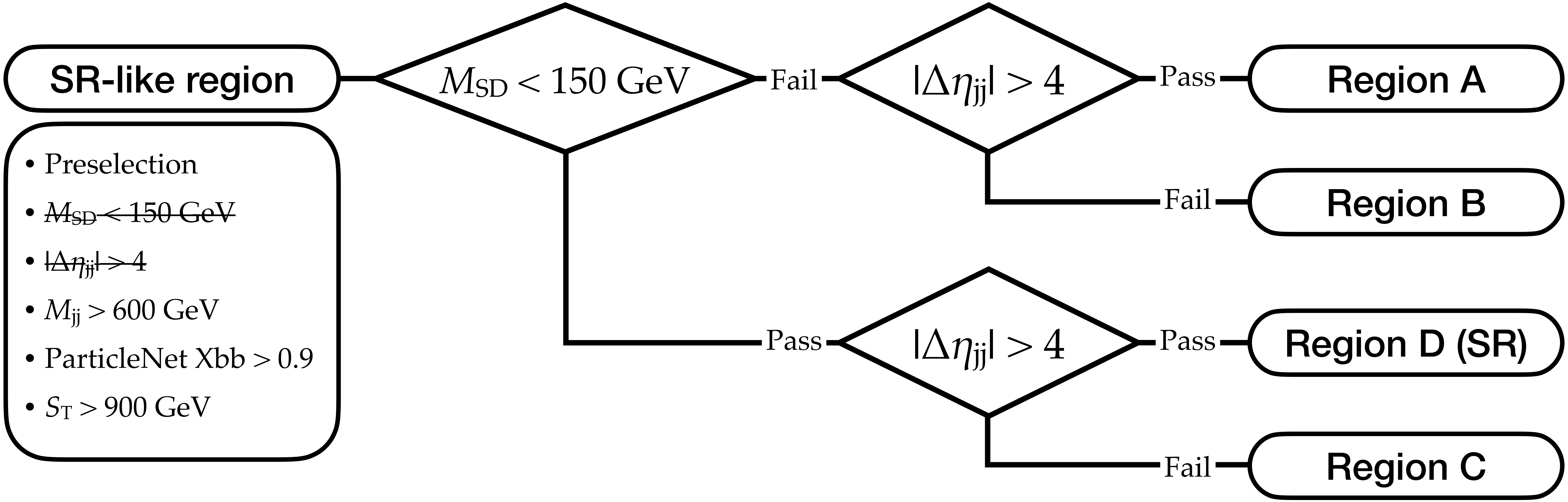
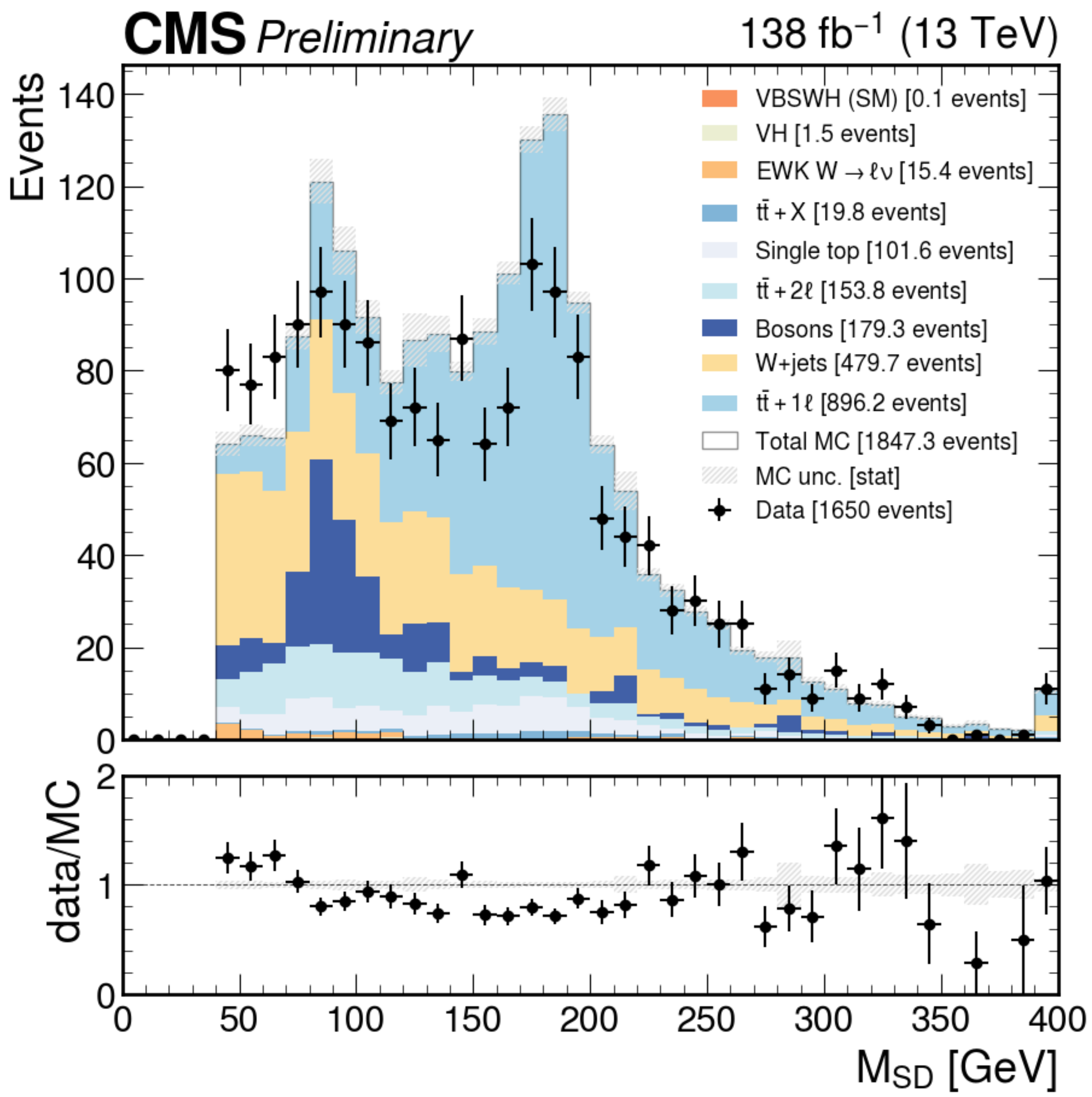
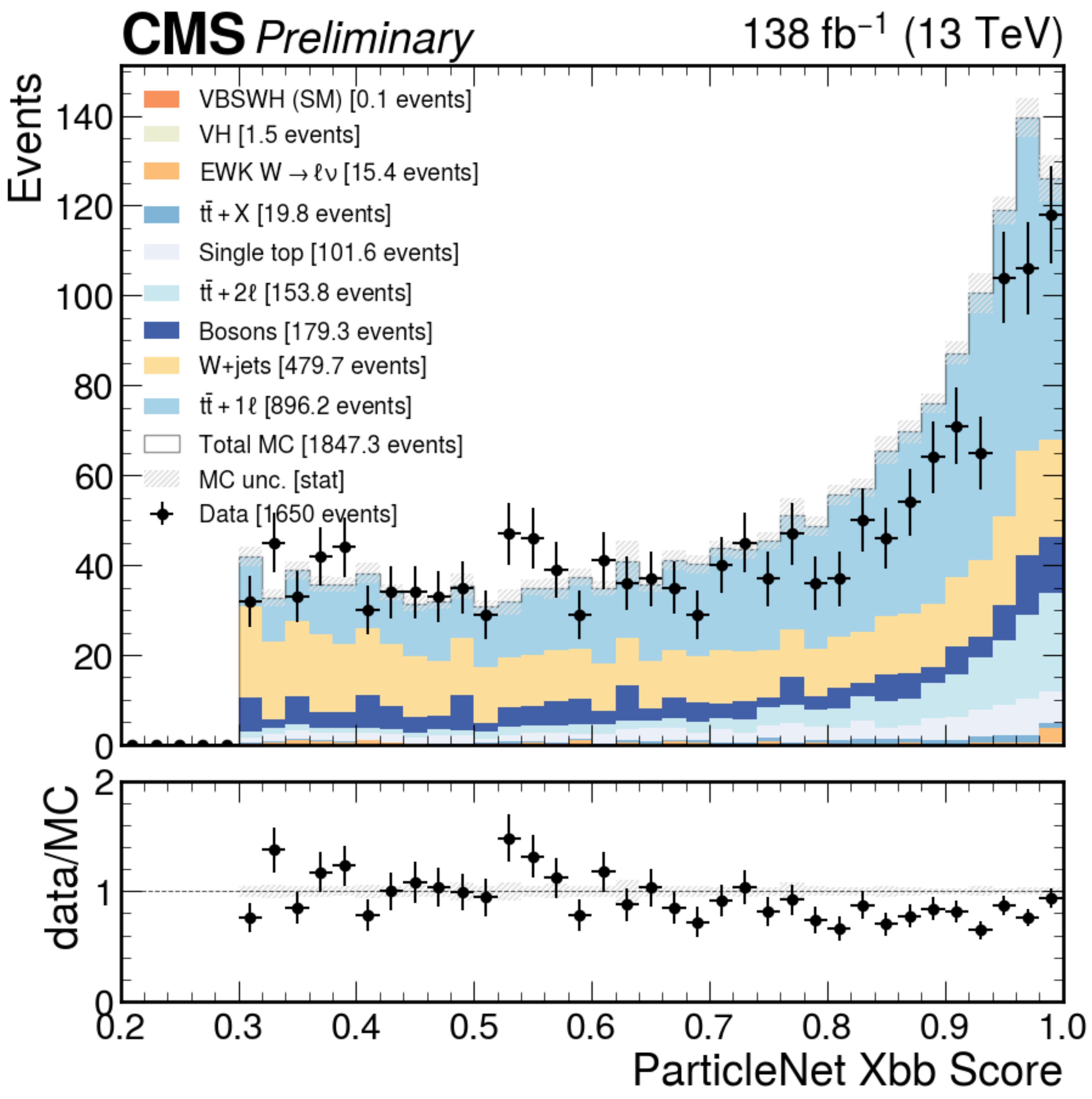

|Δηjj|
4
Region D (SR)
Region A
Region C
Region B
150
MSD [GeV]


SR-like region
$M_{SD} < 150$ GeV
Fail
$|\Delta\eta_{jj}| > 4$
Pass
Region A
Fail
Region B
Pass
$|\Delta\eta_{jj}| > 4$
Pass
Region D (SR)
Fail
Region C
• Preselection
• ~~$M_{SD} < 150$ GeV~~
• ~~$|\Delta\eta_{jj}| > 4$~~
• $M_{jj} > 600$ GeV
• ParticleNet Xbb > 0.9
• $S_T > 900$ GeV

$\Delta\eta_{jj}$ Control Region





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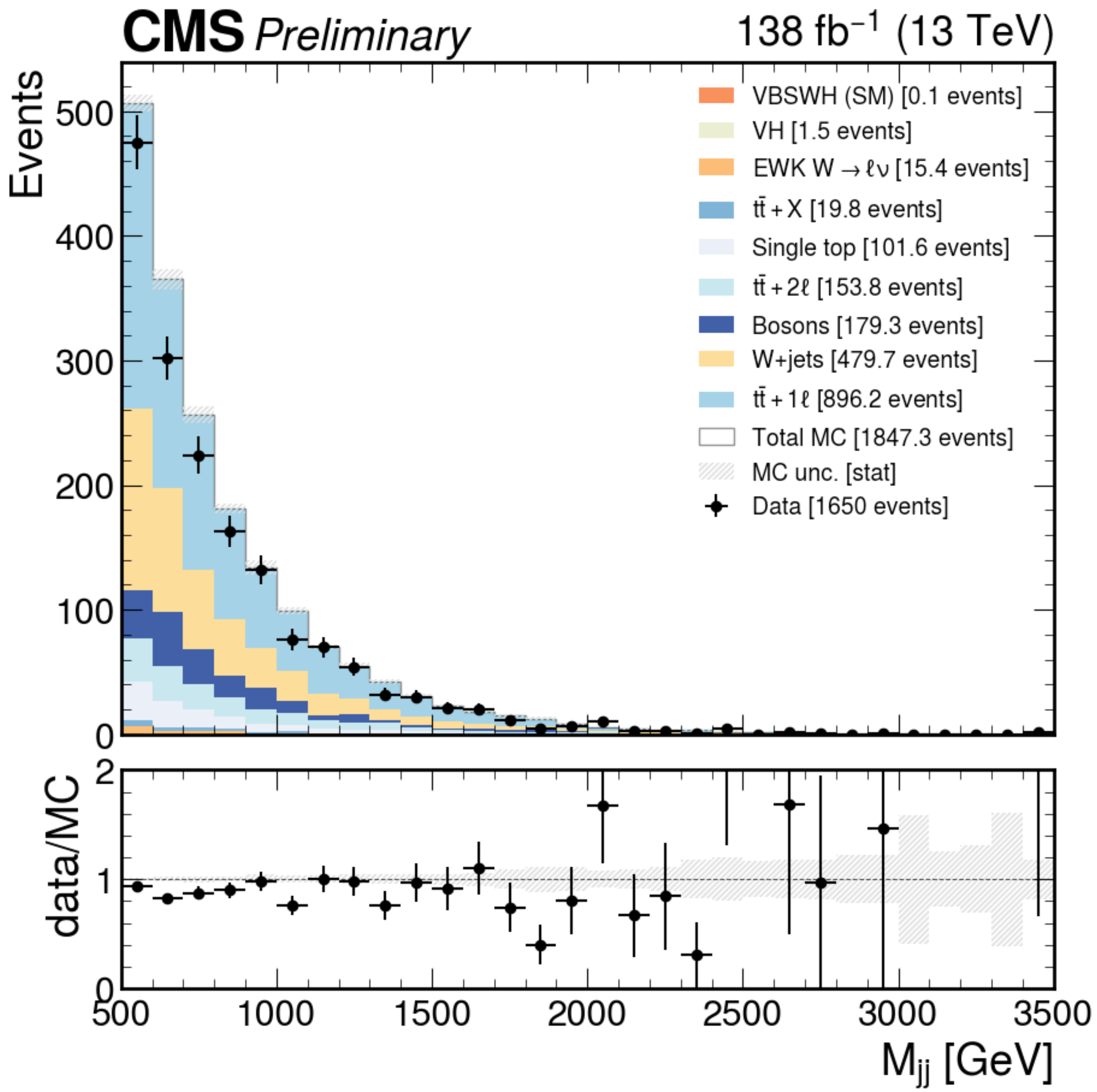
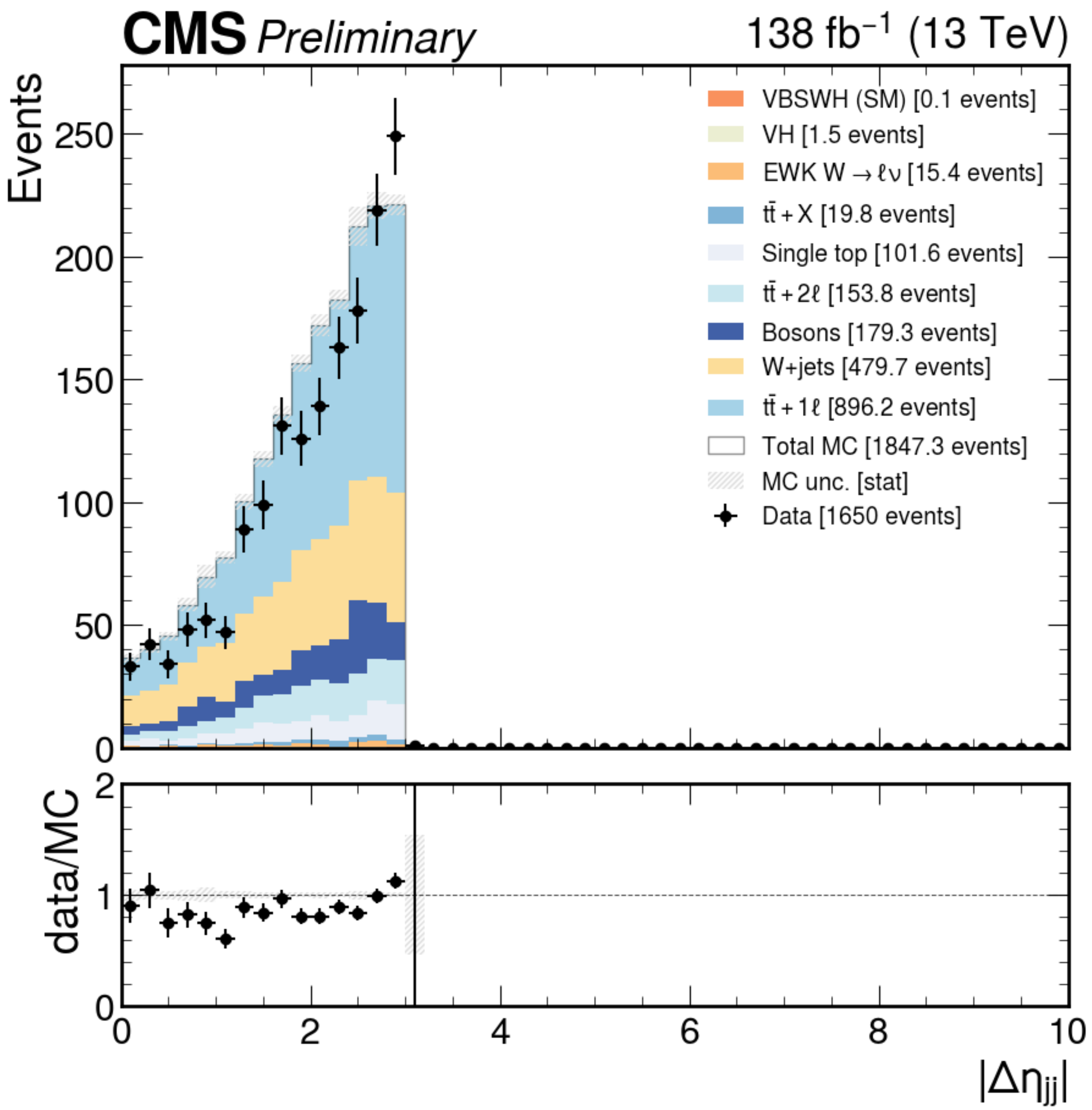
$\Delta\eta_{jj}$ Control Region





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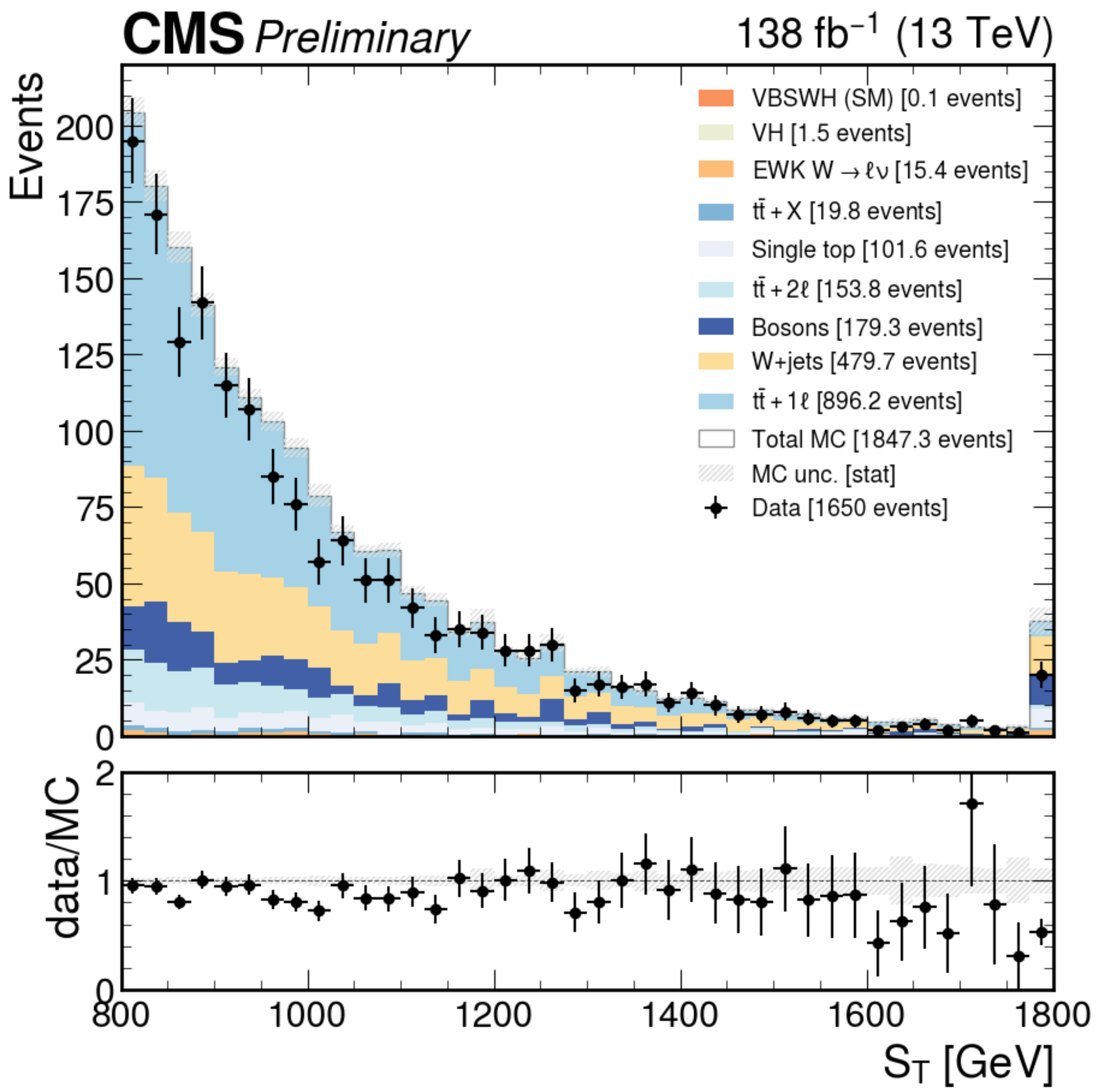
$\Delta\eta_{jj}$ Control Region



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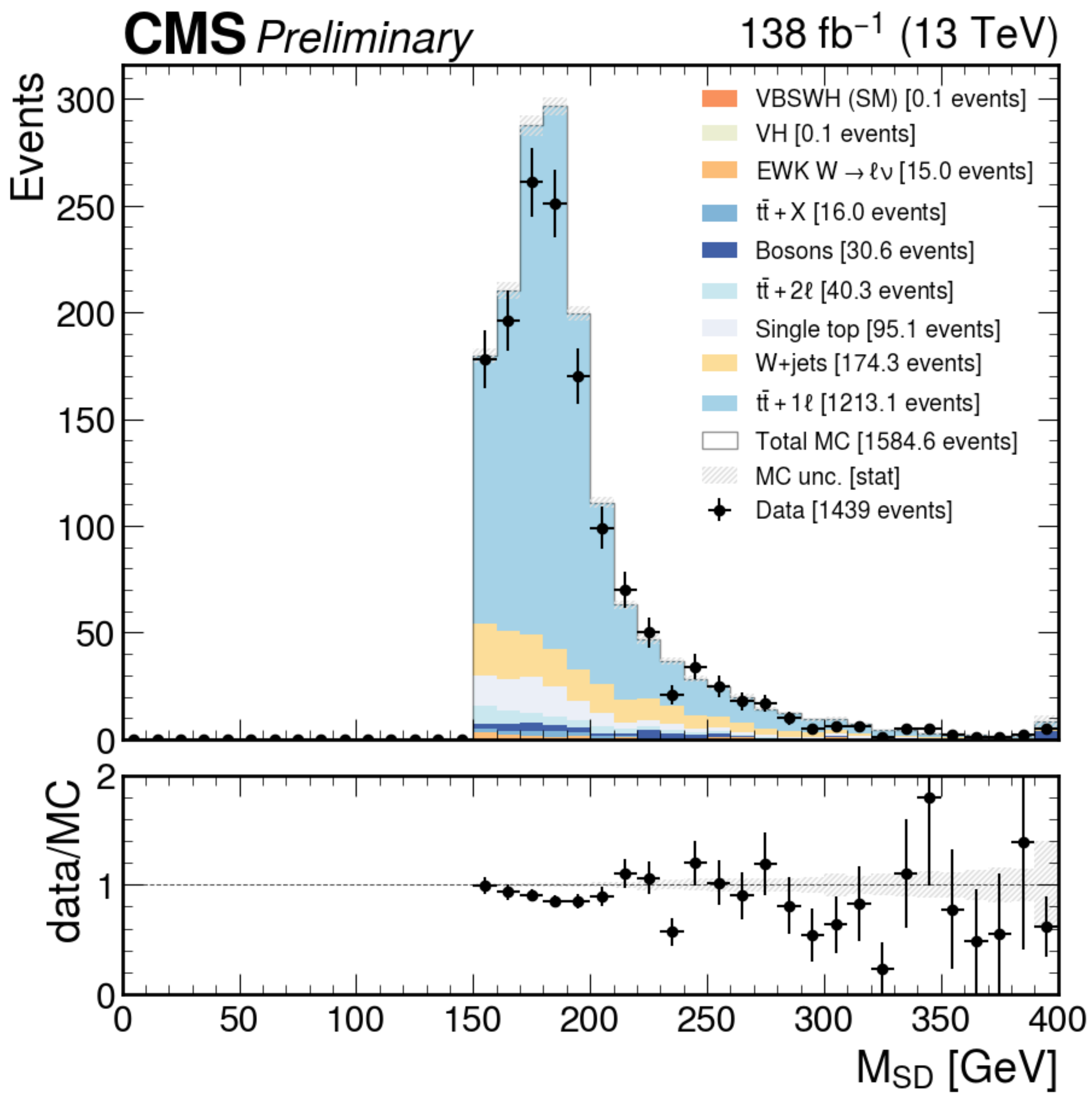
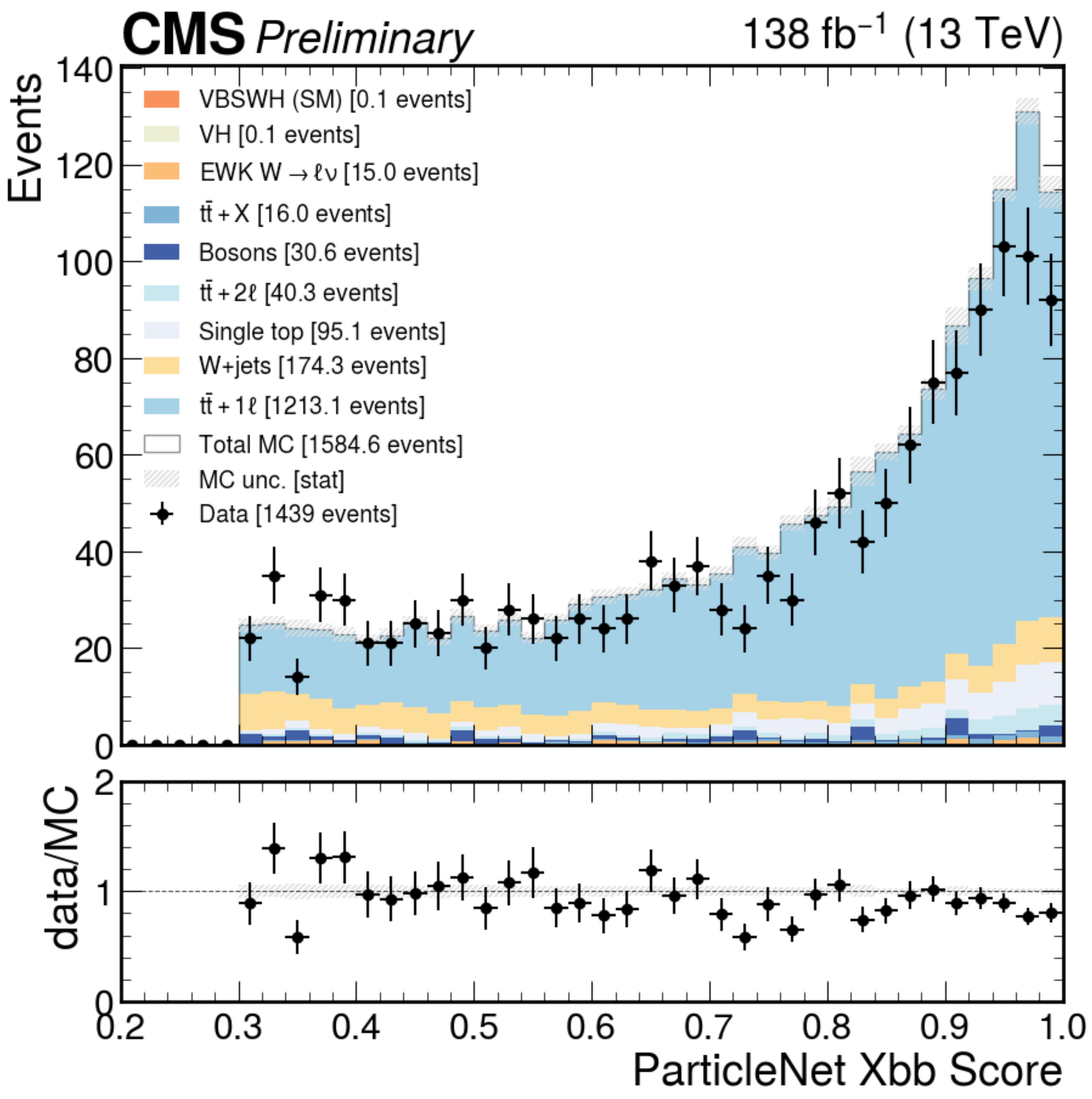
M_{SD} Control Region





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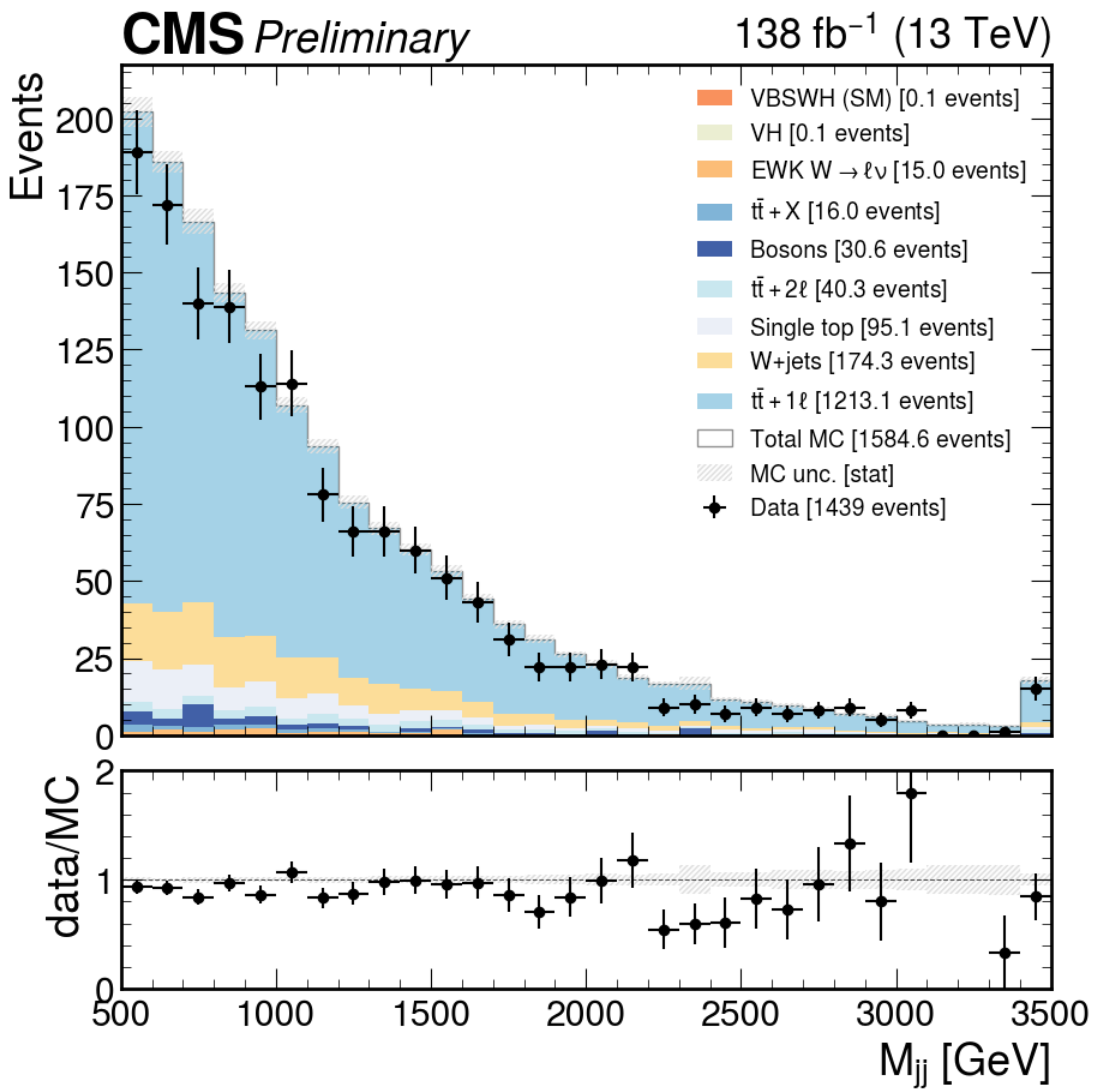
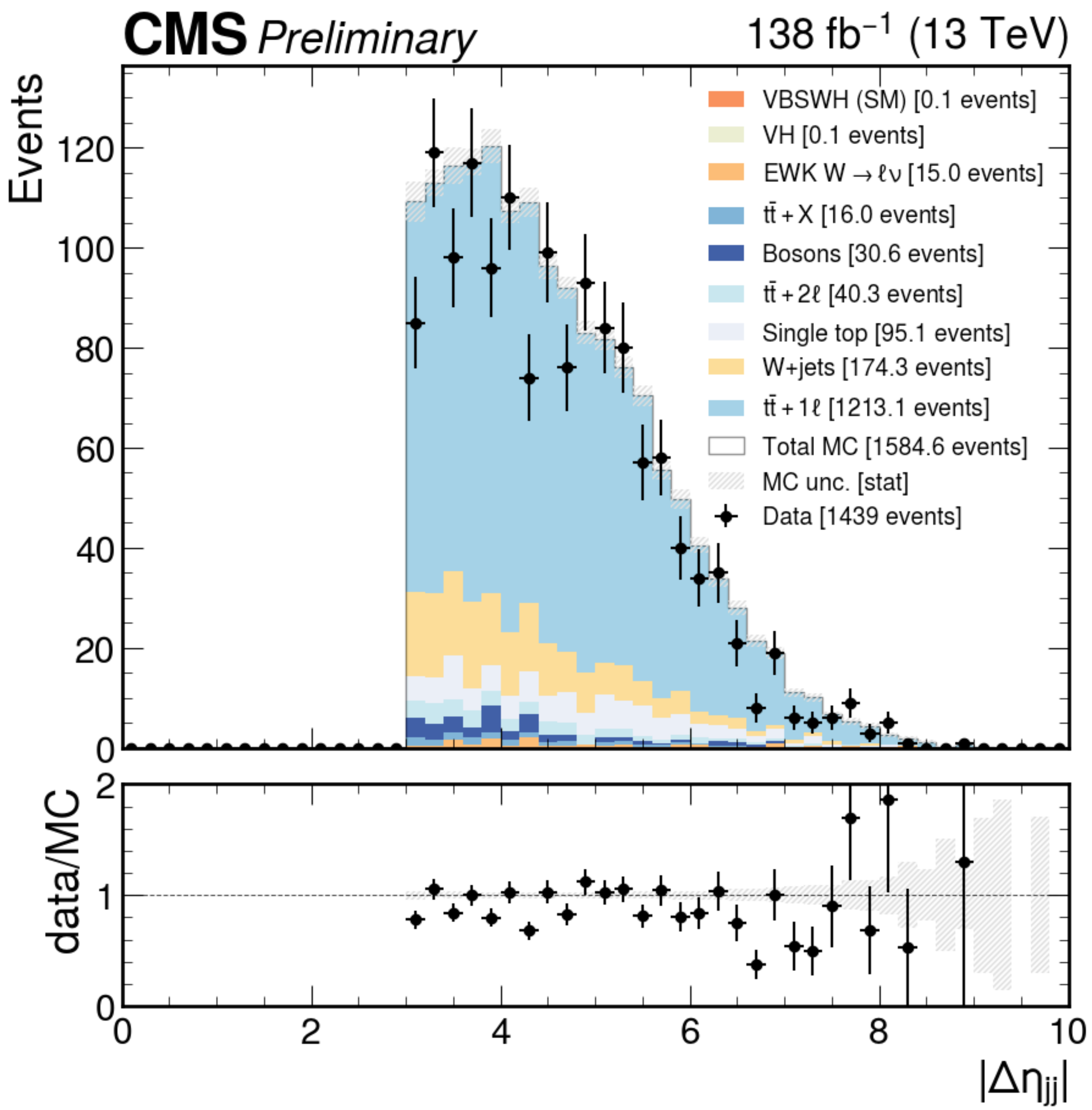
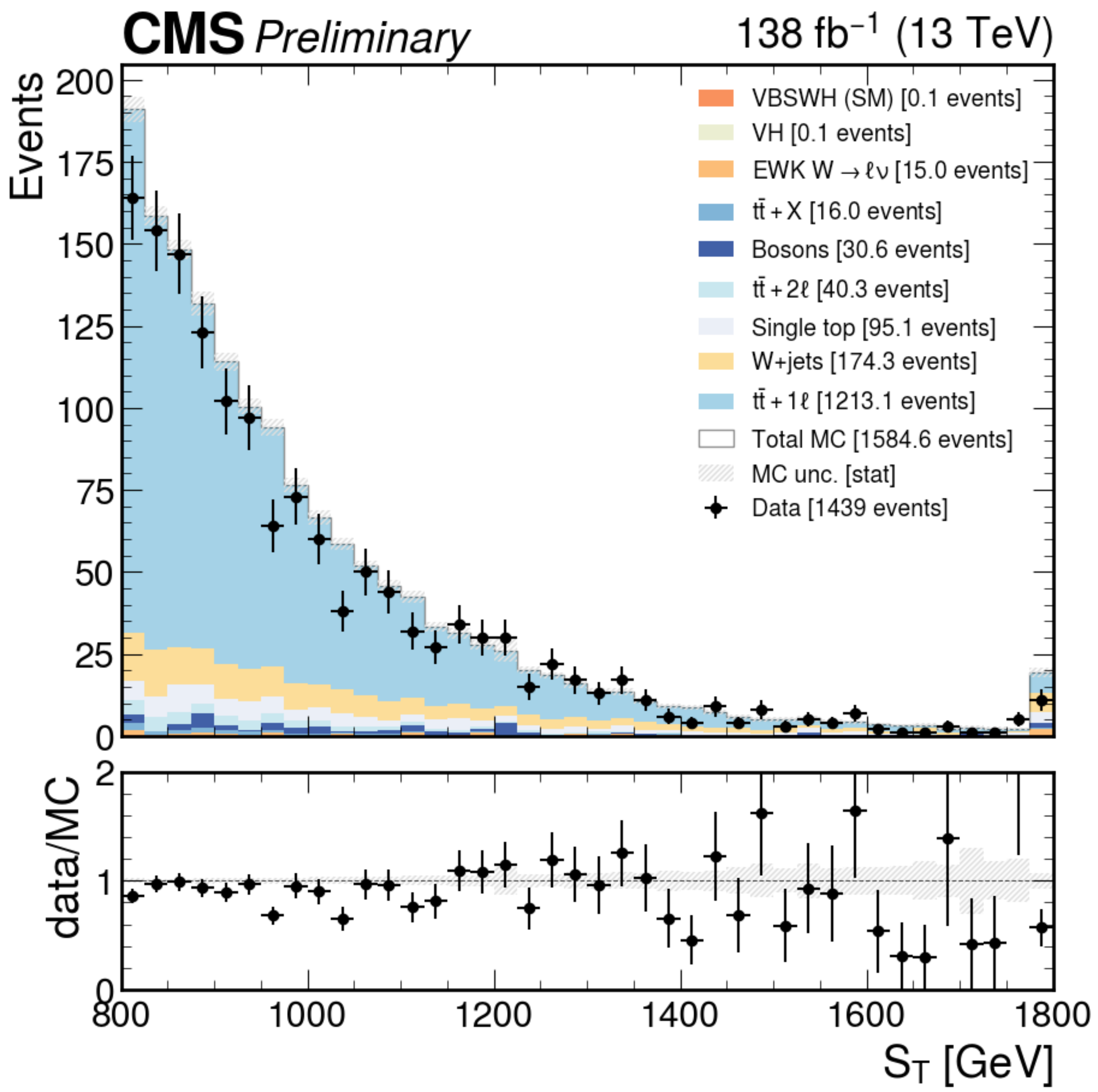
M_{SD} Control Region





M_{SD} Control Region



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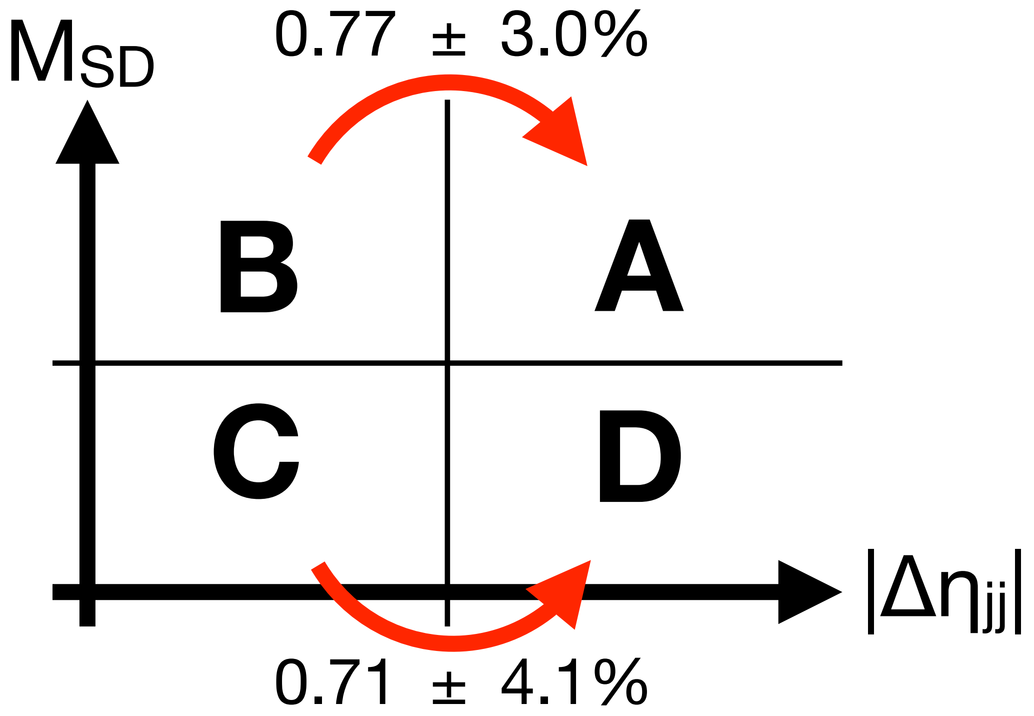
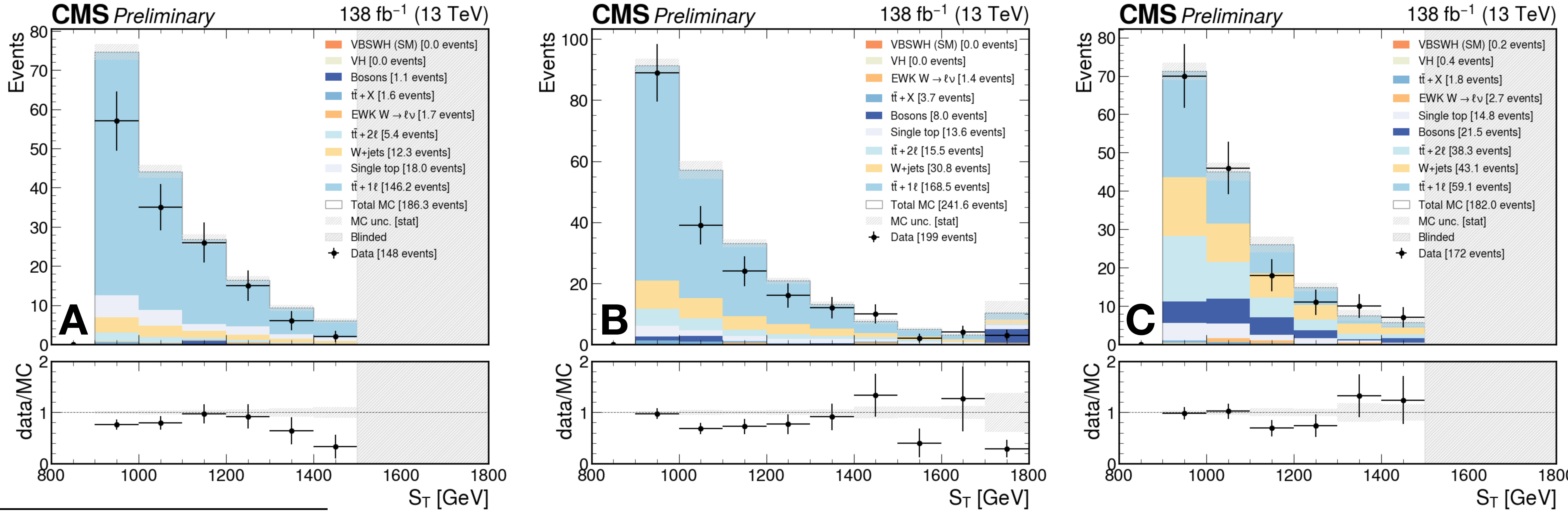
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Preselection 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	186.32	3.41	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	241.61	5.85	0.94	0.42	199	14.11
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR)	D	129.61	4.23	413.34	8.91	—	—





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

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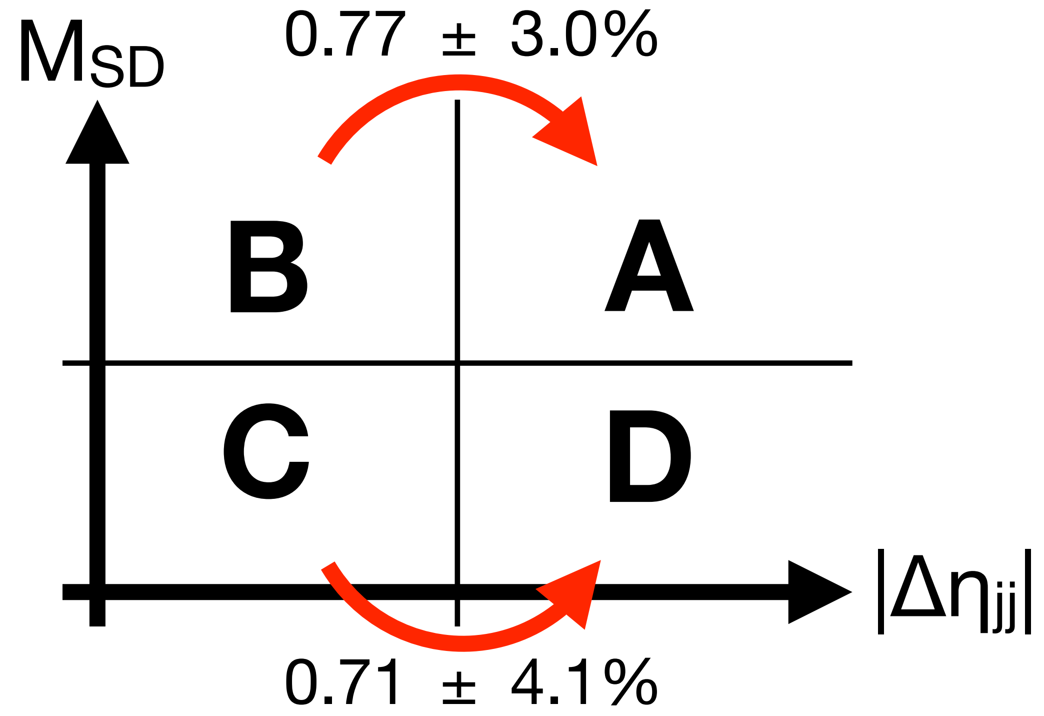
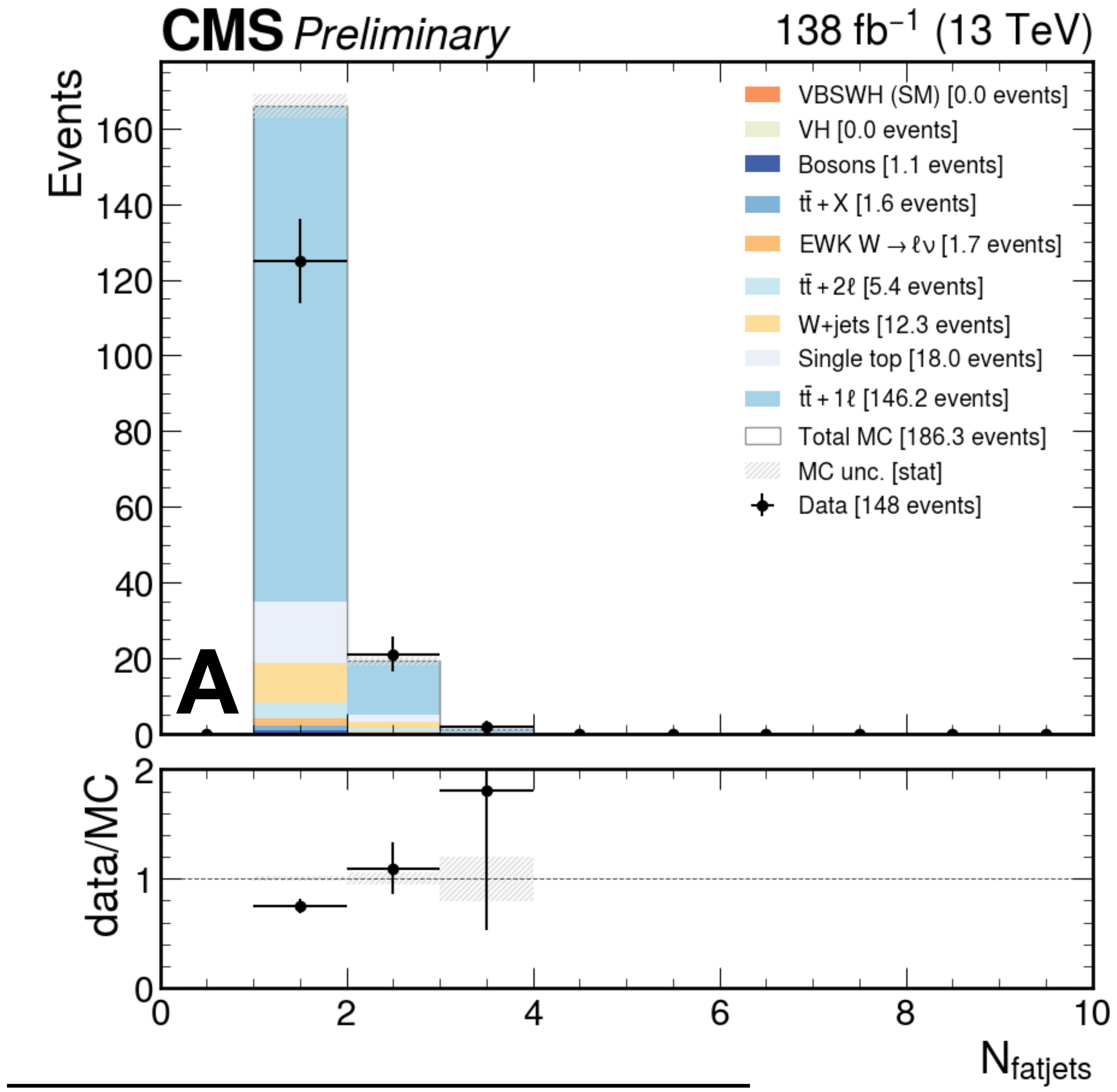
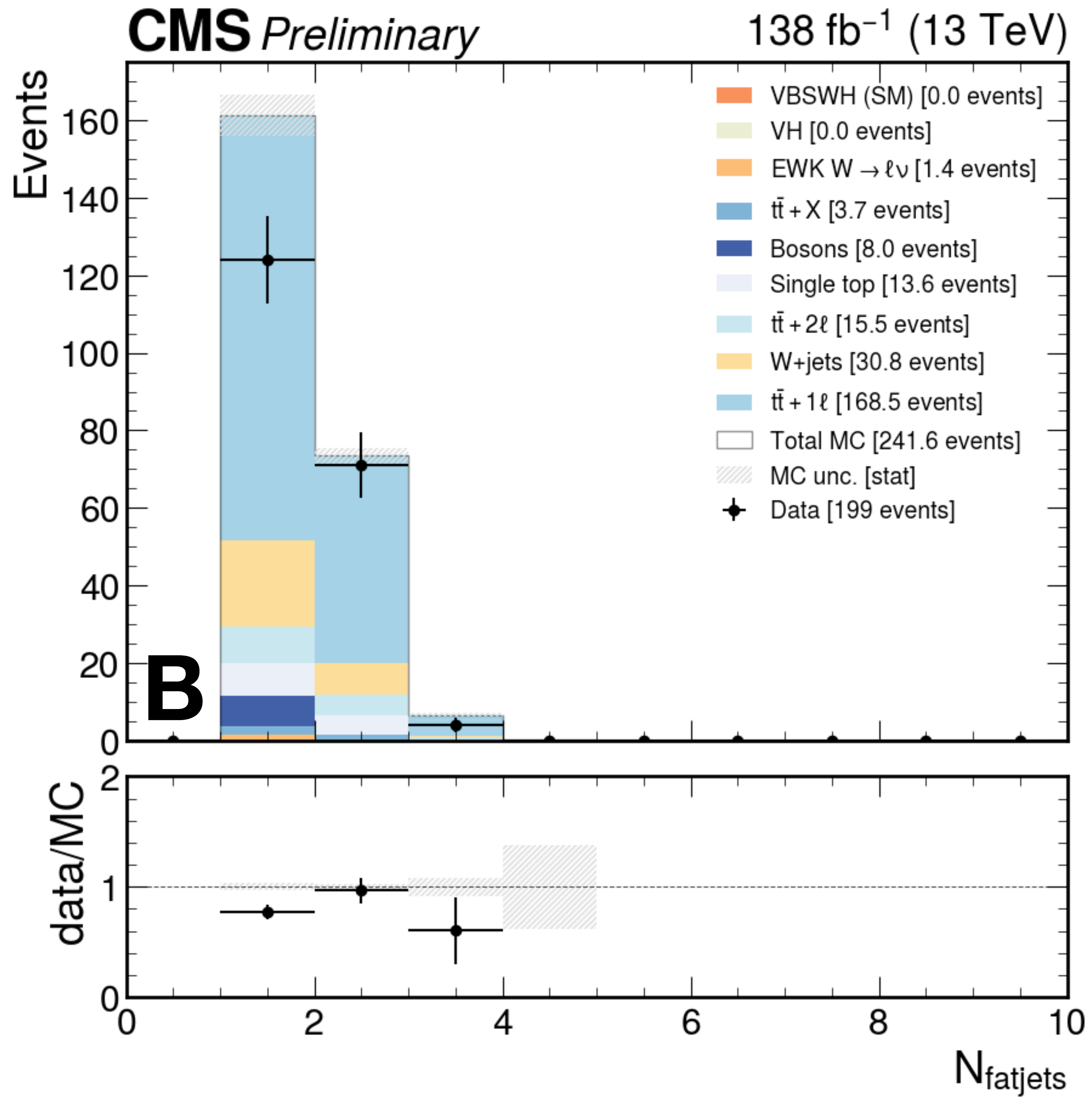
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

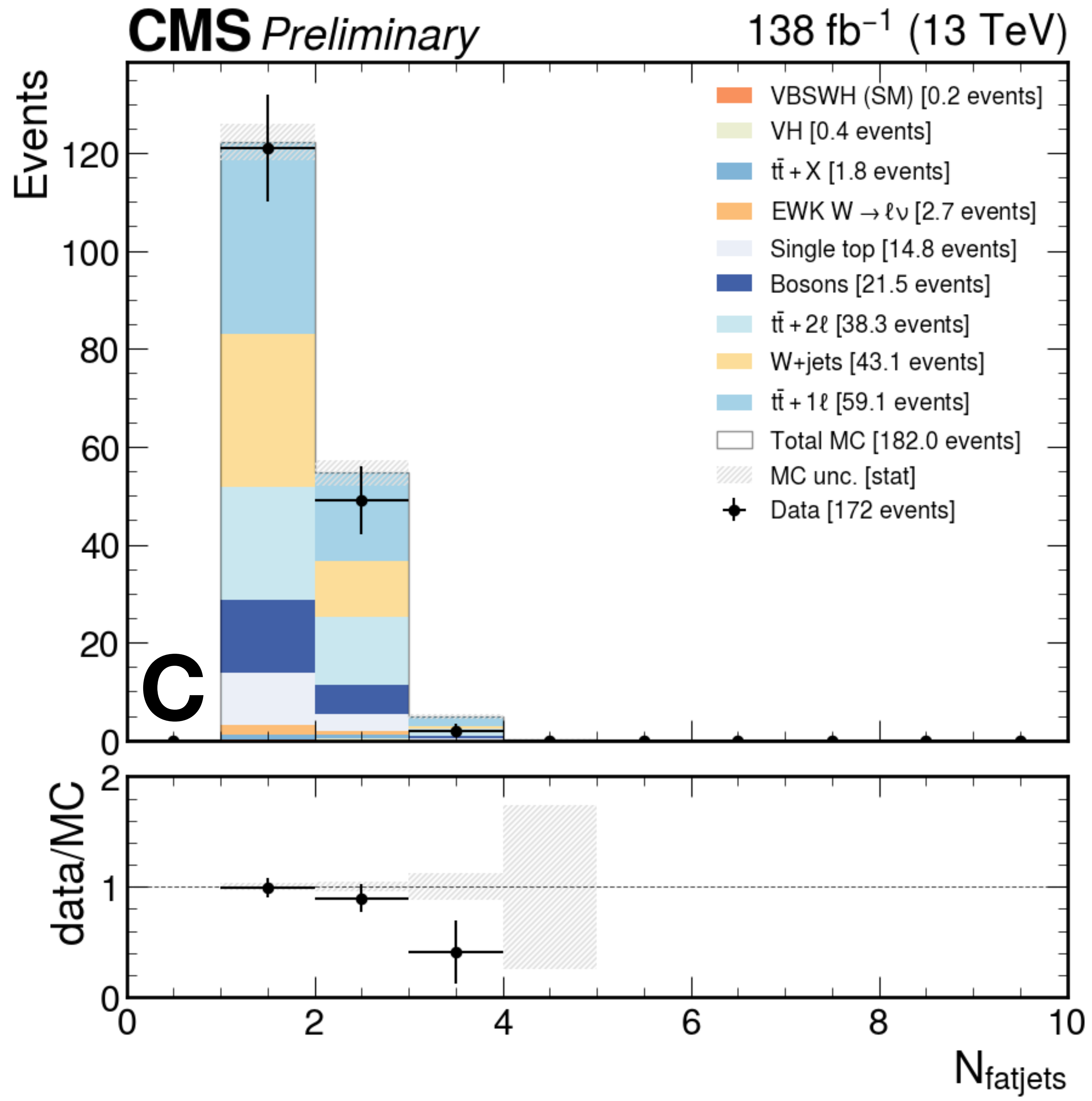
Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} ≥ 150 GeV	A	186.32	3.41	12.57	1.55	148	12.17
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	241.61	5.85	0.94	0.42	199	14.11
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} < 150 GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} < 150 GeV (SR1)	D	129.61	4.23	413.34	8.91	—	—





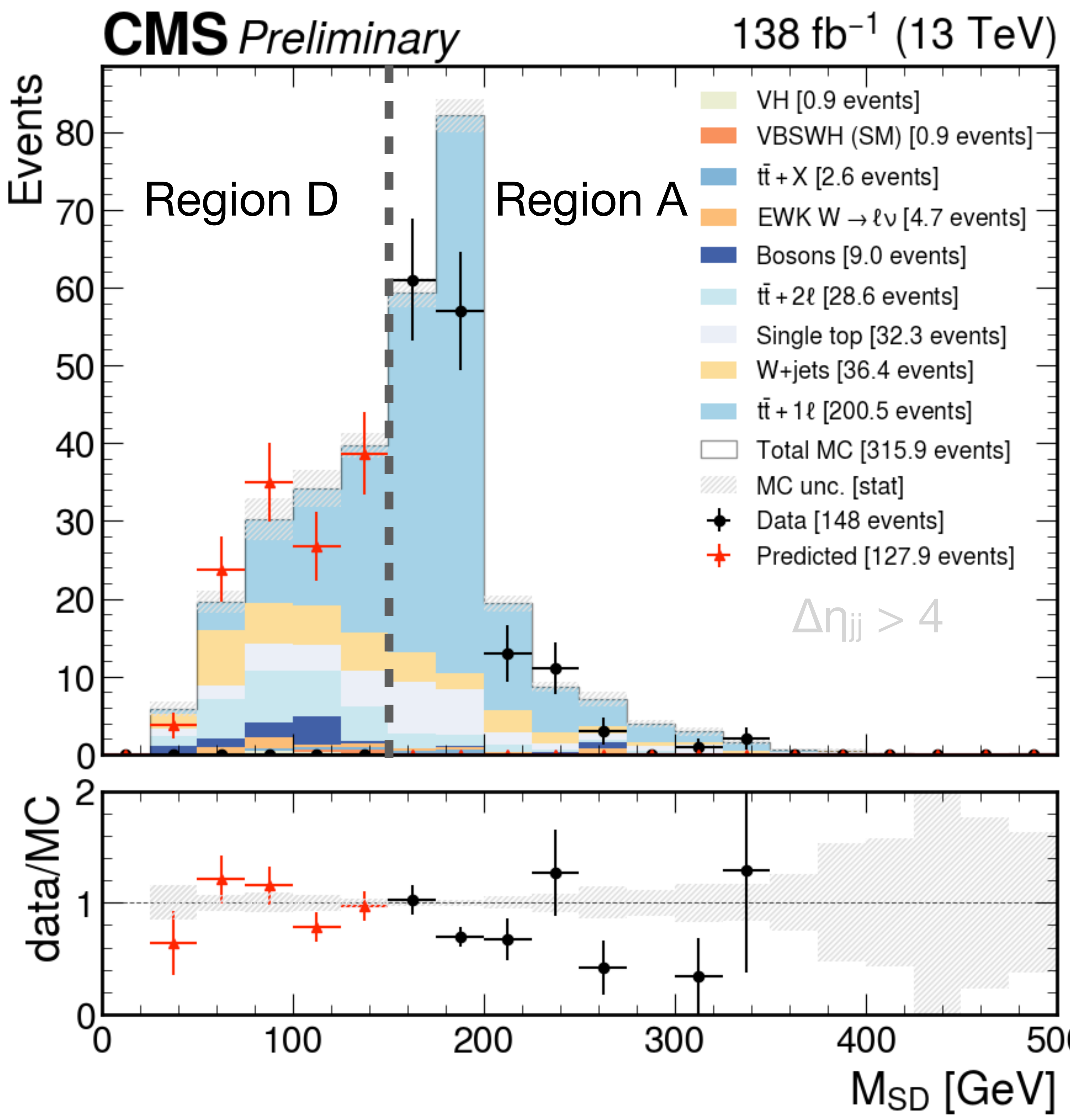


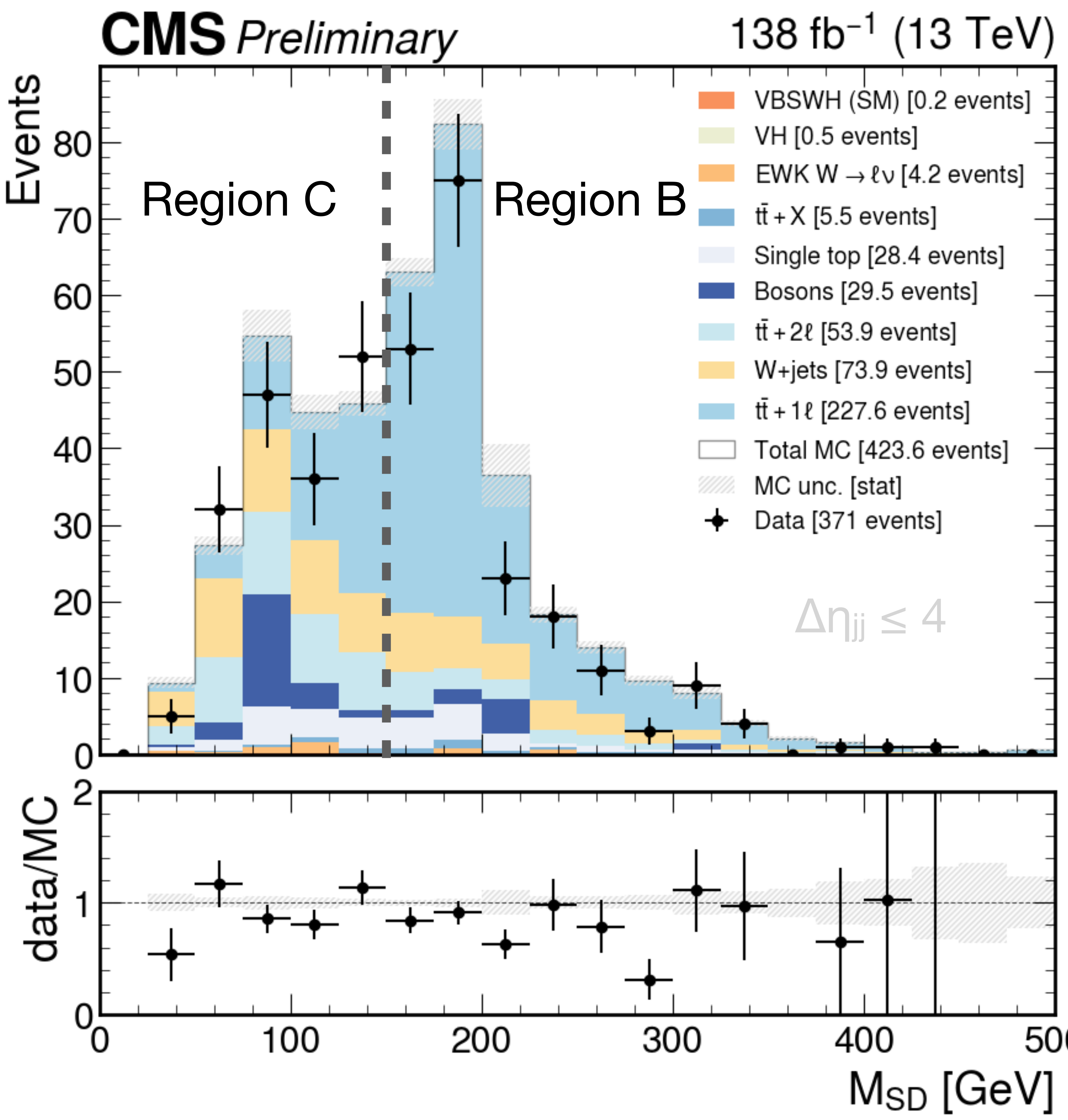


*err = $\sqrt{(\Sigma_i w_i^2)}$ for MC, $\sqrt{(\text{count})}$ for data

SR1 ABCD

Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9



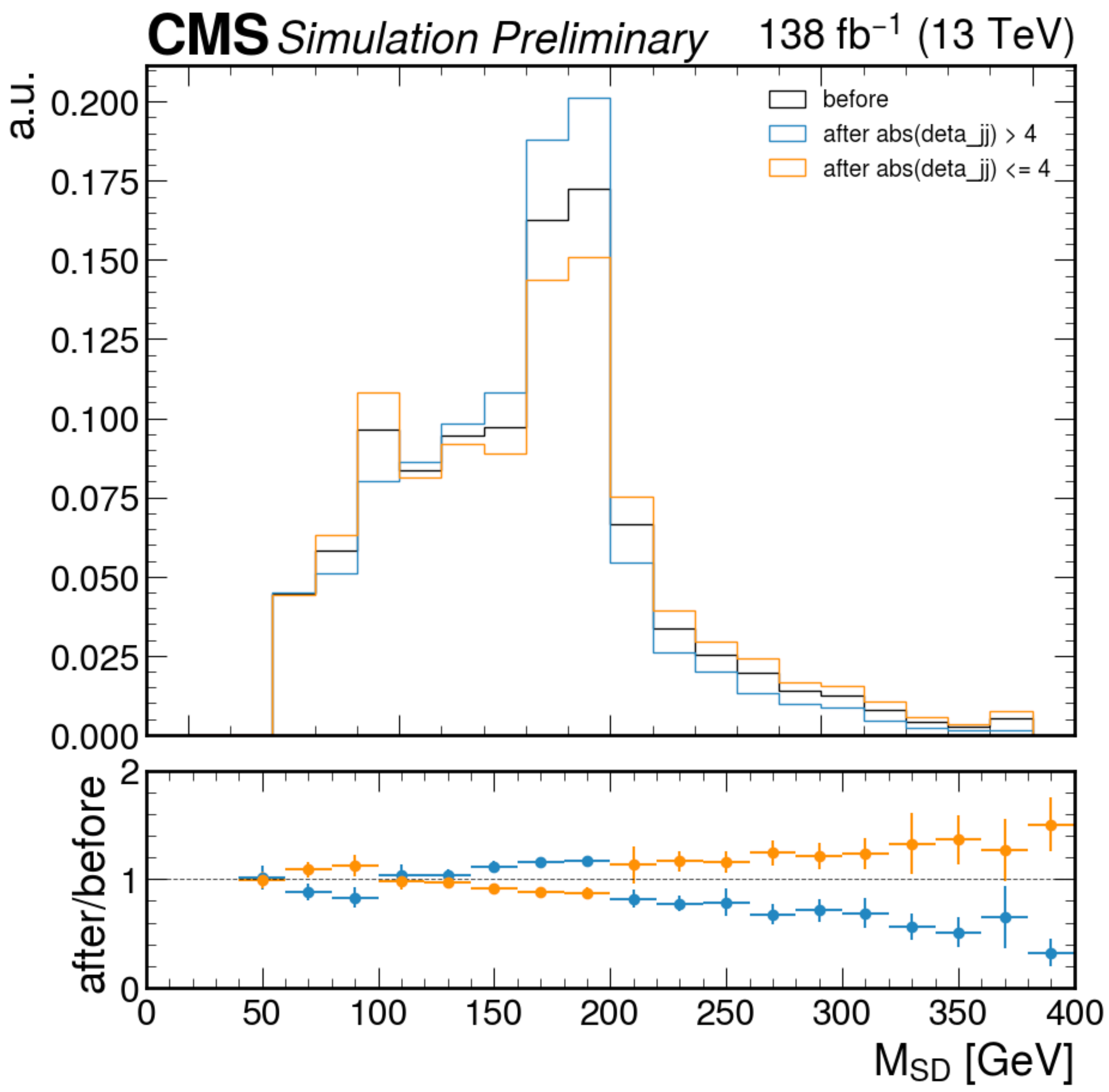


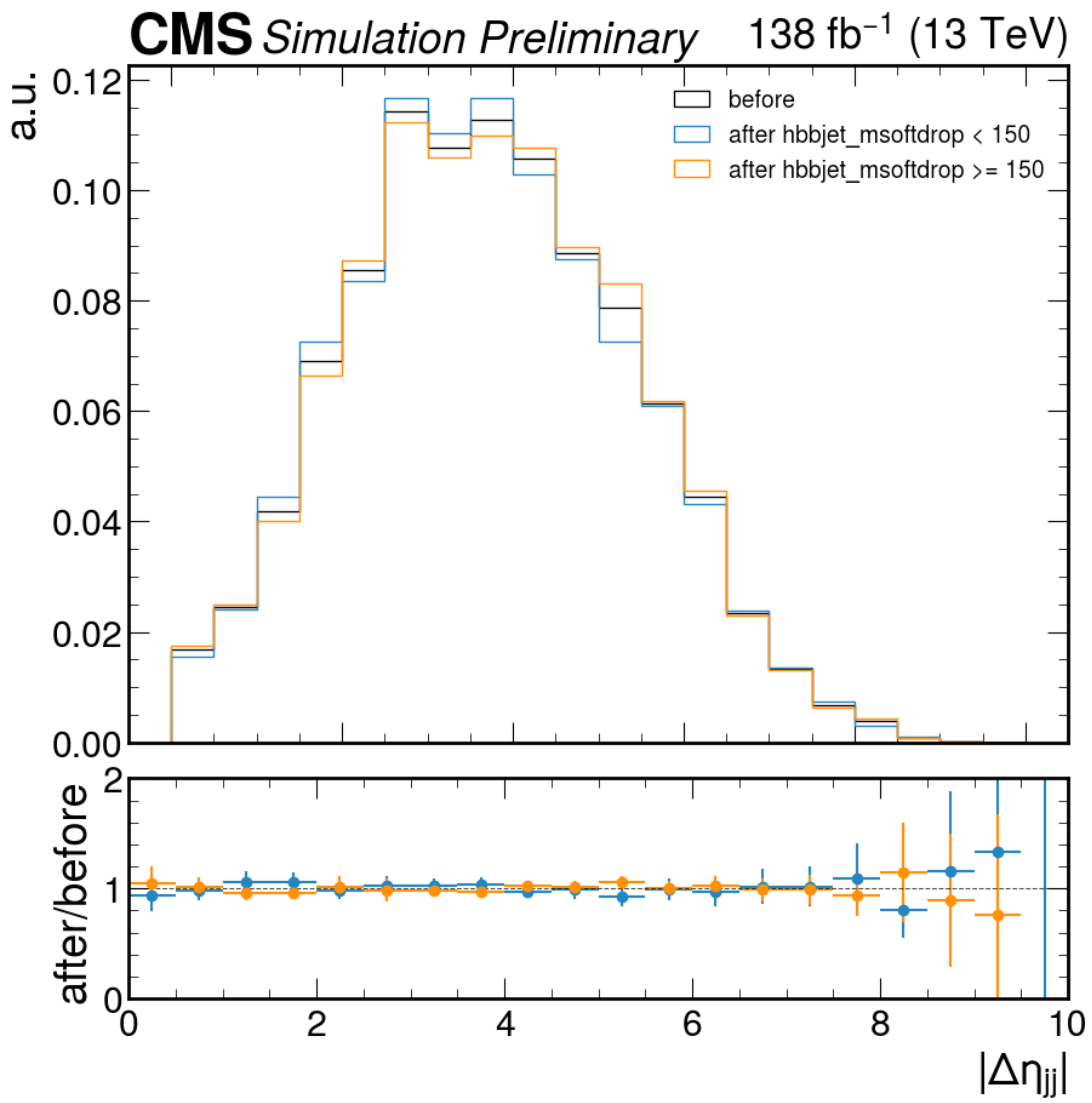
Shape of data in Region D is taken from Region C directly for visualization purposes

(final fit is a single bin)

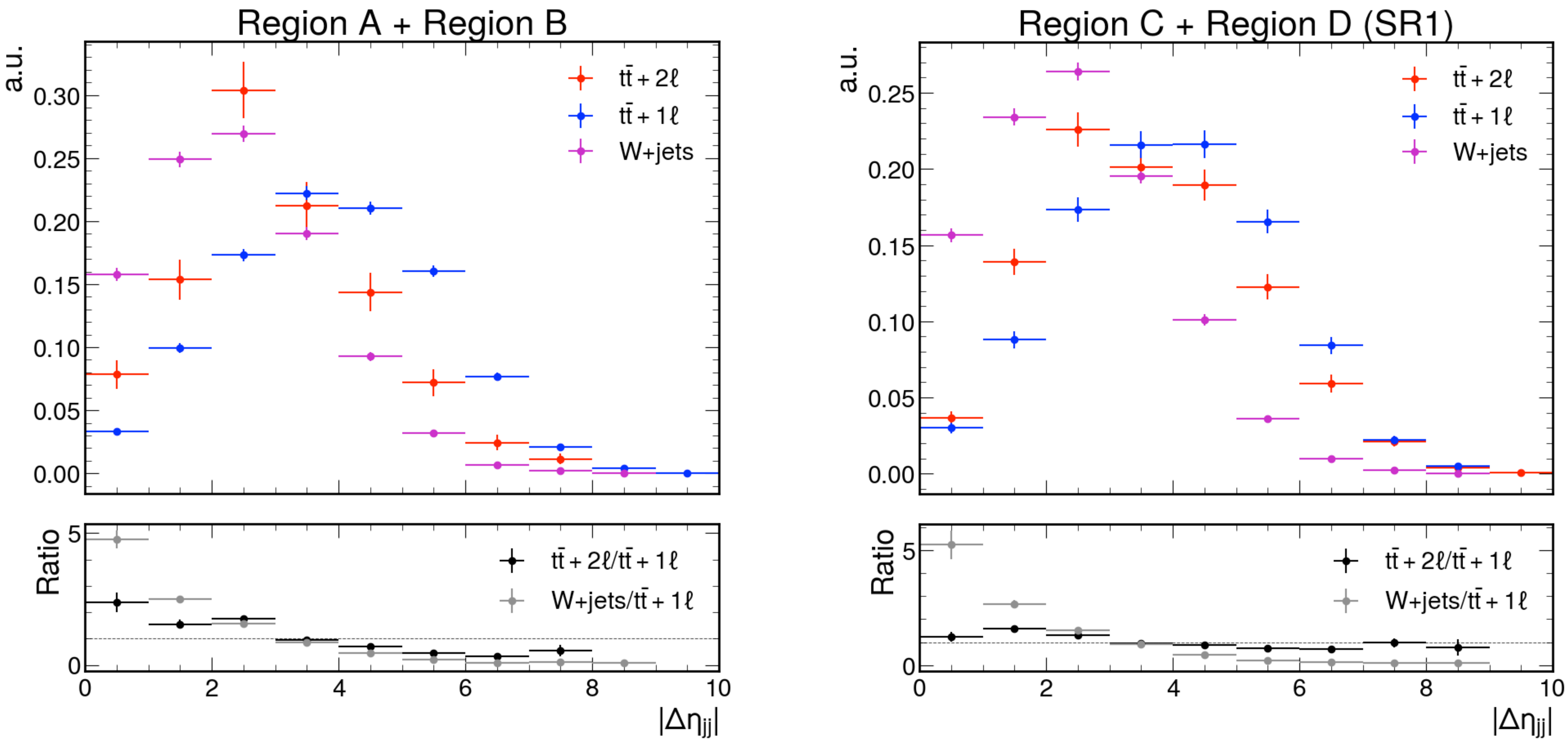
SR1 ABCD: $\Delta\eta_{jj}$ vs. M_{SD} Correlations

Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9





SR1 ABCD: W+jets Composition

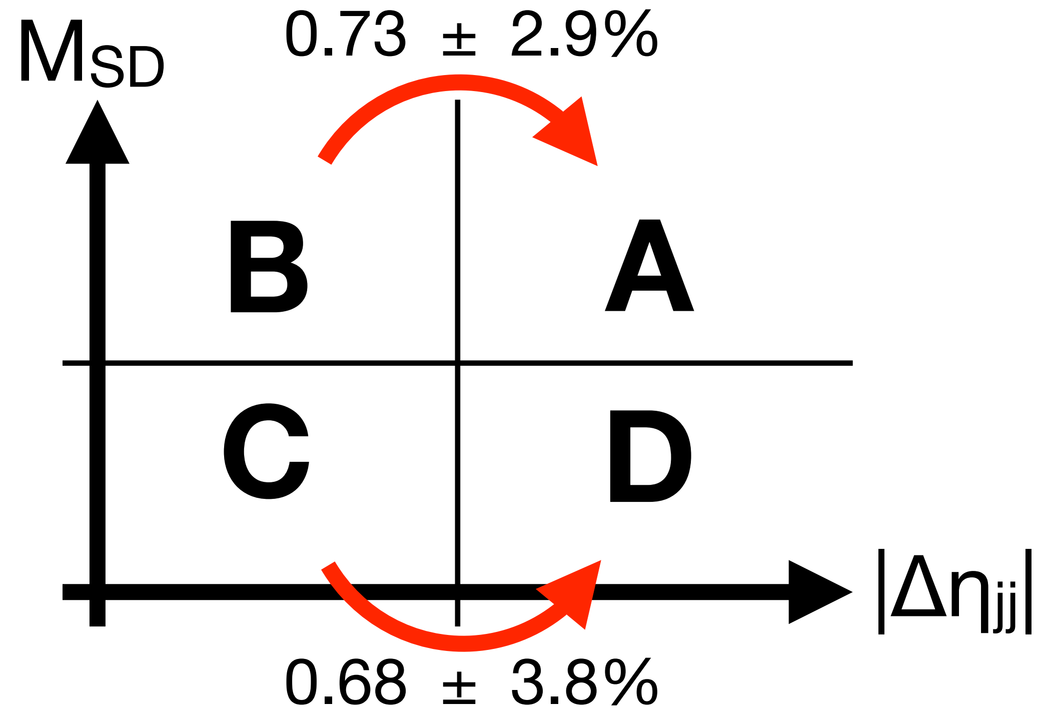


TT1L & TT2L $|\Delta\eta_{jj}|$ shapes roughly consistent, W+Jets is much different

SR1 ABCD: W+jets Composition

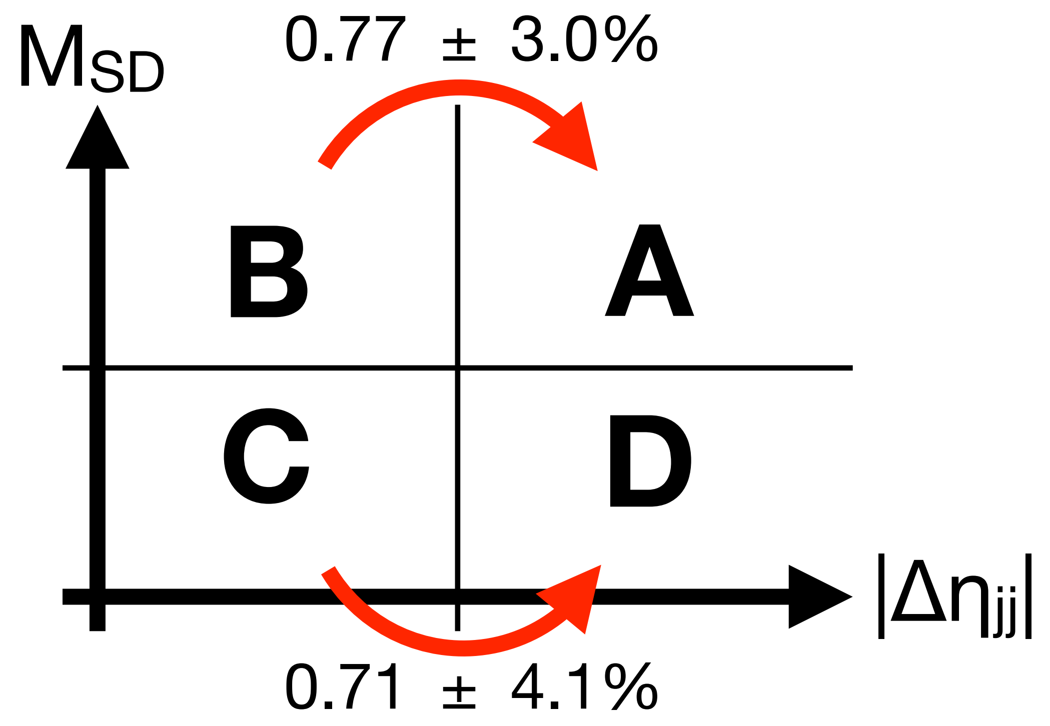
Preselection AND $M_{jj} > 600$ GeV AND $S_T > 900$ GeV AND PNet Xbb > 0.9 (WJets x 2)

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	198.64	3.65	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	272.41	6.01	0.94	0.42	199	14.11
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	225.10	4.85	16.35	1.79	172	13.11
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	153.67	4.90	413.34	8.91	—	—



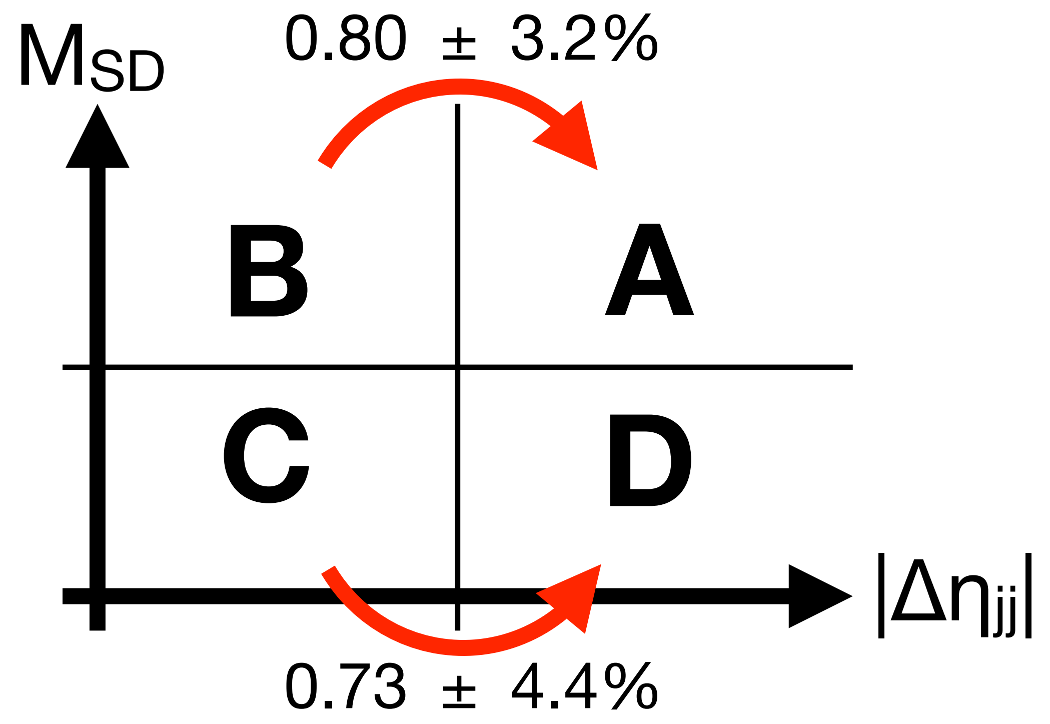
Preselection AND $M_{jj} > 600$ GeV AND $S_T > 900$ GeV AND PNet Xbb > 0.9

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	186.32	3.41	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	241.61	5.85	0.94	0.42	199	14.11
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	129.61	4.23	413.34	8.91	—	—



Preselection 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	180.16	3.34	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	226.20	5.82	0.94	0.42	199	14.11
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	160.42	4.45	16.35	1.79	172	13.11
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	117.59	4.05	413.34	8.91	—	—



5% systematic

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

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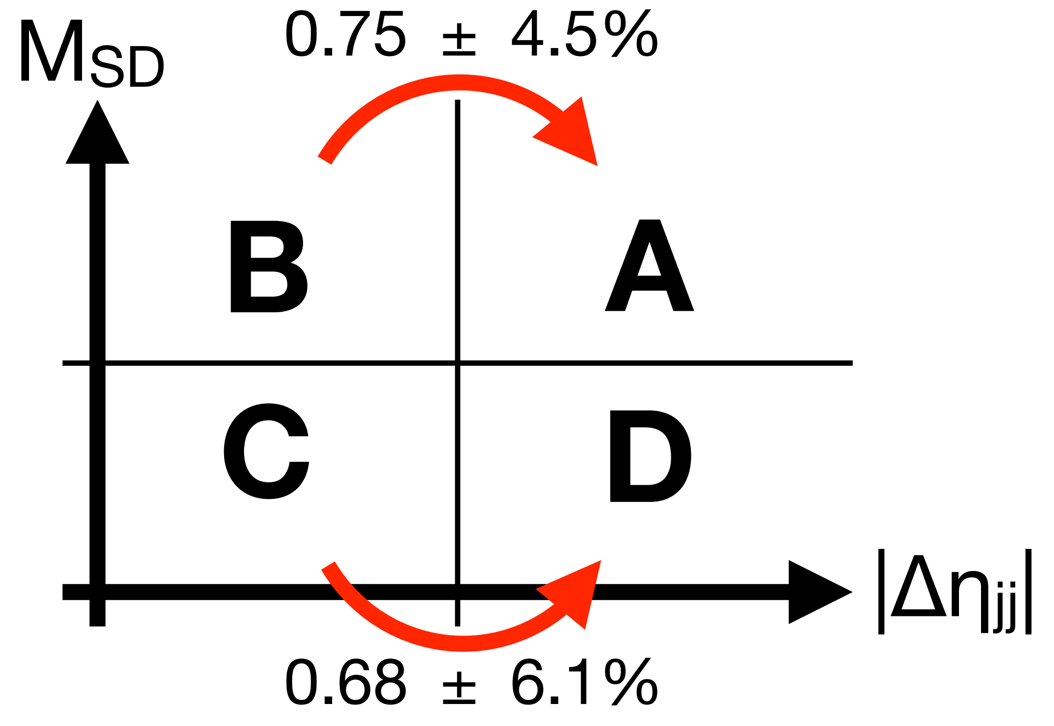
SR1 ABCD: Bosons Composition

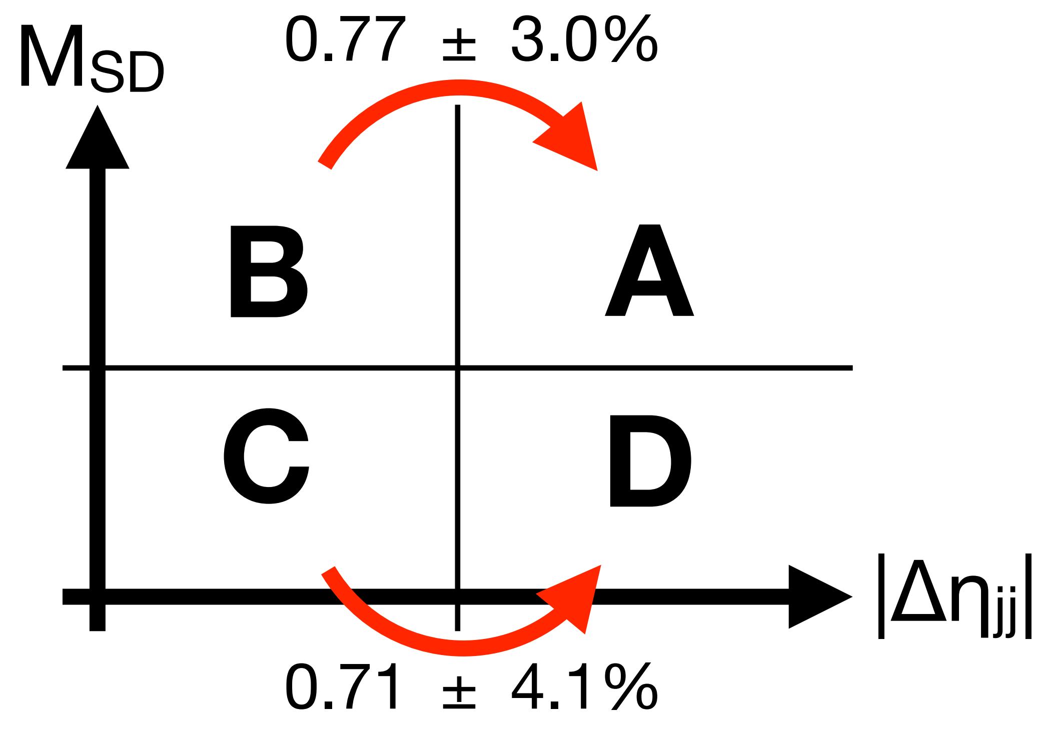
Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9 (Bosons x 2)

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} ≥ 150 GeV	A	187.39	3.61	12.57	1.55	148	12.17
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	249.60	10.05	0.94	0.42	199	14.11
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} < 150 GeV	C	203.45	7.43	16.35	1.79	172	13.11
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} < 150 GeV (SR1)	D	137.51	6.74	413.34	8.91	—	—



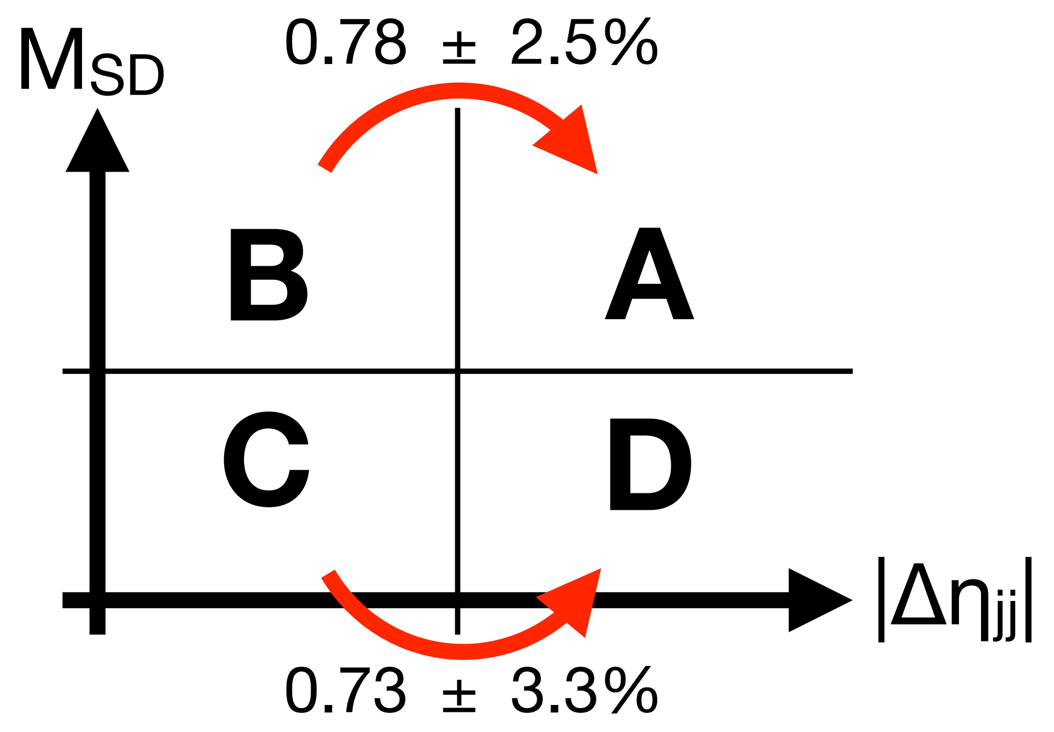
Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} ≥ 150 GeV	A	186.32	3.41	12.57	1.55	148	12.17
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	241.61	5.85	0.94	0.42	199	14.11
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} < 150 GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} < 150 GeV (SR1)	D	129.61	4.23	413.34	8.91	—	—



Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9 (Bosons x 0.5)

Cut	Region	Bkg. (wgt)	Bkg. Err.*	Sig. (wgt)	Sig. Err.*	Data	Data Err.*
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} ≥ 150 GeV	A	185.78	3.35	12.57	1.55	148	12.17
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} ≥ 150 GeV	B	237.61	4.19	0.94	0.42	199	14.11
$\|\Delta\eta_{jj}\|$ ≤ 4 AND M_{SD} < 150 GeV	C	171.24	3.44	16.35	1.79	172	13.11
$\|\Delta\eta_{jj}\|$ > 4 AND M_{SD} < 150 GeV (SR1)	D	125.67	3.32	413.34	8.91	—	—



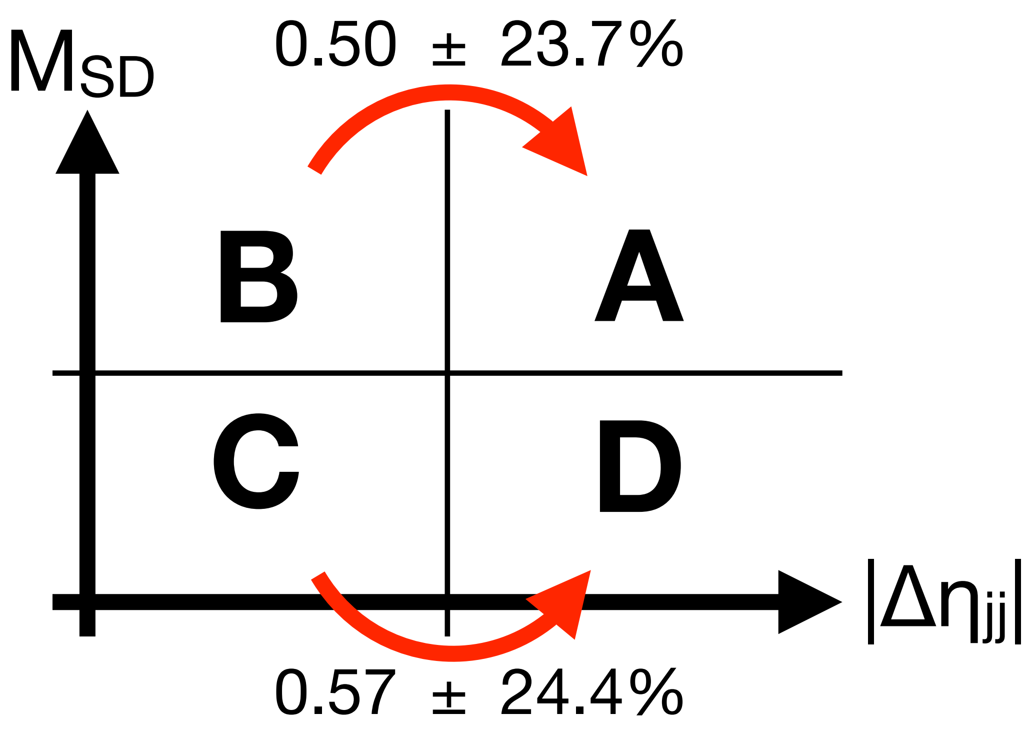
*err = $\sqrt{(\Sigma_i w_i^2)}$ for MC, $\sqrt{(\text{count})}$ for data

3% systematic

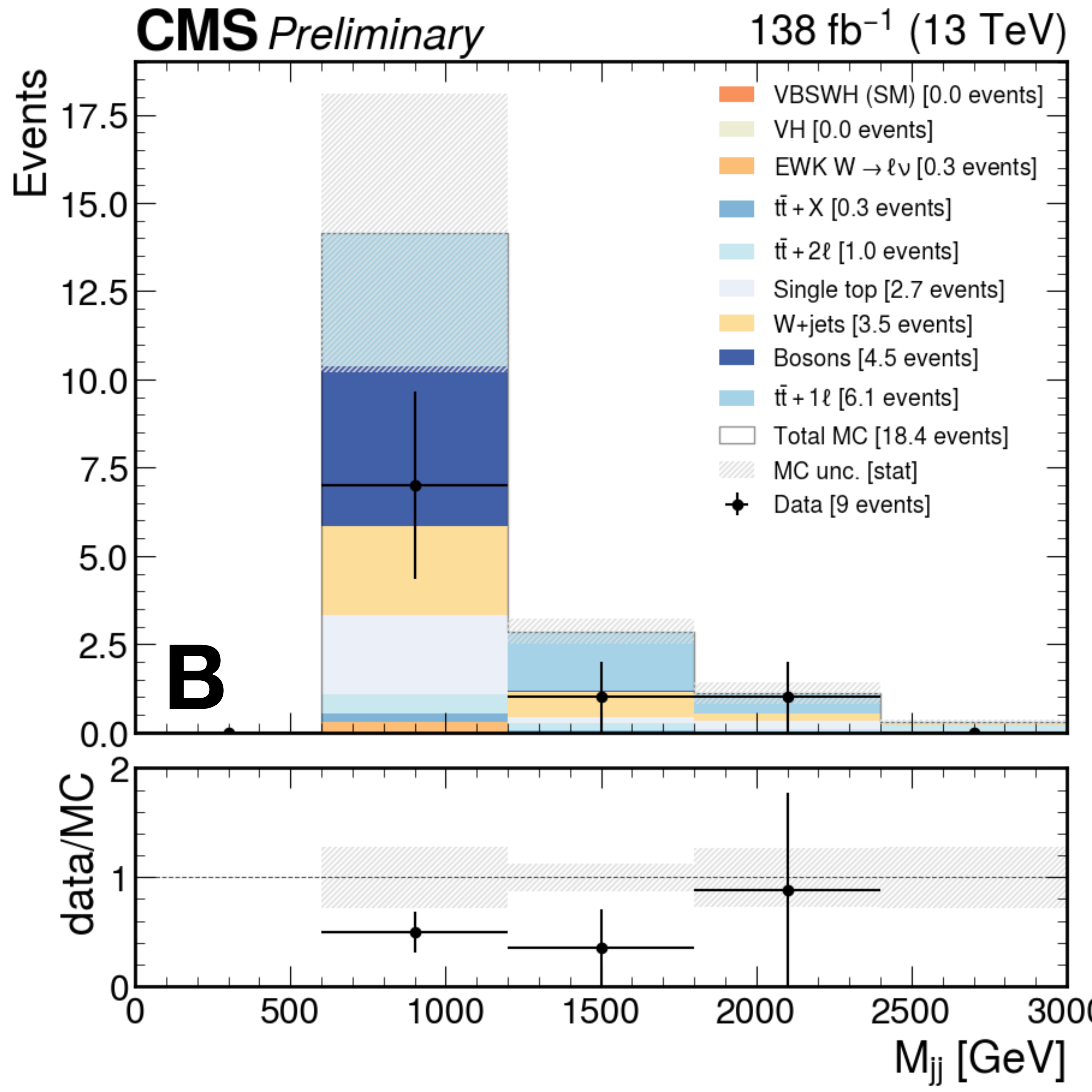
SR2 ABCD: $\Delta\eta_{jj}$ vs. M_{SD}

Preselection 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	9.31	0.96	2.42	0.66	—	—
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	**18.70**	3.99	0.00	0.00	**9**	3.00
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	11.78	1.34	2.31	0.66	10	3.16
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR2)	D	6.72	1.45	111.09	4.65	—	—



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

SR1 to SR2: Validate in Region B

Preselection 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.*
$\|\Delta\eta_{jj}\| > 4$ AND $M_{SD} \geq 150$ GeV	A	9.31	0.96	2.42	0.66	—	—
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} \geq 150$ GeV	B	**18.70**	3.99	0.00	0.00	**9**	3.00
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} < 150$ GeV	C	11.78	1.34	2.31	0.66	10	3.16
$\|\Delta\eta_{jj}\| > 4$ AND $M_{SD} < 150$ GeV (SR2)	D	6.72	1.45	111.09	4.65	—	—

Preselection 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	186.32	3.41	12.57	1.55	148	12.17
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} \geq 150$ GeV	B	**241.61**	5.85	0.94	0.42	**199**	14.11
$\|\Delta\eta_{jj}\| \leq 4$ AND $M_{SD} < 150$ GeV	C	181.98	4.53	16.35	1.79	172	13.11
$\|\Delta\eta_{jj}\| > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	129.61	4.23	413.34	8.91	—	—

$$\frac{B_{data,\ SR2}}{B_{data,\ SR1}} \pm \epsilon_{stat} = \mathbf{0.0452} \pm 34.08\%$$

$$\frac{B_{MC,\ SR2}}{B_{MC,\ SR1}} \pm \epsilon_{stat} = \mathbf{0.0774} \pm 21.47\%$$

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

Preselection 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	9.31	0.96	2.42	0.66	—	—
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	18.70	3.99	0.00	0.00	9	3.00
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	11.78	1.34	2.31	0.66	10	3.16
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR2)	D	**6.72**	1.45	111.09	4.65	—	—

Preselection 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	191.63	3.48	12.57	1.55	148	12.17
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} \geq 150$ GeV	B	247.47	5.90	0.93	0.42	200	14.14
$\lvert\Delta\eta_{jj}\rvert \leq 4$ AND $M_{SD} < 150$ GeV	C	187.08	4.57	16.60	1.81	172	13.11
$\lvert\Delta\eta_{jj}\rvert > 4$ AND $M_{SD} < 150$ GeV (SR1)	D	**136.05**	4.27	415.24	8.93	—	—

- Errors: 34% (syst.), 13% (stat.)

$$D^{pred}_{data,\ SR2} = \frac{D_{MC,\ SR2}}{D_{MC,\ SR1}} \times D^{pred}_{data,\ SR1} = 6.32$$

$$\epsilon_{syst} = \sqrt{(\epsilon_{syst,\ SR1\rightarrow SR2})^2 + (\epsilon_{syst,\ SR1})^2} = 35\%$$

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

Predicted Yield: 6.32 ± 0.84 ± 2.20

stat. *syst.*

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

Signal Systematics

- For most systematics:

1. Get nominal yield in SR
2. Get yield in SR after applying up/down variation
   - If scale factor: first divide each event weight by nominal value
3. Systematic = largest % difference in yield

Systematic	SR1
PDF variations	2.2%
μ_F scale	17.8%
Parton shower ISR weights	0.1%
Parton shower FSR weights	1.5%
Pileup reweighting	0.2%
L1 pre-fire corrections	1.0%
HLT scale factors	0.8%
Simulation stat. unc.	2.2%
Lepton scale factors	1.5%
ParticleNet Xbb scale factors	5.7%
DeepJet b-tagging scale factors	0.3%
MET unc.	0.3%
Jet energy scale	6.6%
Jet energy resolution	0.8%
Luminosity	2.5%

Step 1

$$\text{yield} = y = \sum_{i=1}^{N} W_i$$

$$\text{where } W_i = \prod_j \omega_i$$

Step 2

$$y_{var} = \sum_{i=1}^{N} W_i \times \frac{\omega_{var}}{\omega_{nom}}$$

Step 3

$$\delta_{var} = \left| 1 - \frac{y_{var}}{y} \right|$$

$$\text{syst.} = \max\left(\delta_{up}, \delta_{down}\right)$$

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Signal Systematics: PDF Variations

- For (Hessian) PDF systematics:
  1. Get overall variation/inclusive ratio for each of the 100 PDF variations
  2. Get nominal yield in SR
  3. Get yield in SR after applying a given variation
  4. Systematic = % difference in yield for each variation added in quadrature

Step 1

$$R_{var} = \frac{\sum_{i=0}^{N} \omega_i^{var}}{\sum_{i=0}^{N} \omega_i^{gen}}$$

Step 2

$$\text{yield} = y = \sum_{i=1}^{N} W_i$$

$$\text{where } W_i = \prod_j \omega_j$$

Step 3

$$y_{var} = \sum_{i=1}^{N} W_i \times \frac{\omega_i^{var}}{R_{var}}$$

Step 4

$$\delta_{var} = \left| 1 - \frac{y_{var}}{y} \right|$$

$$\text{syst.} = \left[\sum_{var} \delta_{var}^2 \right]^{1/2}$$

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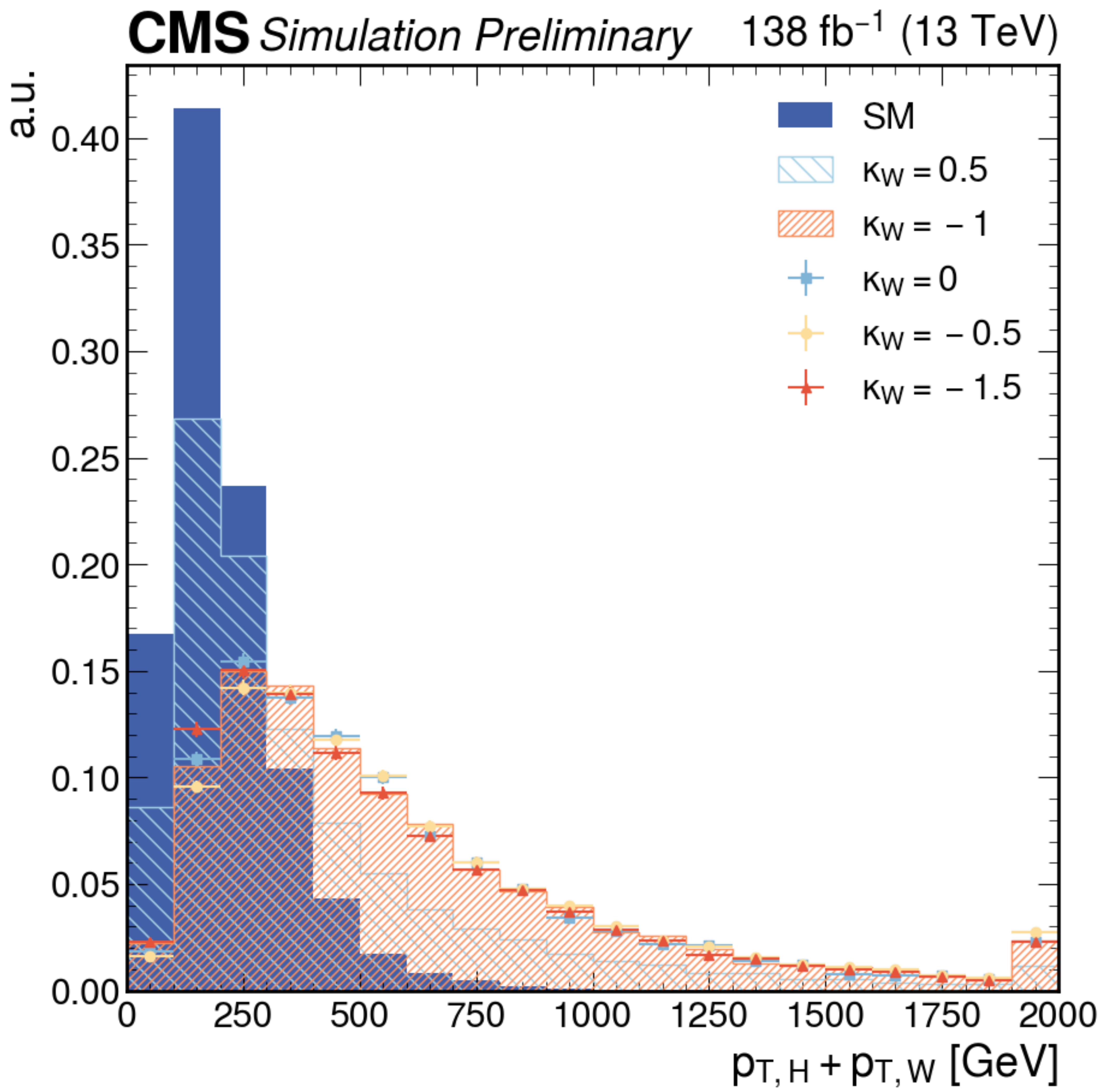
Other λ_{WZ} values

- Generated 10k events for various κ_W values
- Comparing kinematics at LHE level
  - Not much difference across a fairly large range of κ_W values
  - ⇒ Acceptance ~consistent for $\kappa_W = -1 \pm \epsilon$



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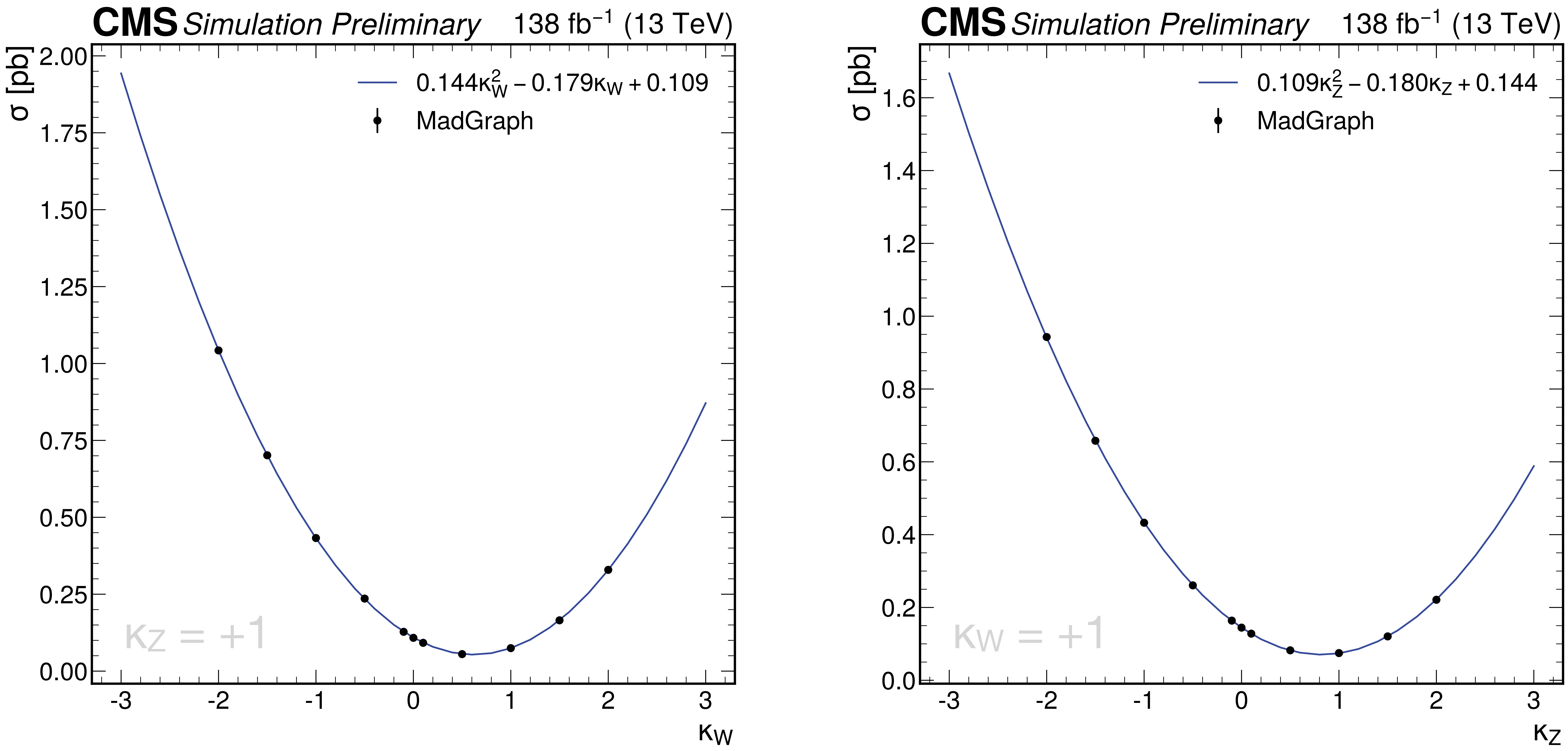
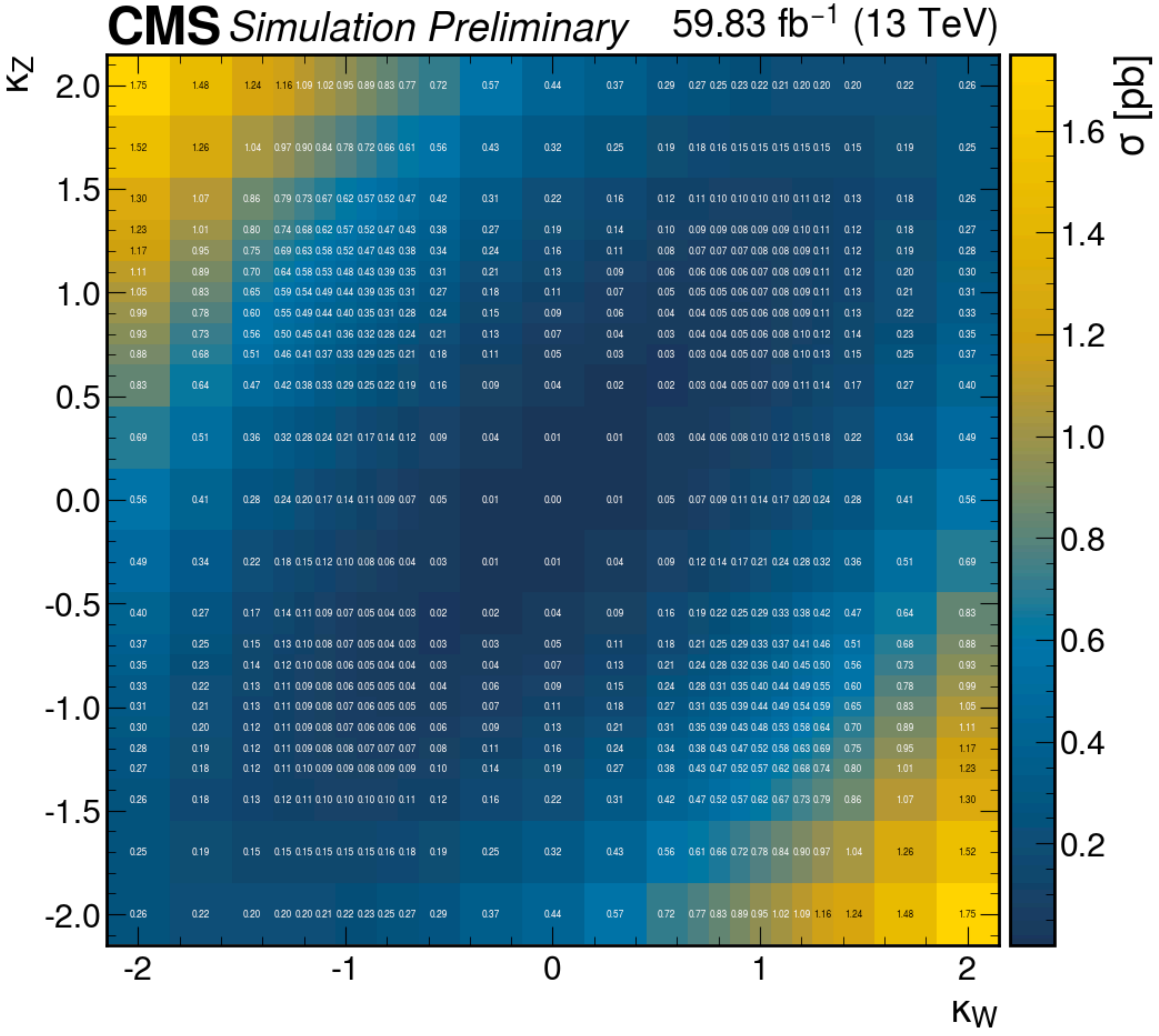
Other λ_{WZ} Values



New Signal Samples

- Generated two signal samples:
  - $\lambda_{WZ} \leq 0$ sample
  - $\lambda_{WZ} > 0$ sample
  - Used PKU reweighting model
  - Full Run 2 samples
  - 100k events per NanoAODv9 “year”
- Reweighted cross section plotted on z-axis here



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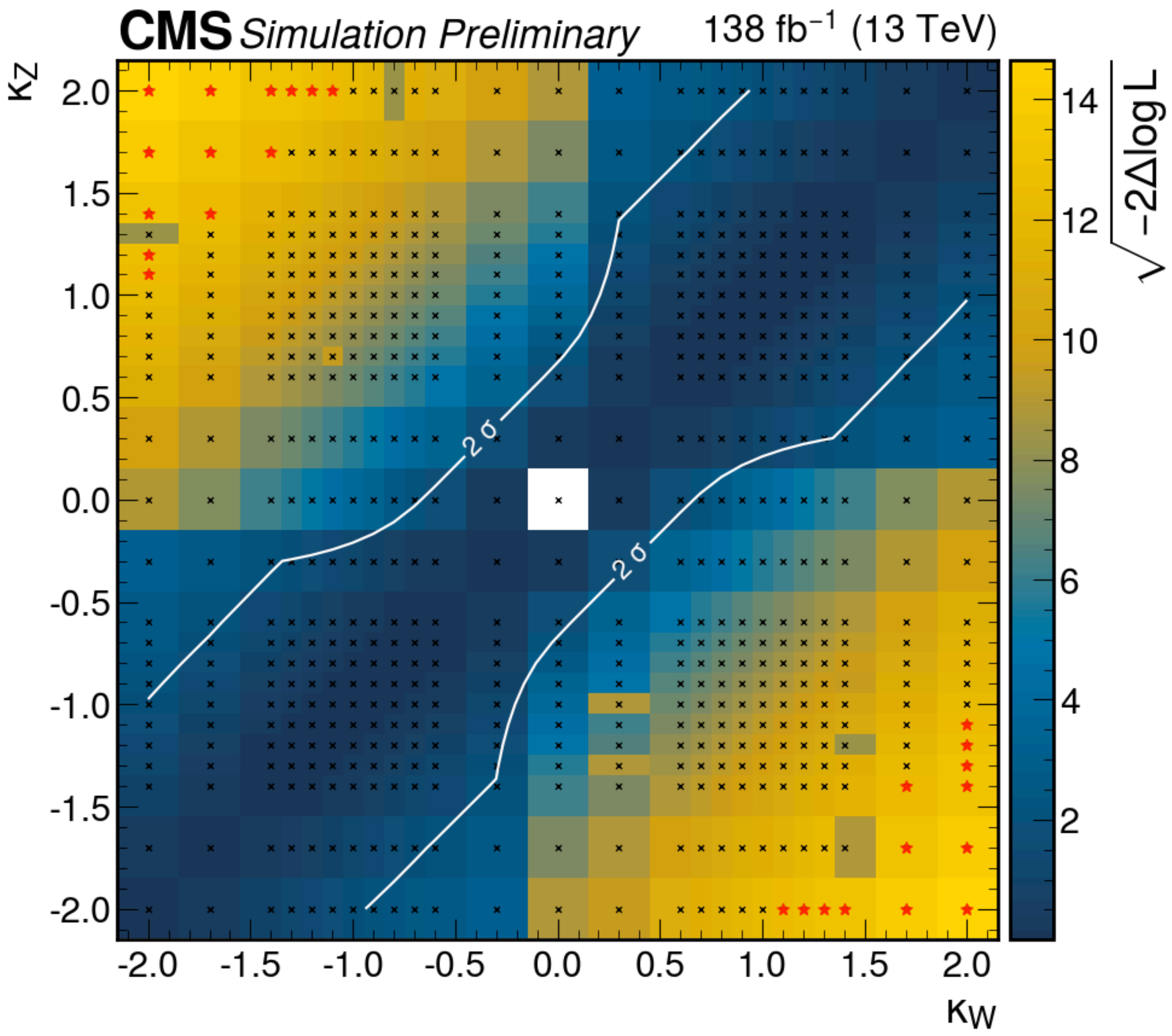
Collected Results

- Bins centered on scanned κ_W, κ_Z points
- Exclusion limit plotted on z-axis
- Contour roughly shows σ = 2 boundary
  - Simplistically derived by Matplotlib
- Black **x**'s taken directly from HiggsCombine plot
- Red ★'s inferred from plot



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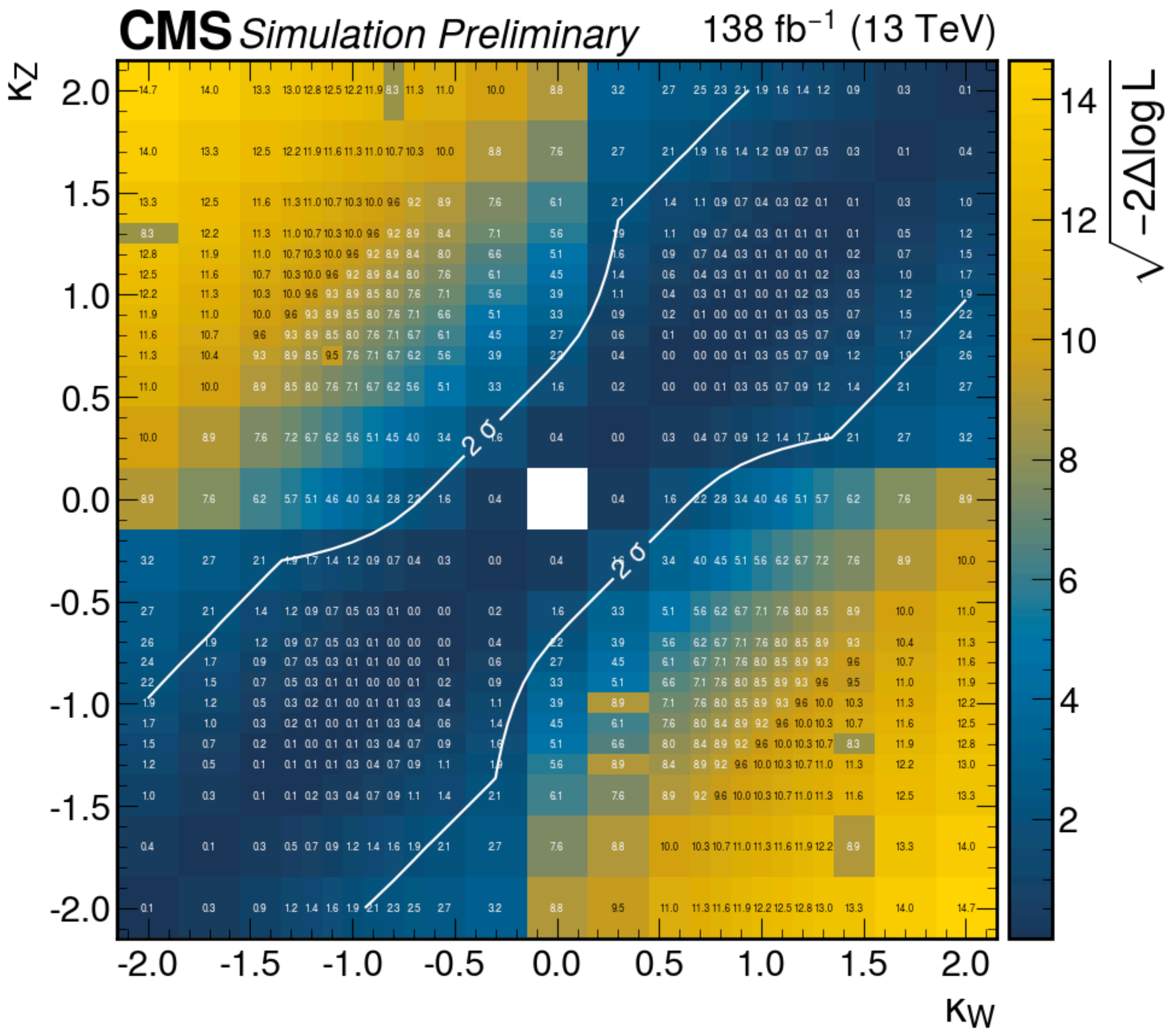
Collected Results

- Bins centered on scanned κ_W, κ_Z points
- Exclusion limit plotted on z-axis
- Contour roughly shows σ = 2 boundary
  - Simplistically derived by Matplotlib
- Discontinuities do not affect contours
  - Caused by some failure in the reweighting
  - Cross sections are reweighted properly, acceptance is not
  - Smoothed out via interpolation



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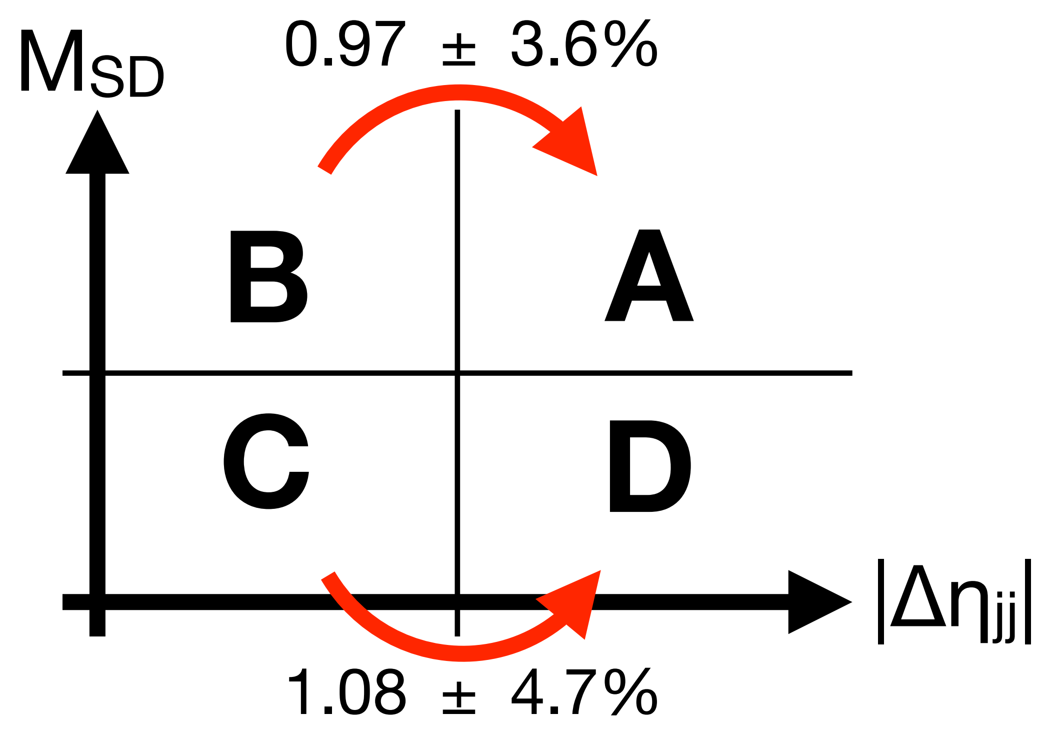
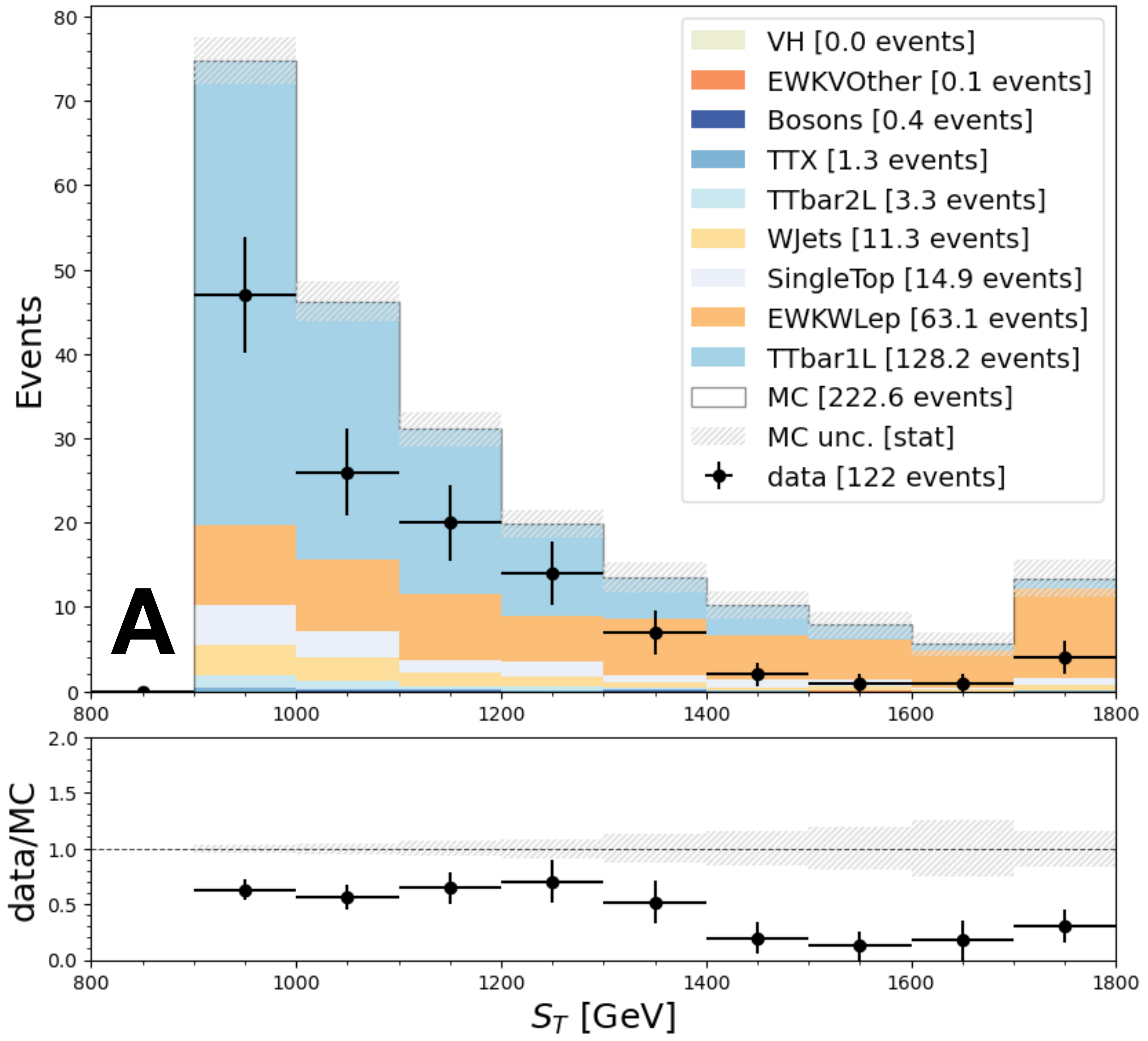
Erroneous EWK Samples

Preselection 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 ($W \to \ell\nu$) 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

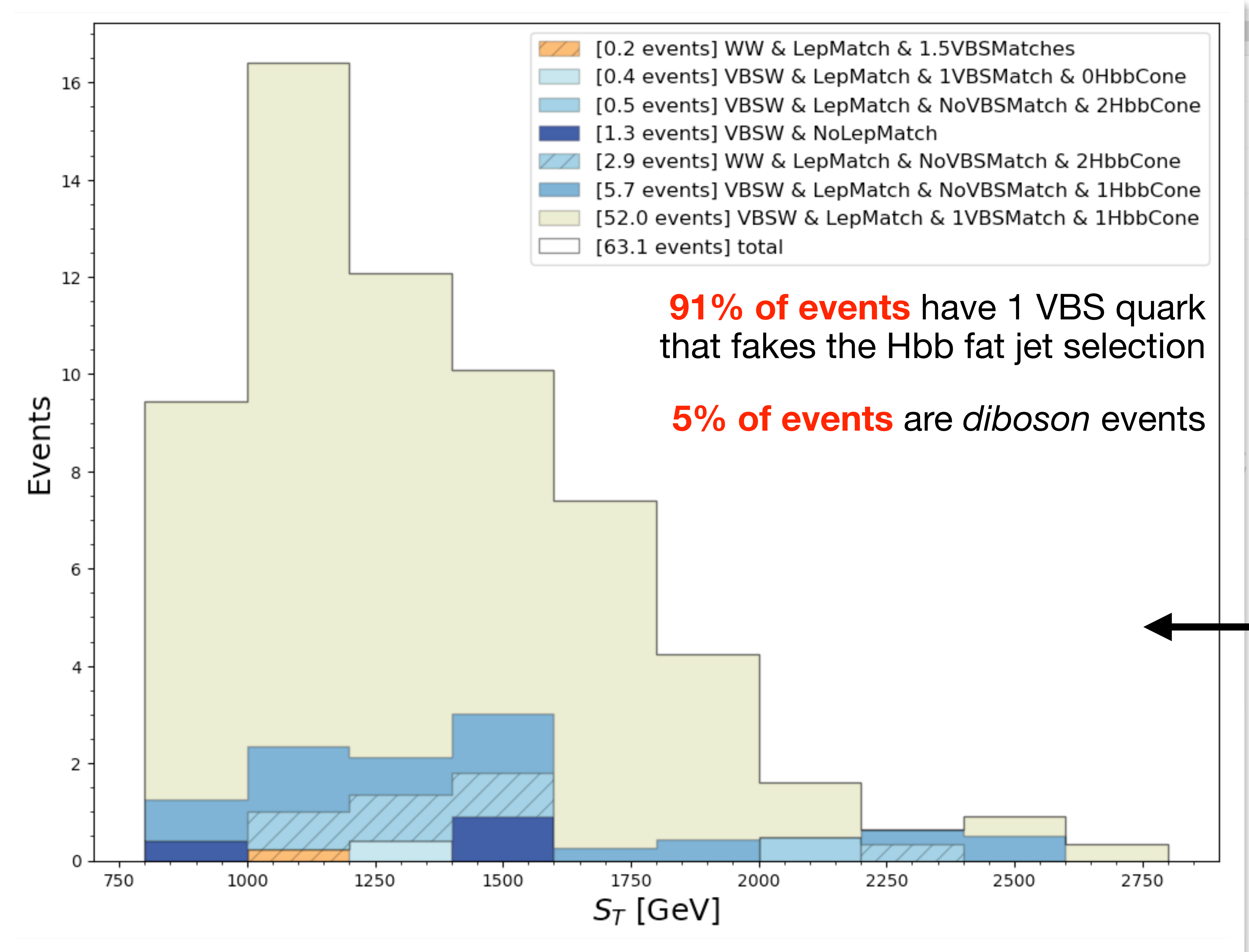


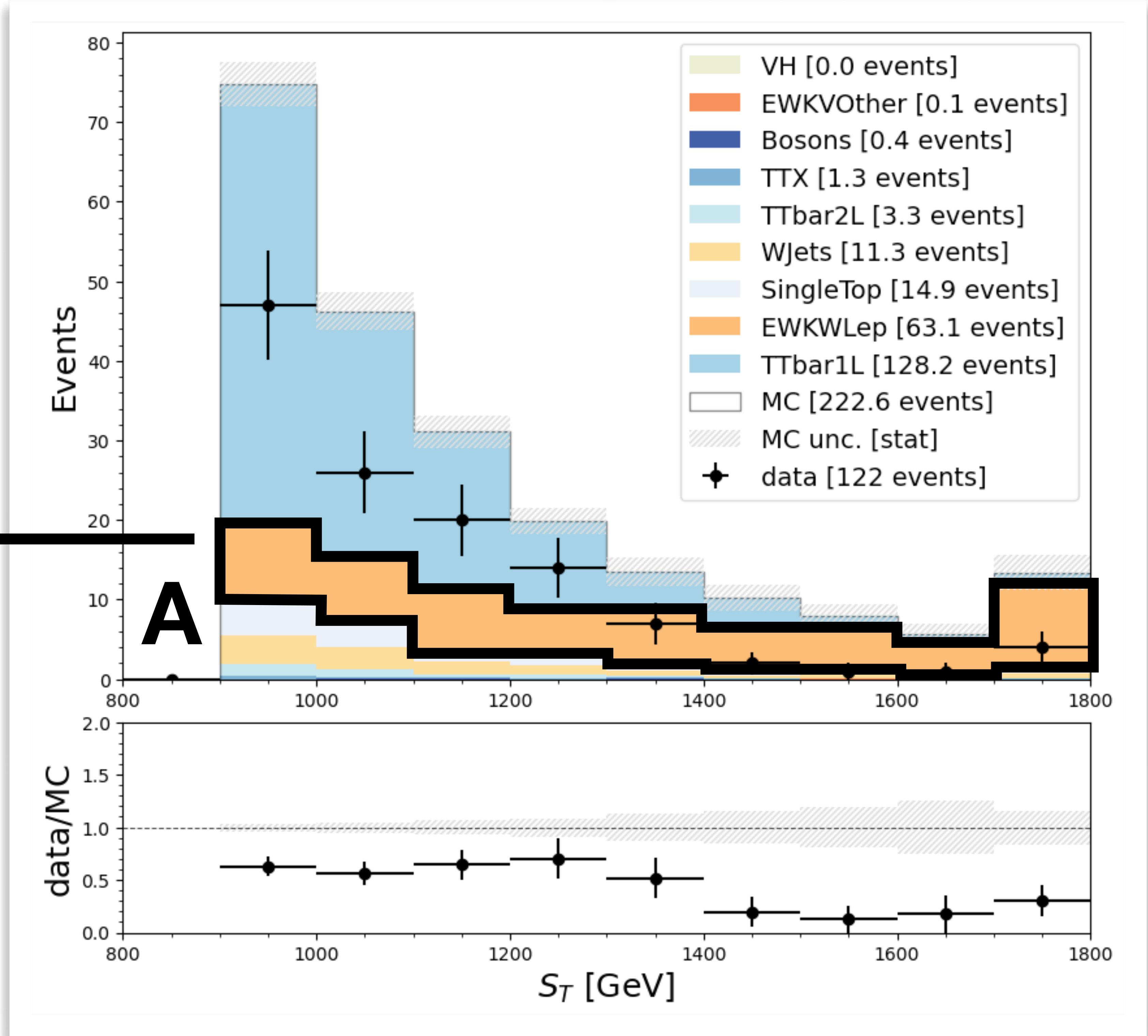
*err = $\sqrt{(\Sigma_i w_i^2)}$ for MC, $\sqrt{(\text{count})}$ for data

Erroneous EWK Samples

Preselection AND M_{jj} > 600 GeV AND S_T > 900 GeV AND PNet Xbb > 0.9

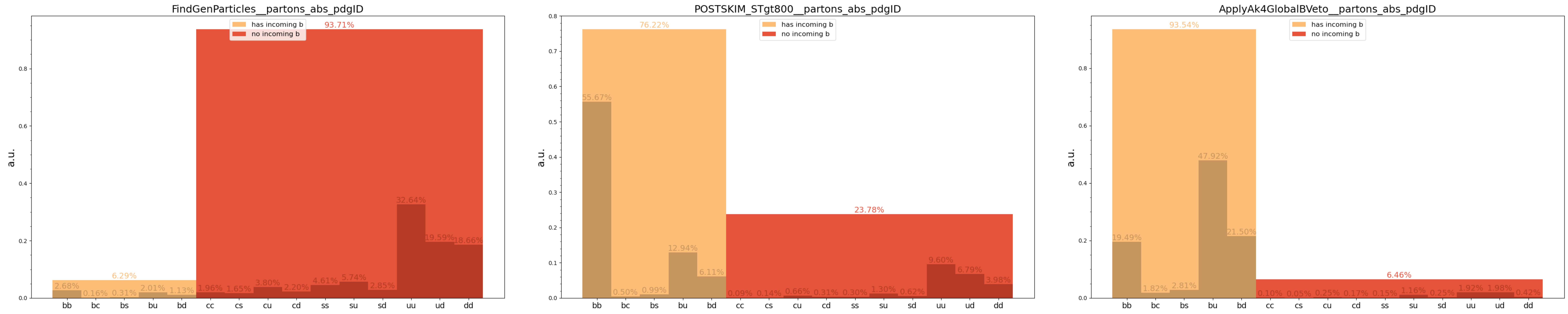
Cut	Data	Data Err.*
$\lvert\Delta\eta_{jj}\rvert$ > 4	122	11.05
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4	179	13.38
$\lvert\Delta\eta_{jj}\rvert$ ≤ 4	142	11.92
$\lvert\Delta\eta_{jj}\rvert$ > 4	—	—





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

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

Erroneous EWK Samples

- EWK W samples generated as follows:

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

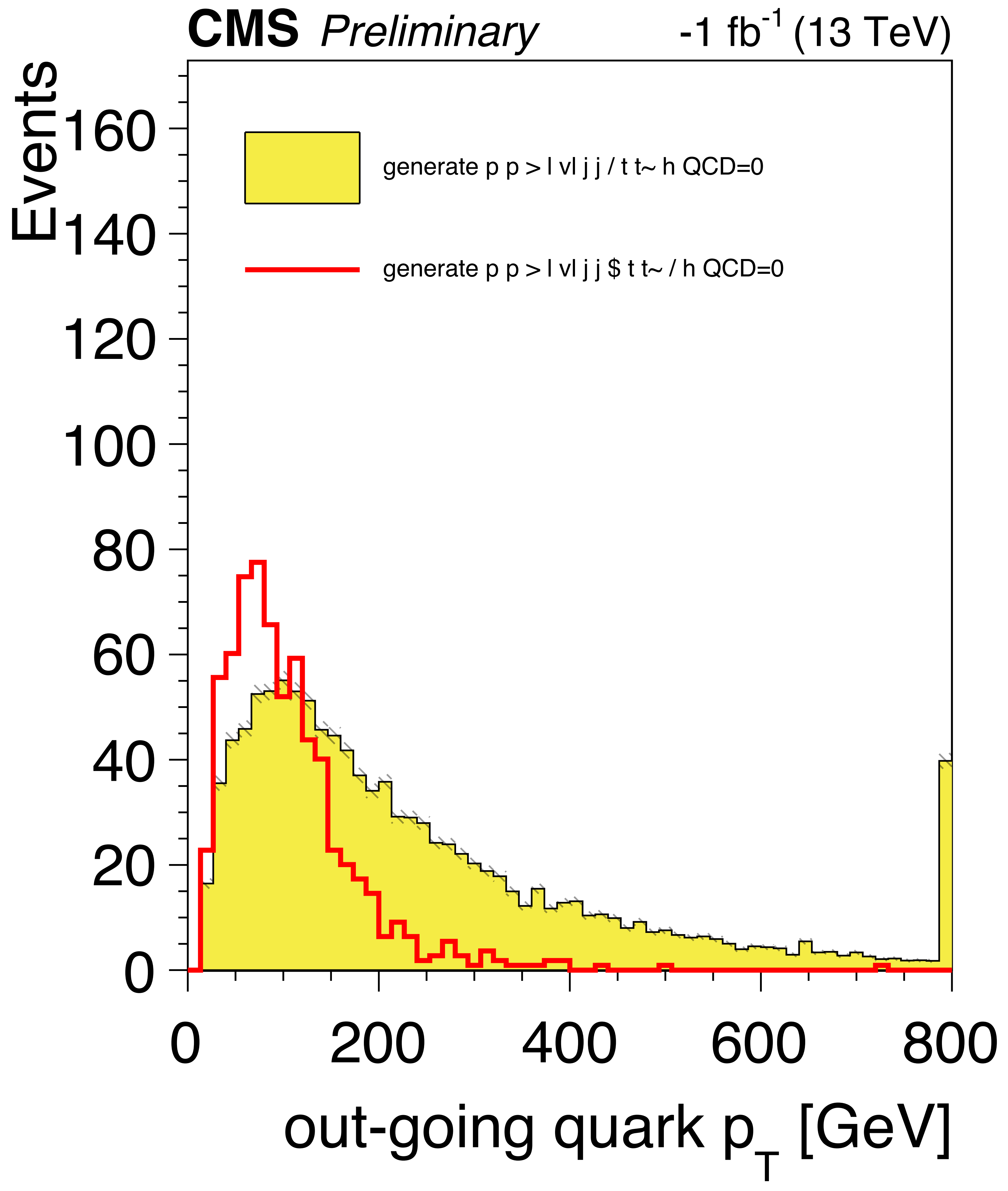
  - The **slash** notation excludes t, $\bar{t}$, and H diagrams from generation, and *ignores* any interference terms from them

- 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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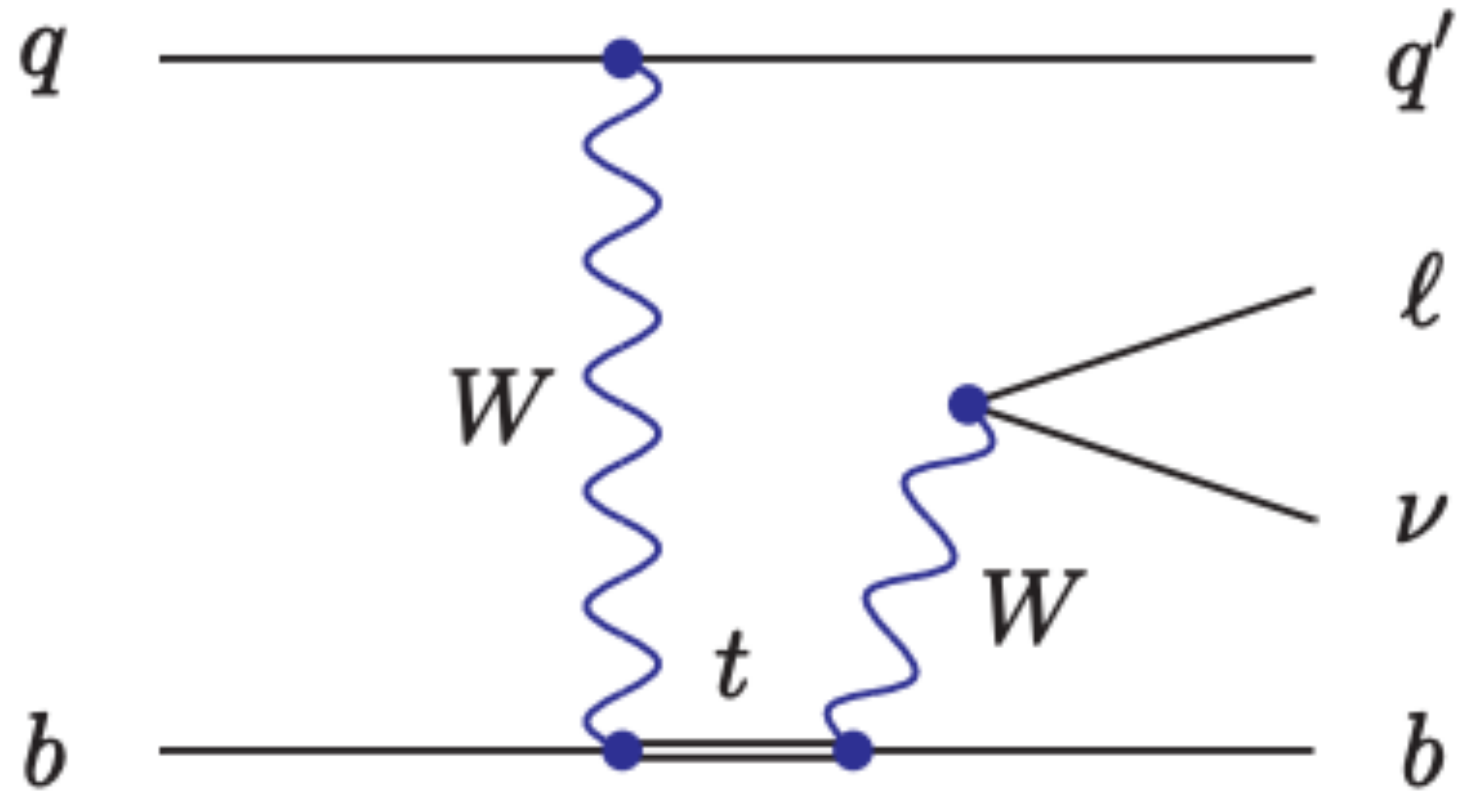
Erroneous EWK Samples

- 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)



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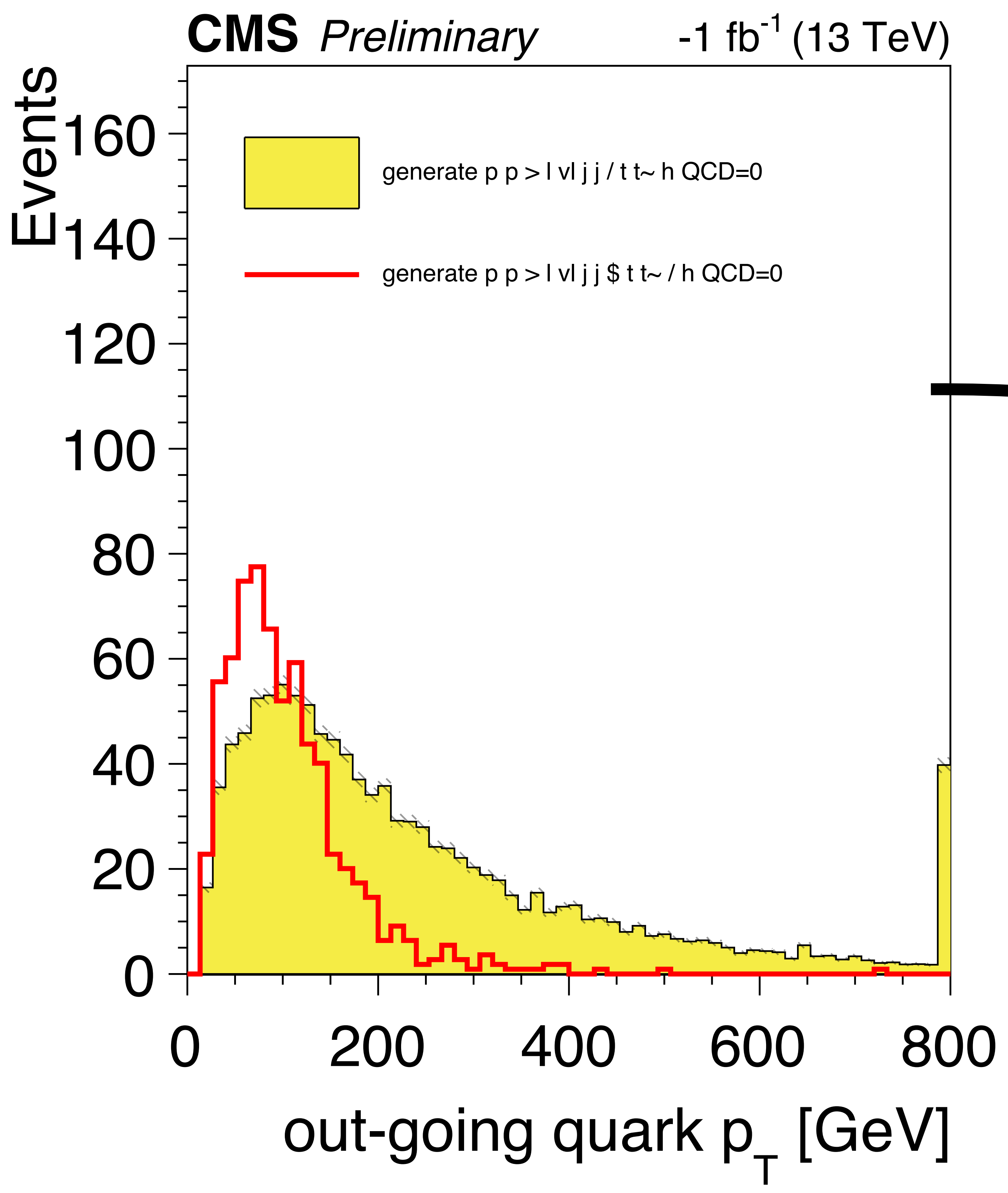
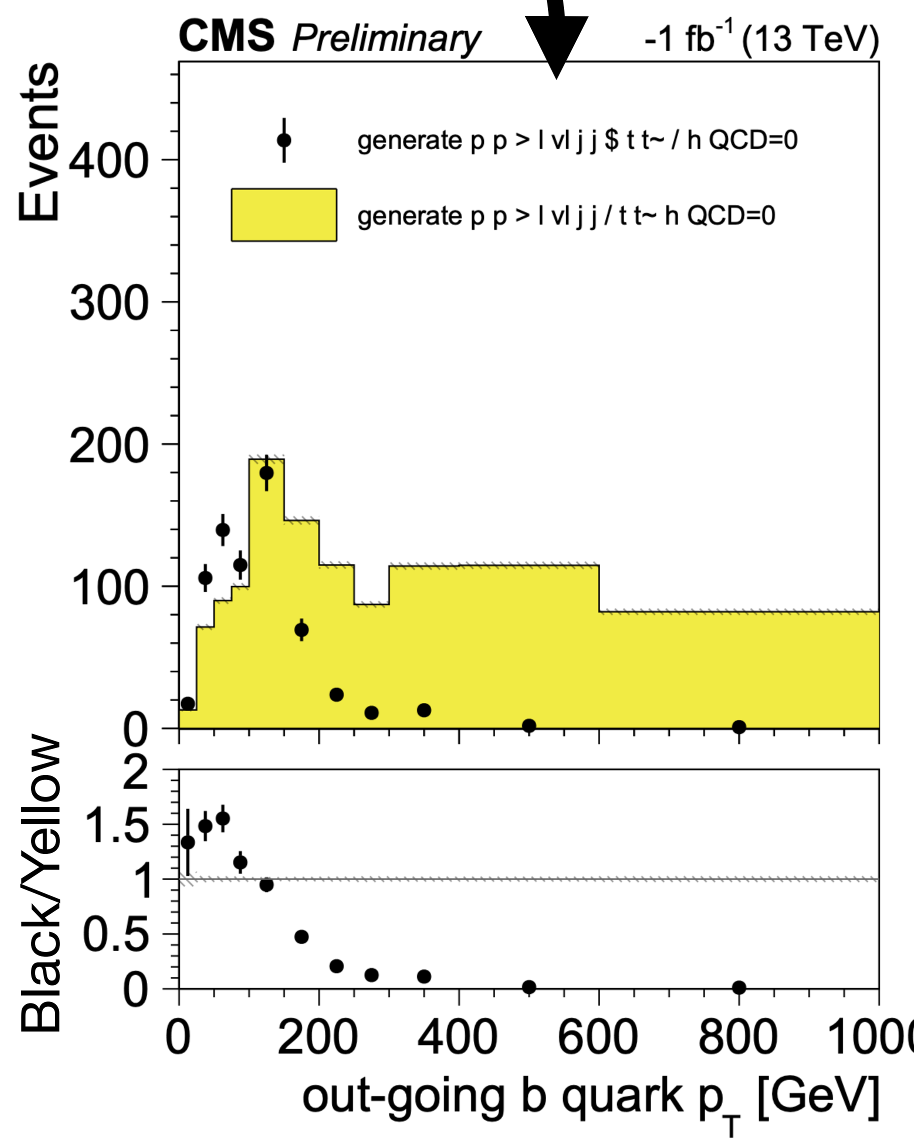
Erroneous EWK Samples

- 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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