Sensitivity to polarized VBS and doubly charged Higgs bosons at future hadron colliders

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FCC-hh meeting

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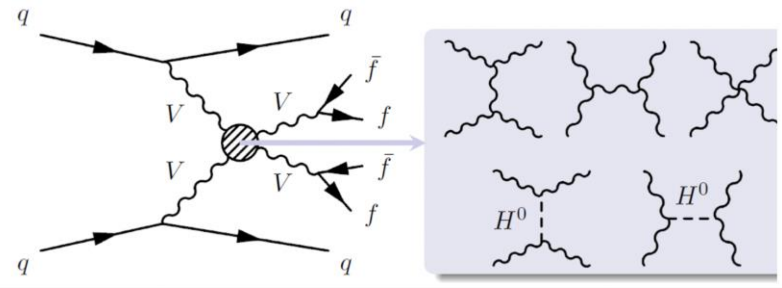
What's new since our last update in September?

- Updated $W^{\pm}W^{\pm}jj$ polarization results **with a breakdown of uncertainties**
- Complete results on the doubly charged Higgs study
- Paper with latest results has been submitted to Physical Review D (PRD)

Vector Boson Scattering (VBS)

- ➔ Important measurements to fully explore electroweak symmetry breaking
  - ◆ Longitudinally polarized VBS is unitarized by the presence of the SM Higgs boson
- ➔ Important window for physics beyond the Standard Model (SM)
- ➔ Our study explores the scattering of two same-sign W bosons ($W^{\pm}W^{\pm}jj$) at the FCC-hh
  - ◆ $W^{\pm}W^{\pm}jj$ has the largest electroweak to strong production cross-section ratio among VBS processes
  - ◆ Sensitive to BSM models such as the doubly charged Higgs model

- ➔ We test the sensitivity to all $W^{\pm}W^{\pm}jj$ polarization states at $\sqrt{s}$ = 27, 50 and 100 TeV
- ➔ Longitudinal VBS has not yet been observed at the LHC



Polarized $W^{\pm}W^{\pm}jj$ at the LHC and HL-LHC

- Access to longitudinally polarized $W^{\pm}W^{\pm}jj$ is challenging at the LHC
  - Cross-section is very small (less than 10% of the total $W^{\pm}W^{\pm}jj$ scattering cross-section)

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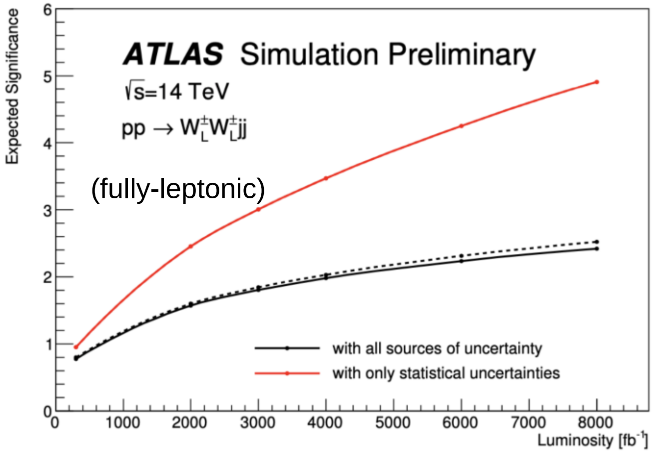
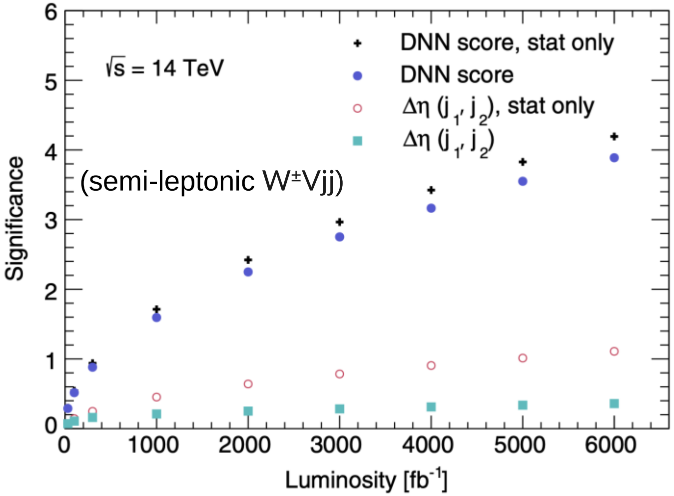


PhysRevD.104.093002



Expected significance at the HL-LHC with 3000 fb^{-1} of data is below 5σ

Polarized $W^{\pm}W^{\pm}jj$ at future hadron colliders

- ➔ This analysis only considers the fully-leptonic final state
- ➔ More detailed follow-up to a study performed for the 2021 US Snowmass process

Additions to the Snowmass study

- ❖ Boosted Decision Tree (BDT) variable to distinguish the signal
- ❖ Theory uncertainties
- ❖ Expected limits on doubly charged Higgs model parameters using the Georgi-Machacek (GM) model as the BSM benchmark

Signal and background samples

- Both signal and background events are simulated using Madgraph5 v3.4.1 + Pythia v8.306
- Delphes is used for the simulation of detector effects
- Background processes include: $W^{\pm}W^{\pm}jj$ QCD, $W^{\pm}Zjj$ QCD, $W^{\pm}Zjj$ EW, tZq processes
  - Detector-specific background processes (charge-flip, fakes) are ignored

- These events are simulated for a 27 TeV, 50 TeV, and 100 TeV FCC-hh collider and are scaled to an expected integrated luminosity of 30 ab^{-1}
- Events for longitudinal, transverse, and mixed $W^{\pm}W^{\pm}jj$ polarization were simulated separately
  - Cross-sections were validated to ensure that they added up to the inclusive cross-section

Event selection and systematic uncertainties

Selection type	Requirement
Number of leptons	Exactly 2 same-charge leptons
Lepton p_T	$p_T \geq 15$ GeV
Number of jets	≥ 2
Jet p_T	$p_T \geq 50$ GeV
Di-lepton invariant mass	$M_{ll} \geq 60$ GeV
$Z-$veto	$\lvert M_{ll} - M_Z \rvert > 10$ GeV
Di-jet invariant mass	$M_{jj} \geq 2$ TeV
Missing transverse momentum	$E_T^{miss} \geq 50$ GeV

- ❖ Only electrons or muons are considered
- ❖ Sources of systematic uncertainties:
  - ◆ Luminosity uncertainty (2%)
  - ◆ MC statistical uncertainties
  - ◆ PDF+α_s uncertainties
  - ◆ QCD scale uncertainties

} theory

★ NLO EW/QCD corrections are unavailable at the center of mass energies we looked at

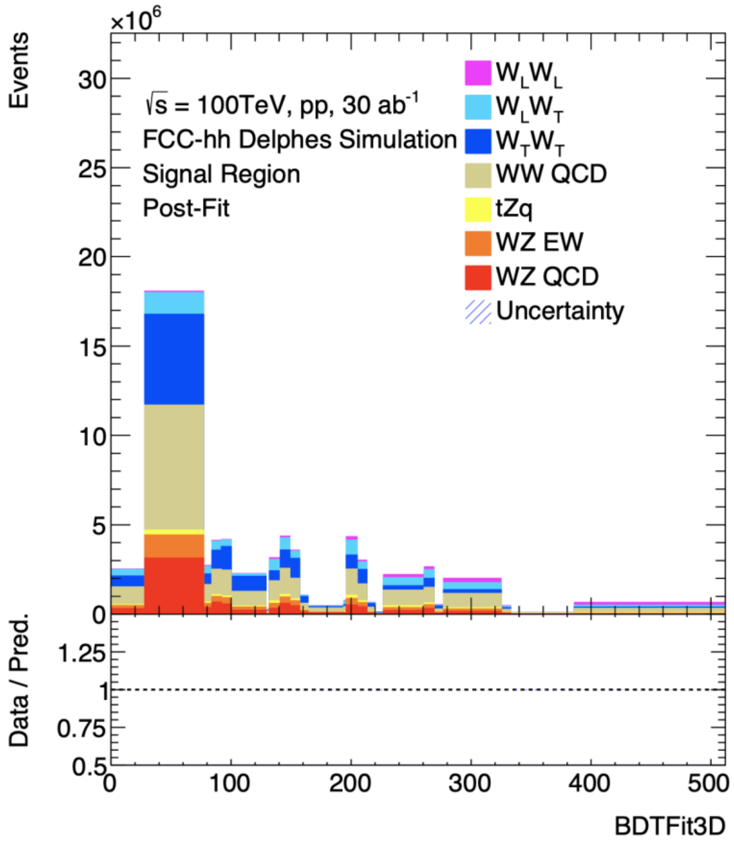
Maximum-likelihood fit

➔ BDTs were trained to isolate the individual polarizations and the backgrounds.

➔ We used a binned maximum-likelihood fit to the BDT and the $\Delta\phi_{jj}$ distributions.

➔ Binning was optimized, with minimum number of background events per bin as one of the criteria used.

➔ Sensitivity is determined from the uncertainty on the signal strength parameters.



Sensitivity measurement

- Improved sensitivity using the BDT variable
- Best sensitivity at 100 TeV
- Systematic uncertainties are largely associated with the theory modelling
- Improved theoretical predictions may result in a better sensitivity
- 2% better LL sensitivity at 100 TeV compared to the Snowmass result (see back-up)

Polarization	Signal Strength: BDT		
	$\sqrt{s} = 27$ TeV	$\sqrt{s} = 50$ TeV	$\sqrt{s} = 100$ TeV
μ_{LL}	1 ± 0.22	1 ± 0.21	1 ± 0.15
μ_{LT}	1 ± 0.13	1 ± 0.095	1 ± 0.096
μ_{TT}	1 ± 0.13	1 ± 0.085	1 ± 0.045
	Signal Strength: $\Delta\phi_{jj}$		
μ_{LL}	1 ± 1.02	1 ± 0.62	1 ± 0.40
μ_{LT}	1 ± 0.45	1 ± 0.42	1 ± 0.14
μ_{TT}	1 ± 0.33	1 ± 0.26	1 ± 0.12

Breakdown of uncertainties

$$\mu_{LL}^{27\ \mathrm{TeV}} = 1.00 \pm 0.22 = 1 \pm 0.17\ (\mathrm{stat.}) \pm 0.14\ (\mathrm{syst.})$$

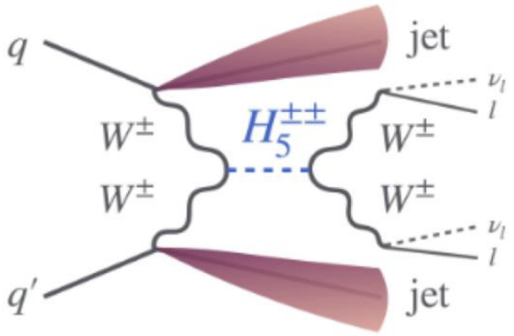
$$\mu_{LL}^{50\ \mathrm{TeV}} = 1.00 \pm 0.21 = 1 \pm 0.18\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})$$

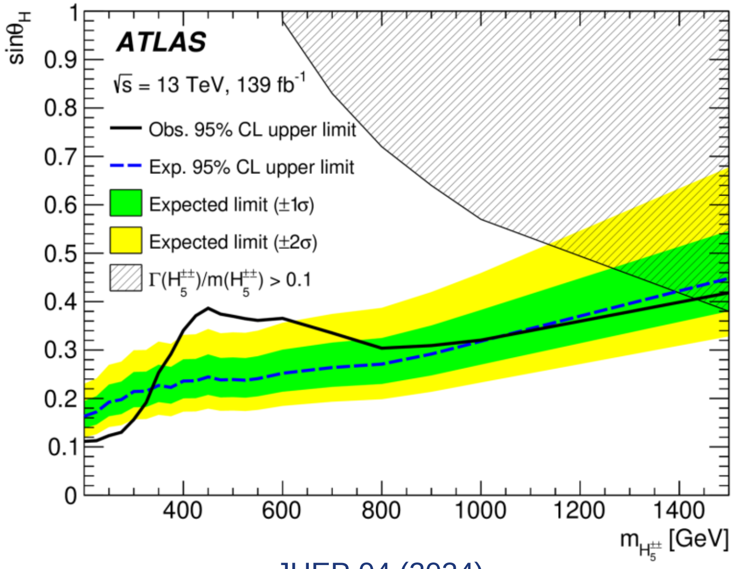
$$\mu_{LL}^{100\ \mathrm{TeV}} = 1.00 \pm 0.15 = 1 \pm 0.12\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.})$$

Theory modelling uncertainty at 100 TeV: 0.089

Doubly charged Higgs searches

- The GM model is a BSM model with extended Higgs sectors
  - Two isospin triplet scalar fields are added to the SM Higgs doublet
  - Scalar potential includes 5-plet states of Higgs bosons: $H_5^{\pm\pm}, H_5^{\pm}, H_5^0$
- ATLAS recently saw an excess of events corresponding to 2.5σ at $m_{H_5^{\pm\pm}}$ = 450 GeV.
  - $\sin\theta_H > 0.11 - 0.41$ for $200 < m_{H_5^{\pm\pm}} < 1500$ GeV were excluded
- In this analysis, we only look at five H_5 masses; 800, 900, 1000, 2000 and 3000 GeV





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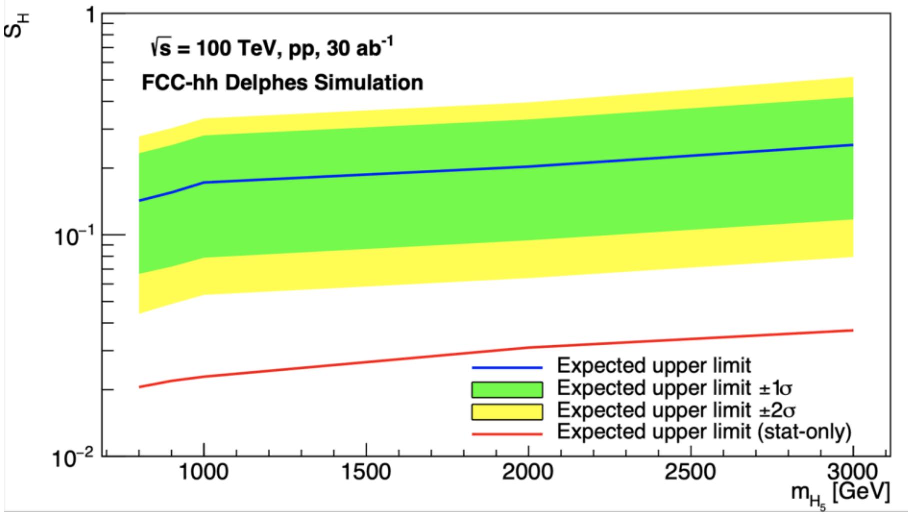
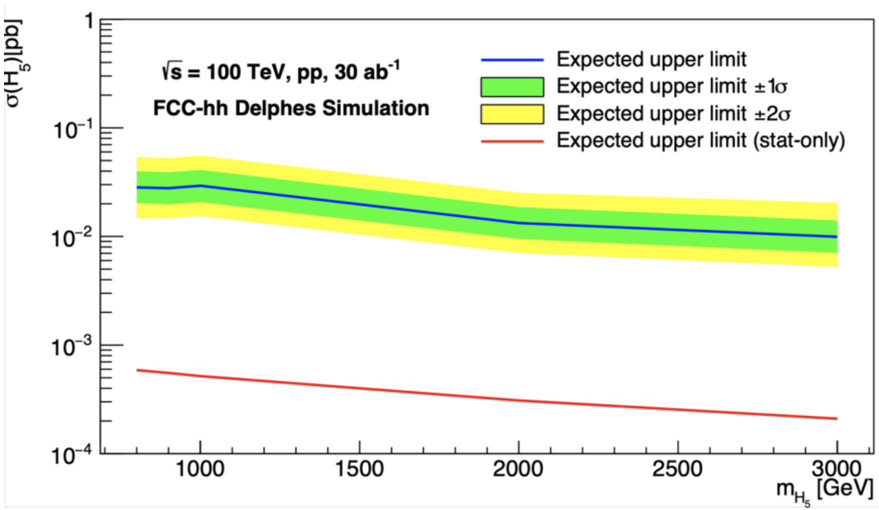
Doubly charged Higgs searches at the FCC-hh

➔ We performed a binned maximum-likelihood fit to the transverse mass (mT) of the dilepton and MET system

➔ Limits range between 0.14 and 0.25 at 100 TeV which promises to be better than current LHC limits

➔ The result is also largely impacted by the limited number of MC events





Summary

- With an integrated luminosity of 30 ab^{-1} at a 100 TeV FCC-hh, we can measure the cross-section of longitudinally polarized $W^{\pm}W^{\pm}jj$ with a relative precision of 15% in the fully leptonic final state.
- The precision is largely limited by the theory modelling.
- We have also set expected limits on doubly charged Higgs bosons in the context of the Georgi-Machacek model. We expect better limits than those currently set at the LHC.
    - Results are impacted by the limited number of MC events

★ Paper with latest results has been submitted to PRD

★ It would be nice to add the current FCC-hh baseline energy (84 TeV) to this study and also increase the number of generated MC events. However, most team members have moved on to other responsibilities

Additional material

Snowmass results

Polarization	Signal Strength		
	$\sqrt{s} = 27$ TeV	$\sqrt{s} = 50$ TeV	$\sqrt{s} = 100$ TeV
μ_{LL}	1 ± 0.39	1 ± 0.22	1 ± 0.17
μ_{LT}	1 ± 0.11	1 ± 0.10	1 ± 0.04
μ_{TT}	1 ± 0.08	1 ± 0.05	1 ± 0.02

Latest results

Polarization	Signal Strength: BDT		
	$\sqrt{s} = 27$ TeV	$\sqrt{s} = 50$ TeV	$\sqrt{s} = 100$ TeV
μ_{LL}	1 ± 0.22	1 ± 0.21	1 ± 0.15
μ_{LT}	1 ± 0.13	1 ± 0.095	1 ± 0.096
μ_{TT}	1 ± 0.13	1 ± 0.085	1 ± 0.045
	Signal Strength: $\Delta\phi_{jj}$		
μ_{LL}	1 ± 1.02	1 ± 0.62	1 ± 0.40
μ_{LT}	1 ± 0.45	1 ± 0.42	1 ± 0.14
μ_{TT}	1 ± 0.33	1 ± 0.26	1 ± 0.12

NLO EW corrections at the LHC

https://arxiv.org/pdf/2409.03620

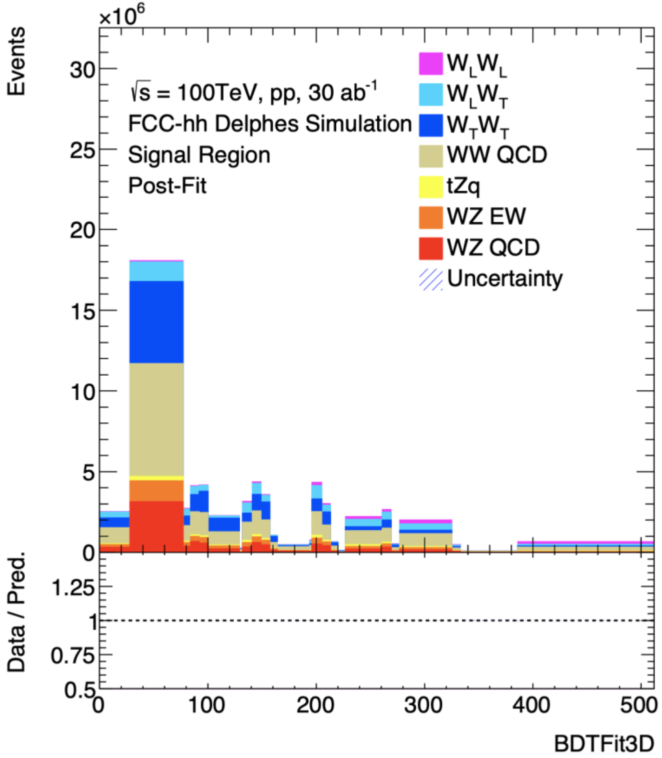
state	σ_{LO} [fb]	$\Delta\sigma_{\mathrm{NLO\,EW}}$ [fb]	$\Delta\sigma_{\mathrm{NLO\,QCD}}$ [fb]	$\sigma_{\mathrm{NLO\,EW+QCD}}$ [fb]
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	$-0.2084(6)$	$-0.0704(7)$	$1.208(1)^{+1.6\%}_{-3.1\%}$
unp.	$1.46455(9)^{+9.2\%}_{-7.8\%}$	$-0.2076(2)$	$-0.0733(5)$	$1.1836(5)^{+1.7\%}_{-3.3\%}$
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	$-0.01505(2)$	$-0.00660(7)$	$0.12715(8)^{+1.0\%}_{-2.1\%}$
LT	$0.23209(2)^{+9.1\%}_{-7.8\%}$	$-0.03040(4)$	$-0.0098(1)$	$0.1919(1)^{+1.4\%}_{-2.8\%}$
TL	$0.23208(2)^{+9.1\%}_{-7.8\%}$	$-0.03051(4)$	$-0.0097(1)$	$0.1918(1)^{+1.4\%}_{-2.8\%}$
TT	$0.87702(7)^{+9.4\%}_{-8.0\%}$	$-0.1352(1)$	$-0.0474(4)$	$0.6944(4)^{+1.9\%}_{-3.7\%}$
int.	$-0.0254(1)^{-8.9\%}_{+10.6\%}$	$0.0035(2)$	$0.0002(6)$	$-0.0217(7)^{-1.6\%}_{+0.7\%}$

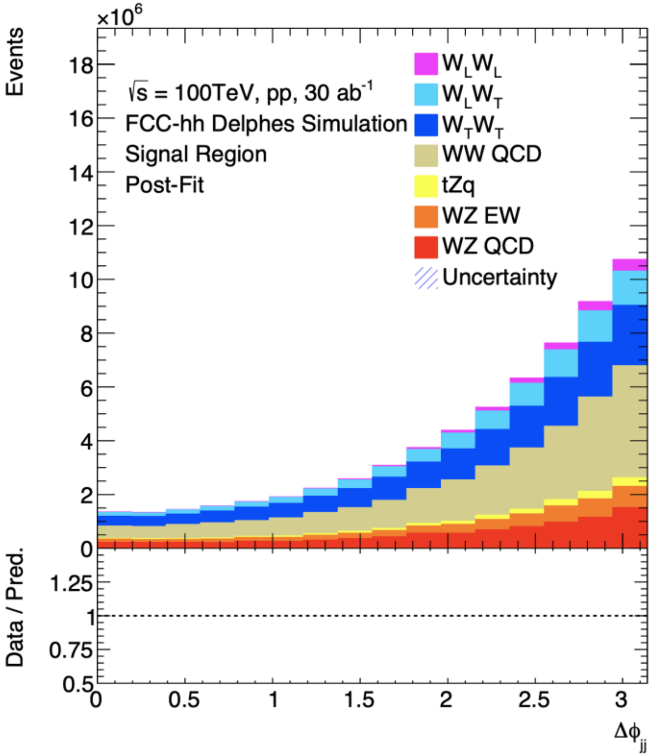
state	δ_{EW}	δ_{QCD}	$\delta_{\mathrm{EW+QCD}}$
full	-0.140	-0.047	-0.188
unp.	-0.142	-0.050	-0.192
LL	-0.101	-0.044	-0.145
LT	-0.131	-0.042	-0.173
TL	-0.131	-0.042	-0.173
TT	-0.154	-0.054	-0.208
int.	-0.139	-0.007	-0.147

BDT variables

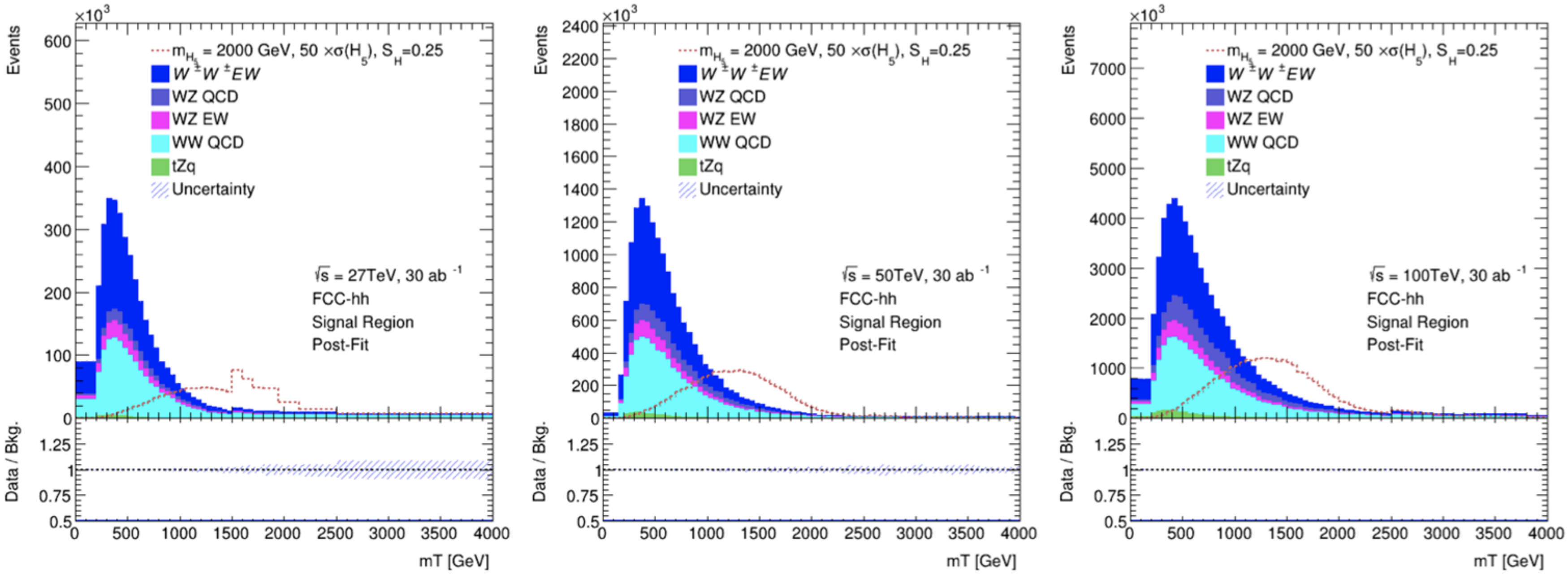
Variable	Description	SB	Pol
$\|\Delta\eta_{\ell\ell}\|$	Difference in rapidity of the leading and sub-leading leptons		✓
$\|\Delta\phi_{\ell_0 E^T_{\text{miss}}}\|$	Difference in azimuthal angles of the leading lepton and missing transverse energy		✓
$\|\Delta\phi_{\ell_1 E^T_{\text{miss}}}\|$	Difference in azimuthal angles of the sub-leading lepton and missing transverse energy	✓	✓
$\|\Delta\phi_{\ell_0\ell_1}\|$	Difference in azimuthal angles of the leading and sub-leading leptons		✓
$\|\Delta\phi_{\ell\ell E^T_{\text{miss}}}\|$	Difference in azimuthal angles of the dilepton system and missing transverse energy	✓	
$\|\Delta R_{j_1\ell_1}\|$	Distance between the leading jet and leading lepton		✓
$\|\Delta R_{j_2\ell_2}\|$	Distance between the sub-leading jet and sub-leading lepton	✓	
$\|\Delta R_{jj}\|$	Distance between the leading jet and sub-leading jet	✓	✓
E^T_{miss}	Missing transverse energy	✓	✓
m_{jj}	Mass of the dijet system	✓	
$m_{\ell\ell}$	Mass of the dilepton system	✓	✓
p_{Tj_1}	Transverse momentum of the leading jet	✓	
p_{Tj_2}	Transverse momentum of the sub-leading jet	✓	
p_{Tj_3}	Transverse momentum of the 3rd leading jet	✓	✓
p_{Tjj}	Transverse momentum of the dijet system		✓
$p_{T\ell_1}$	Transverse momentum of the leading lepton	✓	✓
$p_{T\ell_2}$	Transverse momentum of the sub-leading lepton		✓
$p_{T\text{rel}}$	Transverse momentum ratios for leptons and jets	✓	✓
$\sum\eta_\ell$	Sum of rapidity of all leptons	✓	
$\text{Zeppenfeld}_{\ell 1}$	Zeppenfeld variable for the leading lepton	✓	✓
$\text{Zeppenfeld}_{\ell 2}$	Zeppenfeld variable for the sub-leading lepton	✓	

BDT and $\Delta\phi_{jj}$ post-fit distributions





Post-fit mT distributions for the 2 TeV H5 signal



100 TEV LIMITS

Mass point (GeV)	sH upper limit (no uncertainties)	sH upper limit (only MC stat unc.)	sH upper limit (all uncertainties)
800	0.0205487	0.0889129	0.14235
900	0.0219089	0.1012930	0.155591
1000	0.022891	0.1069130	0.172235
2000	0.0309677	0.1490320	0.203118
3000	0.0370312	0.1760890	0.254512

50 TEV LIMITS

Mass point (GeV)	sH upper limit (no uncertainties)	sH upper limit (only MC stat unc.)	sH upper limit (all uncertainties)
800	0.0268794	0.0843668	0.140401
900	0.0285318	0.0959902	0.149975
1000	0.0301962	0.1024940	0.161021
2000	0.0424294	0.1478210	0.204264
3000	0.0527903	0.175456	0.25385

27 TEV LIMITS

Mass point (GeV)	sH upper limit (no uncertainties)	sH upper limit (only MC stat unc.)	sH upper limit (all uncertainties)
800	0.0371214	0.0850176	0.150819
900	0.0396074	0.0976188	0.148069
1000	0.0420535	0.104288	0.148603
2000	0.064213	0.164406	0.243799
3000	0.0922249	0.242479	0.379768