# A search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states with the ATLAS detector

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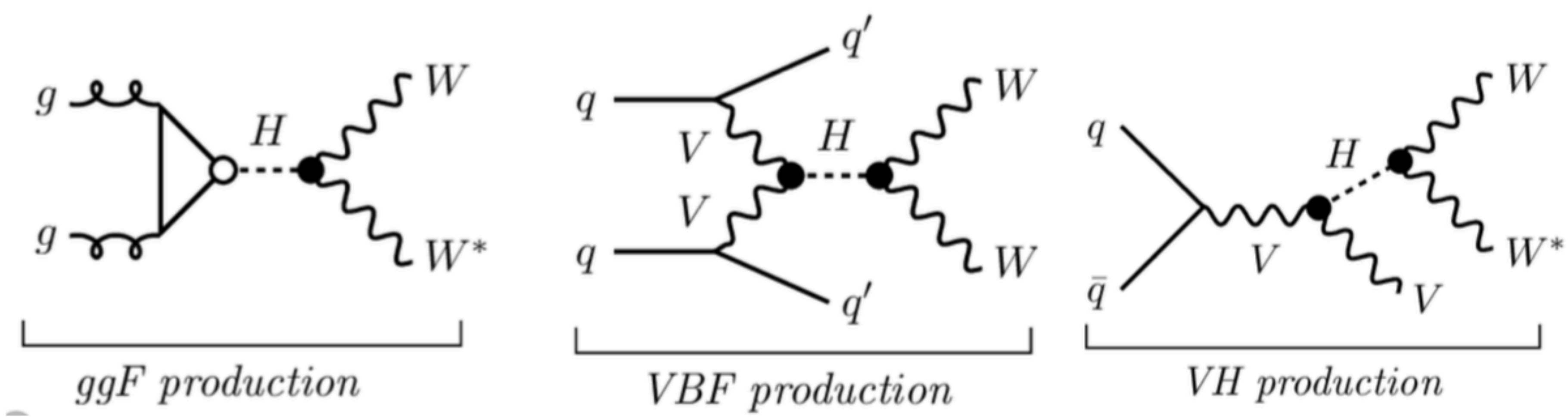
# Introduction

- Many BSM predict heavy Higgs particles decaying to heavy quarks or bosons: 2HDM, MSSM…
- Production of heavy Higgs boson:
  - gluon-gluon fusion (ggF)
  - Vector-boson fusion (VBF)
  - Associated production with vector boson (VH)
- Theoretical study on model-independent heavy Higgs boson from Yu-Ping Kuang
  - ggF: $pp \to t\bar{t}t\bar{t}$ Physics Letters B 747 (2015) 193-199
  - VBF: $pp \to H^* j_1^f j_2^f \to VV j_1^f j_2^f \to \ell^+ \nu_\ell j_1 j_2 j_1^f j_2^f$ Physical Review D 90, 115002 (2014)
  - VH: $pp \to VH^* \to VVV \to \ell^+ \nu_\ell j_1 j_2 j_3 j_4$ Physical Review D 90, 115002 (2014)



# Interactions

- Multiple Higgs field: one SM-like light Higgs (**h**) and one generic neutral heavy Higgs boson (**H**)
- A generic heavy Higgs boson: generic means model-independent, has both dim-4 and effective dim-6 interactions with SM particles.
- Only consider these **four dim-6 operators**, since we just consider the coupling between heavy Higgs and vector bosons(W/Z) and the rest is constrained by electroweak precision data or not relevant for the heavy Higgs boson.

dim-4 operator Lagrangian

Light Higgs

$$\mathcal{L}^{(4)}_{hWW} = \rho_h g m_W h W^\mu W_\mu$$

$$\mathcal{L}^{(4)}_{hZZ} = \rho_h \frac{g m_W}{2\cos^2\theta_W} h Z^\mu Z_\mu$$

$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu$$

$$\mathcal{L}^{(4)}_{HZZ} = \rho_H \frac{g m_W}{2\cos^2\theta_W} H Z^\mu Z_\mu$$

heavy Higgs

dim-6 effective operator Lagrangian

$$\mathcal{L}^{(6)}_{HVV} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n, \quad \Lambda = 5TeV$$

$$\mathcal{L}^{(6)}_{HWW} = \rho_H g m_W \frac{f_W}{2\Lambda^2}(W^+_{\mu\nu}W^{-\mu}\partial^\nu H + h.c.) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu}W^{-\mu\nu} H$$

$$\mathcal{L}^{(6)}_{HZZ} = \rho_H g m_W \frac{c^2 f_W + s^2 f_B}{2c^2\Lambda^2} Z_{\mu\nu}Z^\mu\partial^\nu H - \rho_H h m_W \frac{c^4 f_{WW} + s^4 f_{BB}}{2c^2\Lambda^2} Z_{\mu\nu}Z^{\mu\nu} H$$

$$s = sin\theta_W, \quad c = cos\theta_W$$

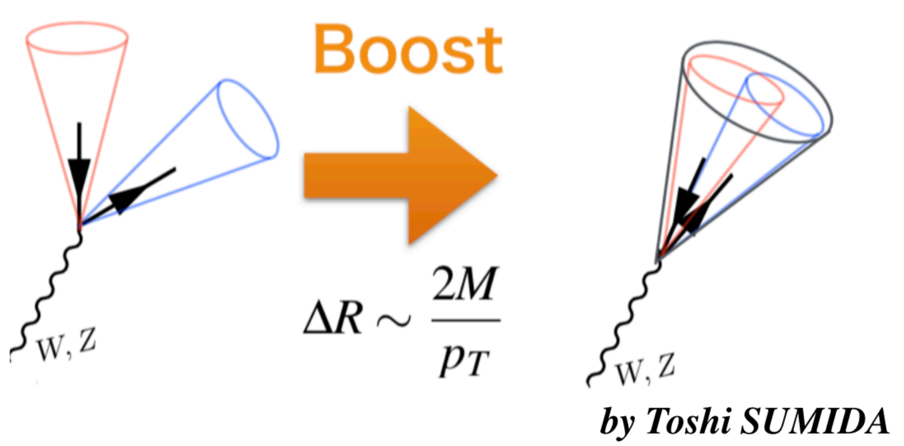
$$f_B = f_{BB} = 0, \quad \rho_h = 1, \ \rho_H = 0.05$$

PLB 804 (2020) 135358

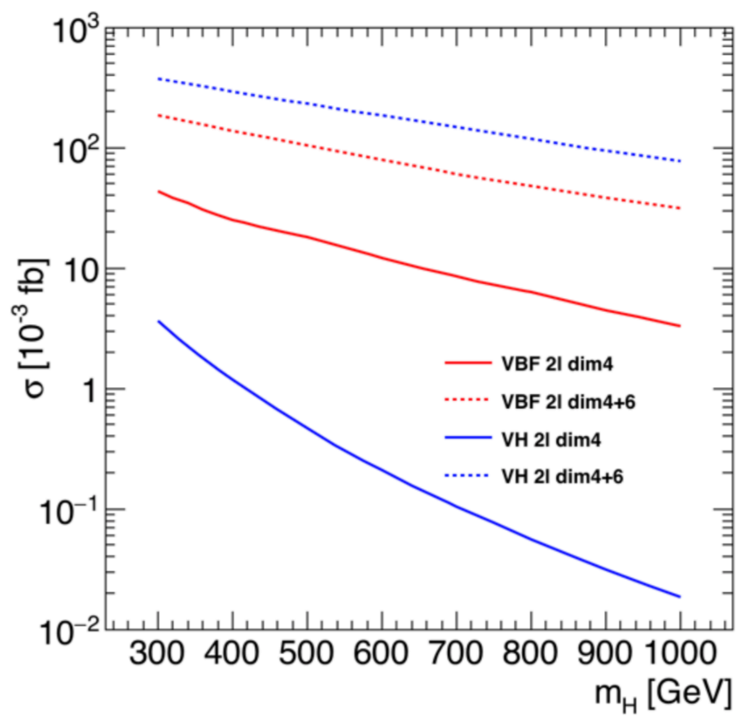
Only $f_W$, $f_{WW}$, $m_H$ are free parameters

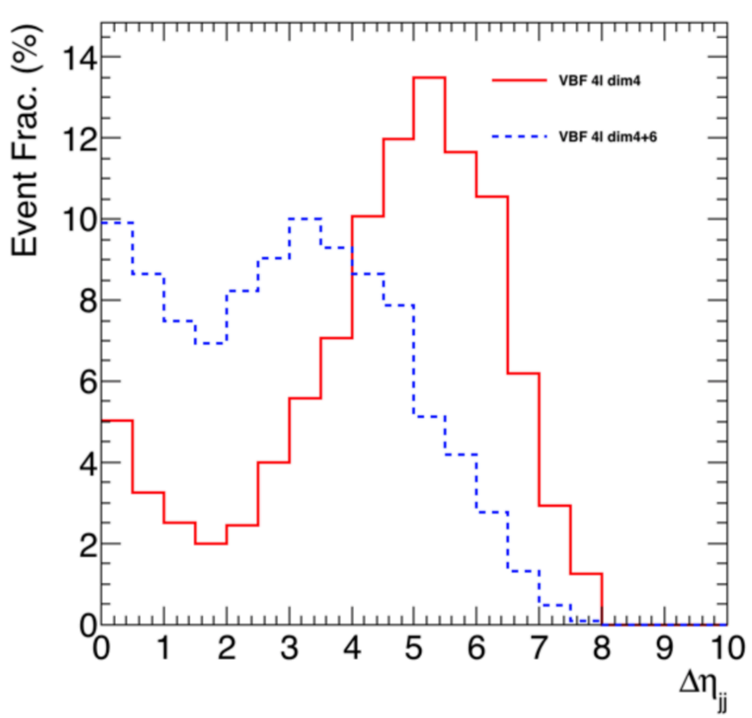
# Why VH?

- The associated **VH**(V=W/Z) production and **H->VV** decay are considered, the V/H is boosted due to dim-6 operators.
  - Don’t consider Yukawa coupling due to large background and low sensitivity
  - Vector boson fusion(VBF) is NOT considered because of accompanied by large background
    - Some traditional variables e.g. $\Delta\eta_{jj}$ become more background-like due to dim-6 operators.



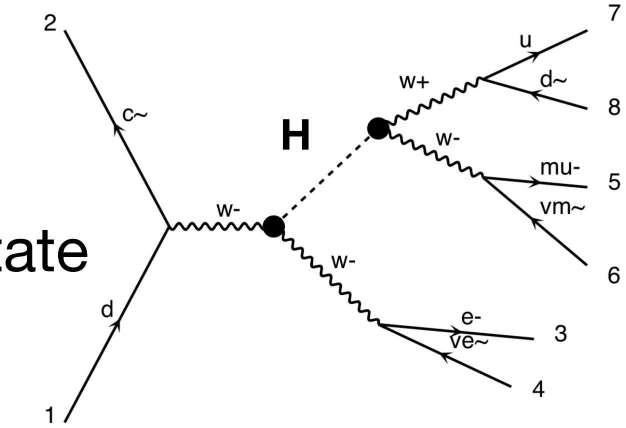

Boosted boson jet: high pT, variable $\tau_1$ and $\tau_2$ describing jet substructure.



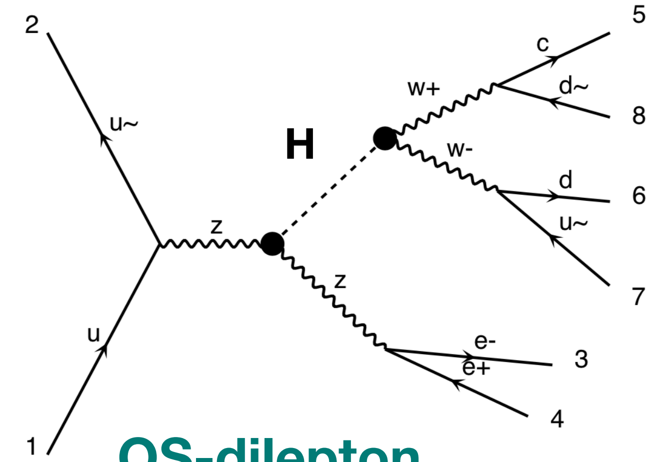



# Why same-sign di-lepton?

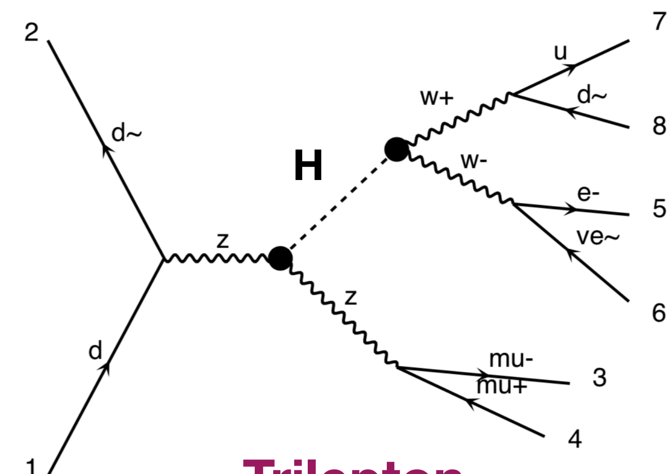
- Three final states are interested:
  - **SS-dilepton**: 2 same-sign lepton final state with two neutrinos from WWW.
  - **OS-dilepton**: 2 opposite-sign lepton final state without neutrino.
  - **Trilepton**: 3 lepton final state with one neutrino.




SS-dilepton

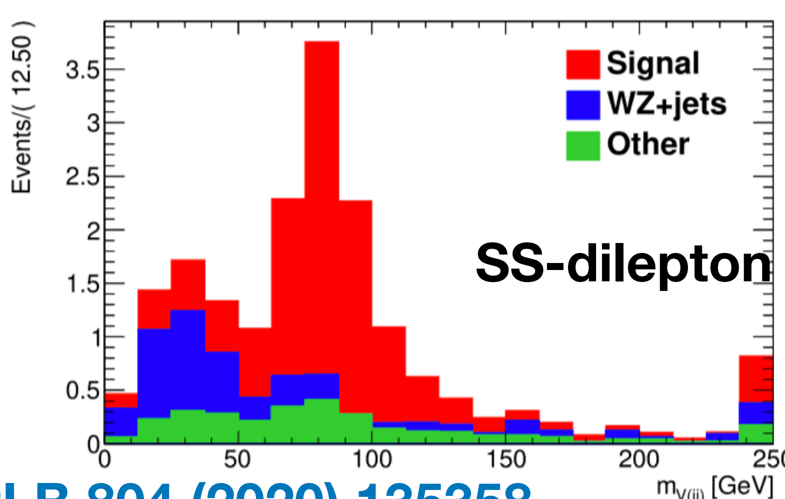


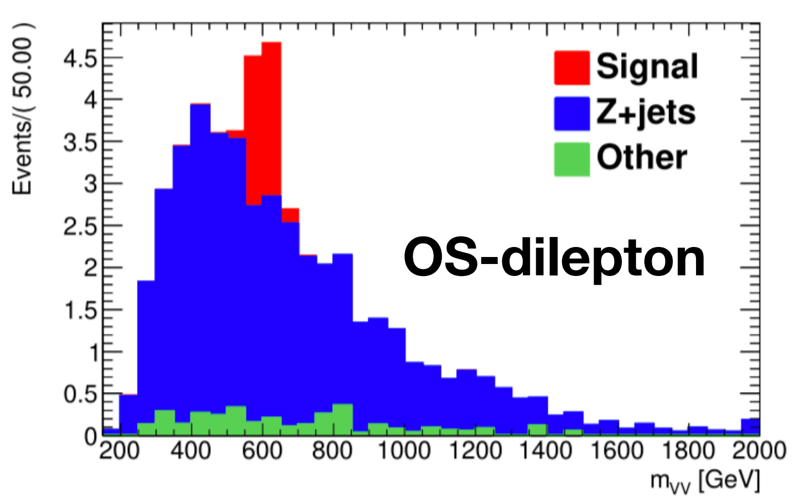

OS-dilepton

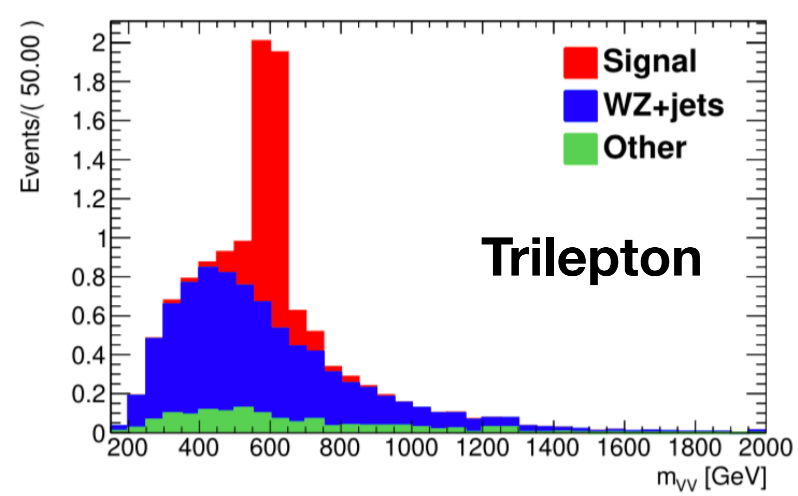



Trilepton

Distributions in phenomenology study with signal point $m_H = 600$ GeV, $\rho_H = 0.05$, $f_W = f_{WW} = 1000$ and $L = 300$ fb$^{-1}$



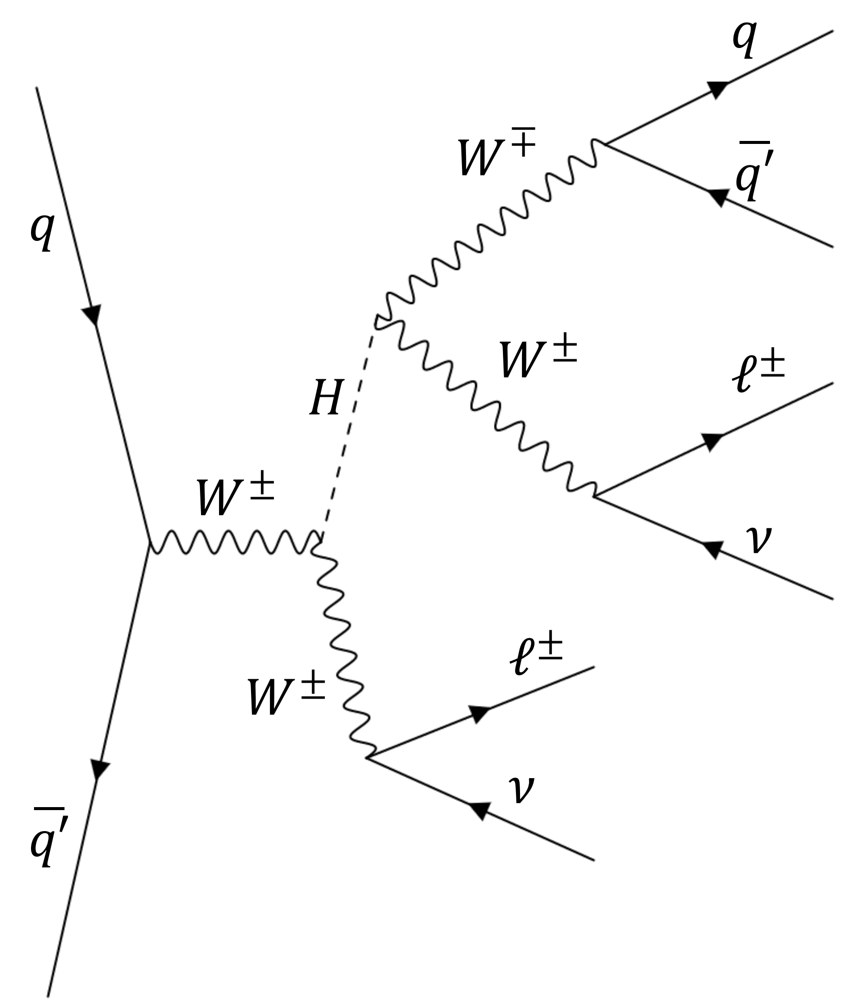




[PLB 804 (2020) 135358](PLB 804 (2020) 135358)

# Analysis strategy

- Signal signature: two same-sign leptons (e or μ) in association with one large-R jet (J) or two small-R jets (j), and $E_T^{\text{miss}}$.
- Two categories according to hadronic Boson kinematics
  - **Boosted**: one large-R jet
  - **Resolved**: two small-R jets




**Same-sign 2 lepton (SS2L)**

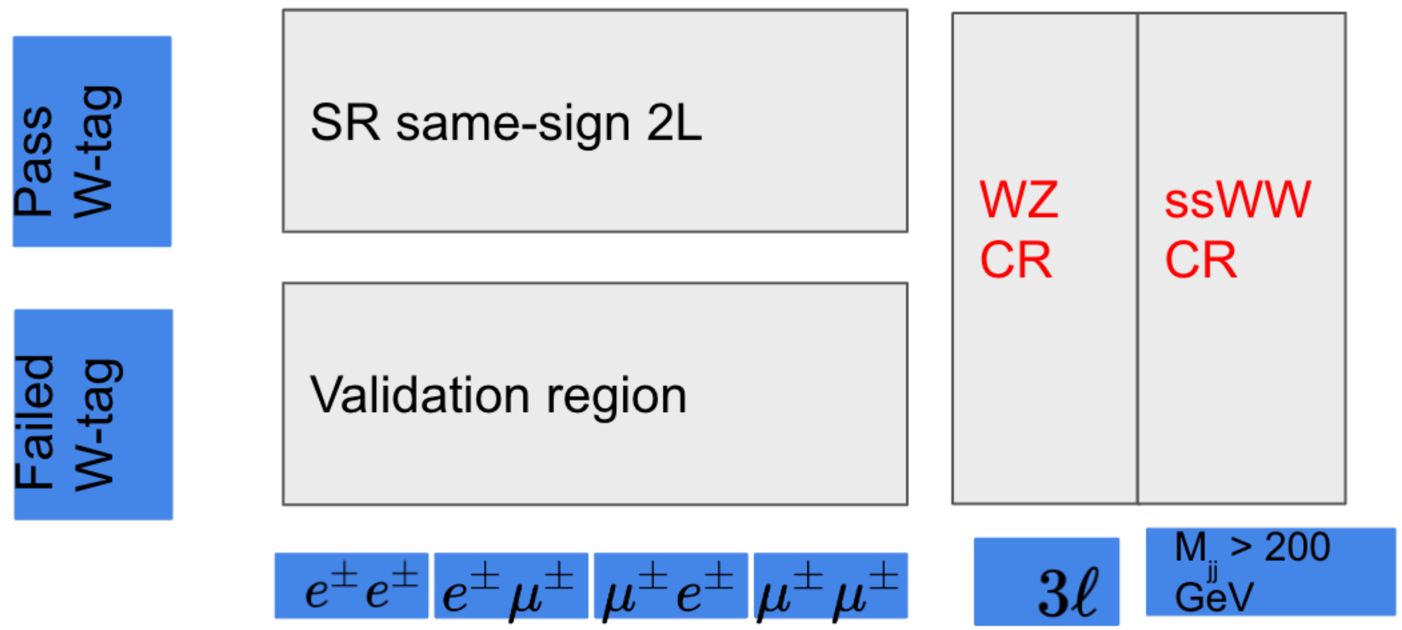
WH(WW)


**Observable:** $M_{eff} = \sum p_T^{\text{Lepton}} + \sum p_T^{\text{V-jets}} + E_T^{\text{miss}}$

# Analysis regions

- Signal region (SR):

| **SS2ℓ** ($l_1^{\pm} l_2^{\pm} = e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm}$) | |
|---|---|
| Boosted | Resolved |
| Two same-sign leptons with $p_T$ > (27)20 GeV | |
| $3^{rd}$ lepton veto | |
| no b-jet @ 85% DL1r | |
| $M_{ll}$ > 100 GeV | |
| Boosted Category | !Boosted Category |
| $E_T^{miss}$ > 80 GeV | $E_T^{miss}$ > 60 GeV |
| $N_J \geq 1$<br>$p_T(J_1)$ > 200 GeV | $N_j \geq 2$<br>$p_T(j_1), p_T(j_2)$ > 20 GeV |
| $J_1$ @ 80% W tagger | $M_{jj} \in (50, 110)$ GeV |



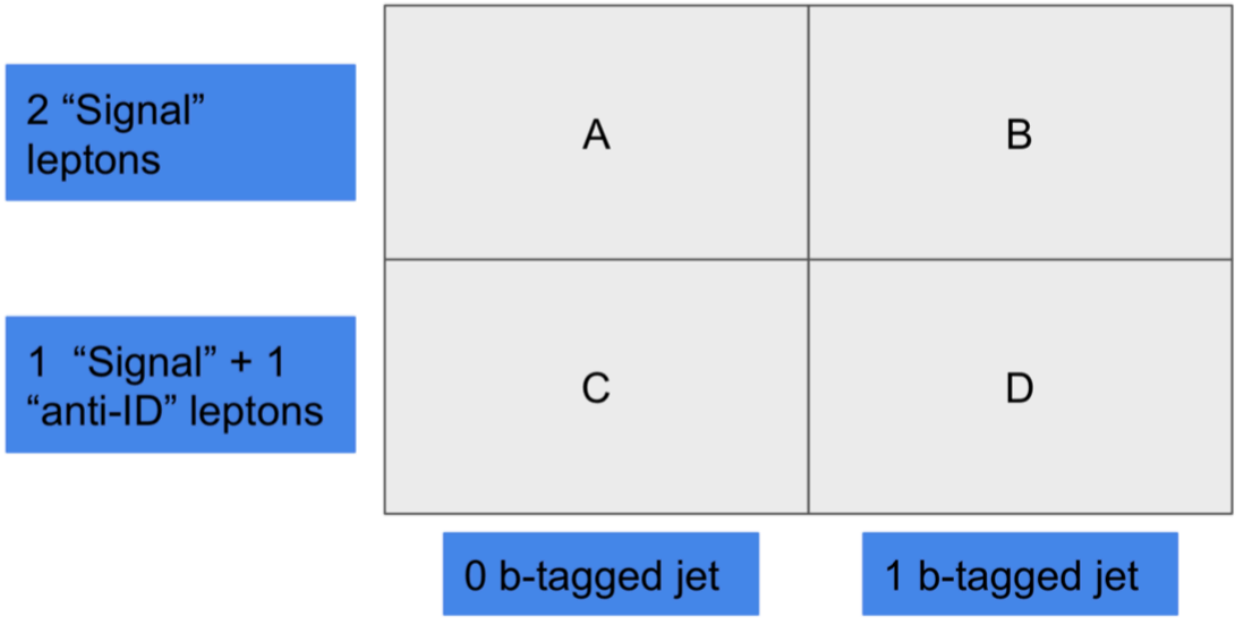

- Validation region (VR) is used to validate main prompt backgrounds.
  - Similar with SR
  - Failed the W-tag (Boosted) or $M_{jj}$ cut (Resolved)

- WZ control region ( WZ CR):
  - Invariant  mass of three leading leptons ($M_{lll}$) > 110 GeV

- Same-sign WW control region (ssWW CR):
  - Invariant mass of two leading small-R jets ($M_{jj}$) > 200 GeV

# Background estimation

- Main background: WZ, same-sign WW (ssWW), WWW, non-prompt leptons background
- Background constrained by control region: ssWW, WZ
- Background estimations from data-driven (limited number of simulated events or difficult to well model the details):
  - Non-prompt background: Background from the non-prompt leptons originating from hadronic jets, mainly from $t\bar{t}$ and W+jets
  - Photon conversion background: due to photon mis-reconstructed as an electron, mainly from $V\gamma$+jets process
  - Charge flip background: charge mis-identification, mainly from Z+jets (ee)

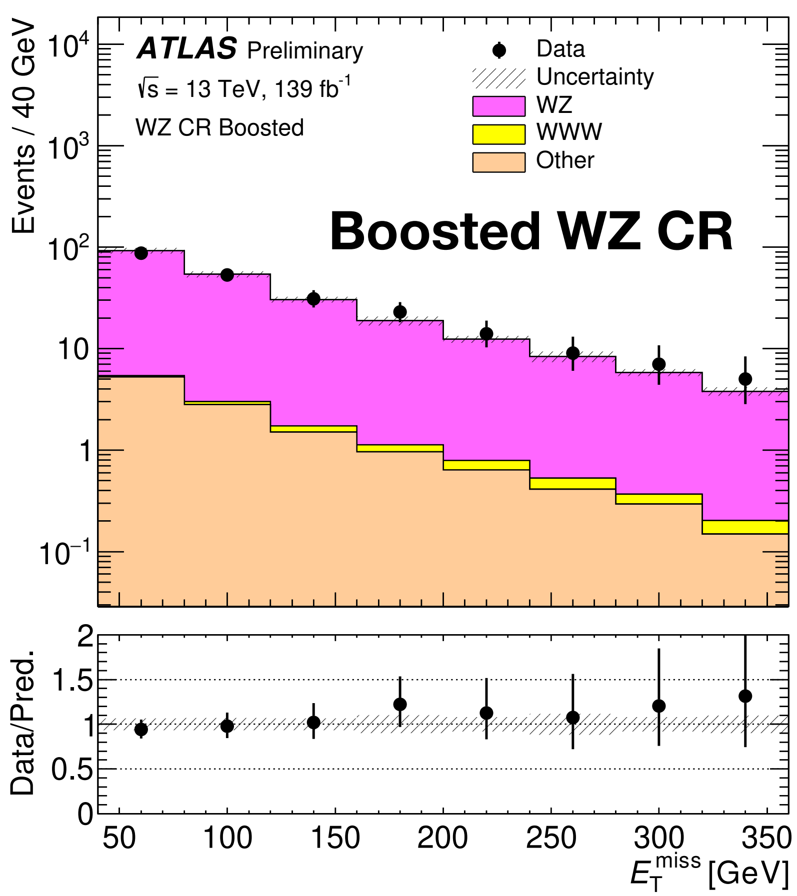



**e.g. non-prompt**

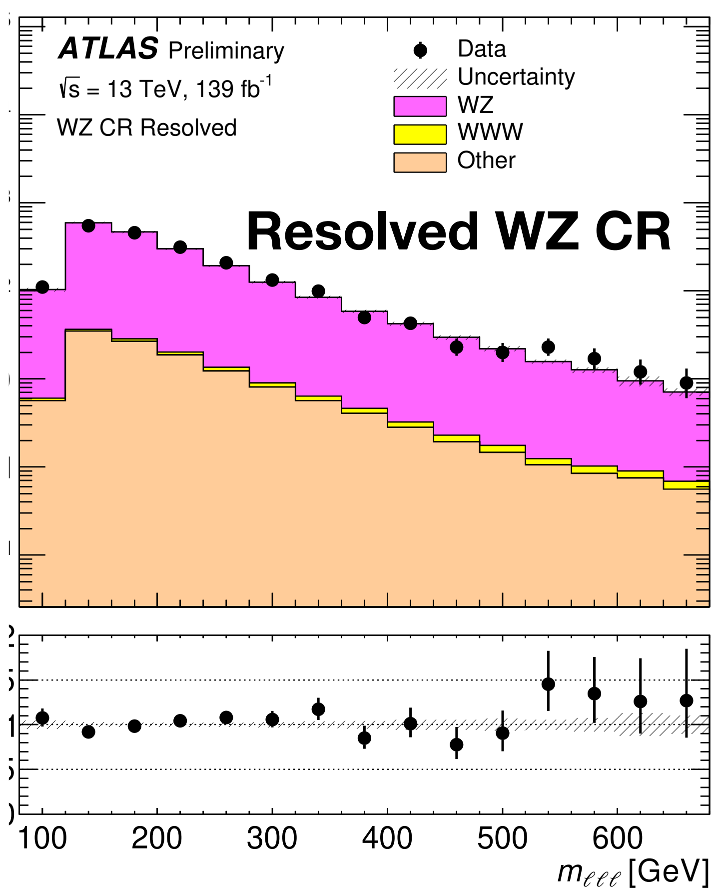
# Control Regions

- WZ and ssWW backgrounds are the dominant background in SR.
- Corresponding CRs are defined to constrain WZ/ssWW in the final fit:
  - Take the shape from MC simulation
  - Normalisation factor (NF) is one of the free parameters

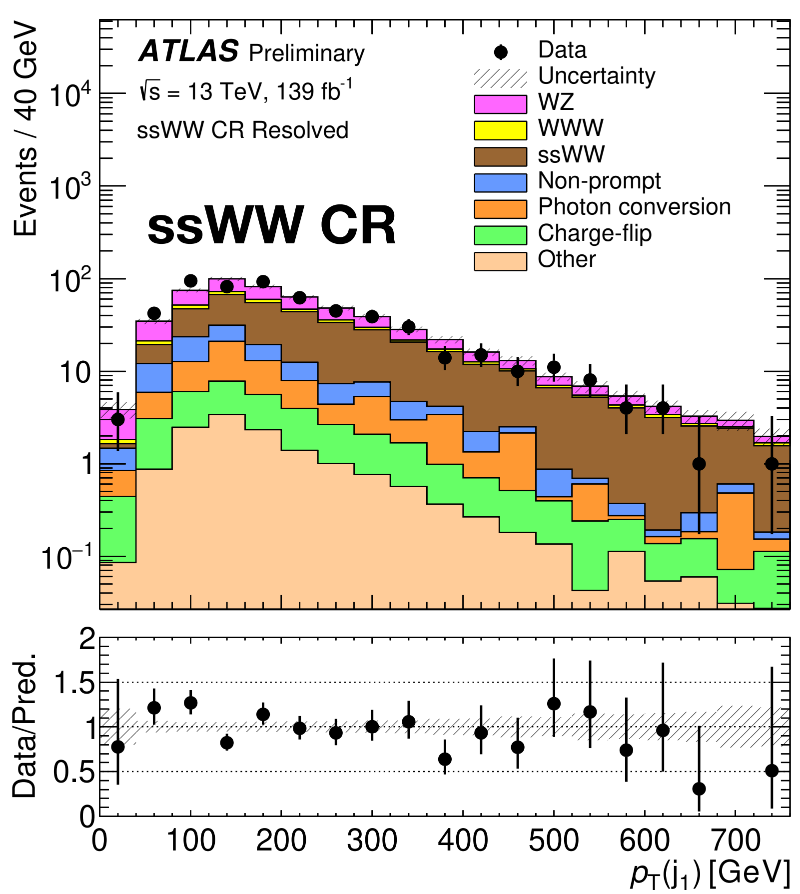
**Plots with NFs applied** **NF of X = (data - other backgrounds) / X**




$\mu_{Boosted\ WZ} = 0.93 \pm 0.07$



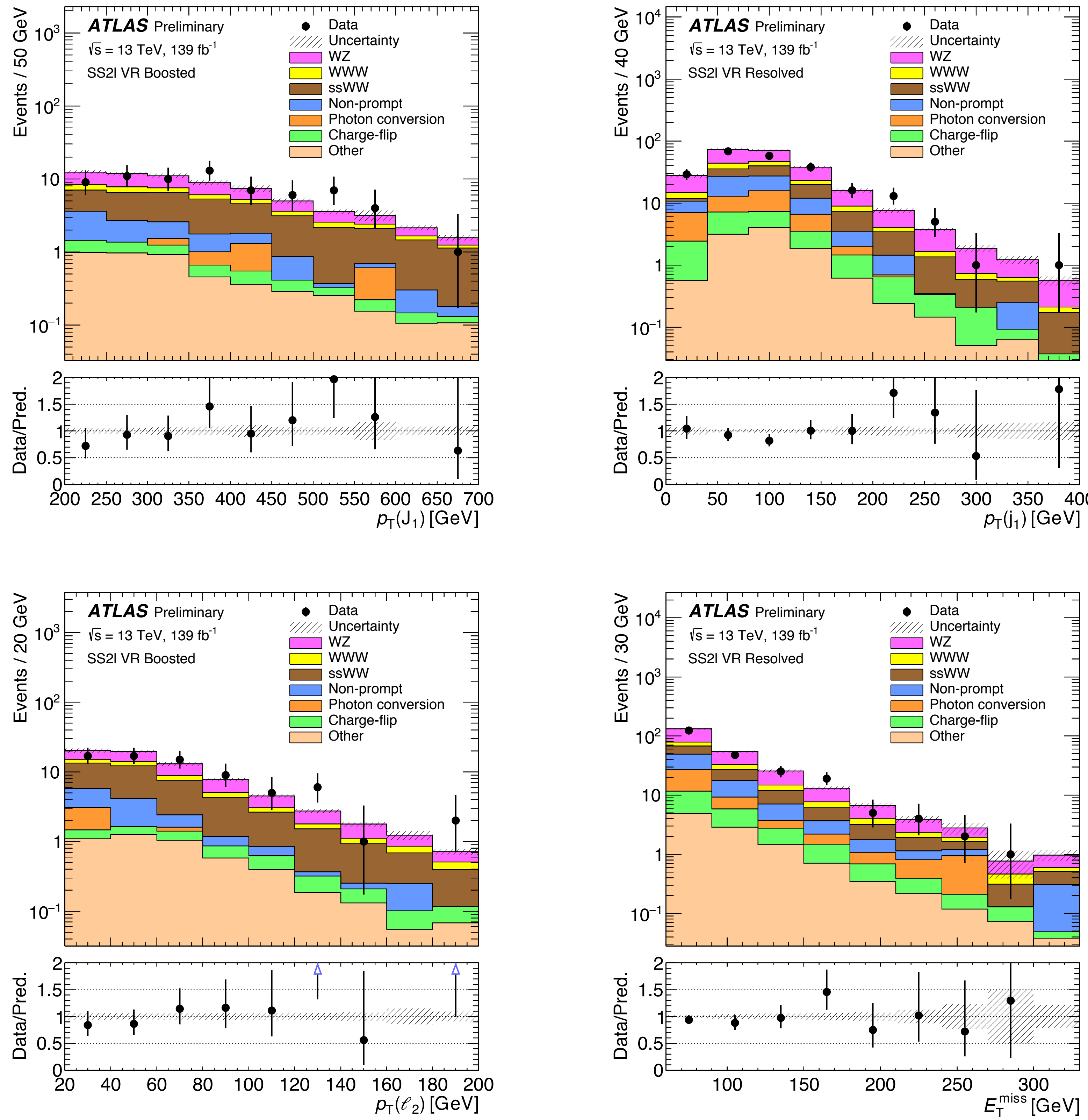

$\mu_{Resolved\ WZ} = 0.83 \pm 0.03$



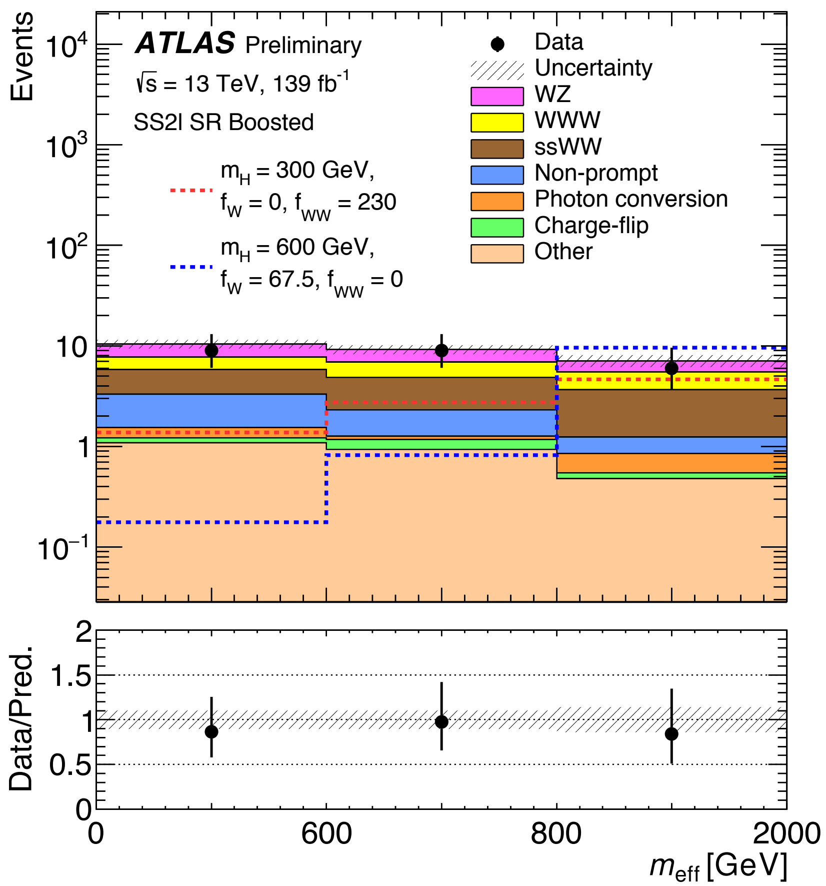

$\mu_{ssWW} = 1.54 \pm 0.20$

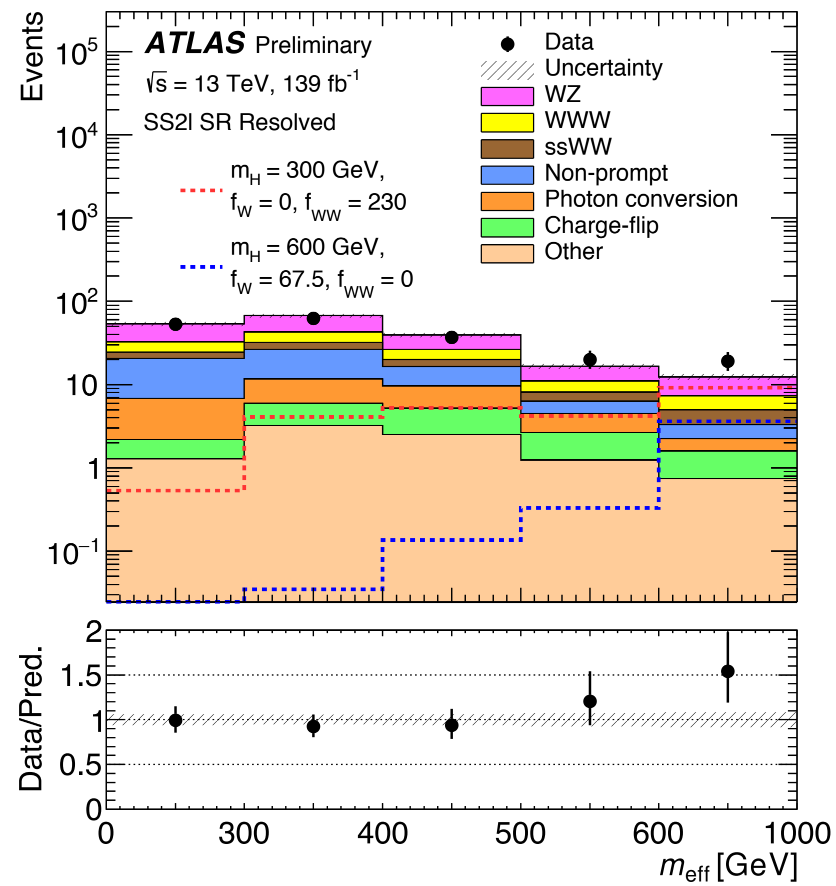
# Validation Region

- Check background estimation of ssWW, WZ and WWW.
- Data-driven backgrounds and NFs are applied



# Fit results in signal region




| **Yields** | Boosted SR | Resolved SR |
|---|---|---|
| Observed events | 24 | 191 |
| Fitted bkg events | $26.8 \pm 2.7$ | $189.0 \pm 7.8$ |
| $WWW$ | $5.8 \pm 1.0$ | $30.4 \pm 2.9$ |
| $ssWW$ | $7.5 \pm 2.3$ | $16.5 \pm 1.9$ |
| $WZ$ | $6.71 \pm 0.76$ | $68.7 \pm 5.0$ |
| Non-prompt | $3.20 \pm 0.36$ | $39.6 \pm 6.3$ |
| Charge-flip | $0.43 \pm 0.03$ | $8.61 \pm 0.57$ |
| Photon conversion | $0.73 \pm 0.07$ | $17.2 \pm 1.7$ |
| Other | $2.50 \pm 0.45$ | $9.0 \pm 1.5$ |

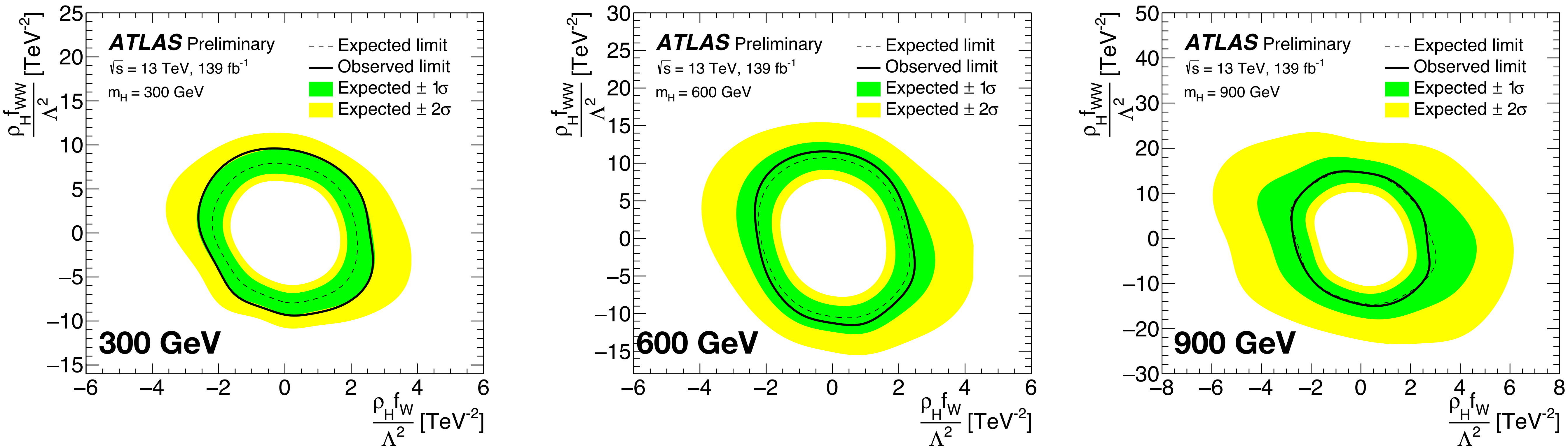
- Post-fit distributions for boosted SR and resolved SR with **background-only fit**
- ssWW is the dominant background in boosted SR, while WZ dominates the resolved SR.
- Good agreement between data and expected background.

# Systematics

- Systematics:
  - Experimental systematics: lumi, jet, muon, electron…
  - Theoretical systematics: PDF, scale, parton shower.
  - Systematics from data-driven background
- Theoretical systematics have the largest impact in boosted SR, while systematics of non-prompt background estimation have the largest impact in resolved SR.

| **Uncertainty of channel** | Boosted SR | Resolved SR |
|---|---|---|
| Total systematic uncertainties | 10.0% | 4.1% |
| Data driven non-prompt | 1.3% | 3.3% |
| Theoretical uncertainties | 8.9% | 2.6% |
| MC statistical uncertainties | 3.0% | 1.9% |
| Floating normalizations | 3.5% | 1.2% |
| Small-$R$ jet | - | 1.1% |
| Data driven photon conversion | 0.2% | 0.9% |
| $E_T^{miss}$ | 0.2% | 0.7% |
| $b$-tagging | 0.8% | 0.5% |
| Data driven charge-flip | 0.1% | 0.3% |
| Electron | 0.5% | 0.2% |
| Muon | 0.6% | 0.2% |
| Pile-up reweighting | 0.2% | 0.2% |
| Large-$R$ jet | 1.1% | 0.2% |
| $W$-tagger | 3.7% | - |

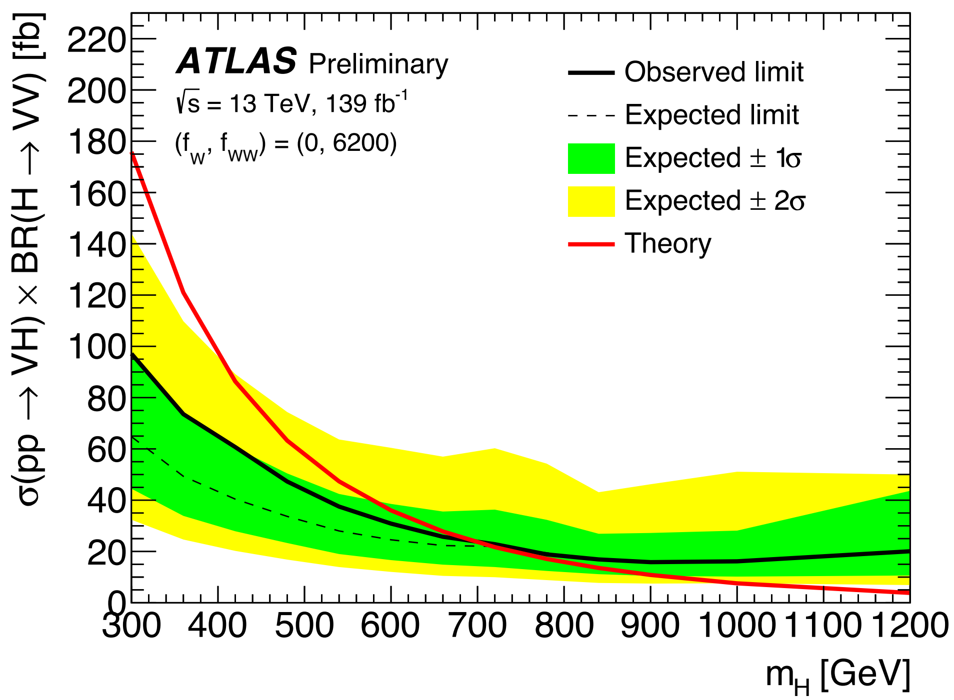
# Upper limits

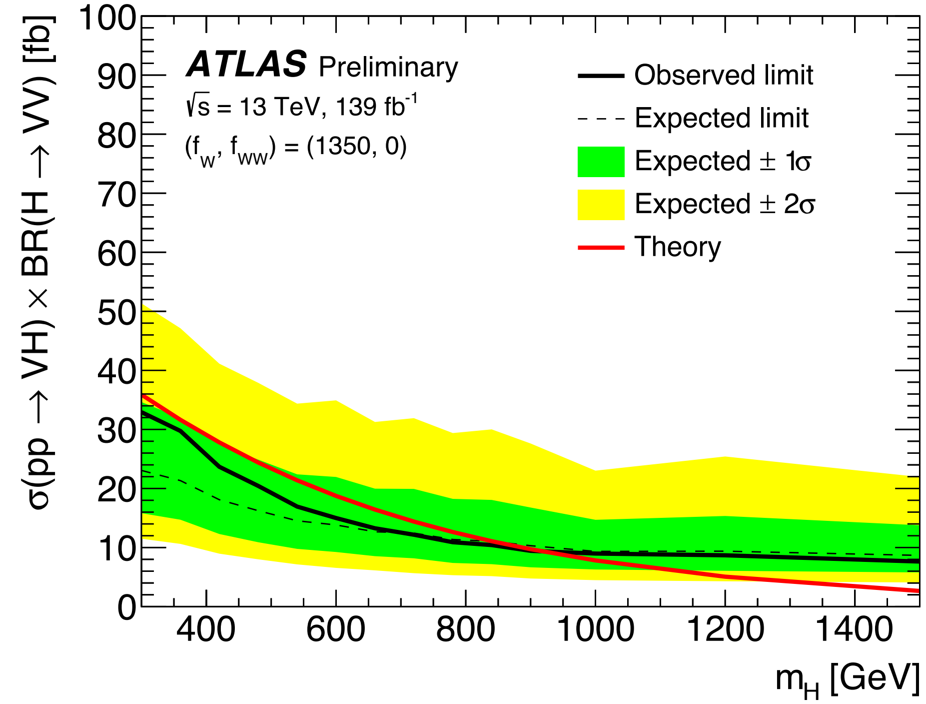



- Observed and expected exclusion contours at 95% confidence level in $(\frac{\rho_H f_W}{\Lambda^2}, \frac{\rho_H f_{WW}}{\Lambda^2})$ parameter space.
  - With $m_H$ = 300 GeV, $|\frac{\rho_H f_W}{\Lambda^2}| > 2.7$ TeV$^{-2}$ and $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 10$ TeV$^{-2}$ can be excluded.
  - With $m_H$ = 600 GeV, $|\frac{\rho_H f_W}{\Lambda^2}| > 2.5$ TeV$^{-2}$and $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 12$ TeV$^{-2}$ can be excluded.
  - With $m_H$ = 900 GeV, $|\frac{\rho_H f_W}{\Lambda^2}| > 2.9$ TeV$^{-2}$ and $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 15$ TeV$^{-2}$ can be excluded.

ATLAS-CONF-2022-033

# Upper limits




- Upper limit on heavy Higgs production (pp->VH) cross section as a function of $m_H$ at 95% confidence level with 2 set of fixed ($f_W$ , $f_{WW}$): (0, 6200) and (1350, 0).
  - With $(f_W, f_{WW})$ = (0, 6200), heavy Higgs boson with mass up to **700** GeV can be excluded, while with $(f_W, f_{WW})$ = (1350, 0), heavy Higgs boson with mass up to **900** GeV can be excluded.

**ATLAS-CONF-2022-033**

# Summary

- Good data and estimated background agreement in validation region.
- No obvious excess is observed in signal region.
- Upper limit on production cross-section as a function of heavy Higgs mass and exclusion in $(f_W, f_{WW})$ parameter space are set.

Thanks!

BACKUP

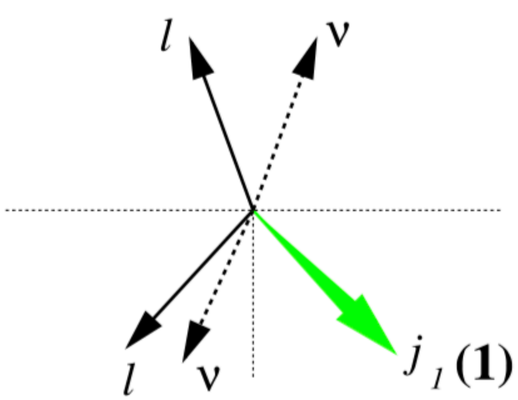
# Part I: Introduction

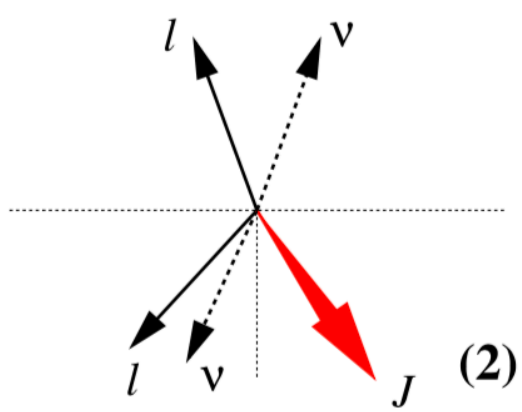
- The discovery of Higgs boson is a milestone of Standard Model (SM).
- Higgs boson may be related to new physics:
  - Precision measurement on Higgs properties
  - Search for new resonances
- Theoretical study on dim-6 operators of heavy Higgs boson from Yu-Ping Kuang
  - ggF: $pp \to t\bar{t}t\bar{t}$ Physics Letters B 747 (2015) 193-199
  - VBF: $pp \to H^* j_1^f j_2^f \to VV j_1^f j_2^f \to \ell^+ \nu_\ell j_1 j_2 j_1^f j_2^f$ Physical Review D 90, 115002 (2014)
  - VH: $pp \to VH^* \to VVV \to \ell^+ \nu_\ell j_1 j_2 j_3 j_4$ Physical Review D 90, 115002 (2014)

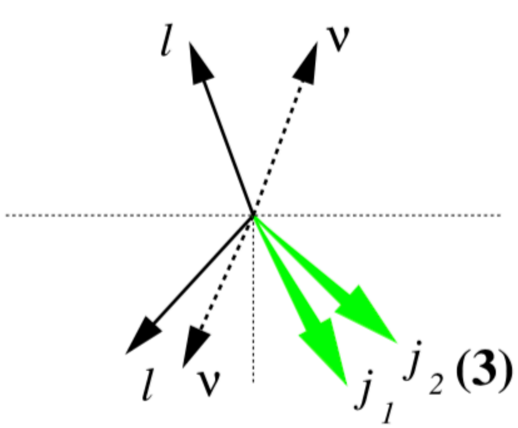
# Signal regions: SS-dilepton

- SS-dilepton region:

1. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet})$
2. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{fatjet})$
3. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet + jet})$




| region (1) | region (2) |
|---|---|
| $m_{\ell\ell} > 300$ GeV, $p_T^{\ell\ell} > 100$ GeV, $p_T^{\ell_1} > 300$ GeV, $p_T^{\ell_2} > 50$ GeV, $\Delta\phi_{\ell\ell} > 2.0$, $E_T^{\text{miss}} > 100$ GeV, no $b$-tagged jets | |
| $p_T^{j_1} > 400$ GeV | $p_T^{J} > 100$ GeV, $\tau_2^J/\tau_1^J < 0.6$ |

| region (3) |
|---|
| $m_{\ell\ell} > 400$ GeV, $p_T^{\ell\ell} > 100$ GeV, $p_T^{\ell_1} > 450$ GeV, $p_T^{\ell_2} > 50$ GeV, $\Delta\phi_{\ell\ell} > 1.6$, $E_T^{\text{miss}} > 100$ GeV |

**large-R jet (fatjet)**
**small-R jet**

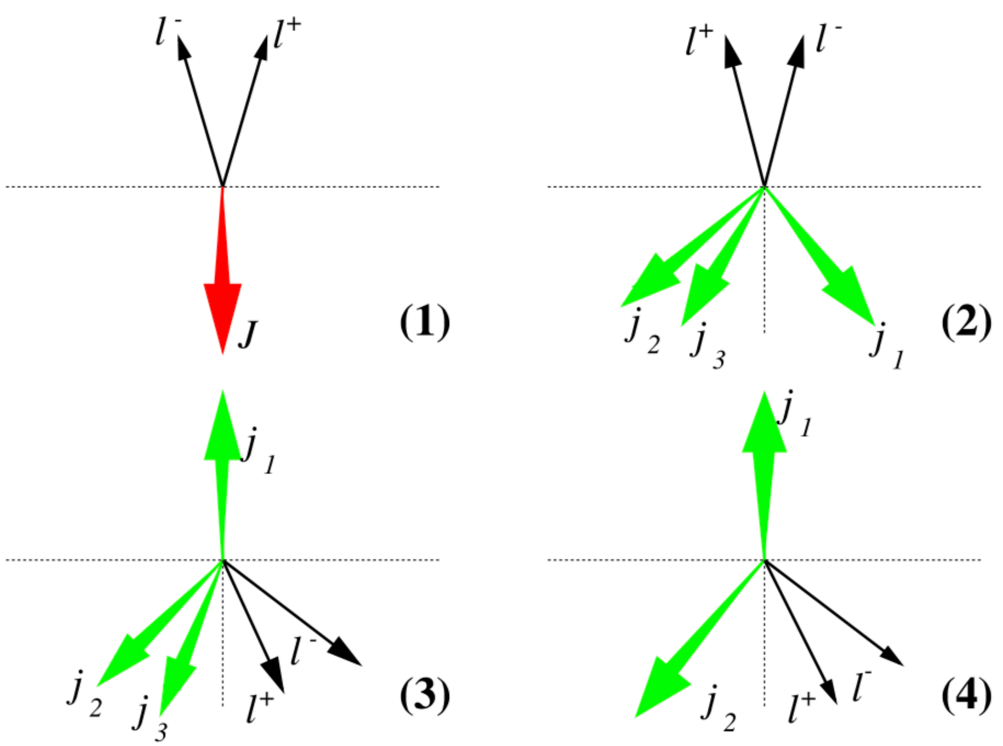
# Signal regions: OS-dilepton

- OS-dilepton region:

  1. $V_0H \to l^-l^+ + V_1$(subjet of leading fatjet)$V_2$(subjet of leading fatjet)
  2. $V_0H \to l^-l^+ + V_1(\text{jet})V_2(\text{jet + jet})$
  3. $V_0H \to \text{jet} + V_1(l^-l^+)V_2(\text{jet + jet})$
  4. $V_0H \to \text{jet} + V_1(l^-l^+)V_2(\text{jet})$

| region (1) | region (2) |
|---|---|
| $80\text{ GeV} < m_{\ell\ell} < 100\text{ GeV}$ | |
| $p_T^{\ell\ell} > 950$ GeV,<br>$p_T^J > 750$ GeV,<br>$N_{sj} = 2$,<br>$70\text{ GeV} < m_{sj_{1,2}} < 150$ GeV,<br>$\tau_2^J/\tau_1^J < 0.45$ | $p_T^{\ell\ell} > 550$ GeV,<br>$p_T^{j_1} > 300$ GeV,<br>$70\text{ GeV} < m_{j_1} < 150$ GeV,<br>$\tau_2^{j_1}/\tau_1^{j_1} < 0.40$,<br>$70\text{ GeV} < m_{j_{23}} < 110$ GeV,<br>$p_T^{j_{23}} > 150$ GeV,<br>$\Delta R(j_1, j_{23}) < \Delta R(\ell\ell, j_1)$,<br>$\Delta R(j_1, j_{23}) < \Delta R(\ell\ell, j_{23})$,<br>$p_T^{j_1+j_{23}} > 550$ GeV |

| region (3) | region (4) |
|---|---|
| $80\text{ GeV} < m_{\ell\ell} < 100\text{ GeV}$, $p_T^{\ell\ell} > 300$ GeV,<br>$p_T^{j_1} > 700$ GeV, $70\text{ GeV} < m_{j_1} < 150$ GeV | |
| $\tau_2^{j_1}/\tau_1^{j_1} < 0.60$,<br>$75\text{ GeV} < m_{j_{23}} < 115$ GeV,<br>$p_T^{j_{23}} > 50$ GeV,<br>$\Delta R(\ell\ell, j_{23}) < \Delta R(j_1, \ell\ell)$,<br>$\Delta R(\ell\ell, j_{23}) < \Delta R(j_1, j_{23})$,<br>$p_T^{\ell\ell+j_{23}} > 700$ GeV | $\tau_2^{j_1}/\tau_1^{j_1} < 0.52$,<br>$p_T^{j_2} > 250$ GeV,<br>$70\text{ GeV} < m_{j_2} < 150$ GeV,<br>$\tau_2^{j_2}/\tau_1^{j_2} < 0.52$,<br>$\Delta R(\ell\ell, j_2) < \Delta R(j_1, \ell\ell)$,<br>$\Delta R(\ell\ell, j_2) < \Delta R(j_1, j_2)$,<br>$p_T^{\ell\ell+j_2} > 700$ GeV |

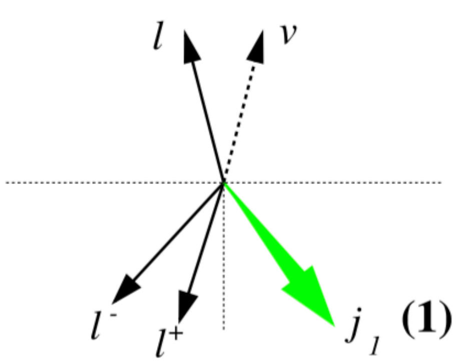


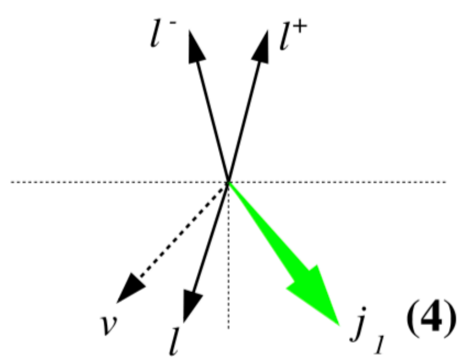
# Signal regions: Trilepton

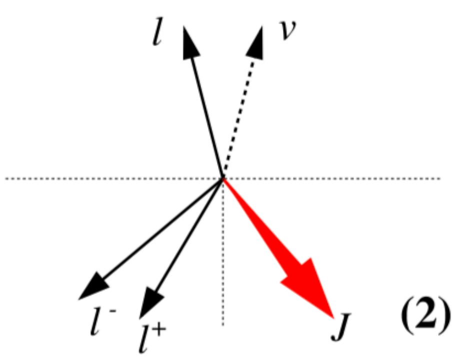
- Trilepton region:

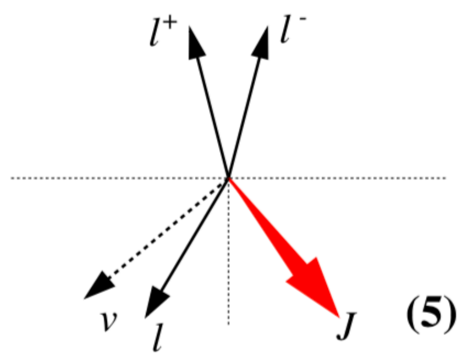
  1. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{jet})$
  2. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{fatjet})$
  3. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{jet + jet})$
  4. $V_0 H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet})$
  5. $V_0 H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{fatjet})$
  6. $V_0 H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet + jet})$

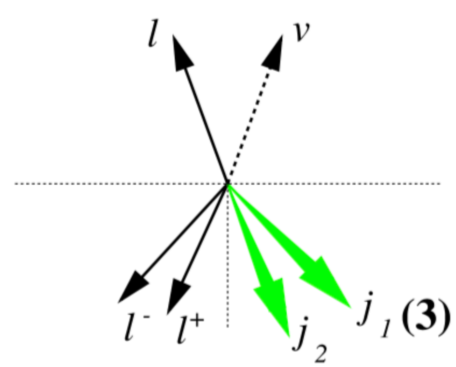
| region (1) | region (4) |
|---|---|
| $p_T^{\ell\nu} > 600$ GeV | $p_T^{\ell\ell} > 600$ GeV |
| 80 GeV $< m_{\ell\ell} <$ 100 GeV, 60 GeV $< m_{j_1} <$ 160 GeV, $\tau_2^{j_1}/\tau_1^{j_1} < 0.60$ | |
| $\Delta R(\ell\ell, j_1) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, j_1) < \Delta R(\ell\nu, j_1)$, $p_T^{\ell\ell+j_1} > 600$ GeV | $\Delta R(\ell\nu, j_1) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, j_1) < \Delta R(\ell\ell, j_1)$, $p_T^{\ell\nu+j_1} > 600$ GeV |
| **region (2)** | **region (5)** |
| $p_T^{\ell\nu} > 600$ GeV | $p_T^{\ell\ell} > 600$ GeV |
| 80 GeV $< m_{\ell\ell} <$ 100 GeV, 70 GeV $< m_J <$ 140 GeV, $\tau_2^J/\tau_1^J < 0.50$ | |
| $\Delta R(\ell\ell, J) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, J) < \Delta R(\ell\nu, J)$, $p_T^{\ell\ell+J} > 600$ GeV | $\Delta R(\ell\nu, J) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, J) < \Delta R(\ell\ell, J)$, $p_T^{\ell\nu+J} > 600$ GeV |
| **region (3)** | **region (6)** |
| $p_T^{\ell\nu} > 600$ GeV | $p_T^{\ell\ell} > 600$ GeV |
| 80 GeV $< m_{\ell\ell} <$ 100 GeV, 60 GeV $< m_{j_{12}} <$ 120 GeV | |
| $\Delta R(\ell\ell, j_{12}) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, j_{12}) < \Delta R(\ell\nu, j_{12})$, $p_T^{\ell\ell+j_{12}} > 600$ GeV | $\Delta R(\ell\nu, j_{12}) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, j_{12}) < \Delta R(\ell\ell, j_{12})$, $p_T^{\ell\nu+j_{12}} > 600$ GeV |

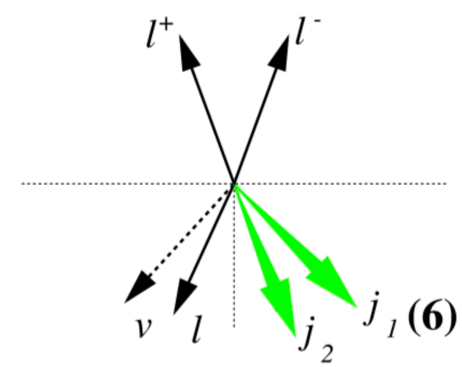






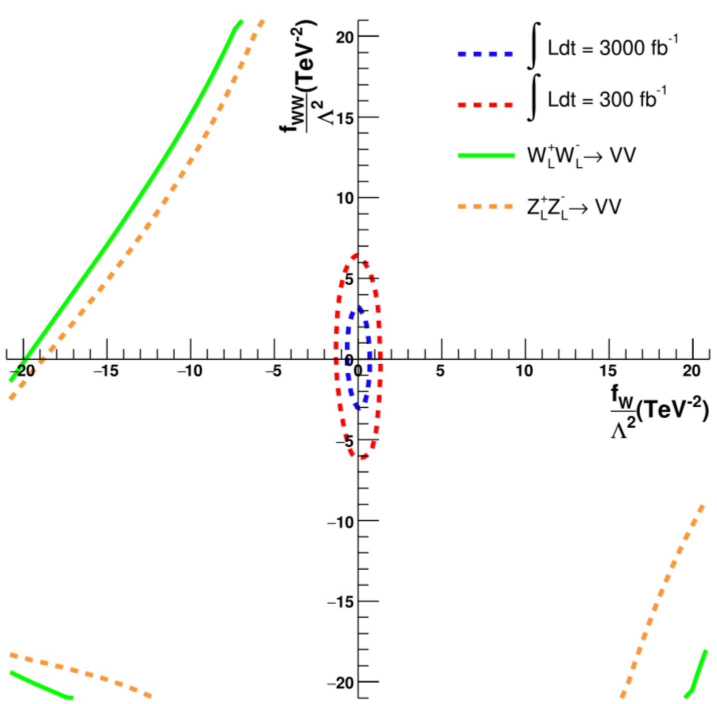




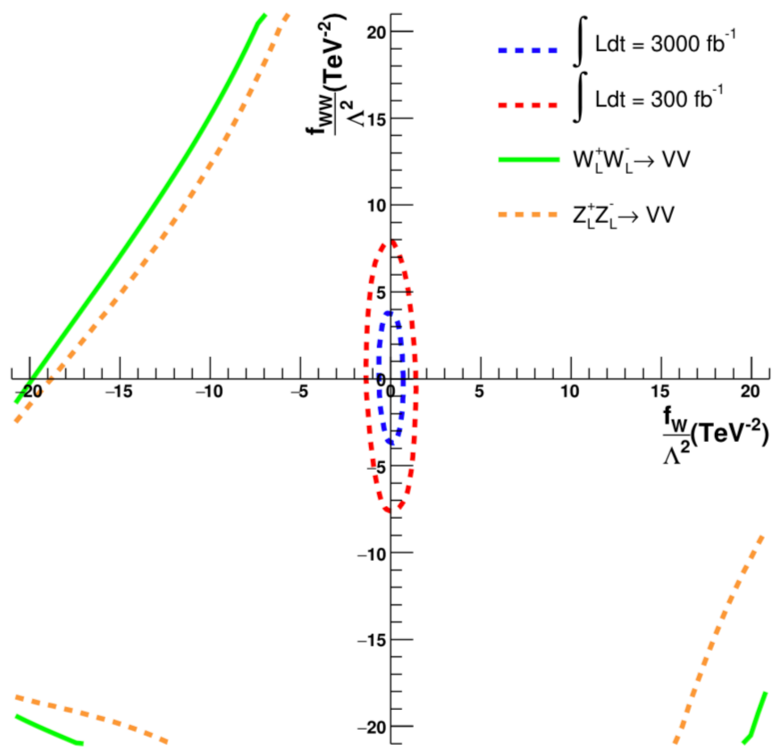


# 95% Confidence Level Exclusion

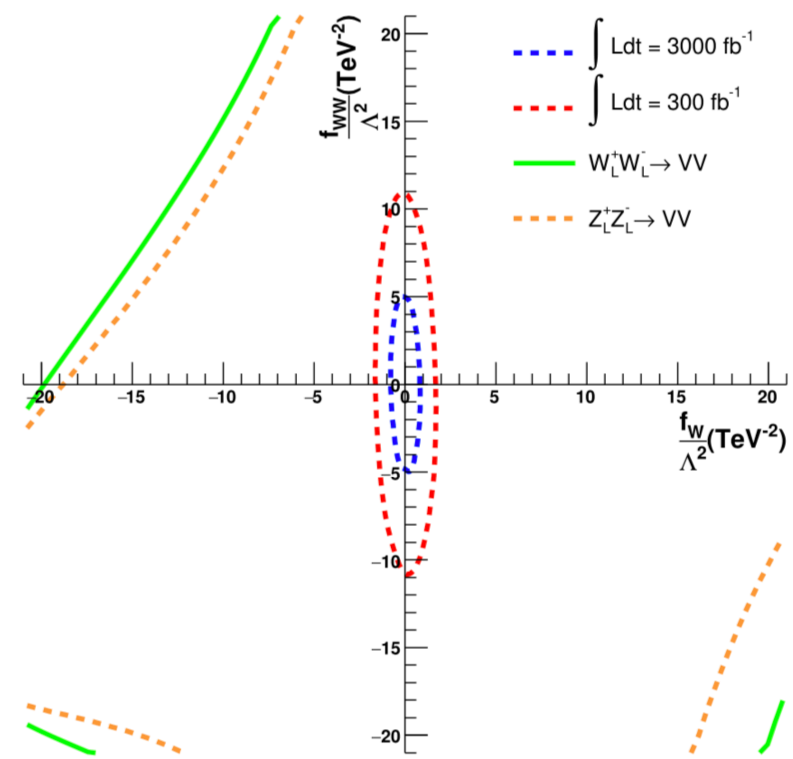
- Take $\rho_h = 1$ and $\rho_H = 0.05$ as benchmark value.
- Get CLs of each parameter point by “template” fits with a large quantity of toy experiments.
- Unitarity bound: $|S^{\dagger}S| = 1$
    - Areas within the unitarity bound are allowed by theory.
- Areas outside the exclusion contours can be excluded.




300 GeV




600 GeV

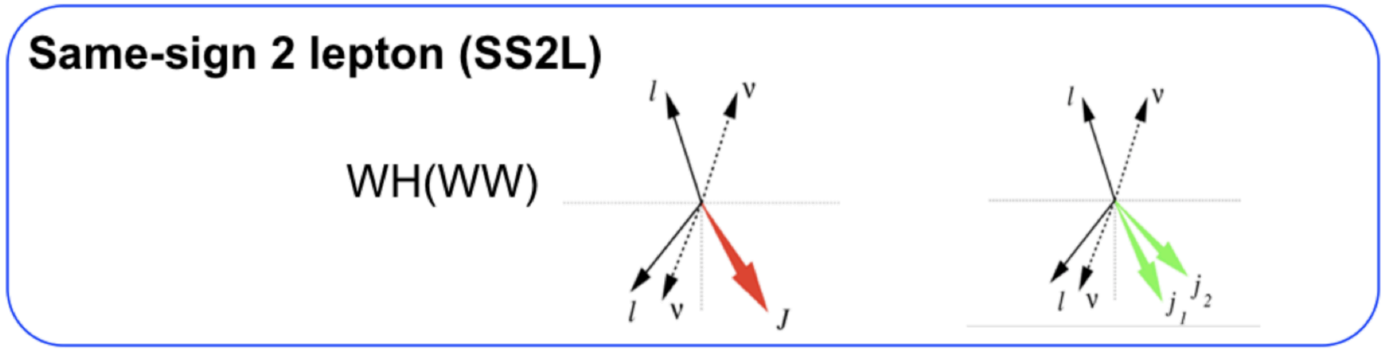



900 GeV

PLB 804 (2020) 135358

# Analysis strategy and selections

- Signal signature: two same-sign leptons (e or μ) in association with one large-R jet (J) or two small-R jets (j), and $E_T^{\text{miss}}$.




- **Boosted SR**: leading large-R jet passing LCTopo W-tagger
- **Resolved SR**: invariant mass of two leading small-R jets consistent with a hadronically decaying W-boson

**Observable:** $M_{eff} = \sum p_T^{\text{Lepton}} + \sum p_T^{\text{V-jets}} + E_T^{\text{miss}}$

- Dominant Backgrounds:
  - **WZ** and same-sign WW (**ssWW**): MC driven with normalisation from data using dedicated CRs.
  - **WWW** : MC driven
  - **Non-prompt**: data driven

| **Selections** | Boosted SR | Resolved SR | *ssWW* CR | Boosted *WZ* CR | Resolved *WZ* CR |
|---|---|---|---|---|---|
| Trigger | Single lepton | | | | |
| Leptons | two same-sign leptons with $p_T > 27, 20$ GeV | | | three leptons with $p_T > 27, 20, 20$ GeV at least one SFOS lepton pair | |
| | zero additional veto leptons | | | | |
| $m_{\ell\ell}$ | $> 100$ GeV | | | - | |
| $m_{\ell\ell\ell}$ | - | | | $> 100$ GeV | |
| $b$-jets | zero $b$-tagged small-$R$ jets | | | | |
| $E_T^{\text{miss}}$ | $> 80$ GeV | $> 60$ GeV | $> 40$ GeV | | |
| Large-$R$ jets | at least one large-$R$ jet with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$ 50 GeV $< m_J <$ 200 GeV and pass 80% $W$-tagger WP | zero large-$R$ jets with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$ 50 GeV $< m_J <$ 200 GeV | | at least one large-$R$ jet with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$ 50 GeV $< m_J <$ 200 GeV and pass 80% $W$-tagger WP | zero large-$R$ jets with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$ 50 GeV $< m_J <$ 200 GeV |
| Small-$R$ jets | - | at least two small-$R$ jets with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$ | | - | at least two small-$R$ jets with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$ |
| $m_{jj}$ | - | 50 GeV $< m_{jj} <$ 110 GeV | $> 200$ GeV | - | - |

# Event selections

| **Selections** | Boosted SR | Resolved SR | *ssWW* CR | Boosted *WZ* CR | Resolved *WZ* CR |
|---|---|---|---|---|---|
| Trigger | Single lepton | | | | |
| Leptons | two same-sign leptons with $p_{\mathrm{T}} > 27, 20$ GeV<br>zero additional veto leptons | | | three leptons with $p_{\mathrm{T}} > 27, 20, 20$ GeV<br>at least one SFOS lepton pair | |
| $m_{\ell\ell}$ | $> 100$ GeV | | | - | |
| $m_{\ell\ell\ell}$ | - | | | $> 100$ GeV | |
| $b$-jets | zero $b$-tagged small-$R$ jets | | | | |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | $> 80$ GeV | $> 60$ GeV | $> 40$ GeV | | |
| Large-$R$ jets | at least one large-$R$ jet with<br>$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$<br>50 GeV $< m_J <$ 200 GeV<br>and pass 80% $W$-tagger WP | zero large-$R$ jets with<br>$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$<br>50 GeV $< m_J <$ 200 GeV | | at least one large-$R$ jet with<br>$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$<br>50 GeV $< m_J <$ 200 GeV<br>and pass 80% $W$-tagger WP | zero large-$R$ jets with<br>$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$<br>50 GeV $< m_J <$ 200 GeV |
| Small-$R$ jets | - | at least two small-$R$ jets with<br>$p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$ | | - | at least two small-$R$ jets with<br>$p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$ |
| $m_{jj}$ | - | 50 GeV $< m_{jj} <$ 110 GeV | $> 200$ GeV | - | - |

# Yields

| **Yields** | Boosted SR | Resolved SR | Boosted $WZ$ CR | Resolved $WZ$ CR | $ssWW$ CR |
|---|---|---|---|---|---|
| Observed events | 24 | 191 | 236 | 2094 | 567 |
| Fitted bkg events | 26.8 ± 2.7 | 189.0 ± 7.8 | 235 ± 15 | 2095 ± 46 | 566 ± 24 |
| $WWW$ | 5.8 ± 1.0 | 30.4 ± 2.9 | 1.30 ± 0.31 | 11.2 ± 2.1 | 28.5 ± 5.5 |
| $ssWW$ | 7.5 ± 2.3 | 16.5 ± 1.9 | – | – | 254 ± 27 |
| $WZ$ | 6.71 ± 0.76 | 68.7 ± 5.0 | 221 ± 15 | 1956 ± 50 | 150.6 ± 5.7 |
| Non-prompt | 3.20 ± 0.36 | 39.6 ± 6.3 | – | – | 48.6 ± 8.8 |
| Charge-flip | 0.43 ± 0.03 | 8.61 ± 0.57 | – | – | 22.8 ± 1.3 |
| Photon conversion | 0.73 ± 0.07 | 17.2 ± 1.7 | – | – | 46.7 ± 4.7 |
| Other | 2.50 ± 0.45 | 9.0 ± 1.5 | 12.3 ± 1.6 | 130 ± 20 | 14.3 ± 2.0 |

# Systematics

| **Uncertainty of channel** | Boosted SR | Resolved SR |
|---|---|---|
| Total systematic uncertainties | 10.0% | 4.1% |
| Data driven non-prompt | 1.3% | 3.3% |
| Theoretical uncertainties | 8.9% | 2.6% |
| MC statistical uncertainties | 3.0% | 1.9% |
| Floating normalizations | 3.5% | 1.2% |
| Small-$R$ jet | - | 1.1% |
| Data driven photon conversion | 0.2% | 0.9% |
| $E_T^{miss}$ | 0.2% | 0.7% |
| $b$-tagging | 0.8% | 0.5% |
| Data driven charge-flip | 0.1% | 0.3% |
| Electron | 0.5% | 0.2% |
| Muon | 0.6% | 0.2% |
| Pile-up reweighting | 0.2% | 0.2% |
| Large-$R$ jet | 1.1% | 0.2% |
| $W$-tagger | 3.7% | - |