17th Workshop of the

FCPPN/L

France-China Particle Physics Network and Laboratory

Lyon, France •

# Searches for VBS WWγ and non-resonant Higgs boson pair production in the WWZZ final state


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# Searches for VBS WWγ @ 13 TeV

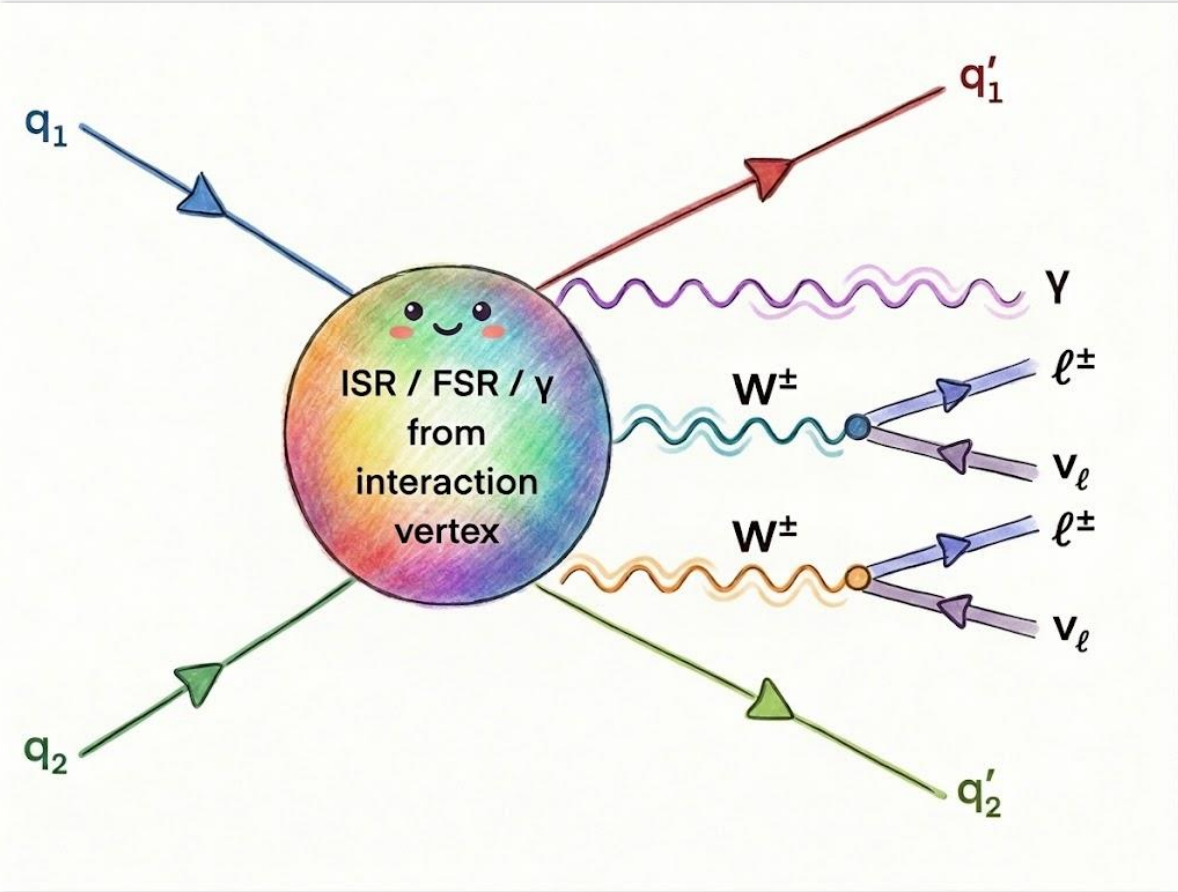
## Motivation for the SM measurement

- **Search for process with:**

  **The first 2→3 VBS tri-boson process！**

- **Signal processes:**
  - $p\ p\ \rightarrow \ell\ \ell\ \upsilon_\ell \upsilon_\ell\ j\ j\ \gamma$ QCD = 0 (the EWK process)

    cross-section:0.001969+-3.871e-06pb

# Motivation for the Doubly Charged Higgs

## First search through a new decay channel!

## Model: Georgi-Machacek Model

- HIG-20-017: "The H5 states are fermiophobic and are assumed to decay to vector boson pairs with a branching fraction of 100%"

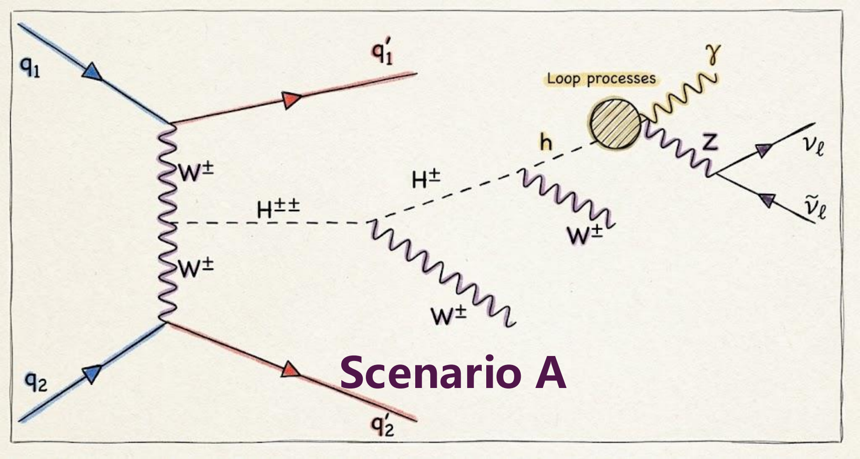
Different

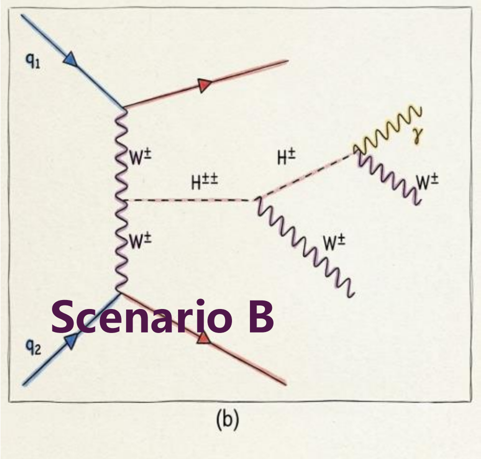
$H_5^{\pm\pm} \rightarrow H_3^{\pm} + W^{\pm}$(high Branch ratio)

Physics Impact:

- Constrains triplet-based electroweak models.
- Implications for neutrino mass mechanisms and future collider searches.

| Collaboration | channel | publication | Luminosity and energy |
|---|---|---|---|
| CMS | Drell–Yan pair production: $H_5^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ | Eur. Phys. J. C 72 (2012) 2189 | 4.9fb$^{-1}$, 7TeV |
| CMS | VBF: $H_5^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ | Eur. Phys. J. C 81 (2021) 723 | 137fb$^{-1}$, 13TeV |
| ATLAS | VBF: $H_5^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ | Phys. Lett. B 860 (2025) 139137 | 140fb$^{-1}$, 13TeV |
| ATLAS | Drell–Yan pair production: $H_5^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ | Eur. Phys. J C 83 (2023) 605 | 139fb$^{-1}$, 13TeV |



(b)

# Georgi-Machacek Model

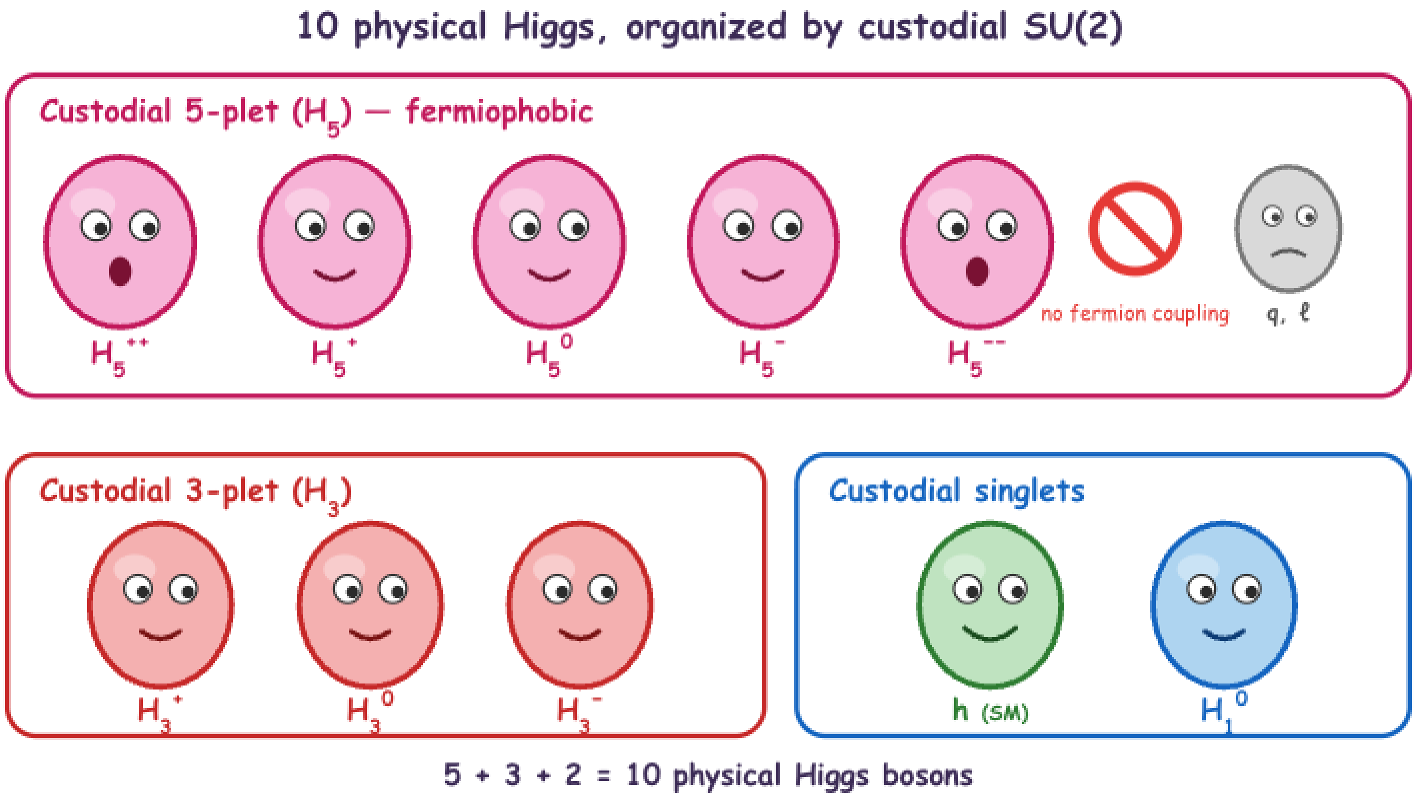
- 1985 Georgi-Machacek (GM) model – expands Higgs sector:
  - Adds one real scalar triplet and one complex scalar triplet to the Standard Model
  - custodial $SU(2)_L \times SU(2)_R$ symmetry
  - Preserves tree-level:
    - ρ = M_W² / (M_Z² cos²θ_W) = 1.

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

- ➢ The quintuplet states are **fermiophobic**: no fermion couplings.
- ➢ simple benchmark parameter scan:
  - ➢ Change the parameters: $M_{1coeff}$, $M_{2coeff}$

$$M_{H^\pm} = \sqrt{v^2\left(\frac{\lambda_5}{2} + \frac{M1coeff}{4v_\chi}\right)}$$

$$M_{H^{\pm\pm}} = \sqrt{12M2coeff \times v_\chi + 8\lambda_3 v_\chi^2 + \frac{3\lambda_5 v_\phi^2}{2} + \frac{M1coeff \times v_\phi^2}{4v_\chi}}$$



# Analysis Strategy (SM&BSM)

## Backgrounds:

- Z+jets, W+jets: fake lepton calculation.
- WZ, ZZ To 4L: di-boson and electron-misidentified as photon.
- VBS_WZ, VBS_ZZ: VBS di-boson category.
- tZQ, $t\tilde{t}\gamma$ +jets: related to top.
- SSWW: fake photon estimation.

| variables | selections |
|---|---|
| The number of jets | >=2 |
| The number of leptons | ==2 |
| The number of photon | >=1 |
| Lepton charge | The same sign |
| zeppenfeld | <0.75 |
| $\lvert M_{\ell\gamma} - M_Z \rvert$ | > 10 GeV |
| Bjets (btagDeepFlavB>btag_medium_WP) | ==0 |

Zeppenfeld $\dfrac{\left|\eta_l - \frac{\eta_{j1}+\eta_{j2}}{2}\right|}{\left|\eta_{j1}-\eta_{j2}\right|}$

$\ell = \ell_1, \ell_2$

| | Region 0 | Region 1 | Region 2 | Region 3 | Region 4 | Region 5 | Region 6 |
|---|---|---|---|---|---|---|---|
| tight leptons | 2 | 0 | 1 | 2 | 2 | 2 | |
| loose leptons | | 2 | 2 | | | | |
| tight photons | ≥1 | ≥1 | ≥1 | 0 | 0 | 0 | |
| fail IsoCharge photons | | | | ≥1 | 0 | 0 | |
| fail $\sigma_{i\eta i\eta}$ photons | | | | 0 | ≥1 | 0 | |
| fail both Isoch and $\sigma_{i\eta i\eta}$ photons | | | | | | ≥1 | |

- Region 0: SR region+CR region (separated in BDT score distribution)
- Region 1 and Region 2: fake leptons estimation
- Region 3, 4, and 5: fake photon evaluations (not used here)
- Region 6: satisfy pre-selections and fail the selections for region 0~5.

# Analysis Strategy---BDT (SM&BSM)

| variables | selections |
|---|---|
| MET Filters | True |
| $M_{jj}$ | > 100 GeV |
| $p_{T,l1}$ | > 30 GeV |
| $p_{T,l2}$ | > 30 GeV |

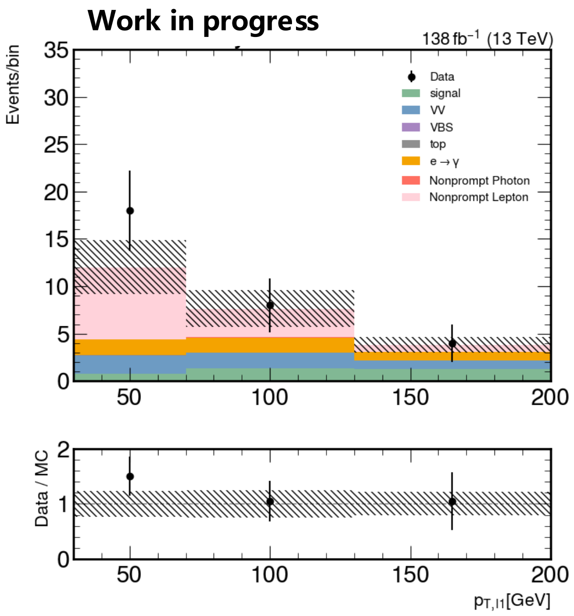
**BDT Training Setup**

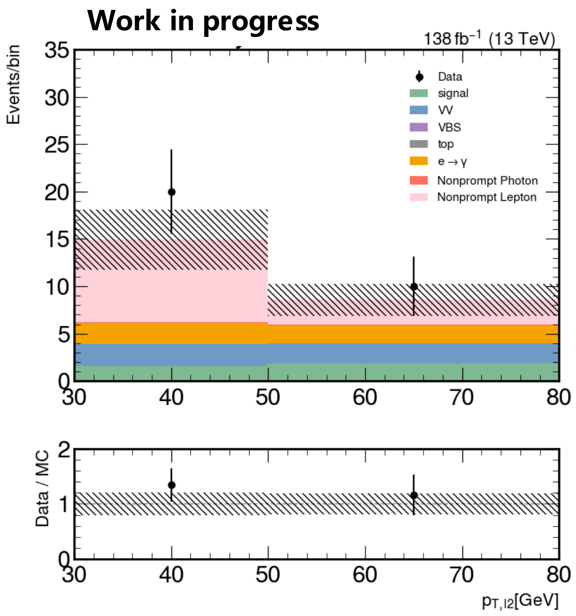
- Signal: Region 0
- Background :
  - Regions 0
  - Including opposite-sign lepton charge samples
- Input Variables (features): $p_{T,jj}, p_{J1}, p_{J2}, m_{\ell\ell}, p_{T,\ell 1}, p_{T,\ell 2}, \eta_{\ell 1}, \eta_{\ell 2}, \phi_{\ell 1}, \phi_{\ell 2}, MET, LT, m_{jj}, \Delta R_{jj},$ $|\Delta\eta_{jj}|,\ \Delta R_{\ell\ell}, |\Delta\eta_{\ell\ell}|, p_{T,\gamma}, \eta_{\gamma}, \phi_{\gamma}, zeppenfeld,\ p_{T,\ell\ell}$

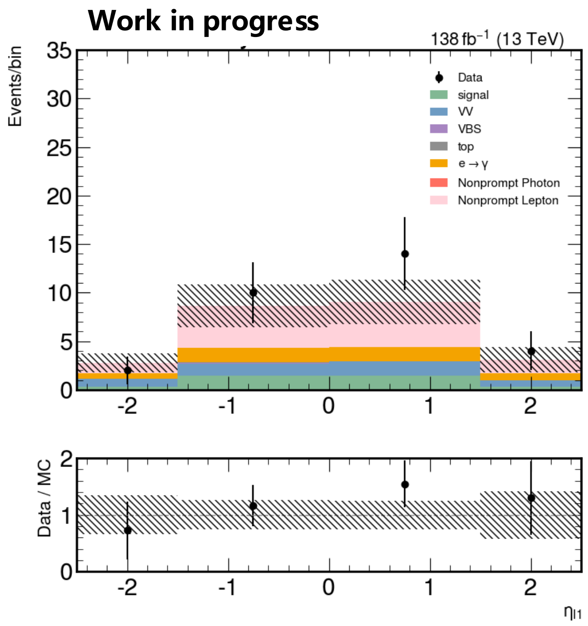
**Details:**

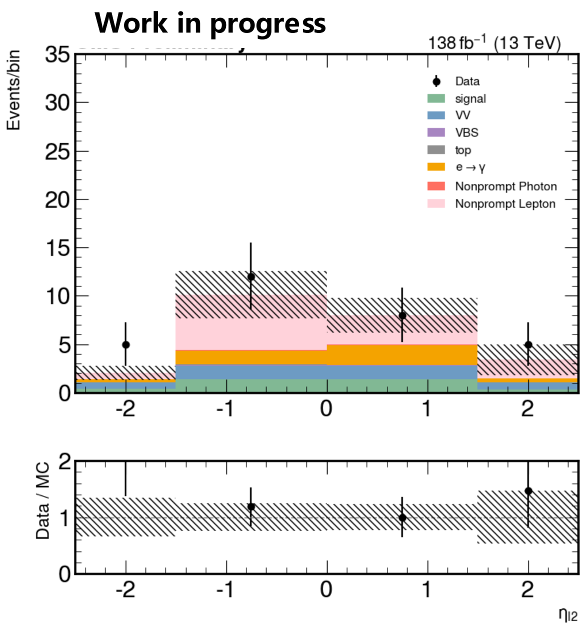
- Training:Test = 2:1
- Signal and background training weights normalized to same total weight
- Model:

XGBRegressor
(n_estimators=800, learning_rate=0.1, max_depth=3, gamma=0.05)



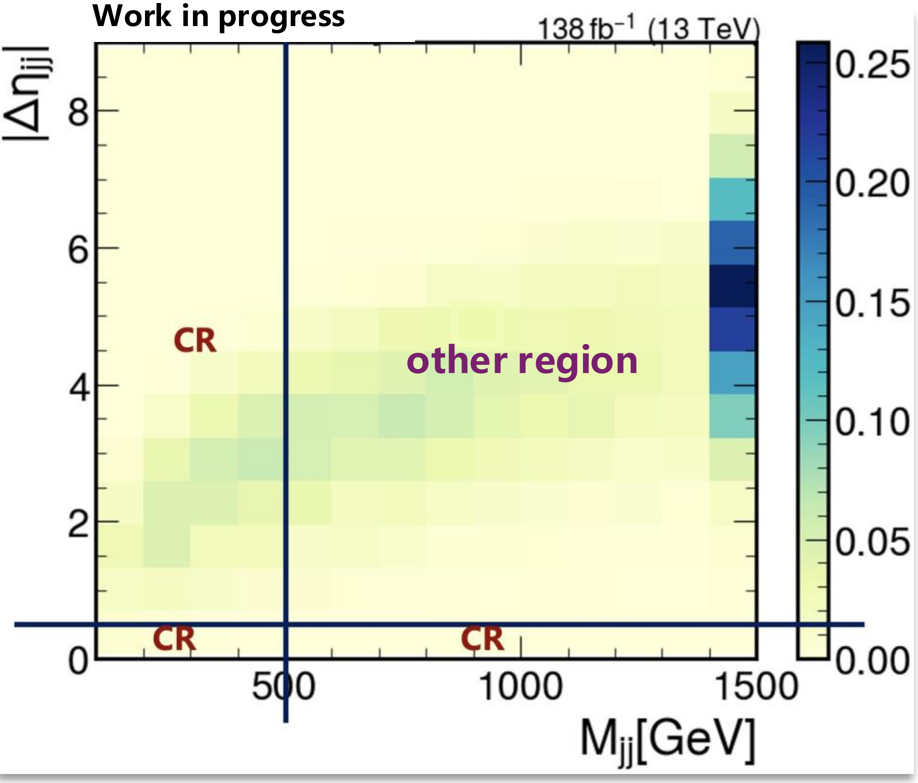



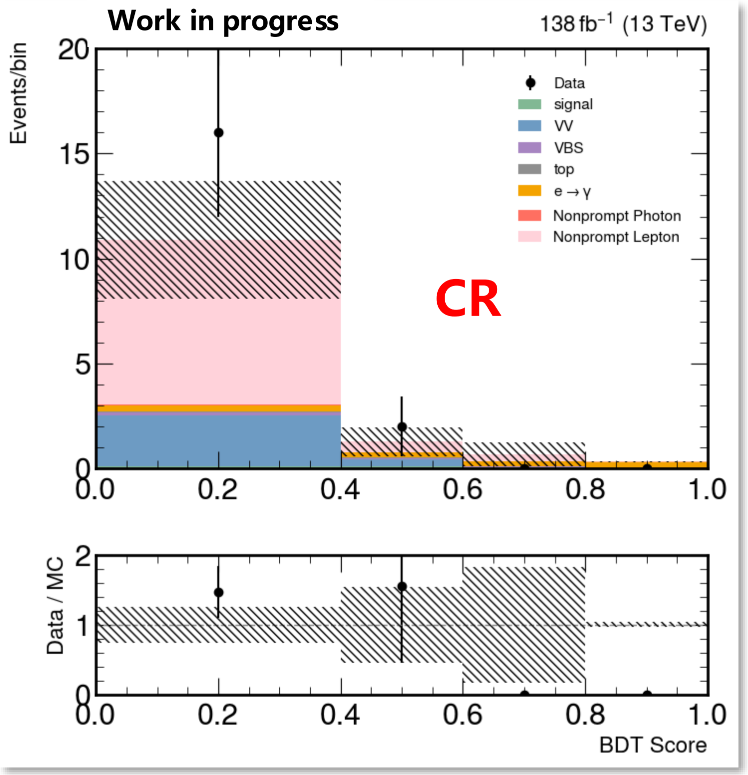



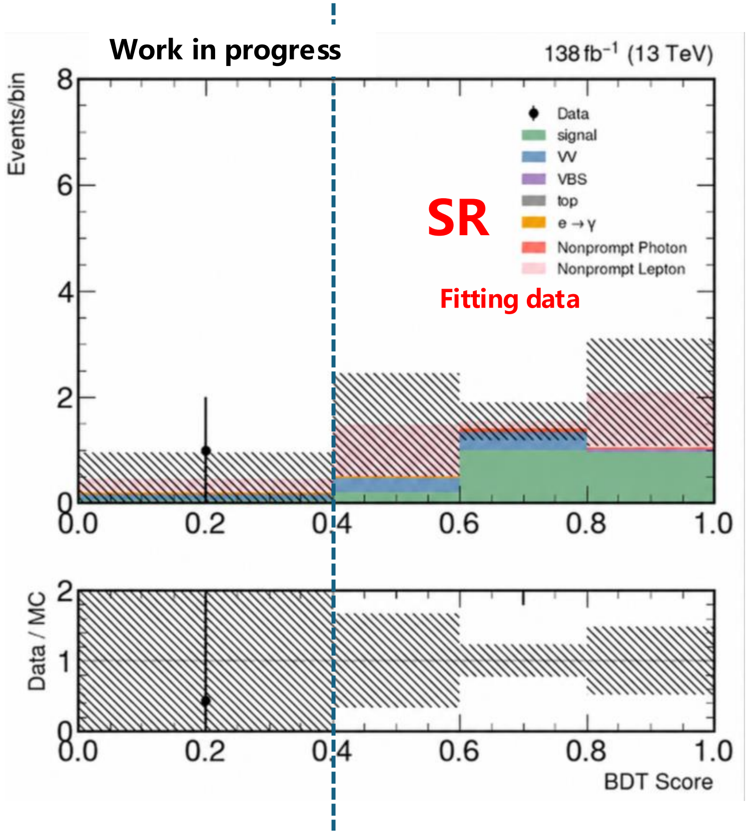



# Signal extraction---SM

## 2D plot for signal in the region 0




**The signal region (SR) is defined as region 0 with two additional cuts:**

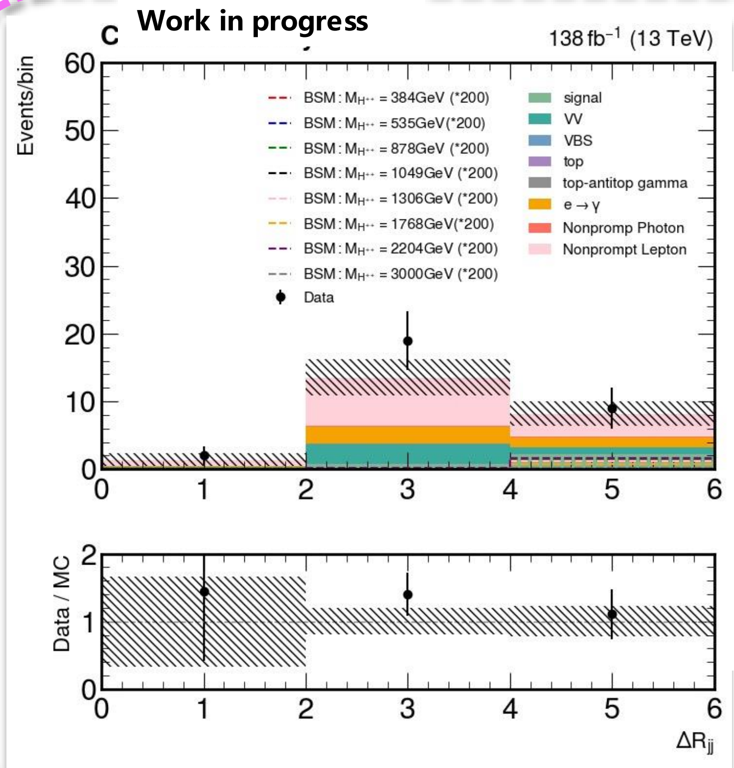
- $M_{jj} > 500$ **GeV**
- $\Delta\eta_{jj} > 0.5$
- **Counting experiment in three bins: BDT score > 0.4**

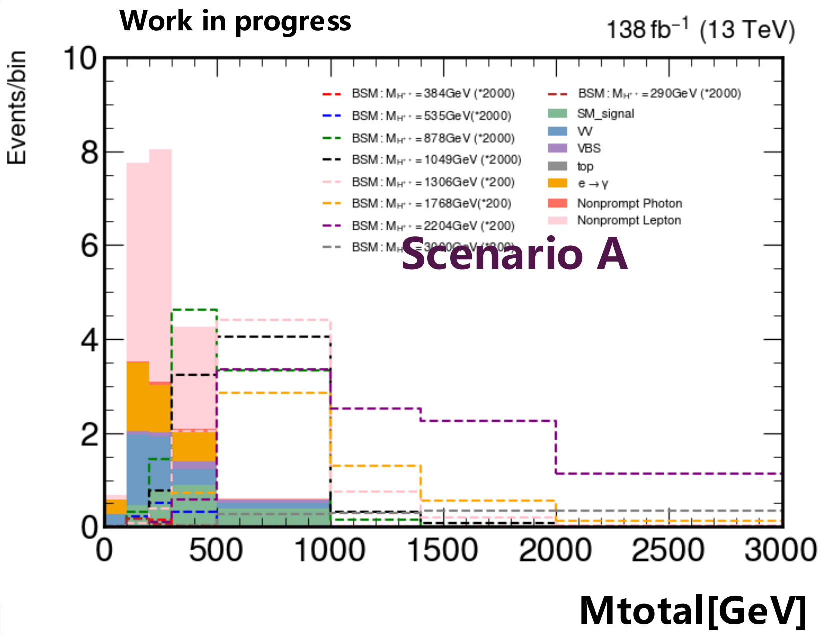
# Signal extraction---Doubly Charged Higgs

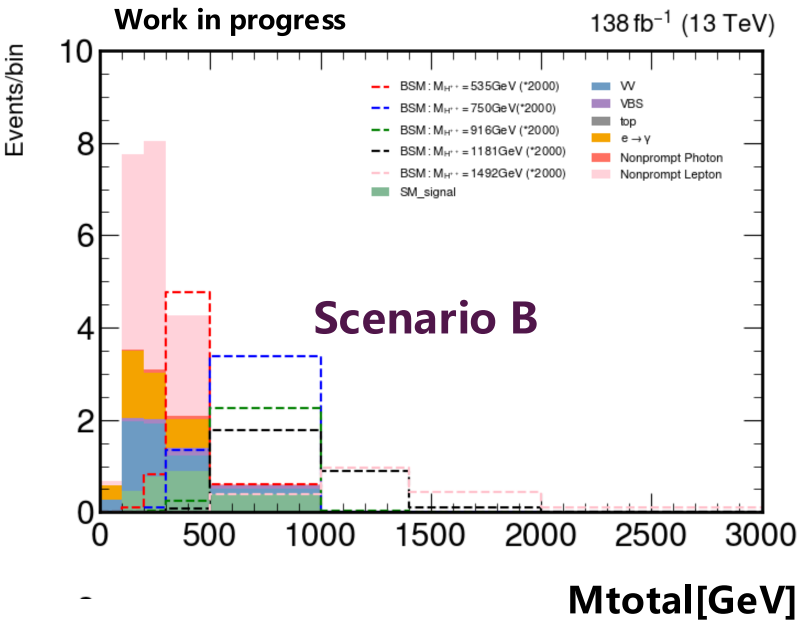
- The same pre-selections as SM: a similar distribution in region 0.
- The same BDT model was used: generally used
- Optimized further for every mass point: reconstruct $M_{total}$

**Mtotal:**

- Invariant mass of two leptons
- MET,
- photon pt



# Signal extraction---Doubly Charged Higgs

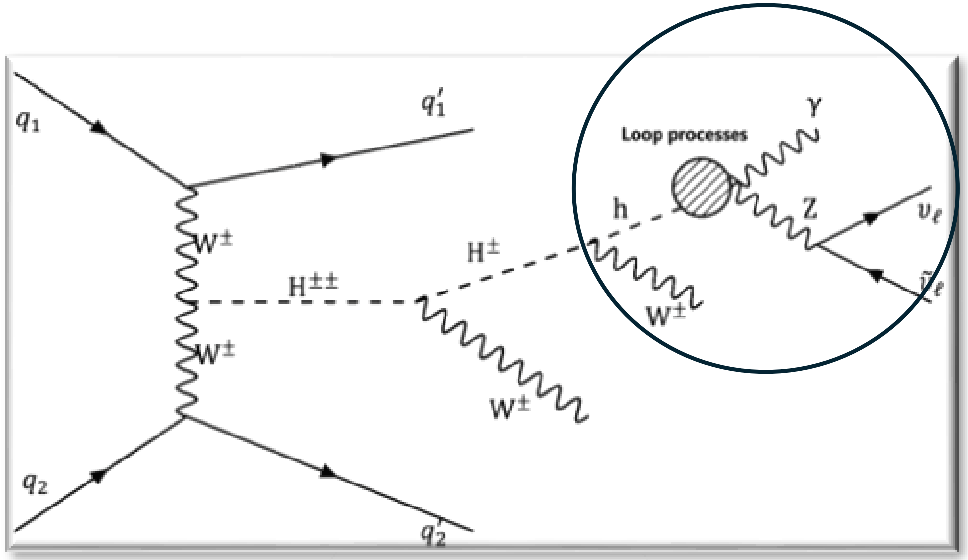
## scenario a

**Processes:**

$pp \to H5^{\pm\pm}jj, H5^{\pm\pm} \to W^{+}H3^{+},$

$H3^{+} \to W^{+}h, h \to Z\gamma, Z \to \upsilon\upsilon\sim$

- In the GM_UFO model: produced directly.
- suppressed by $Br(h \to Z\gamma, Z \to \upsilon\upsilon\sim)$




| M1coeff | 22 | 50 | 100 | 200 | 300 | 500 | 900 | 1500 | 2000 |
|---|---|---|---|---|---|---|---|---|---|
| M2coeff | 400 | 500 | 1000 | 4000 | 5500 | 8000 | 15,000 | 30000 | 60000 |
| $M_{H5pp}$ | 290GeV | 384GeV | 535GeV | 878GeV | 1.0TeV | 1.3TeV | 1.7TeV | 2TeV | 3.1TeV |
| $M_{H3pp}$ | 205GeV | 300GeV | 422GeV | 594GeV | 726GeV | 936GeV | 1.2TeV | 1.4TeV | 1.8TeV |
| $Br(H^{\pm\pm} \to H^{\pm} + W^{+})$ | 7.3% | 26.3% | 81.2% | 98.5% | 93.4% | 94.0% | 87.1% | 70% | 50% |
| $Br(H^{\pm\pm} \to W^{+}W^{+})$ | 20.5% | 73.6% | 18.6% | 1.45% | 3.5% | 4.3% | 3.7% | 4.0% | 4.0% |

| optimize | 290GeV | 384GeV | 535GeV | 878GeV | 1049GeV | 1306GeV | 1768GeV | 3000GeV |
|---|---|---|---|---|---|---|---|---|
| Mtotal | - | - | - | >400GeV | >400GeV | >400GeV | >400GeV | >400GeV |
| Mjj | >500GeV | >500GeV | >500GeV | >500GeV | >500GeV | >500GeV | >500GeV | >500GeV |
| $\Delta\eta_{jj}$ | >0.5 | >0.5 | >0.5 | >0.5 | >0.5 | >0.5 | >0.5 | >0.5 |
| BDT score | [0.55,1] | [0.55,1] | [0.55,1] | [0.2,1] | [0.2,1] | [0.2,1] | [0.2,1] | [0.2,1] |

# Signal extraction---Doubly Charged Higgs

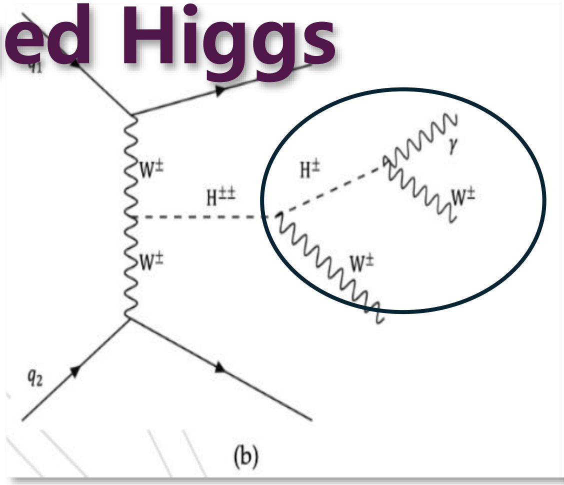
## scenario b

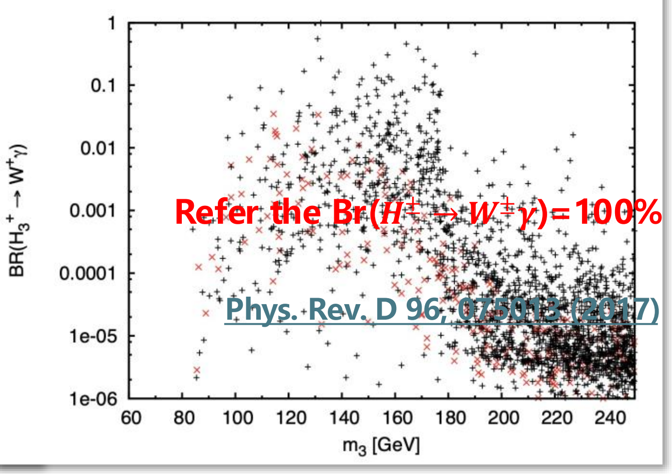
**Processes:**

$pp \to H^{\pm\pm}jj, pp \to H^{\pm\pm} \to W^{+}H^{+}$, $H^{+} \to W^{+}\gamma$

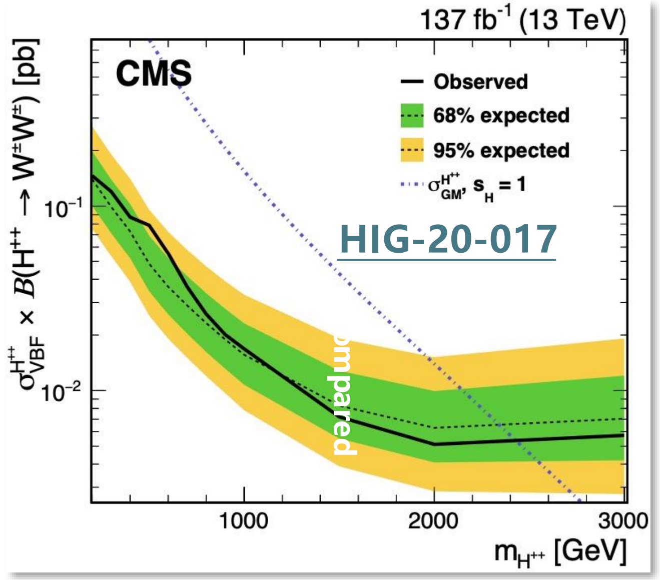
| M1coeff | 50 | 100 | 200 | 300 | 500 | 800 |
|---|---|---|---|---|---|---|
| M2coeff | 500 | 1000 | 2000 | 3000 | 5000 | 8000 |
| $M_{H5PP}$(GeV) | 384 | 535 | 750 | 916 | 1181 | 1492 |
| $M_{H3P}$(GeV) | 300 | 422 | 594 | 726 | 936 | 1184 |
| BR($H5^{\pm\pm} \to H3^{\pm} + W^{\pm}$) | 26.3% | 81.2% | 87.4% | 88.6% | 89.4% | 89.4% |
| BR($H5^{\pm\pm} \to W^{\pm} + W^{\pm}$) | 73.6% | 18.6% | 12.3% | 11% | 10% | 9.6% |

M2coeff = M1coeff*10




- Model Modification: Enabling $H^{\pm} \to W^{\pm}\gamma$:
  - Avoids suppression from small decay branching ratios.
    - Br($H^{\pm} \to W^{\pm}\gamma$)=0 in the original GM model.
    - Br($H^{\pm} \to W^{\pm}\gamma$) can be higher with some theoretical corrections.




| optimize | 384GeV | 535GeV | 750GeV | 916GeV | 1181GeV | 1492GeV |
|---|---|---|---|---|---|---|
| Mtotal | >300GeV | >300GeV | >500GeV | >500GeV | >500GeV | >500GeV |
| Mjj | >500GeV | >500GeV | >100GeV | >100GeV | >100GeV | >100GeV |
| $\Delta\eta_{jj}$ | >0.5 | >0.5 | - | - | - | - |
| BDT score | [0.4,1] | [0.4,1] | [0.4,1] | [0.4,1] | [0.4,1] | [0.4,1] |

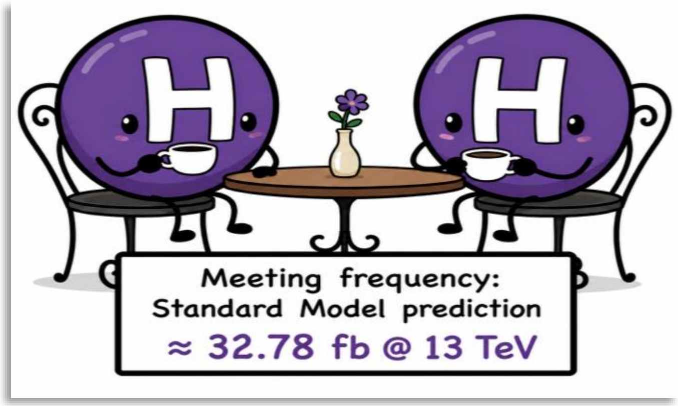
# Search for HH→ WWZZ @ Full run2 + early Run3(2022+2023)

## Motivation for Di-Higgs

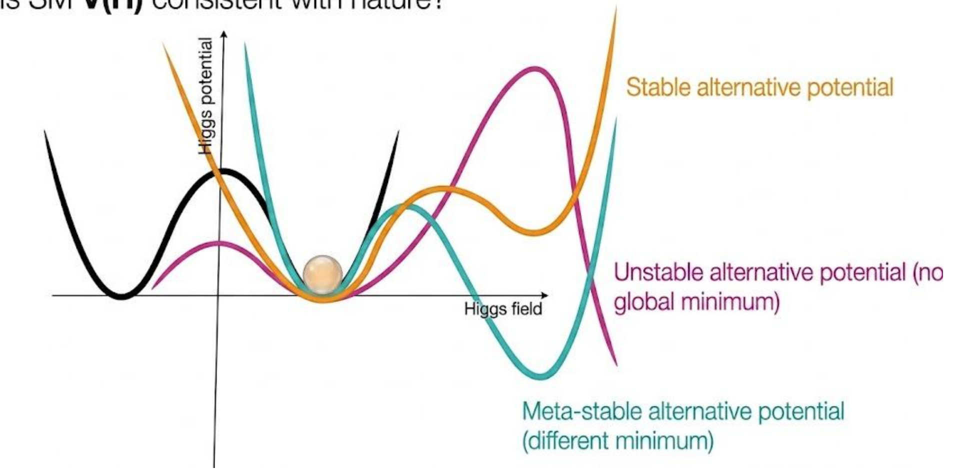
- Higgs sector in SM: with the measured value of the Higgs boson mass, all the parameters are known
- Still many unknowns about the Higgs field:
  - The origin of EWSB
  - The strength of the EW phase transition
  - The Shape of the Higgs potential
- Although HH production allows for a direct test of the Higgs cubic coupling, such events are extremely rare in the Standard Model

Higgs mass term — Higgs self-interaction term

$$V(H) = \boxed{-\frac{1}{2} m_H H^2} \boxed{- \lambda_3 v H^3 - \lambda_4 H^4}$$

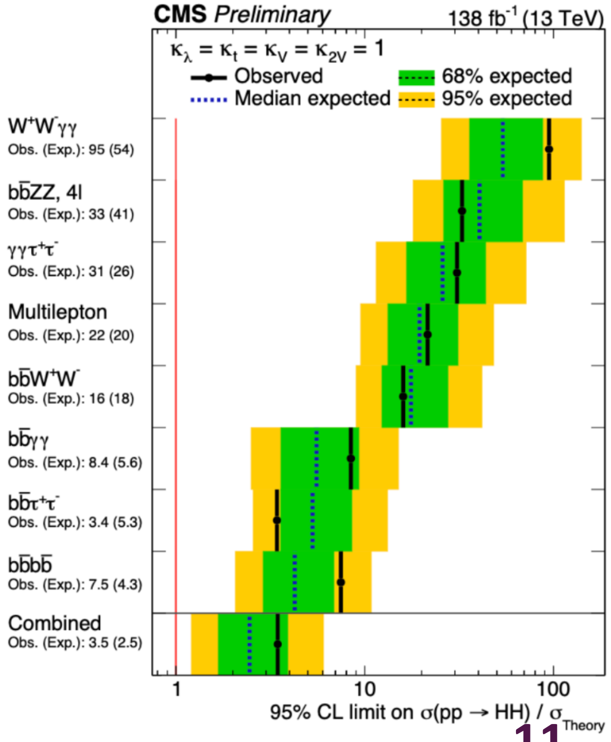



Is SM **V(H)** consistent with nature?




| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.3% | 2.7% | 0.39% | | |
| ZZ | 3.1% | 1.1% | 0.33% | 0.069% | |
| γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |

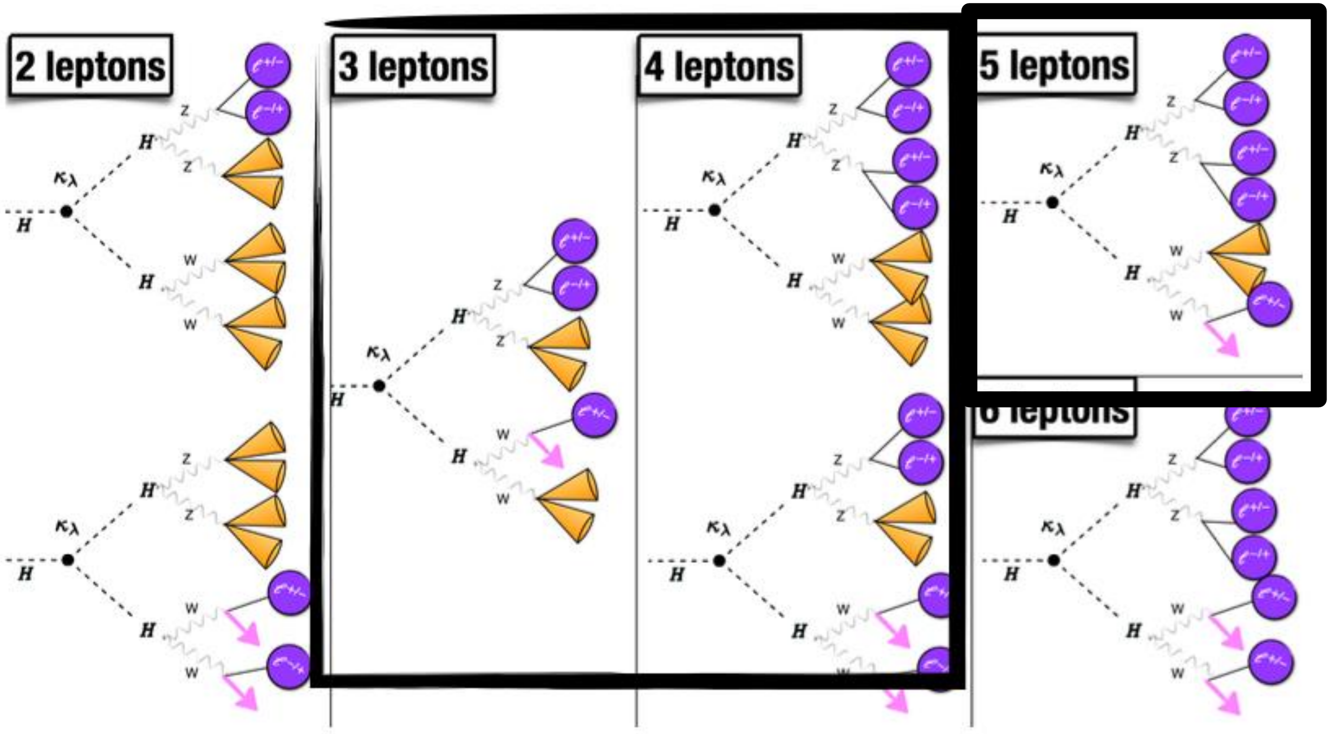
"Silver bullet" channels — Analyzed in CMS

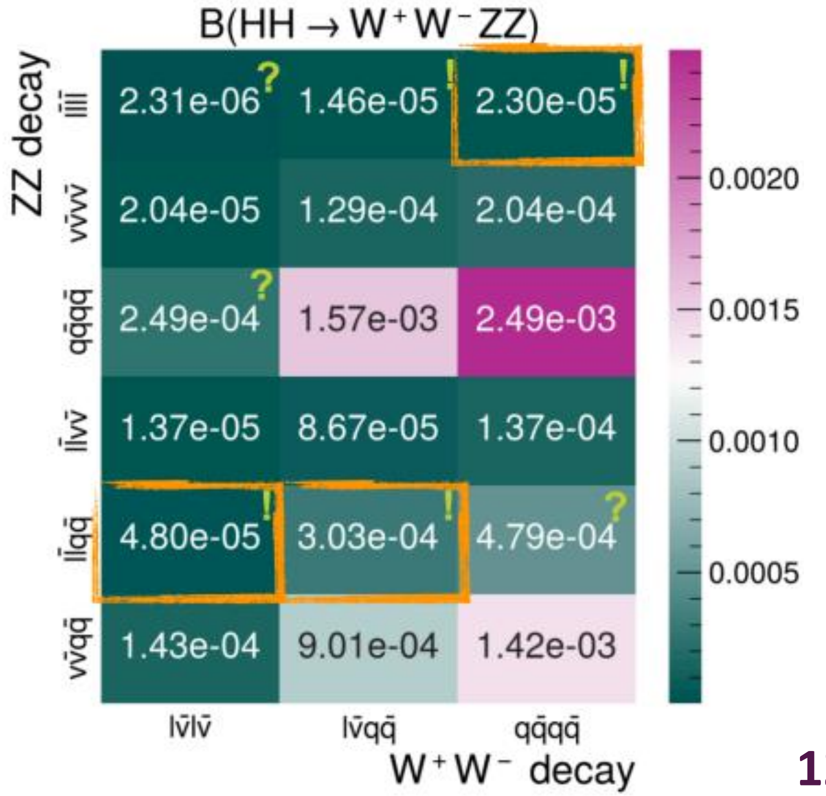


# Motivation for HH→ WW*ZZ*---New HH channel investigated in CMS!!

- Similar ATLAS multilepton (JHEP 08 (2024) 164):
  - 10 HH decay modes (incl. WW, ZZ)
  - categorised by N(leptons/taus/photons) rather than per-mode.
- Targeting **multilepton** and **multijet** final states: maximize the signal
- Challenging multiple objects analysis: **leptons, jets, and MET**

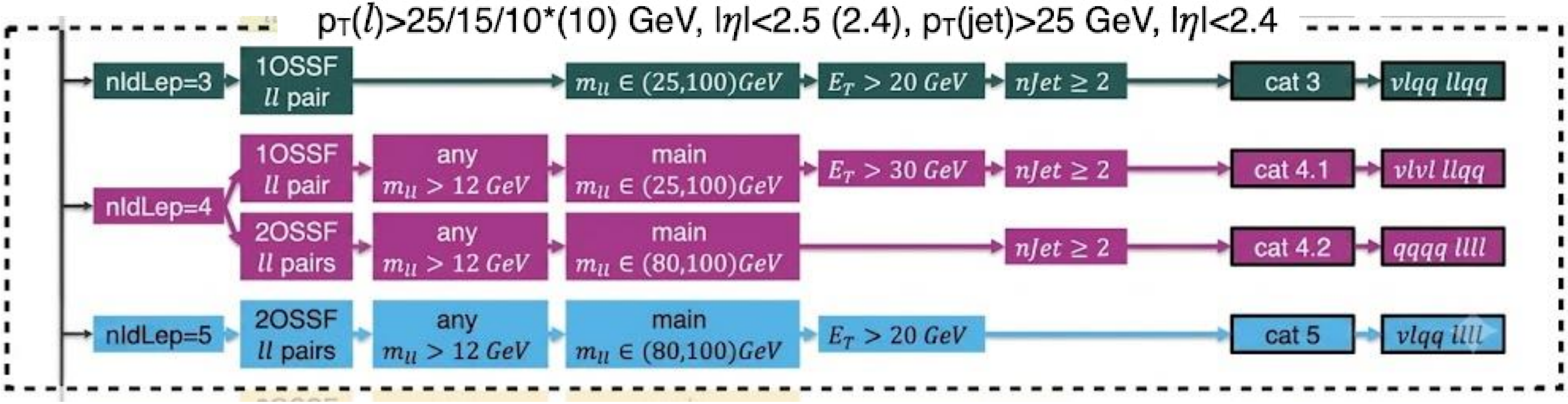
| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 34% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.3% | 2.7% | 0.39% | | |
| ZZ | 3.1% | 1.1% | 0.33% | 0.069% | |
| γγ | 0.26% | 0.10% | 0.028% | 0.012% | 0.0005% |



# Analysis strategy


- **Combine fully leptonic and semileptonic** channels to benefit from the higher BR->jj
- **Categorise events** using simple cuts by applying a preselection aiming at the multi-boson phase space
- Keep the **most sensitive categories** and **extract the signal using a dedicated BDT per category**
- **Cut-and-count** to estimate signal and background yields
  - **limits** on HH→WWZZ
  - **limits** on pp→WWZZ ( qq→WWZZ + qq→HWW/HZZ + gg→HH->WWZZ)



# Analysis strategy---3$\ell$ category

Exactly 3 leptons: $n_{lep} = 3$

**+**

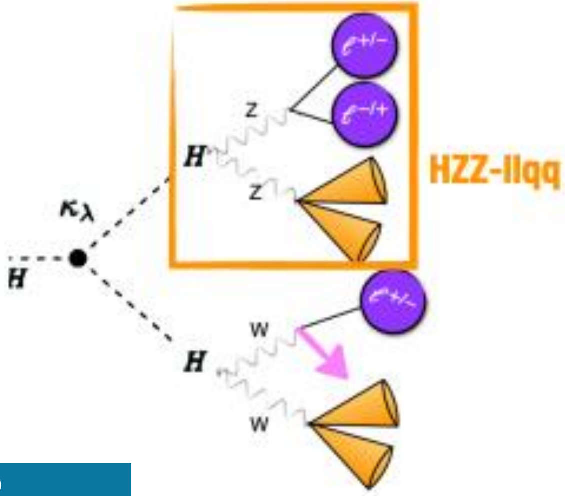
At least one **opposite-sign same-flavor** $\ell\ell$ pair
- **3l on-shell category** $m_{\ell\ell} \in$ (80, 100) GeV
- **3l off-shell category** $m_{\ell\ell} \in$ (25, 80) GeV

**+**

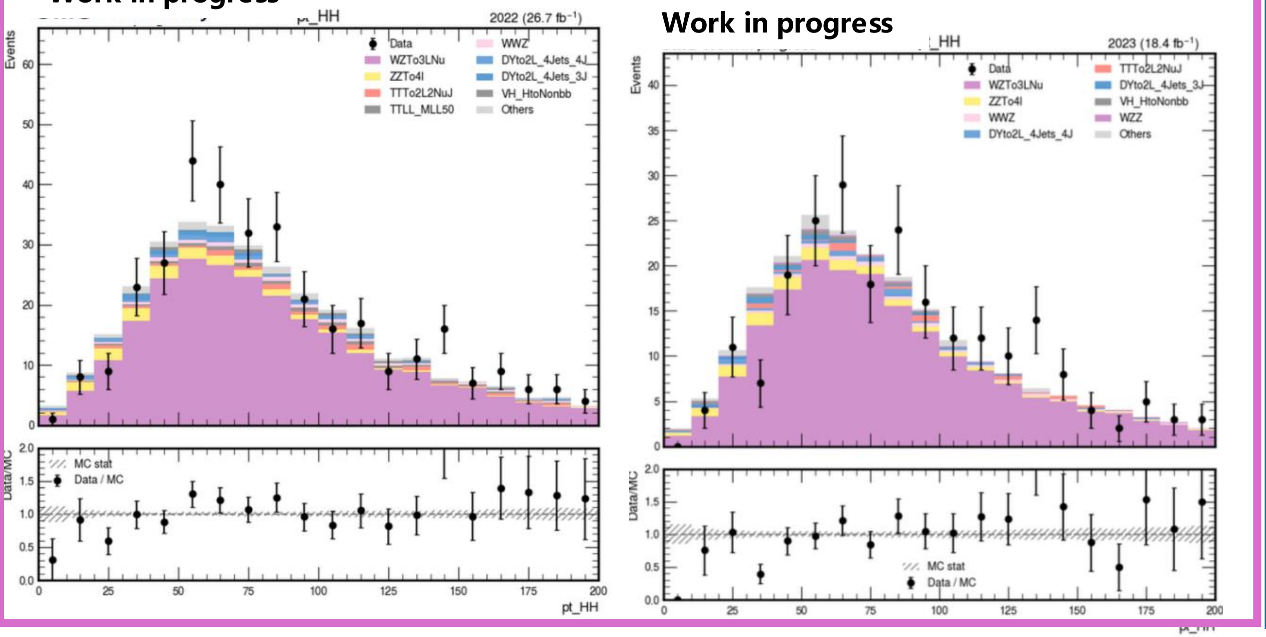
**MET**>20GeV

**+**

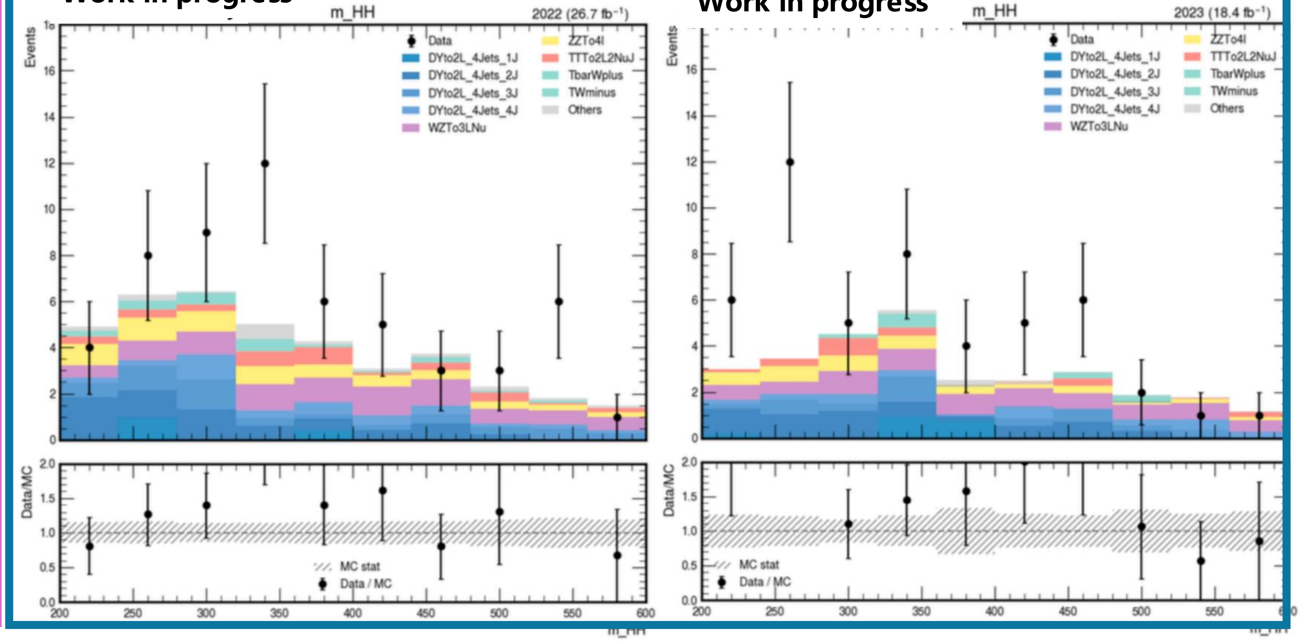
At least 2 non b-jets: $n_{jet}^{noB-tag} \geq 2$




## WZ CR




## DY CR




- 2 control regions for dominating backgrounds: Enriched in WZTo3LNu and Enriched in DYToJets
- A data-driven jet pt correction has been implemented in WZ CR for 3rd, 4th and 5th jet

# Analysis strategy--- 4$\ell$ category

Exactly 4 leptons: $n_{lep} = 4$ + 

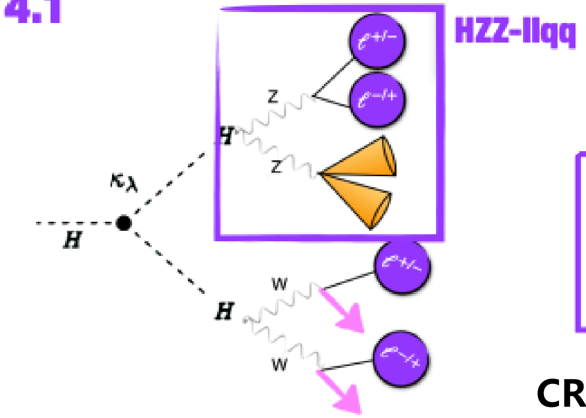
At least one **opposite-sign same-flavor** $\ell\ell$ pair
- **4.1 category** $m_{\ell\ell} \in$ (25, 100) GeV

\+ **MET**>30GeV + At least 2 non b-jets: $n_{jet}^{noB-tag} \geq 2$

At least two **opposite-sign same-flavor** $\ell\ell$ pair
- **4.2 category** $m_{\ell\ell} \in$ (80, 100) GeV

\+ At least 2 non b-jets: $n_{jet}^{noB-tag} \geq 2$

**4.1**



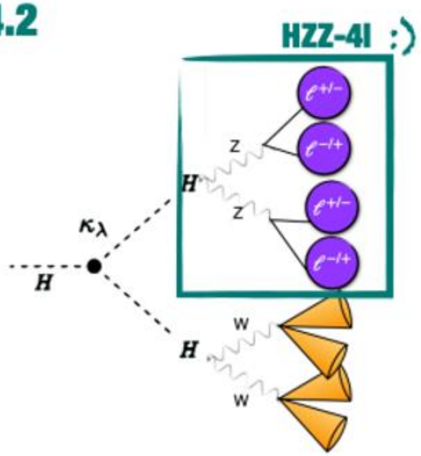

**BACKGROUNDS**

Background mixture of **ZZ, ttZ, tt̄, WWZ and tW** in similar contribution

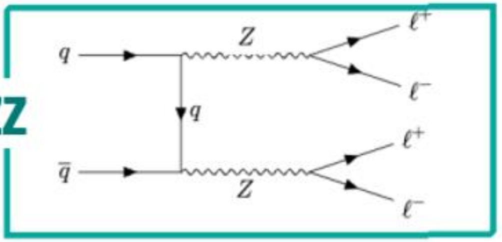
**CRs are very close to the SR:**

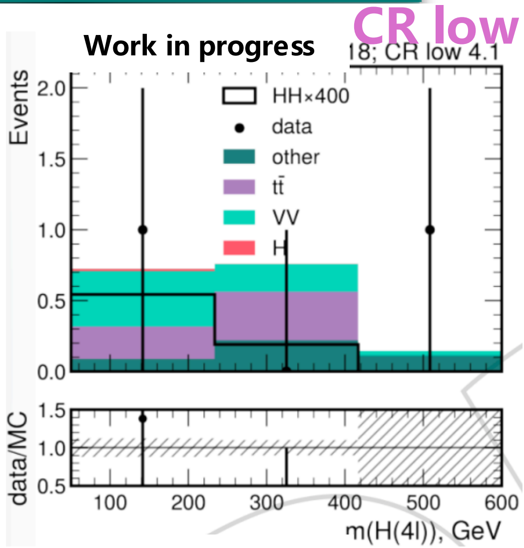
- **Inverted BDT score threshold (CRlow)**
- **Inverted jet multiplicity requirement (CRno)**
- **$t\bar{t}$ and H CR**

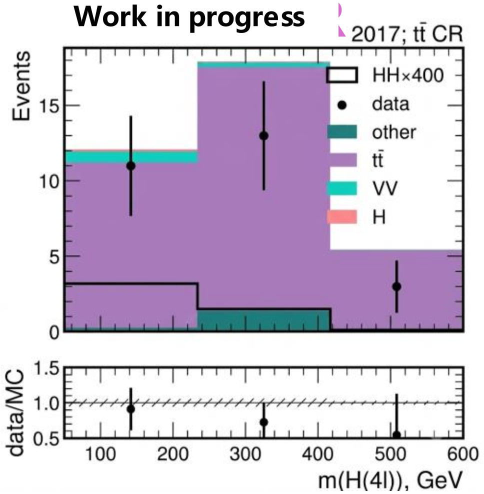
**4.2**

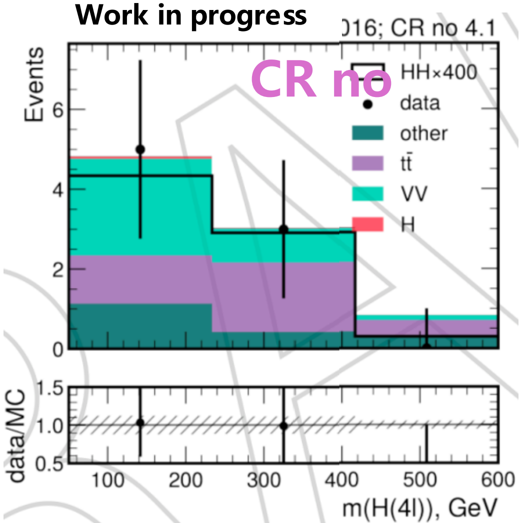


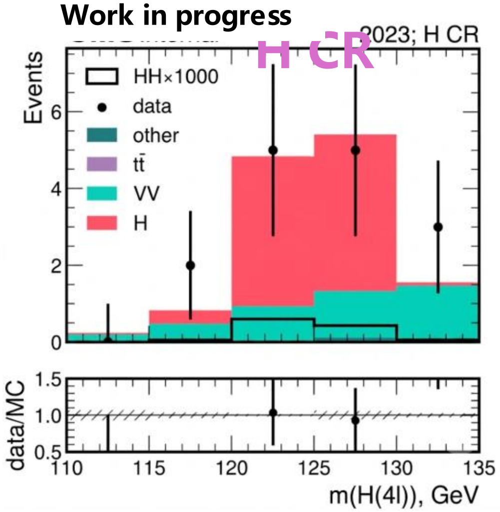

**ZZ**



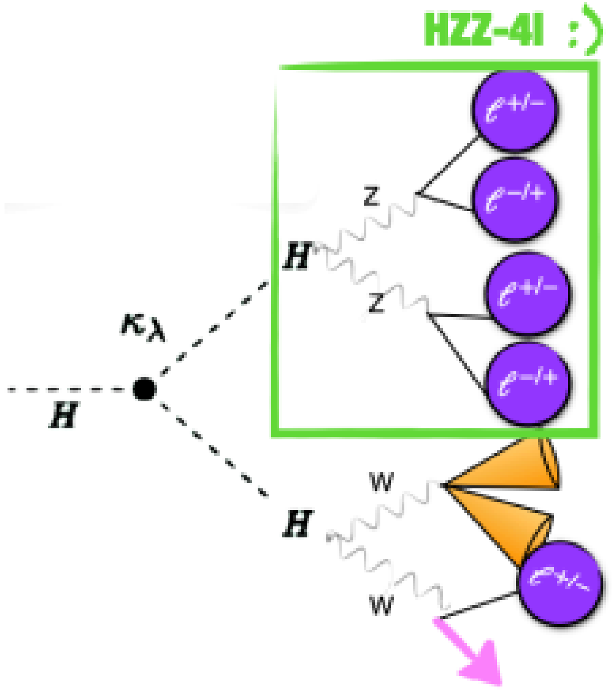



# Analysis strategy--- 5$\ell$ category




| yield | sample or group |
|---|---|
| $0.0066 \pm 0.0013$ | HH→2W2Z |
| $0.0213 \pm 0.0005$ | WWZZ |
| $0.0415 \pm 0.0005$ | VVH |
| $0.0030 \pm 0.0010$ | HH other |
| $0.4589 \pm 0.0073$ | VH |
| $0.0186 \pm 0.0031$ | H other |
| $0.6037 \pm 0.0441$ | ZZ |
| $0.2305 \pm 0.1514$ | VV other |
| $1.4835 \pm 0.0890$ | WZZ |
| $0.1671 \pm 0.0101$ | VVV other |
| $0.0000 \pm 0.0000$ | $t\bar{t}$ |
| $0.0799 \pm 0.0294$ | $t\bar{t}Z$ |
| $0.1528 \pm 0.0926$ | t other |
| $0.9184 \pm 0.9184$ | DY |
| $0.0613 \pm 0.0143$ | other |

Table 25: Signal and background yields with uncertainties after pre-selection for 5-lepton category, summed across all data taking periods.

Main backgrounds **WZZ**, **ZZ** and **VH**

Exactly 5 leptons: $n_{lep} = 5$

+

At least two **opposite-sign same-flavor** $\ell\ell$ pair

- $m_{\ell\ell} \in$ (80, 100) GeV

+

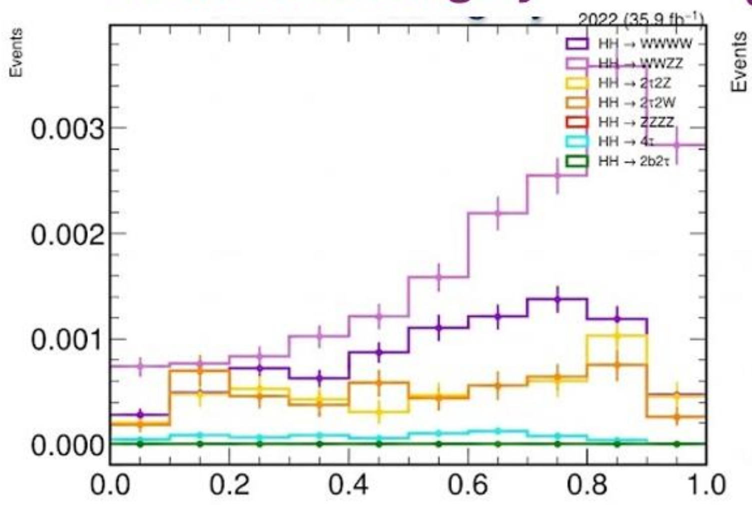
**MET**>20GeV

**A simple counting experiment is performed in the 5$\ell$ after the preselection**

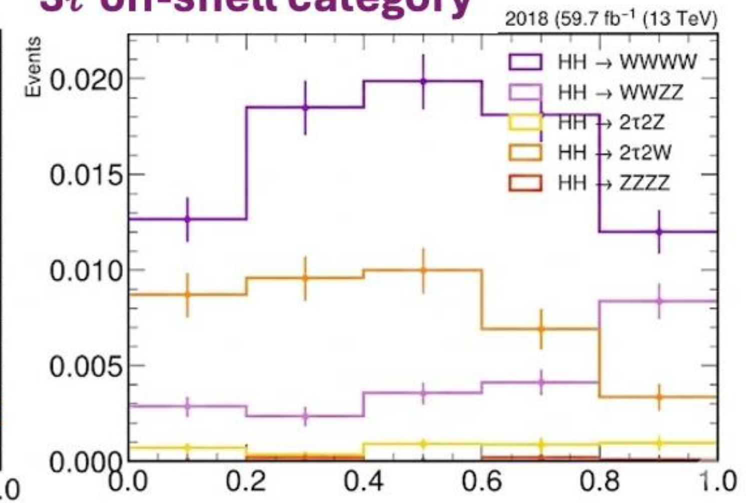
# Signal contributions: HH

- Other HH contribution have been evaluated using HHTo4V, HHTo2Tau2V, HHTo4Tau and HHTo2B2V($4\ell$ only)
- HHTo2B2Mu, HHTo2B2Tau were considered but gave no contribution
- Adding additional SR bin in $3\ell$ offshell to capture HHTo4W contribution

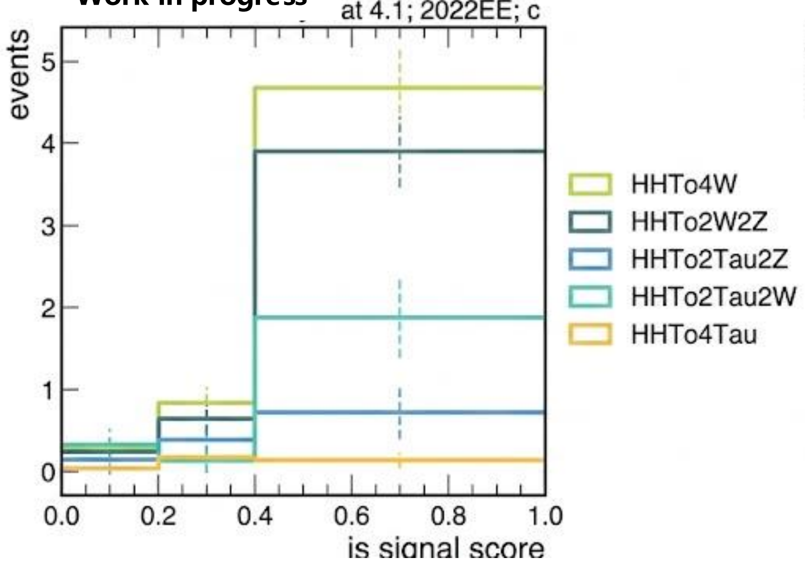
$3\ell$ on-shell category



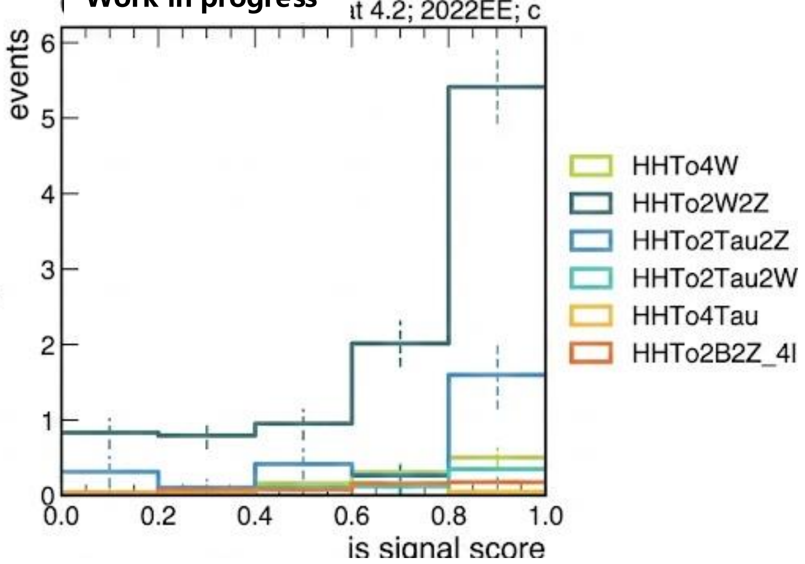

$3\ell$ off-shell category




Work in progress

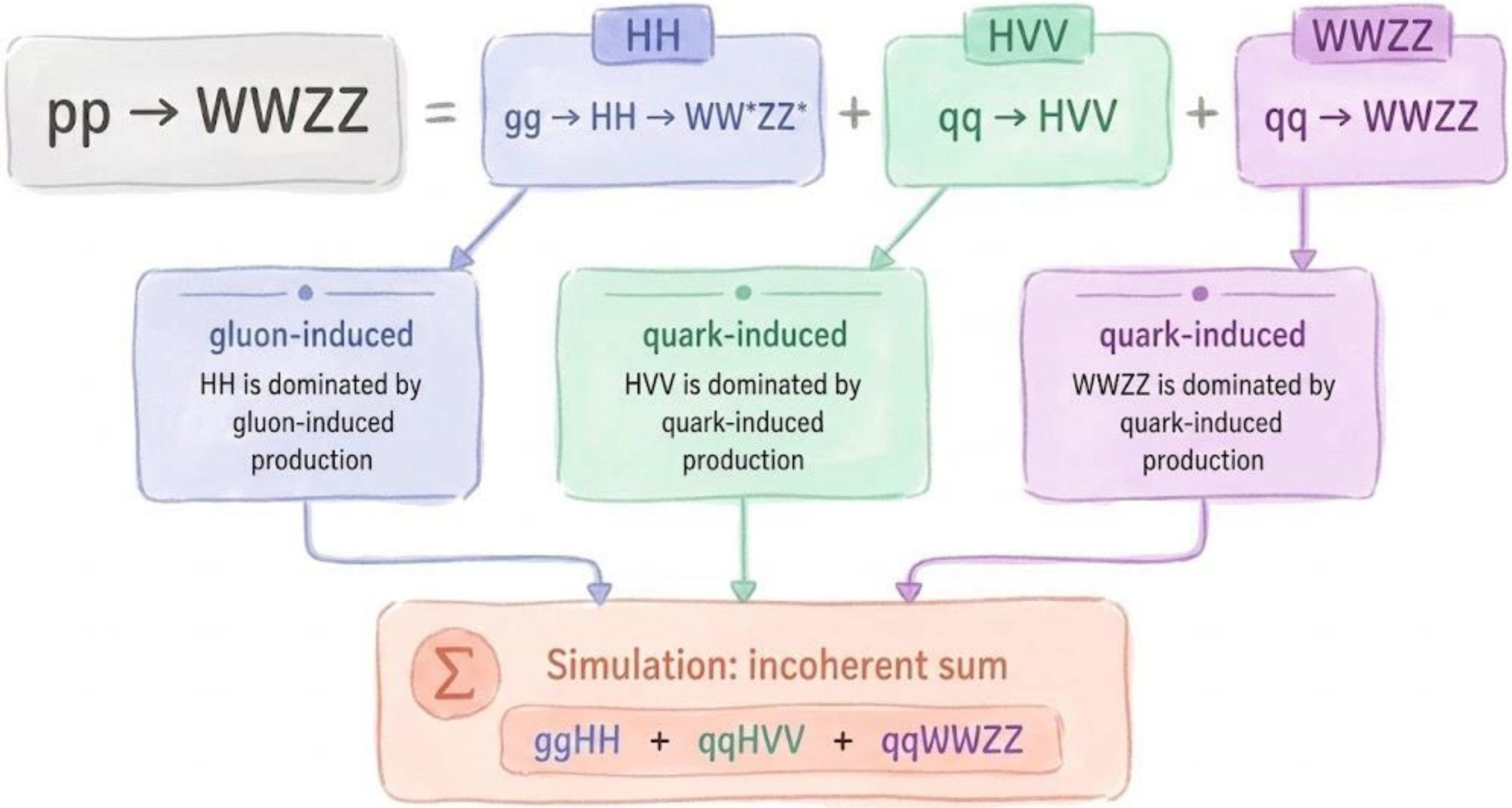


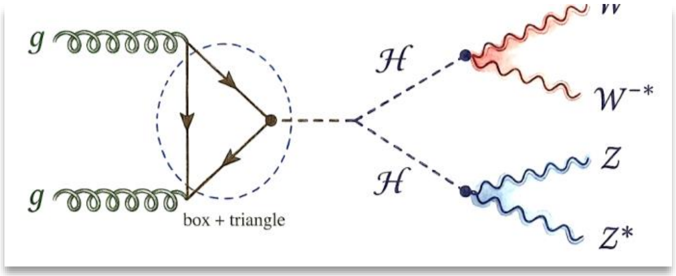

Work in progress

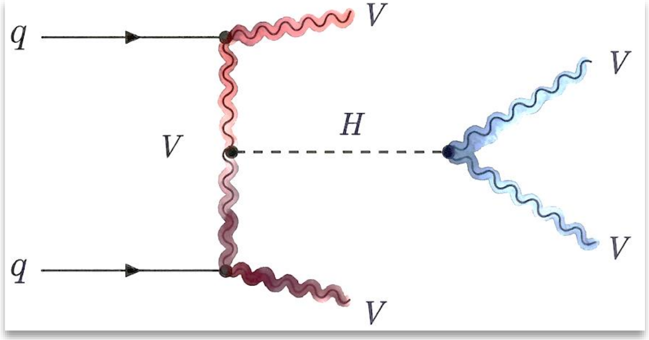


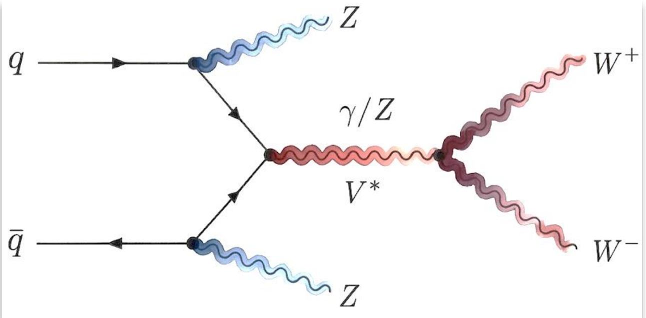
# Signal contributions: HH+HVV+WWZZ

## Goal: measure $pp \to WWZZ$ including all main contributions.



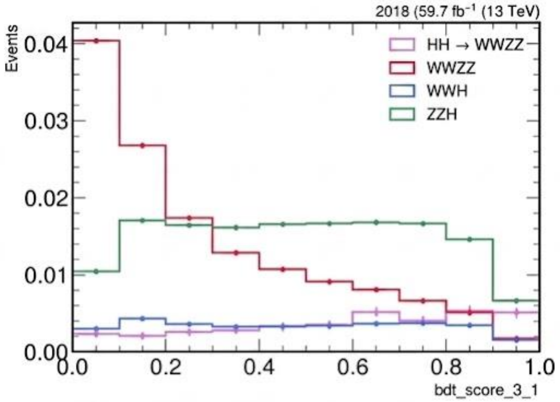



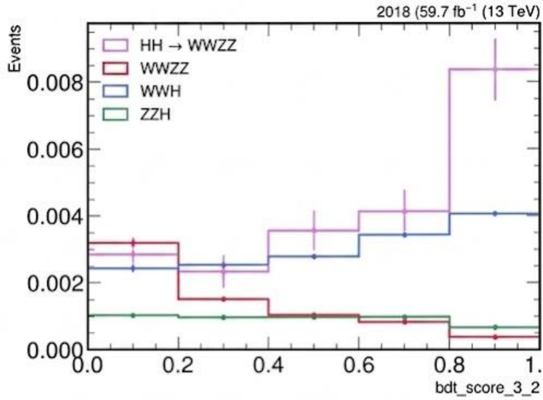



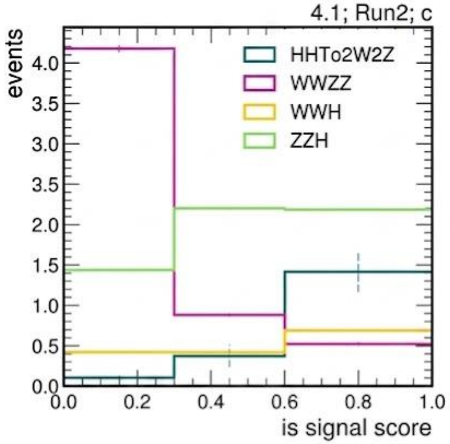



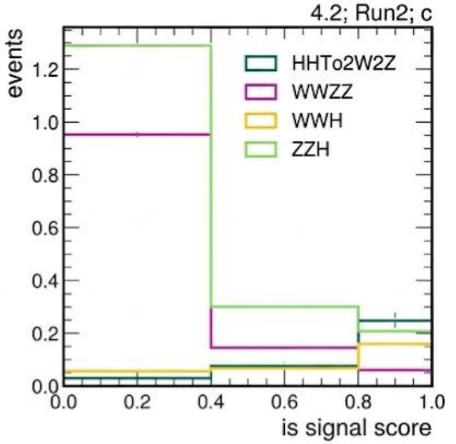
# Signal contributions: SMP-WWZZ & HVV

- Other possible pp->WWZZ contributions have been evaluated using SMP samples **WWZZ, HZZ, and HWW**
- The contribution is compared to the HH one in the signal region
- Significant contribution from HVV
- qq->WWZZ contribution is negligible in the SR
- **5l category very sensitive to pp->WWZZ!**
- Added limit on pp->WWZZ, including HVV and 4V production without HH

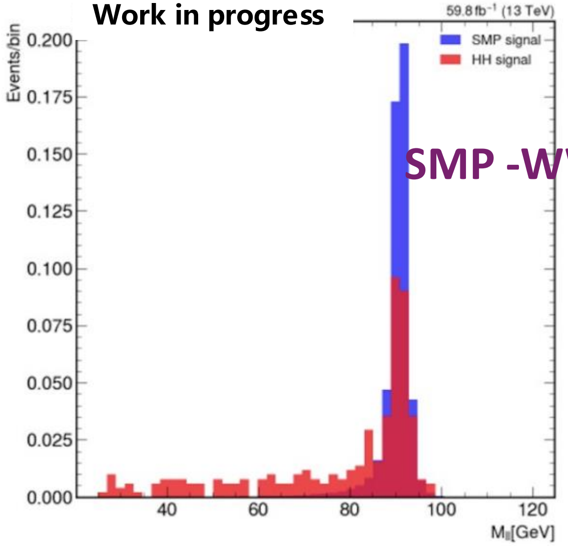


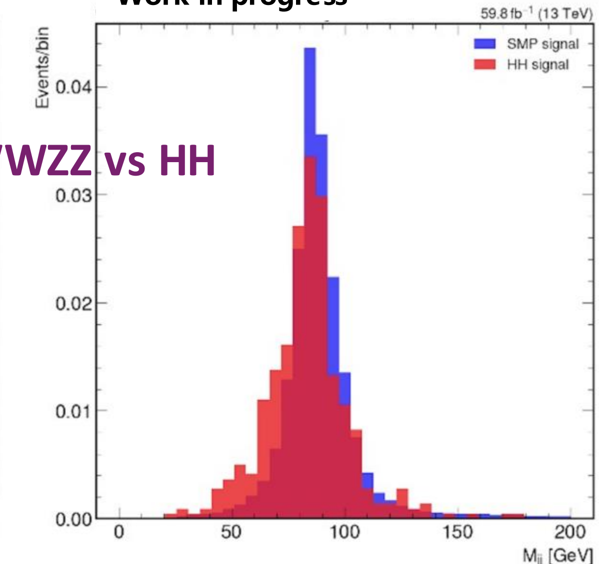




Work in progress




SMP -WWZZ vs HH

Work in progress




| Process | 5 |
|---|---|
| $HH \to 2W2Z$ | $0.0065 \pm 0.0007$ |
| HH other | $0.0030 \pm 0.0005$ |
| WWZZ | $0.0211 \pm 0.0002$ |
| VVH | $0.0413 \pm 0.0002$ |

# Summary

## Same-sign $WW\gamma$

### ❖ SM Part:

A first 2 →3 SM VBS measurement @full run2 is presented here.

- ❖ Performing a counting experiment in BDT score > 0.4 bins to extract the significance

### ❖ BSM Part:

A first $H5^{\pm\pm} \rightarrow H3^{\pm}W^{\pm}$ measurement is presented here.

- ❖ Consider two scenarios for $H3^{\pm}$ decay.

## HH→ WWZZ

❖ New analysis for HH non-resonant production in WWZZ decay mode developed

- ❖ Consider full Run2 + early Run3 (200fb$^{-1}$)
- ❖ Consider the $3\ell$, $4\ell$, and $5\ell$ categories.
- ❖ Combined HH, SMP-WWZZ, HVV in signal.


*Thank you!*

# Back Up

# BDTs for signal extraction (HHWWZZ)