Université Clermont Auvergne
Technische Universität Dortmund
Alma Mater Studiorum • University of Bologna

IMAPP
International Master of Advanced Methods in Particle Physics

Search for Vector-Like Leptons coupling to first and second generation leptons in multi-lepton final states with the ATLAS detector

Presented by: Elena Cuppini

Supervisors: Prof. Oliver Stelzer-Chilton
Prof. Maximiliano Sioli
Co-supervisor: Callum McCracken

Overview

- Introduction
- The $VLL_{e/\mu}$ analysis
- The mass reconstruction algorithm
- Conclusions and outlook

Introduction

Many experimental results show good agreement with the SM predictions

Hiccups

Evidence of new physics:
- Neutrino oscillation
- Rare decay processes of B-mesons
- Observation of dark matter
- Anomalous magnetic moment of the muon

A possible extension

Vector-like fermions
- particles whose left-handed and right-handed components transform the same way
- do not interact with the W and Z bosons as V − A currents, but as pure V currents

$m\overline{\psi_L}\psi_R$ directly in the Lagrangian

INTRODUCTION

Many experiment results show good agreement with the SM predictions

Hiccups

Evidence of new physics:
- Neutrino oscillation
- Rare decay processes of B-mesons
- Observation of dark matter
- Anomalous magnetic moment of the muon

Vector-like quarks (VLQs)
Vector-like leptons (VLLs)

A possible extension

Vector-like fermions
- particles whose left-handed and right-handed components transform the same way
- do not interact with the W and Z bosons as V − A currents, but as pure V currents

$m\overline{\psi_L}\psi_R$ directly in the Lagrangian

Current limits on VLL masses:
- × < 100 GeV (LEP)
- × Singlet 114-176 GeV (ATLAS)
- × Doublet VLL_τ 120-790 GeV (CMS)
- × Singlet VLL_τ 125-170 GeV + Doublet VLL_τ < 1045 Gev (CMS)
- × Doublet VLL_τ 120-900 GeV (ATLAS)

Vector Like Leptons

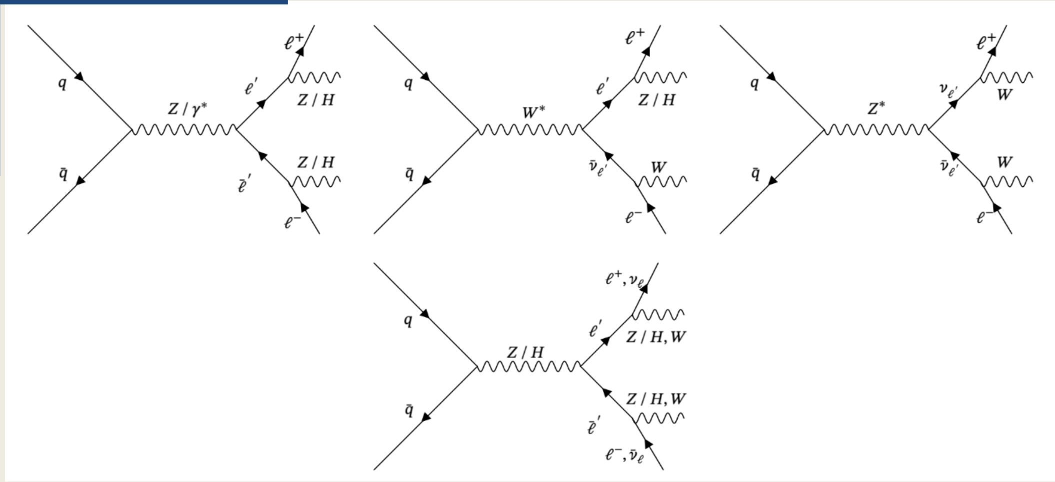
Search for Vector-Like electrons/muons ($VLL_{e/\mu}$) assuming a small mixing with the SM leptons through Yukawa interactions

Decays to SM leptons and Higgs, W or Z bosons (SM couplings)

Vector Like Leptons

Search for Vector-Like electrons/muons ($VLL_{e/\mu}$) assuming a small mixing with the SM leptons through Yukawa interactions

Decays to SM leptons and Higgs, W or Z bosons (SM couplings)



Two VLL models: as SU(2) **doublets** or **singlets** with quantum numbers

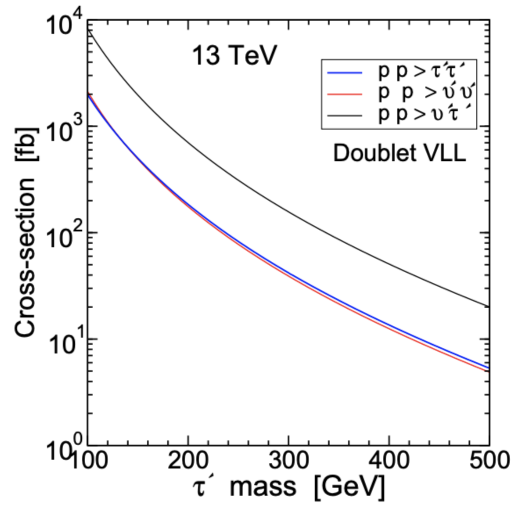
$$L_{L,R} + \overline{L_{L,R}} = (1, 2, -\frac{1}{2}) + (1, 2, \frac{1}{2}).$$

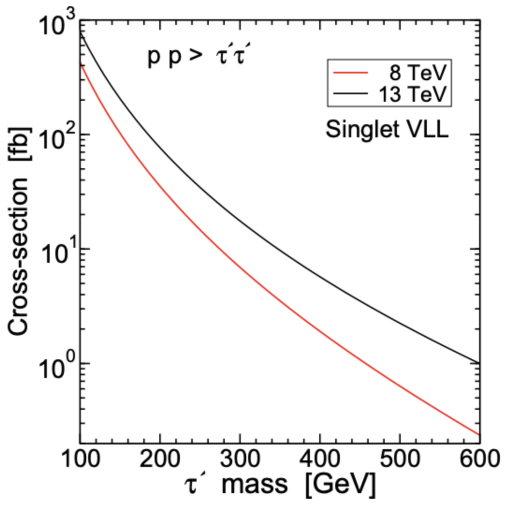
$$\ell'_{L,R} + \overline{\ell'_{L,R}} = (1, 1, -1) + (1, 1, 1).$$

$L_{L,R} = (\nu'_{\ell';L,R}, \ell'_{L,R})$

Same framework as the analysis that exluded

- × Singlet VLL_τ 125-170 GeV + Doublet VLL_τ < 1045 Gev (CMS)



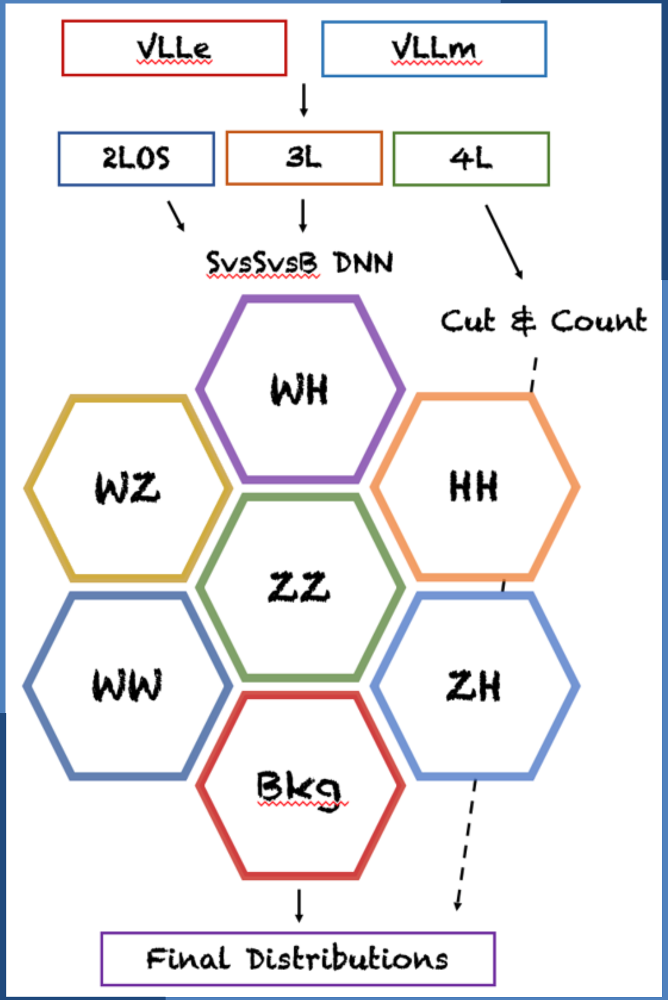


The $\text{VLL}_{e/\mu}$ analysis

Still a work in progress!

Signal Samples: *$VLL_{e/\mu}$* singlet & doublet samples @ NLO

- Masses: {150, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300} GeV
- **Blinding:** S/B > 5%. S = combined yield from $VLL_{e/\mu}$ doublet at 600 GeV and at 1 TeV
- Events are classified into channels based on lepton multiplicity (2ℓOS, 3ℓ, 4ℓ) and then classified into orthogonal Signal Regions targeting a specific signal topology
  - ❖ Single shot **Signal vs Signal vs Background** (**SvsSvsB**) **Deep Neural Network (DNN)** to discriminate between signal topologies in the 2ℓOS and 3ℓ channels
  - ❖ **Shape analysis strategy** for the 4ℓ channel due to reduced statistics/complexity
  - ❖ Individual SM backgrounds treated with appropriate x-section
- Target VLL_e and VLL_μ separately by placing flavor requirements on the leptons entering the signal regions



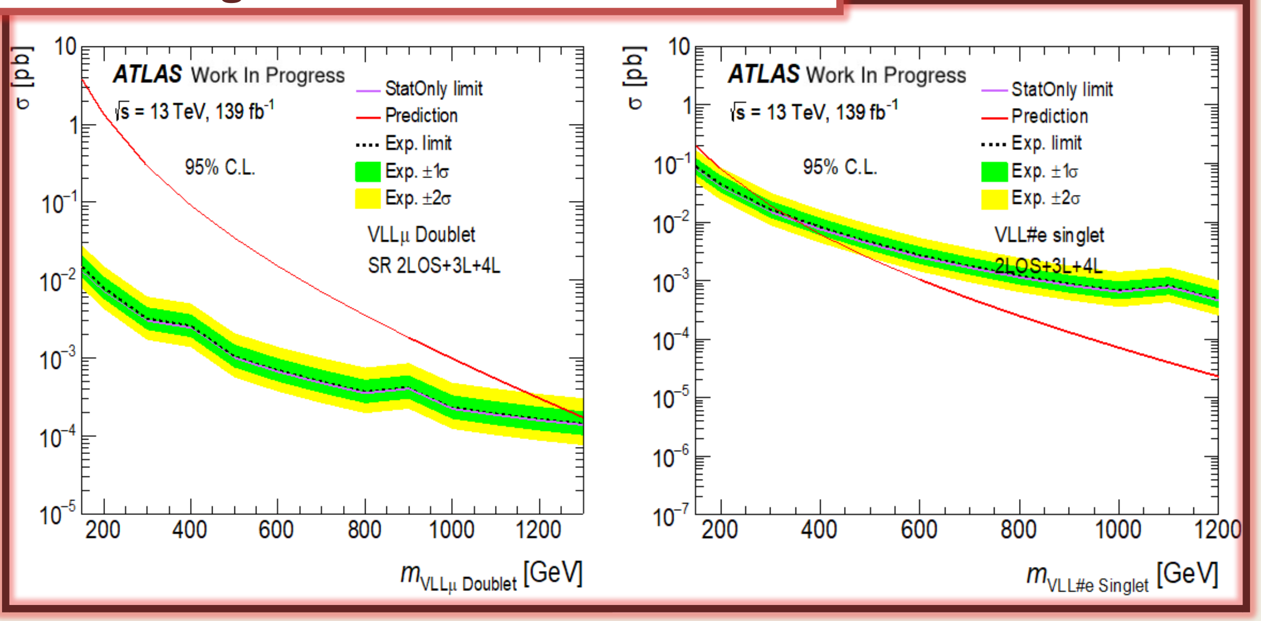
From Harry's update

From [Harry's update]

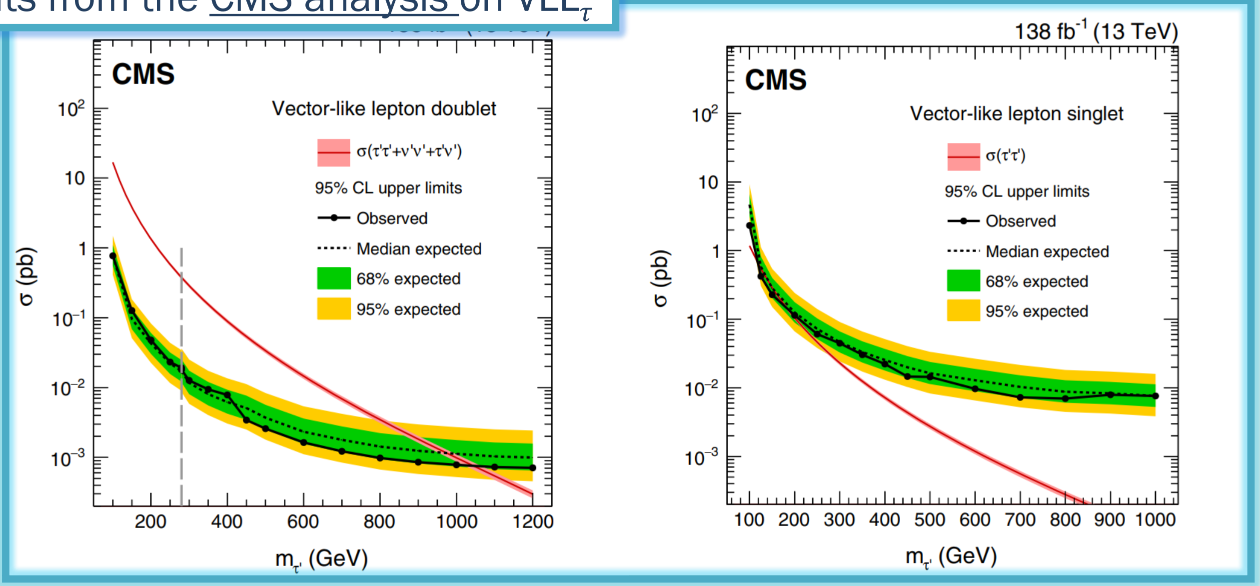
FITTING

- Simultaneous profile likelihood fit of BSM signal together with major SM backgrounds using TREXFITTER
  - ➢ Fit variable: HTlep+MET
  - ➢ Norm factors of the major backgrounds as free parameters
- **Results:** In case of no excess, the 95% CL upper limit will be evaluated on the production cross-section × branching ratio of the VLL signals as a function of the mass.

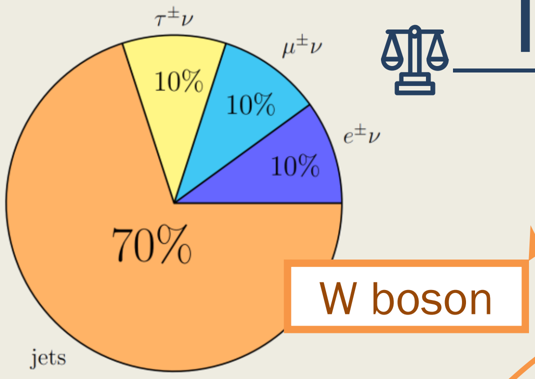
Fit with modelling uncertainties across all SRs



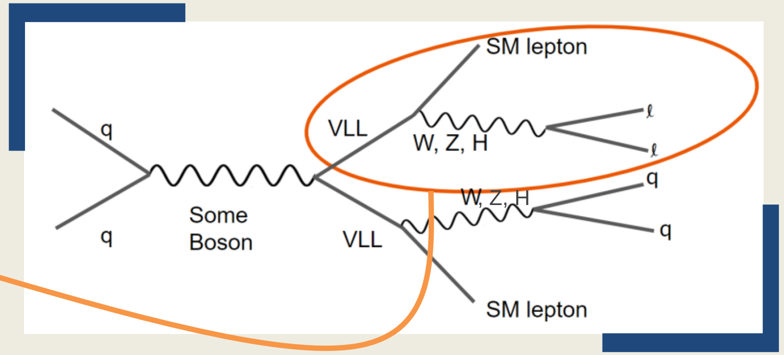
Limits from the [CMS analysis] on VLL_τ

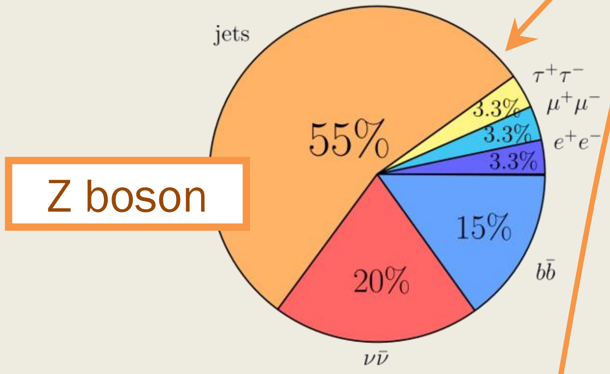


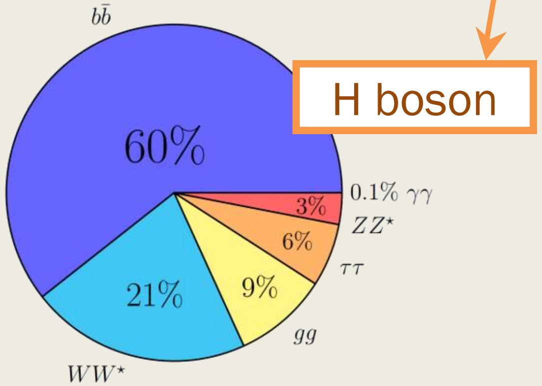
THE MASS RECONSTRUCTION ALGORITHM



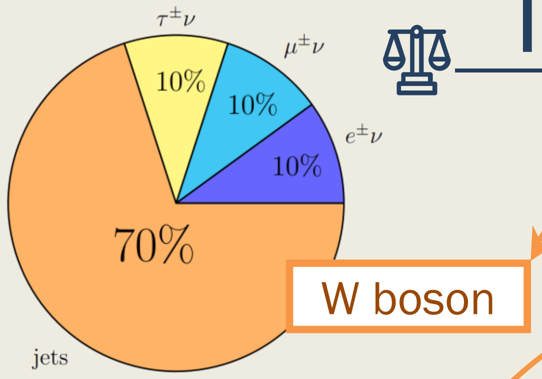
- Reconstruction of only one VLL per event
- Final state characterised by the decay mode of the boson coming from the VLL



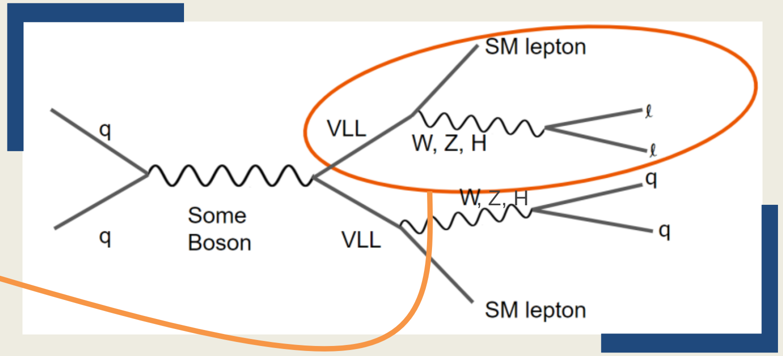


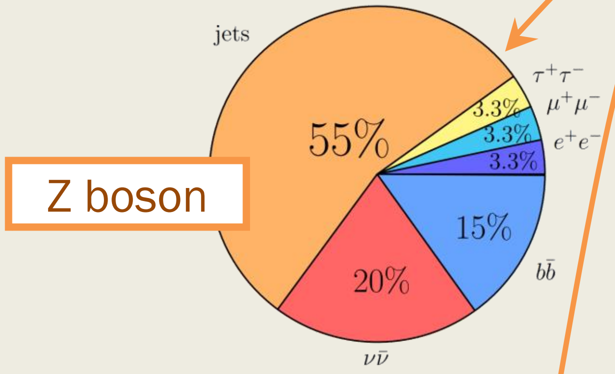


THE MASS RECONSTRUCTION ALGORITHM



- Reconstruction of only one VLL per event
- Final state characterised by the decay mode of the boson coming from the VLL





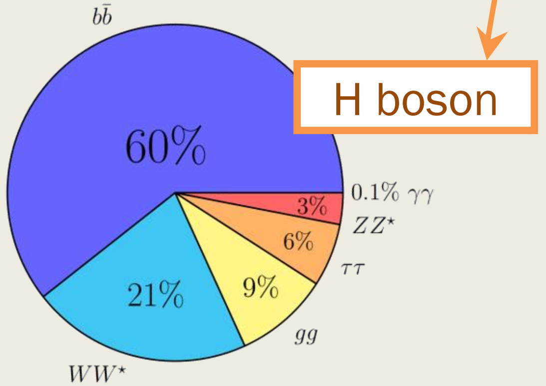
Four main decay topologies are reconstructed:

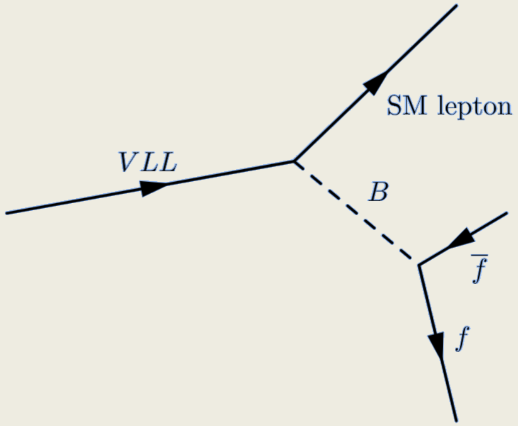
- ➢ Boson to two visible fermions ($B \rightarrow f\bar{f}'$)
- ➢ Leptonic W decay
- ➢ Z or W to one boosted jet
- ➢ Higgs to electroweak bosons to four fermions

Reconstruction unfolds in two steps:

1. Boson reconstruction
2. VLL reconstruction

Use the reconstructed boson and the unused lepton with the highest transverse momentum to get the VLL





$B \rightarrow f\bar{f}'$

Decays compatible with this type of reconstruction: $W \rightarrow qq$, $Z \rightarrow qq$, $Z \rightarrow \ell^+\ell^-$, $H \rightarrow bb$, and $Z \rightarrow bb$

$W \rightarrow \ell\nu$ is similar but has an additional step due to the reconstruction of the neutrino

First Step

Jets

0	1	2	3	4
Jet_0	Jet_1	Jet_2	Jet_3	Jet_4

Index, integer

Jet, TLorentzVector

Zs

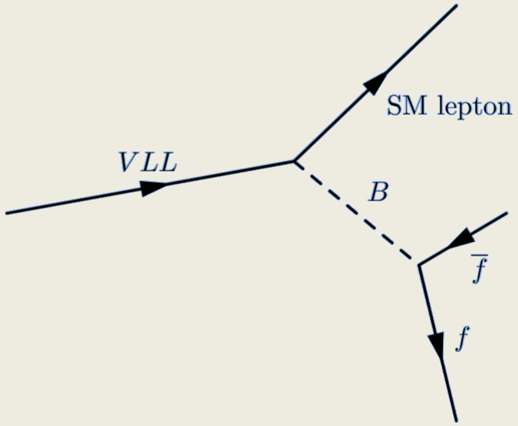
0	1	2	3	4	5	6
Z_0	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
0	0	0	0	1	1	1
1	2	3	4	2	3	4
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}	ΔR_{13}	ΔR_{14}

Z boson, TLorentsVector. With n jets, one gets $\frac{n(n-1)}{2}$ Z bosons

Indices of the jets that make up the Zs

Angular distance between the jets

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2},$$
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



$B \to f\bar{f}'$

$W \to \ell\nu$ is similar but has as additional step due to the reconstruction of the neutrino

Decays compatible with this type of reconstruction: $W \to qq$, $Z \to qq$, $Z \to \ell^+\ell^-$, $H \to bb$, and $Z \to bb$

First Step

Jets

0	1	2	3	4
Jet_0	Jet_1	Jet_2	Jet_3	Jet_4

Index, integer

Jet, TLorentzVector

Zs

0	1	2	3	4	5	6
Z_0	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
0	0	0	0	1	1	1
1	2	3	4	2	3	4
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}	ΔR_{13}	ΔR_{14}

Z boson, TLorentsVector. With n jets, one gets $\frac{n(n-1)}{2}$ Z bosons

Indices of the jets that make up the Zs

Angular distance between the jets

Second Step

Select one boson to reconstruct the VLL with. Two possible strategies:

- χ^2-only approach
- χ^2+ΔR approach

χ^2-ONLY APPROACH

The χ^2 is defined as

$$\chi^2_B = \frac{(m_B^{\text{reco}} - m_B^{\text{on-shell}})^2}{\sigma_B^2}$$

For each decay mode

1. Calculate the χ^2 for all bosons

Zs

0	1	2	3	4
Z_0	Z_1	Z_2	Z_3	Z_4
0	0	0	0	1
1	2	3	4	2
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}

χ^2

0	1	2	3	4
χ^2_0	χ^2_1	χ^2_2	χ^2_3	χ^2_4
0	1	2	3	4

χ^2-ONLY APPROACH

The χ^2 is defined as

$$\chi_B^2 = \frac{(m_B^{\text{reco}} - m_B^{\text{on-shell}})^2}{\sigma_B^2}$$

For each decay mode

1. Calculate the χ^2 for all bosons
2. Sort the χ^2s

Zs

0	1	2	3	4
Z_0	Z_1	Z_2	Z_3	Z_4
0	0	0	0	1
1	2	3	4	2
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}

χ^2

0	1	2	3	4
χ^2_0	χ^2_1	χ^2_2	χ^2_3	χ^2_4
0	1	2	3	4

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

χ^2-ONLY APPROACH

The χ^2 is defined as

$$\chi_B^2 = \frac{(m_B^{\text{reco}} - m_B^{\text{on-shell}})^2}{\sigma_B^2}$$

For each decay mode

1. Calculate the χ^2 for all bosons
2. Sort the χ^2s
3. Use the boson with the lowest χ^2 (<5) to reconstruct the VLL

Zs

0	1	2	3	4
Z_0	Z_1	Z_2	Z_3	Z_4
0	0	0	0	1
1	2	3	4	2
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}

χ^2

0	1	2	3	4
χ^2_0	χ^2_1	χ^2_2	χ^2_3	χ^2_4
0	1	2	3	4

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

The VLL will be reconstructed using Z_2

χ^2-ONLY APPROACH

The χ^2 is defined as

$$\chi_B^2 = \frac{(m_B^{\text{reco}} - m_B^{\text{on-shell}})^2}{\sigma_B^2}$$

For each decay mode

1. Calculate the χ^2 for all bosons
2. Sort the χ^2s
3. Use the boson with the lowest χ^2 (<5) to reconstruct the VLL

Zs

0	1	2	3	4
Z_0	Z_1	Z_2	Z_3	Z_4
0	0	0	0	1
1	2	3	4	2
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}

χ^2

0	1	2	3	4
χ^2_0	χ^2_1	χ^2_2	χ^2_3	χ^2_4
0	1	2	3	4

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

The VLL will be reconstructed using Z_2

$\chi^2+\Delta R$ APPROACH

Calculate the χ^2 for all bosons and sort the χ^2s as with the other method

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

χ^2-ONLY APPROACH

The χ^2 is defined as

$$\chi_B^2 = \frac{(m_B^{\text{reco}} - m_B^{\text{on-shell}})^2}{\sigma_B^2}$$

For each decay mode

1. Calculate the χ^2 for all bosons
2. Sort the χ^2s
3. Use the boson with the lowest χ^2 (<5) to reconstruct the VLL

Zs

0	1	2	3	4
Z_0	Z_1	Z_2	Z_3	Z_4
0	0	0	0	1
1	2	3	4	2
ΔR_{01}	ΔR_{02}	ΔR_{03}	ΔR_{04}	ΔR_{12}

χ^2

0	1	2	3	4
χ^2_0	χ^2_1	χ^2_2	χ^2_3	χ^2_4
0	1	2	3	4

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

The VLL will be reconstructed using Z_2

$\chi^2 + \Delta R$ APPROACH

Calculate the χ^2 for all bosons and sort the χ^2s as with the other method

1. Select the bosons with
   $$\Delta m = \left| m_Z^{reco} - m_Z^{reco,min} \right| < \sigma_Z$$
   and sort them according to their ΔR_{ij}
2. Use the first boson of the new list to build the VLL

χ^2

0	1	2	3	4
χ^2_2	χ^2_4	χ^2_0	χ^2_3	χ^2_1
2	4	0	3	1

Zs

0	1	2
Z_2	Z_4	Z_0
0	1	0
3	2	1
ΔR_{03}	ΔR_{12}	ΔR_{01}

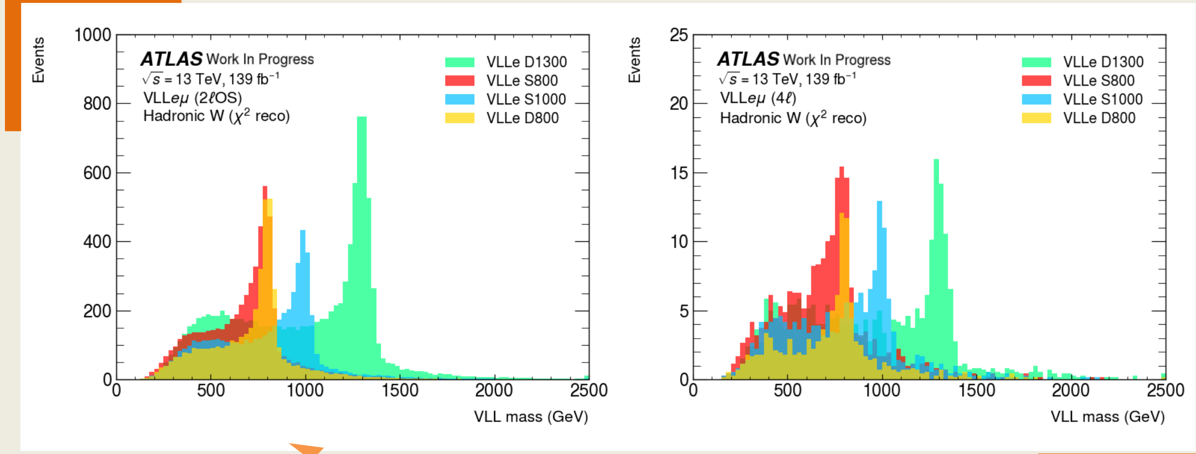
0	1	2
Z_4	Z_2	Z_0
1	0	0
2	3	1
ΔR_{12}	ΔR_{03}	ΔR_{01}

The VLL will be reconstructed using Z_4

Only seven signal samples are available:

- 2 for VLL_e doublet model (800 and 1300 GeV),
- 2 for VLL_e singlet model (800 and 1000 GeV),
- 1 for VLL_μ doublet model (900 GeV),
- 2 for VLL_μ singlet model (300 and 400 GeV)

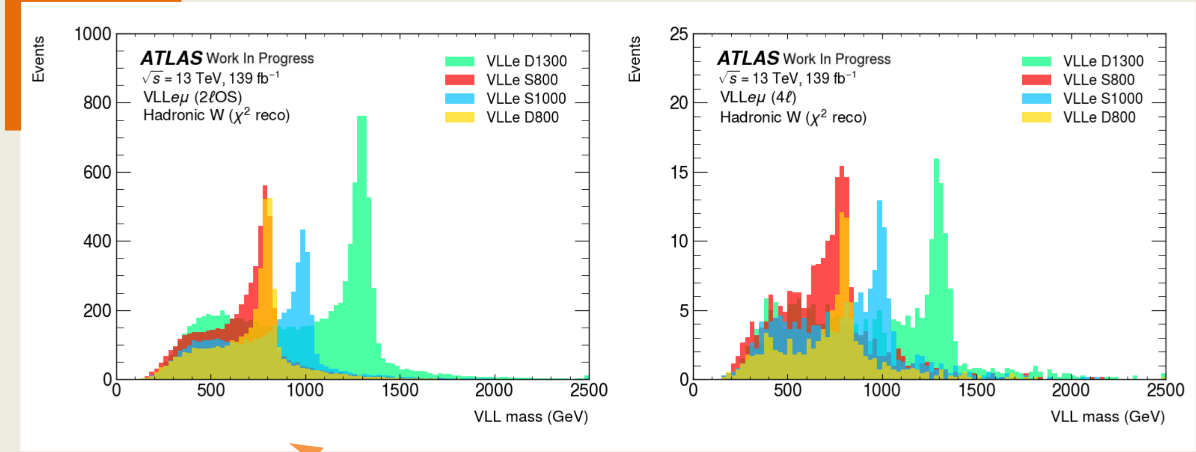
Even if one decay is compatible with multiple channels, the different lepton multiplicity final states might lead to plots of varying quality.

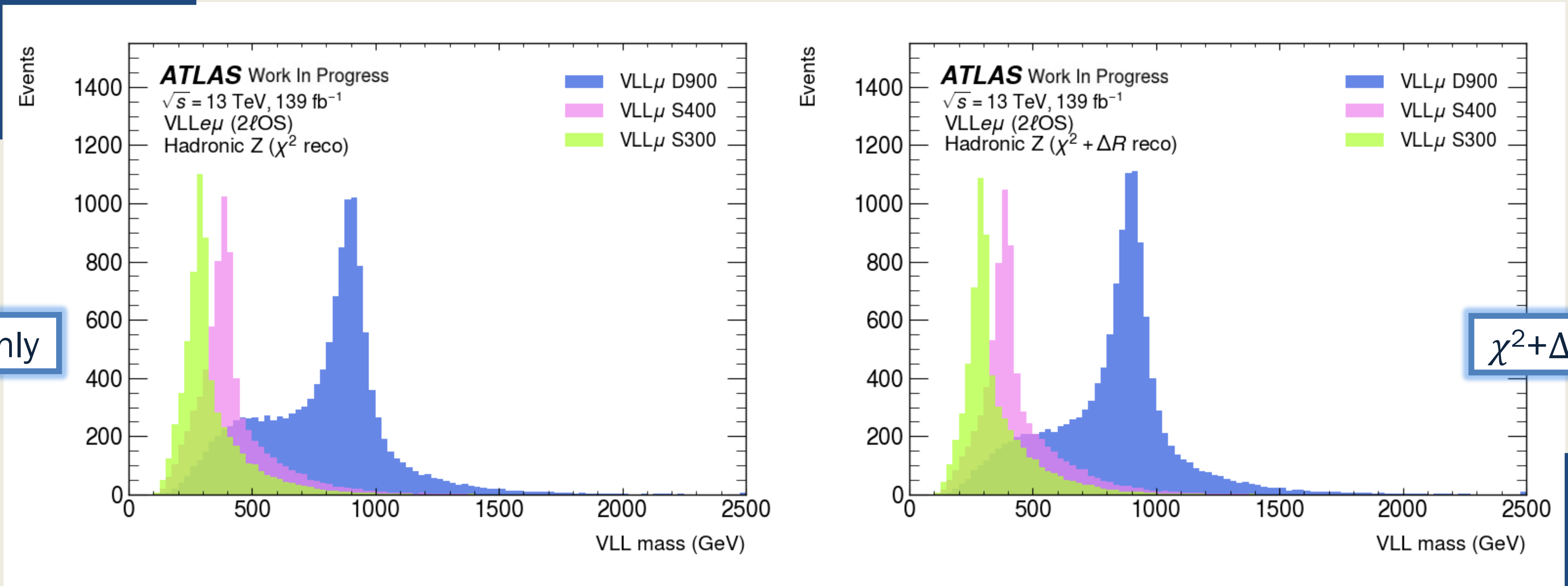


Only seven signal samples are available:

- 2 for VLL_e doublet model (800 and 1300 GeV),
- 2 for VLL_e singlet model (800 and 1000 GeV),
- 1 for VLL_μ doublet model (900 GeV),
- 2 for VLL_μ singlet model (300 and 400 GeV)

Even if one decay is compatible with multiple channels, the different lepton multiplicity final states might lead to plots of varying quality.





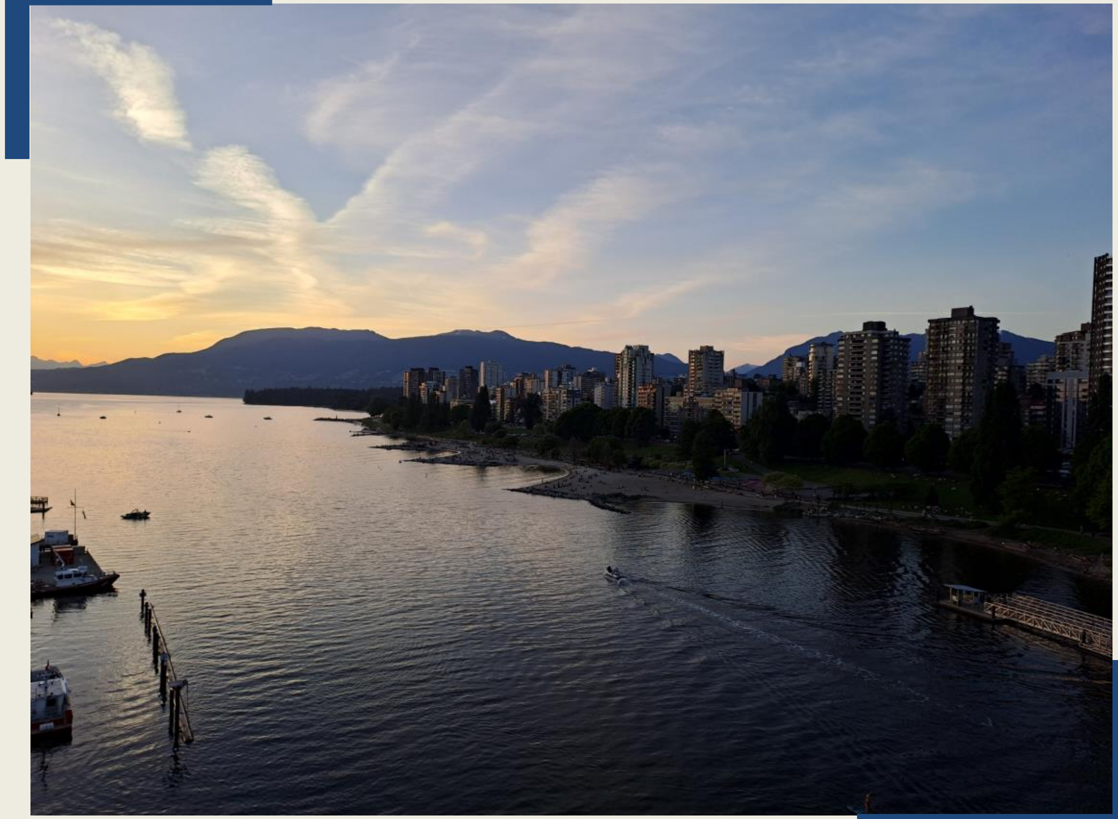
χ^2-only

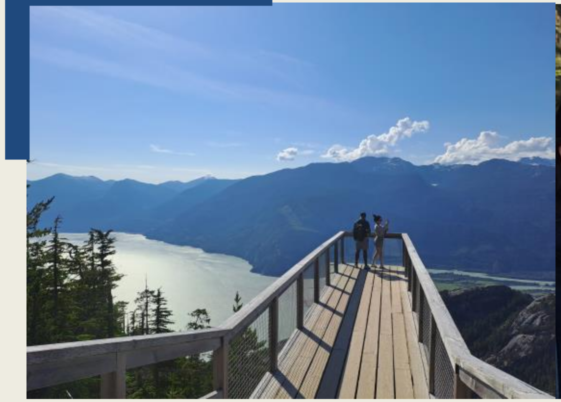
χ^2+ΔR

Conclusions and outlook

- Vector-like fermions are predicted by numerous BSM theories
- Vector-like leptons coupling to light leptons have yet to be investigated experimentally in ATLAS
- The invariant mass reconstruction algorithm was created to fit seamlessly into the framework of the analysis
- In the future
  - The algorithm can be tested on a wider range of samples
  - More decay modes can be added
  - The mass reconstruction can be used by the DNN or during the fitting procedure

THANK YOU






TRIUMF

INTRODUCTION

Many experiment results show good agreement with the SM predictions

Hiccups

However, there is evidence of new physics:

- Neutrino oscillation
- Rare decay processes of B-mesons
- Observation of dark matter
- Anomalous magnetic moment of the muon

A possible extension

Vector-like fermions

- particles whose left-handed and right-handed components transform the same way
- do not interact with the W and Z bosons as V −A currents, but as pure V currents

Compatible with: super-symmetric theories, string theories, …

$m\overline{\psi_L}\psi_R$ directly in the Lagrangian

Vector Like Fermions

Vector-like quarks (VLQs)
- Interact strongly
- Both single and pair production possible with proton-proton machines
- Constrains from QCD
- Searches are quite advanced (e.g. VLQs with ATLAS)

Vector-like leptons (VLLs)
- Do not interact strongly
- Only pair-production, primarily in Drell-Yan processes
- Production cross-section depends on the choices of weak isospin and weak hypercharge for the new states
- Searches on VLLs coupling to third generation leptons are quite advanced

Vector Like Fermions

Vector-like quarks (VLQs)
- Interact strongly
- Both single and pair production possible with proton-proton machines
- Constrains from QCD
- Searches are quite advanced (e.g. VLQs with ATLAS)

Vector-like leptons (VLLs)
- Do not interact strongly
- Only pair-production, primarily in Drell-Yan processes
- Production cross-section depends on the choices of weak isospin and weak hypercharge for the new states
- Searches on VLLs coupling to third generation leptons are quite advanced

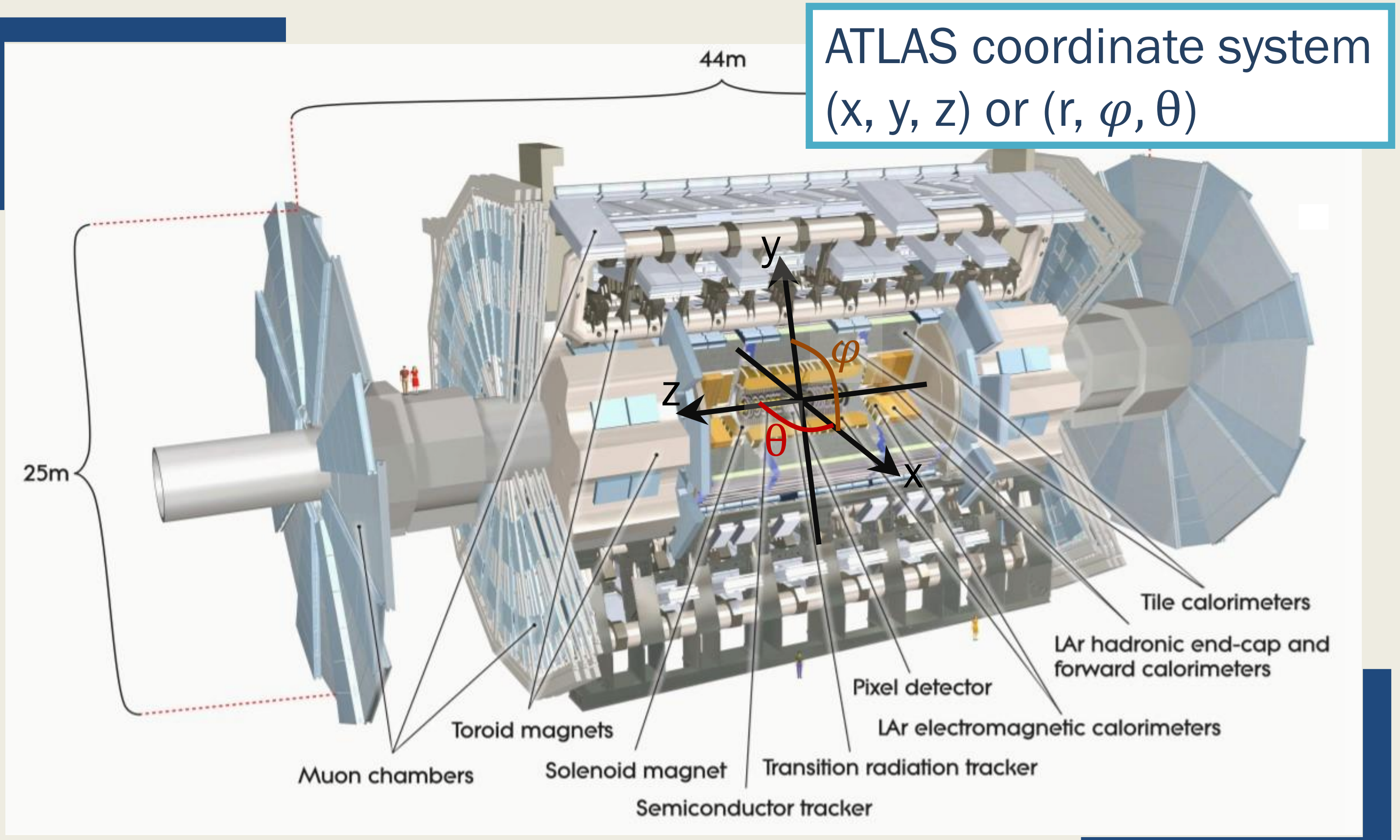
Current limits on VLL masses:
- × < 100 GeV (LEP)
- × Singlet 114-176 GeV (ATLAS)
- × Doublet VLL_τ 120-790 GeV (CMS)
- × Singlet VLL_τ 125-170 GeV + Doublet VLL_τ < 1045 Gev (CMS)
- × Doublet VLL_τ 120-900 GeV (ATLAS)

The ATLAS experiment

The analysis uses Run 2 proton-proton collision data collected with the ATLAS detector at $\sqrt{s}$= 13 TeV and 139 fb^{-1} of integrated luminosity.

Rich variety of final states requires all sub-detectors

- Inner detector for e, μ and b-quark identification
- Electromagnetic and hadronic calorimeters to detect showers
- Muon chambers for μ

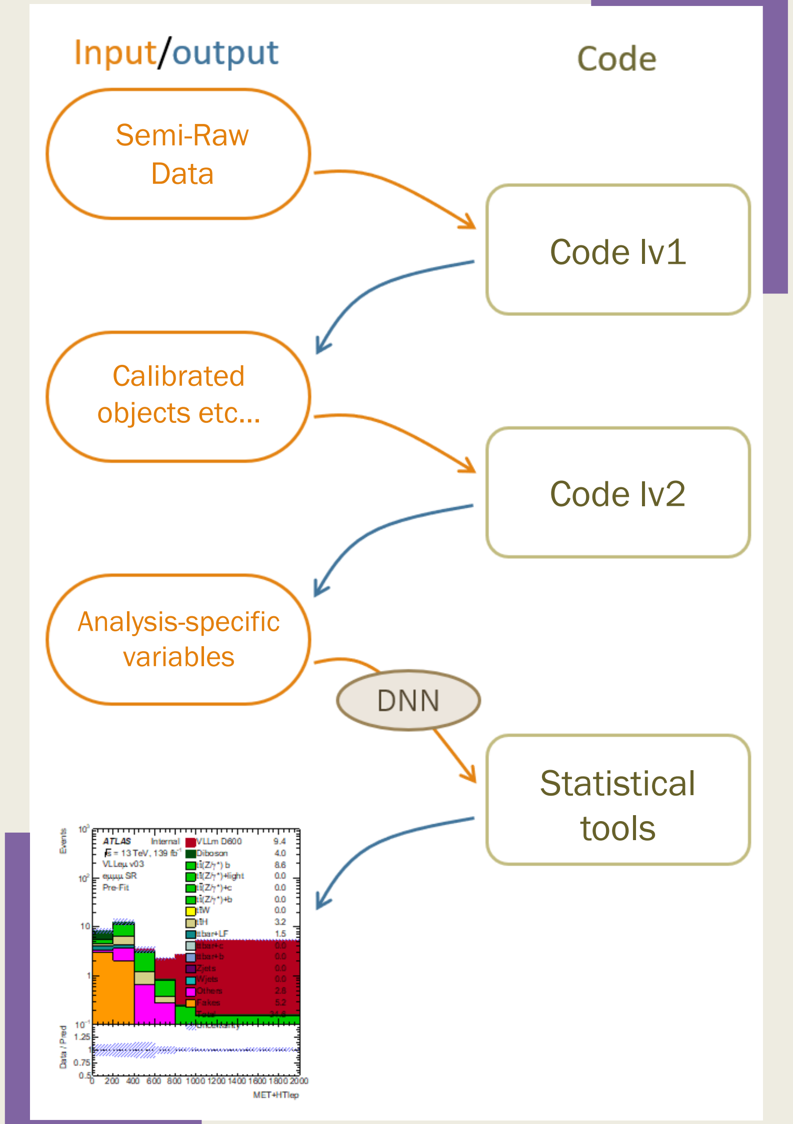


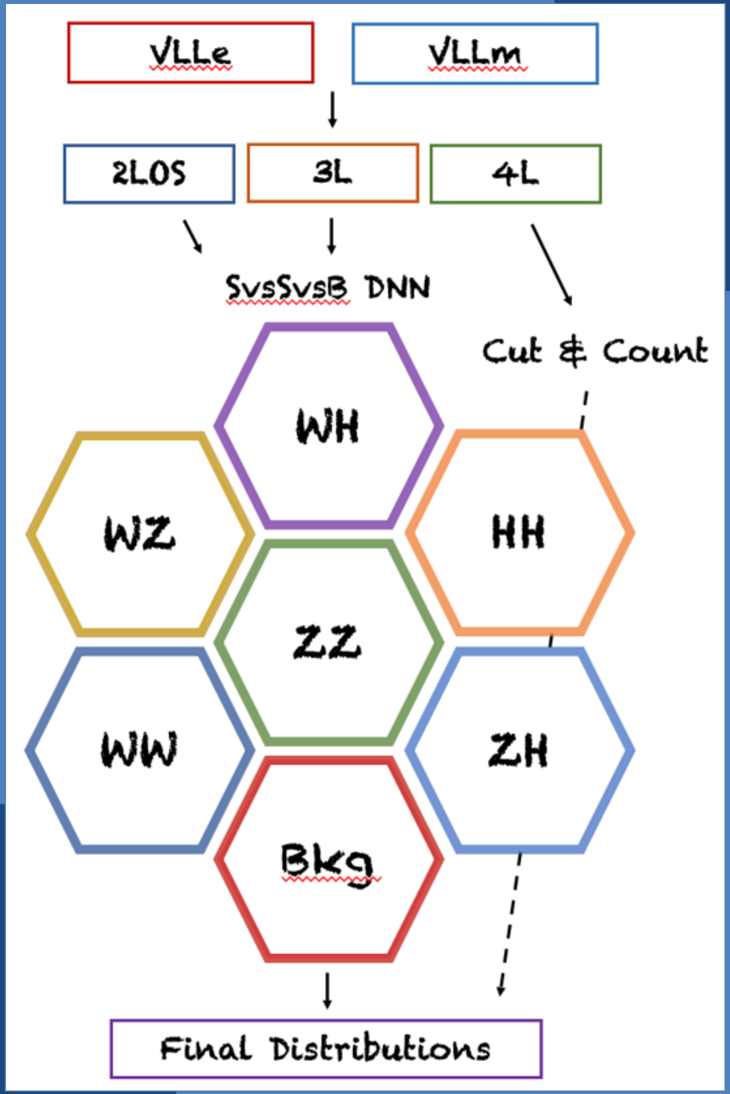
The $VLL_{e/\mu}$ analysis

Still a work in progress!

Signal Samples: *$VLL_{e/\mu}$* singlet & doublet samples @ NLO

- Masses: {150, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300} GeV
- **Blinding:** S/B > 5% where S = combined yield from *$VLL_{e/\mu}$* doublet at 600 GeV and at 1 TeV
- Orthogonal **Signal Regions** each targeting a specific signal topology, defined using lepton multiplicity (2ℓOS, 3ℓ, 4ℓ), and neural network cuts
- Target *VLL_e* and *VLL_μ* separately





From Harry's update

ANALYSIS STRATEGY

Single shot **Signal vs Signal vs Background** (**SvsSvsB**) **Deep Neural Network (DNN)** to discriminate between signal topologies in the 2ℓOS and 3ℓ channels

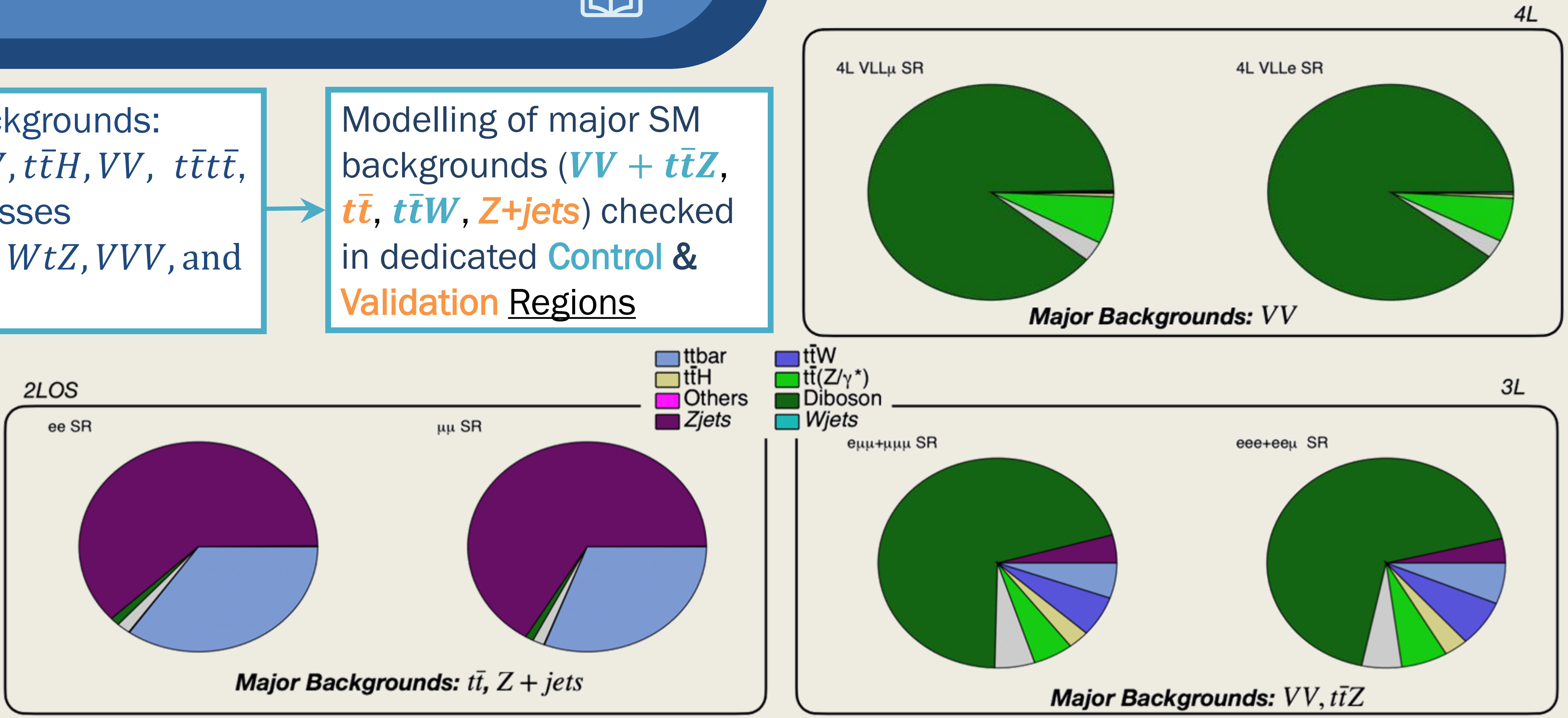
- Trained using VLL mass and flavour independent input variables
- 5 input variables, 2 hidden layers with 22 nodes each, 6 (4) output categories for 2ℓOS (3ℓ)
- Individual SM backgrounds treated with appropriate x-section

Shape analysis strategy for the 4ℓ channel due to reduced statistics/complexity

Backgrounds

Irreducible backgrounds: $t\bar{t}, Z + \text{jets}, t\bar{t}V, t\bar{t}H, VV,\ t\bar{t}t\bar{t}$, and rare processes ($t\bar{t}WW, tH, tZ, WtZ, VVV$, and $t\bar{t}t$)

→ Modelling of major SM backgrounds (***$VV + t\bar{t}Z$***, ***$t\bar{t}$***, ***$t\bar{t}W$***, ***Z+jets***) checked in dedicated Control & Validation Regions



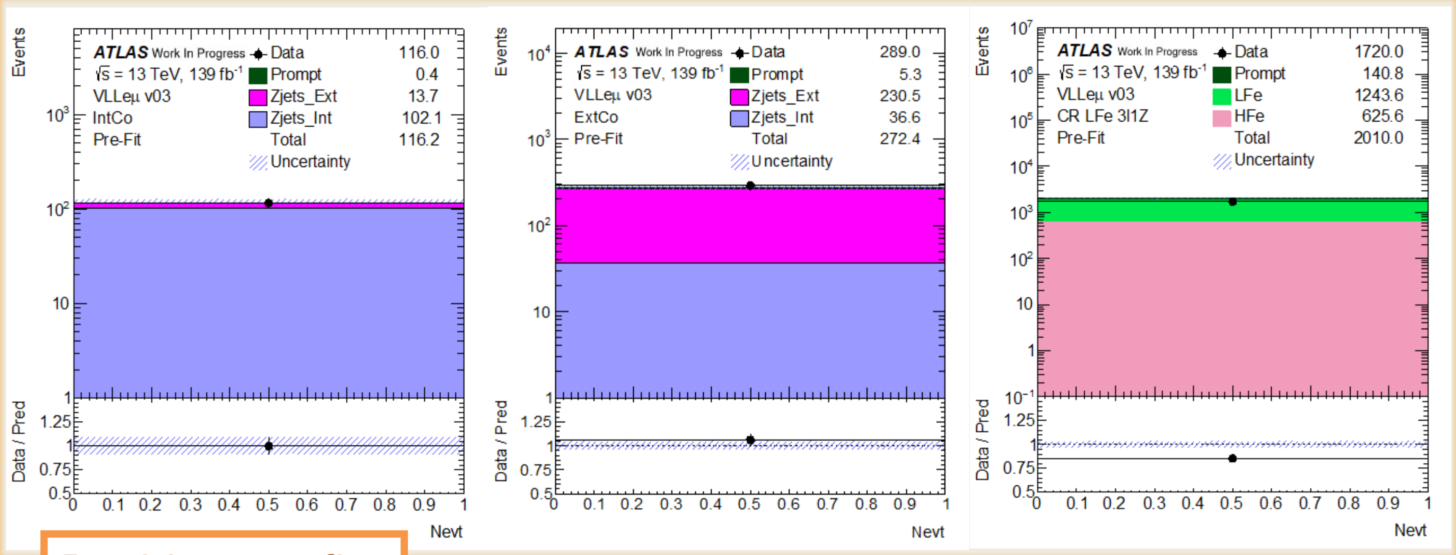
Reducible backgrounds with at least one fake or non-prompt lepton, mainly due to $t\bar{t}$ production.

→ Template fit method → Dedicated fake-enriched CRs

From Harry's update

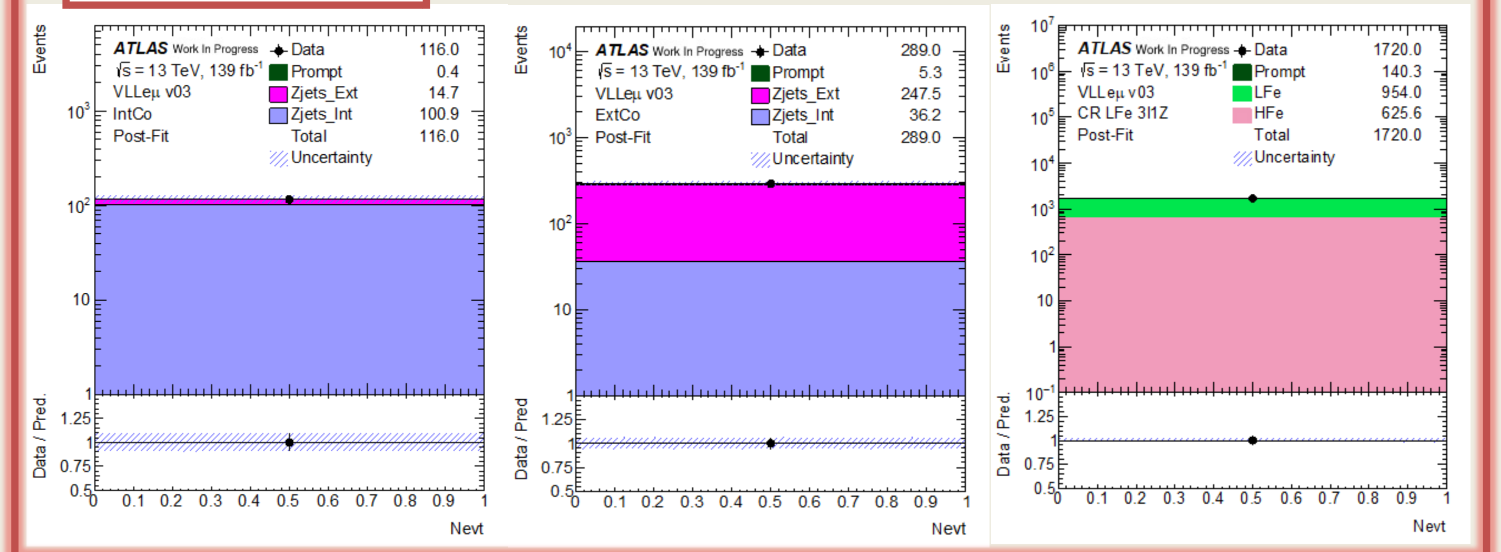
FITTING

- Simultaneous profile likelihood fit of BSM signal together with major SM backgrounds using TREXFITTER
  - ➢ Fit variable: HTlep+MET
  - ➢ Norm Factors: $t\bar{t}W$, $WZt\bar{t}Z$, fakes (HF_e, HF_μ, LF_e Internal/Material Conversions)
- **Results:** In case of no excess, the 95% CL upper limit will be evaluated on the production cross-section × branching ratio of the VLL signals as a function of the mass.

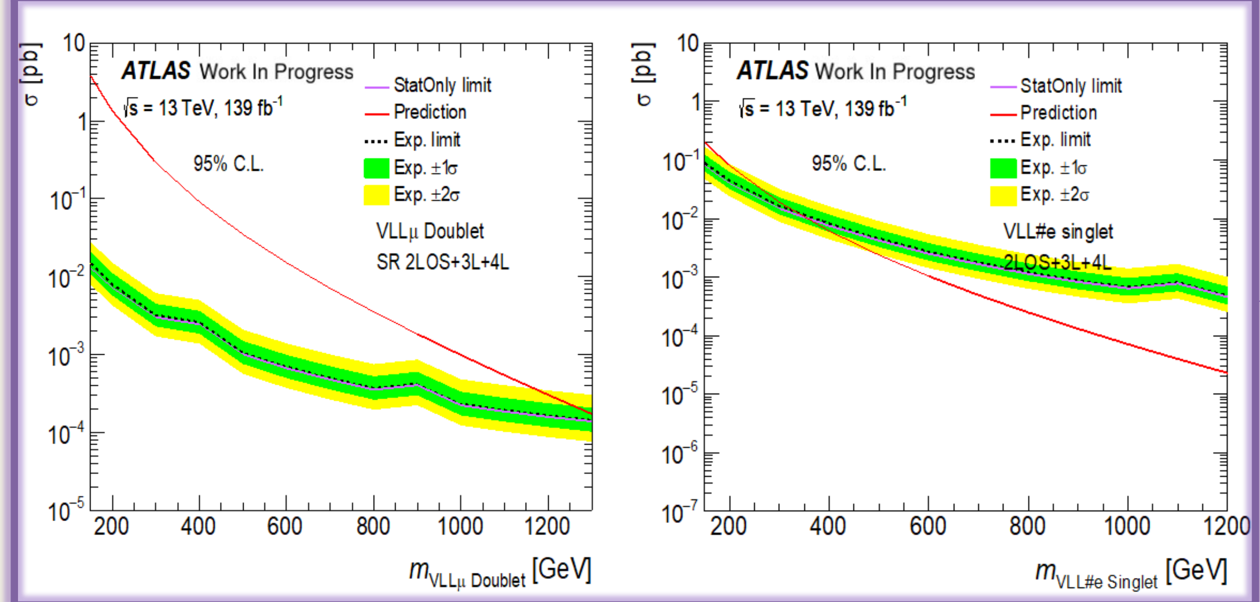


Pre bkg-only fit

Post bkg-only fit



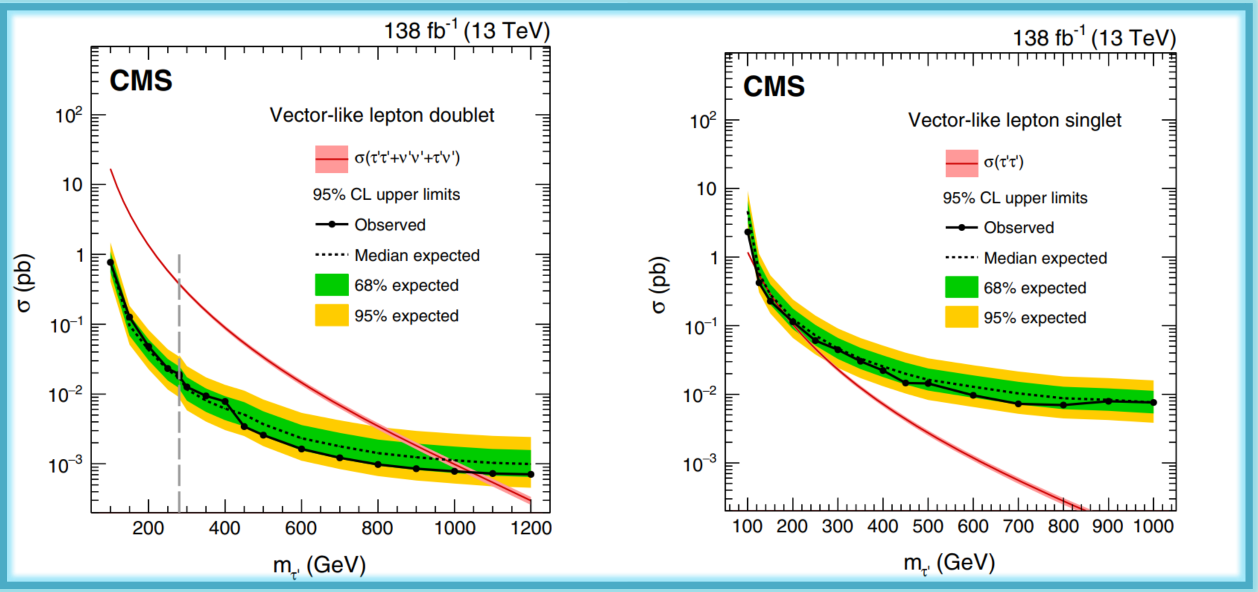
Preliminary results



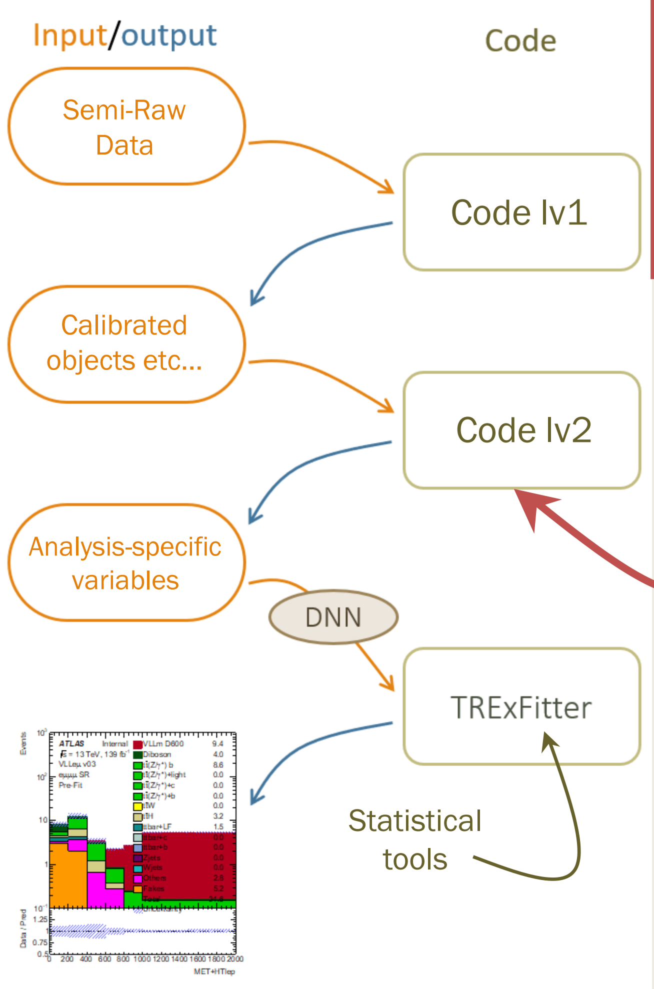
Fit with modelling uncertainties across all the SRs; using HTlep+MET as the fit variable

No final results, analysis is still blinded

Limits from the [CMS analysis]on VLL_τ



THE MASS RECONSTRUCTION ALGORITHM



WHY?

It can be a useful visualisation tool and a possible discriminating variable for the DNN or the fitting procedure

WHERE?

At the second coding level, using calibrated objects and producing variables plotted with TREXFITTER

HOW?

Let's get into it!

LEPTONIC W DECAYS

Additional reconstruction step in order to obtain the four-momentum of the ν

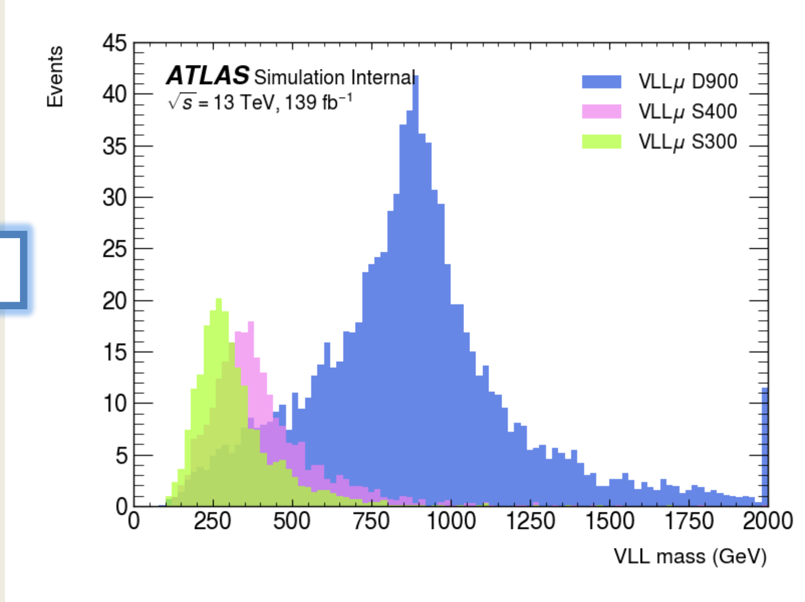
- Constraining the W to be on-shell
- Assuming all MET is due to one neutrino

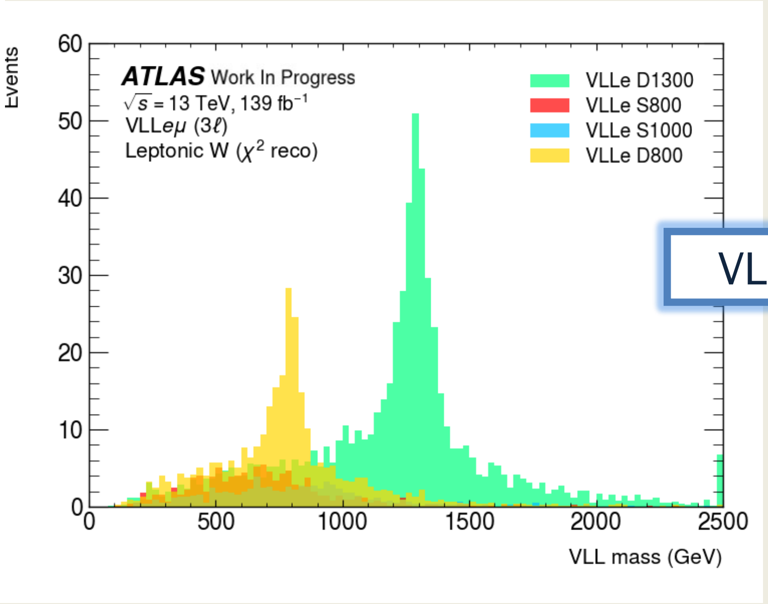
Calculate the neutrino's longitudinal momentum

Once one neutrino is reconstructed out of each charged lepton, a corresponding W boson is calculated

Selection of the boson to use for the VLL performed with the χ^2-only reconstruction.

VLL$_\mu$

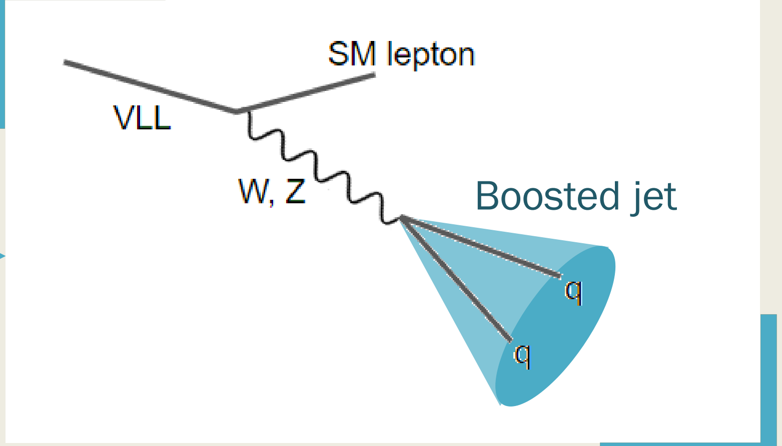




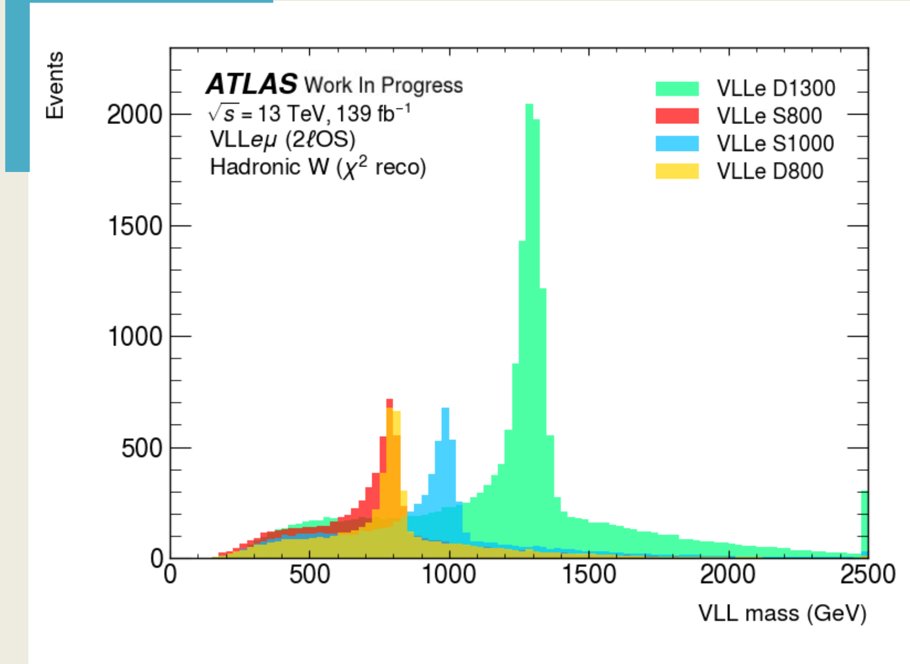
VLL$_e$

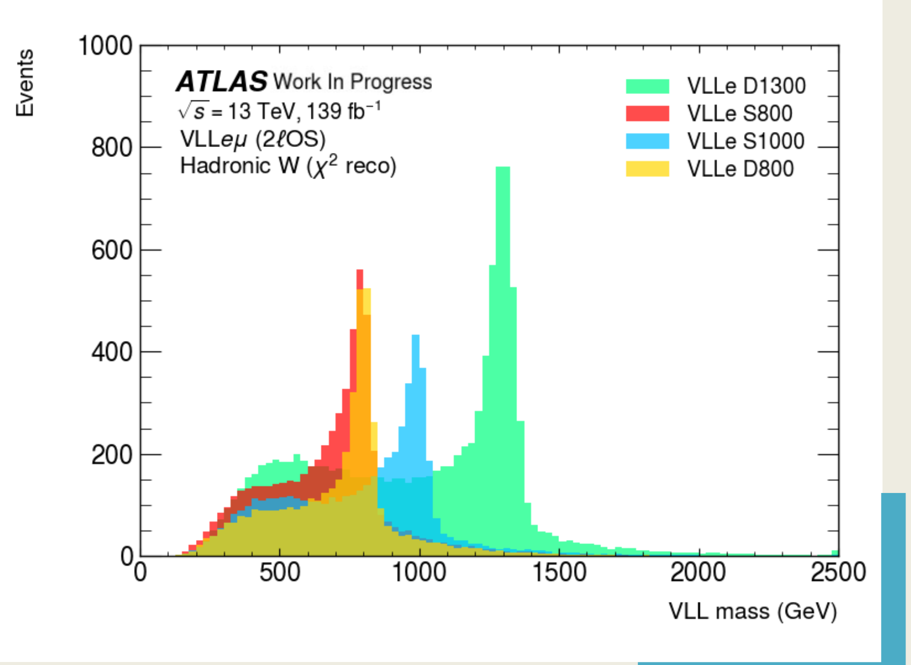
Boosted one-jet decays

Two jets can be too close to be reconstructed as two separate objects.



Reconstruct vector bosons out of a single boosted (pT > 50 GeV) jet whenever possible, otherwise employ the two-jet approach described for the $B \to f\bar{f}'$ topology





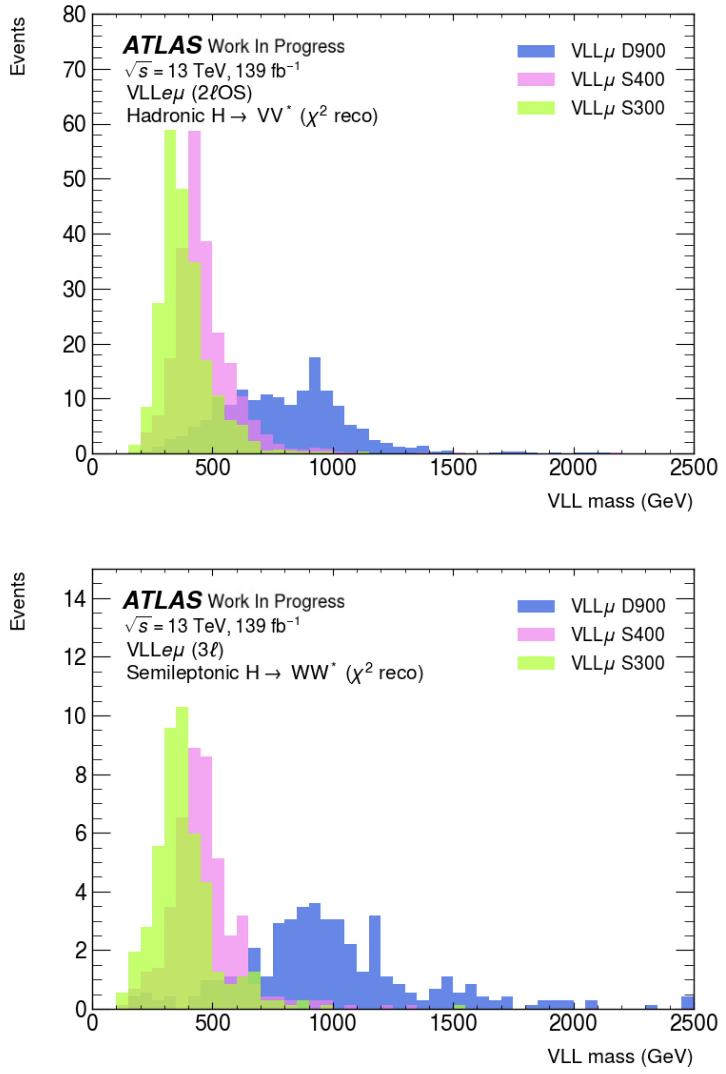
HIGGS DECAYS TO VECTOR BOSONS

$H \to WW^* \to 4q$ and $H \to ZZ^* \to 4q$,
$H \to WW^* \to 2q + \ell^{\pm}\nu$, and
$H \to ZZ^* \to 2q + 2\ell$

1. Fermions are paired up to form all possible bosons V
2. Set of Higgs bosons obtained by summing the four-momenta of all possible pairs of V's
3. Calculate the χ^2 defined as

$$\chi_H^2 = \frac{(m_H^{\text{reco}} - m_H^{\text{on-shell}})^2}{\sigma_H^2} + \frac{(m_V^{\text{reco}} - m_V^{\text{on-shell}})^2}{\sigma_V^2},$$

twice (using each V as the on-shell boson) and picking the lowest of the two
4. Pick the H boson with the lowest χ^2 (<10)



EXTRA THEORY BITS

A single weak-isosinglet bare fermion mass parameter M is mostly responsible for the new fermion masses, with a small Yukawa couplings ε to the Higgs field providing the mixing mass with the Standard Model τ lepton, which also has its own Yukawa coupling y_τ to the Higgs field.

The charged fermion mass matrix for the τ, τ' system in each case then can be written in the form

$$\mathcal{M} = \begin{pmatrix} y_\tau v & 0 \\ \epsilon v & M \end{pmatrix}$$

The tree-level mass eigenvalues, obtained from the square roots of the eigenvalues of $\mathcal{M}^\dagger\mathcal{M}$ after expanding for $y_\tau v$, $\varepsilon v \ll M$, are

$$M_\tau = y_\tau v(1 - \epsilon^2 v^2/2M^2 + \cdots)$$
$$M_{\tau'} = M(1 + \epsilon^2 v^2/2M^2 + \cdots)$$

while the tree-level neutral VLL mass in the doublet model is simply $M_{\nu'} = M$

- In the special case of no mixing with the tau lepton, ε = 0, the lightest VLL would be absolutely stable due to a conserved global symmetry.
- We assume instead that ε is a tiny perturbation in the mass matrix, but that it exceeds about 2×10^{-7}, which is large enough to allow the VLLs to decay promptly on collider detector length scales to Standard Model states
  - The fermion mass eigenstates then consist of a charged Dirac pair τ'^+, τ'^- in both models, and a neutral Dirac pair $\nu', \overline{\nu'}$ in the doublet VLL model only

EXTRA FITTING BITS

The TRExFitter framework is used to perform the statistical analysis

Simultaneous maximum-likelihood fit of BSM signal together with major SM backgrounds

- In 8 of the control regions, the fit is performed on the total event yield.
- In the WZttZ CR control region the fitting variable is the b-jet multiplicity.
- In the signal regions targeting $VLL_{\mu,e}$, the HTlep+MET distribution is fitted to measure the $VLL_{\mu,e}$ signal cross sections, separately for the doublet and singlet models.

The likelihood function depends on three types of parameters:

- the signal-strength, defined as a multiplicative factor to the yield of all the VLL signal events;
- A set of 9 normalisation factors for the main backgrounds;
- A set of nuisance parameters (NPs) encoding systematic uncertainties in the signal and background expectations.

The test statistic

$$q_0 = -2\ln\left(\frac{\mathcal{L}(\mu = 0, \hat{\hat{\vec{\lambda}}}_{\mu=0}, \hat{\hat{\vec{\theta}}}_{\mu=0})}{\mathcal{L}(\hat{\mu}, \hat{\vec{\lambda}}_{\hat{\mu}}, \hat{\vec{\theta}}_{\hat{\mu}})}\right)$$

the values of the parameters that maximise the likelihood function when μ is fixed to zero

values of the parameters that maximise the likelihood function

is used to quantify the agreement between the observed data and the background-only hypothesis (no VLL-like phenomena), as well as to make statistical inferences about the signal strength.

Neutrino momentum reconstruction

$$p_{z,\nu} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \quad \text{with}$$

$$a = \left(\frac{p_{z,\ell}}{p_\ell}\right)^2 - 1,$$

$$b = 2\left(\frac{p_{x,\ell}\not{p}_x + p_{y,\ell}\not{p}_y}{p_\ell} + \frac{m_W^2}{2p_\ell}\right)\frac{p_{z,\ell}}{p_\ell},$$

$$c = \left(\frac{p_{x,\ell}\not{p}_x + p_{y,\ell}\not{p}_y}{p_\ell} + \frac{m_W^2}{2p_\ell}\right)^2 + \not{p}_T^2.$$

Here, $\not{p}_{(x,\,y)}$ are the (x, y) components of the missing transverse momentum and $p_{(x,\,y,\,z),\,\ell}$ are the (x, y, z) components of the transverse momentum of the charged lepton.

The twofold ambiguity in the longitudinal component can be solved by choosing the smallest root in absolute value

TEMPLATE FIT METHOD

Technique used to estimate multiple fake lepton backgrounds by performing a simultaneous fit of numerous control regions

Leaving the normalisation of various "fake" contribution templates free-floating in a fit to data.

Obtained from MC simulations of all processes contributing to the non-prompt lepton background,

These normalisation factors are then employed to correct the fake MC estimates.

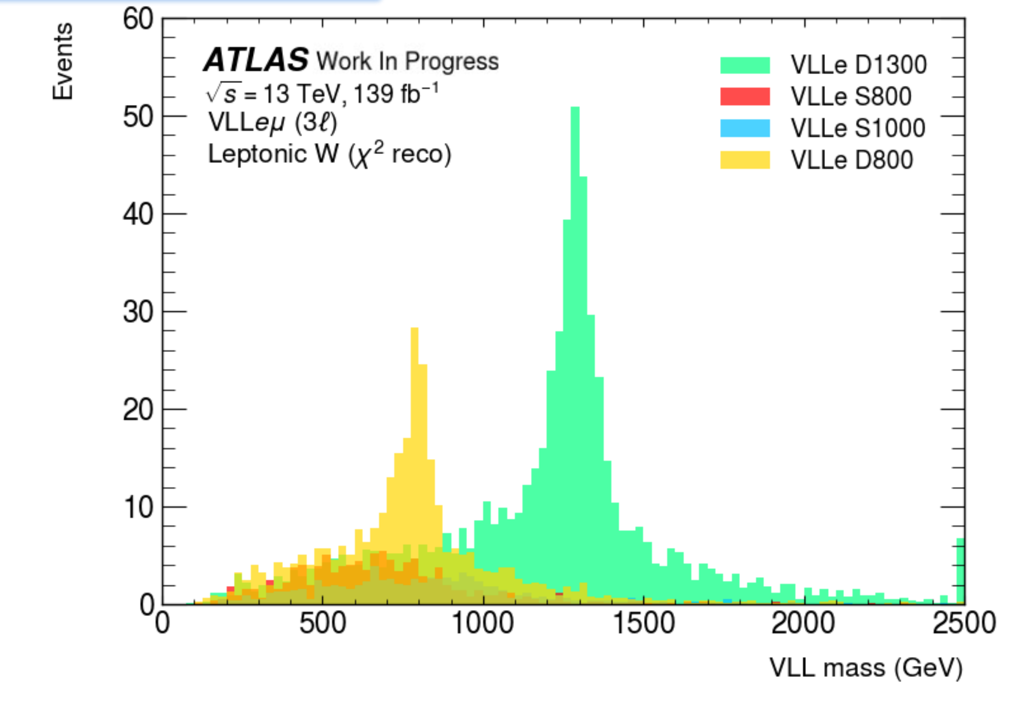
Uses a profile likelihood fit, assigning one scale factor per fake source (along with any additional non-fake correction factors), and a minimal set of nuisance parameters.

Defines distinct types of fake/non-prompt leptons using truth information from MC

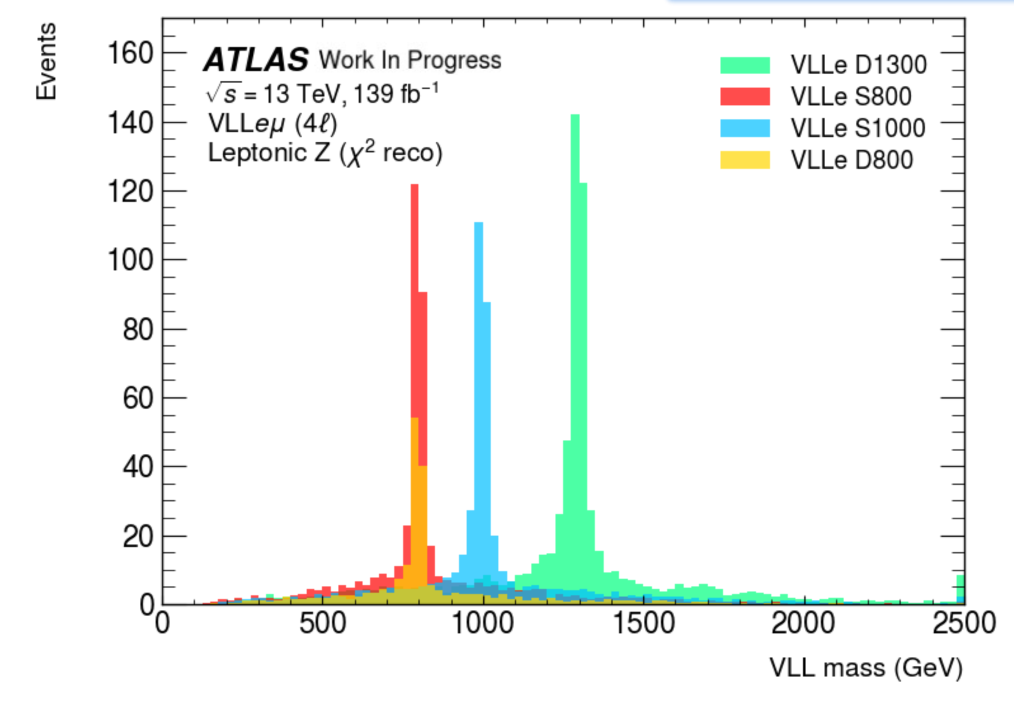
	$2\ell OS$				3ℓ		
	HF_e^{PLIV}	HF_μ^{PLIV}	$HF_e^{FCLoose}$	$HF_\mu^{FCLoose}$	IntCO	MatCO	LF_e
Signature	μe	$\mu\mu \mid\mid e\mu$	μe	$\mu\mu \mid\mid e\mu$	$e\mu\mu$		$eee \mid\mid e\mu\mu$
Isolation WPs	TM		TL		TTT		TTL
ℓ p_T [GeV]	> 20				$> 10, 20, 20$		> 10
Total Charge	± 1						
Ntaus	0						
Njets	≥ 2				≥ 0		
Nbjets	1 @ 77%				0 @ 77%		0 @ 85%
Z Veto	No				OS Pair		No
Inv Mass	-				$\lvert M_{lll} - M_Z \rvert < 10$		$\lvert M_{01} - M_Z \rvert <$ 10 & $150 \leq M_{lll} \leq 250$
CO Candidate	!MatCO & !IntCO				IntCO	MatCO	!MatCO & !IntCO
Additional Cuts	M_T (all ℓ, MET) < 250 GeV				-		$nWZ_{had} = 0$ & $8 \leq MET \leq 30$
Fitted Variable	No. of events						

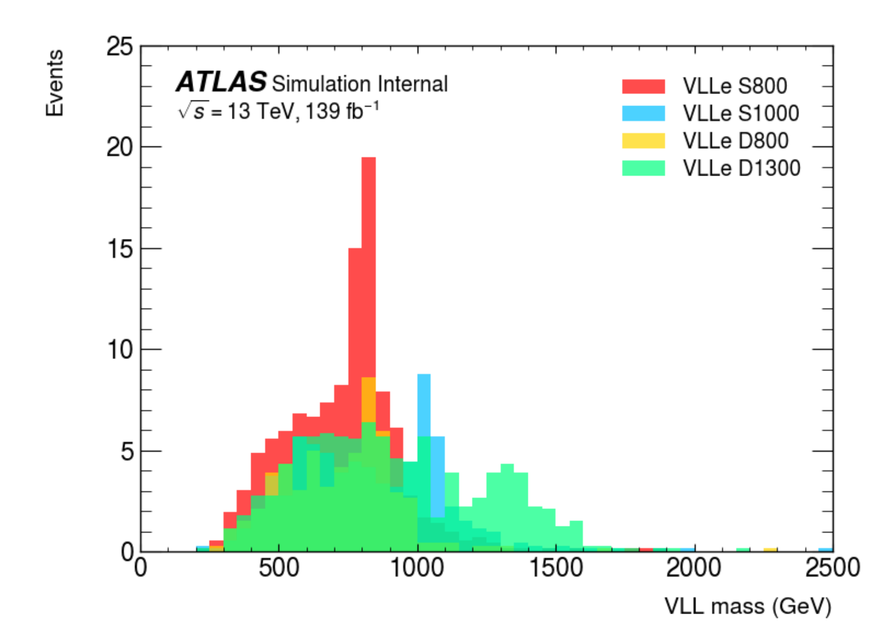
Leptonic decays

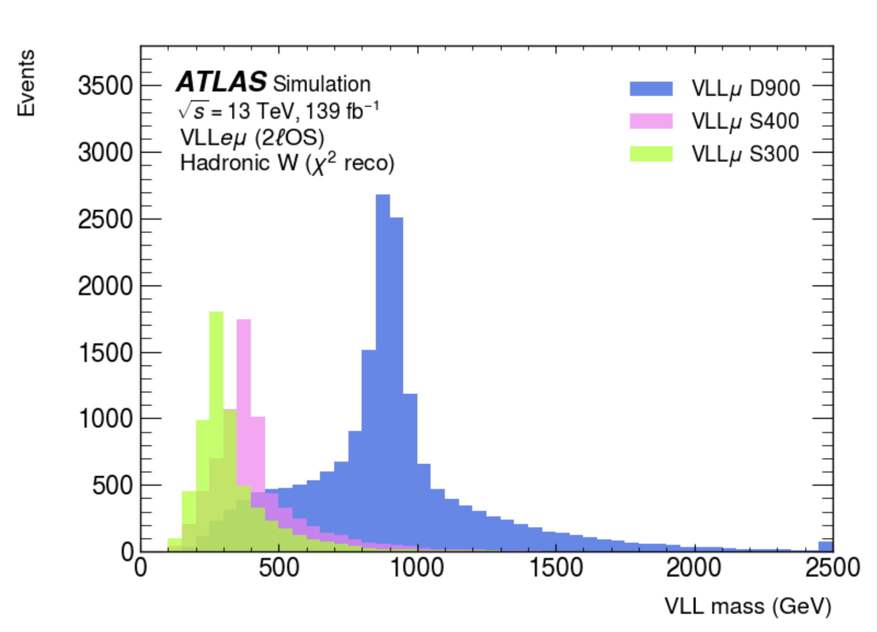
VLL$_e$ $(W \to \ell\nu)$

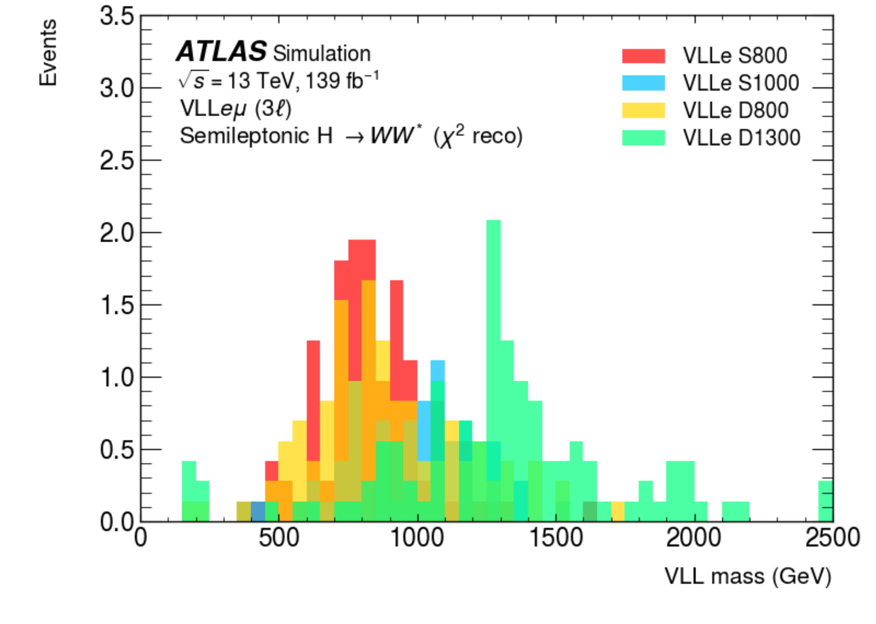


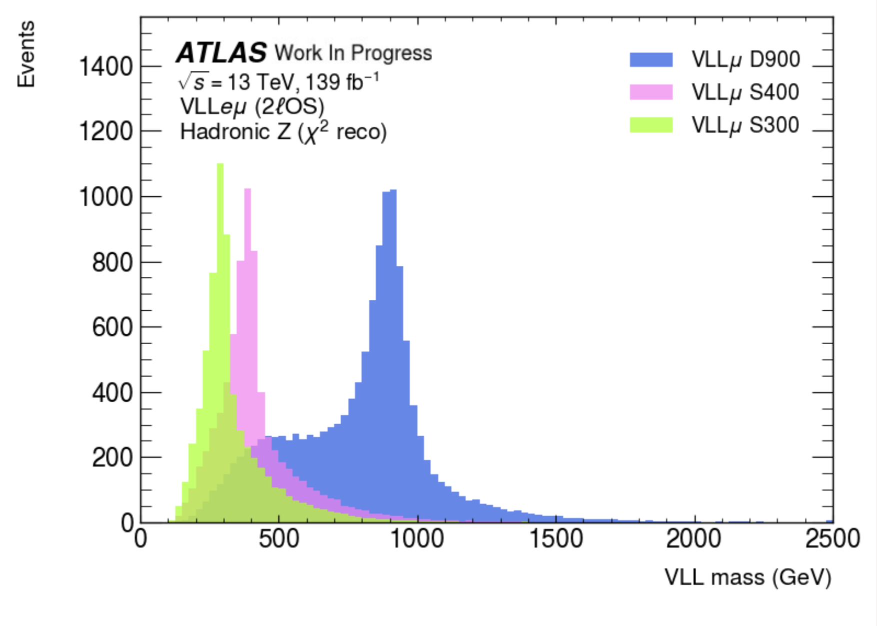
VLL$_e$ $(Z \to \ell^+\ell^-)$




ATLAS Simulation Internal
√s = 13 TeV, 139 fb⁻¹
VLLe S800
VLLe S1000
VLLe D800
VLLe D1300
Events
VLL mass (GeV)


ATLAS Simulation
√s = 13 TeV, 139 fb⁻¹
VLLeμ (2ℓOS)
Hadronic W (χ² reco)
VLLμ D900
VLLμ S400
VLLμ S300
Events
VLL mass (GeV)


ATLAS Simulation
√s = 13 TeV, 139 fb⁻¹
VLLeμ (3ℓ)
Semileptonic H → WW* (χ² reco)
VLLe S800
VLLe S1000
VLLe D800
VLLe D1300
Events
VLL mass (GeV)


ATLAS Work In Progress
√s = 13 TeV, 139 fb⁻¹
VLLeμ (2ℓOS)
Hadronic Z (χ² reco)
VLLμ D900
VLLμ S400
VLLμ S300
Events
VLL mass (GeV)

Signal regions

Lepton category	2ℓOS	3ℓ	4ℓ
Lepton p_T[GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
Lepton Quality	Electrons: FCLooseIso + TightLH ID Muons: FCLooseIso + Medium ID		Electrons: FCLooseIso Muons: FCLooseIso
PLIV	–	Tight or Medium on SS leptons	–
mllOSSF [GeV]	>15	–	
$\|mllOSSF - m_Z\|$ [GeV]	>10	>10	–
N_{jets}	≥ 2	≥ 1	≥ 0 (1SFOS) ≥ 1 (2SFOS)
Misc	total_lep_charge = 0		
Region split	{(HH, HV, VV, lvHV, lvVV, SM) × (e, μ)}	{(HH+HW, VV+HZ, lvHW, SM) × (e, μ)}	(1SFOS, 2SFOS) × (e, μ)

Signal-vs-Signal-vs-Background Neural Networks (S-vs-S-vs-B NNs) trained in each channel (2LOS and 3L) to discriminate between signal topologies

- Remain optimal for the target VLL search as 100% of the accepted signal is analysed in the fit
- Advantages: approach has the potential to catch any similar non VLL-like BSM signature in the absence of an overall excess in the search + easy close-to-optimal re-interpretation for other BSM theories.

Input variables for training:

- No. of jets
- Sum of pseudo-continuous b-tagging score
- No. of Higgs⟶bb
- No. of hadronic W/Z decays
- Missing Transverse Energy

Variables are chosen to be mass and flavour independent, so DNN is correlated to but does not learn specifically about VLL topologies

DNN Architecture

- The training of the DNN is done using the **Keras** library with **Tensorflow** as a backend and the variables listed to the right are used to discriminate between the categories
- 2 dense layers with 22 nodes each with a drop-out rate of 0.2 between the layers
- Activation functions for the 2 dense layers are rectified linear units (ReLu)
- The network is trained with batch size of 2,000 with a maximum number of epochs set to a large number of $\mathcal{O}(100)$, and the model evaluated in the last epoch is chosen
- Each event is classified in one of the 6(4) classes in the 2ℓOS (3ℓ) channel by the NN - the predicted class for each event is interpreted as the highest amongst the class probability assigned to it

Input variables for training:

- ❑ No. of jets
- ❑ Sum of pseudo-continuous b-tagging score
- ❑ No. of Higgs→bb
- ❑ No. of hadronic W/Z decays
- ❑ Missing Transverse Energy

Variables are chosen to be mass and flavour independent

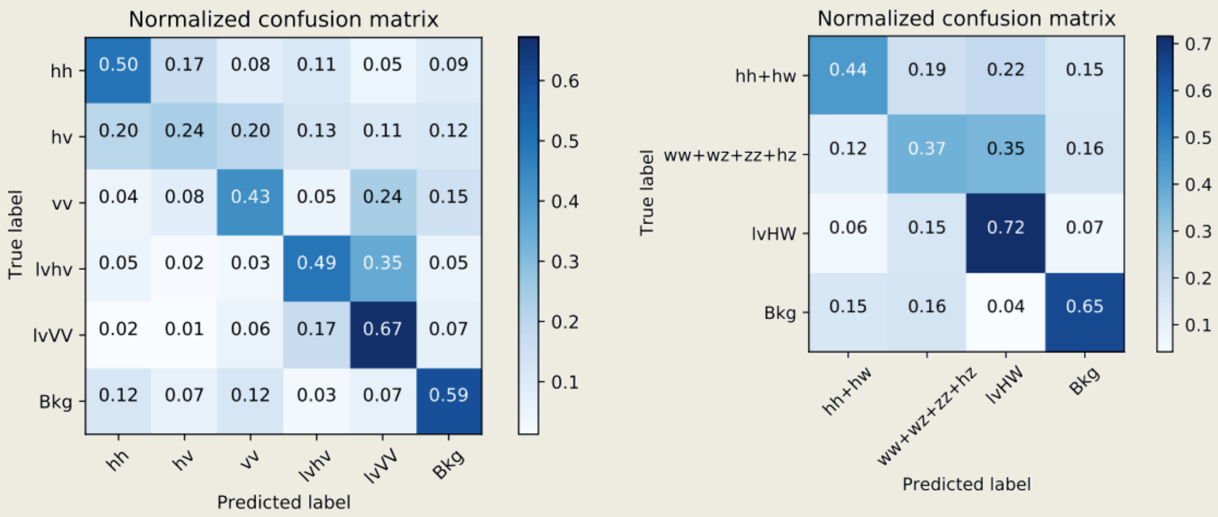


Figure 5: Normalised confusion matrices for 2ℓSS (left) and 3ℓ (right).

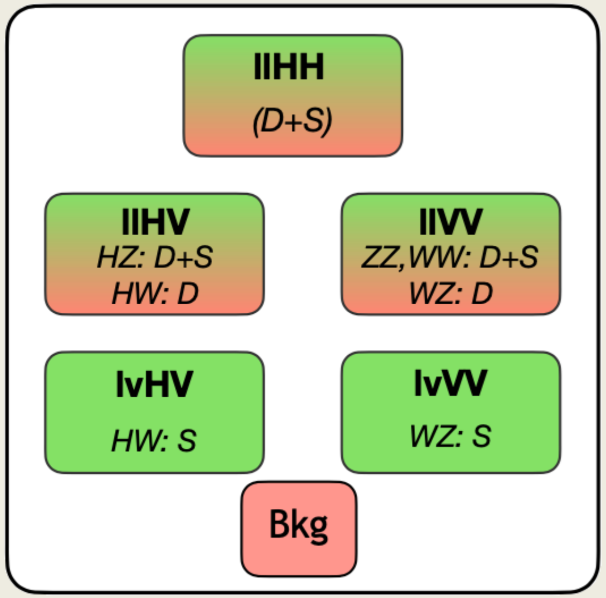
Signal Categories

From Harry's update

2LOS

OS leptons pT>20 GeV; FCLoose Iso; Medium ID mu/TightLH ID e; nJ >=2, Z veto

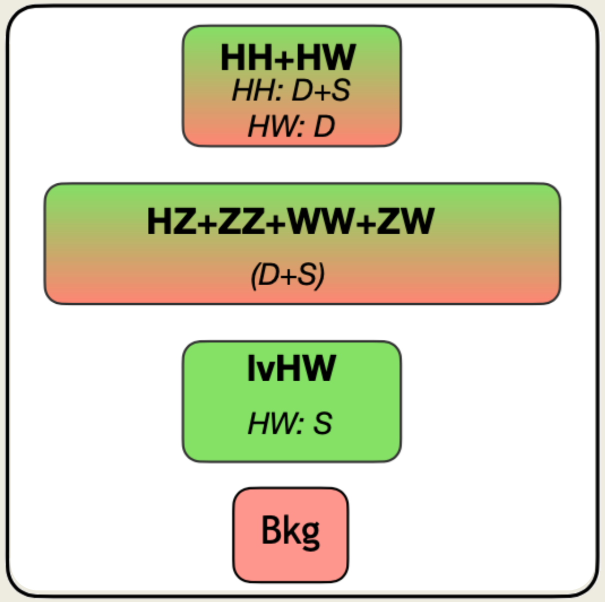
- **llHH:** 2 $h \to bb$ (high n(b)Jets, low MET)
- **llHV:** 1 $h \to bb$ & 1 $Z/W \to qq$ (high nJets, nbjets, low MET)
- **llVV:** 2 $Z/W \to qq$ (high nJets, low MET)
- **lvHV: 1** $h \to bb$ & 1 $W \to l\nu$ (low nJets, bjets, High MET)
- **lvVV:** 1 $Z/W \to qq$ & 1 $W \to l\nu$ (low nJets, High MET)



3L

pT>10,20,20 GeV; FCLoose Iso; Medium ID mu/TightLH ID e; T|| M on SSlepton pair; nJ >=1, Z veto; lepQ = +-1

- **HH+HW:** 1 h & 1 $W \to l\nu$ (from h in the case of hh production): high n(b)Jets, low MET
- **HZ+ZZ+WW+ZW:** 1 $Z \to qq$ and 1 $h \to WW$ (low nJets, low MET)
- **lvHW:** 1$W \to qq$ & 1 $h \to WW$ (low nJets, High MET)



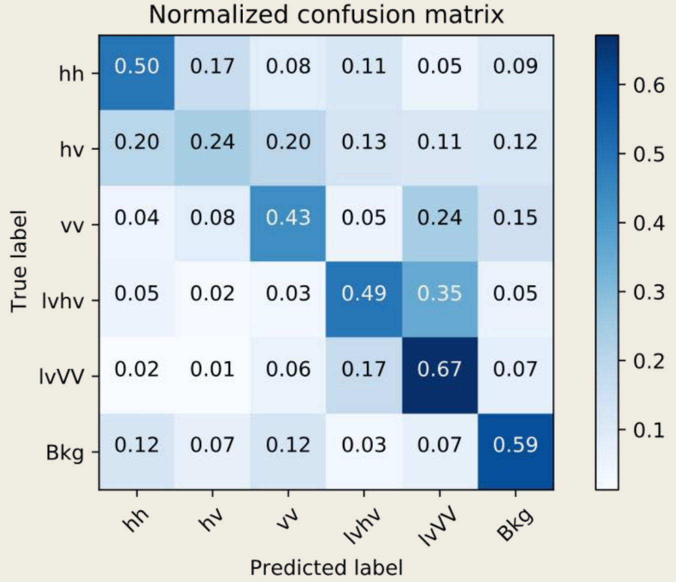
SIGNAL CATEGORIES

From [Harry's update]

2LOS

OS leptons pT>20 GeV; FCLoose Iso; Medium ID mu/TightLH ID e; nJ >=2, Z veto

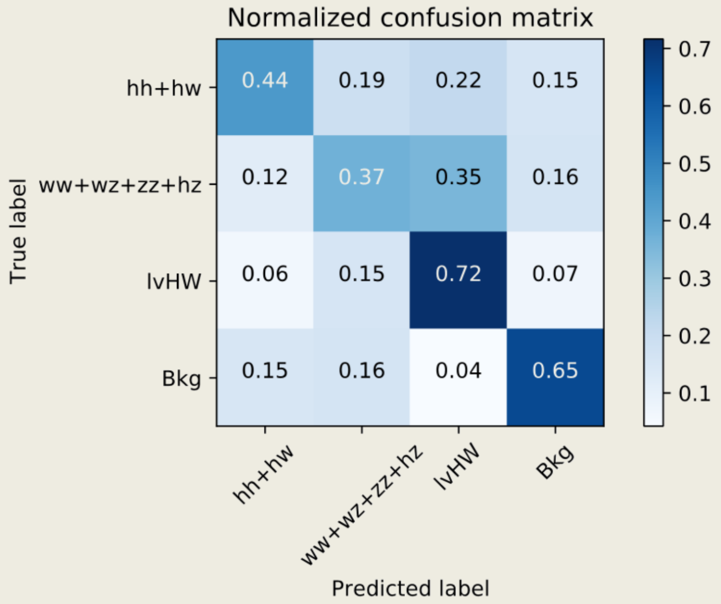
- **llHH:** 2 $h \rightarrow bb$ (high n(b)Jets, low MET)
- **llHV:** 1 $h \rightarrow bb$ & 1 $Z/W \rightarrow qq$ (high nJets, nbjets, low MET)
- **llVV:** 2 $Z/W \rightarrow qq$ (high nJets, low MET)
- **lvHV: 1** $h \rightarrow bb$ & 1 $W \rightarrow l\nu$ (low nJets, bjets, High MET)
- **lvVV:** 1 $Z/W \rightarrow qq$ & 1 $W \rightarrow l\nu$ (low nJets, High MET)



3L

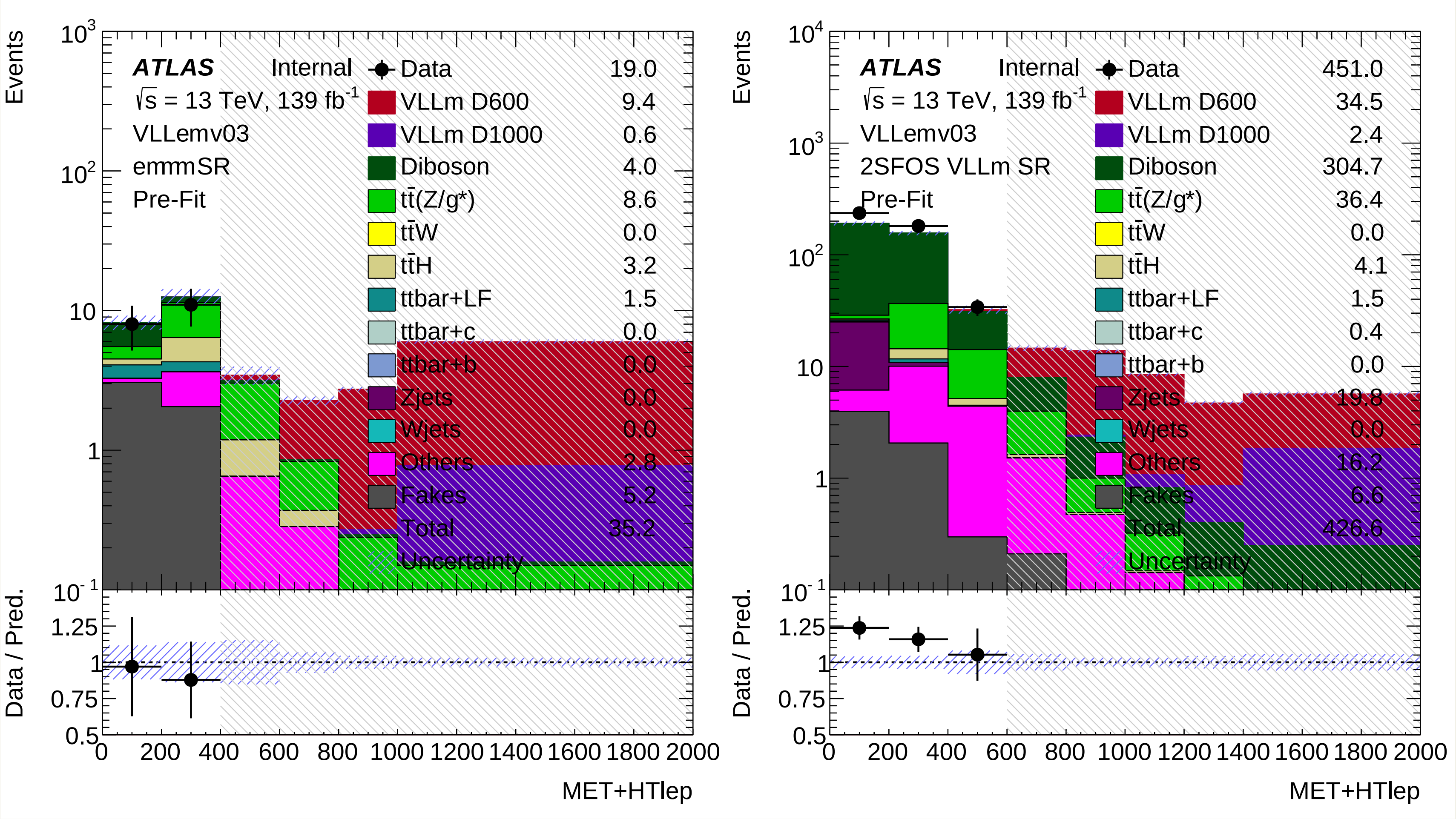
pT>10,20,20 GeV; FCLoose Iso; Medium ID mu/TightLH ID e; T|| M on SSlepton pair; nJ >=1, Z veto; lepQ = +-1

- **HH+HW:** 1 h & 1 $W \rightarrow l\nu$ (from h in the case of hh production): high n(b)Jets, low MET
- **HZ+ZZ+WW+ZW:** 1 $Z \rightarrow qq$ and 1 $h \rightarrow WW$ (low nJets, low MET)
- **lvHW:** 1$W \rightarrow qq$ & 1 $h \rightarrow WW$ (low nJets, High MET)



4ℓ Signal Regions

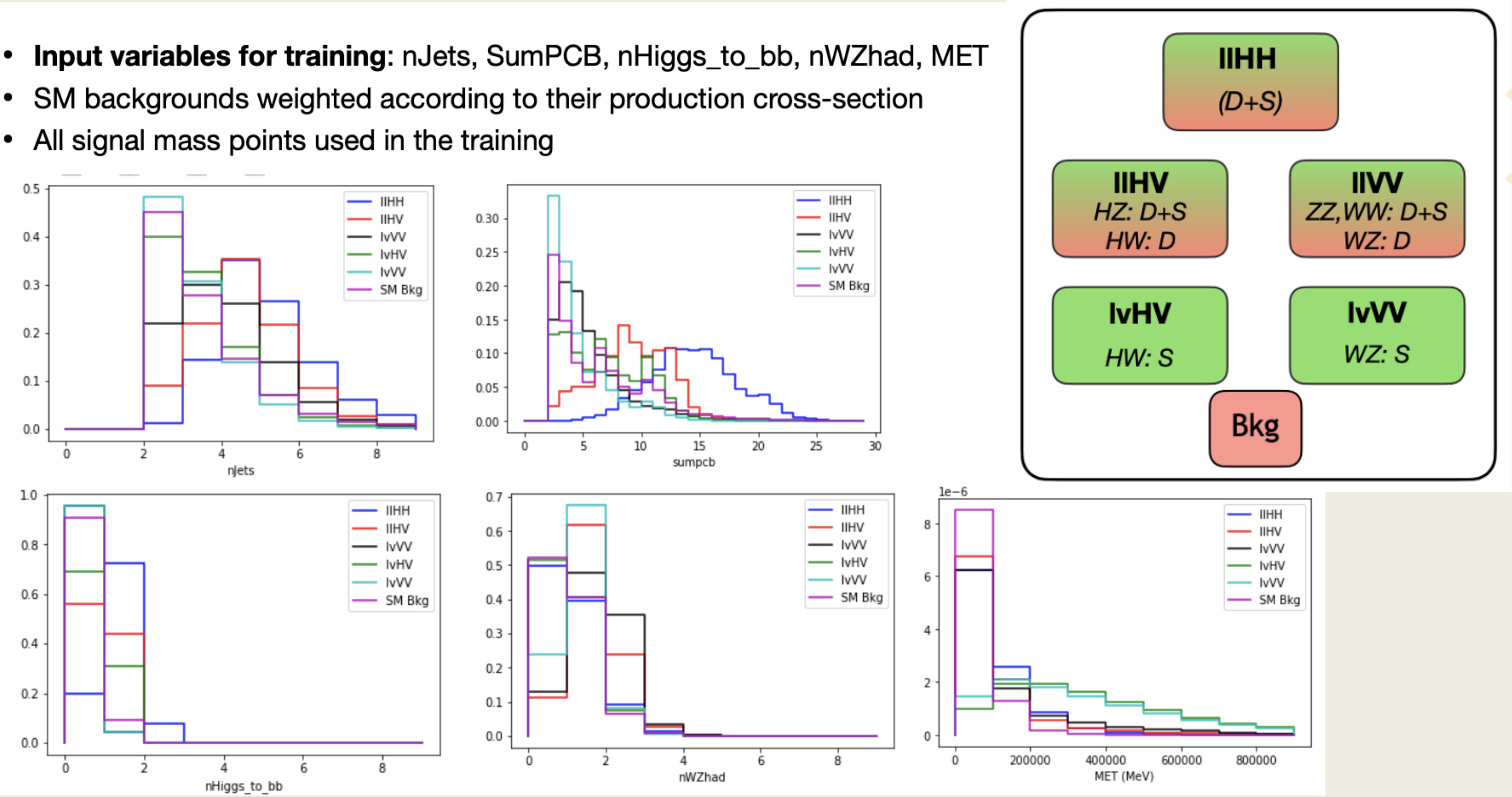
From Harry's update



2ℓOS SvsSvsB DNN

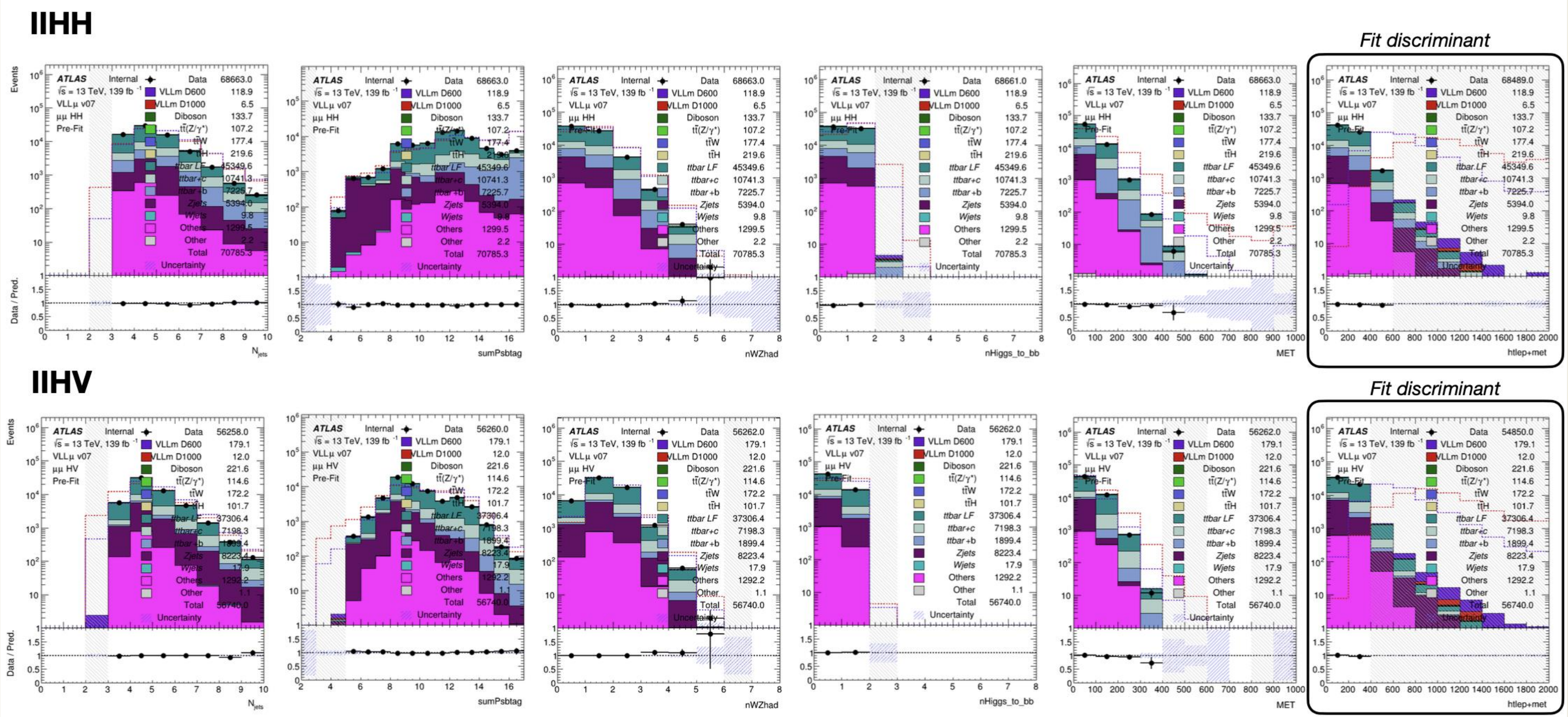
From Shalini's update

- **Input variables for training**: nJets, SumPCB, nHiggs_to_bb, nWZhad, MET
- SM backgrounds weighted according to their production cross-section
- All signal mass points used in the training



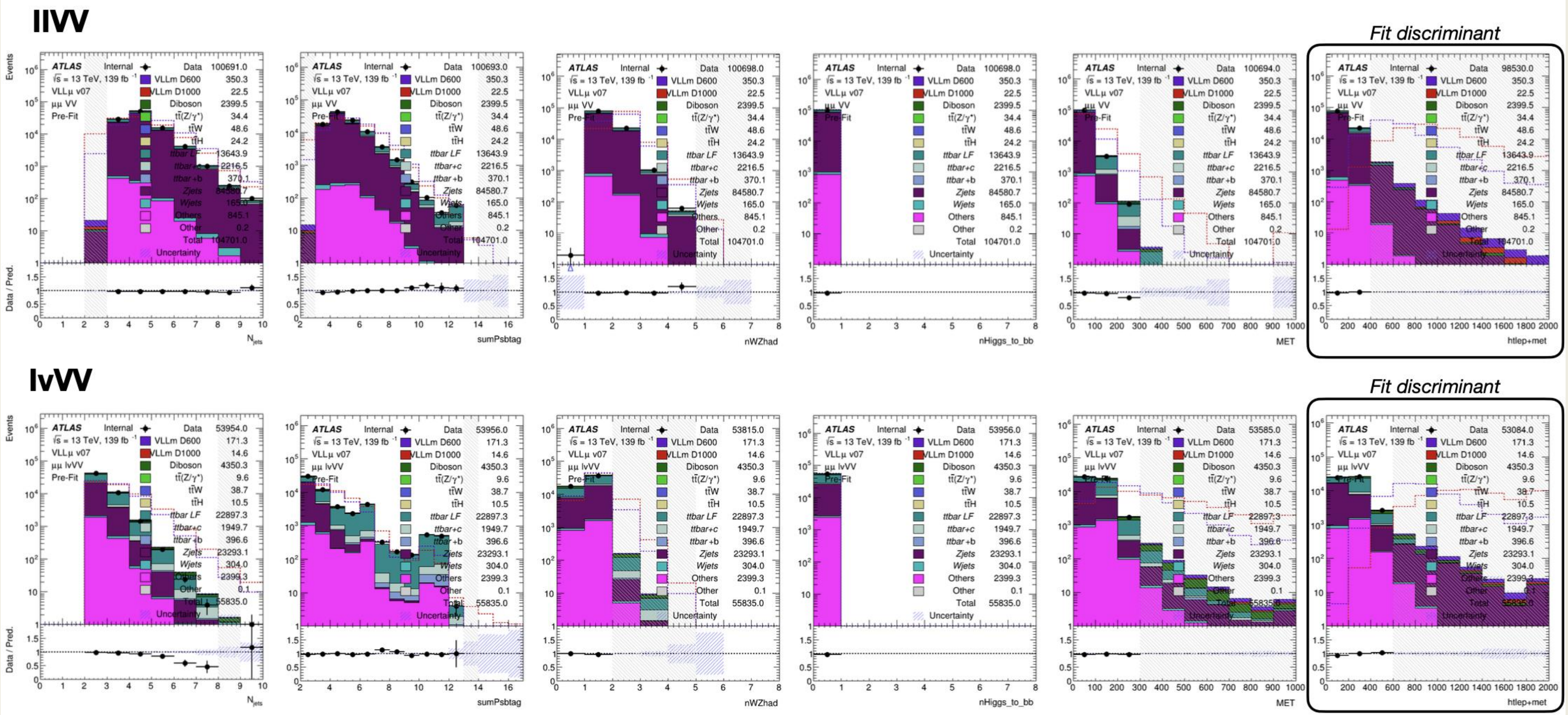
2ℓOS SvsSvsB DNN

From [Shalini's update]()



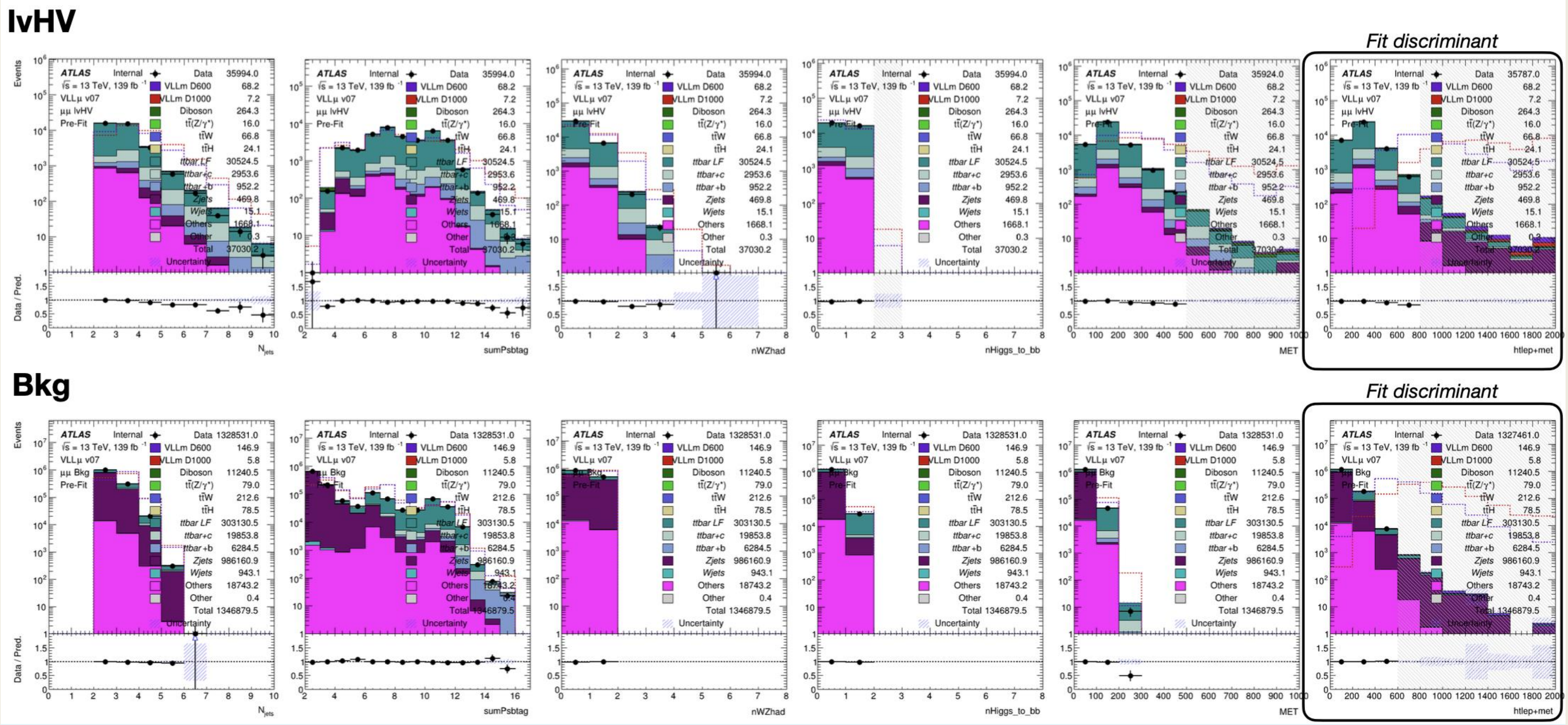
2ℓOS SvsSvsB DNN

From Shalini's update



2ℓOS SvsSvsB DNN

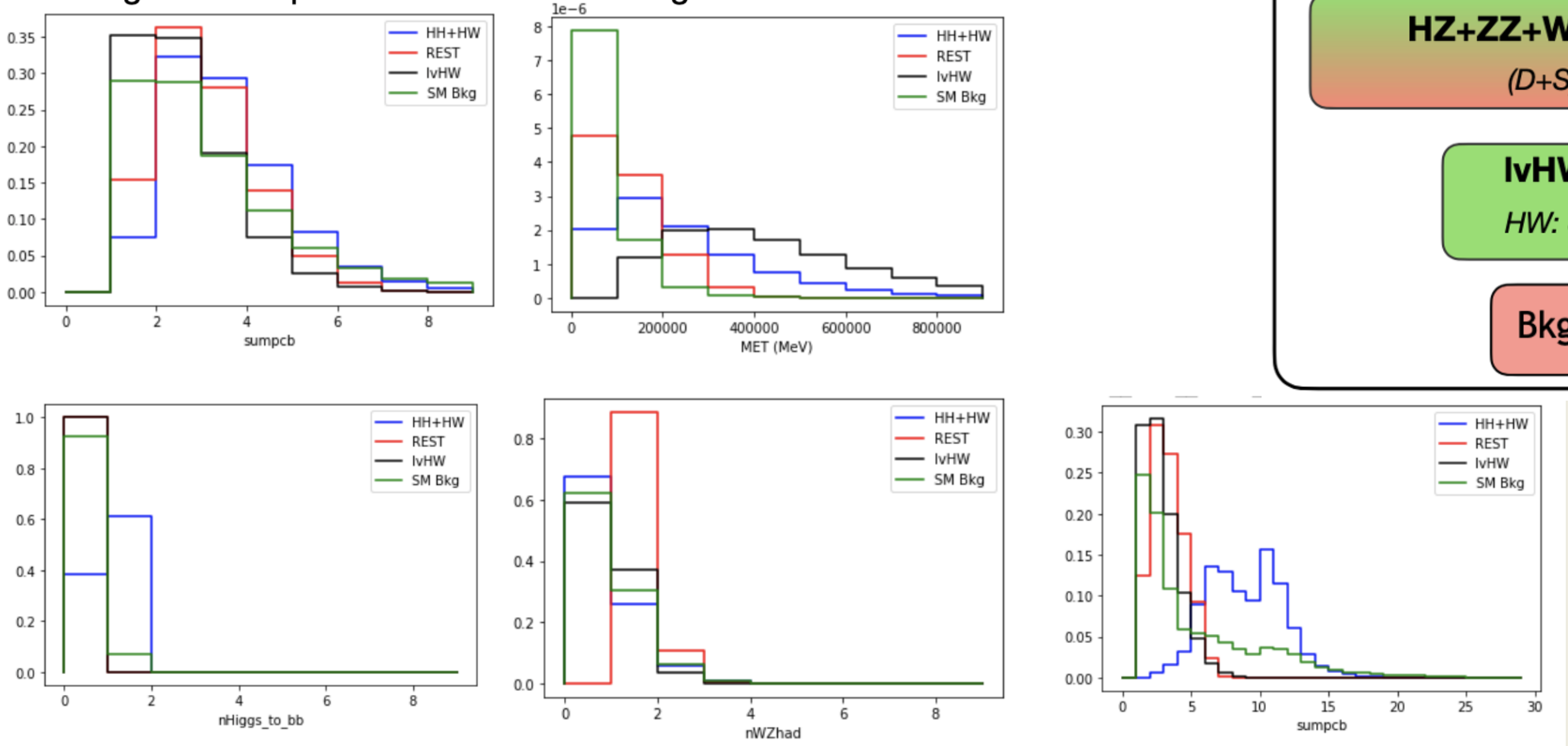
From Shalini's update

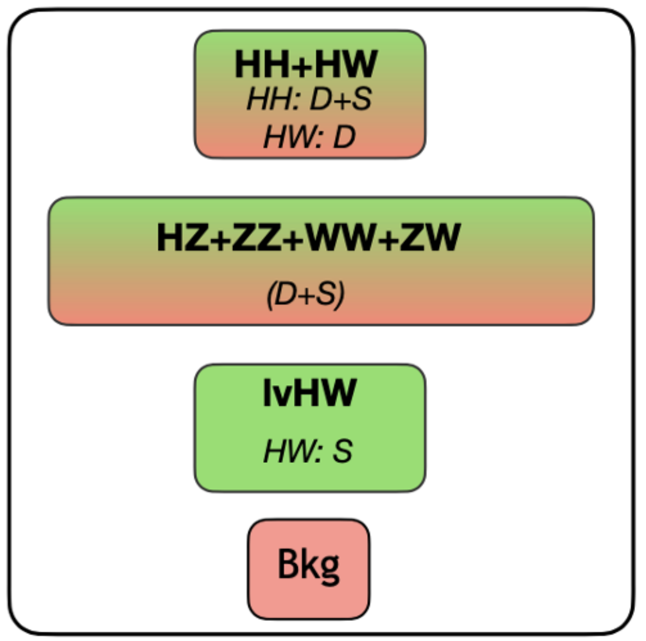


3ℓ SvsSvsB DNN

From Shalini's update

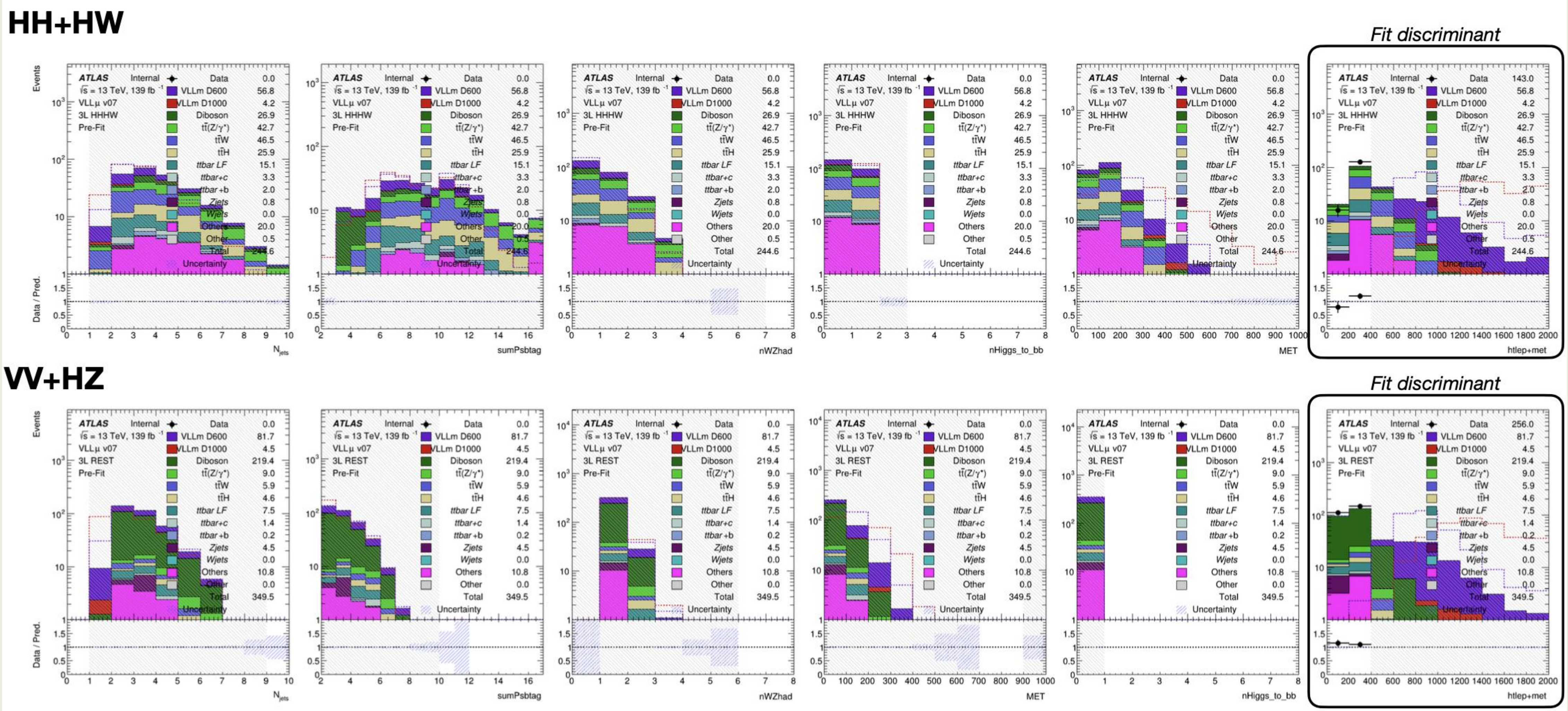
- **Input variables for training**: nJets, SumPCB, nHiggs_to_bb, nWZhad, MET
- SM backgrounds weighted according to their production cross-section
- All signal mass points used in the training





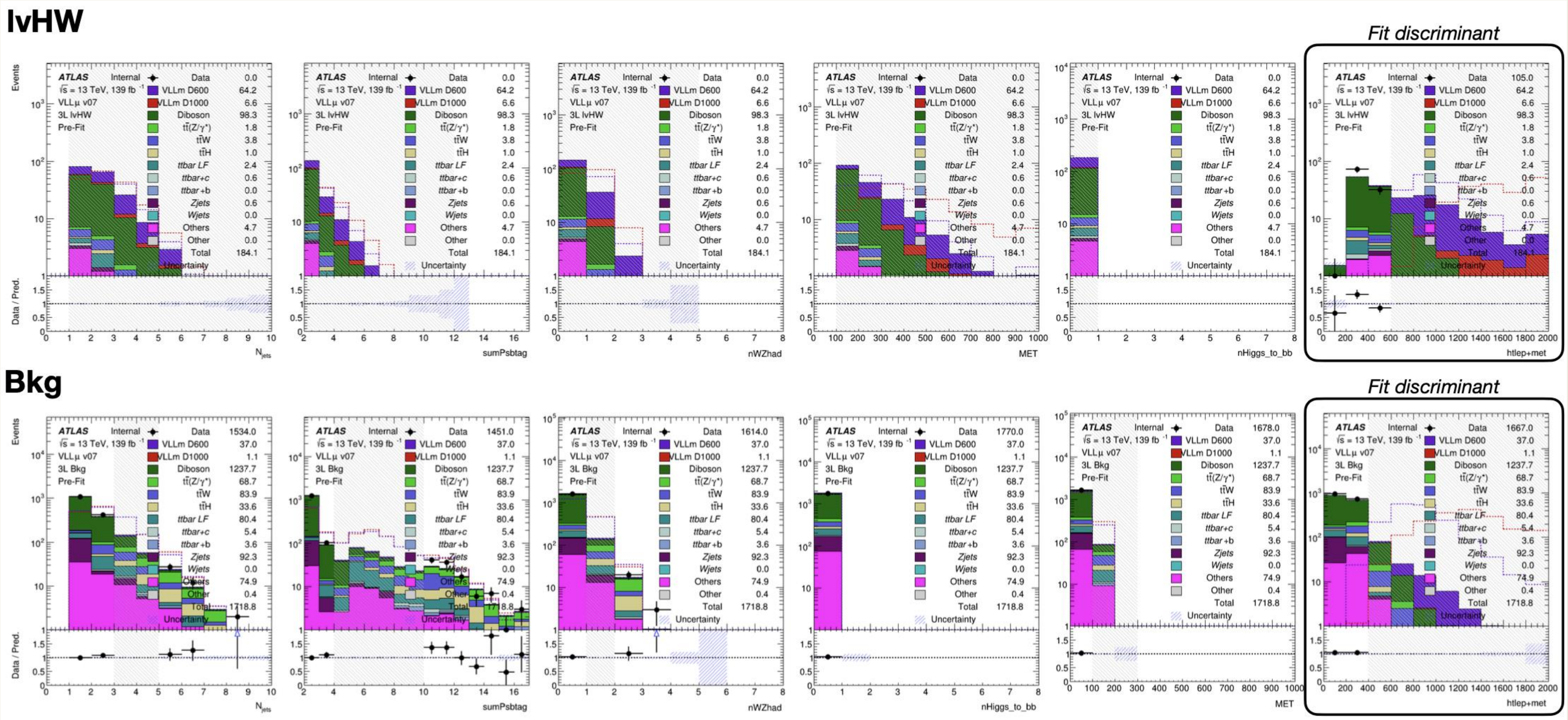
3ℓ SvsSvsB DNN

From [Shalini's update]



3ℓ SvsSvsB DNN

From Shalini's update



Control Regions	WZttZ	$t\bar{t}W$
Lepton requirement	3ℓ	2ℓOS
Lepton p_T[GeV]	(10, 20, 20)	(20, 20)
Lepton Quality	Electrons: FCLooseIso + TightLH ID	
	Muons: FCLooseIso + Medium ID	
PLIV	Tight or Medium on SS leptons	
$\lvert mllOSSF - m_Z \rvert$ [GeV]	<10	–
N_{jets}	≥ 2	
$N_{b-\text{jets}}$	≥ 1 @77%	≥ 2@77%
nWZhad	≥ 0	–
nHiggs_to_bb	0	–

Validation Regions	$t\bar{t}$	Z+jet	$t\bar{t}W$
Lepton requirement	2ℓOS $e\mu$	2ℓOS ee or $\mu\mu$	2ℓSS
Lepton p_T[GeV]	(20, 20)		
Lepton Quality	Electrons: FCLooseIso + TightLH ID		
	Muons: FCLooseIso + Medium ID		
N_{jets}	≥ 2		
mllOSSF [GeV]	>15	–	
PLIV	–		Tight or Medium on SS leptons
$\lvert mllOSSF - m_Z \rvert$ [GeV]	–	<10	–
Region split	{(HH, HV, VV, lvHV, lvVV, SM) × (e, μ)}		

Control Regions	VV	$t\bar{t}Z$
Lepton requirement	4μ or $2e2\mu$ or $4e$	$e3\mu$ or $3e\mu$
Lepton p_T[GeV]	(10, 10, 10, 10)	
Lepton Quality	Electrons: FCLooseIso + TightLH ID	
	Muons: FCLooseIso + Medium ID	
$N_{b-\text{jets}}$	–	≥ 1@77%
nZlep	2	1

Control Regions	WZttZ	WZlight
Lepton requirement	3ℓ	
Lepton p_T[GeV]	(10, 20, 20)	
Lepton Quality	Electrons: FCLooseIso + TightLH ID	
	Muons: FCLooseIso + Medium ID	
PLIV	Tight or Medium on SS leptons	
$\lvert mllOSSF - m_Z \rvert$ [GeV]	<10	
N_{jets}	≥ 2	≥ 1
$N_{b-\text{jets}}$	≥ 1 @77%	$= 0$@77%
nWZhad	≥ 0	$= 0$
nHiggs_to_bb	0	