A Search for Higgs Boson Pair Production in $HH \rightarrow bbWW$ using CMS Data

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Outline

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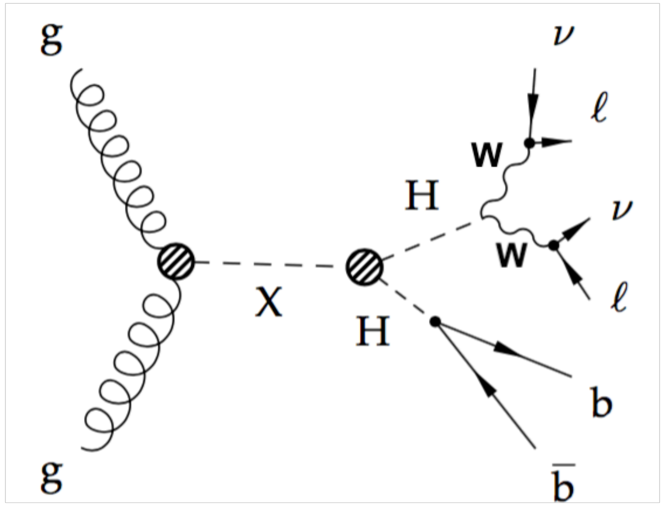
- The LHC and CMS
- Run 2 $HH \rightarrow bbWW$ Analysis Summary
  - Techniques
  - Heavy Mass Estimator
  - Results
  - Potential Improvements
- New Ideas for Run 3
  - Resonant Mass Estimation for Single Lepton Channel
  - Better background control
- Conclusions



Introduction to the LHC and CMS

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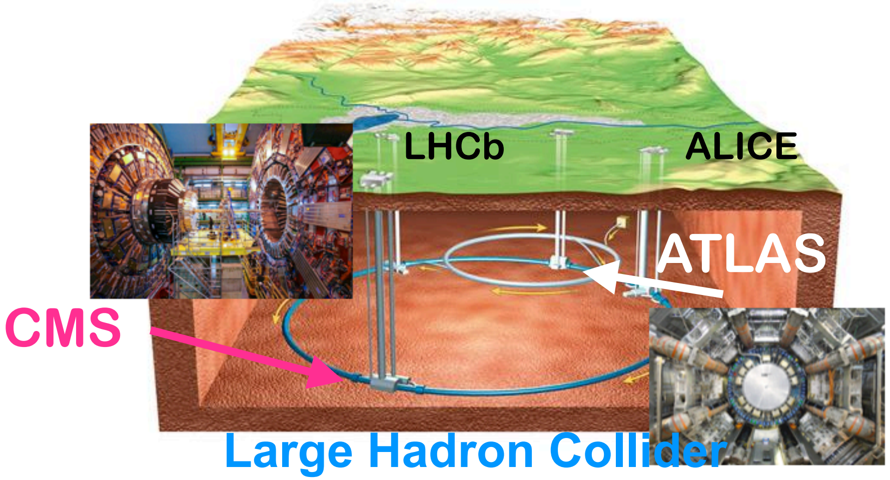
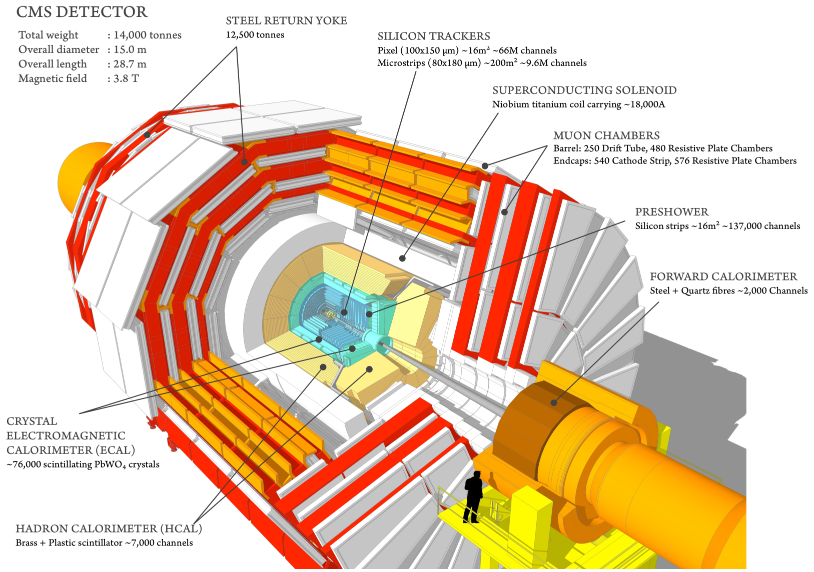
- Large Hadron Collider (LHC) — The largest particle accelerator in the world
  - Collide protons and heavy ions at high energy and high intensity to study particle physics
    - Located near Geneva Switzerland
    - 27km long, 100m underground
    - Run2 data period of 2015-2018 at center-of-mass energy ($\sqrt{s}$) 13 TeV
    - Run3 data period of 2022-2025 at center-of-mass energy ($\sqrt{s}$) 13.6 TeV
    - LHC Design center-of-mass energy ($\sqrt{s}$) 14 TeV
  - LHC delivers collisions at 4 points along the ring
    - Up to experiments to detect the collision results



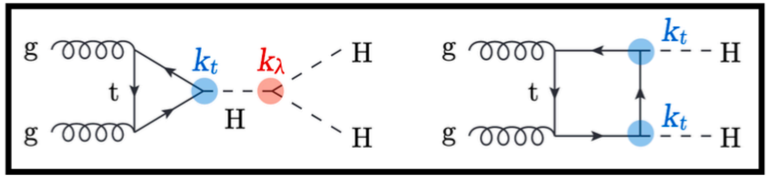
- Compact Muon Solenoid (CMS)
  - General purpose detector at the LHC, detects collision data
  - Based around a superconducting solenoid magnet (3.8 Tesla)
    - Magnet bends charged particles to help identification
  - Built in layers to best measure all types of particles
    - Tracker, ECal, HCal, Solenoid, Muon System
    - Subdetectors measure hit time, position, deposited energy
  - Reconstructs physics objects — Muons, Electrons, Taus, Jets, MET, etc



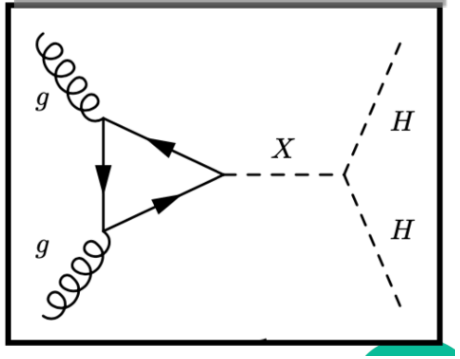
$HH \to bbWW$

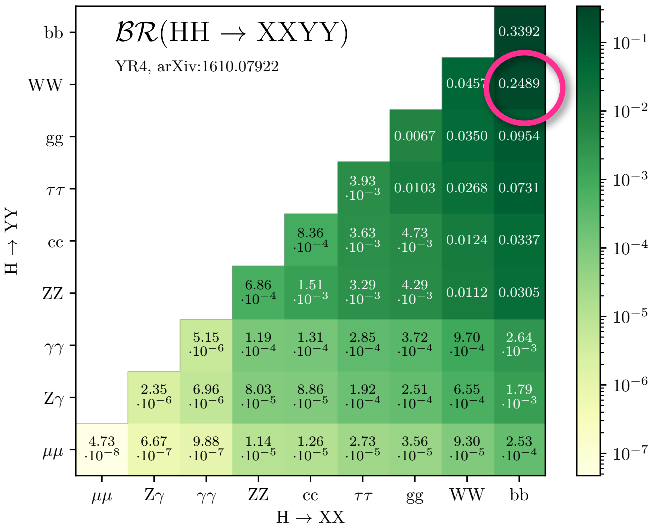
- Non-Resonant (NonRes) Production
  - Predicted in the SM — destructive interference between box diagram and tree diagram
    - Some Beyond Standard Model (BSM) scenarios
  - Measurement of HH Cross Section
  - Access to Higgs self trilinear coupling
- Resonant (Res) Production
  - Massive new resonance X decaying to HH
  - Several models explain existence of resonance
    - Spin-0 — Radion
    - Spin-2 — Gravitons
- Investigate both Single Lepton (SL) and Double Lepton (DL) Channels
  - Previous CMS analysis with 2016 data covered only DL channel
- Background
  - DL Channel — $t\bar{t}$
  - SL Channel — W+Jets
  - Others — Drell-Yan, single top, Fake leptons, etc

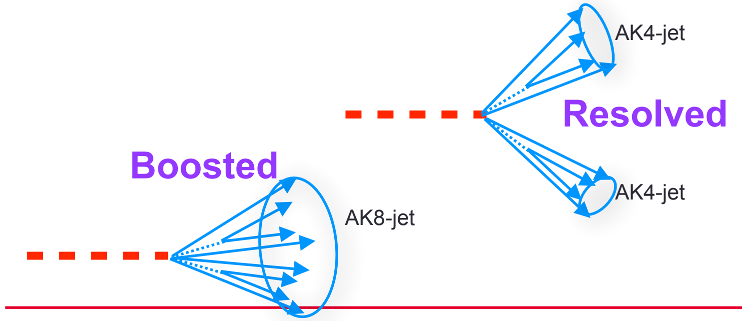
GGF couplings



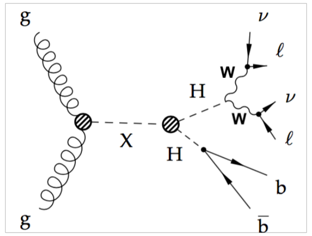
Resonant production



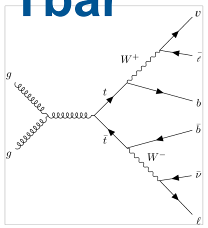




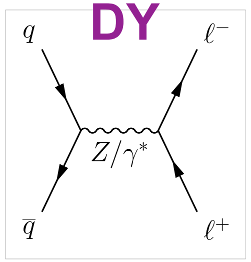
Generic Res DL



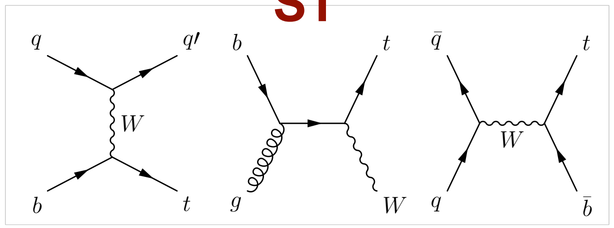
TTbar



DY



ST



Analysis Strategy

Single Lepton (SL) — $HH \to bbWW \to bbl\nu qq$

Single Lepton Triggers
1 Lepton
3 small radius jets (resolved)
1 large radius jet + 1 small radius jet (boosted)

Data Driven: Fake Leptons and QCD
Simulation Driven: Others

Lorentz Boost Network (LBN) and DNN
For Res Category, Parametric DNN

Fit on DNN output

Event Selection
138fb^{-1} **CMS Run2 Data**

→ **Background Estimation** → **Signal Extraction** → **Systematics and Fit**

Single or Double lepton triggers
2 Opposite Sign Leptons
2 small radius jets (resolved)
1 large radius jet (boosted)

Data Driven: Fake Leptons and Drell-Yan
Simulation Driven: Others

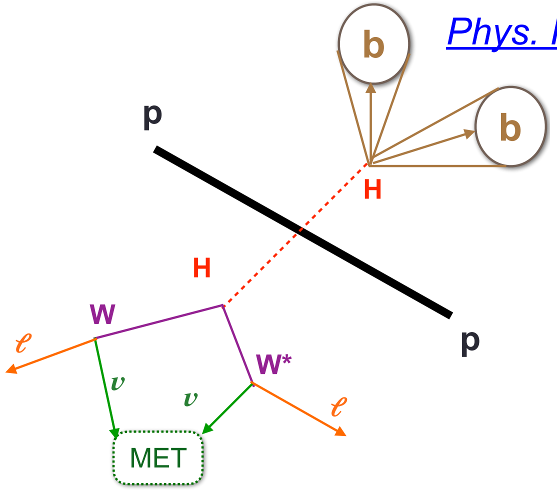
Lorentz Boost Network (LBN) and DNN
For Res Category, Parametric DNN and HME (Next Slide)

Fit on DNN output
Res Category — Fit on DNNxHME output

Double Lepton (DL) — $HH \to bbWW \to bbl\nu l\nu$

Heavy Mass Estimator

- Problem for Res DL Channel
  - $H \to WW \to l\nu l\nu$ cannot be fully reconstructed due to 2 neutrinos
    - 4 equations and one bound constraint
    - 6 unknowns from two neutrinos
  - If we can constrain the resonance mass, we could improve the analysis

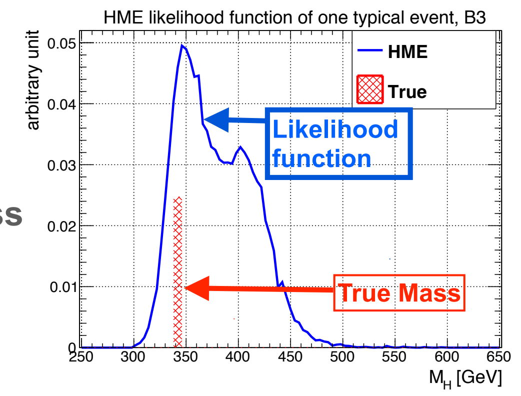


Phys. Rev. D 96, 035007

Apply the HME to all selected events

most probable mass as estimator, HME mass

Likelihood for single event



- Heavy Mass Estimator (HME)
  1. Randomly generate η and ϕ of one neutrino
  2. Jet-MET corrections to ensure the invariant mass of dijet is equal to Higgs mass
  3. Check if this random generation is kinematically allowed by solving constraints
  4. Combine corrected dijet and record this estimation of the heavy resonance
  5. Repeat this procedure many times and build a likelihood for a single event
  6. Return the most probable mass as the final heavy resonance for this event

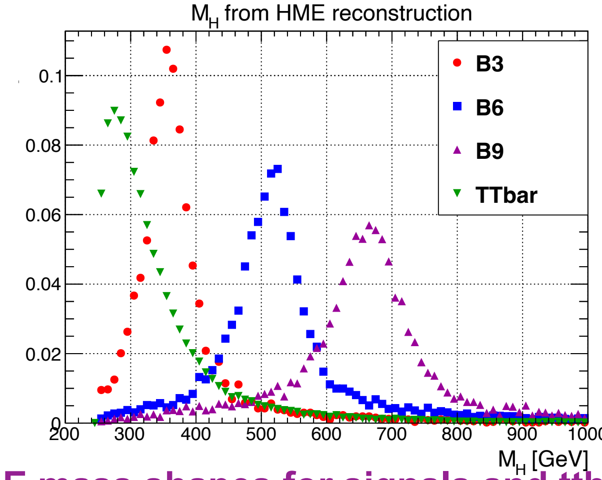
$$E^{miss}_{T,x} = p_x(\nu_{\ell_1}) + p_x(\nu_{\ell_2})$$

$$E^{miss}_{T,y} = p_y(\nu_{\ell_1}) + p_y(\nu_{\ell_2})$$

$$m_W(\text{onshell}) = \sqrt{p^2(\ell_1, \nu_{\ell_1})}$$

$$m_H^2 = \left(p(\ell_1) + p(\ell_2) + p(\nu_{\ell_1}) + p(\nu_{\ell_2})\right)^2$$

$$m_W(\text{offshell}) = \sqrt{p^2(\ell_2, \nu_{\ell_2})} < M_H/2$$



HME mass shapes for signals and ttbar

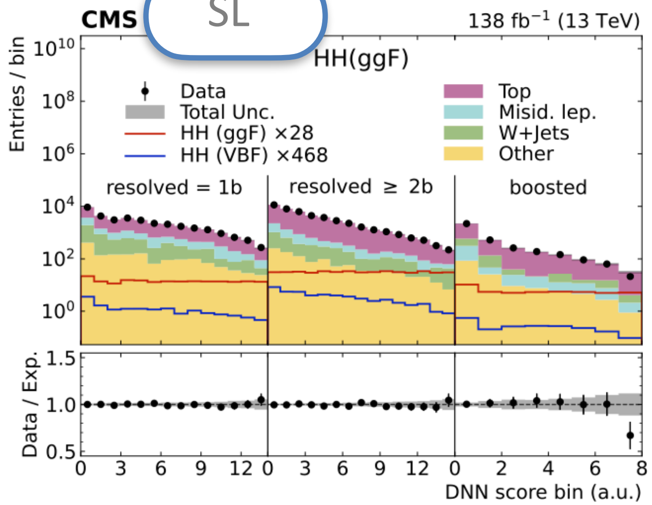
Signal	B3	B6	B9
Mass, GeV	353	511	662

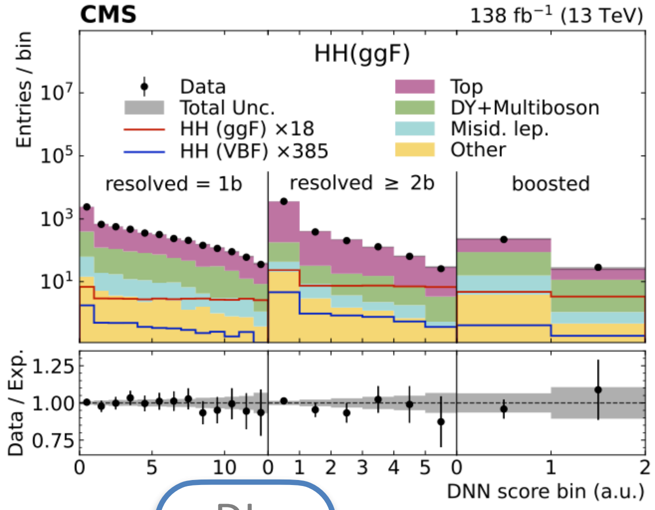
Results: Non Resonant

[CMSHHbbWW, HIG-21-005](#)

- NonRes MVA
  - Trained separately in SL and DL channels
  - Preprocessing Lorentz Boost Network (LBN) then multi-class DNN
- NonRes Results
  - Limits fit over MVA output
  - Observed (expected) limits for $pp \rightarrow HH$ production cross section is 14 (18) times that predicted by the standard model
  - Higgs trilinear coupling κ_λ is constrained between $[-7.2, 13.8]$ (expected $[-8.7, 15.2]$)

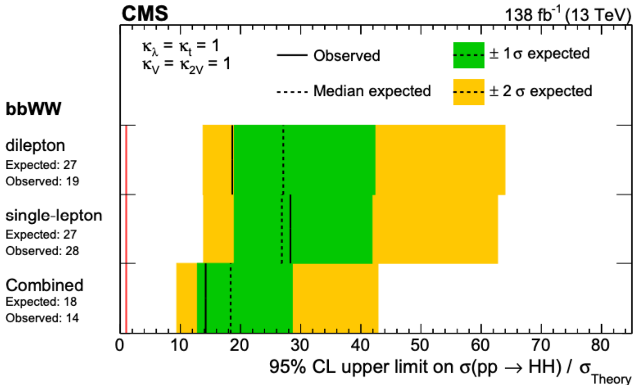
SL

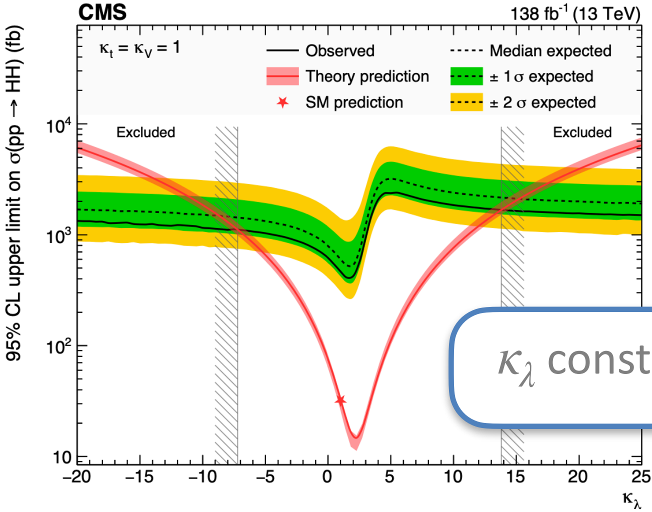




DL

SL+DL
14(18) x SM Cross Section
Observed (Expected)





κ_λ constraint

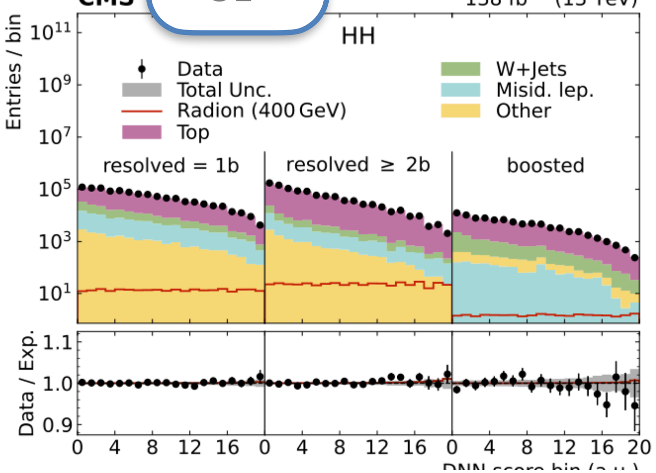
Results: Resonant Spin-0 and Spin-2

- Resonant MVA
  - Trained separately in SL and DL channels
  - Preprocessing Lorentz Boost Network (LBN) then parametric multi-class DNN
    - Train over multiple signal mass points
    - Applied separately per mass point

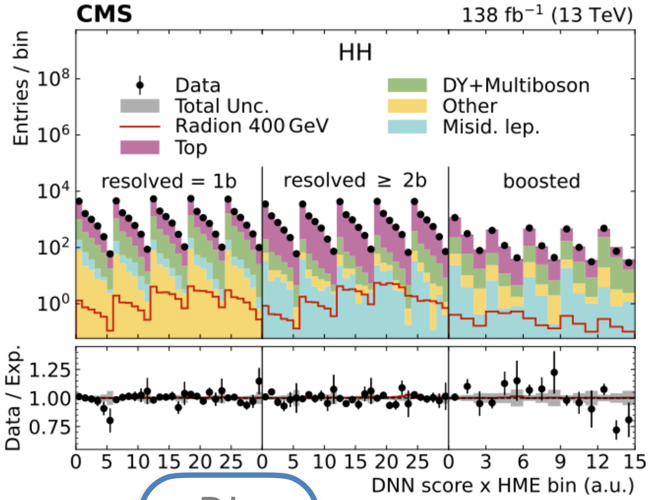
- Resonant Results
  - Limits fit over MVA output
    - DL channel fit over MVAxHME 2D
  - Results show no evidence of a spin-0 or spin-2 boson

CMSHHbbWW, HIG-21-005

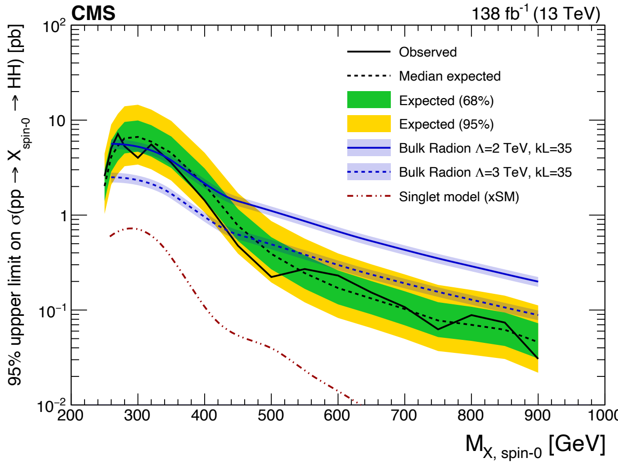
SL



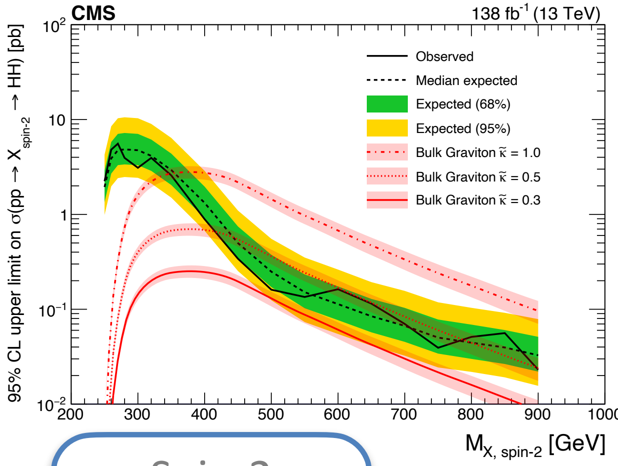
DL



Spin-0



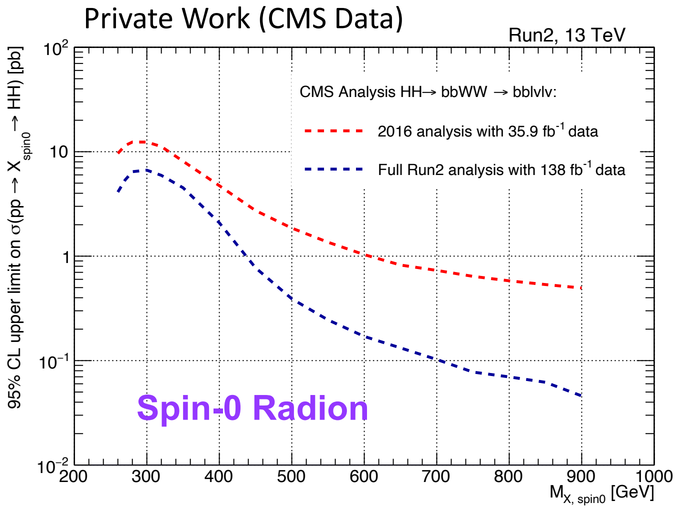
Spin-2

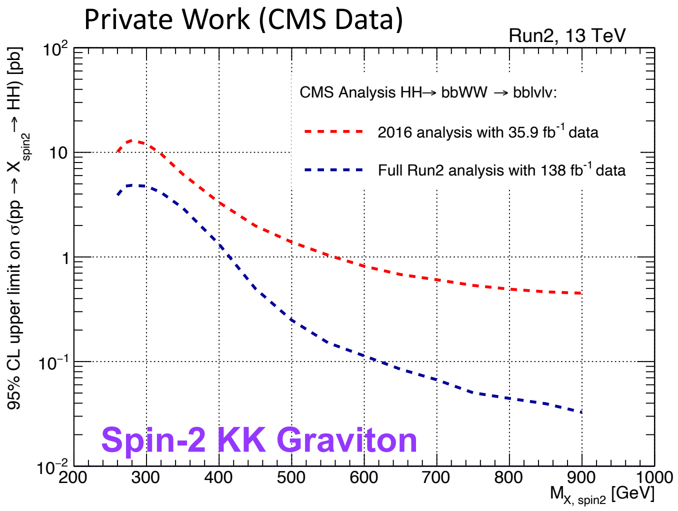


Results Compared to 2016 CMS Analysis

- **SL Channel is completely new in full Run 2 analysis**

- **Large improvement in high mass region compared to [previous 2016 CMS Analysis](#)!**
  - 10x improvement is much better than expected improvement from only luminosity $\sqrt{138/36} \approx 2$





2016 CMS
$35.9\mathbf{fb}^{-1}$
$HH \to bbWW \to bbl\nu l\nu$

Full Run2 CMS
$138\mathbf{fb}^{-1}$
$HH \to bbWW \to bbl\nu l\nu$

Preparing for Run 3 Analysis

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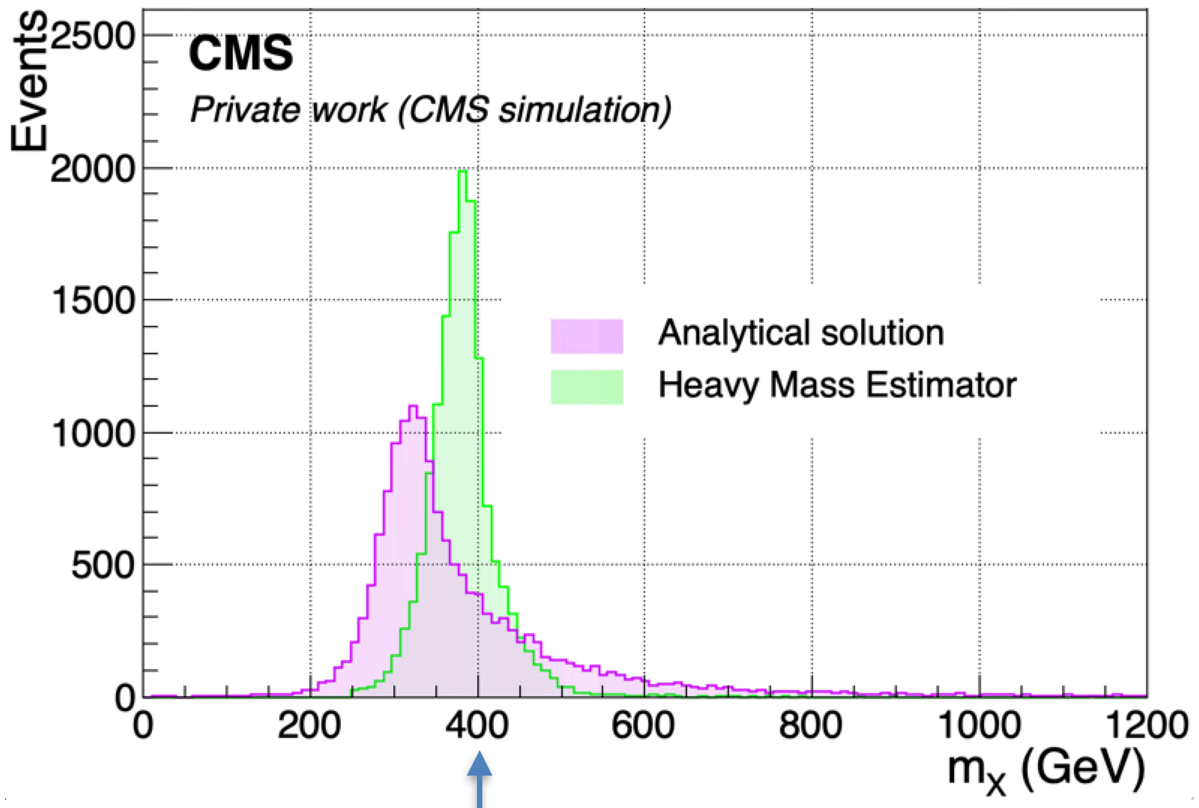
- How can we improve for Run 3
  - **Improvement to Fake Rate estimation**
    - Fakes estimation was taken from a previous analysis, lead to difficulties in Run 2 analysis
  - **New HLT paths designed for bbWW in progress**
    - Trigger requiring 2 b jets and 1 lepton
  - **Bring HME to Single Lepton Channel**
    - Run 2 SL limits were higher than DL limits — Especially in the high mass region
    - Adding HME could show major improvement
    - In SL channel there was no attempt to reconstruct resonance mass
    - While SL channel has only one ν from W, a straight-forward calculation is obscured by jet mis-measurements
    - **Early generator level results show HME performs better than the purely analytical solution**
  - **Improve background rejection (Next Slide)**

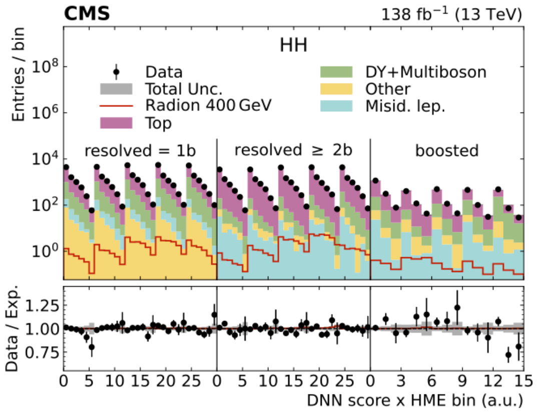
HME for Resonant Single Lepton Channel

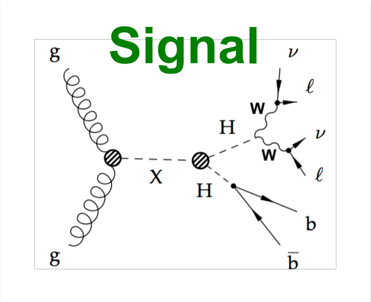


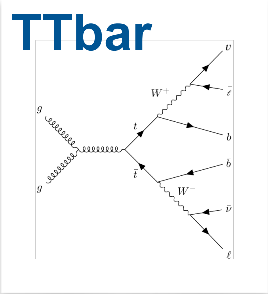
True Simulated Mass

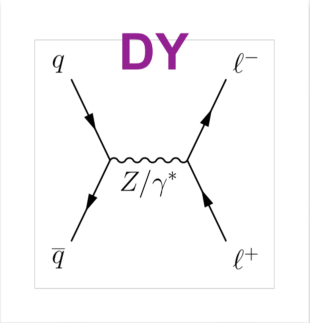
Improved Background Control

- Resonant Run 2 Analysis was a big improvement, but was still not perfect
  - As mass increases, $t\bar{t}$ **is no longer leading background**, and DY/Fakes become larger
    - **$t\bar{t}$ is only irreducible background, all others should be fixable**
  - Potential reason for poor performance could be poor background control for non $t\bar{t}$ backgrounds
    - Run 2 assumed that $t\bar{t}$ was most important background
    - Only $t\bar{t}$ shares the same final state as signal $(bbll)$
    - **Reducible background contribution should be further suppressed**









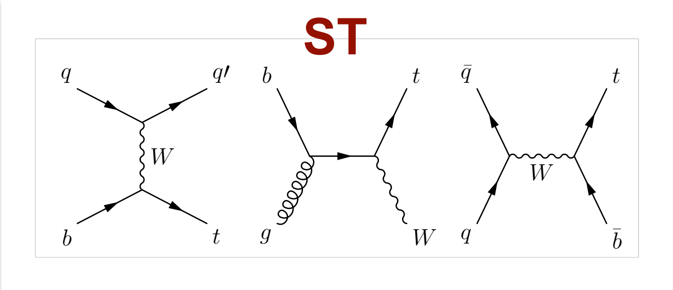


Table 5.13: Overview of expected total background contributions and the breakdown of major background sources in the most sensitive signal region of this analysis for the 2018 data-taking year.

Private Work

M_X, GeV	N(tt̄)	N(DY)	N(ST)	N(Fakes)	N(totBKG)	N(tt̄)/N(totBKG)
250	988	142	23	24	1200	0.82
300	5520	467	150	70	6268	0.88
350	4464	300	123	46	4965	0.90
400	1355	100	54	20	1542	0.88
450	176	34	20	2.6	249	0.74
500	61	21.8	14.6	1.75	104	0.59
550	8.6	6.7	6.4	2.3	25.7	0.33
600	4.8	5.6	6.4	0.3	17.5	0.28
650	4.1	7.3	3.0	0.39	16.6	0.25
700	2.1	4.8	1.7	0.65	10.4	0.20
750	1.1	4.8	0.40	1.0	5.8	0.19
850	0.75	1.53	0.64	0.64	4.4	0.17

Mostly $t\bar{t}$

Backgrounds changing

Mostly DY

- Values taken from 2018 Res DL Channel DNNxHME Shape Distribution in Signal Region

Conclusion

- Full CMS Run 2 Analysis $HH \rightarrow bbWW$ with 138fb^{-1} data
  - Non-Res — Observed (Expected) limits on the $pp \rightarrow HH$ cross section are 14 (18) times SM
  - Res — No evidence for spin-0 or spin-2 boson
  - Large improvement compared to 2016 CMS analysis (DL only) with 36fb^{-1}
- Further improvement is still possible — on-going work for Run3 analysis
  - **Better reducible background control in the high mass region can have a significant effect on limits**
  - **For resonant SL channel, the addition of a Heavy Mass Estimator** technique to control jet met resolution may show a large improvement similar to what was seen in DL channel
  - Other optimizations to the analysis are including using newer MVA techniques, new High Level Triggers, and new background estimations (Fakes/DY)

Backup

Analysis Strategy

Analysis Strategy

- Target both GGF and VBF production modes
- 2 leptonic channels based on W decay
  - Single Lepton (SL) — $WW \to l\nu qq$
  - Double Lepton (DL) — $WW \to l\nu l\nu$
- 2 jet channels based on reconstructed b jets
  - Resolved — 2 small radius jets coming from b quarks
  - Boosted — 1 large radius jet containing 2 subjets from nearby b quarks
- bJet identification done by Deep Neural Net (DeepJet)

Event Selection

- Leptons
  - 2 (1) lepton in DL (SL)
  - Remove Z resonance (DY) $81 < m_{ll} < 101$ GeV
- Jets
  - Resolved
    - ≥ 2 (≥ 3) small radius jets in DL (SL)
  - Boosted
    - 1 large radius jet in DL and SL
    - And ≥ 1 small radius jet in SL

Background Estimation

- Main Backgrounds
  - $t\bar{t}$, Drell-Yan, single top, fakes (misidentified leptons), W+jets
- Data Driven Estimations
  - Fake leptons, QCD Multijet (SL), Drell-Yan (DL)
- Simulation Driven Estimations — All else

Signal Extraction

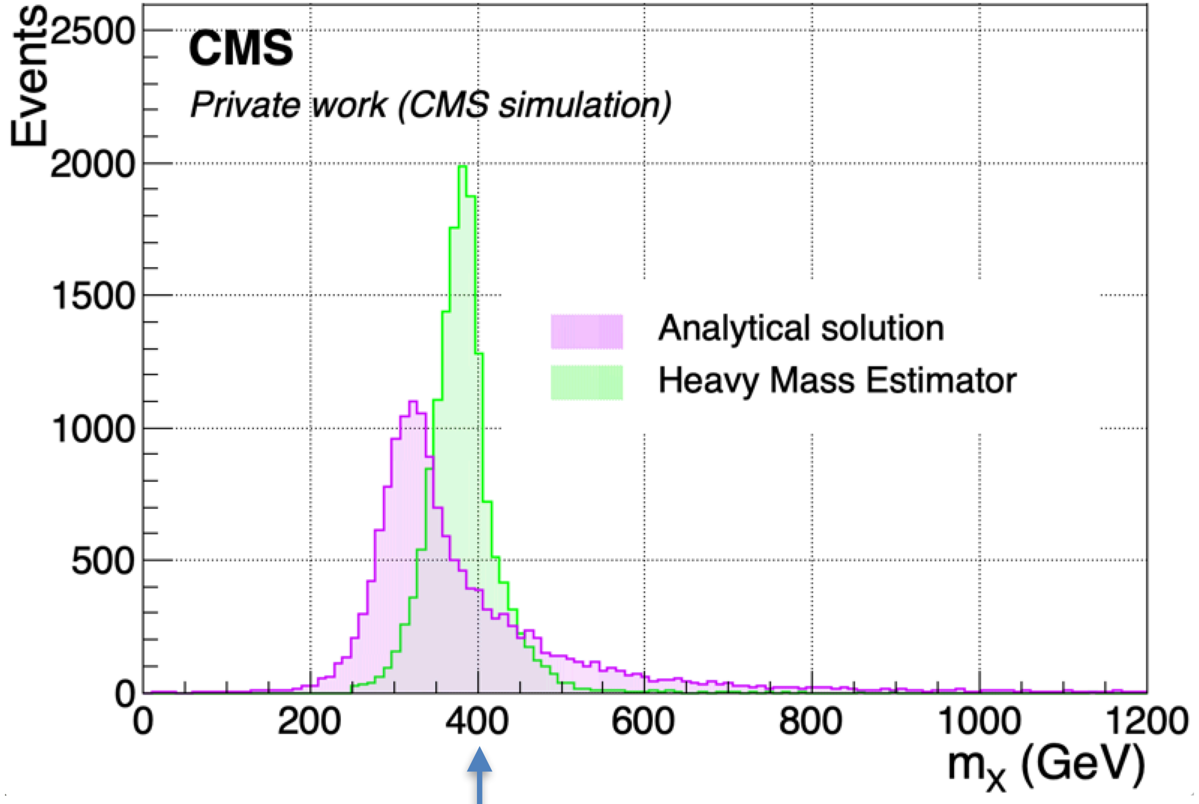
- Heavy Mass Estimator (Resonant DL)
  - Scans phase space for ν possibilities to find most probably resonant mass
- MVA
  - Deep Neural Net to separate signal and background (separate for SL/DL and resonant/non-resonant)

Single Lepton HME

- HME for Single Lepton (SL)
  - Sensitivity in SL channel is comparable with sensitivity in DL channel
  - In SL channel there was no attempt to reconstruct resonance mass
  - While SL channel has only one ν from W, a straight-forward calculation is obscured by jet mis-measurements
  - HME is capable of ealing with these mis-measurements by scanning the phase space

- Method
  - Rescale leading b jet by PDF estimated from simulation
  - Rescale subleasing b jet to constrain Higgs mass
  - Missing Transverse Energy (MET) consistently corrected with b jet corrections

- Preliminary Results
  - **Early generator level results show HME performs better than the purely analytical solution**
  - Tested with simulated $m_X = 400$ GeV resonance



True Simulated Mass

Why $X \to HH \to bbWW$

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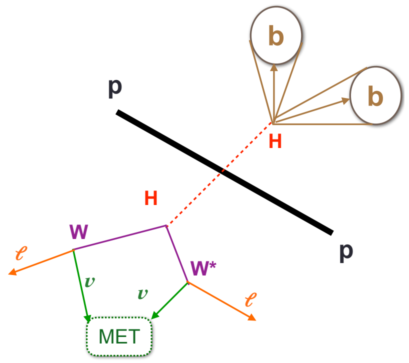
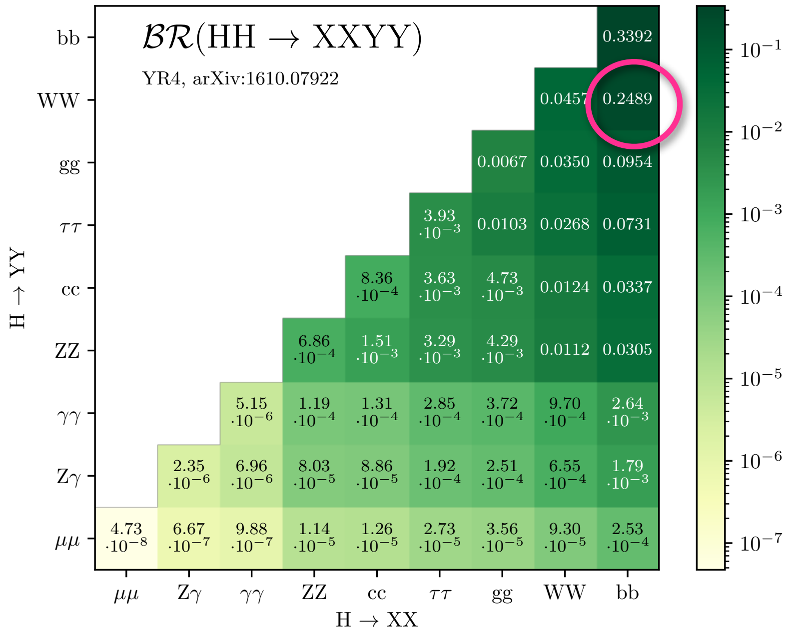
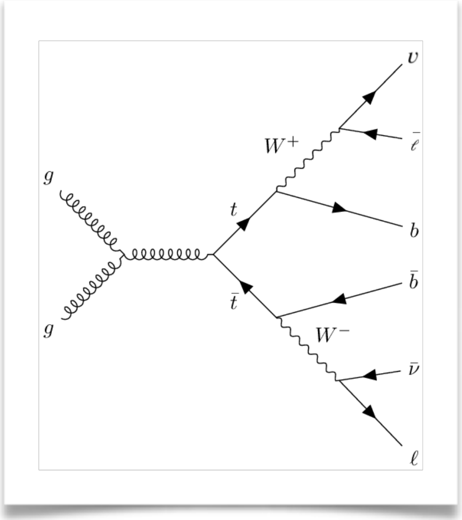
Old projected limits
NOT NEW

- The bbWW channel has the second highest $HH \to XXYY$ branching ratio
- Important to investigate multiple channels
- W bosons decaying into leptons
  - Leptons are clean
- Has large overlap with $t\bar{t}$ (same final states)
  - Problematic at low mass ($t\bar{t} \approx 350GeV$)
  - **Clean at high mass**







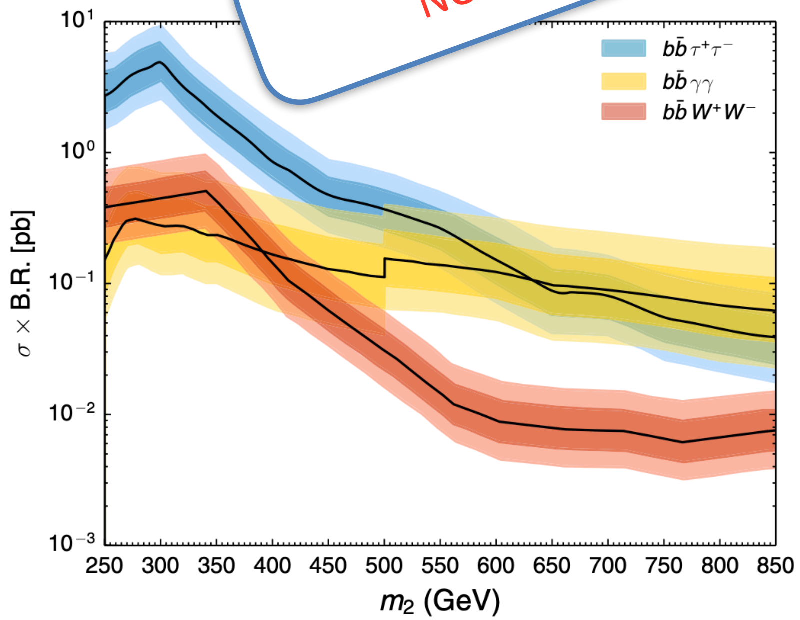


FIG. 8. 13 TeV LHC projected 95% C.L. limits (solid black lines) on $\sigma_{pp\to h_2} \times \mathrm{BR}_{h_2\to h_1 h_1}$ (in pb) for an integrated luminosity $\mathcal{L} = 300$ fb^{-1} and assuming an ATLAS-CMS combination, in the $b\bar{b}W^+W^-$ final state [as shown in Fig. 5 (right)] and in the $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ final states (through a naive $\sqrt{\mathcal{L}}$ extrapolation of the resonant di-Higgs 13 TeV CMS analysis in the $b\bar{b}\tau^+\tau^-$ [78] and $b\bar{b}\gamma\gamma$ [79] final states). In all cases, the dark (pale) colored bands correspond to the confidence intervals for the expected limit at 68% (95%) coverage probability.

Run 2 Object Selection

For Reference

Object	Pre-selected	Fakeable	Tight
Muon	$P_T \geq 5$ GeV, $\|\eta\| \leq 2.4$, $\|d_{xy}\| \leq 0.05$ cm, $\|d_z\| \leq 0.1$ cm, mini ISO ≤ 0.4, $SIP_{3d} \leq 8$, loose POG Id	Cone-$P_T \geq 10$ GeV, no associated jet passing medium btag, [$MVA_{ttH} \geq 0.5$ or (mini ISO < 0.8 and no bjet looking associated jet)]	Medium POG Id, $MVA^*_{ttH} \geq 0.5$
Electron	$P_T \geq 7$ GeV, $\|\eta\| \leq 2.4$, $\|d_{xy}\| \leq 0.05$ cm, $\|d_z\| \leq 0.1$ cm, mini ISO ≤ 0.4, $SIP_{3d} \leq 8$, Loose working point Fall17 v2 noIso MVA-based electron ID, missing inner hits ≤ 1, cleaned against preselected muons by $\Delta R \geq 0.3$	Cone-$P_T \geq 10$ GeV, $\sigma_{i\eta i\eta}$ cuts, H/E ≤ 0.1, [$MVA_{ttH} \geq 0.3$ or (mini ISO ≤ 0.7 and noIso Fall17 v2 WP90 MVA-based electron ID)], missing inner hits = 0, convertion veto	$MVA^*_{ttH} \geq 0.3$
Tau	$P_T \geq 20$ GeV, $\|\eta\| \leq 2.3$, $\|d_z\| \leq 0.2$ cm, idDecayModeNewDMs, decaysModes = {0,1,2,10,11}, Very loose WP of idDeepTau2017v2p1VSjet, idDeepTau2017v2p1VSe, idDeepTau2017v2p1VSmu	Cleaning against fakeable leptons by $\Delta R \geq 0.3$	

Jet	Jet selection	B-jet selection
AK4	Loose/tight jetID, $P_T \geq 25$ GeV, $\|\eta\| \leq 2.4$, loose jet-puID, cleaned against fakeable leptons (selected in SL or DL) by $\Delta R \geq 0.4$	Medium DeepJet b WP
AK8	Loose jetID, $P_T \geq 200$ GeV, $\|\eta\| \leq 2.4$, each subjet with $P_T \geq 20$ GeV, $\|\eta\| \leq 2.4$, $30 < M_{softfrop} < 210$ GeV, $\tau_{21} \leq 0.75$, cleaned against fakeable leptons (selected in SL or DL) by $\Delta R \geq 0.8$	At least one subjet with $P_T \geq 30$ GeV and passing medium DeepCSV b WP

- Object Selection
  - **Give general ID tags to leptons and jets**
  - **Organizes objects that are considered for future steps**
  - Leptons
    - Preselected tier is very loose
    - Fakeable tier is used for the Lepton Fake Rate background estimation
      - Objects reconstructed as leptons that are not truly leptons
    - Tight tier is used for main analysis
  - Jets
    - Selection tier is loose to remove jets with low p_T and outside of acceptance region
      - Cleaned against leptons to remove jets containing these leptons
    - B-Selection is to ID which jets look like they come from a b quark

Data Selection and Simulation
For data, select High Level Trigger (HLT) Paths

Scale Factor Corrections

Object Selection
General object identification, leptons/jets)

Event Topology
Events that look like bbWW

Background Estimation

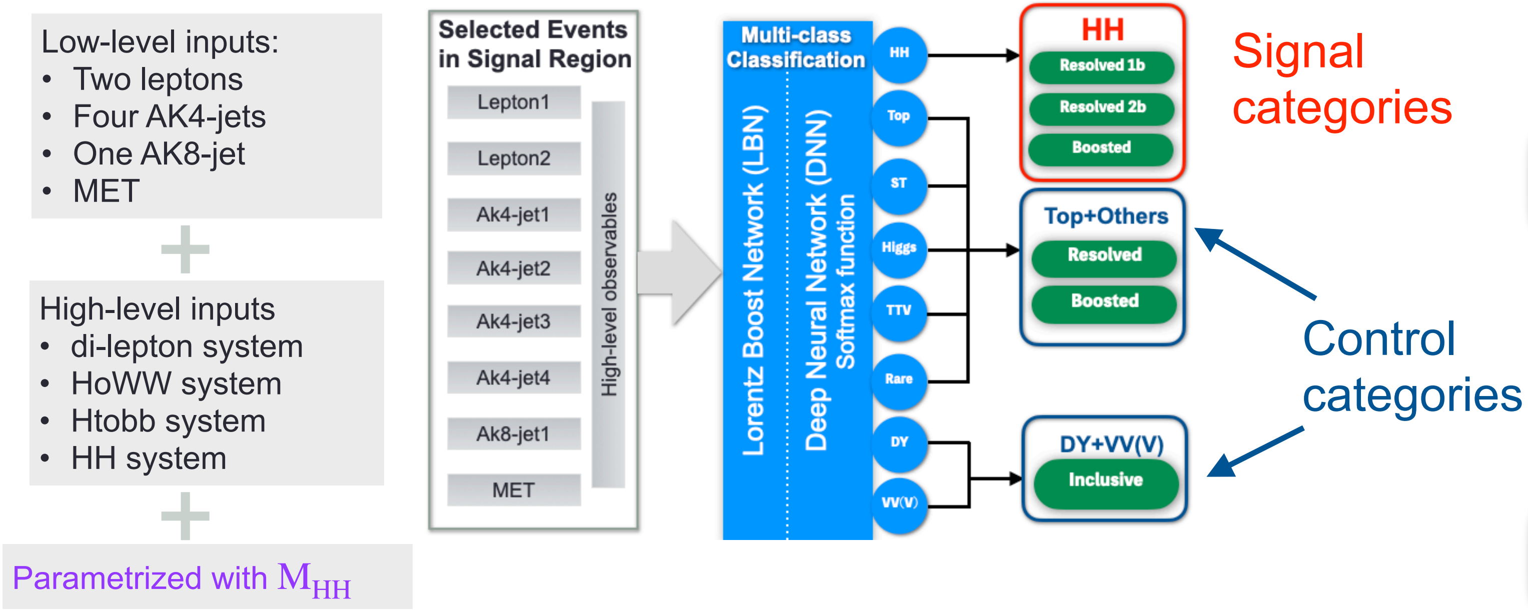
Heavy Mass Estimator
Estimates resonance mass

MVA
Separate Signal from Background

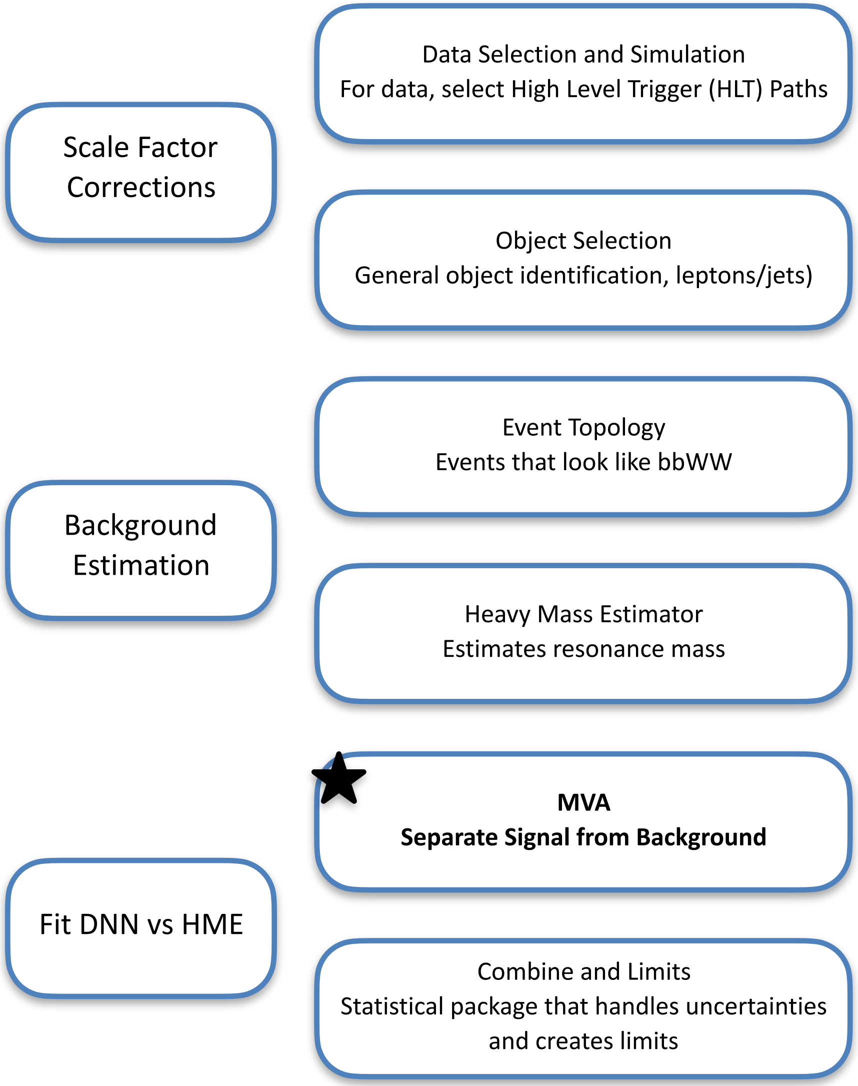
Fit DNN vs HME

Combine and Limits
Statistical package that handles uncertainties and creates limits

Run 2 MVA

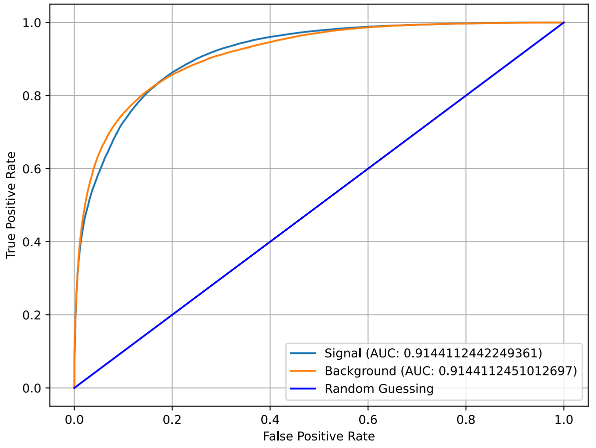


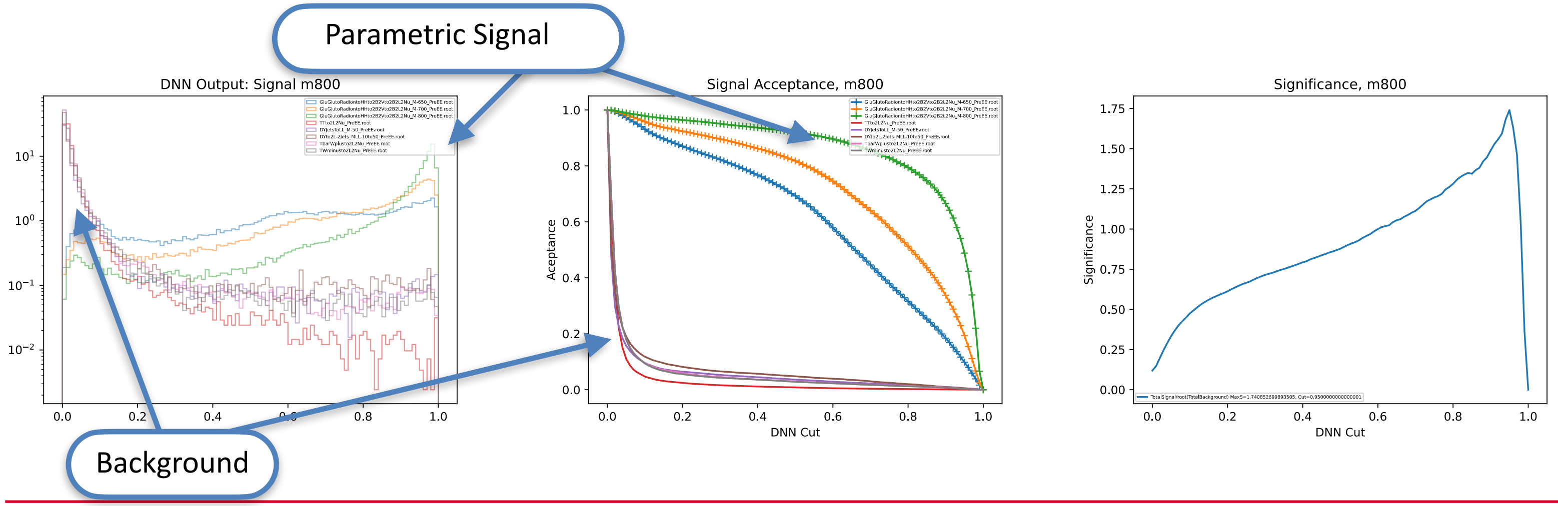
- MVA Step done in two parts
  - Lorentz Boost Network (LBN) as a pre-processing layer (developed by Aachen)
  - **Parametric DNN**
    - Parametric DNN allows training on multiple signal masses within a single DNN Model
    - DNN gives different outputs when applied at different mass points
    - Correctly applied parametric DNN should give similar results for nearby masses, **so DNN prediction can be continuous at any signal mass point when only trained at binned mass values**
      - If trained at 700 GeV and 800 GeV, will still perform well at 750 GeV



Run 3 MVA

- Simple Parametric DNN Signal/Background binary classifier has been built and is being tested
  - Signal:
    - GluGlutoRadiontoHHto2B2Vto2B2L2Nu
    - Masses [250, 260, 270, 280, 300, 350, 450, 550, 600, 650, 700, 800]
  - Backgrounds:
    - TTto2L2Nu
    - DYJetsToLL_M-50
    - DYto2L-2Jets_MLL-10to50
    - TbarWplusto2L2Nu
    - TWminusto2L2Nu
- Currently being worked on, but early results show working separation of signal and background, and good parametric performance
- **Need to add other backgrounds and include Graviton signal**





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Run 2 Background Estimation

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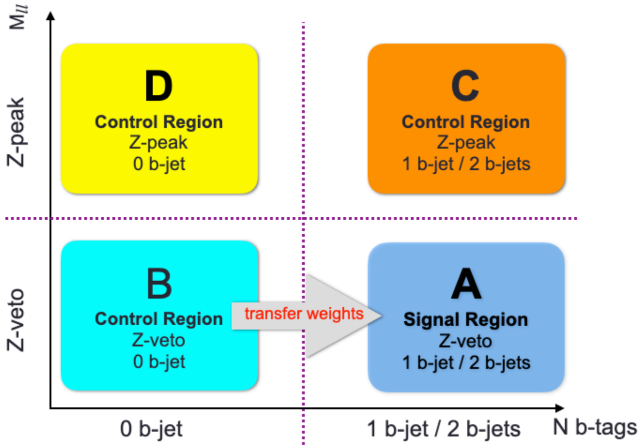
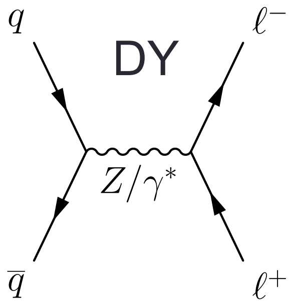
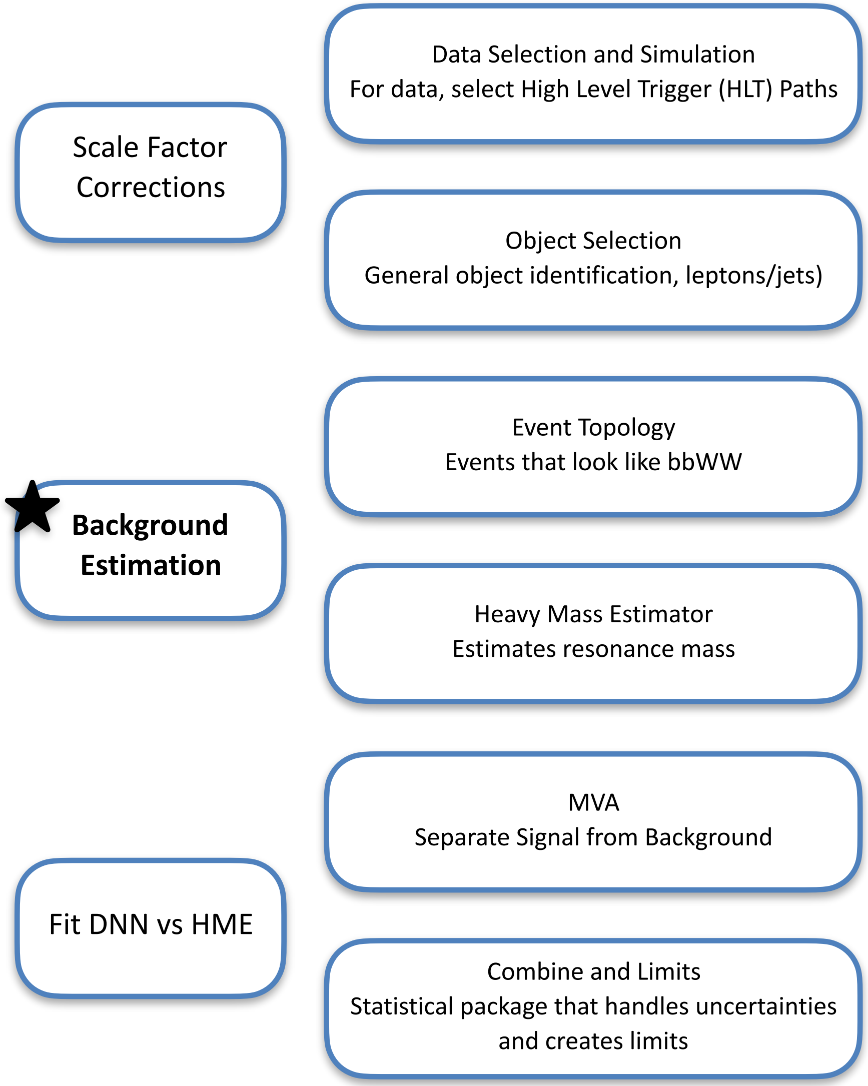




ABCD: $N^{1b/2b}_{Z-veto}(A) = N^{0b}_{Z-veto}(B) \times weight_{1b/2b} = N^{0b}_{Z-veto}(B) \times \frac{N^{1b/2b}_{Z-peak}(C)}{N^{0b}_{Z-peak}(D)}$

$weight_{1b/2b}$

- Background Estimation
  - Some backgrounds can be estimated by MC
    - $t\bar{t}$, single top, W+jets, VV(V), SM Higgs, Rares, etc
    - Corrections are applied to simulated events to match data
  - Some backgrounds are poorly modeled in our signal region and must be estimated using data
    - Data driven estimations are required for Drell-Yan and Fake Leptons
- Drell-Yan Estimation — ABCD Method
  - Invert 2 event topology selections to create 4 regions, 1 signal and 3 control
  - Ratio of regions should by identical $\left(\frac{A}{B} = \frac{C}{D}\right)$, so $A = B \cdot \frac{C}{D}$
- **Fake Estimation was inherited from a previous ttH analysis (problematic for Run 3, more later)**



Run 3 Background Estimation

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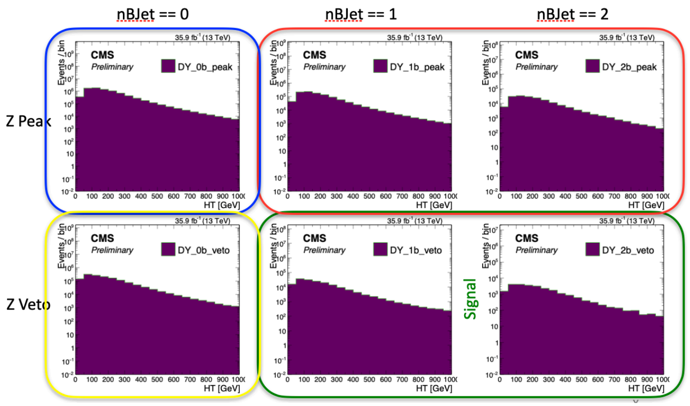
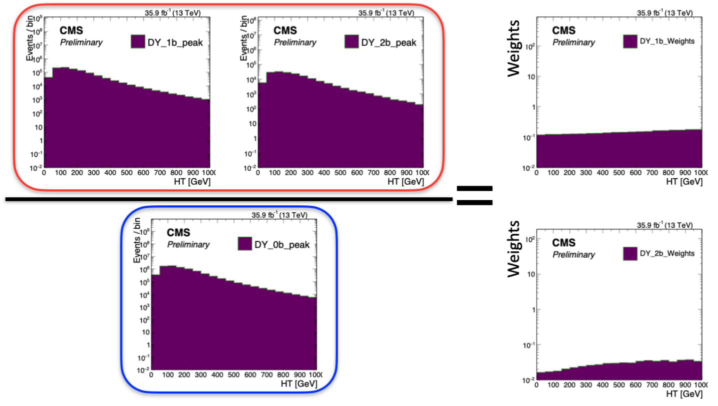
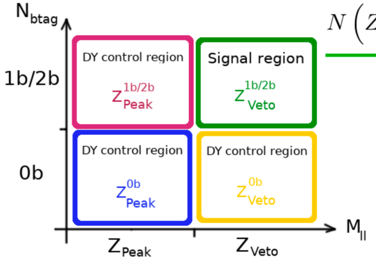


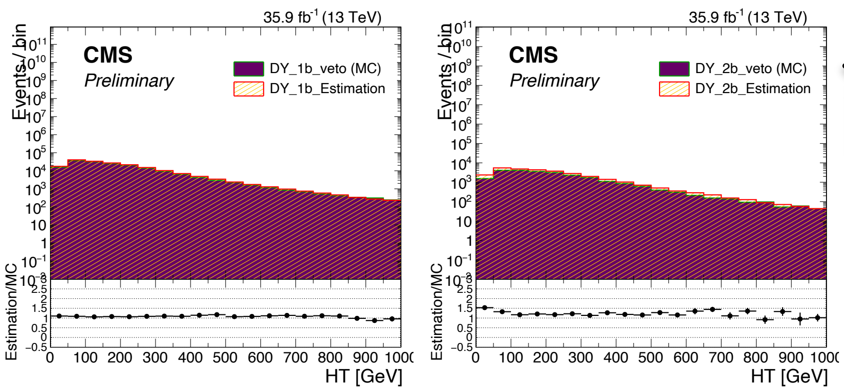


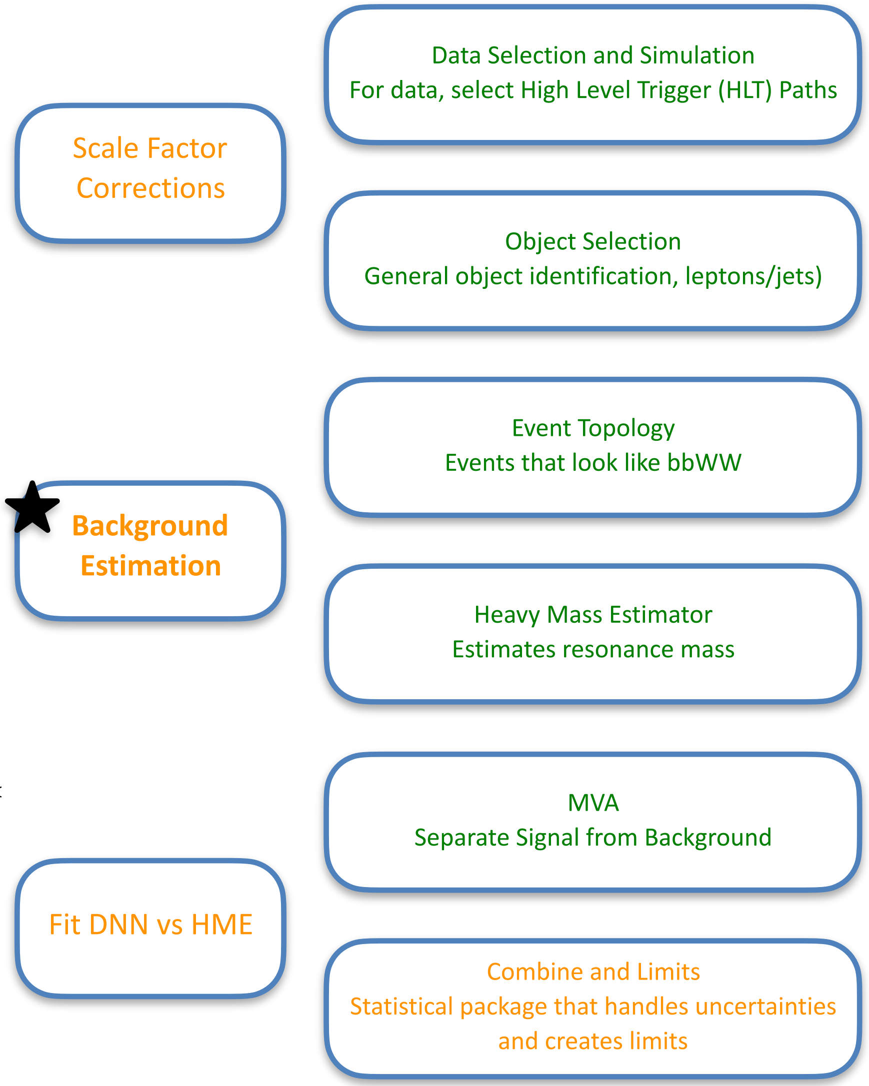
and applied as well (back-up)



$$N\left(Z^{1b/2b}_{Veto}\right) = N\left(Z^{0b}_{Veto}\right)\frac{N\left(Z^{1b/2b}_{Peak}\right)}{N\left(Z^{0b}_{Peak}\right)}$$

Z_{veto} = | M_{ll} – M_Z | > 10 GeV
Z_{peak} = | M_{ll} – M_Z | ≤ 10 GeV
0b/1b/2b = N(Ak4 bjets)





- ABCD closure test — If ABCD estimation is close to simulation, then it is modeled well
  - Where estimation is not matching, then a data-driven approach is required
  - **Early results show 2bJet category has non-closure (further work required)**
- **Fake Rate Estimation still must be done**
  - This involves work in previous steps (move away from ttH analysis)

Run 3 MVA

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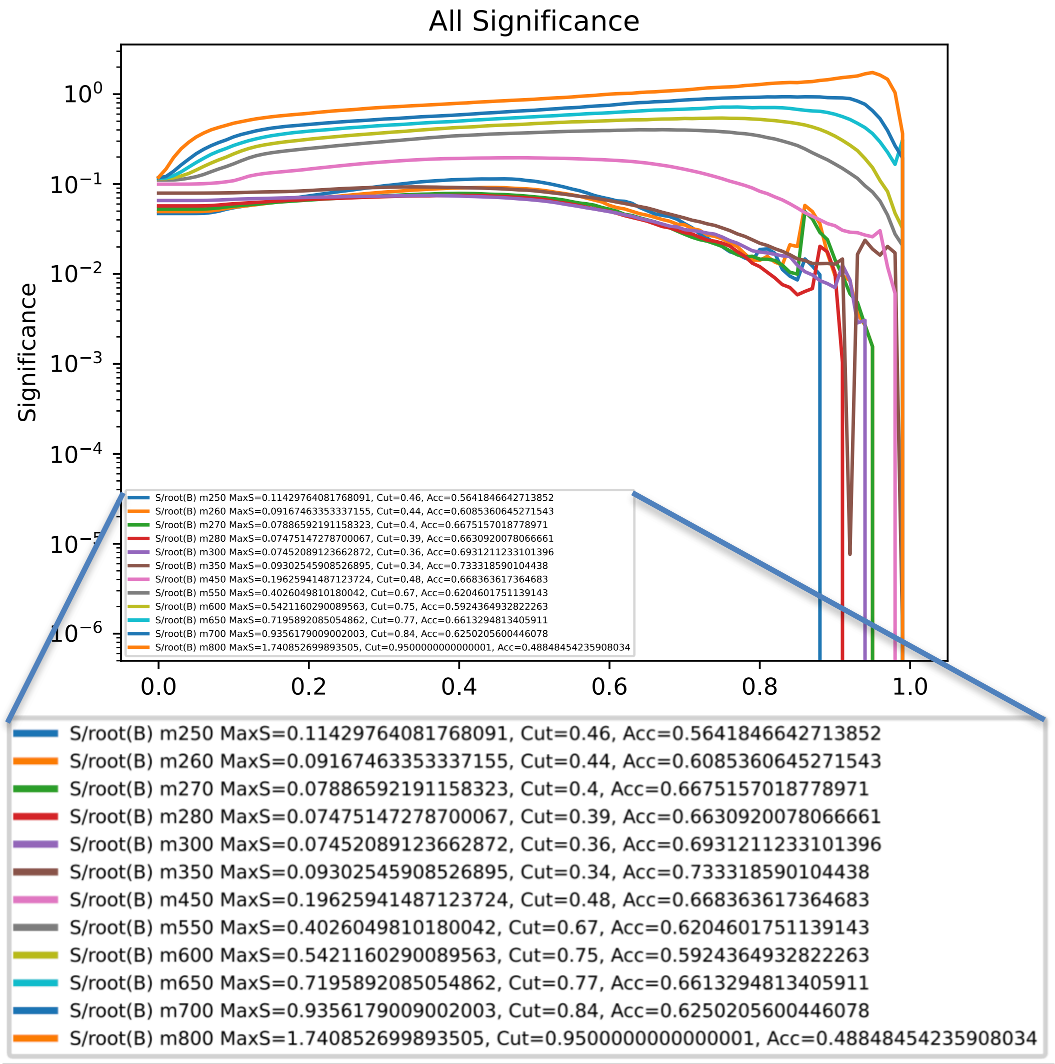
- Early parametric MVA results show DNN is increasing significance for all masses
  - Significance: $\frac{S}{\sqrt{B}}$
  - Acceptance: $\frac{S_{cut}}{S_{total}}$
- Lowest significance around mass 300
  - Working on adding variables to better discriminate $t\bar{t}$ and signal at this region



Scale Factor Corrections

Background Estimation

Fit DNN vs HME

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Run 2 Event Selection

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For Reference

Full Event Selection for the $X \to HH \to b\bar{b}W^+W^- \to b\bar{b}\ell^+\nu\ell^-\bar{\nu}$			
Trigger	Single- or Double-lepton triggers		
Event vertex	One primary vertex with $\|Z_{vtx}\| < 24$ cm, $\|d_0\| < 2$ cm and $n_{DoF} >= 4$		
Filters	Passing filter algorithms given in Appendix Table B.2		
Leptons*	Exact two tight leptons with opposite sign charges, cone-$p_T > 25$ (15) GeV for leading (sub-leading) lepton, $m^{\ddagger}_{\ell\ell} > 12$ GeV and $\|m^{\ddagger}_{\ell\ell} - m_Z\| > 10$ GeV for same flavor lepton pairs		
Jets†	Resolved 1b	Resolved 2b	Boosted
	$\geq$ two AK4-jets, with exactly one passing medium b-tagging WP	$\geq$ two AK4-jets, with $\geq$ two passing medium b-tagging WP	$\geq$ one AK8-jet, with $\geq$ one subjet passing medium b-tagging WP

- Event Selection
  - Pass an HLT
    - Redundant for Data, but MC is also required to pass HLT
  - Good primary vertex
  - Two tight leptons with opposite charge and a minimum p_T
    - Opposite charge requirement from H->WW having opposite charged W's
  - Remove Z decays $|m_{ll} - m_Z| > 10GeV$
  - Filter into categories
    - Resolved 1b — At least 2 AK4-Jets with only one passing medium b-tagged WP
    - Resolved 2b — At least 2 AK4-Jets with at least 2 passing medium b-tagged WP
    - Boosted — At least 1 AK8-Jet with at least 1 subjet passing medium b-tagged WP
  - Category priority goes to Boosted

Scale Factor Corrections

Background Estimation

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★ **Event Topology**
Events that look like bbWW

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MVA Categories

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Multivariate analysis

SL

- Non-resonant : multi-class DNN (resolved + boosted, eras combined)
- Resonant : multi-class DNN (separated for resolved and boosted, separated per era)
- → Parameterized over M_{HH}, split training between spin-0 and spin-2

Process	Description	Resonant	Non-R.
HH(*GGF*)	Gluon fusion Higgs boson pair production	✓	✓
HH(*VBF*)	Vector boson fusion Higgs boson pair p.	X	✓
$t\bar{t}$	Top quark pair p.	✓	✓
ST	Single top quark p.	✓	✓
WJets	W boson with additional jets p.	✓	✓
H	Single Higgs boson p.	✓	✓
Other SL	All other, among them Drell-Yan	✓	✓

DL

- Non-resonant : multi-class DNN (resolved + boosted, eras combined)
- Resonant : 2 multi-class DNN (resolved + boosted, eras combined) : low mass and high mass separated → Parameterized over M_{HH},training over spin-0 + spin-2

Process	Description	Resonant	Non-R.
HH(*GGF*)	Gluon fusion Higgs boson pair production	✓	✓
HH(*VBF*)	Vector boson fusion Higgs boson pair p.	X	✓
$t\bar{t}$	Top quark pair p.	✓	✓
ST	Single top quark p.	✓	✓
DY	Drell-Yan	✓	✓
H	Single Higgs boson p.	✓	✓
$t\bar{t}$V(X)	Top quark pair associate vector boson p. with possible additional vector or Higgs boson ($t\bar{t}$V, $t\bar{t}$VV, $t\bar{t}$VH)	✓	✓
VV(V)	Multiple vector boson p. (WW, WZ, ZZ, WWW, WWZ, WZZ, ZZZ)	✓	✓
Other DL	All other, among them W boson p. with additional jets	✓	✓

Statistical analysis

Process Group	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF) *	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets	Inclusive		
Other	Inclusive		

SL Full Run 2 limit

Combined Full Run 2 limit

DL Full Run 2 limit

Process Group	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF) *	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + VV(V)	Inclusive		

* Resonant does not have VBF category