# Search For Double Higgs Production in bb$\ell\nu\ell\nu$ Final State


Tao Huang, on behalf of CMS Collaboration

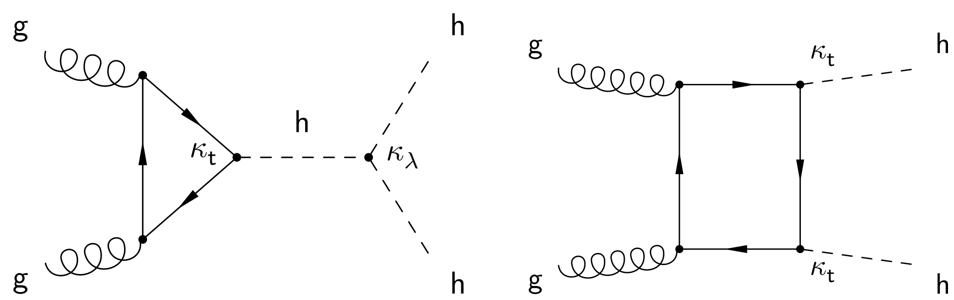
Texas A&M University

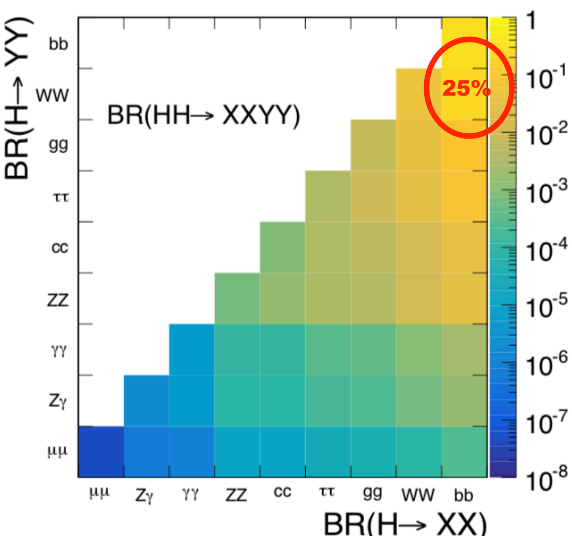

September 6th, 2018 @ LHC Double Higgs Workshop, Fermilab

# Di-Higgs Production at LHC

- Standard Model(SM) context: two main diagrams
  - ➡ Higgs self coupling $\kappa_{\lambda} = \lambda/\lambda_{SM}$
  - ➡ Top Yukawa $\kappa_t = y_t/y_{SM}$
- Constraints on SM Higgs self-coupling
- Destructive interface: ~34fb@13TeV

## SM Production (non-resonant)



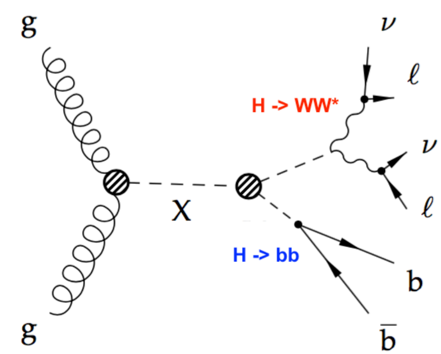




Large BR

But huge ttbar background

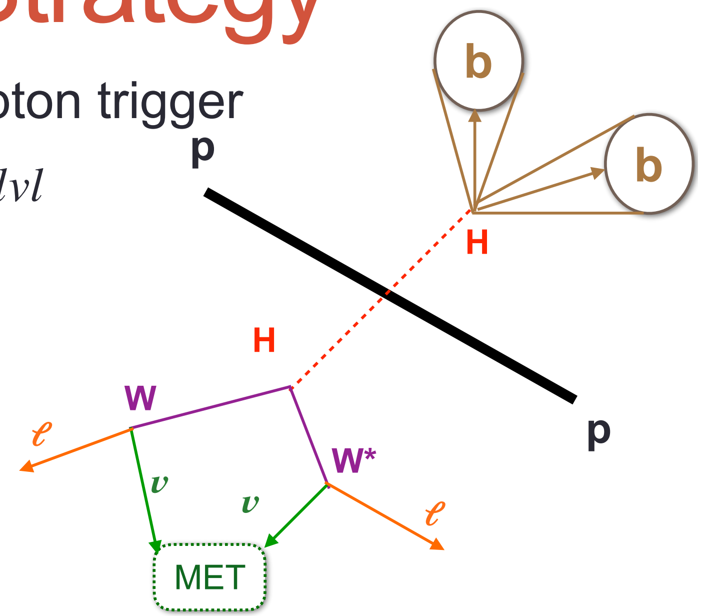
## Resonant Production

- Beyond SM models:
  - ➡Radion(spin=0), Graviton(spin=2) for warped extra dimensions
  - ➡Heavy Higgs in singlet extended SM
  - ➡2HDM…
- Focus on Radion and Graviton model with narrow width




Covered papers: JHEP01(2018)054, FTR-15-002-pas, FTR-16-002-pas, Phys. Rev. D 96, 035007

# Analysis Strategy




- Dataset: CMS 2016 data, 35.9 $fb^{-1}$, dilepton trigger
- Signal signatures: HH $\rightarrow b\bar{b}WW^* \rightarrow b\bar{b}l\nu l\nu l$
- SM Backgrounds
  - Leading irreducible: ttbar
  - Subheading: Drell-Yan
  - Others: single top ..
- Baseline selections
  - 2 opposite sign isolated leptons
  - 2 jets passing medium working point of MVA based b-tagging
  - Zmass - $M_{\ell\ell}$ > 15 GeV to remove Z resonance and tail
- Data-driven method estimation for Drell-Yan process in ee and μμ channel
  - Drive 2 b-tags from untagged sample to avoid poor MC statistics
- Parametric deep neutral network (DNN): train signal bench marks only once
  - One for non-resonant search and one for resonant search
- Fit template: DNN output vs Mjj

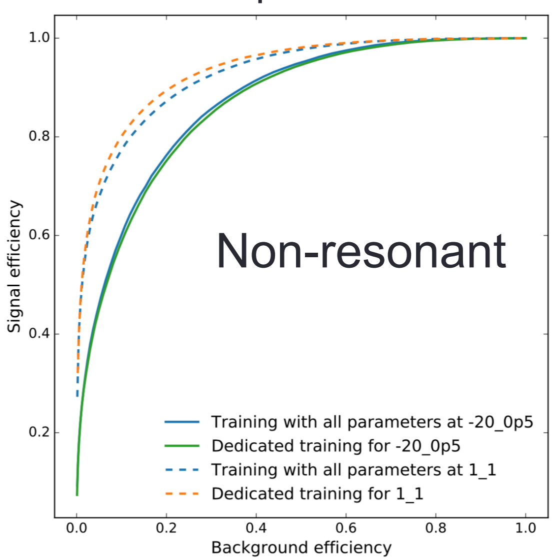
# Parametric Deep Neutral Network(DNN)

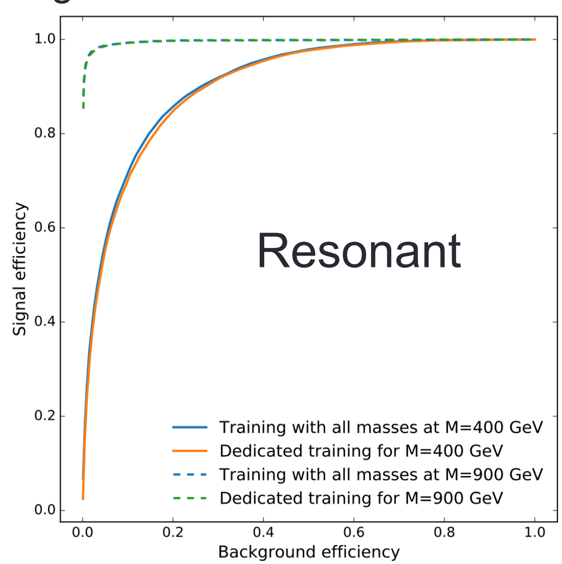
Eur. Phys. J. C (2016) 76: 235

- Two trainings : non-resonant and resonant
  - ➡ In each case, train the all signal bench marks once
- DNN training inputs
  - ➡ Kinematics: $m_{ll}, \Delta R_{ll}, \Delta R_{jj}, \Delta\phi_{ll}, p_T^{ll}, p_T^{jj}, \min\Delta R_{l,j}$, MT
  - ➡ Lepton flavors: same flavor or not (1 or 0)
  - ➡ Non-resonant: 32 combinations of $\kappa_\lambda, \kappa_t$
  - ➡ Resonant: $m_X$ = 260, 270, 300, 350,400, 450,500,550, 600, 650, 750, 800, 900 GeV

Parametric input

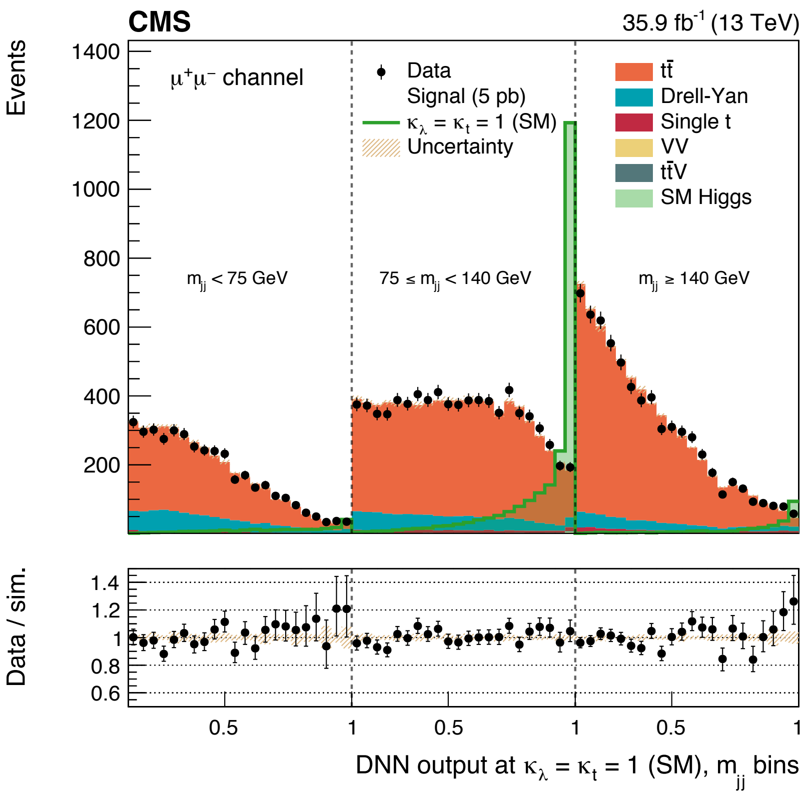
- Benefits from parametric DNN
  - ➡ Similar performance to the model with dedicated training on each bench mark
  - ➡ Reliable to interpolate between different signal bench marks



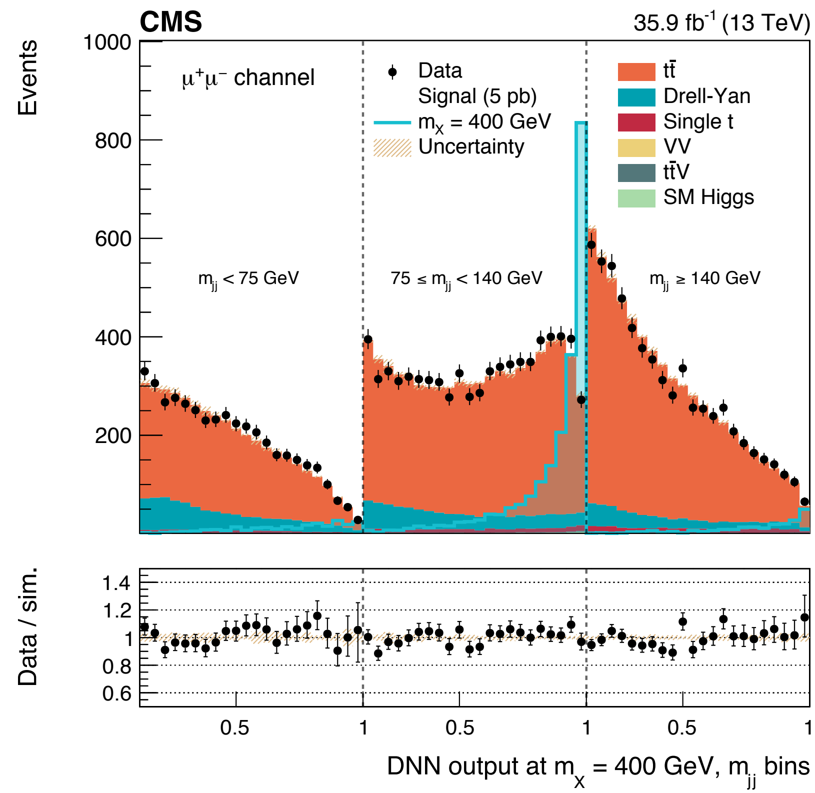




JHEP01(2018)054

# Final Discriminants: DNN output vs Mjj




Non-resonant

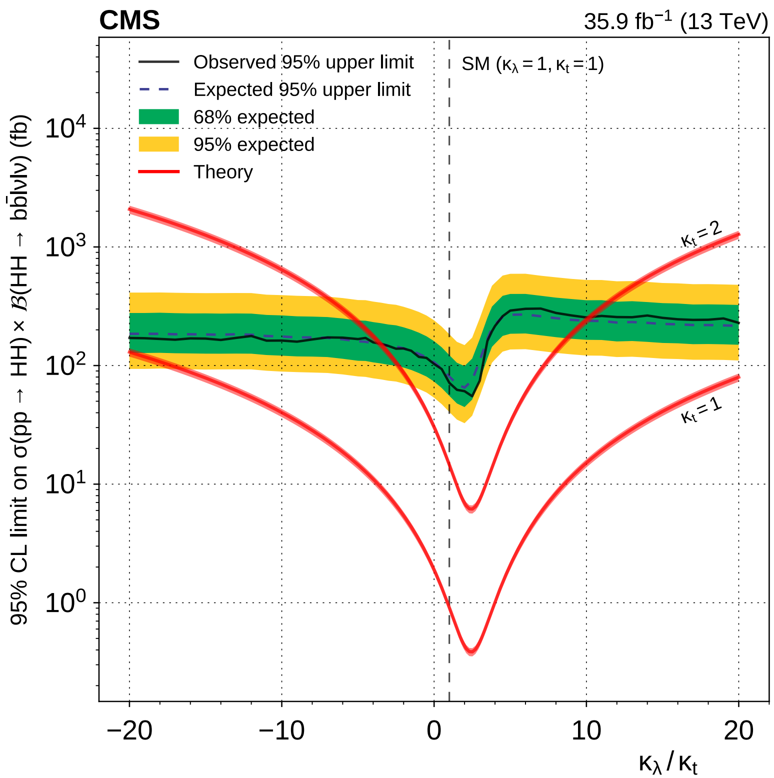


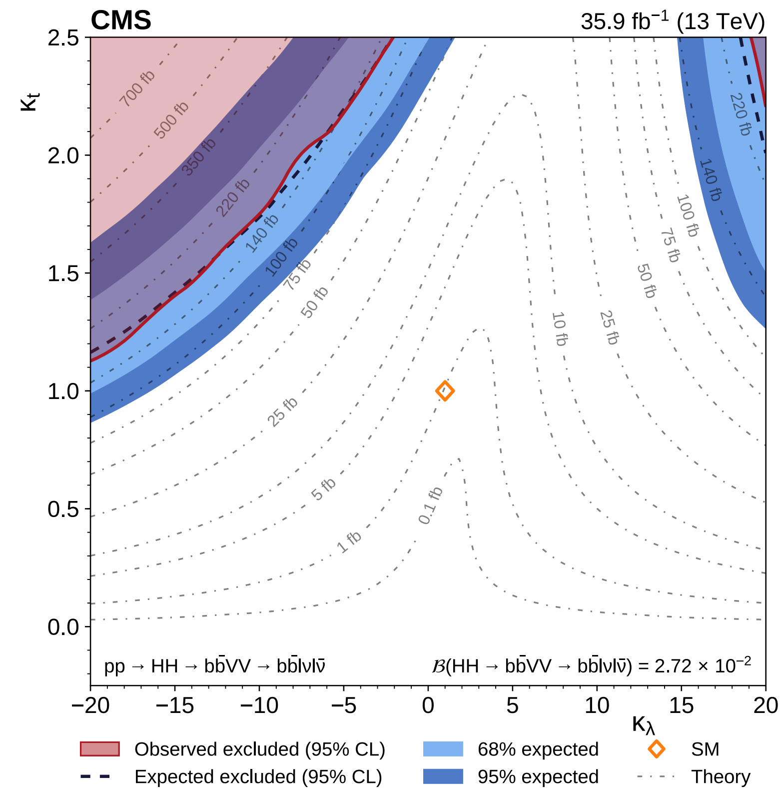

Resonant

- X-axis: DNN output in 3 macro Mjj bins
- GOOD agreement between data and MC
  - |Data/MC-1| < 4%, within uncertainty
  - Uncertainties are post-fit

JHEP01(2018)054

# Non-resonant: Contraints on SM HH Production

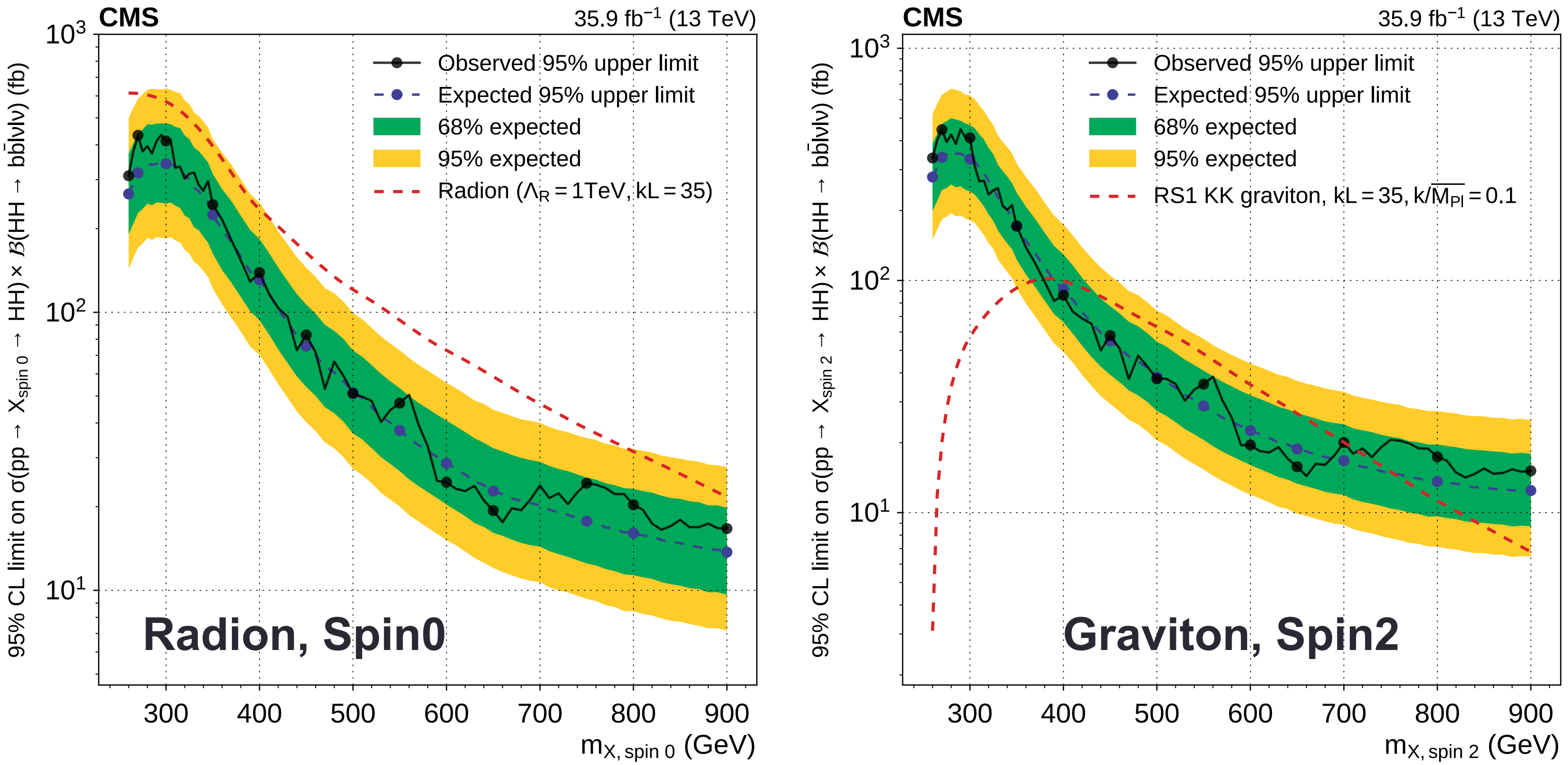



[JHEP01(2018)054](JHEP01(2018)054)

- With SM HH hypothesis, 2016 CMS data excludes $\sigma$xBr(HH->bblvlv) above 72fb at 95% confidence level
  - ➡ 95% C.L. upper limit on signal strength $\sigma/\sigma_{SM}$ : Observed = 79 and Expected = $89^{+46}_{-28}$
  - ➡ Stringent limits could be expected by combing other channels

# Resonant: Constraints on BSM




JHEP01(2018)054

- In low mass region, large ttbar background limits the exclusion power of this channel
- No deviation from SM prediction
  - ➡ Observed limits agreed with expected limits within 1$\sigma$

# New Development: Heavy Mass Estimator

- In our phenomenological study on bbWW*(lvlv) with Delphes, heavy mass estimator (HME) was developed to reconstruct the heavy resonance mass with two neutrinos in final state [Phys. Rev. D 96, 035007](Phys. Rev. D 96, 035007)

$H \to b\bar{b}$ **Inputs:** 2 b-jets

$H \to WW^* \to l\nu l\nu$

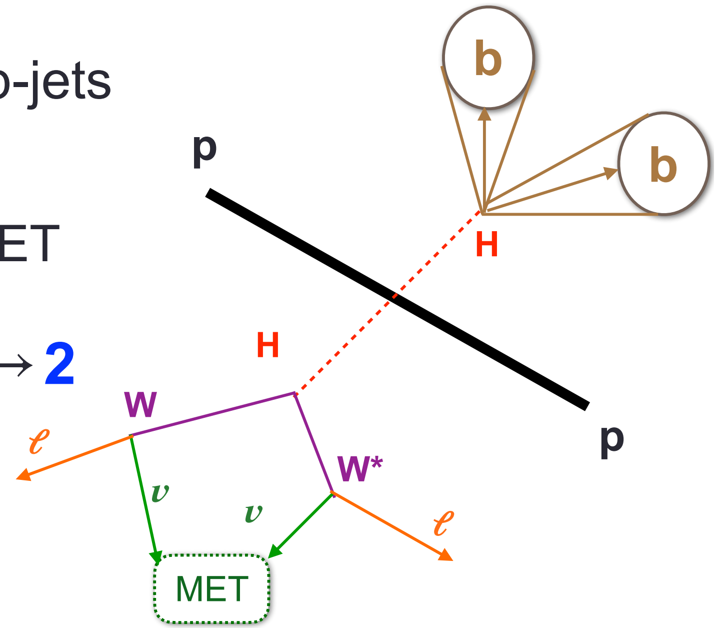
**Inputs:** 2 leptons, MET

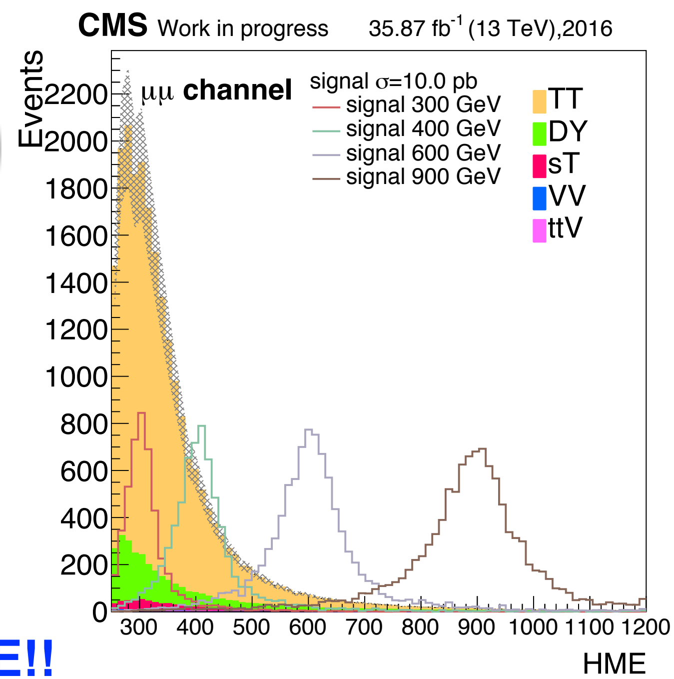
**Contraints:**

- $\overrightarrow{p_T}(\nu + \bar{\nu}) = \text{MET} \to$ **2**
- $M_W$(onshell) $\to$ **1**
- $M_H \to$ **1**

**Unknowns:**

$\nu, \bar{\nu} \to$ **6**

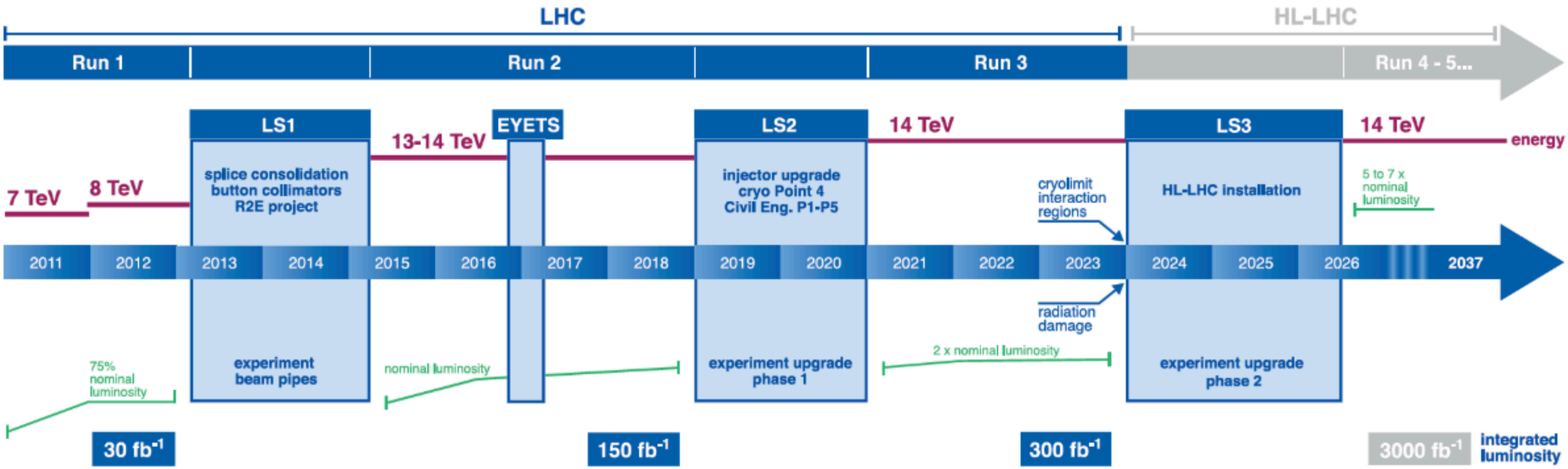



**how to get 2 more "constraints"? HME!!**

1. Randomly generate η and ϕ of one neutrino, 10k trials
2. Generations in kinematic allowed region gives analytic solutions
3. With 2 b-jets, each solution gives one estimator of heavy resonance mass
4. Select the most probable estimator as final estimator for this event

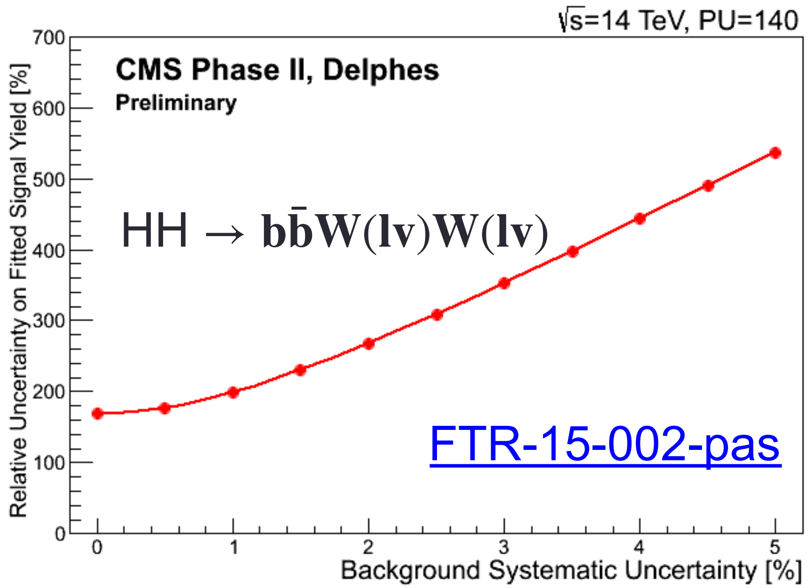
**Application of HME technique to CMS analysis under study**

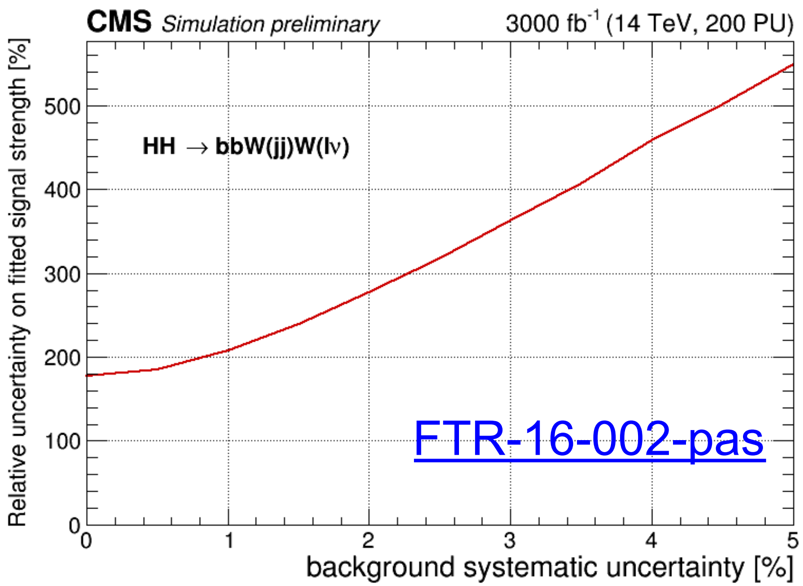



# HL-LHC Upgrade and Projection

- HL-LHC
  - ➡ Higher collision energy: 14TeV. $\sigma_{\mathrm{HH,\,SM}}$ increased to ~40fb
  - ➡ Higher instantaneous luminosity: 5-7.5 x $10^{34}$ $cm^{-2}s^{-1}$. <PU>=140-200
  - ➡ More data: ~3000 $fb^{-1}$ at end of HL-LHC
- CMS upgrade plans: [Phase-II UpgradeTP]
  - ➡ Detectors and electronics: new silicon tracker, new GEM detectors …
  - ➡ L1 Trigger: adding track-trigger and rate @ 750k…
- Delphes parameterized with extrapolated CMS condition to model phase-2 CMS detector

# HH To bbWW* in HL-LHC: non-resonant




- Signal: SM diHiggs with $\sigma$=40fb
- Main background: ttbar
- Event selections:
  - 2 b-tagged jets
  - 2 opposite sign lepton
  - Neural network (NN) discriminator
- Final results: #Signal=37.1; #Background =3875
- More sophisticated analysis of this channel in HL-LHC is being explored for YellowReport

- Signal: SM diHiggs with $\sigma$=40fb, 10% systematics uncertainty
- Main background: ttbar
- Event selections:
  - 2 b-tagged jets out of >= 4 jets
  - Exact one lepton
  - Missing ET >= 20 GeV
  - Boosted decision tree discriminator
- Final results: #Signal=68.1; #Background =8698
  - With 5% background uncertainty, 95% upper limit on signal strength is ~10

Further improvement can be expected from precision timing detector in Phase-2 upgrade, which improves b-tagging efficiency by >10% while controls the mistagging rate at current level

# Summary

- Resonant and non-resonant analysis with 2016 data collected by CMS were published. No significant deviation from SM predication
  - ➡ Non-resonant : Observed (expected) signal strength $\sigma/\sigma_{\mathrm{SM}} = 79\ (89^{+46}_{-28})$
  - ➡ Resonant: limits on Radion(spin-0) and Graviton(spin-2) with $m_X$ in [260, 900] GeV
- Sensitivities of dilepton and single lepton channel in bbWW* in non-resonant production are projected to HL-LHC, which showed promising results
- Prospects for the future
  - ➡ Extend the search to 2017 and 2018 data
  - ➡ Evaluate the heavy mass estimator technique to improve sensitivity
  - ➡ Possibly investigate the HH production also in bbjjlv final state

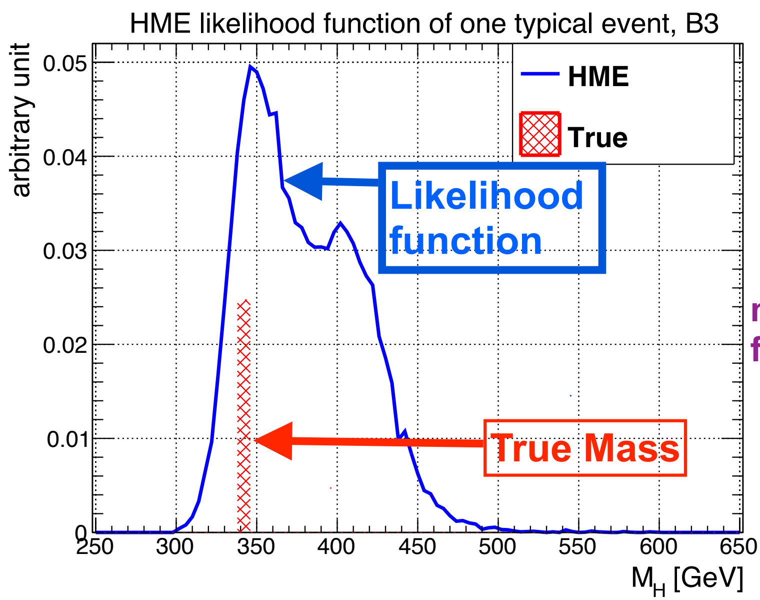
# Backup

# Heavy Mass Estimator

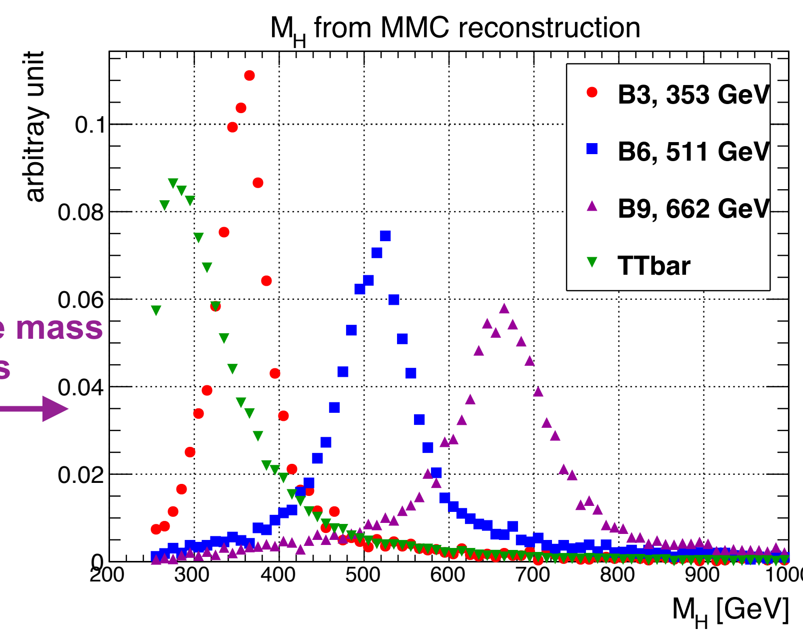
- Construct the likelihood function of each event via the random generations of η and φ of one neutrino
- The most probable mass in likelihood function is taken as the estimator of heavy resonance in each event
- All estimators reconstruct a narrow shape of the resonance, for each signal benchmark

$$\not{E}_{Tx} = p_x(\nu_{\ell_1}) + p_x(\nu_{\ell_2})$$
$$\not{E}_{Ty} = p_y(\nu_{\ell_1}) + p_y(\nu_{\ell_2})$$
$$\sqrt{p^2(\ell_1, \nu_{\ell_1})} = M_W$$
$$\left(p(\ell_1) + p(\ell_2) + p(\nu_{\ell_1}) + p(\nu_{\ell_2})\right)^2 = m_{h_1}^2$$

[Phys. Rev. D 96, 035007]



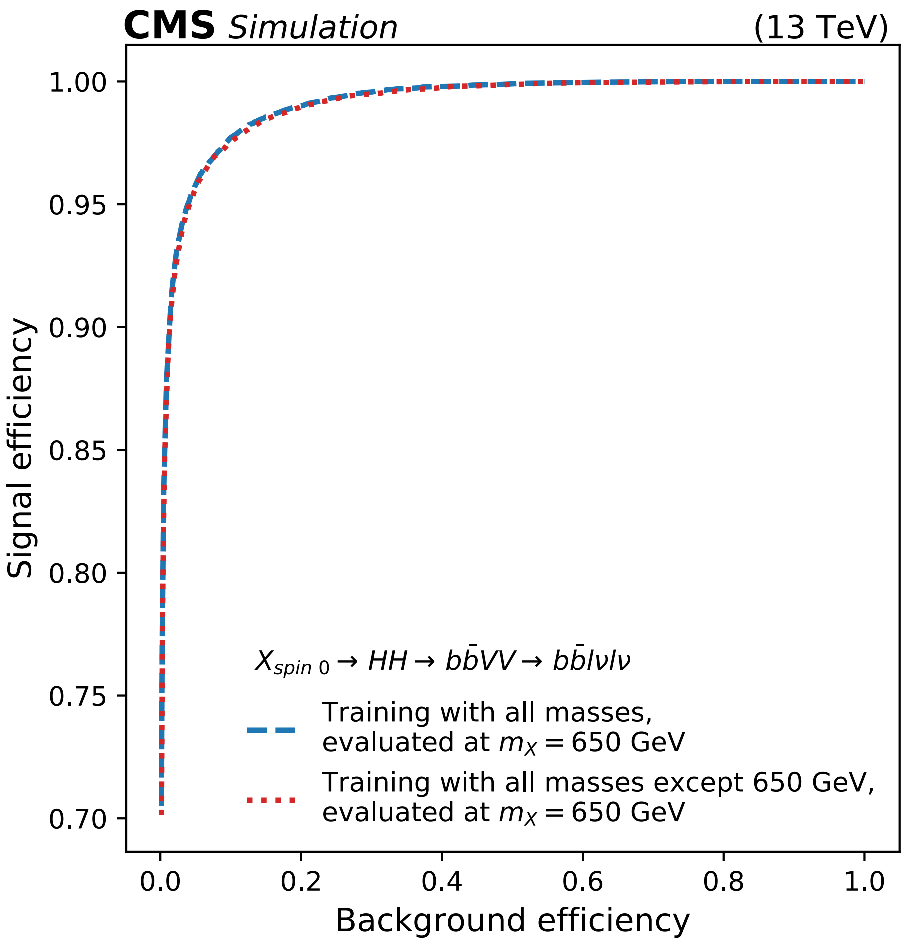

most probable mass from all events




**Likelihood for single event**

**Reconstructed mass shape for signal and ttbar**

# Parametric DNN




JHEP01(2018)054

- Parametric DNN gives similar performance w/wo including Mx=650 in training

# Systematics

| Source | Background yield variation | Signal yield variation |
|---|---|---|
| Electron identification and isolation | 2.0–3.2% | 1.9–2.9% |
| Jet b tagging (heavy-flavour jets) | 2.5% | 2.5–2.7% |
| Integrated luminosity | 2.5% | 2.5% |
| Trigger efficiency | 0.5–1.4% | 0.4–1.4% |
| Pileup | 0.3–1.4% | 0.3–1.5% |
| Muon identification | 0.4–0.8% | 0.4–0.7% |
| PDFs | 0.6–0.7% | 1.0–1.4% |
| Jet b tagging (light-flavour jets) | 0.3% | 0.3–0.4% |
| Muon isolation | 0.2–0.3% | 0.1–0.2% |
| Jet energy scale | <0.1–0.3% | 0.7–1.0% |
| Jet energy resolution | 0.1% | <0.1% |
| Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.) | | |
| $\mu_R$ and $\mu_F$ scales | 12.8–12.9% | |
| $t\bar{t}$ cross section | 5.2% | |
| Simulated sample size | <0.1% | |
| Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.) | | |
| $\mu_R$ and $\mu_F$ scales | 24.6–24.7% | |
| Simulated sample size | 7.7–11.6% | |
| DY cross section | 4.9% | |
| Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.) | | |
| Simulated sample size | 18.8–19.0% | |
| Normalisation | 5.0% | |
| Affecting only single top quark (2.5–2.9% of the total bkg.) | | |
| Single t cross section | 7.0% | |
| Simulated sample size | <0.1–1.0% | |
| $\mu_R$ and $\mu_F$ scales | <0.1–0.2% | |
| Affecting only signal | SM signal | $m_X = 400$ GeV |
| $\mu_R$ and $\mu_F$ scales | 24.2% | 4.6–4.7% |
| Simulated sample size | <0.1% | <0.1% |

JHEP01(2018)054

# Semi-lepton in bbWW* in HL-LHC

FTR-16-002-pas