

Recent ML-usage in searches with boosted jets in CMS

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On Behalf of the CMS Collaboration

Overview

ML4Jets always has many great ideas on jet tagging

What has actually 'trickled down' to usage in experiments?

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- Architectures?

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What has actually 'trickled down' to usage in experiments?

- Architectures?
- Usage in analyses?
 - $X \rightarrow VV/VH$
 - $X \rightarrow WW$
 - VLQ pair production
 - $X \rightarrow YH \rightarrow 4b$
 - Non-resonant $HH \rightarrow 4b$

CMS Jet Taggers

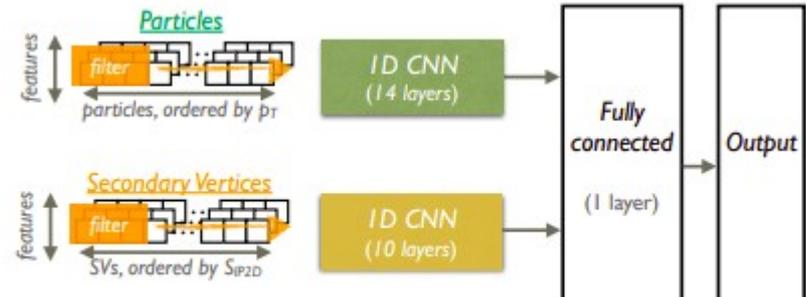
Jets : Anti-kt $R=0.8$, PUPPI
Up to 100 jet constituents (42 feats. per)
Up to 7 secondary vertices (15 feats per.)

Taggers : Deep AK8

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DeepAK8

- Architecture : **1D CNN's**
 - Order inputs by p_T & 2D IP
- Output: Multi-class scores
 - W/Z/t/H/other, split by decay modes (17 scores)
 - Build discriminants by taking ratios
- Mass-decorrelated version trained with an adversary



Taggers : ParticleNet

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ParticleNet

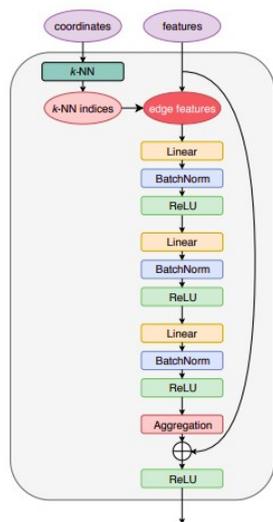
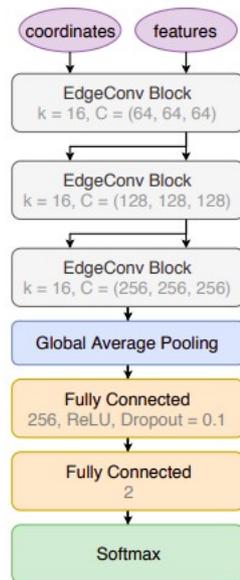


FIG. 1: The structure of the EdgeConv block.

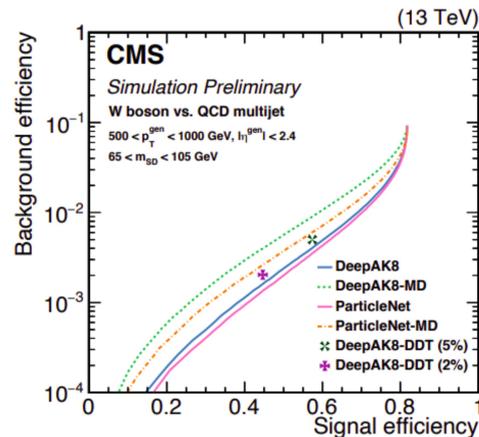
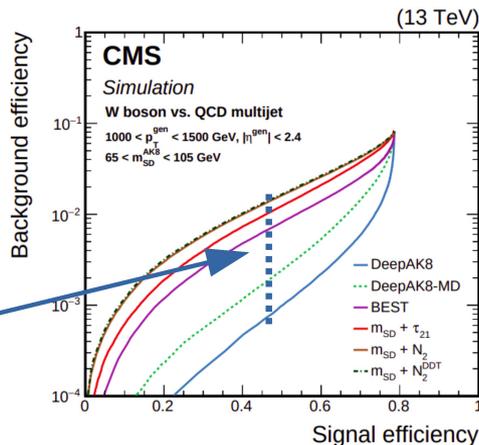


(a) ParticleNet

- Architecture : **Graph based**
 - Processes inputs in permutation invariant way
 - Based on EdgeConv blocks
- Output: binary classification scores
 - X vs QCD
- Mass decorrelated version trained using samples with flat mass & pt spectra
- Same architecture used to predict **jet mass**

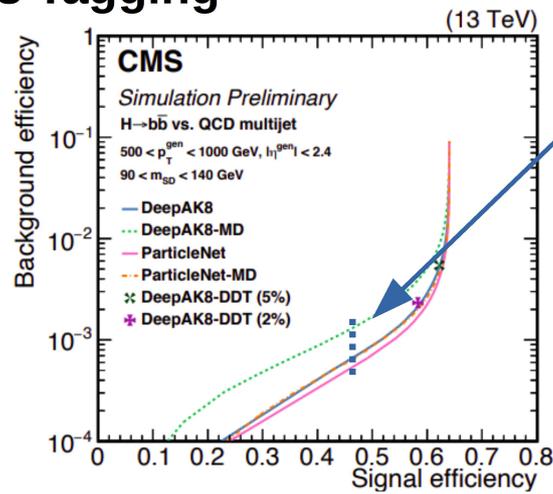
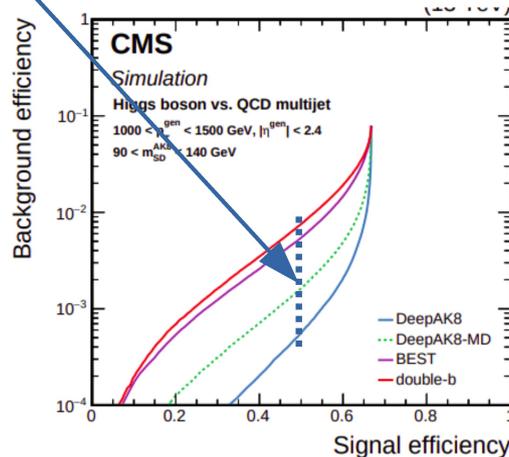
Performance

W Tagging



DeepAK8 gives
~10x improvement
in bkg rejection
wrt traditional vars

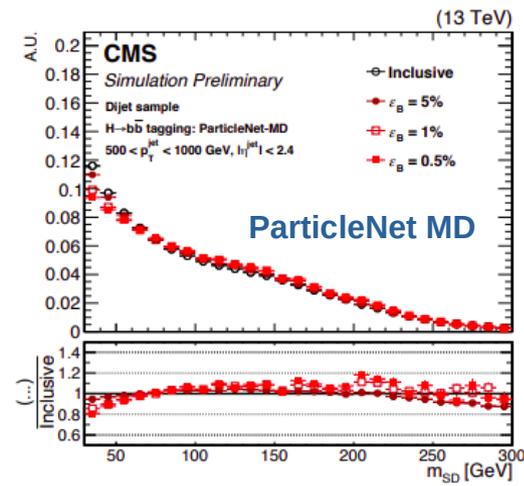
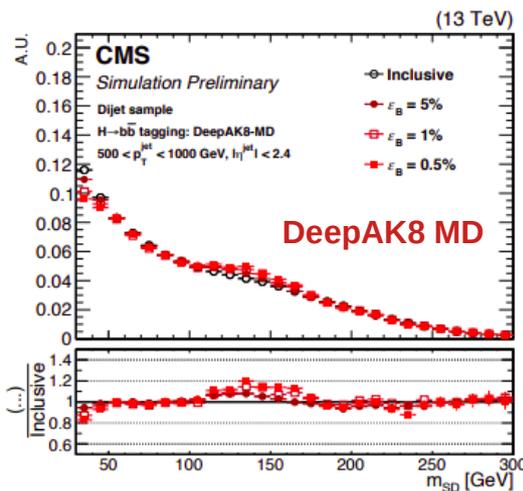
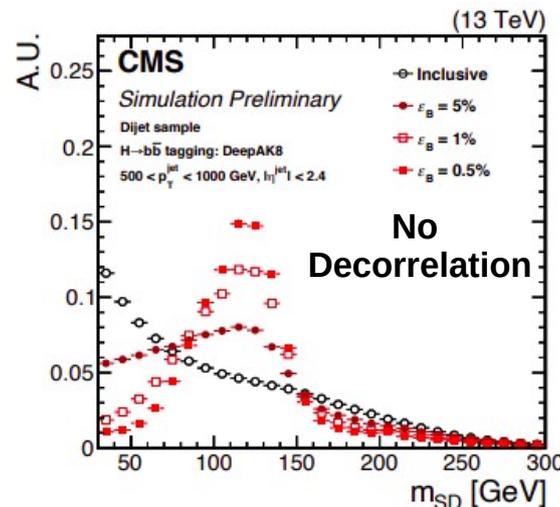
Higgs Tagging



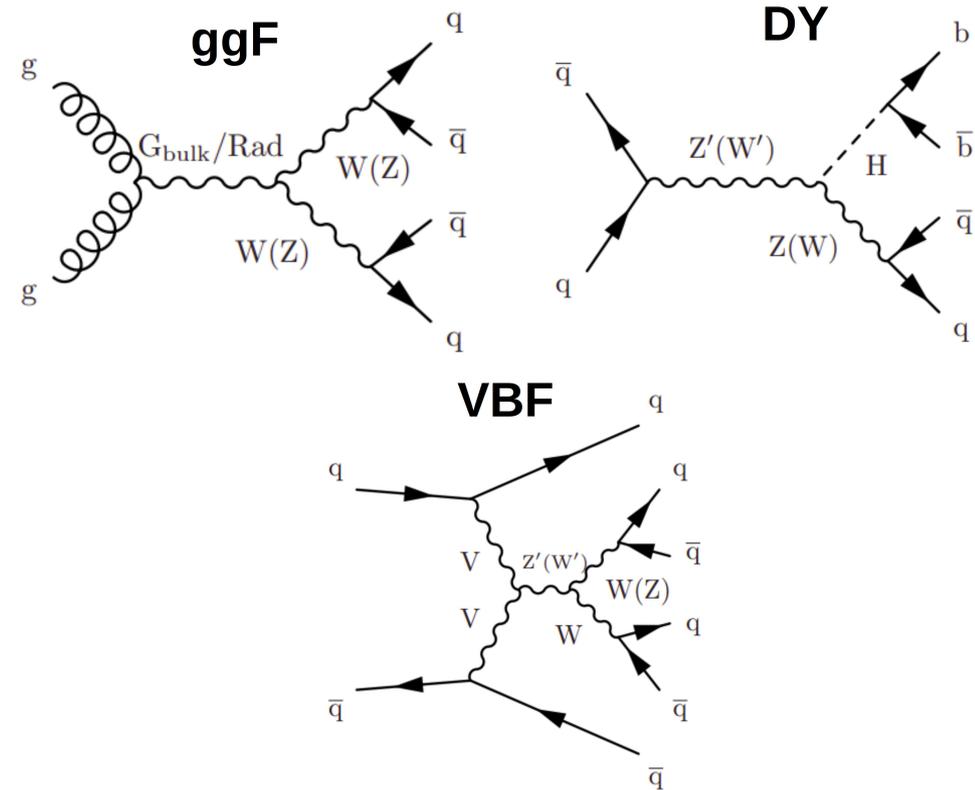
ParticleNet ~2x
bkg rejection wrt
DeepAK8 for H → bb

Mass Decorrelation Performance

- **Crucial** for analyses doing bump-hunts in jet mass
 - QCD sculpting is a big headache for experimenters
- Both methods significantly reduce mass sculpting
- **ParticleNet** achieves slightly better decorrelation on Higgs peak

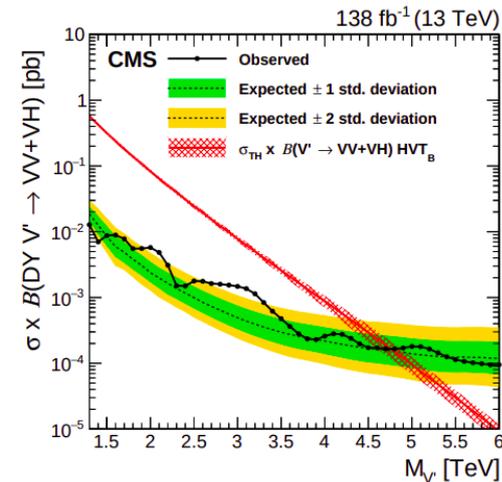
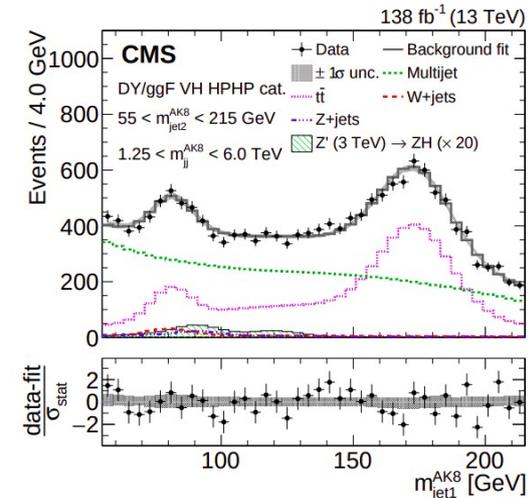
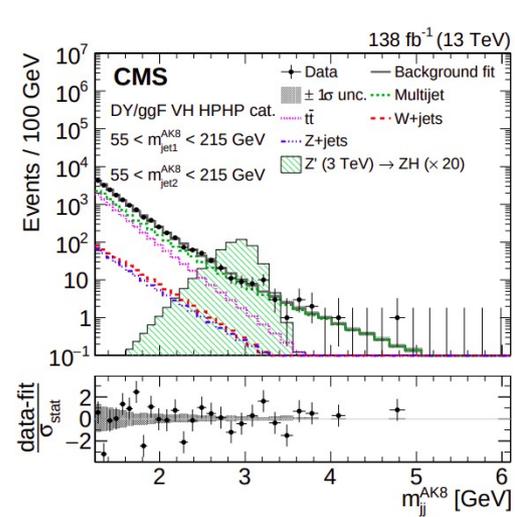


- Search for resonance decaying to two bosons
 - Boosted \rightarrow 2 fat jets
- **DeepAK8** tagger selection targeting $V \rightarrow q\bar{q}$ or $H \rightarrow b\bar{b}$ decays
- 3D bump-hunt in dijet and 2 jet masses



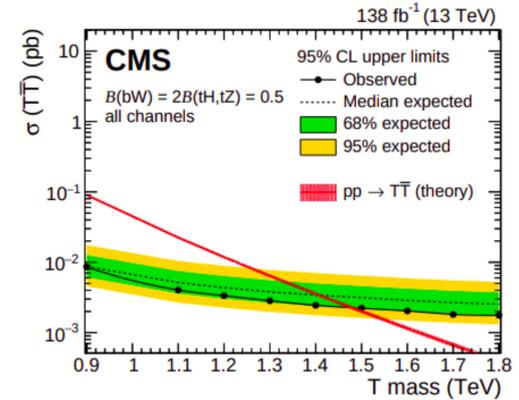
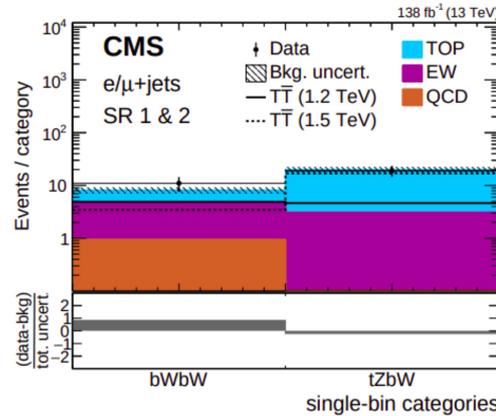
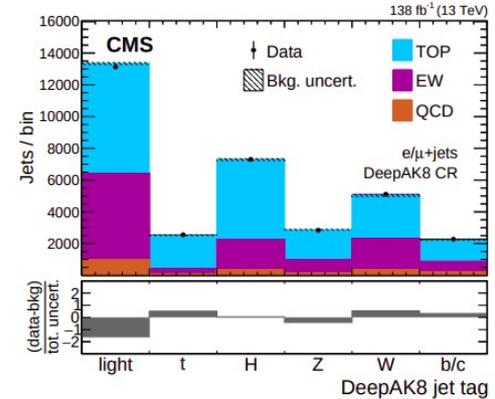
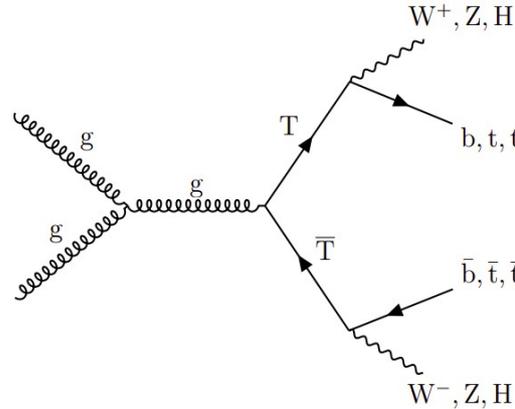
$X \rightarrow VV/VH$: Results

- Modest excesses at 2.1 and 2.9 TeV
 - 2.3 σ global (3.6 σ local)
- Most stringent limits to date
 - Larger data set size & improved tagging roughly equal contribution



Pair Produced VLQ's

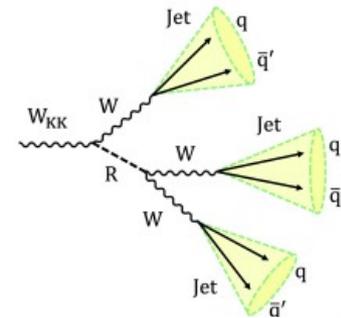
- Multitude of different decays possible
- Single lepton channel uses **DeepAK8** to tag & categorize fat jets
 - Multi-class discrimination crucial!
- Using **DeepAK8** jet tagging led to limits surpassing lumi-based projections of 2016 analysis



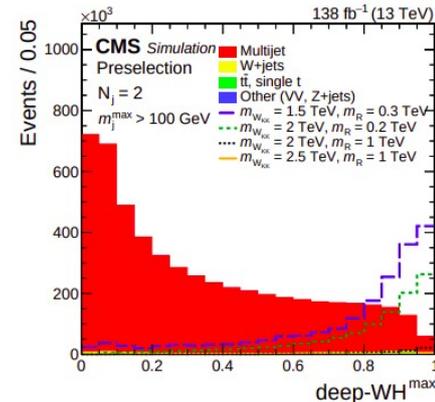
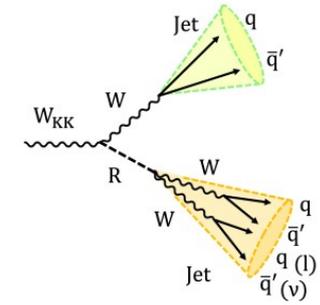
X → WWW

- Search for a KK excitation of W boson (W_{KK}) decaying into W and Radion ($\rightarrow WW$)
 - Consider both **merged** and **resolved** Radion decays
- First analysis tagging merged WW (4 prongs!)
 - Uses **DeepAK8** $H \rightarrow 4q + W$ classes
 - Top jets with additional hard gluon used as a proxy for 4-prong jets \rightarrow derive SF

Resolved



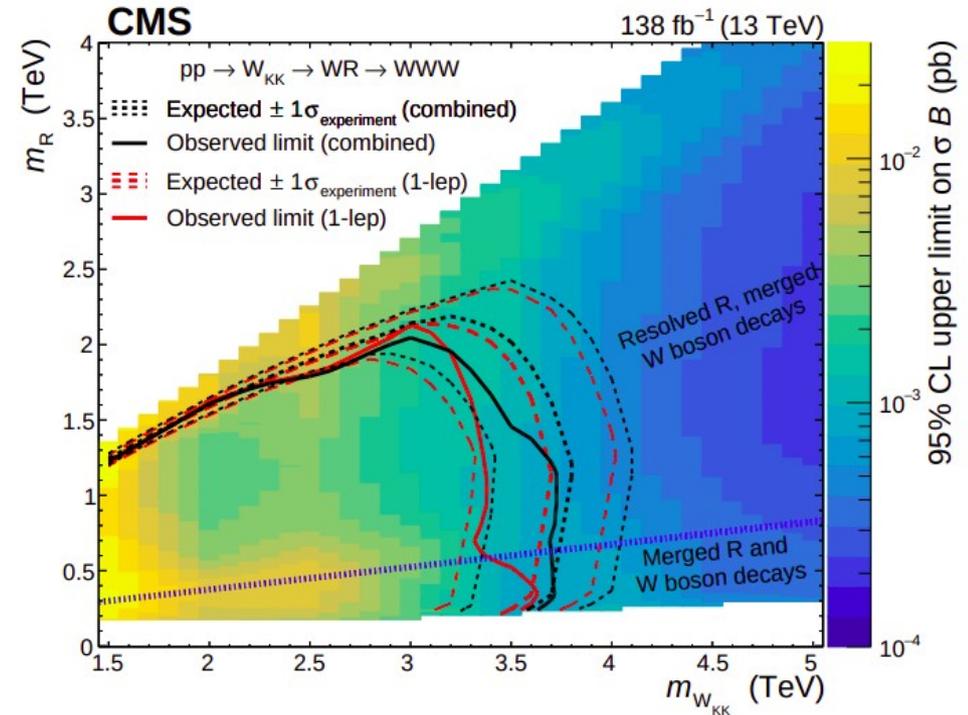
Merged



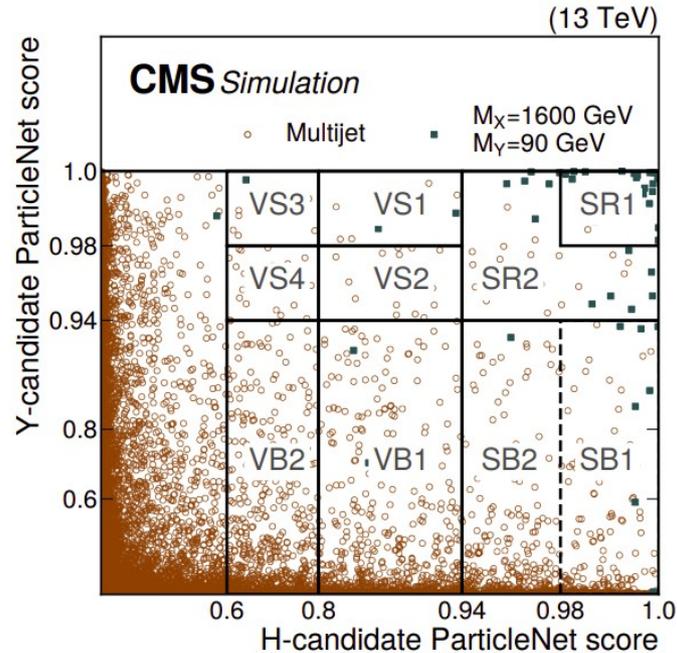
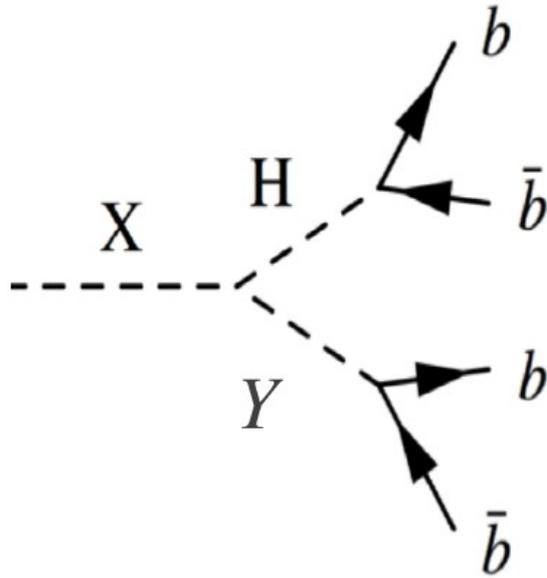
Overall SF's
 W's: $\sim 0.8 \pm 0.2$
 Radion: $\sim 0.7 \pm 0.4$

$X \rightarrow WW$: Results

- Bump-hunt in dijet or trijet mass
- All hadronic channel combined with semi-leptonic one for best limits
- No significant excesses observed
- First limits on this type of model!



$X \rightarrow YH$

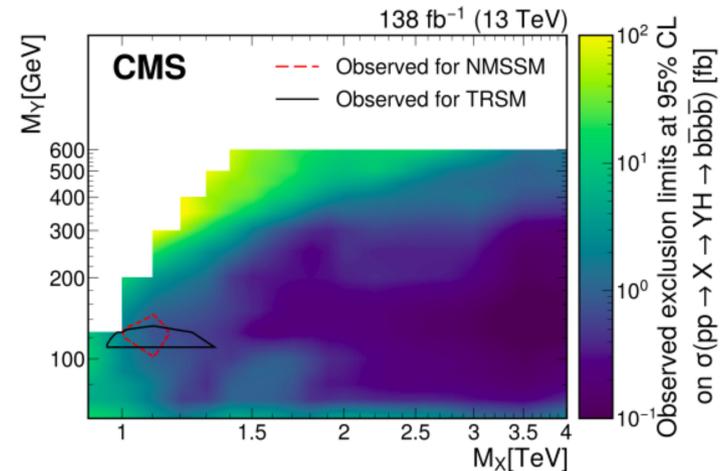
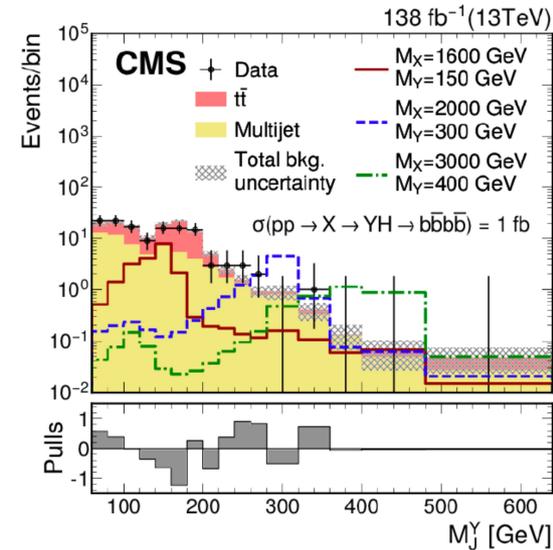


- Search for resonance decaying to Higgs + scalar (Y)
 - **ParticleNet** used to tag each fat jet
- 2D bump-hunt in dijet mass + Y mass

$X \rightarrow YH$: Results

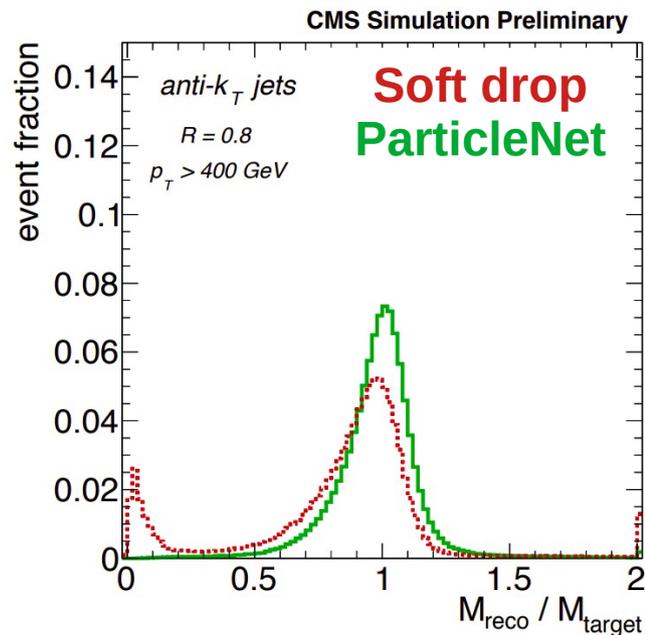
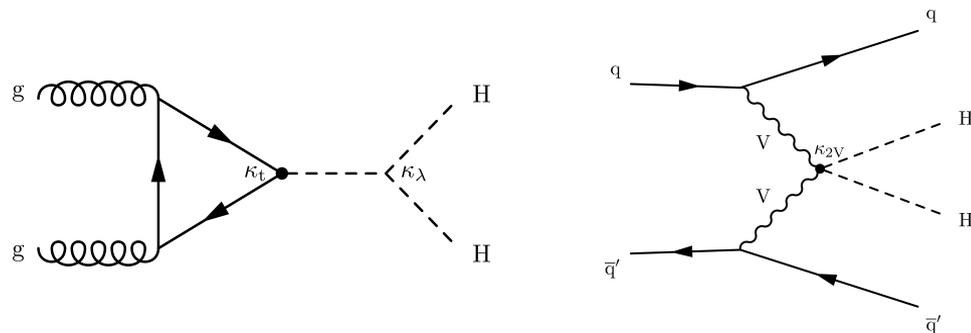
- 2D Bump hunt in dijet and Y mass
 - No significant excesses

- For $M_Y = 125$ GeV, improves $\sim 2x$ over previous CMS di-Higgs search b/c of **ParticleNet**



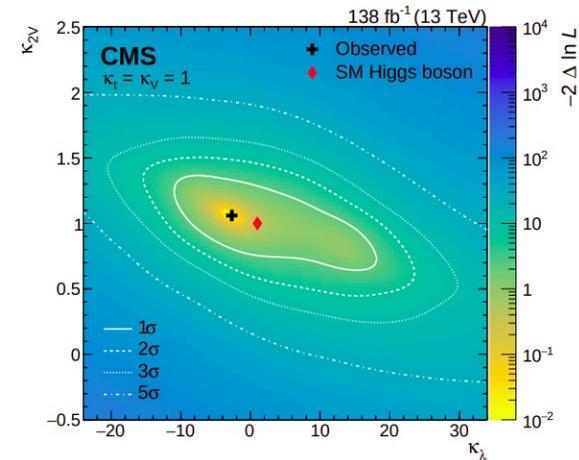
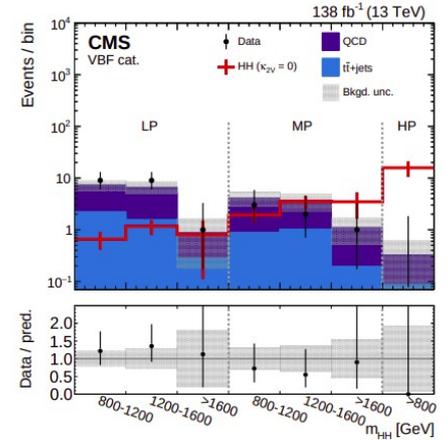
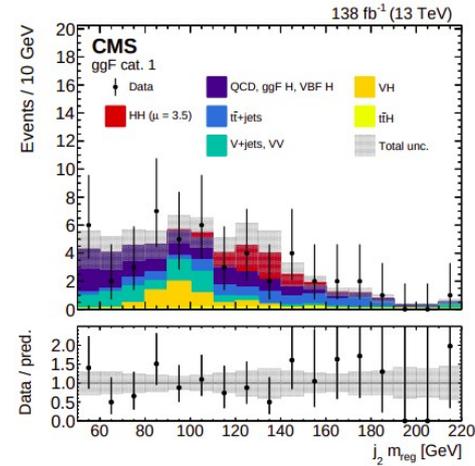
Non-resonant $HH \rightarrow 4b$

- **Boosted** regime \rightarrow 2 fat jets (20% of HH prod.)
 - Separate resolved analysis (2202.09617)
- Split into ggF and VBF production modes
- $H \rightarrow bb$ tagging and **mass regression** done with **ParticleNet**
 - Scale factors calibrated using $g \rightarrow bb$
 - $\sim 2x$ improvement wrt **DeepAK8** + soft drop



HH → 4b : Results

- No significant excess
- Obs. (exp.) limit on HH xsec at 9.9 (5.1) times SM
- $K_{2V} = 0$ excluded for first time! (6.3σ)
- Comparable limits on λ to resolved HH → 4b
 - Enabled by excellent tagging performance!



Conclusions

- ML-based jet tagging extending CMS's physics reach
 - Factors of ~ 2 in sensitivity b/c improved tagging
- Graph-based network, **ParticleNet** now being used in flagship CMS analyses
 - A version is now running at CMS high level trigger! ([link](#))
- More exciting results to come!

Backup

Tagger Backup

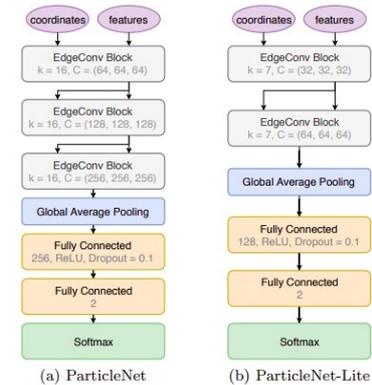
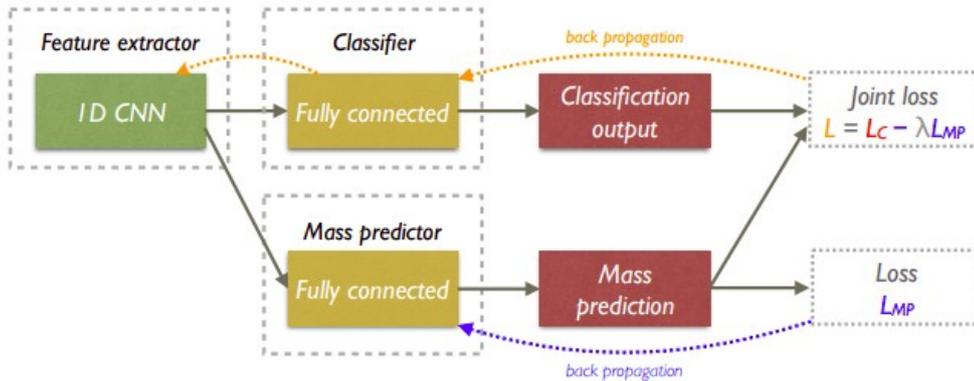
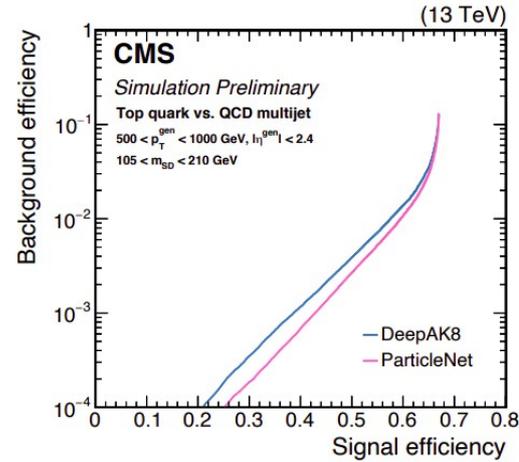
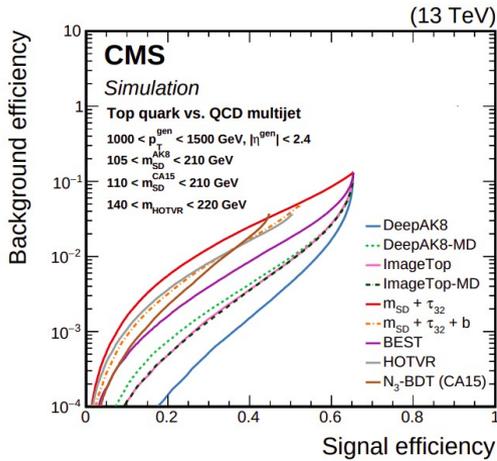
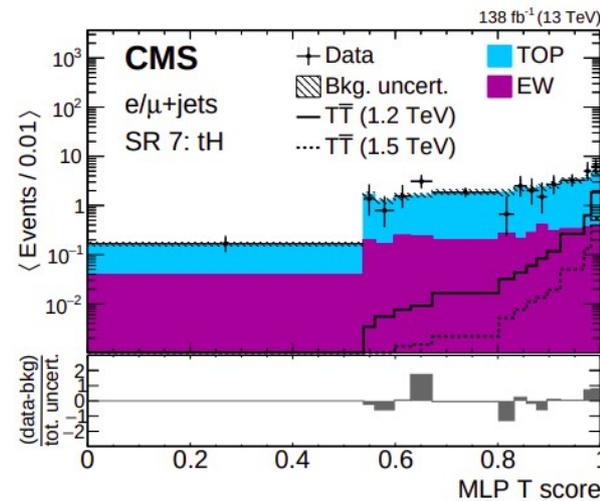
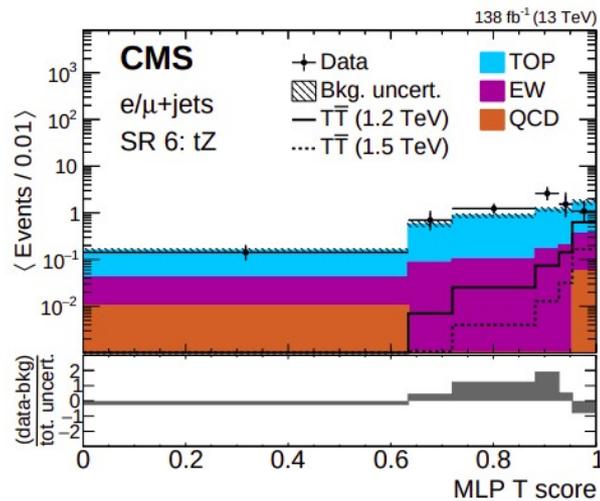
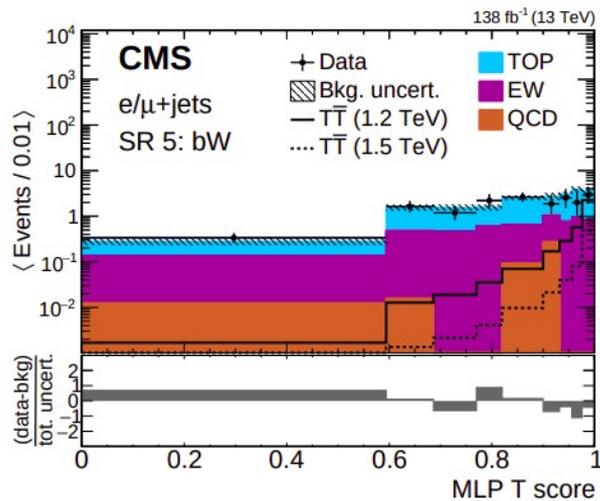
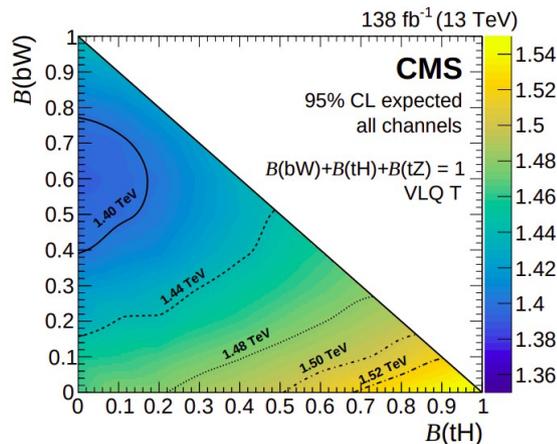
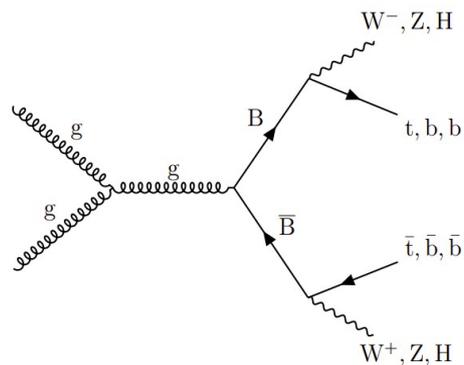


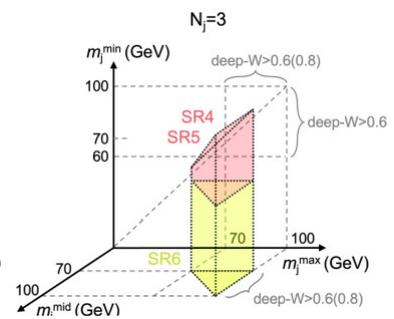
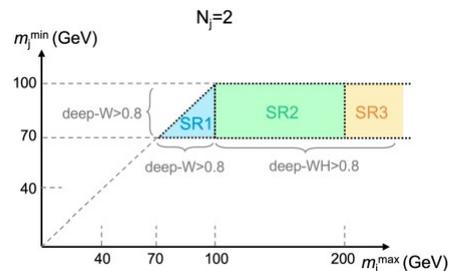
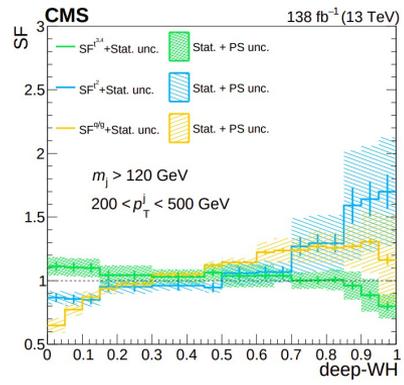
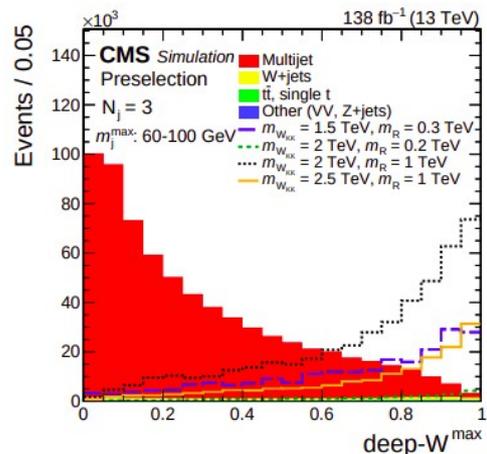
FIG. 2: The architectures of the ParticleNet and the ParticleNet-Lite networks.

VLQ Backup

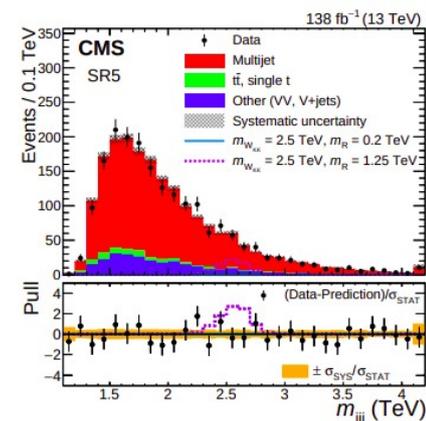
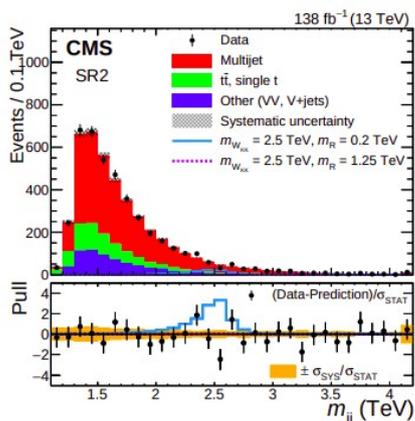
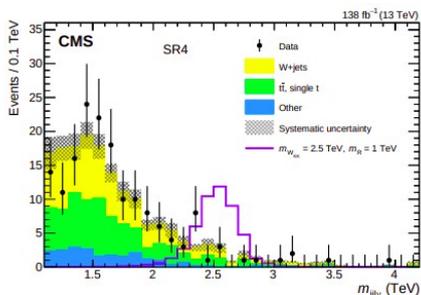


X → WWW Backup

$$\text{deep-WH} = \frac{\text{r.s.}(W \rightarrow qq) + \text{r.s.}(H \rightarrow 4q)}{\text{r.s.}(W \rightarrow qq) + \text{r.s.}(H \rightarrow 4q) + \text{r.s.}(\text{QCD})'}$$



$$\text{deep-W} = \frac{\text{raw score}(W \rightarrow qq)}{\text{raw score}(W \rightarrow qq) + \text{raw score}(\text{QCD})'}$$



HH Backup

