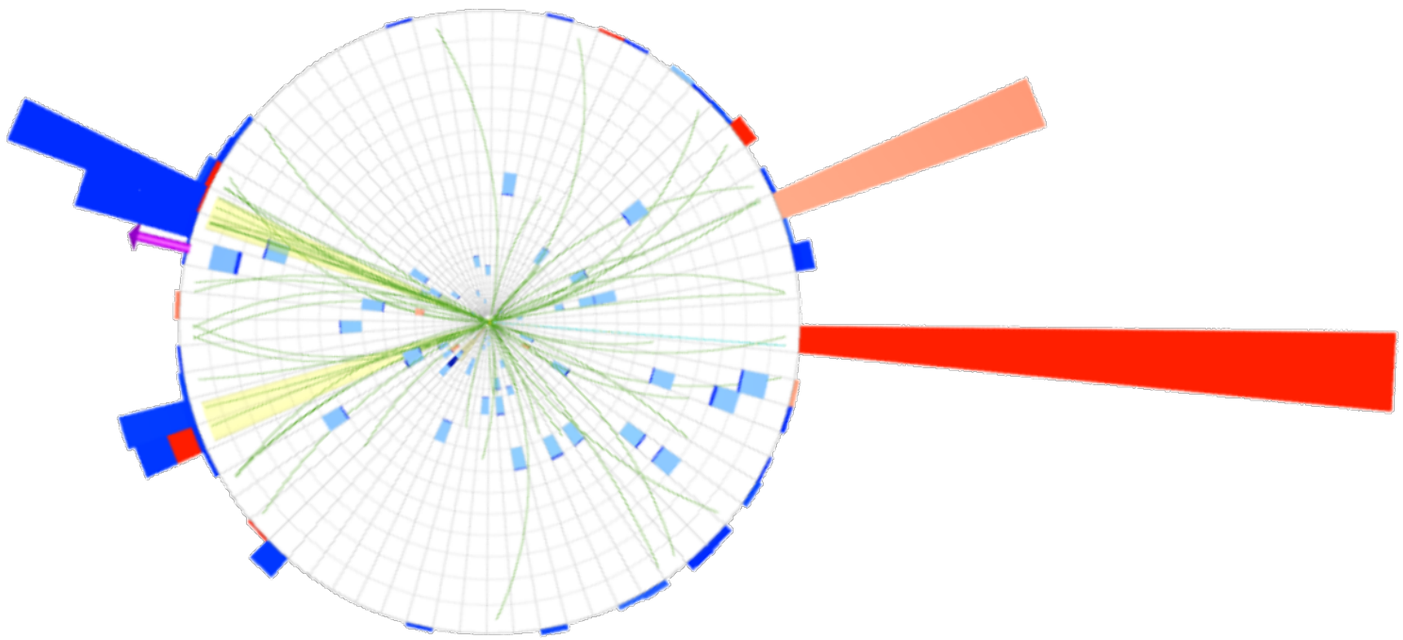
VHbb including 2017 CMS data and Hbb observation

(focus on Deep Neural Network Classifiers)

Pirmin Berger, on behalf of the CMS Collaboration



SPS2018: Swiss Physical Society Annual Meeting 2018, 28-31 Aug 2018

Outline

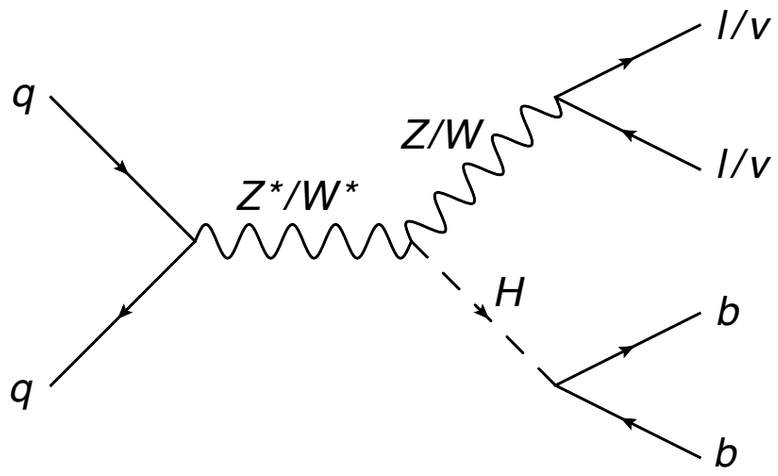
- Introduction
  - Motivation and definition of VHbb analysis
  - CMS detector

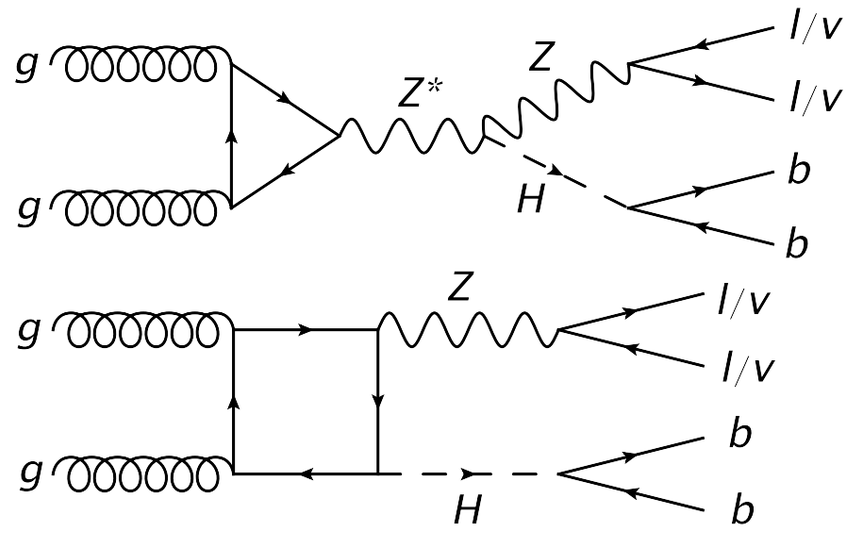
- Analysis strategy
  - object reconstruction, regression
  - backgrounds and selection
  - signal/background classification
  - multi-output classifier for backgrounds
  - fit strategy

- Results
  - 2017 VHbb analysis
  - combination with Run 1 and full Run 2
  - combination with other Higgs production channels with decay to bb

Introduction

- **what are we looking for?**



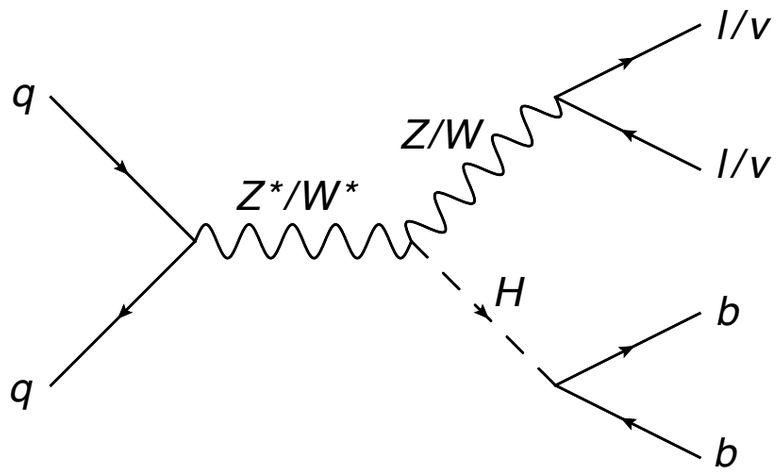


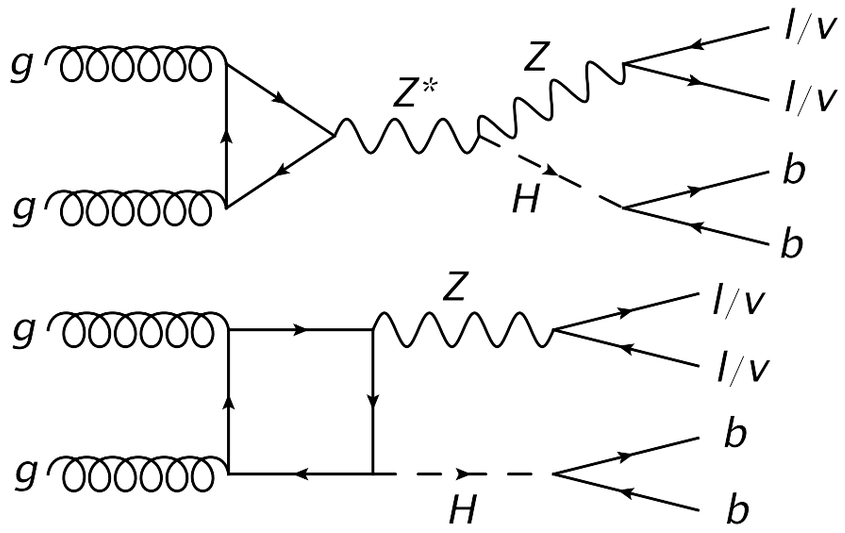
l = e or μ

- Higgs production associated with vector bosons (“Higgs-Strahlung”) with H decay to $b\bar{b}$ quark pair

Introduction

- **what are we looking for?**

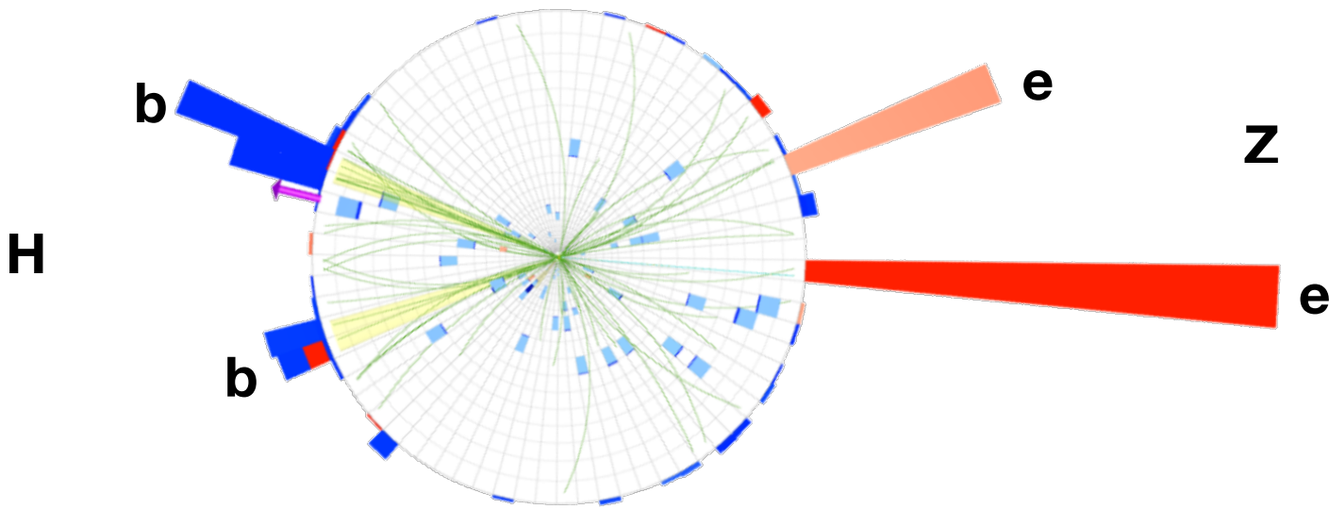




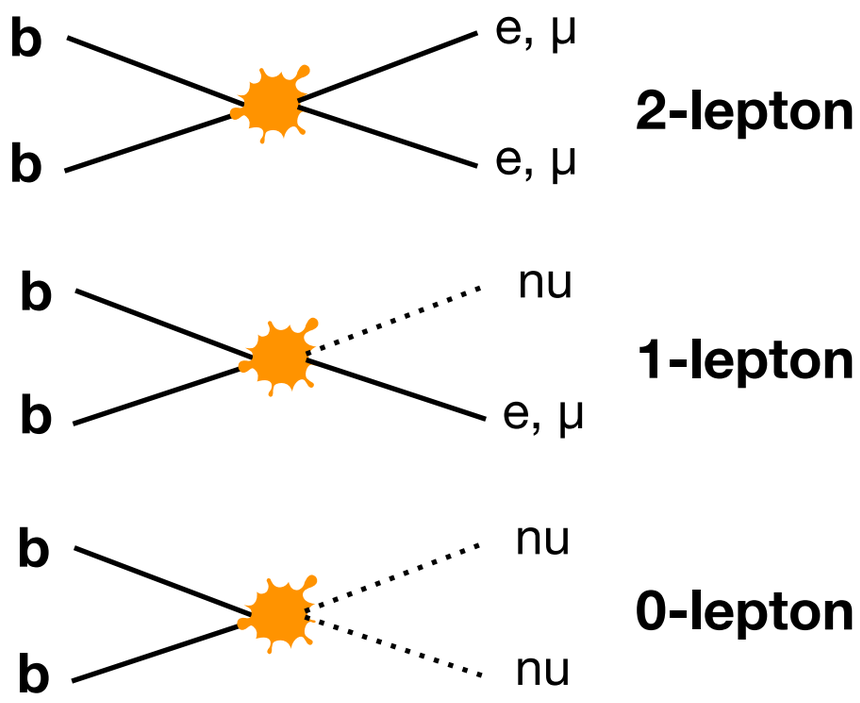
l = e or μ

- Higgs production associated with vector bosons ("Higgs-Strahlung") with H decay to $b\bar{b}$ quark pair

example event display for 2-lepton channel

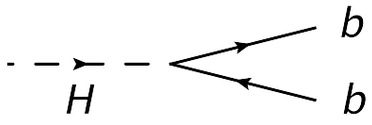


3-channels



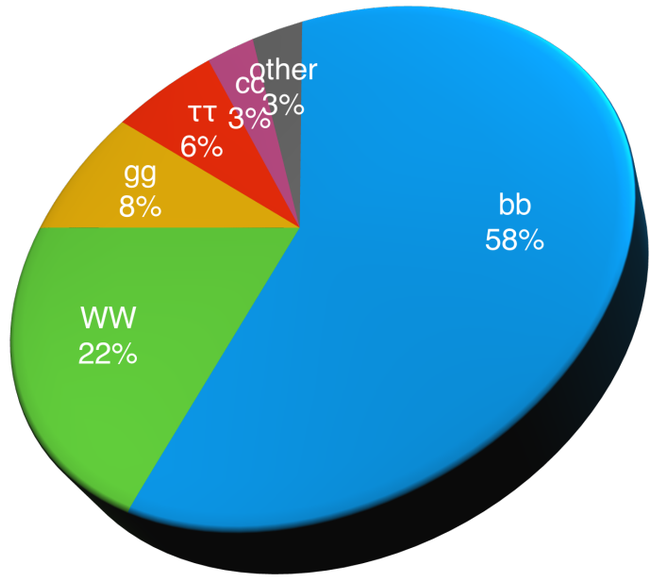
Introduction

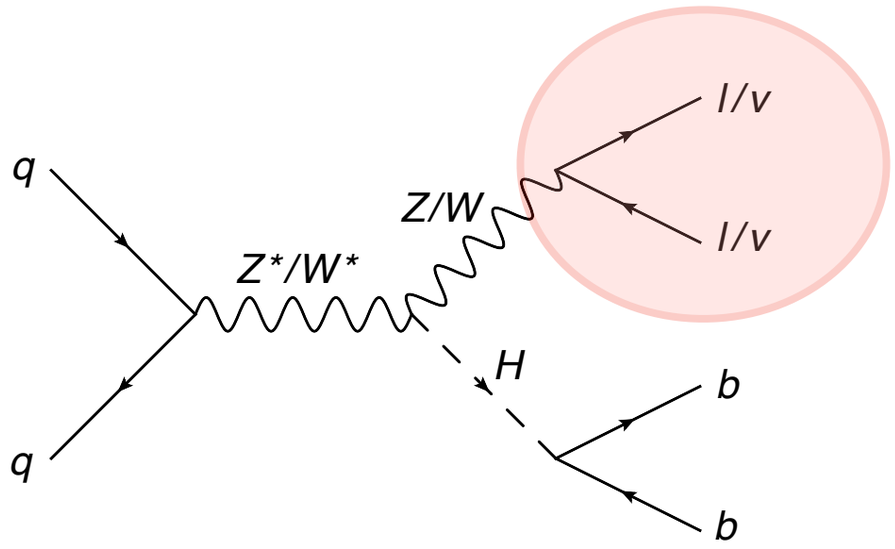
- **why?**
  - Higgs has largest **branching ratio** for decay to $b\bar{b}$ quark pair
  - Measure the coupling of Higgs boson to b quarks
    - predicted by Higgs mechanism in Standard Model



  - <u>challenges:</u>
    - large **background** which also has 2 jets from b-quarks in the event

  - reminder:
    - discovery 2012 was with decay to 2 photons / ZZ->4l



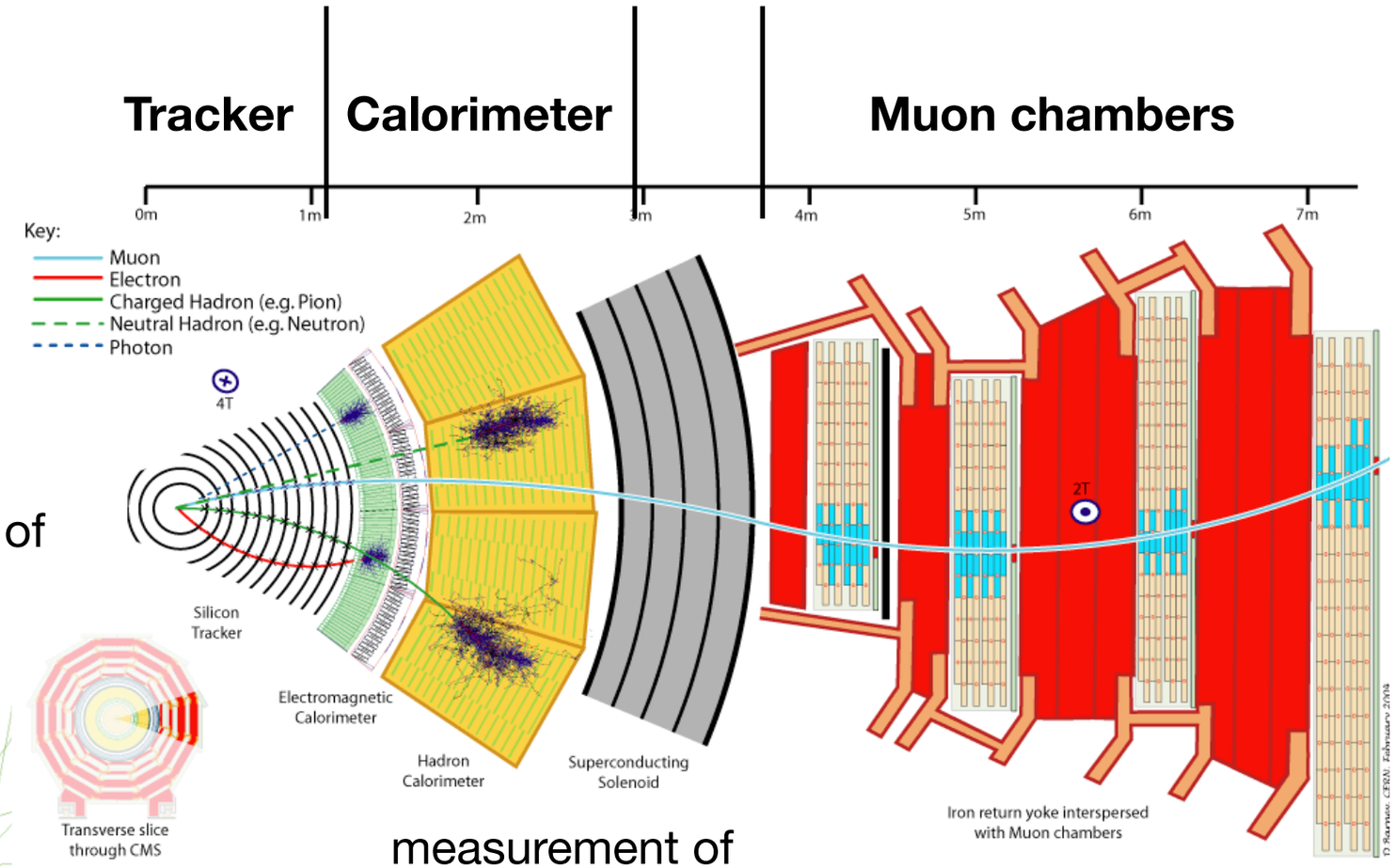


- associated production with a Vector Boson (VH) reduces the background (from QCD) since it requires additional leptons (or missing energy) with invariant mass of vector boson

- require large transverse momenta of H and V reduces background from V+jets production

CMS detector

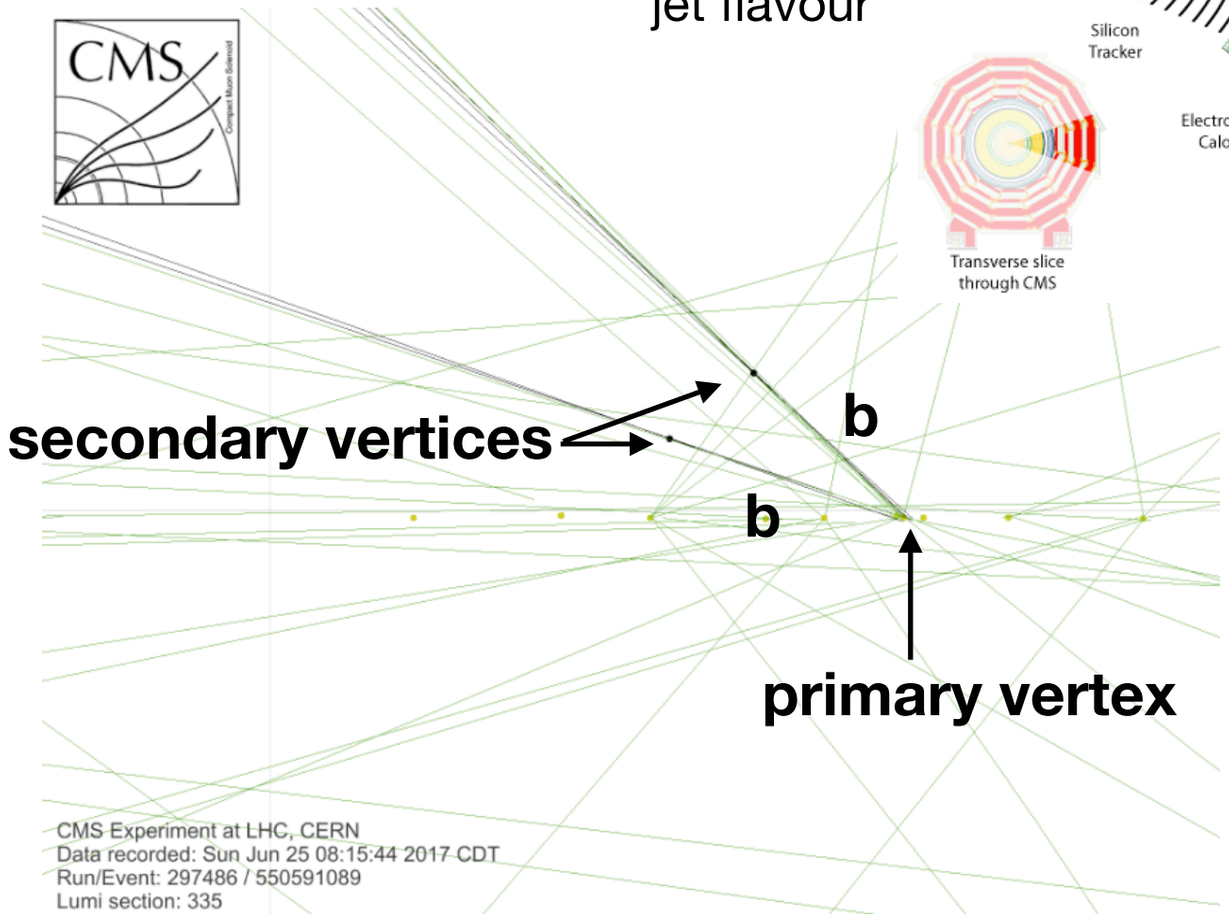
- **how?**
  - CMS (Compact Muon Solenoid) detector at LHC
  - pp collisions
  - 41.3 fb^{-1} of 2017 data, combined with data from previous years with $\sqrt{s}$ = 7,8 and 13 TeV



identification of jet flavour

measurement of jet energy

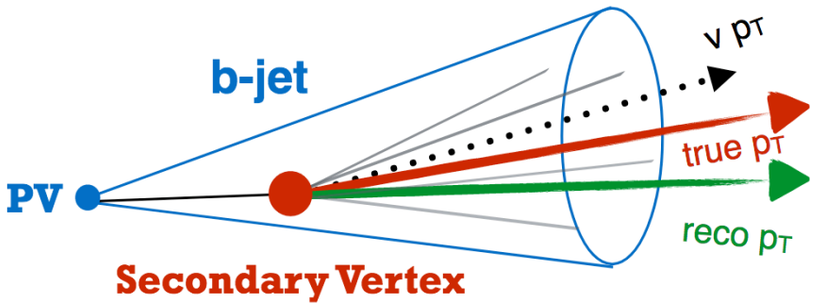
muon identification/ reconstruction



experimental key ingredients:

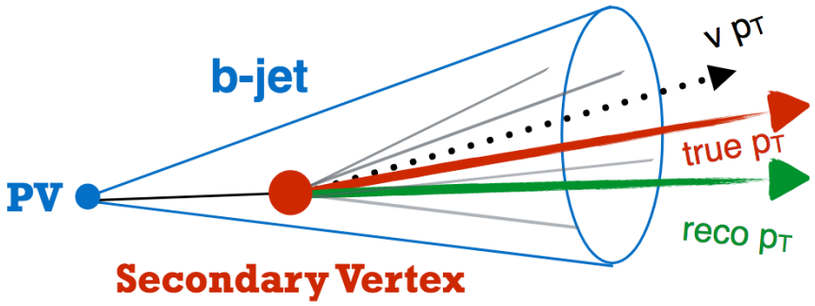
- jet flavour tagging (b-tagging)
- jet energy measurement
- electron/muon identification and measurement

Object reconstruction



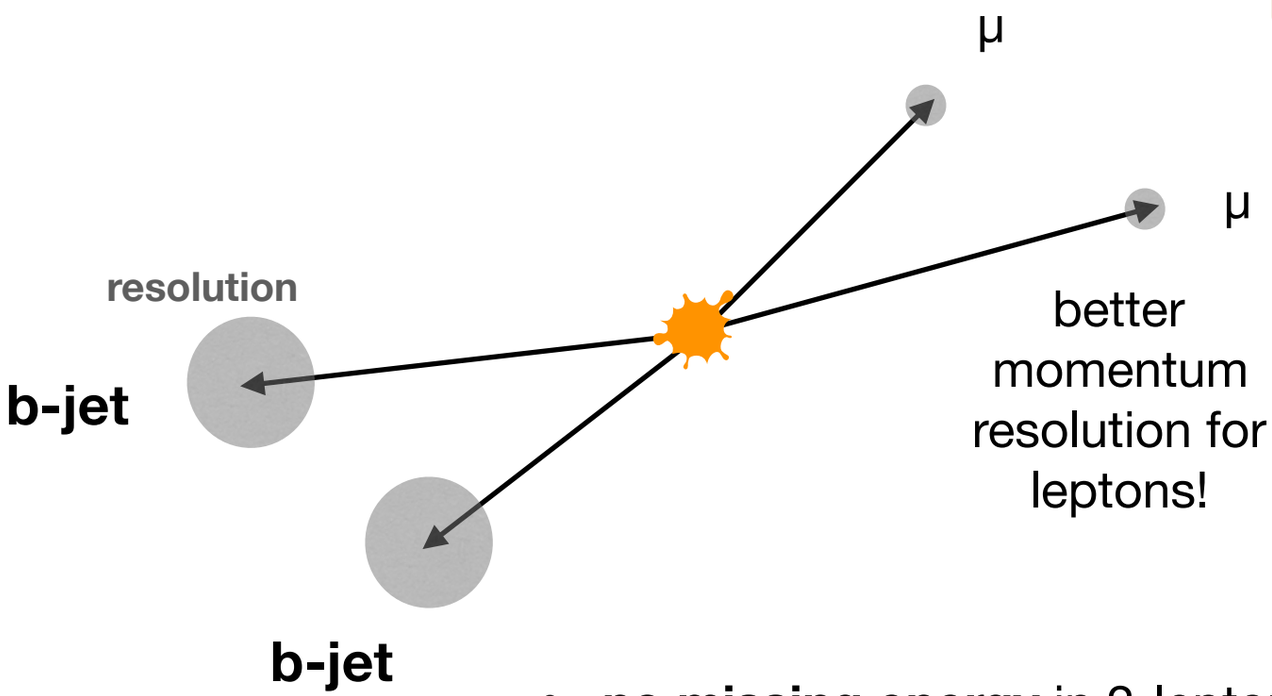
- **DNN regression** for b-jets to recover the escaping neutrino in semi-leptonic decays (see talk of N. Chernyavskaya)

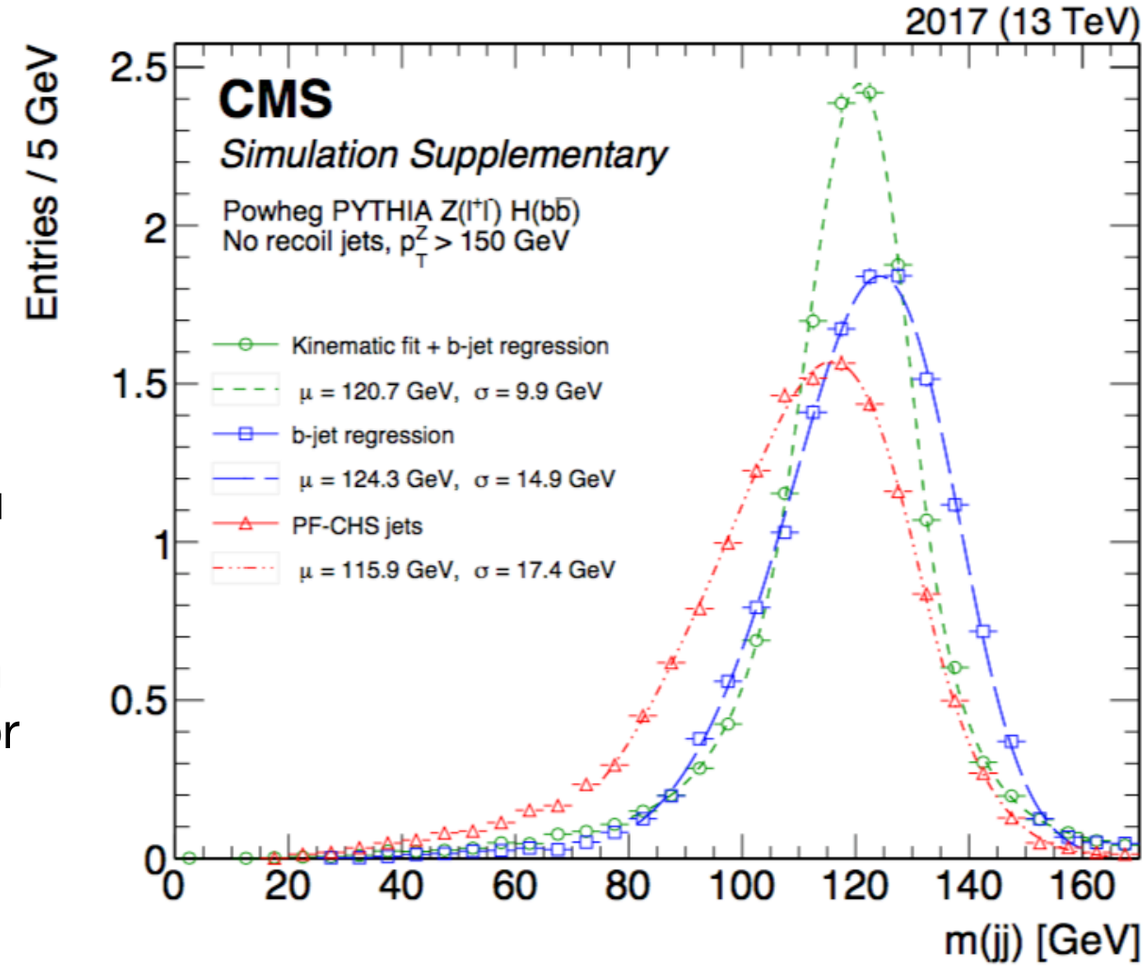
Object reconstruction



- **DNN regression** for b-jets to recover the escaping neutrino in semi-leptonic decays (see talk of N. Chernyavskaya)

- **kinematic fit** in the 2-lepton channel to improve resolution of dijet mass



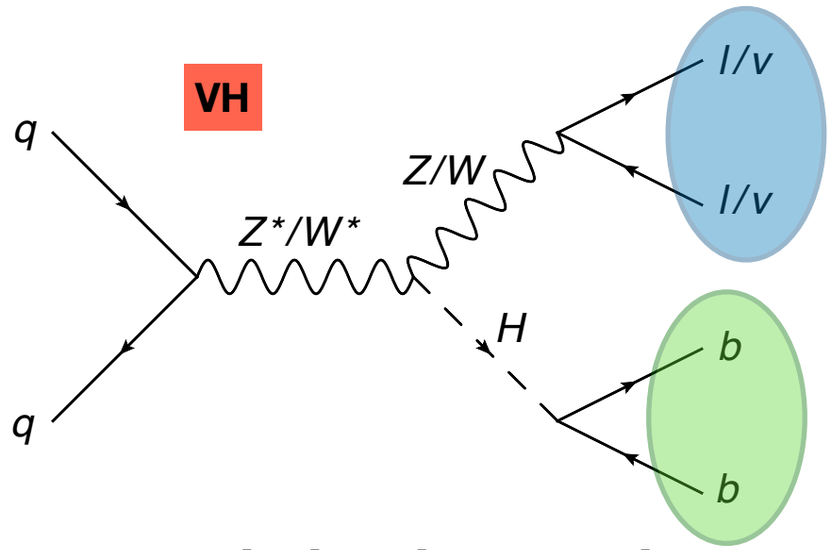


- **no missing energy** in 2-lepton channel

=> perform a fit to use good resolution on leptons to improve resolution of b-jets

Signal and backgrounds

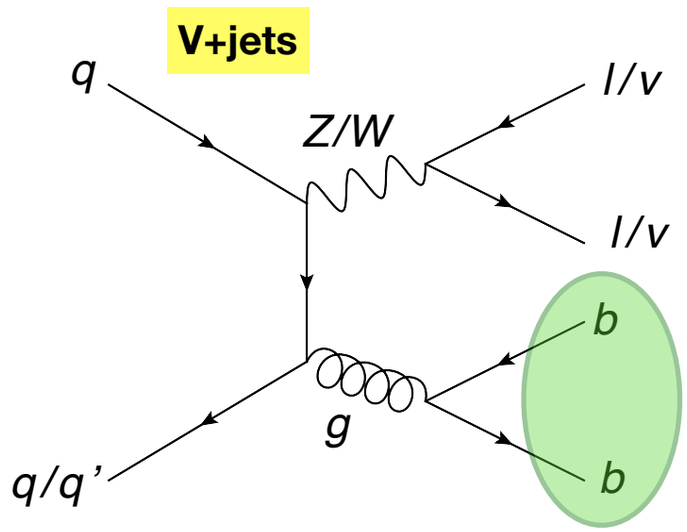
signal



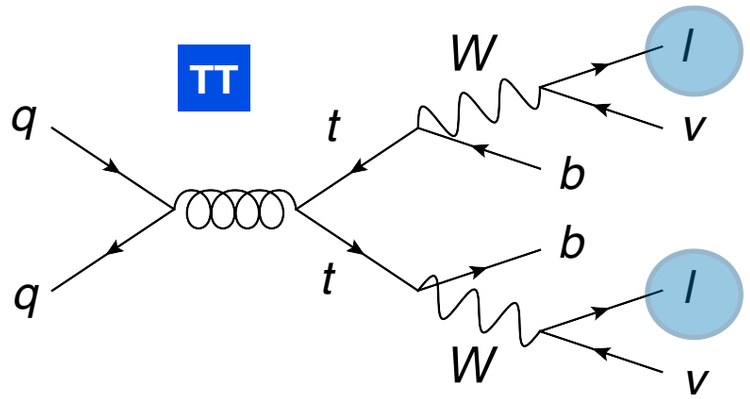
invariant mass has a peak at m_V

invariant mass has a peak at m_H ~ 125 GeV

main backgrounds



falling distribution without peak

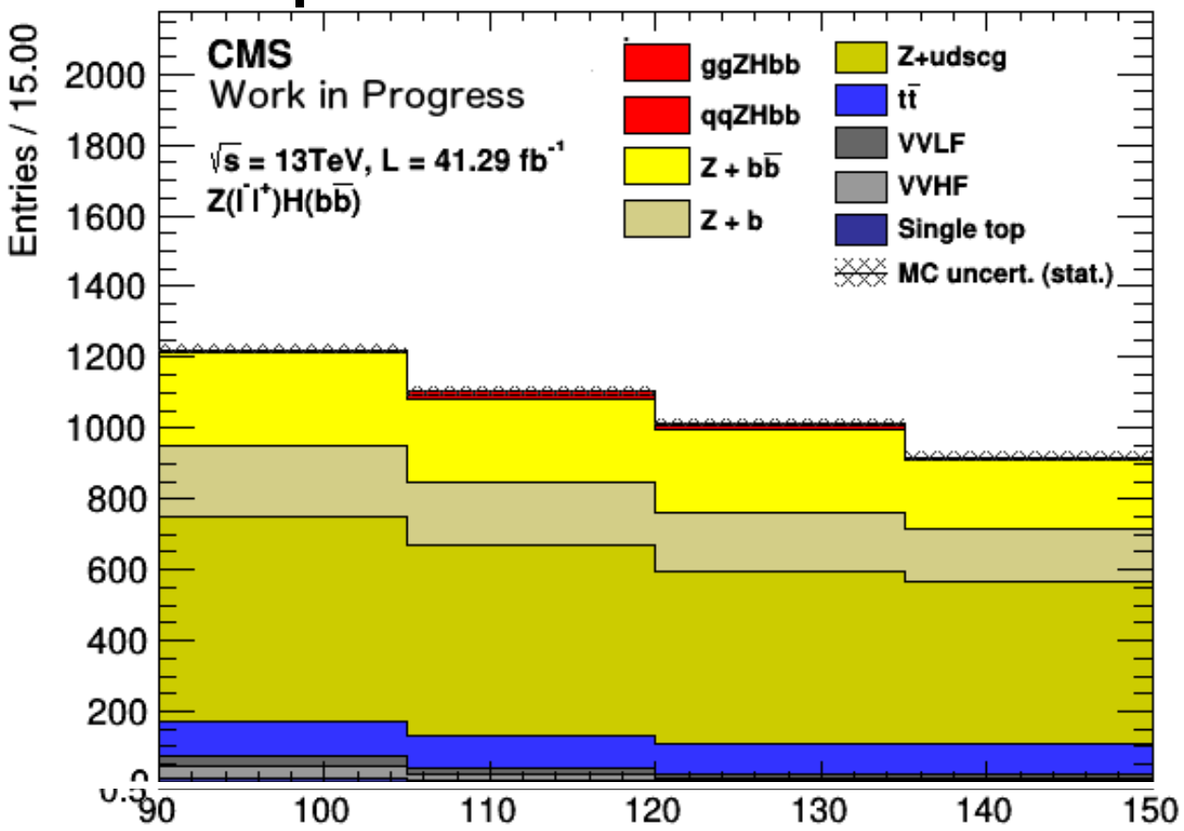


invariant mass has flat distribution

Analysis Strategy - backgrounds

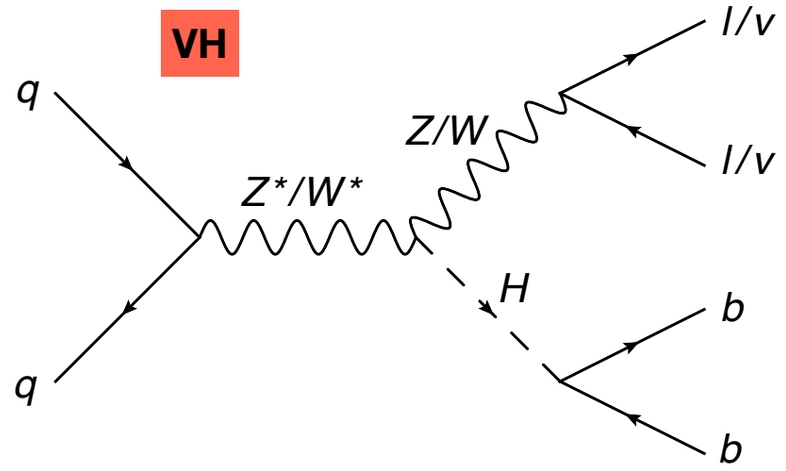
- **Analysis strategy**
  - signal region is still background dominated, mostly from:
    - V+jets (dominates in 2-lepton channel)
    - $t\bar{t}$ (dominates in 0-lepton channel)
    - di-boson

2-lepton channel MC simulation

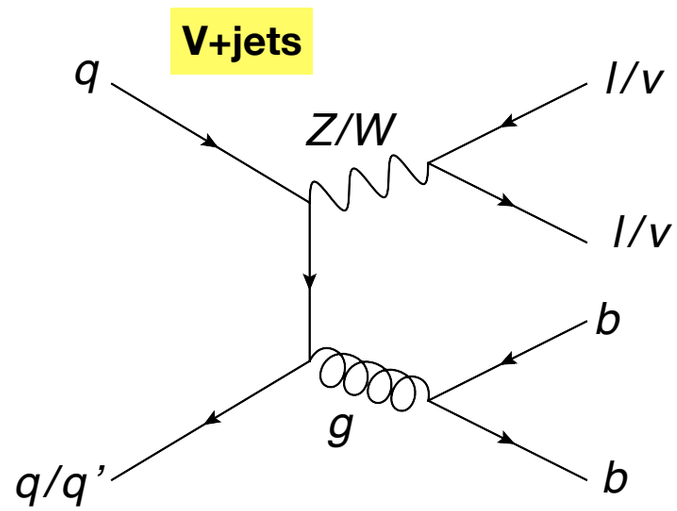


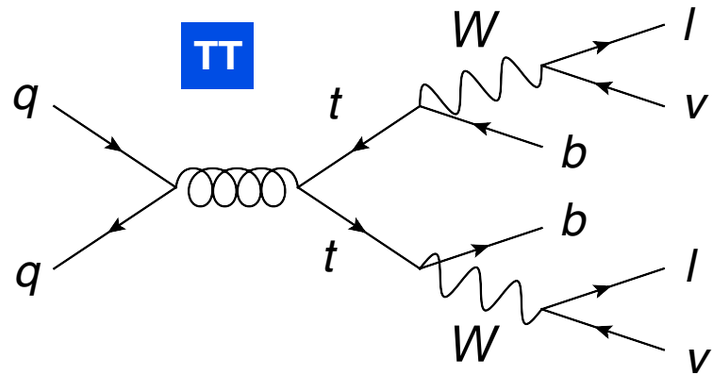
inv. mass of b jets alone not discriminating enough
=> use MVA (e.g. BDT or new: **DNN classifier**)

signal



main backgrounds

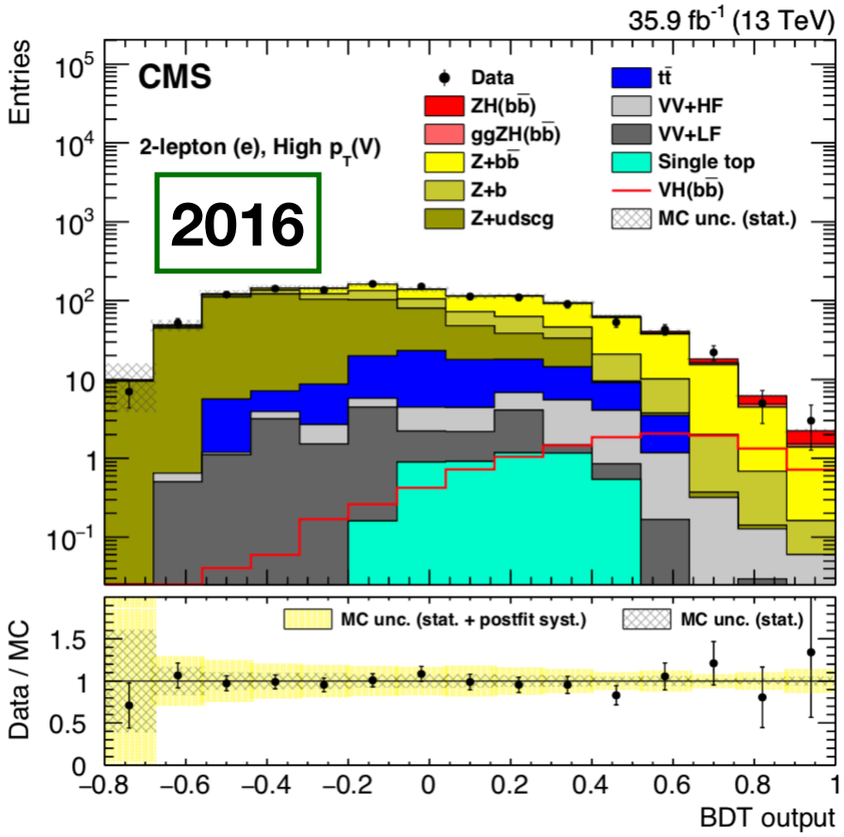




Event selection

Signal region

- high signal efficiency
- S/B ~ 1/100 - 5/100
- used for:
  - extracting signal strength / significance in combined fit



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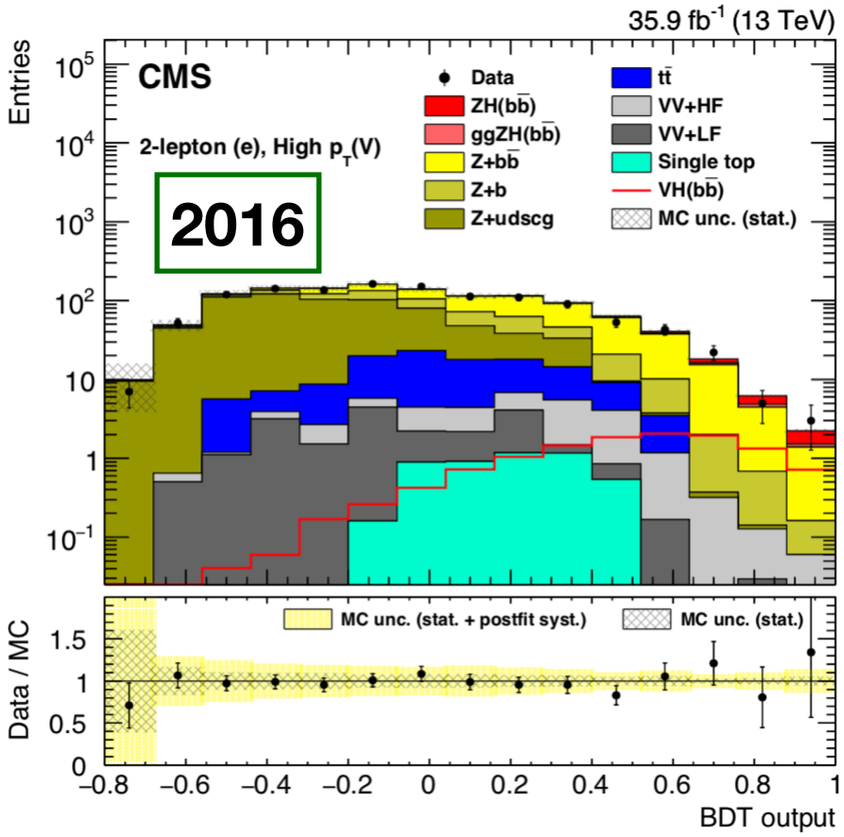
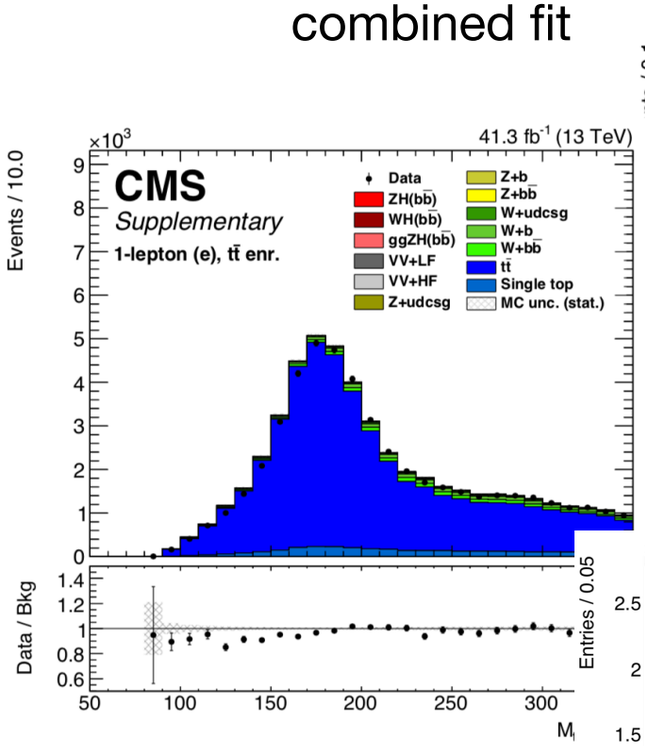
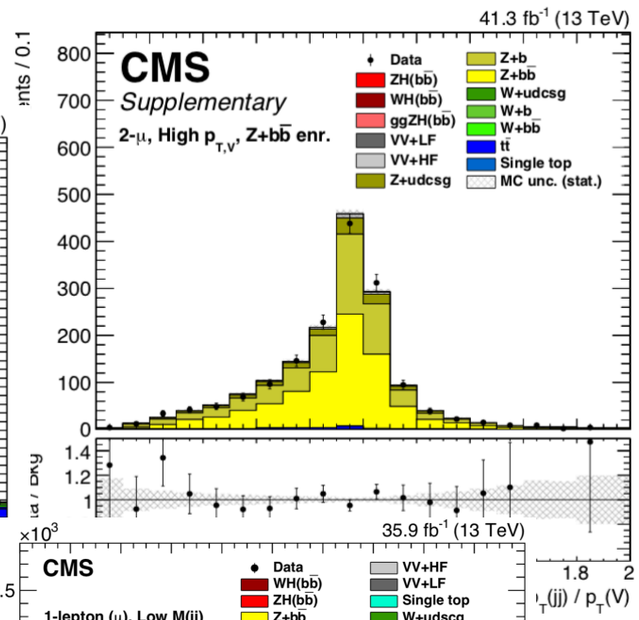
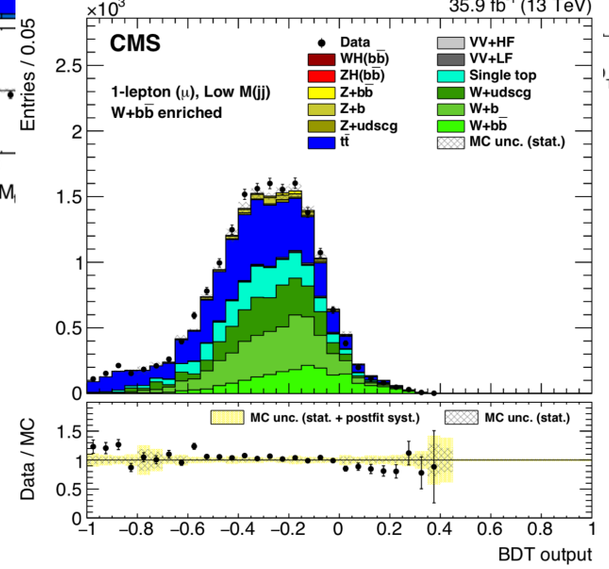


Control regions

- enriched in the different background types
- contain almost no signal
- used for:
  - verifying DATA/MC shape agreement
  - constrain normalization of MC in the combined fit





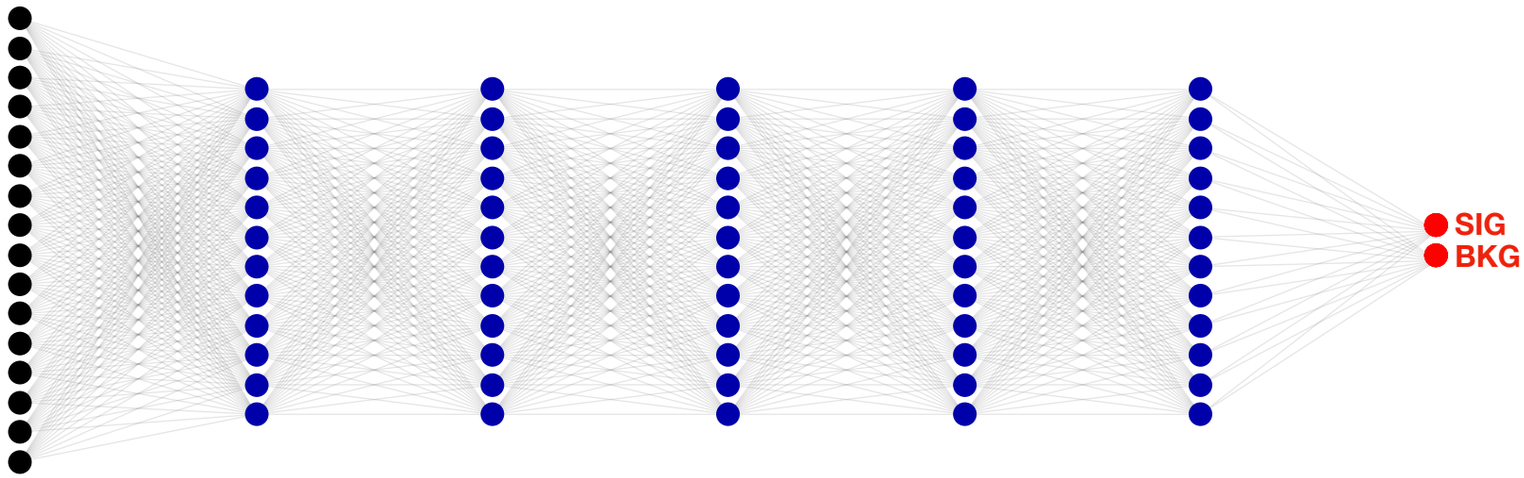


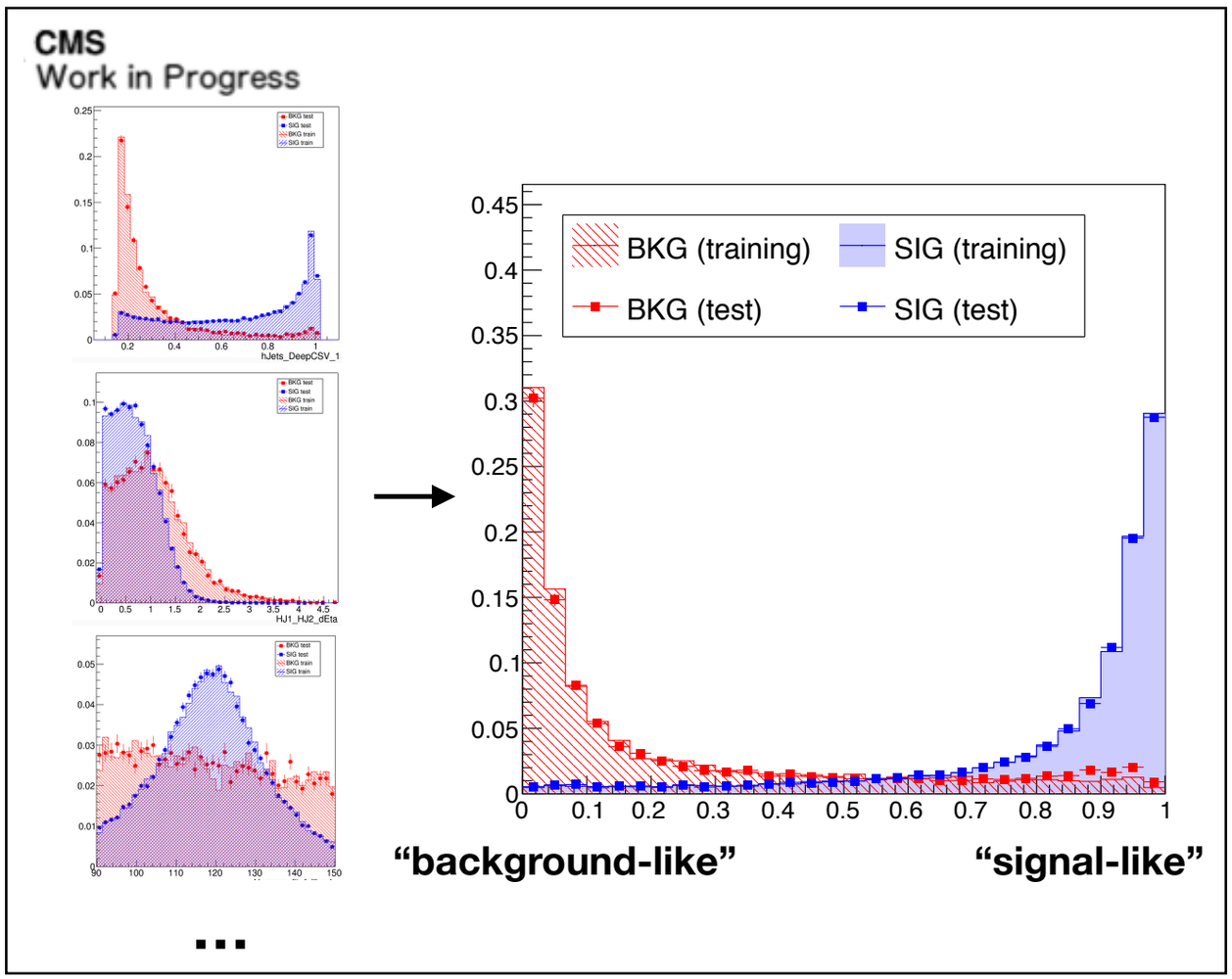
separated by cuts on:
m_{jj}, m_{ll}, b-tagging score, number of additional jets etc.

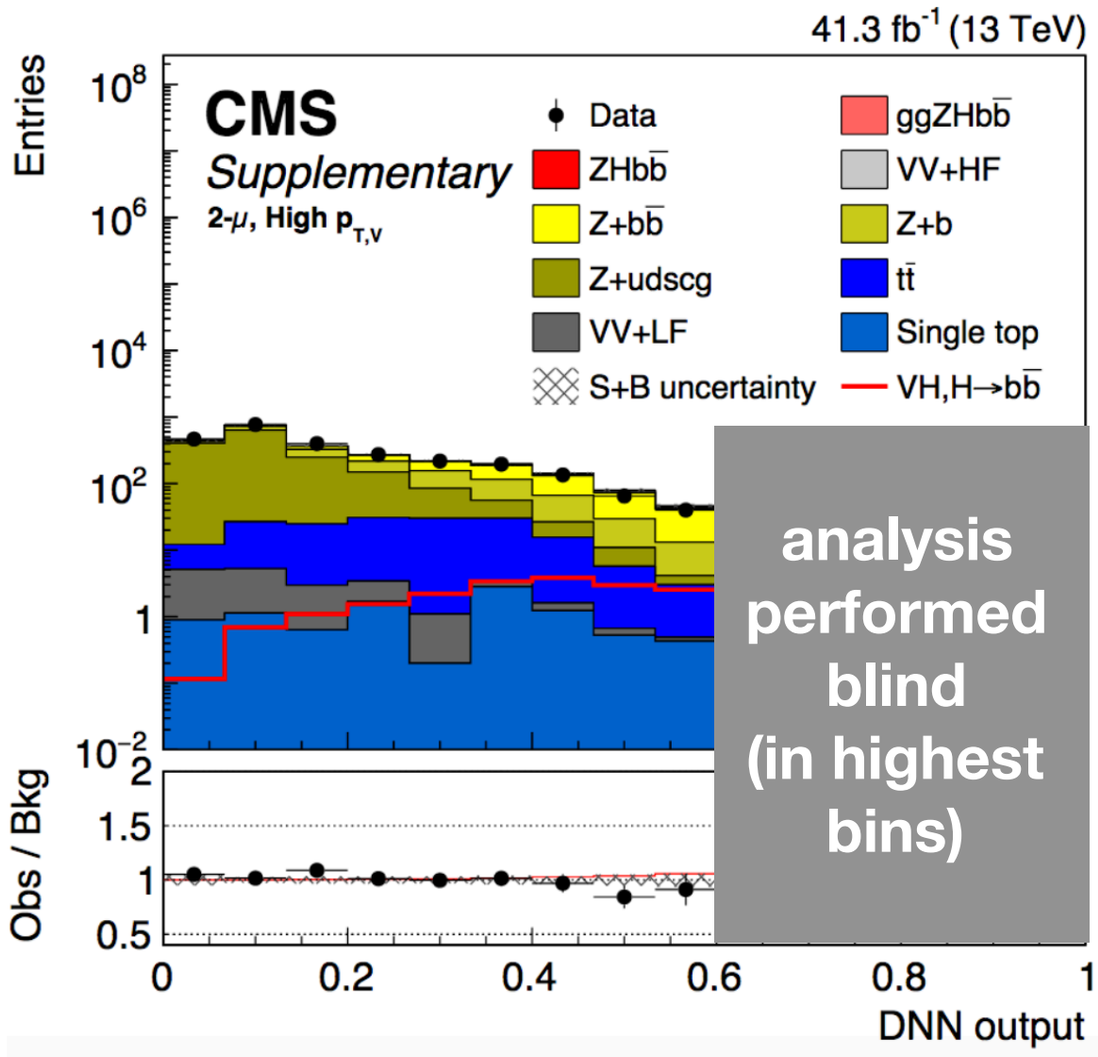
=> we perform a **simultaneous fit** of signal and control regions!

Analysis Strategy - MVA

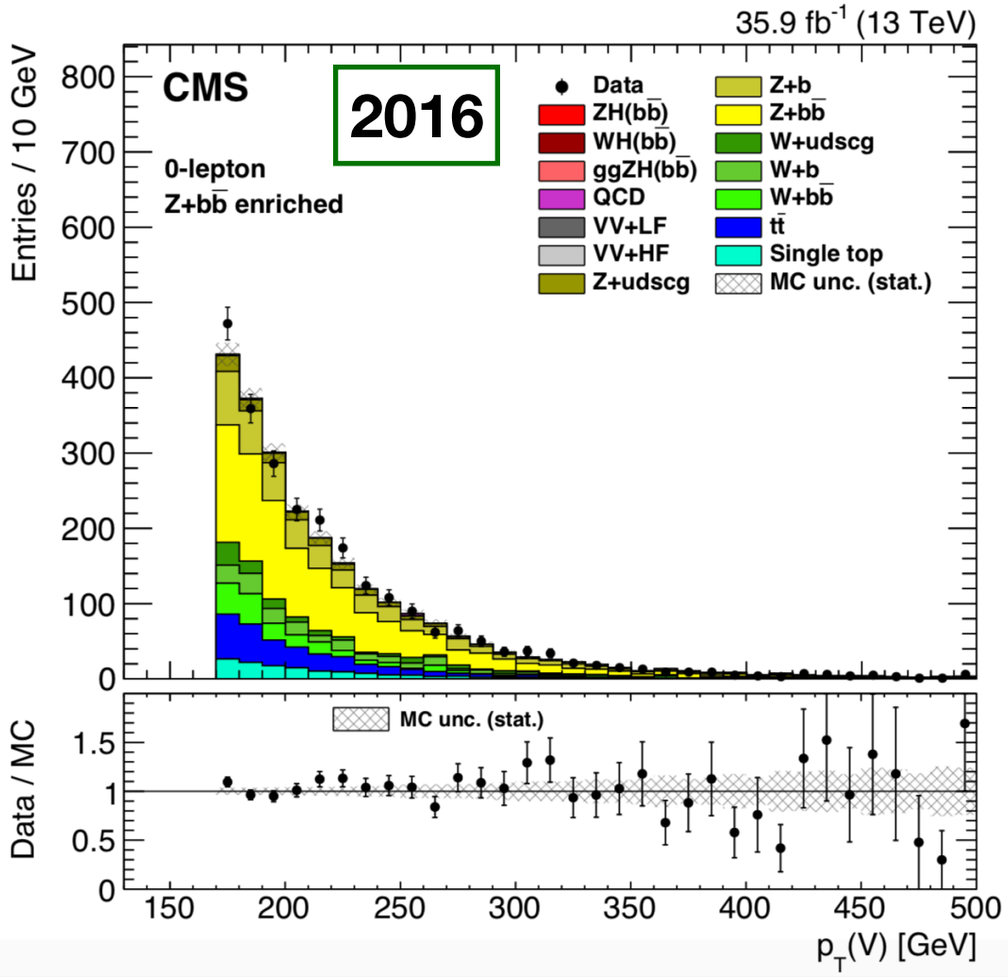
- **MVA**
  - feed-forward DNN
  - implementation in tensorflow
  - between 14 and 16 inputs (depending on channel)
  - 5 hidden layers (up to 32 nodes)
  - dropout for regularization
  - cross-entropy loss
  - independent test/training samples







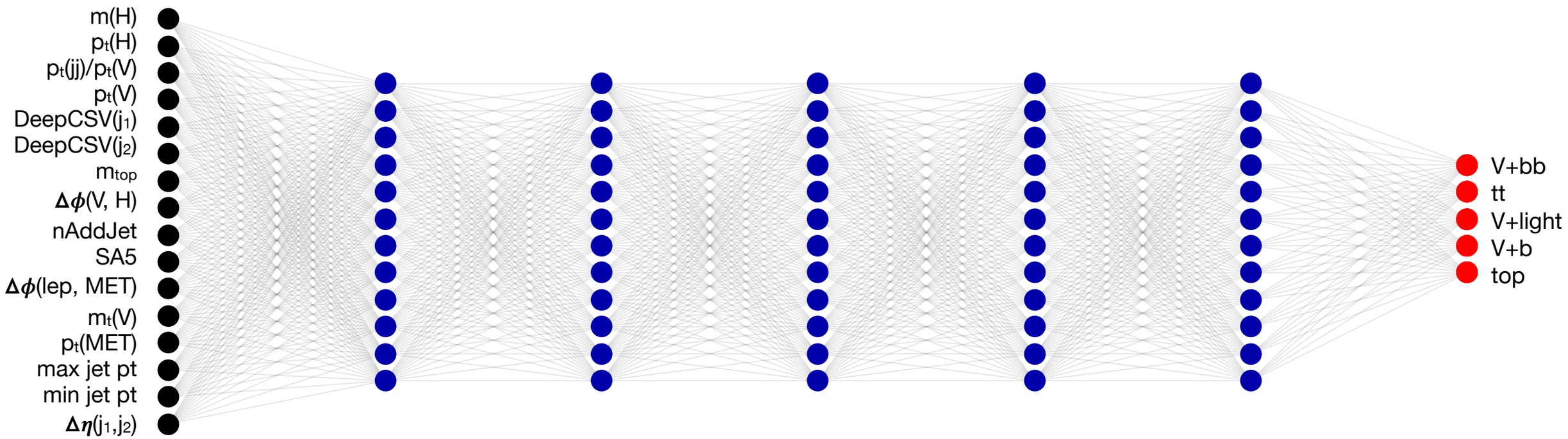
Multi-output background classifier



- For some backgrounds difficult to reach high purity by control region selection
- e.g. 0-lepton Z+bb

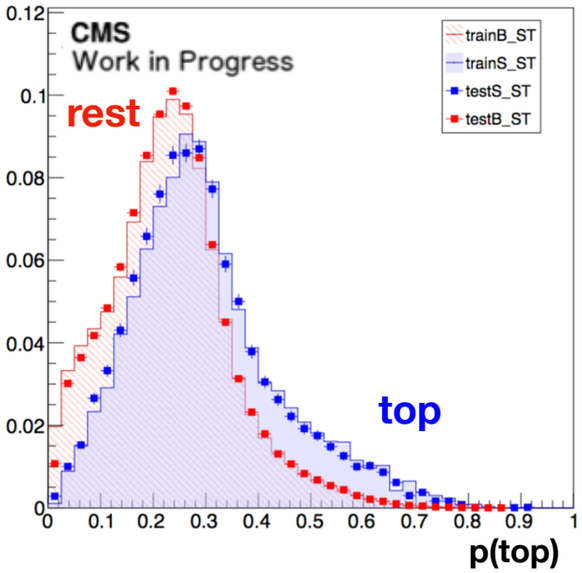
- MVAs can also separate between the different backgrounds instead of signal vs. background only
- used in Run 1 for 7/8 TeV data with multiple BDTs trained separately for backgrounds

- Neural networks can be easily extended to **multi-output classifiers**
  - single training is enough to separate all backgrounds

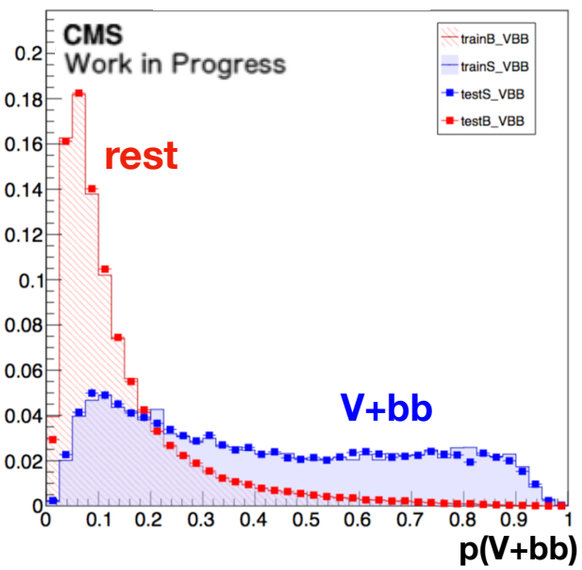


Multi-output background classifier

top vs. rest



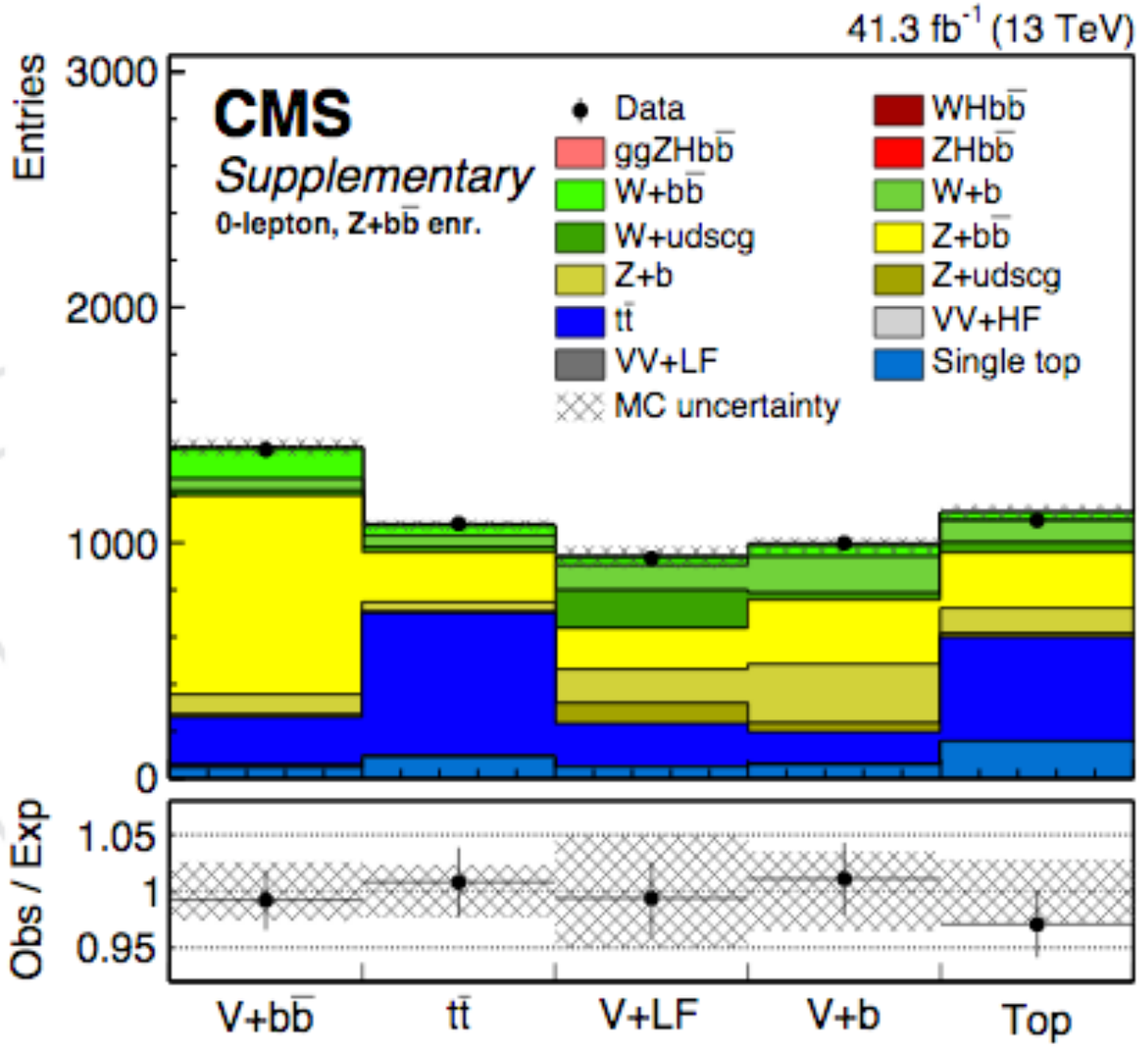
V+bb vs. rest



...

5 probabilities
(which sum up to 1)

simple linearization:
put each event into the bin with the highest probability



5 bins which are used in the fit

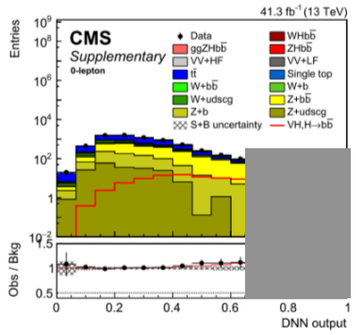
this plot is the distribution after the fit!

Simultaneous fit

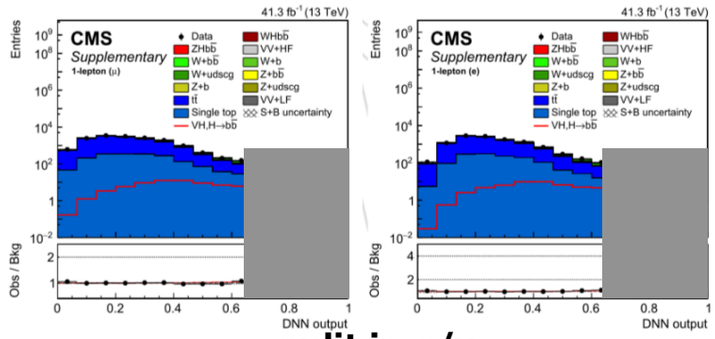
- **what do we fit?**

Signal regions for the 3 channels

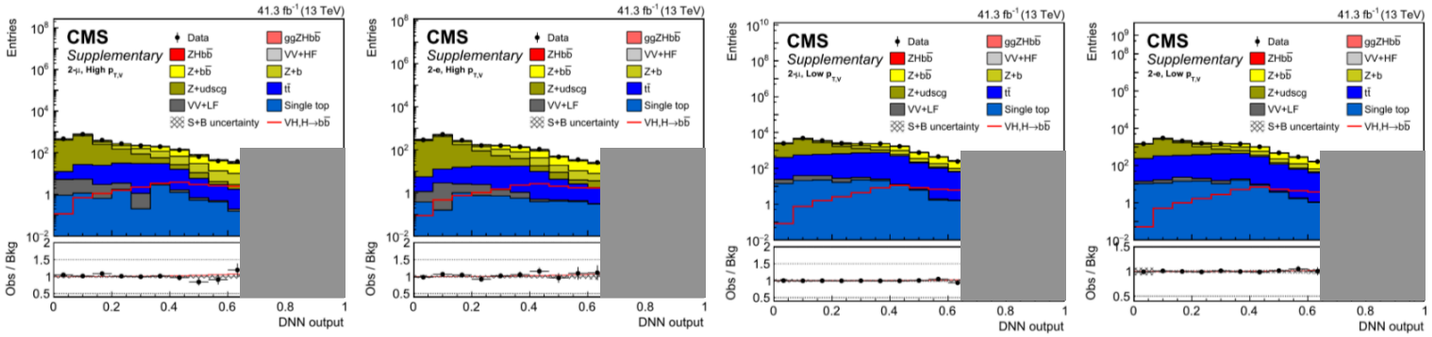
0-lepton



1-lepton

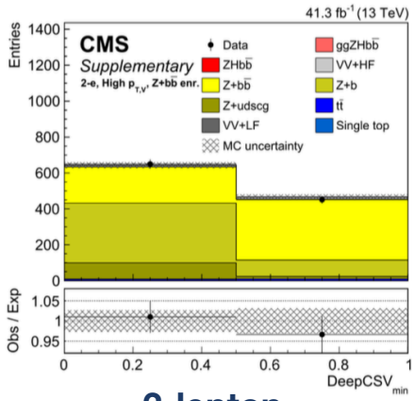


2-lepton split in e/μ



split in e/μ and two categories of $p_T(V)$

Heavy flavour control regions for 2-lepton channel

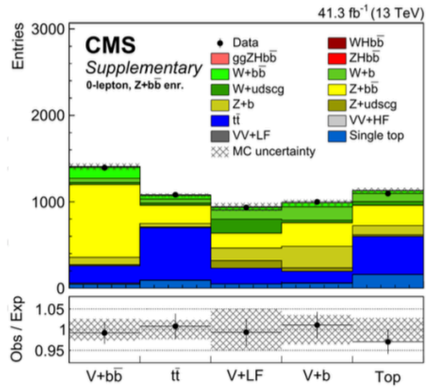


2-lepton

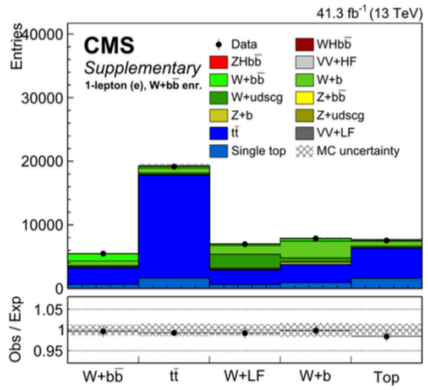
for 2-lepton channel:
2-bins of b-tag score
instead
(is enough)

split in e/μ and two categories of $p_T(V)$

Heavy flavour control regions with multi-output classifier



0-lepton



1-lepton

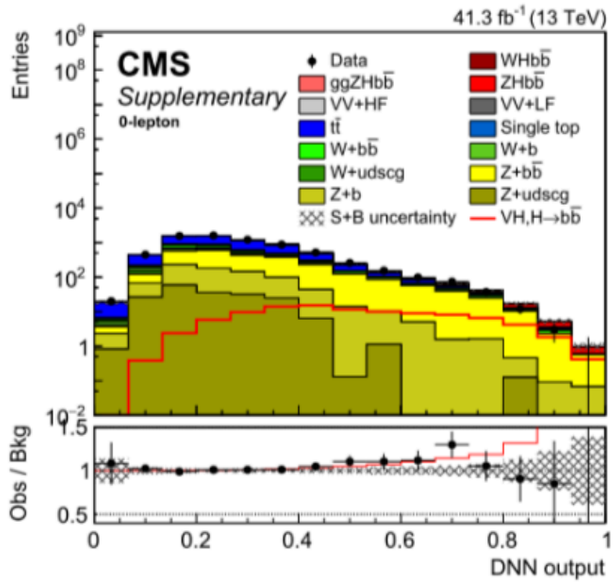
Light flavour and TT control regions

- fit normalisation only for remaining 16 control regions
- ~250 sources of systematic uncertainties also included in the fit

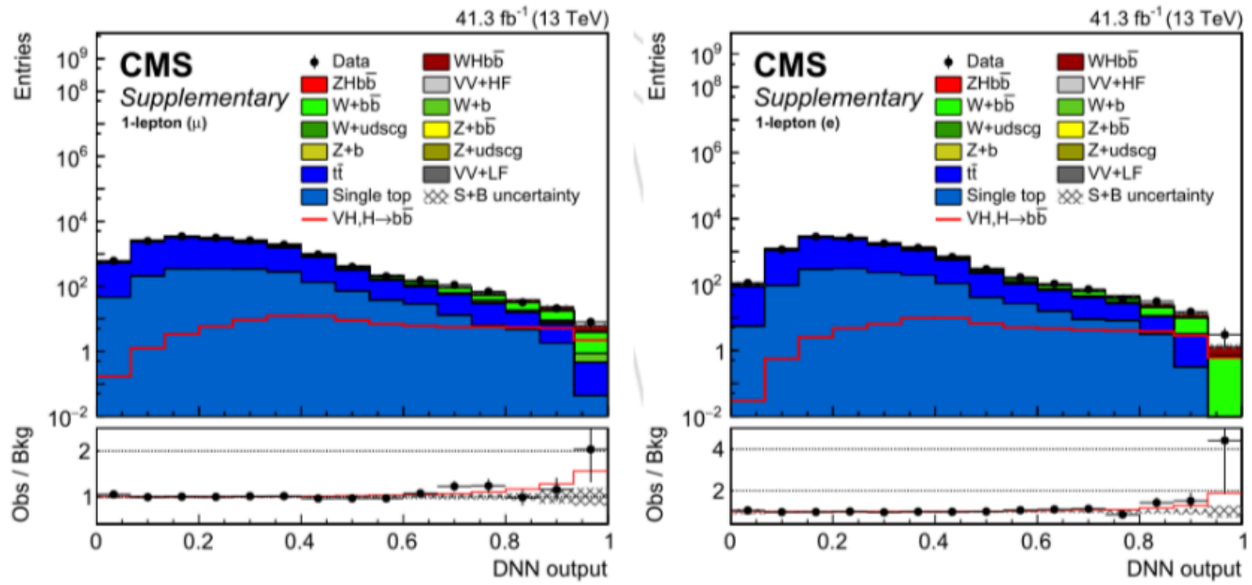
DNN post-fit

- **result of the fit:**

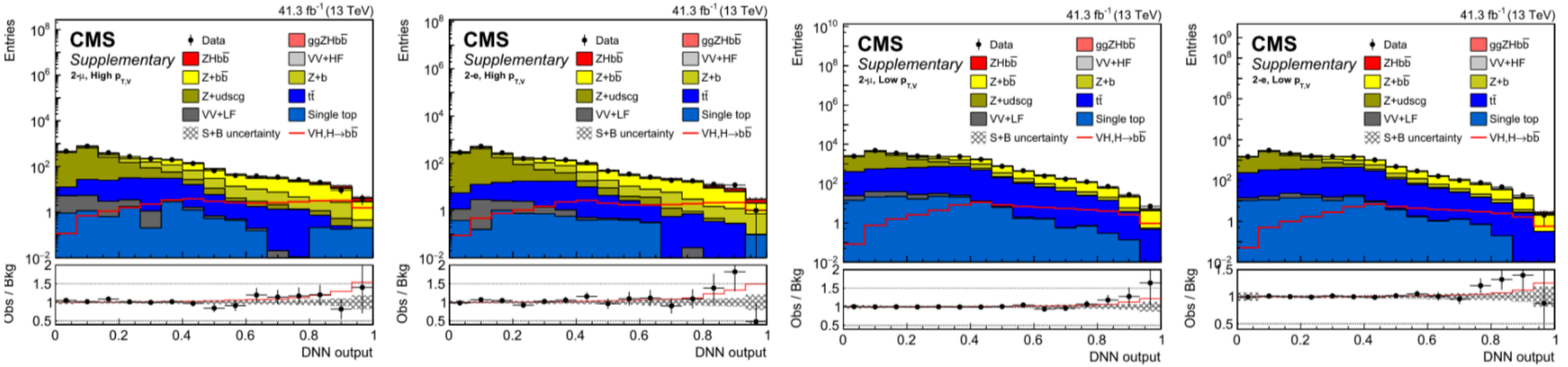
0-lepton



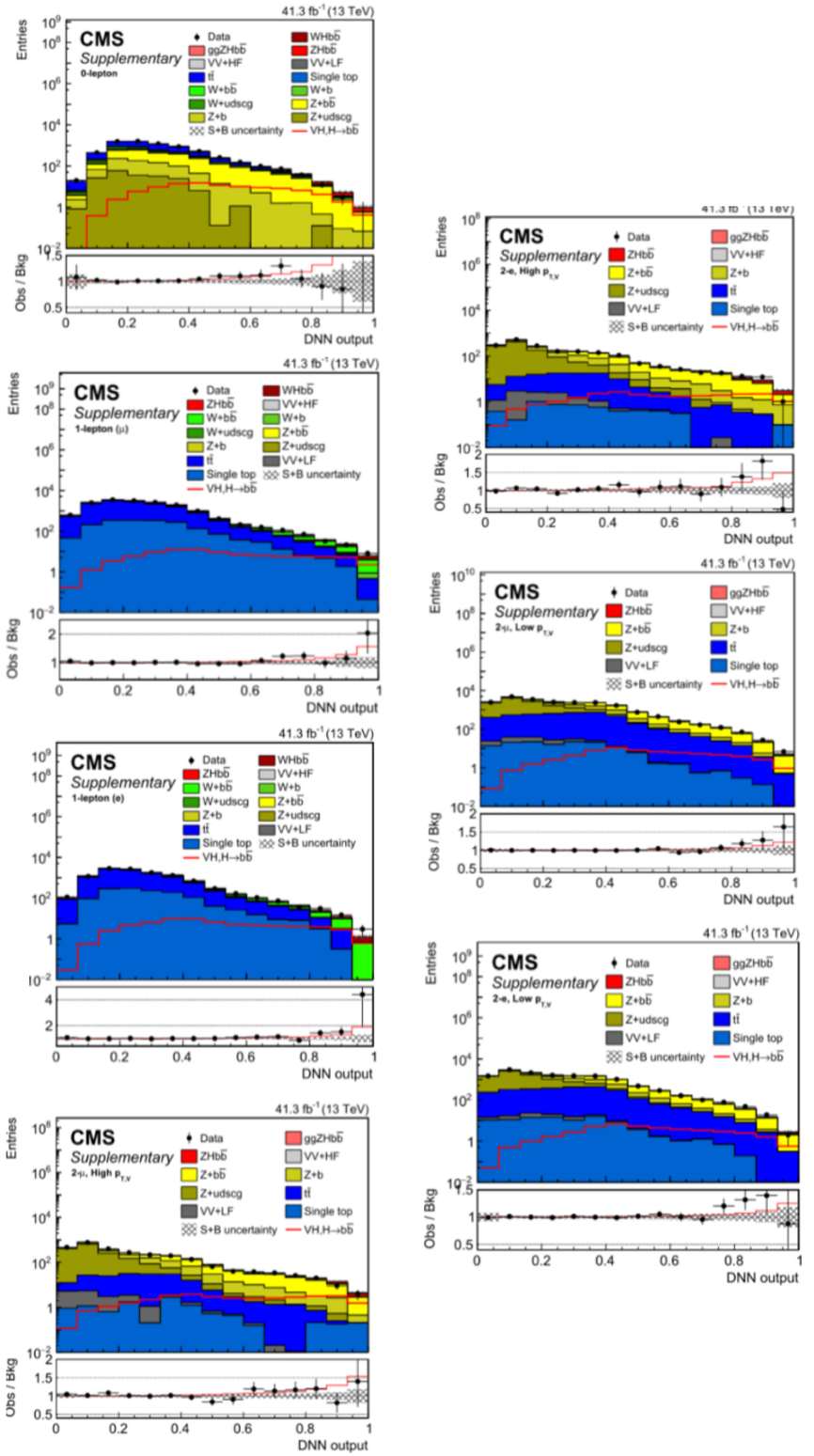
1-lepton

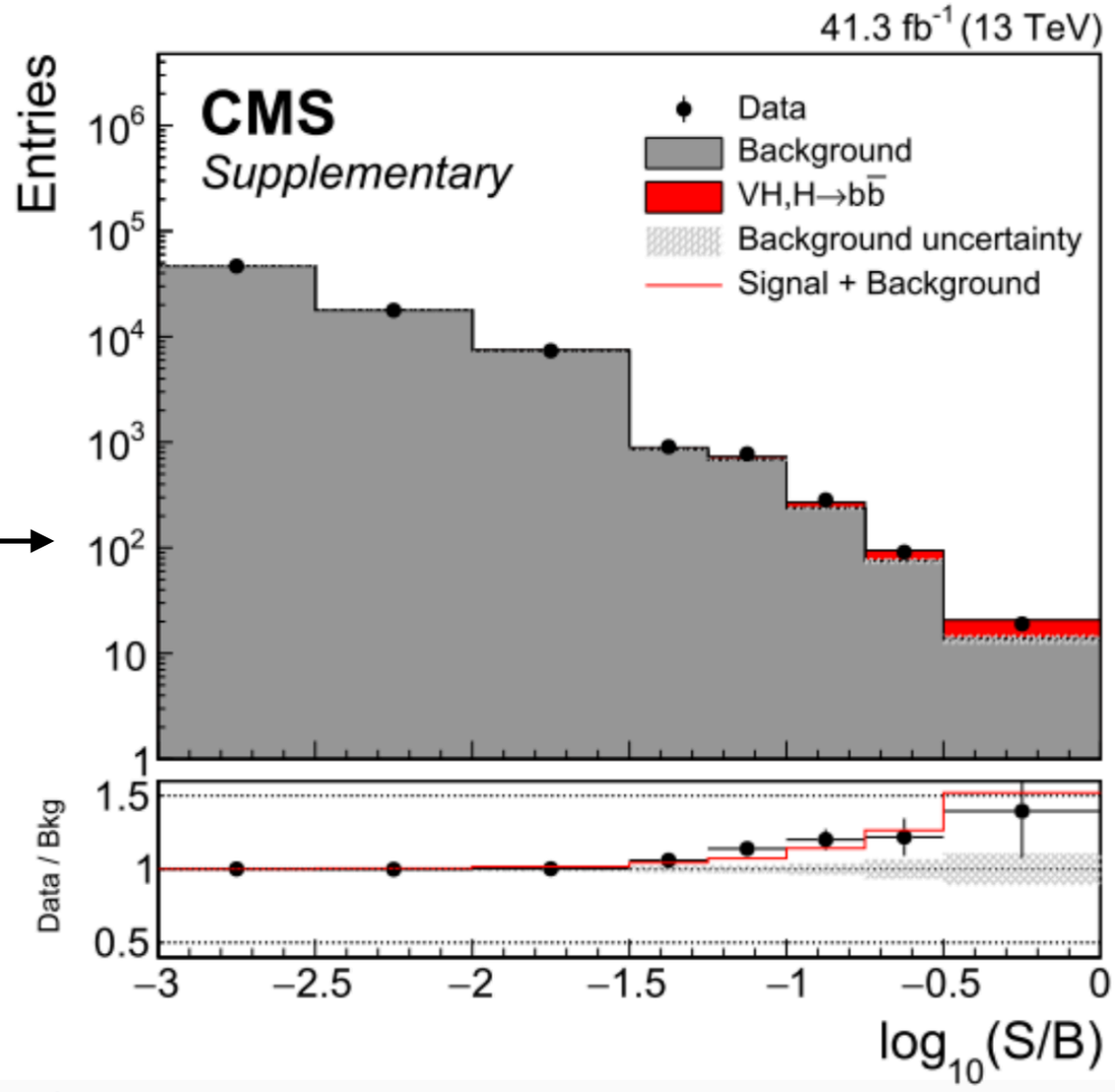


2-lepton



Combination of channels



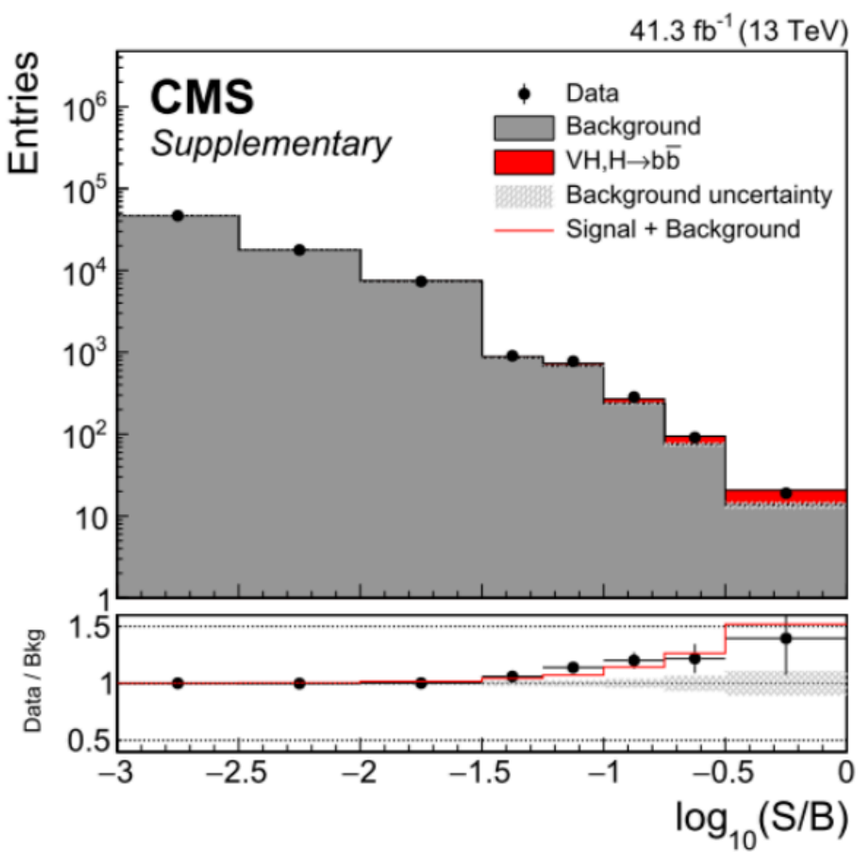


combine result of all 7 signal regions by combining bins with similar S/B

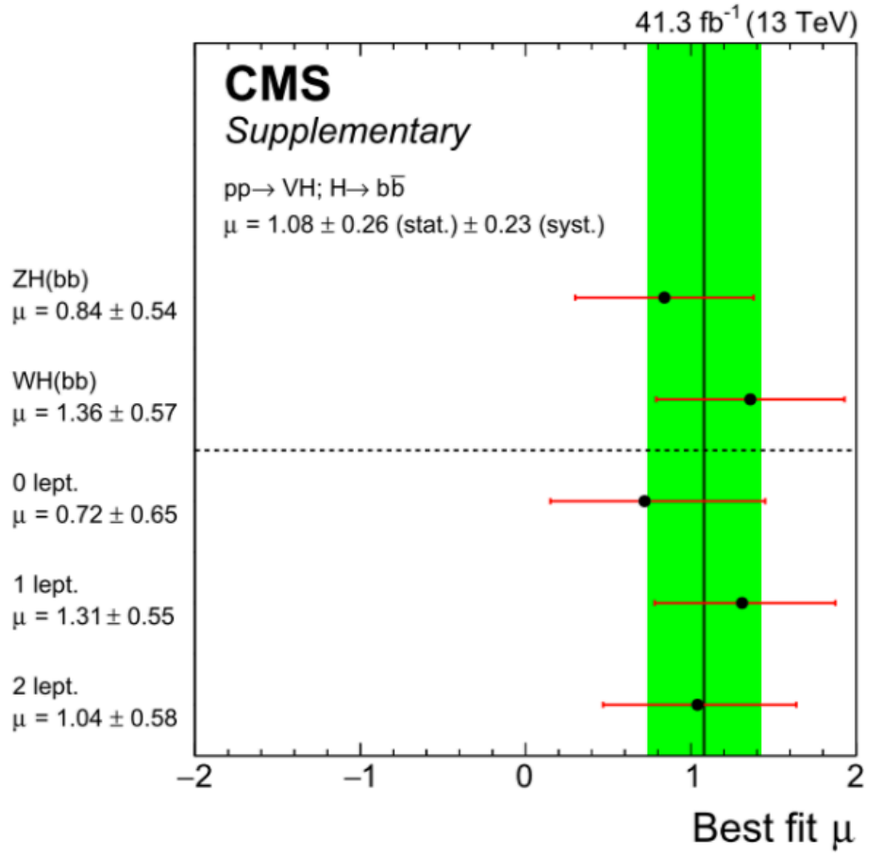
Results for 2017 data only

Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34

Excess of events behaves as SM Higgs

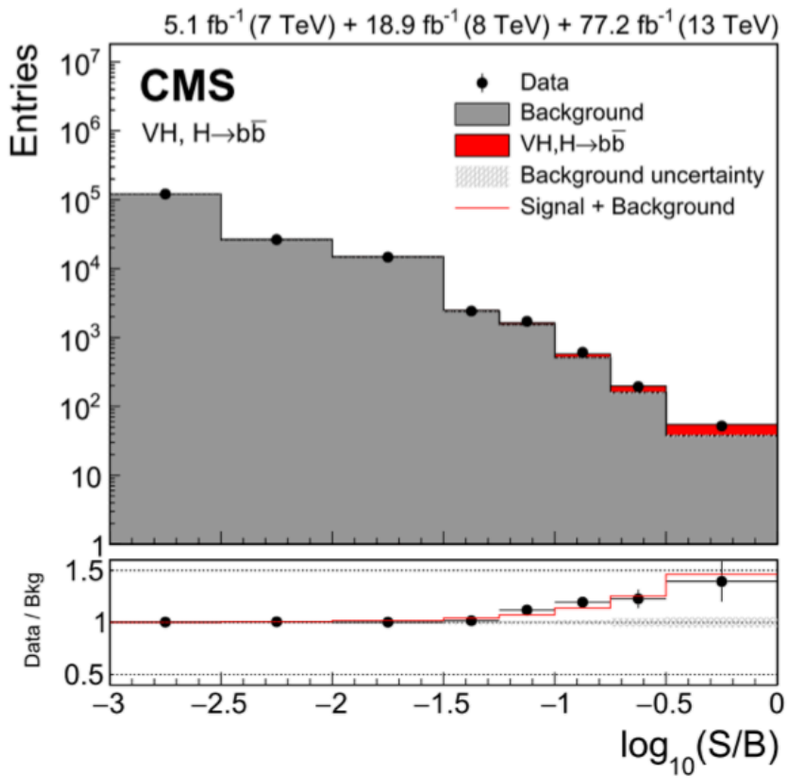


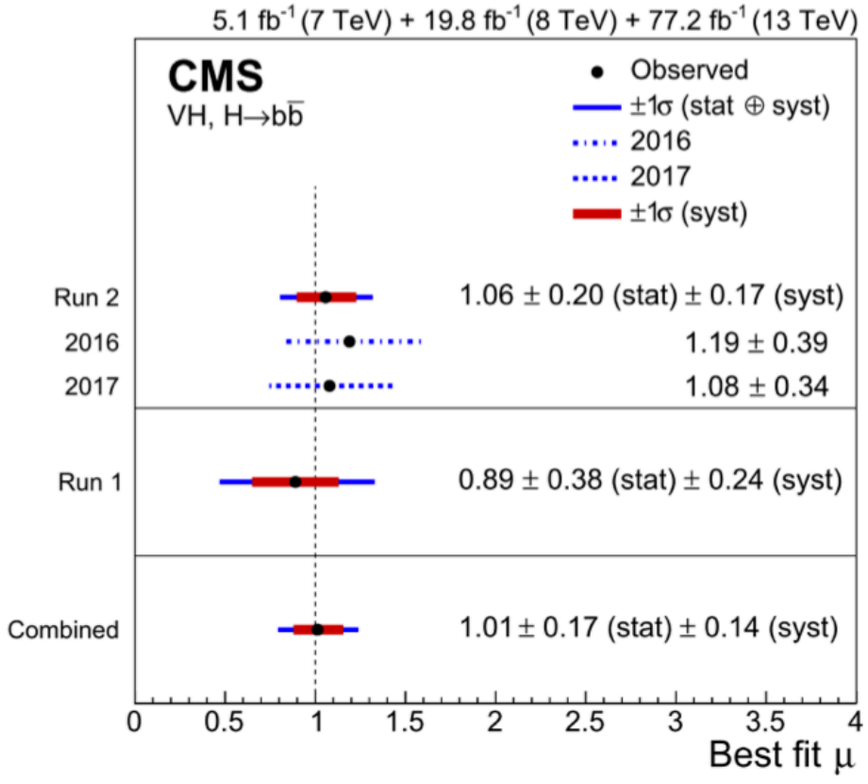
Channel compatibility is 97%



Combination with previous runs

Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23





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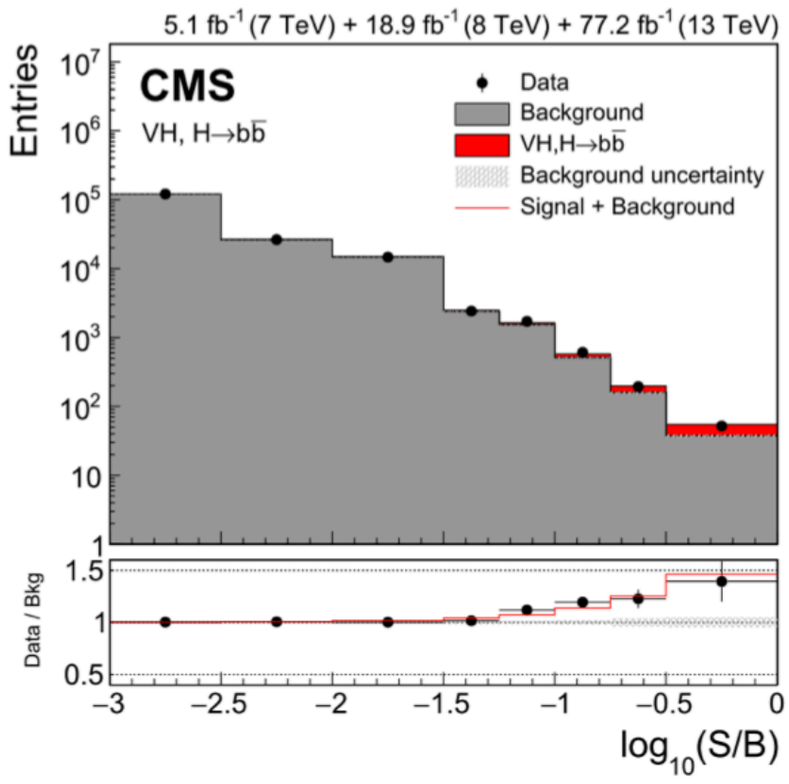
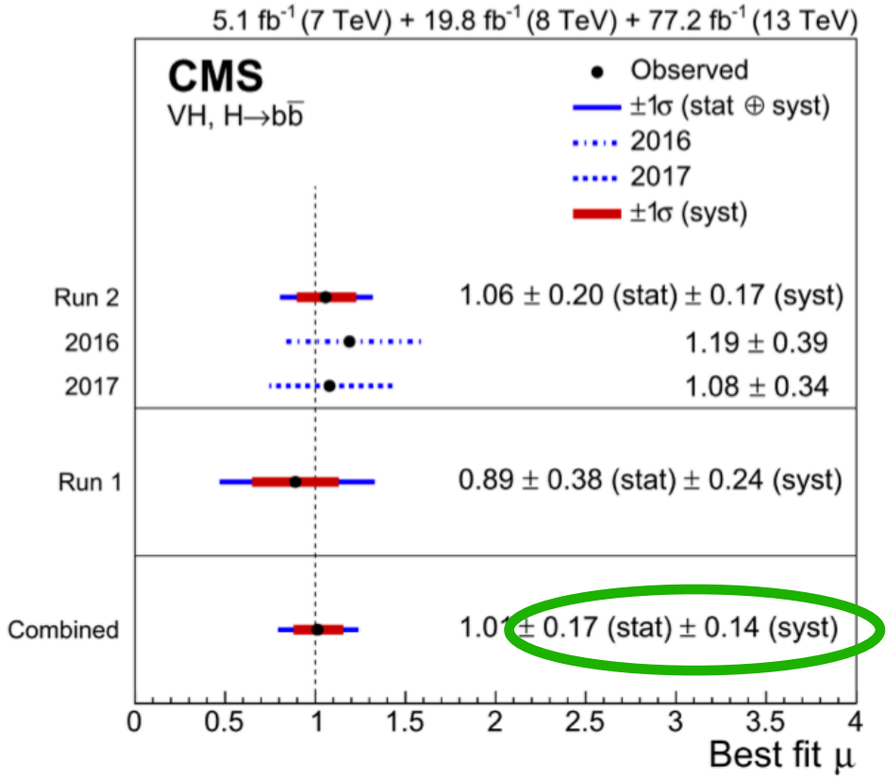
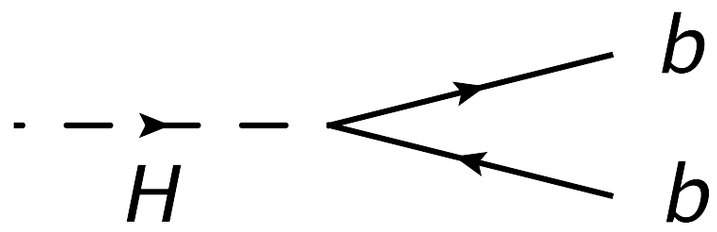




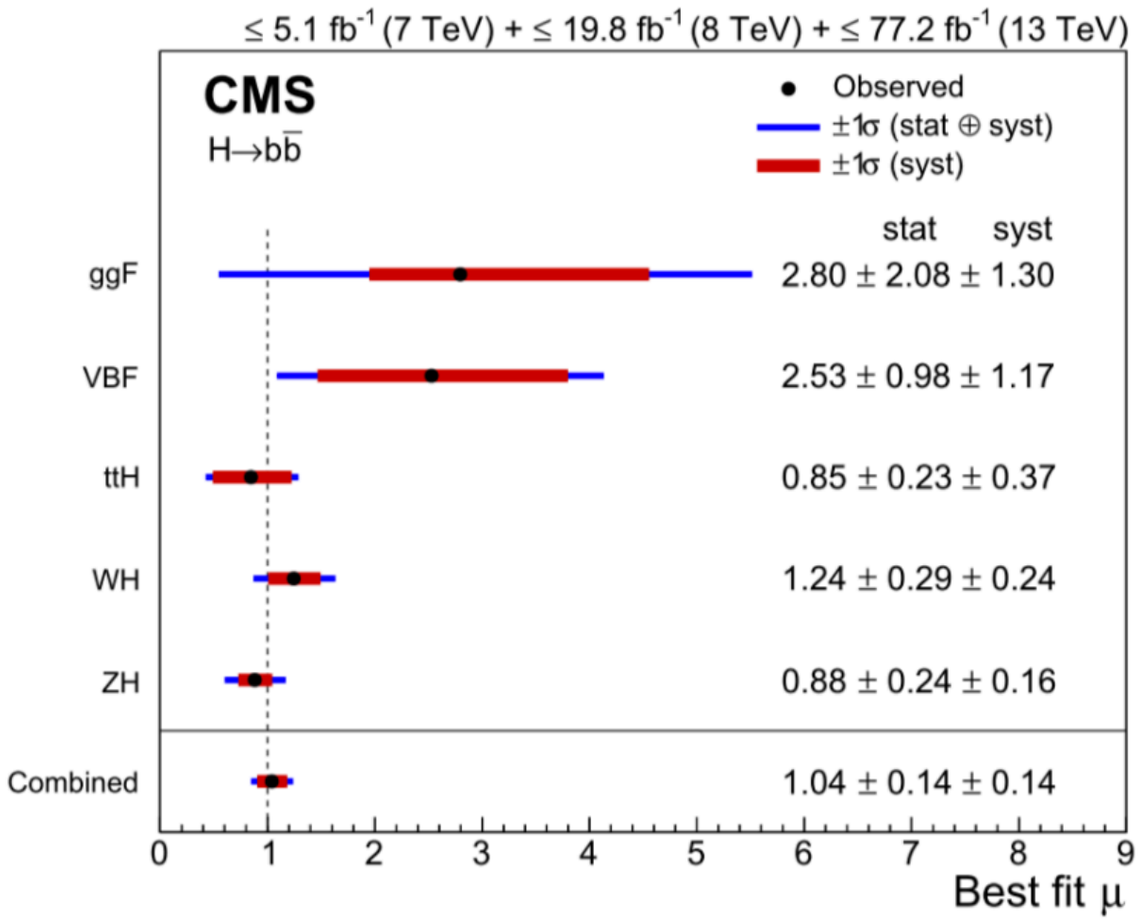
Uncertainties are still statistically dominated!

Combination with other production channels

- remember we wanted to look at the decay H->bb



- can combine results of VH(bb) with CMS results for other production channels:
  - boosted ggH (gluon fusion)
  - VBF (vector boson fusion)
  - ttH (H in association with $t\bar{t}$ pair)



significance

5.5 σ expected

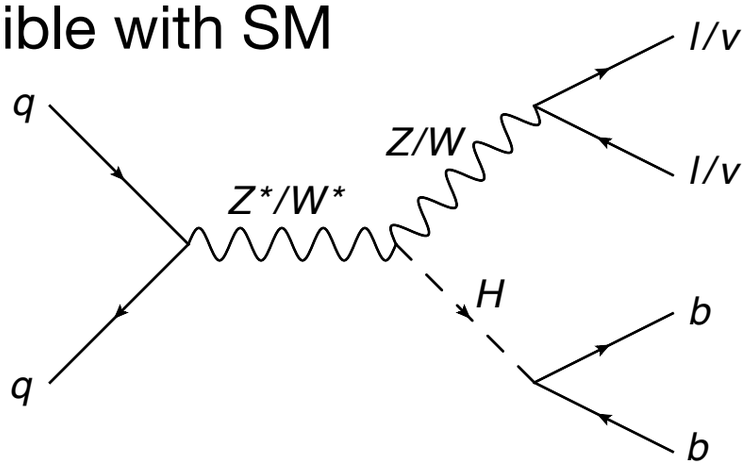
5.6 σ observed

Observation of the H → bb decay by the CMS Collaboration

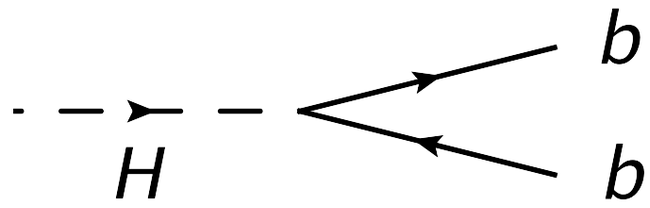
Summary

- VHbb analysis of 2017 data completed
  - observed significance of 3.3 sigma
  - including new (wrt. 2016) DNN signal/ background classifier and multi-output classifier for backgrounds

- observed combination of all VHbb data from CMS is at 4.8 sigma
- 23% uncertainty on signal strength, compatible with SM

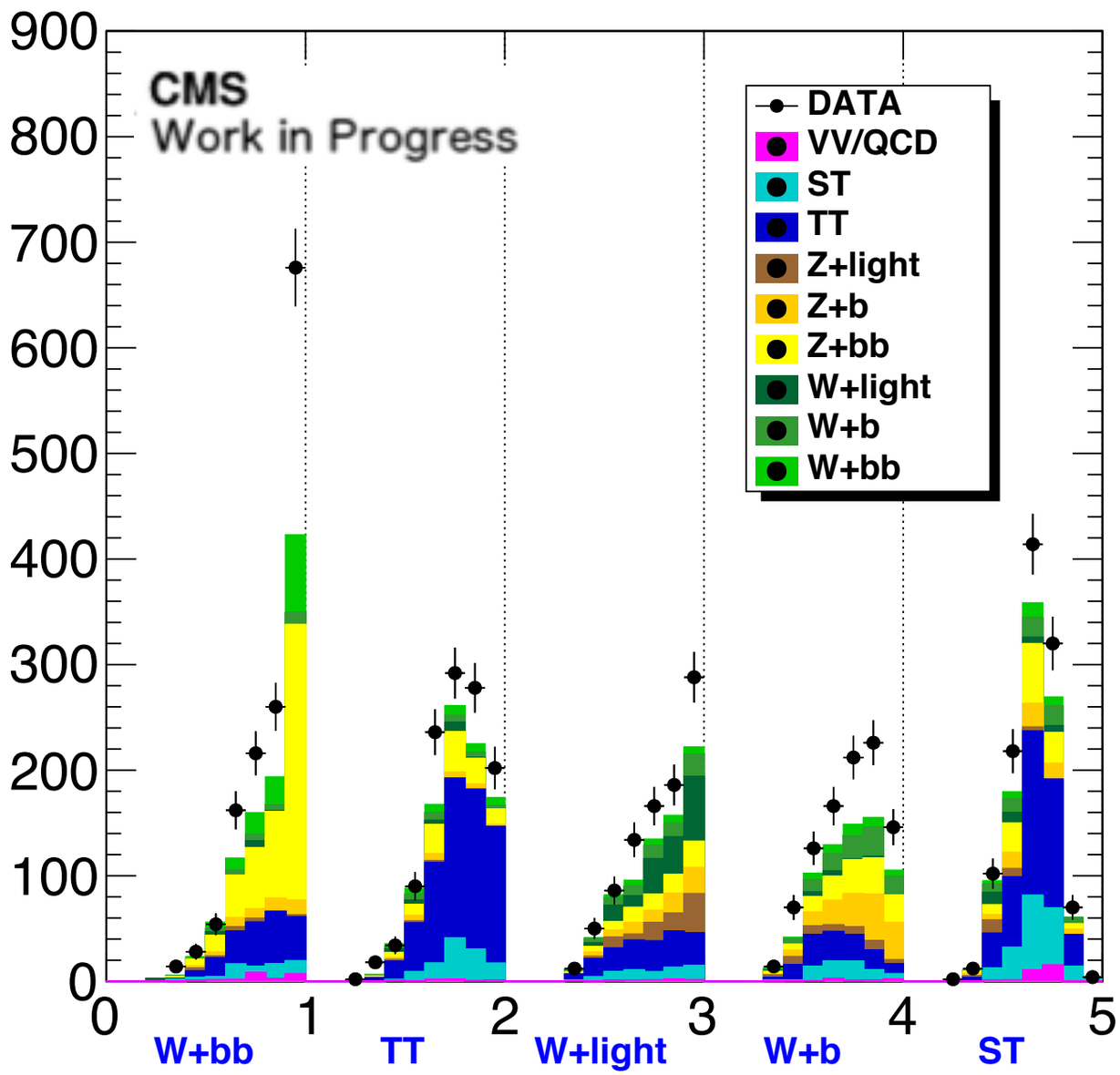


- combination with other Higgs production channels done
  - **first observation (5.6 σ) of Hbb at CMS!**



Backup

Title


CMS
Work in Progress
DATA
VV/QCD
ST
TT
Z+light
Z+b
Z+bb
W+light
W+b
W+bb
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
W+bb
TT
W+light
W+b
ST