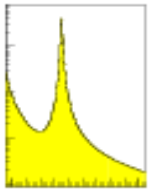

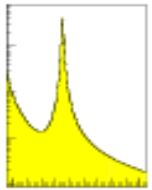

Event 4

Machine Learning Techniques in the CMS Higgs to Di-muons Search

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Physics Motivation

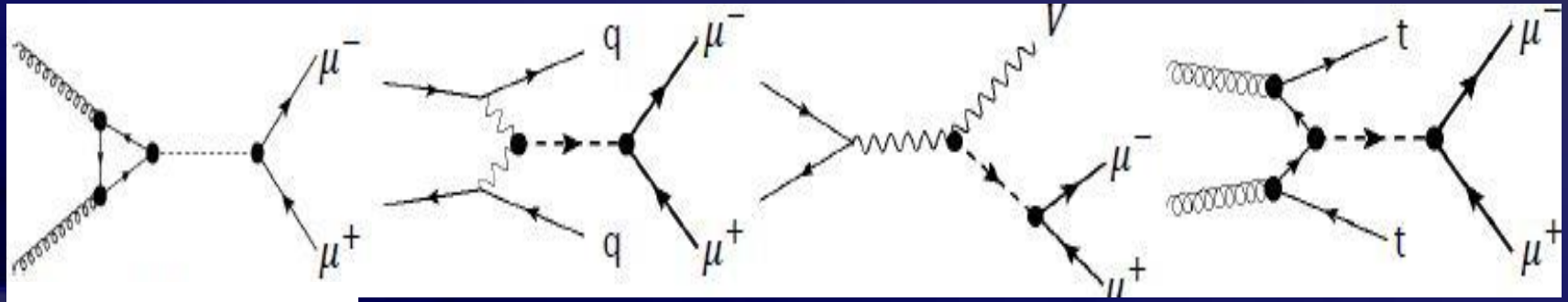
- Probe the Higgs couplings to the 2nd generation (couplings to the 3rd generation and to gauge bosons show SM-like features)
- A very difficult analysis:
  - small branching ratio of the muon decay ~ $2 \cdot 10^{-4}$
  - large irreducible backgrounds: dominated by Drell-Yan to $\mu\mu$ and di-top to $\mu\mu$ (+ di-bosons and single top)
- On the plus side: excellent mass resolution for muon pairs, narrow Higgs peak
- HIG-17-009 (PAS & PAPER, 35.9 fb^{-1}, 2016 data)

Production Channels

Several channels with different cross sections, topologies and backgrounds:

gg fusion, VV fusion, associate VH, ttH

ratios 1 : 0.078 : 0.046 : 0.010



V = W± or Z

Event Classification

- Boosted Decision Tree (BDT) in TMVA (ROOT): binary signal-background separation; BDT score [-1, 1]
- Signal trained on: gg→H (ggF), VV→H (VBF), associate VH
- Variables with some discriminating power for S/B used

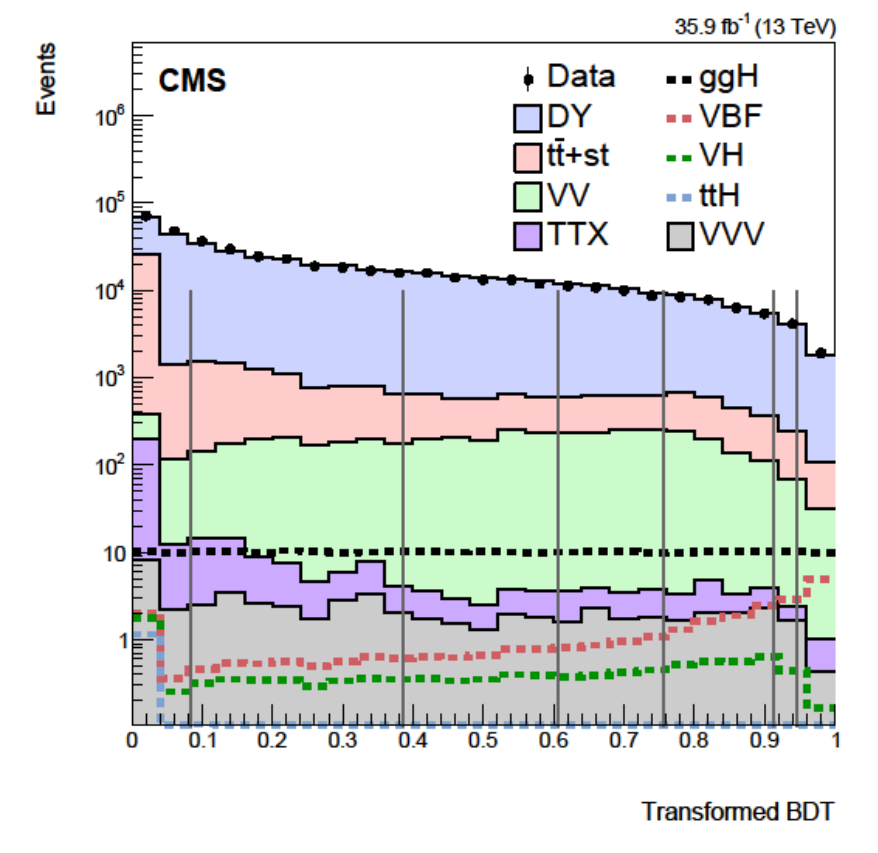
- The p_T and η of the dimuon system
- The $|\delta\eta|$ and $|\delta\phi|$ between the muons
- The η values of the two highest–p_T jets
- The masses of the two highest–mass dijet pairs
- The $|\delta\eta|$ bewteen the jets in the two highest–mass pairs
- The number of jets with $|\eta| < 2.4$ and $|\eta| > 2.4$
- The number of jets passing the CSVv2 medium b-tag working point
- The E_T^{miss}

Variable Ranking by BDT

- BDT ranks the used variables by importance
- The di-muon system p_T and η come on top
- Jet variables important for VV→H
- Signal sample split in 3 independent chunks: training, test, limit setting
- Background: train/test

Feature	Importance
Dimuon p_T	5.342e-02
Dimuon η	3.896e-02
$\lvert\delta\phi(\mu\mu)\rvert$	3.500e-02
Number of medium b-tags	2.842e-02
$\eta(jet1)$	1.724e-02
E_T^{miss}	1.706e-02
Number of forward jets	1.218e-02
$\lvert\delta\eta(jj_1)\rvert$	8.310e-03
Number of central jets	8.036e-03
$\eta(jet2)$	7.460e-03
$\lvert\delta\eta(\mu\mu)\rvert$	6.793e-03
$M(jj_1)$	6.546e-03
$\lvert\delta\eta(jj_2)\rvert$	3.304e-03
$M(jj_2)$	2.199e-03

BDT Output



Transformed BDT response in quantile in data and MC:

sum of all signal events in all production processes has a uniform distribution. The VBF channel has the highest BDT scores. B-tagging helps to suppress the top backgrounds.

Decision Tree Autocategorizer I

- "Greedily" optimize the sensitivity (and the expected upper limit)
- Events categorized on:
  - BDT score: from -1 ⇒ background-like to +1 ⇒ signal-like
  - the maximum muon $|\eta|$: proxy for the mass resolution (2.8 to 7.6 GeV FWHM for barrel/endcap categories: 0.0-0.9-1.9-2.4 in $|\eta|$)
- Events (S/B) in 0.5 GeV bins for [120, 130] GeV
- Significance of each bin i given by S/√B: add in quad

$$\text{Net Significance} = \sum_{c,i} S_{c,i}^2 / B_{c,i}$$

- We start with one (inclusive) category c: 1st iteration

Decision Tree Autocategorizer II

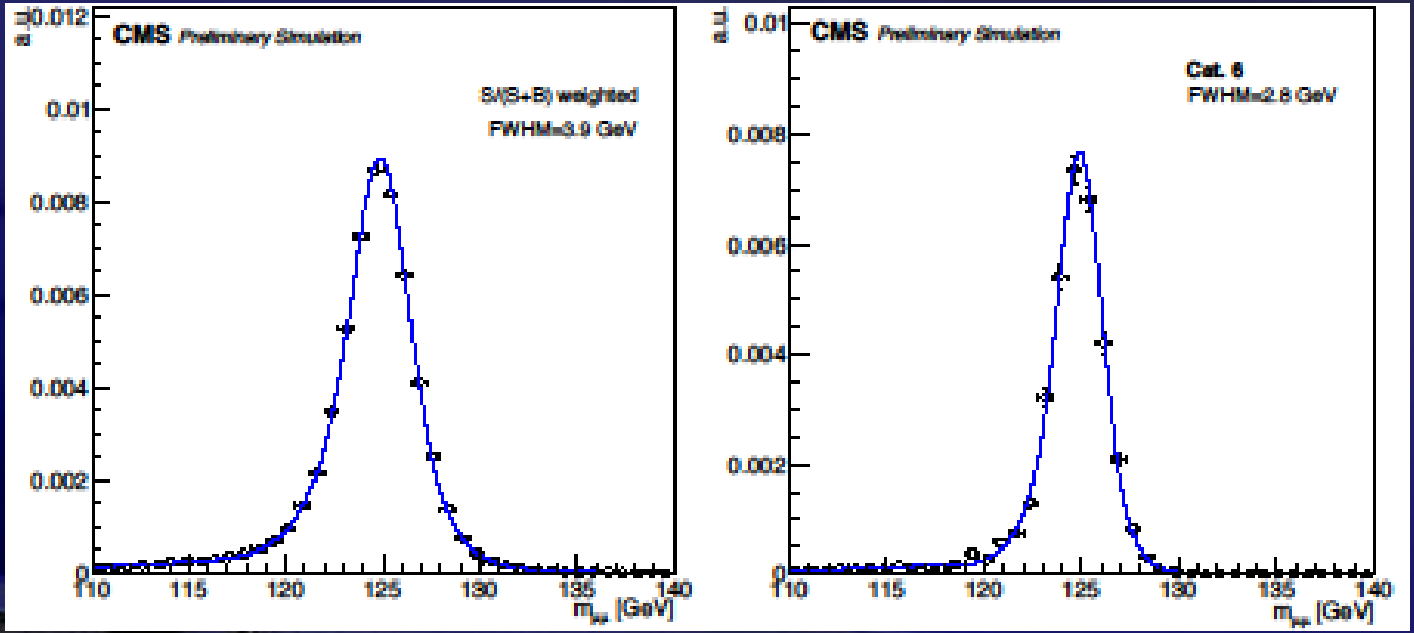
- Fine binning ⇒ central bins contribute most ⇒ account for resolution
- Check all split values for $|\eta|$ and BDT score and find the values giving maximum gain for $c \rightarrow c1 + c2$

$$\text{Gain} = \sum_i S_{c1,i}^2 / B_{c1,i} + \sum_i S_{c2,i}^2 / B_{c2,i} - \sum_i S_{c,i}^2 / B_{c,i}$$

- Split in 2 categories by max gain - either on BDT score or $|\eta|$: 2nd iteration
- Next iterations: repeat the procedure on the newly created categories, "greedily" going for the max gains
- Stop when desired # of categories is reached

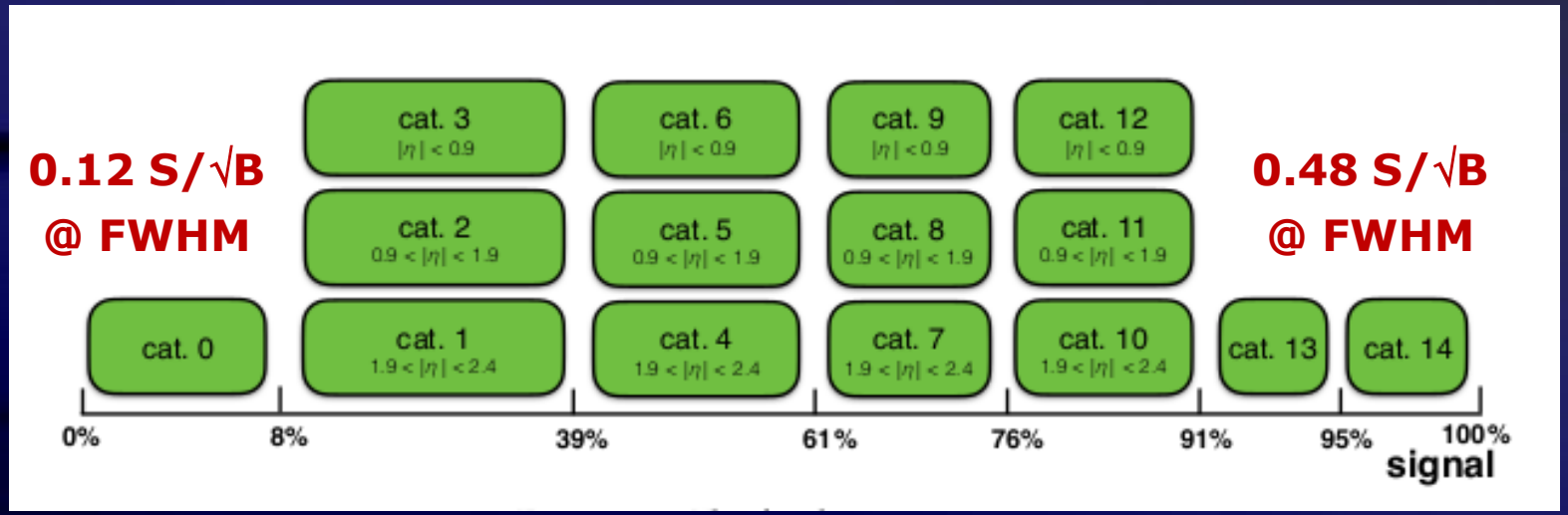
Mass Resolution - Categories

Signal model compared to MC: weighted sum of contributions from all processes and all categories, and for one of the best - category 6 (normalized to unity)



Final Categories I

- Simplification: rounding some of the cuts (~ no loss)
- 15 event categories
- Gain of 23% relative to the 7/8 TeV BDT categories



BDT response quantile [%]

Final Categories II

BDT response quantile [%]	Maximum muon $\lvert\eta\rvert$	ggH [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]	Signal	Bkg./GeV @125 GeV	FWHM [GeV]	Bkg. fit function	$S/\sqrt{B}$ @FWHM
0 – 8	$\lvert\eta\rvert < 2.4$	4.9	1.3	3.3	6.3	32	21.2	3.13×10^3	4.2	mBW $\cdot B_{deg4}$	0.12
8 – 39	$1.9 < \lvert\eta\rvert < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1.34×10^3	7.2	mBW $\cdot B_{deg4}$	0.16
8 – 39	$0.9 < \lvert\eta\rvert < 1.9$	10	2.8	6.5	6.4	5.2	41.1	2.24×10^3	4.1	mBW $\cdot B_{deg4}$	0.29
8 – 39	$\lvert\eta\rvert < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	7.83×10^2	2.9	mBW $\cdot B_{deg4}$	0.18
39 – 61	$1.9 < \lvert\eta\rvert < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	4.37×10^2	7.0	mBW $\cdot B_{deg4}$	0.14
39 – 61	$0.9 < \lvert\eta\rvert < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	9.70×10^2	4.0	mBW $\cdot B_{deg4}$	0.31
39 – 61	$\lvert\eta\rvert < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	4.81×10^2	2.8	mBW	0.26
61 – 76	$1.9 < \lvert\eta\rvert < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	1.48×10^2	7.6	mBW $\cdot B_{deg4}$	0.11
61 – 76	$0.9 < \lvert\eta\rvert < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	5.12×10^2	4.2	mBW $\cdot B_{deg4}$	0.29
61 – 76	$\lvert\eta\rvert < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	3.22×10^2	3.0	mBW	0.28
76 – 91	$1.9 < \lvert\eta\rvert < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	1.04×10^2	7.1	mBW $\cdot B_{deg4}$	0.14
76 – 91	$0.9 < \lvert\eta\rvert < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	3.60×10^2	4.2	mBW $\cdot B_{deg4}$	0.35
76 – 91	$\lvert\eta\rvert < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	2.36×10^2	3.2	mBW	0.34
91 – 95	$\lvert\eta\rvert < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	96.0	4.0	mBW	0.28
95 – 100	$\lvert\eta\rvert < 2.4$	2.0	19	1.5	1.4	0.7	13.7	83.4	4.1	mBW	0.48
0 – 100	$\lvert\eta\rvert < 2.4$	59	61	51	52	49	253	1.30×10^4	3.9		

Outlook

- Boosted Decision Trees help to improve the separation of signal and background for the different channels of the very challenging $H \to \mu\mu$ search
- By creating automatic event categories, the highest sensitivity of the analysis can be achieved
- Future work: try additional variables and deep neural networks