CMS H(125) fermionic decay results

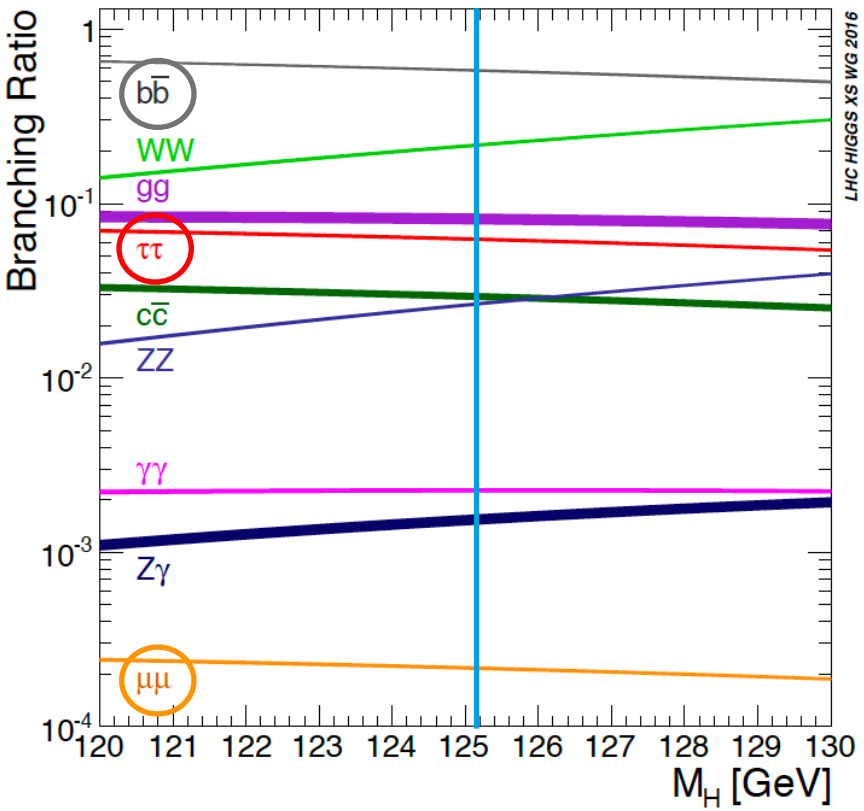
Mareike Meyer (DESY) on behalf of the CMS collaboration

Higgs Hunting 2019, Orsay-Paris, 29/07/2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction

precise measurements of Higgs Yukawa couplings important test of SM



41.3 fb^{-1} (2017 data)

H → $b\bar{b}$ (BR ~ 58%)
- large background, VH most sensitive production mode

77.4 fb^{-1} (2016 + 2017 data)

H → ττ (BR ~ 6.3%)
- highest experimental sensitivity to Higgs production via VBF

35.9 fb^{-1} (2016 data)

H → μμ (BR ~ 2 * 10^{-2} %)
- high di-muon mass resolution
- probes Yukawa coupling to 2nd-generation fermions

$t\bar{t}$H: Marco Peruzzi on Tuesday
HL-LHC prospects: Elisa Fontanesi on Tuesday
H → $c\bar{c}$: Loukas Gouskos on Wednesday

H → $b\bar{b}$ in WH & ZH production

Phys. Rev. Lett. 121 (2018) 121801

41.3 fb^{-1} (2017 data)

channels:

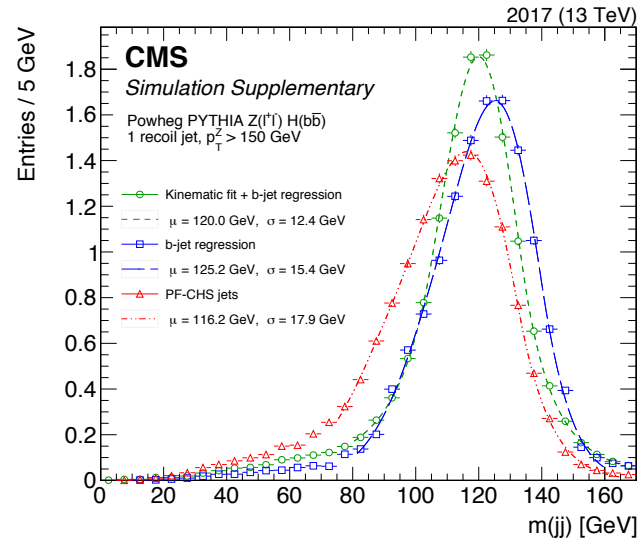
- Z (→ **$\nu\nu$**) H (→ **$b\bar{b}$**)
- W (→ **$e\nu$ / $\mu\nu$**) H (→ **$b\bar{b}$**)
- Z (→ **ee / $\mu\mu$**) H (→ **$b\bar{b}$**)

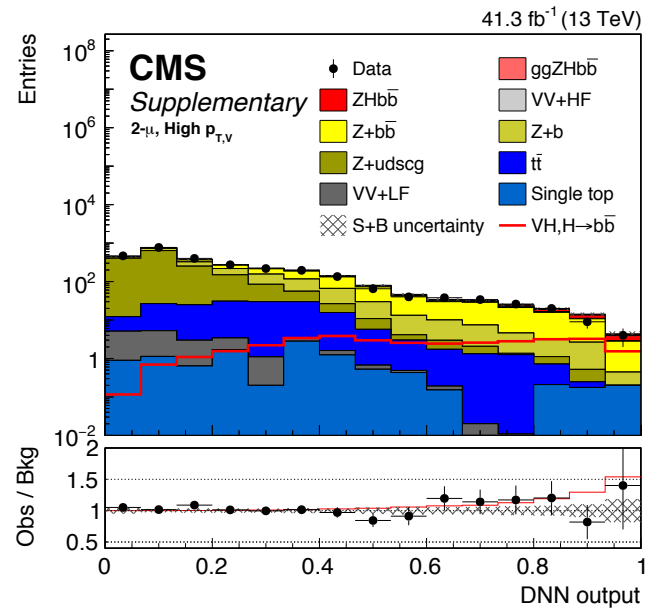
improvements:

- more efficient b jet identification
- better dijet mass resolution
- better signal and background separation due to improved machine learning techniques

signal extraction:

- deep neural network (DNN) discriminant in signal regions
- control regions for
  - $t\bar{t}$ & W/Z + light-flavor jets (yields)
  - W/Z + heavy-flavor jets (shape of b tagging / DNN discriminant)





$H \to b\bar{b}$: combination

Phys. Rev. Lett. 121 (2018) 121801

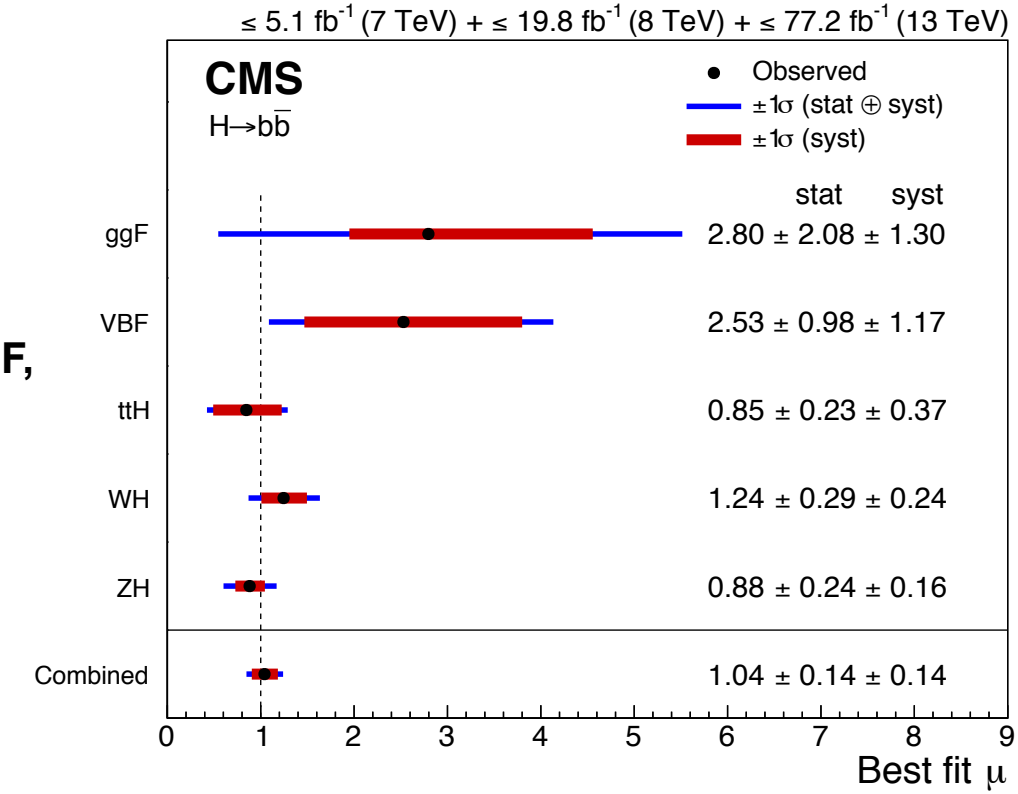
2017 + 2016 + Run I data:

- best-fit signal strength : **$\mu = 1.01 \pm 0.22$**
- obs. (exp.) significance of **4.8 σ** (4.9 σ)

combination with analyses targeting ggF, VBF & $t\bar{t}H$ production modes:

- best-fit signal strength : **$\mu = 1.04 \pm 0.20$**
- obs. (exp.) significance of **5.6 σ** (5.5 σ)

➡ **observation of $H \to b\bar{b}$ by CMS**



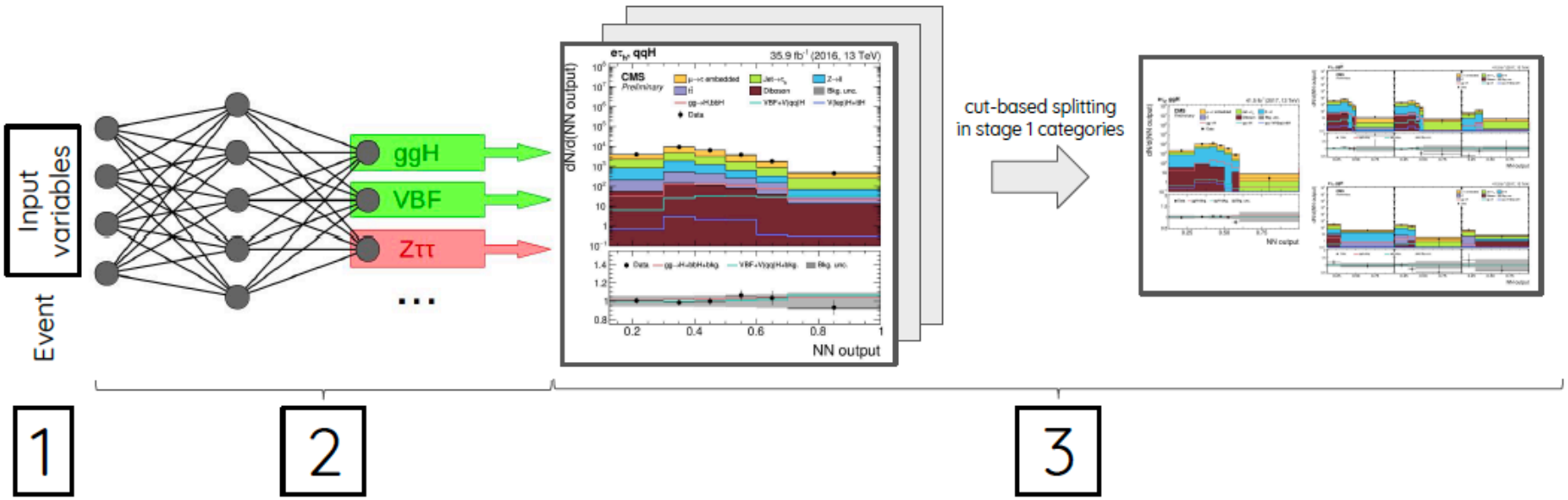
H → ττ in ggF & VBF production

CMS PAS HIG-18-032
NEW!

77.4 fb^{-1} (2016 + 2017 data)

analysis strategy:

- channels: **eμ / eτh / μτh / τhτh**



(1) input variable selection and validation (based on 1D and 2D goodness-of-fit tests)

(2) **multi-class neural nets** → two signal classes & several background classes

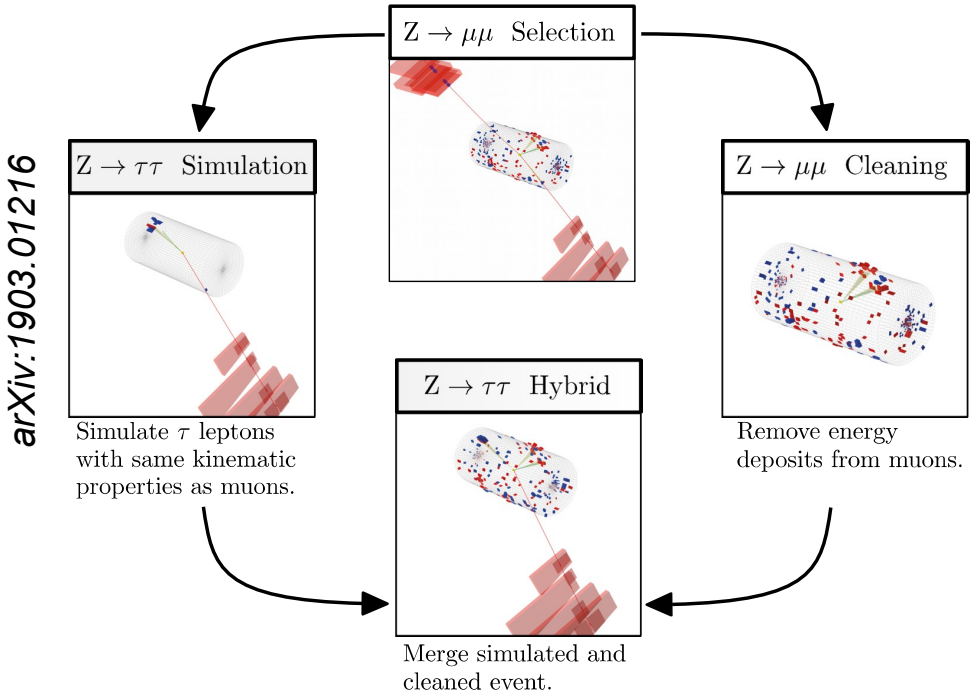
(3) cut-based splitting in **stage-1 simplified template cross section** categories

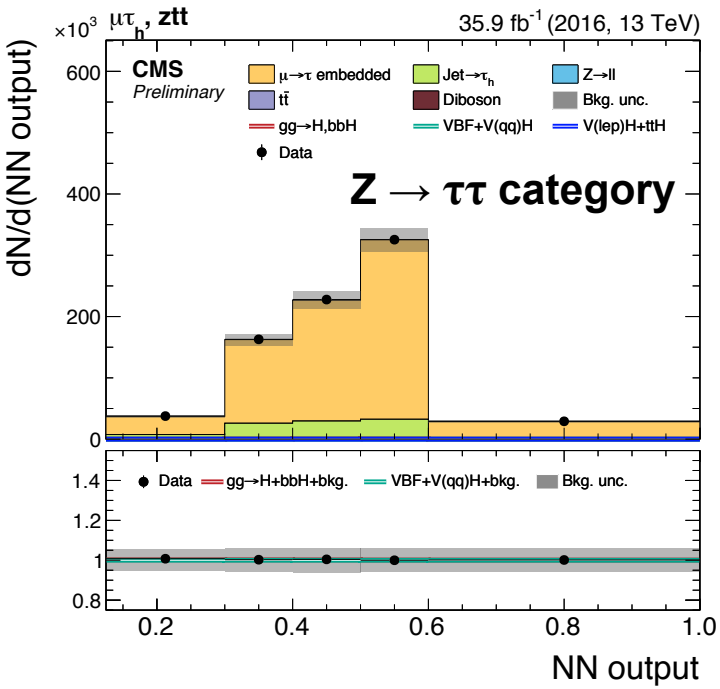
H → ττ in ggF & VBF production

CMS PAS HIG-18-032
NEW!

~ 90 % of total background estimated from data

τ-embedding: real taus (mainly Z → ττ)



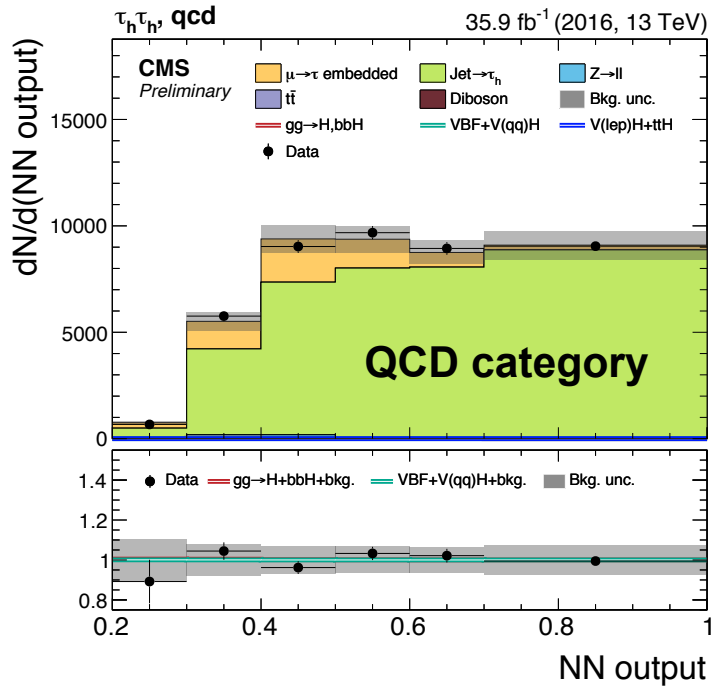


H → ττ in ggF & VBF production

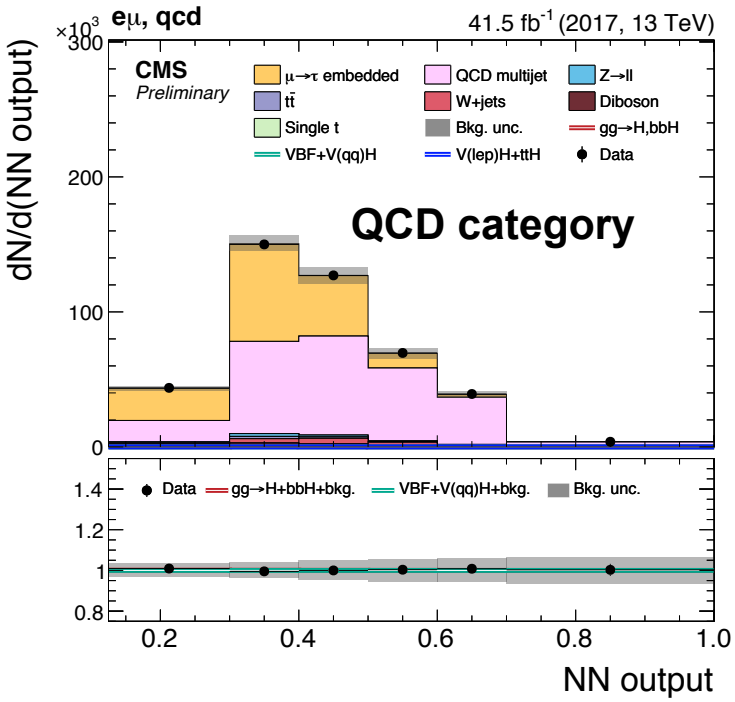
CMS PAS HIG-18-032
NEW!

~ 90 % of total background estimated from data

fake factor method: jet → τ_h



eμ : QCD from SS region



high purity background categories serve as control regions

H → ττ in ggF & VBF production

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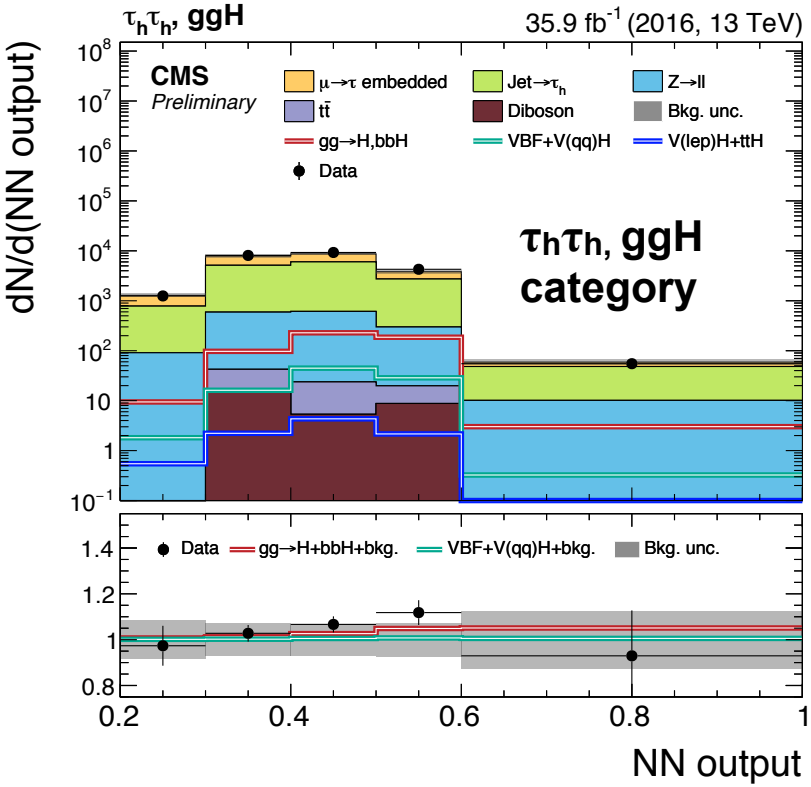
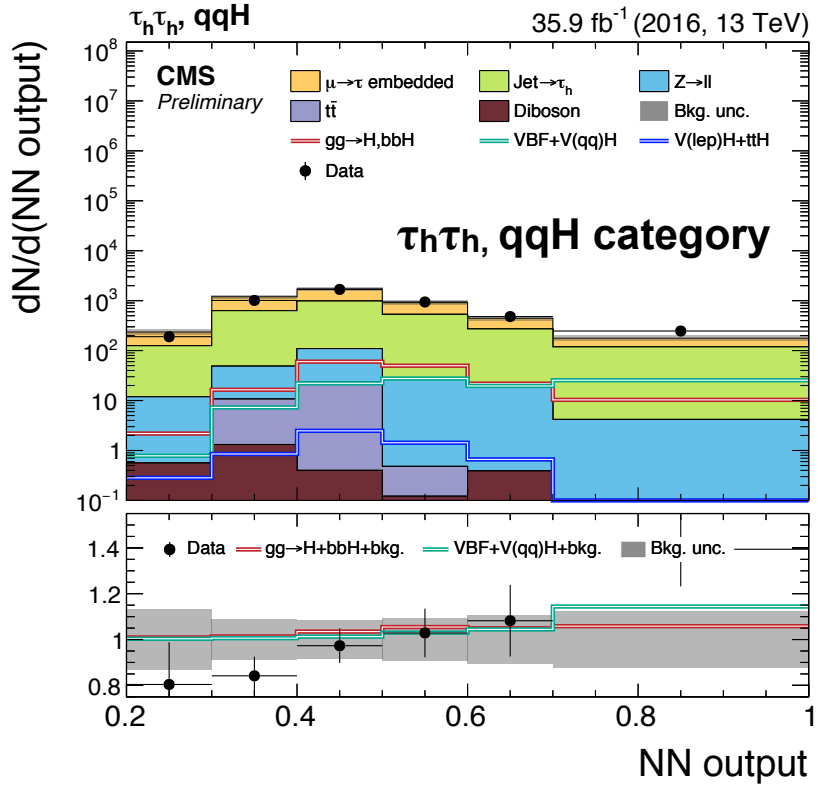
Signal categories





- increasing purity within category from low to high NN output

➡ additional signal and background separation

H → ττ in ggF & VBF production

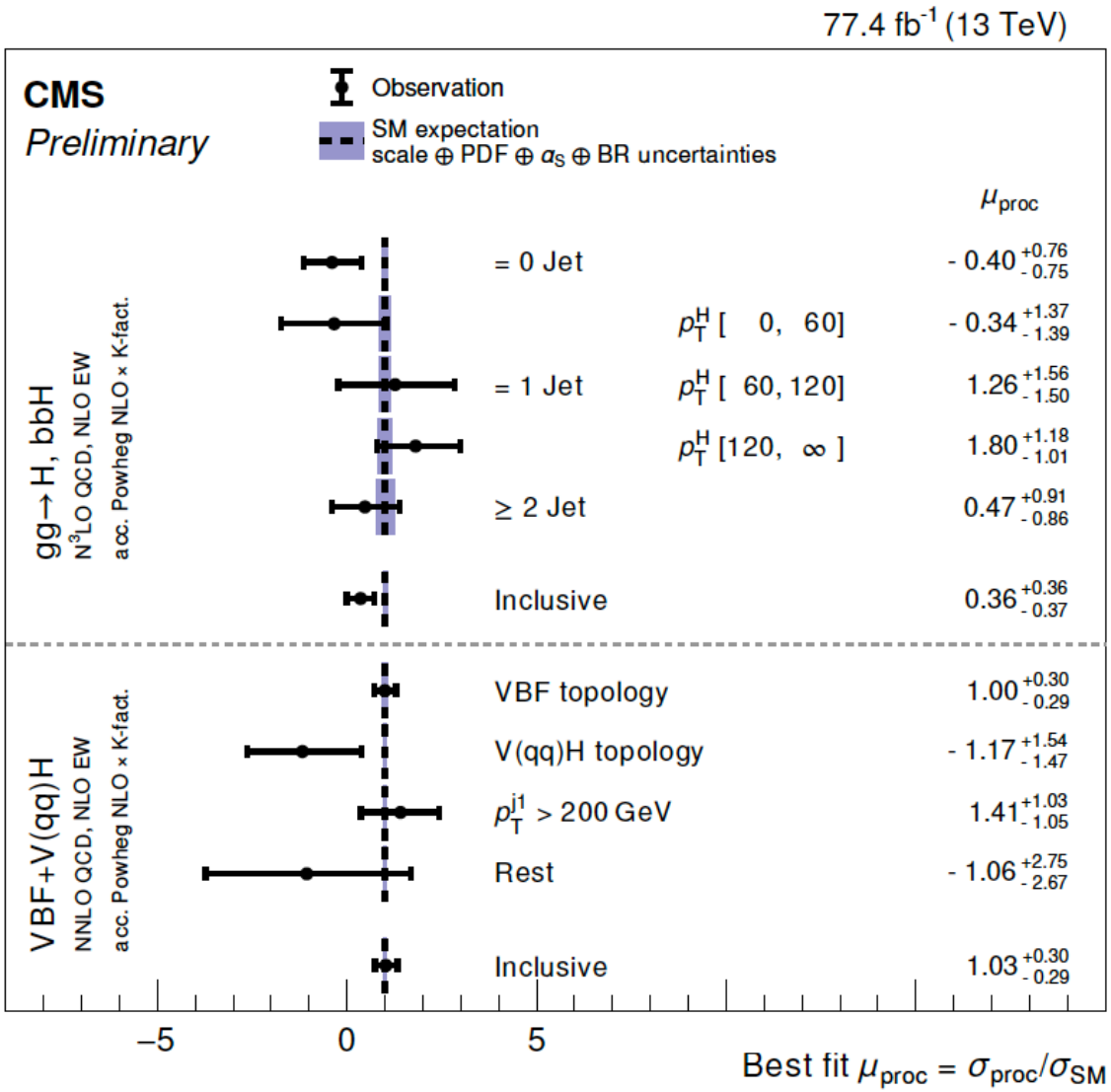
CMS PAS HIG-18-032
NEW!

inclusive measurement:

- best-fit signal strength
  $\mu = 0.75^{+0.18}_{-0.17}$

cross section measurements split by production modes & different kinematic regimes

- presented as stage-1.0 **simplified template cross sections**, as defined by LHC Higgs Cross Section Working Group
- few categories merged due to low sensitivity



H → ττ in WH & ZH production

35.9 fb^{-1} (2016 data)

arXiv:1809.03590, accepted by JHEP

channels:

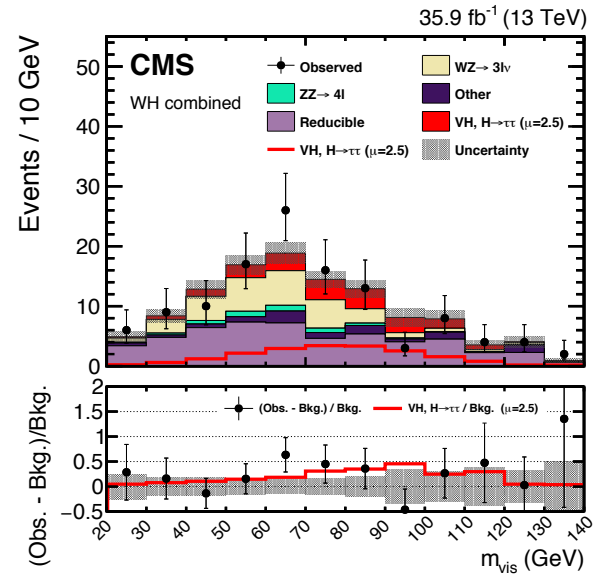
- W (→ **eν / μν**) H (→ ττ → **μτh / eτh / τhτh**), except for W (→ **eν**) H (→ ττ → **eτh**)
- Z (→ **ee / μμ**) H (→ ττ → **eτh / μτh / eμ / τhτh**)

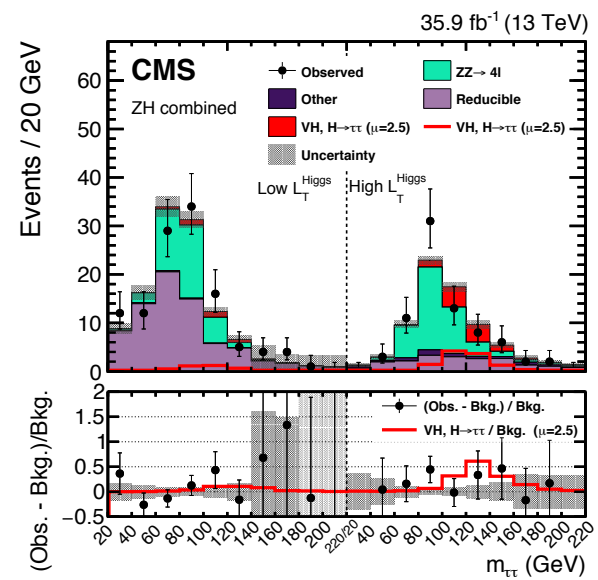
reconstruction of Higgs candidate

- m_{vis} in WH: sub-leading light lepton, τ_h / $\tau_h\tau_h$
- $m_{\tau\tau}$ in ZH: leptons not assigned to Z boson candidate
- ➡ reconstructed masses used for extraction of results

background estimation:

- background with jet misidentified as e/μ/τ_h from data
- di- & tri-boson production, $t\bar{t}V$, H → VV & $t\bar{t}H$ from simulation





H → ττ: ggF, VBF, VH combination

arXiv:1809.03590, accepted by JHEP

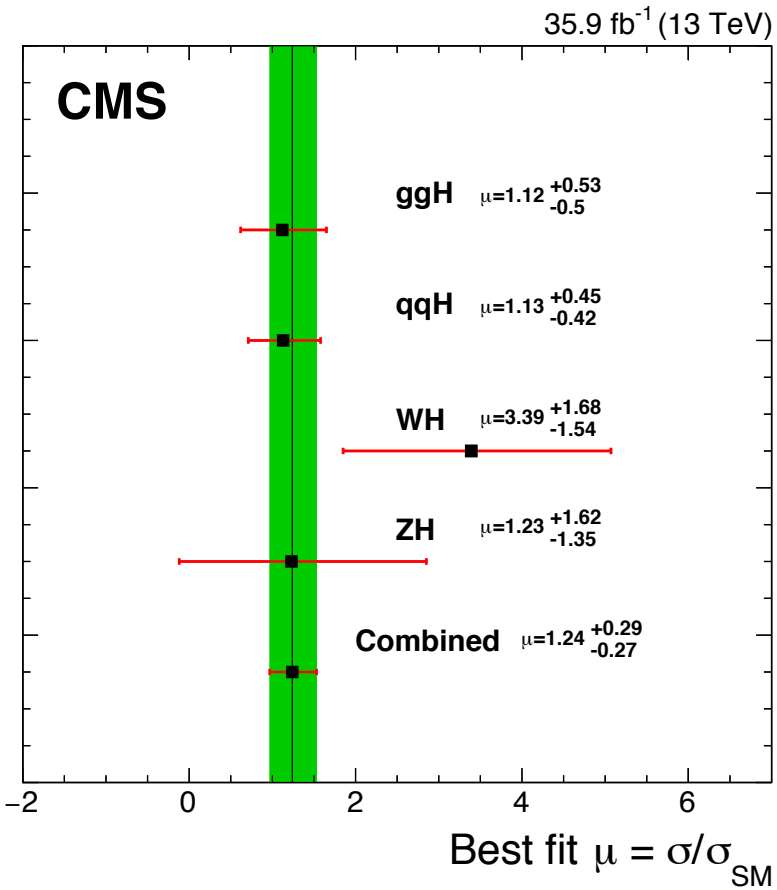
WH / ZH alone:

- best-fit signal strength : $\mu = 2.5^{+1.4}_{-1.3}$
- obs. (exp.) significance of **2.3 σ** (1.0 σ)

combination with ggF & VBF analysis
(**2016 data only**, Phys. Lett. B 779 (2018) 283):

- re-weighting of p_T^H in ggF to spectrum from NNLOPS generator, updated ggF cross section uncertainty
- obs. (exp.) significance of **5.5 σ** (4.8 σ)

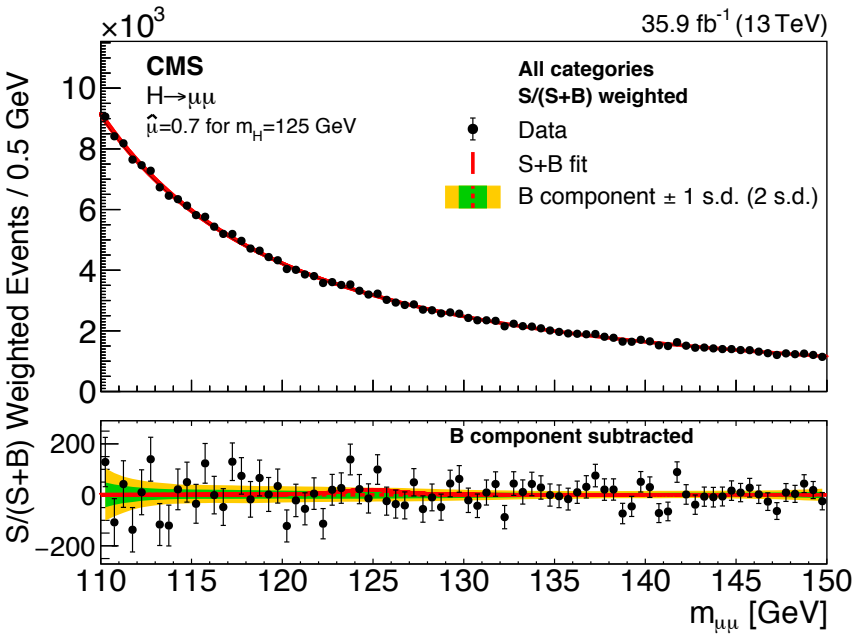
➡ **observation level reached with 2016 data alone**

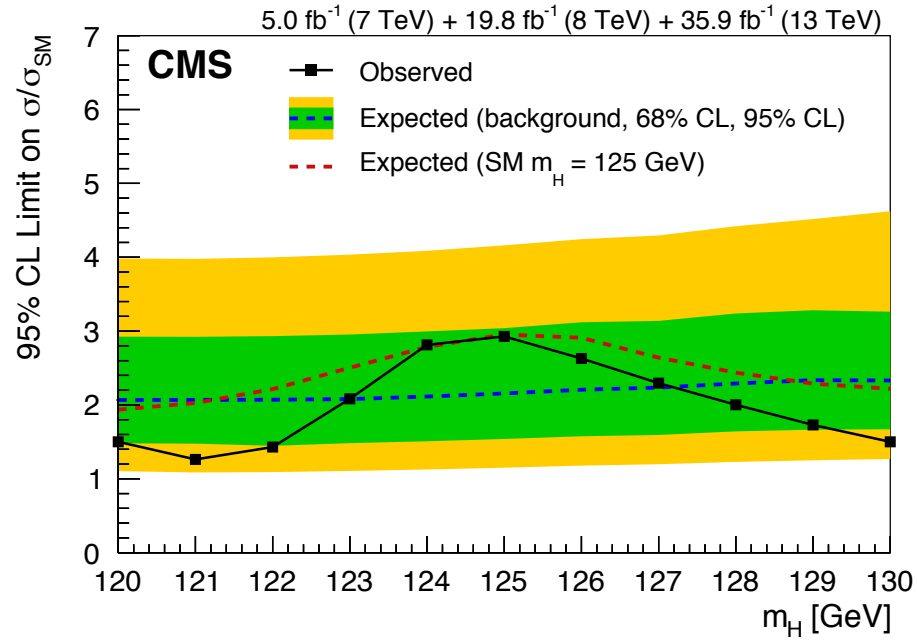


H → μμ

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 122 (2019) 021801





combined 2016 data + Run I results (at m_H = 125.09 GeV) :

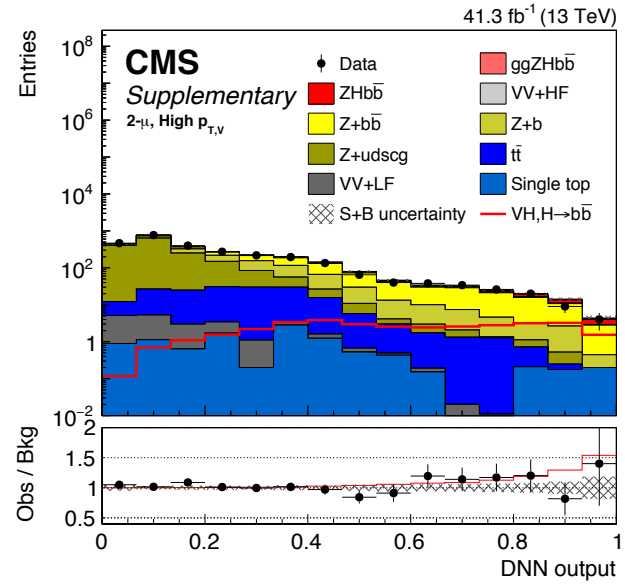
- upper limit on **σ/σ_{SM} : 2.9 (2.2)** obs. (exp. for μ = 0) at 95% C.L.
- best fit signal strength **μ** of **1.0 ± 1.0 (stat) ± 0.1 (syst)**
- obs. (exp.) significance of **0.9 σ** (1.0 σ)

Summary

after discovery of Higgs decays into 3rd generation fermions

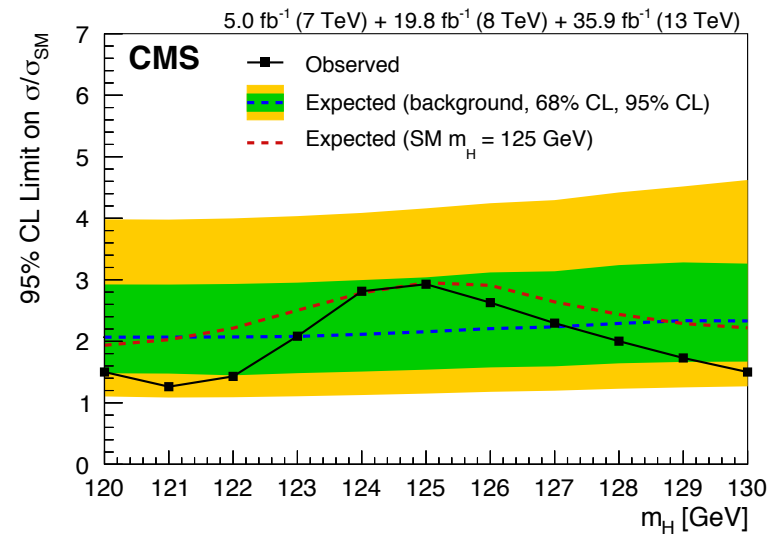
➡ **focus on measurements of properties of Higgs bosons couplings to 3rd generation fermions**

- observation of **$H \to b\bar{b}$** by CMS
- first measurement based on simplified template cross sections in **$H \to \tau\tau$**



next steps in establishment of coupling to 2nd generation fermions:

- **$H \to \mu\mu$:** no significant excess seen, but remarkable sensitivity achieved already in middle of Run II
- **$H \to c\bar{c}$** : see talk by Loukas Gouskos on Wednesday



Thank you for your attention!

Backup

Boosted H → $b\bar{b}$

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 120 (2018) 071802

signature:

- high p_T AK8 jet (p_T > 450 GeV) that has two-prong substructure and is double-b tagged

trigger:

- requirements on total hadronic transverse energy or jet p_T & trimmed jet mass

event categorization

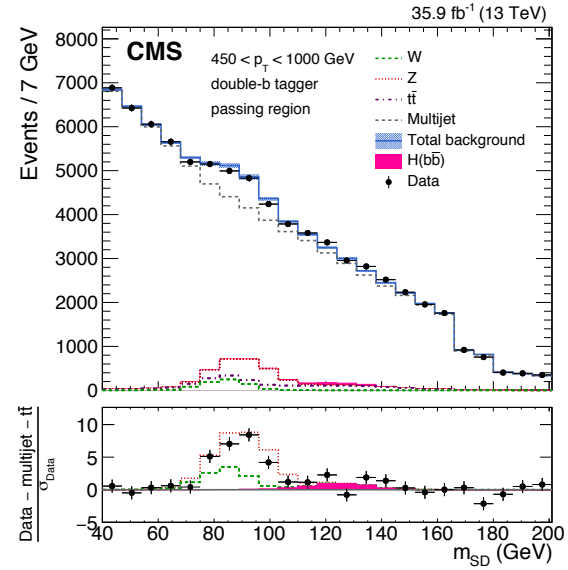
- six p_T categories from 450 GeV to 1 TeV

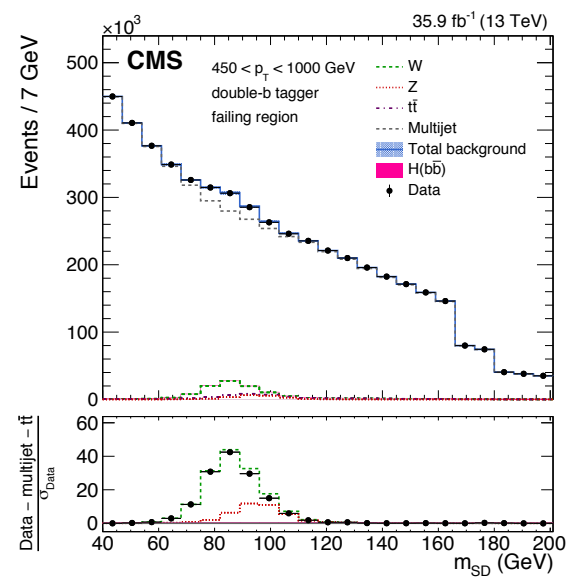
background estimation:

- data-driven estimation of QCD multijet background by inverting the b tagging requirement
- $t\bar{t}$ control region

simultaneous fit of jet mass (soft-drop grooming) in all categories (passing and failing) in mass range from 40 GeV to 201 GeV & tt CR

validation of analysis strategy with Z → $b\bar{b}$ decays





Boosted $H \to b\bar{b}$

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 120 (2018) 071802

Systematic source	W/Z	H
Integrated luminosity	2.5%	2.5%
Trigger efficiency	4%	4%
Pileup	<1%	<1%
$N_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	4.3%
Double-b tag	4% (Z)	4%
Jet energy scale / resolution	10/15%	10/15%
Jet mass scale (p_T)	0.4%/100 GeV (p_T)	0.4%/100 GeV (p_T)
Simulation sample size	2–25%	4–20% (ggF)
H p_T correction	—	30% (ggF)
NLO QCD corrections	10%	—
NLO EW corrections	15–35%	—
NLO EW W/Z decorrelation	5-15%	—

Boosted $H \to b\bar{b}$

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 120 (2018) 071802

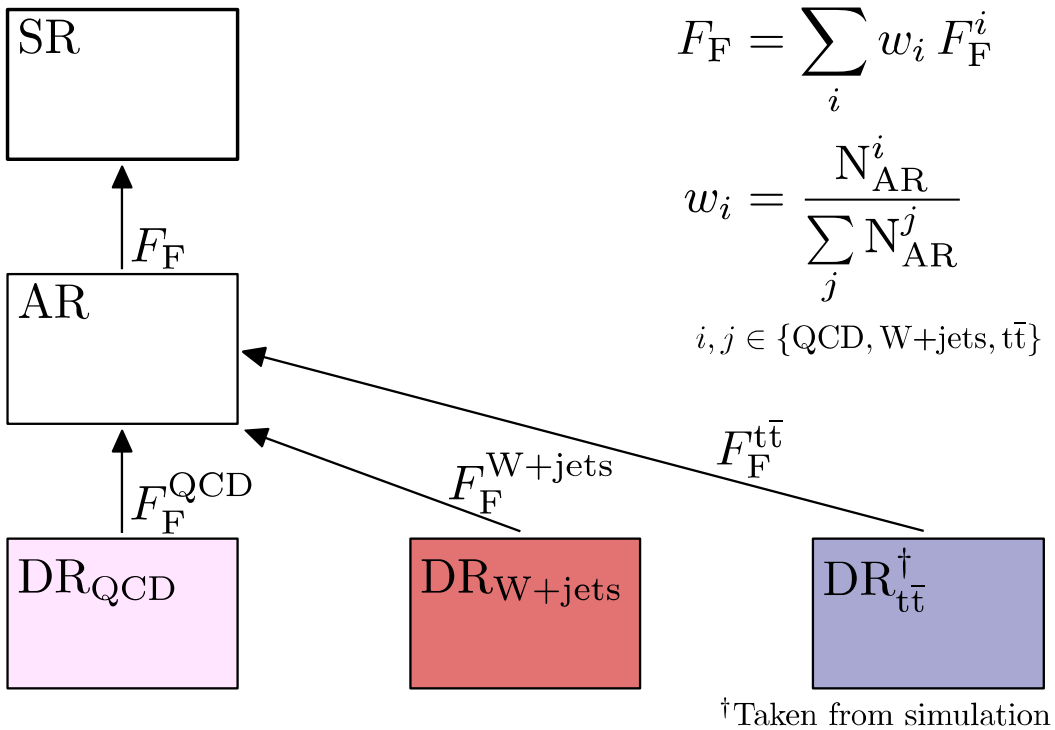
	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

➡ **first observation of the $Z \to b\bar{b}$ process in the single-jet topology**

$H \to \tau\tau$ in ggF & VBF production

Fake factor method

JHEP 09 (2018)007



$$F_F = \sum_i w_i \, F_F^i$$

$$w_i = \frac{N_{AR}^i}{\sum_j N_{AR}^j}$$

$i, j \in \{QCD, W+jets, t\bar{t}\}$

H → ττ in ggF & VBF production

Performance of Neural Net

CMS PAS HIG-18-032
NEW!

$e\tau_h$ (2017) CMS *Simulation Preliminary*

NN predicted event class \ True event class	ggH	qqH	ztt	qcd	tt	misc	zll	wj
ggH	0.23	0.08	0.07	0.04	0.01	0.03	0.12	0.06
qqH	0.22	0.72	0.07	0.05	0.05	0.11	0.06	0.05
ztt	0.20	0.06	0.66	0.18	0.01	0.10	0.08	0.09
qcd	0.03	0.02	0.03	0.21	0.03	0.10	0.05	0.15
tt	0.01	0.04	0.02	0.07	0.76	0.26	0.01	0.02
misc	0.01	0.03	0.04	0.05	0.12	0.21	0.03	0.08
zll	0.22	0.02	0.07	0.14	0.00	0.04	0.55	0.12
wj	0.07	0.02	0.04	0.26	0.02	0.15	0.10	0.43

- columns normalized to 1

example: 72% of true qqH events are also classified as qqH events

- good separation of the processes achieved

$H \rightarrow \tau\tau$ in ggF & VBF production

Simplified Template Cross Sections Stage 1.0

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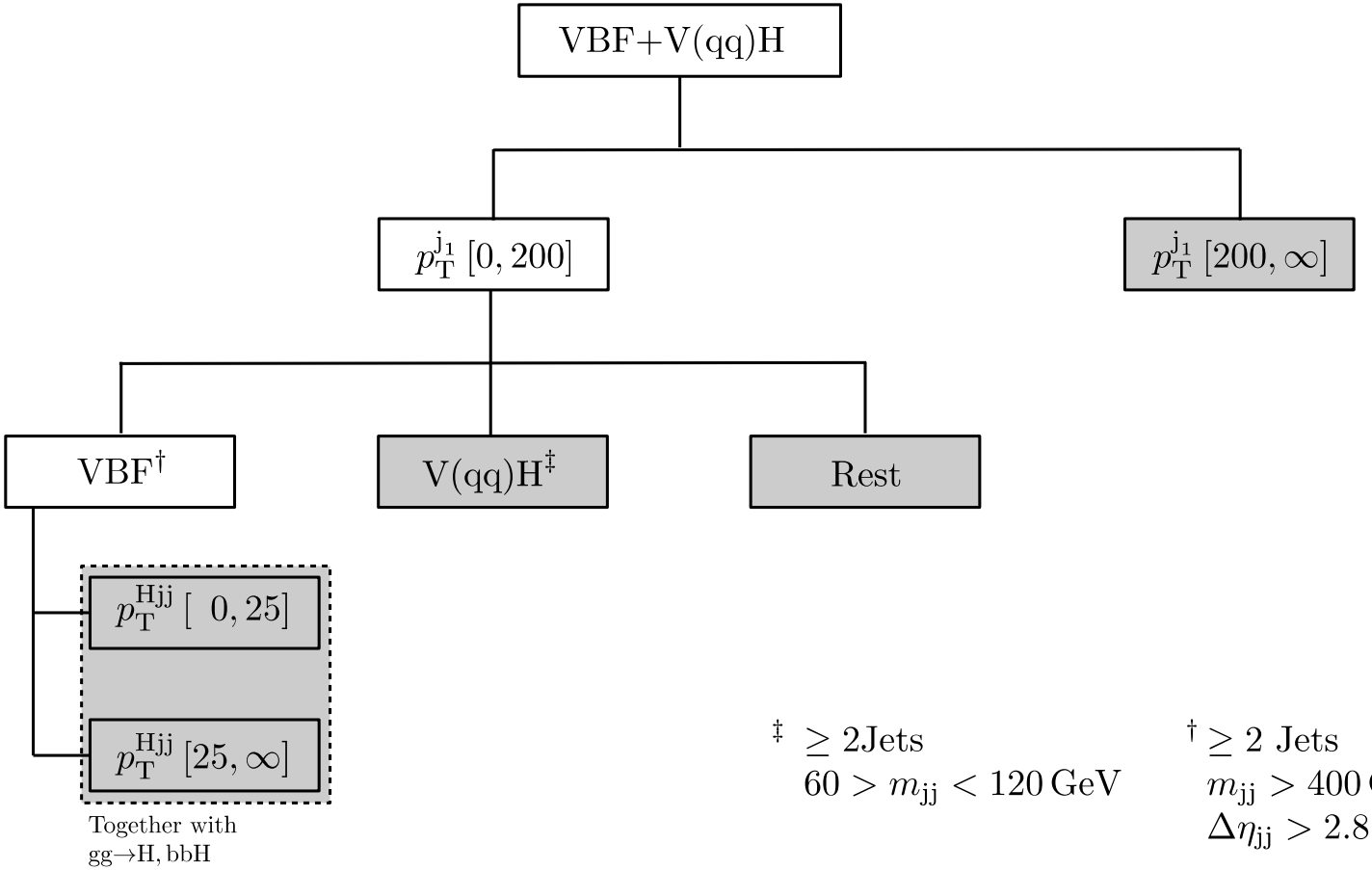

‡ $\geq$ 2Jets
$60 > m_{jj} < 120\,\text{GeV}$

† $\geq$ 2 Jets
$m_{jj} > 400\,\text{GeV}$
$\Delta\eta_{jj} > 2.8$

$H \to \tau\tau$ in ggF & VBF production

Simplified Template Cross Sections Stage 1.0

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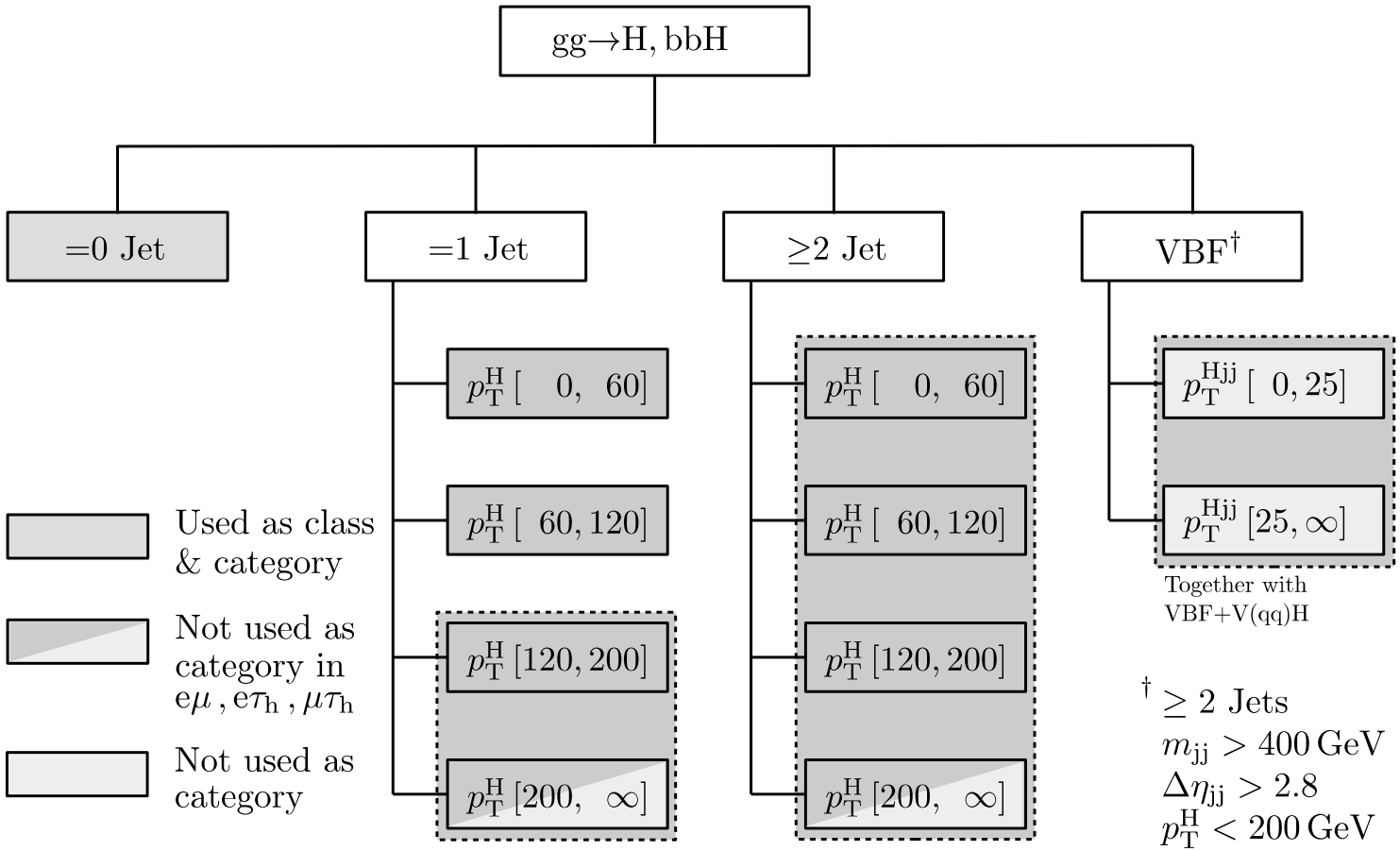
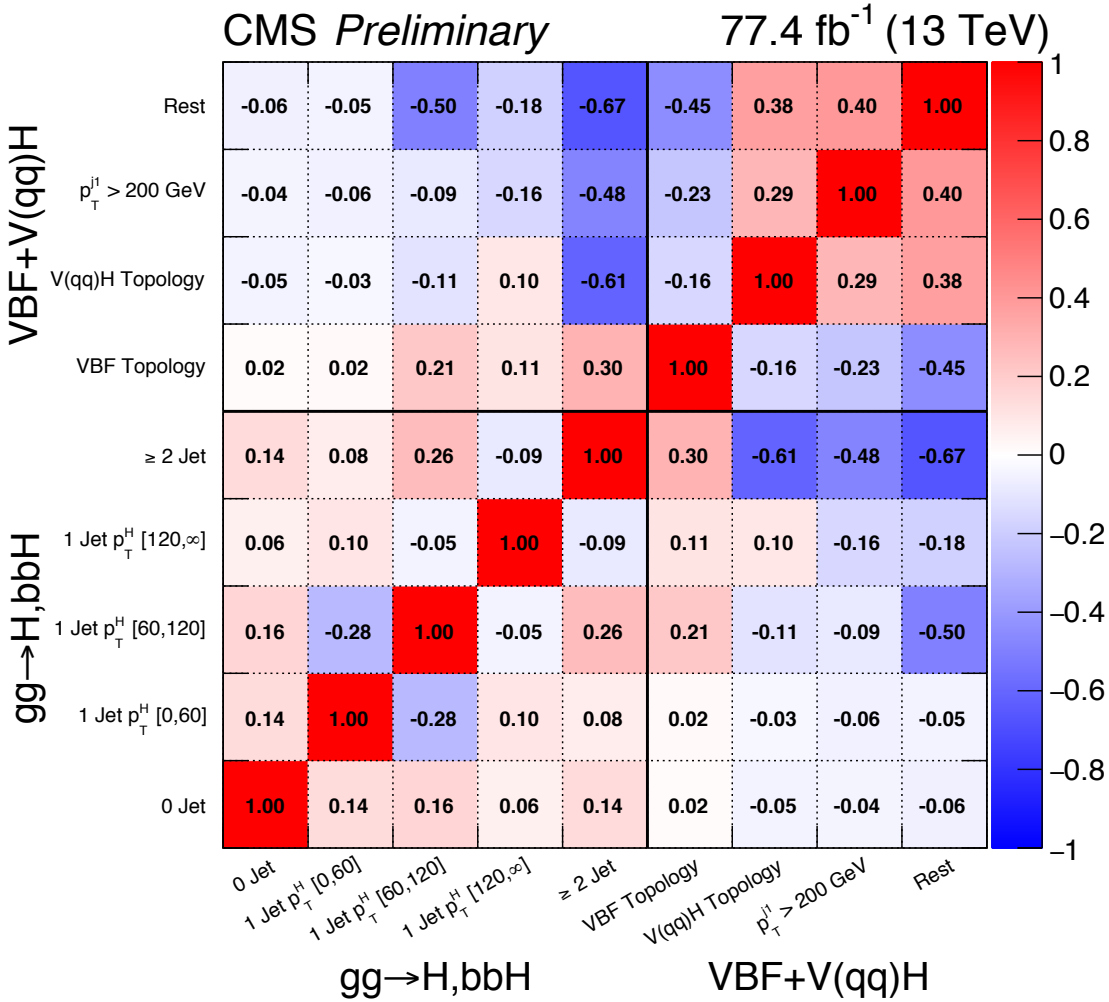


H → ττ in ggF & VBF production

Correlation matrix

CMS PAS HIG-18-032
NEW!



$H \rightarrow \tau\tau$ in WH & ZH production

35.9 fb^{-1} (2016 data)

arXiv:1809.03590, accepted by JHEP

Source of uncertainty	Magnitude	Process
τ_h ID & isolation	5%	All simulations
τ_h energy† (1.2% energy shift)	0.1–1.9%	All simulations
e ID & isolation & trigger	2%	All simulations
e energy† (1–2.5% energy shift)	0.3–1.4%	All simulations
μ ID & isolation & trigger	2%	All simulations
b veto	0.15–4.50%	All simulations
Diboson theoretical uncertainty	5%	WZ, ZZ
$gg \rightarrow ZZ$ NLO K factor	10%	$gg \rightarrow ZZ$
$t\bar{t} + W/Z$ theoretical uncertainty	25%	$t\bar{t} + W/Z$
Signal theoretical uncertainty	Up to 4%, see text	Signal
Reducible background uncertainties:		Reducible bkg.
WH statistical error propagation†	1–2%	
WH prompt lepton normalization†	2.6% in $e + \mu\tau_h/\mu + e\tau_h$, 4% in $\mu + \mu\tau_h$	
ZH prompt lepton normalization†	20% in $\ell\ell + e\mu$, <1% elsewhere	
WH normalization	20%	
ZH normalization	25–100%	
$\vec{p}_T^{miss}$ energy†	Up to 1.5% in WH, <1% in ZH	All simulations
Limited number of events	Stat. uncertainty per bin	All
Integrated luminosity	2.5%	All simulations

Search for H → μμ

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 122 (2019) 021801

selection strategy:

- 2 oppositely charged muons
- 110 GeV < $m_{\mu\mu}$ < 150 GeV

main backgrounds:

- $Z/\gamma^* \rightarrow \mu\mu$
- leptonic $t\bar{t}$ decays

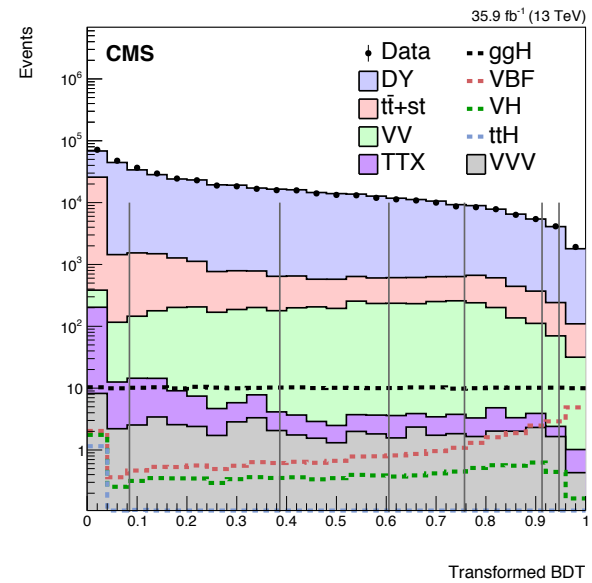
event categorization:

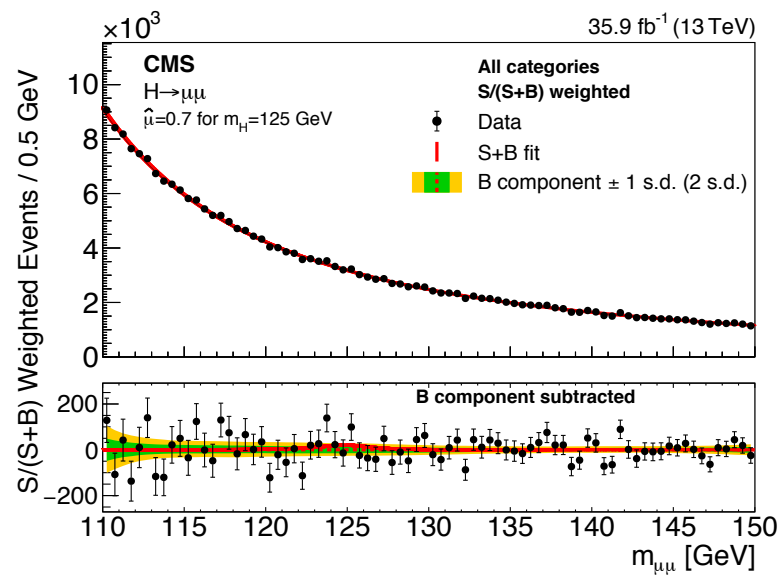
- **15 categories** based on optimized cuts on **BDT output and $|\eta^{\mu}|$**

➡ exploit better di-muon mass resolution in central detector parts

BDT variables: m_{jj}, $p_T^{\mu\mu}$, $\Delta\eta_{jj}$, $\Delta\eta_{\mu\mu}$ …

analytic functions used to describe signal and background distributions





Search for H → μμ

35.9 fb^{-1} (2016 data)

Phys. Rev. Lett. 122 (2019) 021801

BDT response quantile [%]	Maximum muon $\lvert\eta\rvert$	ggH [%]	VBF [%]	WH [%]	ZH [%]	$t\bar{t}H$ [%]	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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 $B_{\mathrm{deg}\,4}$	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		