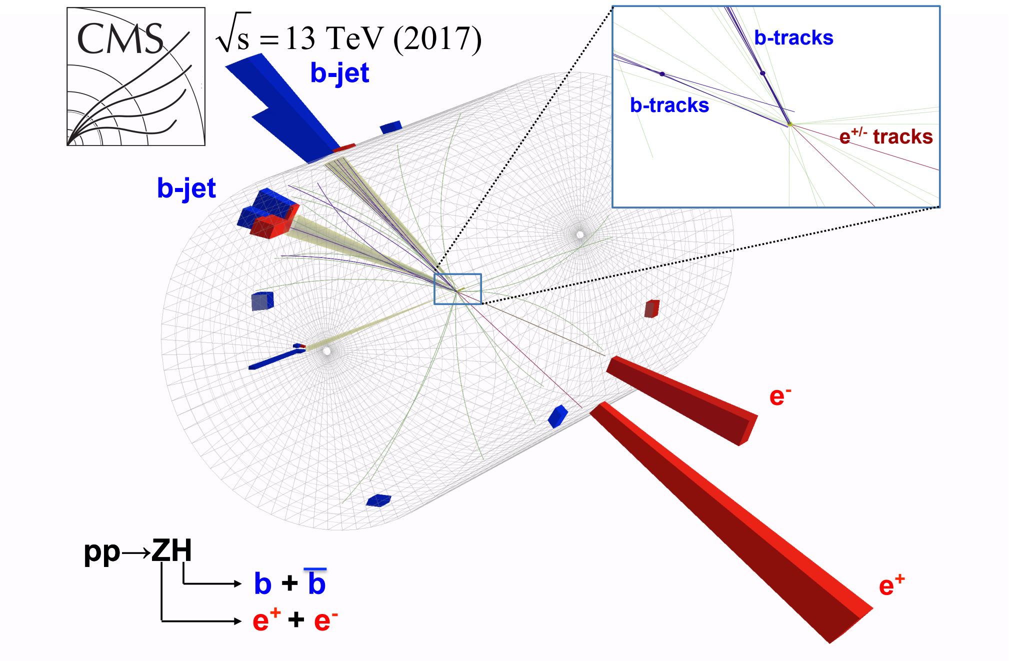
Observation of Higgs boson decay to bottom quarks

DESY Particle and Astroparticle Physics Colloquium



Heiner Tholen (DESY)

August 28, 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Higgs boson discovery in 2012

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NATURE | NEWS

Higgs triumph opens up field of dreams

Experimentalists now hope to pin down the properties of the fabled particle.

Geoff Brumfiel

10 July 2012

MEYRIN, SWITZERLAND

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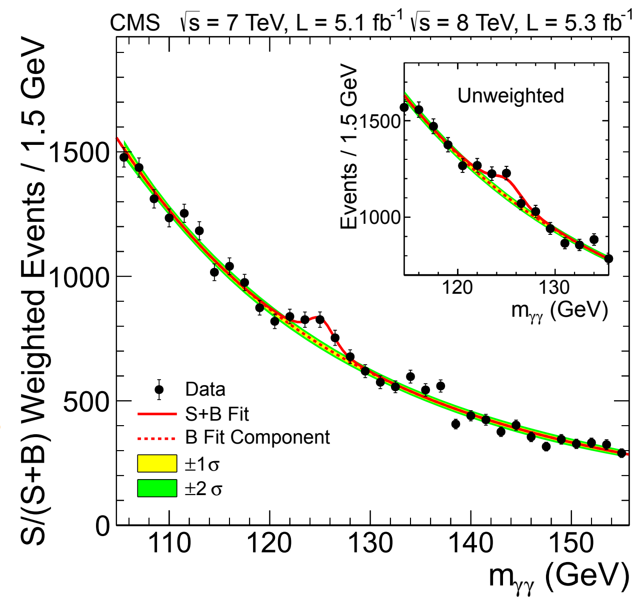
D. Balibouse/AP

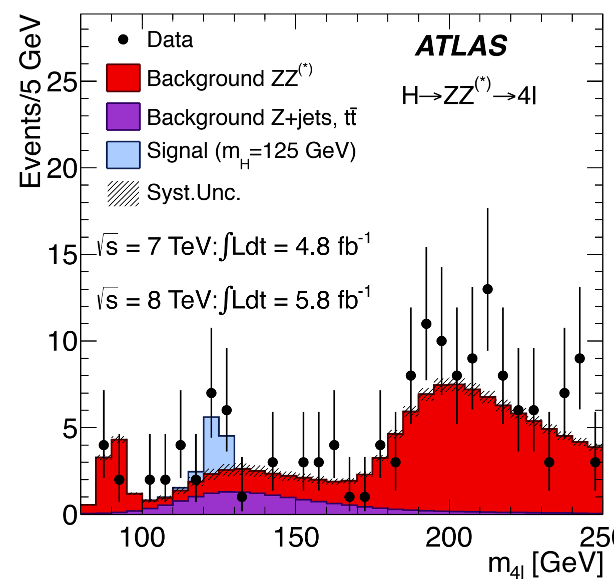
A rapt crowd watches as physicists Fabiola Gianotti (standing, left), Rolf Dieter-Heuer (right) and Joe Incandela (far right) unveil evidence for the Higgs boson.

Many physicists here spent the night huddled in the hall so that they could secure a prized seat. By 8:00 a.m., the fire brigade was turning away bleary-eyed scientists who had queued for hours. The lucky few who made it inside the lecture theatre at CERN, Europe's particle-physics laboratory near Geneva,

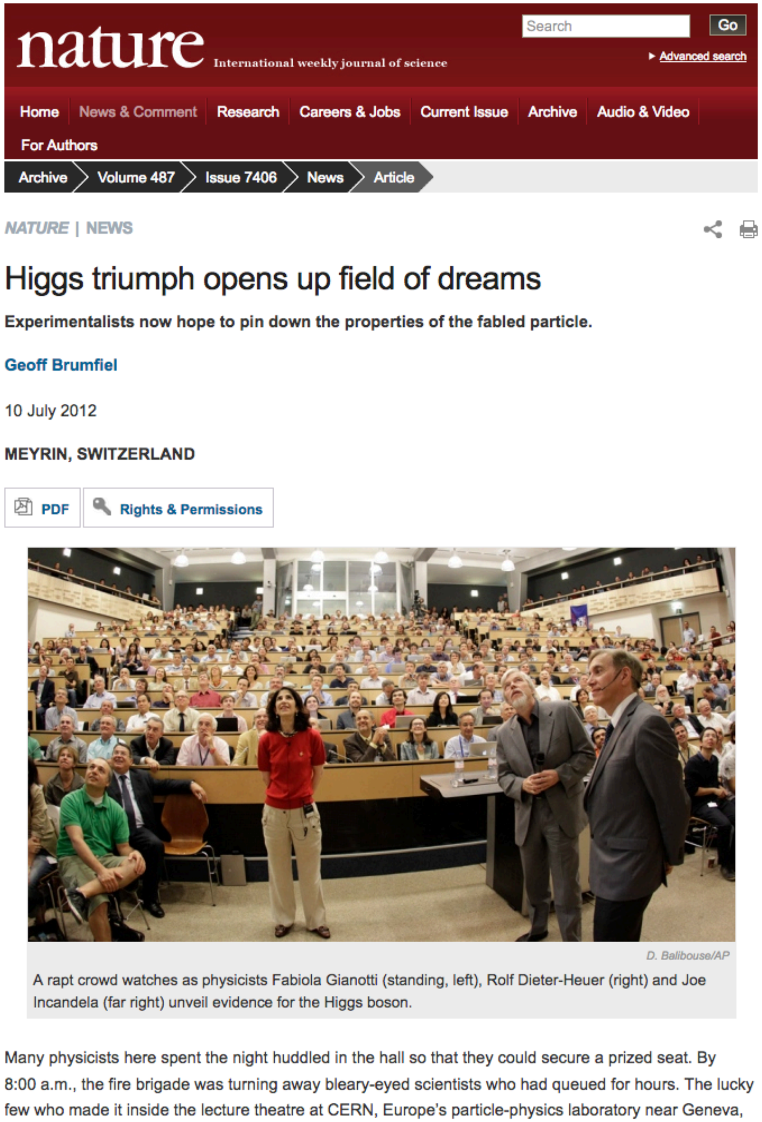
2 photons



4 leptons



Higgs boson discovery in 2012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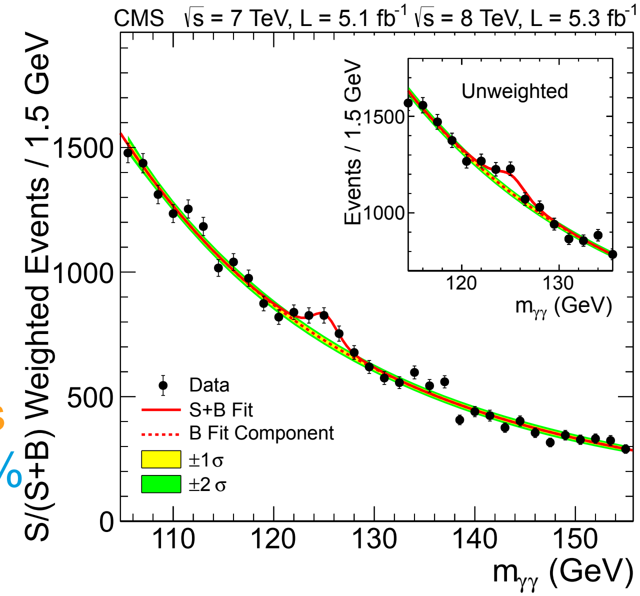
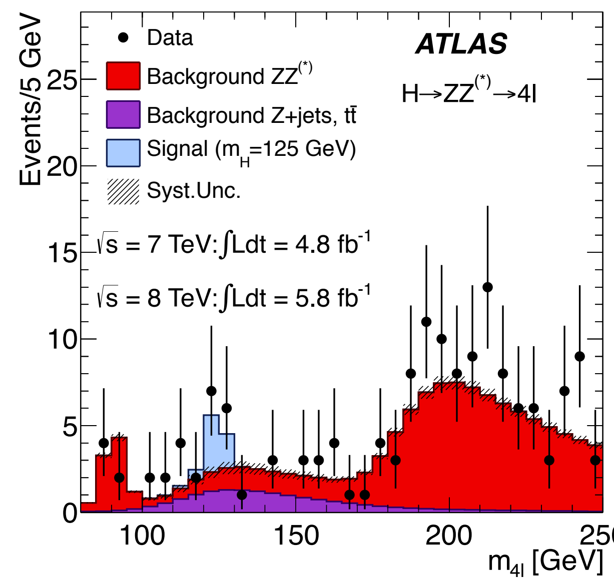
2 photons
BR: 0.23%

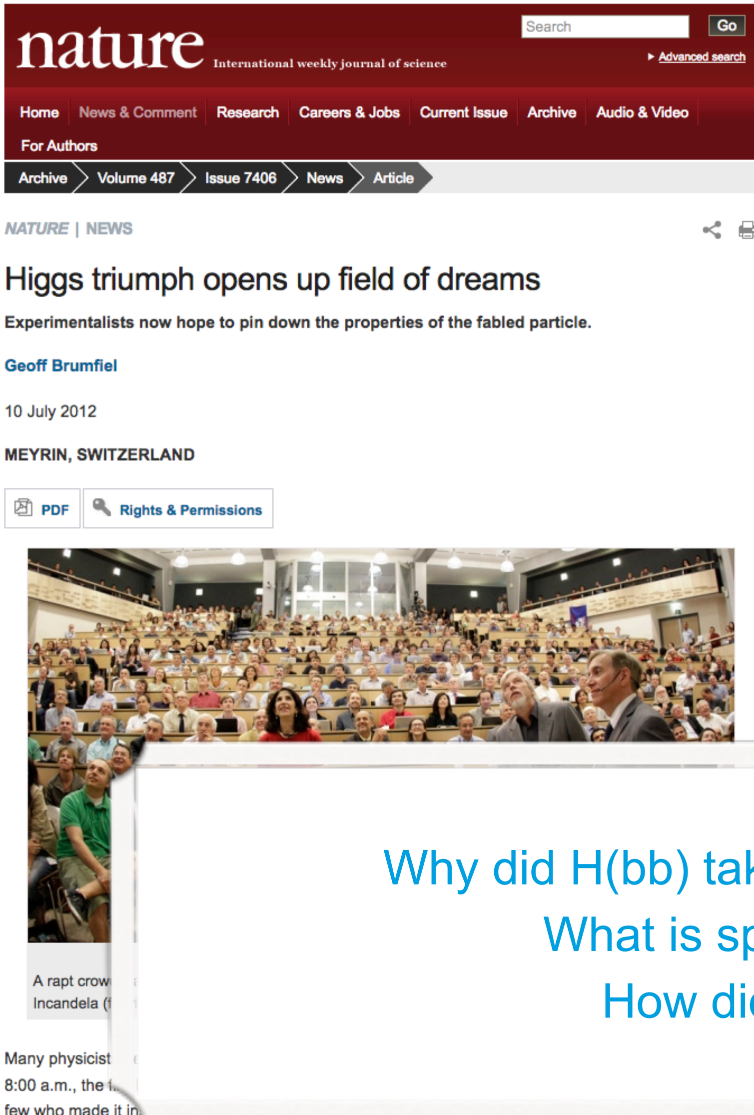


4 leptons
BR: 0.03%

compare:
H → bb
BR: 58.2%



Higgs boson discovery in 2012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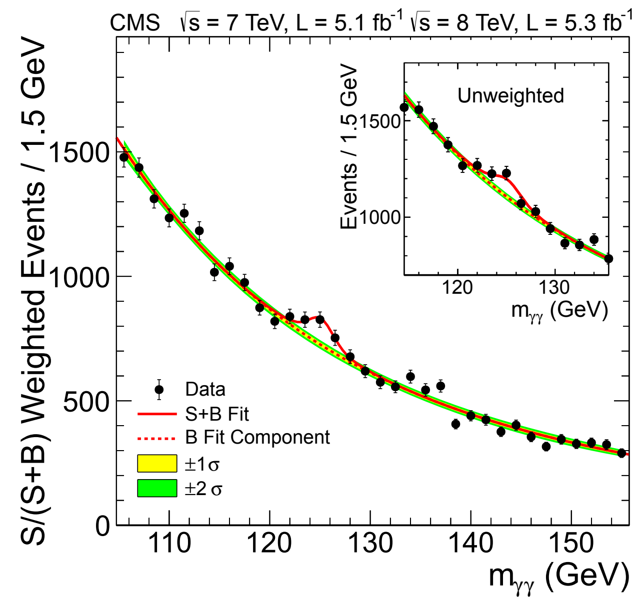
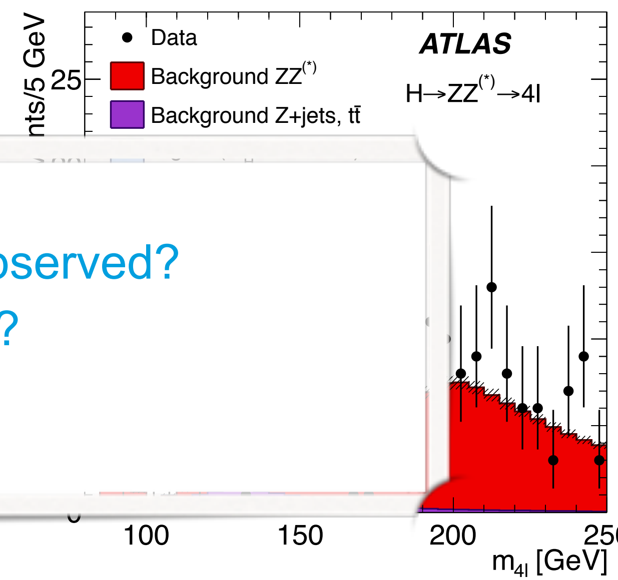
A rapt crow…
Incandela (…

Many physicist…
8:00 a.m., the f…
few who made it in…





Why did H(bb) take so long to be observed?

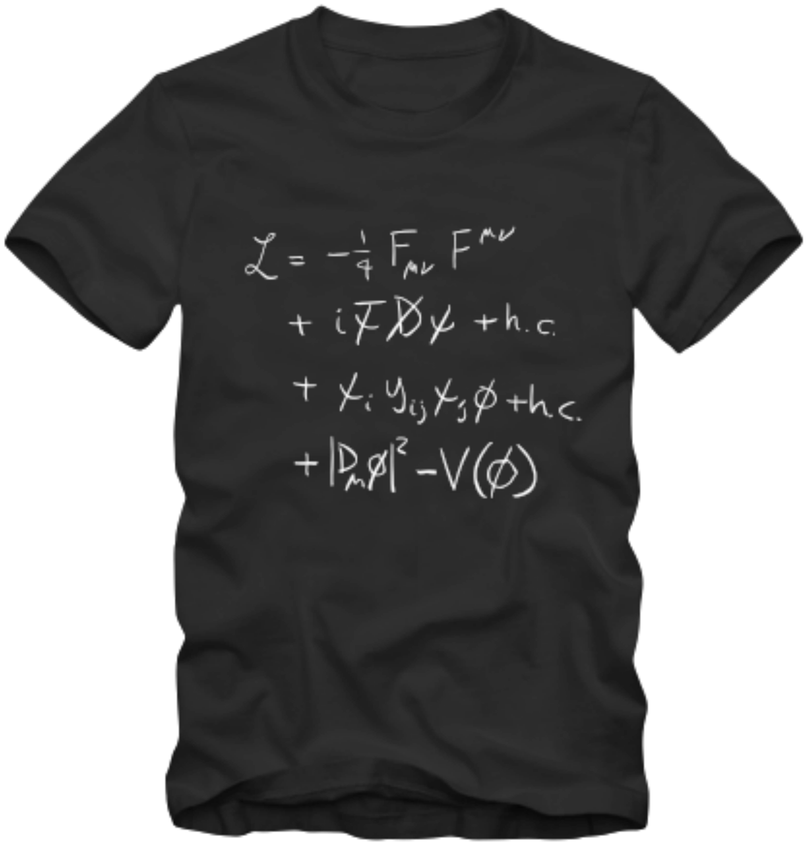
What is special about H(bb)?

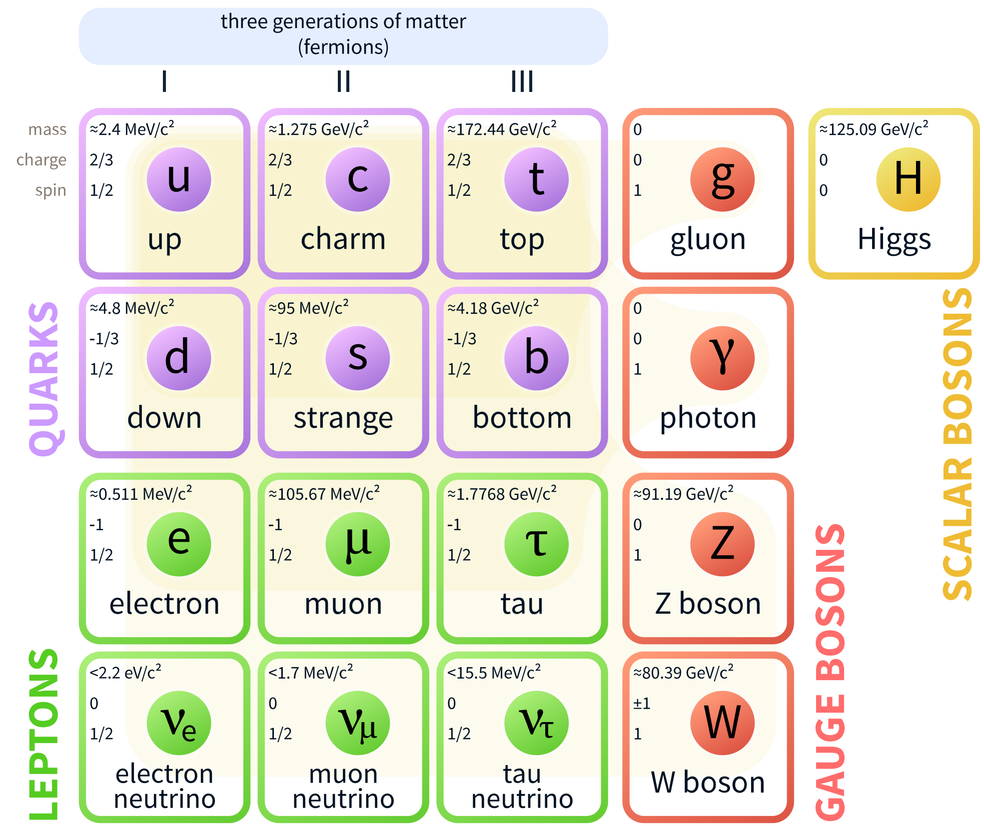
How did we observe it?

outline

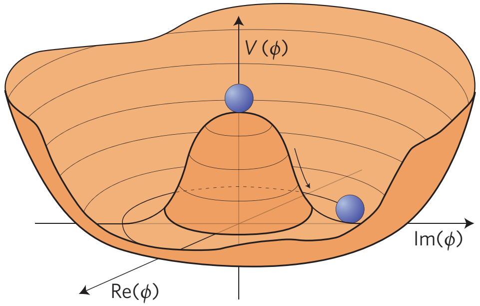
- the Higgs boson
  - standard model couplings
  - established properties
- experiment
- VH(bb) analysis
  - strategy
  - highlight of techniques
  - results
- summary & outlook

the standard model of particle physics





the BEH potential

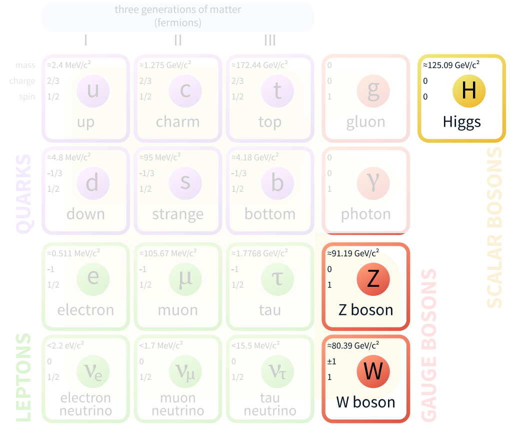


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Brout-Englert-Higgs potential:

$$-\mu^2\phi^2 + \lambda\phi^4$$

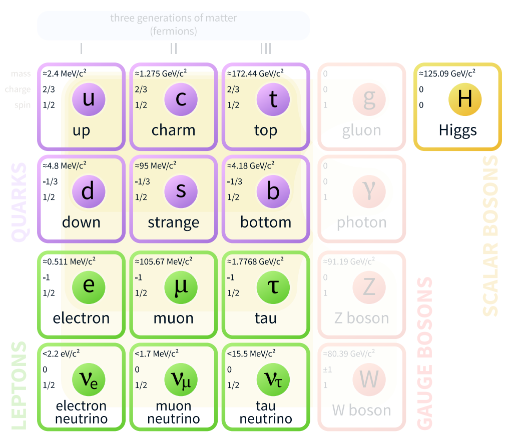
- allows mass terms for Z^0, $W^{\pm}$
- $|D_\mu\phi|$: interaction of H with Z^0, $W^{\pm}$
  - direct evidence seen in Higgs boson discovery



Yukawa couplings

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \boxed{\psi_i y_{ij}\psi_j\phi + h.c.} + |D_\mu\phi|^2 - V(\phi)$$

"gives mass to fermions"



- highly motivated presumption that fermion masses also generated by Higgs field
- such couplings not seen before
- not accessible through EW precision tests

- seen indirectly in discovery channels
- direct observation is difficult
  - coupling strength ~ m_f
  - 3rd gen particles have complicated decay modes
  - seen 2014 in ATLAS+CMS combination in $H(\tau\tau)$
- many BSM theories predict Yukawa couplings different from the SM

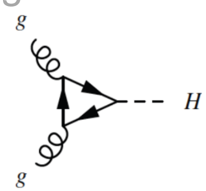
=> SM Yukawa couplings need dedicated confirmation

Higgs boson properties (SM)

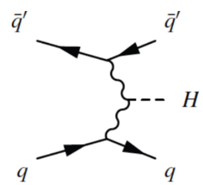
- mass: not predicted by SM
- width: 4.15 MeV (m_H=125 GeV)
- spin^{parity}: 0^+
- coupling strengths

production at the LHC

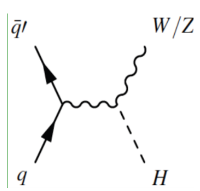
gluon fusion



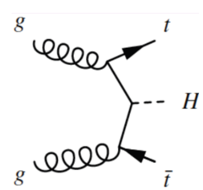
vector-boson fusion

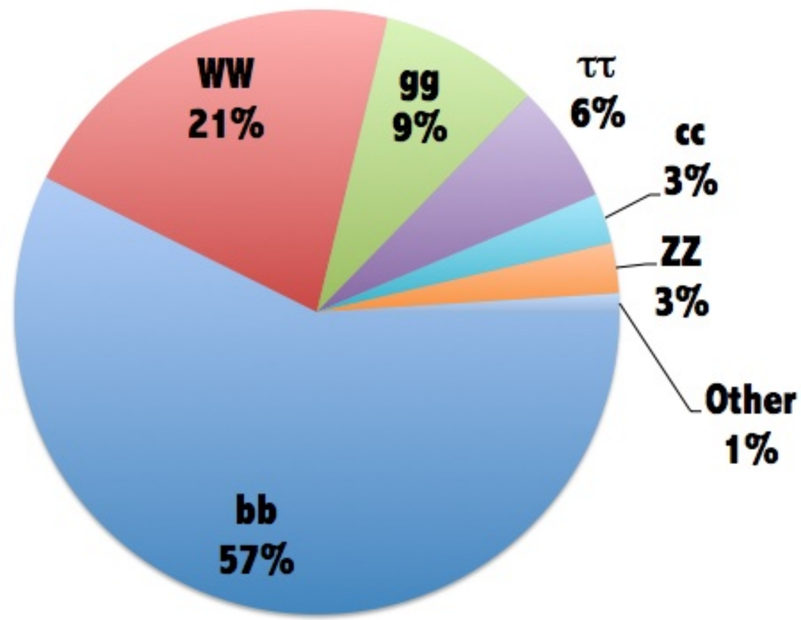


Higgs-strahlung



top-quark fusion ttH





H branching ratios
(m_H=125 GeV)

established properties

PDG 2018
Review of Particle Physics

H^0 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

- mass: di-photon and 4 lepton channels most sensitive
- width:
  - from indirect measurement
  - direct: $\Gamma_H < 1$ GeV

signal strength: $\mu = \frac{\sigma}{\sigma_{\mathrm{SM}}}$

bb, $\boldsymbol{\tau\tau}$ and ttH are sensitive to 3rd generation Yukawa couplings

is this *the* SM H^0?

width, spin/parity and coupling
measurements show SM-like
properties

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Full width $\Gamma < 0.013$ GeV, CL = 95%

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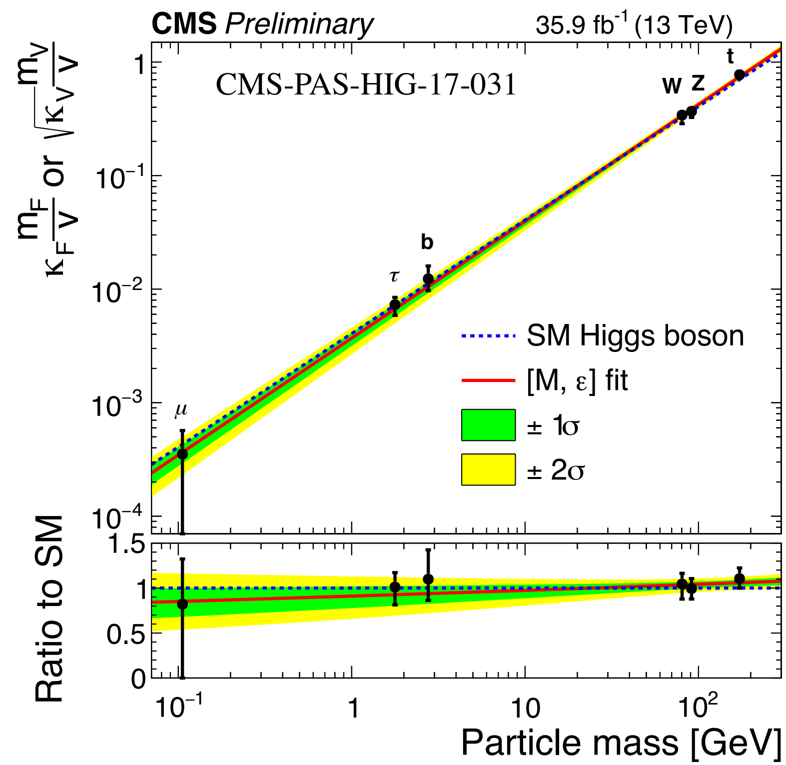
Higgs boson coupling



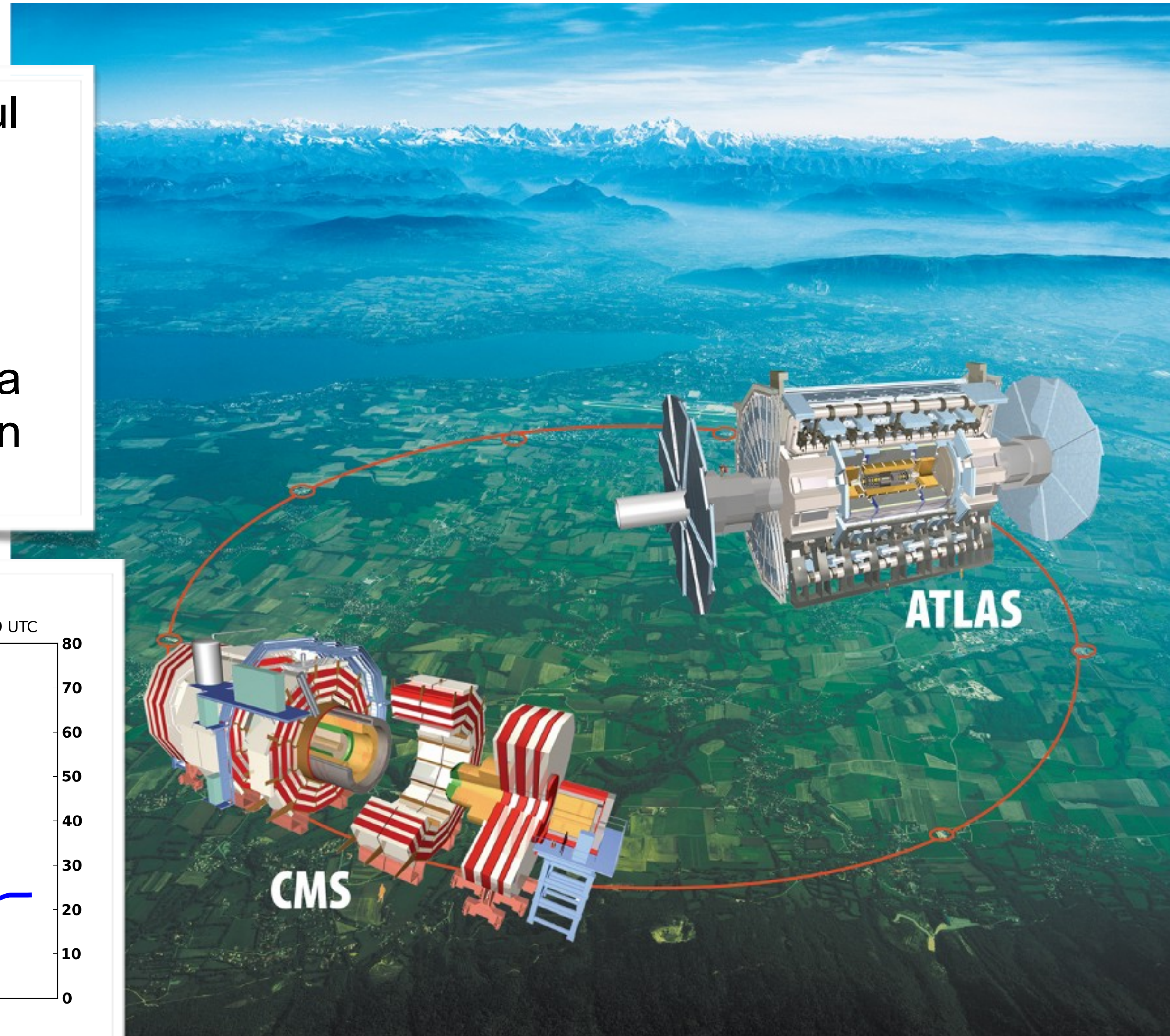
self-coupling?
are there non-SM properties?

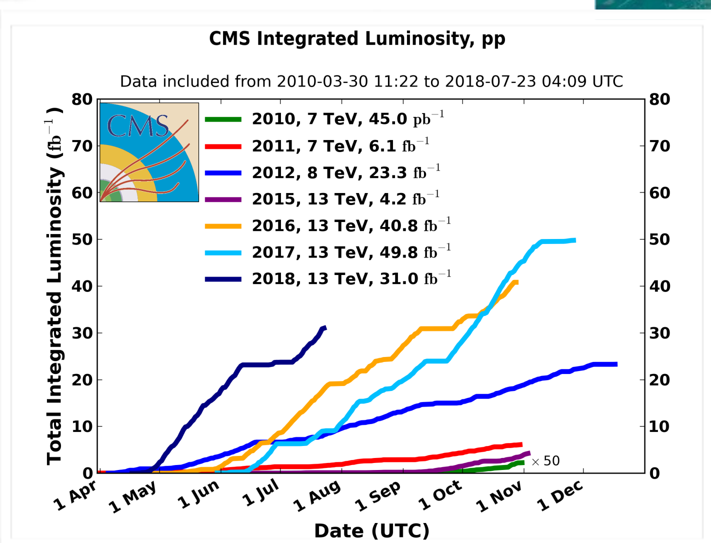
so far the data is in agreement with the standard model

experiment

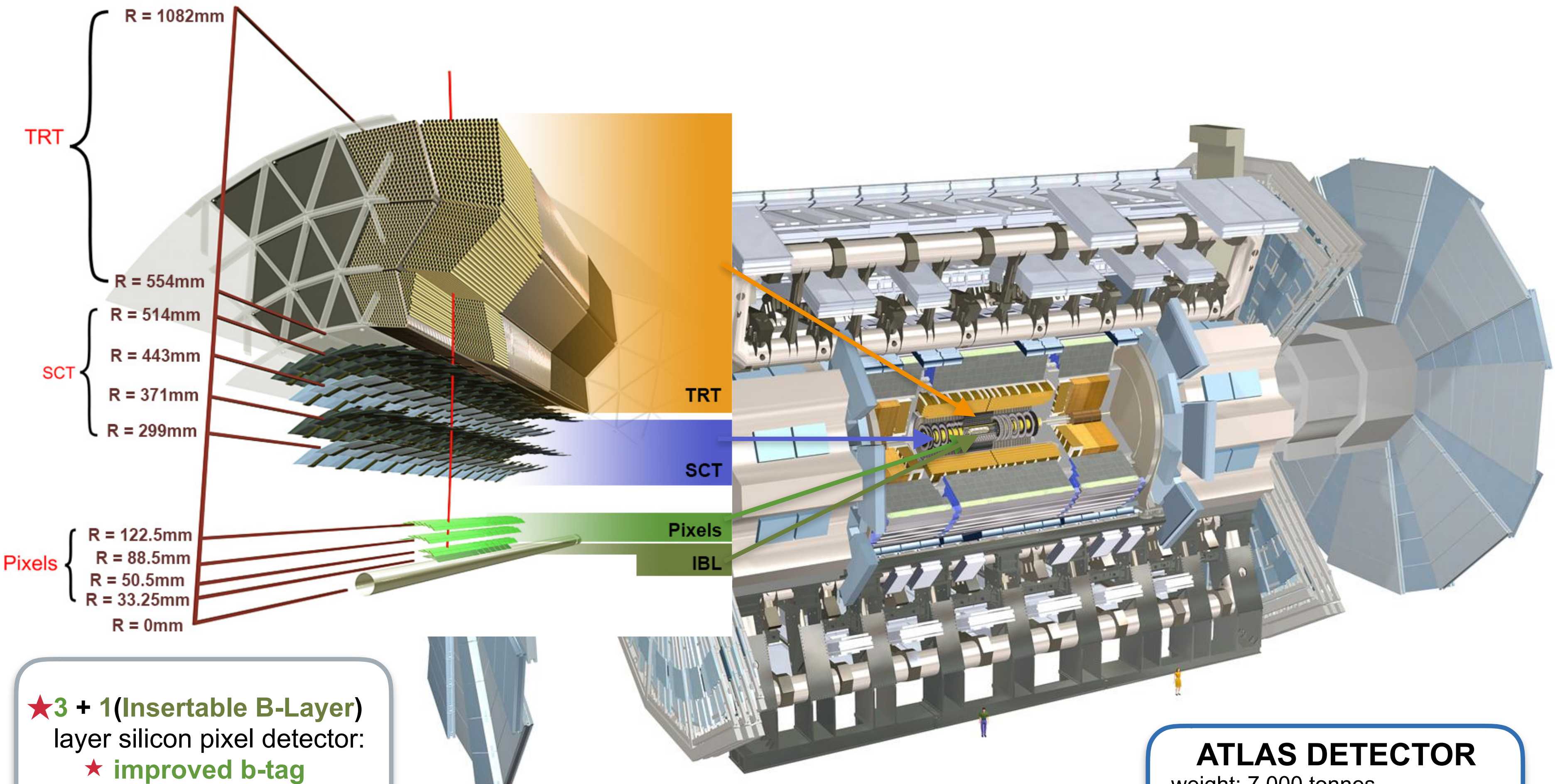
Large Hadron Collider (LHC)

- many years of successful data taking
- two run periods
  - Run I: 7, 8 TeV
  - Run II: 13 TeV
- today 10 times more data than used in Higgs boson discovery





ATLAS in run II



★3 + 1(Insertable B-Layer) layer silicon pixel detector:

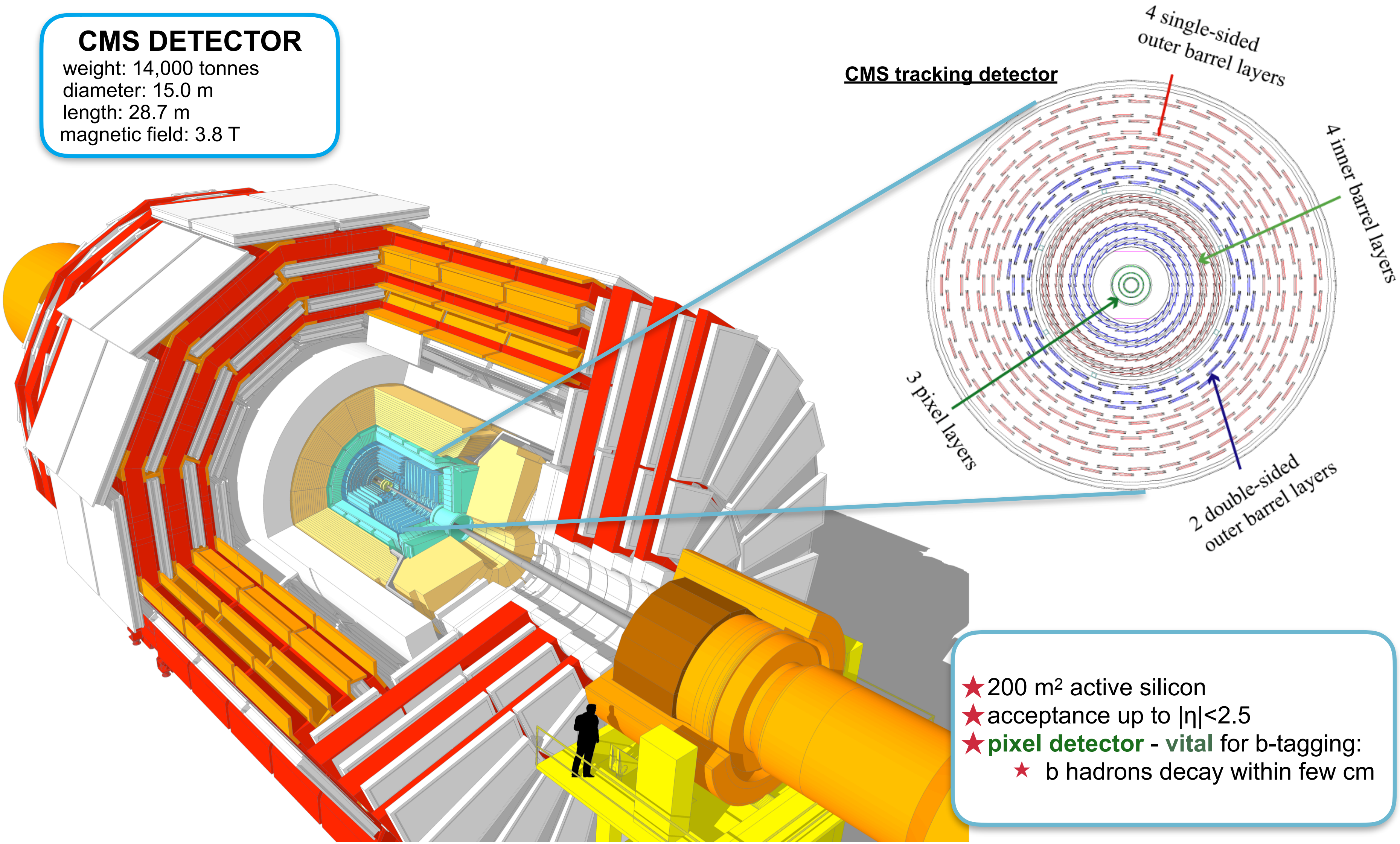
★ improved b-tag performance

ATLAS DETECTOR

weight: 7,000 tonnes
diameter: 22.0 m
length: 44.0 m
magnetic field: 2.0 T

CMS in run II

CMS DETECTOR
weight: 14,000 tonnes
diameter: 15.0 m
length: 28.7 m
magnetic field: 3.8 T

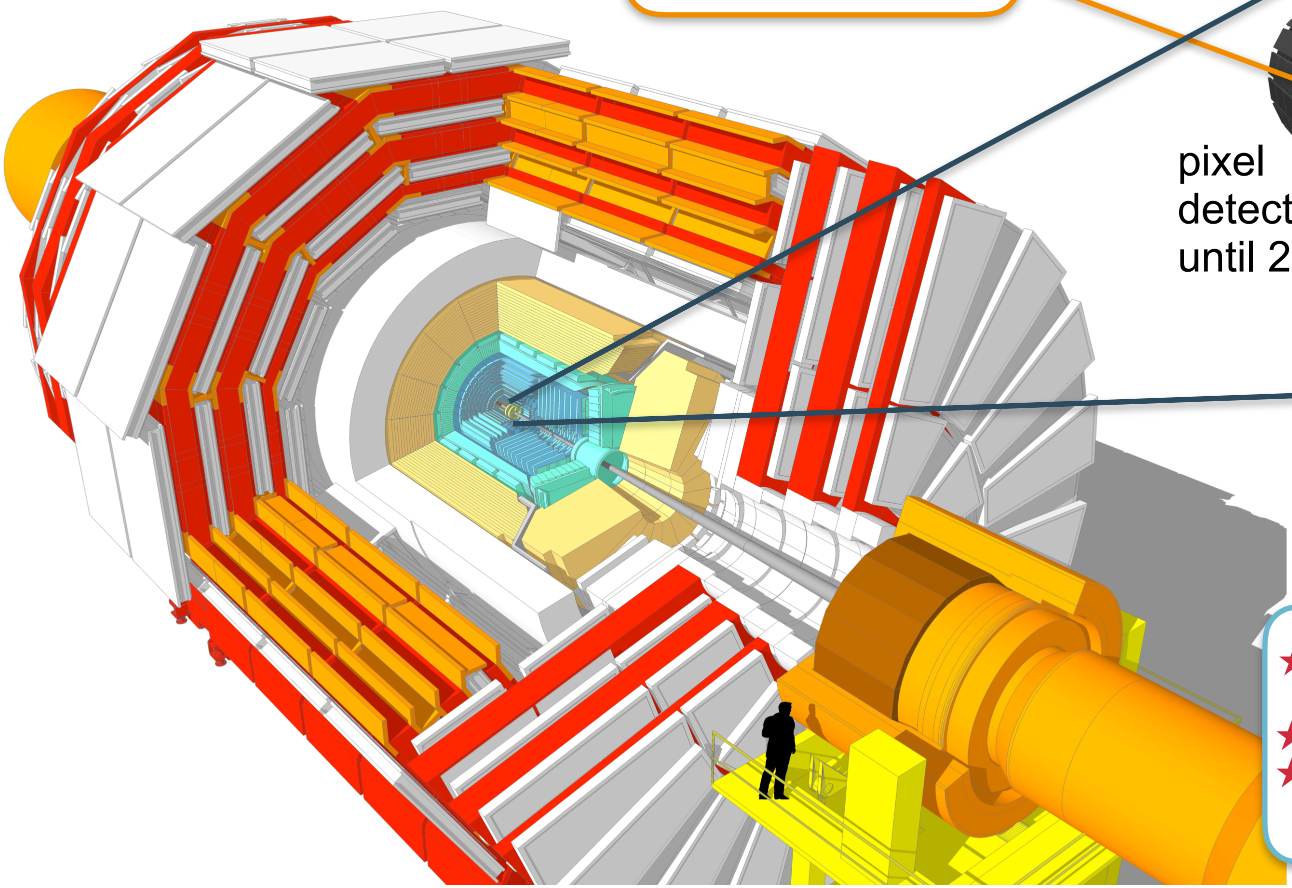


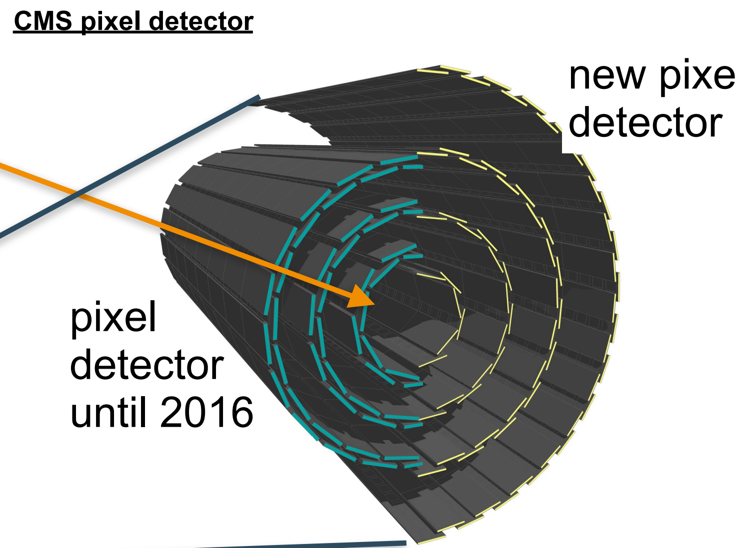
- 200 m² active silicon
- acceptance up to $|\eta|<2.5$
- **pixel detector** - **vital** for b-tagging:
  - b hadrons decay within few cm

CMS in run II (cont'd)

CMS DETECTOR
weight: 14,000 tonnes
diameter: 15.0 m
length: 28.7 m
magnetic field: 3.8 T

b-jet identification
b-tagging: look for displaced tracks and secondary vertices within jets

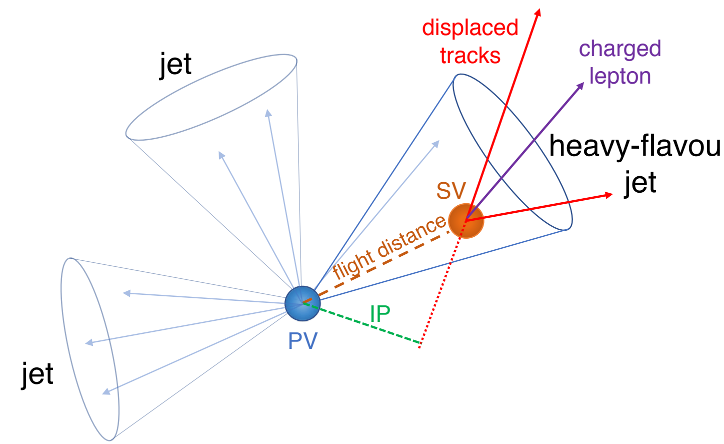




- ★new pixel detector since Winter 2016/2017
- ★4 layers
- ★innermost layer closer to interaction point

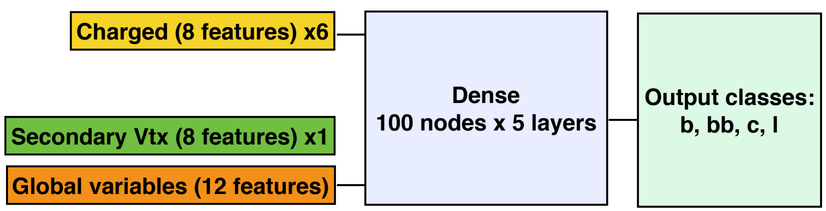
b tagging: algorithms

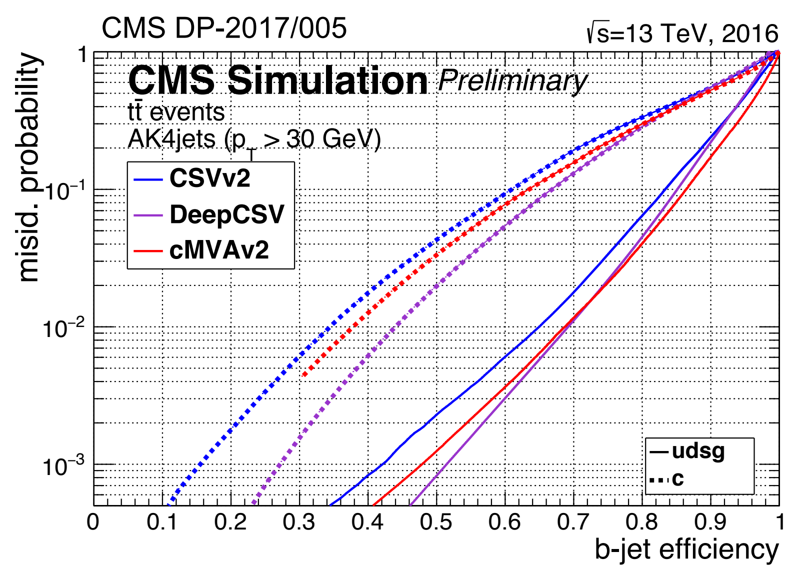
- many decay modes of b-flavoured hadrons
- even with tertiary c-flavoured hadron decay
- with or without soft electron or muon in jet



DeepCSV algorithm:

- deep neural network (DNN) architecture

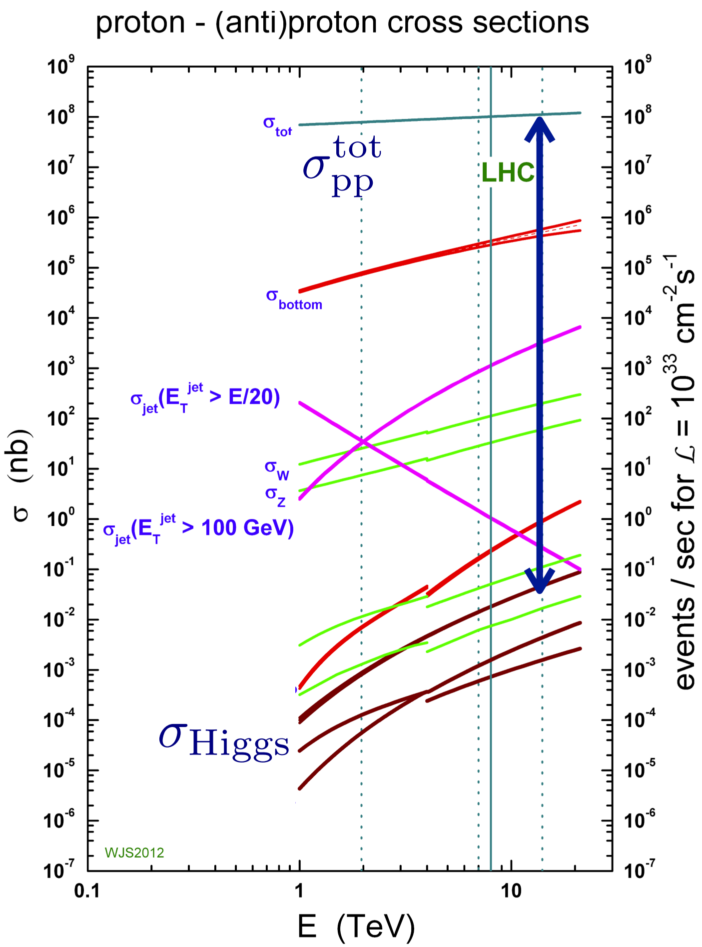




DNN and using low-level variables bring dramatic improvement in b-tagging wrt. previous methods

analysis

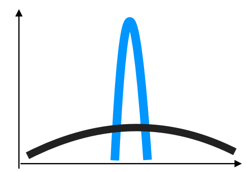
what is the challenge with H → bb?

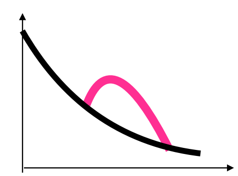


- Higgs boson production is ...
    - 9 orders o.m. below total pp cross section
    - 7 orders o.m. below b quark production

comparison with a discovery channel

	H → 4ℓ	H → $b\bar{b}$
Branching Ratio	0.03%	58%
mass resolution	~ 1%	~ 10%
S/B	~ 2	~ 0.05

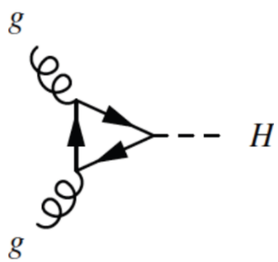




- compared to H → bb, the discovery channels have a striking signature

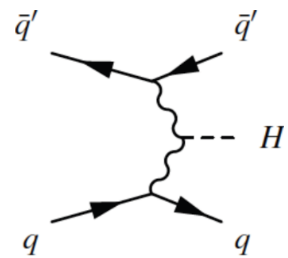
- largest impact on S/B:
    - b jet identification
    - m(jj) mass resolution

H production at the LHC



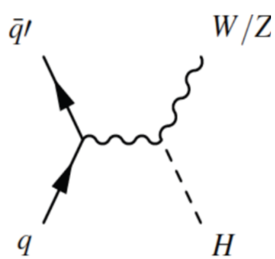
gluon fusion (87%)

- largest production cross section
- 10^7 times larger multijet background (still 10^3 in mass region of interest)



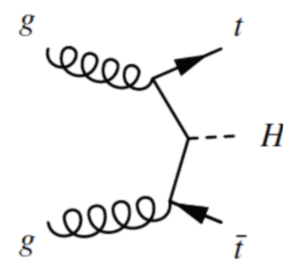
vector-boson fusion (7%)

- slightly more distinctive than gluon fusion, but still very large multijet background



Higgs-strahlung (4%)

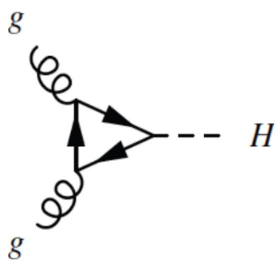
- features leptons and/or E_T^{miss} for trigger and selection
- smaller production cross section



top-quark fusion ttH (1%)

- small production cross section
- large top quark pair background

H production at the LHC



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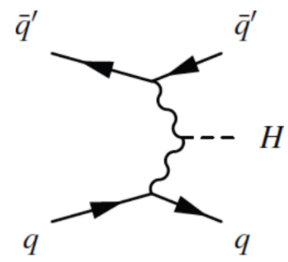

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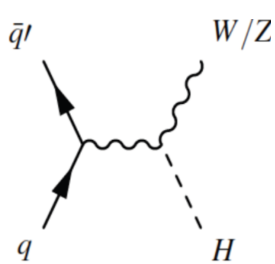
VH



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- features leptons and/or E_T^{miss} for trigger and selection
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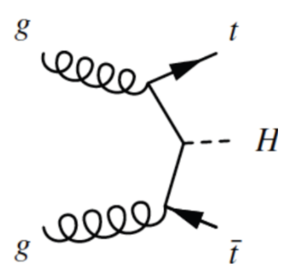


top-quark fusion ttH (1%)

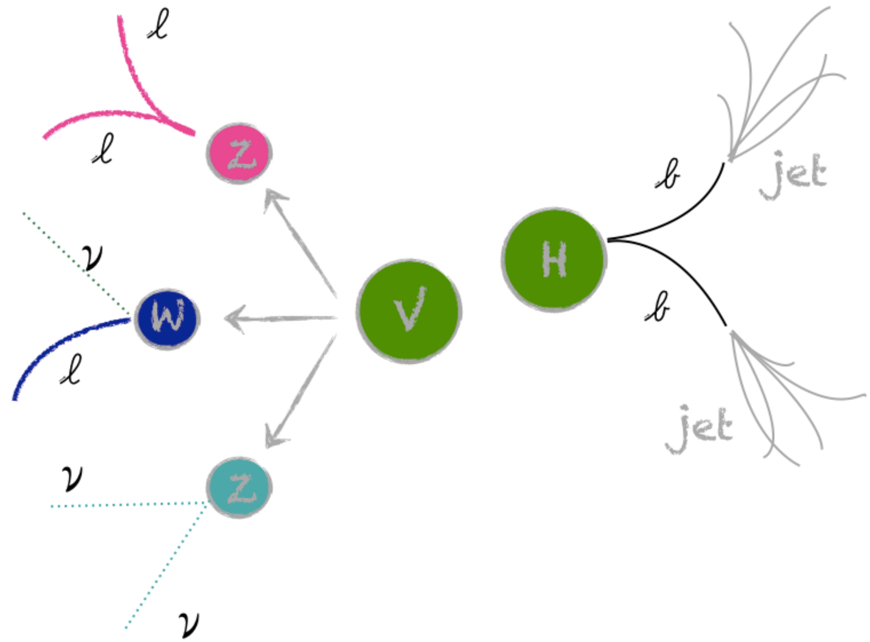
- small production cross section
- large top quark pair background

signature

2 leptons

1 lepton + E_T^{miss}

0 lepton (E_T^{miss})



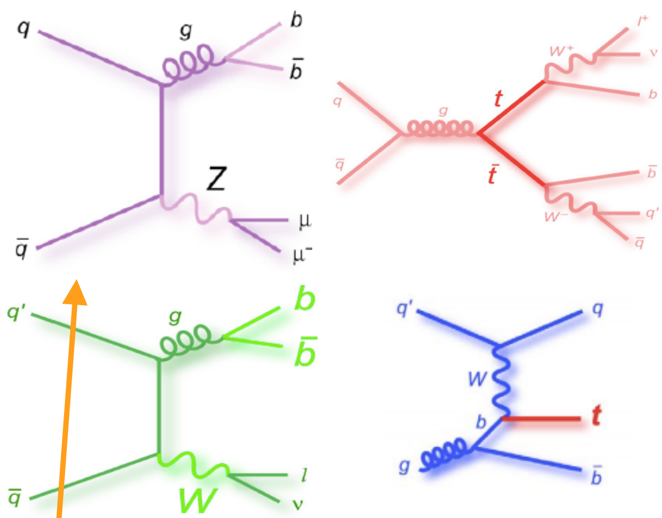
- channels:
  - 0-, 1- and 2-leptons
  - triggers: E_T^{miss}, 1-, 2-lepton
- V and H are back-to-back
- most sensitivity at high p_T of V and H

reconstruction:
- H candidate
  - 2 jets with highest b-tag score
- V candidate
  - 2 leptons
  - 1 lepton + E_T^{miss}
  - E_T^{miss}

backgrounds

Z+jets

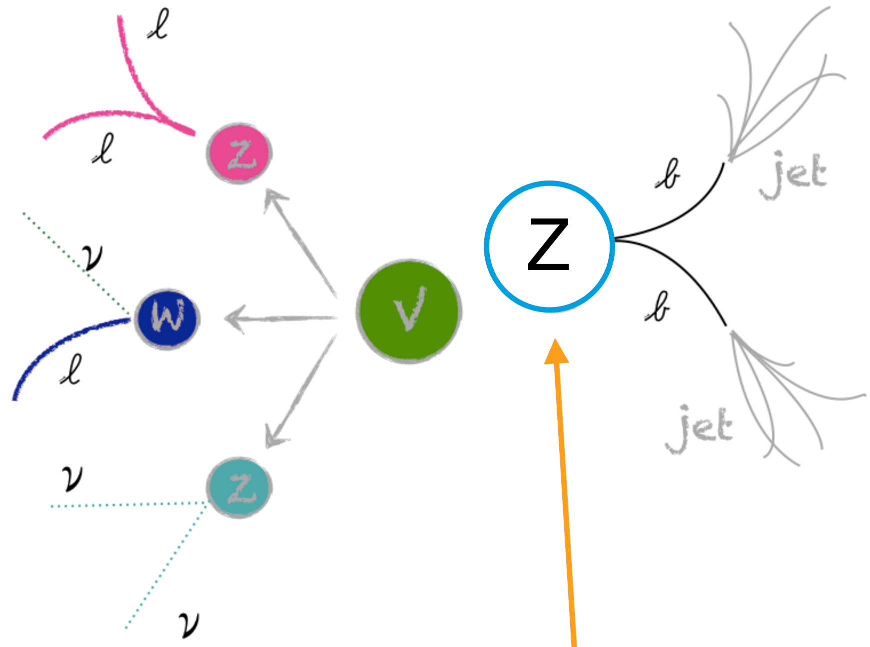
top pair



W+jets

single top

Di-boson



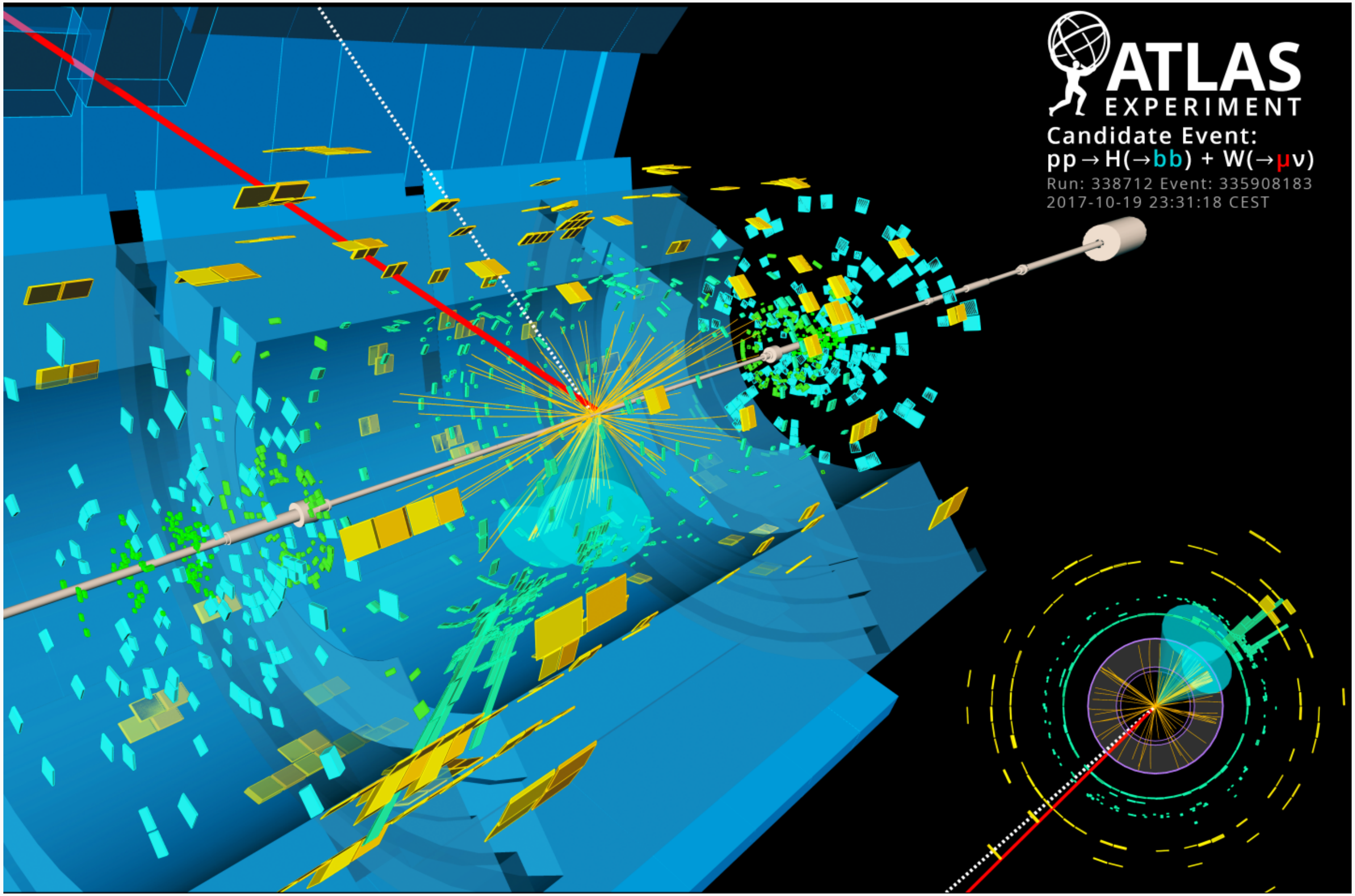
V+bb is most
difficult background

VZ is the background
most similar to VH
- only differs in m(jj)
- used for validation

event display

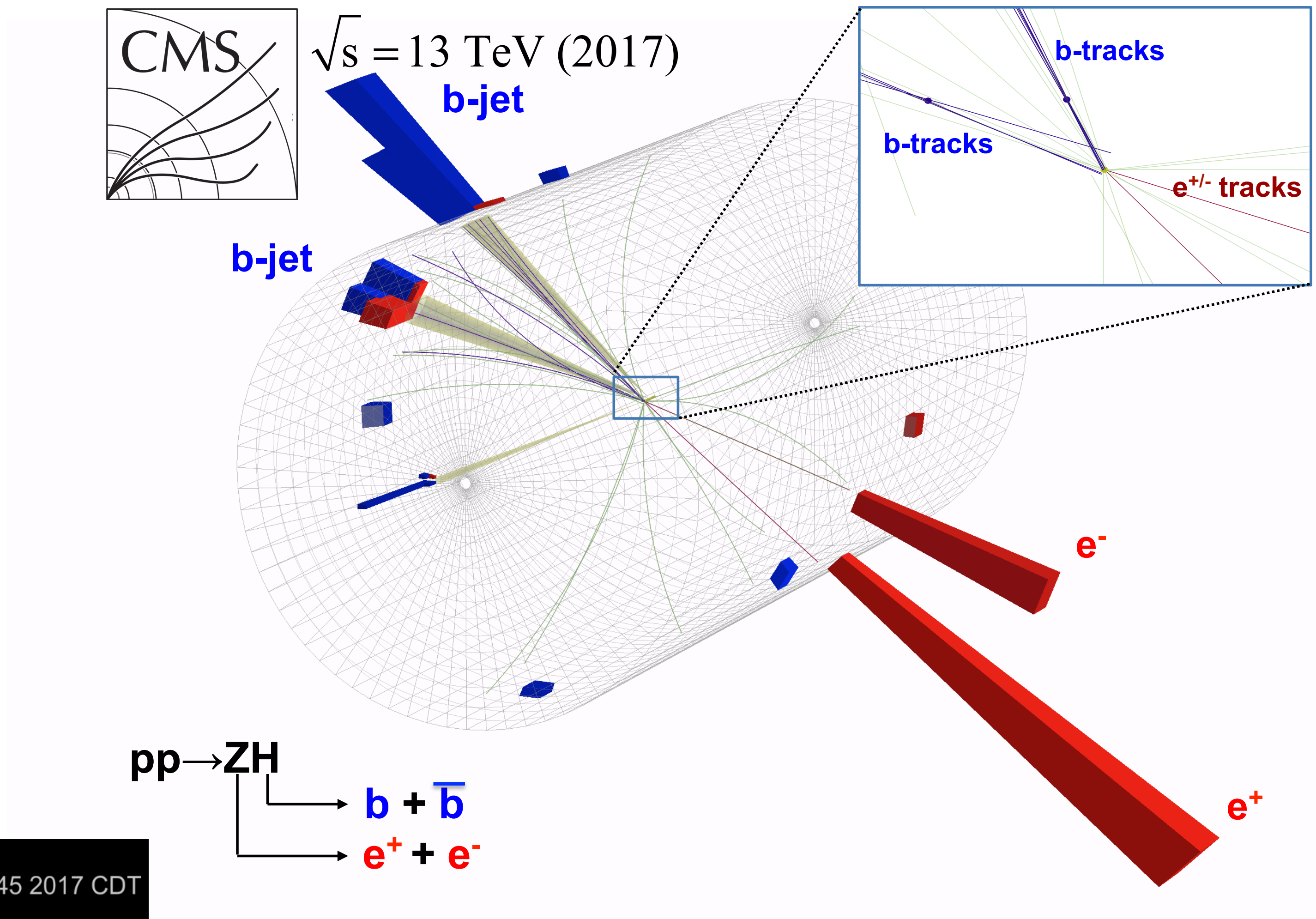
Z(vv)H(bb) candidate event

1-lepton channel



event display

Z(ee)H(bb) candidate event



m(jj) = 114 GeV

pp→ZH

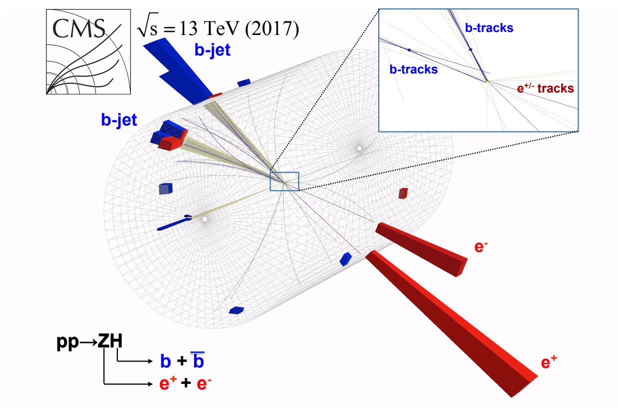
→ b + $\bar{b}$

→ e+ + e-

CMS Experiment at LHC, CERN
Data recorded: Sun Aug 20 13:16:45 2017 CDT
Run/Event: 301472 / 634226645
Lumi section: 664

analysis strategy

simplified example
2-lepton channel



preselection

$m(ll) \in [m_Z]$

yes

2 b-tags

yes

$m(jj) \in [m_H]$

yes

signal region

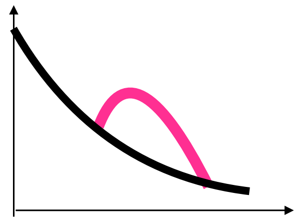
SR

"loose" selection:

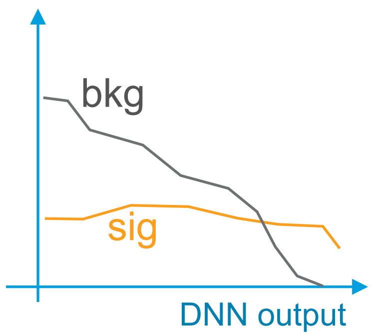
- high signal efficiency
- still high levels of background in SR

analysis strategy

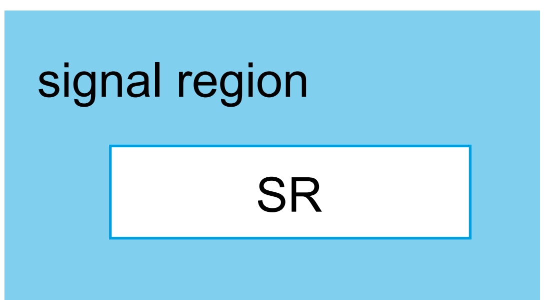
simplified example
2-lepton



- option 1: fit m(jj) directly
  - not most sensitive
  - used as a cross check



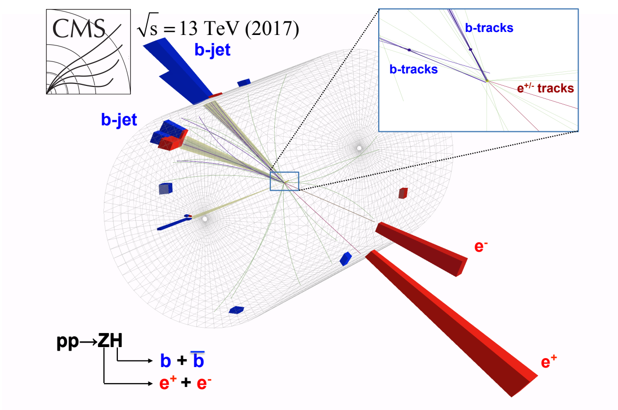
- option 2: use a DNN
  - signal: VH(bb)
  - bkg: all SM bkg
  - fit DNN output distribution
  - shape from MC
  - bkg normalisation from data



analysis strategy

simplified example

2-lep…



preselection

$m(ll) \in [m_Z]$ — no → Top CR

yes ↓

2 b-tags — no → Z+LF CR (light flavor)

yes ↓

$m(jj) \in [m_H]$ — no → Z+HF CR (heavy flavor)

yes ↓

signal region

SR

control regions

Top CR

Z+LF CR
(light flavor)

Z+HF CR
(heavy flavor)

(more requirements are applied for purification)

analysis strategy

simplified example

pre

- enriched in primary backgrounds
- scrutinize MC simulation
- extract normalisation for
  - single top
  - top pair
  - Z+bb
  - Z+b
  - Z+light flavour

control regions

Top CR

Z+LF CR
(light flavor)

Z+HF CR
(heavy flavor)

signal region

SR

are applied for purification)

analysis strategy (cont'd)

- simultaneous fit in 0-, 1- and 2-lepton channels and across all control and signal regions

- next slides: techniques to obtain the needed sensitivity
  - improving jet energy resolution
  - bkg normalisation extraction
  - signal extraction

  - analysis of data taken in 2017 by CMS

$$\sqrt{s} = 13\,\mathrm{TeV}$$
$$\mathcal{L}^{\mathrm{int}} = 41.3\,\mathrm{fb}^{-1}$$

techniques

improving b jet energy resolution

particle-flow jets

↓

DNN energy regression

↓

2-lepton channel: kinematic fit

improving b jet energy resolution

particle-flow jets

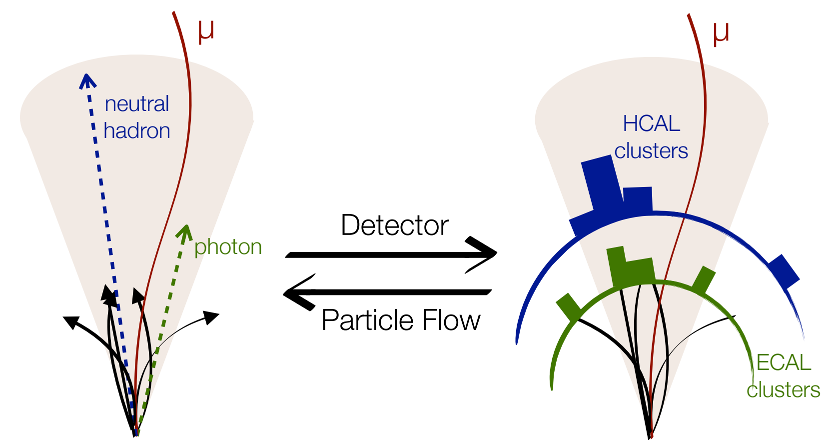
↓

DNN energy regression

↓

2-lepton channel: kinematic fit

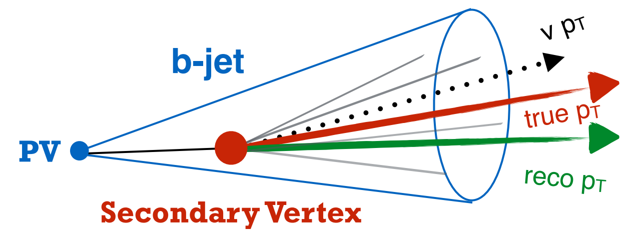
starting point: particle flow jets



particles in nature → tracks, calorimeter deposits → single particle candidates → jets (initial particle)

90% of jet energy carried by:
- charged hadrons (65%)
- photons (25%)

improving b jet energy resolution



particle-flow jets

↓

DNN energy regression

↓

2-lepton channel: kinematic fit

DNN with 41 inputs:

- jet kinematics: p_T, η, etc.
- pileup information
- energy fractions and number of:
    - e.m., charged, neutral particles
- soft lepton track
  (=> neutrino in jet; missing energy)
- secondary vertex information

output:

- regressed p_T
- resolution estimate

improving b jet energy resolution

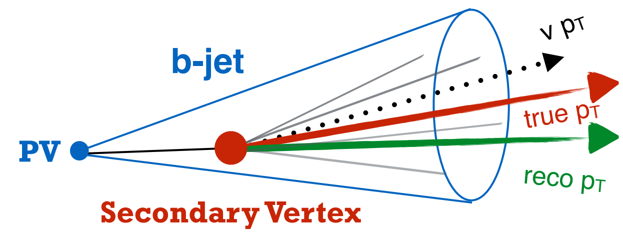
particle-flow jets

↓

DNN energy regression

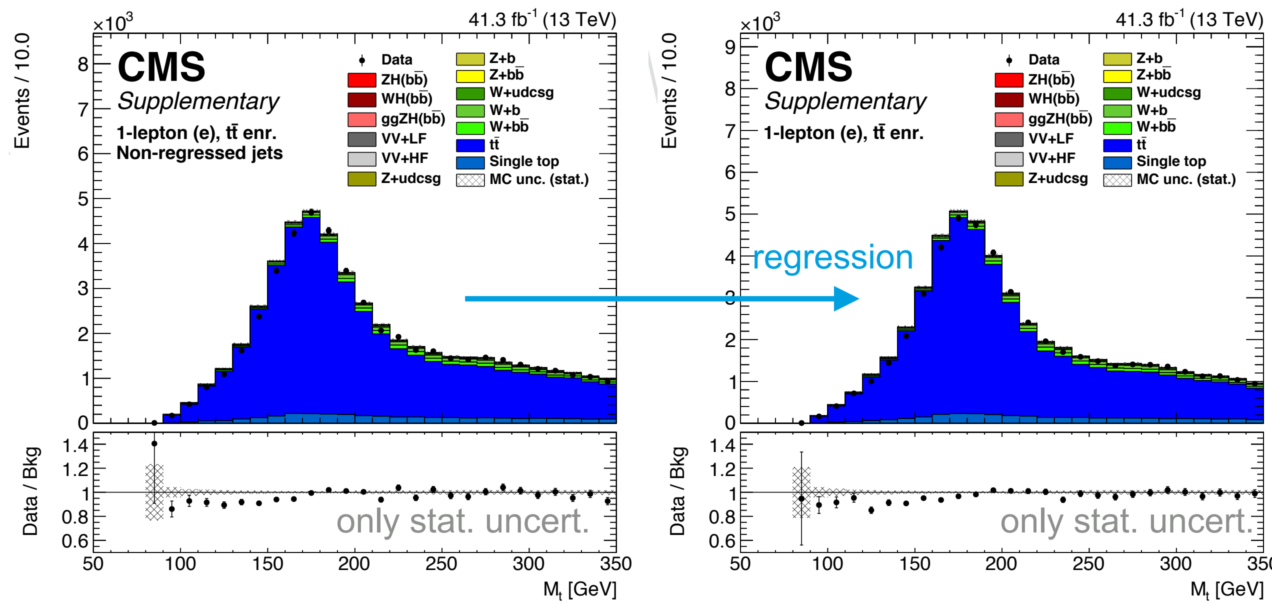
↓

2-lepton channel: kinematic fit

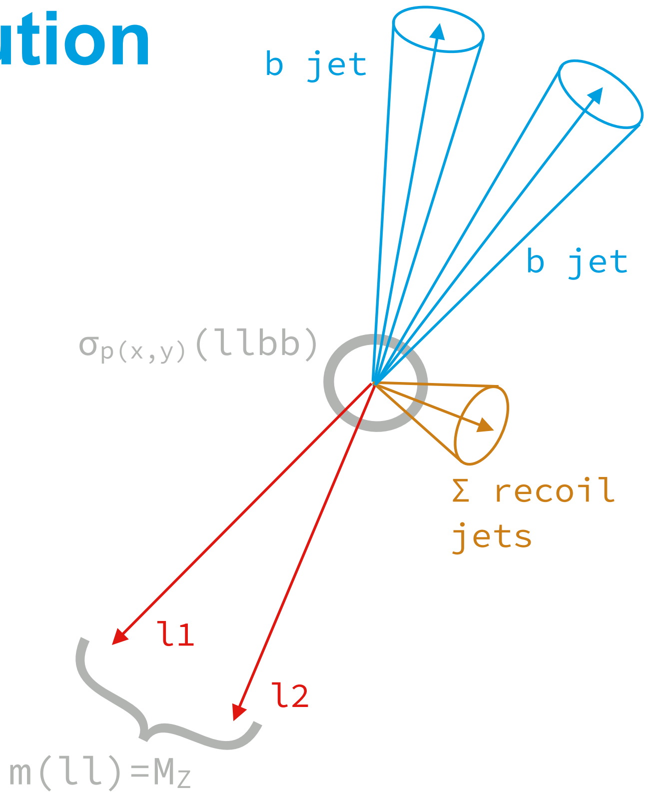


no "sculpting" seen in top quark mass distribution

1-lepton channel
- reconstructed mass of top quark candidate
- "combinatorial" background in tail



improving b jet energy resolution



particle-flow jets

↓

DNN energy regression

↓

2-lepton channel: kinematic fit

- no intrinsic E_T^{miss} in 2-lepton topology
- electrons/muons have better energy resolution than jets
- per event:
  - construct constraints between particles
  - fit jets and leptons within their uncertainty
- recoil jets:
  - best performance without add. jets

kinematic fit "transfers" good resolution from leptons to jets

improving b jet energy resolution

particle-flow jets

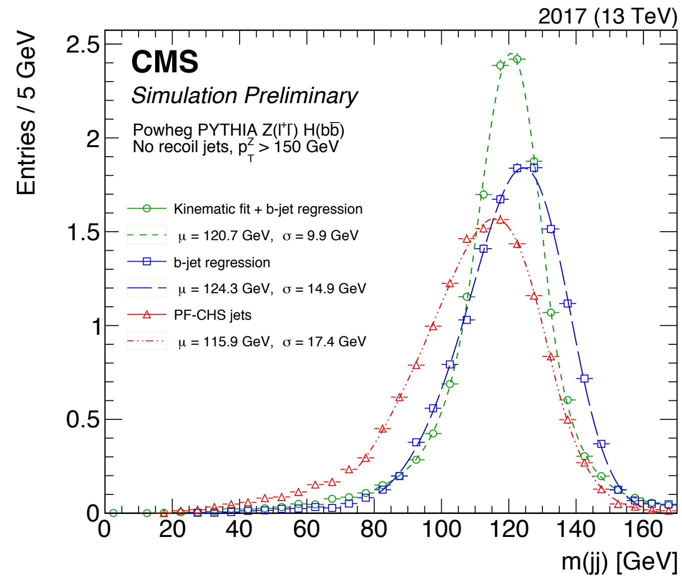
↓

DNN energy regression

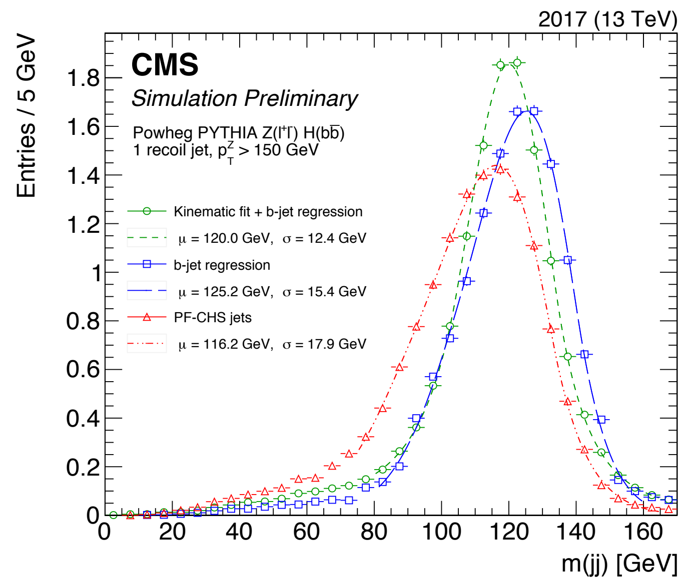
↓

2-lepton channel: kinematic fit

no recoil jets



one recoil jet



improvement of m(jj)

energy regression: 14%

kinematic fit: up to 43%

resolution on m(jj): 10-13%

improving b jet energy resolution

particle-flow jets

↓

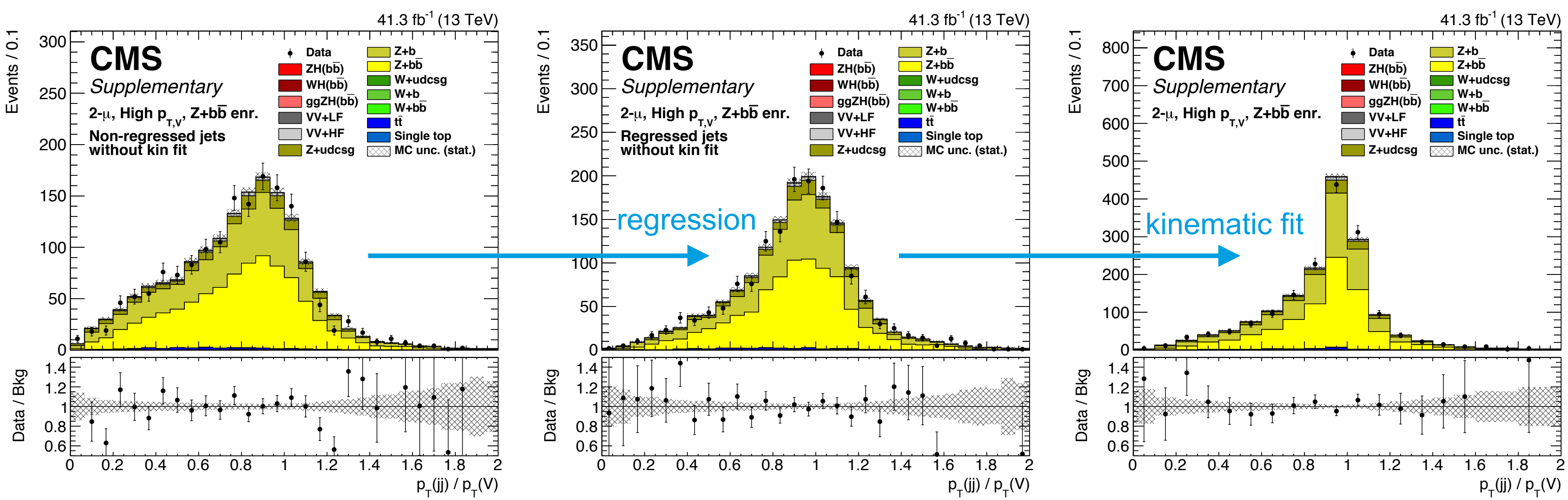
DNN energy regression

↓

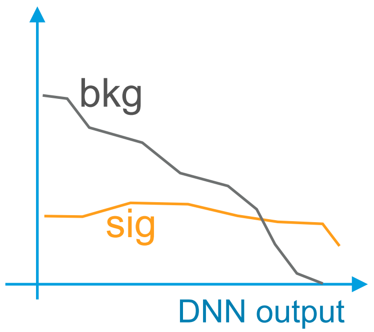
2-lepton channel: kinematic fit

p_T balance of H and V candidates improves with both steps

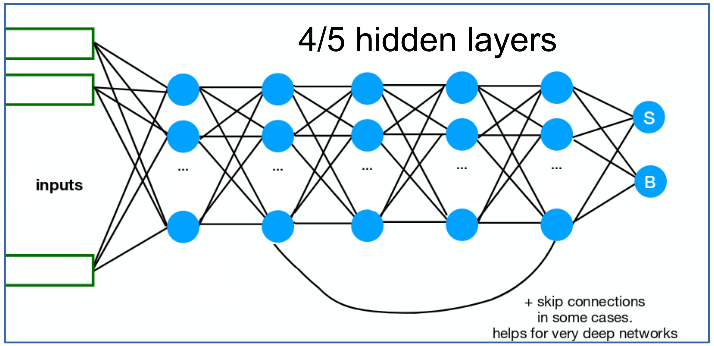
improvement well described by simulation



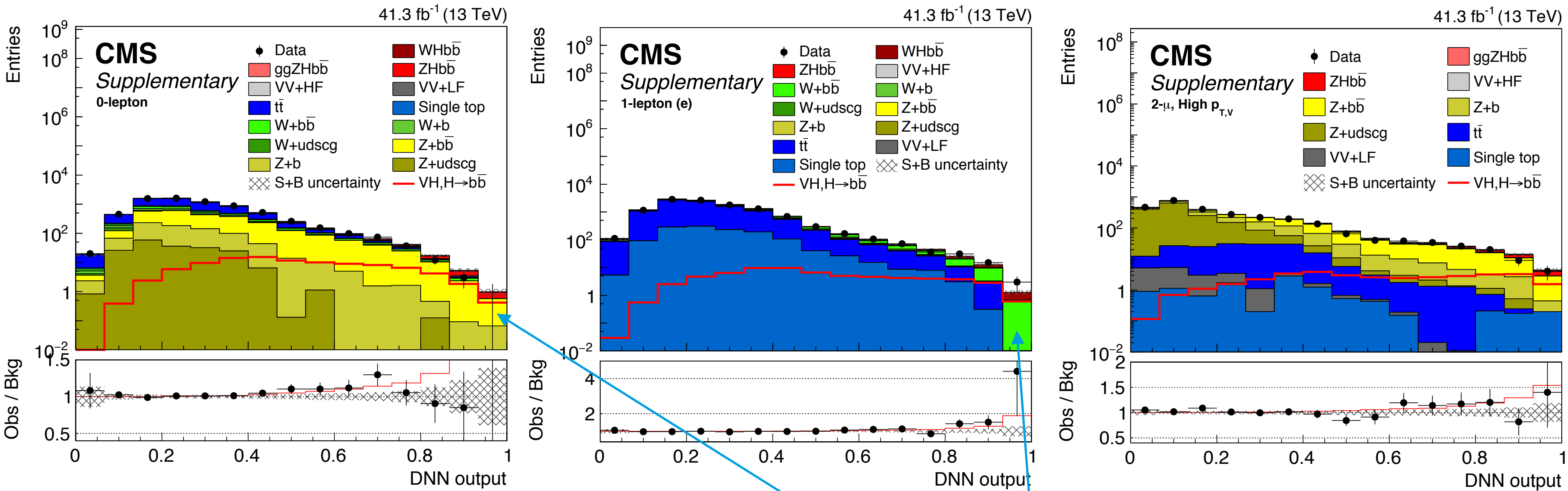
signal region DNN



- DNN for separation of signal and background in SR
- DNN output is fitted to extract signal strength and significance
- trained on MC separately in 7 channels:
  - 0-lepton
  - 1-lepton mu / el
  - 2-lepton mu / el in low / high $p_T(Z)$
- up to 16 variables, most discriminating:
  - m(jj)
  - $p_T(V)$
  - b-tag discriminator value
  - number of additional jets
  - ΔR(jj)



signal region DNN (cont'd)



- trained on MC separately in 7 channels:
  - 0-lepton
  - 1-lepton mu / el
  - 2-lepton mu / el in low / high $p_T(Z)$
- up to 16 variables, most discriminating:
  - m(jj)
  - $p_T(V)$
  - b-tag discriminator value
  - number of additional jets
  - ΔR(jj)

most difficult background: V+bb

one of the largest uncertainties from background normalisation

background classification in V+HF CR

0- and 1-lepton channels V+HF CR's:

- large syst. impact from V+(b)b normalisation (difficult to separate from each other and from single top)
- no single variable provides good separation

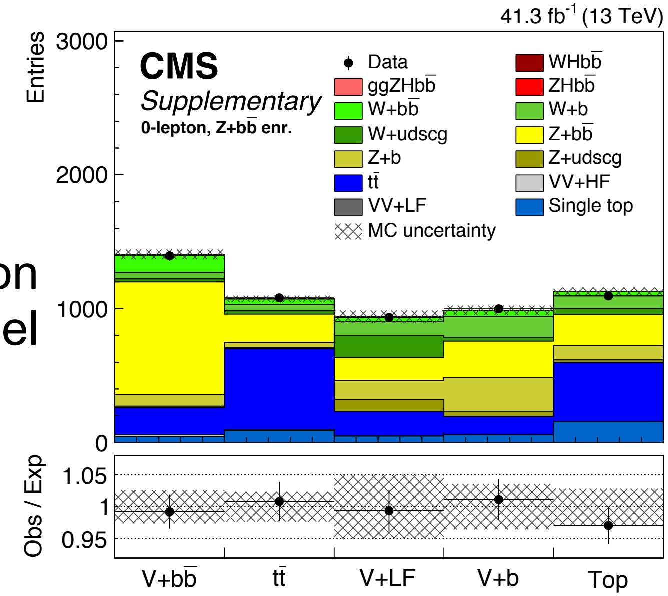
- improve by using a DNN to distinguish the primary backgrounds
- trained separately in 3 control regions:
  - 0 lepton Z+HF
  - 1 lepton W(e+-, nu)+HF
  - 1 lepton W(mu+-, nu)+HF

- using up to 11 event variables
  - m(jj)
  - $p_T(V)$
  - b-tag discriminator value
  - number of additional jets
  - ΔR(jj)
  - etc.

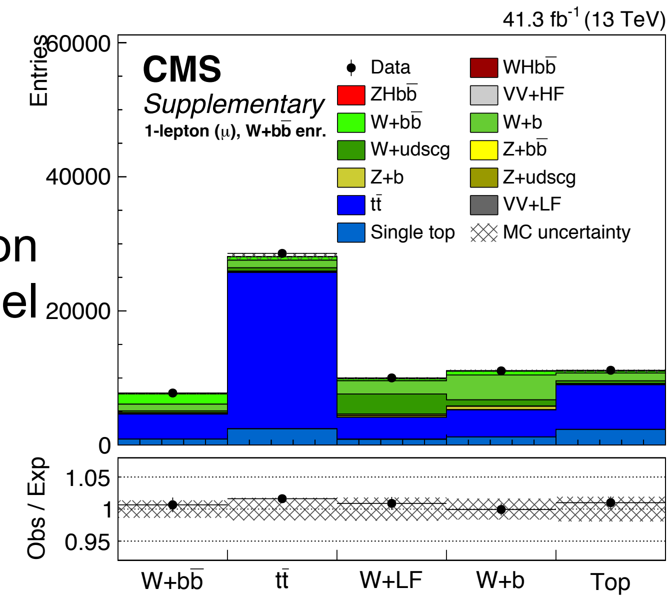
other regions:

- use event yield or b-tag discriminator shape

0 lepton channel



1 lepton channel

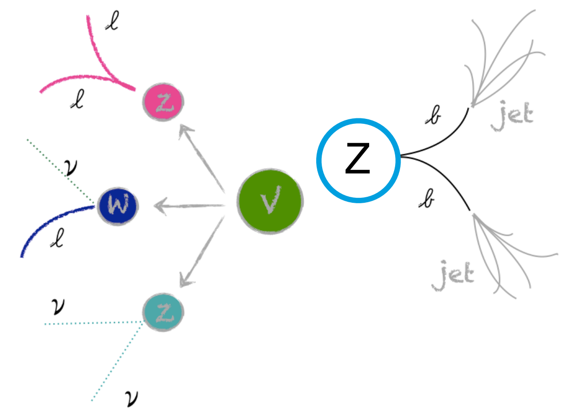


uncertainties

Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33

results

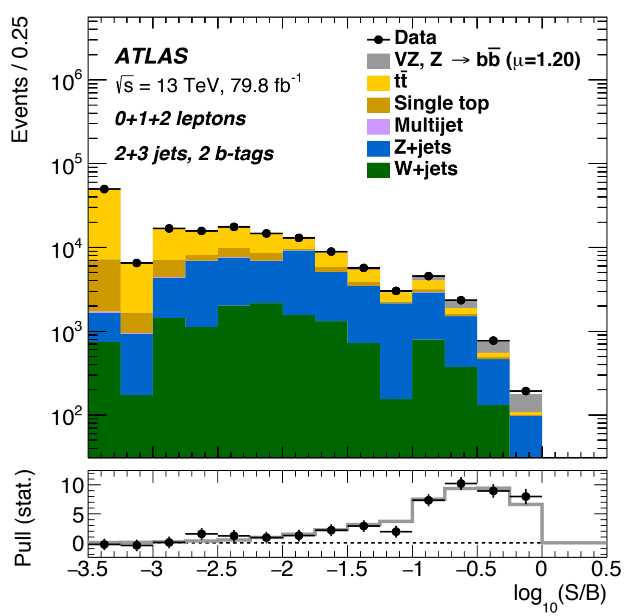
VZ cross check

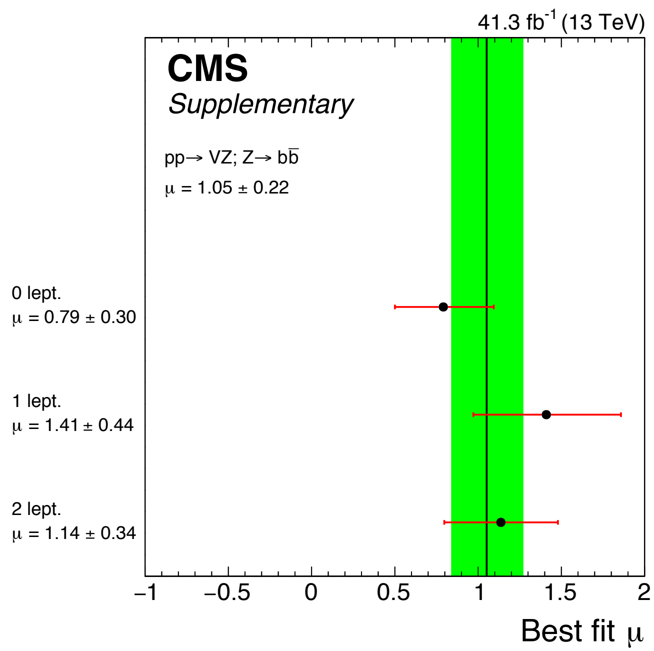


- reminder: VZ(bb) and VH(bb) have similar topology
- verify full analysis setup
- here, MVA in signal region trained with VZ(bb) as signal

ATLAS: $\mu_{VZ}^{bb} = 1.20^{+0.20}_{-0.18}$
(79.8 fb^{-1}) 9.6σ (8.7σ exp.)

CMS: $\mu = 1.05 \pm 0.22$
(41.3 fb^{-1}) 5.2σ (5.0σ exp.)



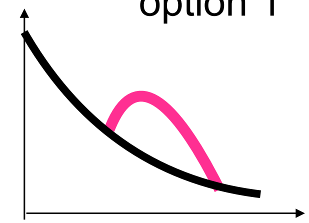


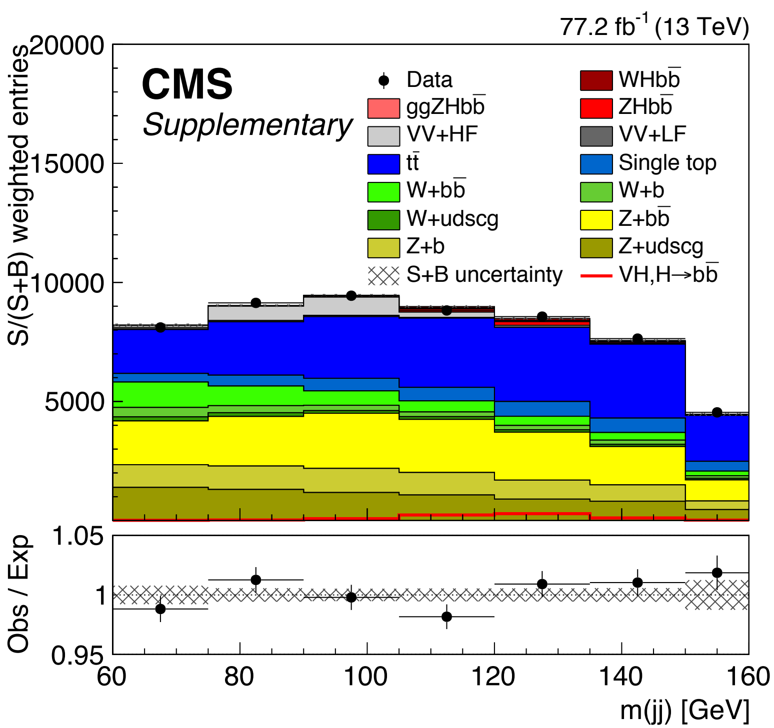
compatible with standard model

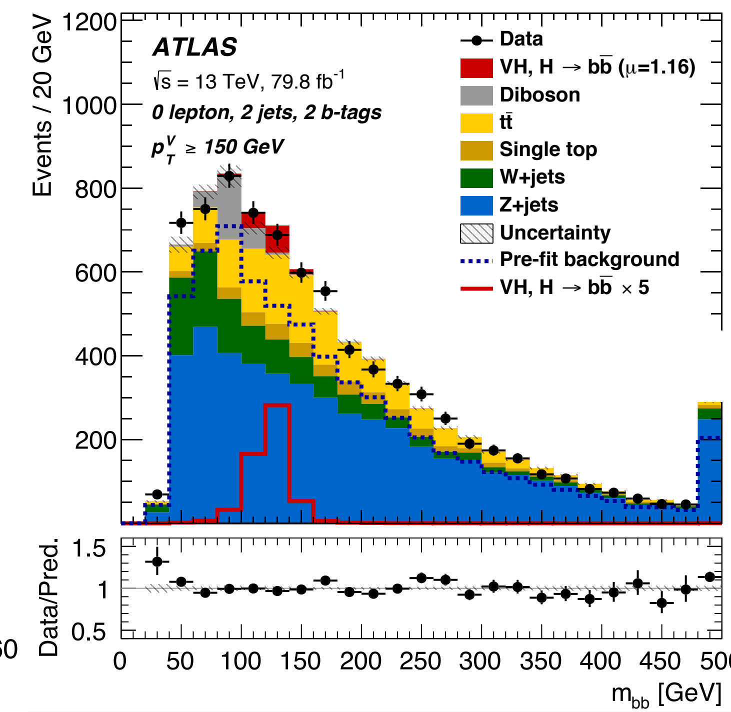
VH(bb) mass analysis

- di-jet mass analysis
- MVA analysis without m(jj)-correlated variables
- events weighted by
    - S/(S+B) (CMS)
- fit mass templates to data

"option 1"





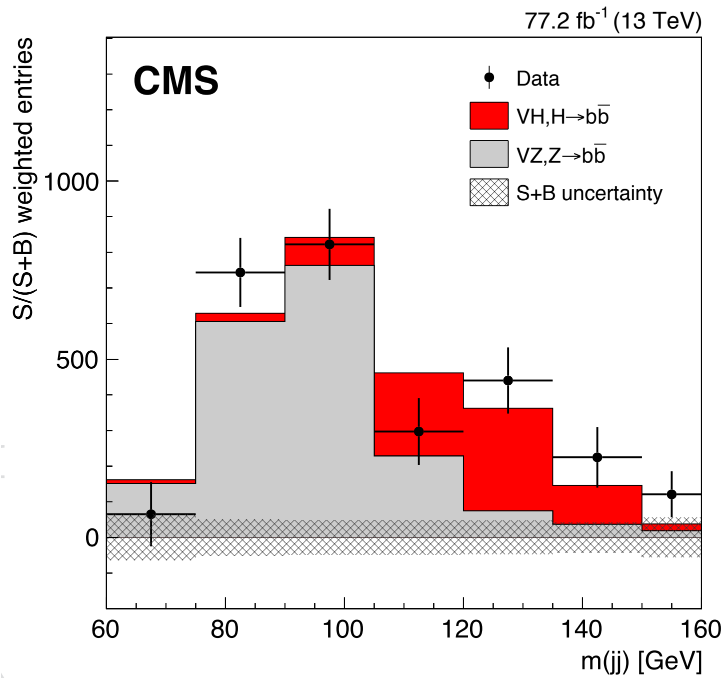


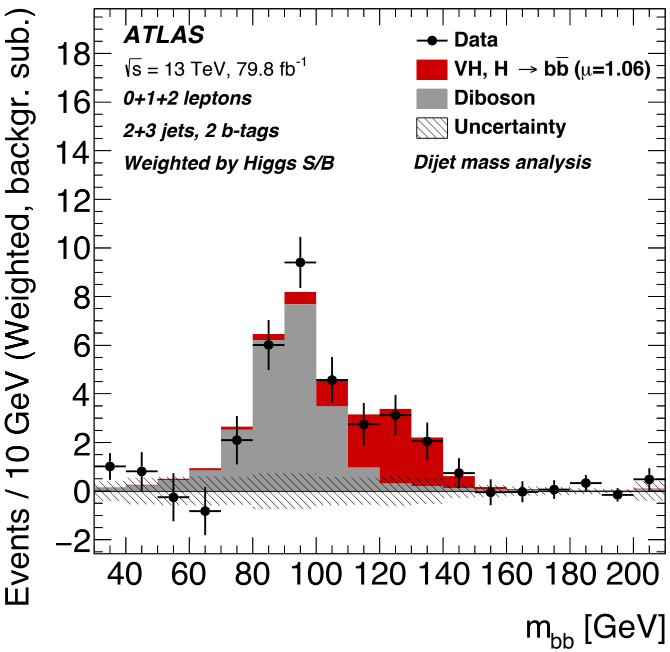
VH(bb) mass analysis (cont'd)

- di-jet mass analysis
- MVA analysis without m(jj)-correlated variables
- events weighted by
  - S/B (ATLAS)
  - S/(S+B) (CMS)
- fit mass templates to data
- background subtracted

ATLAS significance: 3.6σ (3.5σ exp.)

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

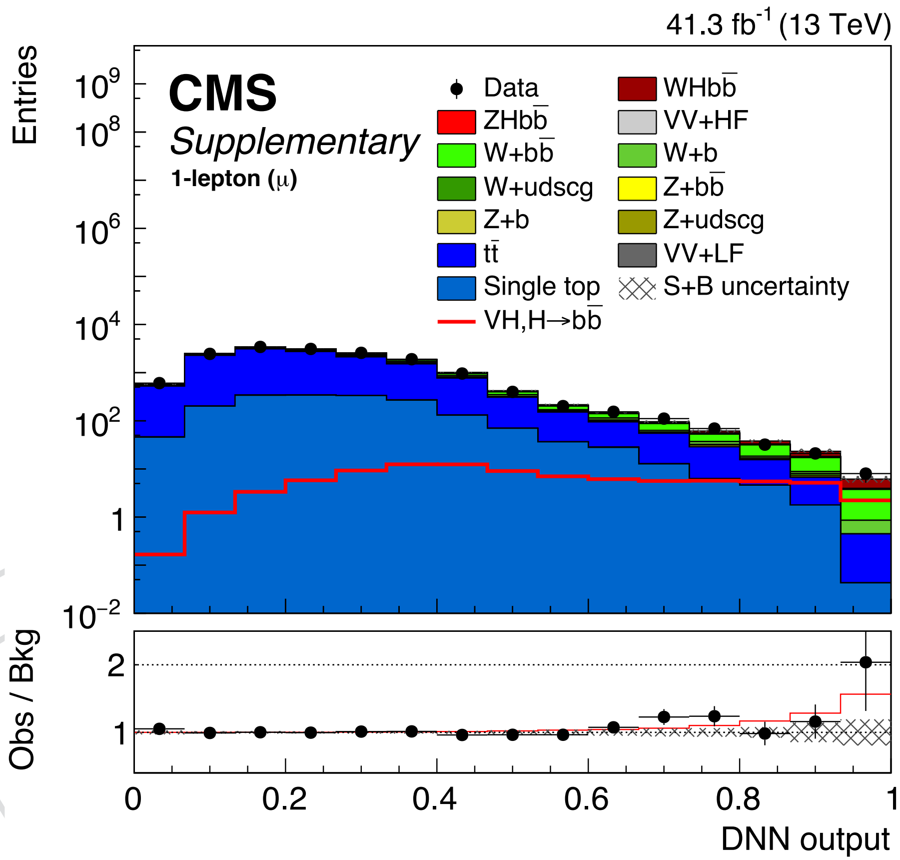




good jet energy resolution is crucial to separate VH(bb) from VZ(bb)

CMS VH(bb) result with 2017 data

1-lepton channel (μ)



- reminder: new pixel detector since early 2017 => separate analysis of data taken in 2017

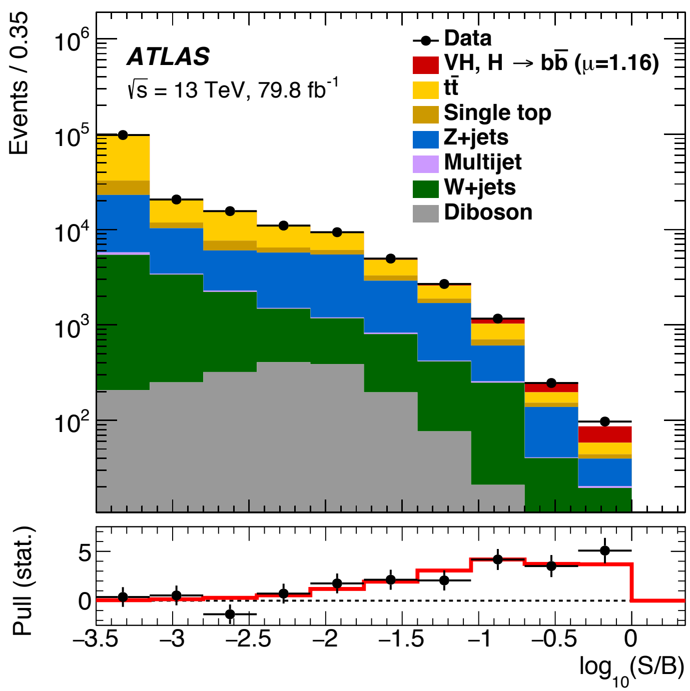
$$\sqrt{s} = 13\,\mathrm{TeV}$$
$$\mathcal{L}^{\mathrm{int}} = 41.3\,\mathrm{fb}^{-1}$$

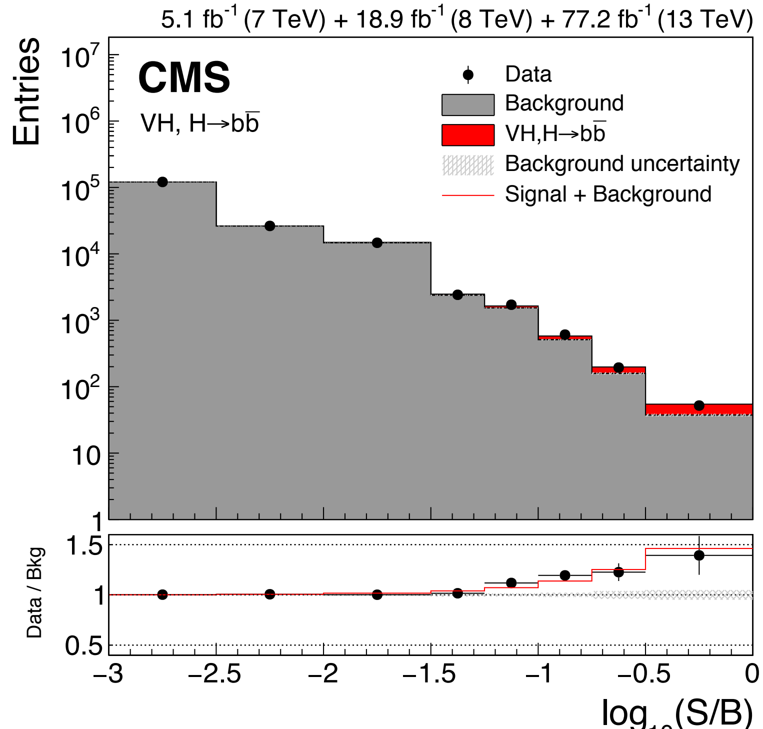
- signal strength
  μ = 1.08 ± 0.35

- significance VH
  - 3.3σ (3.1σ exp.)

run I and II combination of VH(bb)

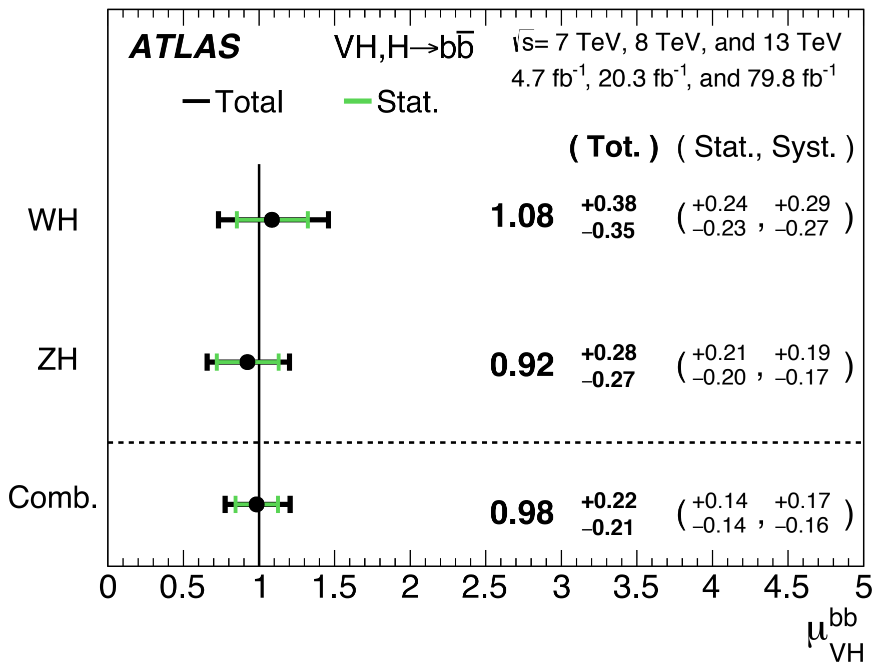
- post-fit S/B ordered distribution of final discriminant values
- Higgs boson signal scaled according to observed signal strength

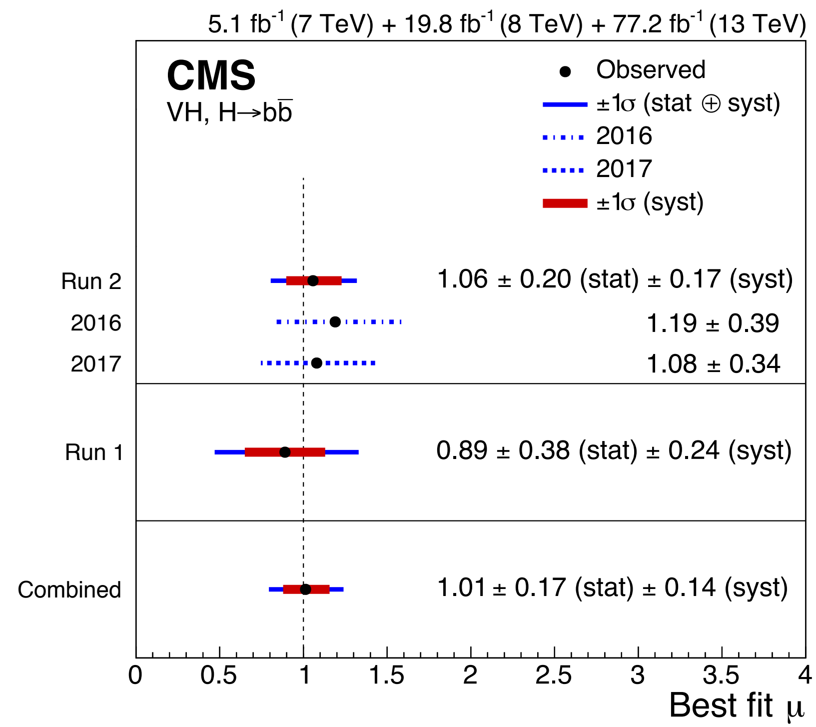




large excesses of events visible in the distributions

run I and II combination of VH(bb) (cont'd)

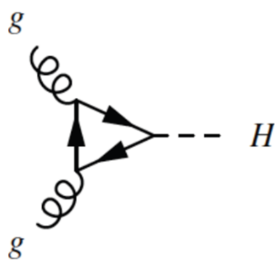




CMS Run 1+2: **4.8 σ (4.9 σ exp.)**
ATLAS Run 1+2: **4.9 σ (5.1 σ exp.)**

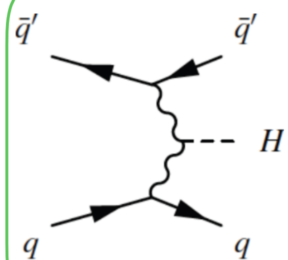
combination with other production channels

boosted H → bb analysis



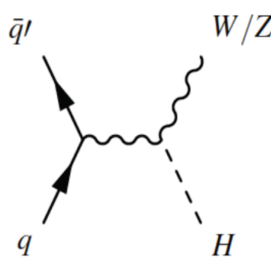
gluon fusion (87%)

- largest production cross section
- 10^7 times larger multijet background (still 10^3 in mass region of interest)



vector-boson fusion (7%)

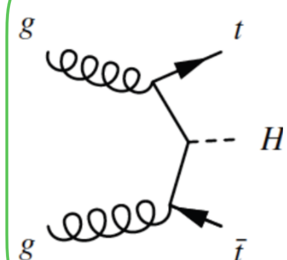
- slightly more distinctive than gluon fusion, but still very large multijet background



Higgs-strahlung (4%)

- features leptons and/or E_T^{miss} for trigger and selection
- smaller production cross section

ttH analysis with H → bb

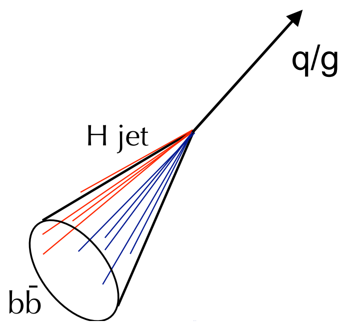


top-quark fusion ttH (1%)

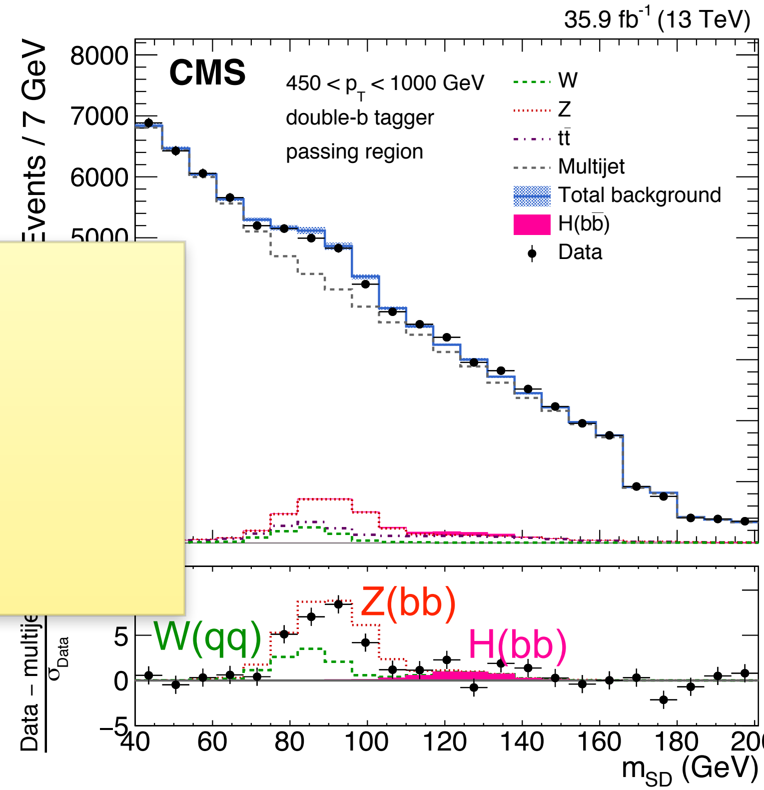
- small production cross section
- large top quark pair background

boosted H(bb)

search for boosted H(bb) decays
- large-cone jet (R = 0.8)
- $\Delta R(bb) \sim 2m_H/p_T$
  - starting at $p_T(H)$ = 450 GeV
- dedicated double-b tagging algorithm



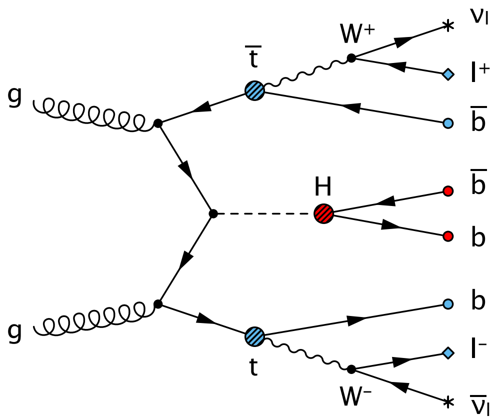
new Technique!



groomed mass of large-cone jet

- first observation of Z → bb in one-jet topology: 5.1σ (5.8 σ exp)
- H → bb significance: **1.5 σ (0.7 σ exp)**

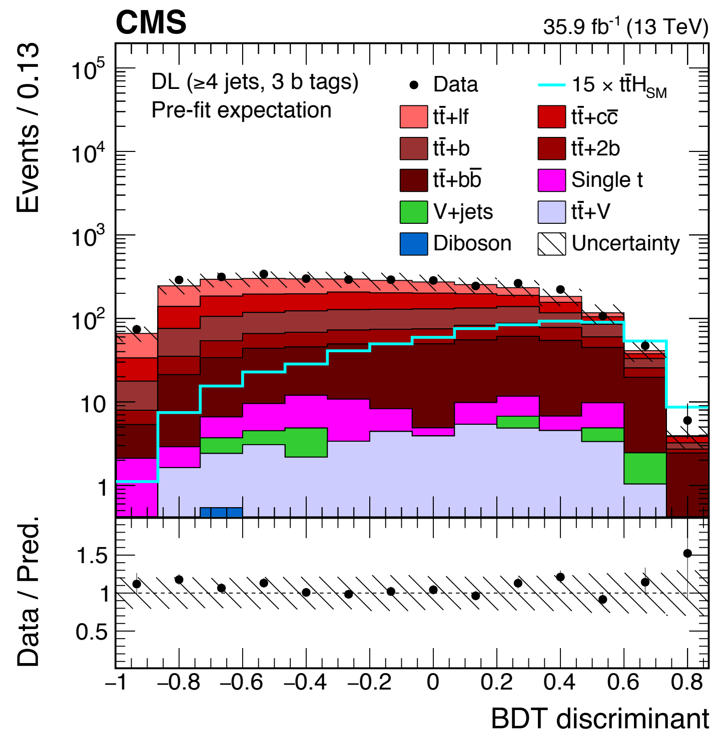
ttH with H → bb



lepton + b jet

2 b jets

lepton + b jet



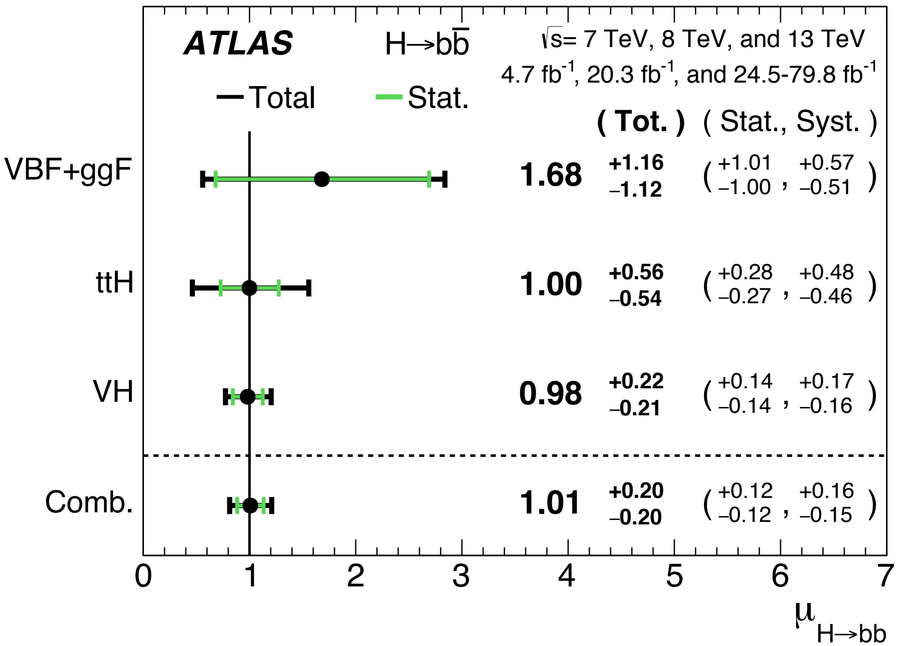
- large combinatorics in the event reconstruction
- dominant background is tt+bb with large theory uncertainty
- our combination uses all top-pair decay modes (only di-lepton shown here)

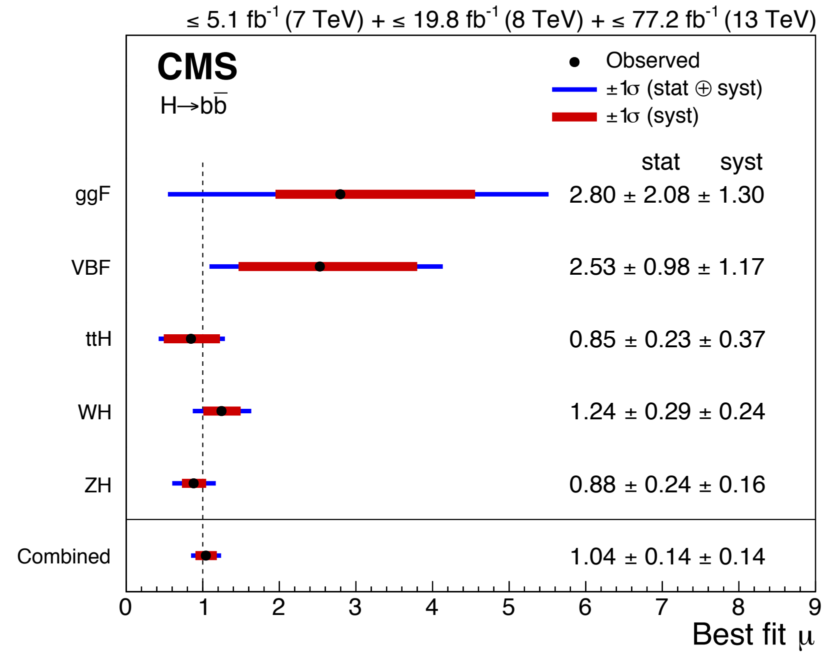
ttH(bb)
- leptonic: Best-fit $\mu = 0.72^{+0.45}_{-0.45}$, at 1.6 (2.2) σ obs. (exp.) significance
- hadronic: Best-fit $\mu = 0.9^{+1.5}_{-1.5}$, upper 95% C.L. limit 3.8 (3.1) obs. (exp.) $\times$ SM

H → bb observation

arXiv:1808.08238 (ATLAS)
submitted to PLB

arXiv:1808.08242 (CMS)
submitted to PRL





excellent agreement between experiments and SM

CMS Run 1+2: **5.6 σ (5.5 σ exp.)**
ATLAS Run 1+2: **5.4 σ (5.5 σ exp.)**

first observation of H → bb decay

summary & outlook

https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

summary

arXiv:1808.08238 (ATLAS)
submitted to PLB

arXiv:1808.08242 (CMS)
submitted to PRL

- H(bb) observed individually by ATLAS and CMS
  - VH production most significant
  - intensive use of machine learning techniques
- LHC Run II allows us to investigate Higgs Yukawa couplings in depth
- key contributions to the results coming from DESY
  - VH(bb), H($\tau\tau$), ttH
- direct confirmation of Higgs couplings to third generation fermions: τ, t, b
- six years after its discovery, fundamental progress in measuring Higgs boson properties
- fully consistent with the SM Higgs boson.

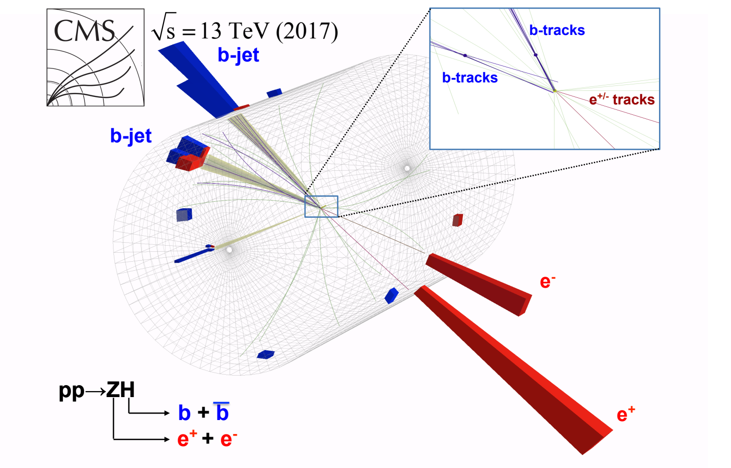
CMS Run 1+2: **5.6 σ (5.5 σ exp.)**

$\mu = 1.04^{+0.20}_{-0.19} \left({}^{+0.14}_{-0.14}, {}^{+0.14}_{-0.13} \right)$

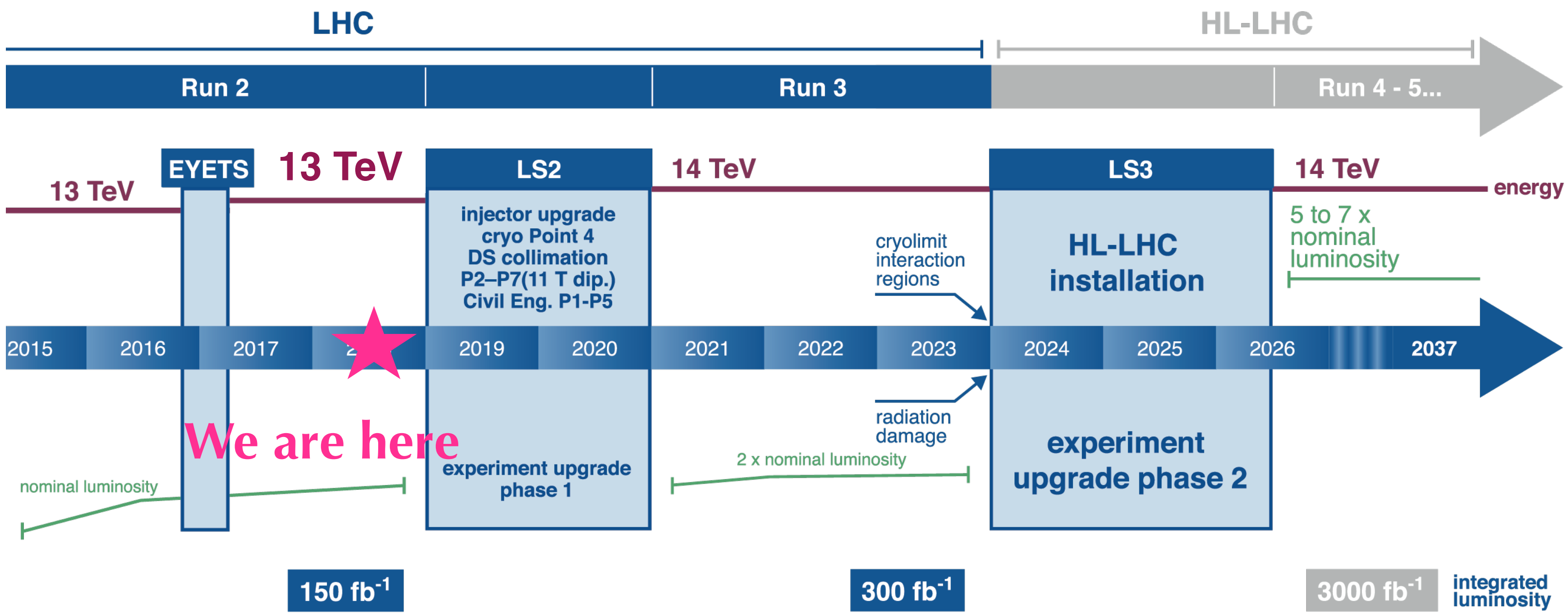
ATLAS Run 1+2: **5.4 σ (5.5 σ exp.)**

$\mu = \mathbf{1.01}^{+0.20}_{-0.20} \left({}^{+0.12}_{-0.12}, {}^{+0.16}_{-0.15} \right)$

first observation of H(bb) decay



outlook



Run 3 and ultimately HL-LHC will allow for precision measurements of Higgs boson (self-)couplings and to probe the existence of very rare new physics processes

thank you for your attention!

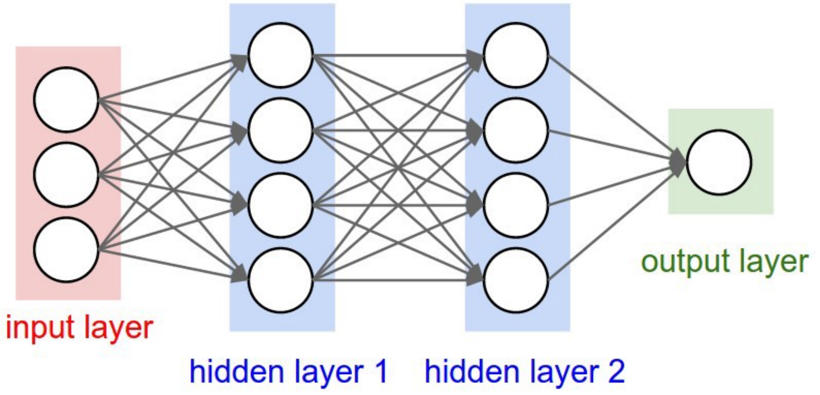
additional material

background classification: scale factors

Table 2: Data/MC scale factors for the 2017 analysis in the 0-, 1- and 2-lepton channels from SR+CRs fit. The errors include both statistical and systematic uncertainties. Compatible fitted values are obtained from the CR-only fit.

Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
W + udscg	1.04 ± 0.07	1.04 ± 0.07	–	–
W + b	2.09 ± 0.16	2.09 ± 0.16	–	–
$W + b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
$Z + b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

Deep Learning in a Nutshell



- Each node is the weighted sum of inputs mapped to an activation function

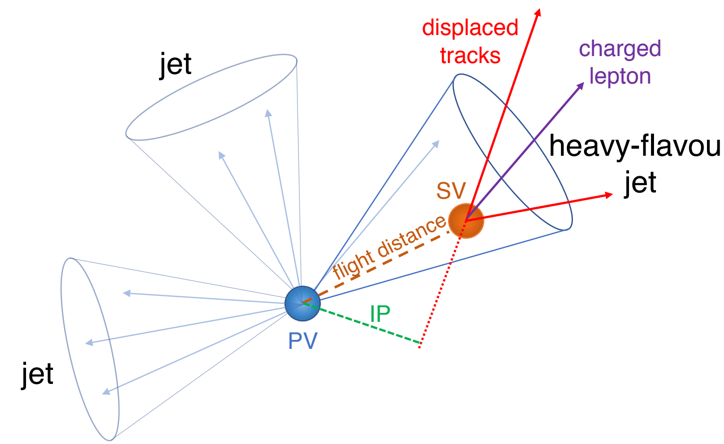
$$y=\mathbf{f}\left(b + \sum_{i=1}^{n} w_i \; xi \right)$$

- Deep means many layers
- Can approximate any function

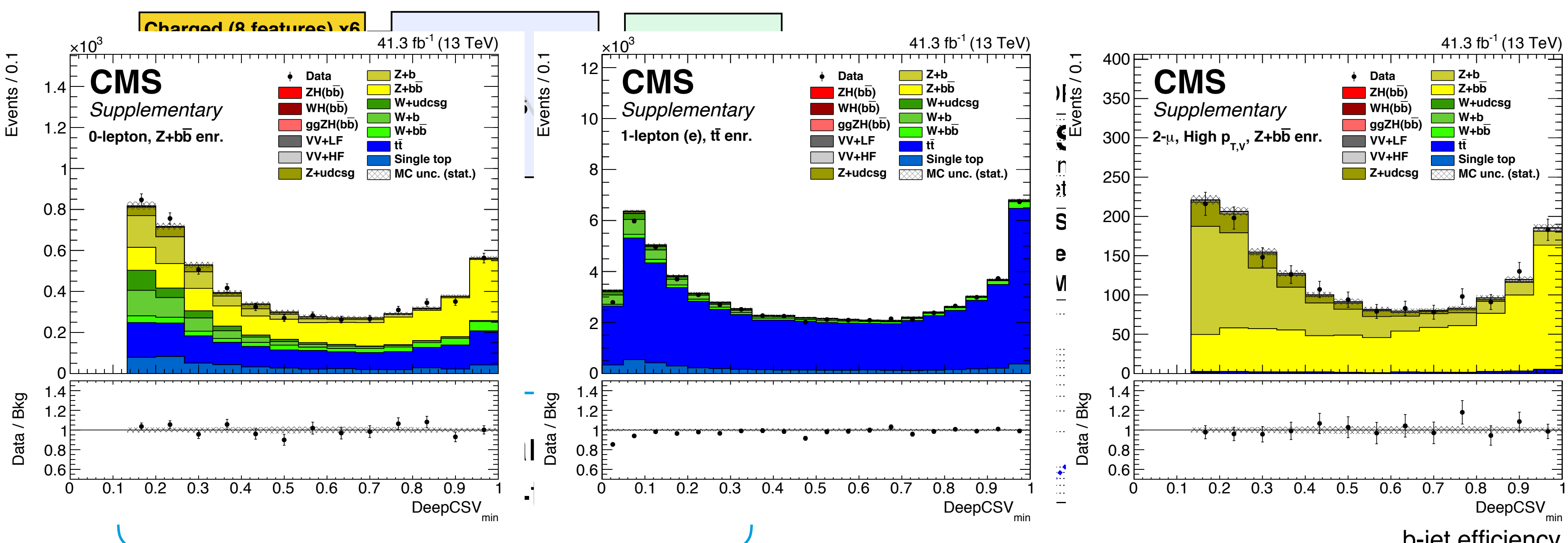
- Different architectures
  - Classification/regression
    - DNN: Dense NN
    - cDNN convolutional DNN
    - RNN: Recurrent NN
  - Generative
    - GAN: Generative Adversarial Networks
    - VAE: Variational Autoencoder
- Training by backpropagation, i.e. iterative updating of weights by e.g. stochastic gradient decent

b tagging: algorithm development

- many decay modes of b-flavoured hadrons
- even with tertiary c-flavoured hadron decay
- with or without soft electron or muon in jet



DeepCSV:
- DNN architecture



b-jet efficiency

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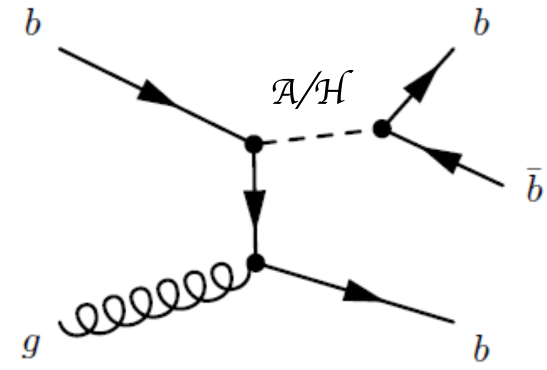
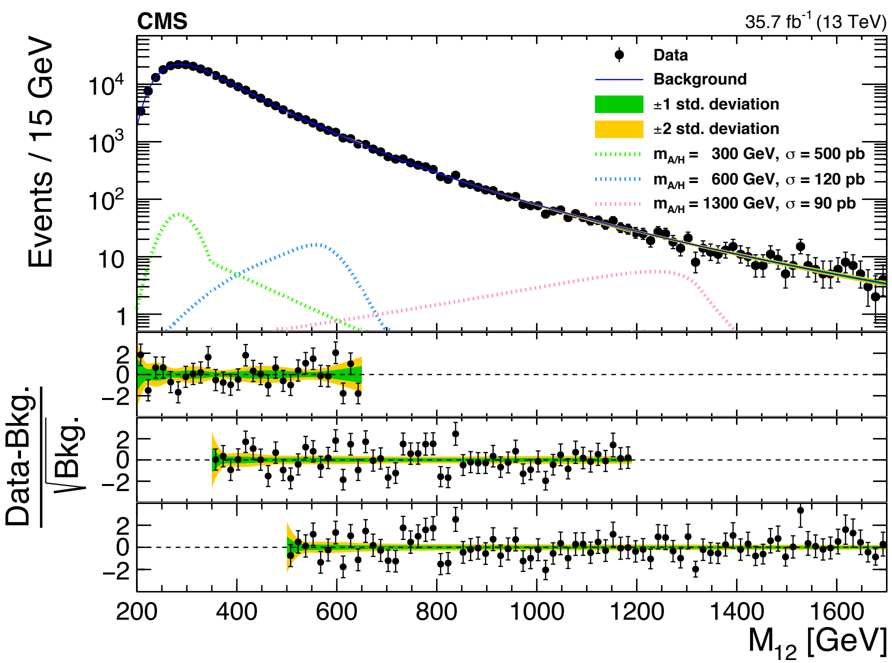
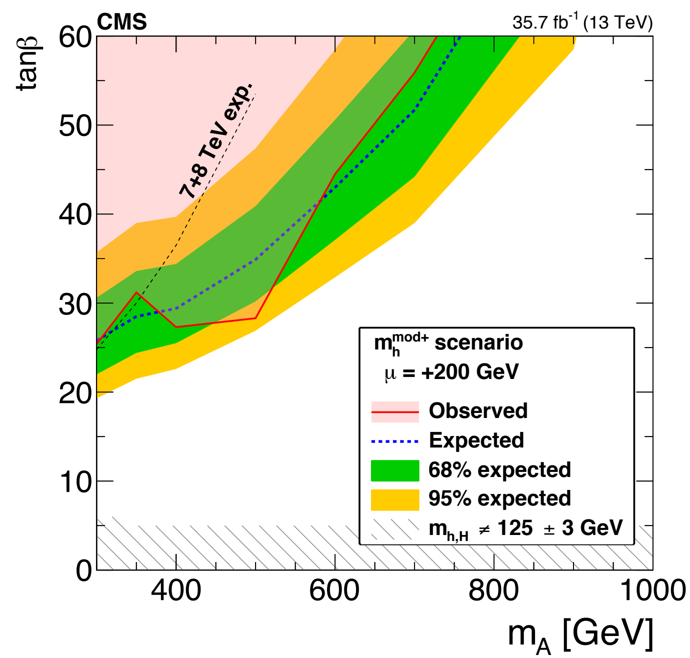
H(bb) high mass search (BSM)



Search for the b-associated production of degenerate H/A → $b\bar{b}$
- Cross-section enhanced up to factor ~ 2tan²β
- Largest BR in many MSSM and 2HDM scenarios

Main challenge: huge QCD multi jet production
- dedicated b-tag trigger developed





model-independent exclusion limits translated to **onto MSSM** parameters - **tanβ** and **M_A**