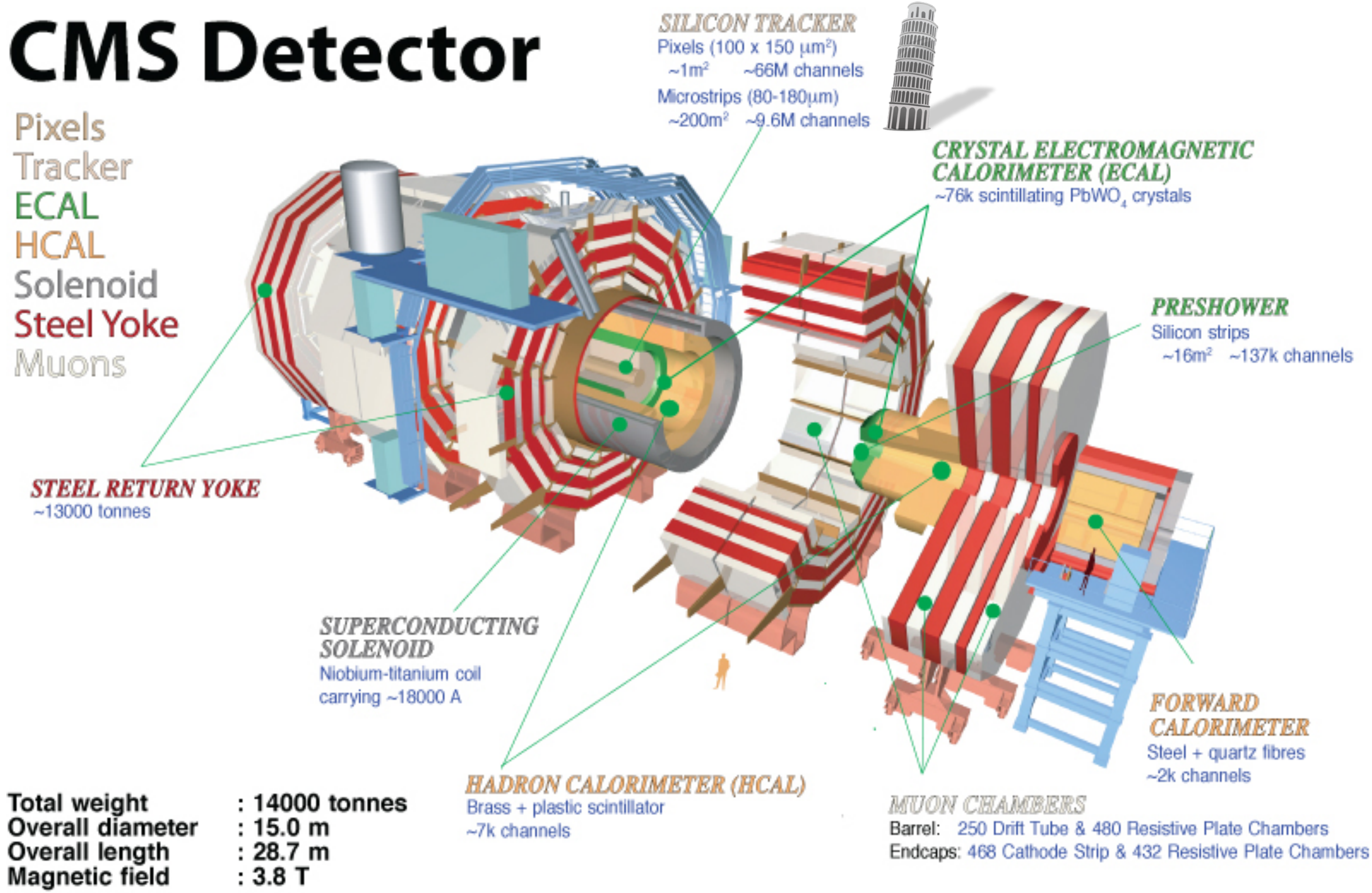
Evidenza del decadimento del bosone di Higgs in muoni con l'esperimento CMS

arXiv:2009.04363 CERN-EP-2020-164
Submitted to JHEP

Paolo Azzurri – INFN Pisa

10 Novembre 2020



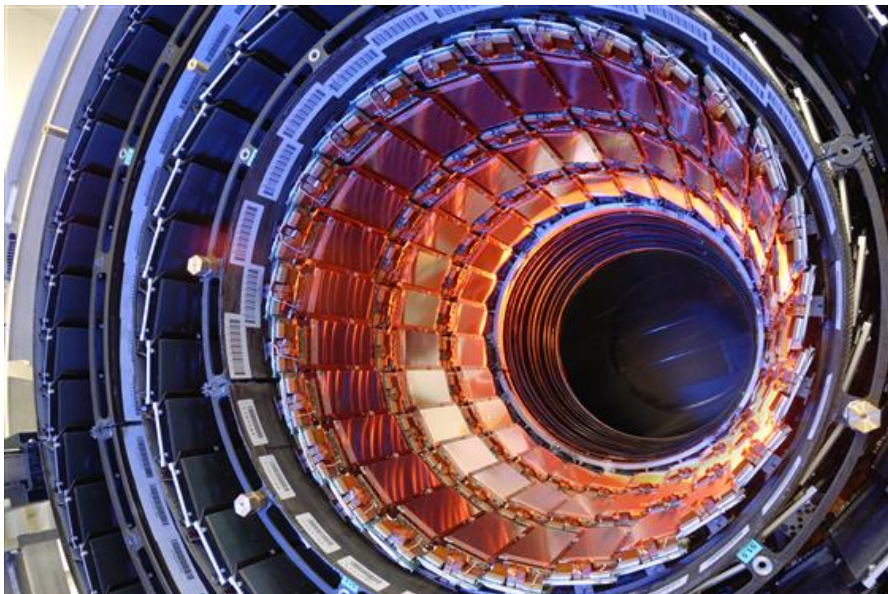
75M 3D camera taking 40M frames/sec

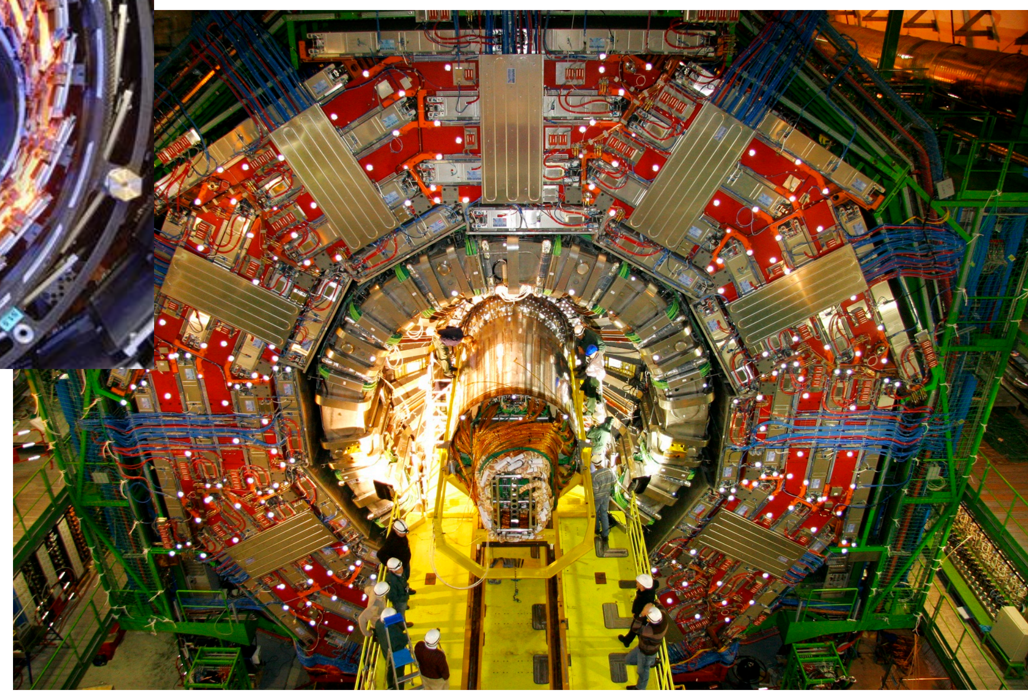
Tracciatore interno

1997-2007

~ 5 anni di R & D

~ 5 anni di costruzione





a Pisa

Inserimento in CMS Dic 2007

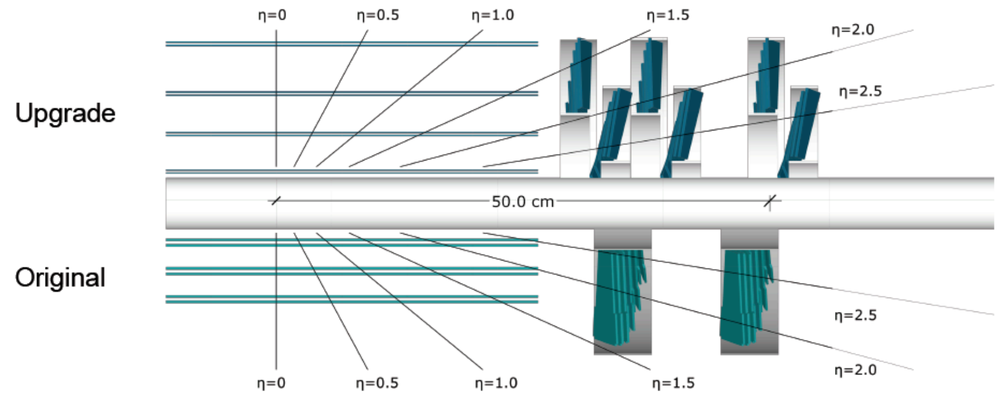
Nuovo rivelatore a pixel (2017)

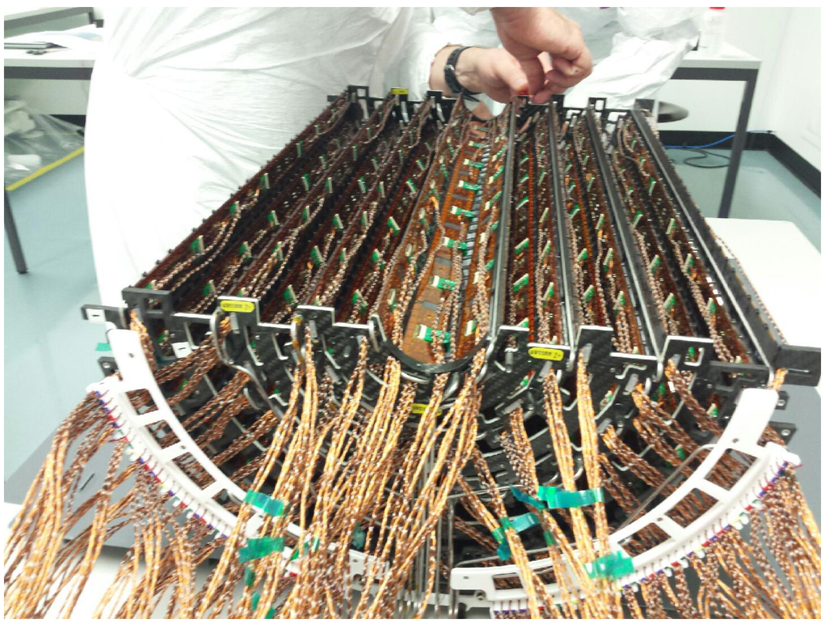
- Quattro punti per ogni traccia
- Più vicino al fascio (2.8 cm)
- Più leggero
- Efficiente fino a L = 2.2-2.5 $cm^{-2}s^{-1}$

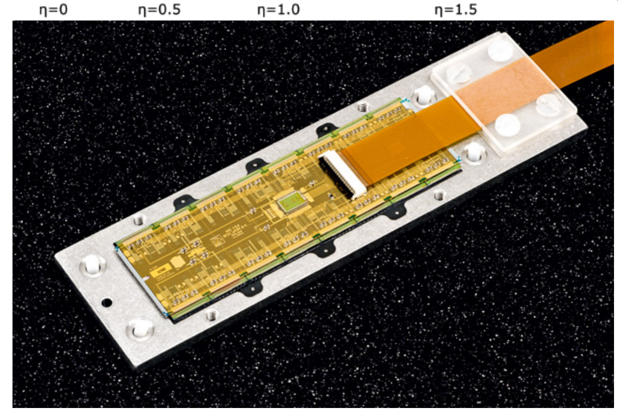
⍰ Maggiore efficienza tracciatura

⍰ Migliore b-tagging

⍰ Migliore risoluzione High Level Trigger



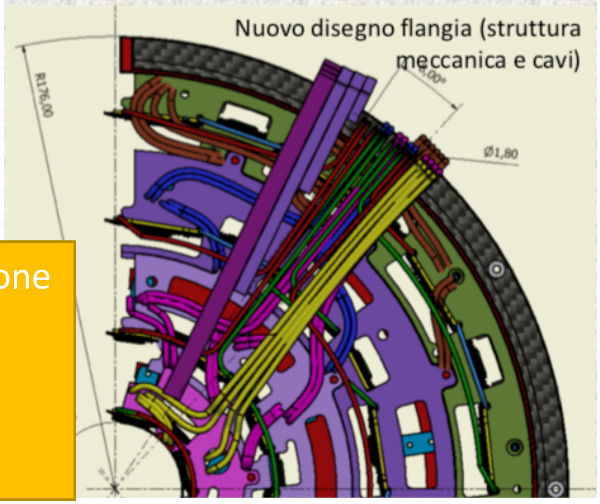




- Costruiti in Italia 15% dei moduli del barrel
- **Pisa ha testato tutti questi moduli**
- **Pisa ha contribuito allo sviluppo del processo di bump-bonding di una delle ditte**

Fase-2 upgrade tracciatore di CMS

- Nuovo tracciatore (200 m^2 pixel e strip) da sostituire completamente
  - Capace di sostenere L=7 10^{34} cm^{-2} s^{-1} e 4000 fb^{-1}
  - Capace di fornire tracce p_t > 2-3 GeV ad ogni collisione per trigger livello 1
  - Estensione fino a $|\eta| = 4$

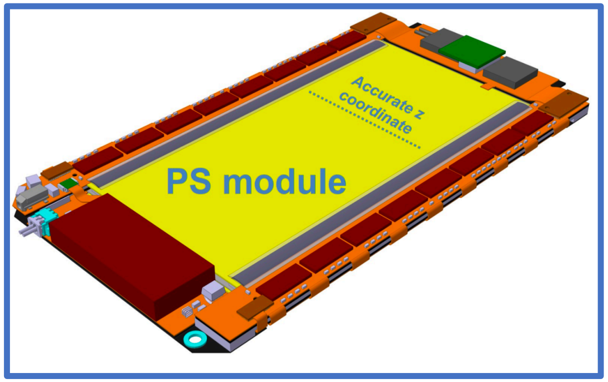


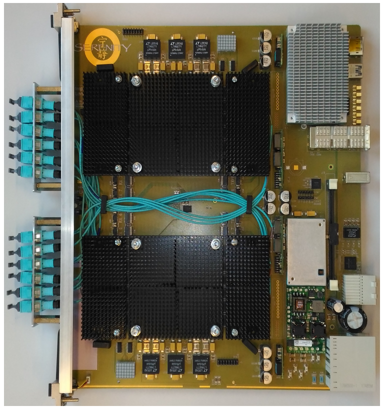
- Sviluppo e costruzione meccanica barrel rivelatore a pixel
- Sviluppo sensori a pixel

A Pisa (ora – 2026)

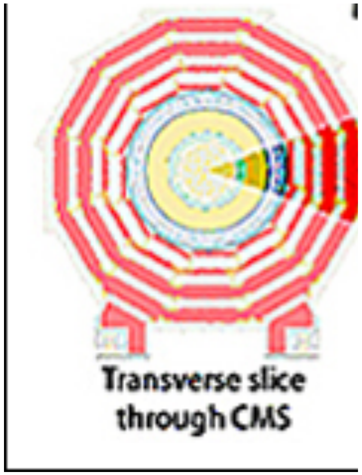
Sviluppo hardware e firmware schede di acquisizione e ricostruzione tracce «online» (Trigger livello 1)

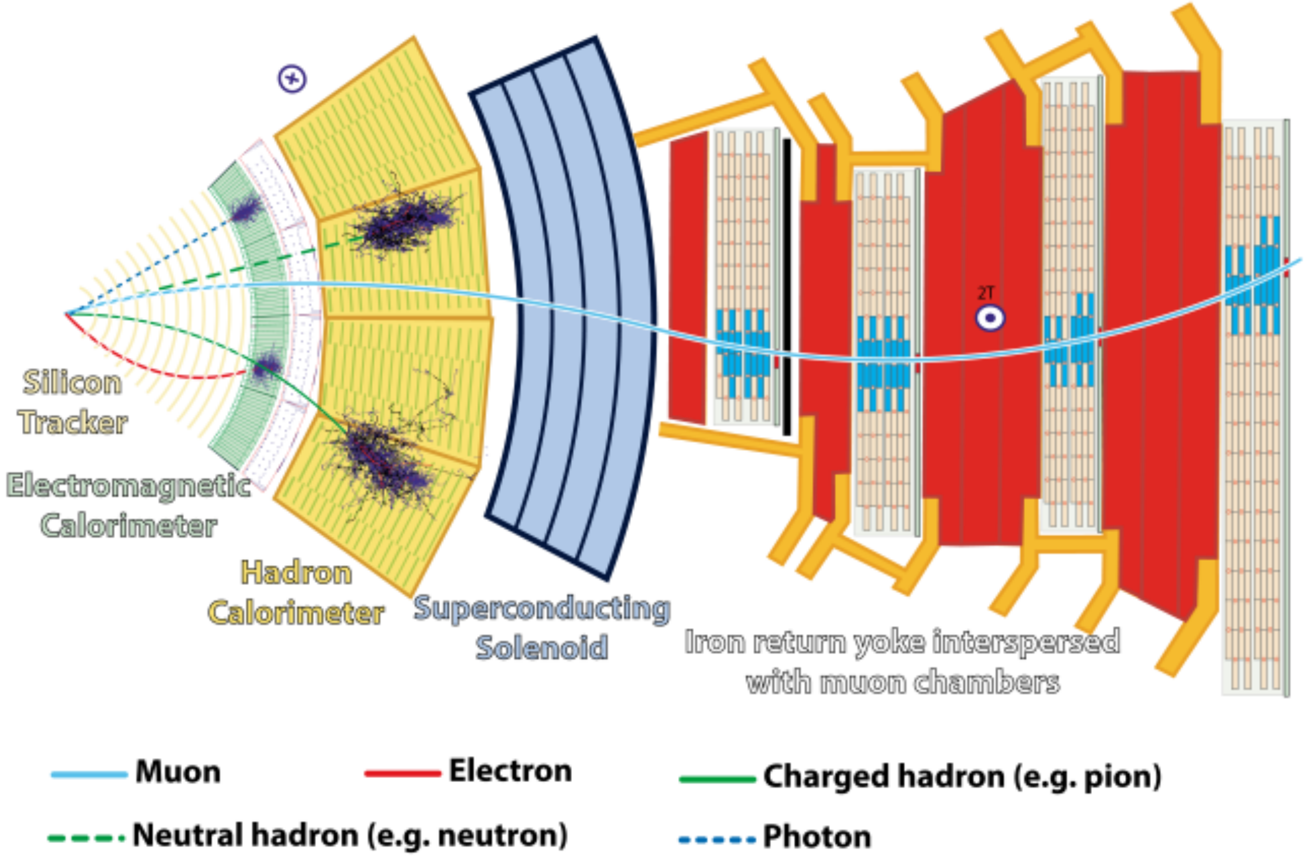
Test di 2000 moduli Outer Tracker e integrazione su meccanica

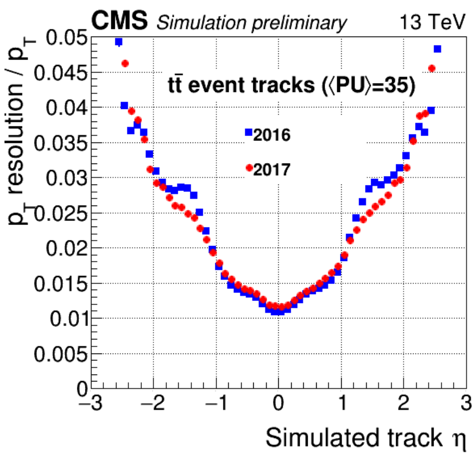




Particles through CMS slice



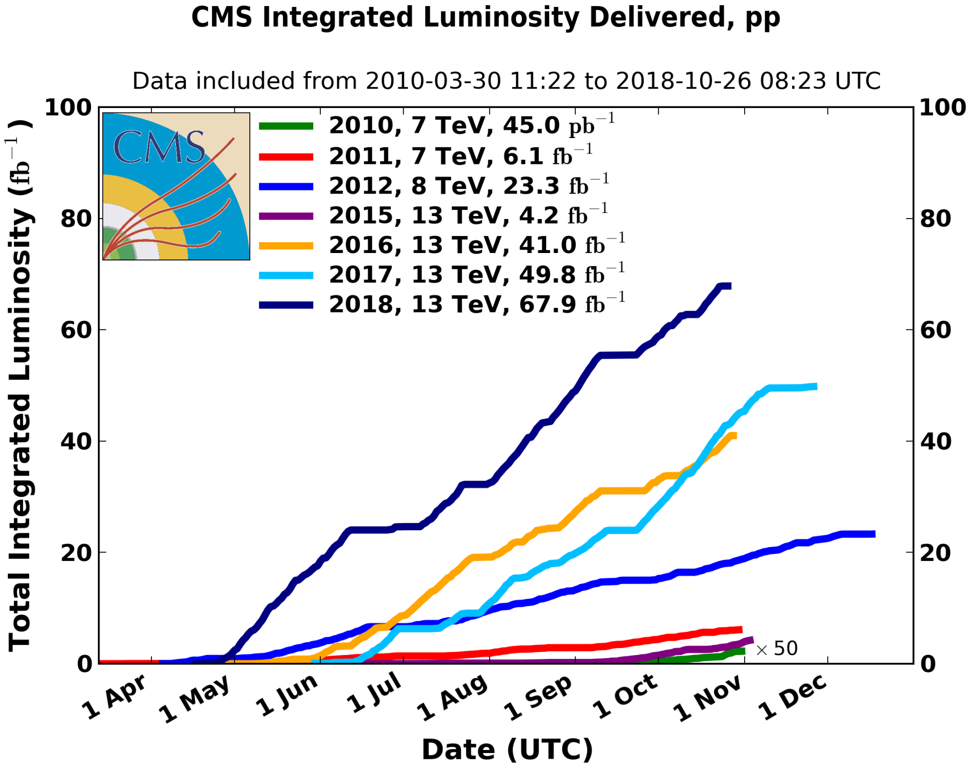


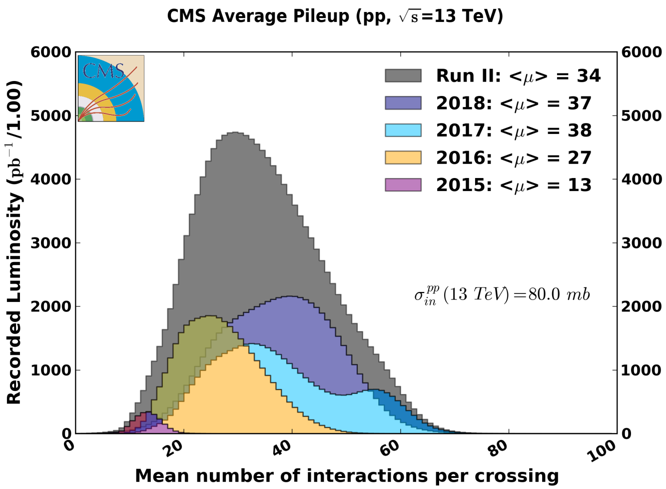


Charged tracks transverse momentum resolution

$\Delta p_T/p_T \simeq 0.01 \cdot \cosh(\eta) \oplus 2 \cdot 10^{-4} \cdot p_T$ (GeV)

CMS Run2 data





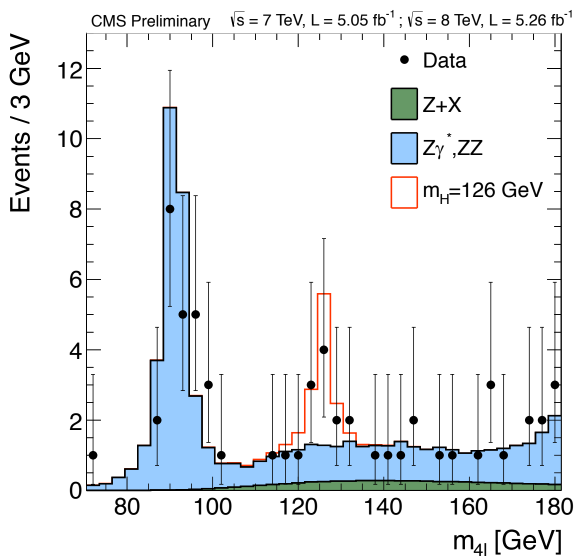
Run2 pp @13 TeV

2016-2017-2018

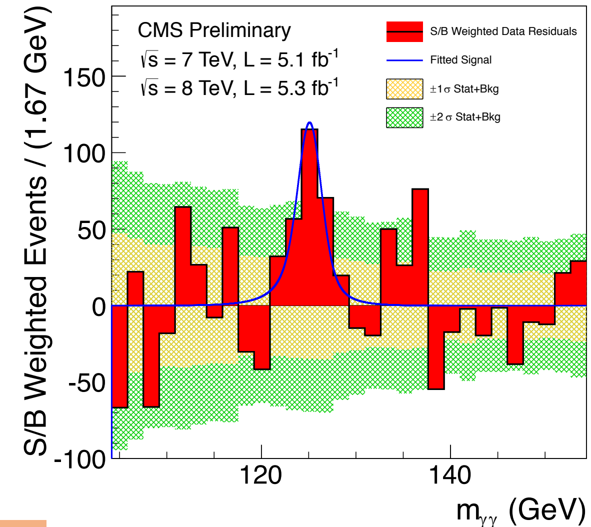
36/fb + 41/fb + 60/fb

137/fb

Higgs : dalla scoperta ad oggi

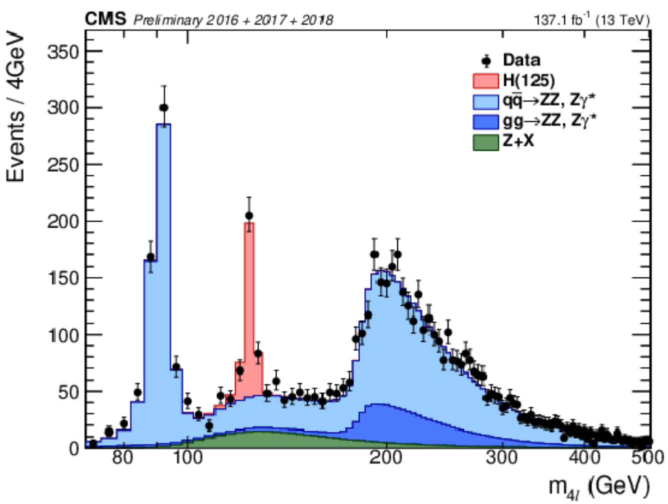


2012



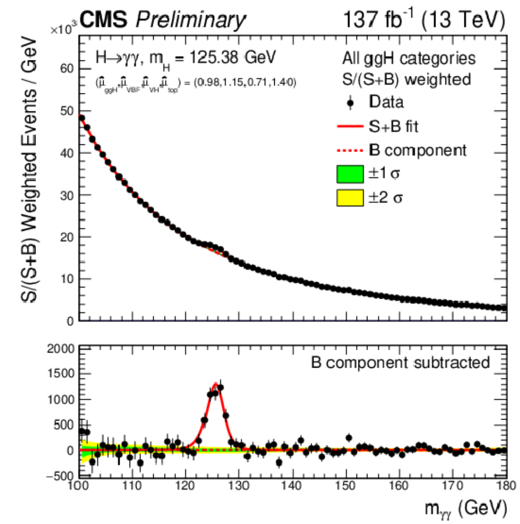
$H \to 4\ell$

$H \to \gamma\gamma$



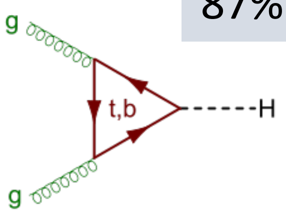
2020

Higgs x 30



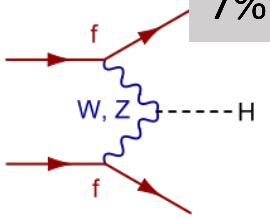
Produzione e decadimento

87%



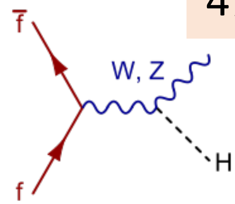
gluon fusion (ggF)

7%



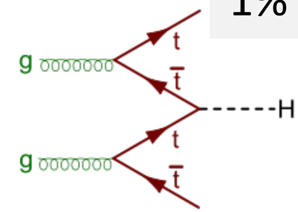
vector boson fusion (VBF)

4%

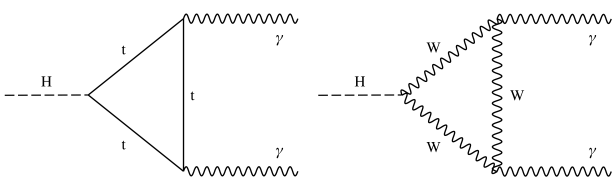


Higgs-strahlung (VH)

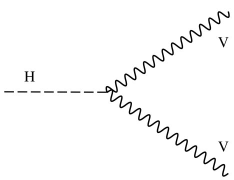
1%



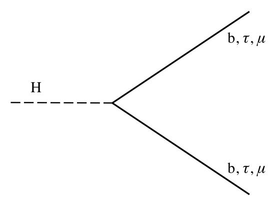
top quark fusion (ttH)



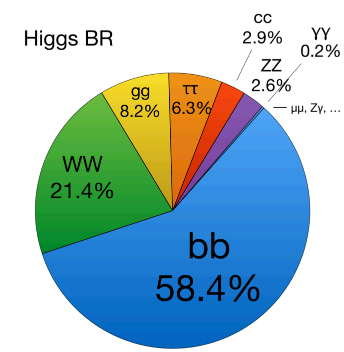
H→$\gamma\gamma$



H→ZZ, WW



H→ff



Decadimenti in fermioni : ττ bb

nature physics | LETTERS
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Evidence for the direct decay of the 125 GeV Higgs boson to fermions

The CMS Collaboration†

The discovery of a new boson with a mass of approximately 125 GeV in 2012 at the Large Hadron Collider[1-3] has heralded a new era in understanding the nature of electroweak symmetry breaking and possibly completing the standard model of particle physics[4-9]. Since the first observation in decays to $\gamma\gamma$, *WW* and *ZZ* boson pairs, an extensive set of measurements of the mass[10,11] and couplings to *W* and *Z* bosons[11-13], as well as multiple tests of the spin-parity quantum numbers[10,11,13,14], have revealed that the properties of the new boson are consistent with those of the long-sought agent responsible for electroweak symmetry breaking. An important open question is whether the new particle also couples to fermions, and in particular to down-type fermions, as the current measurements mainly constrain the couplings to the up-type top quark. Determination of the couplings to down-type fermions requires direct measurement of the corresponding Higgs boson decays, as recently reported by the Compact Muon Solenoid (CMS) experiment in the study of Higgs decays to bottom quarks[15] and τ leptons[16]. Here, we report the combination of these two channels, which results in strong evidence for the direct coupling of the 125 GeV Higgs boson to down-type fermions, with an observed significance of 3.8 standard deviations, when 4.4 are expected.

the heaviest elementary particle known to date, is implied by an overall agreement of the gluon–gluon fusion production channel cross-section with the standard model prediction. However, the masses of down-type fermions may come about through different mechanisms in theories beyond the standard model[19]. Therefore, it is imperative to observe the direct decay of this new particle to down-type fermions to firmly establish its nature. As a consequence of the Yukawa interaction discussed above, the most abundant fermionic Higgs boson decays will be to third-generation quarks and leptons, namely the bottom quark and the τ lepton, as the decay of a Higgs boson with a mass around 125 GeV to top quarks is kinematically not allowed. Therefore, the most promising experimental avenue to explore the direct coupling of the standard model Higgs boson to fermions is in the study of the decay to bottom quark–antiquark pairs (denoted as $b\bar{b}$) as well as to tau lepton–antilepton pairs (denoted as $\tau\tau$).

Recently, the CMS Collaboration reported on a search for the decays of the new boson to $b\bar{b}$ quark pairs[15] as well as to $\tau\tau$ lepton pairs[16] based on data collected in 2011 and 2012. In this Letter, we report on the combination of the results from the study of these two decays to down-type fermion–antifermion pairs, performed for the first time at the LHC.

The CMS apparatus comprises several detectors specialized in

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Evidence for the Higgs boson decay to a bottom quark–antiquark pair

The CMS Collaboration *
CERN, Switzerland

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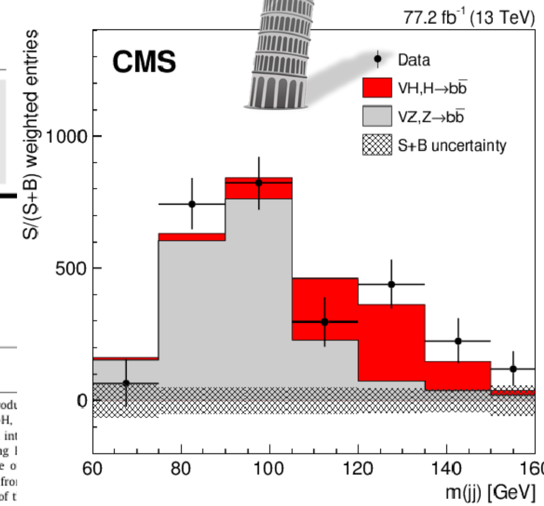
ABSTRACT

A search for the standard model (SM) Higgs boson (H) decaying to $b\bar{b}$ when produ with an electroweak vector boson is reported for the following processes: $Z(\nu\nu)$H, $Z(\mu\mu)$H, and Z(ee)H. The search is performed in data samples corresponding to an int of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC during excess of events is observed in data compared to the expectation in the absence o The significance of this excess is 3.3 standard deviations, where the expectation fro production is 2.8. The signal strength corresponding to this excess, relative to that of t production, is 1.2 ± 0.4. When combined with the Run 1 measurement of the same p significance is 3.8 standard deviations with 3.8 expected. The corresponding signal strength, relative to that of the SM Higgs boson, is $1.06^{+0.31}_{-0.29}$.



Physics Letters B 779 (2018) 283–316
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Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector

The CMS Collaboration *
CERN, Switzerland

arXiv:1708.00373

ARTICLE INFO

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Tau
Higgs
Observation

ABSTRACT

A measurement of the $H \to \tau\tau$ signal strength is performed using events recorded in proton–proton collisions by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV. The data set corresponds to an integrated luminosity of 35.9 fb^{-1}. The $H \to \tau\tau$ signal is established with a significance of 4.9 standard deviations, to be compared to an expected significance of 4.7 standard deviations. The best fit of the product of the observed $H \to \tau\tau$ signal production cross section and branching fraction is $1.09^{+0.27}_{-0.26}$ times the standard model expectation. The combination with the corresponding measurement performed with data collected by the CMS experiment at center-of-mass energies of 7 and 8 TeV leads to an observed significance of 5.9 standard deviations, equal to the expected significance. This is the first observation of Higgs boson decays to τ leptons by a single experiment.

PHYSICAL REVIEW LETTERS **121,** 121801 (2018)
Editors' Suggestion | Featured in Physics

Observation of Higgs Boson Decay to Bottom Quarks

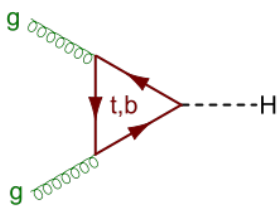
A. M. Sirunyan *et al.**
(CMS Collaboration)

(Received 24 August 2018; published 17 September 2018)

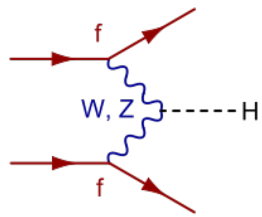
The observation of the standard model (SM) Higgs boson decay to a pair of bottom quarks is presented. The main contribution to this result is from processes in which Higgs bosons are produced in association with a W or Z boson (VH), and are searched for in final states including 0, 1, or 2 charged leptons and two identified bottom quark jets. The results from the measurement of these processes in a data sample recorded by the CMS experiment in 2017, comprising 41.3 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV, are described. When combined with previous VH measurements using data collected at $\sqrt{s} = 7$, 8, and 13 TeV, an excess of events is observed at $m_H = 125$ GeV with a significance of 4.8 standard deviations, where the expectation for the SM Higgs boson is 4.9. The corresponding measured signal strength is 1.01 ± 0.22. The combination of this result with searches by the CMS experiment for $H \to b\bar{b}$ in other production processes yields an observed (expected) significance of 5.6 (5.5) standard deviations and a signal strength of 1.04 ± 0.20.

Accoppiamenti verificati

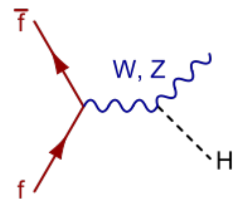
Htt ✓



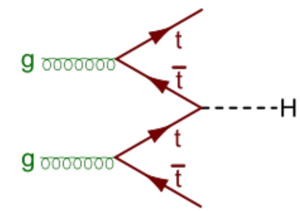
gluon fusion (ggF)



vector boson fusion (VBF)

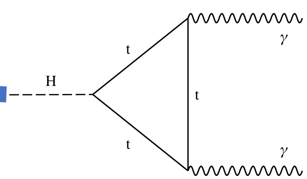


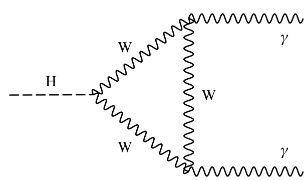
Higgs-strahlung(VH)

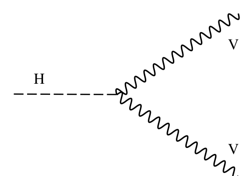


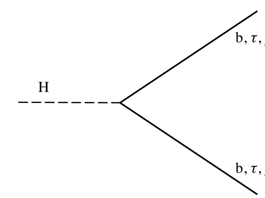
top quark fusion (ttH)

Htt ✓









$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ, WW$

HZZ ✓

HWW ✓

$H \rightarrow ff$

Hττ ✓

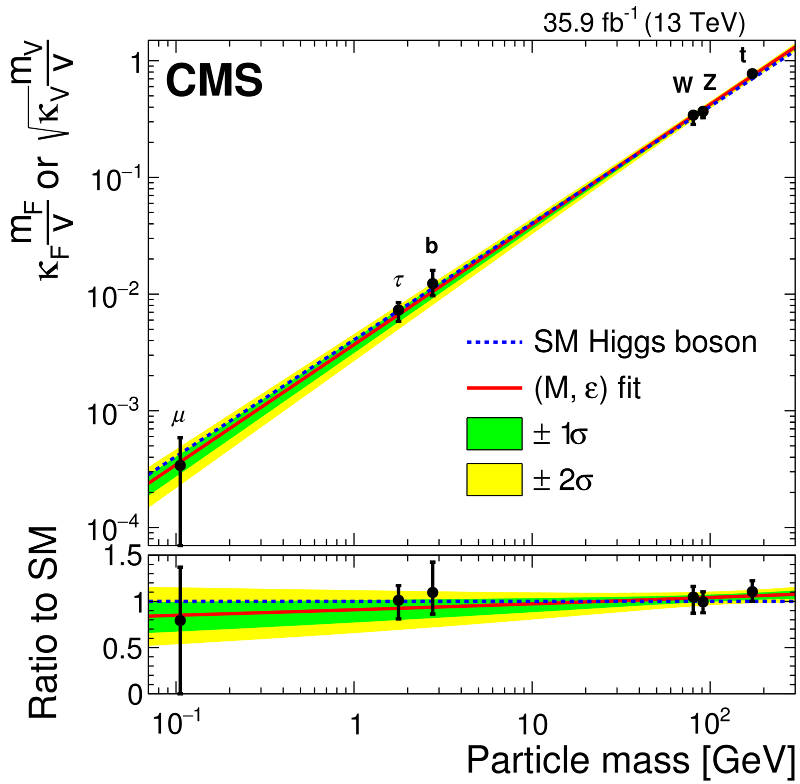
Hbb ✓

Proprietà misurate

Most recent CMS Higgs boson results combination

pp@13TeV **2016** (**36**/fb)

Combined measurements of Higgs boson couplings _[Eur. Phys. J. C 79 (2019) 421]_



Other measured properties

Quantum numbers

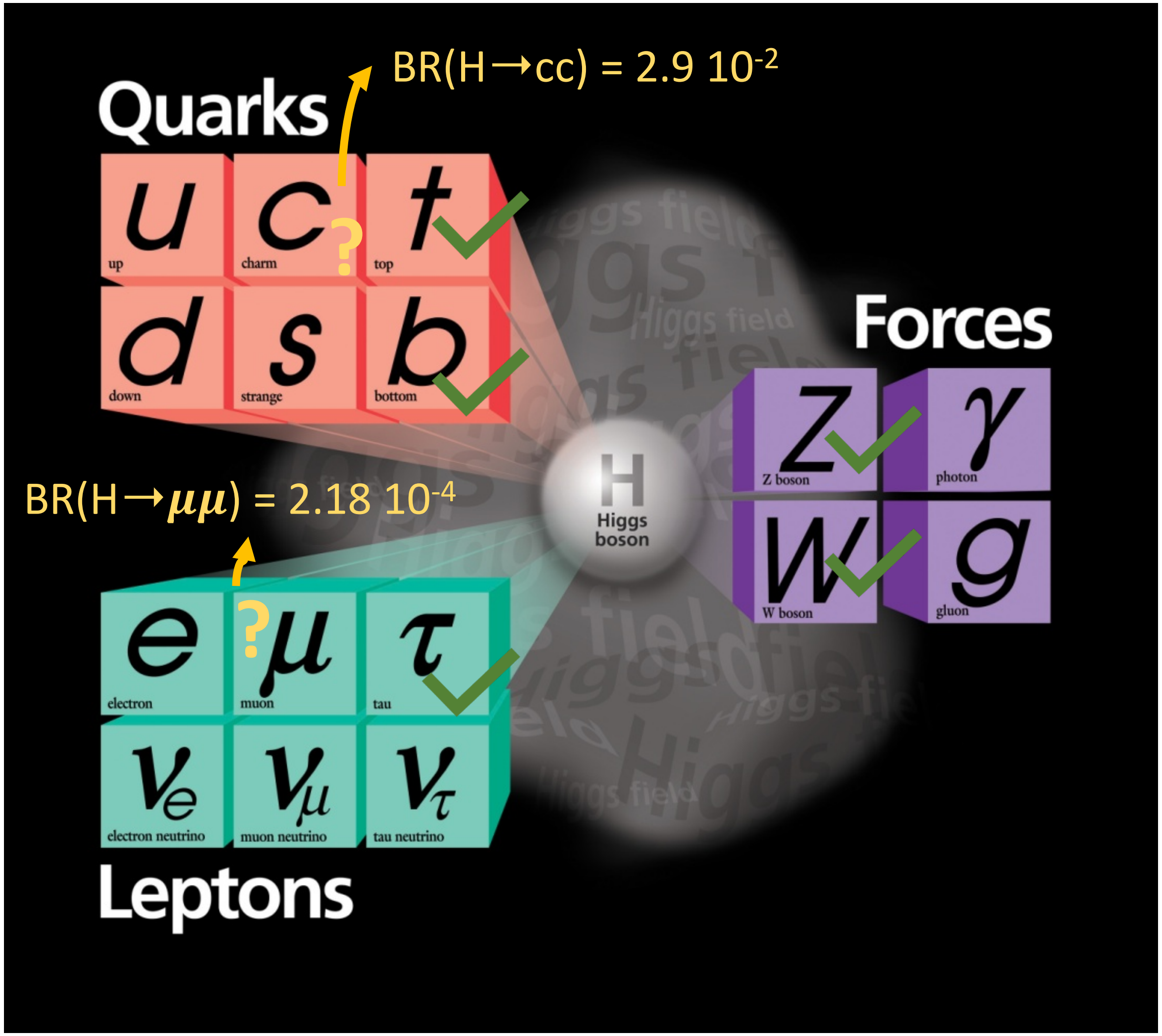
- C=+1 ($\gamma\gamma$)
- J^P= 0+ from angular analysis of H→4ℓ

$\boldsymbol{\Gamma}_H$=3.2+2.8-2.2 MeV (off shell 4ℓ)
arXiv:1901.00174

m_H = **125.38** ± 0.14 GeV
arXiv:2002.06398

⇒ *reference mass value used for the analysis*

High-hanging couplings



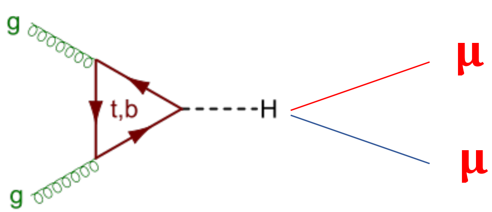
H→cc :
- Not extremely rare decay
- Huge bkg from QCD cc productions

Couples to
2nd fermion generation ?

H→$\mu\mu$:
- Extremely rare decay
- Large but not huge bkg from DY/EW $\mu\mu$ productions

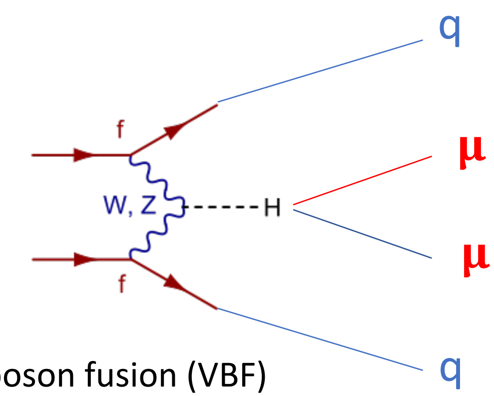
H→$\mu\mu$: gli stati finali da cercare

87%



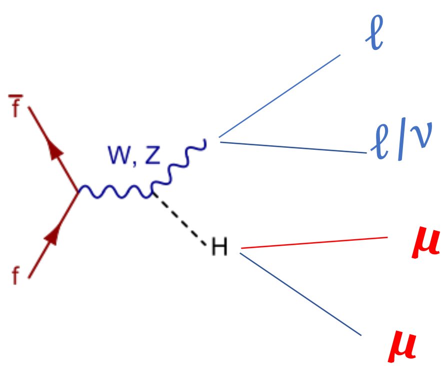
gluon fusion (ggF)

7%



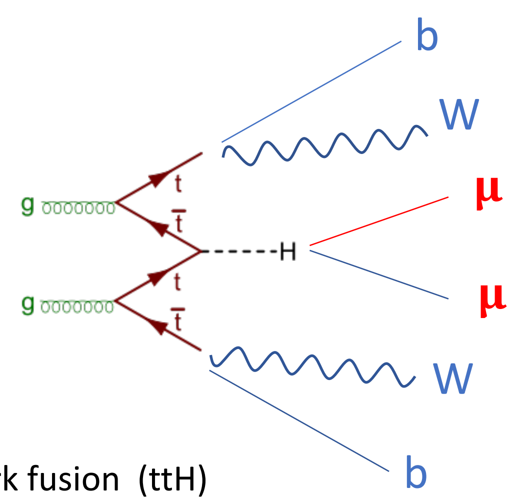
vector boson fusion (VBF)

4%



Higgs-strahlung(VH)

1%



top quark fusion (ttH)

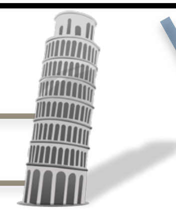
Panoramica dell'analisi CMS

analysis divided into four exclusive channels

ttH channel

- Phase-space defined to be: 1 medium or 2 loose b-tagged jets
- Targets leptonic and hadronic decay of top quark

VBF channel



- **MC template analysis**
- Mjj > 400 GeV, $\Delta\eta(jj) > 2.5$
- Veto VH events
- Veto ttH events

VH channel

- Targets leptonic decays of gauge bosons
- WH: $2\mu + \mu$ or e
- ZH: $2\mu + 2\mu$ or 2e
- Veto ttH

ggH channel

- Collects all events not selected by other channels (ttH, VH(lep), and VBF)
- Phase space dominated by 0 and 1-jet events with no extra leptons

Strategia generale

VBF channel

ggH channel

ttH channel

VH channel

Data-Driven

Train signal v/s bkg. multivariate classifier

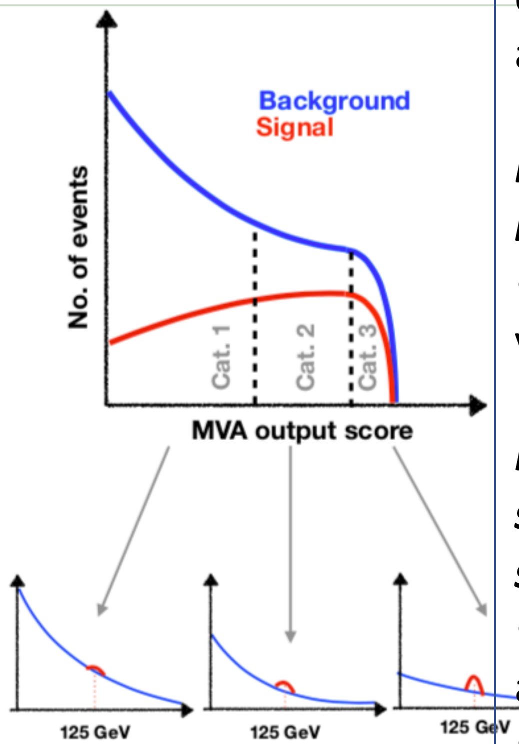
- Exploit information of the event wih input variables that are <u>not</u> correlated with $m_{\mu\mu}$

Divide events into categories based on the classifier output

- Several subcategories with varying signal purity

Fit the $m_{\mu\mu}$ distribution in each subcategory to extract the signal

- Signal and background models are parametric functions
- Data-driven background predictions



MC-based

Train signal v/s bkg. multivariate classifier

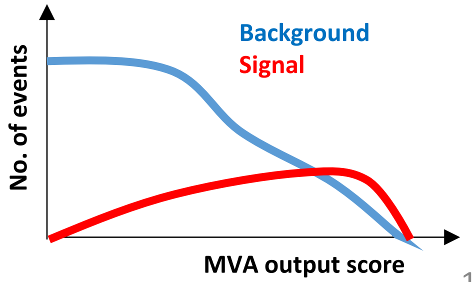
- Exploit full information of the event including $m_{\mu\mu}$

Define Signal and Control Regions

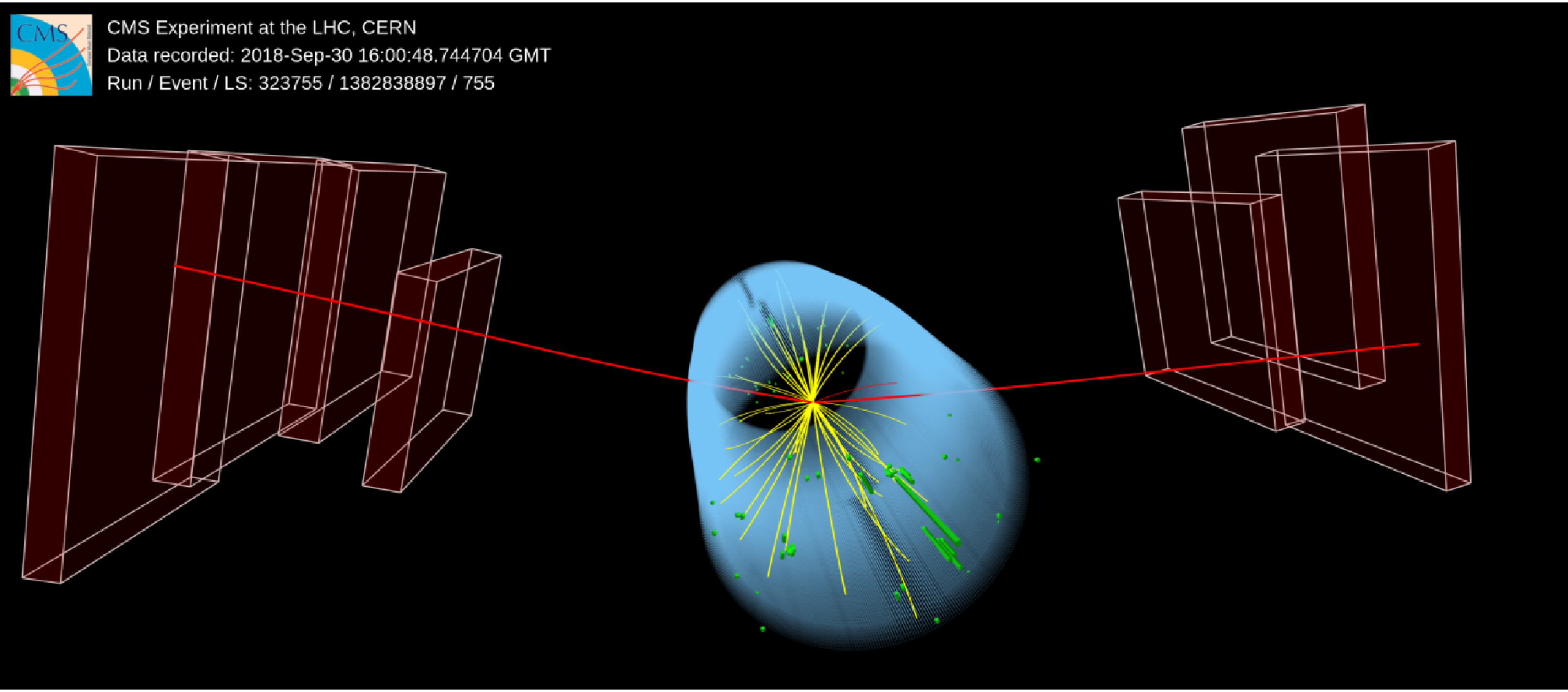
- $115 < m_{\mu\mu} < 135$ GeV
- $m_{\mu\mu}$ [110, 115] or [135, 150]

Fit the MVA output distribution in both regions to extract the signal

- Signal and background modeled with Monte Carlo



Eventi inclusivi (ggH) H→ **μμ**



$m_{\mu\mu}$ = 125.46 ±1.13 GeV. No additional jets with pT> 25 GeV or leptons (electrons or muons) with pT> 20 GeV are present in this event.

Analisi degli eventi inclusivi

Signal characterized by a sharp dimuon mass peak at 125 GeV $m_{\mu\mu}$ resolution plays a defining role in determining analysis sensitivity

Single muon trigger p_T> 24 (27) GeV in 2016,2018 (2017) data

Offline selection

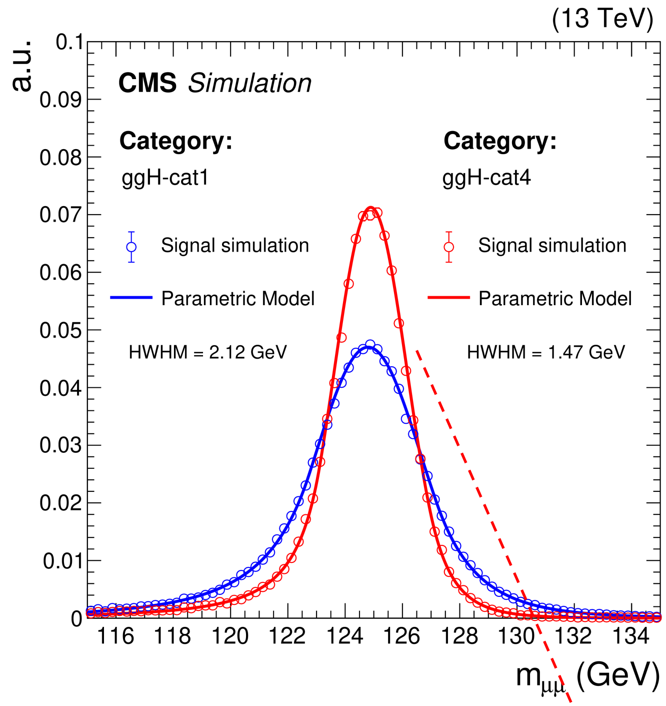
- one muon with p_T> 26 (29) GeV
- opposite sign muon p_T> 20

All muons |η| < 2.4 : p_T resolution

- 1-2% in barrel region (|η| < 0.9)
- 2-3.5% in endcaps (|η| > 1.2)

FSR photon identification & recovery:

- 3% increase in signal acceptance
- 2% improvement in mass resolution



double-sided Crystal Ball

Best $m_{\mu\mu}$ resolution with both muons in the barrel

Categorizzazione eventi inclusivi

BDT classifier

inputs related to dimuon system :

- $p_T(\mu\mu)$ & $\eta(\mu\mu)$, decay angles: ϕ_{CS}, $\cos\theta_{CS}$
  $\eta(\mu)$, $p_T(\mu)/m\mu\mu$

inputs related to add jets activity

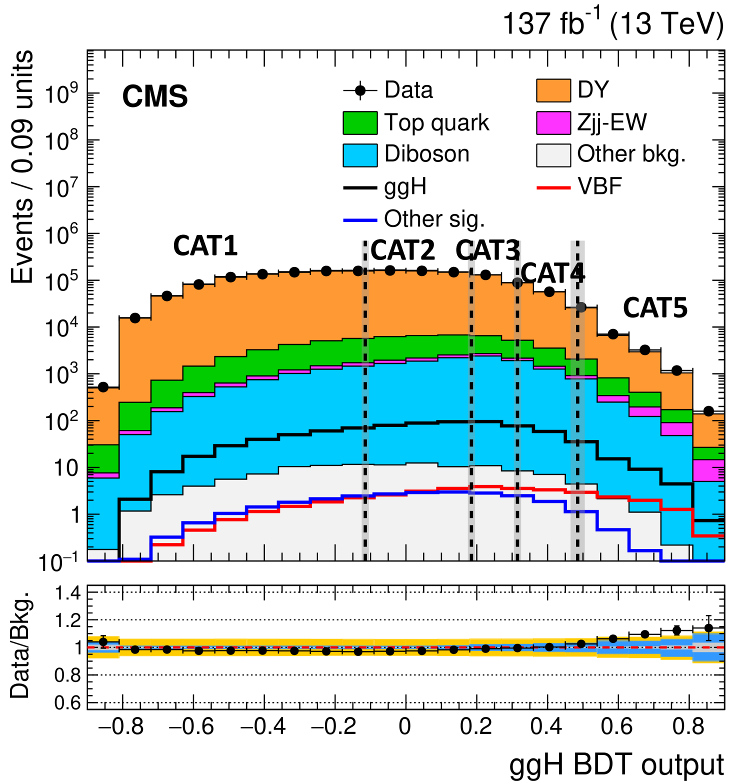
- p_T, η of the leading jet

With one jet : $\Delta\eta(H, j)$, $\Delta\phi(H, j)$

With two or more jets :

min-$\Delta\eta(H, j)$, min-$\Delta\phi(H, j)$, mjj , $\Delta\eta jj$, $\Delta\phi jj$

Events with better $\Delta m_{\mu\mu}$ go to high BDT output
$1/\sigma(\mathbf{m_{\mu\mu}})$ weight applied for signal training

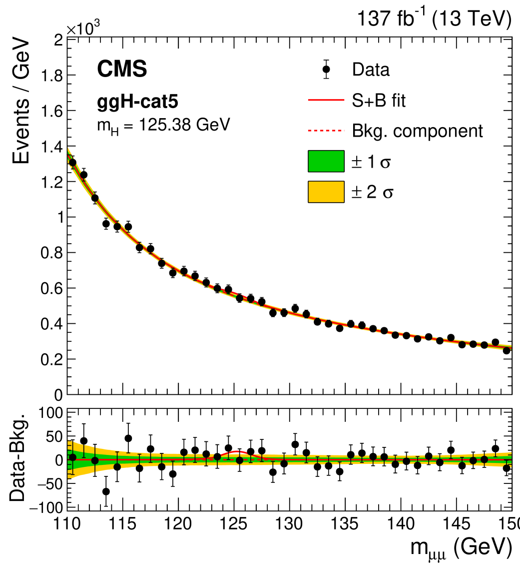


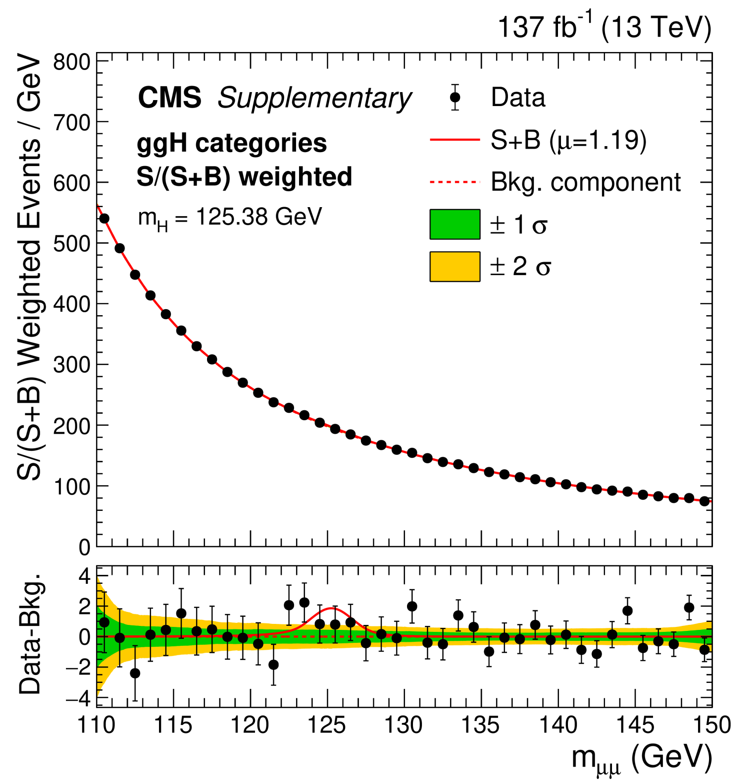
Event category	Total signal	ggH (%)	VBF (%)	Other (%)	HWHM (GeV)	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	$S/\sqrt{B}$ @HWHM
ggH-cat1	268	93.7	2.9	3.4	2.12	86 360	86 632	0.20	0.60
ggH-cat2	312	93.5	3.4	3.1	1.75	46 350	46 393	0.46	0.98
ggH-cat3	131	93.2	4.0	2.8	1.60	12 660	12 738	0.70	0.80
ggH-cat4	126	91.5	5.5	3.0	1.47	8260	8377	1.03	0.96
ggH-cat5	53.8	83.5	14.3	2.2	1.50	1680	1711	2.16	0.91

Divide in 5 categories and **fit $m_{\mu\mu}$ distributions**

Analisi degli eventi inclusivi

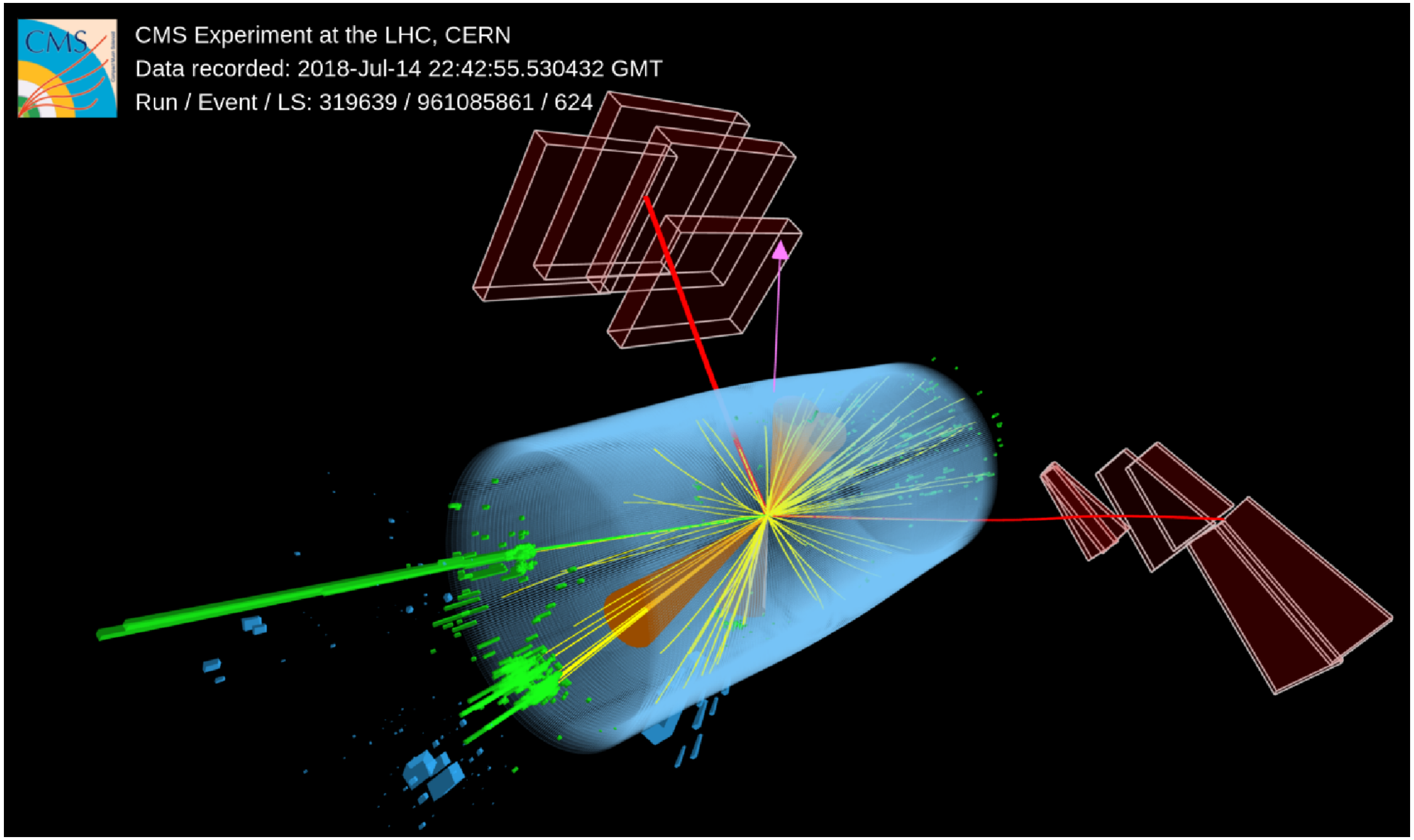
Fit of dimuon mass distribution with *core PDF* shape **x transfer functions**
discrete profiling of 3 core functions x 2nd/3rd order polynomial arXiv:1506.01010
(arXiv:1408.6865)





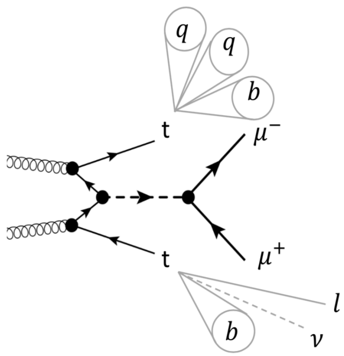
Obs (exp) significance : 1.0 (1.6)σ
Signal Strength
$\mu = \sigma/\sigma_{SM} = 0.63+0.65-0.64$

Eventi ttH (→bb qq eν **μμ**)



$m_{\mu\mu}$ = 125.30 ±1.22 GeV. One of the two top quarks produces an electron (green line), and a neutrino that yields missing transverse energy (pink arrow). The other top quark candidate decays into jets (orange cones).

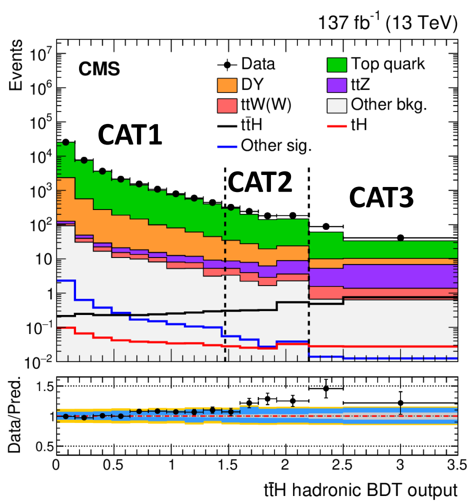
Analisi dei candidati ttH

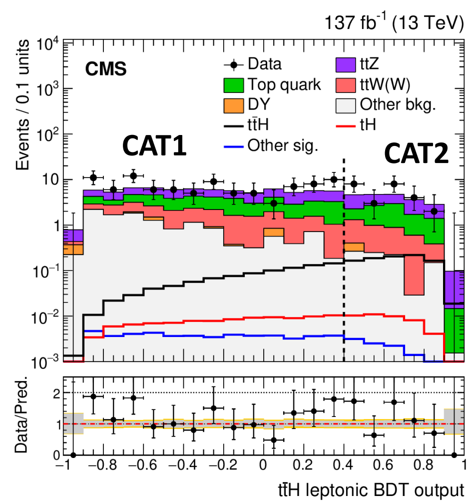


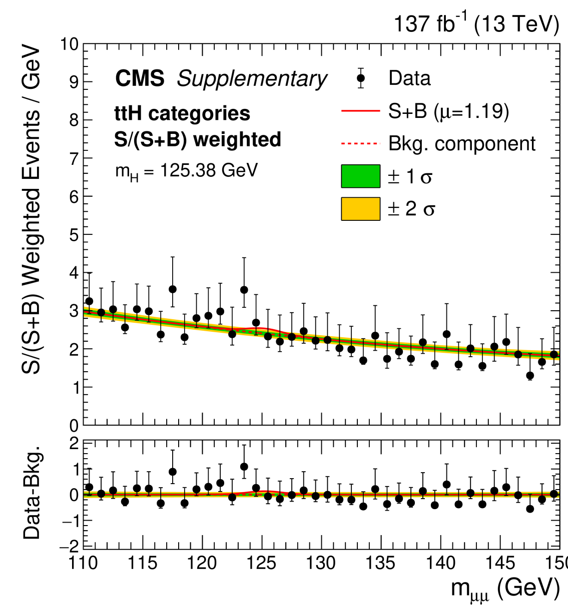
Observable	$t\bar{t}$H hadronic	$t\bar{t}$H leptonic
Number of b quark jets	>0 medium or >1 loose b-tagged jets	
Number of leptons ($N(\ell = \mu, e)$)	=2	=3 or 4
Lepton charge ($q(\ell)$)	$\sum q(\ell) = 0$	$N(\ell) = 3\ (4) \rightarrow \sum q(\ell) = \pm 1\ (0)$
Jet multiplicity ($p_T > 25$ GeV, $\|\eta\| < 4.7$)	≥3	≥2
Leading jet p_T	>50 GeV	>35 GeV
Z boson veto	—	$\|m_{\ell\ell} - m_Z\| > 10$ GeV
Low-mass resonance veto	—	$m_{\ell\ell} > 12$ GeV
Jet triplet mass	$100 < m_{jjj} < 300$ GeV	—

Two dedicated BDT discriminant used to separate major bkgs

- ttZ for leptonic channels → 2 categories
- dileptonic tt for hadronic channel → 3 categories



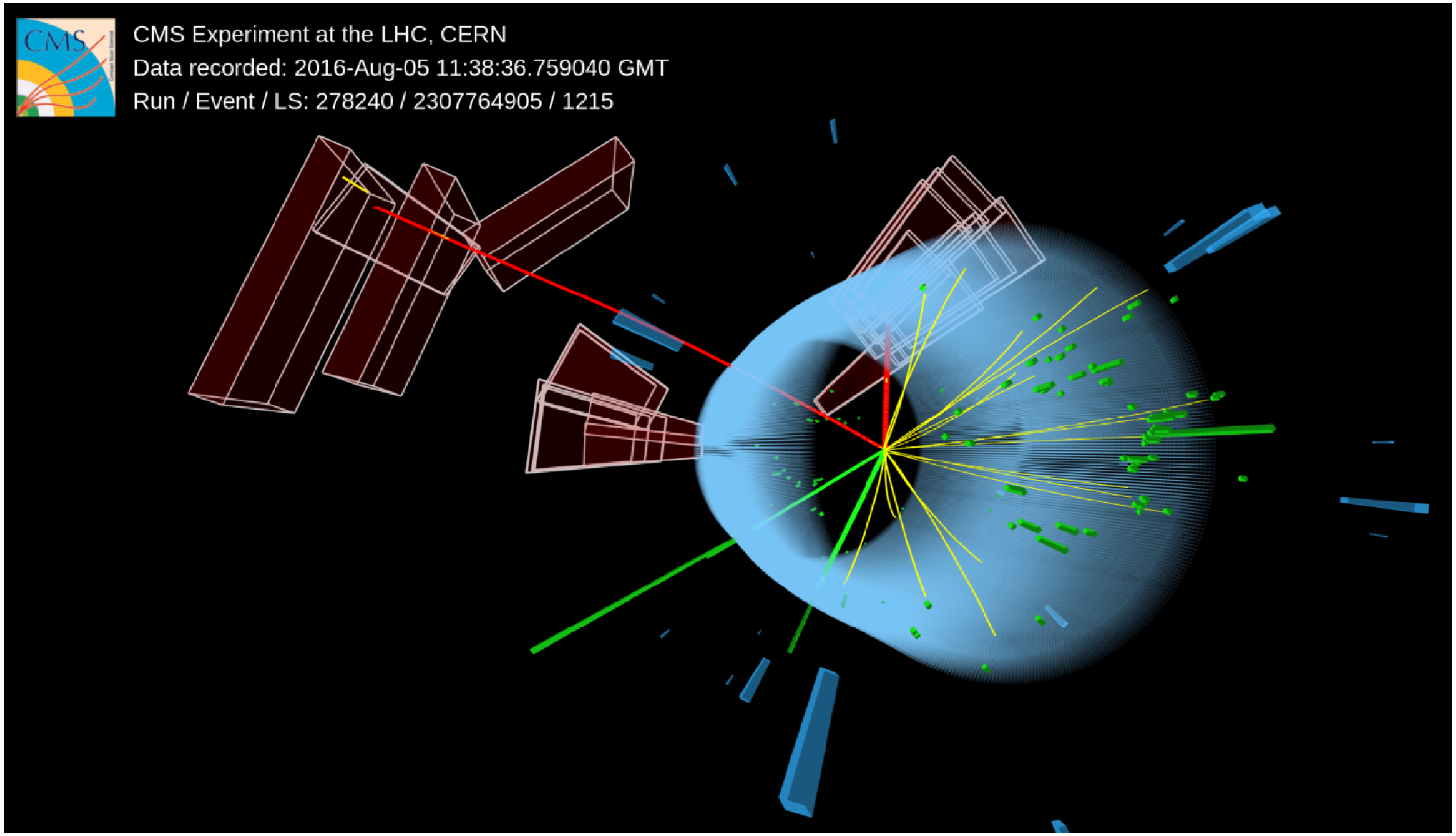




Obs (exp) significance : 1.2 (0.5)σ

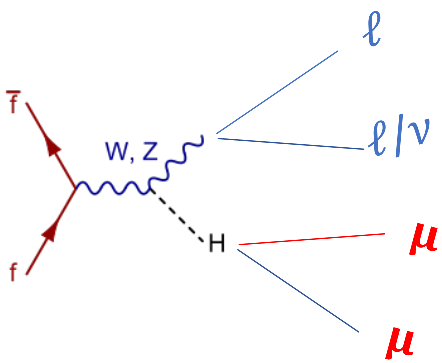
Signal Strength 2.32+2.27-1.95

Eventi VH (ZH→ ee **μμ**)



$m_{\mu\mu}$ = 125.69 ±1.55 GeV. The Z boson candidate decays into a pair of electrons indicated by the solid green lines. No additional leptons (electrons or muons) with *p*T > 20 GeV or jets with *p*T > 25 GeV are present in the event.

Analisi dei candidati VH

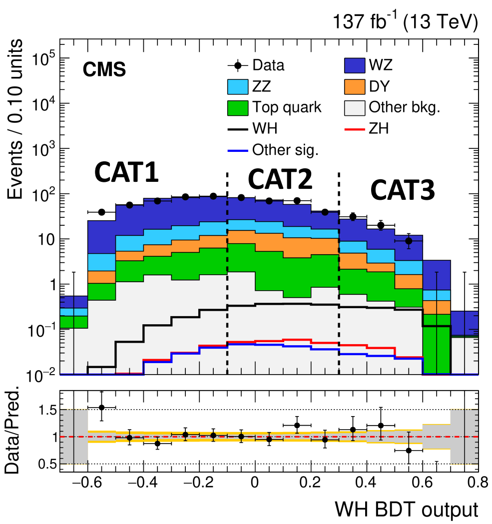


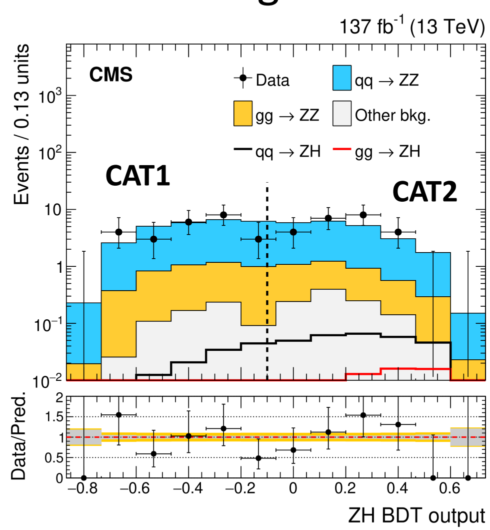
Higgs decays to muons, + at least one charged lepton

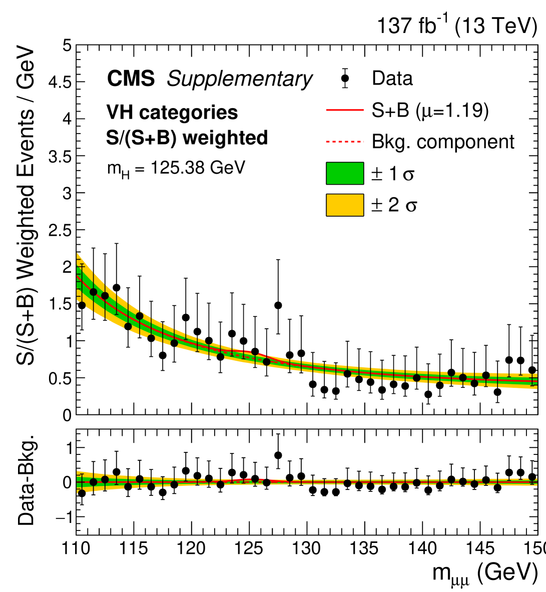
WH leptonic :		ZH leptonic :	
additional lepton (e or μ)		additional e^+e^- $\mu^+\mu^-$	
$\mu\mu e$ case	$\mu\mu\mu$ case	$\mu\mu ee$ case	$\mu\mu\mu\mu$ case

BDT used to separate (VZ) bkgs and categorize

- WH → 3 categories ZH → 2 categories



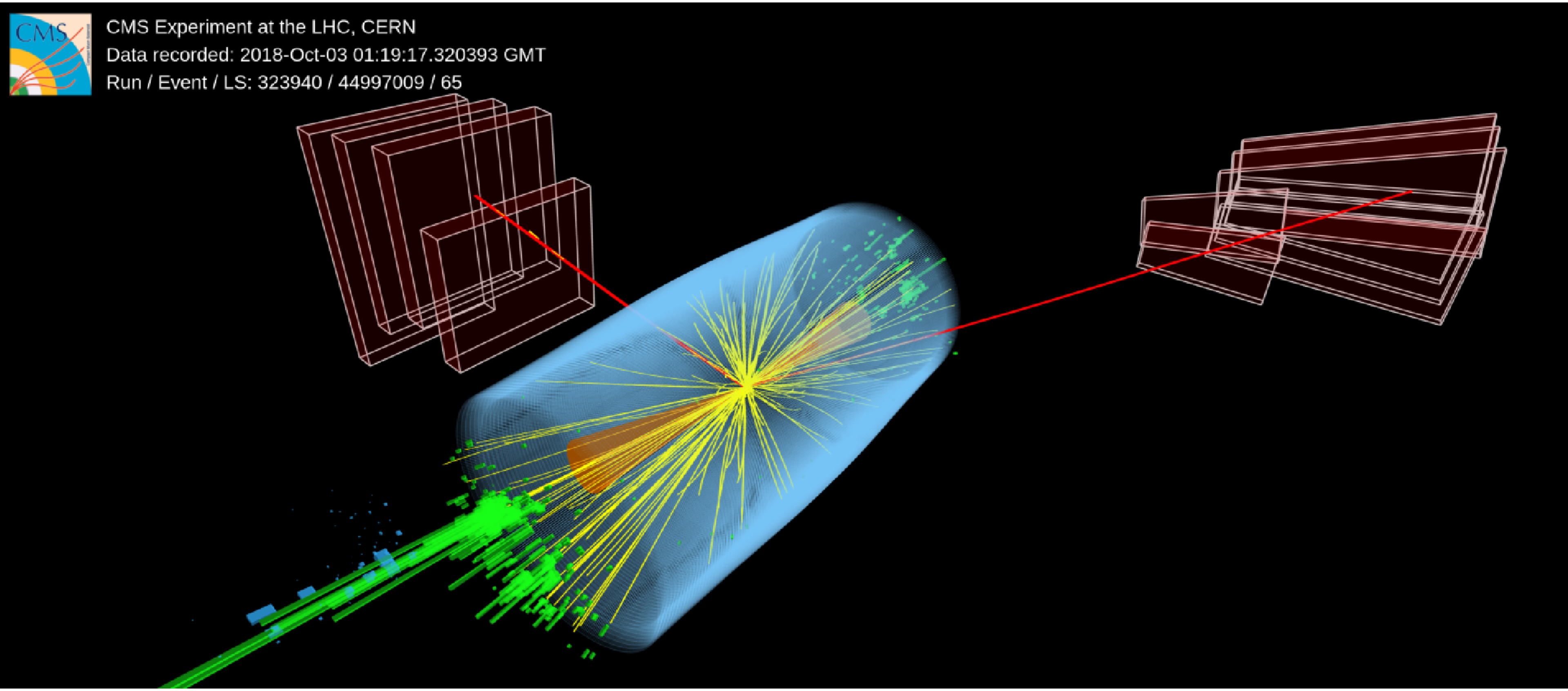




Obs (exp) significance : 2.0 (0.4)σ

Signal Strength $\mu = \sigma/\sigma_{SM}$ =5.48+3.10-2.83

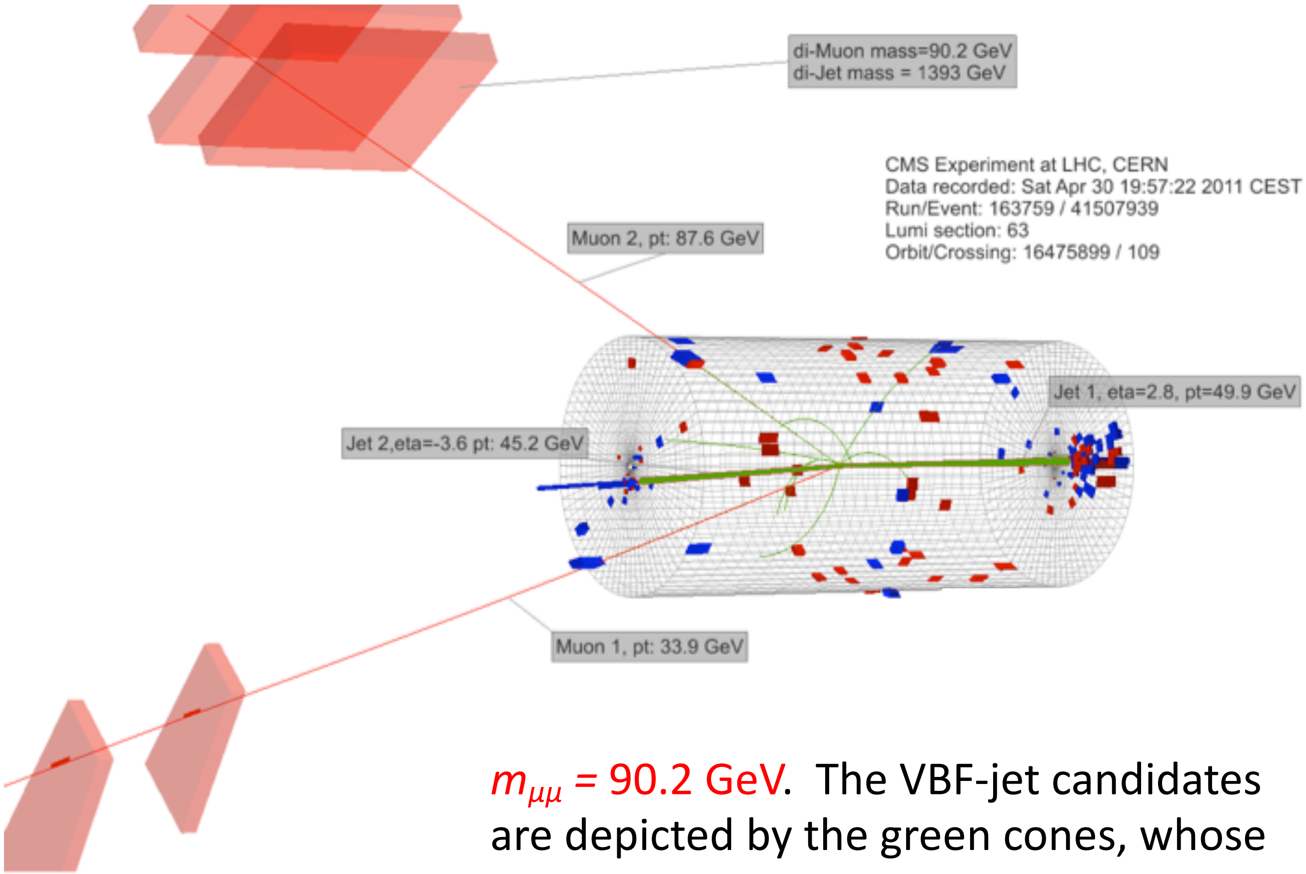
Eventi VBF

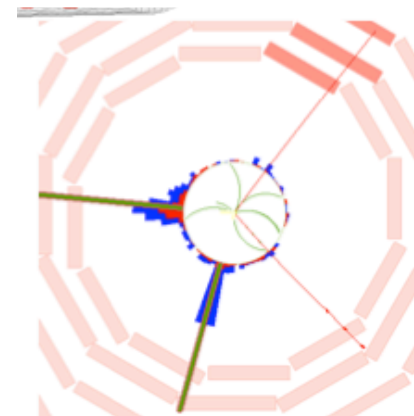


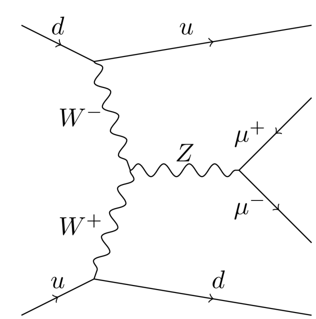
$m_{\mu\mu}$ = 125.01 ±1.83 GeV. The VBF-jet candidates are depicted by the orange cones whose invariant mass (*m*jj) is 2.19 TeV. No additional leptons (electrons or muons) with *p*T > 20 GeV are present in the event.

Un salto indietro nel tempo
VBF Z→ μμ

2011 pp @7TeV





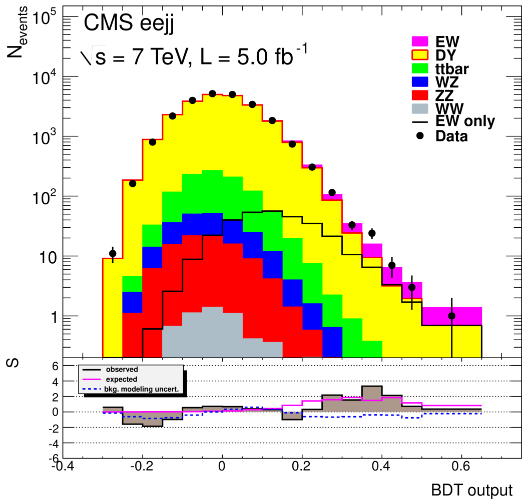


$m_{\mu\mu}$ = 90.2 GeV. The VBF-jet candidates are depicted by the green cones, whose invariant mass (*m*jj) is 1.39 TeV.

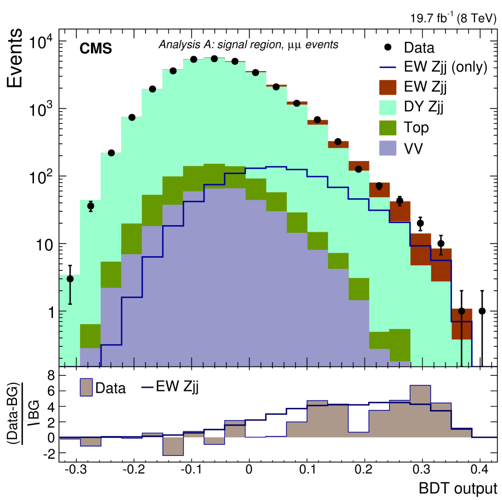
VBF Z→ ℓℓ

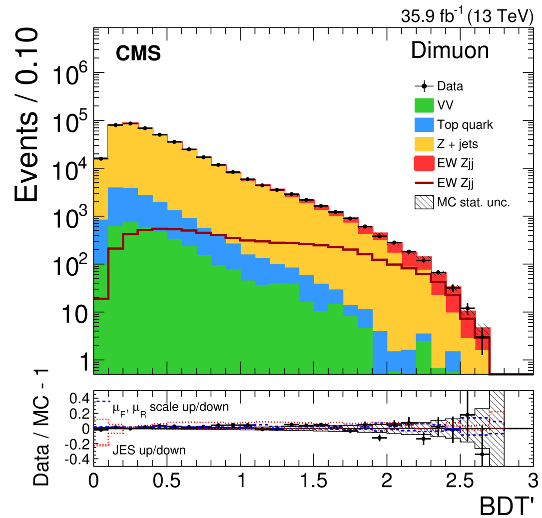
J. High Energy Phys. 10 (2013) 062

The first measurement of the electroweak production cross section of a Z boson with two jets (Zjj) in pp collisions at sqrt(s) = 7 TeV is presented, based on a data sample recorded by the CMS experiment at the LHC with an integrated luminosity of 5 inverse femtobarns …
These results establish an important foundation for the more general study of vector boson fusion processes, of relevance for Higgs boson searches and for measurements of electroweak gauge couplings and vector boson scattering.



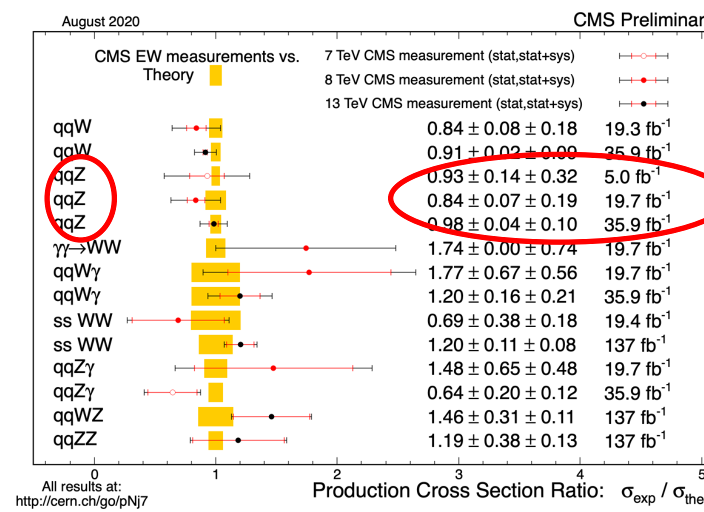
Eur. Phys. J. C 75 (2015) 66





Eur. Phys. J. C 78 (2018) 589

Summary of VBF/VBS results

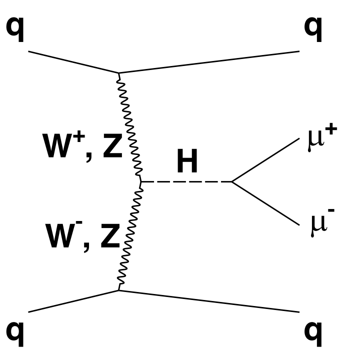


~10% precision on VBF Z

91 GeV → 125 GeV

Let's go for VBF H→μμ !

VBF H → μμ



- Highest achievable signal purity but with low event statistics (~10)
- Good simulation precision in modelling the relevant backgrounds

➔ signal extraction method **fully based on Monte Carlo**

➔ **20% improvement** wrt data-driven fit

Observable	VBF-SB	VBF-SR
Number of loose (medium) b-tagged jets	$\leq$1 (0)	
Number of selected muons	=2	
Number of selected electrons	=0	
Jet multiplicity ($p_T > 25$ GeV, $\lvert\eta\rvert < 4.7$)	$\geq$2	
Leading jet p_T	$\geq$35 GeV	
Dijet mass (m_{jj})	$\geq$400 GeV	
Pseudorapidity separation ($\lvert\Delta\eta_{jj}\rvert$)	$\geq$2.5	
Dimuon invariant mass	$110 < m_{\mu\mu} < 115$ GeV or $135 < m_{\mu\mu} < 150$ GeV	$115 < m_{\mu\mu} < 135$ GeV

MVA classifier includes $m_{\mu\mu}$!

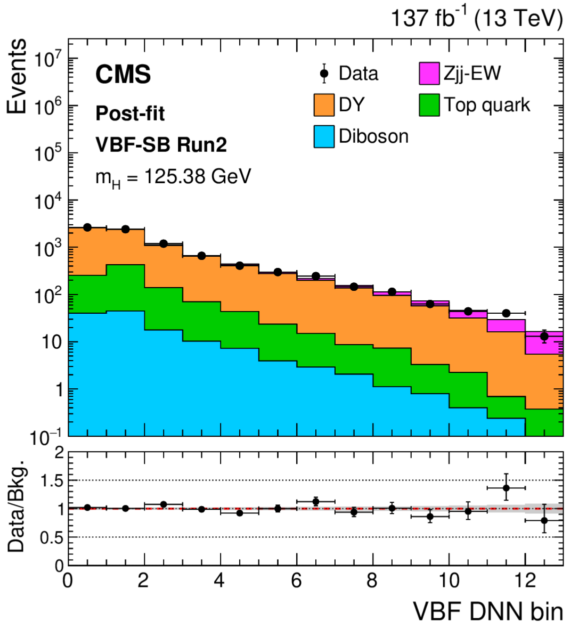
Variables used and/or studied in the VBF Z measurements

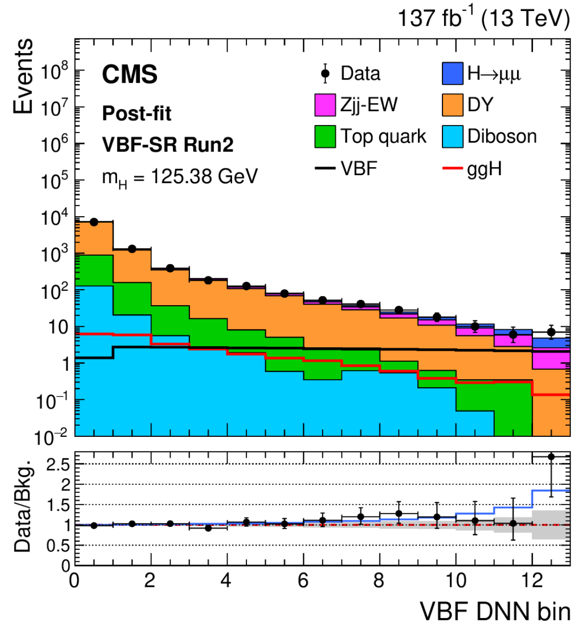
- $m(\mu\mu)$, $\Delta m(\mu\mu)_{rel}$, $\Delta m(\mu\mu)$ - the dimuon mass and the relative and absolute mass resolutions
- $m(jj)$, $\log m(jj)$ - the dijet mass and its logarithm
- $R(p_T)$
- $z*$
- $\Delta\eta(jj)$ - the pseudorapidity difference between the 2 selected jets
- N_5^{soft} - # soft jet with $p_T > 5$ GeV
- $\min_j \Delta\eta(\mu\mu, j)$ - the minimum pseudorapidity difference between a jet and the dimuon system
- $p_T(\mu\mu)$, $\log p_T(\mu\mu)$, $\eta(\mu\mu)$ - dimuon 4-vector components
- $p_T(j_1)$, $p_T(j_2)$, $\eta(j_1)$, $\eta(j_2)$, $\phi(j_1)$, $\phi(j_2)$ - jets' 4-vectors components
- $qgl(j_1)$, $qgl(j_2)$ - the the quark-gluon likelihood discriminators for the selected jets.

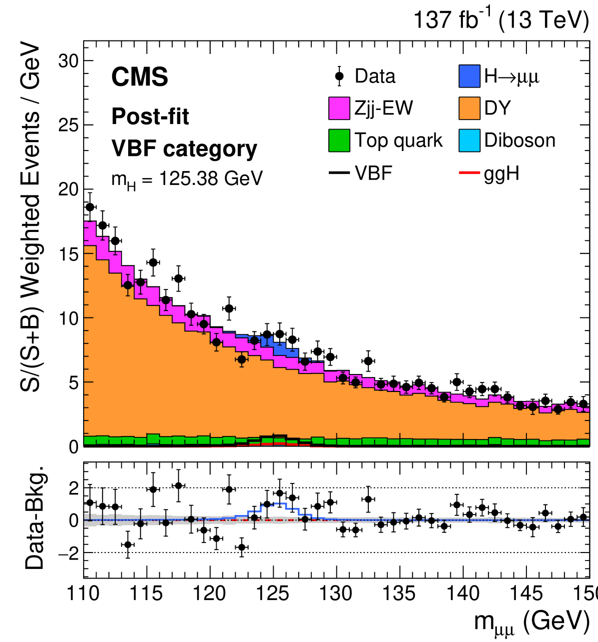
Some peculiar inputs :

- (soft) track-jet activity in the rapidity gap
- quark-gluon jet likelihood

VBF H→ **μμ**







$m_{\mu\mu}$ → [110, 115] or [135, 150] GeV

115 < $m_{\mu\mu}$ < 135 GeV

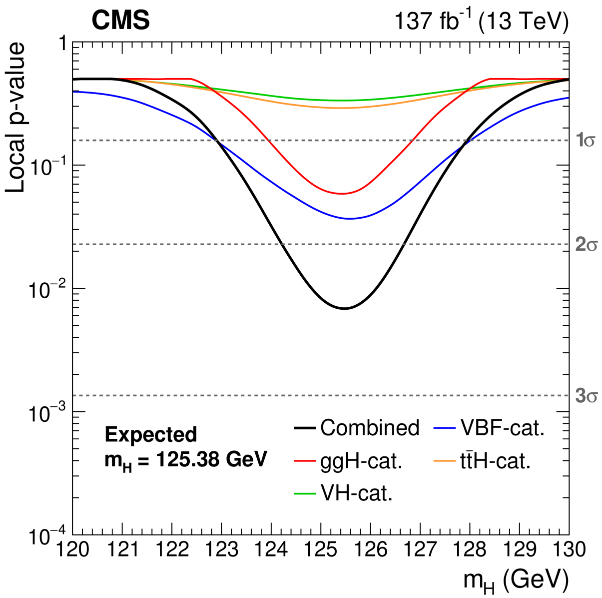
DNN bin	Total signal	VBF (%)	ggH (%)	Bkg. ± ΔB	Data	S/(S+B) (%)	$S/\sqrt{B}$
1–3	19.5	30	70	8890 ± 67	8815	0.22	0.21
4–6	11.6	57	43	394 ± 8	388	2.86	0.58
7–9	8.43	73	27	103 ± 4	121	7.56	0.83
10	2.30	85	15	15.1 ± 1.4	18	13.2	0.59
11	2.15	88	12	9.1 ± 1.2	10	19.1	0.71
12	2.10	87	13	5.8 ± 1.1	6	26.6	0.87
13	1.87	94	6	2.6 ± 0.9	7	41.8	1.16

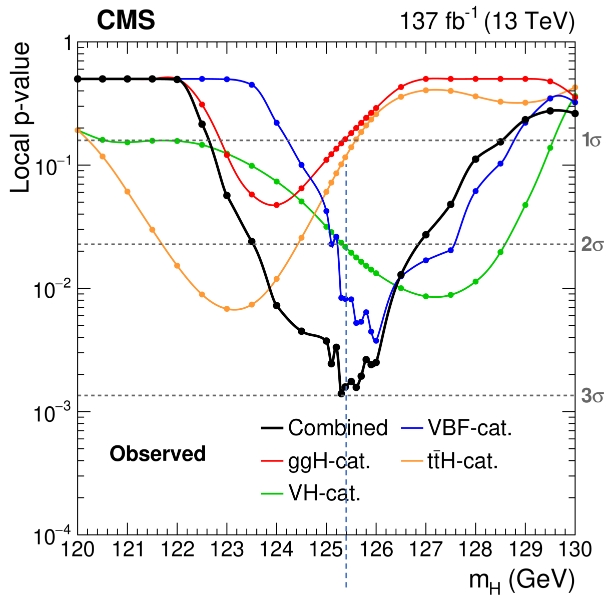
Obs (exp) significance : 2.4 (1.8)σ

Signal Strength

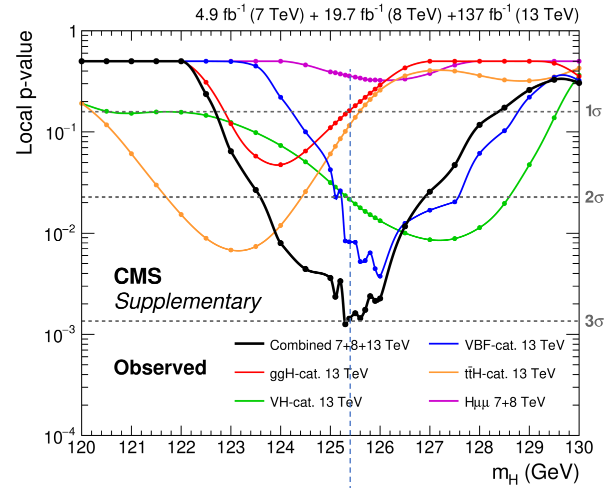
$\mu = \sigma/\sigma_{SM}$=1.36 +0.69 -0.61

Risultati combinati : p-value vs m_H





125.38

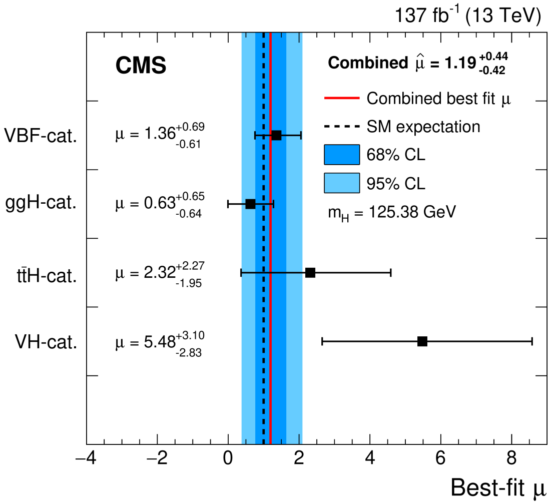


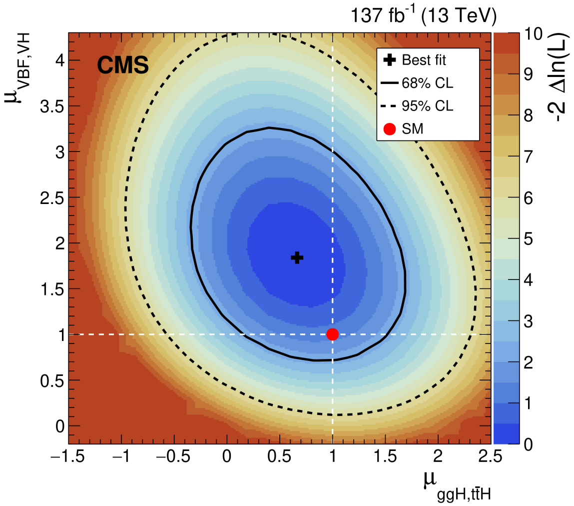
125.38

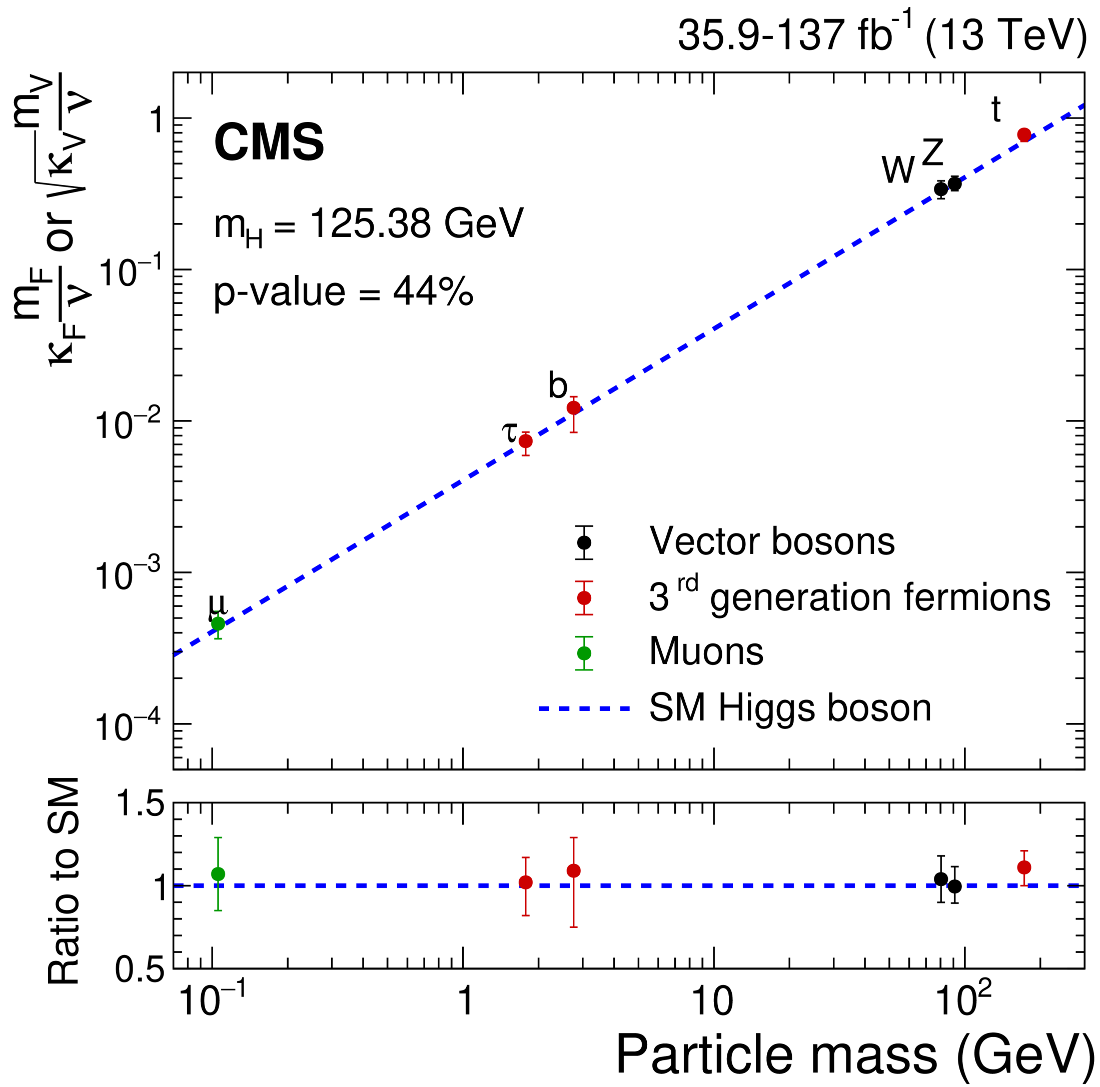
Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
$t\bar{t}$H	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7, 8, 13$ TeV	2.98 (2.48)	1.93 (0.81)

Obs. (Exp.) Significance
3.0σ (2.5σ) at 125.38 GeV

Risultati combinati







Dove si sono prodotti i risultati

il Tier-2 CMS a Pisa ha avuto un ruolo essenziale in questa e in tante altre analisi dei dati CMS

Le parti dell'analisi H$\rightarrow\mu\mu$ svolte a Pisa sono state interamente realizzate sulle risorse di calcolo locali

Evidenza del decadimento del bosone di Higgs in muoni !

- Prima prova dell'*accoppiamento ai fermioni più leggeri della seconda generazione* : un altra conferma delle predizioni del Modello Standard.
- Analisi CMS condotta da *Pisa* e UCSD, MIT, Caltech, Hamburg, UFlorida, Purdue
- *Miglioramento molto sostanziale delle prestazioni dell'analisi* rispetto a risultati e proiezioni precedenti
- Questa misura, e tante altre analisi di LHC, sono chiaramente *limitate dalla statistica*
- I dati del Run3 (e HL) *miglioreranno* queste misure, e ne porteranno a galla altre. Sia grazie alla luminosità che all'evoluzione delle prestazioni delle analisi.

Backup

Selezione degli eventi

Observable	VBF-SB	VBF-SR
Number of loose (medium) b-tagged jets	$\leq$1 (0)	
Number of selected muons	=2	
Number of selected electrons	=0	
Jet multiplicity ($p_T > 25\,\text{GeV}$, $\|\eta\| < 4.7$)	$\geq$2	
Leading jet p_T	$\geq$35 GeV	
Dijet mass (m_{jj})	$\geq$400 GeV	
Pseudorapidity separation ($\|\Delta\eta_{jj}\|$)	$\geq$2.5	
Dimuon invariant mass	$110 < m_{\mu\mu} < 115\,\text{GeV}$ or $135 < m_{\mu\mu} < 150\,\text{GeV}$	$115 < m_{\mu\mu} < 135\,\text{GeV}$

Observable	Selection
Number of loose (medium) b-tagged jets	$\leq$1 (0)
Number of selected muons	=2
Number of selected electrons	=0
VBF selection veto	if $N_{jets} \geq 2$ $m_{jj} < 400\,\text{GeV}$ or $\|\Delta\eta_{jj}\| < 2.5$ or $p_T(j_1) < 35\,\text{GeV}$

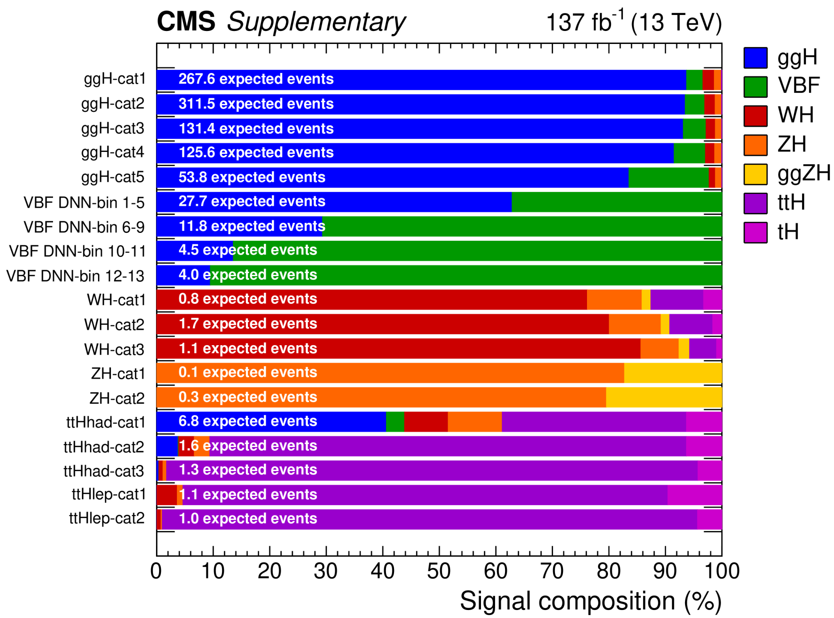
Observable	WH leptonic		ZH leptonic	
	$\mu\mu\mu$	$\mu\mu$e	4μ	2μ2e
Number of loose (medium) b-tagged jets	$\leq$1 (0)	$\leq$1 (0)	$\leq$1 (0)	$\leq$1 (0)
Number of selected muons	=3	=2	=4	=2
Number of selected electrons	=0	=1	=0	=2
Lepton charge ($q(\ell)$)	$\sum q(\ell) = \pm 1$		$\sum q(\ell) = 0$	
Low-mass resonance veto	$m_{\ell\ell} > 12\,\text{GeV}$			
$N(\mu^+\mu^-)$ pairs with $110 < m_{\mu\mu} < 150\,\text{GeV}$	$\geq$1	=1	$\geq$1	=1
$N(\mu^+\mu^-)$ pairs with $\|m_{\mu\mu} - m_Z\| < 10\,\text{GeV}$	=0	=0	=1	=0
$N(e^+e^-)$ pairs with $\|m_{ee} - m_Z\| < 20\,\text{GeV}$	=0	=0	=1	=1

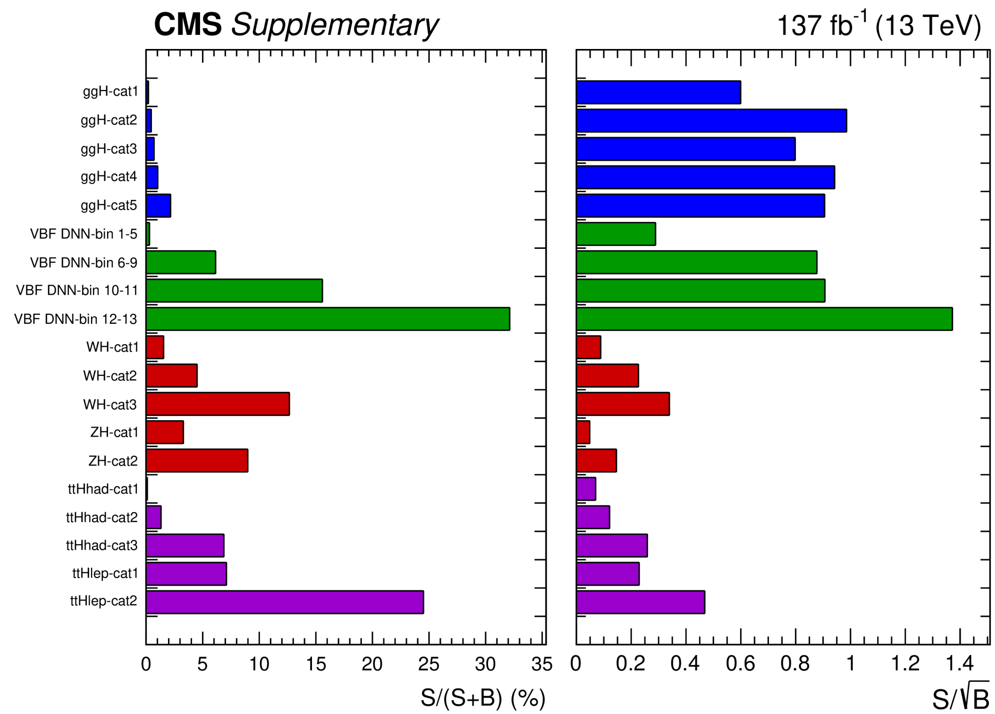
Selezione degli eventi

Event category	Total signal	WH (%)	qqZH (%)	ggZH (%)	$t\bar{t}H$+tH (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	$S/\sqrt{B}$ @HWHM
WH-cat1	0.82	76.2	9.6	1.6	12.6	2.00	BWZγ	32.0	34	1.54	0.09
WH-cat2	1.72	80.1	9.1	1.5	9.3	1.80	BWZ	23.1	27	4.50	0.23
WH-cat3	1.14	85.7	6.7	1.8	4.8	1.90	BWZ	5.48	4	12.6	0.35
ZH-cat1	0.11	—	82.8	17.2	—	2.07	BWZ	2.05	4	3.29	0.05
ZH-cat2	0.31	—	79.6	20.4	—	1.80	BWZ	2.19	4	8.98	0.14

Event category	Total signal	$t\bar{t}H$ (%)	ggH (%)	VH (%)	Other (%)	HWHM (GeV)	Bkg. fit function	Bkg. @HWHM	Data @HWHM	S/(S+B) (%) @HWHM	$S/\sqrt{B}$ @HWHM
$t\bar{t}$Hhad-cat1	6.87	32.3	40.3	17.2	10.2	1.85	Bern(2)	4298	4251	1.07	0.07
$t\bar{t}$Hhad-cat2	1.62	84.3	3.8	5.6	6.2	1.81	Bern(2)	82.0	89	1.32	0.12
$t\bar{t}$Hhad-cat3	1.33	94.0	0.3	1.3	4.4	1.80	S-Exp	12.3	12	6.87	0.26
$t\bar{t}$Hlep-cat1	1.06	85.8	—	4.7	9.5	1.92	Exp	9.00	13	7.09	0.22
$t\bar{t}$Hlep-cat2	0.99	94.7	—	1.0	4.3	1.75	Exp	2.08	4	24.5	0.47

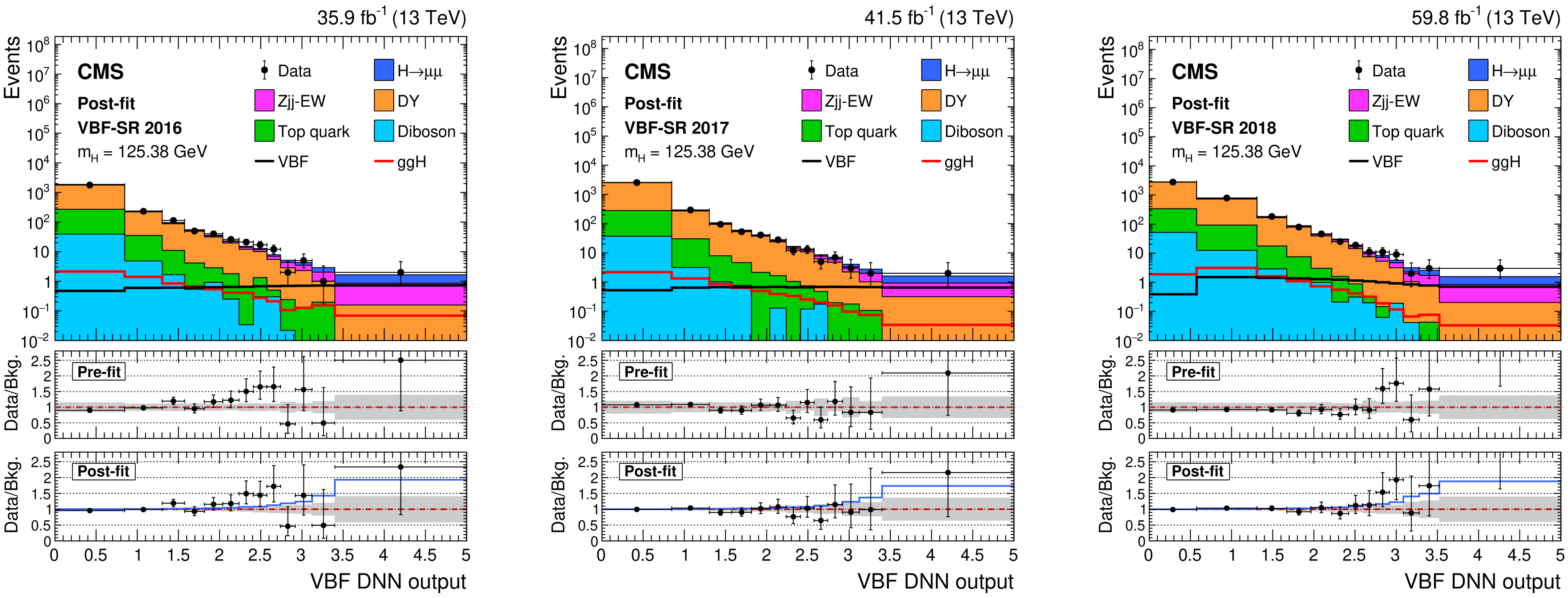
Purezza, significanza



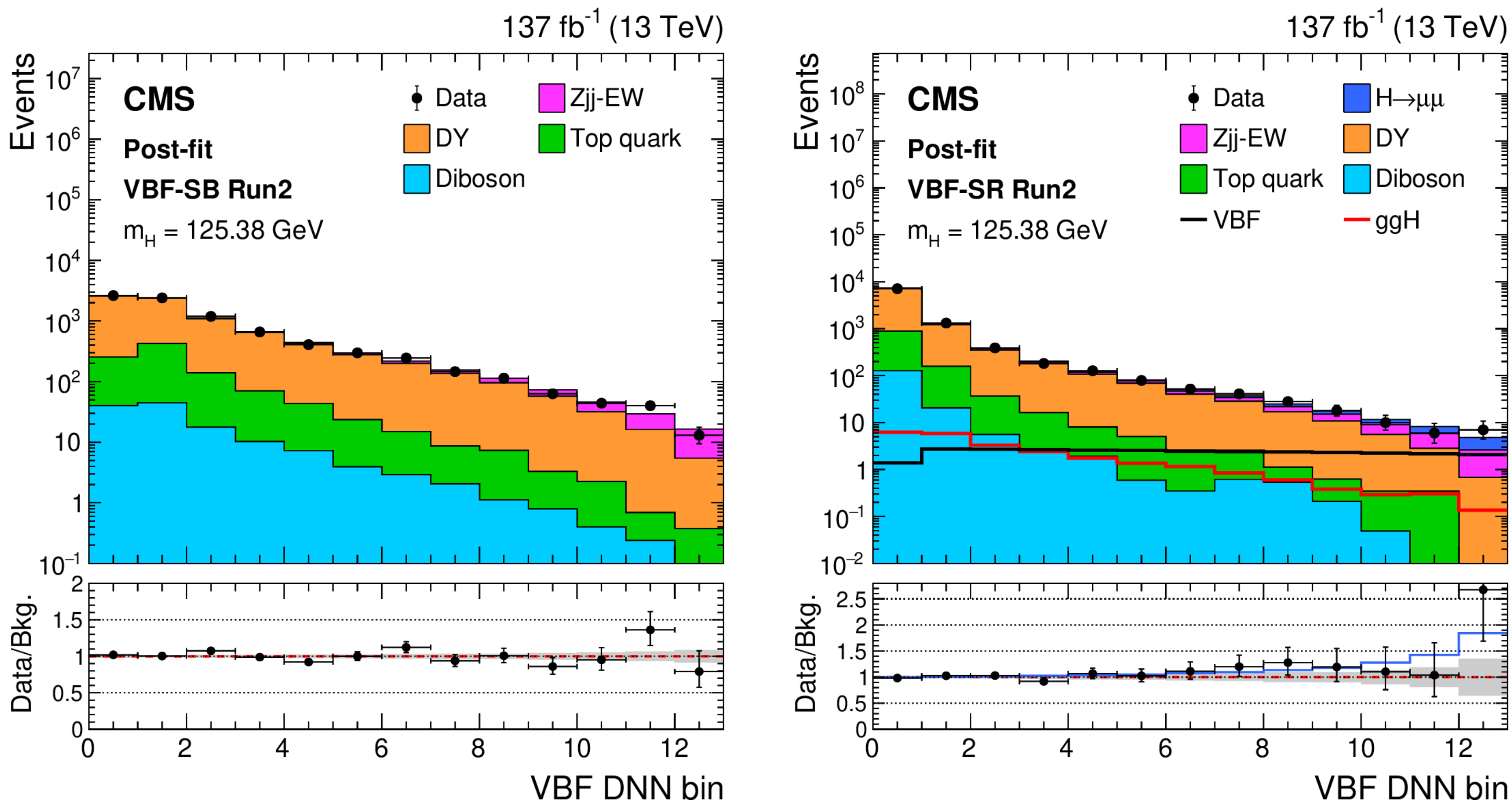


Composizione

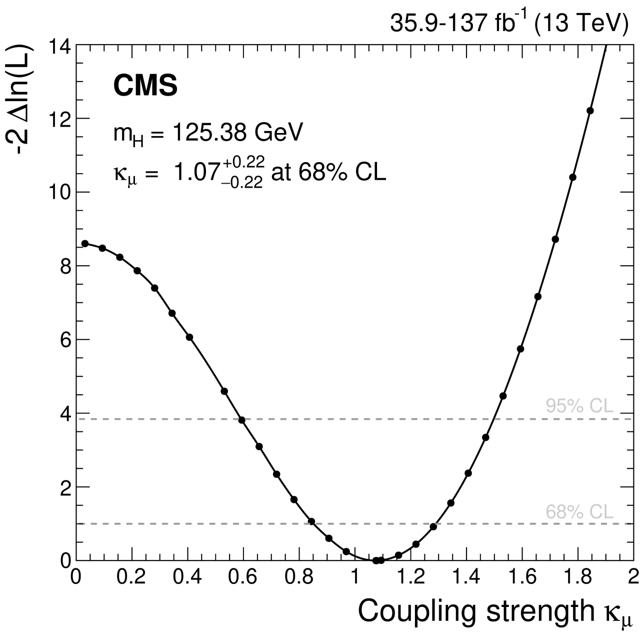
VBF DNN per anno

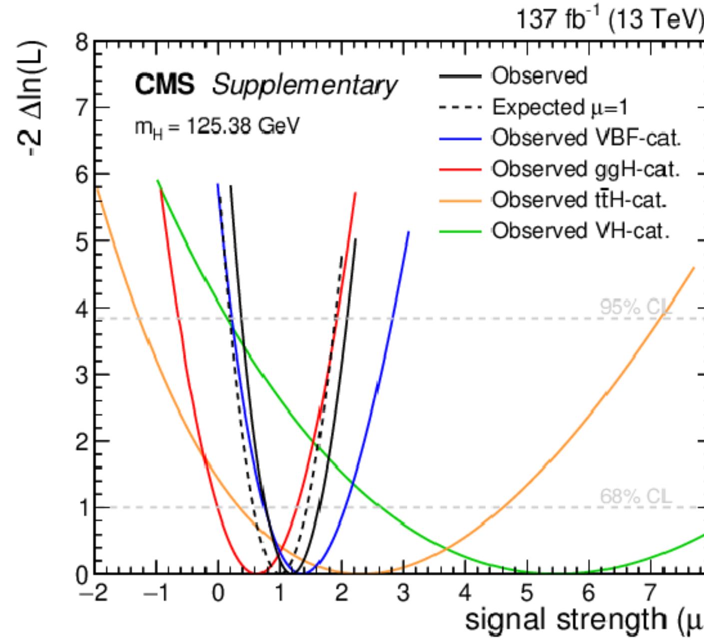


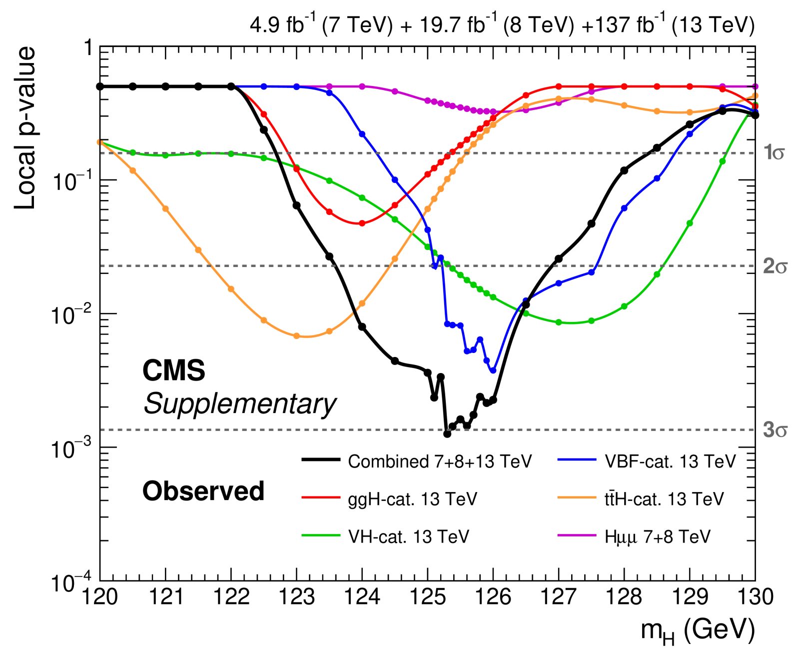
VBF Sideband vs Signal



Risultati


35.9-137 fb-1 (13 TeV)
CMS
mH = 125.38 GeV
κμ = 1.07+0.22−0.22 at 68% CL
95% CL
68% CL
-2 ΔIn(L)
Coupling strength κμ


137 fb-1 (13 TeV)
CMS Supplementary
mH = 125.38 GeV
Observed
Expected μ=1
Observed VBF-cat.
Observed ggH-cat.
Observed tt̄H-cat.
Observed VH-cat.
95% CL
68% CL
-2 ΔIn(L)
signal strength (μ)


4.9 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) +137 fb-1 (13 TeV)
Local p-value
1σ
2σ
3σ
CMS
Supplementary
Observed
Combined 7+8+13 TeV
VBF-cat. 13 TeV
ggH-cat. 13 TeV
tt̄H-cat. 13 TeV
VH-cat. 13 TeV
Hμμ 7+8 TeV
mH (GeV)

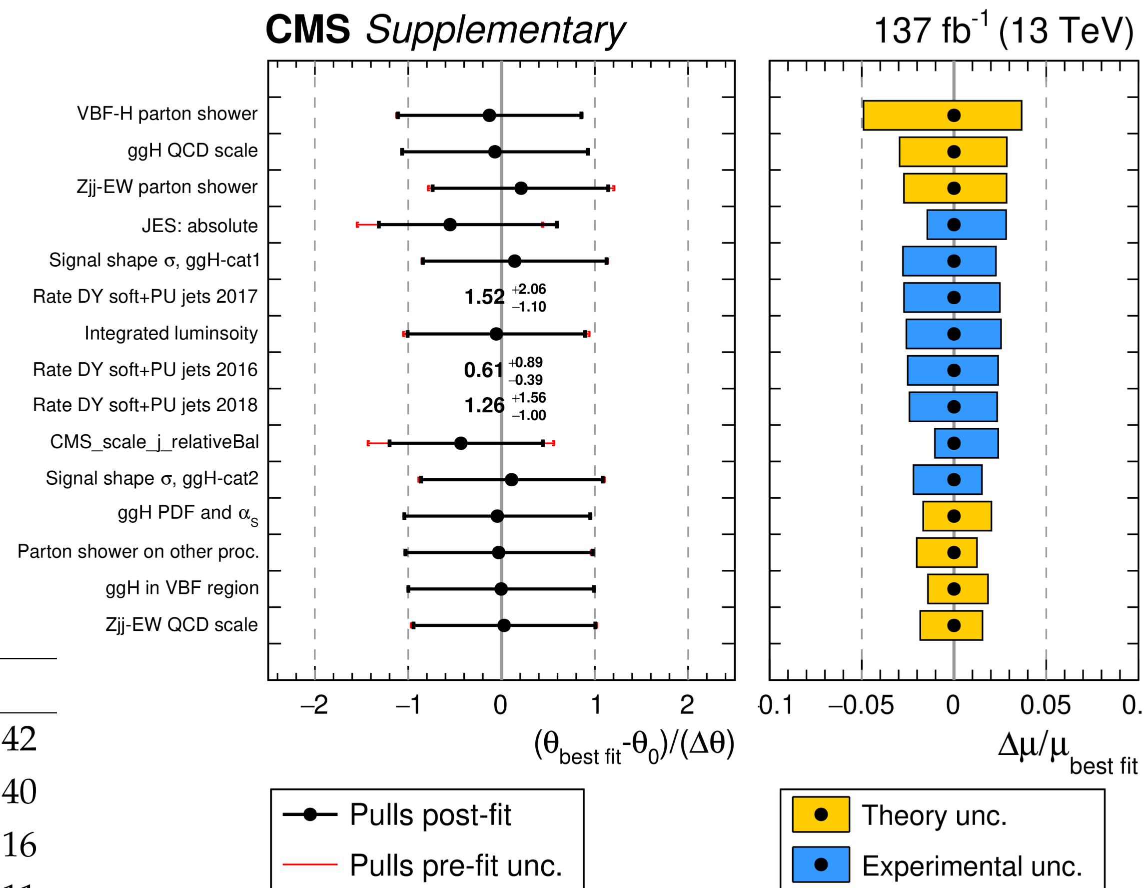
Simulazioni

Process	Generator (Perturbative order)	Parton shower	Cross section	Additional corrections
ggH	MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	N3LO QCD, NLO EW	$p_T(H)$ from NNLOPS
VBF	POWHEG (NLO QCD)	PYTHIA dipole shower	NNLO QCD, NLO EW	—
$qq \to VH$	POWHEG (NLO QCD)	PYTHIA	NNLO QCD, NLO EW	—
$gg \to ZH$	POWHEG (LO)	PYTHIA	NNLO QCD, NLO EW	—
$t\bar{t}H$	POWHEG (NLO QCD)	PYTHIA	NLO QCD, NLO EW	—
$b\bar{b}H$	POWHEG (NLO QCD)	PYTHIA	NLO QCD	—
tHq	MadGraph5_aMC@NLO (LO)	PYTHIA	NLO QCD	—
tHW	MadGraph5_aMC@NLO (LO)	PYTHIA	NLO QCD	—
Drell–Yan	MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	NNLO QCD, NLO EW	—
Zjj-EW	MadGraph5_aMC@NLO (LO)	HERWIG++/HERWIG 7	LO	—
$t\bar{t}$	POWHEG (NLO QCD)	PYTHIA	NNLO QCD	—
Single top quark	POWHEG/MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	NLO QCD	—
Diboson (VV)	POWHEG/MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	NLO QCD	NNLO/NLO K factors
$gg \to ZZ$	MCFM (LO)	PYTHIA	LO	NNLO/LO K factors
$t\bar{t}V$, $t\bar{t}VV$	MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	NLO QCD	—
Triboson (VVV)	MadGraph5_aMC@NLO (NLO QCD)	PYTHIA	NLO QCD	—

Sistematiche

Source of uncertainty	Categories and processes	Type	Correlation vs cat.	Correlation vs year
		Experimental uncertainties		
Integrated luminosity	Sig. in all cat., bkg. in VBF	Rate	Correlated	Partial
Muon efficiency	Sig. in all cat., bkg. in VBF	Rate	Correlated	Correlated
Electron efficiency	Sig. in $t\bar{t}H$ and VH	Rate	Correlated	Correlated
Muon trigger	Sig. in all cat., bkg. in VBF	Rate	Correlated	Correlated
Muon p_T scale	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
Nonprompt leptons	Sig. in $t\bar{t}H$ and VH	Rate	Correlated	Correlated
Pileup model	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
L1 inefficiency	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
B-tagging efficiency	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
Jet energy scale	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Partial
Jet energy resolution	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Uncorrelated
		Theoretical uncertainties		
μ_R and μ_F for ggH	ggH in all cat.	Rate	Correlated	Correlated
μ_R and μ_F for VBF	VBF in all cat.	Rate	Correlated	Correlated
μ_R and μ_F for $t\bar{t}H$	$t\bar{t}H$ in all cat.	Rate	Correlated	Correlated
μ_R and μ_F for VH	VH in all cat.	Rate	Correlated	Correlated
PDF for ggH	ggH in all cat.	Rate	Correlated	Correlated
PDF for VBF	VBF in all cat.	Rate	Correlated	Correlated
PDF for $t\bar{t}H$	$t\bar{t}H$ in all cat.	Rate	Correlated	Correlated
PDF for VH	VH in all cat.	Rate	Correlated	Correlated
ggH accept. vs (p_T(H),N_j,m_{jj})	ggH in all cat.	Shape in VBF, rate in others	Correlated	Correlated
VBF accept. vs (p_T(H),N_j,m_{jj})	VBF in all cat.	Shape in VBF, rate in others	Correlated	Correlated
$t\bar{t}H$ accept. from μ_R and μ_F	$t\bar{t}H$ in all cat.	Rate	Correlated	Correlated
VH accept. from μ_R and μ_F	VH in all cat.	Rate	Correlated	Correlated
$t\bar{t}H$ accept. from PDF	$t\bar{t}H$ in all cat.	Rate	Correlated	Correlated
VH accept. from PDF	VH in all cat.	Rate	Correlated	Correlated
PYTHIA ISR and FSR	Sig. in all cat., bkg. in VBF	Shape in VBF, rate in others	Correlated	Correlated
PYTHIA vs HERWIG)	VBF and Zjj-EW in VBF cat.	Shape	Correlated	Correlated
μ_R and μ_F for Drell–Yan	VBF cat.	Shape	Correlated	Correlated
μ_R and μ_F for Zjj-EW	VBF cat.	Shape	Correlated	Correlated
μ_R and μ_F for top bkgs.	VBF cat.	Shape	Correlated	Correlated
μ_R and μ_F for diboson	VBF cat.	Shape	Correlated	Correlated
PDF for Drell–Yan	VBF cat.	Shape	Correlated	Correlated
PDF for Zjj-EW	VBF cat.	Shape	Correlated	Correlated
PDF for top bkgs.	VBF cat.	Shape	Correlated	Correlated
PDF for dibosons	VBF cat.	Shape	Correlated	Correlated
Size of simulated samples	VBF cat.	Bin-by-bin	—	Uncorrelated

Sistematiche



Uncertainty source	$\Delta\mu$	
Post-fit uncertainty	+0.44	−0.42
Statistical uncertainty	+0.41	−0.40
Systematic uncertainty	+0.17	−0.16
Experimental uncertainty	+0.12	−0.11
Theoretical uncertainty	+0.10	−0.11
Size of simulated samples	+0.07	−0.06