Search for the Higgs boson at

D0, CMS and ATLAS

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Outline

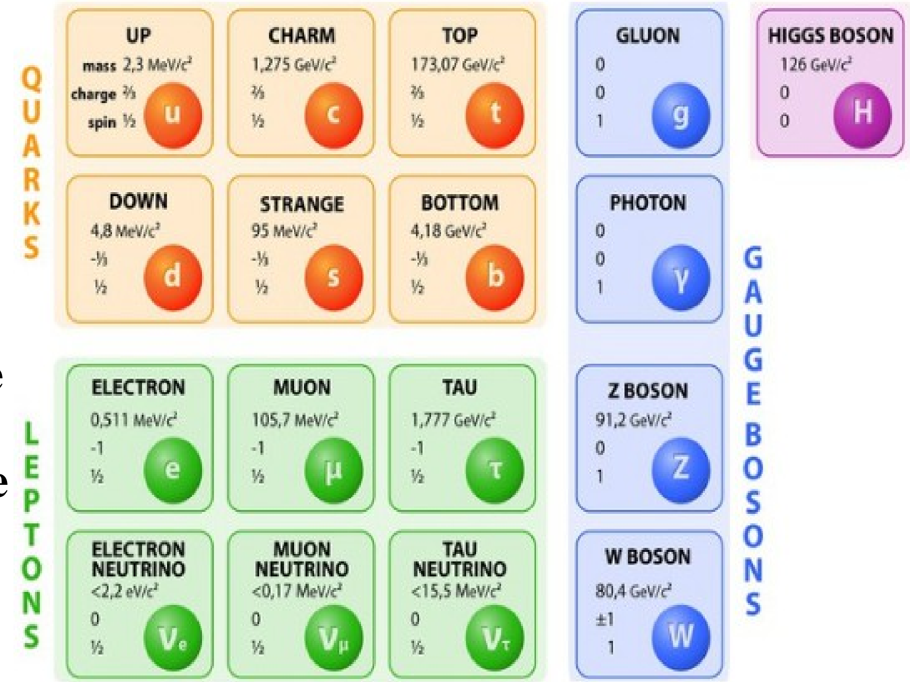
1. Introduction
2. Search for ZH in b jets channel at D0
3. Search for WH in hadronic taus channel at CMS
4. Search for ttH in mutileptonic channels at ATLAS
5. Combined ATLAS and CMS run 1 Higgs results
6. Summary

1. Introduction

1.a The Higgs boson particle

- **The Standard Model (SM *) of particle physics, developed in the 20th century, describes elementary particles and their interactions.**

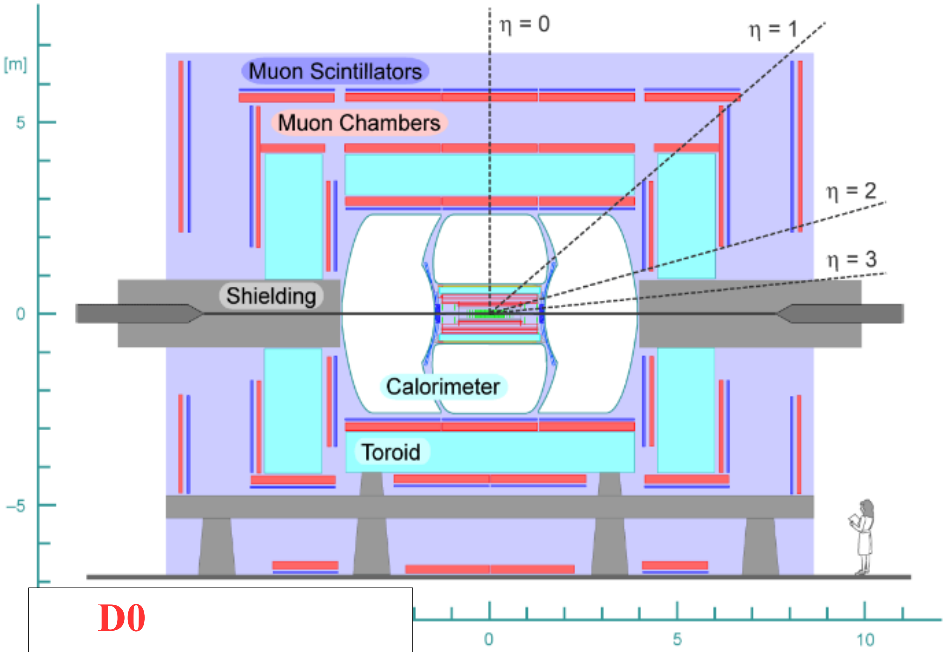
(*)



- **The discovery of the The Higgs boson particle (a quantum excitation of the Higgs field which gives mass to particles) in 2012 at the LHC, is an epilogue to a search started 35 years ago. It top a remarkable list of experimentally confirmed SM predictions.**

- **Several experiments have search for the Higgs boson:**
  - **LEP: CERN, e^+e^-, 100 GeV, 1989-2000.**
  - **Tevatron: FERMILAB (CDF, D0), pp^{bar}, 2 TeV, 1983-2011.**
  - **LHC: CERN (CMS, ATLAS), pp, 13 TeV, 2009-present.**

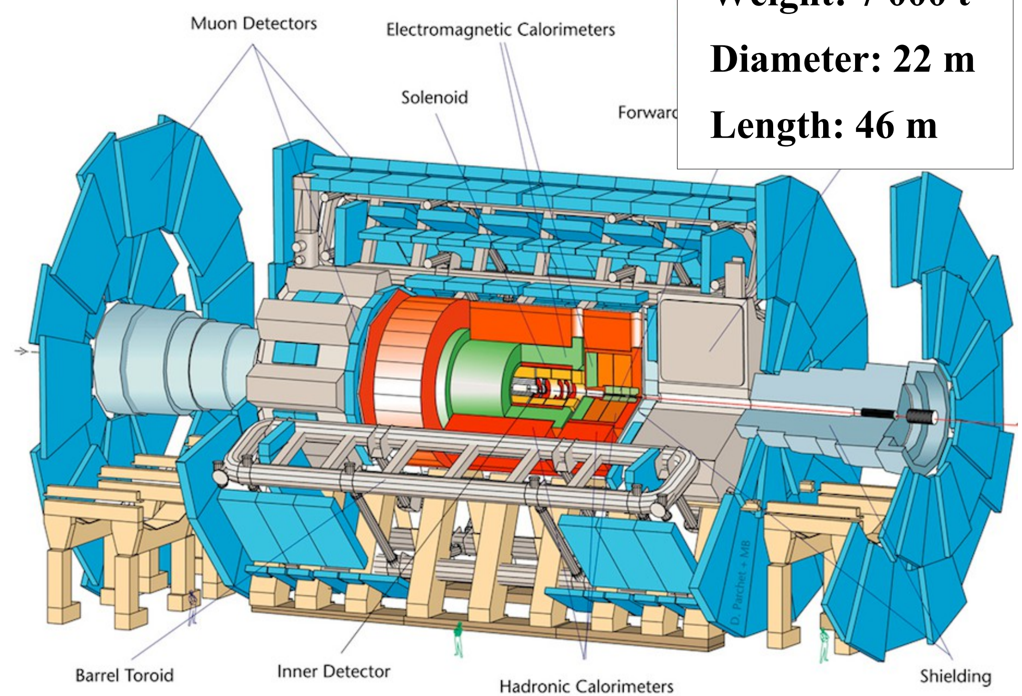
1.b D0, CMS and ATLAS detectors



D0

Diameter: 7 m

Length: 18 m

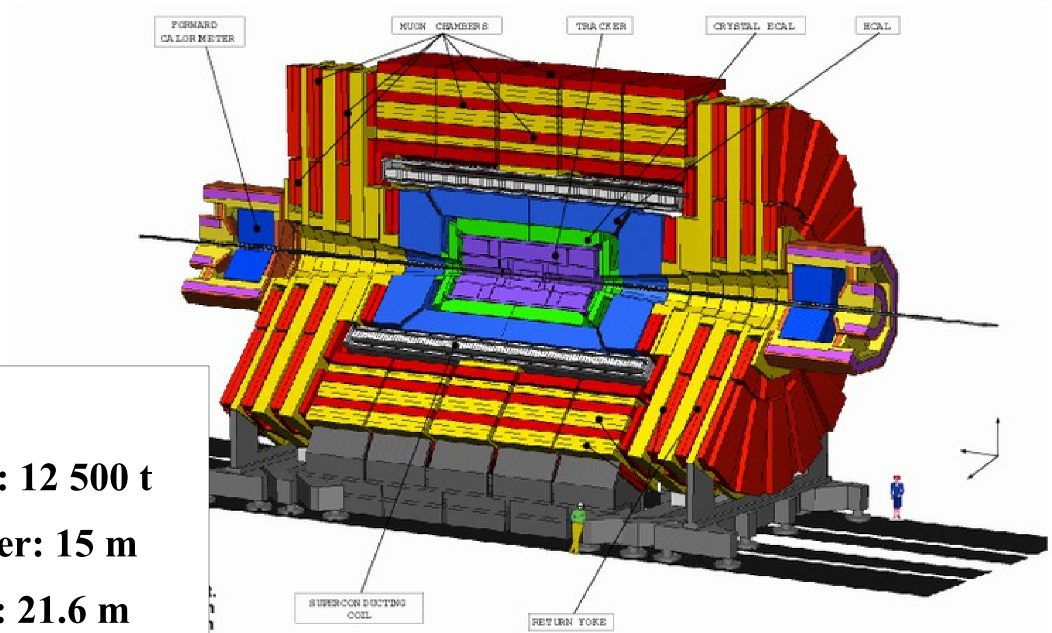


ATLAS

Weight: 7 000 t

Diameter: 22 m

Length: 46 m



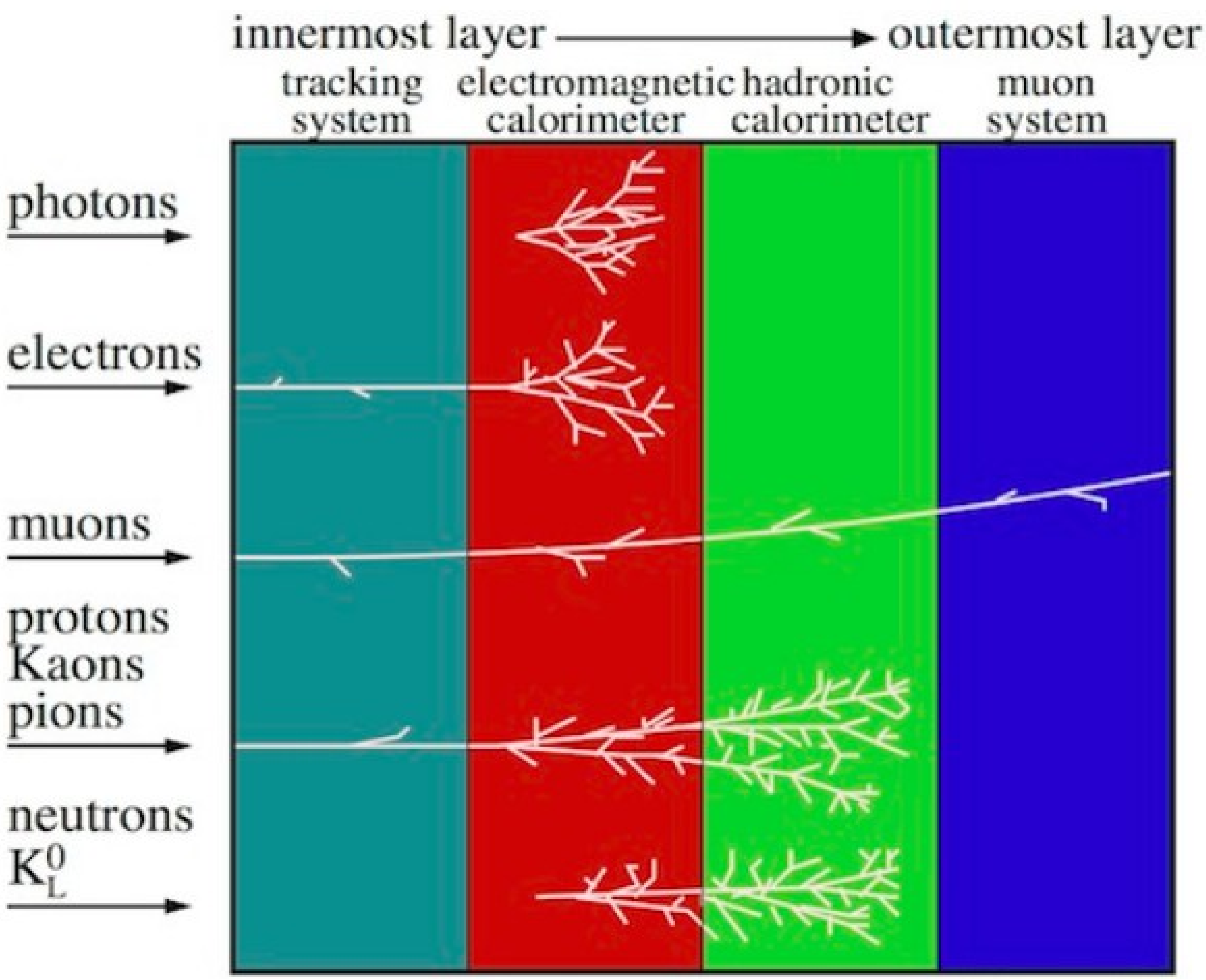
CMS

Weight: 12 500 t

Diameter: 15 m

Length: 21.6 m

1.c Main components of particle physics detector



Each particle type has its own signature in the detector.

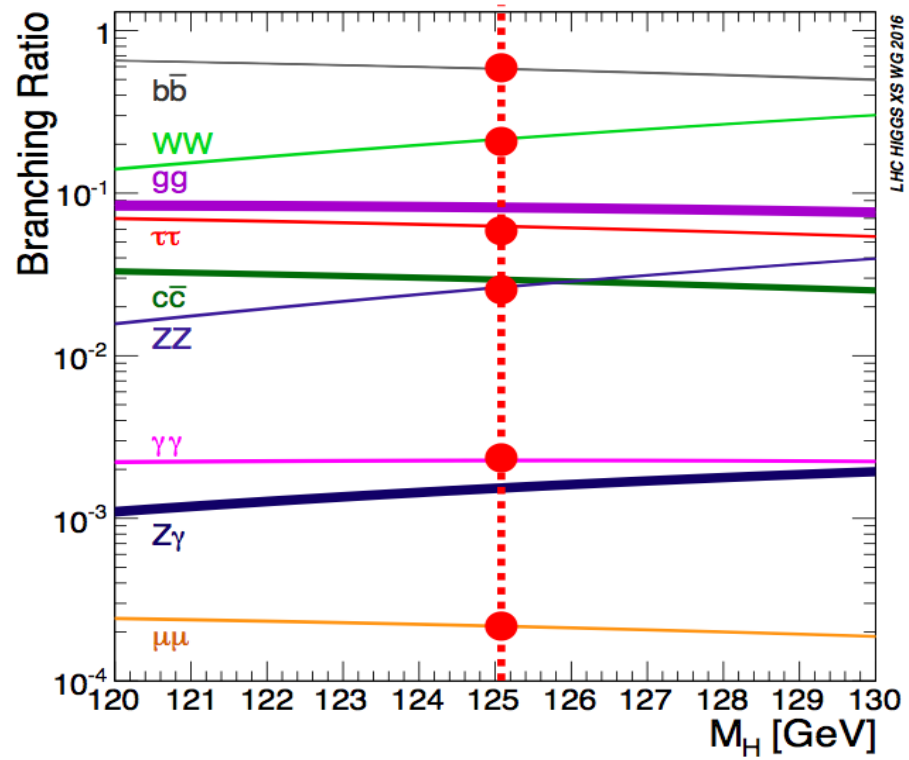
1.d SM Higgs boson decay and production mode

Higgs boson life time 1,56.10^{-22} s

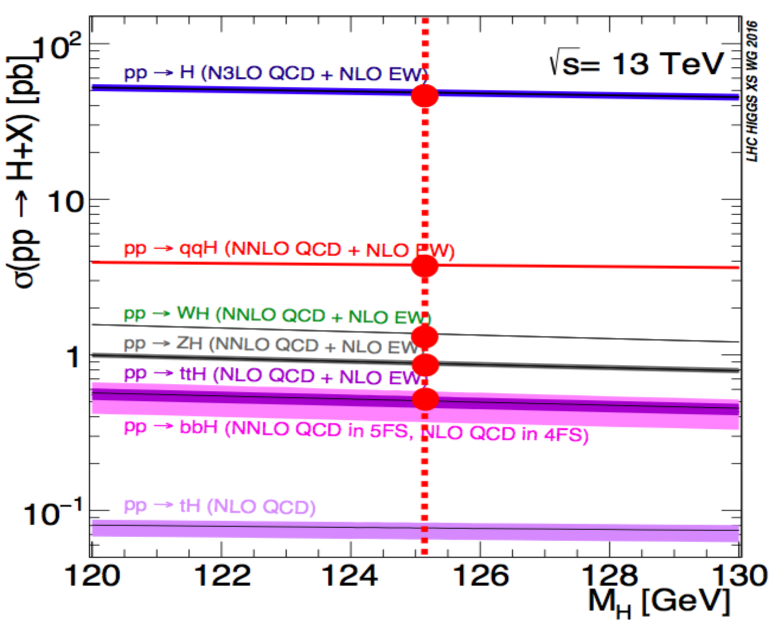
Channels presented today

- ZH → leptons, bb (D0)
- WH → lepton, ττ (CMS)
- ttH → lepton/jet, WW/ZZ/ττ (ATLAS)

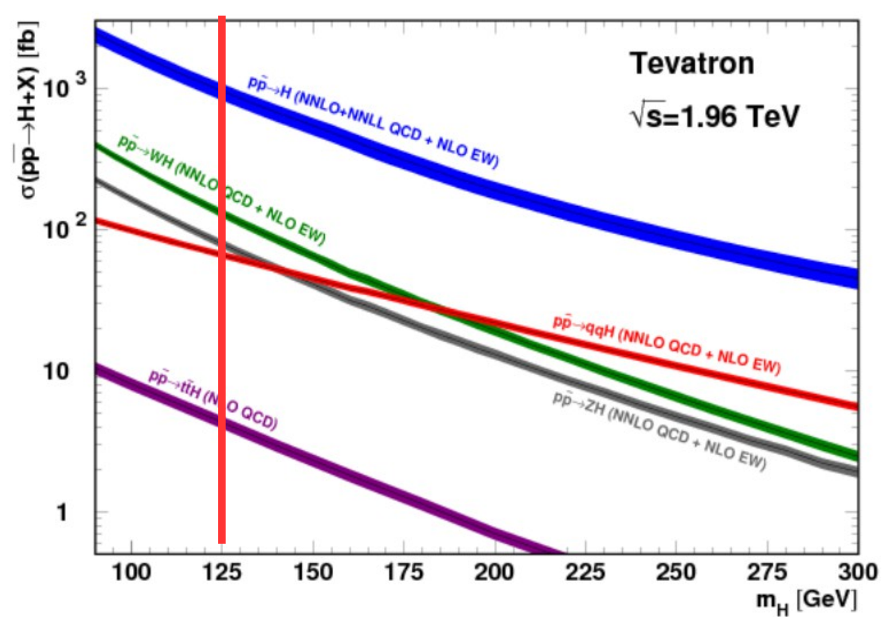
Higgs boson decay rate



Higgs boson production at LHC



Higgs boson production at Tevatron

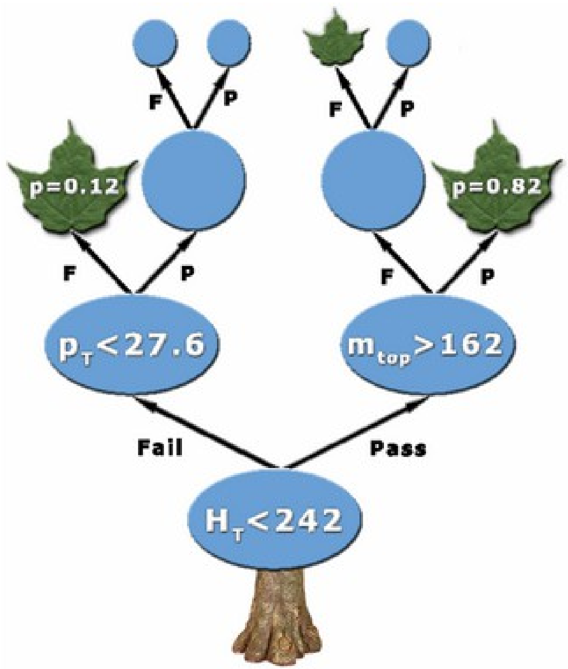


1.e Technics used to identify the Higgs boson decay products

- **Traditional**

  - Cut and Count (C&C): cuts are apply independently on different variables.

(*)



- **Multivariable (MVA) exploit the variables correlation**

  - Boosted decision tree (BDT), random forest (RF) (*),

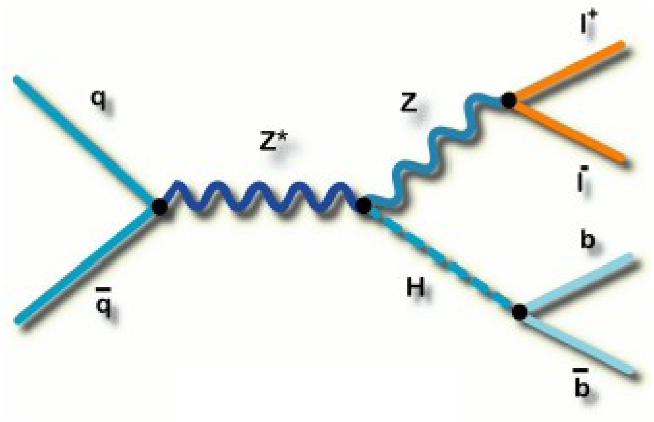
  Deep Neural Network: combined experimental variables into a single discriminant.

  - Matrix element method: combined experimental and theoretical variables into a single discriminant.

2. Search for ZH in b jets channel at D0

2.a signal and backgrounds (bkg)

- Signal (simulation)



- Electroweak bkg (simulation)

Z+jets, dibosons (WW, WZ, ZZ), tt_{bar}

- Multijet bkg (data)

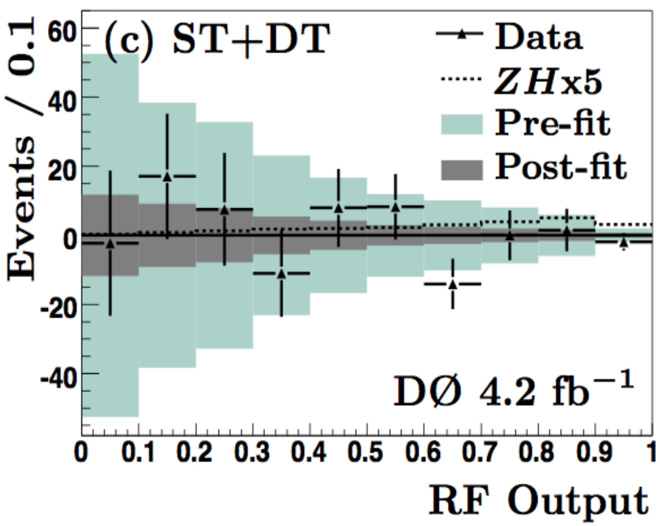
jets misidentified as leptons

2.b Event selection (4.2 fb^{-1})

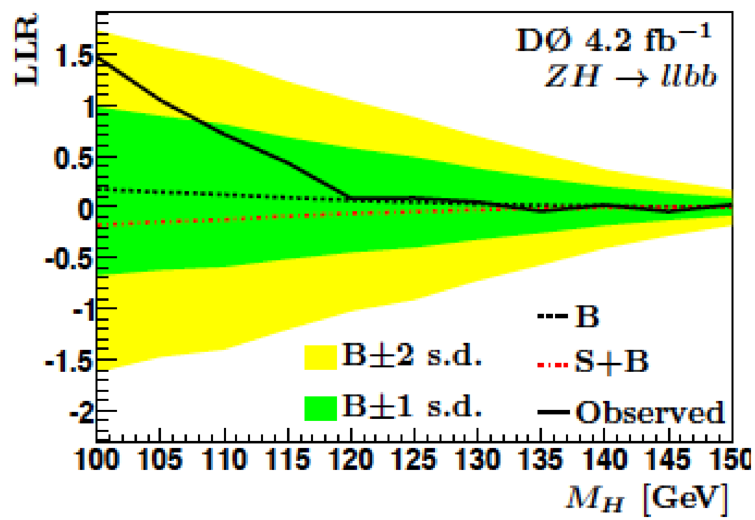
- >= 2 electrons/muons ; 1 Z boson ; >=1 b jet ; other cuts to veto bkg
- Final discriminant: MVA (RF)

2.c Results 4.2 fb^{-1}: Phys. Rev. Lett. 105, 251801 (2010)

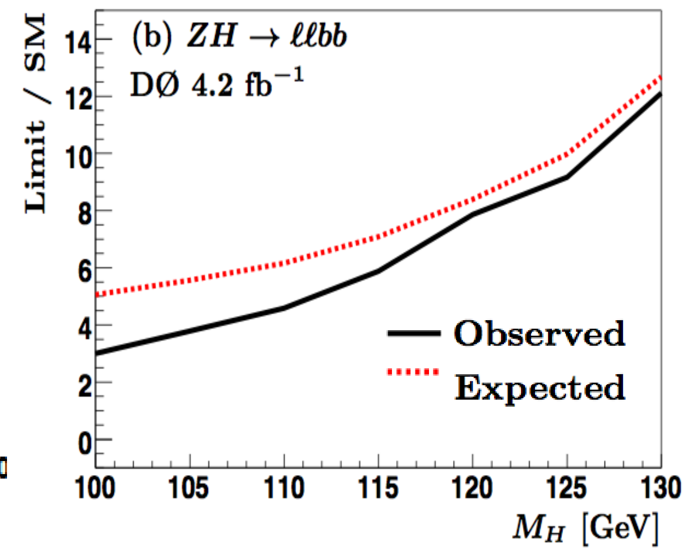
Bkg-subtracted discriminant



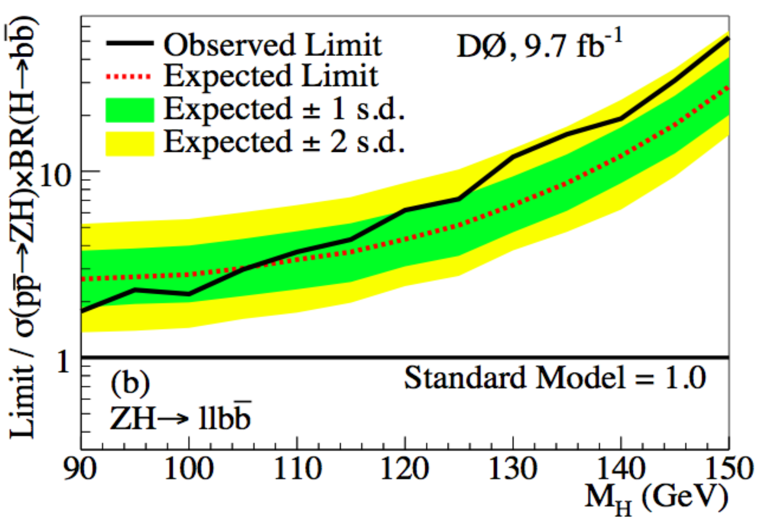
LLR VS Higgs boson mass



95% CL limit VS Higgs mass



2.d Updated results 9.7 fb^{-1}: Phys. Rev. D88 n° 5, 052010 (2013)



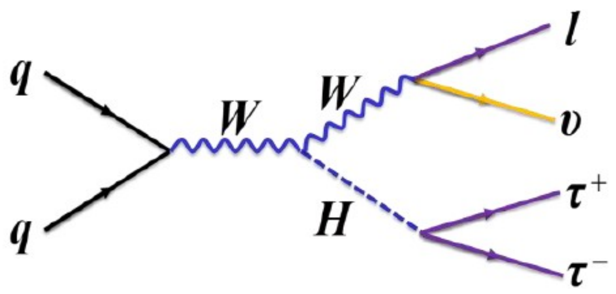
95% CL limit VS Higgs mass

M_H (GeV)	90	95	100	105	110	115	120	125	130	135	140	145	150
Expected	2.6	2.7	2.8	3.0	3.4	3.7	4.3	5.1	6.6	8.7	12	18	29
Observed	1.8	2.3	2.2	3.0	3.7	4.3	6.2	7.1	12	16	19	31	53

3. Search for WH in hadronic taus channel at CMS

3.a signal and backgrounds

- Signal (simulation)



- Irreducible bkg (simulation)

WZ, ZZ

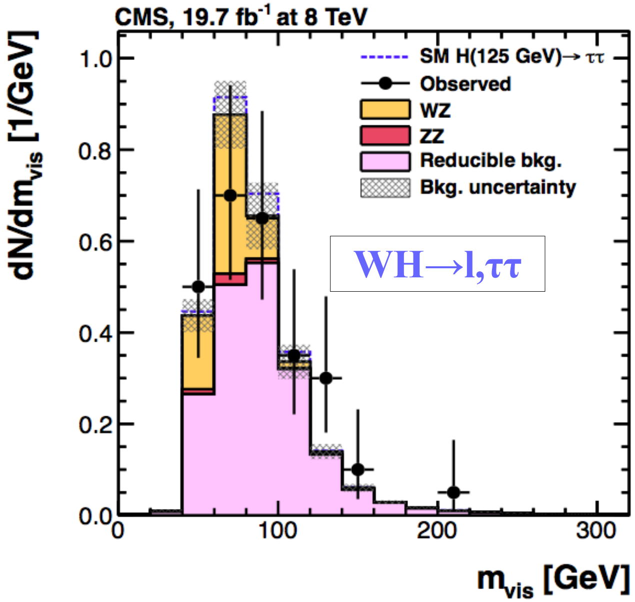
- Reducible bkg (data)

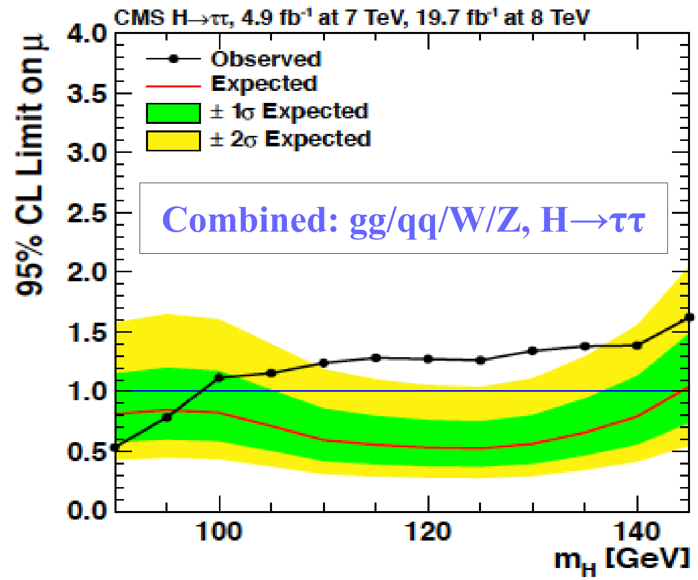
W/Z+jets/γ, tt_{bar}, multijet

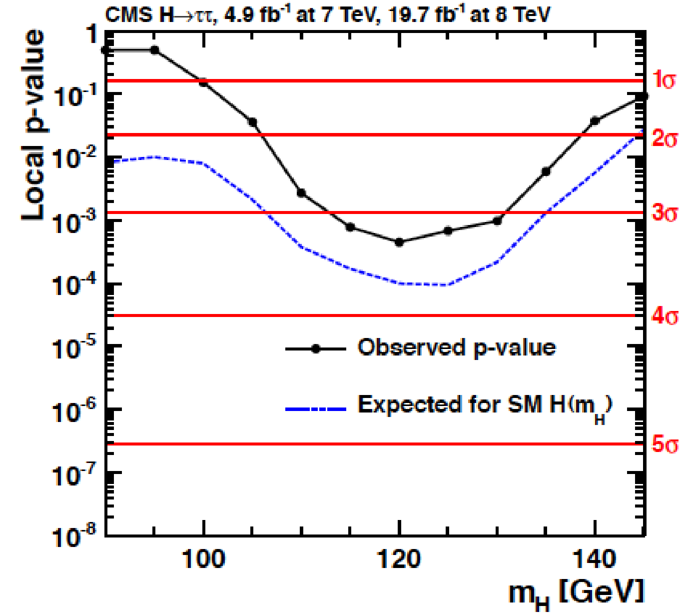
3.b Event selection

- 1 muon or electron ; 2 hadronic tau ; other cuts to veto bkg
- Final discriminant: visible mass of the 2 taus

3.c) Combined results 24.6 fb^{-1}: JHEP 05, (2014) 104 EVIDENCE

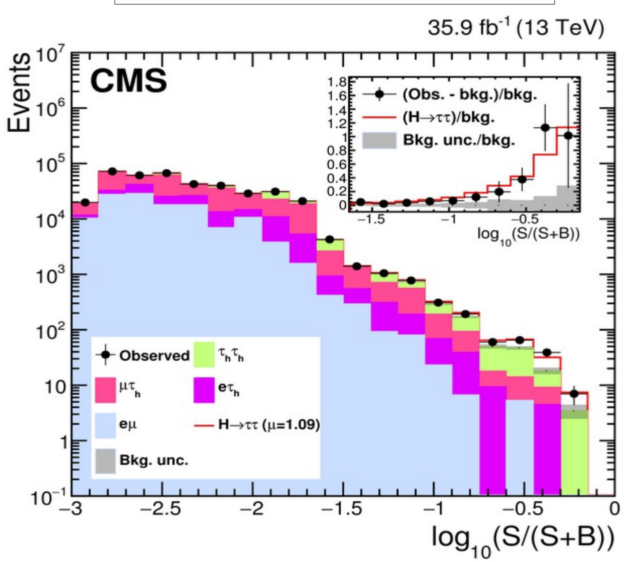


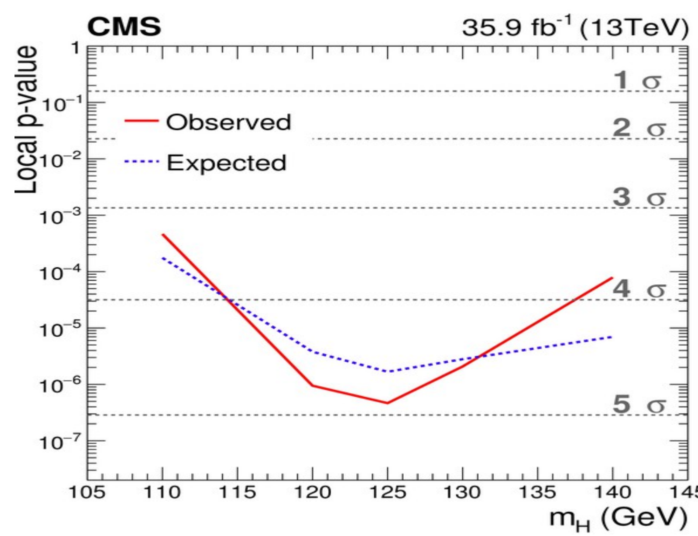


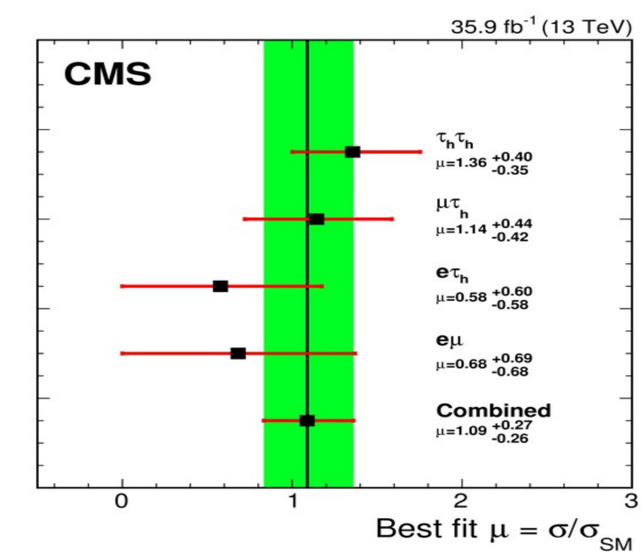


3.d) Updated results 35.9 fb^{-1}: Phys. Lett. B 779 (2018) 283 OBSERVATION

Combined: gg/qq, H→ττ

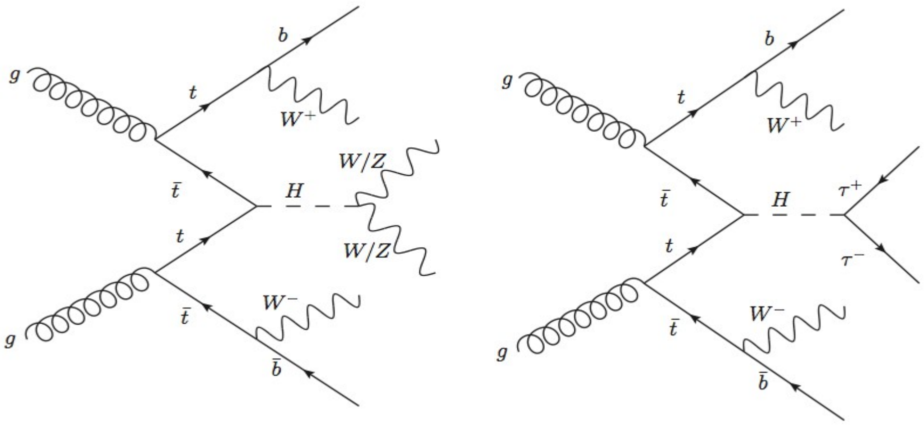


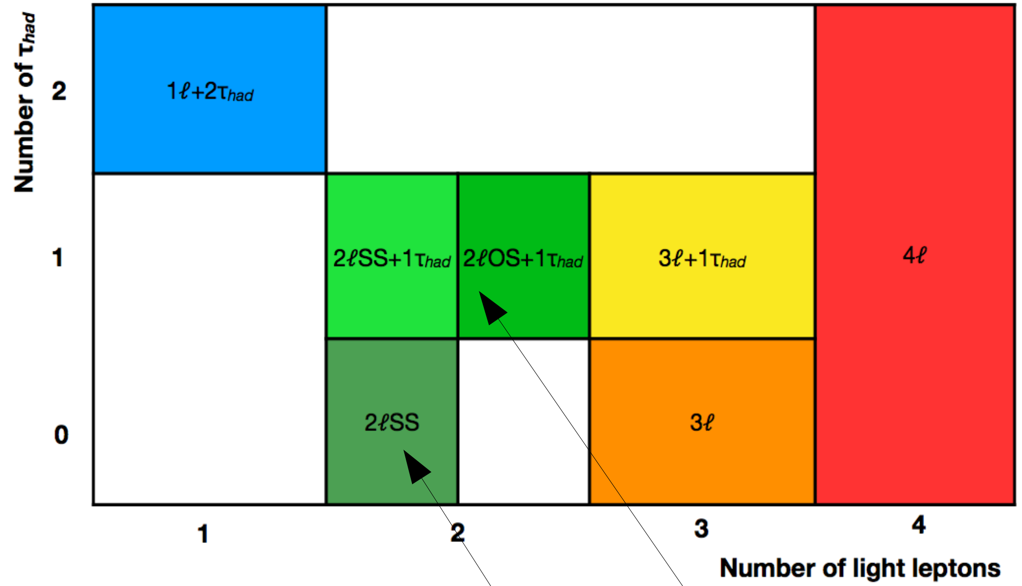




4. Search for ttH in mutileptonic channels at ATLAS

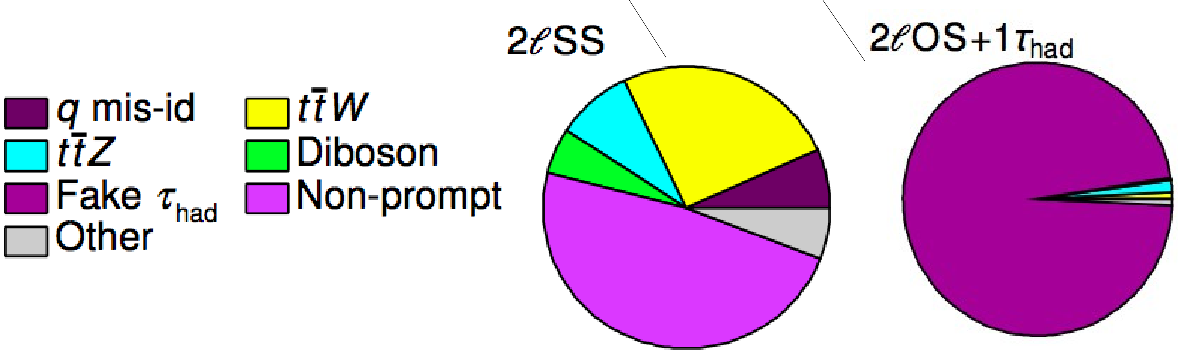
4.a Signals





4.b Backgrounds

- **Reducible (non-prompt, fake, q mis-id): data**
- **Other: simulation**



4.c Events selection

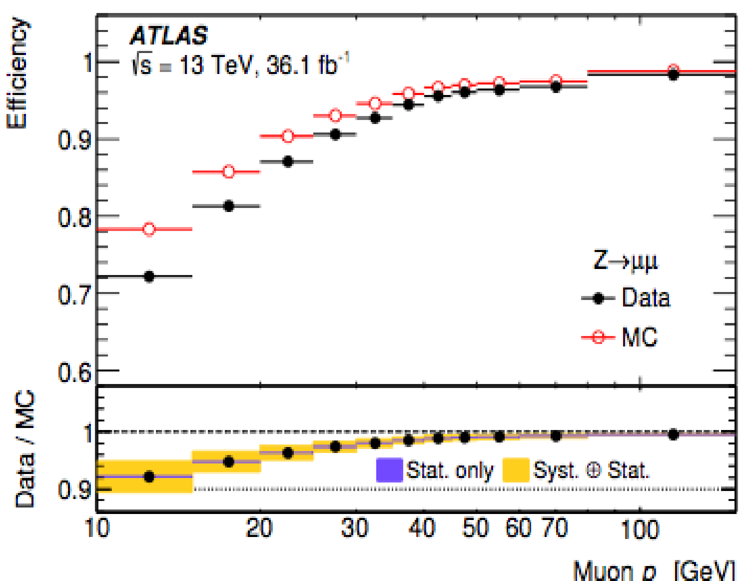
	$2\ell SS$	3ℓ	4ℓ	$1\ell+2\tau_{had}$	$2\ell SS+1\tau_{had}$	$2\ell OS+1\tau_{had}$	$3\ell+1\tau_{had}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, $N_{b\text{-}jets}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

4.d Main keys of the analysis

- **Efficient lepton identification cuts**

	e					*μ*		
	L	L†	L*	T	T*	L	L†	L*/T/T*
Isolation	No	Yes				No	Yes	
Non-prompt lepton BDT	No		Yes			No		Yes
Identification	Loose			Tight		Loose		
Charge misassignment veto BDT	No				Yes	No		
Transverse impact parameter significance, $\|d_0\|/\sigma_{d_0}$	< 5					< 3		
Longitudinal impact parameter, $\|z_0 \sin\theta\|$	< 0.5 mm							

BDT input: dist(lepton, jet), btag info, calo- and track-iso variables, nb track etc...



B-jet efficiency: 5%

- **Tau discriminator**

BDT: calorimeter- and tracking-based variables.

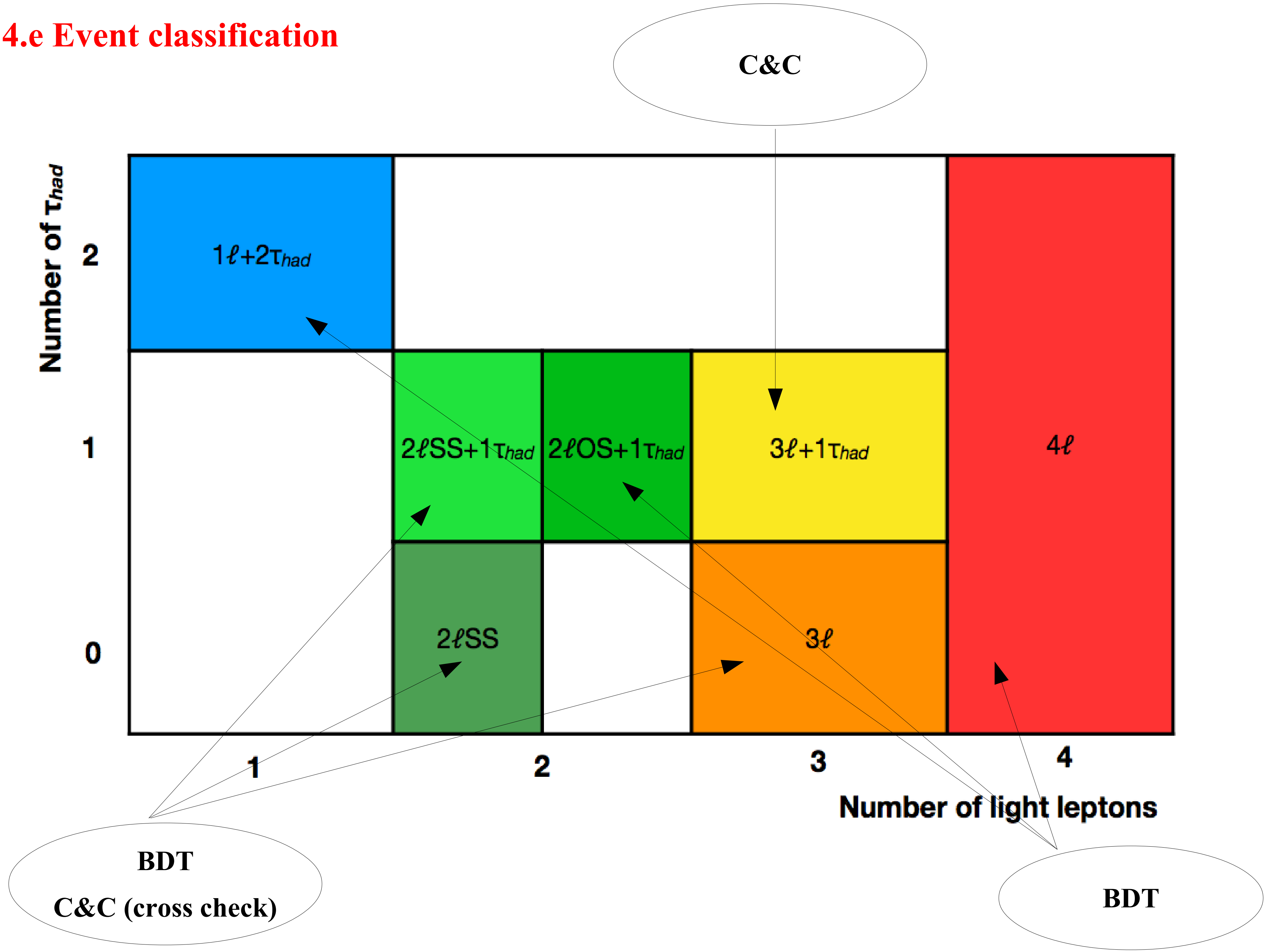
Medium efficiencies: 55% (40%) for 1 (3) prong tau.

- **B jet discriminator**

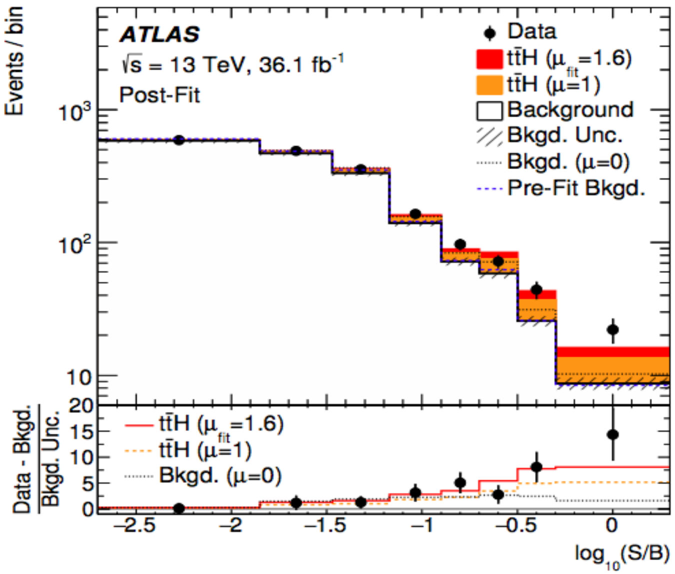
BDT: impact parameter, secondary vertices.

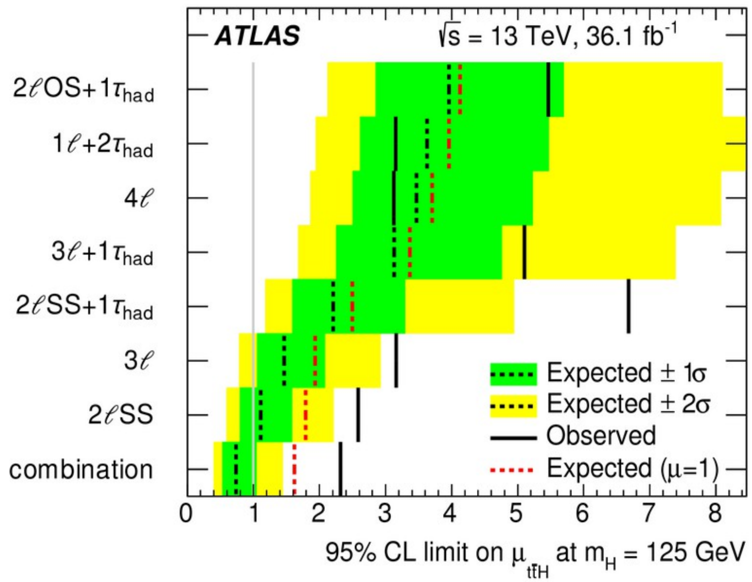
Medium efficiency: 70%.

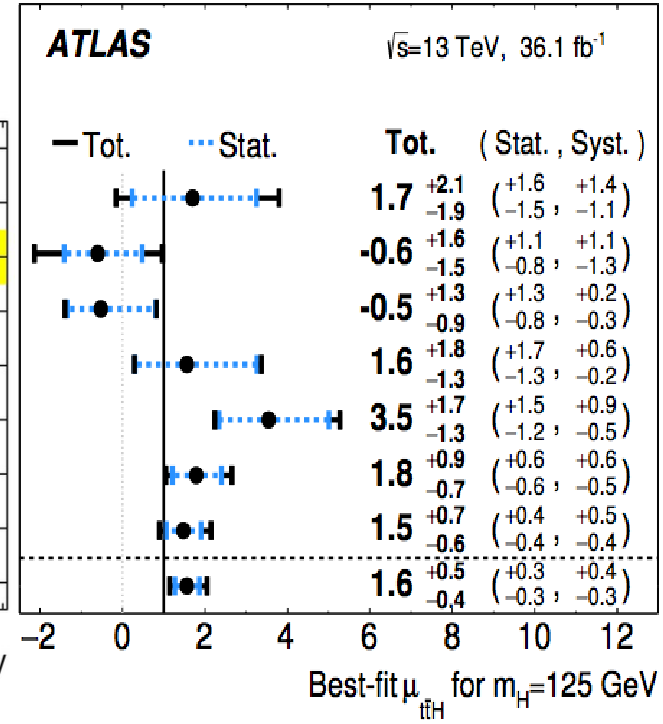
4.e Event classification



4.f Results, 36.1 fb^{-1}: Phys. Rev. D. 97 (2018) 072003 EVIDENCE







ATLAS combined channels

- 7 channels
- Observed (expected) significance: 4.1 (2.8) σ
- Observed (expected) best-fit value: $1.6^{+0.5}_{-0.4}$ ($1.00^{+0.4}_{-0.4}$)
- Measured (SM) ttH cross section: 790^{+230}_{-210} (507^{+35}_{-50}) fb^{-1}

CMS combined channels compatible w/ ATLAS

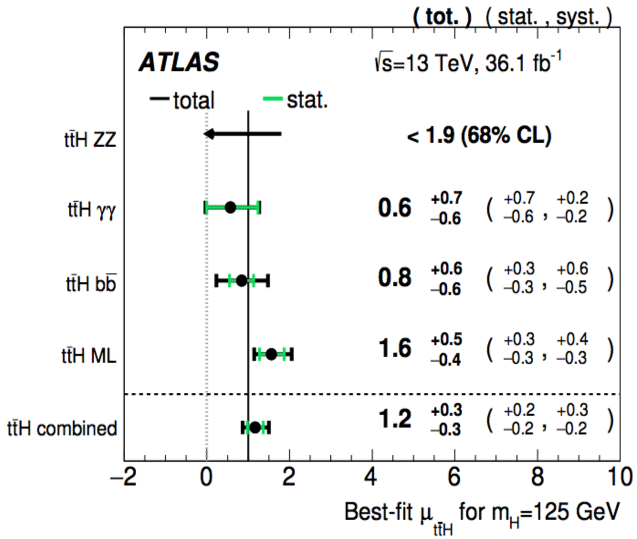
- 6 channels (no 2lOS+1τ)
- Observed (expected) significance: 3.2 (2.8) σ
- Observed best-fit value: $1.23^{+0.45}_{-0.43}$

4.g ttH multilepton prospects

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modelling	+0.20	−0.11
Jet energy scale and resolution	+0.17	−0.15
Non-prompt light lepton estimates	+0.16	−0.16
$t\bar{t}W$ modelling	+0.11	−0.10
Luminosity	+0.11	−0.09
$t\bar{t}Z$ modelling	+0.10	−0.09
Other background modelling	+0.11	−0.10
Jet flavour tagging and τ_{had} identification	+0.07	−0.06
Fake τ_{had} estimates	+0.05	−0.06
Charge misassignment	+0.04	−0.04
Other experimental uncertainties	+0.05	−0.04
MC statistics	+0.04	−0.04
Total systematic uncertainty	+0.39	−0.30

- **New simulation generator**
- **Particle flow new technic (use at CMS): combined information from all subdetectors**
- **More statistic**
- **With more statistic, we can used data, or improve theory uncertainty**
- **Improvement of lepton BDT identification**
- **...**

4.h Combined ttH searches results EVIDENCE

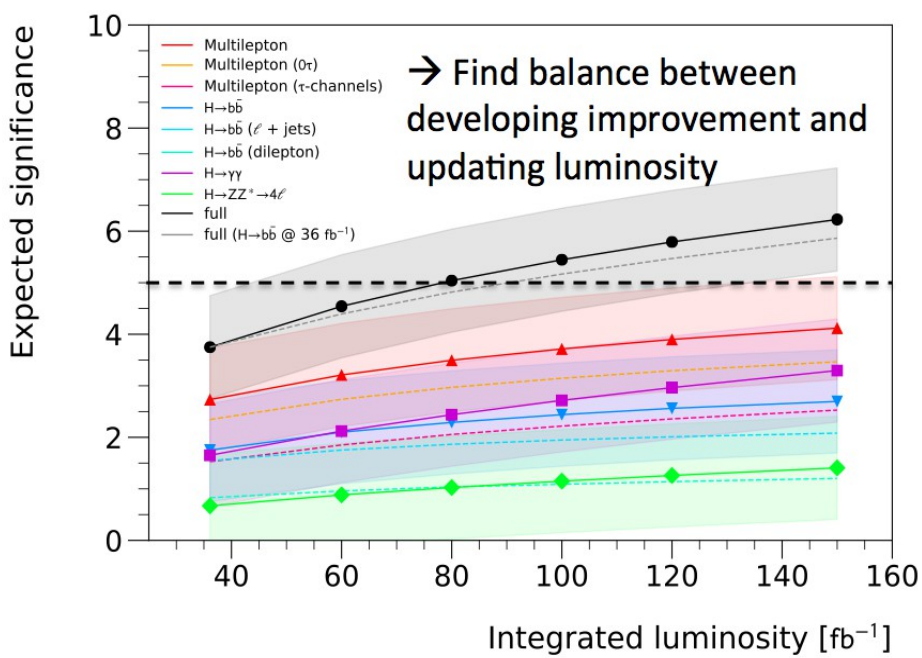


Combined channels

- H → ZZ
- H → γγ
- H → bb
- H → multilepton

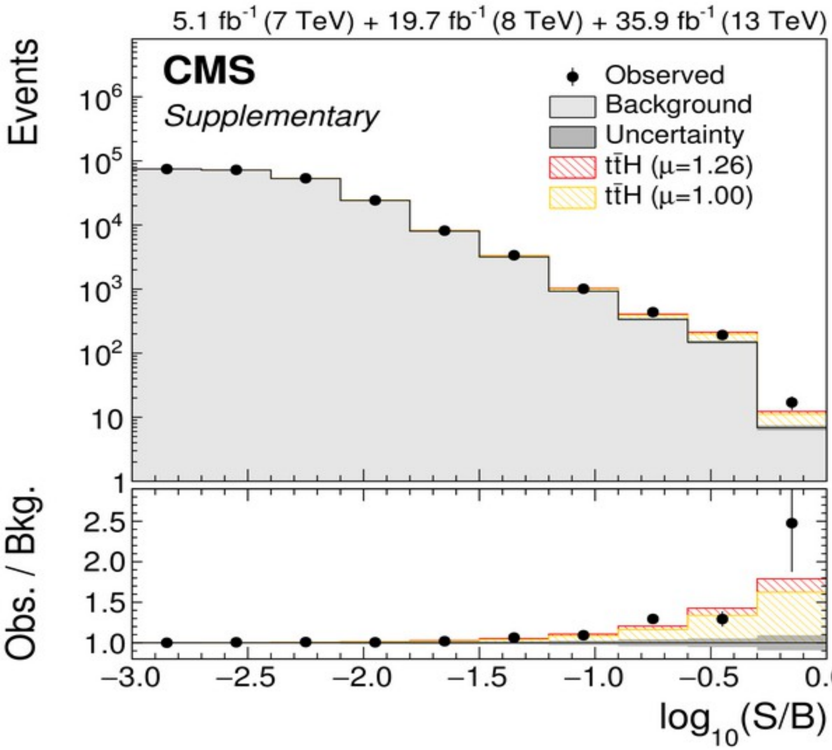
- **Observed (expected) significance:** 4.2 (3.8) σ
- **Observed best-fit value:** 1.17 ± 0.19
- **Measured (SM) ttH cross section:** 590^{+160}_{-150} (507^{+35}_{-50}) fb^{-1}

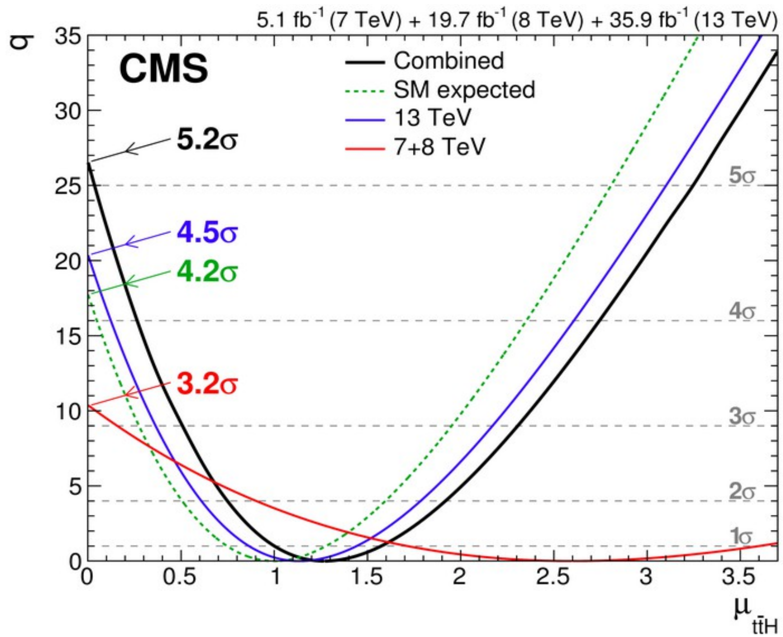
4.i Expected improvement with run 2 data



- **Considering all current analyses with the same level of systematics without any improvements, 5σ can be reach with 80 fb**$^{-1}$**.**

60 fb^{-1} (7 + 8 + 13 TeV) !



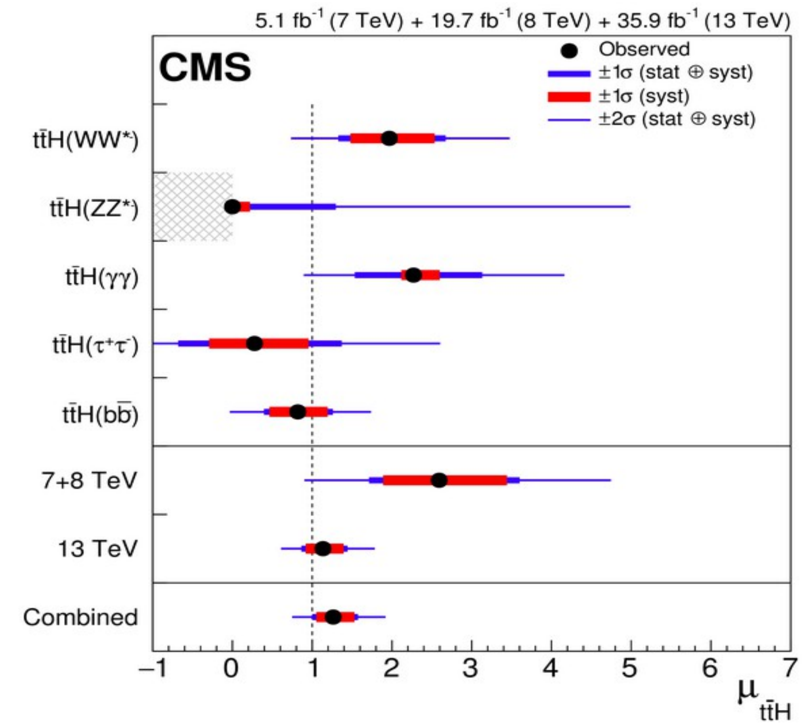


Sensitivity:

- **observed: 5.2σ**
- **Expected: 4.2σ**

Signal strength:

- $1.26^{+0.31}_{-0.26}$

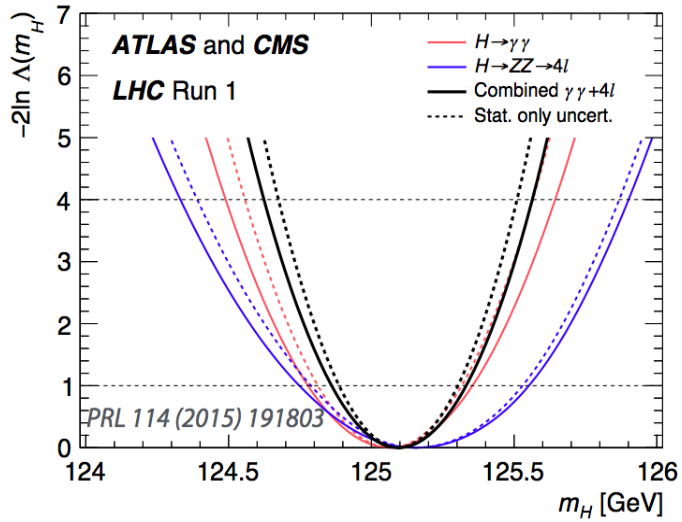


5. Combined ATLAS and CMS run 1 Higgs results

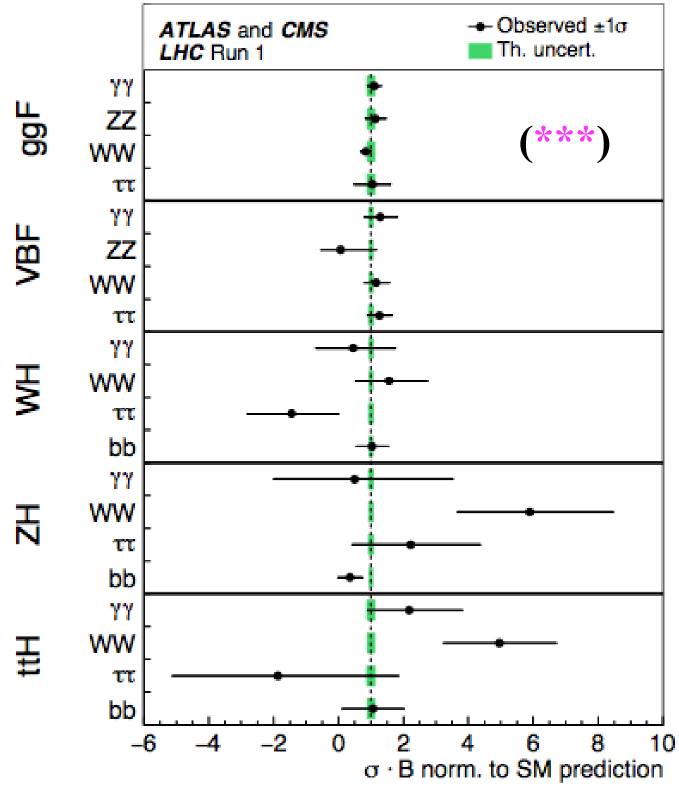
ATLAS + CMS run 1 combination results: JHEP08 (2016) 045

(*)

- **Production:** H, qqH, W/ZH, ttH
- **Decay:** bb, WW, ZZ, ττ, γγ, μμ
- **50 fb^{-1} (7 + 8 TeV)**
- **New production and decay observation (**)**
- **Signal yield compare to SM: 1.09 ± 0.11 (***)**
- **Mass Higgs (H→γγ, H→ZZ) = 125.09 ± 0.21(stat.) ± 0.11(syst.) GeV (*)**



Compatibility with SM



(**) **Significance**

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

- **Production H and decay WW, ZZ, γγ already observe.**

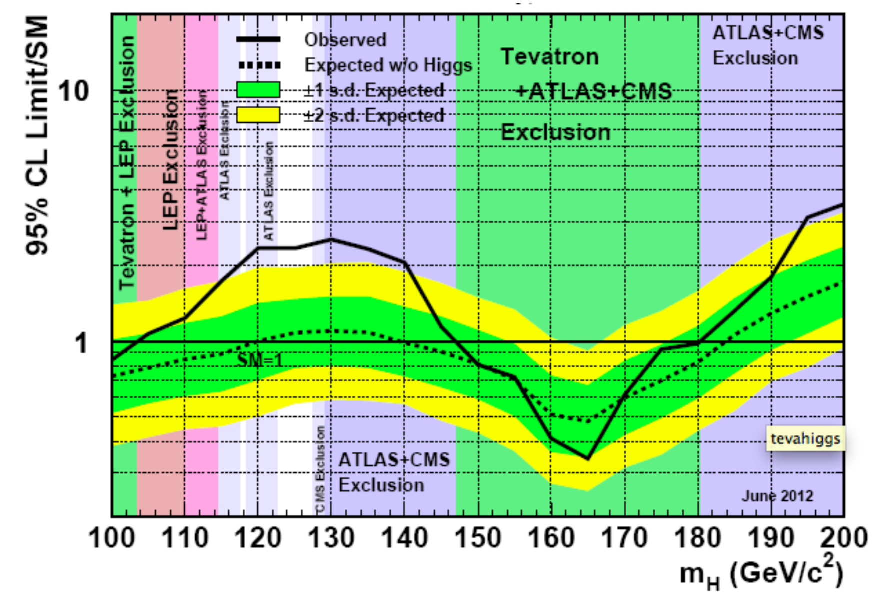
6. Summary

- The Higgs boson search has been a challenging topic involving several collaborations (1).

- Before it's discovery announcement in 2012 by ATLAS and CMS experiment (2).

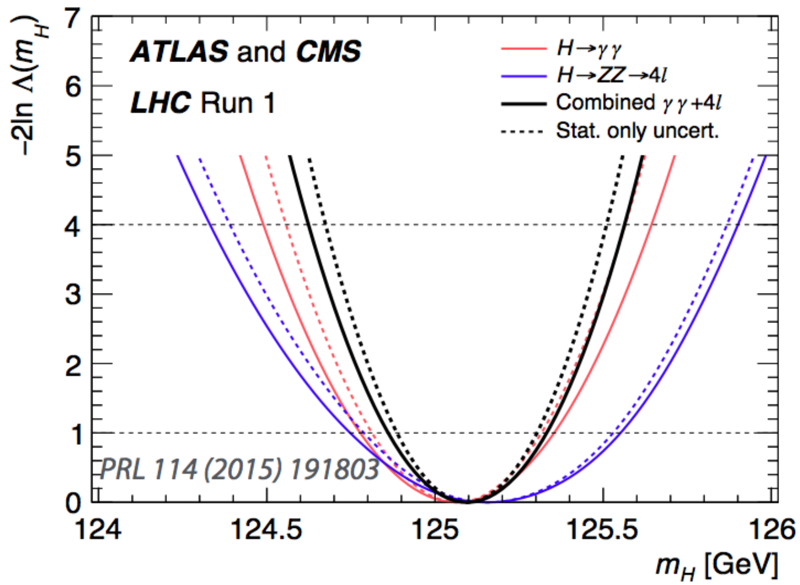
- Current Higgs searches and study focus on measuring it's properties with more accuracy (3).

(1)

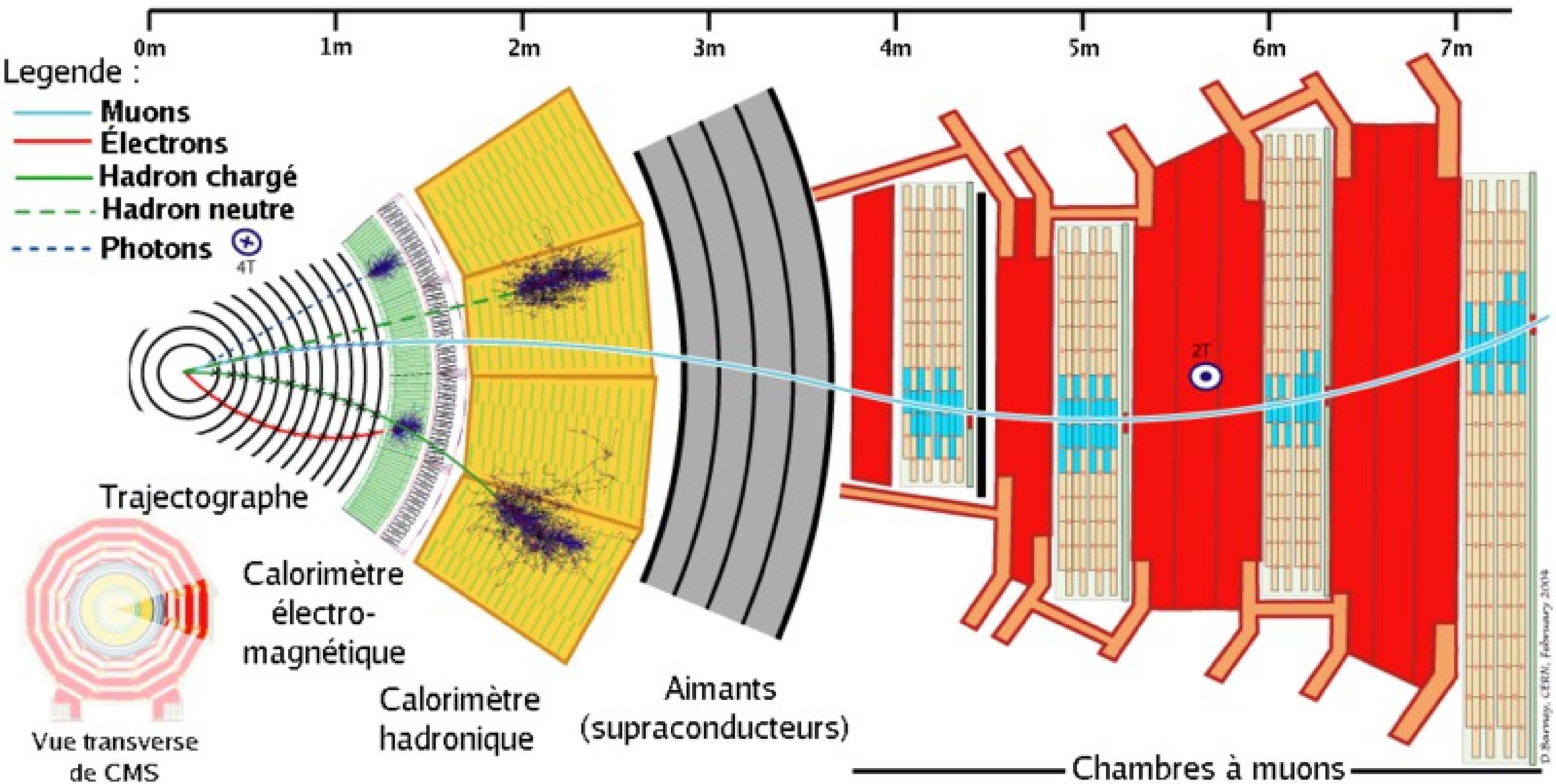


(2)

(3)



Back up

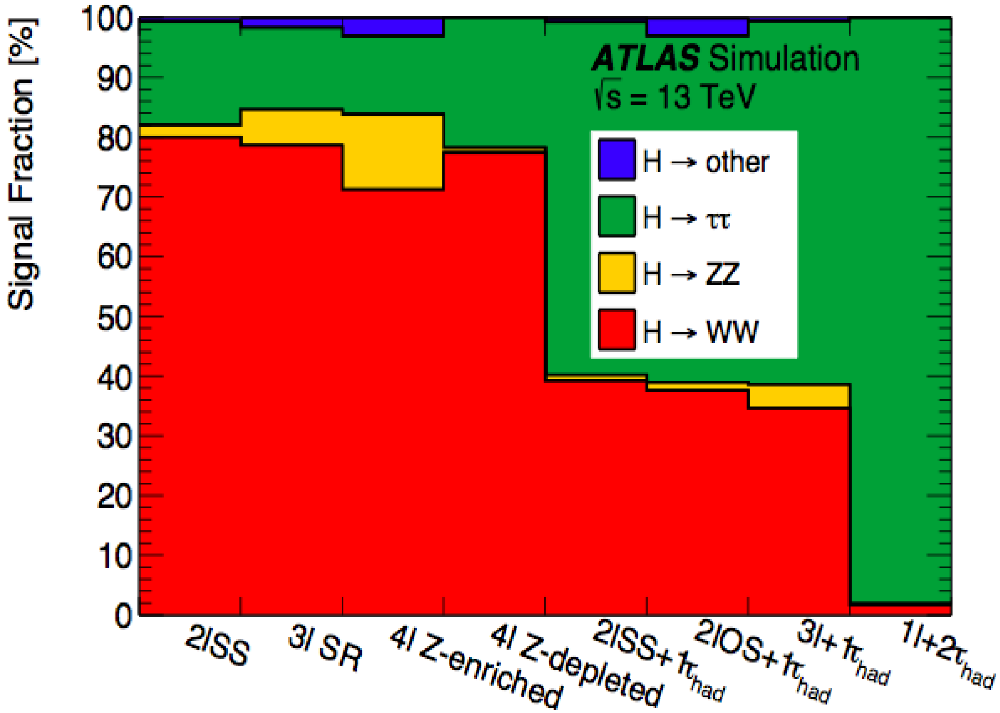

0m
1m
2m
3m
4m
5m
6m
7m
Legende :
Muons
Électrons
Hadron chargé
Hadron neutre
Photons
4T
2T
Trajectographe
Calorimètre électro-magnétique
Calorimètre hadronique
Aimants (supraconducteurs)
Chambres à muons
Vue transverse de CMS
D.Barney, CERN, February 2004

Higgs boson with a mass of 125.09 GeV

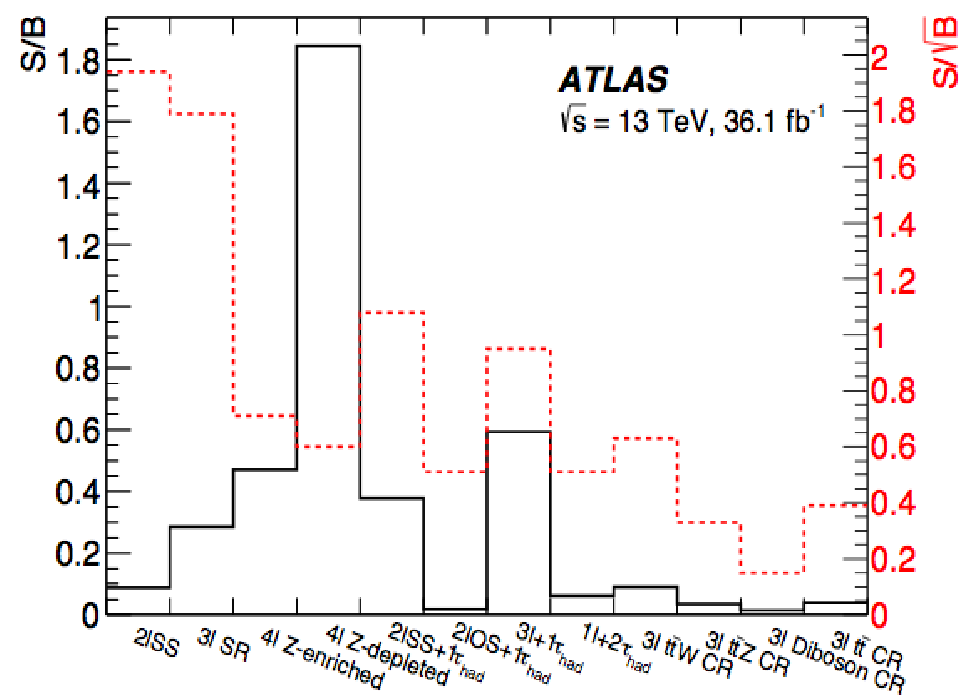
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.577 ± 0.016	0.703 ± 0.018
ZH	0.334 ± 0.013	0.414 ± 0.016
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010
ttH	0.086 ± 0.009	0.129 ± 0.014

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Signal fraction



The signal-to-background ratio



Electron charge mis ID BDT input variables (tight WP: 95% electron eff, and 6% electron with mis charge ID):

- **electron pt, η,**
- **track curvature significance (ratio of the electric charge to the track momentum divided by the estimated uncertainty in the measurement) and its transverse impact parameter times the electric charge**
- **cluster width along the azimuthal direction**
- **quality of the matching between the track and the cluster, in terms of both energy/momentum and azimuthal position.**

Table 6: Variables used in the multivariate analysis (denoted by ×) for the 2ℓSS, 3ℓ, 4ℓ (Z-enriched category), $1\ell+2\tau_{\mathrm{had}}$, 2ℓSS+$1\tau_{\mathrm{had}}$ and 2ℓOS+$1\tau_{\mathrm{had}}$ channels. For 2ℓSS and 2ℓSS+$1\tau_{\mathrm{had}}$, lepton 0 and lepton 1 are the leading and subleading leptons, respectively. For 3ℓ, lepton 0 is the lepton with charge opposite to that of the same-charge pair, while the same-charge leptons are labeled with increasing index (lepton 1 and lepton 2) as p_{T} decreases. The best Z-candidate dilepton invariant mass is the mass of the dilepton pair closest to the Z boson mass. The variables also used in the cross-check analyses are indicated by a $*$.

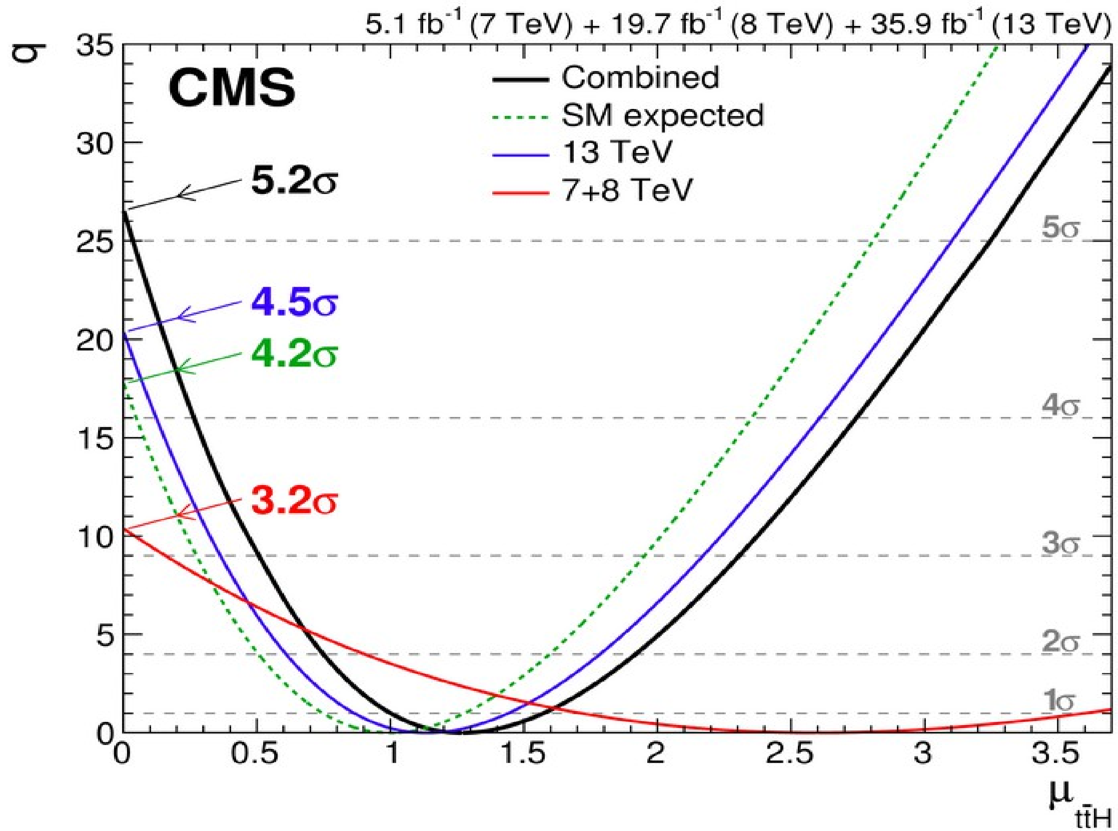
	Variable	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\mathrm{had}}$	2ℓSS+$1\tau_{\mathrm{had}}$	2ℓOS+$1\tau_{\mathrm{had}}$
Lepton properties	Leading lepton p_{T}		×				
	Second leading lepton p_{T}	×	×			×	
	Third lepton p_{T}		×				
	Dilepton invariant mass (all combinations)	×	×$*$				×
	Three-lepton invariant mass		×				
	Four-lepton invariant mass			×			
	Best Z-candidate dilepton invariant mass			×			
	Other Z-candidate dilepton invariant mass			×			
	Scalar sum of all leptons p_{T}			×			×
	Second leading lepton track isolation					×	
	Maximum $\vert\eta\vert$ (lepton 0, lepton 1)	×				×$*$	
	Lepton flavor	×$*$	×$*$				
	Lepton charge		×				
Jet properties	Number of jets	×$*$	×$*$		×	×	×
	Number of b-tagged jets	×$*$	×$*$		×	×	×
	Leading jet p_{T}						×
	Second leading jet p_{T}		×			×$*$	
	Leading b-tagged jet p_{T}		×				
	Scalar sum of all jets p_{T}		×		×	×	×
	Scalar sum of all b-tagged jets p_{T}						×
	Has leading jet highest b-tagging weight?		×				
	b-tagging weight of leading jet		×				
	b-tagging weight of second leading jet		×			×	
	b-tagging weight of third leading jet					×	
	Pseudorapidity of fourth leading jet					×	
τ_{had}	Leading τ_{had} p_{T}				×		×
	Second leading τ_{had} p_{T}				×		
	Di-τ_{had} invariant mass				×		
	Invariant mass τ_{had}–furthest lepton					×	
Angular distances	ΔR(lepton 0, lepton 1)		×				
	ΔR(lepton 0, lepton 2)		×				
	ΔR(lepton 0, closest jet)	×	×				
	ΔR(lepton 0, leading jet)		×			×	
	ΔR(lepton 0, closest b-jet)		×				
	ΔR(lepton 1, closest jet)	×	×				
	ΔR(lepton 2, closest jet)		×				
	Smallest ΔR(lepton, jet)		×				×
	Smallest ΔR(lepton, b-tagged jet)						×
	Smallest ΔR(non-tagged jet, b-tagged jet)						×
	ΔR(lepton 0, τ_{had})						×
	ΔR(lepton 1, τ_{had})						×
	Minimum ΔR between all jets				×		
	ΔR between two leading jets					×	
$\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$	×		×			
	Azimuthal separation $\Delta\phi$(leading jet, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$)		×				
	Transverse mass leptons (H/Z decay) - $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$			×			
	Pseudo-Matrix-Element			×			

For a specific production process and decay mode $i \to H \to f$,

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

• Test statistic q as a function of μ.

• To quantify the ttH significance, we compute the probability of the bkg-only hypothesis (p-value) as the tail integral of the test statistic using the overall combination evaluated at μ = 0 under the asymptotic approximation.



2.b Event selection (4.2 fb^{-1})

- **At least 2 electrons in the calorimeter:**

  - in CC $|\eta| < 1.1$ or EC $1.5 < |\eta| < 2.5$
  - $p_T > 15$ GeV; isolation < 0.1; Emfrac > 0.95; 1 track
  - cuts based on calorimeter shower shape
  - NN variable (EM and CPS energy deposit, track isolation...).

- **To increase the Z acceptance (17%) the e selection is extended to include events with 1 e^{icr}:**

  - ICR, Et>10 GeV
  - >= 1 track with $p_T > 20$ GeV
  - medium NN_{icr}
  - other cuts depending on the tau type.

- **Z boson selection:**

  - 60 <Mee < 150 GeV.

- **B jet selection:**

  - >= 2 jets in $|\eta| < 2.5$, coming from the PV, with at least 1 b jets
  - ΔR(jet, e)>0.5
  - leading (subleading) jet $p_T > 20$ (15) GeV.

- **Multijet selection:**

  invert electron selection cuts:
  - isolation and shower shape for e
  - NN_{icr} for e^{icr}.

3.b) Event selection

- 1 Muon
  - pT > 24 GeV, |η| < 2.1
  - Tight PF Muon ID
  - A good primary vertex
  - Tight isolation < 0.1

- 2 hadronic tau
  - |η| < 2.3
  - Loose isolation
  - against Muon Tight
  - ΔR(μ,τ1) > 0.5
  - |zτ–zμ|< 0.14cm

  +

  leading τ1
  - pT > 25 GeV
  - against Electron Loose

  subleading τ2
  - pT > 20 GeV
  - against Electron Medium

- Additional cuts
  - 2 hadronic tau with opposite charge
  - Et miss > 20 GeV
  - tt_{bar} veto: No b tag jet with pT > 20 GeV
  - Z→μμ veto: no other muon passing the selection criteria
  - Z→ ττ veto: pT(τ1,τ2) > 50 GeV ; M(μ,τ_h^{OS}) > 80 GeV ; Mt (μ, Et miss) >20 GeV
  - electron veto

Random Forest (RF)

The RF combines several trees. Each is trained to separate signal from background using a randomly selected subsample of simulated events. In addition, a random subset of input variables is considered for each decision in each tree. The RF output is a performance- weighted average of the output from each decision tree.

Variables selected for the RF

- transverse momenta and the invariant mass of the bjets;
- angular differences within and between the dijet and dilepton;
- the angle between the proton beam and the Z boson candidate;
- composite kinematic variables: the scalar sum of the transverse momenta of the leptons and jets...

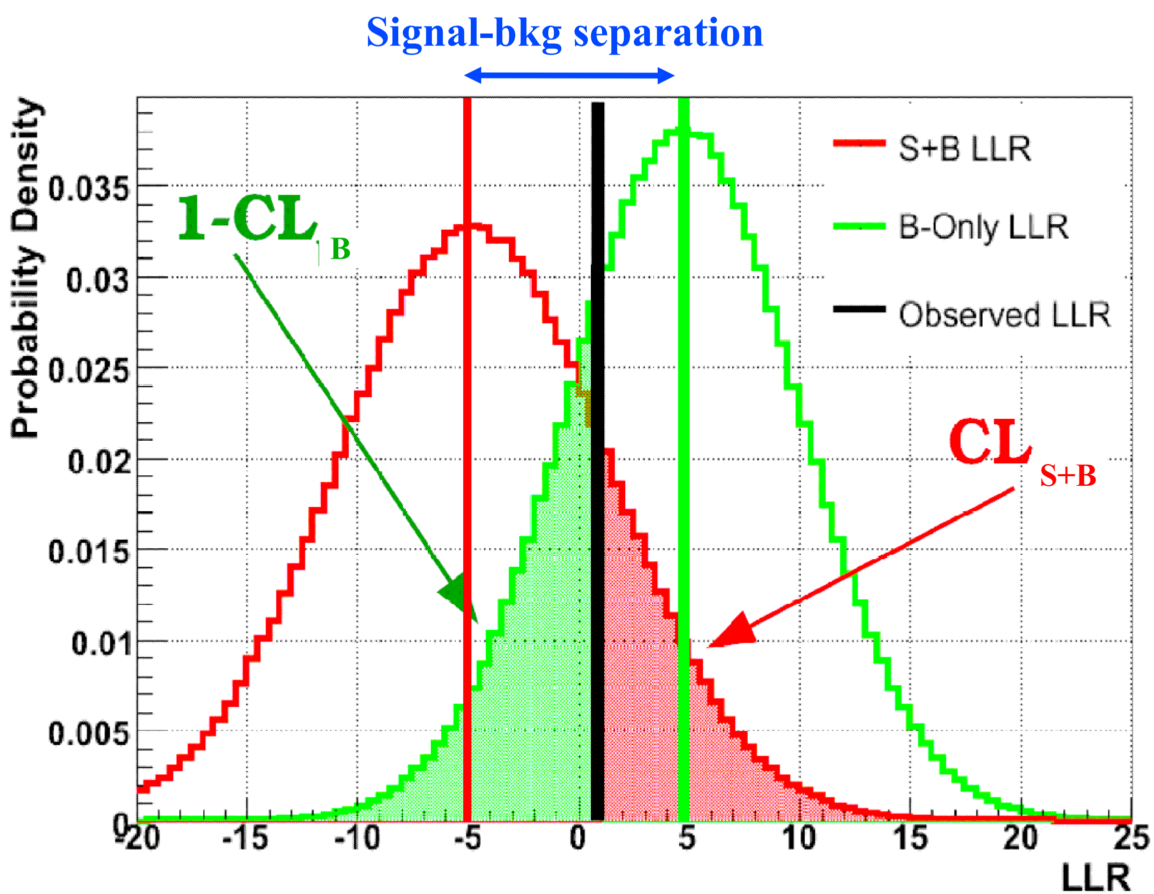
Limit calculation at D0

- The upper limit on the Higgs production cross section is calculated at 95% CL with a Poisson log-likelihood ratio (LLR) as test statistics: $LLR = -2\ln P(N|H_{S+B}) / P(N|H_B)$:

  H_{S+B} and H_B: test hypotheses of background with and without signal

  N : number of events

  P : poissonian pdf of N: $P = e^{-\mu} \mu^N/N!$



- Profile likelihood method: LLR is minimized wrt the nuisance parameters.

- Confidence level:

  $CL_{S+B} = p(LLR_{S+B} > LLR_{Obs} | H_{S+B})$

  $CL_B = P(LLR_B > LLR_{Obs} | H_B)$

  $CL_S = CL_{S+B} / CL_B$

- A signal $R = (\sigma_{Obs} \times BR) / (\sigma_{Obs} \times BR)_{SM}$ is excluded at 95% CL if $CL_s(R) = 0.05$.