Higgs boson production results at CMS

Francesco Fabozzi

INFN-Napoli & Università della Basilicata

On behalf of the CMS collaboration

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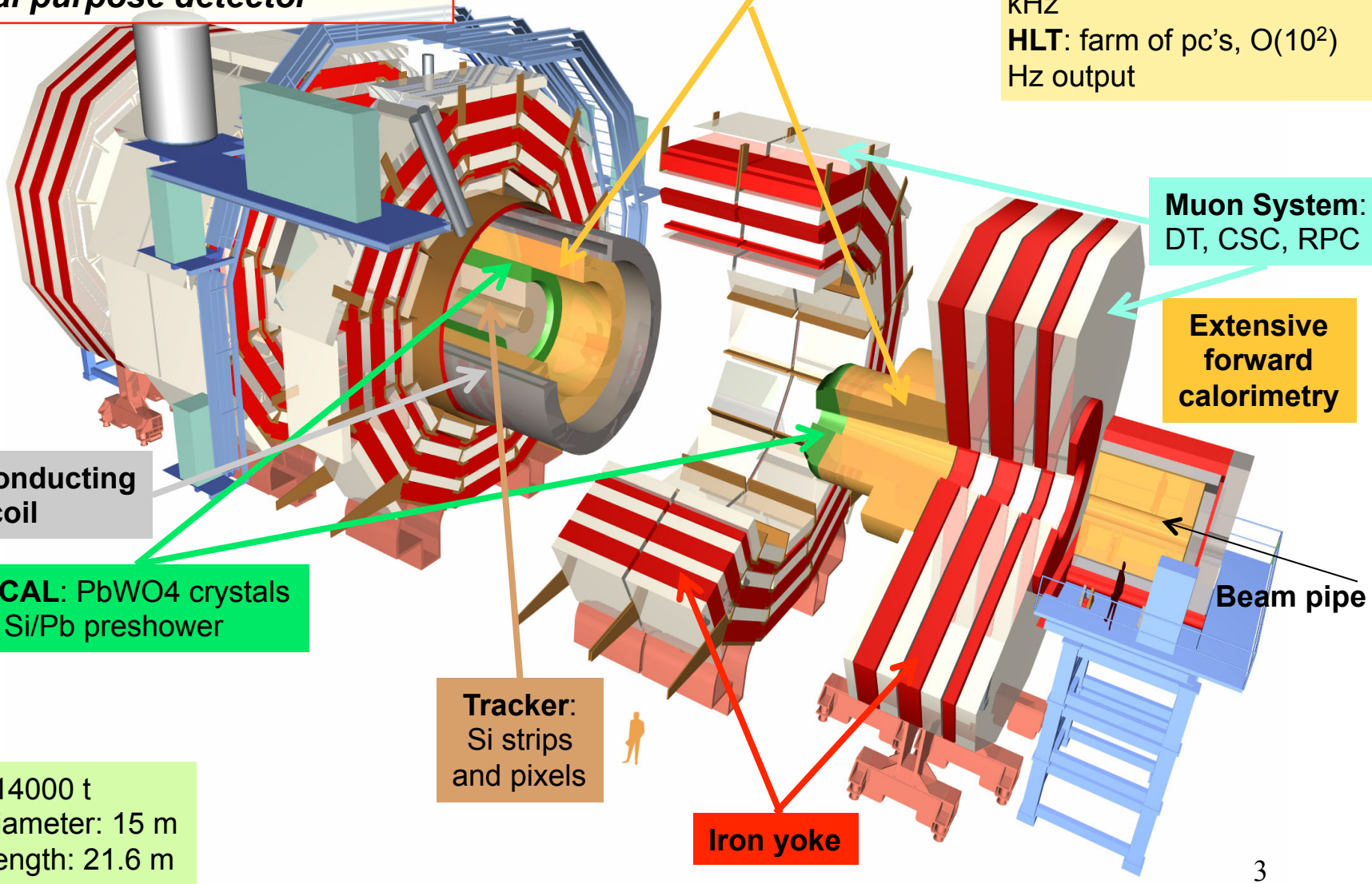
Outline

- This talk will be focused on recent measurements of Standard Model (SM) Higgs boson production at CMS based on LHC Run 2 dataset
- $H \to \gamma\gamma$, $H \to ZZ(4l)$
  - PAS-HIG-16-040, PAS-HIG-17-015, PAS-HIG-16-041
- $H \to \tau\tau$
  - PAS-HIG-16-043
- ttH production measured in multilepton final states
  - PAS-HIG-17-003, PAS-HIG-17-004
- tHq production
  - PAS-HIG-17-005
- Boosted inclusive $H \to bb$
  - PAS-HIG-17-010

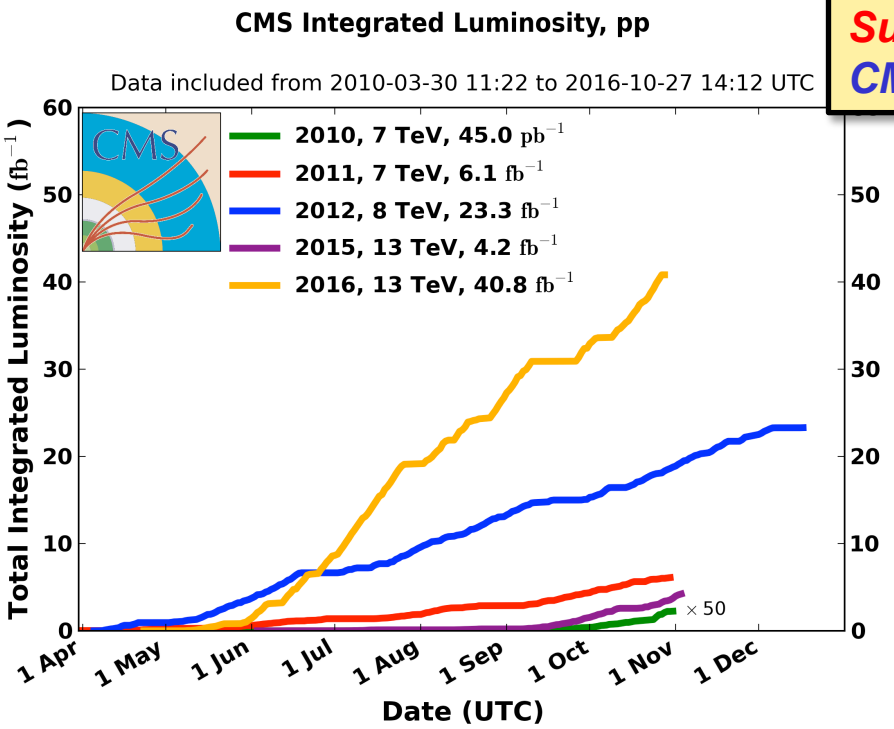
The CMS experiment @ LHC

The Compact Muon Solenoid: general purpose detector



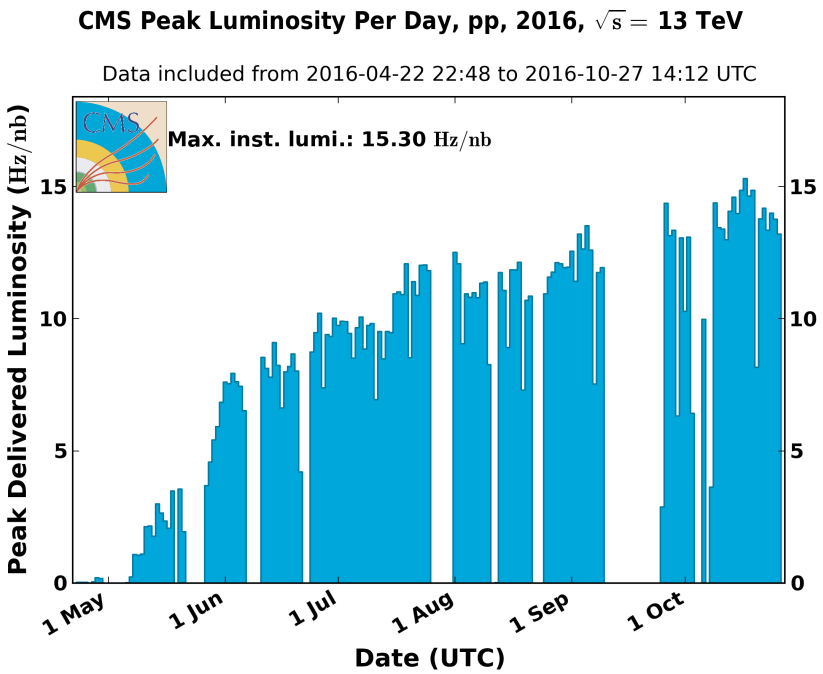
Weight: 14000 t
Overal diameter: 15 m
Overall length: 21.6 m
Magnetic field: 3.8 T

LHC impressive performance!



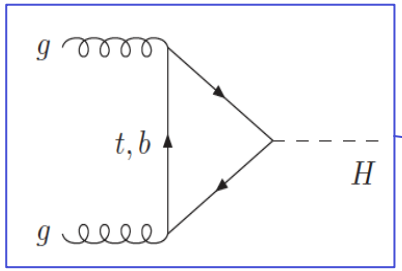
Summary of p-p runs in 2010-2016
CMS data taking efficiency always > 90%

•Peak luminosity record =
1.53 10^{34} cm^{-2} s^{-1}

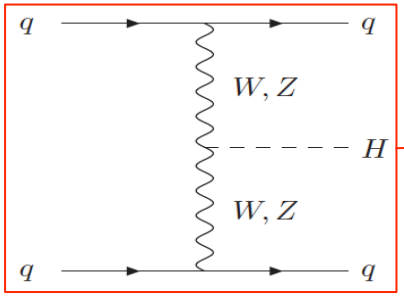


The results presented in this talk
are based on the full 2016 data sample
validated for physics analysis in CMS
(integrated luminosity ~ 36 fb^{-1})

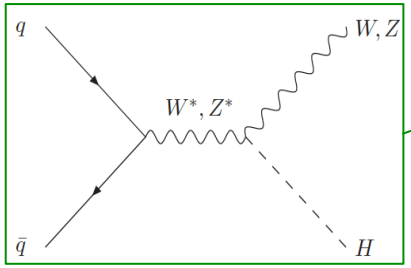
SM Higgs production and decay at LHC



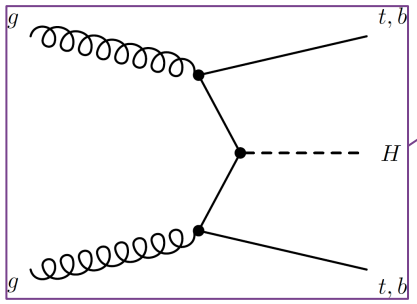
gg fusion



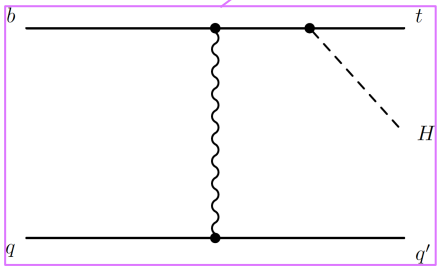
Vector Boson Fusion



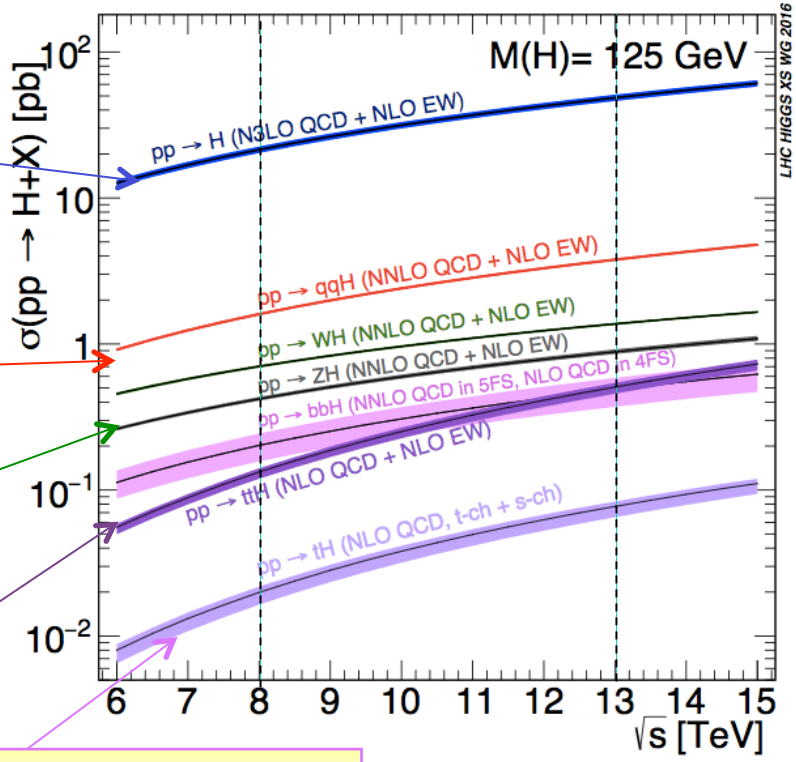
Associated VH production



Associated ttH (bbH) production

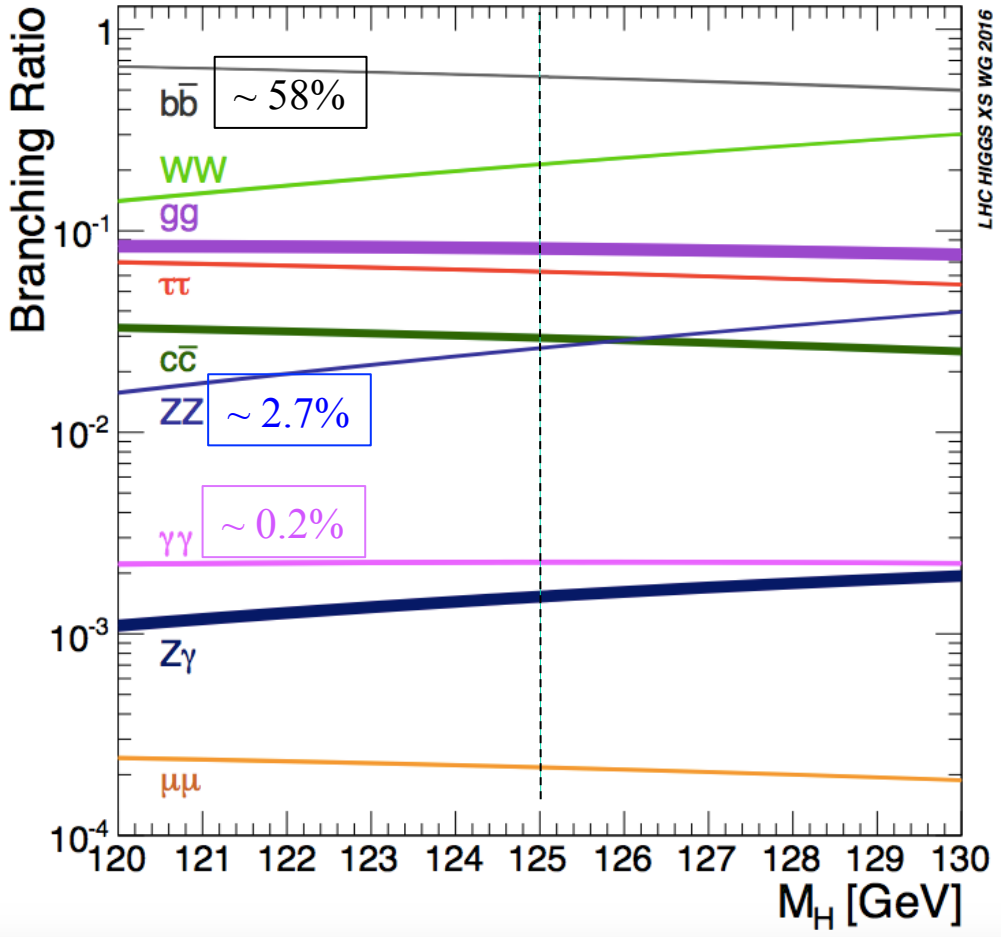


tH production



Cross-section increase from 8 to 13 TeV:
~ factor 2 for ggH and VBF
~ factor 4 for ttH and tH

SM Higgs production and decay at LHC



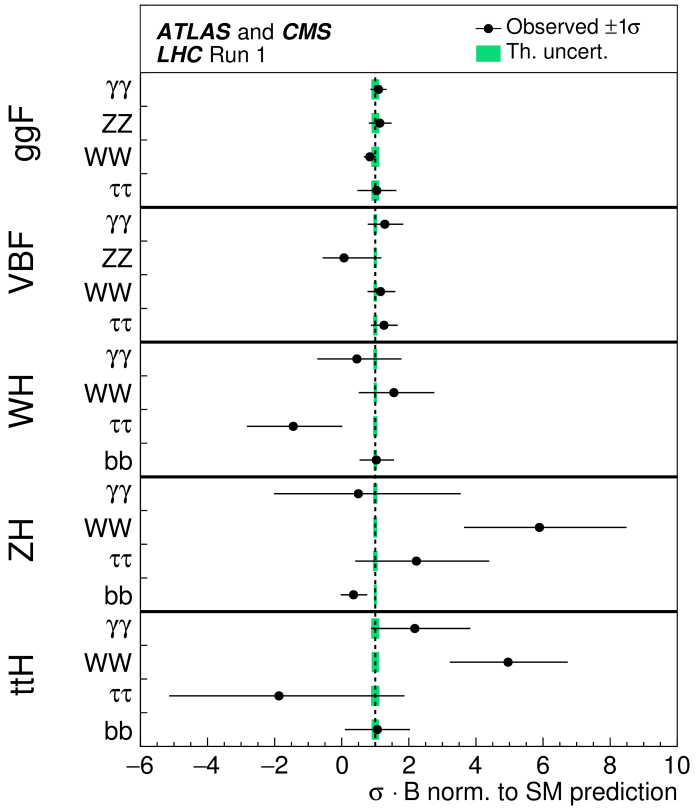
bb: challenging @ LHC due to overwhelming QCD background
- Traditional approach: study production modes with characteristic signatures, e.g. VH
- Novel approach: boosted inclusive H->bb analysis (new CMS result reported in this talk)

ZZ and γγ: clean signature and narrow mass resolution (1-2%): Higgs discovery channels in Run1

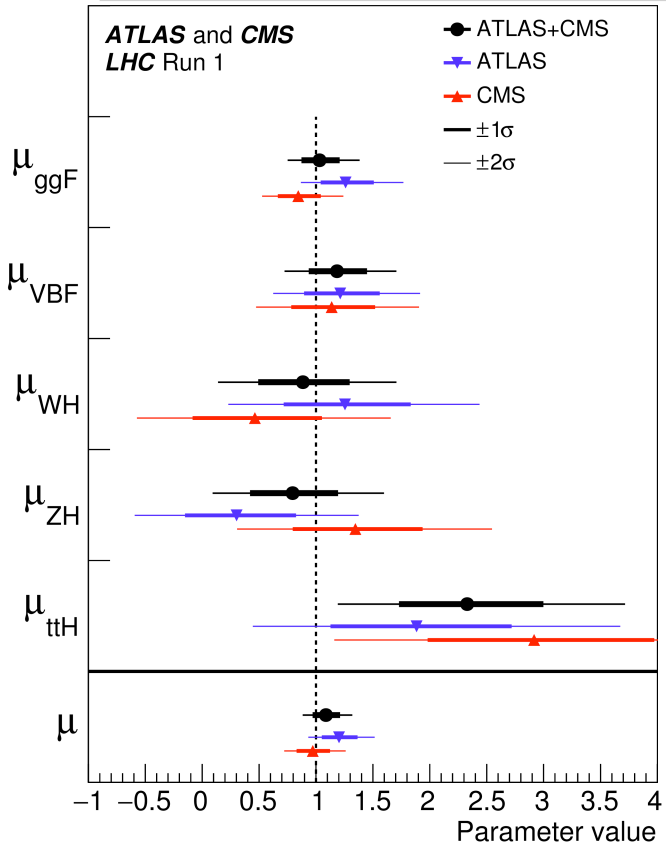
Run1 production measurements summary

JHEP08 (2016) 045

Many production and decay channels investigated with LHC Run 1 dataset



Signal strenght: $\mu=\sigma/\sigma_{SM}$



Overall consistent with predictions from SM

H→γγ channel

PAS HIG-16-040

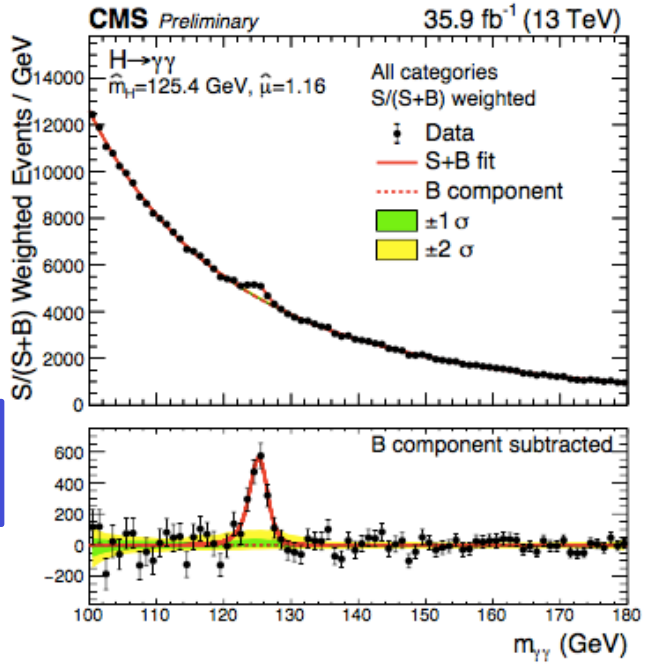
Clean signature: two isolated, high E_T gamma; narrow peak (1-2% resolution) in $m_{\gamma\gamma}$ over decreasing background

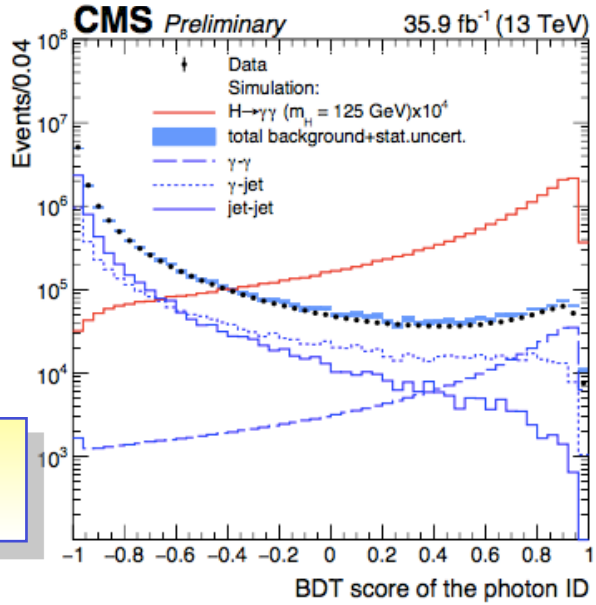
Mass resolution dominated by ECAL energy resolution (crucial is correct assignment of the di-photon vertex)

Photon energy and uncertainty estimated event-by-event with multivariate regression technique

Main backgrounds:
- prompt γγ production (irreducible)
- γ+jet and jet-jet

Multivariate discriminators used for photon identification and event classification

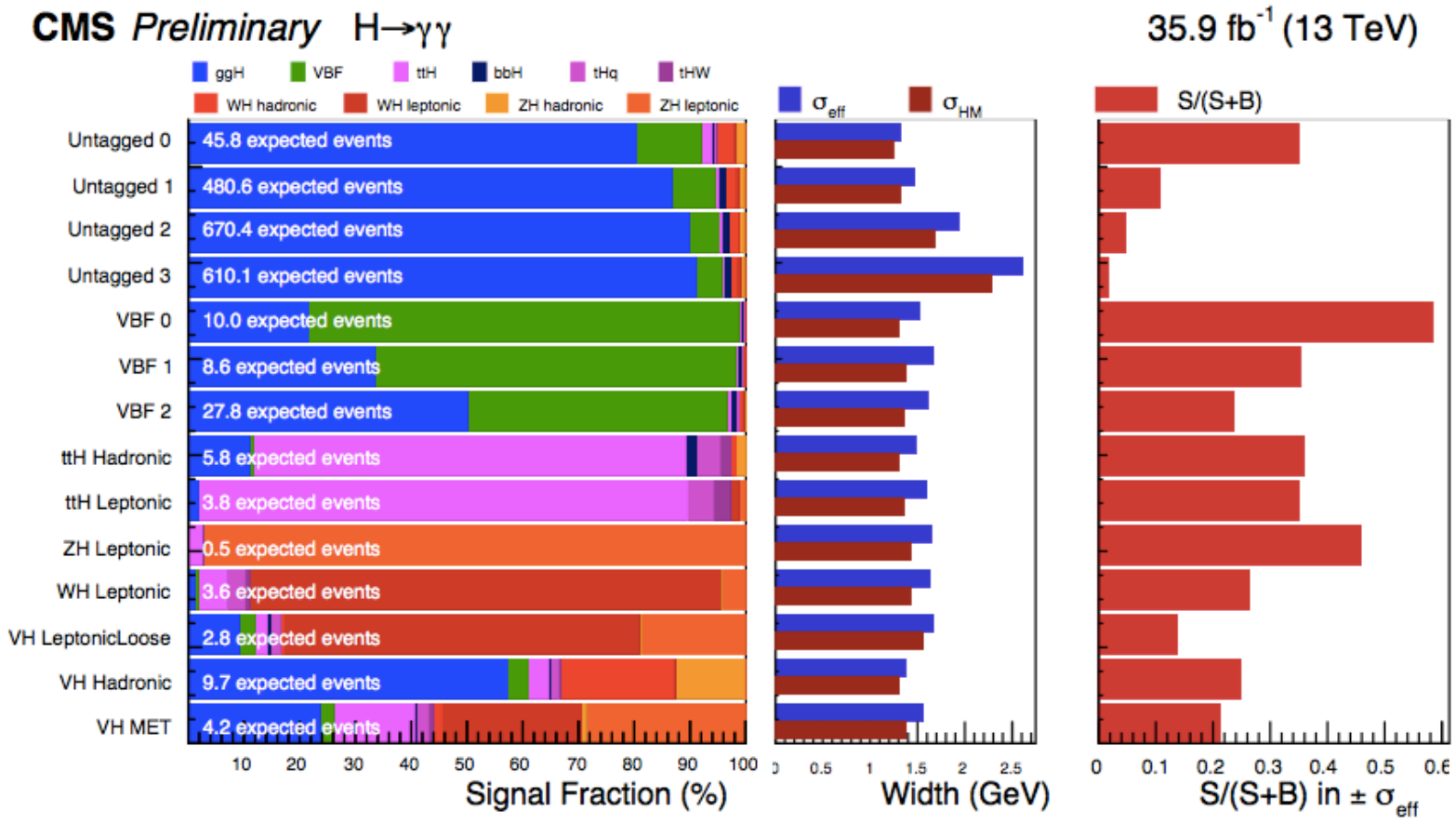




H→γγ: event classification

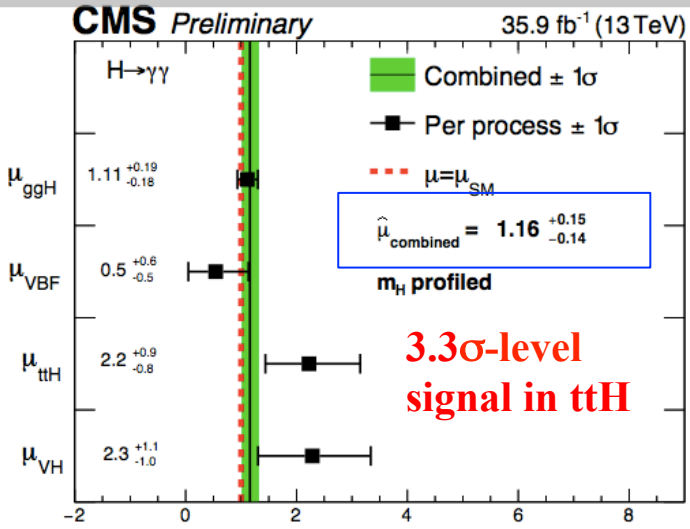
Events classification in exclusive categories targeting different production mechanisms and according to mass resolution and predicted S/B

- *selection optimized for each category*

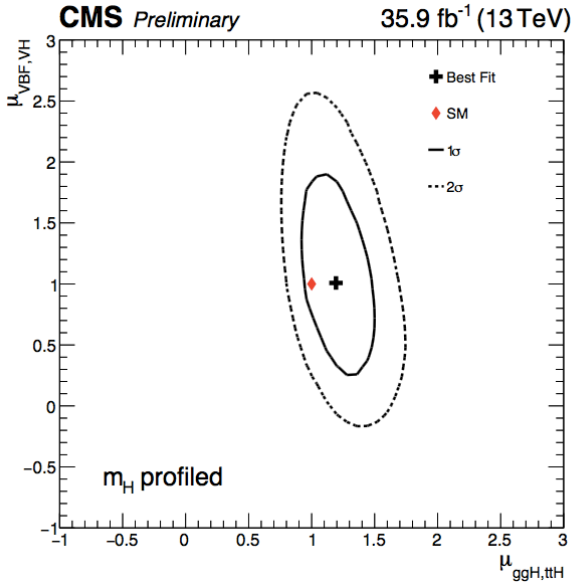


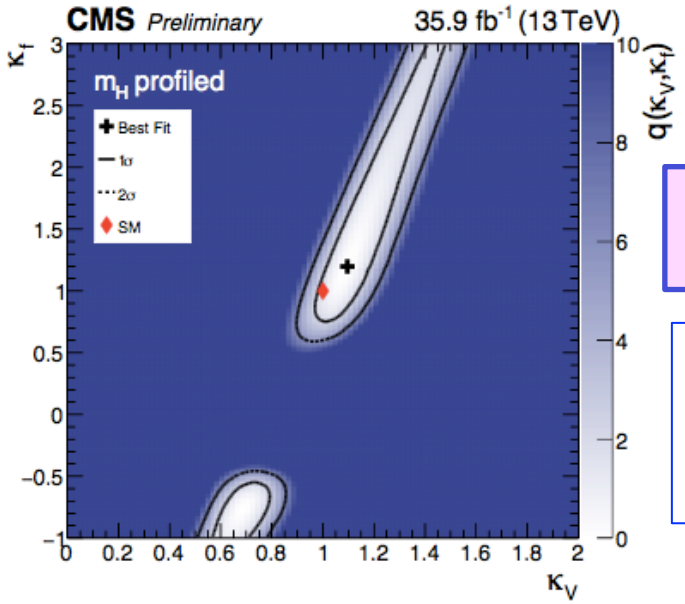
H→γγ results

Signal strenght by production modes



Best fit of fermionic and bosonic production signal strenghts





Best fit of fermion and boson coupling modifiers

(-1, 1) inconsistent with best fit at > 5σ level

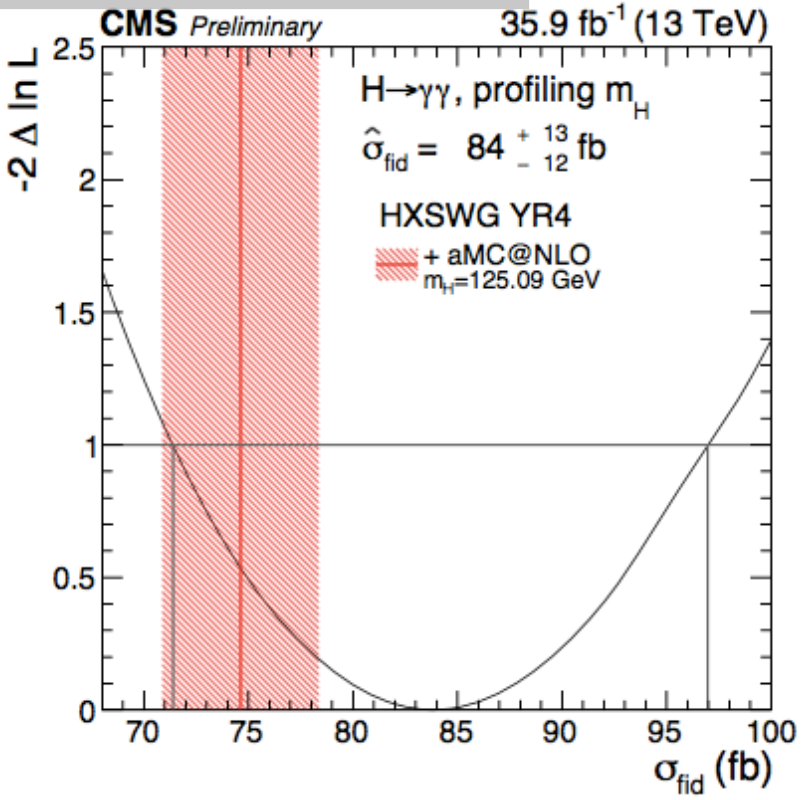
H→γγ fiducial cross section measurement

Fiducial volume defined to match closely the experimental acceptance

PAS HIG-17-015

Integral and differential measurements performed

Integral cross section best fit



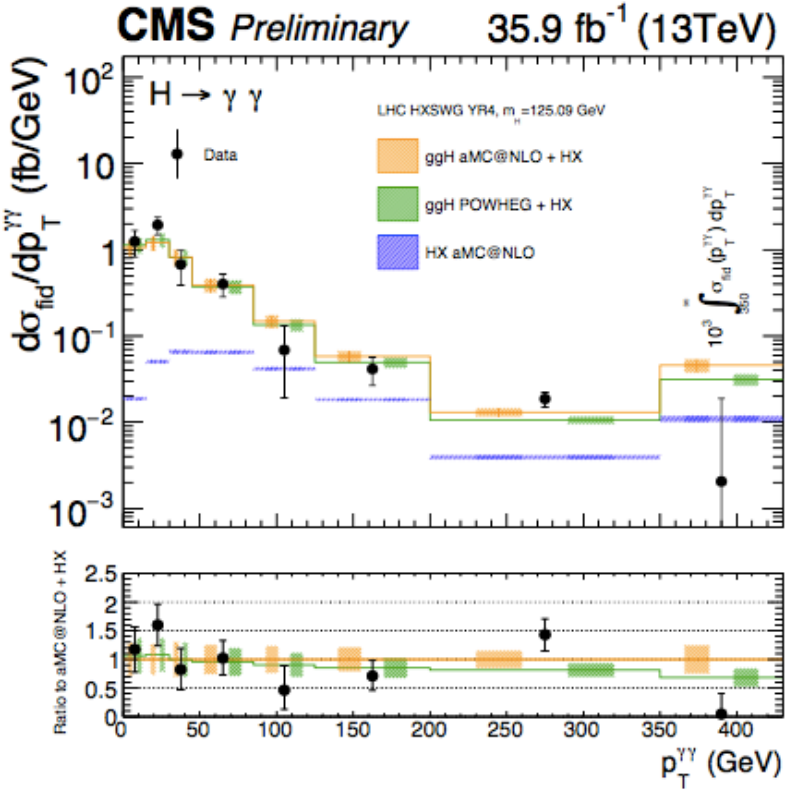
Fiducial region:
$|\eta_\gamma| < 2.5$
$p_{T\gamma1(\gamma2)} / m_{\gamma\gamma} > 1/3\ (1/4)$
$Iso_\gamma(\Delta R<0.3) < 10GeV$

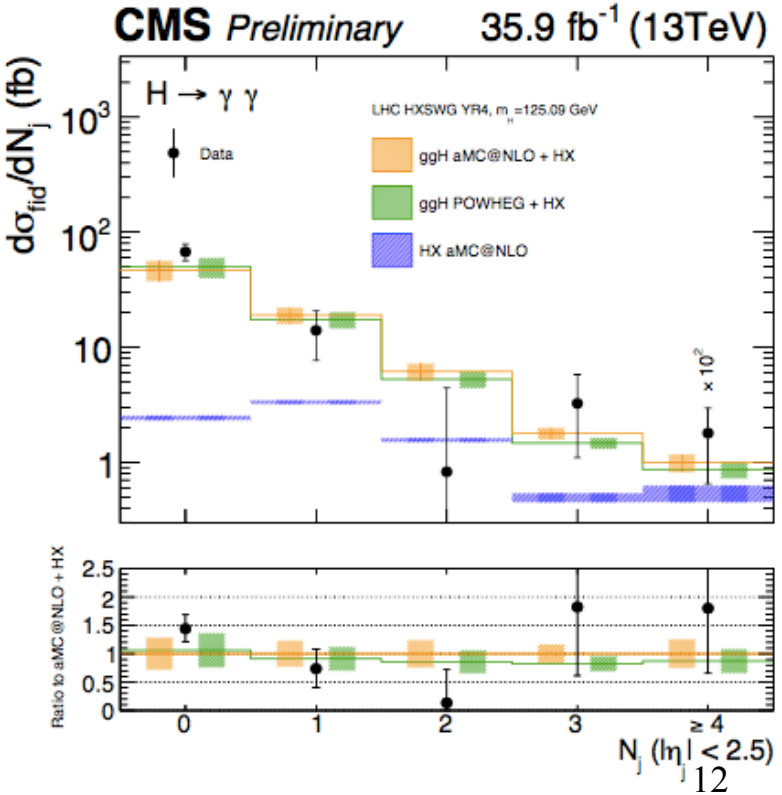
H→γγ fiducial cross section measurement

Differential measurements important to minimize dependency of measurement on model of Higgs boson kinematics

Investigate possible deviations from the SM prediction

Differential measurements in bins of $p_T^{\gamma\gamma}$ and N_{jet}





H→ZZ(4l) channel

4l channel (=4μ, 4e, 2e2μ)

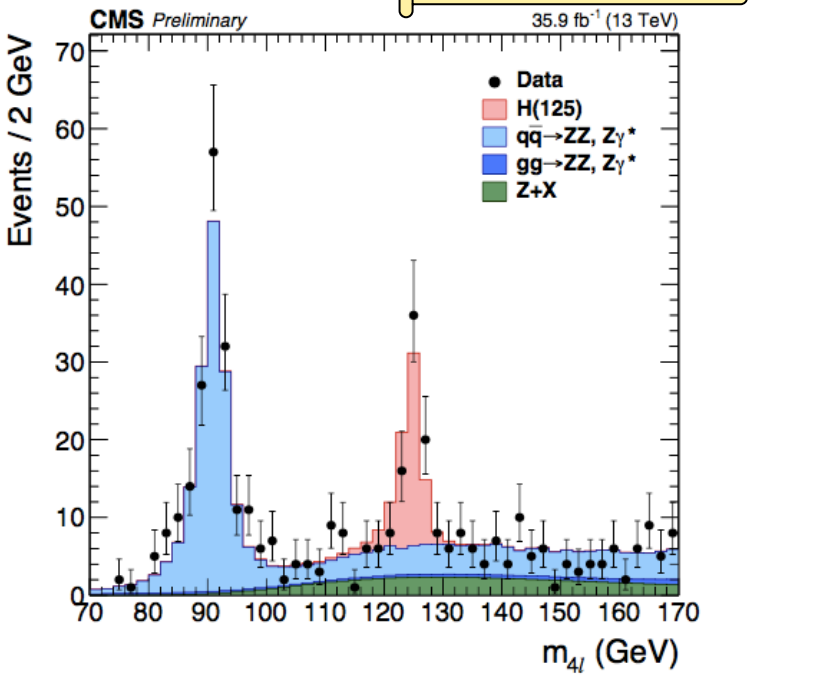
Signature: two pairs of isolated, high p_T leptons of opposite sign and originating from the primary vtx; one Z boson can be off-mass shell

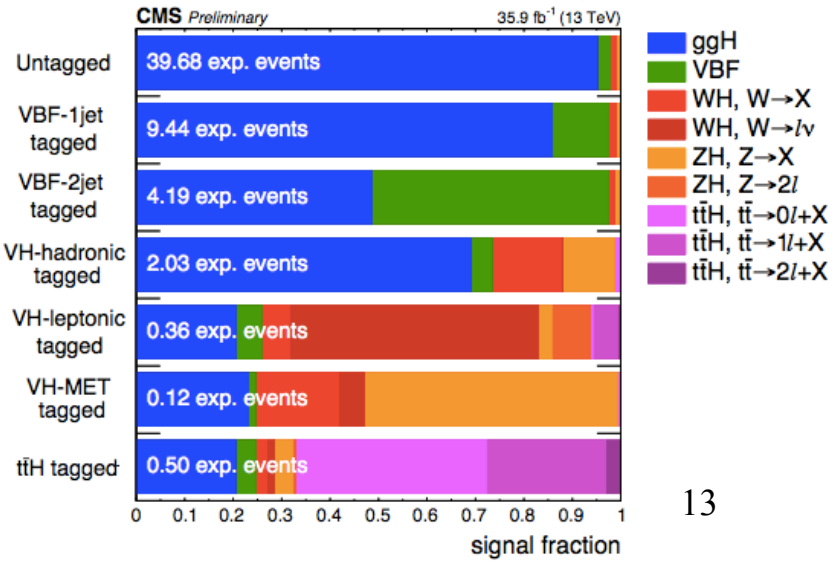
High lepton efficiency through a broad p_T range is crucial

Dominant backgrounds:
- non resonant ZZ (irreducible)
- Z+jets processes

Selected events are classified into mutually exclusive categories targeting different production modes
Purity of categories enhanced using kinematic discriminants (matrix element calculation)

PAS HIG-16-041

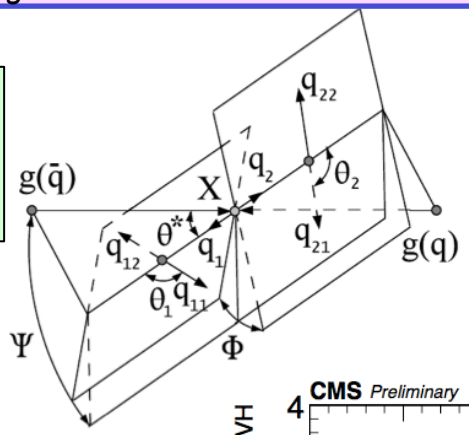




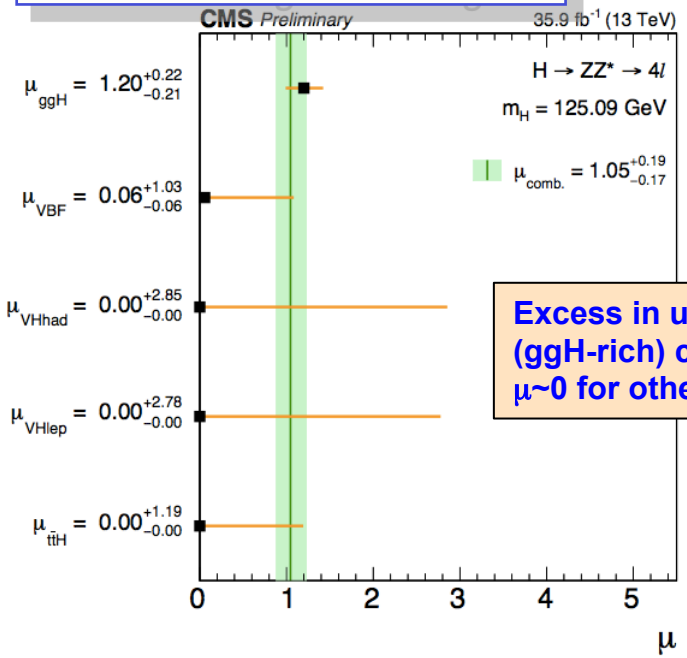
H→ZZ(4l) results

Simultaneous likelihood fit of (m_{4l}, D^{kin}_{bkg}) distribution to all categories

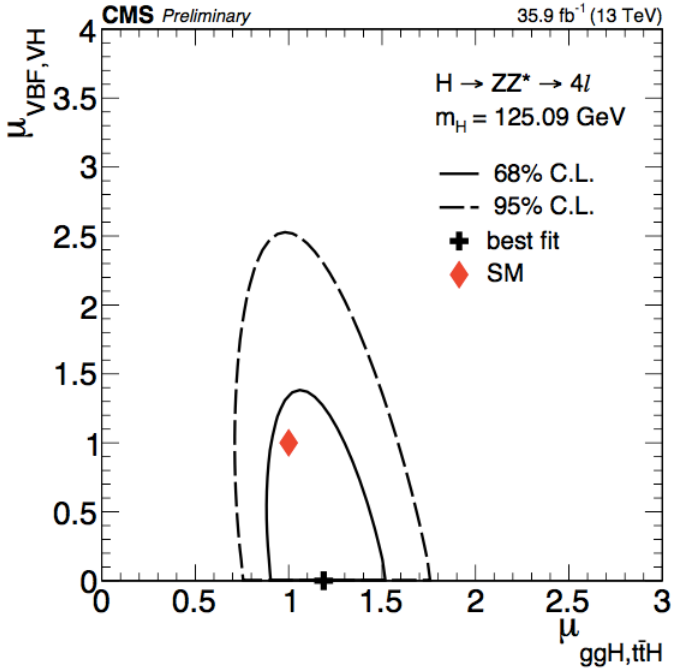
D^{kin}_{bkg} : kinematic discriminant exploiting variables fully describing the kinematics of Higgs boson decay



Best-fit to signal strenghts



Excess in untagged (ggH-rich) category → μ~0 for other processes



$\sigma/\sigma_{SM} = 1.05\ ^{+0.15}_{-0.14}\,(stat.)\ ^{+0.11}_{-0.09}\,(syst.)$

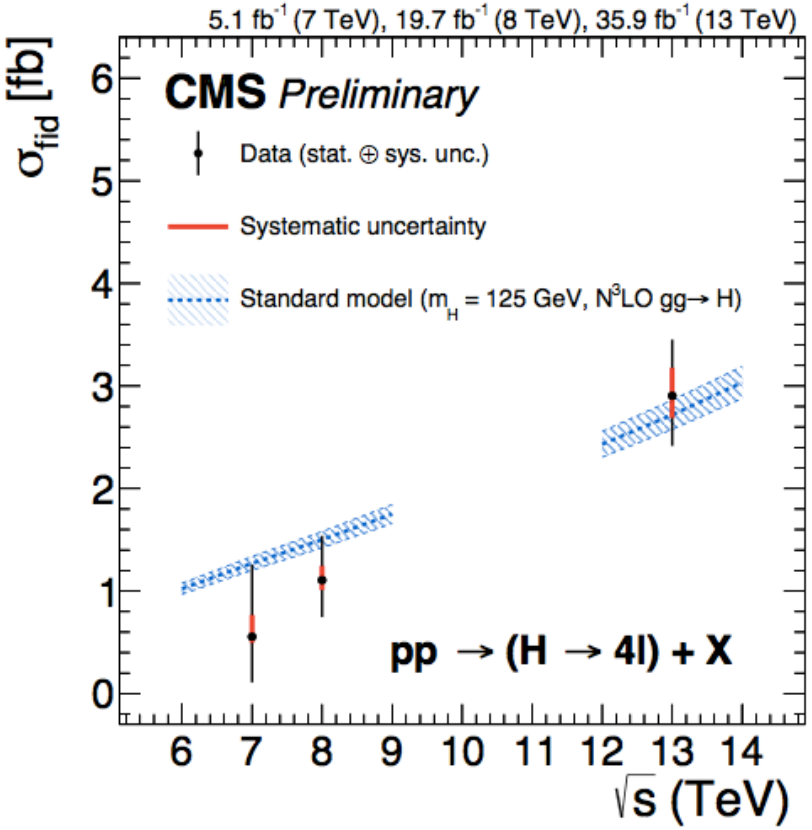
Measurement compatible with SM expectation

H→ZZ fiducial cross section measurement

Fiducial volume defined to match closely the experimental acceptance

Integral cross section measurement in Run1 and Run2

Integral and differential measurements performed

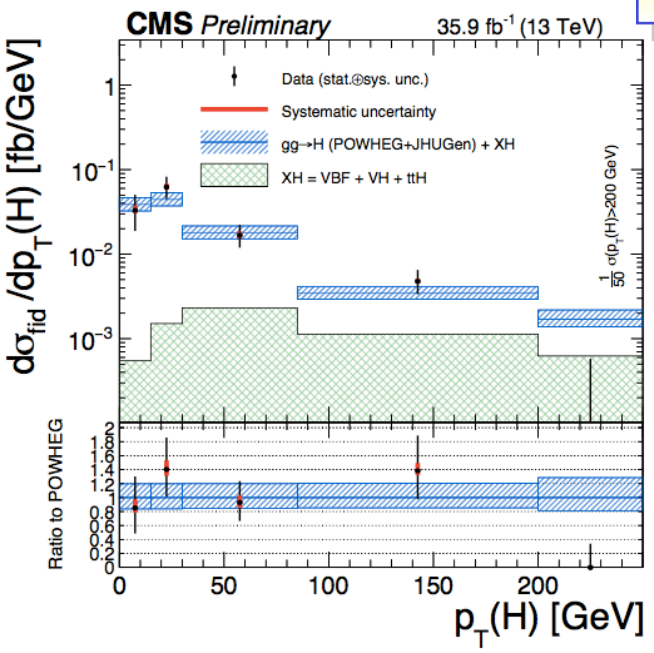


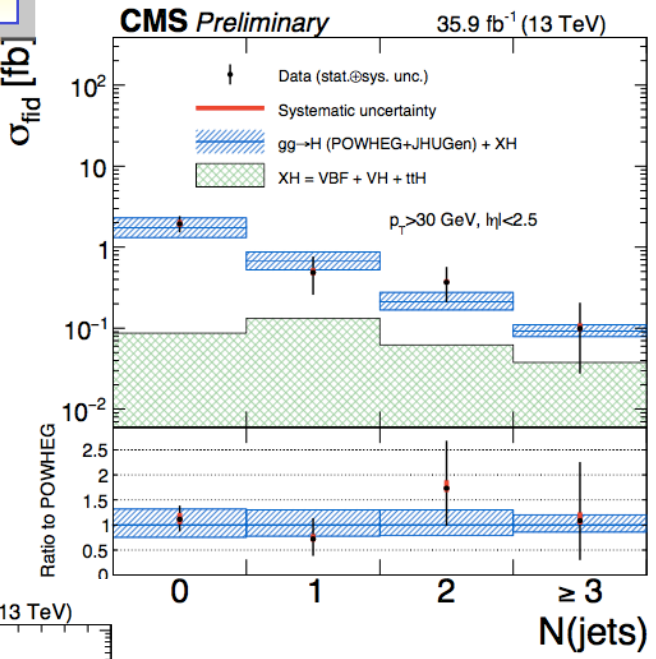
σ_{fid} (13TeV)= $2.90^{+0.48}_{-0.44}$ (stat.) $^{+0.27}_{-0.22}$ (syst.) fb

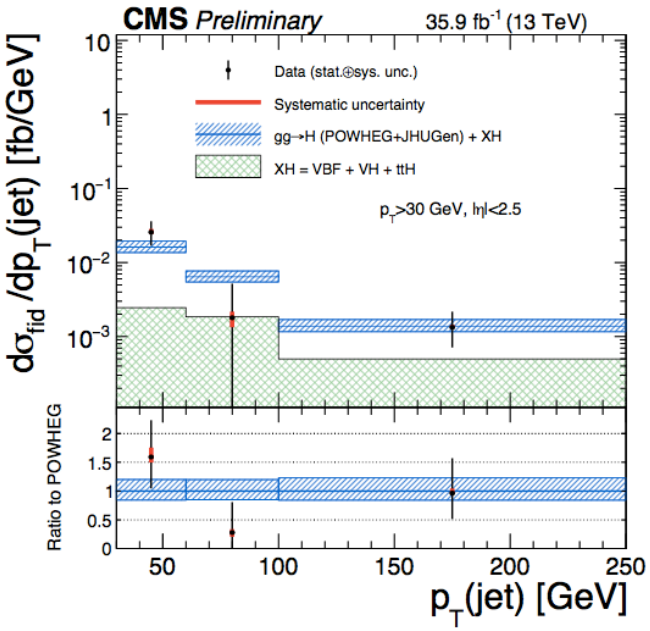
σ^{SM}_{fid} (13TeV)= 2.72 ± 0.14 fb

H→ZZ fiducial cross section measurement

Differential measurements







H→ττ channel

Channels considered: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$

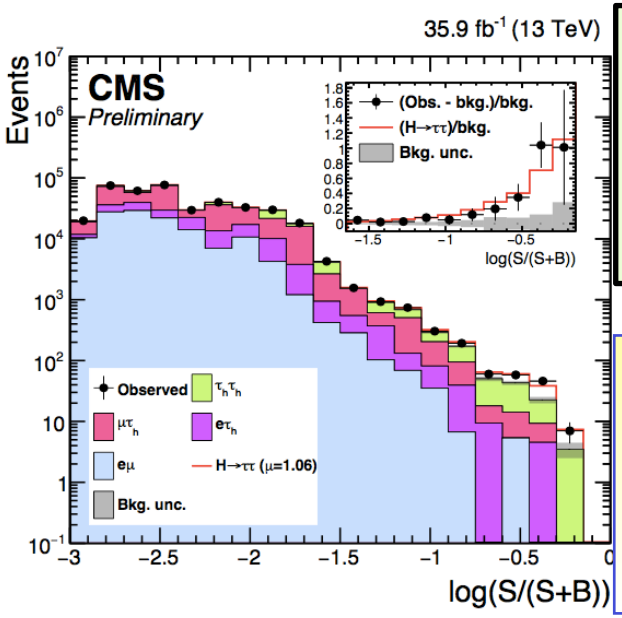
PAS HIG-16-043

Main backgrounds: DY→ττ/ll (irreducible), W+jets

Selection criteria optimized for each channel

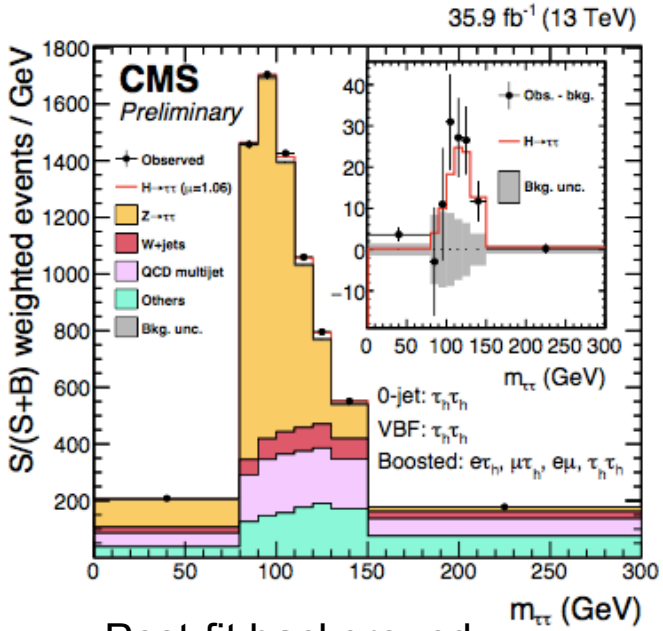
For each channel, further splitting of events in mutually exclusive categories by counting jets with p_T >30 GeV

- 0-jet (targeting ggH)
- VBF
- Boosted (targeting ggH with H recoiling against jet)



Signal extraction: Simultaneous binned likelihood fit on 2-D distributions for each category

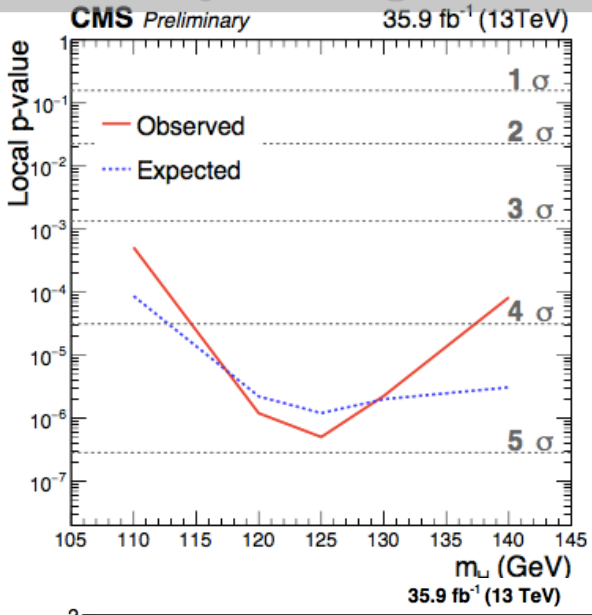
Excess of events in data wrt to SM background in the most sensitive bins of the distributions



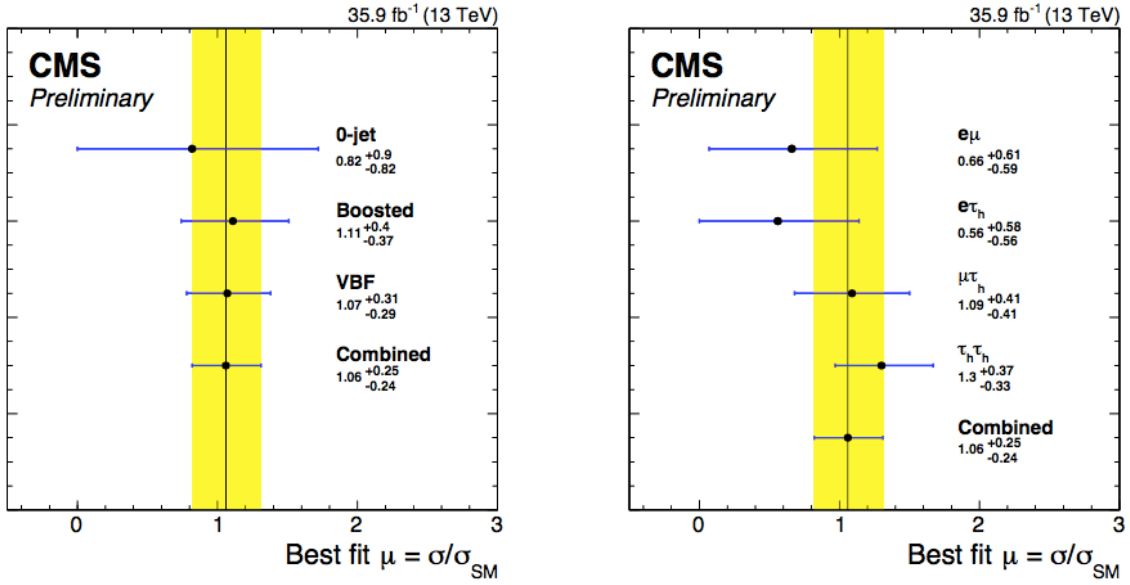
Post-fit background

H→ττ results

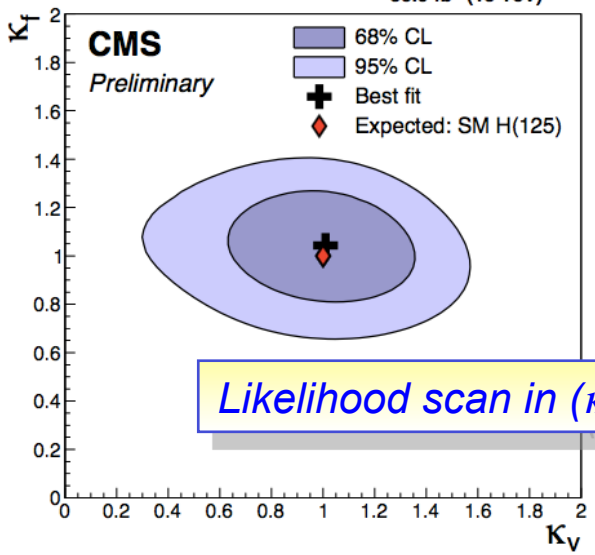
Observed significance @ 125GeV = 4.9σ



Best-fit per category and channel



Combined: σ/σ_{SM}= 1.06 ± 0.25 @ 125 GeV



Likelihood scan in (κ_f, κ_V) plane

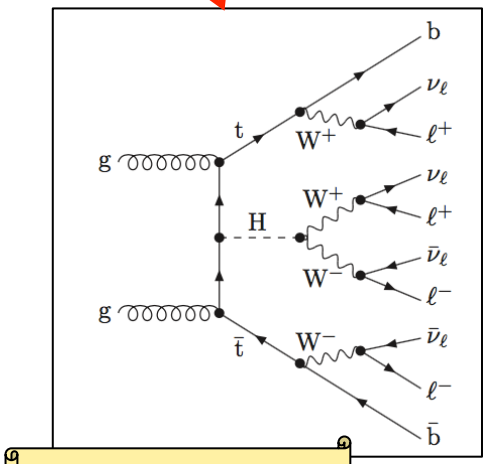
Fermion and vector boson coupling modifiers consistent with SM

ttH production channel

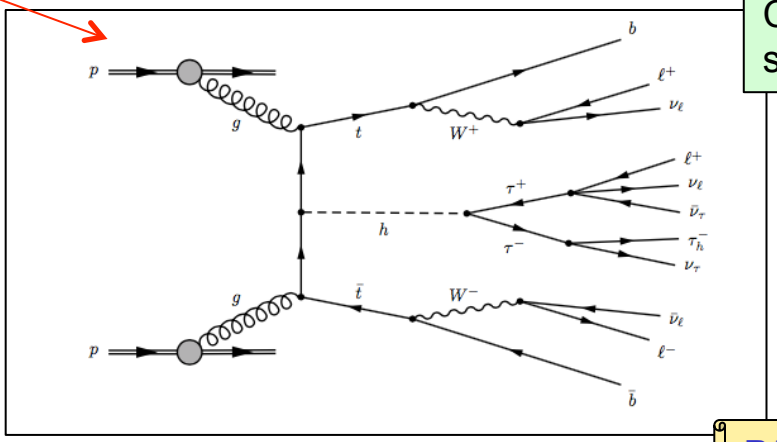
- *Direct probe of top Yukava coupling (complementary to indirect probe in channels with top loop)*
- *Cross section enhanced by ~ 4 when going from 8 TeV to 13 TeV center of mass energy*

Several final states considered:

- *H->γγ, H->ZZ(4l): higher purity, smaller BR (results reported in previous slides)*
- *H->bb: largest BR but also large background (no evidence of ttH from analysis on fraction of 2016 data, result is systematics limited)*
- *Multilepton final states: targeting H->WW, ZZ, ττ where at least 1 top decays leptonically*



PAS HIG-17-004



Dedicated analysis in CMS to study final states with at least $1\tau_h$

PAS HIG-17-003

ttH (multilepton)

Events classified in independent categories defined according to multiplicity, flavours and sum of charge of leptons, multiplicity of jets and b-jets, multiplicity of τ_h

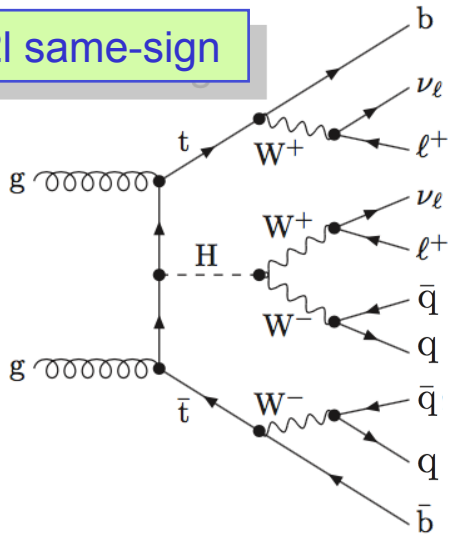
- *same-sign 2l, 3l, 4l*
- *1l+2*τ_h, *same-sign 2l+1*τ_h, *3l+1*τ_h

Background: ttZ, ttW (irreducible), processes with 1 non-prompt lepton (e.g. from b-jets in ttbar process) or misidentified charge lepton, or misidentified τ_h

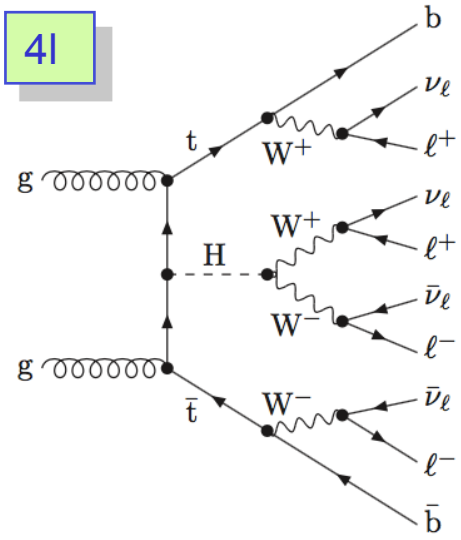
Use of multivariate-analysis techniques (BDT, MEM) to enhance sensitivity

- For each event category, classifier are defined to discriminate against tt and ttV events

2l same-sign



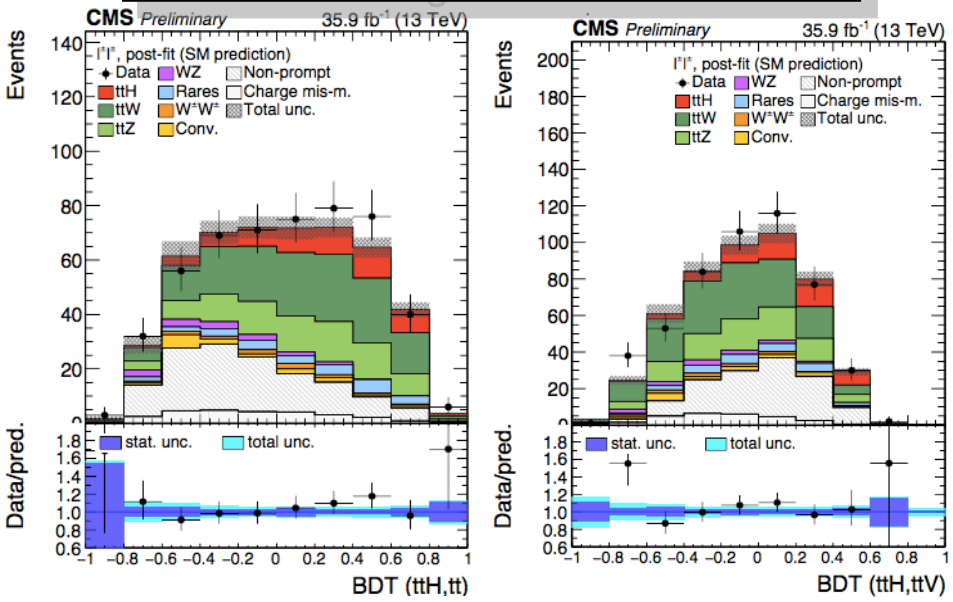
4l

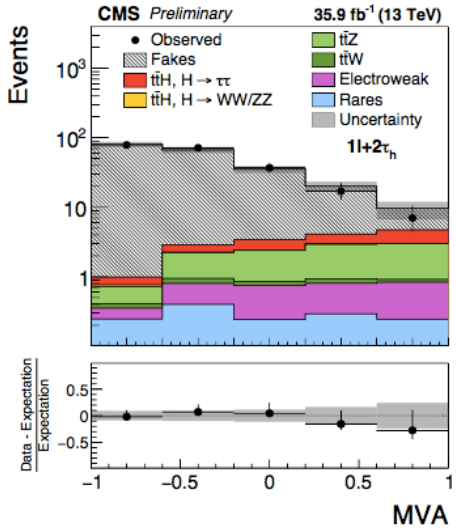


Main systematics from background estimation:
- ttV modeled using SM prediction (~ 10% uncertainty)
- Misidentified leptons or τ_h *from data with (~ 30% uncertainty)*

ttH multilepton results

Signal extracted by fit to classifiers for all the categories





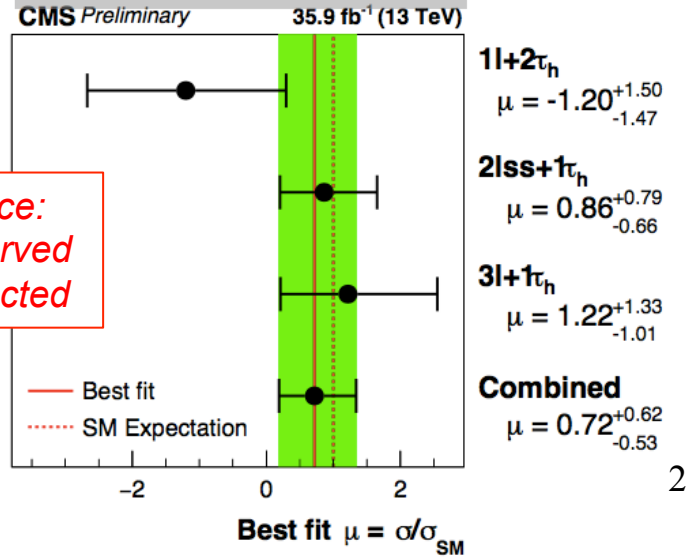
Multilepton: best-fit for σ/σ_{SM}

Category	Observed μ fit $\pm 1\sigma$
Same-sign di-lepton	$1.7\,(-0.5)\,(+0.6)$
Three lepton	$1.0\,(-0.7)\,(+0.8)$
Four lepton	$0.9\,(-1.6)\,(+2.3)$
Combined (2016 data)	$1.5\,(-0.5)\,(+0.5)$
Combined (2015 data) [42]	$0.6\,(-1.1)\,(+1.4)$
Combined (2015+2016 data)	$1.5\,(-0.5)\,(+0.5)$

Comparable statistical and systematics errors

Significance:
3.3σ observed
2.5σ expected

Final states with τ_h

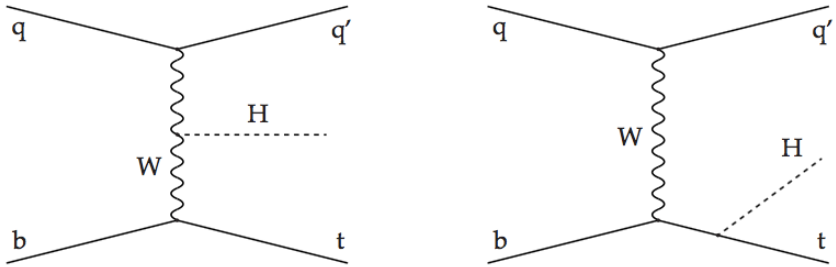


Significance:
1.4σ observed
1.8σ expected

tHq production

PAS HIG-17-005

Destructive interference from dominant leading order diagram



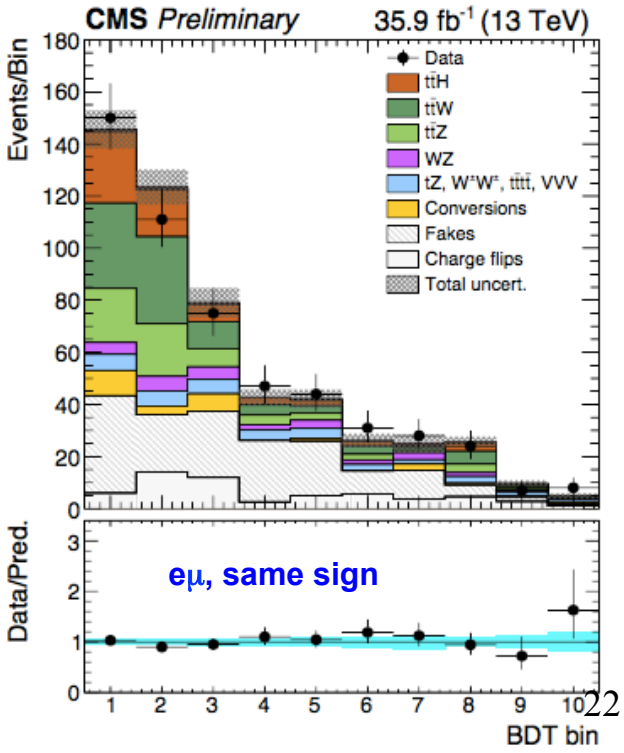
Sensitive to relative sign of top coupling w.r.t. vector boson coupling
New physics could enhance signal rate

Multilepton final states targeting leptonic decay of top + H->WW (ZZ) (ττ)
Event categories : 2l same-sign, 3l

BDT discriminants in all categories to separate signal from ttV and tt backgrounds

Selected events are sorted in 10 bins distributions according to the output of the BDT classifiers

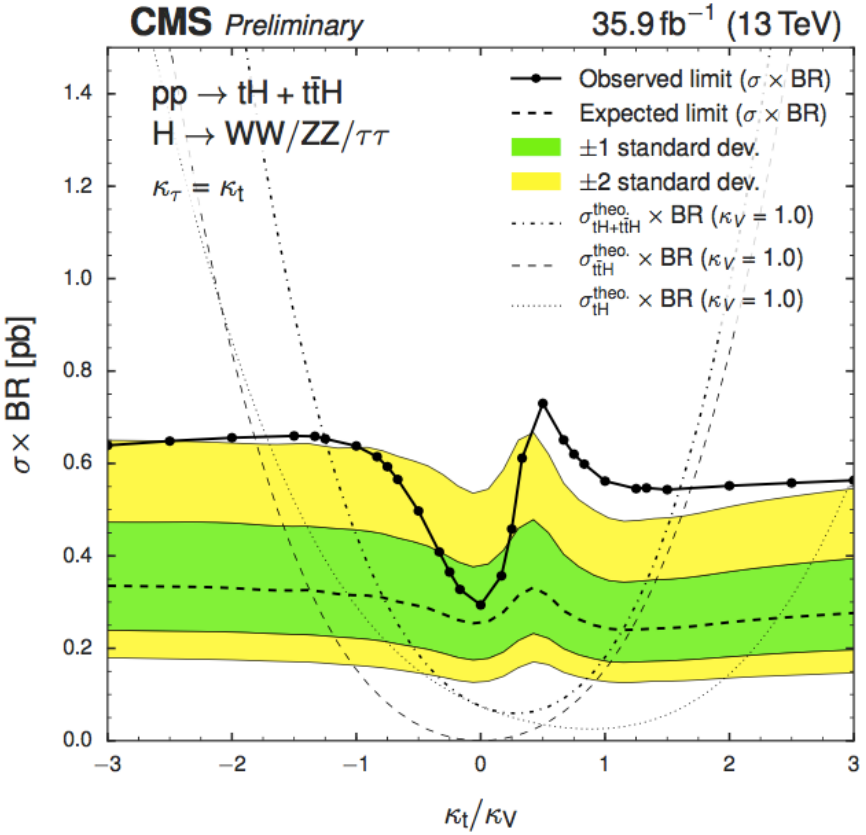
Combined fit to all categories for signal extraction



tHq results

Best fit of common signal strenght for tH and ttH signals

$(\sigma/\sigma_{SM})_{tH+ttH}$ = 1.8 ± 0.3 (stat.) ± 0.6 (syst.)



Significance of SM signal @ 2.7 σ-level w.r.t. background-only hypothesis (1.5 σ expected)

σ x BR < 0.56 pb @ 95% CL in SM scenario

(κ_t =-1, κ_V=1) scenario: σ x BR < 0.64 pb @ 95% CL

κ_t values (κ_V=1) outside [-1.25, 1.60] range excluded @95% C.L.

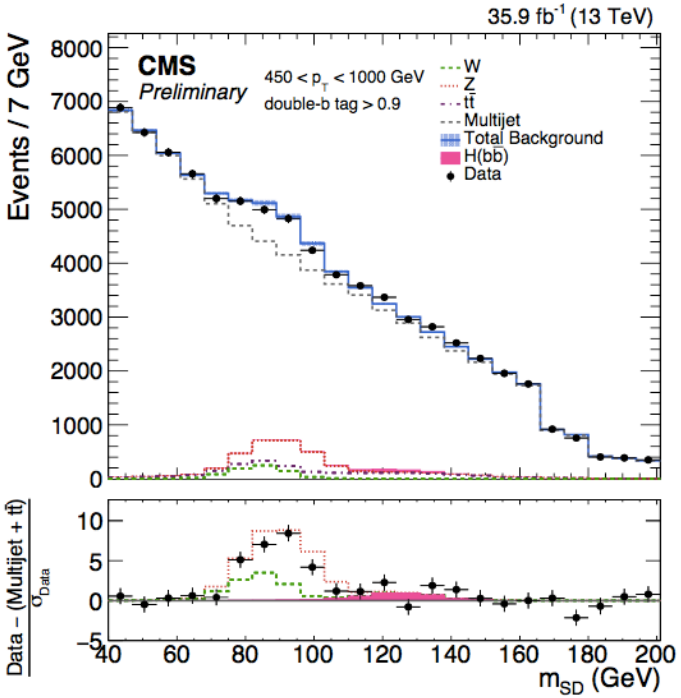
Boosted inclusive H(→bb)

PAS HIG-17-010

Inclusive search of H→bb decays exploiting production of high p_T Higgs boson in association with high p_T jet

Higgs boson decay products reconstructed as single jet
Identification based on 2-prong jet substructure and dedicated b-tagging

Search for as a resonance in jet mass distribution



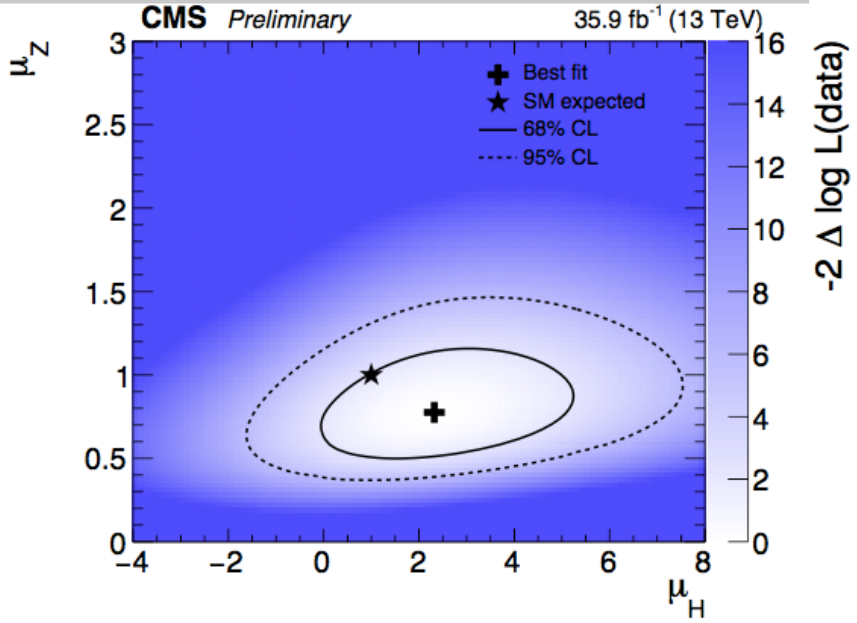
Data-driven estimate of QCD background

Combined fit to jet mass distributions in b-tag passing and failing regions for several p_T categories and in tt-enriched control region

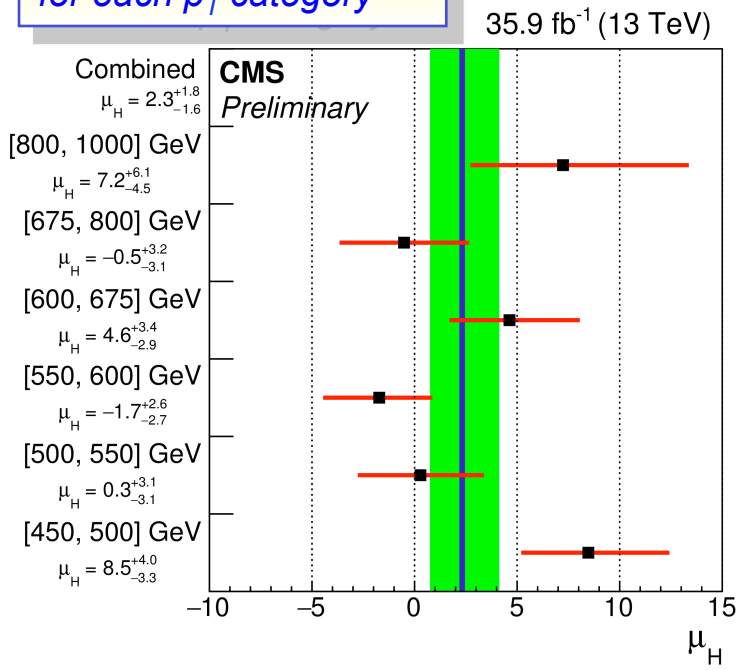
Boosted inclusive H(→bb) results

Z->bb background extracted together with signal

Best fit for Z→bb and H→bb signal strenghts



Fitted signal strenghts for each p_T category



$\mu_H = 2.3^{+1.8}_{-1.6}$

$\mu_Z = 0.78^{+0.23}_{-0.19}$

Z->bb observed with significance of 5.1 σ

First observation of Z->bb process in single-jet topology

Significance of H->bb excess is 1.5 σ (0.7 σ expected)

Conclusions

- After discovery of Higgs boson in LHC Run 1 a broad program of studies exploiting variety of production and decay channels aiming to measure its properties
  - Is the behavious compatible with SM Higgs boson? Any deviation (hint of New Physics)?

- In this talk we have reviewed recent production measurements based on 2016 dataset of LHC Run 2 @ 13 TeV
  - Higher center of mass energy and large dataset
    - Increased precision, improved measurement strategies
    - New channels investigated in order to study coupling of Higgs boson to SM particles
  - Fiducial and differential measurements to provide model independent measurements and search for deviation from SM predictions

- Current measurements are compatible with predictions for a SM Higgs boson but most of the measurements still statistically limited

- Increased data samples @ 13 TeV we expect from 2017-18 run will allow more stringent studies

Backup slides

H→ZZ(4l) fiducial volume definition

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\text{GeV} < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12\,\text{GeV} < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$