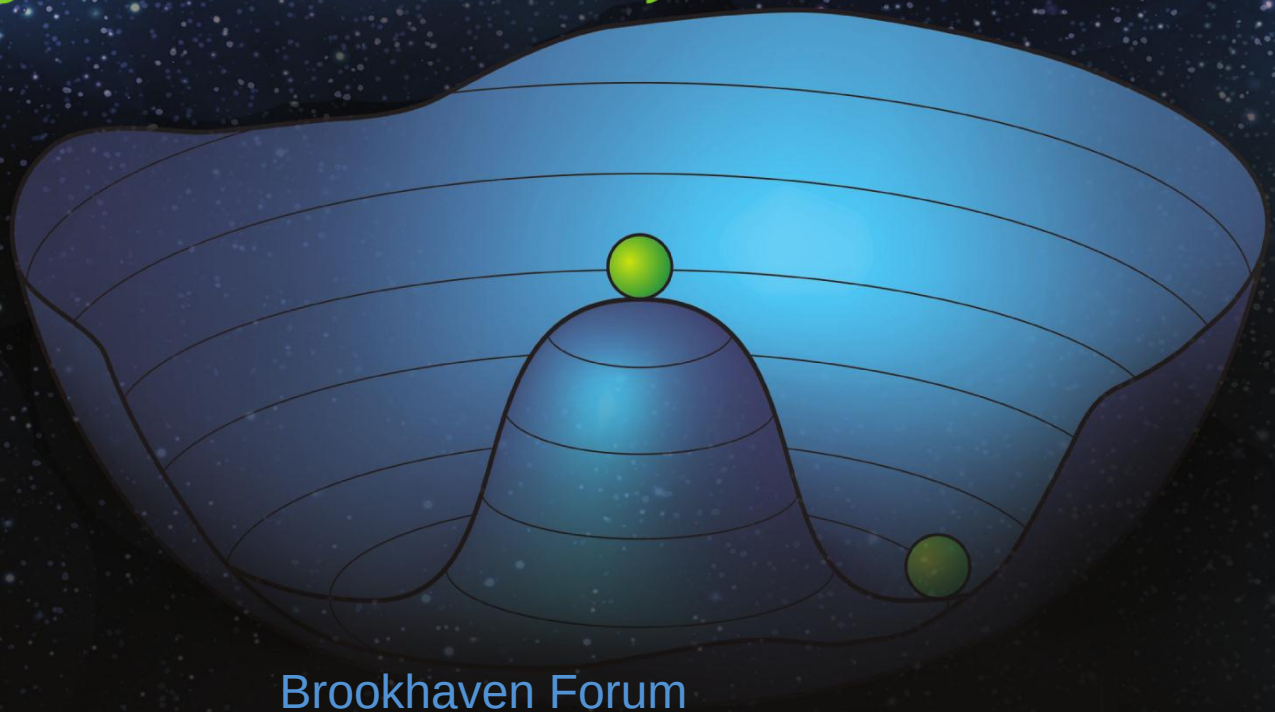
Yuriy Pakhotin (Texas A&M)
on behalf of CMS Collaboration

Higgs Results from CMS



Brookhaven Forum
May 1-3, 2013
Upton, NY

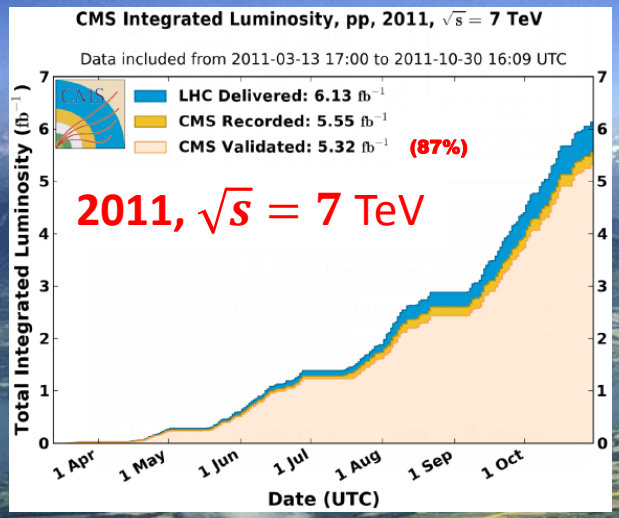
Outline

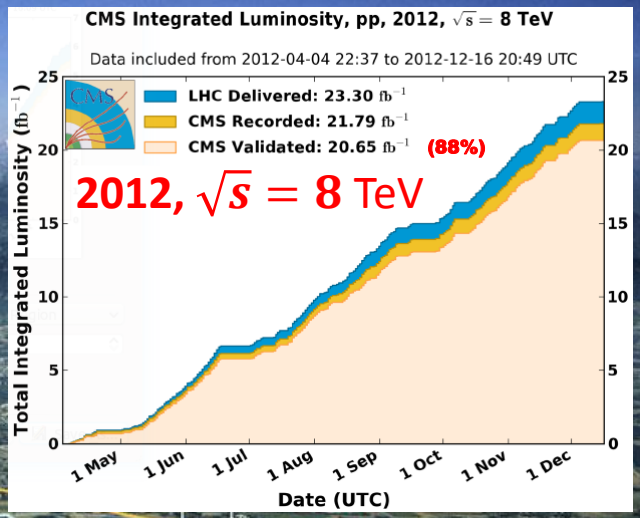
- ✓ LHC and CMS
- ✓ Higgs production and decay channels
- ✓ Strategy of data analyses at CMS
- ✓ Searches for SM Higgs
  - mass and cross section measurements
  - focus on $H \to \gamma\gamma$ and $H \to ZZ$ analyses
- ✓ Searches for exotic Higgs
  - focus on NMSSM $h_{1,2} \to a_1 a_1$ analysis
- ✓ Conclusion

For details look into

- backup slides or links to articles → ***CMS-PAS-HIG-13-005***
- PAS = “Physics Analysis Summary”

Large Hadron Collider (LHC)





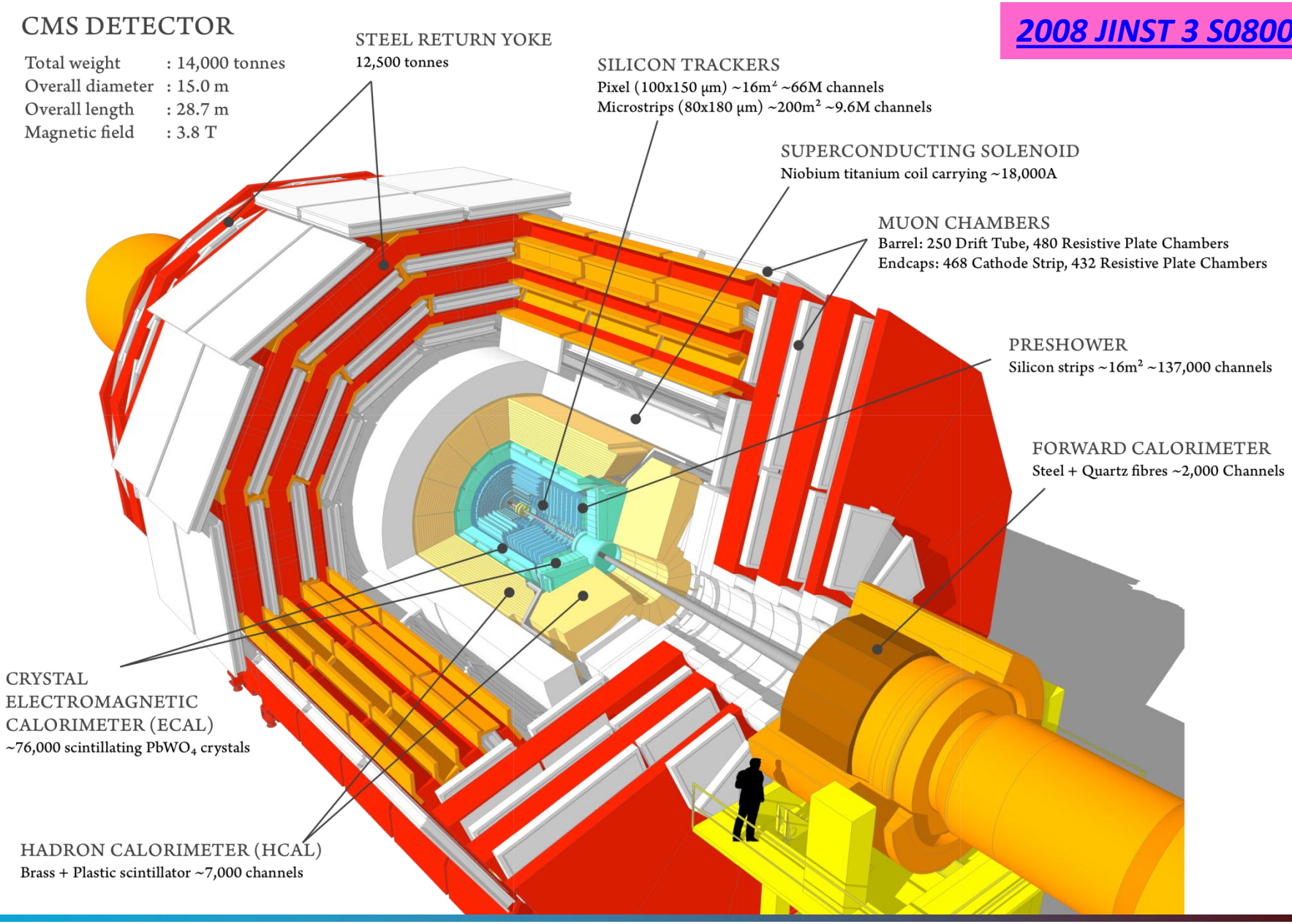
Analyses presented in this talk:

- $L < 5.1\ fb^{-1}$ at $\sqrt{s} = 7$ TeV in 2011
- $L < 19.6\ fb^{-1}$ at $\sqrt{s} = 8$ TeV in 2012

LHC: proton-proton collider

*No results from Heavy-ions collisions in this talk

CMS Experiment



[2008 JINST 3 S08004]

Higgs Boson Observation

✓ Higgs boson "birthday": July 4th, 2012

- special event at CERN: http://indico.cern.ch/conferenceDisplay.py?confId=197461

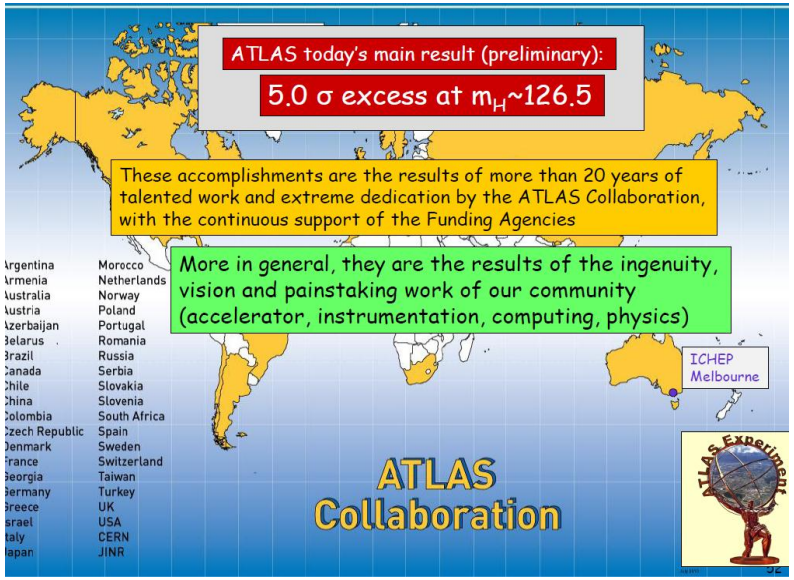
Excerpt from CMS slides

In summary

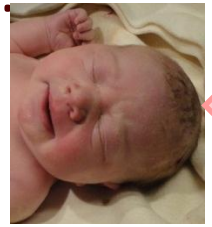
We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !

J. Incandela UCSB/CERN
July 4, 2012 Boulder Colorado

Excerpt from ATLAS slides



- special event at my home:

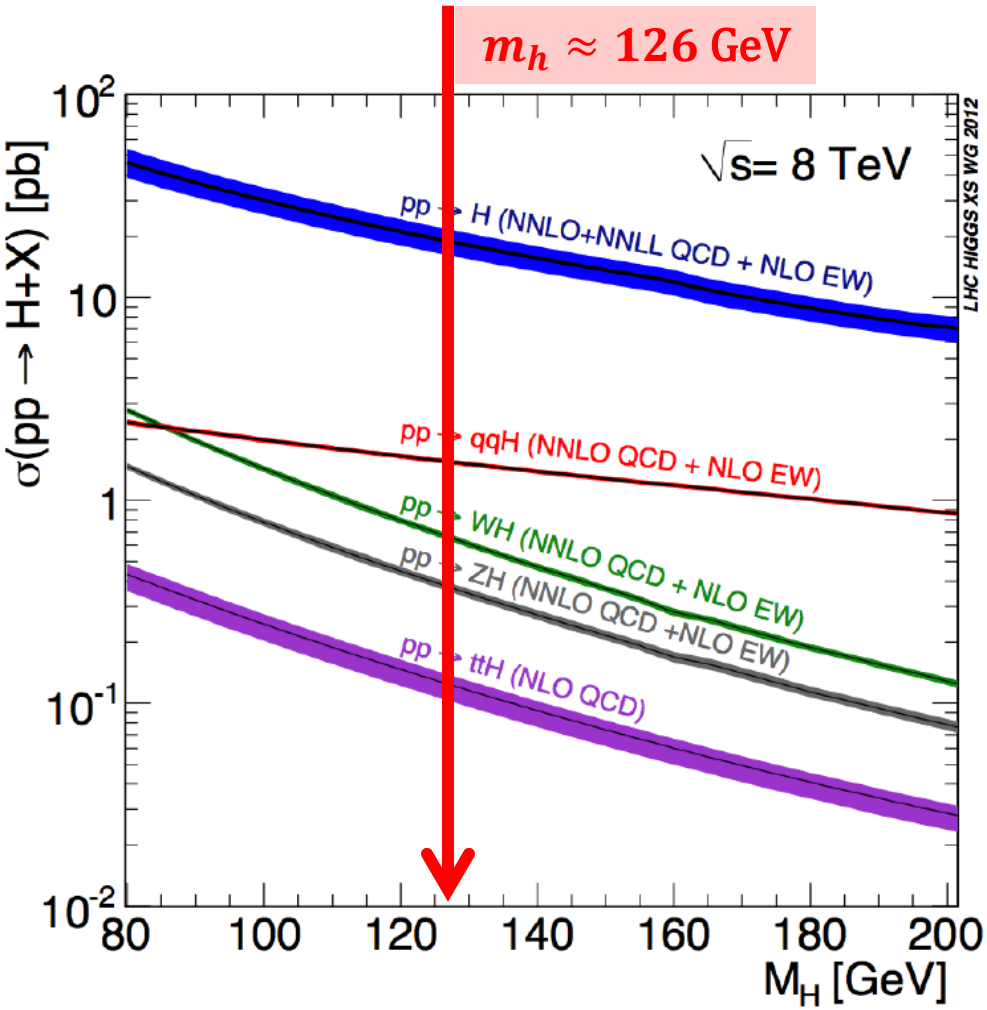


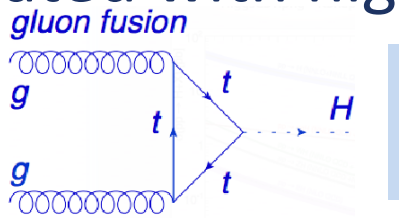
This is NOT Peter Higgs!
Her name is Anna, born on July 4th '12

Higgs Production at LHC

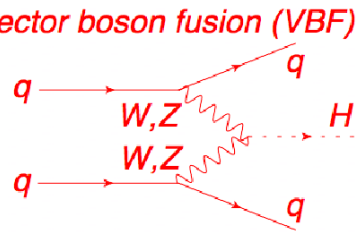
✓ Cross section of the Higgs production in pp collisions at $\sqrt{s} = 8$ TeV is calculated with high precision

arXiv:1101.0593

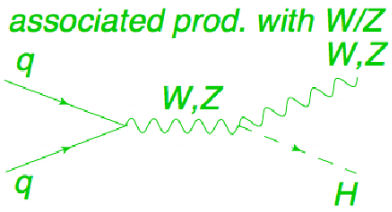




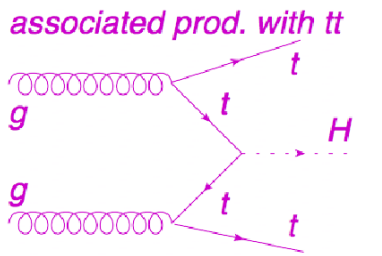
- *Large uncertainty from QCD*
- *Probes fermion coupling*
- *Sensitive to BSM in loops*



- *Small uncertainty*
- *Probes W/Z coupling*
- *Tagged with forward jets*



- *Small uncertainty*
- *Access to W/Z coupling*
- *Tagged with W/Z lepton decay*



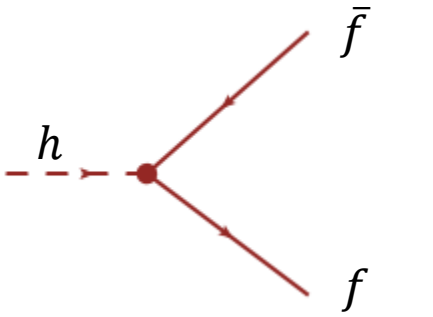
- *Large uncertainty from QCD*
- *Probes top coupling*
- *Tagged with b-jets*

Standard Model Higgs Decay Channels

✓ Five most sensitive channels studied

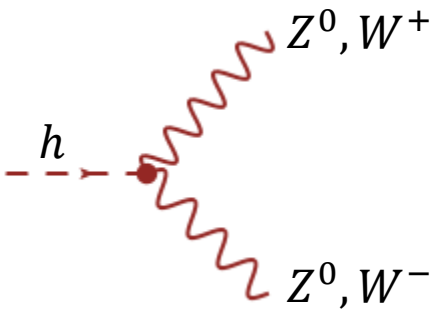
- High yield: $h \to WW/\tau\bar{\tau}/b\bar{b}$
- High mass resolution: $h \to \gamma\gamma/ZZ$

arXiv:1101.0593



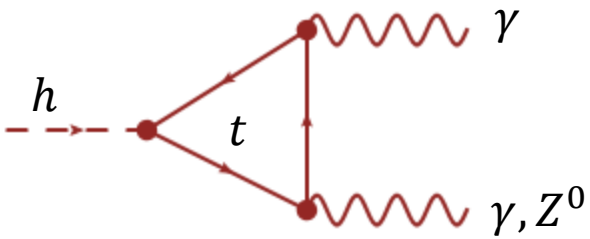
$h \xrightarrow{57\%} b\bar{b}$

$h \xrightarrow{6\%} \tau\bar{\tau}$

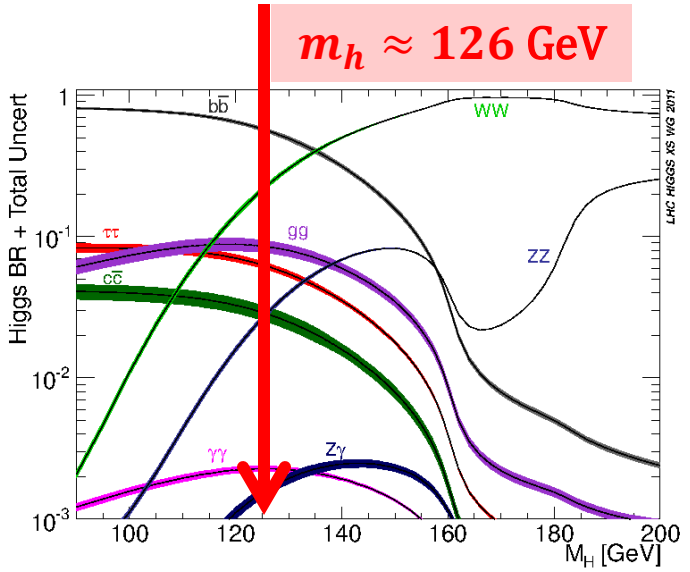


$h \xrightarrow{21\%} WW \to 2l + 2\nu$

$h \xrightarrow{3\%} ZZ \to 4l \text{ or } 2l + 2\tau$



$h \xrightarrow{9\%} \gamma\gamma$



@ 125GeV	signature	S/B	Mass Resol.	N events in 20fb^{-1}	Good For
H→bb	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	~10^5 ~50 (sel)	couplings to fermions
H→ττ	had tau, leptons, MET	low O(0.1)	15%	~10^4 ~40 (sel)	couplings to fermions
H→WW	two leptons with opposite charge MET	medium O(1)	-	~10^3 ~120 (sel)	cross section, BR, couplings to V
H→γγ	two photons peak in inv. mass	low O(0.1)	2%	800 ~400 (sel)	H mass, couplings $K_V K_F$, discovery
H→ZZ	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	40 ~12 (sel)	H mass, discovery

Data Collection, Reconstruction and Analysis

- ✓ Data for Higgs analyses: 7 TeV + 8 TeV
  - collected with single/double lepton/photon triggers
  - challenge: large pileup!

CMS-PAS-HIG-13-005

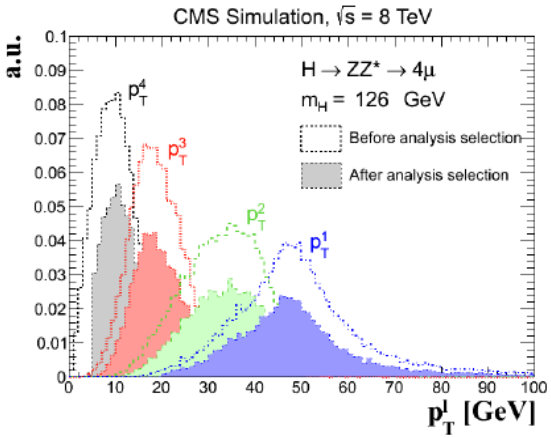
- ✓ Physics objects
  - Leptons (μ, e, τ) and photon reconstruction
    - identify and select relatively high p_T isolated objects
    - study momentum scale & resolution
  - Jet reconstruction
    - algorithm based on particle flow
    - study pile-up identification and pile-up subtraction of the energy
    - reject backgrounds and/or select VBF events
  - b-tagging
    - algorithm based on displaced tracks and soft leptons
    - reject top backgrounds and/or select b-jets
  - MET :
    - algorithm based on all particles pointing to primary vertex
    - select events with neutrinos and/or reject backgrounds
- ✓ Analyses
  - "Blind"
    - Selection criteria defined before looking at the signal region
  - Data-driven
    - Backgrounds estimation and systematics uncertainties study
  - Large number of independent analyses and cross-checks

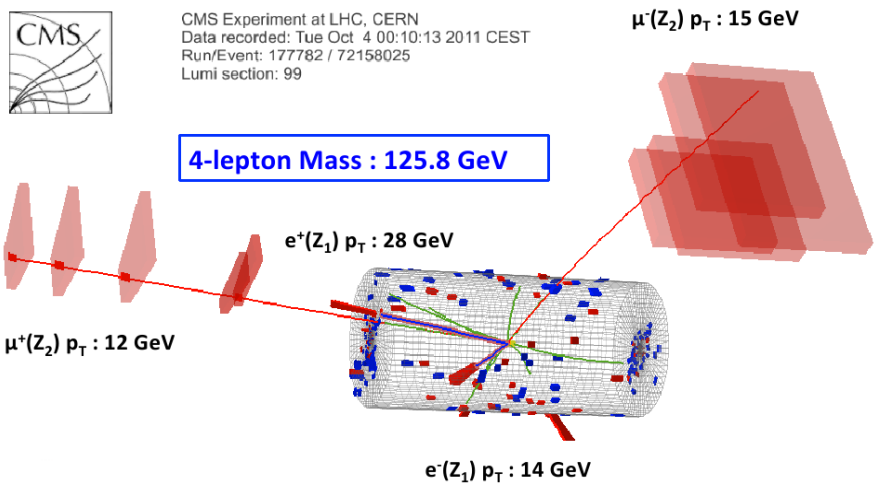
Full 2011+2012 dataset is now analyzed

Search for $h \to ZZ \to 4l$: Analysis

CMS-PAS-HIG-13-002

- ✓ Signal signature
  - Four high-quality isolated leptons (e and μ) from the same vertex
  - Small rate but signal-to-background ratio is high
  - Golden channel!
- ✓ Standard Model Backgrounds
  - $ZZ \to 4l$
    - different mass shape
  - $Z + jets: Z + \bar{c}c/\bar{b}b/\bar{t}t$
    - isolation and b-tagging
  - Kinematic discriminators
    - Matrix Element techniques used to build the K_D discriminant variable (see definition in backup)

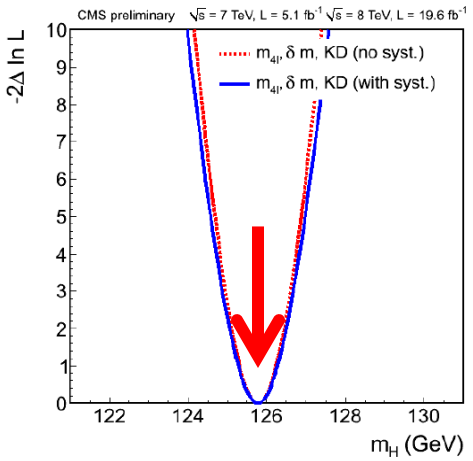


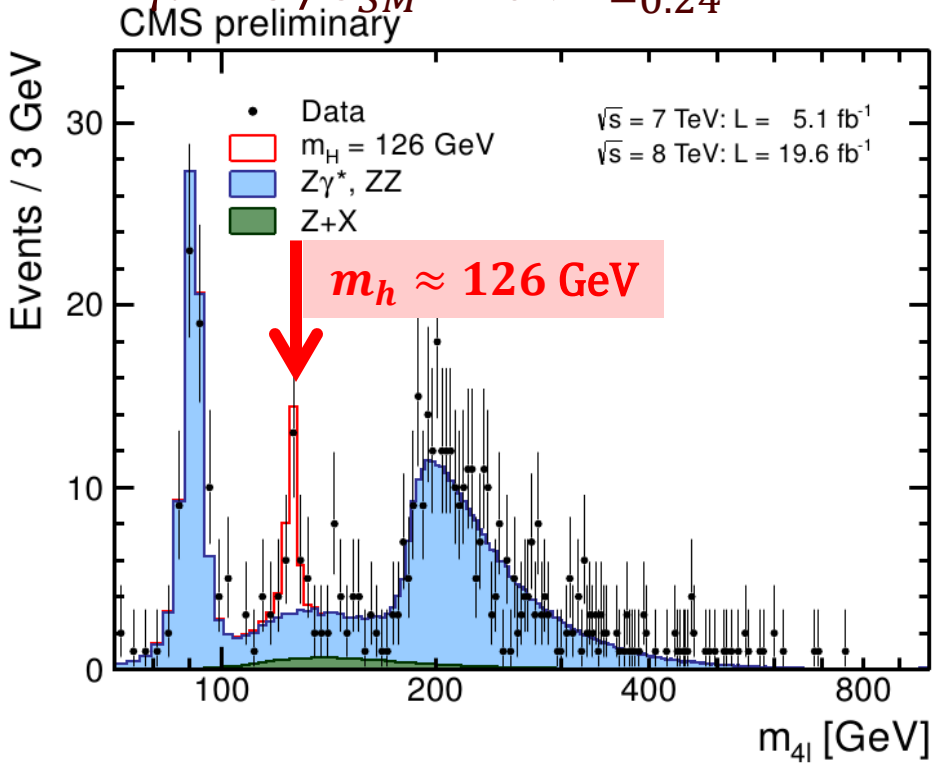


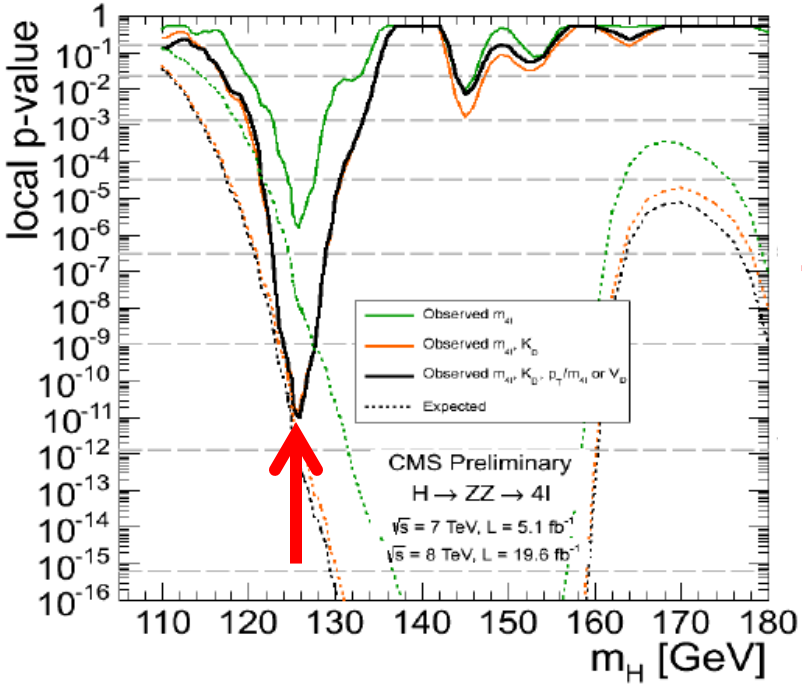
Search for $h \to ZZ \to 4l$: Results

CMS-PAS-HIG-13-002

- ✓ Mass measurement
  - $m_h = 125.8 \pm 0.5(stat) \pm 0.2(syst)$ GeV
  - p-value: 7.1σ (exp.) *and* 6.7σ (obs.)
    - Probability that background fluctuates to give an excess as large as the (average) signal size expected for a SM Higgs
- ✓ Cross section (at $m_h = 125.8$ GeV)
  - $\mu = \sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$



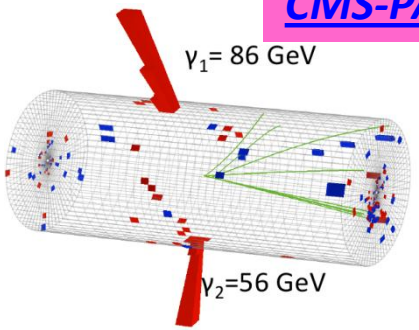


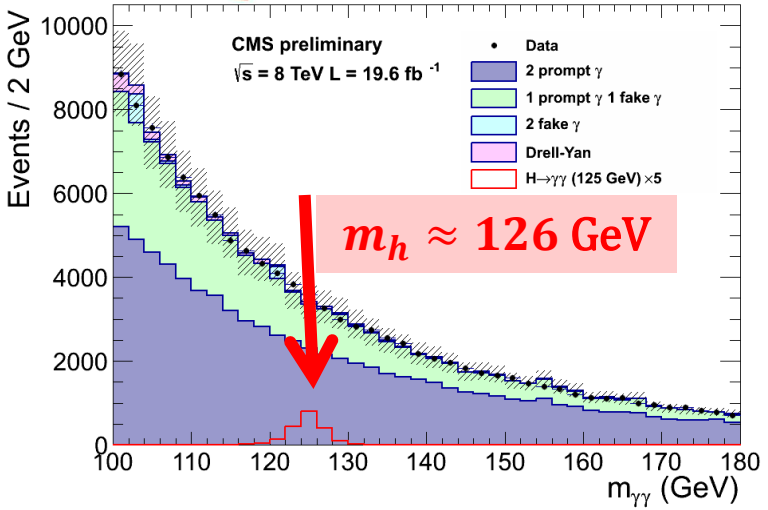


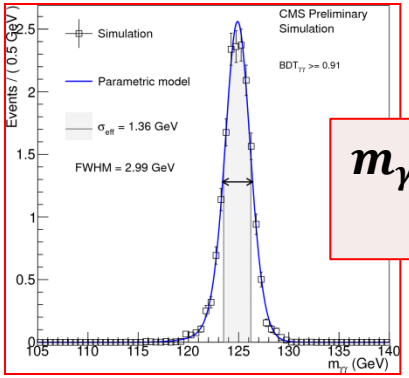
Search for $h \to \gamma\gamma$: Analysis

- ✓ Signal signature
  - Two isolated photons with high p_T
  - Small rate but narrow mass peak on top of a large steeply falling background
- ✓ Backgrounds
  - Direct $\gamma\gamma$ production
  - Fake photons
- ✓ Two independent analyses
  - mass factorized MVA (primary)
    - photon kinematics,
    - photon ID (shower shape, isolation)
    - di-photon mass resolution
  - cut based (cross check)

[CMS-PAS-HIG-13-001]





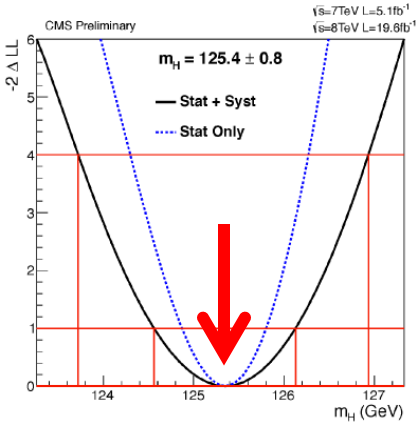


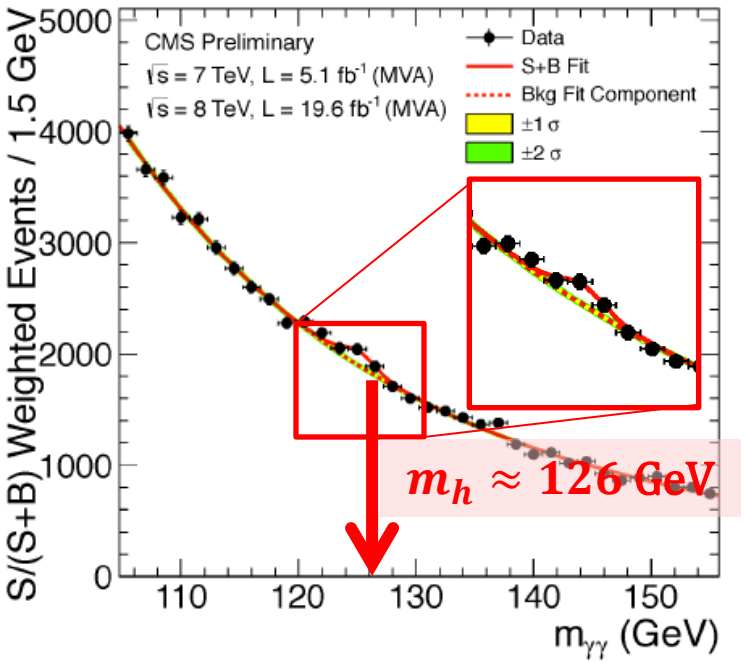
$m_{\gamma\gamma}$ resolution ~1%

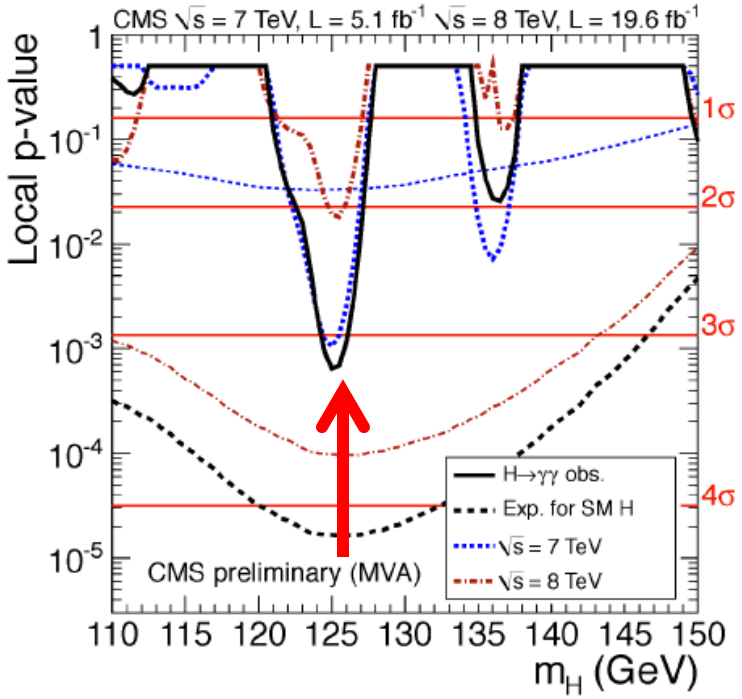
Search for $h \to \gamma\gamma$: MVA Results

[CMS-PAS-HIG-13-001]

- ✓ Mass measurement (MVA analysis)
  - $m_h = 125.4 \pm 0.5(stat) \pm 0.6(syst)$ GeV
  - p-value: 4.2σ (exp.) and 3.2σ (obs.)
- ✓ Cross section (at $m_h = 125$ GeV)
  - $\mu = \sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$







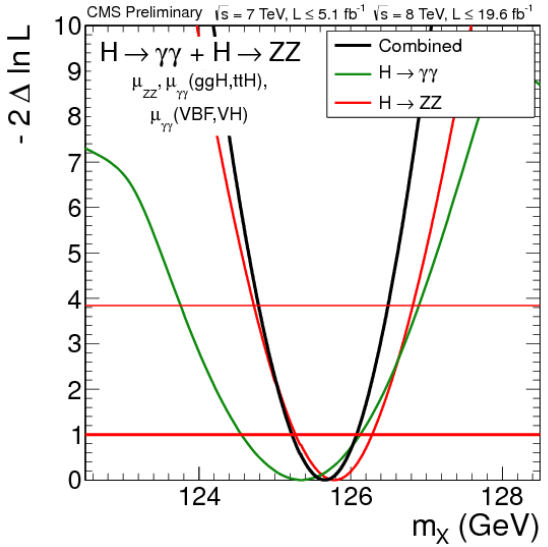
Search for h: All Channels Combined

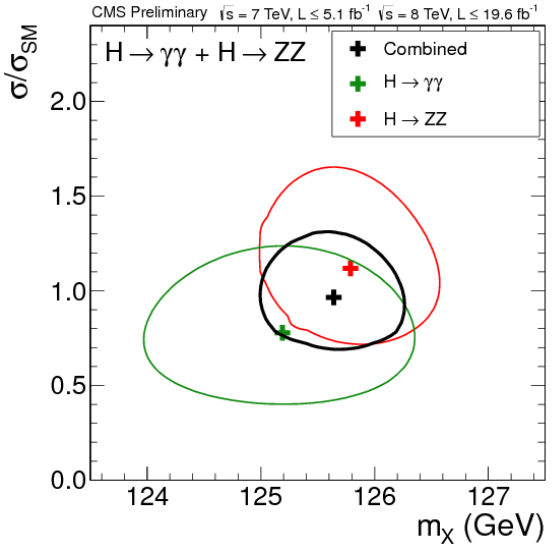
CMS-PAS-HIG-13-005

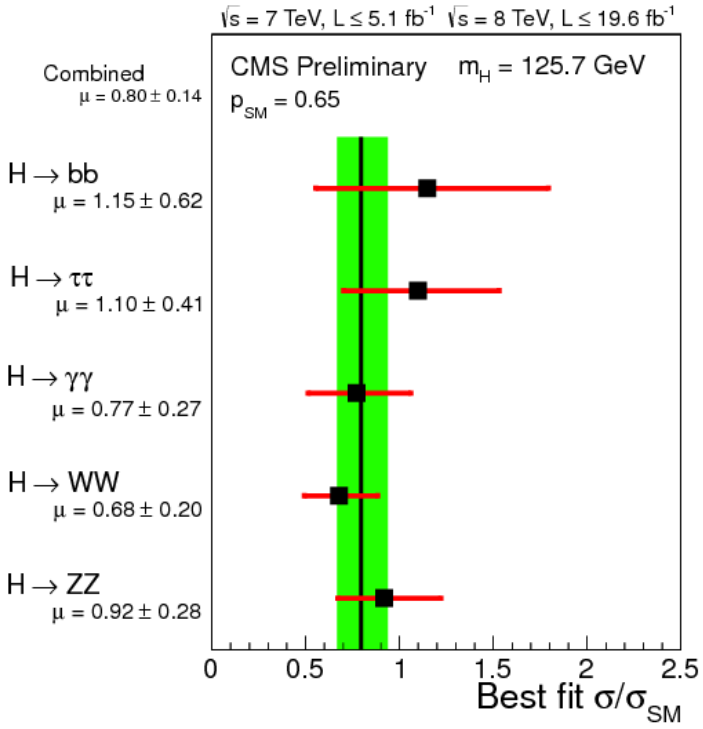
- ✓ Combined measurements
  - mass from $h \to \gamma\gamma$ and $h \to ZZ \to 4l$ analyses
  - $m_h = 125.7 \pm 0.3(stat) \pm 0.3(syst)$ GeV
- ✓ Consistency with SM
  - $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.14$

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.0 σ
ττ	2.6 σ	2.8 σ

$> 5\sigma$

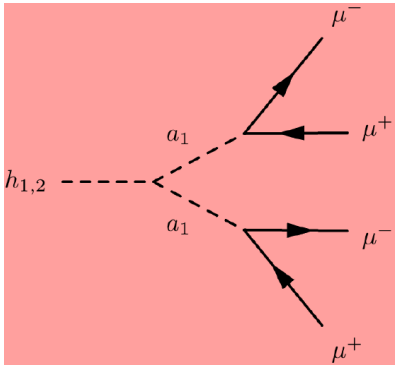






Exotic Higgs

- ✓ Next question after discovery: is it SM Higgs?
  - Answer by precise measurements of its branching ratios
    - current combination of the CMS results sets the limits at 95% C.L.:
      $$0 \leq Br_{BSM} \leq 0.64$$
    - may take many years
  - Answer by direct search for non-SM Higgs decays
    - In case of observation: non-SM Higgs!
    - In case of no signal: restrict broad class of non-SM scenarios
- ✓ Searches for exotic decays are very important
  - Additional bosons
    - NMSSM $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$
  - MSSM Higgs (neutral and charged)
  - Double-charged Higgs
  - SM rare decays and several other channels

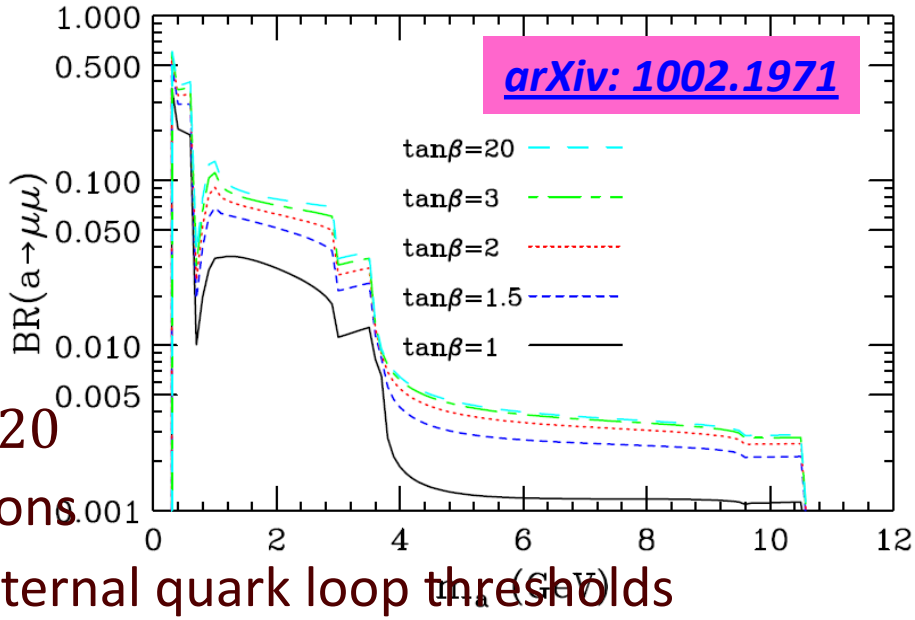


Search for NMSSM $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$

- ✓ In this analysis we explore
  - $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$ signature
  - $0.25 \leq m(a_1) \leq 3.55$ GeV

  $[2m(\mu) \lesssim m(a_1) \lesssim 2m(\tau)]$
- ✓ Typical branching
  - $Br(a_1 \rightarrow \mu^+\mu^-) \sim$ 10% at $\tan\beta = 20$
  - significant structures due to variations

  in $Br(a_1 \rightarrow gg)$ when m_{a_1} crosses internal quark loop thresholds



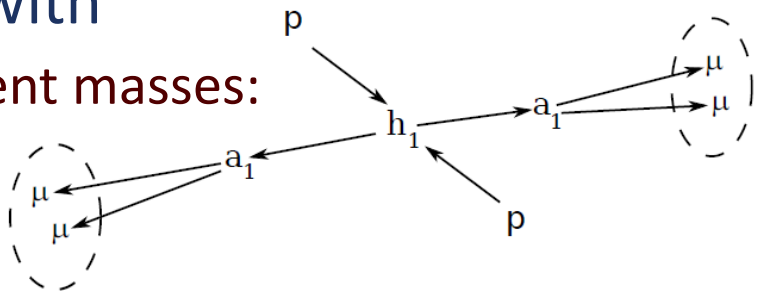
- ✓ Typical Higgs masses
  - $90 < m(h_1) \lesssim 120$–135 GeV
  - 120-$135 \lesssim m(h_2) < ?$ GeV

One of them SM-like Higgs

- ✓ In this analysis we search for events with
  - 2 boosted isolated dimuons with consistent masses:

  $m(\mu\mu_1) = m(\mu\mu_2) = m(a_1)$

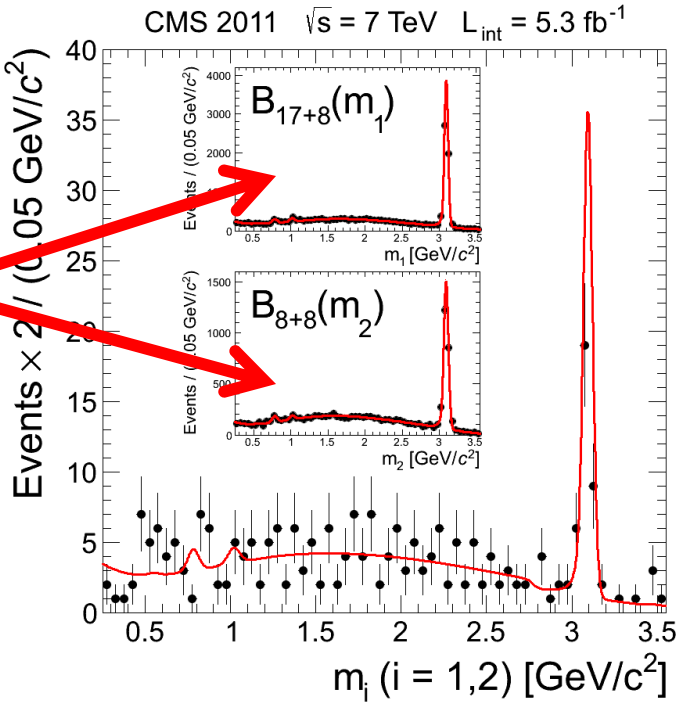
  .



Search for non-SM $h \to 2a_1 \to 4\mu$

arXiv:1210.7619
submitted to PLB

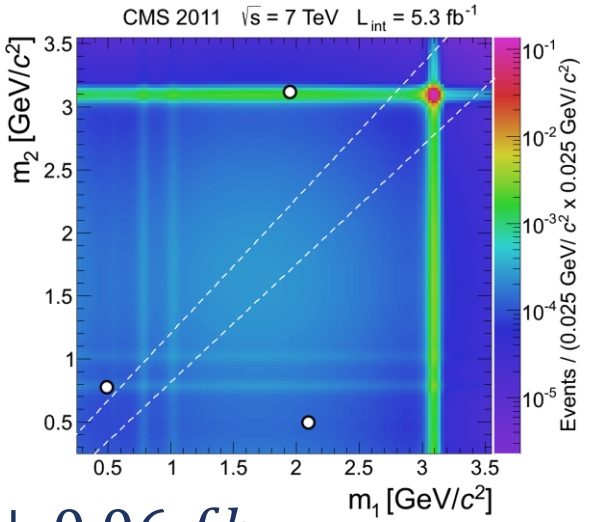
- ✓ Data collected with double muon trigger
- ✓ Selection requirements: at least 4 isolated μ
  - $p_T > 8$ GeV and $|\eta| < 2.4$
  - one of them with $p_T > 17$ GeV and $|\eta| < 0.9$
    - to avoid reduced trigger efficiency in forward regions
  - combined into 2 dimuons with $m_{\mu\mu} < 5$ GeV
- ✓ Standard Model Backgrounds
  - $\bar{b}b \to 4\mu + X$
    - isolation
    - 2D background template $B_{17+8} \times B_{8+8}$ obtained from $b\bar{b}$ enriched sample with 3 muons and no isolation requirement applied
  - Double J/ψ production
    - 2D Gaussian mass template normalized to data



Results of the search $h \to 2a_1 \to 4\mu$

- ✓ Zero events in the signal region
  - signal region is diagonal: $m_{\mu\mu_1} \approx m_{\mu\mu_2}$
  - three events in the off-diagonal

  region have been observed

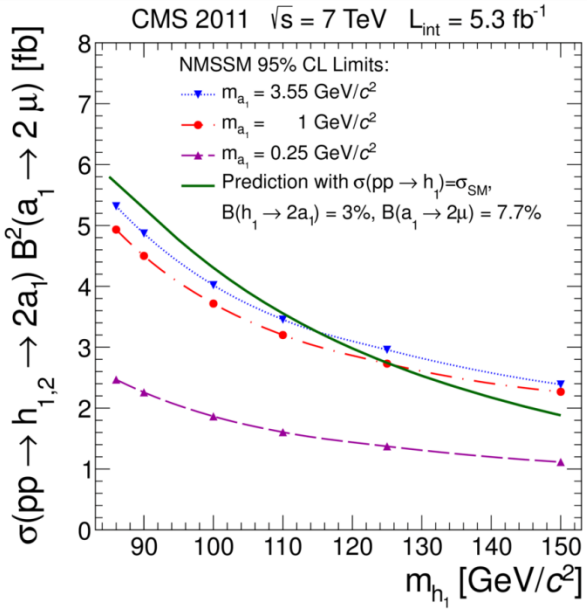


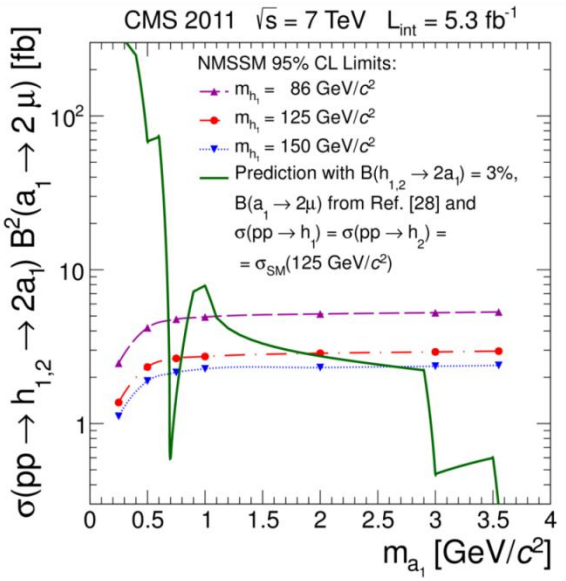
- ✓ Model independent 95% C.L. Limit:

$$\sigma(pp \to 2a + X) \times Br^2(a \to 2\mu) \times \alpha_{gen} < 0.86 \pm 0.06\ fb$$

analysis selection acceptance on generator level

arXiv:1210.7619





Conclusion

- ✓ Higgs-like particle at $m_h \approx 126$ GeV is observed
  - full 2011@7TeV and 2012@8TeV data samples are used
  - Five main channels are explored (large number of independent analyses and cross-checks)
  - Combined mass measurement
    - $m_h = 125.7 \pm 0.3(stat) \pm 0.3(syst)$ GeV
  - Consistency with SM Higgs boson
    - $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.14$
- ✓ Properties of the Higgs-like particle are being measured
  - All consistent with SM predictions within uncertainties
- ✓ Search for non-SM decays of the Higgs-like boson is important
  - Current limit on exotic decays: $0 \leq Br_{BSM} \leq 0.64$
  - Several exotic channels are studied
    - example: 95% C.L. limit on non-SM decay $h \to 2a_1 + X \to 4\mu + X$ is obtained
- ✓ Stay tuned! Many analyses are being finalized towards final papers with full 2011+2012 data

Back Up

Higgs Boson: from original idea to observation

- ✓ It took almost 50 years to find Higgs
  - 1964 → 2012

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BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

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GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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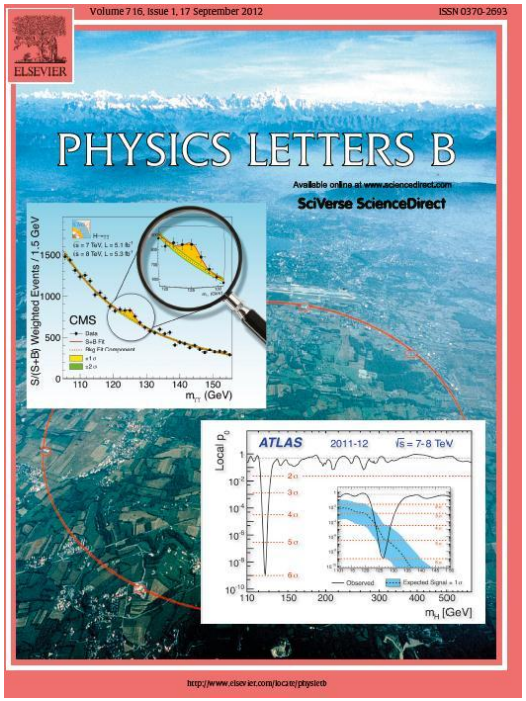
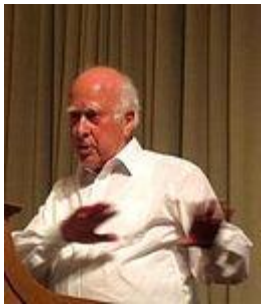
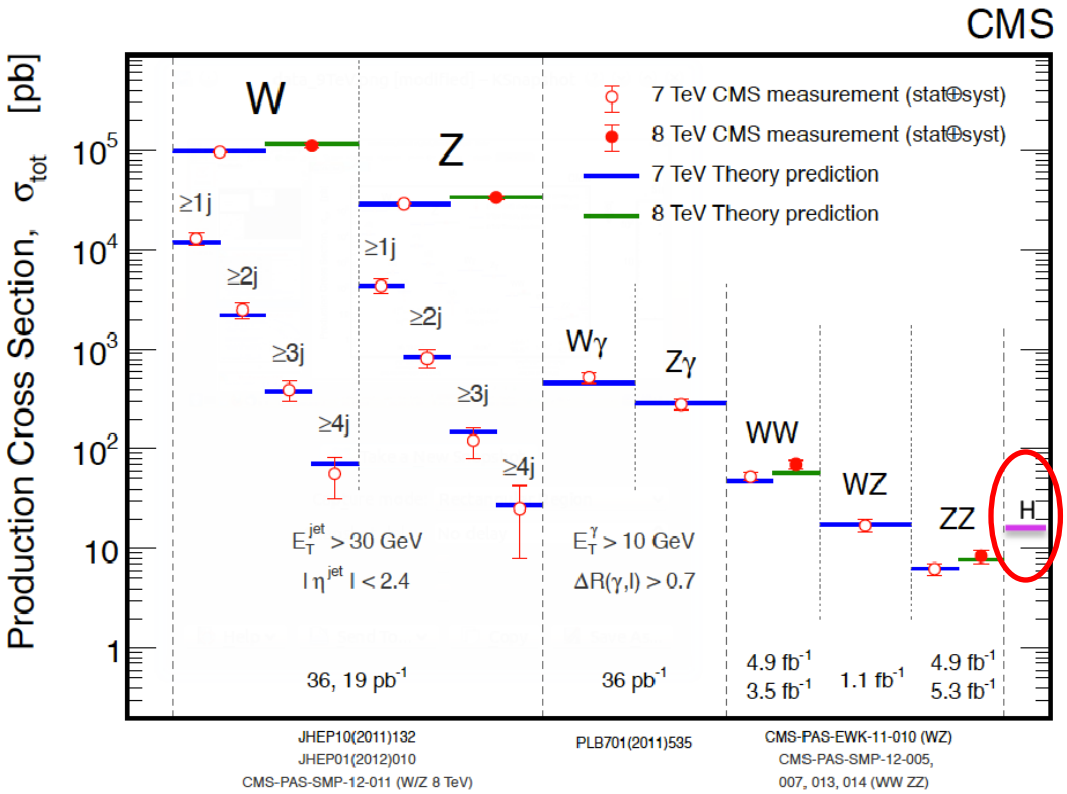




Road to Higgs with CMS

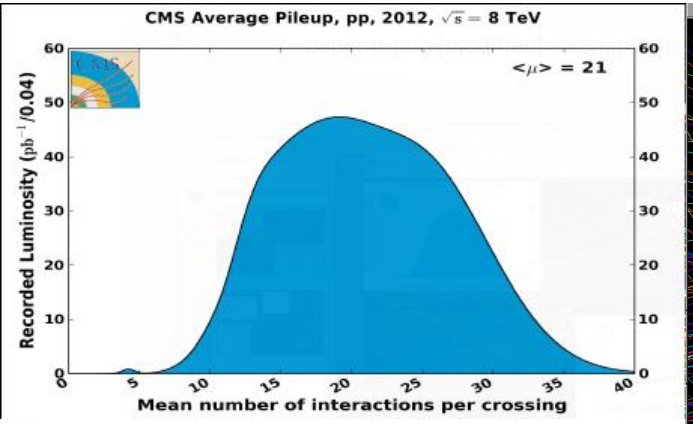
- ✓ On the road to Higgs:
  - Understand detector very well
  - Accurately calculate theory predictions
  - Precisely measure SM processes
  - Study backgrounds to Higgs analyses

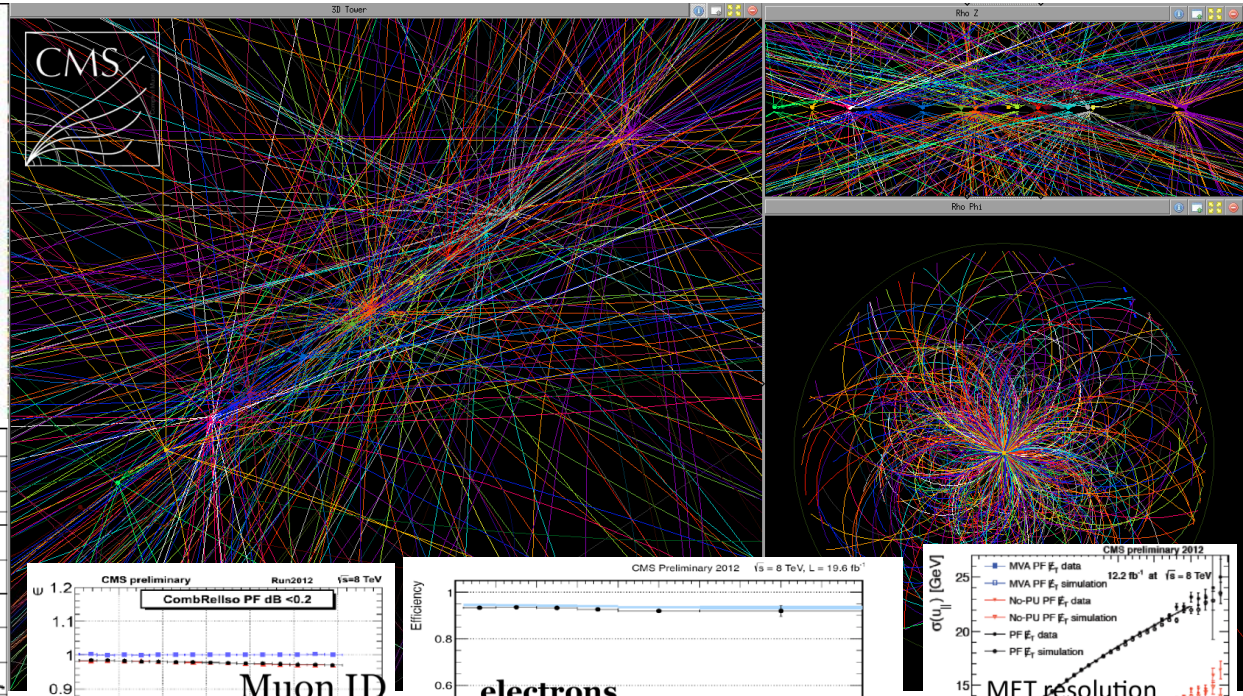


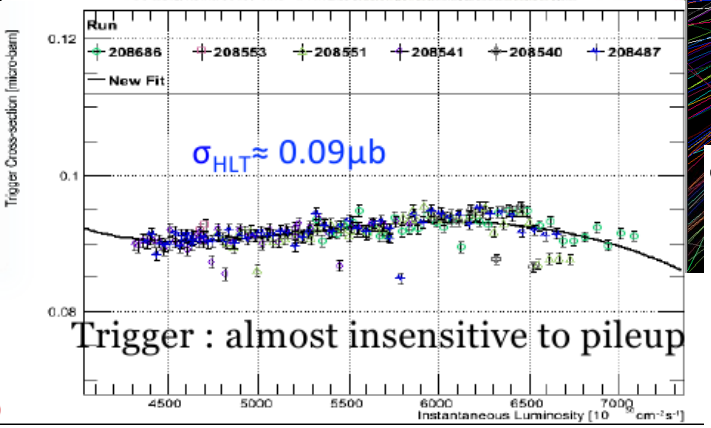
Higgs boson

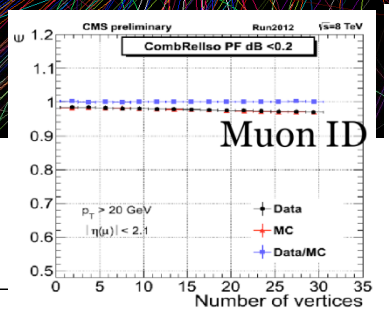
Pileup at $\sqrt{s} = 8$ TeV

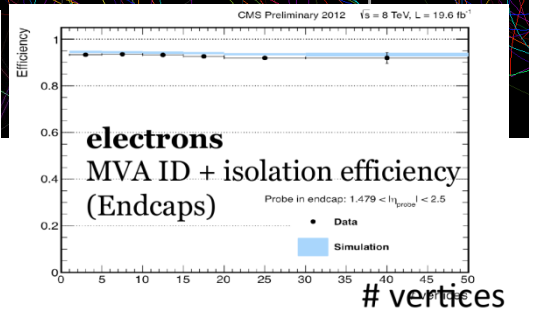
- ✓ Multiple proton-proton interactions in one bunch crossing
  - ~ 21 interactions per crossing in 2012 at $\sqrt{s} = 8$ TeV
  - trigger almost insensitive to pileup
  - reconstruction of leptons and MET almost insensitive to pileup

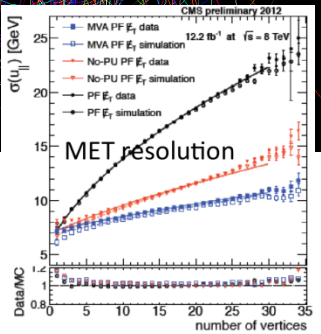










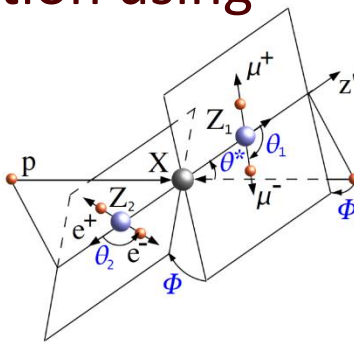


Search for $h \to ZZ \to 4l$: Kinematic Discriminant

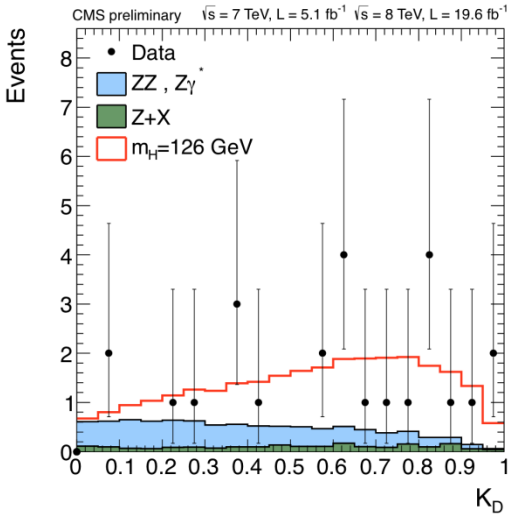
✓ Matrix Element Likelihood Analysis

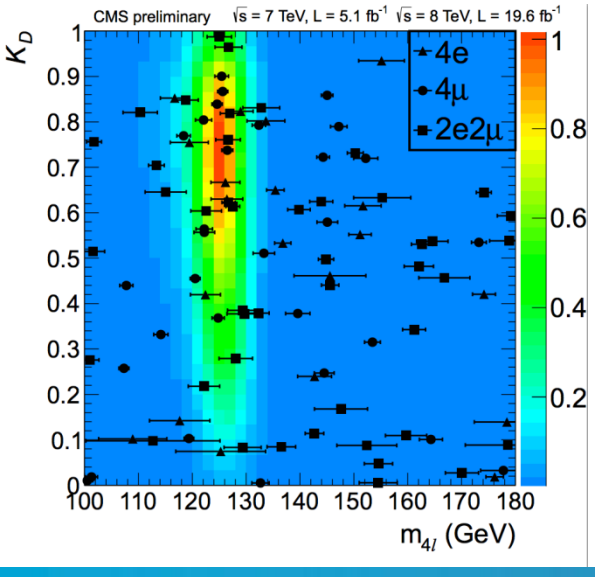
CMS-PAS-HIG-13-002

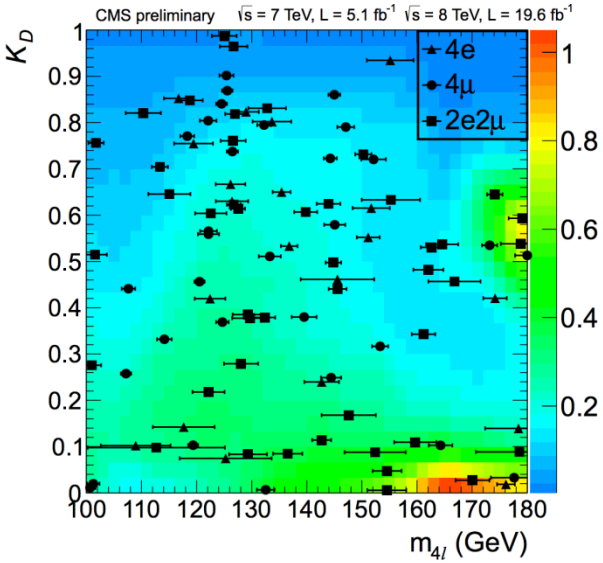
- signal-to-background discrimination using kinematical inputs
  - 2 masses (m_1, m_2)
  - 5 angles $(\theta_1, \theta_2, \theta^*, \Phi, \Phi_1)$

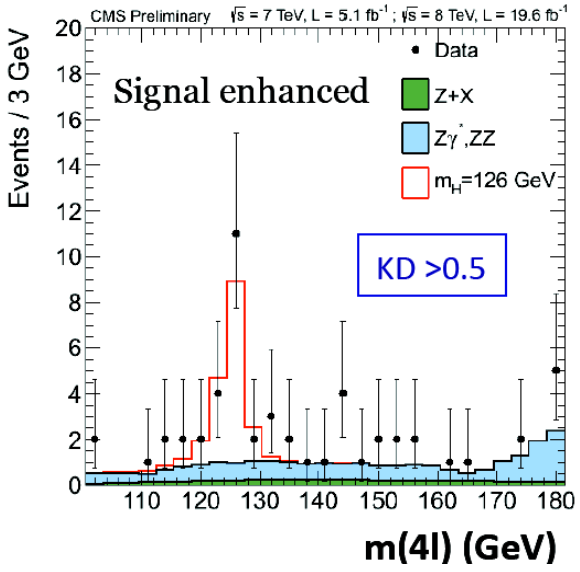


$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



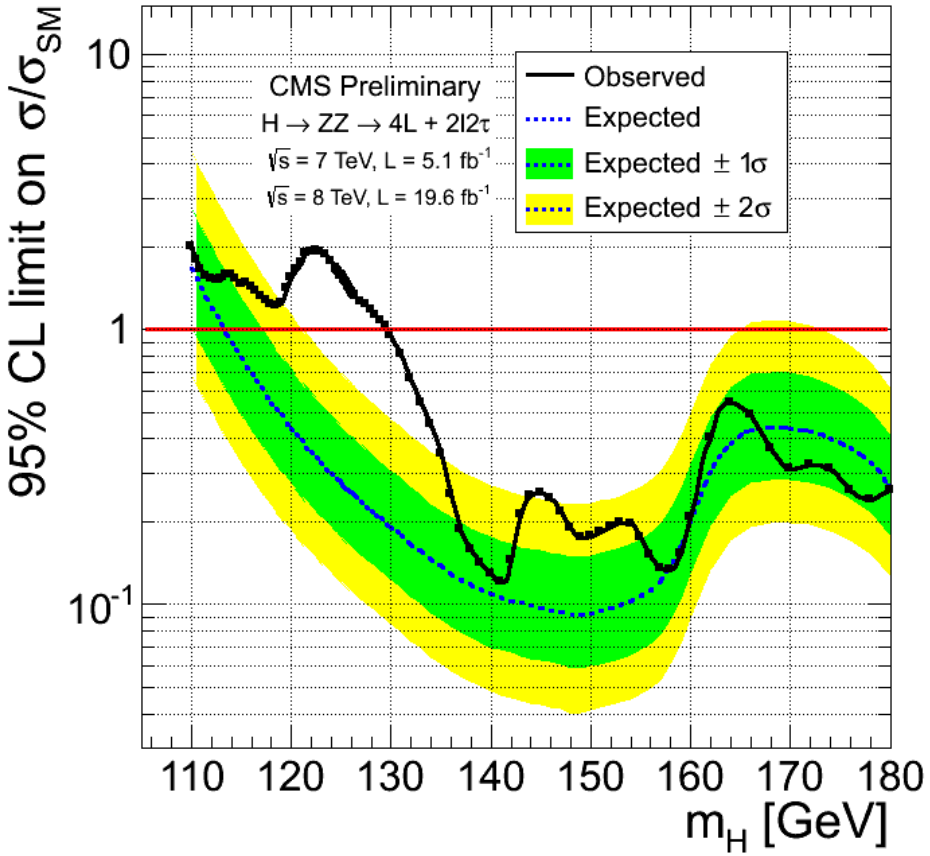






$h \to ZZ \to 4l$: Limits and Signal Strength

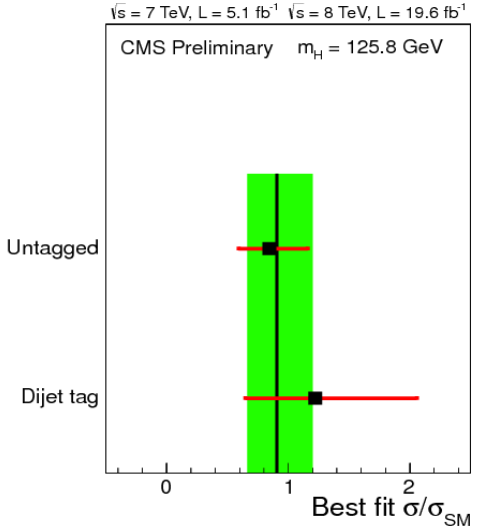
Expected and observed 95% CL limits for a SM Higgs boson, with mass in the range 110-180 GeV

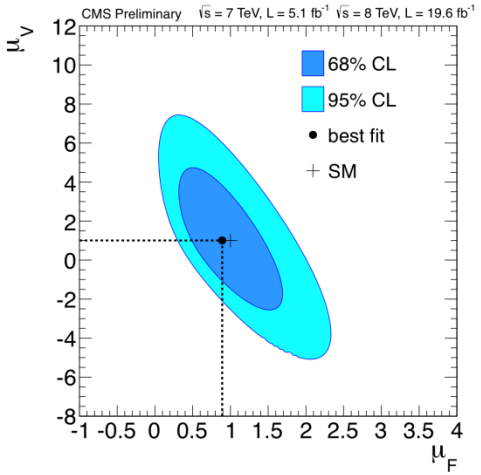


$$\mu\big|_{125.8\,GeV} = \sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$$

[CMS-PAS-HIG-13-002]

Use different jet categories to measure couplings

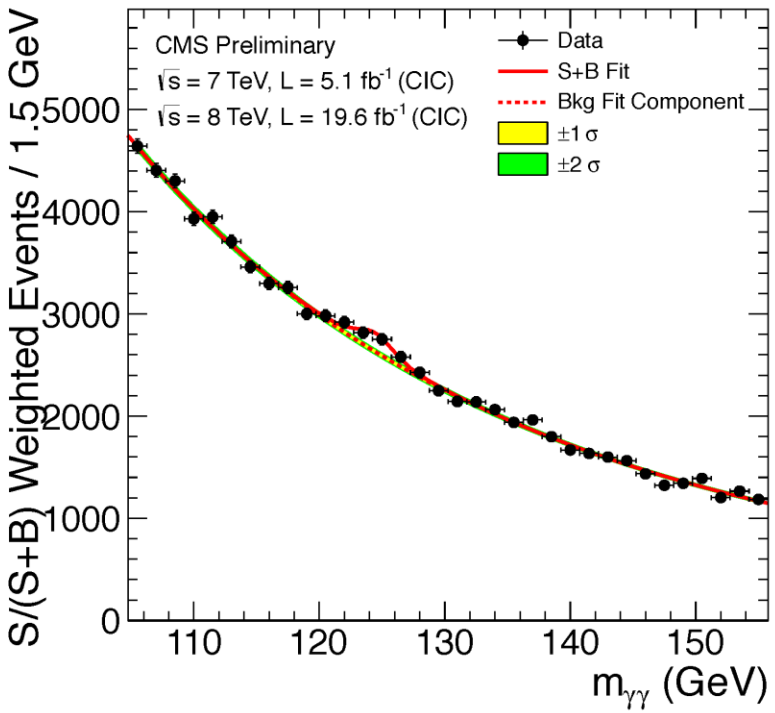


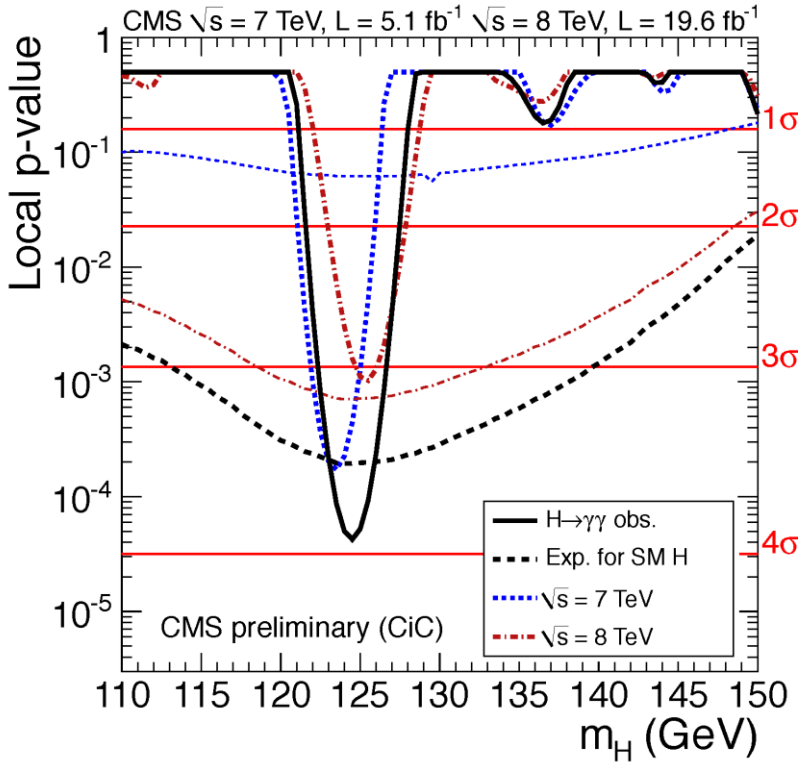


Search for $h \to \gamma\gamma$: Cut-based Results

CMS-PAS-HIG-13-001

- ✓ Mass measurement (Cut-based analysis)
  - $m_h = 125.4 \pm 0.5(stat) \pm 0.6(syst)$ GeV
  - p-value: 4.5σ (exp.) and 3.9σ (obs.)
- ✓ Cross section (at $m_h = 124.5$ GeV)
  - $\mu = \sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$

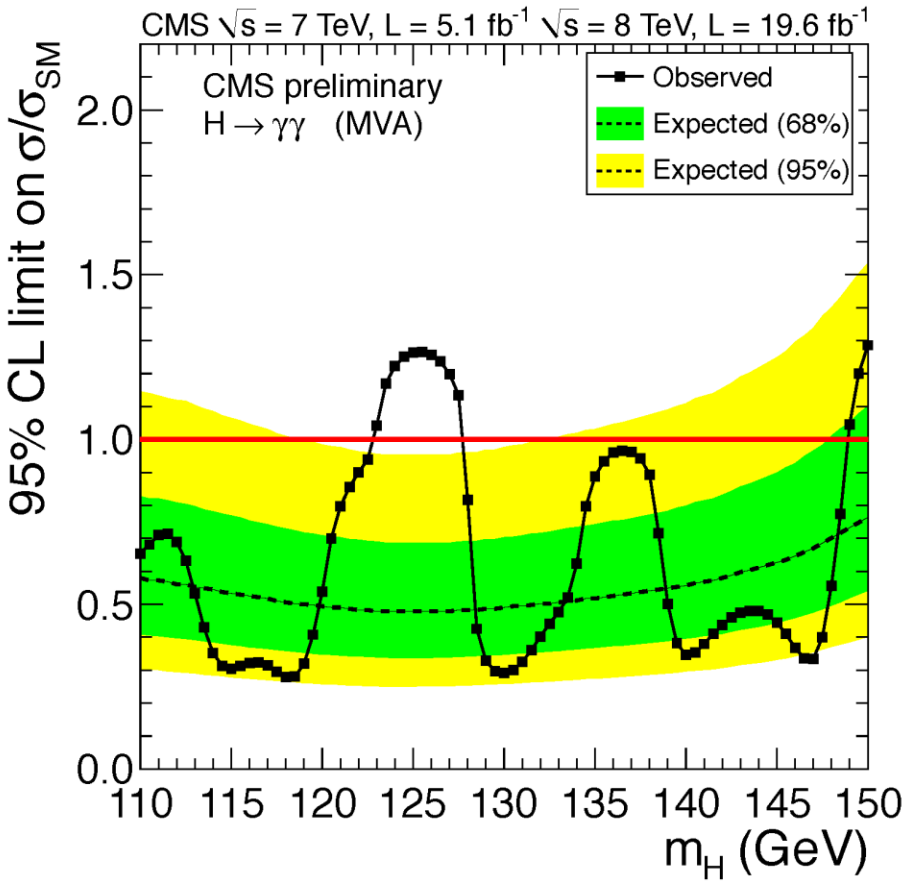




Search for $h \to \gamma\gamma$: Limits

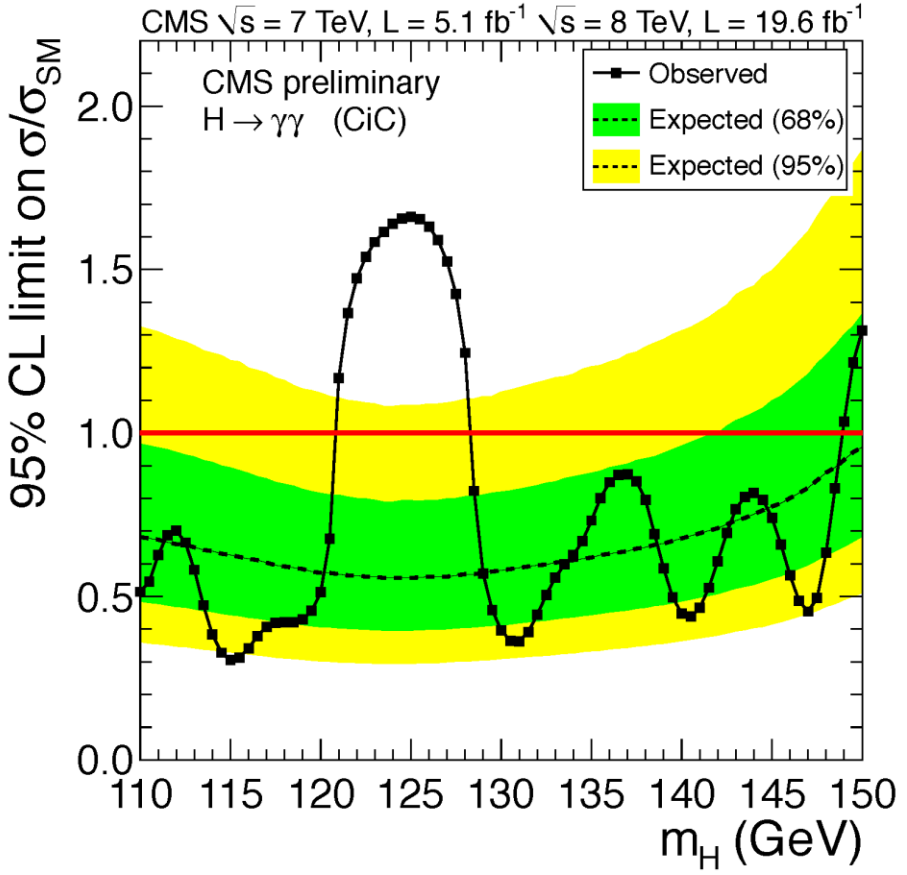
CMS-PAS-HIG-13-001

MVA analysis



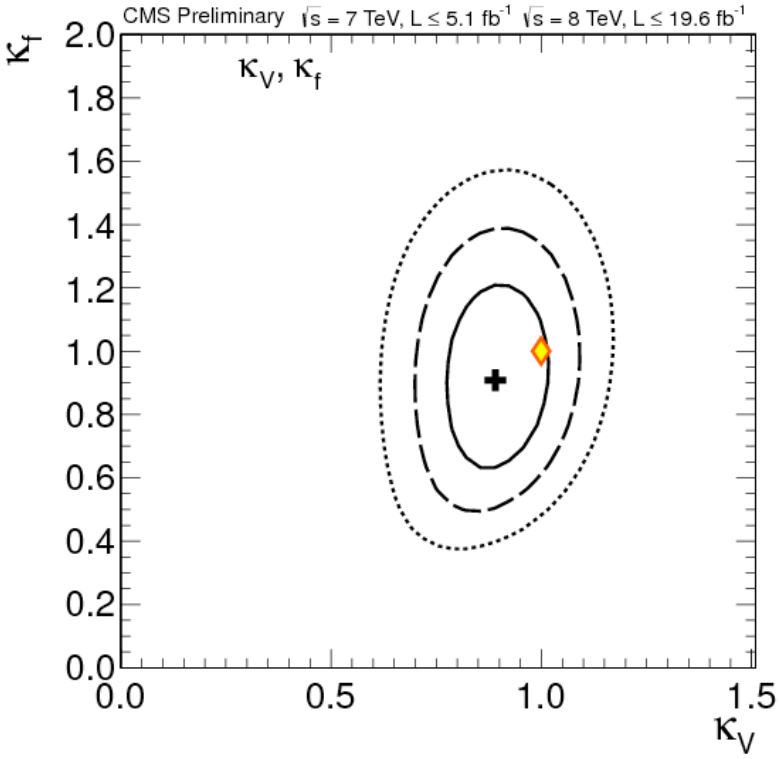
$$\mu\big|_{125\ GeV} = \sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$$

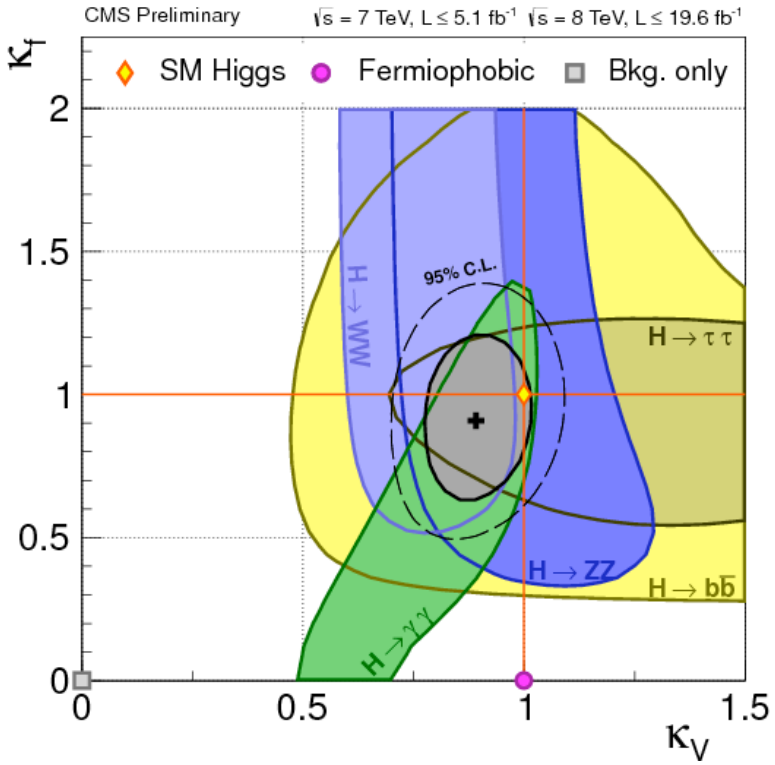
Cut-based analysis



$$\mu\big|_{125\ GeV} = \sigma/\sigma_{SM} = 1.11^{+0.32}_{-0.30}$$

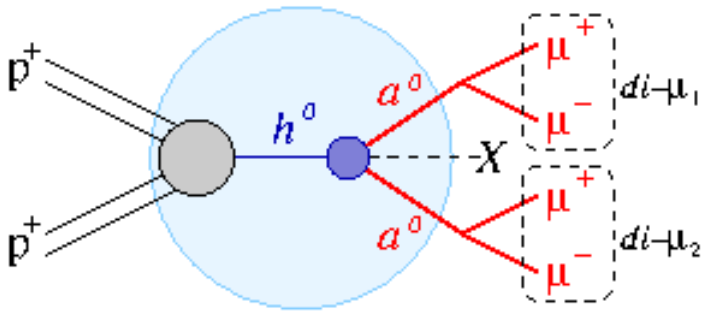
Higgs Coupling Measurements





Higgs Decay to Two Light Bosons

- ✓ Explore non-SM decay modes of the Higgs boson (h^0), which include production of two new light bosons (a^0), that can decay to pairs of muons:



- ✓ Analysis is designed to remain model independent:
  - Minimize dependence on the details of specific models
- ✓ Two specific scenarios as benchmark models:
  - Next-to-Minimal Supersymmetric Standard Model (NMSSM)
  - SUSY with hidden ("dark") sector