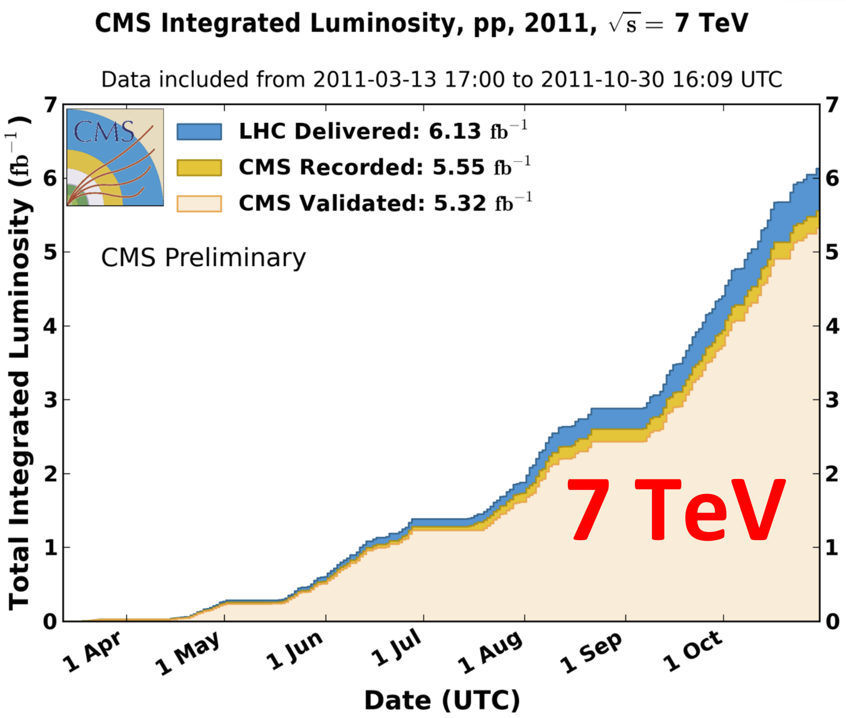
H125 Higgs boson studies with the CMS Detector

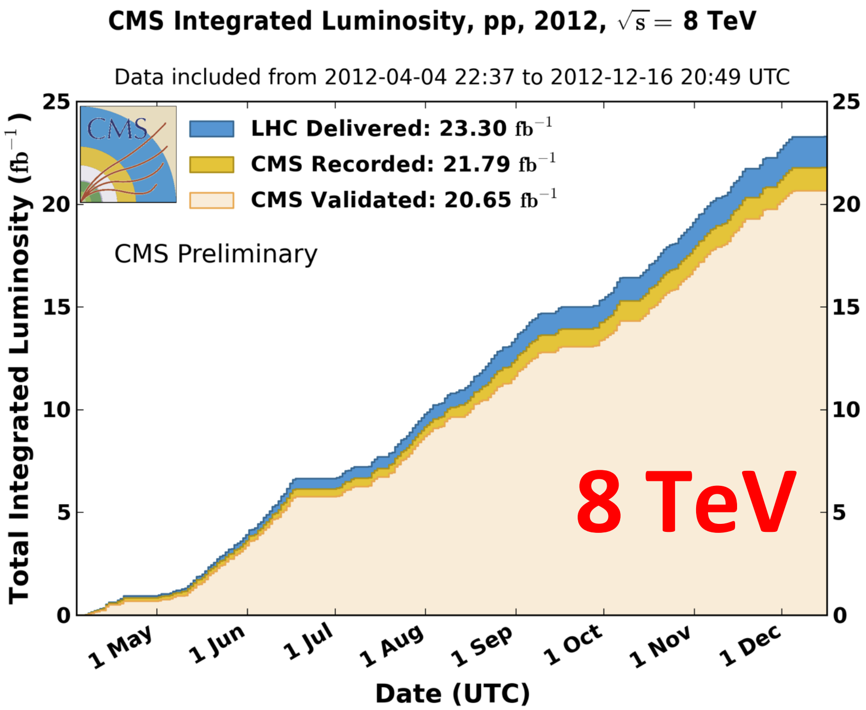
- Observation/search channels

- Properties
  - mass
  - quantum numbers
  - couplings
  - width

- Prospects

LHC Run I CMS dataset

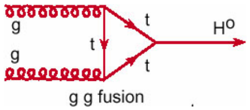


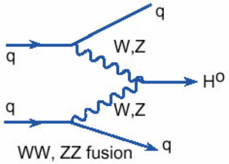


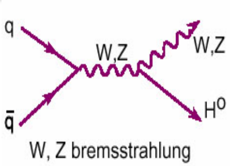
– **recorded**:
94% of delivered

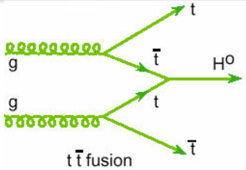
– **validated for physics**:
95% of recorded

H125: status of Run I legacy results





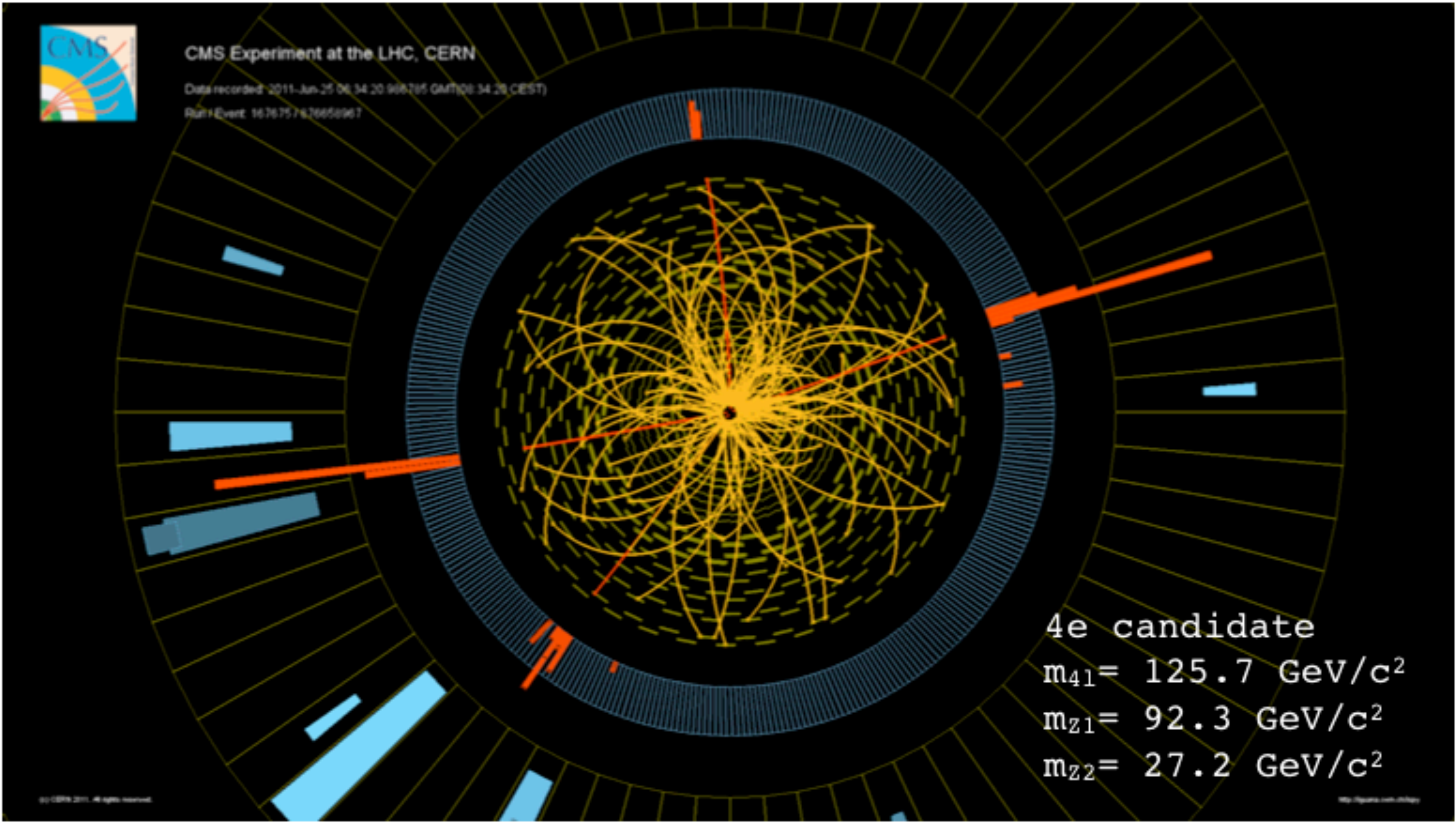




	Decays		ggF (19.5 pb)	VBF (1.6 pb)	VH (1.1 pb)	ttH (0.1 pb)
			"untagged"	"VBF tag"	"VH tag"	"ttH tag"
*	ZZ → 4l	0.00014	published			preliminary
*	γγ	0.0023	preliminary			
*	WW → lvlv	0.0028	published			
*	ττ	0.062	published			
*	bb	0.56	*not feasible*	in progress	published	
*	μμ	0.00021	preliminary			
	Zγ → 2l γ	0.00011	published			
	γ*γ→ 2μ γ	2×10^{-5}	preliminary			
	invisible	0.0012	*not feasible*	published		
	other (gg, cc, ...)	0.37	*not feasible*			

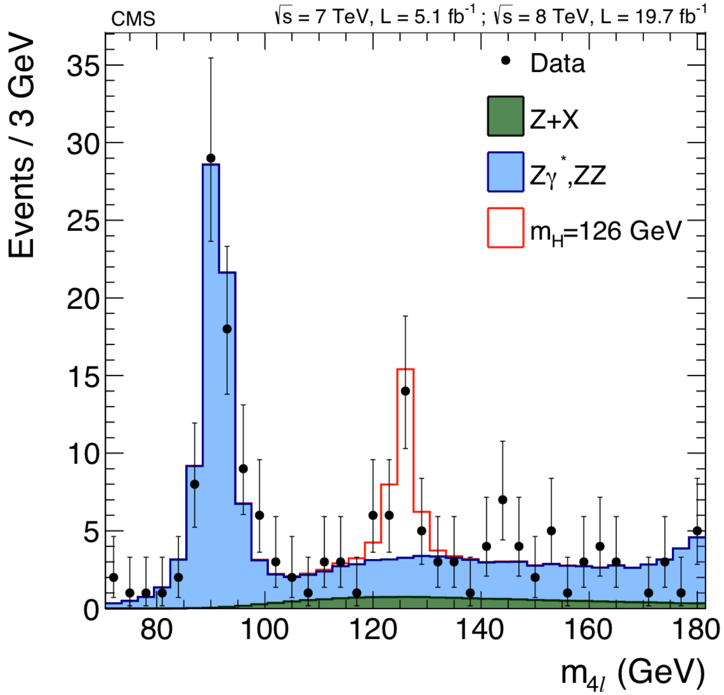
- cross sections (fb) are for 8 TeV
- **BEWARE: Tags are never pure**; e.g. VBF-tags can have 20%-80% of ggF, depending on analysis

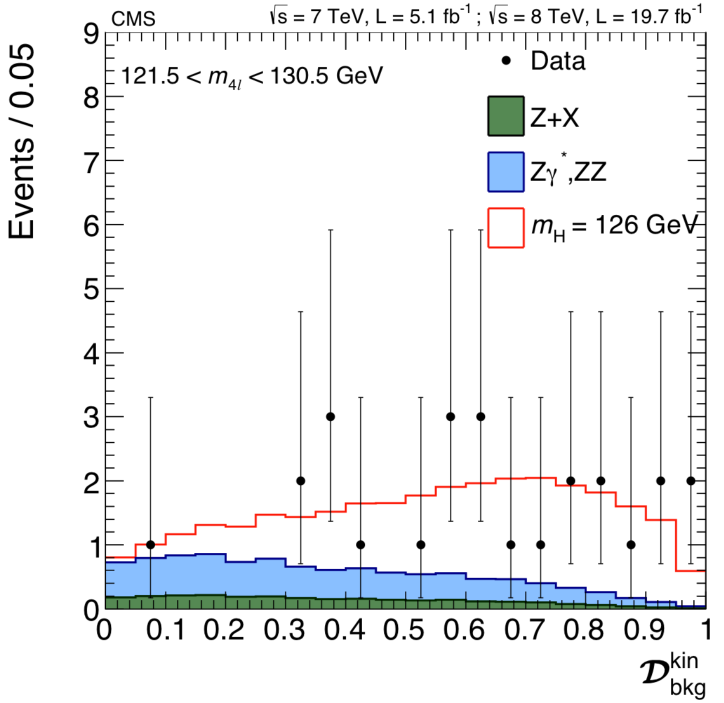
H → ZZ → 4l


CMS
CMS Experiment at the LHC, CERN
4e candidate
m_{4l}= 125.7 GeV/c²
m_{Z1}= 92.3 GeV/c²
m_{Z2}= 27.2 GeV/c²

H → ZZ → 4l

published





Strategy:

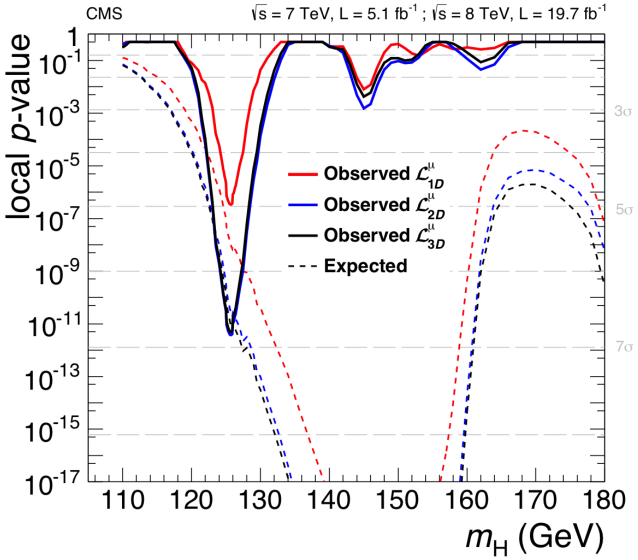
- four prompt leptons (low p_T is important!)
- split events into 4e, 4μ, 2e2μ channels:
  - different mass resolutions
  - different S/B rates (for reducible bkgd with "fake" leptons)
- **four-lepton mass** is the key observable
- add **ME-based discriminant D_{bkg}** (2nd observable)
- split events further into exclusive categories:
  - VBF-like di-jet tagged (add a 3rd observable: **$V_D(m_{jj}, \Delta\eta_{jj})$**)
  - untagged (add a 3rd observable: **four-lepton p_T/m**)
- Backgrounds:
  - ZZ (dominant) from MC
  - reducible (with "fake" leptons): from control region

Analysis features to note:

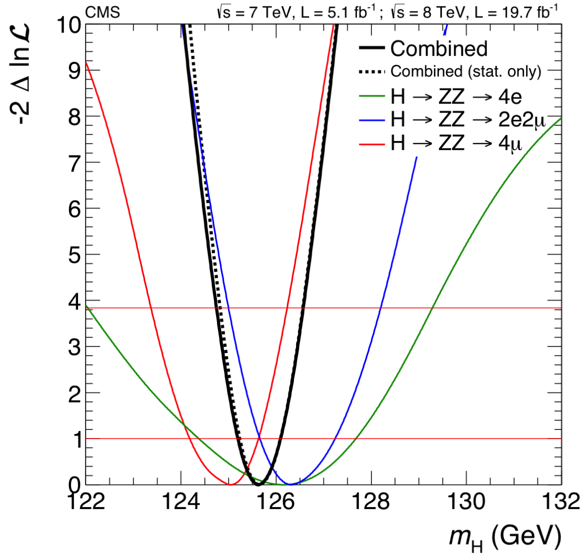
- small event yield: **20 events**
- high S/B-ratio: **better than 2:1**
- good mass resolution = **1-2%**

H → ZZ → 4l: results

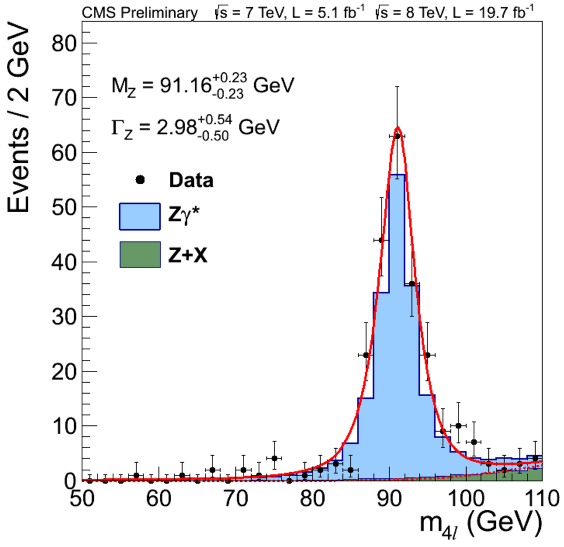
published



Z_{obs} = 6.7 (expected 7.2)
$\mu = 0.93^{+0.29}_{-0.24}$



m_H = 125.6 ± 0.4 GeV
Γ_H < 3.4 GeV at 95% CL

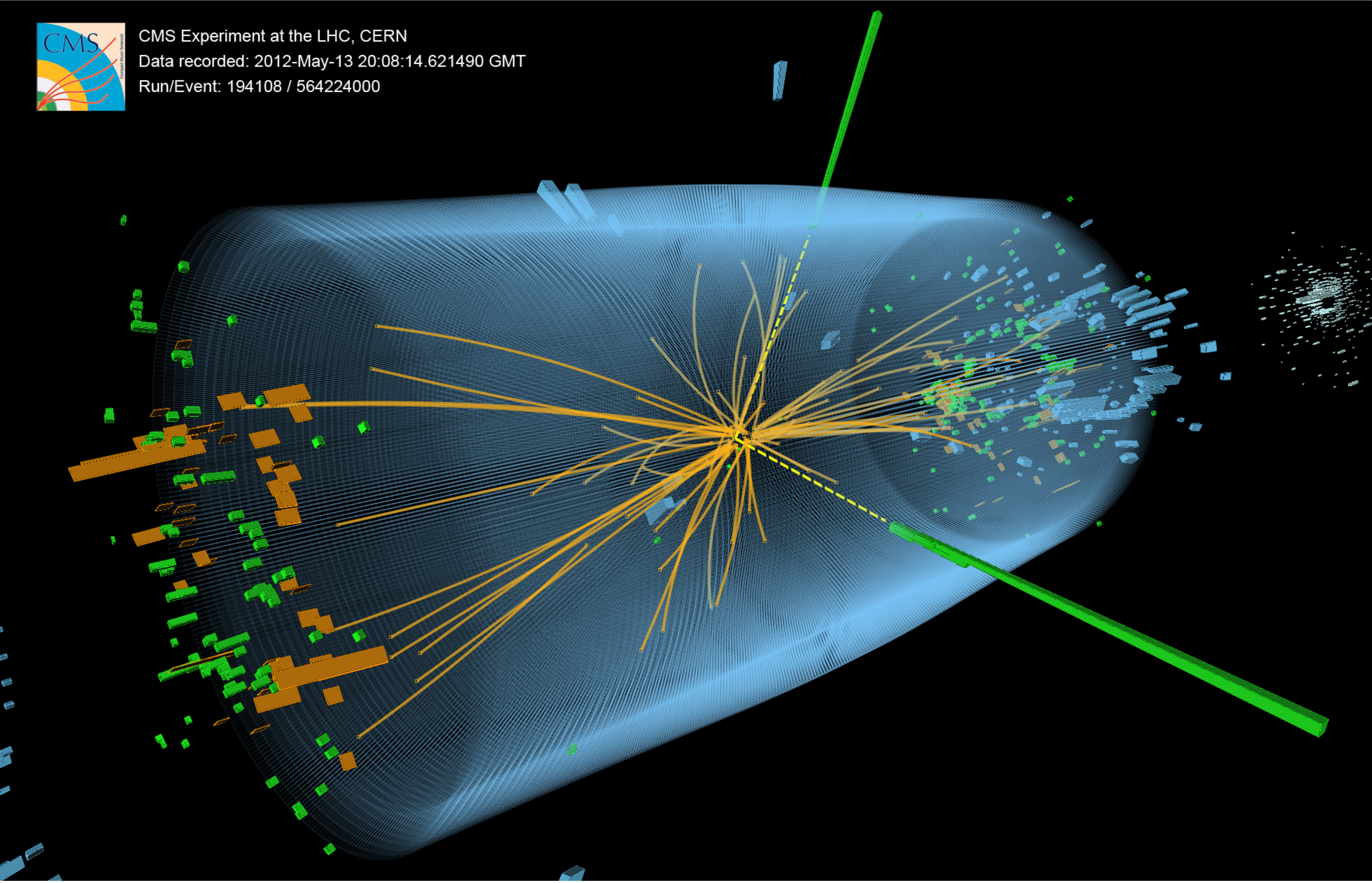


Z→4l standard candle
m_Z = 91.2 ± 0.2 GeV
Γ_Z = 3.0 ± 0.5 GeV

Summary:

- **solid observation** in the H→ZZ→4l decay mode alone
- ME discriminant boosts sensitivity by 20%
- di-jet tag does not help much in sensitivity (too few expected events)
- ZZ→4l channel provides the **most accurate mass measurement**
  (using per-event mass uncertainties improves the mass measurement by about 8%)
- Z→4l standard candle allows one to validate absence of biases in the mass measurements
- **signal strength is about equal to the expected** for the SM Higgs boson
- direct width measurement is limited by the experimental mass resolution, much worse than Γ_{SM} = 4 MeV

H → γγ

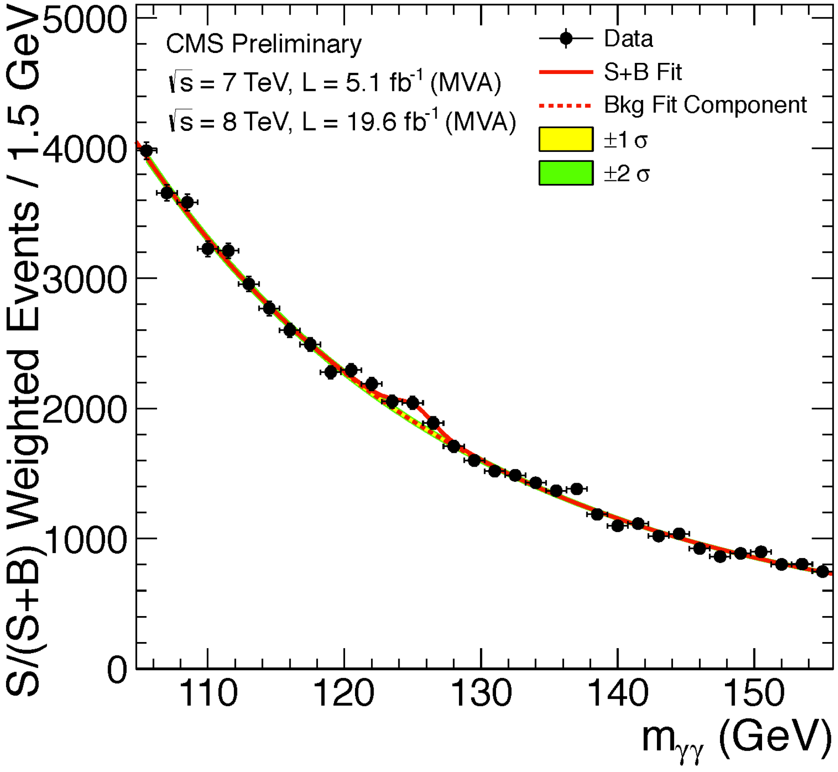


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

H → γγ

preliminary

Final results will be released shortly



- **Strategy:**
  - two isolated high-p_T photons
  - vertex from recoiling charged particles

    $m_{\gamma\gamma}$
  - **di-photon mass** is the key observable
  - split events into exclusive categories:
    - untagged, and further divided into 4 classes based on
      - expected mass resolution
      - expected S/B-ratio
    - di-jet tagged, and further divided into 2 classes based on
      - expected S/B-ratio
    - MET-tagged
    - electron-tagged
    - muon-tagged
  - background: from $m_{\gamma\gamma}$-distribution sidebands

Two versions of analysis:

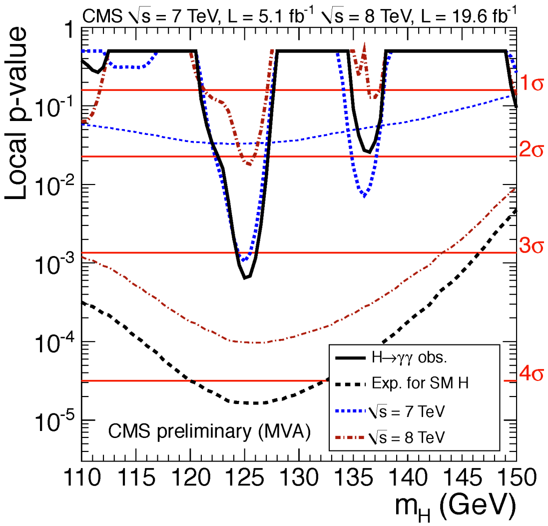
- MVA for photon-ID and event classification
- Cuts for photon-ID and event classification

- **Analysis features to note:**
  - fairly high event yield: **470 events**
  - bad “effective” S/B-ratio: **1:20**
  - good mass resolution = **1-2%**

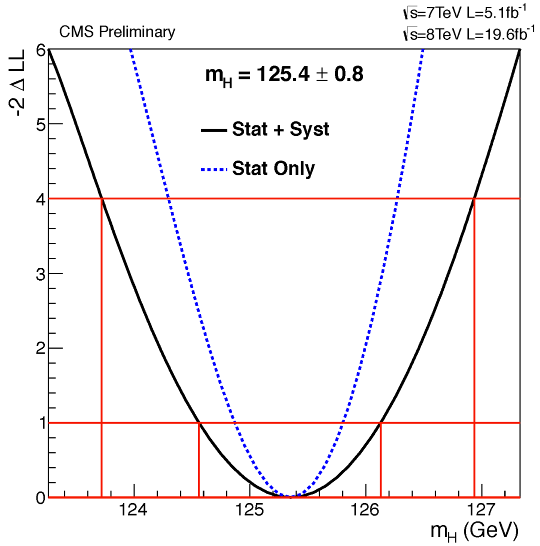
H → γγ: results

preliminary

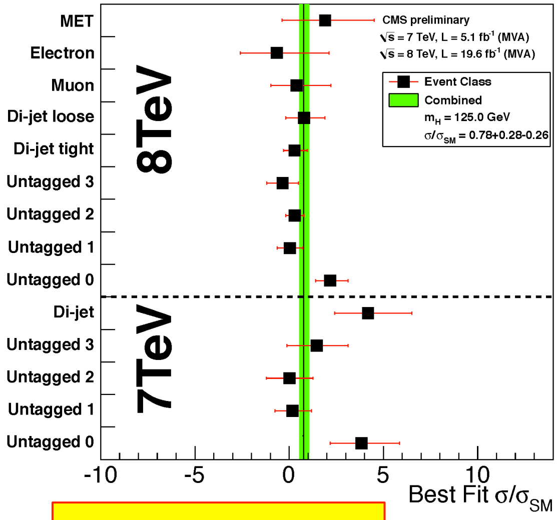
Final results will be released shortly



Z_{obs} = 3.2 (expected 4.2)



m_H = 125.4 ± 0.8 GeV
Γ_H < 6.9 GeV at 95% CL

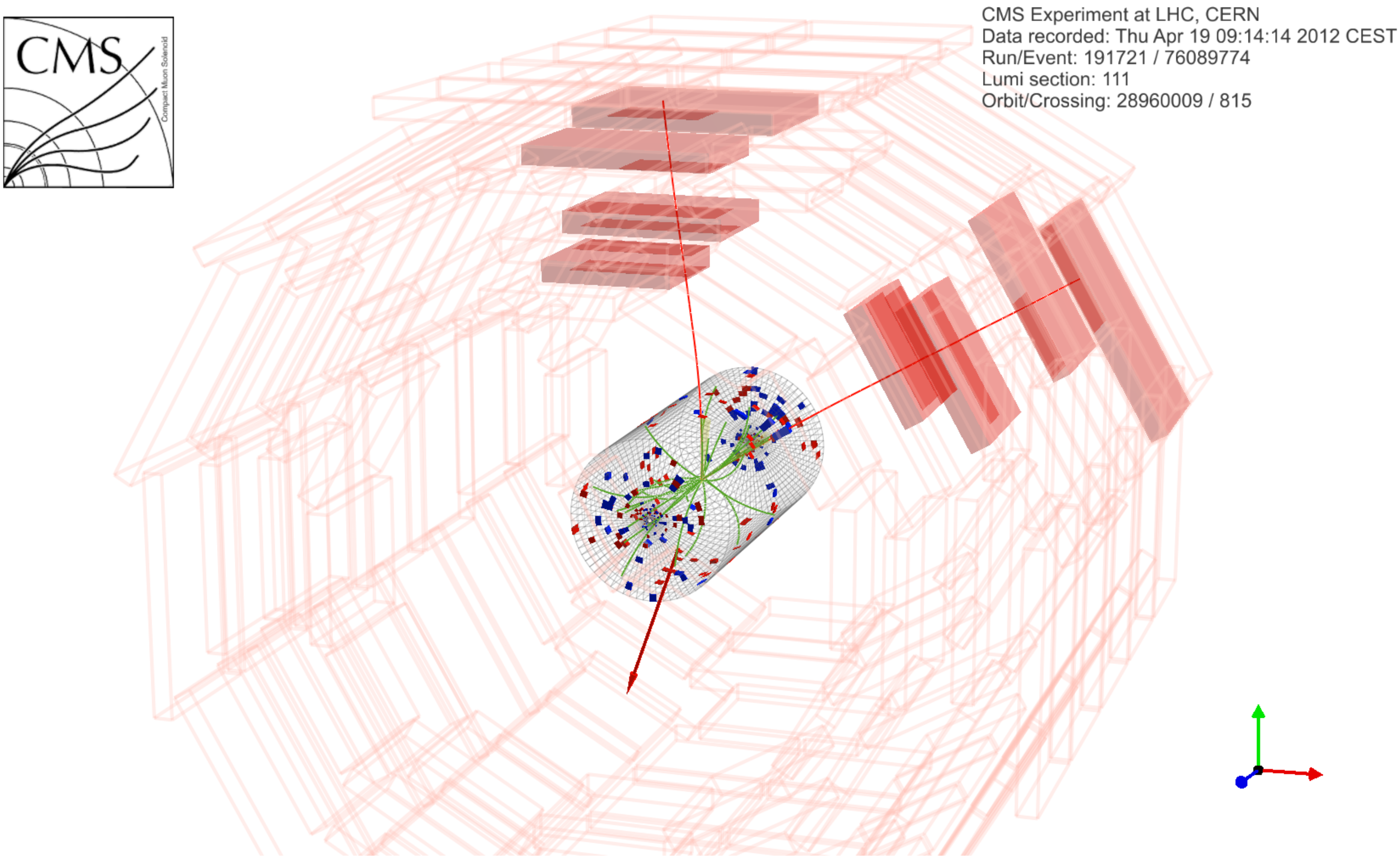


μ = 0.78 ± 0.27
(at m_H=125 GeV)

Summary:

- significance is reduced compared to 2012:
  - ICHEP 2012 (10 fb^{-1}): **observed = 4.1**, expected = 2.7 (±1)
  - 2013 (25 fb^{-1}): **observed = 3.2**, expected = 4.2 (±1)
  - fewer than expected signal-like events in new data (luck) plus a re-optimized analysis (event reshuffle)
  - the expected sensitivity evolves as sqrt(L)
  - signal strength is consistent with SM: **μ = 0.78 ± 0.27**
- improving mass measurement systematics is important ($\delta m_{syst} > \delta m_{stat}$)

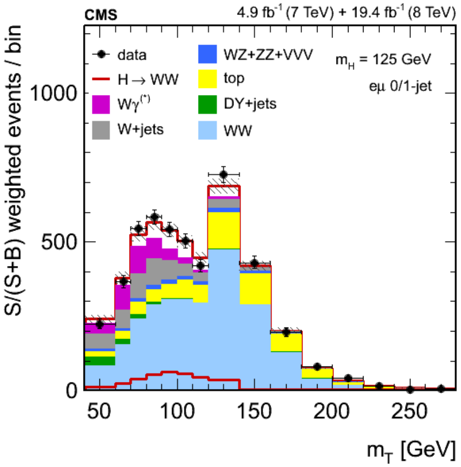
H → WW → lνlν


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012 CEST
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815

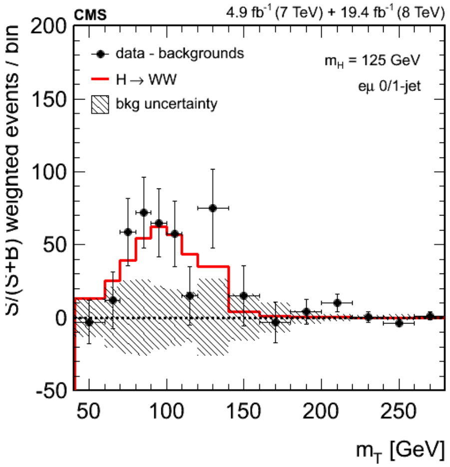
H → WW → lvlv

published

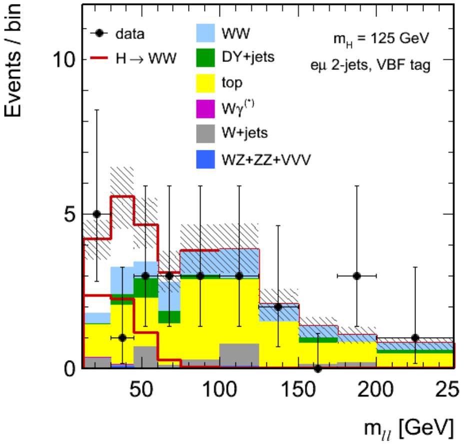
eμ 0/1-jet



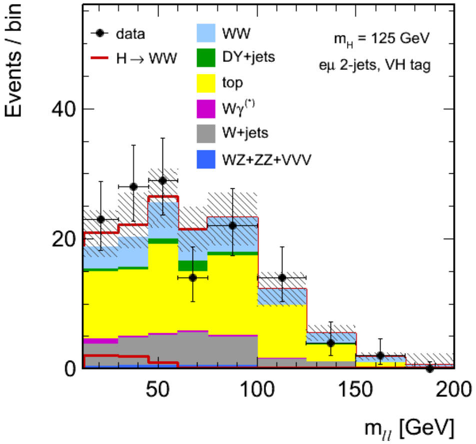
eμ 0/1-jet



eμ VBF 2-jet



eμ VH 2-jet



Analysis strategy:

- two prompt leptons (ee, μμ, eμ) + MET
- main discriminating observables: **m_T, m_{ll}**
- split events into exclusive categories:
  - untagged: 0- and 1-jet categories: expect **252 evts**
  - VBF di-jet tag: **8 events**
  - VH di-jet tag: **8 events**
  - WH -> 3l3v tag: **4 events**
  - ZH -> 3l1v + di-jet: **1 event**

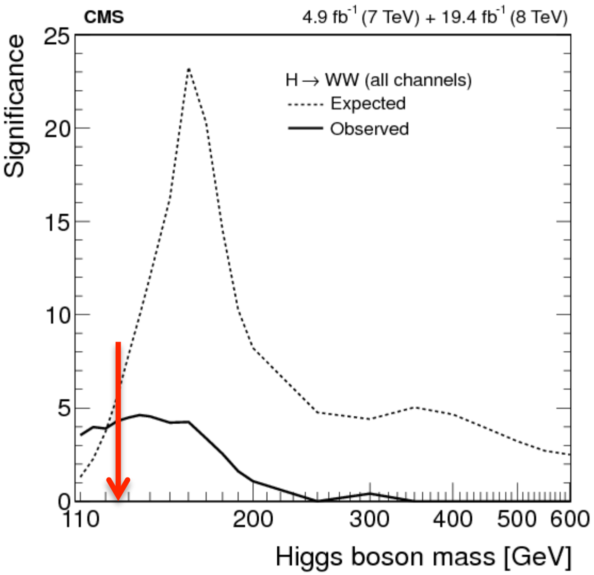
- Backgrounds (for low mass Higgs):
  - WW, tt, W+jets, DY+jets, Wγ: from control regions
  - ZW, ZZ: from MC (very small contribution)

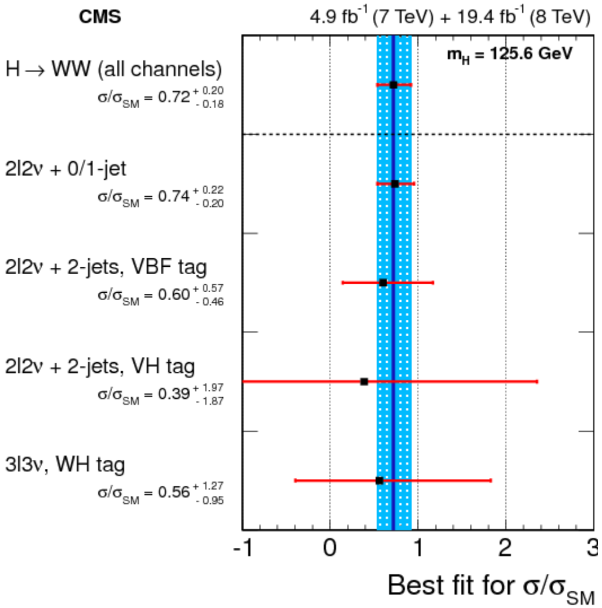
Analysis features to note (m_H=125):

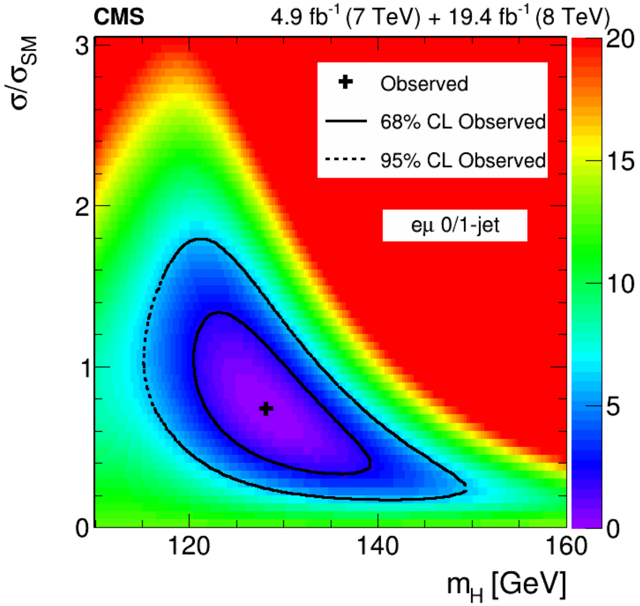
- fair signal event yield: **270**
- not too good "effective" S/B-ratio: **1:10**
- poor mass resolution: **≈20%**

H → WW → lvlv: results

published







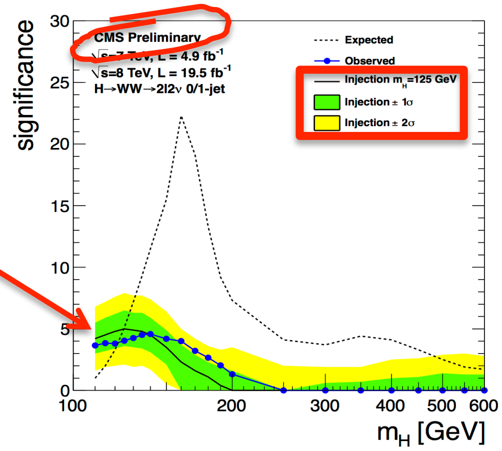
Z_{obs} = 4.3 (expected 5.8)
(at m_H = 125.6 GeV)

$\mu = 0.72^{+0.20}_{-0.18}$
(at m_H = 125.6 GeV)

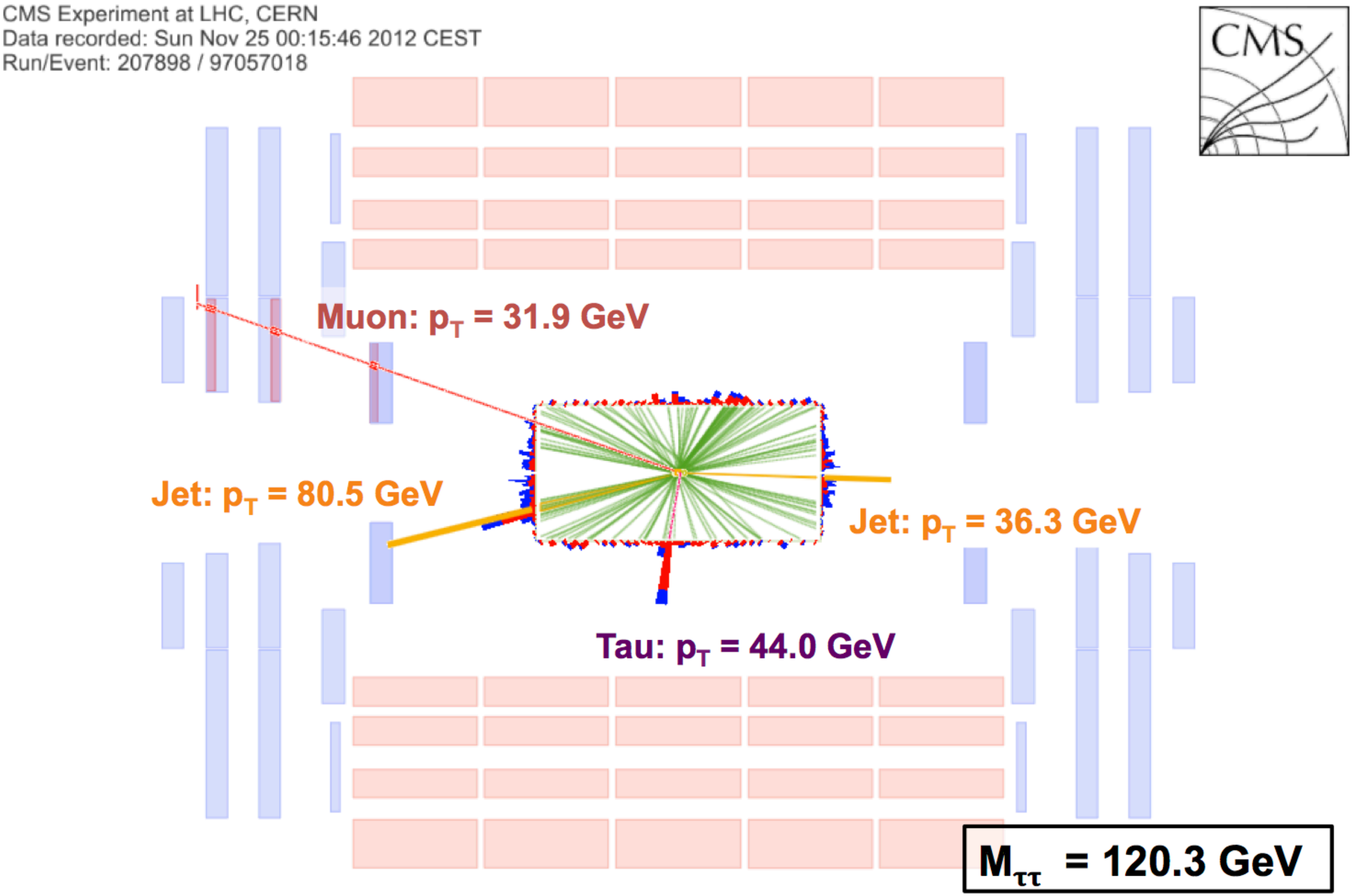
$m_H = 128.2^{+6.6}_{-5.3}$ GeV

Summary:

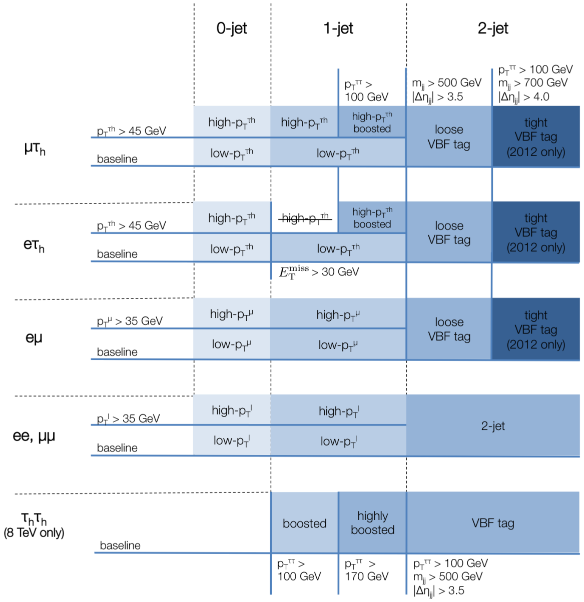
- **broad 4σ access**, consistent with the SM Higgs boson $m_H \sim$ 125 GeV
- signal strength for m_H = 125.6 GeV: **μ = 0.7 ± 0.2**
- 0/1-jet channel has a max sensitivity, VBF—the next best
- H→WW standalone best-fit mass: **m_H = 128 ± 6 GeV**

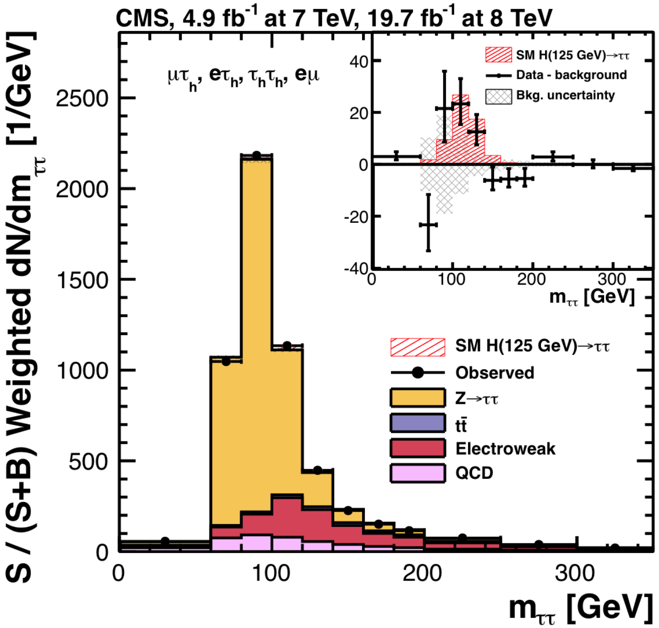


H → ττ


CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018
CMS
Muon: p_T = 31.9 GeV
Jet: p_T = 80.5 GeV
Jet: p_T = 36.3 GeV
Tau: p_T = 44.0 GeV
$M_{\tau\tau}$ = 120.3 GeV

H → ττ





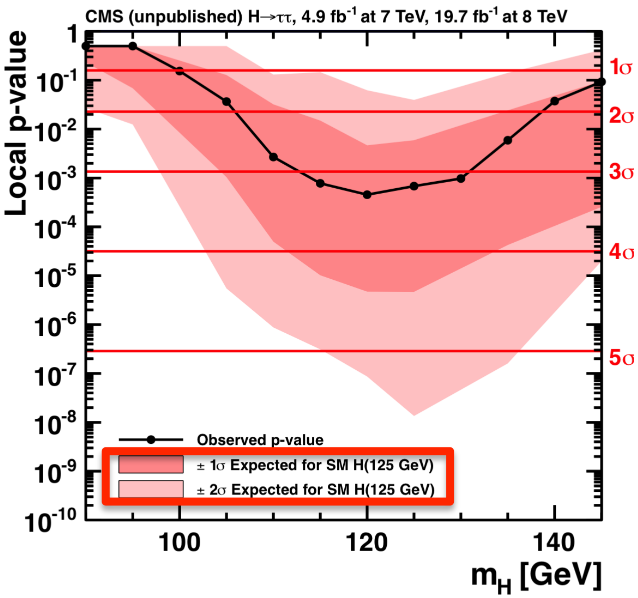
- **Strategy:**
  - di-tau candidates LL'=($e\tau_h$, $\mu\tau_h$, eμ, ee, μμ, $\tau_h\tau_h$) + MET
  - **DiTau mass (including MET)**: key observable
  - split events into categories:
    - **2-jets (VBF-tag)**: best S/B-ratio; further split into tight/loose VBF
    - **1-jet (ggF)**: acceptable S/B-ratio; further split into high/low p_T tau
    - **untagged:** ggF, but S/B≅0 (basically, a control region)
    - **WH-tag:** $l\nu + L\tau_h$ (good S:B, but very few events)
    - **ZH-tag:** $ll + LL'$ (good S:B, but very few events)
  - Main backgrounds:
    - Z→ττ: Z→μμ (data) with a simulated μ-τ swap
    - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
    - QCD: from control regions
    - di-boson: from MC
    - H→WW (relevant only for VH tags)

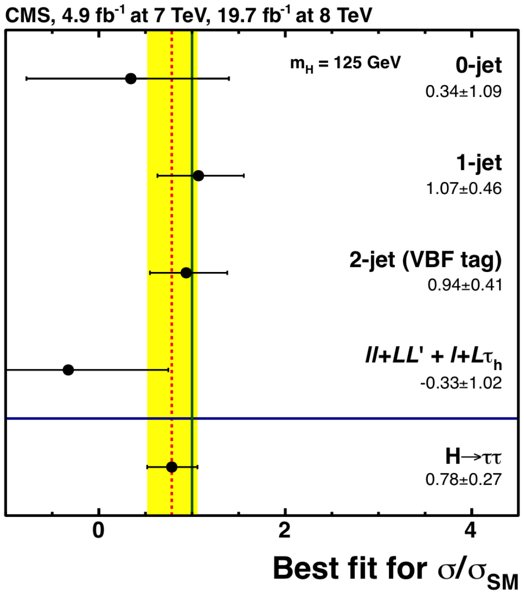
Analysis features to note:

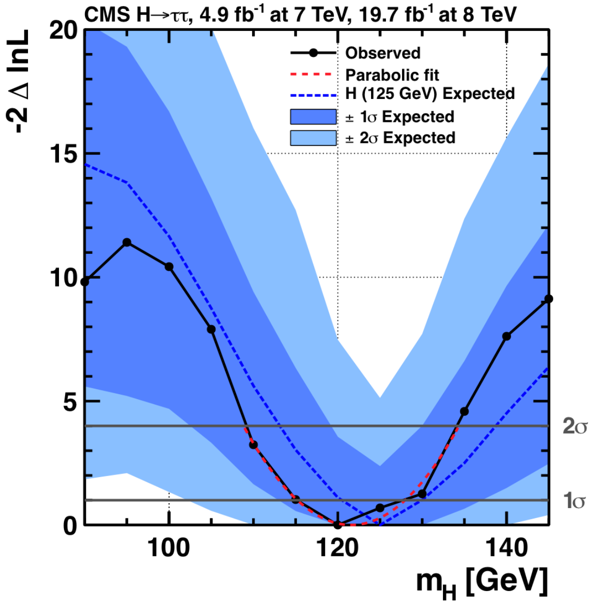
- small signal event yield: tens of events
- poor "effective" S/B-ratio: **1:50**
- Higgs boson "blip" is on the falling slope of the Z peak
- mass resolution: **10%($\tau_h\tau_h$), 15%($l\tau_h$), 20%(ll)**

H → ττ: results

published







Z_{obs} = **3.2** (expected 3.7)
(at m_H = 125)

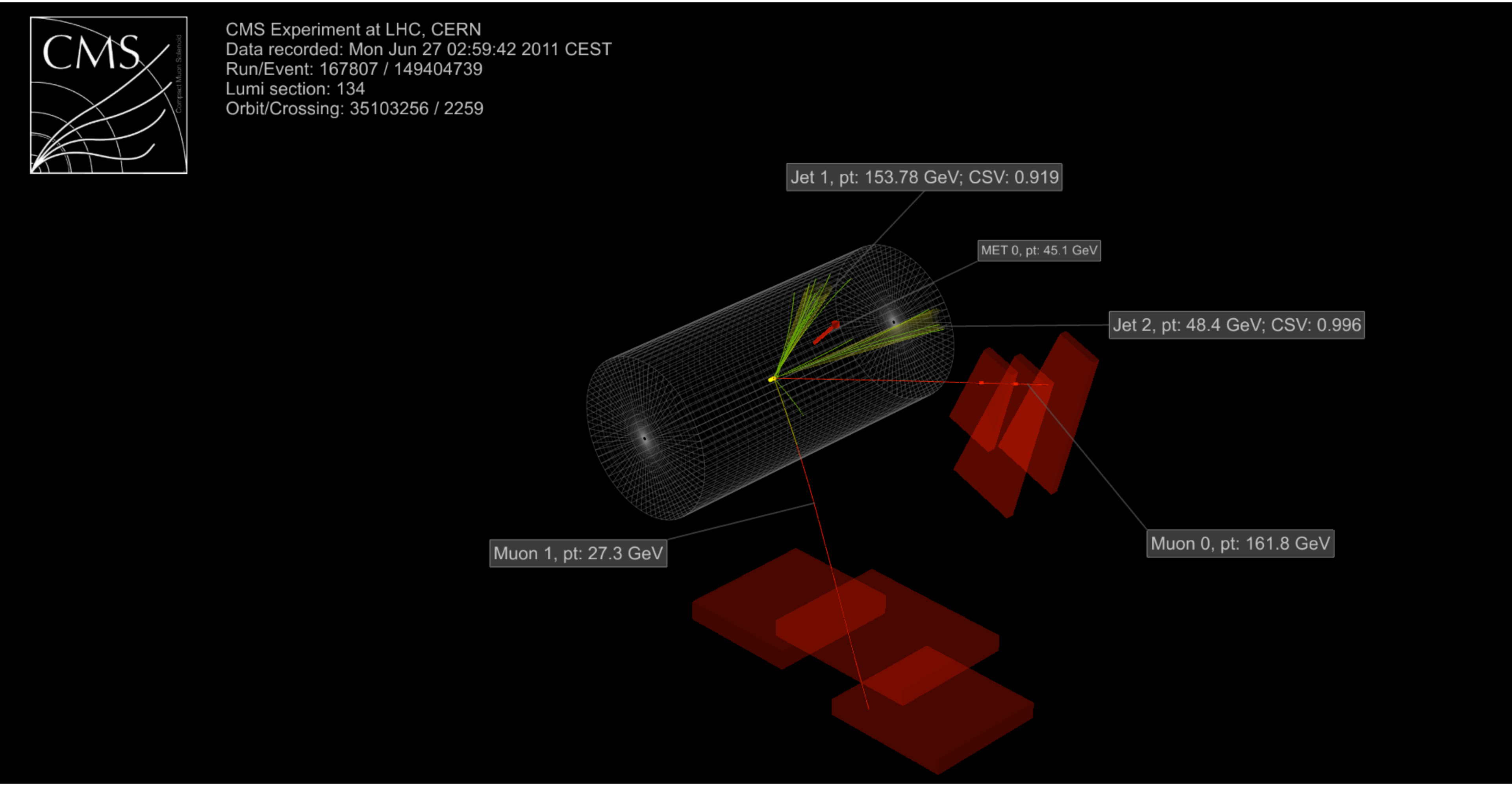
μ = 0.78 ± 0.27
(at m_H = 125)

m_H = 122 ± 7 GeV

Summary:

- **broad 3σ access** (poor mass resolution), consistent with **SM Higgs boson**
- signal strength for m_H = 125 GeV: **μ = 0.8 ± 0.3**
- 0/1-jet channel has a max sensitivity, VBF—the next best
- H→ττ standalone best-fit mass: **m_H = 128 ± 6 GeV**

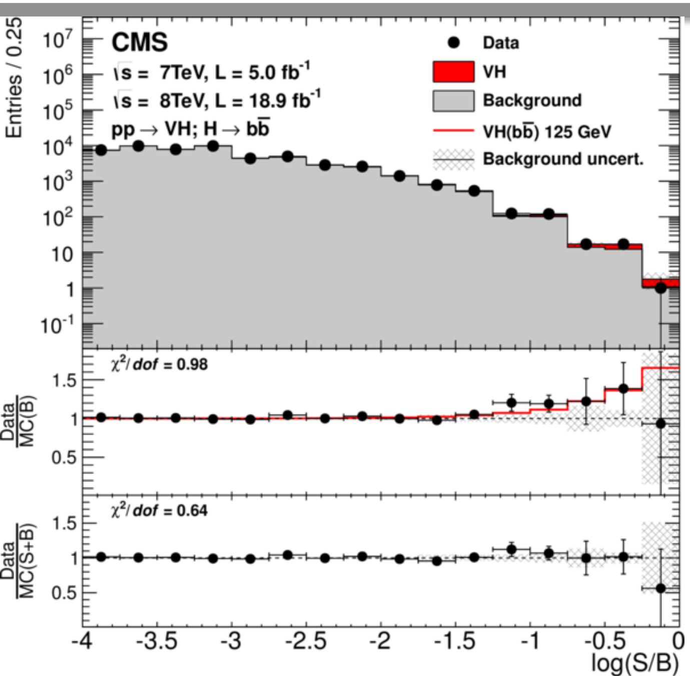
VH, H → bb

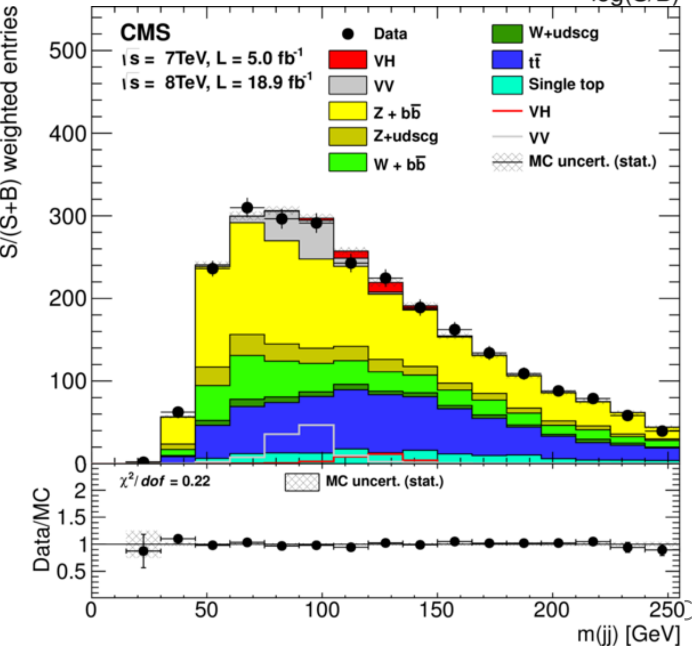

CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 27 02:59:42 2011 CEST
Run/Event: 167807 / 149404739
Lumi section: 134
Orbit/Crossing: 35103256 / 2259
Jet 1, pt: 153.78 GeV; CSV: 0.919
MET 0, pt: 45.1 GeV
Jet 2, pt: 48.4 GeV; CSV: 0.996
Muon 1, pt: 27.3 GeV
Muon 0, pt: 161.8 GeV

VH, H → bb

published

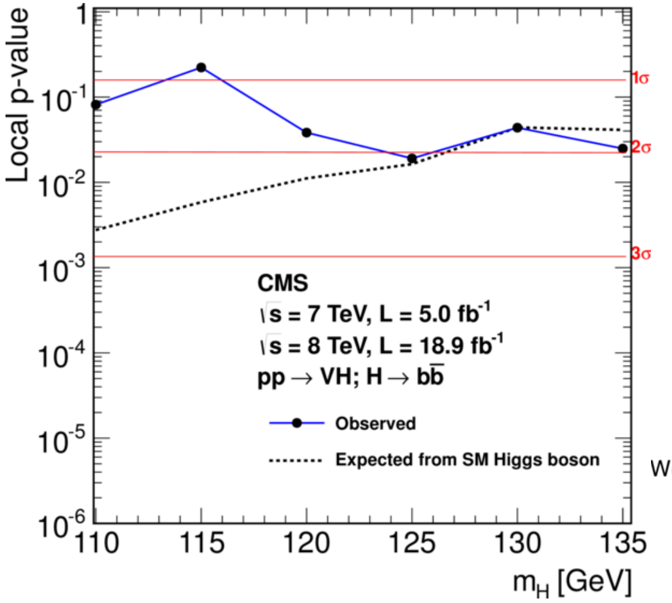
- **Strategy:**
  - Two b-tagged jets
  - split events into categories:
    - **Z(vv)-tag:** 29 events
    - **Z(ll)-tag**: 12 events
    - **W(lv)-tag**: 17 events
    - **W(τ_hv)-tag:** 1 event
  - split event further by p_T(V)
    - higher pT(V): better S:B, better δm_{bb}
  - key observable:
    - **Final BDT** of many observables
    - **bb di-jet mass** in the crosscheck analysis
  - Main backgrounds:
    - V + b-jets, ttbar, single top: from control regions
    - di-boson: from MC
- **Analysis features to note**:
  - largely BDT-based analysis
  - small signal event yield: **60 events**
  - poor "effective" S/B-ratio = **1:20**
  - mass resolution: **10%**

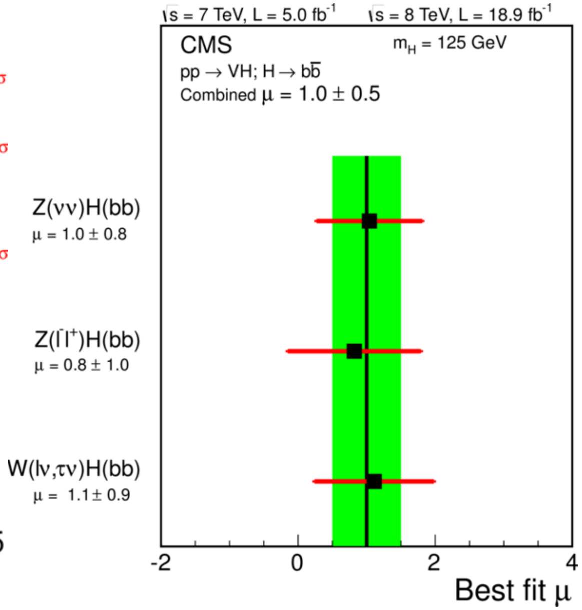




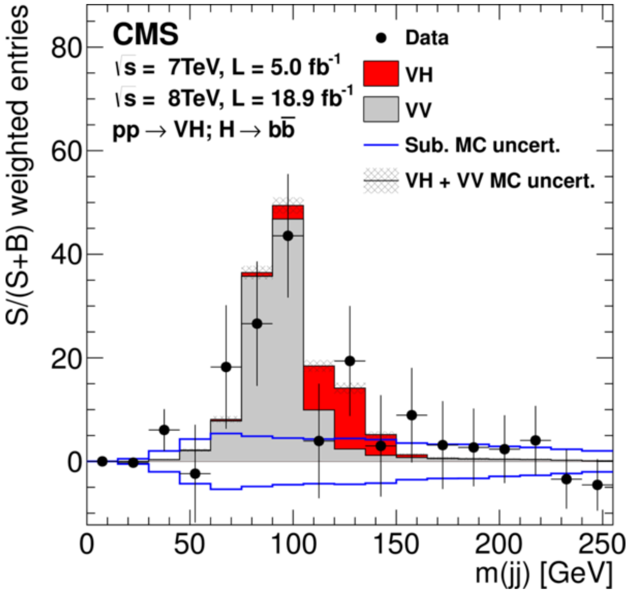
VH, H → bb

published





all bkg subtracted, except for VV



Z_{obs} = 2.1 (expected 2.0)
(m_H = 125)

μ = 1.0 ± 0.5
(m_H = 125 GeV)

standard candle:
qq → VZ → V+(bb)

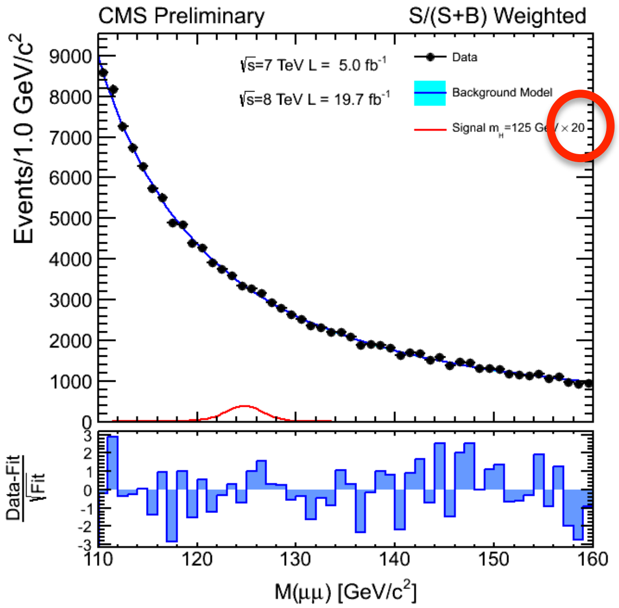
Summary:

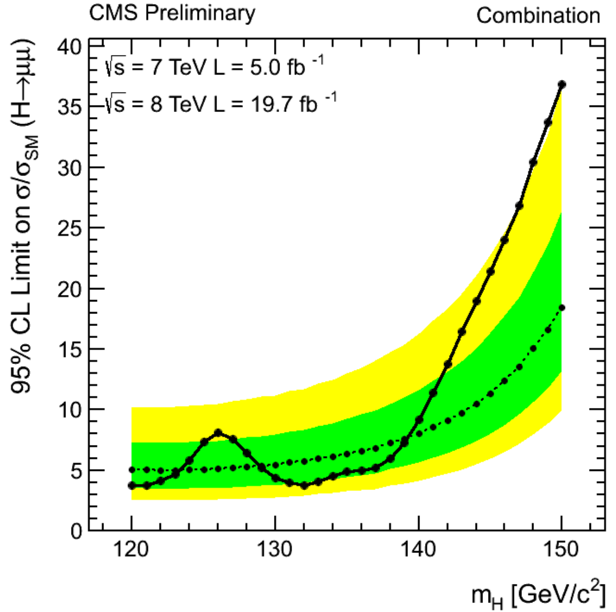
- **broad 2σ-excess** consistent with the SM Higgs boson
- signal strength: **μ = 1.0 ± 0.5**
- **standard candle qq → VZ → V+(bb)** allows one to validate the analysis

H→μμ

preliminary

Final results will be released shortly





- **Strategy:**
  - two isolated high-p_T muons
  - **di-muon mass** is the key observable
  - split events into exclusive categories:
    - di-jet tagged:
      - tight VBF-like, ggF-like, loose
    - untagged:
      - high $p_T(\mu\mu)$, further divided into 6 classes based on the expected di-muon mass resolution
      - low $p_T(\mu\mu)$
  - background:
    - dominated by Drell-Yan
    - fit of the $m_{\mu\mu}$-distribution sidebands

- **Analysis features to note:**
  - small signal: **~45 events**
  - bad "effective" S/B-ratio: **~1:150**
  - good mass resolution = **1-2%**

- **Summary:**
  - observed limit on signal strength $\mu<7.4$ (expected 5.1)
  - **confirmed non-universality of Higgs boson couplings to different fermion generations!** *(If H coupled to muons and taus with the same strength, we'd expect to see μ~O(100) for di-muon decays.)*
  - naively, we need 25 times more data to reach a 2σ-sensitivity for the SM Higgs boson

H125 GeV: summary by decay mode

Observation in good mass resolution channels:

✓ ZZ → 4l	6.8 σ	$\mu = 0.93 \pm 0.27$	
✓ γγ	3.2 σ	$\mu = 0.78 \pm 0.27$	[preliminary]

Observation in poor mass resolution channels (at m_H=125):

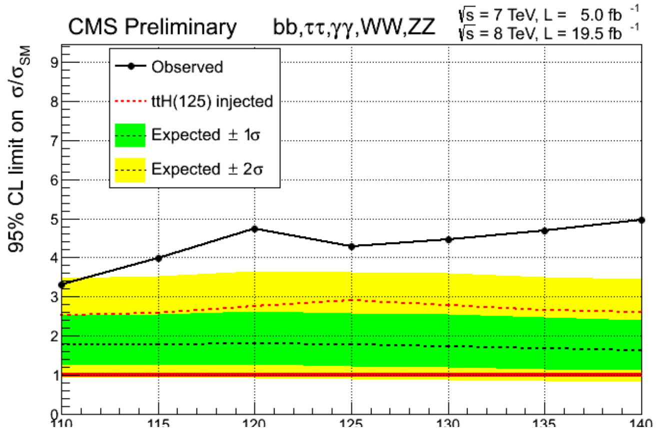
✓ WW → lνlν	4.3 σ	$\mu = 0.72 \pm 0.19$
✓ ττ	3.2 σ	$\mu = 0.78 \pm 0.27$
✓ bb	2.1 σ	$\mu = 1.0 \pm 0.5$

Rare decay searches:

○ H → μμ (2nd generation fermions)	$\mu < 7.4$	[preliminary]
○ H → Zγ→llγ	$\mu < 10$	
○ H → γ*γ→μμγ	$\mu < 11$	[preliminary]
○ H → invisible	B(H→inv) < 0.58	(=10^{-3} for SM Higgs)

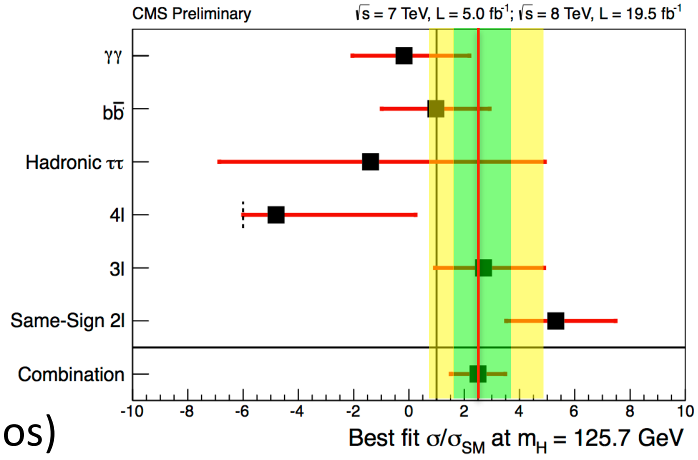
ttH production search

preliminary



Channels included in the grand ttH analysis

- H→bb
- H→γγ
- H→ττ
- multileptons (WW, ZZ, ττ)



Summary:

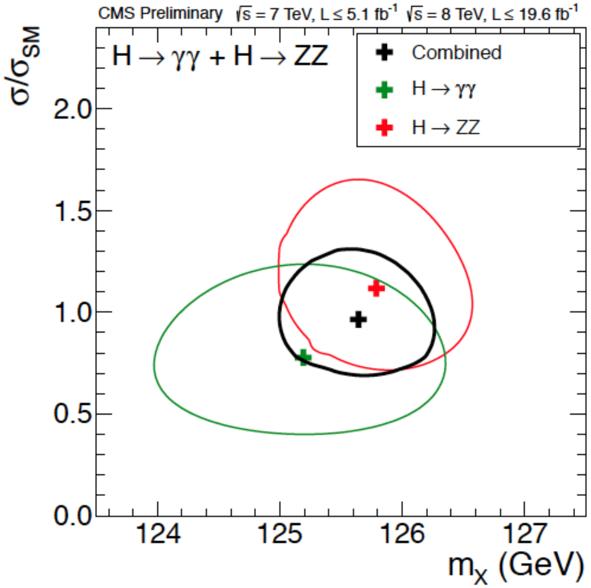
- difficult!
- very small cross section
- collect many channels (small event yields, poor S/B ratios)
- expected sensitivity about 1.2σ
- broad 2.7σ excess (1.5σ upward fluke? 6% compatibility with the SM Higgs boson)
- signal strength: $\mu = 2.5 \pm 1.0$
- the only definitive statement: **signal strength $\mu < 4.2$ at 95% CL**

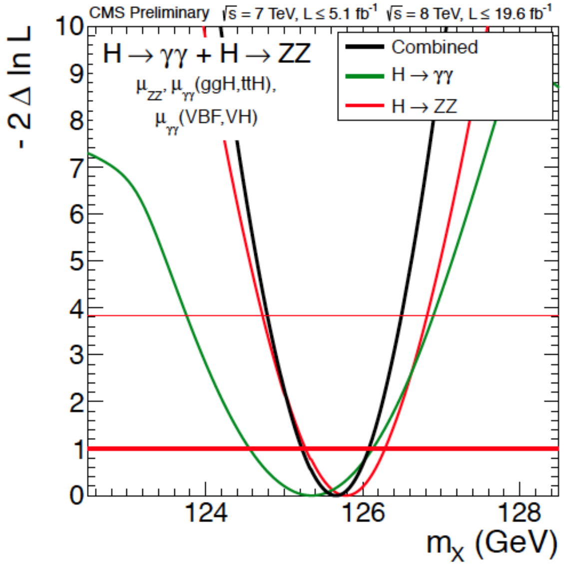
- Observation/search channels

- **Properties**
    - **mass**
    - **quantum numbers**
    - **couplings**
    - **width**

- Prospects

Combined ZZ + γγ mass measurement





- **A narrow resonance is seen with high significance in the two good mass resolution channels, ZZ(4l) and γγ**

ZZ(4l): March 2013 m_X = 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV

FINAL m_X = 125.6 ± 0.4 (stat) ± 0.2 (syst) GeV

main sources of systematic uncertainties:

- electron energy scale: 0.3%
- muon energy scale: 0.1%

γγ: March 2013 m_X = 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV

FINAL awaiting…

main sources of systematic uncertainties:

- electron-photon extrapolation
- E_T scale extrapolation from $m_Z/2$ to $m_H/2$

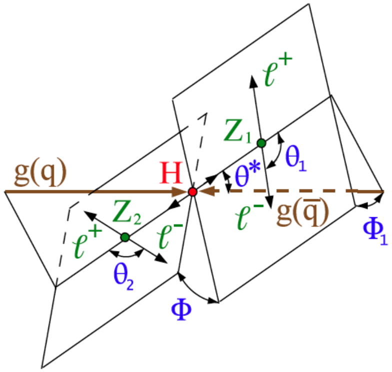
- **Results are consistent with one particle X**
  - **→ proceed with a combined mass measurement**
  - **→ do not assume that ZZ and γγ event rates are tied by SM**

March 2013 m_X = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

Spin-parity tests

H→ZZ→4l

- 4l system is fully reconstructed
- use leptons’ momenta to compute matrix elements

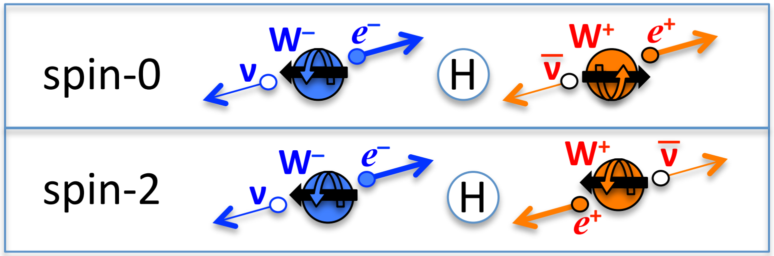


ME-based discriminat

$$d = \frac{|ME(event\,|\,J^P)|^2}{|ME(event\,|\,H)|^2}$$

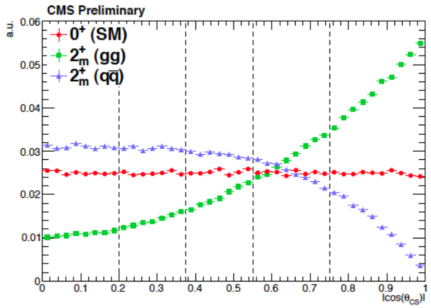
H→WW→lvlv

- dilepton angle is sensitive to spin of the original H-boson



H→γγ

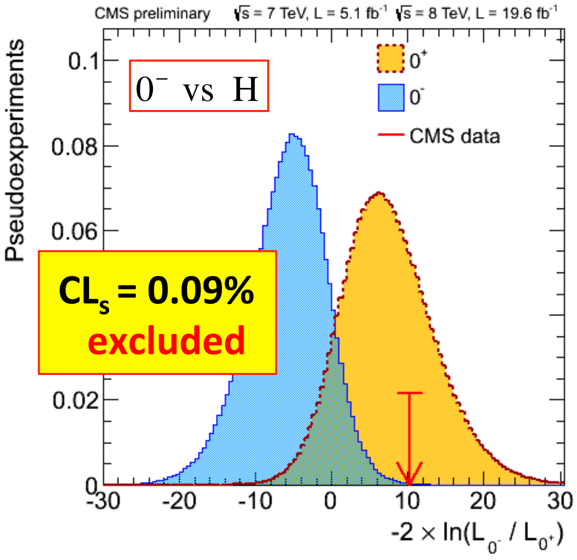
- J=1 forbidden (Landau-Yang theorem)
- cosθ* is the only variable sensitive to J^P information at leading order



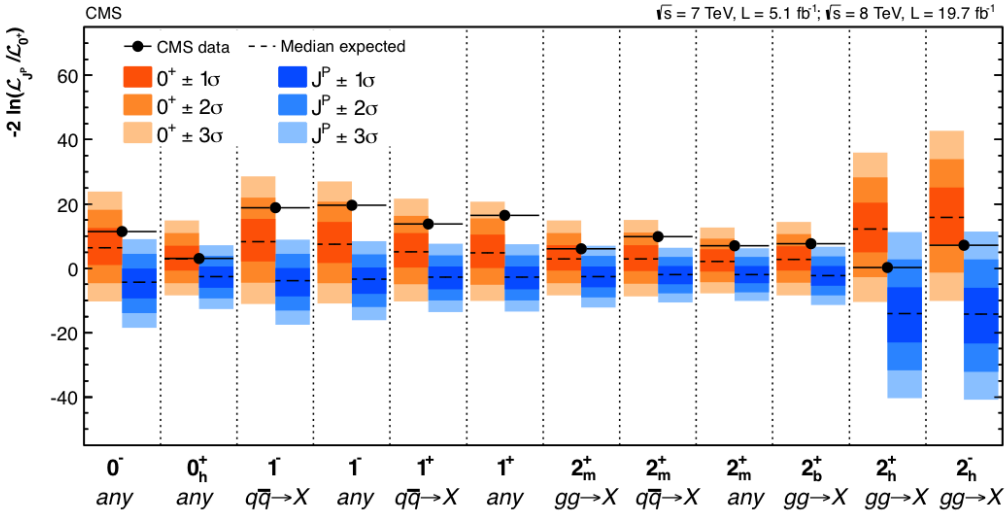
- before acceptance and reconstruction
- after acc x reco, discrim. power lessens
- poor S:B makes measurements difficult

Spin-parity results

published



CL_s = 0.09% excluded



	0^-	0^+_h	$q\bar{q} \to 1^-$	$q\bar{q} \to 1^+$	$gg \to 2^+_m$	$q\bar{q} \to 2^+_m$	$gg \to 2^+_b$	$gg \to 2^+_h$	$gg \to 2^-_h$
ZZ	0.09%	7.1%	0.001%	0.03%	1.9%	0.03%	0.9%	3.1%	1.7%
WW	35%				16%	0.2%			
γγ			**forbidden**		poor sensitivity				

Summary:

- 0^-, $1^\pm$, five J=2 models excluded at 95% CL or higher
- 0^+_h – on a borderline of being excluded
- data are better than ±2σ compatible with 0^+ in all tests performed so far
- more results on other spin-two models are coming soon…

Combination: Production × Decay

7 + 1 = 8 independent parameters to describe all currently relevant decays and production mechanisms:

$$\sigma(xx \rightarrow H) \cdot BR(H \rightarrow yy) \;\propto\; \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{TOT}}}$$

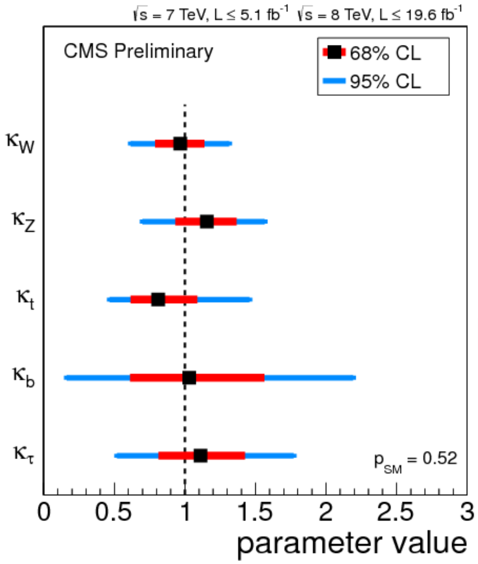
- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- $\Gamma_{TOT} = \Gamma_{WW} + \Gamma_{ZZ} + \ldots + \Gamma_{BSM}$
- gray: not yet used in combination

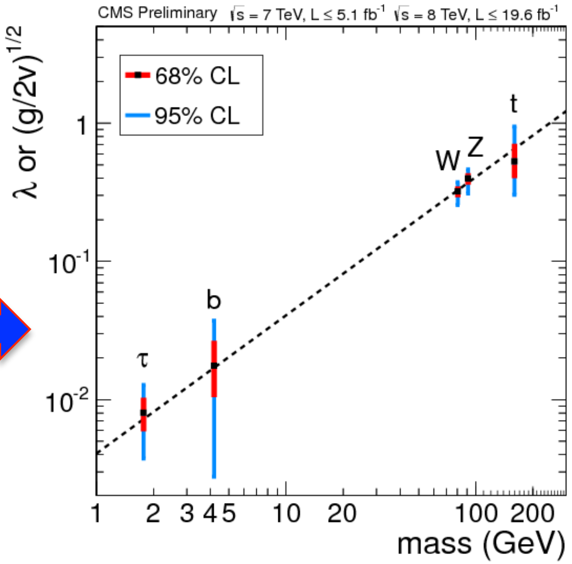
	untagged	VBF-tag	VH-tag	ttH-tag
WW	✔	✔	✔	✓
ZZ	✔	✔		✓
bb			✔	✔
ττ	✔	✔	✔	✓
γγ	✔	✔	✔	✓
Zγ	✓	✓		
μμ	✓	✓		
invisible		✓	✓	

Couplings: compatibility with SM

preliminary

- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\gamma\gamma}$ (loop) → κ_W, κ_t
- Γ_{gg} (loop) → κ_t, κ_b
- Assumed:
  - **B(H→BSM)=0**
  - couplings to the 1st, 2nd, 3rd generations are modified the same way





Summary:

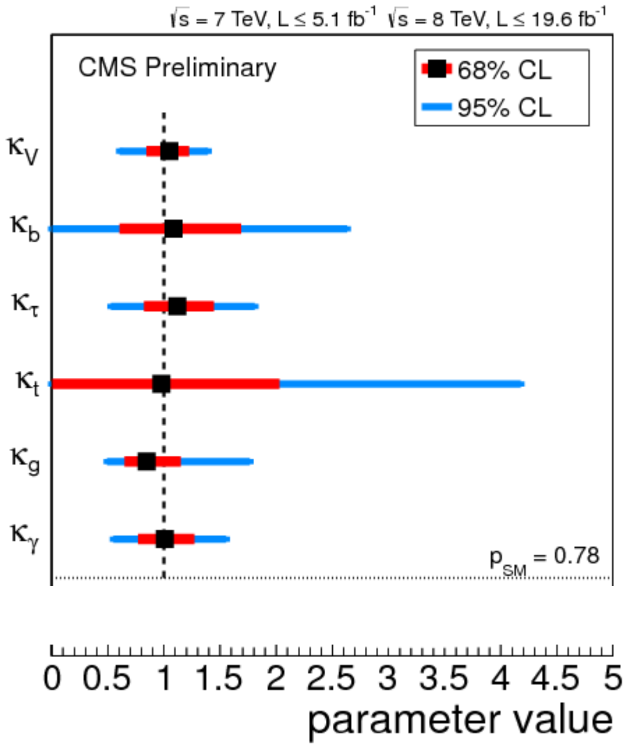
- Good compatibility with the SM Higgs couplings (**current accuracy: 20-50%**)
- NB: range of couplings tested is O(100); O(1000) with H→μμ included

Couplings: search for new physics

preliminary

Test #1

- Γ_{ZZ} **assume: $\kappa_Z = \kappa_W$** → κ_V
- Γ_{WW}
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{bb} → κ_b
- Γ_{tt} → κ_t
- $\Gamma_{\gamma\gamma}$ (allow BSM in loop) → κ_γ
- Γ_{gg} (allow BSM in loop) → κ_g
- assume **B(H→BSM)=0**



Summary:

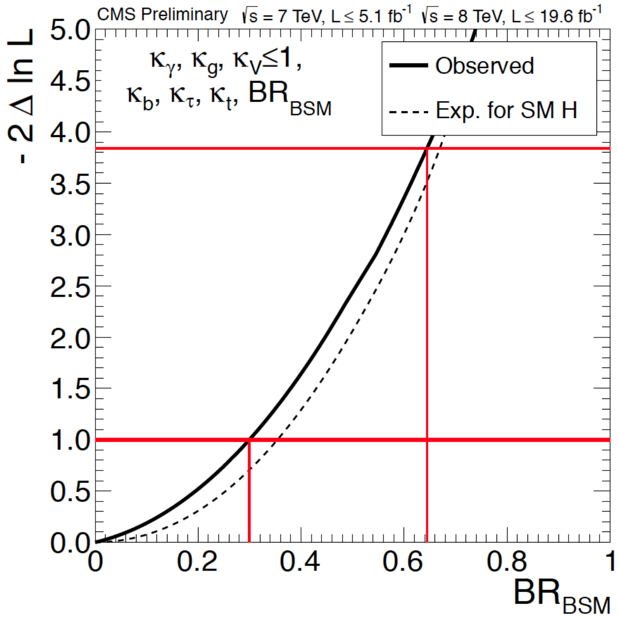
- κ_g and κ_γ remain to be close 1, implying no new physics in the loops
- accuracy on the top-quark coupling is now solely defined by the ttH analysis

Couplings: search for new physics

preliminary

Test #2

- Γ_{ZZ} **assume: $\kappa_Z = \kappa_W$** → κ_V
- Γ_{WW}
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{bb} → κ_b
- Γ_{tt} → κ_t
- $\Gamma_{\gamma\gamma}$ (allow BSM in loop) → κ_γ
- Γ_{gg} (allow BSM in loop) → κ_g
- **allow B(H→BSM) ≠ 0**



Assume: $k_V \leq 1$

- some constrain is needed to remove the degeneracy in $\sigma(xx \rightarrow H) \cdot BR(H \rightarrow yy) \propto \dfrac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{TOT}}$
- $k_V \leq 1$ is natural: $k_V > 1$ overshoots the unitarity recovery in WW scattering with no remedy

Result: B(H→BSM) < 0.62

NB: With all other couplings ~SM-like, this implies that **$\Gamma_{TOT} < \Gamma_{SM}/(1\text{-}0.62) \sim 2.5\ \Gamma_{SM}$**

[*this is a back-of-envelope estimate; the actual result will come out in near future*]

Width limits from off-shell H*→ZZ

preliminary

Final results will be released shortly

- Breit-Wigner production gg→H→ZZ (up to partonic luminosities)

$$\frac{d\sigma_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{dm^2_{\mathrm{ZZ}}} \propto g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}} \frac{F(m_{\mathrm{ZZ}})}{(m^2_{\mathrm{ZZ}} - m^2_{\mathrm{H}})^2 + m^2_{\mathrm{H}} \Gamma^2_{\mathrm{H}}}$$

- On-peak and off-peak cross sections:

$$\sigma^{\mathrm{on-peak}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}} \propto \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{\Gamma_{\mathrm{H}}}, \qquad \sigma^{\mathrm{off-peak}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}} \propto g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}$$

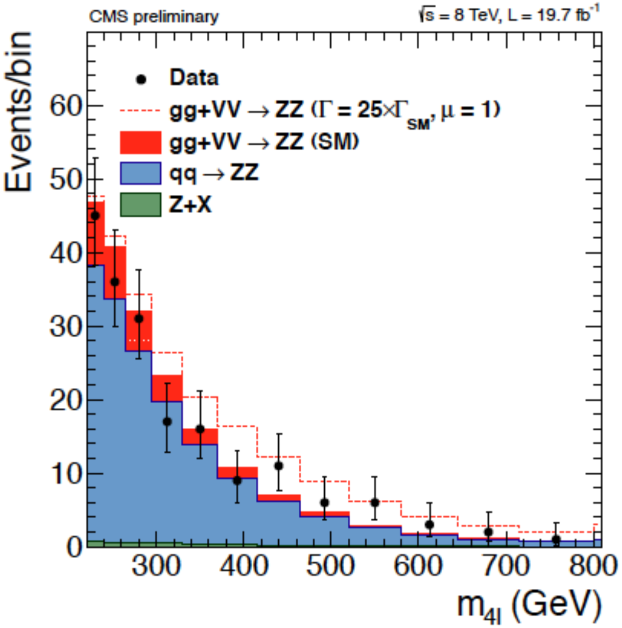
- **The off-peak to on-peak ratio is proportional to Γ_H**

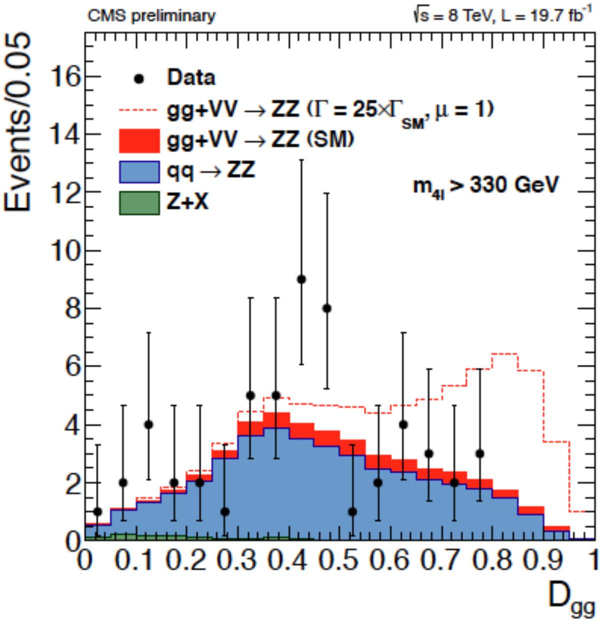
- **CAVIATS IN REAL LIFE ANALYSIS:**
  - **evolution of $g_{ggH}(m_{H*})$ depends on what is in the loop → assume top-loop dominance**
  - **assume that ggF and VBF are dominant production mechanisms (relative role can be extracted from on-peak analysis)**
  - **off-peak production depends strongly on tensor structure of HZZ → assume SM-like 0^+**
  - **must include negative interference between gg→H→ZZ and gg→(box)→ZZ**

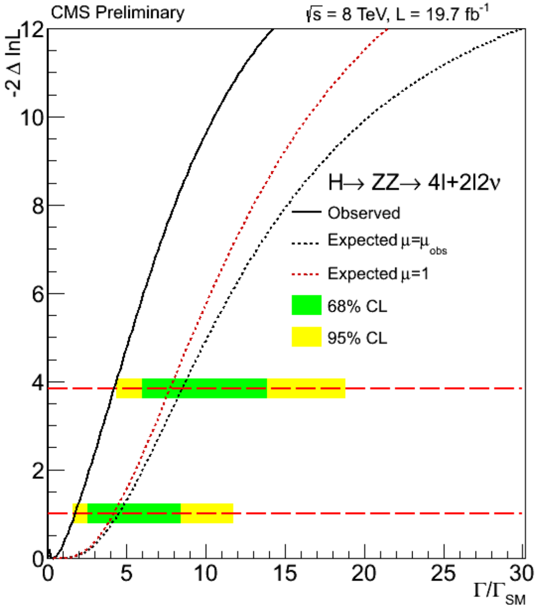
Width limits from off-shell $H^* \rightarrow ZZ$

preliminary

Final results will be released shortly







Analysis strategy:

- for large Γ_H, expect an excess of events at high m_{ZZ}
- for $H \rightarrow ZZ \rightarrow 4l$, use ME discriminant ($gg \rightarrow ZZ$ vs $qq \rightarrow ZZ$) to improve sensitivity
- add $H \rightarrow ZZ \rightarrow 2l2\nu$ for probing off-shell production rate at high m_{ZZ}

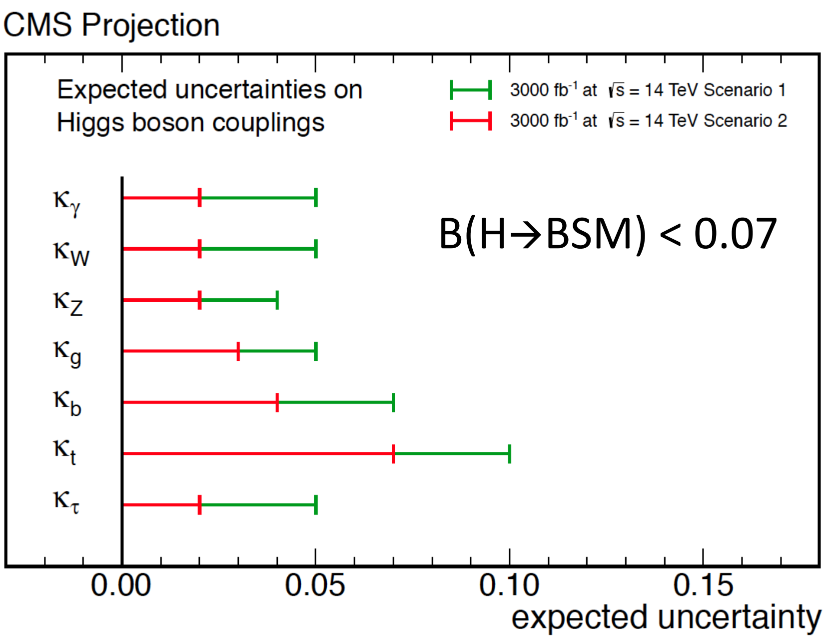
Results: $\Gamma_H < 4.2\ \Gamma_{SM}$

- Observation/search channels

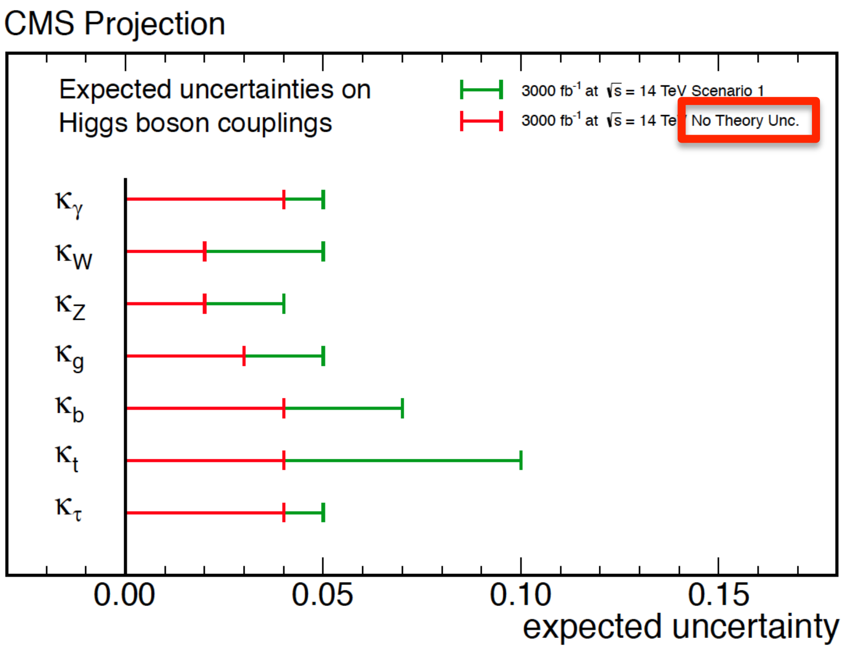
- Properties
  - mass
  - quantum numbers
  - couplings
  - width

- **Prospects**

Projections: couplings



B(H→BSM) < 0.07



Extrapolation scenarios:

- assume the same CMS performance (efficiencies, resolutions, etc.) as achieved in the 8 TeV Run
- **scenario 1**: keep all syst. uncertainties unchanged
- **scenario 2**: all instr. syst. uncertainties scaled as 1/sqrt(L); theoretical uncertainties are halved

Summary:

- expected measurement precision for Higgs boson couplings: **δκ ~ 2-5%** (10% for ttH)
- **B(H→BSM) < 0.07** at 95% CL
- theory uncertainties must be decreased to be on par with the expected experimental precision

Projections: anomalous spin-zero tensor structure (H→4l)

$$\begin{aligned}\mathcal{L} \supset \frac{h}{4v}\Big(2A_1^{ZZ} m_Z^2 Z^{\mu} Z_{\mu} &+ A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \widetilde{Z}_{\mu\nu} \quad\longleftarrow\quad \mathbf{H\to ZZ\to 4l}\\ &+ 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \widetilde{Z}_{\mu\nu} \quad\longleftarrow\quad \mathbf{H\to Z\gamma^*\to 4l}\\ &+ A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu}\Big) \quad\longleftarrow\quad \mathbf{H\to \gamma^*\gamma^*\to 4l}\end{aligned}$$

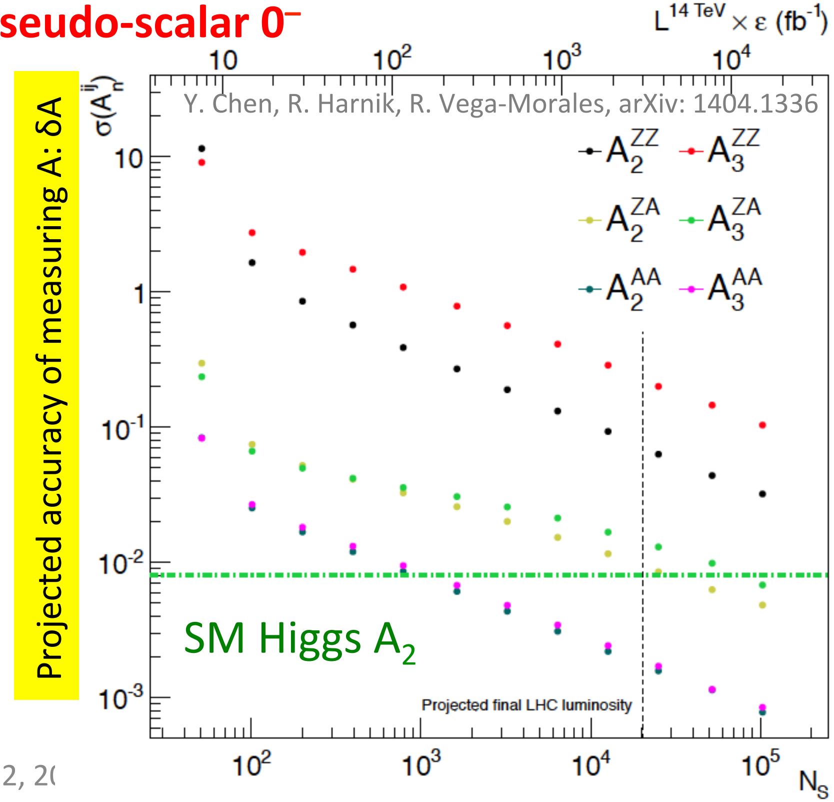
SM Higgs 0^+ (A_1=1)

higher-dim. scalar 0^+

higher-dim. pseudo-scalar 0^-

Summary:

- Detecting "anomalous" A_3 term would likely imply a new portal for CP violation (SM-induced "anomalous" A_3 terms are immeasurably small)
- SM-induced "anomalous" A_2 terms are small, O(10^{-2}), but perhaps measurable for γ*γ* and Zγ*
- Should we detect a sizable A_2 or A_3 term, BSM physics would be in order
- **The first stub by CMS:** $\left|\frac{A_3^{ZZ}}{A_1}\right| < 5.2 \quad \text{at } 95\% \text{ CL}$



Summary

- The **H125 GeV** is by now established in many **individual decay channels**:
  ZZ (6.8σ), WW (4.3σ), γγ (3.2σ), ττ (3.2σ), bb (2.1σ)

- **New boson's mass: m_X = 125.7 ± 0.4 GeV** (from ZZ+γγ channels)

- **Is H125 boson the SM Higgs boson?**
  - **event yields in all individual channels are consistent with the SM Higgs boson**
  - **couplings agree with the SM Higgs** with the current statistical accuracy (20-50%)
  - **J^{CP} = 0^-, $1^\pm$, and a number of J=2 states are excluded** at >95% CL or higher

- As far as H125 boson is concerned, **it certainly looks *mostly* like SM Higgs**
- We are at the beginning of the long haul program of **precision measurements of Higgs boson properties** with a hope to pin down small deviations from the SM
- And there is always a chance to find more scalars…