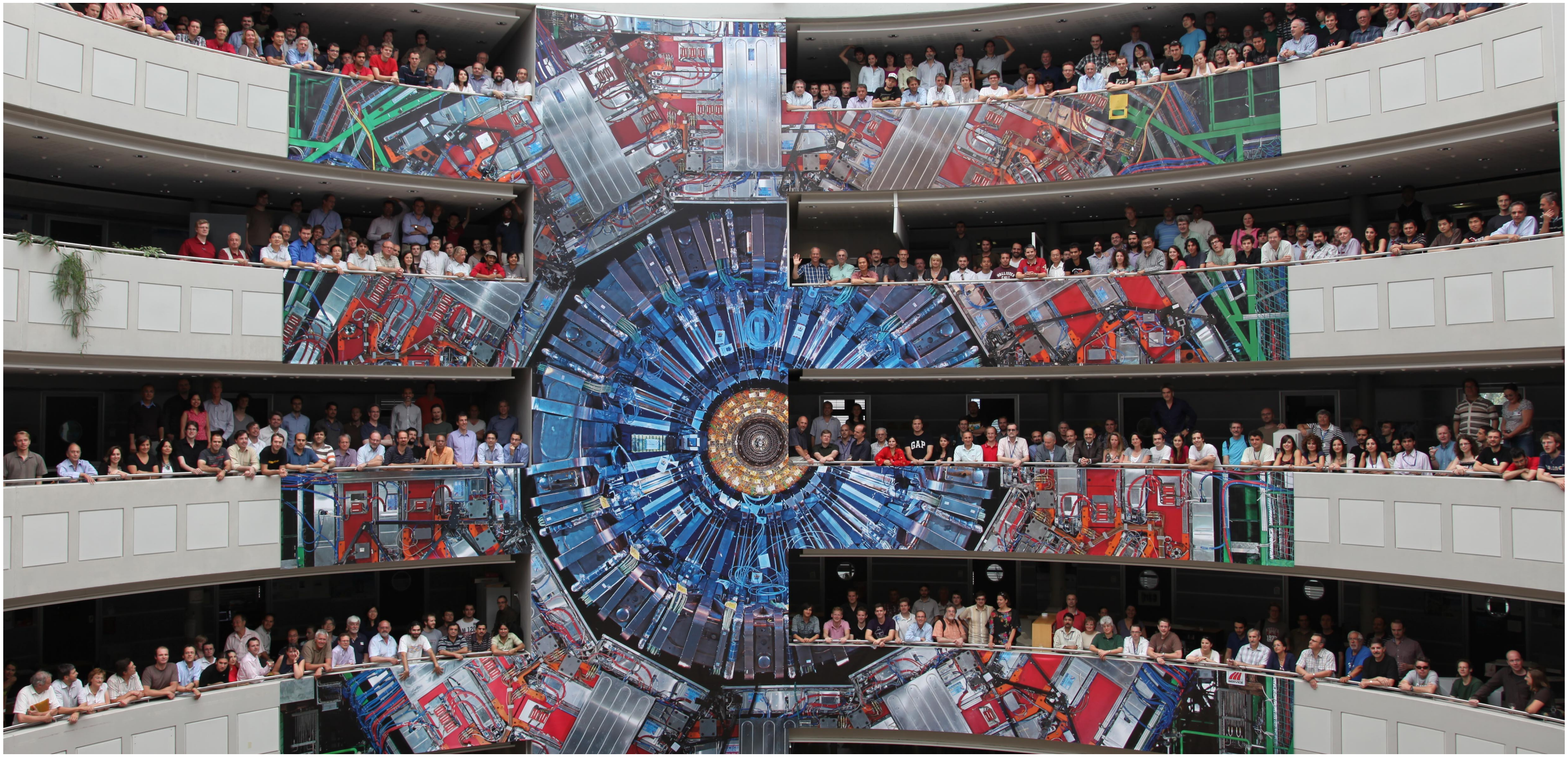


CMS studies of the Higgs boson

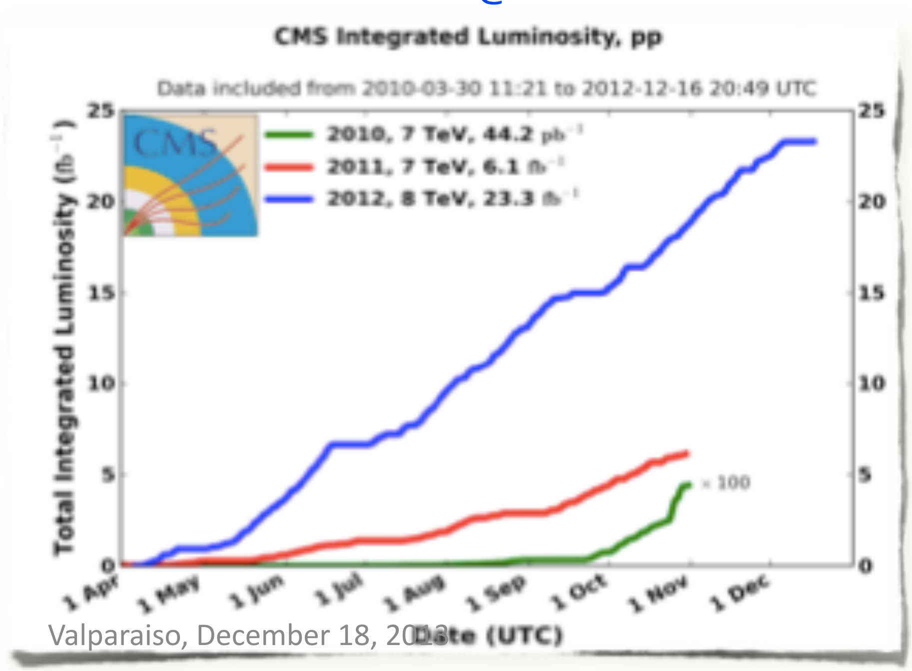
Guenakh Mitselmakher
University of Florida
Valparaiso, Chile, December 18, 2013

Content

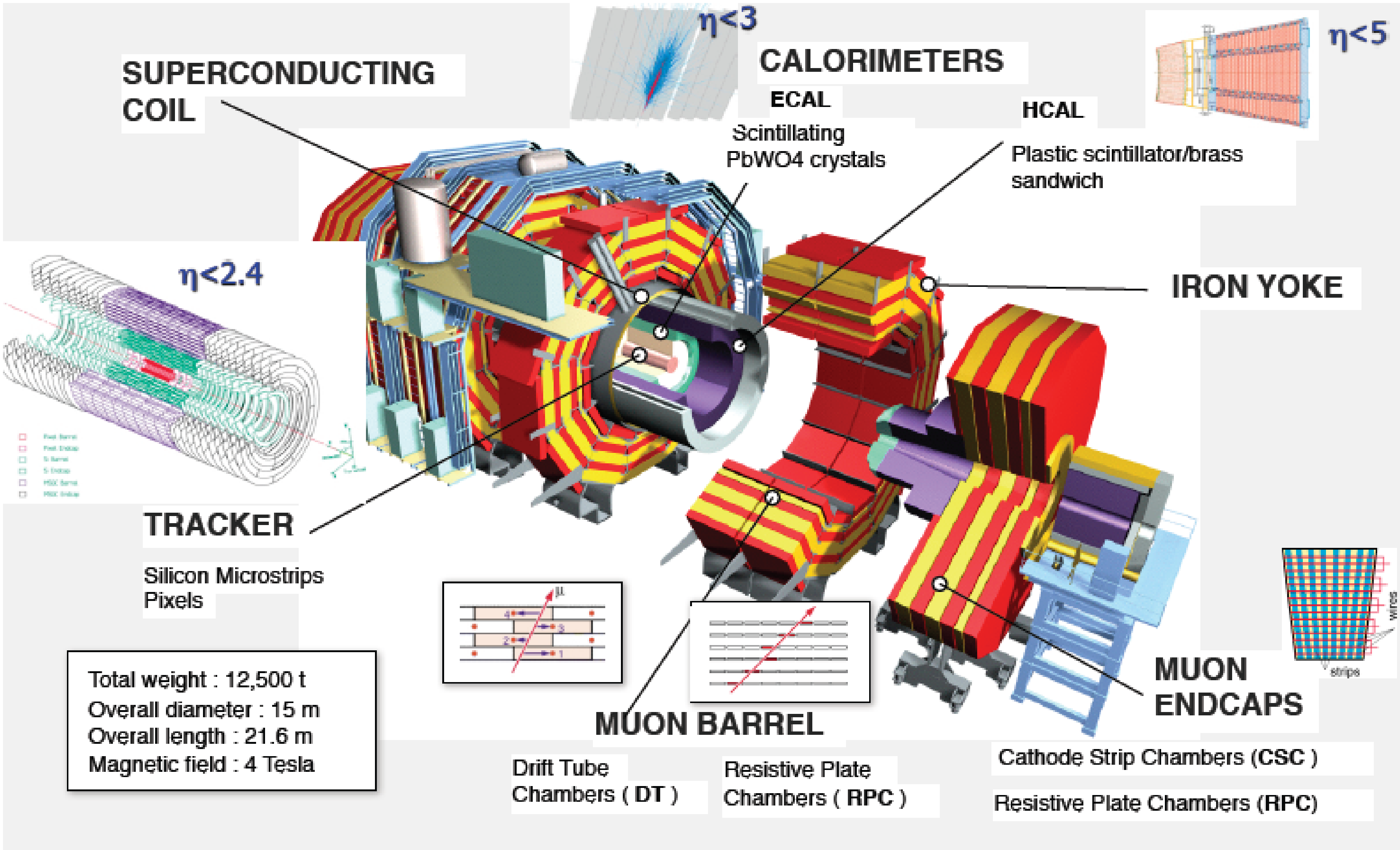
- Introduction: LHC and CMS
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow \gamma\gamma$.
- $H \rightarrow WW$ (updated)
- $H \rightarrow \tau\tau$ (very recent updates)
- $H \rightarrow bb$
- ttH (updated)
- $H \rightarrow \mu\mu$ (updated)
- Coupling constants (partially updated)
- Conclusions

LHC performance

pp collisions in CMS
2011: ~6 fb^{-1} @ 7 TeV
2012: ~23 fb^{-1} @ 8 TeV

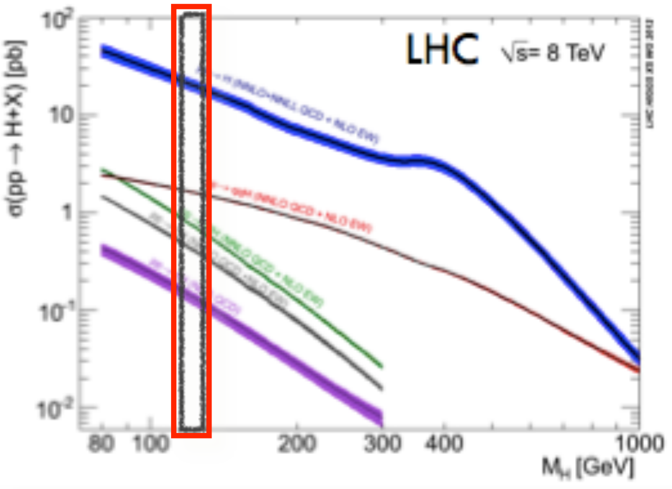


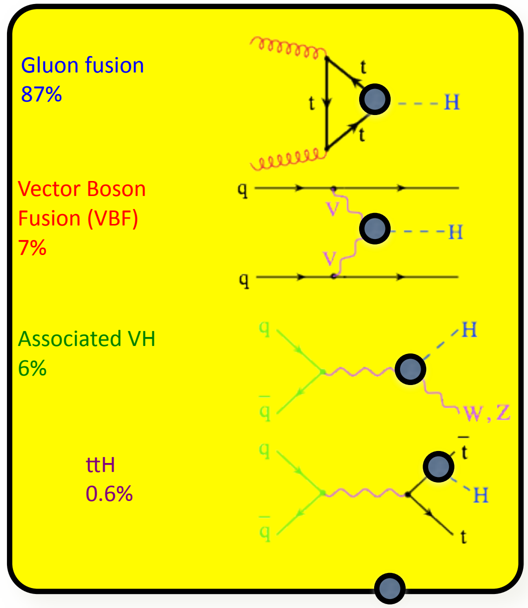
The Compact Muon Solenoid



Predicted Higgs production and decay

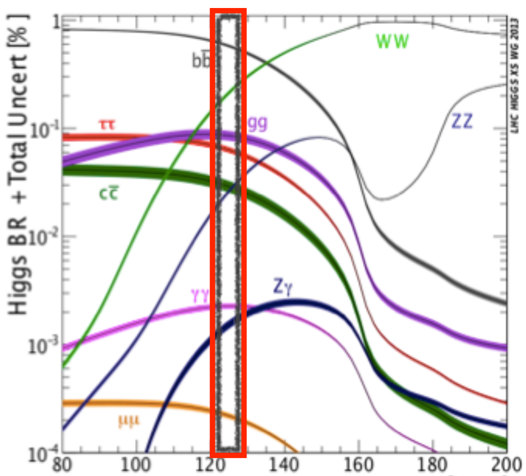
Production

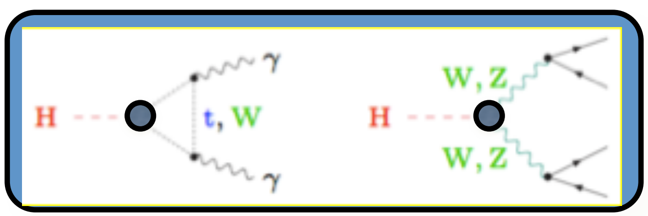


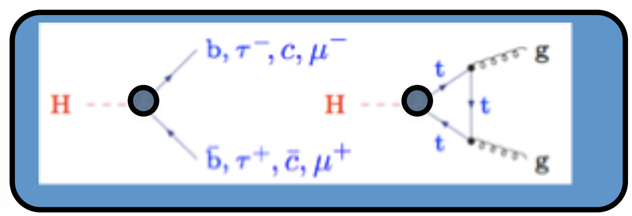


At Higgs mass
~125 Gev we have access
to several decay modes,
which allows
for detailed studies
Of couplings
We are lucky!

Decays







$BR(h \to b\bar{b}) = 58\%$, $BR(h \to WW^*) = 21.6\%$, $BR(h \to \tau^+\tau^-) = 6.4\%$,
$BR(h \to ZZ^*) = 2.7\%$, $BR(h \to gg) = 8.5\%$, $BR(h \to \gamma\gamma) = 0.22\%$,
$BR(h \to c\bar{c}) = 2.7\%$

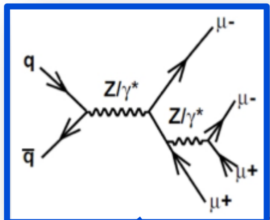
Higgs particles produced in CMS (estimate)

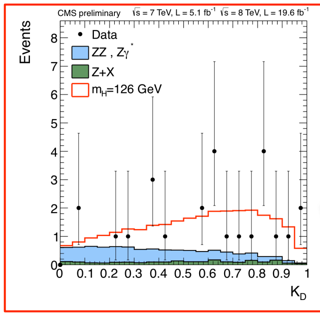
- Number of Higgs particles produced in CMS in 2011-2012 = 550,000
  (total CS 22 pb) x (25 fb-1)

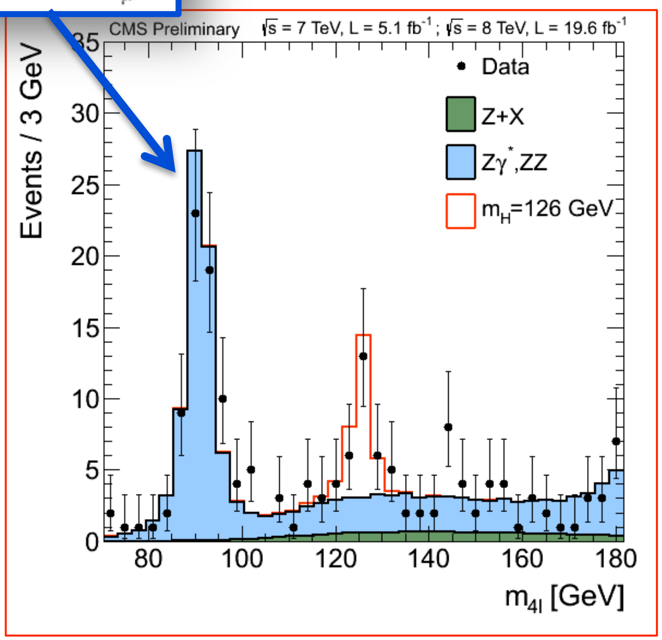
- Contribution of different production mechanisms (wrt the total CS)
- ggF = 87%
- VBF = 7%
- VH = 5%
- ttH = 0.6%

- Decay modes (l = e or mu)
- BR(bb) = 57%
- BR(tautau) = 6%
- BR(WW->2l2v) = 22% x (0.22)^2 = 1.1%
- BR(gamgam) = 0.23%
- BR(ZZ->4l) = 2.8% x (0.06)^2 = 0.013%
- BR(mumu) = 0.022%

H $\rightarrow$ ZZ $\rightarrow$ 4l







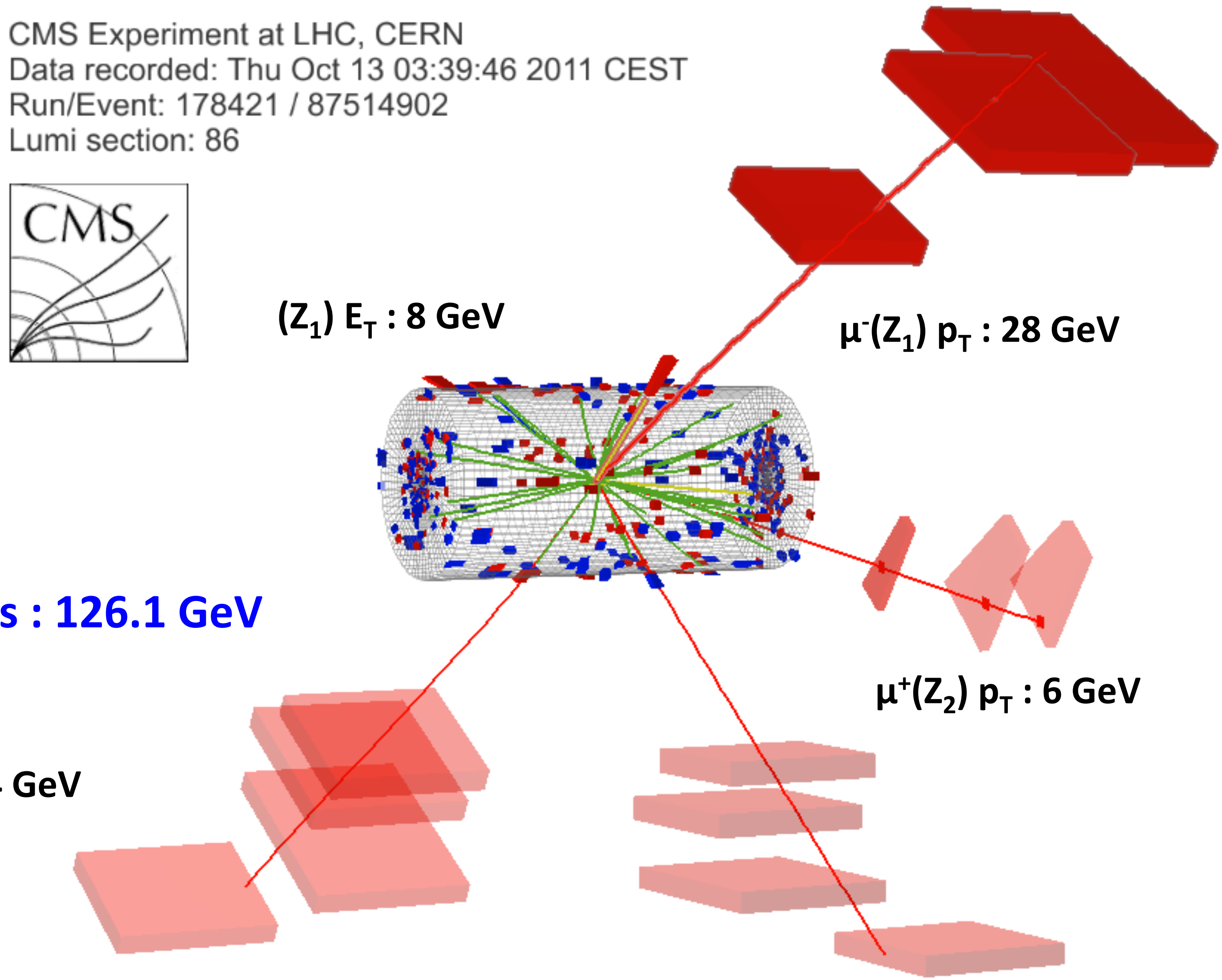
Analysis strategy:

- Four leptons
- **four-lepton mass** is the key observable
- split events into 4e, 4μ, 2e2μ channels:
  - different mass resolutions
  - different S/B rates (for reducible bkgd with "fake" leptons)
- CMS: add **ME-based discriminant K_D** (2^{nd} observ.), more details about K_D later
- Backgrounds:
  - ZZ (dominant) from Monte Carlo (MC)
  - reducible (with non-isolated or "fake" leptons): from control region

Analysis features:

- high S/B-ratio (~2:1)
- but small event yield
- excellent mass resolution = 1-2%"
- "Standard candle" Z$\rightarrow$4l decay peak nearby, natural validation of the discovered peak

4μ+γ computer event display



7 TeV DATA

4μ+γ Mass : 126.1 GeV

Higgs →4l : Signal/Background ratio ~ 2:1 observed: 25 events total (S+B)

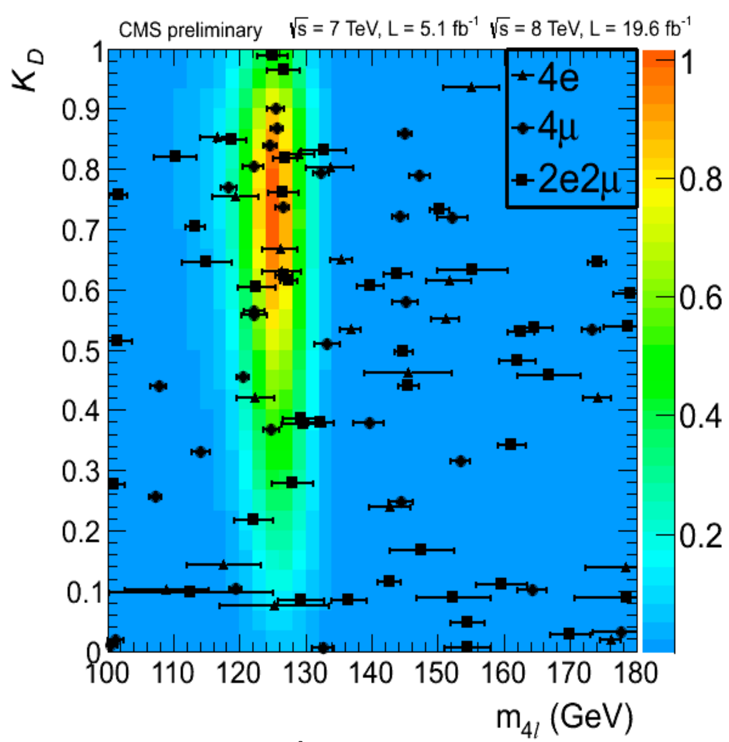
For 121.5 < m4l < 130.5 GeV

	4e	4μ	2e2μ
H(126) expected	3.0	6.7	8.9
ZZ expected	1.2	2.7	3.5
Z+X & top expected	0.6	0.5	0.9
Total Bkg	1.8	3.2	4.4
Signal+Bkg expected	4.8	9.9	13.3
Observed	5	8	12

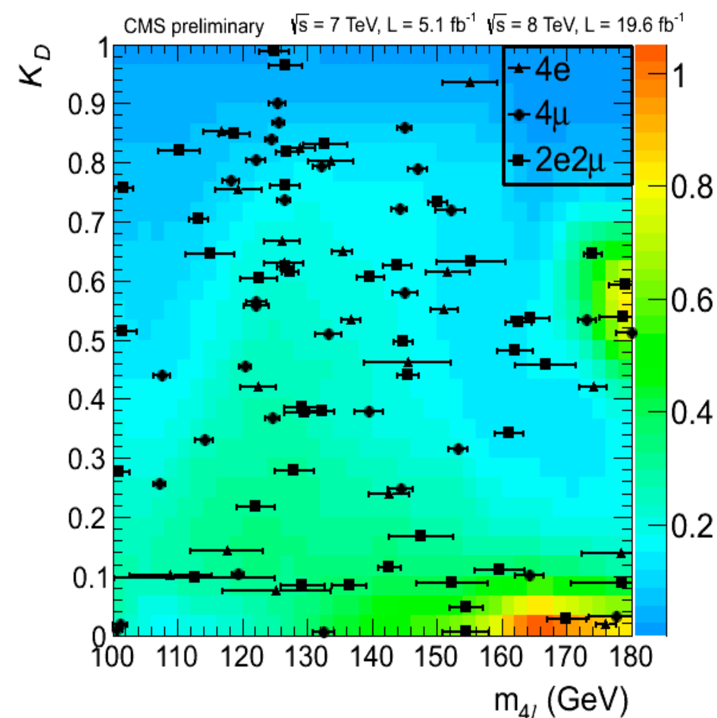
S/B improvement: Kinematic Discriminant

- To further improve signal to background ratio, we use a discriminant based on kinematic 4l information

$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{c \times \mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

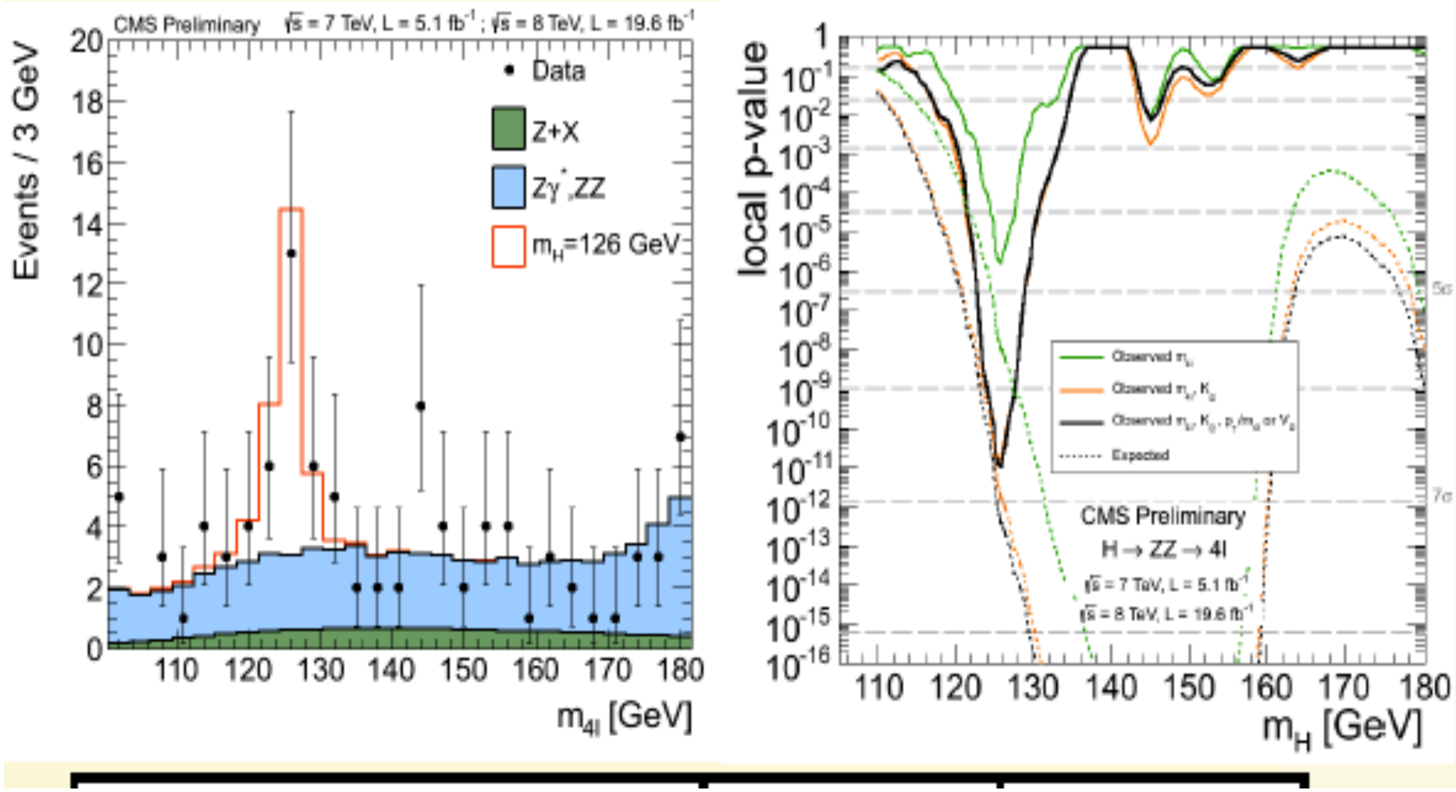


Higgs signal



ZZ^* background

Statistical significance of 4l peak

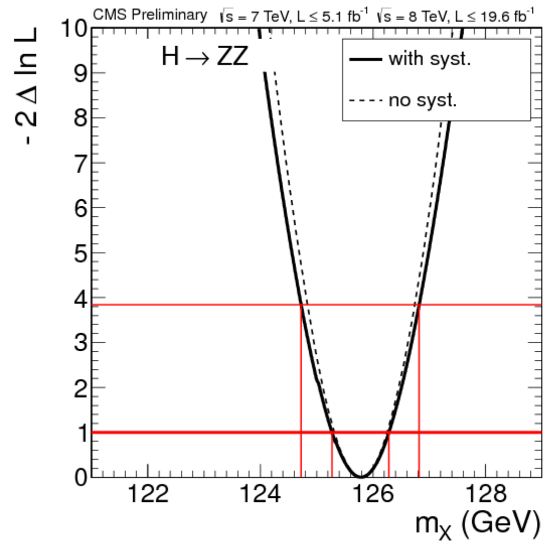


Expected/observed significance : 7.2 σ / 6.7 σ

Signal strength: **μ=0.91+0.30-0.24**

More than 5σ significance in a single decay channel, both expected and observed

New boson mass measurement from H→4l channel



m_X = 125.8 ± 0.5 (stat) ±0.2 (syst) GeV

Statistics dominated! Can be significantly improved in the future.

Main sources of systematic uncertainties:

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

H→4l: Spin and Parity J^P

- Use kinematic information to separate different spin-parity hypotheses **J^P**
- The following **J^P** considered (pure cases, no mixing):

J^P	production	description
0^+	$gg \to X$	SM Higgs boson
0^-	$gg \to X$	pseudoscalar
0_h^+	$gg \to X$	BSM scalar with higher dim operators (decay amplitude)
2^+_{mgg}	$gg \to X$	KK Graviton-like with minimal couplings
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	KK Graviton-like with minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector

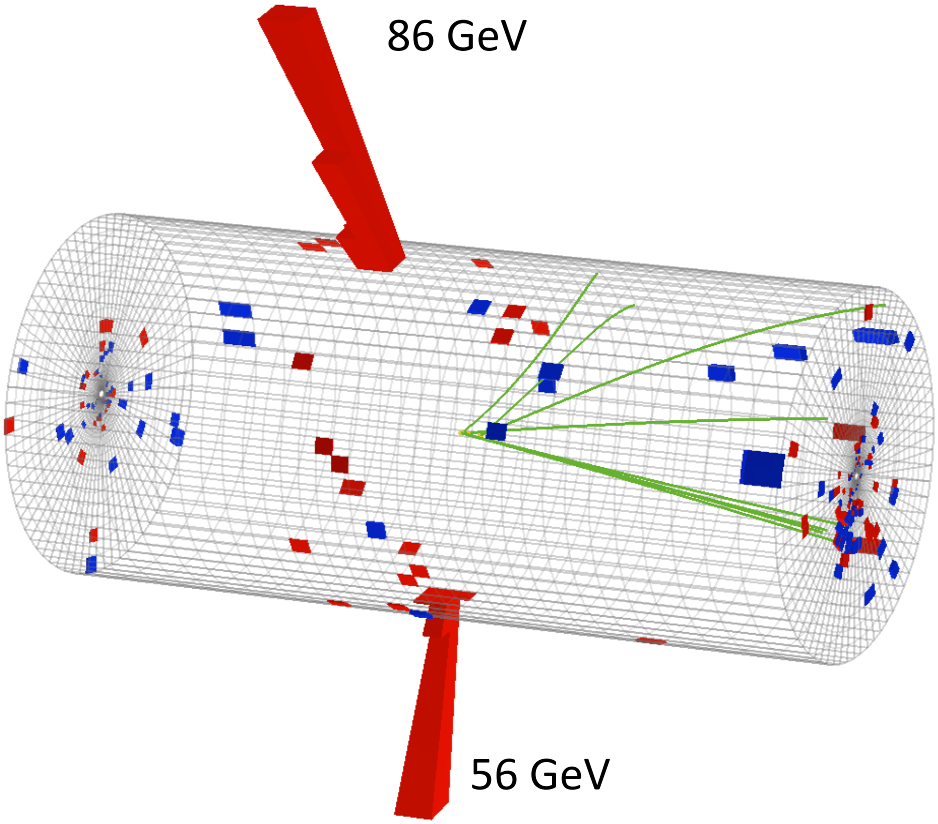
:

Spin-parity: H→4l studies results

	Expected [σ]		Observed (μ from data)		
	μ=1	μ from data	P(q > Obs | alternative) [σ]	P(q > Obs | SM Higgs) [σ]	CLs [%]
$gg \rightarrow 0^-$	2.8	2.5	3.3	-0.5	0.16
$gg \rightarrow 0_h^+$	1.8	1.7	1.7	+0.0	8.12
$qq \rightarrow 1^+$	2.6	2.3	> 4.0	-1.7	< 0.01
$qq \rightarrow 1^-$	3.1	2.8	> 4.0	-1.4	< 0.01
$gg \rightarrow 2_m^+$	1.9	1.8	2.7	-0.8	1.46
$qq \rightarrow 2_m^+$	1.9	1.7	4.0	-1.8	0.09

The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher .
Data is consistent with SM Higgs

H→ γγ



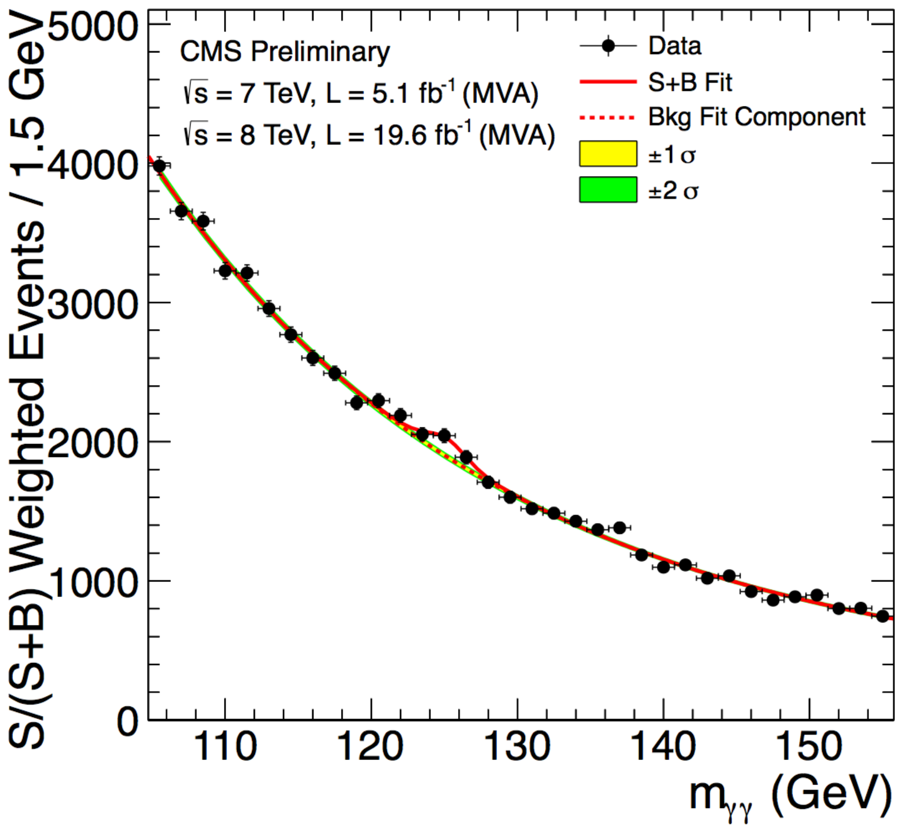
Analysis

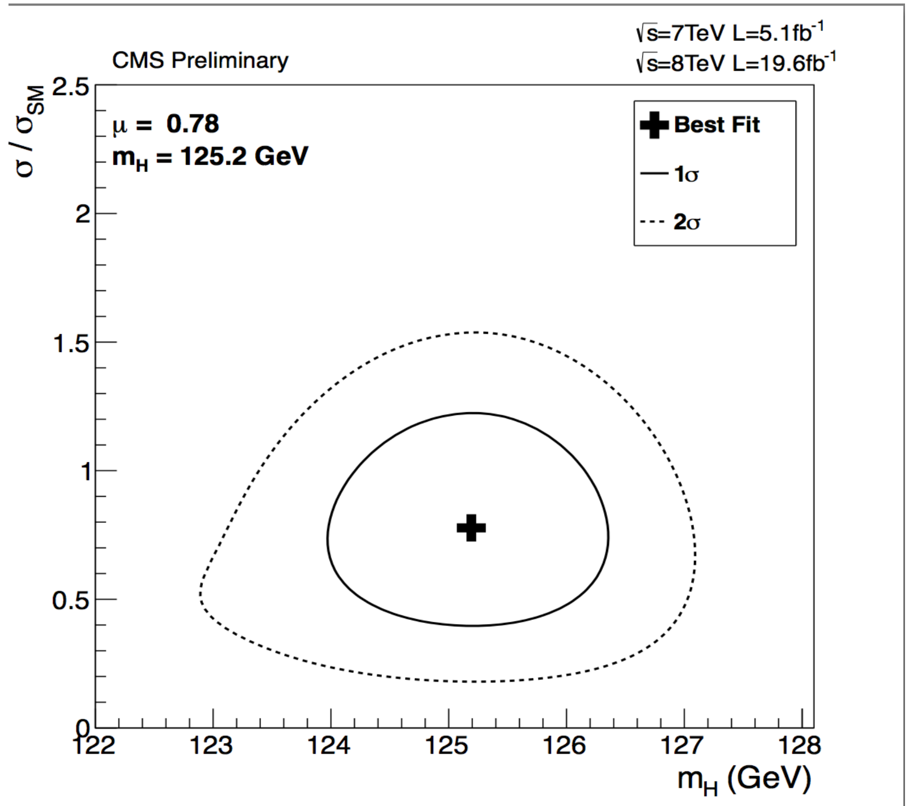
- Two high momentum photons
- Higgs is narrow (at low mass)
- Two photon resolution is excellent
- Large irreducible background from direct two photons
- Smaller “reducible” fake photon background

Key analysis features

- Energy resolution (calibration)
- Fake photon rejection
- Use of kinematics

H→ γγ



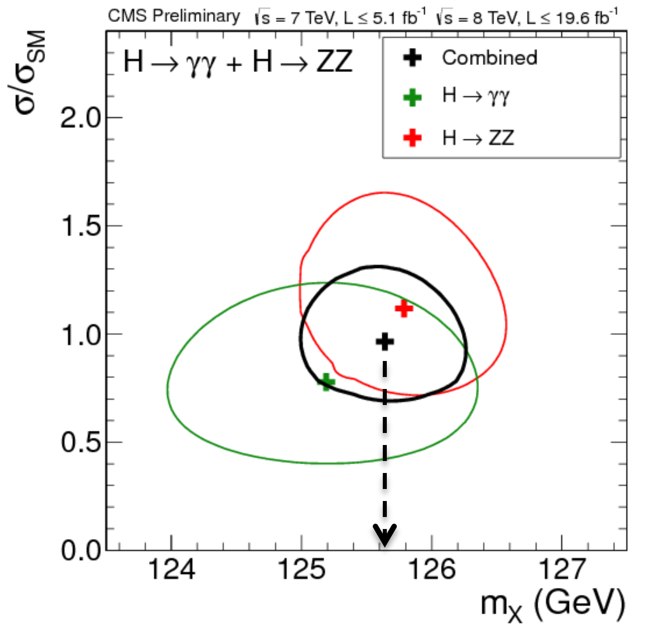


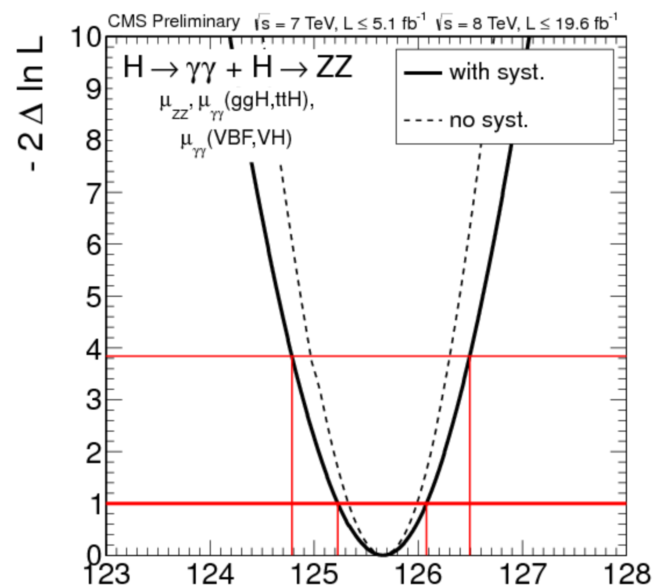
Each event category is weighted by its S/(S+B)
(only for visualization purposes)

Significance 3.2σ (expected 4.2σ)

m_X=125.4 ± 0.5(stat) ± 0.6(syst)

Combined mass measurement





Assuming that we see one particle X, combine the mass measurements in two high resolution channels: H→4l and H→γγ

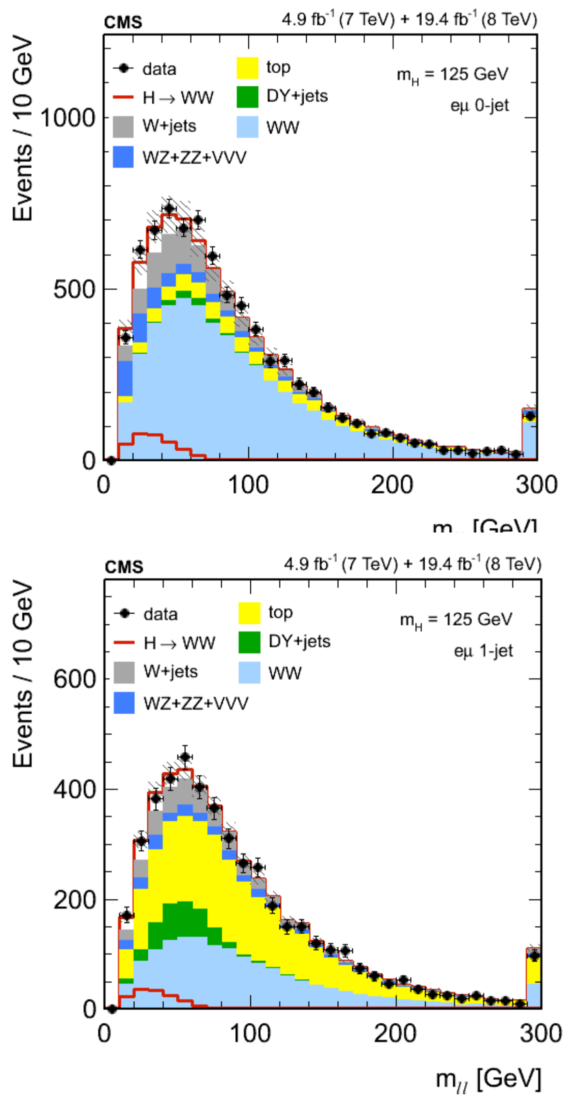
- **Two channels: compatible results (top plot)**

- letting relative event yields float free in the almost-model-independent fit (bottom plot):

  m_X = 125.7 ± 0.4 (0.3%) GeV

  = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

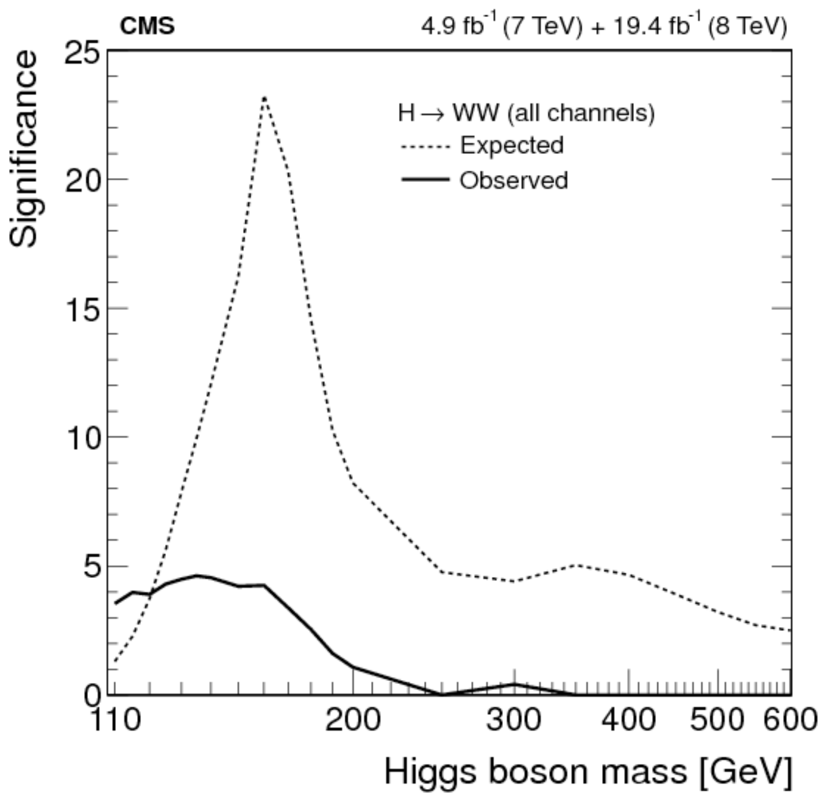
H → WW → lvlv (updated)

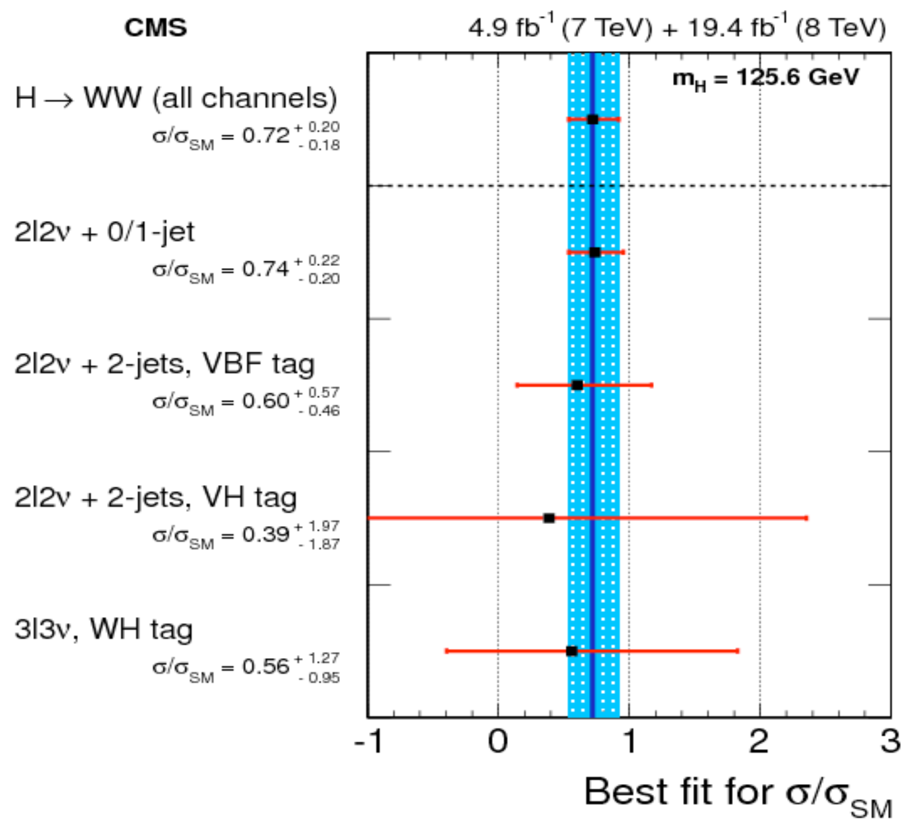


- Analysis strategy:
  - two prompt high-p_T leptons
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ
  - split events further into 0/1-jet
    - different S/B rates: ttbar in 1-jet
  - Add VBF and VH (recent updates)
  - Backgrounds (for low mass Higgs):
    - WW, tt, W+jets, DY+jets, Wγ: from control regions
    - ZW, ZZ: from MC (very small contribution)

- Analysis features:
  - OK S/B-ratio
  - fair signal event yield (200 events)
  - poor mass resolution ≈20%

$H \rightarrow WW \rightarrow 2l\ 2\nu$

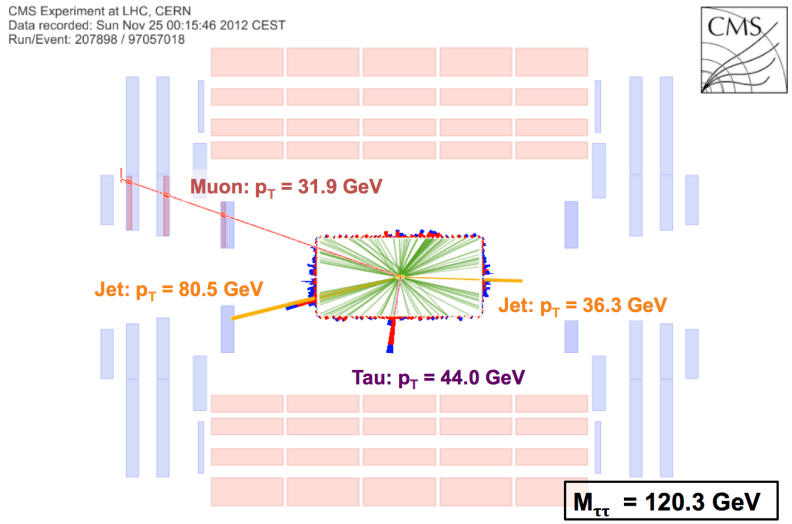


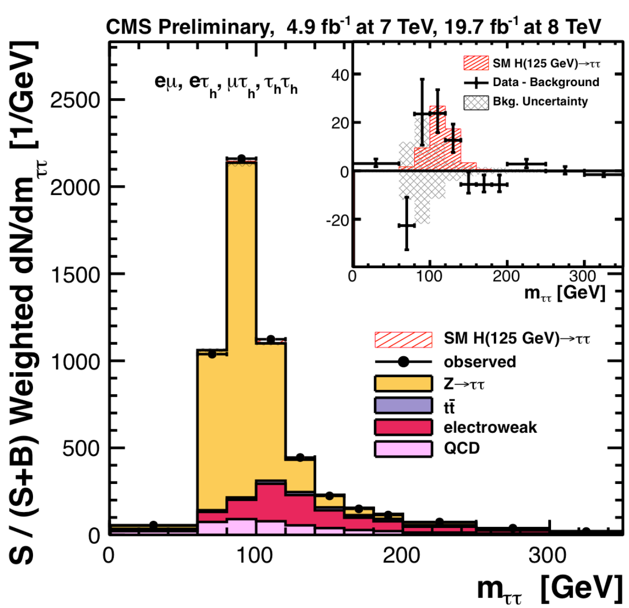


A 4.3σ significance observed at $m_H \sim 125.6$ GeV

σ/σ_{SM} signal strength: $0.72^{+0.20}_{-0.18}$

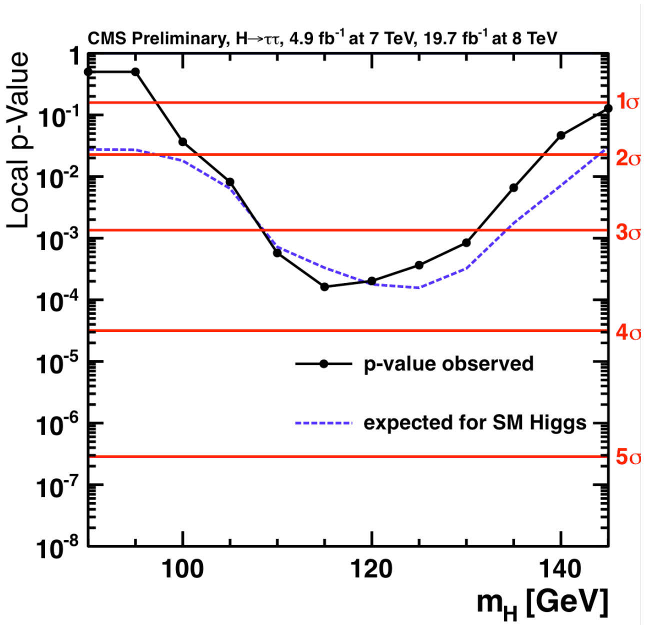
$H \rightarrow \tau\tau$ (updated)



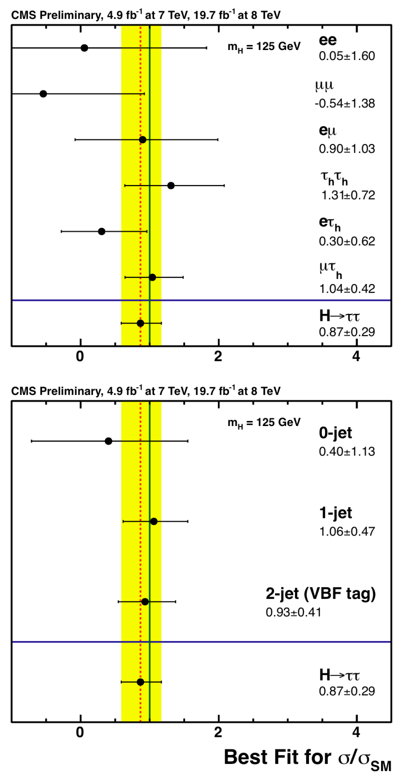


- Analysis strategy
  - $\tau\tau$ - candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, ee, $\tau_h\tau_h$
  - MET
  - $\tau\tau$ - mass (including MET): the key distribution
  - split events into jet categories (2,1,0 jets)
- Analysis features:
  - low S/B-ratio
  - small signal event yield
  - Higgs is on falling slope of Z-decays
  - poor mass resolution ≈15%

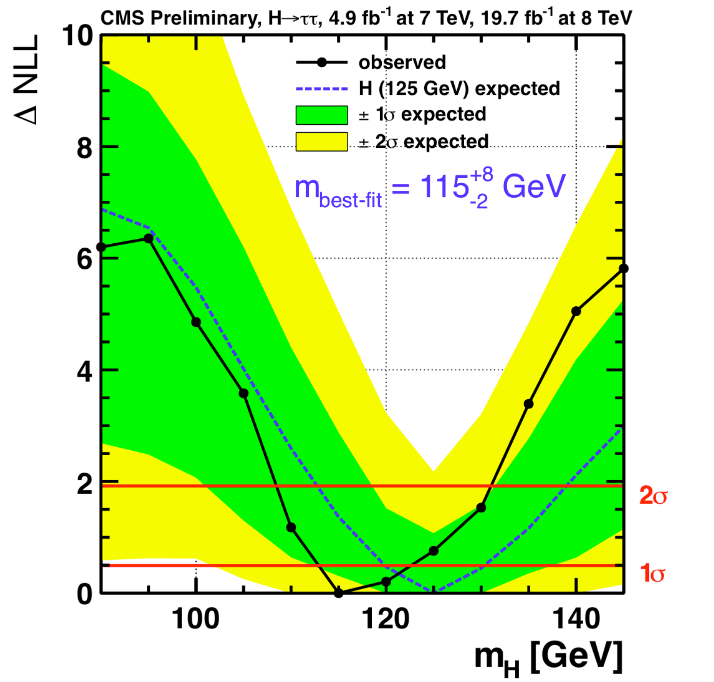
H → ττ: CMS results (updated)



Z_{obs} =3.4 σ (m=125 GeV)
Z_{exp} =3.6 σ (m=125 GeV)



$\mu = 0.87 \pm 0.29$
(m = 125 GeV)

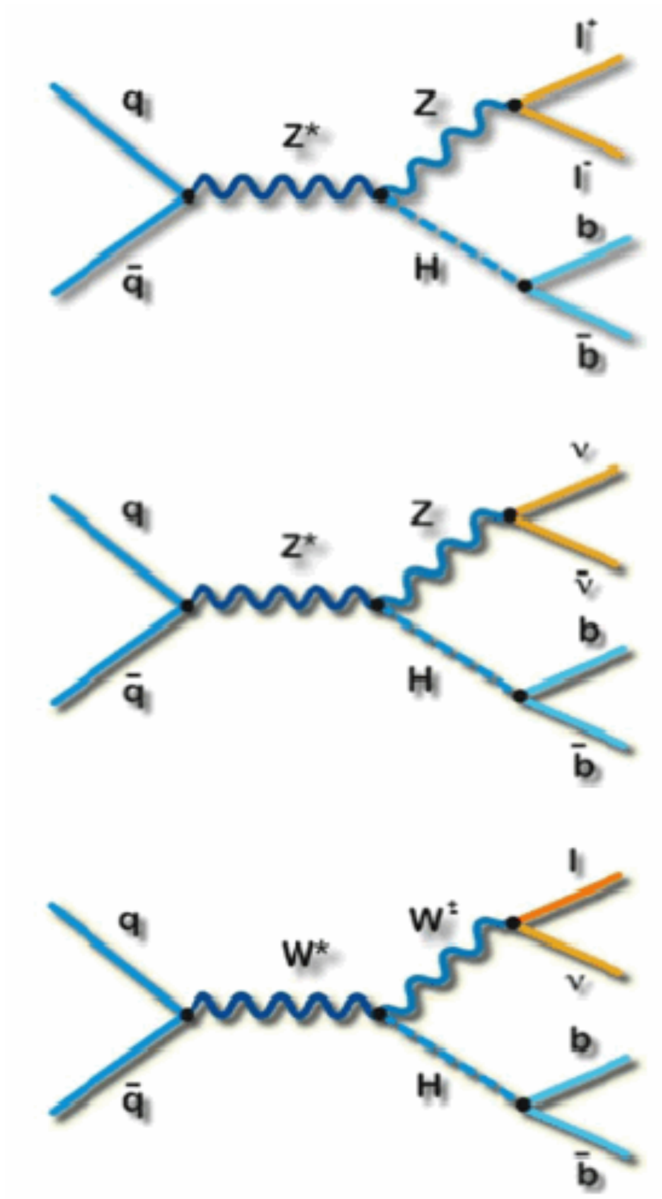


$m_X = 115^{+8}_{-2}$ GeV

Points to note:

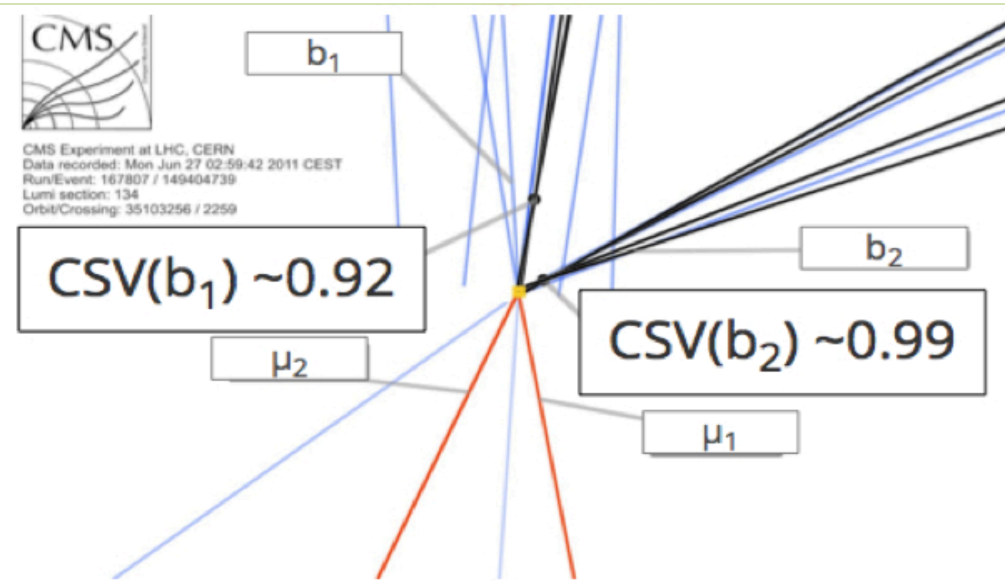
- broad access (poor mass resolution), consistent with SM Higgs rate
- > 3σ-sensitivity at 110< m <130 GeV
- despite poor mass resolution, the ττ-channel is not completely mass-blind

H→bb



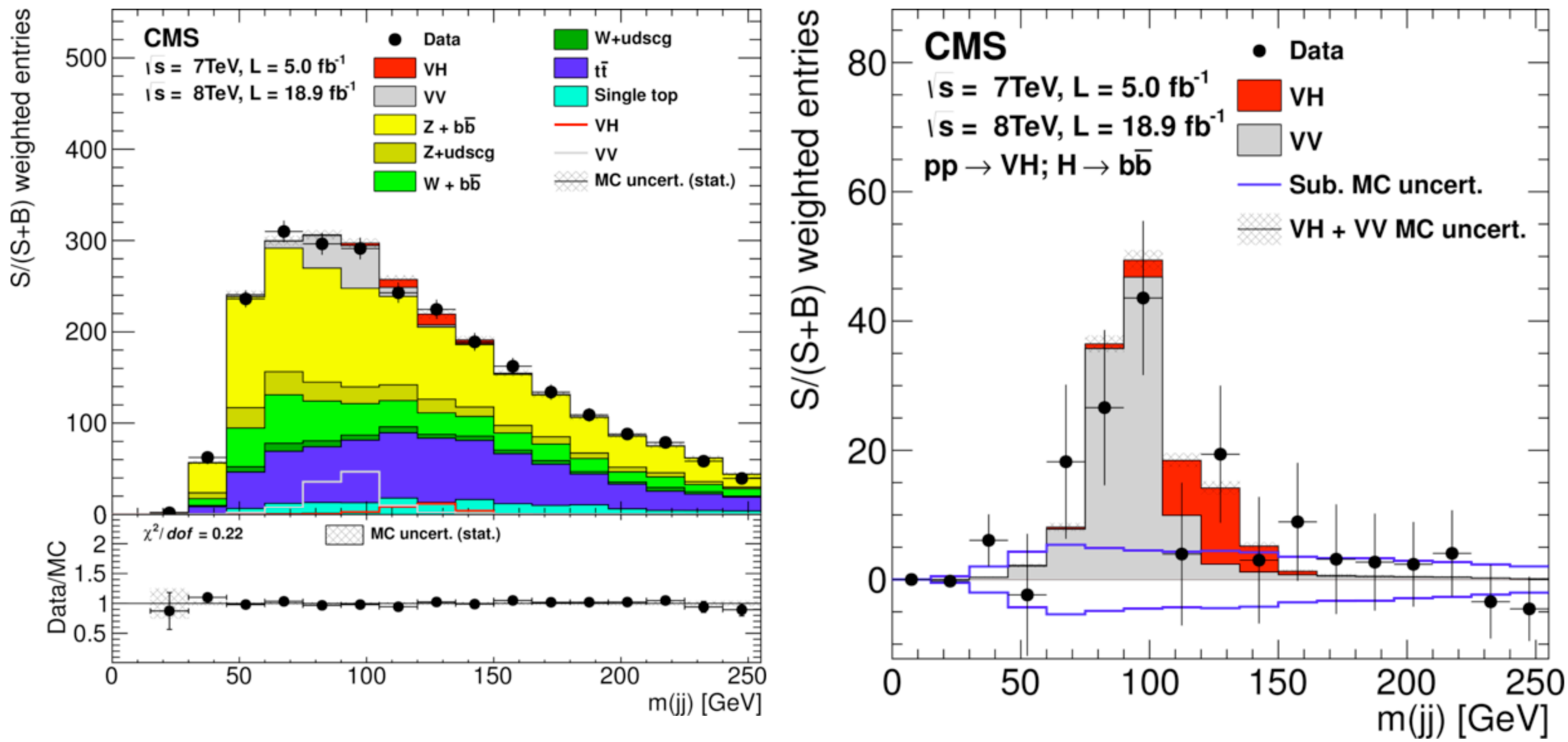
Analysis

- By far the largest number of Higgs decays
- But lots of QCD background (jets)
- Trigger based on leptons and missing E_T
- b-jets identified through displaced tracks
- Go to high p_T where Higgs is enhanced
- Main background W/Z+jets and top



H→bb (continuation)

M_{bb} for all categories and 7+8 TeV



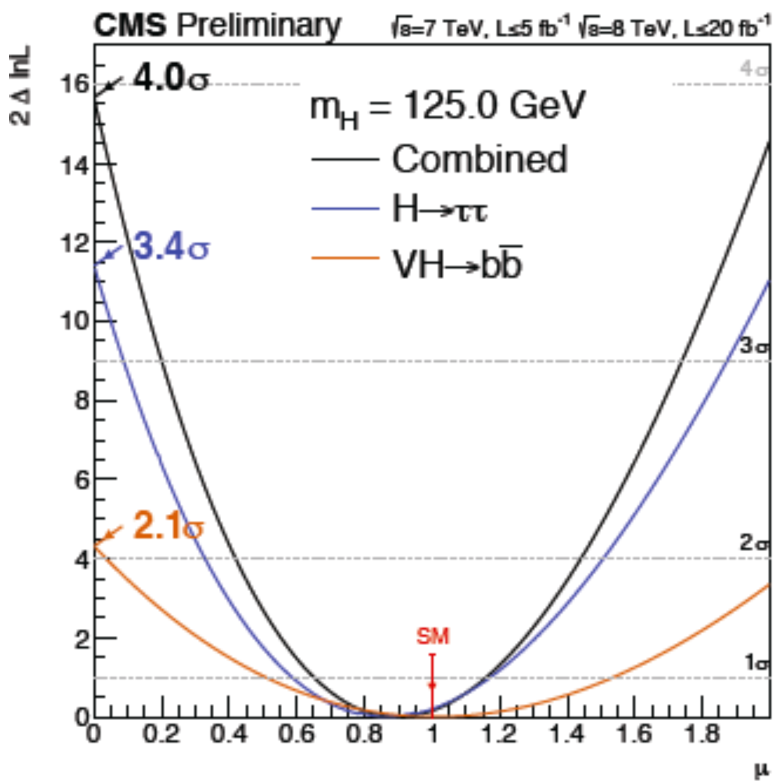
For 125 GeV:

- Significance = 2.1σ (2.1σ expected)
- Signal strength μ = 1.0± 0.5

H→ττ & H→bb combination @ 125 GeV

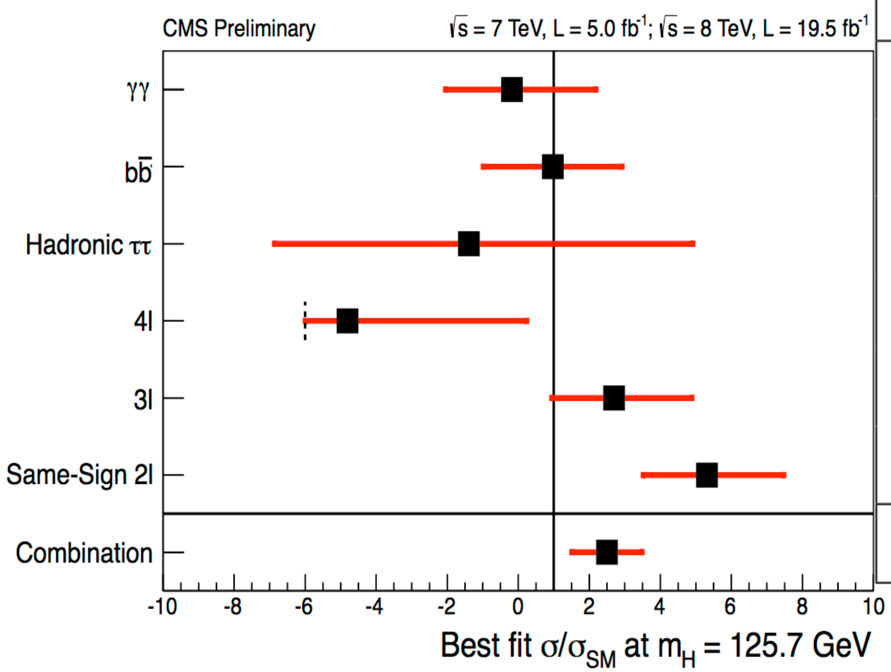
CMS Preliminary

Channel M_H= 125 GeV	Significance		μ
	Expected	Observed	
VH→bb	2.1 σ	2.1σ	1.0±0.5
H→ττ	3.6σ	3.4σ	0.87±0.29
Combination	4.2σ	4.0σ	0.90±0.26



Direct 4σ evidence for couplings
to the 3rd generation bottom-type fermions

ttH search update



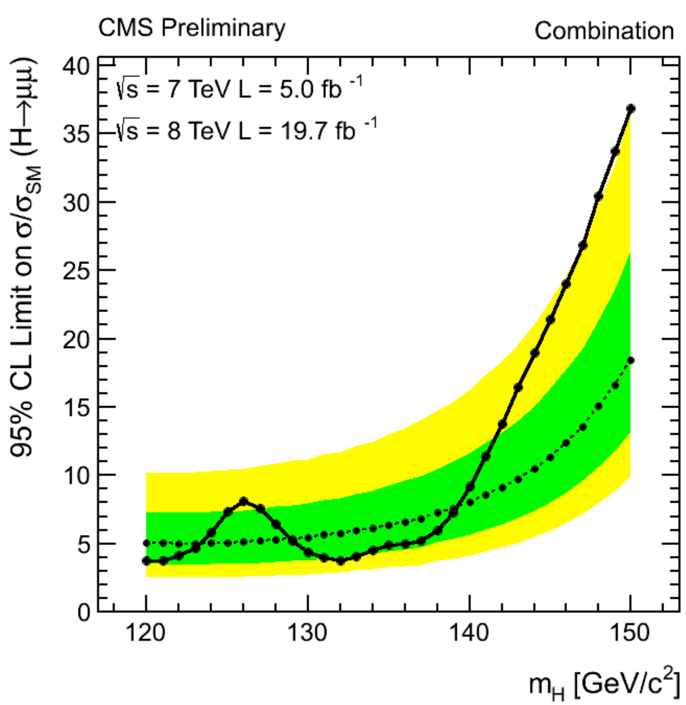
ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

Excess > 2 σ

direct experimental hint for coupling of H to top quarks

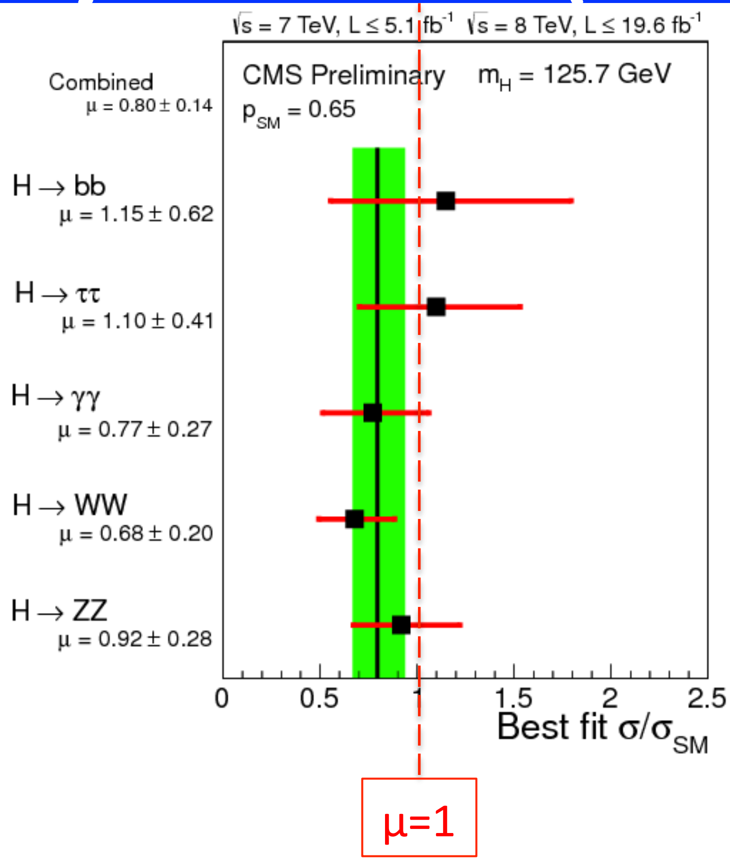
Search for H→μμ

- Small branching fraction in SM: 2.2×10^{-4} at m=125 GeV
- Compared with H→ ττ, is the most sensitive test for non-universality of H-couplings to 2nd and 3rd generations



- Observed limit: 7.4 SM
- Expected limit: 5.1 SM
- Contradicts universality of H couplings, when compared to observed evidence for H→ττ

Consistency of event yields in 5 main Higgs decay channels (March 2013)



CMS best-fit signal strength

$\mu = 0.80 \pm 0.14$

Production × Decay parameterization

8 independent parameters to describe all currently relevant decays and production mechanisms:

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

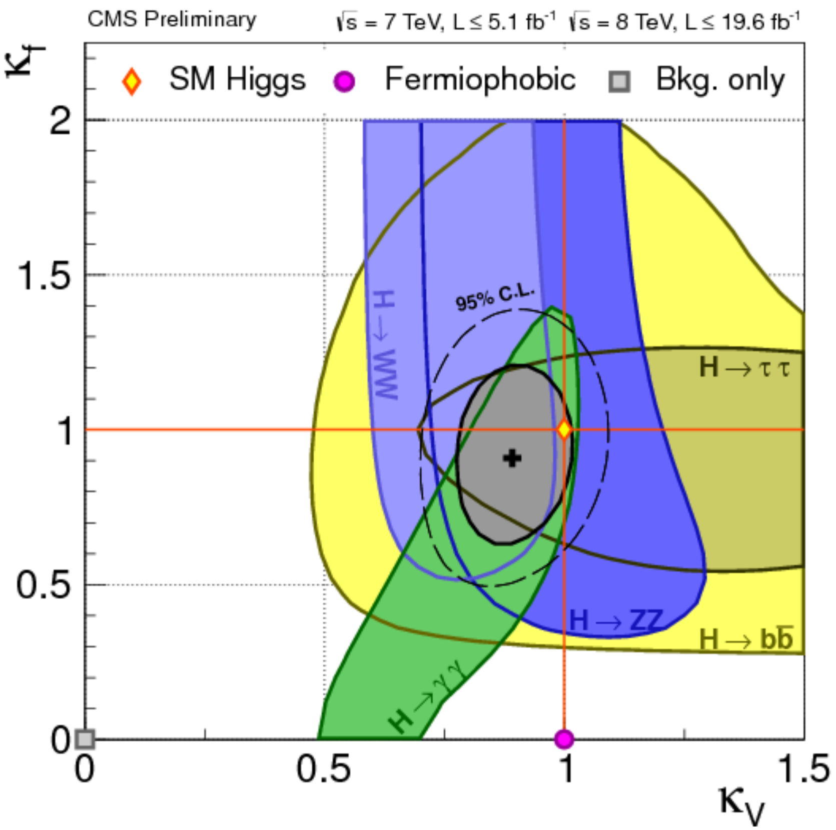
- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- Γ_{TOT} (including H → "invisible")
- Zγ and μμ still have too little sensitivity to affect anything in the combination

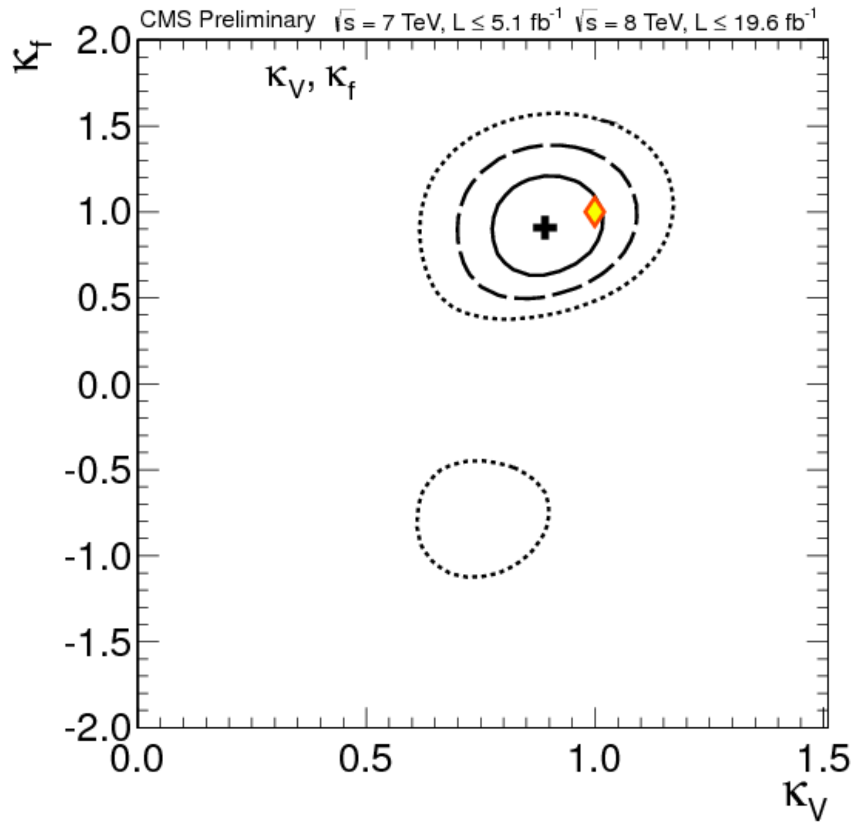
	untagged	VBF-tag	VH-tag	ttH-tag
WW	✔	✔	✔	
ZZ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
γγ	✔	✔	✔	

Introduce scaling factors *κ* w.r.t. the S/M Higgs couplings

Since statistics is small, will check compatibility with SM fitting smaller number than of couplings, making different assumptions

Two parameters: κ_V and κ_F (March 2013)

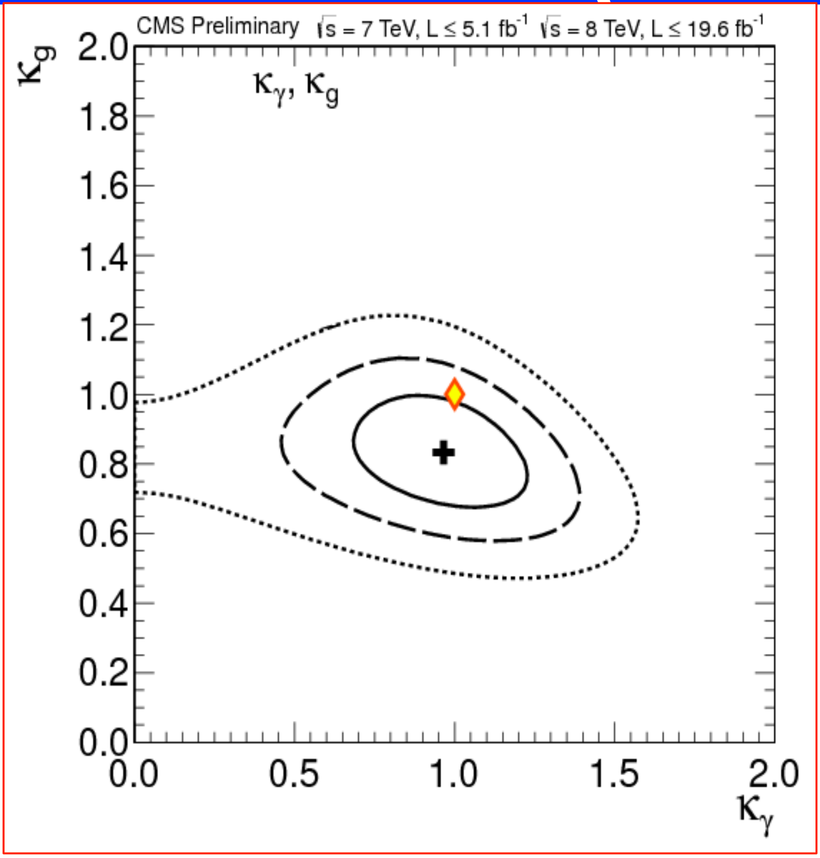




Data are consistent with $(\kappa_V; \kappa_F)=(1; 1)$

The local minimum of the likelihood in the (+; –) quadrant is not significant, since the γγ-channel is not enhanced compared to SM

Look for new physics in loops: κ_g and κ_γ (March 2013)



Two-parameter fit

– use all channels

– assume tree-level couplings = SM

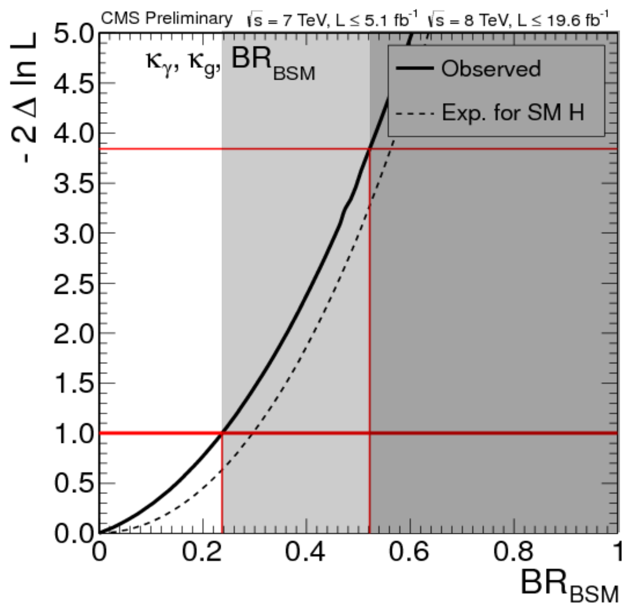
– assume BR(BSM)=0

– **Fit for:** κ_γ , κ_g

Data are consistent with (κ_γ; κ_g)=(1; 1)

Look for new physics: BR(BSM), κ_g , κ_γ

March 2013



Three-parameter fit:

BR(“invisible”), κ_γ , κ_g

– use all channels

– assume tree-level couplings = SM

– allow for BR(BSM) ≠ 0

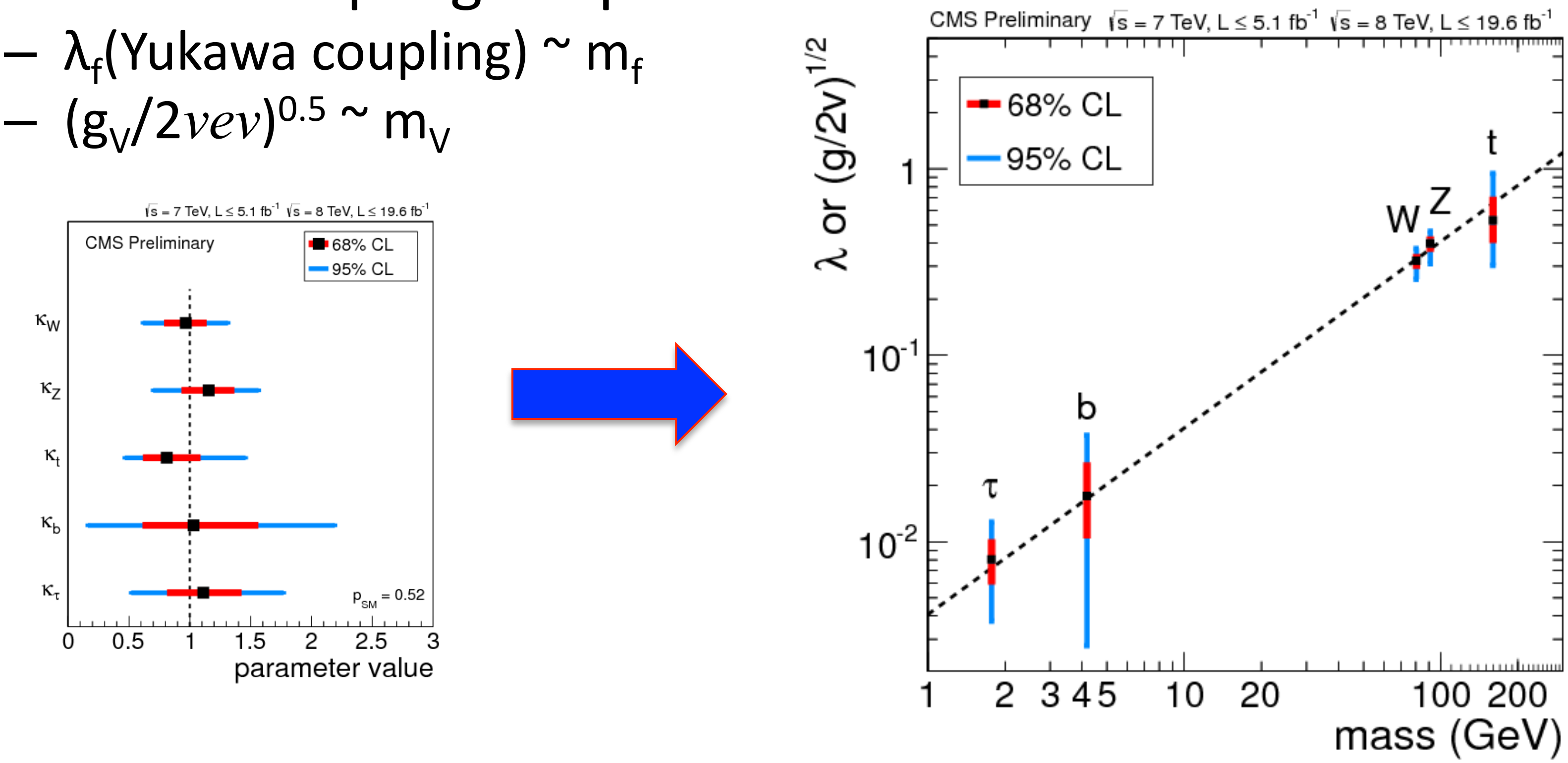
Conclusion:

Branching Ration for Invisible

H- decays < 52% at 95% CL

5 parameter model (March 2013)

- Scale SM couplings by measured scale factors, and plot modified couplings vs particle masses:
  - λ_f(Yukawa coupling) ~ m_f
  - $(g_V/2vev)^{0.5}$ ~ m_V



Note: the magnitude of couplings we assess range by a factor of 100!
Upper limit for the coupling in H→μμ is not on the plot, but is much lower, an evidence for the non-universality of H interactions with τ and μ (3rd and 2nd generations!)

Summary

- In a **combined search** for the SM Higgs boson in CMS, **a significant excess of events near m_H=126 GeV** observed
- The following decay channels contribute to the sensitivity: **ZZ, γγ, WW, ττ, bb**
- **New boson's mass as measured by CMS is: 125.7 ± 0.4 GeV**
- **Is X126 the SM Higgs boson?**
  - **event yields in all individual channels are consistent with the SM Higgs boson**
  - **100% pure $J^{CP} = 0^-$, $1^\pm$, 2^+_m states are excluded at >99% CL**
  - **couplings agree with the SM Higgs boson** with the current statistical accuracy
  - **H→μμ , compared to H→ττ, is an evidence for couplings non-universality**
  - **no significant modifications for loop-induced couplings (deviations < 2σ)**
  - **BR(H→BSM) < 0.5 at 95%CL**
- **Still a lot of room for deviation from the SM Higgs exists.**
- **The precision of the measurements in many cases is statistically dominated, and can be significantly improved in the future years**

Backup slides

ZZ->4L J^{CP} analysis: discriminants

- Analysis considers alternative signal+background hypotheses, where signal *X* can be either gg→H or *xx* → J^{CP}

  - Construct two ME-based discriminating observables:

    where *ME* are complete LO matrix elements, and $m_X = m_{4\ell}$

$$KD(\mathrm{H;ZZ}) = \frac{|ME_{\mathrm{H}}(gg \to H \to 4\ell)|^2}{|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)|^2}$$

$$KD(J^{CP};\mathrm{ZZ}) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2}{|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)|^2}$$

  - Extend KDs to include discriminating information from four-lepton mass:

$$D(H;\mathrm{ZZ}) = \frac{|ME_X(xx \to H \to 4\ell)|^2 \cdot pdf(m_{4\ell} | m_H)}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} | ZZ)}$$

$$D(J^{CP};\mathrm{ZZ}) = \frac{|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)|^2 \cdot pdf(m_{4\ell} | m_{J^{CP}})}{|ME_{ZZ}(q\bar{q} \to 4\ell)|^2 \cdot pdf(m_{4\ell} | ZZ)}$$

  - Without any loss of information, one can change "variables":

$$D(\mathrm{H;ZZ})$$

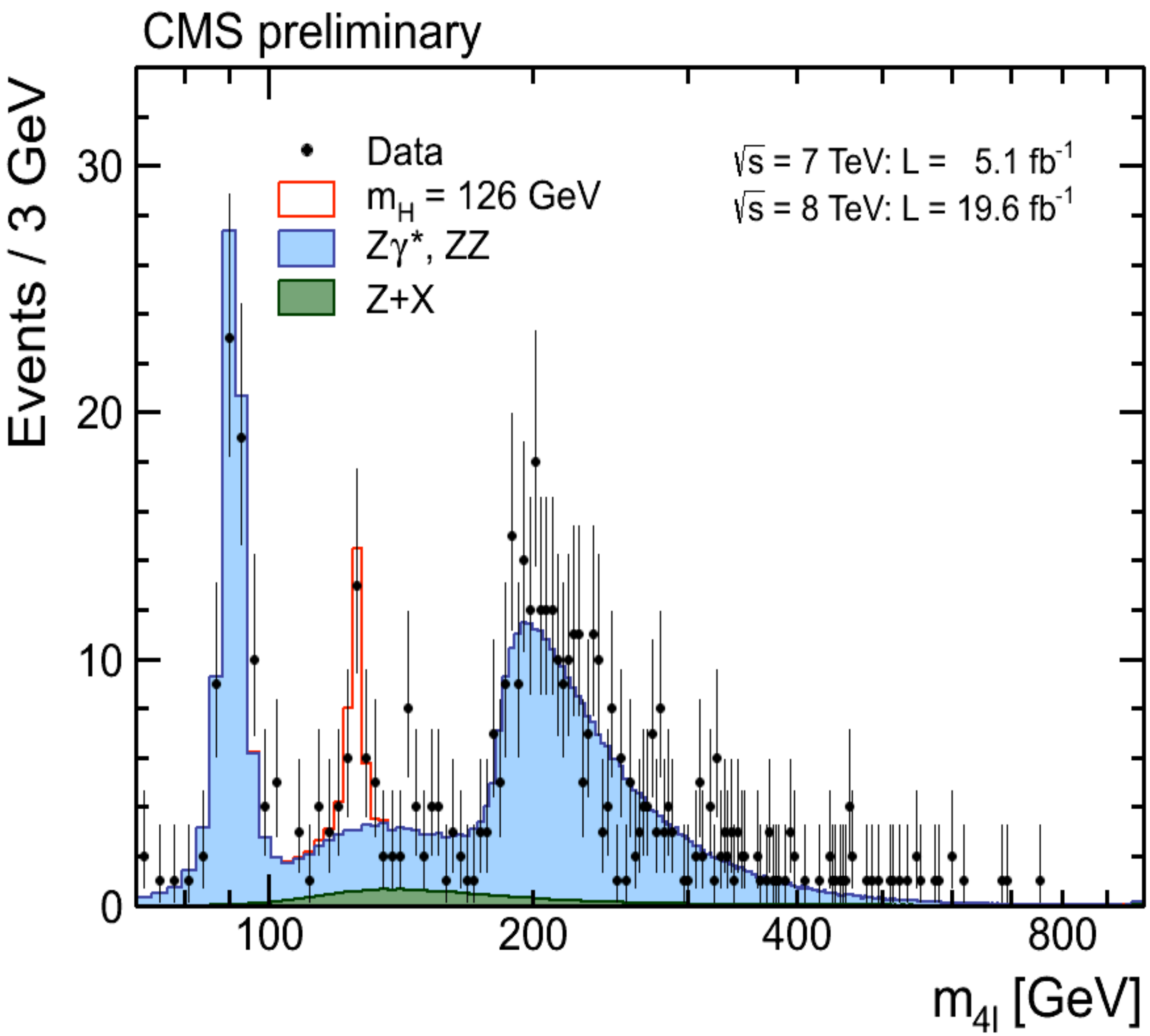
$$D(J^{CP};\mathrm{H}) = \frac{D(\mathrm{J^{CP};ZZ})}{D(\mathrm{H;ZZ})} = \frac{|ME_{J^{CP}}(xx \to \mathrm{J^{CP}} \to 4\ell)|^2}{|ME_{\mathrm{H}}(gg \to \mathrm{H} \to 4\ell)|^2}$$

  - And again without any loss of information, compress discriminants to be between 0 and 1

$$D_{bkg} = \frac{1}{1 + const \cdot D(\mathrm{H;ZZ})}$$

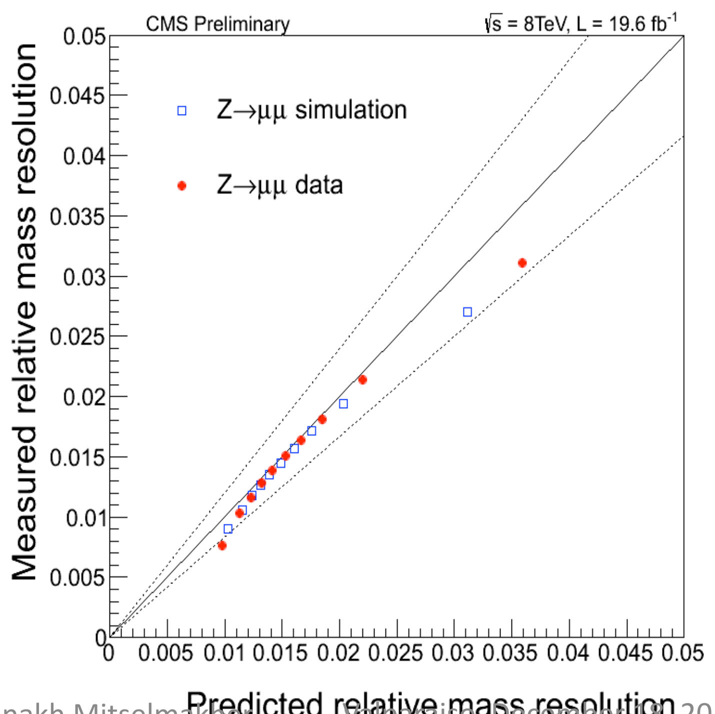
$$D_{J^{CP}} = \frac{1}{1 + const \cdot D(J^{CP};\mathrm{H})}$$

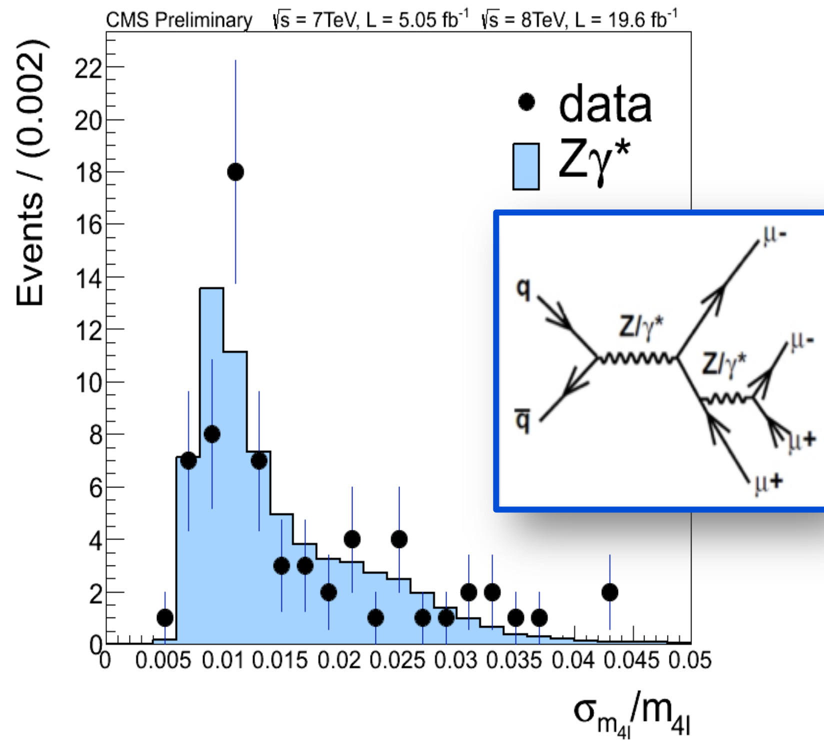
Full statistics in 4l channel, color-filled: SM background



Per-event mass errors

- To improve precision of the mass measurement, we estimate per-event mass uncertainty and KD
- Per-event mass uncertainty validated using Z→ll data
- Additional cross-check performed using the Z→4l decays:





Test statistics

Signal model parameters a (signal strength modifier μ can be one of them) are evaluated from a scan of the profile likelihood ratio $q(a)$:

$$q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, s(a) + b,\, \hat{\theta}_a)}{\mathcal{L}(\text{obs} \,|\, s(\hat{a}) + b,\, \hat{\theta})}, \tag{6}$$

Parameters $\hat{a}$ and $\hat{\theta}$ that maximize the likelihood, $\mathcal{L}(\text{obs} \,|\, s(\hat{a}) + b,\, \hat{\theta}) = \mathcal{L}_{\text{max}}$, are called the best-fit set. The 68% (95%) CL on a given parameter of interest a_i is evaluated from $q(a_i) = 1$ (3.84) with all other unconstrained model parameters treated in the same way as the nuisance parameters. The 2D 68% (95%) CL contours for pairs of parameters are derived from $q(a_i, a_j) = 2.3$ (6). One should keep in mind that boundaries of 2D confidence regions projected on either parameter axis are not identical to the 1D confidence interval for that parameter.

Fit for CP-odd contribution

- Perform a fit for the fraction f_{a3} of a CP-odd contribution in the observed peak

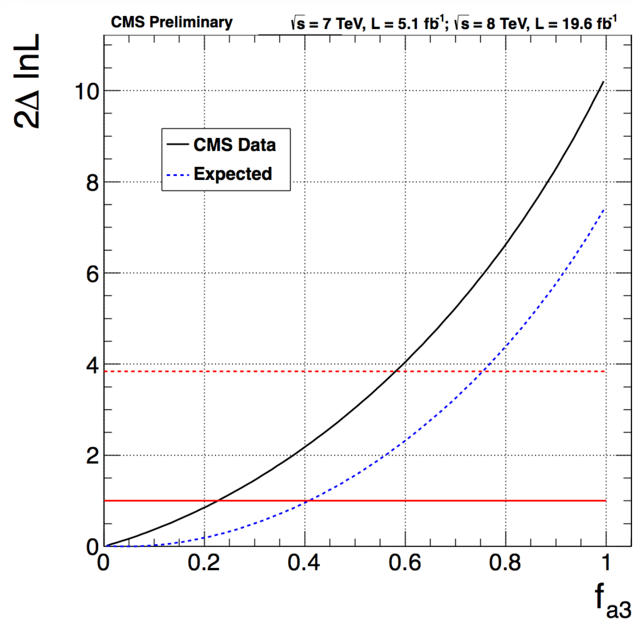
$$f_{a3} = \frac{|A_3^2|}{|A_1^2| + |A_3^2|}$$

$$A(X \to VV) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right) = A_1 + A_2 + A_3$$

(A2 contribution assumed to be 0)

  – decays of state 0_m^+ governed by the A1 amplitude
  – decays of state 0^- governed by A3 amplitude

- Fit the data for the ratio SM Higgs (A1) and 0- (A3) states
- Measurement of the f_{a3} fraction in data: **$f_{a3} = 0.00^{+0.23}_{-0.00}$**

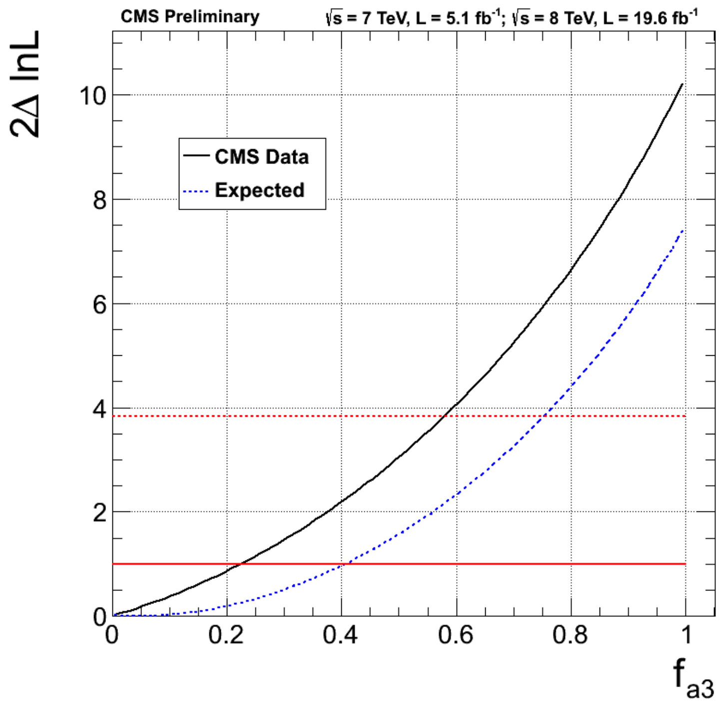


Is X126 one particle?

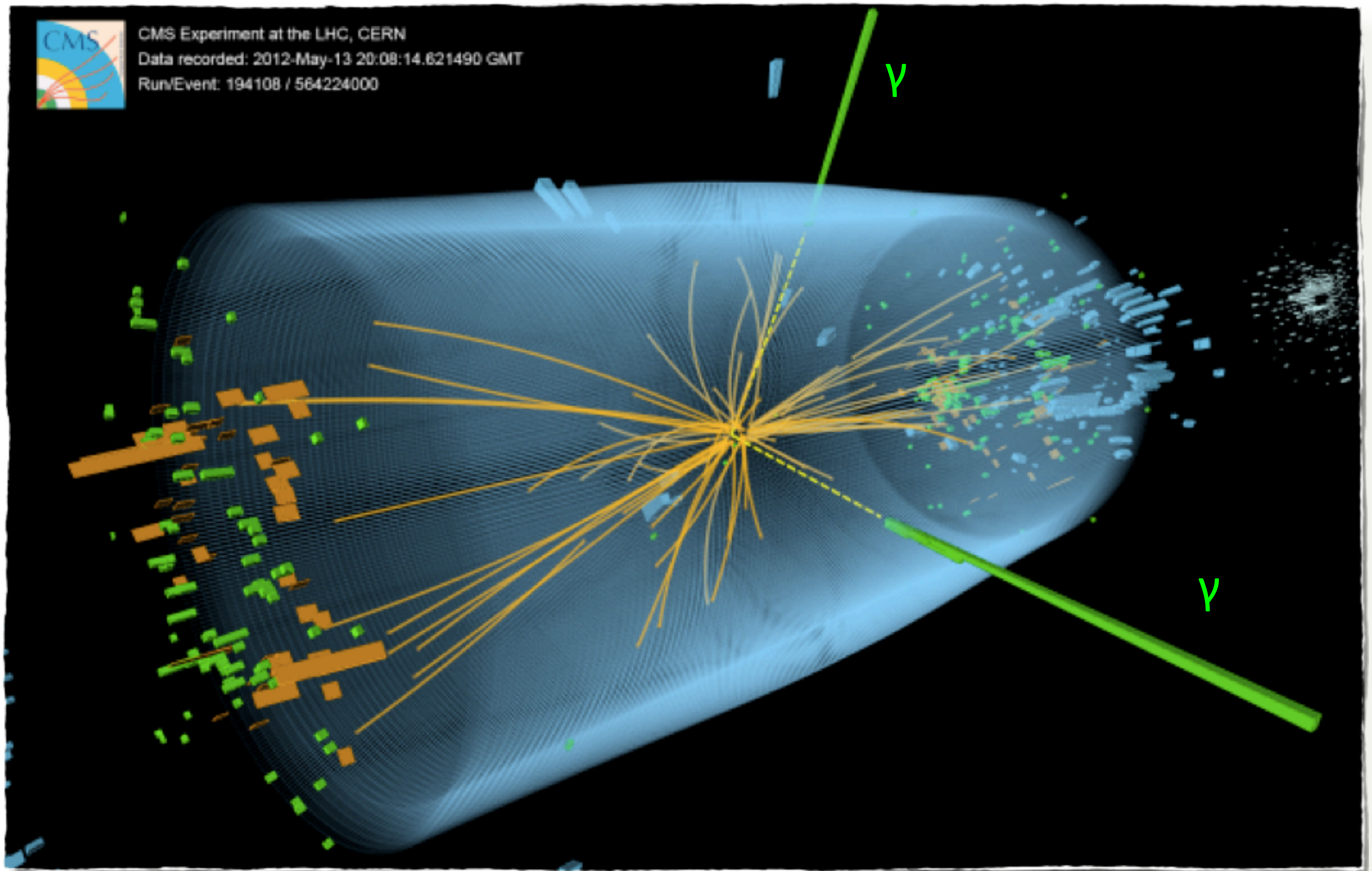
What if X126 is two bosons with near degenerate masses?

– What can we infer from kinematics of decays?
  - From the previous fit for CP-odd contribution **$f(0^-) < 0.58$ at 95% CL**
  - Non-zero $f(0^-)$ may be due to
    – a 0^- particle with a nearly the same mass;
    – a single particle $X = H(0^+) + A(0^-)$ with mixed CP-even/odd states

  - No public results on other $f(J^{CP})$ fractions



Event display H → γγ

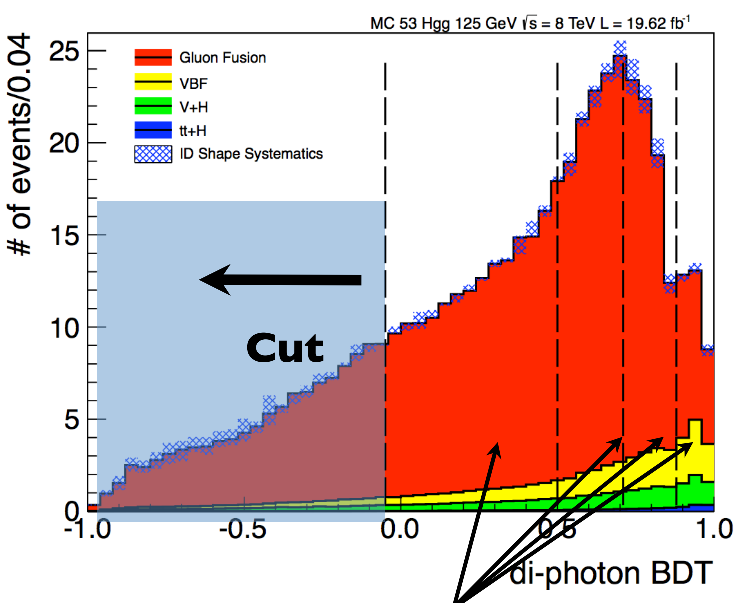


The decay H→ γγ

- Two inclusive analyses:
  - MVA: photons selected with an MVA. Variable in the MVA: photon kinematics, photon ID MVA score (shower shape, isolation), di-photon mass resolution. 4 MVA categories with different S/B
  - Cut-based: photons selected with cuts. 4 categories based on: γ in Barrel/Endcap, (un)converted γ. Each category has different mass resolution and S/B
- 3 VH channels (e, μ and MET tag) + VBF (2 dijet categories)

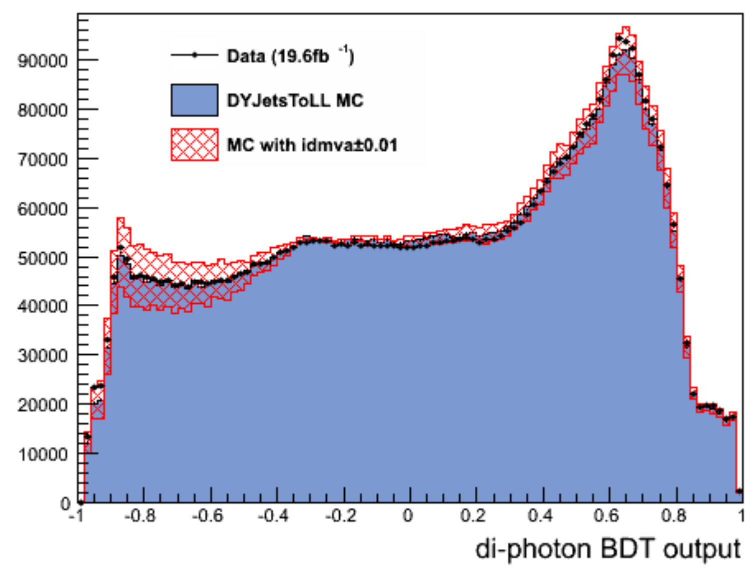
PRIMARY

CROSS-CHECK



MVA Event categories

Output of the MVA validated using Z→ee (where e are reconstructed as γ)



LHC in 2015

Potential performance

	Number of bunches	Ib LHC FT[1e11]	Collimator scenario	Emit LHC (SPS) [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2760	1.15	S1	3.5 (2.8)	9.2e33	21	24
25 ns low emit	2320	1.15	S4	1.9 (1.4)	1.6e34	43	42
50 ns	1380	1.6	S1	2.3 (1.7)	1.7e34 level 0.9e34	76 level 40	~45*
50 ns low emit	1260	1.6	S4	1.6 (1.2)	2.2e34	108	...

- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics, HF = 0.2
- 70 mb visible cross-section
- * different operational model – caveat - unproven

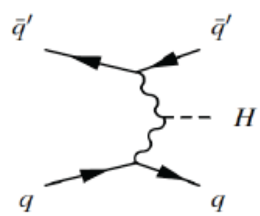
All numbers approximate

LHCP 2013
Sergio Bertolucci CERN

Tagging Vector-Boson Fusion: separation of production diagrams

To have sensitivity to couplings of the new particle with vector bosons, as well as with fermions, we split events into two categories:

1) Di-jet tag (sensitive to coupling with vector bosons):
PT > 30 GeV, |n| < 4.7; Jet ID to reject fake jets from pileup



2) Untagged (majority of events, sensitive to couplings with fermions)