GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

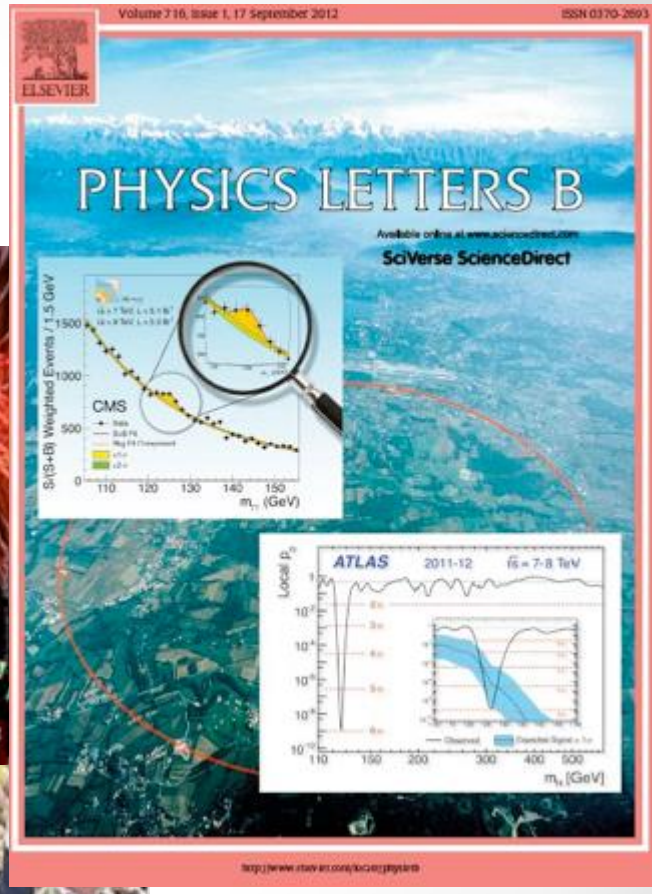
CMS (Higgs) Results

Begoña de la Cruz (CIEMAT, Madrid)

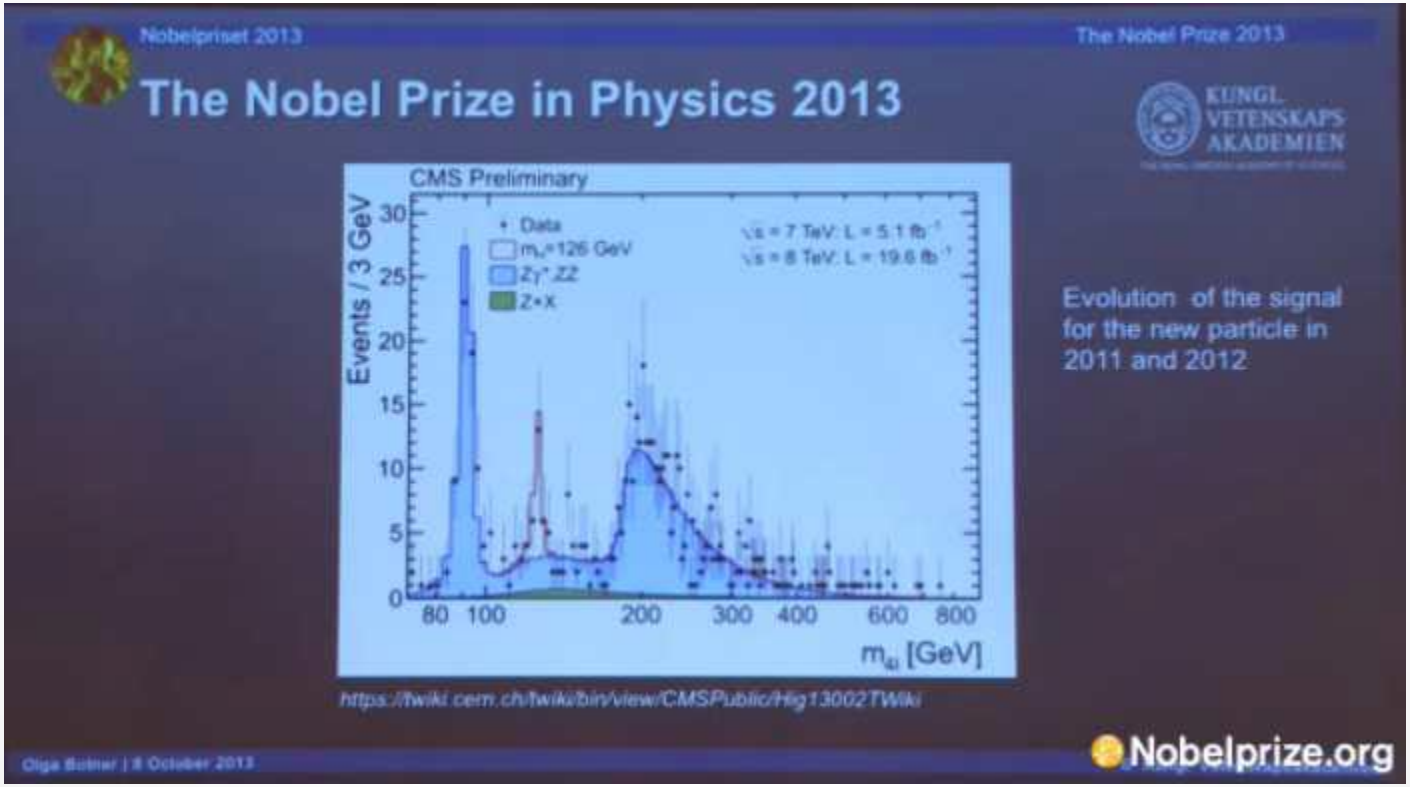
On behalf of CMS Collaboration

APC 2013 - IFT/UAM (Oct 21st, 2013)

Discovery…



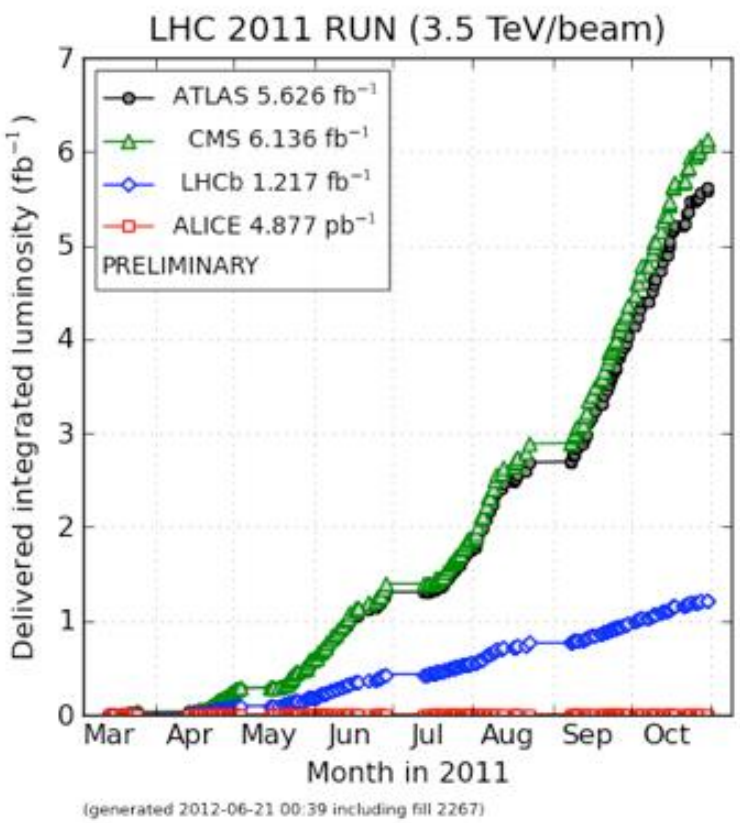
Phys. Lett. B 716 (2012) 30

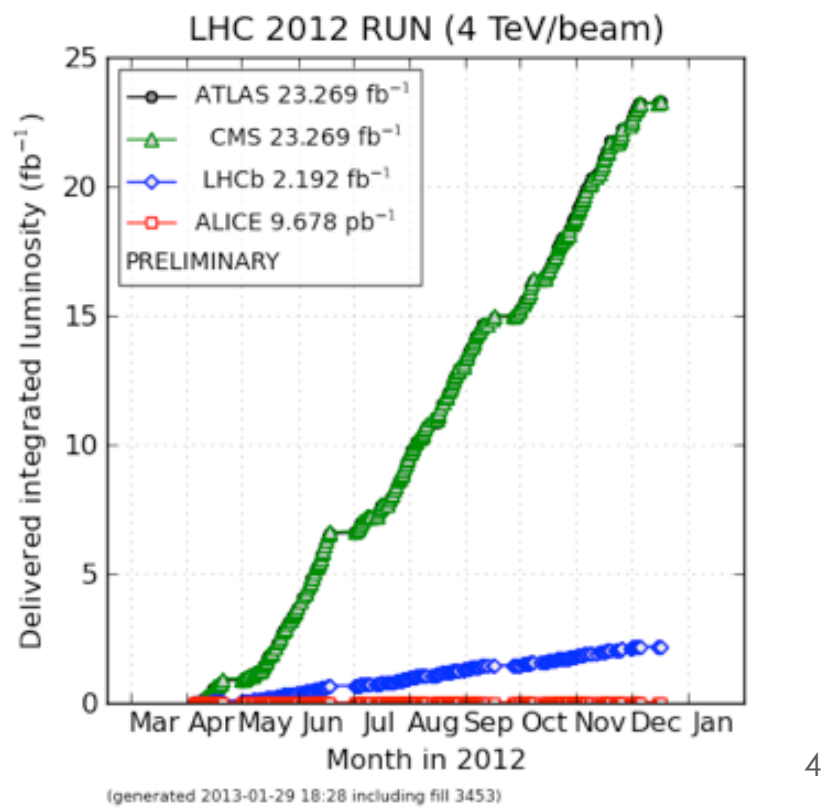


https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsHIG/HZZ4l_date_animated.gif

LHC Operation

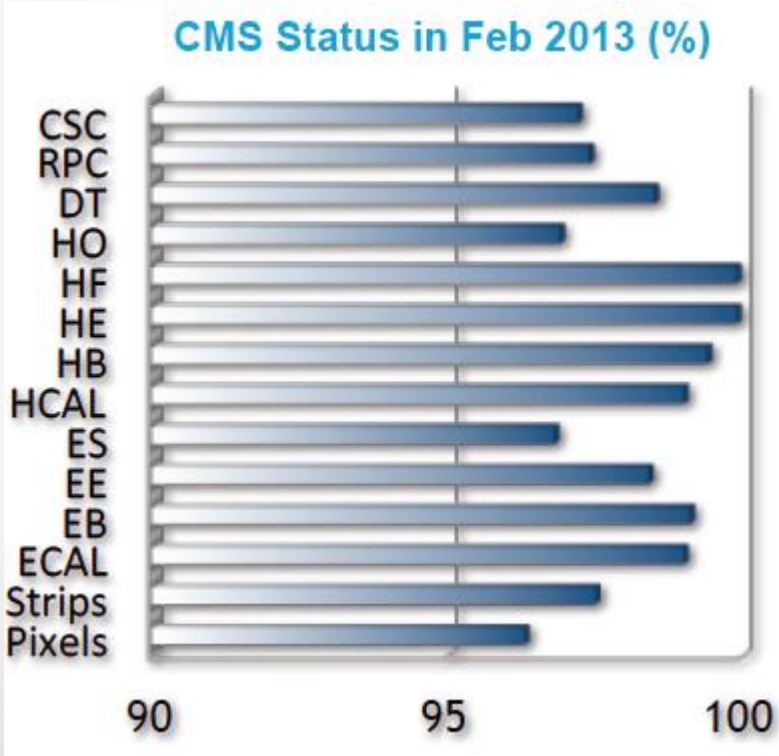
- Incredible 3 years of LHC operation, continuously beating luminosity records, L_{int} ~30/fb delivered
- Providing increasing fraction of data used for physics

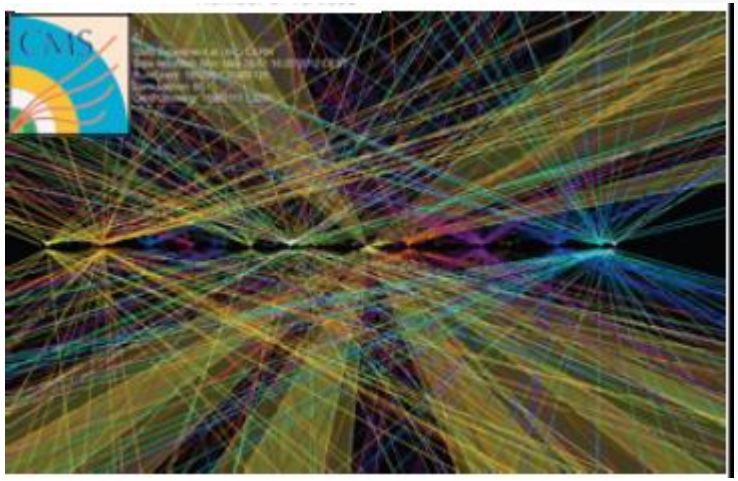


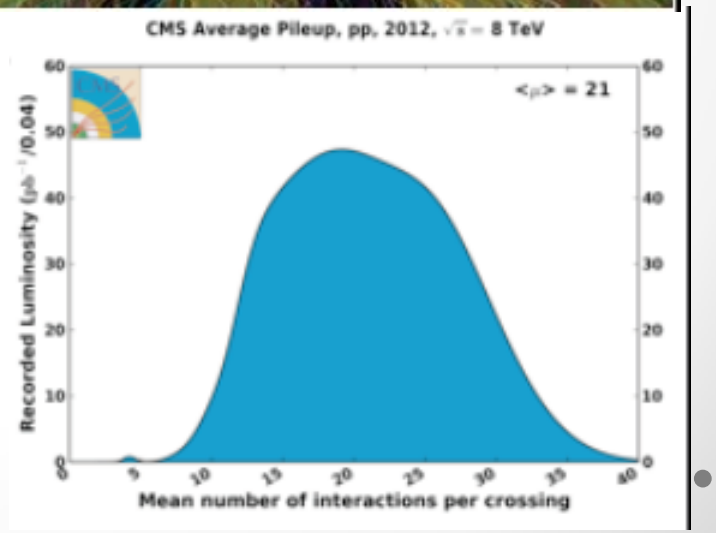


CMS detector operation

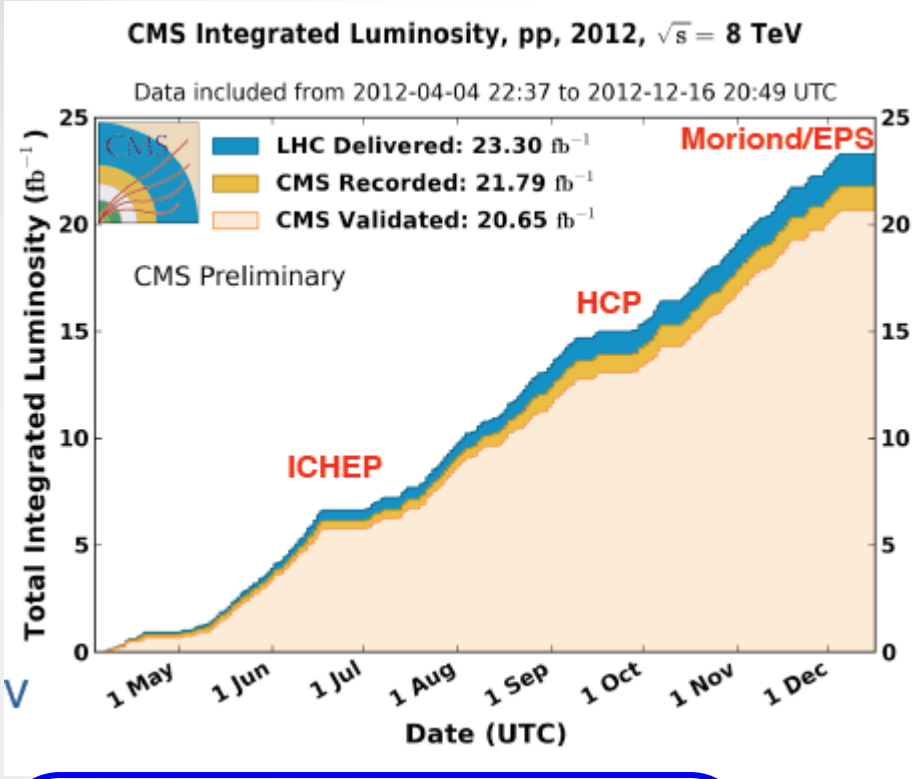
- Excellent performance of subdetectors during the 3 years
- Despite the hostile conditions of nominal pile up rate reached





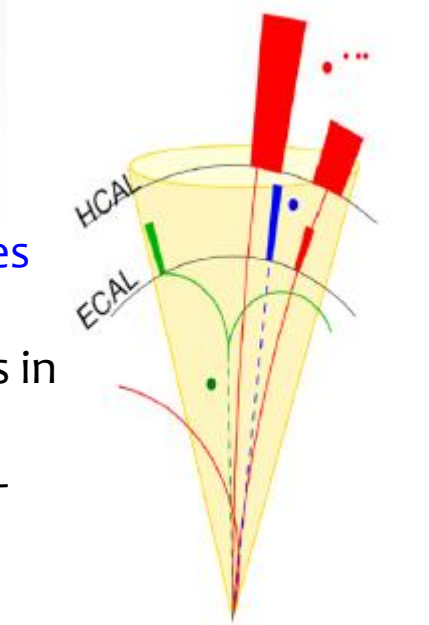


CMS data collected in 2012



Particle Flow reconstruction tecniques

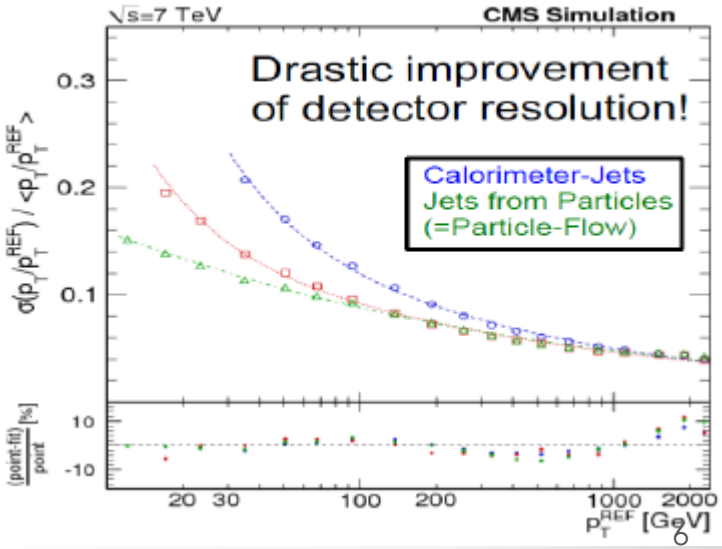
Reconstruct all particles in detector volume
Combine info from sub-detectors



Total certified good data set

- 5.32 fb^{-1} @ $\sqrt{s}$ = 7 TeV
- 20.65 fb^{-1} @ $\sqrt{s}$ = 8 TeV

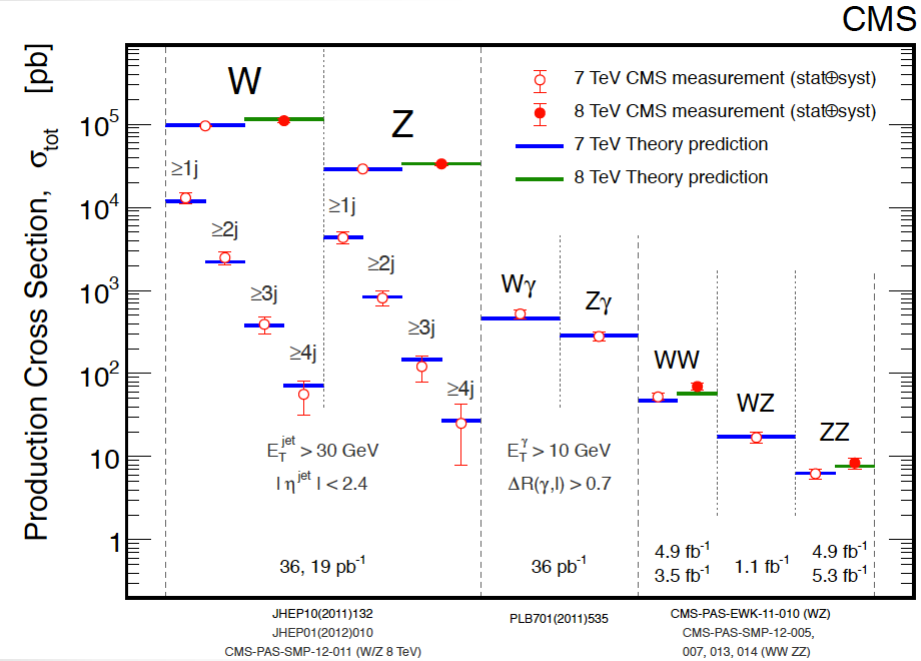
~88% of delivered luminosity



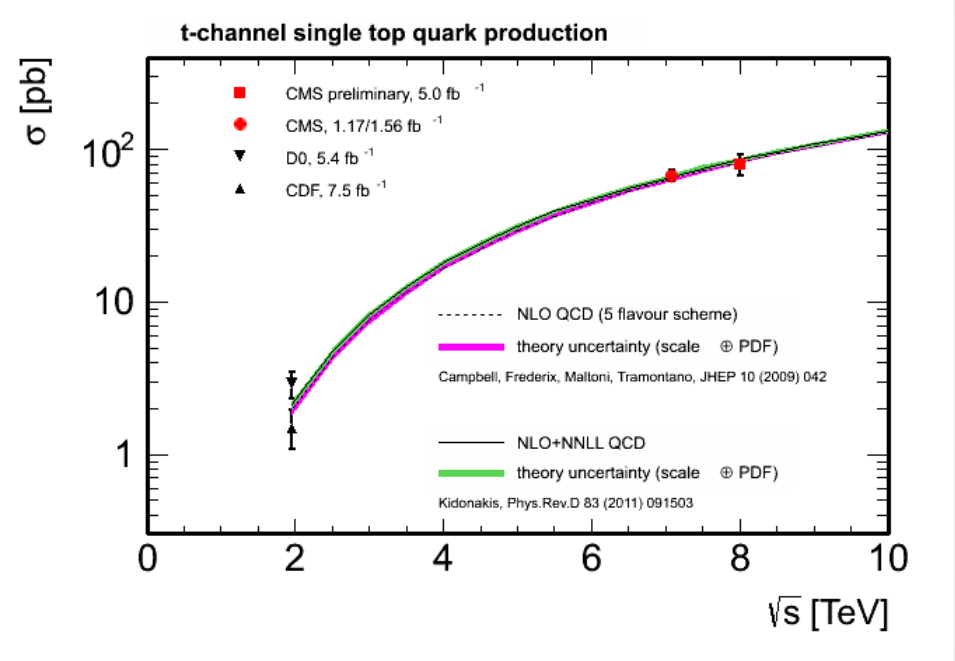
Result of enormous effort

Precise SM measurements

Boson production



Single top quark production



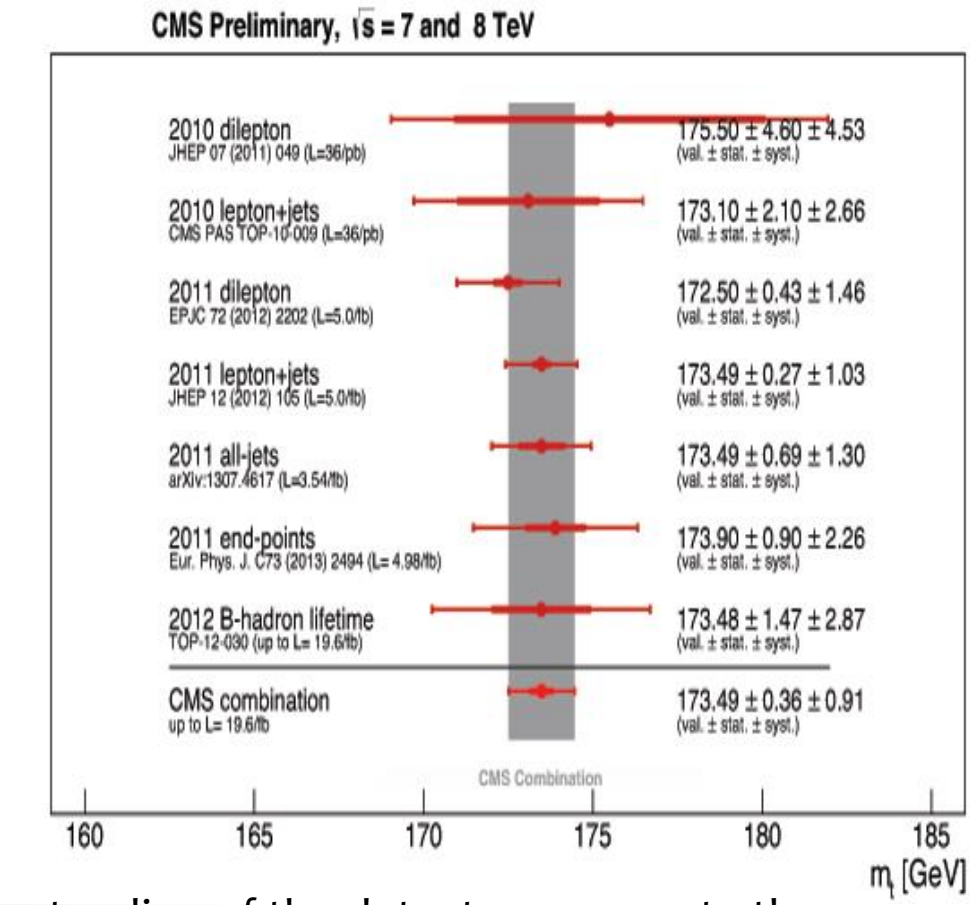
Good understanding of the detector + accurate theory predictions

- Precise measurements of the SM processes over many orders of magnitude
- Good knowledge of the background to Higgs analyses

Top mass

CMS TOP-13-002

Important to measure top mass accurately, reducing uncertainties (also theoretical)



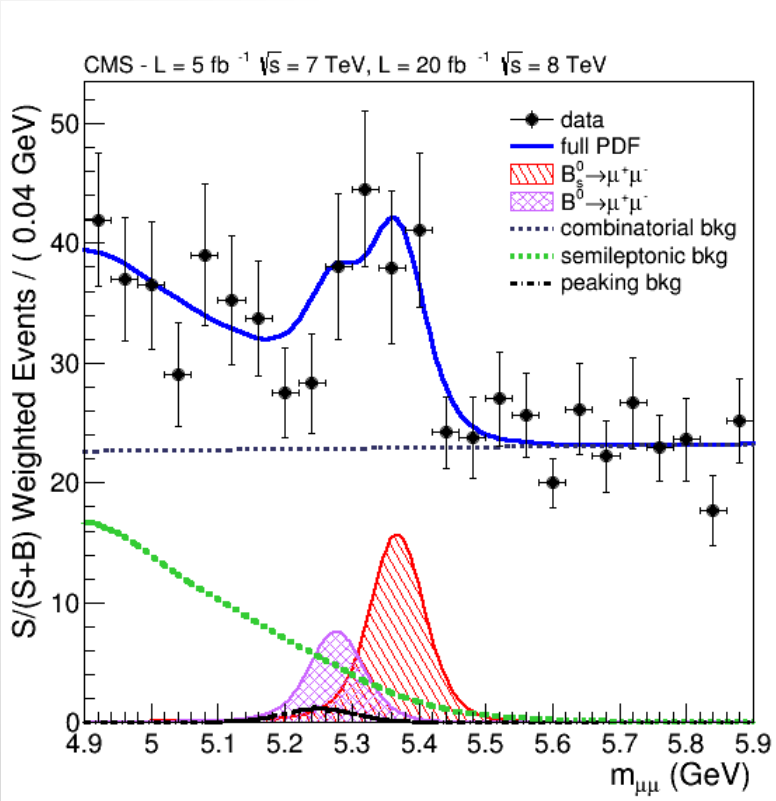
Good understanding of the detector + accurate theory predictions

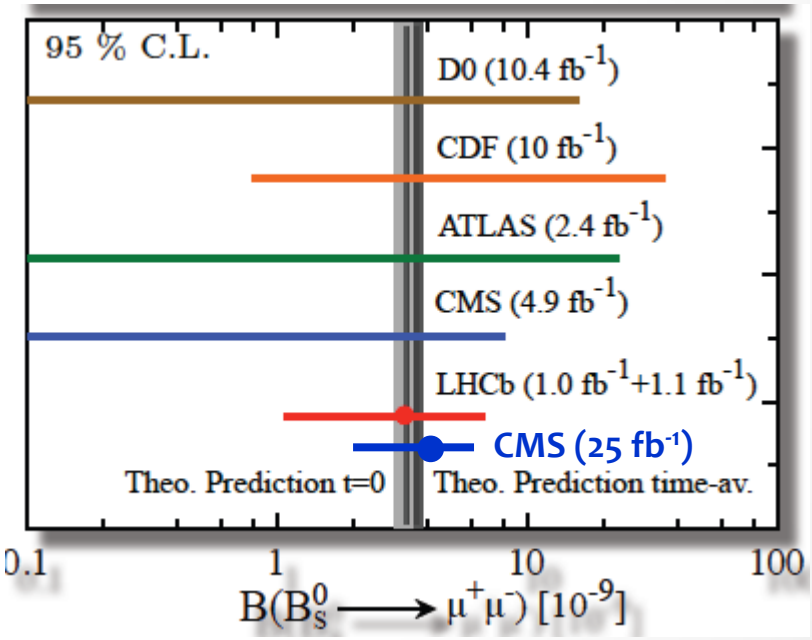
- Precise measurements of the SM processes over many orders of magnitude
- Good knowledge of the background to Higgs analyses

$B_s \to \mu\mu$

PRL 111 (2013) 101804

- Quest for many years to find a deviation of the SM prediction is coming to an end
- Evidence (and measurement) of decay, consistent with SM
- No sign of new physics on this front



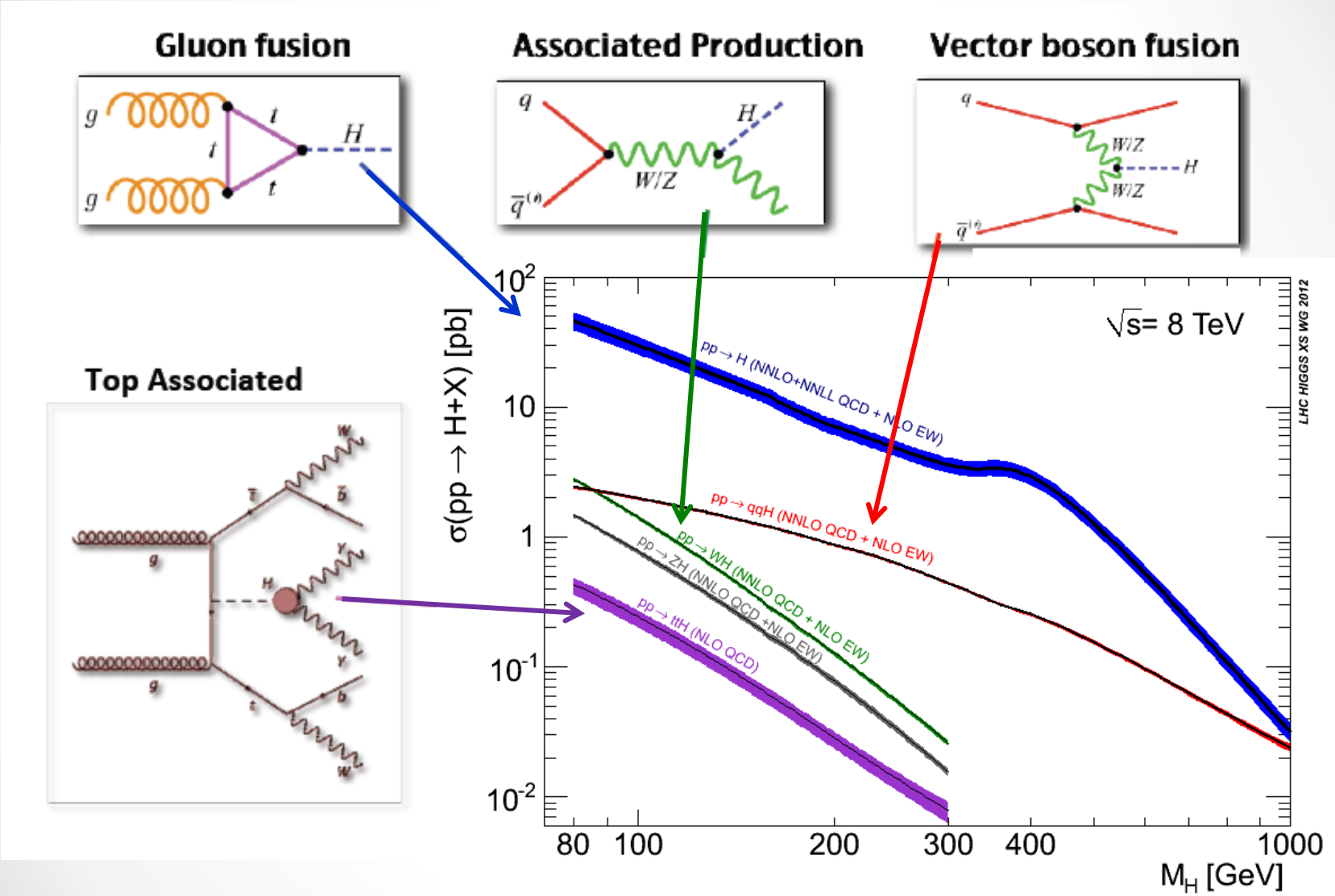


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$$

Higgs story

Standard Model Higgs Production

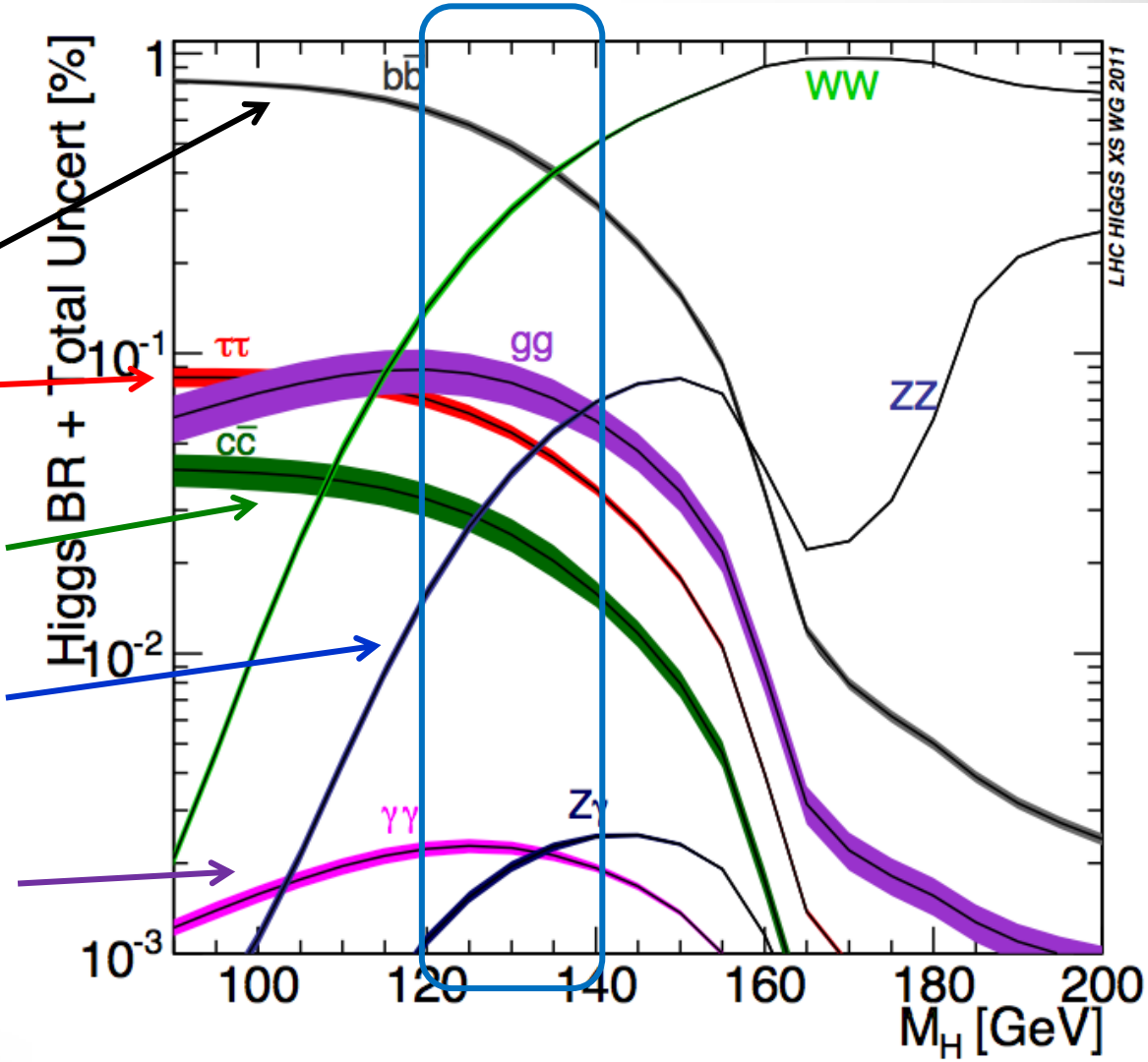


Important input provided by LHC Higgs Working Group :

- Theory predictions and their uncertainties

Standard Model Higgs Decay

Exp. Sig. 125.7 GeV	σ_M/M	
2.2σ	10%	H → bb
2.7σ	15%	H → ττ
5.1σ	20%	H → WW
7.1σ	1-2%	H → ZZ
4.2σ	1-2%	H → γγ



Signatures explored at CMS

Production Modes

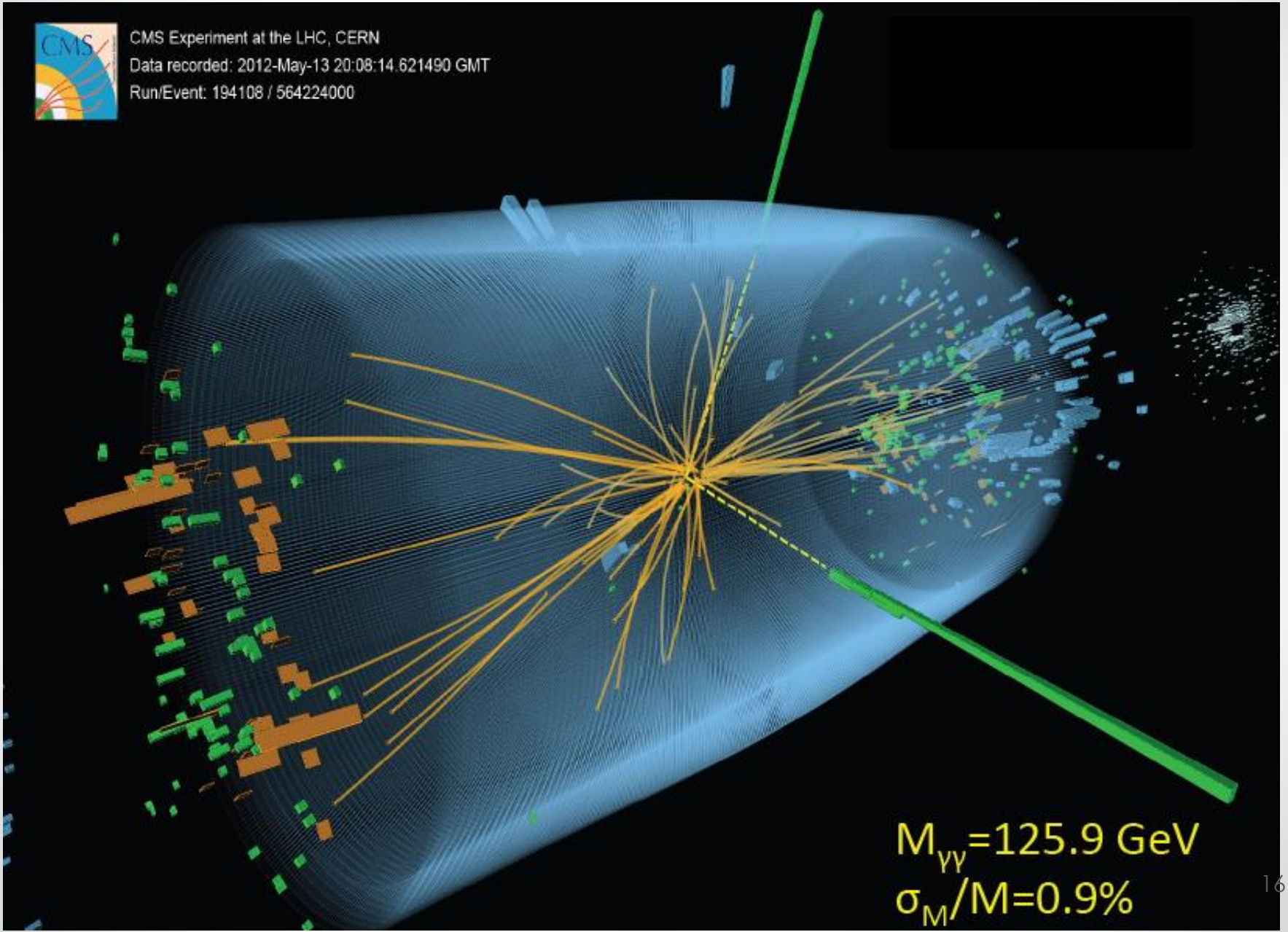
Decay Modes	incl. (ggH)	VBF tag	VH tags	ttH tag
bb		✔	✔	✔
ττ	✔	✔	✔	✔
WW	✔	✔	✔ (3ℓ, Vjj)	✔
ZZ	✔	✔		✔
γγ	✔	✔	✔	✔
Zγ	✔	✔		
μμ	✔	✔		
invis.		✔	✔	

✔= full 8 TeV dataset analyzed, often full 7 TeV too.

Higgs Couplings to Vector Bosons

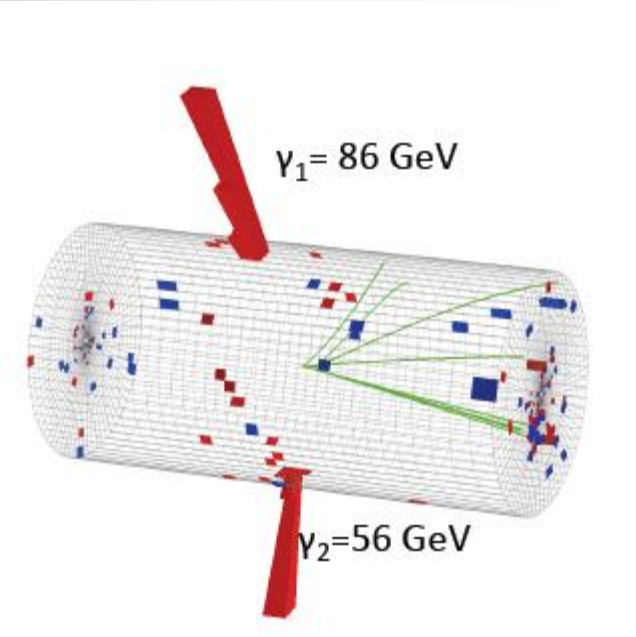
Indications of role in EWK Symmetry breaking

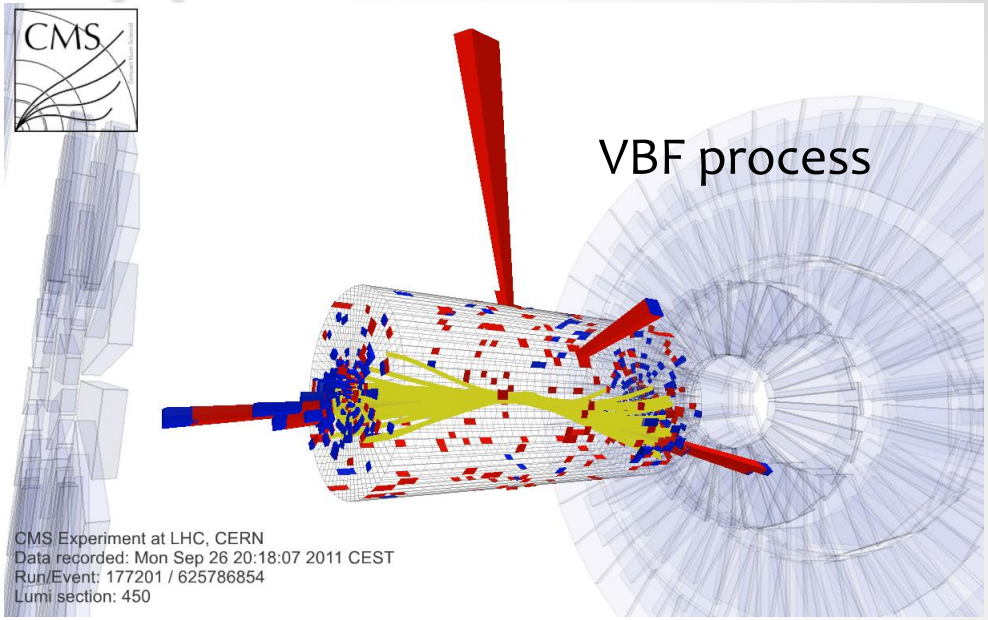
$H \rightarrow \gamma\gamma$



$H \rightarrow \gamma\gamma$

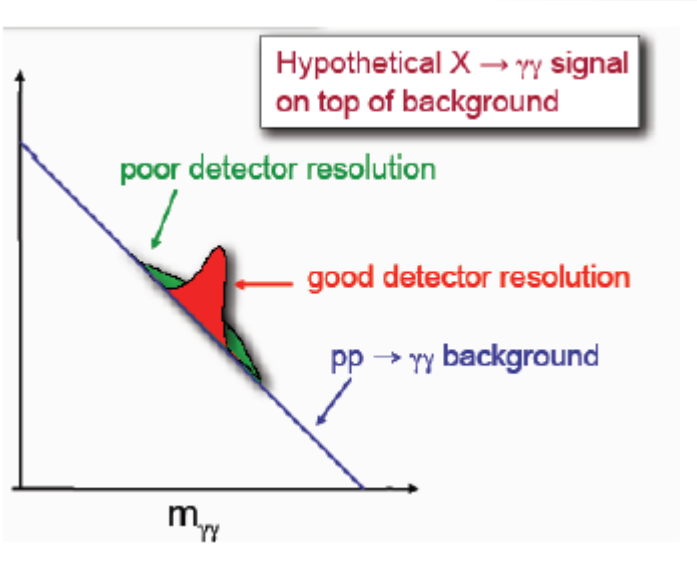
CMS HIG-13-001



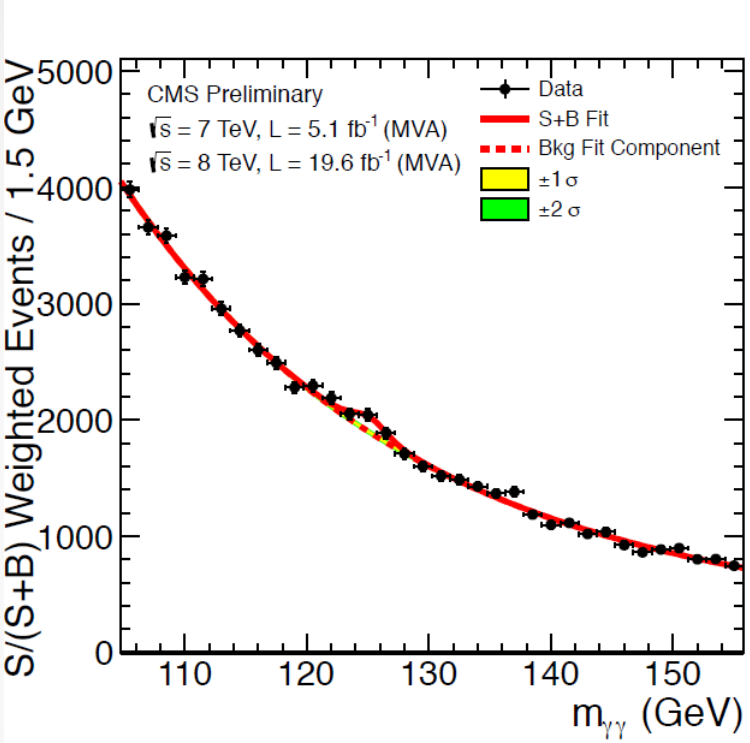


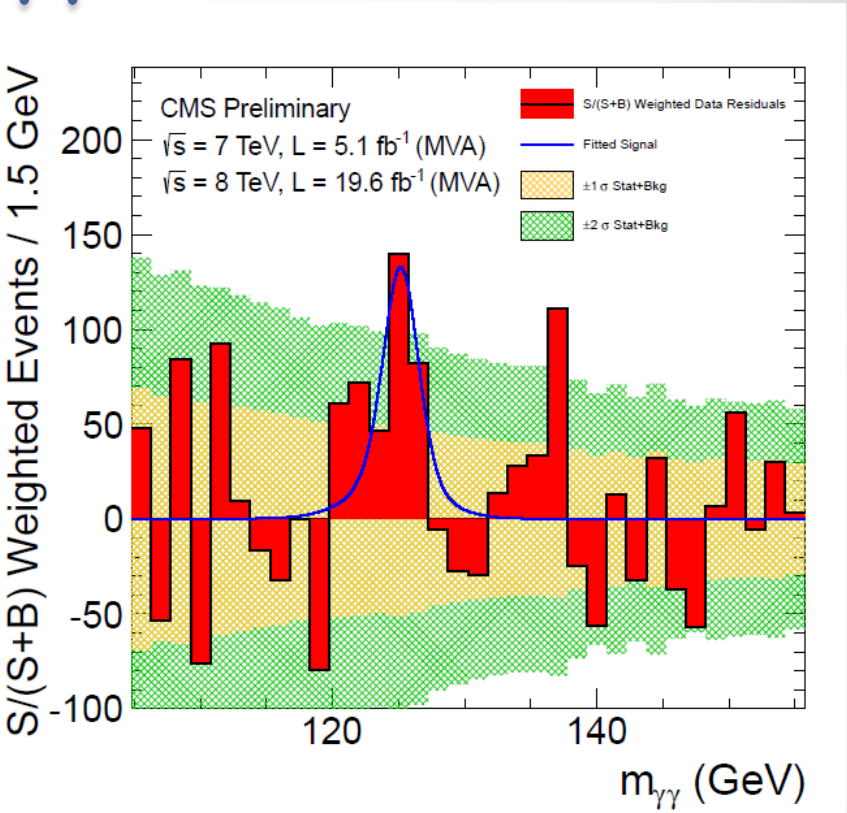
- Search for a narrow mass peak with 2 isolated, very energetic photons on a smoothly falling background

- Excellent resolution measuring photon energy ➔ 1% precision in $m_{\gamma\gamma}$ (in barrel)



H→γγ



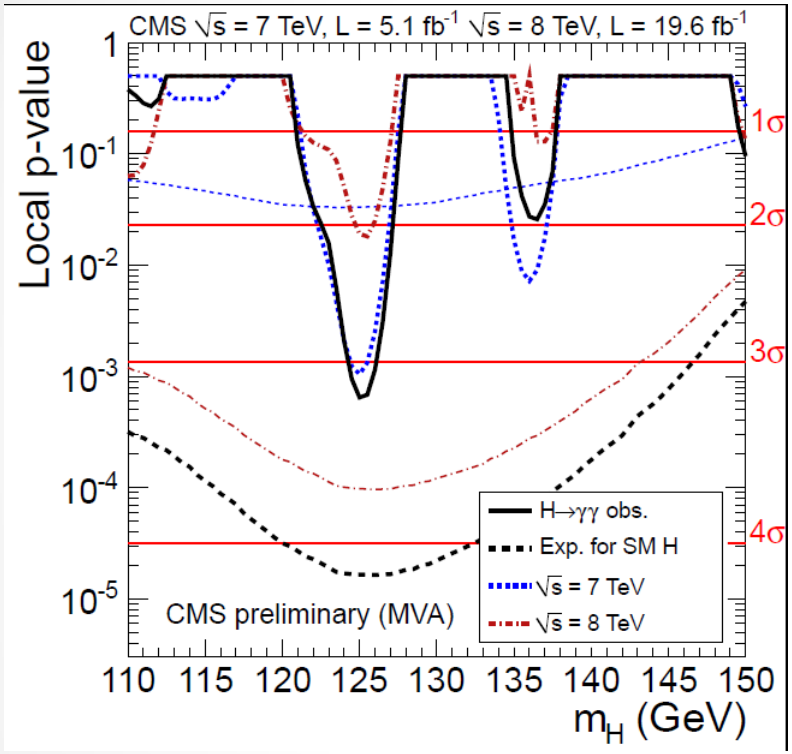


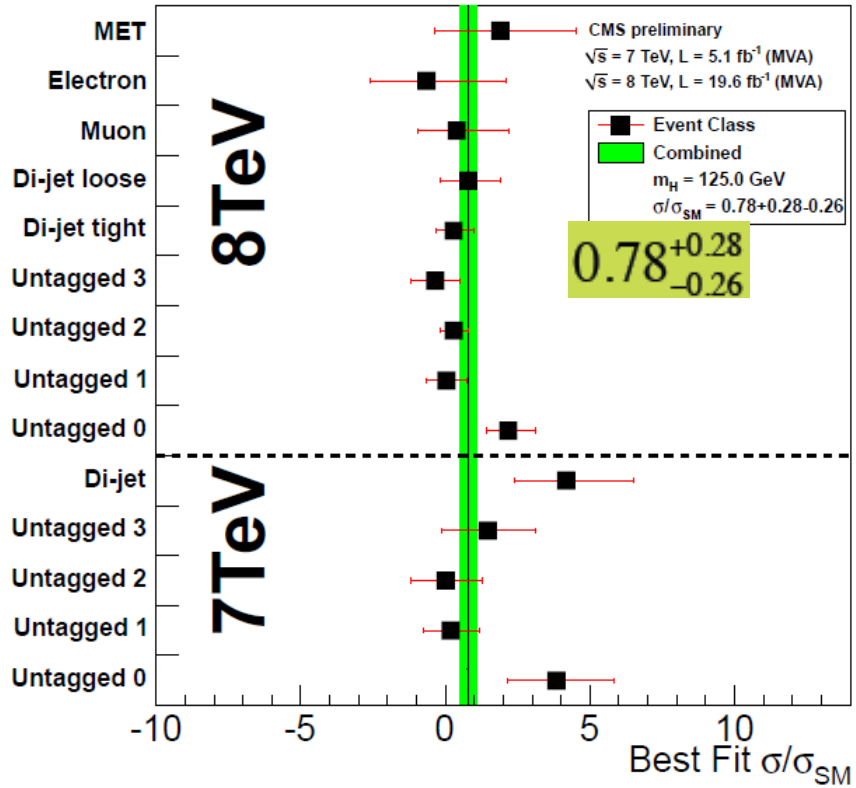
$$m_H = 125.4 \pm 0.5(stat.) \pm 0.6(sys.) GeV$$

- Categories by S/B, resolution and pT
- Dijet (VBF) categories with ~70% purity
- Mass fit with polynomial background chosen to minimize the bias on signal

Signal Strength

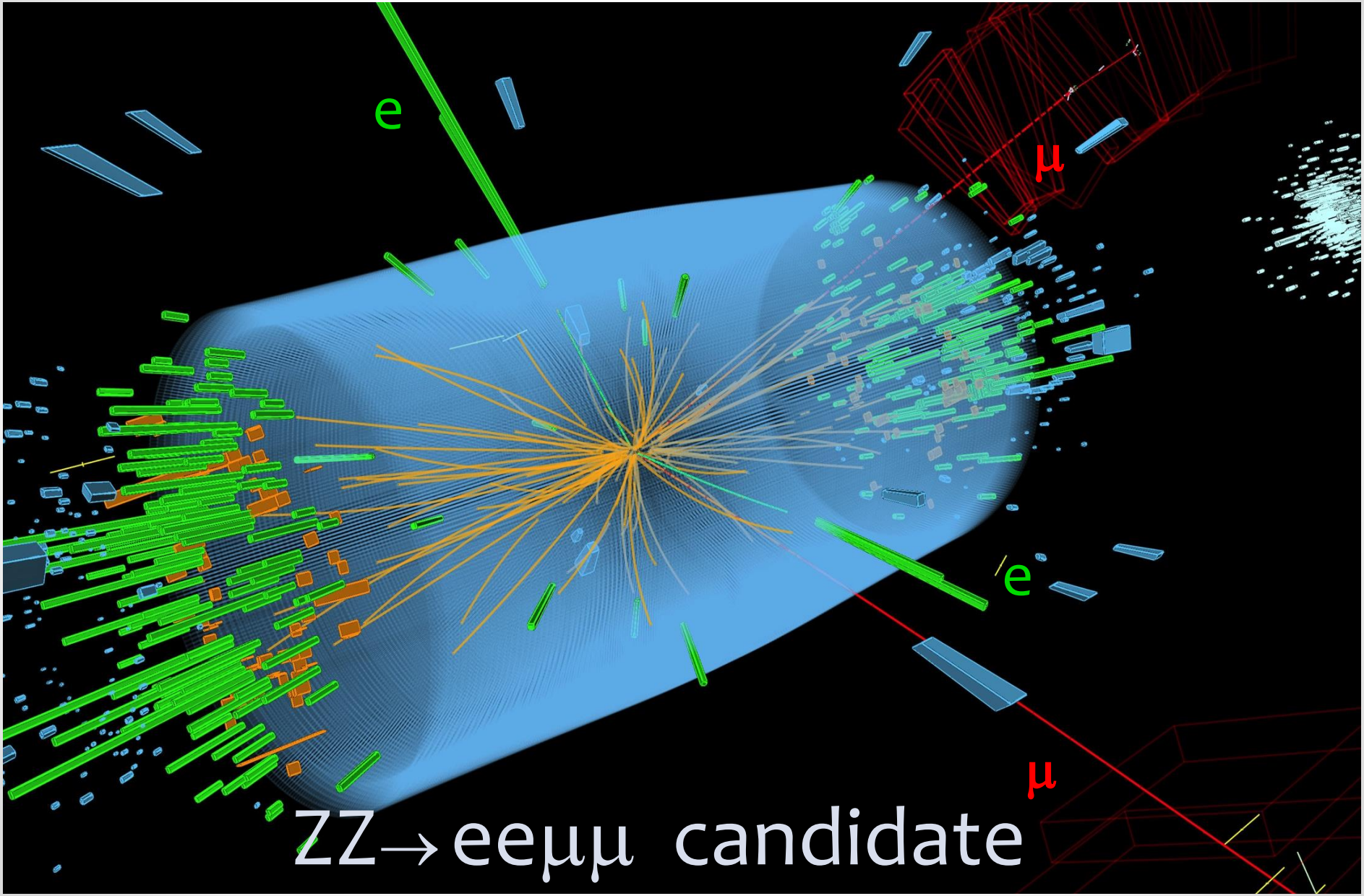
CMS HIG-13-001





Significance: 3.2σ (4.2σ expected)

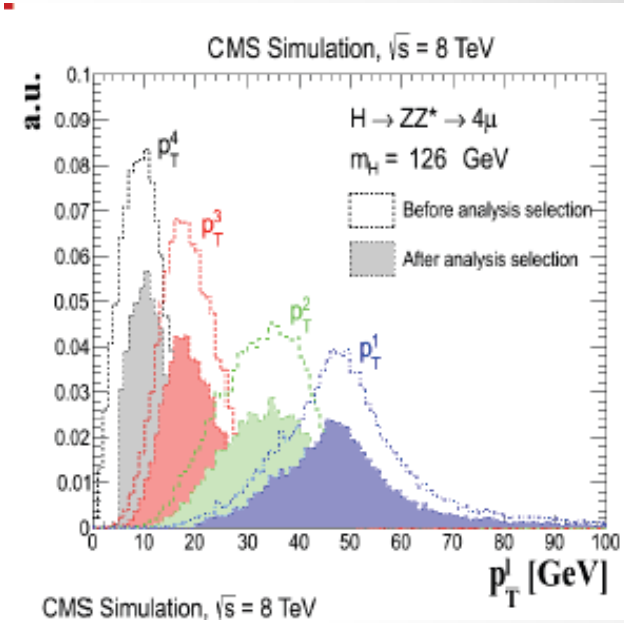
H→ ZZ* → 4l (l=e,μ)

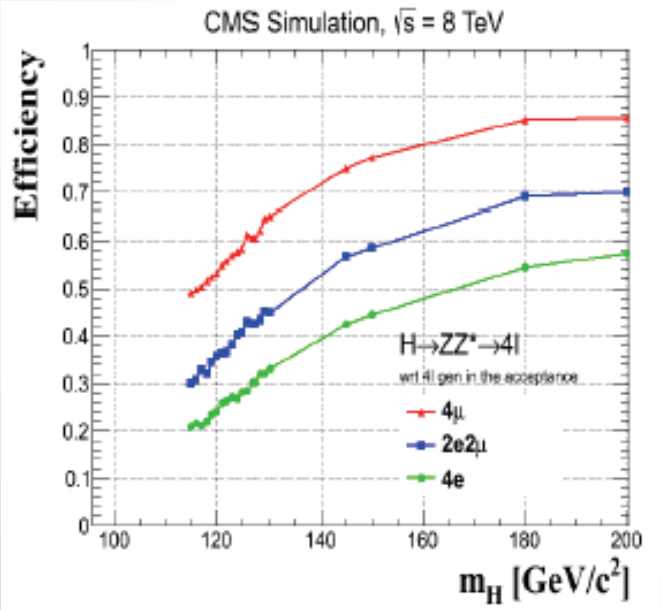


H→ZZ* →4l

Clean experimental signal

- 4 energetic and isolated leptons (e / μ)
- Coming from same primary interaction vertex
- Consistent from originating from Z boson

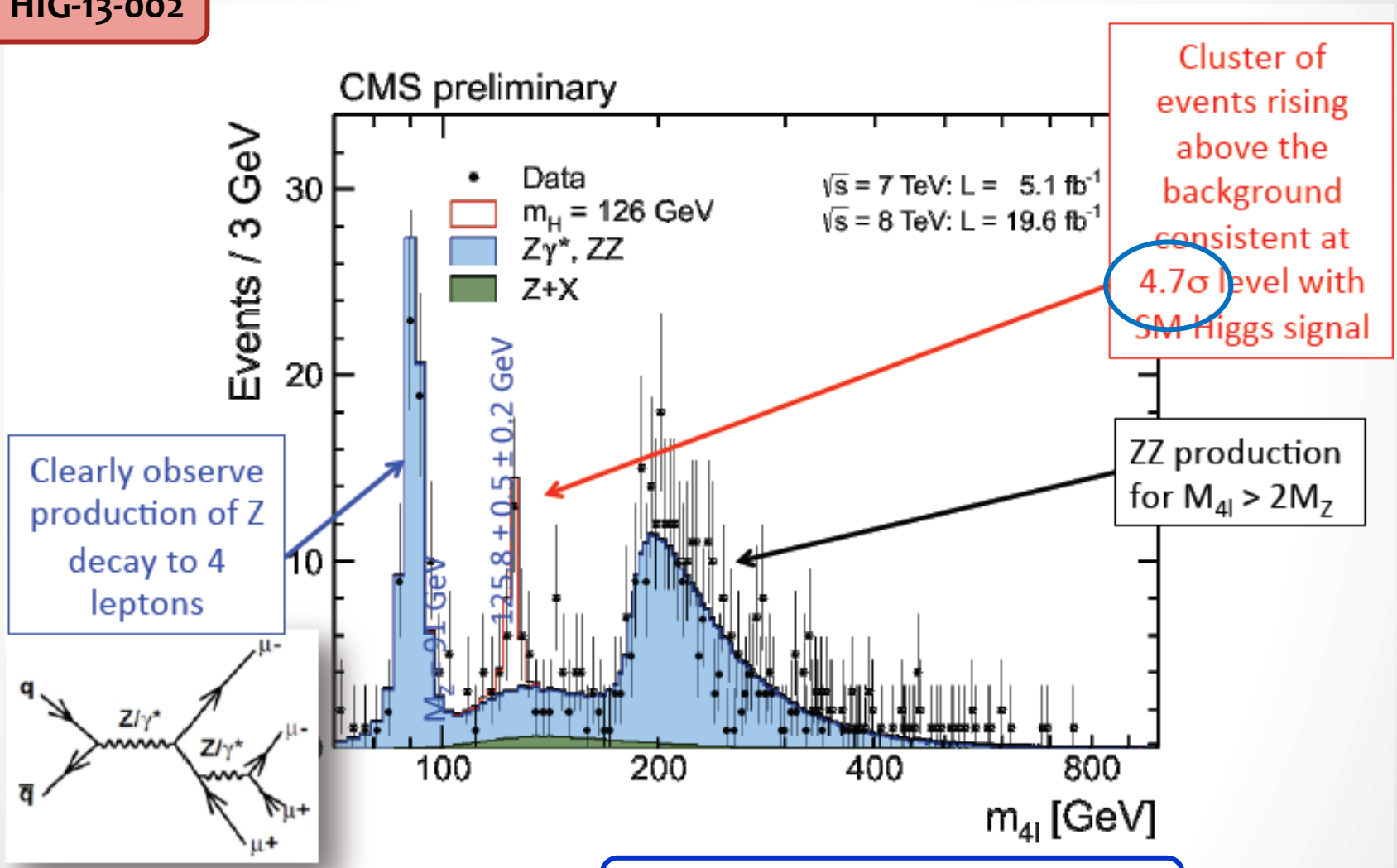




- Very tiny cross section, but low background level
- Require high selection and lepton id efficiencies
- Narrow peak (resolution 1-2 GeV) in m_{4l} mass distribution.

ZZ decays into 4l (l=e,μ)

CMS HIG-13-002



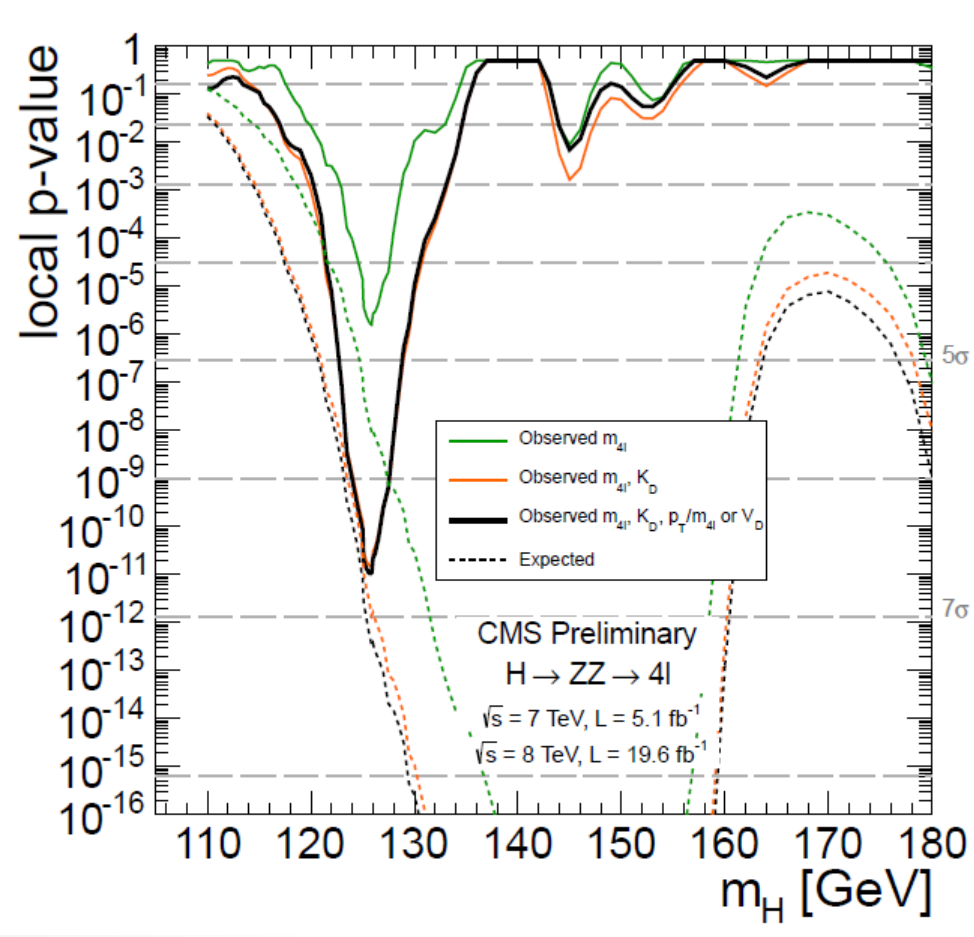
$BR(Z \to 4\ell) = 4.4^{+1.0}_{-0.8}(\text{stat}) \pm 0.2(\text{syst}) \times 10^{-6}$

$m_H = 125.8 \pm 0.5 \pm 0.2$ GeV

H→ZZ* →4l

CMS HIG-13-002

Compatibility with background only hypothesis

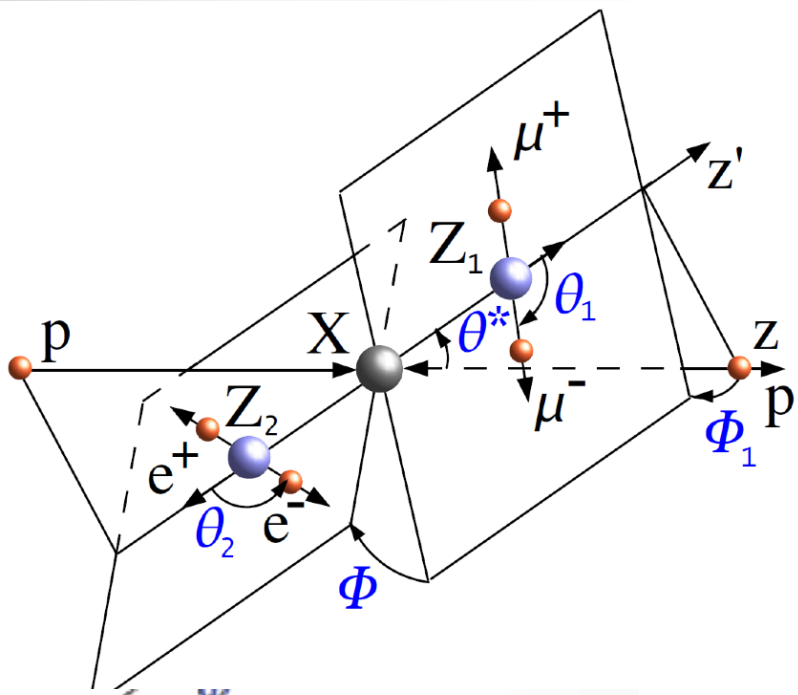


Gain in sensitivity using Matrix Element Likelihood Analysis

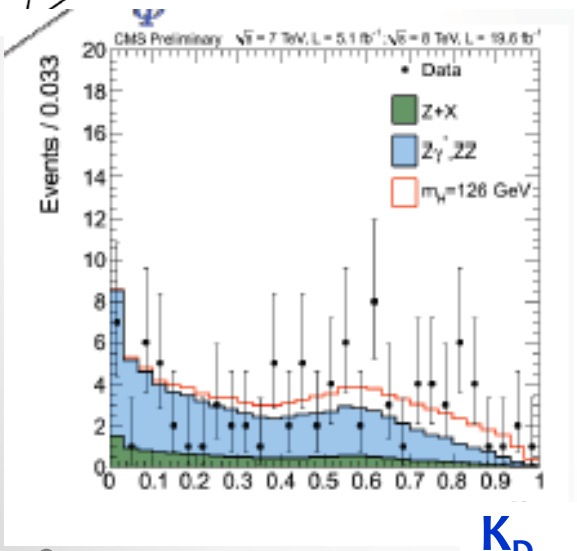
p-value	Expected:	7.1 σ
	Observed:	6.7 σ

σ/σ_{SM} @ 125.7 GeV = 0.92 ± 0.28

Kinematic Discriminant

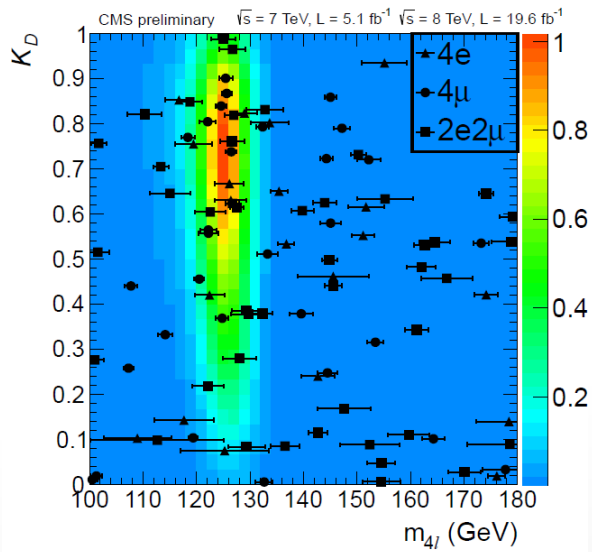


- Decay angles carry information on particle spin (ZZ production vs scalar, pseudo-scalar or spin-2)
- Build variable (**Kinematic Discriminant**) based on Matrix Element Likelihood Analysis:
  uses kinematic inputs for
  signal to background discrimination
  $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

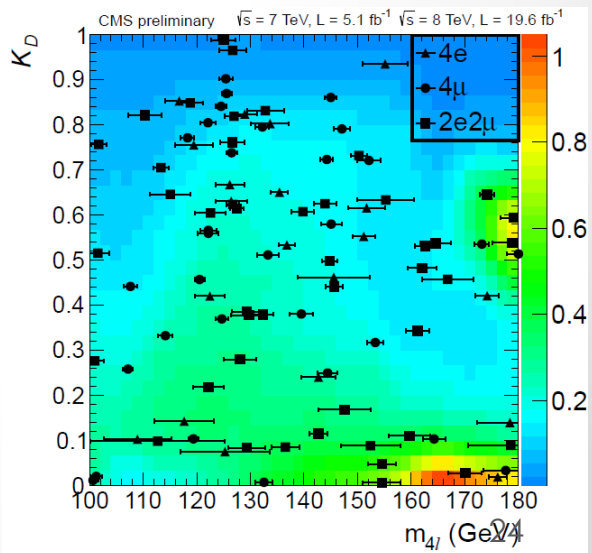


K_D

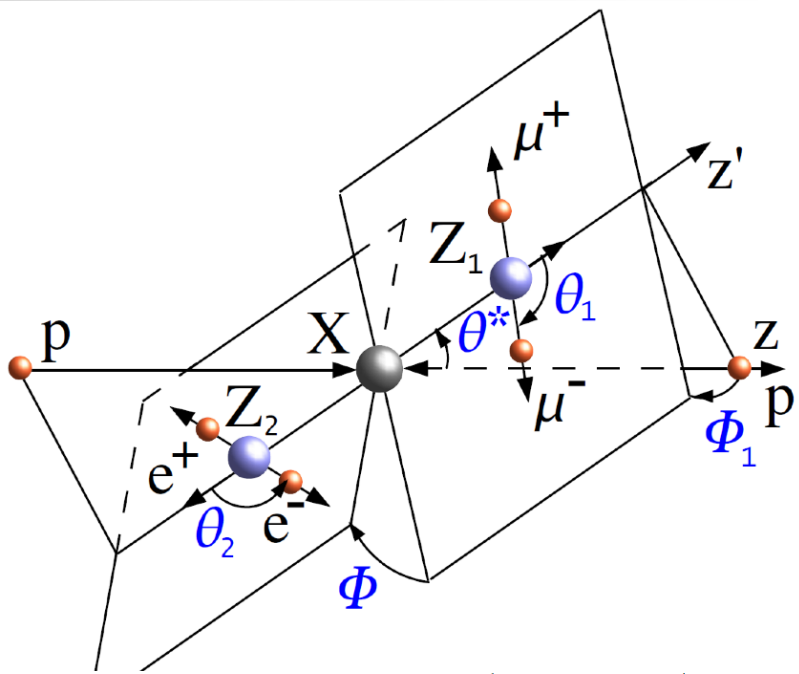
Signal



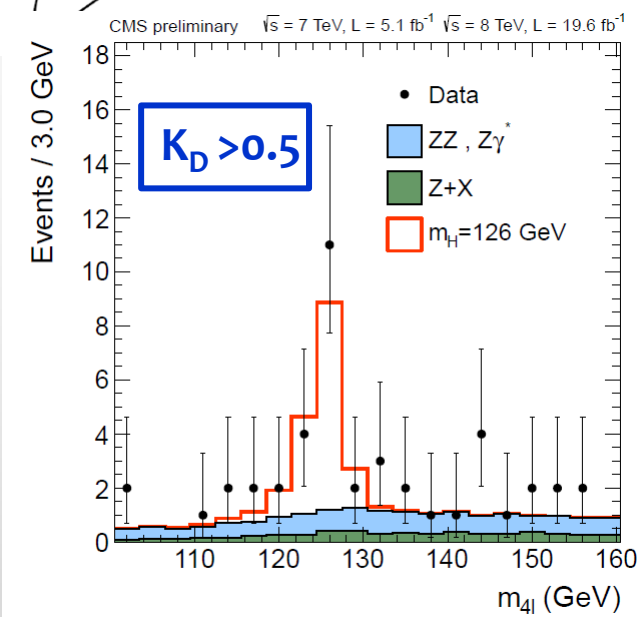
Background



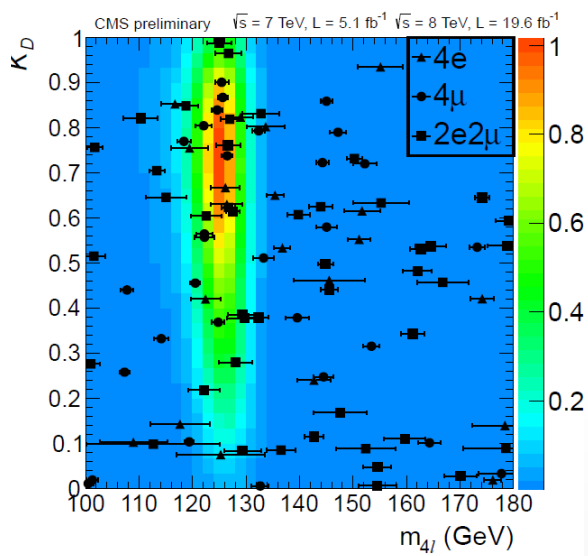
Kinematic Discriminant



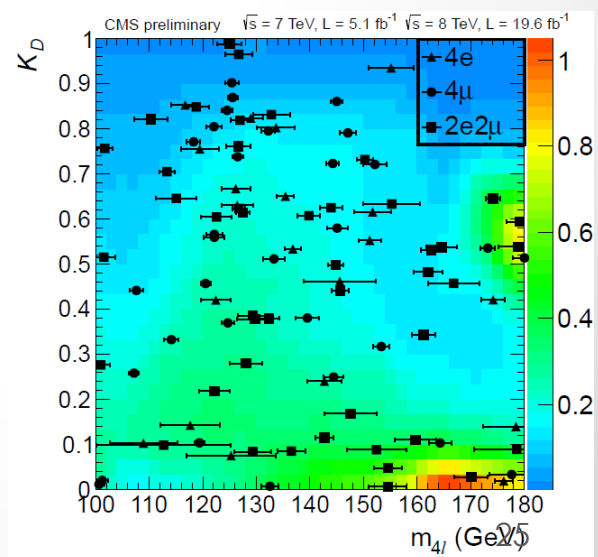
- Decay angles carry information on particle spin (ZZ production vs scalar, pseudo-scalar or spin-2)
- Build variable (Kinematic Discriminant) based on Matrix Element Likelihood Analysis: uses kinematic inputs for signal to background discrimination $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$



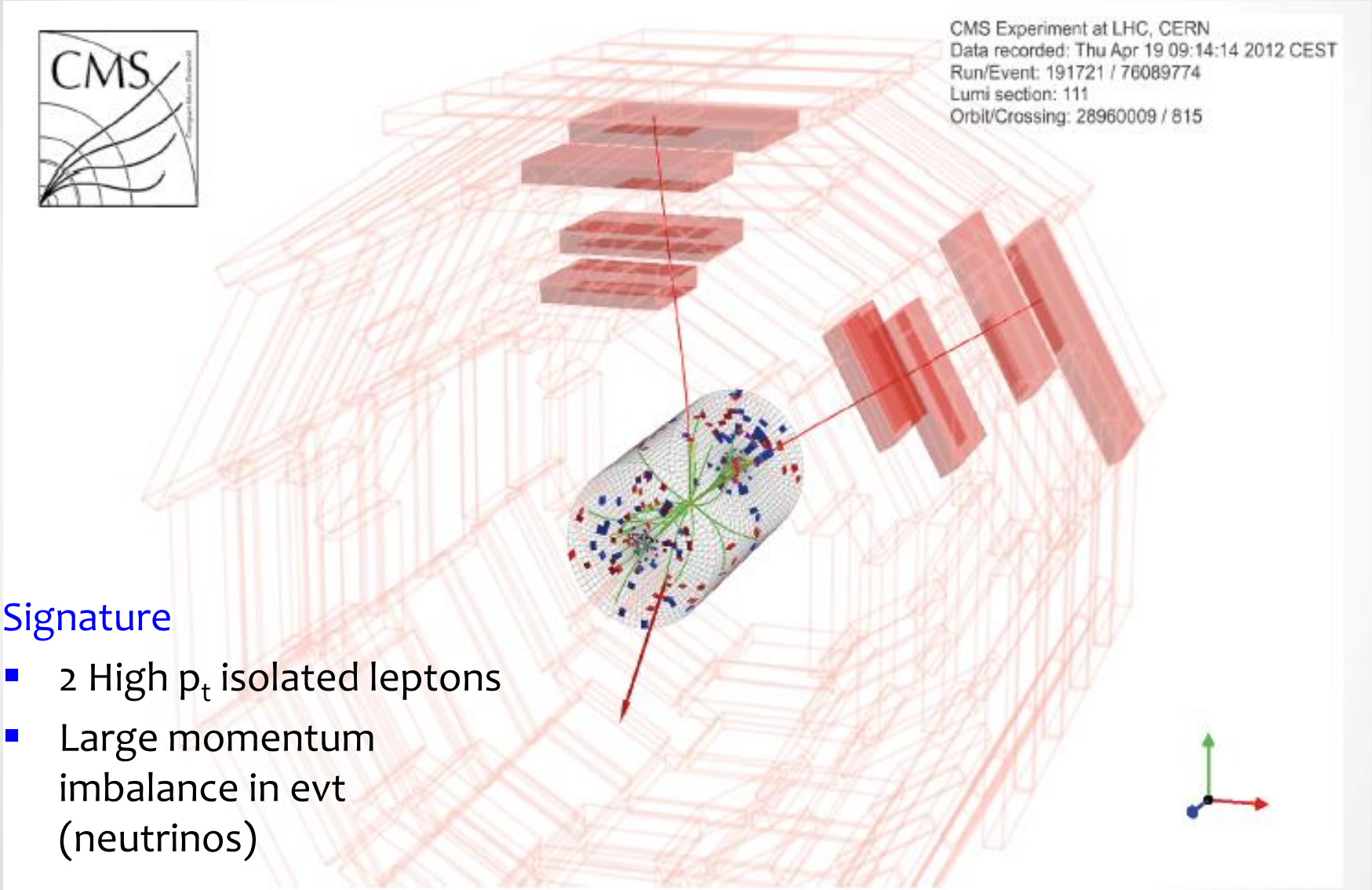
Signal



Background



$H \rightarrow WW^* \rightarrow l\nu l\nu$

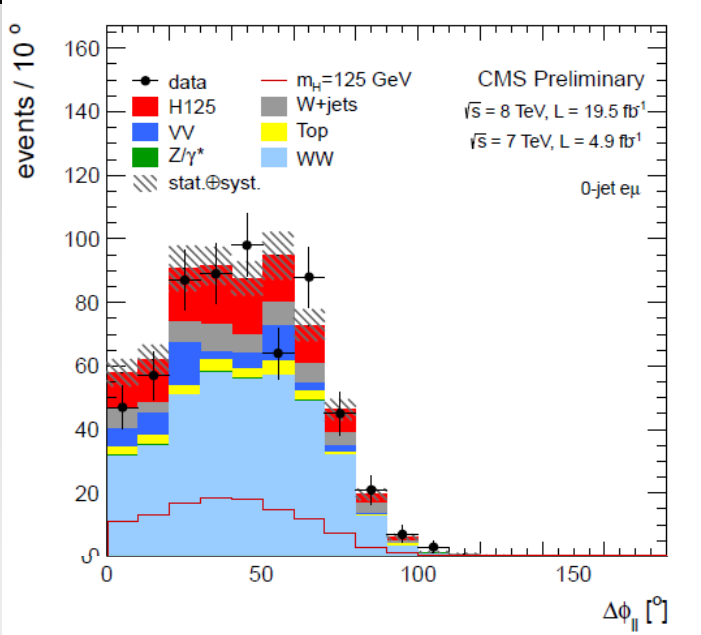


Signature

- 2 High p_t isolated leptons
- Large momentum imbalance in evt (neutrinos)

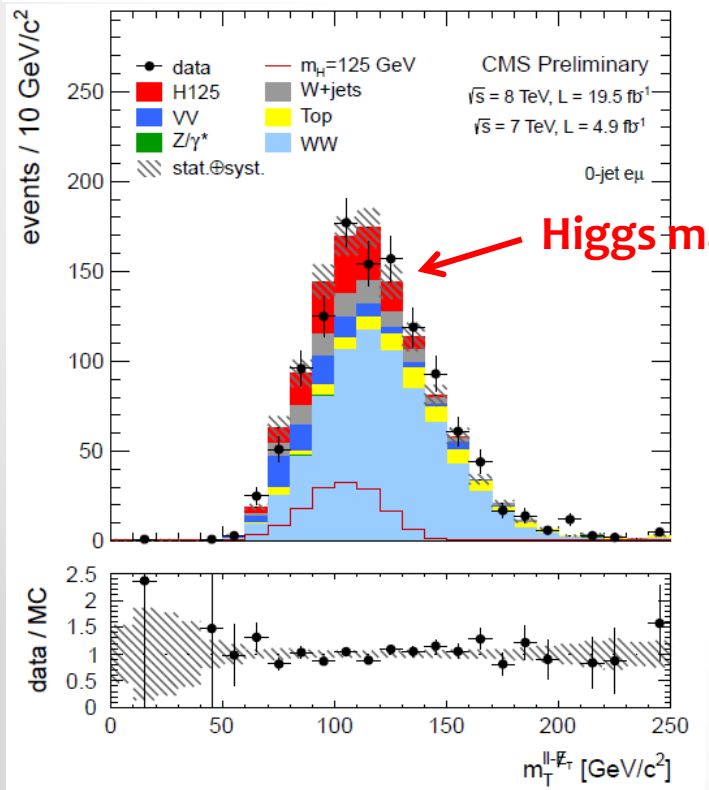
$H \rightarrow WW^*$

CMS HIG-13-003

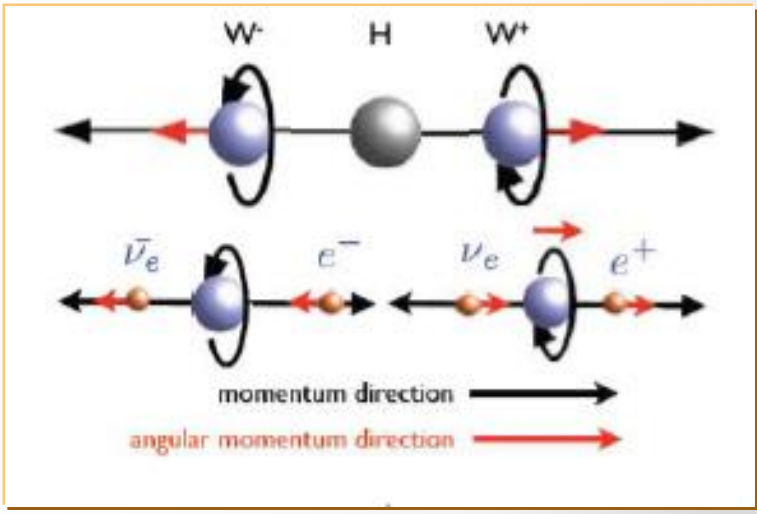


- High sensitivity channel
- No mass peak reconstructed
- Analysis optimized depending on m_H hypothesis

  p_{Tl}, m_{ll}, m_T, $\Delta\phi$
- Categories according to jet multiplicities 0,1,2 (VBF) and SF/DF lepton flavours



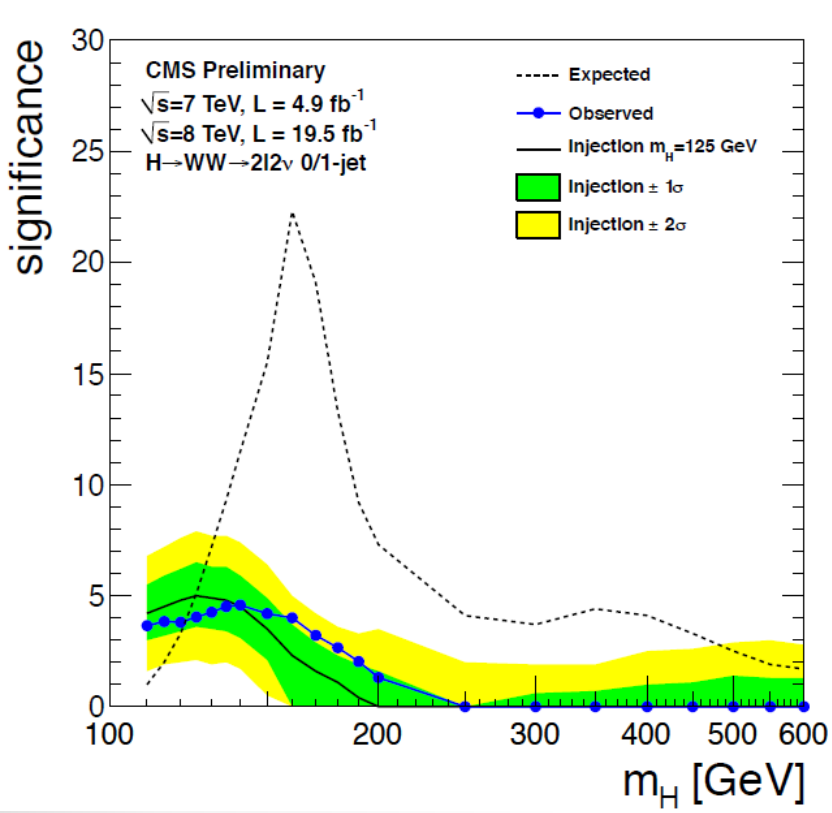
Vectors from the decay of a scalar and V-A structure of W decay lead to small leptons opening angle (especially true for on-shell Ws)

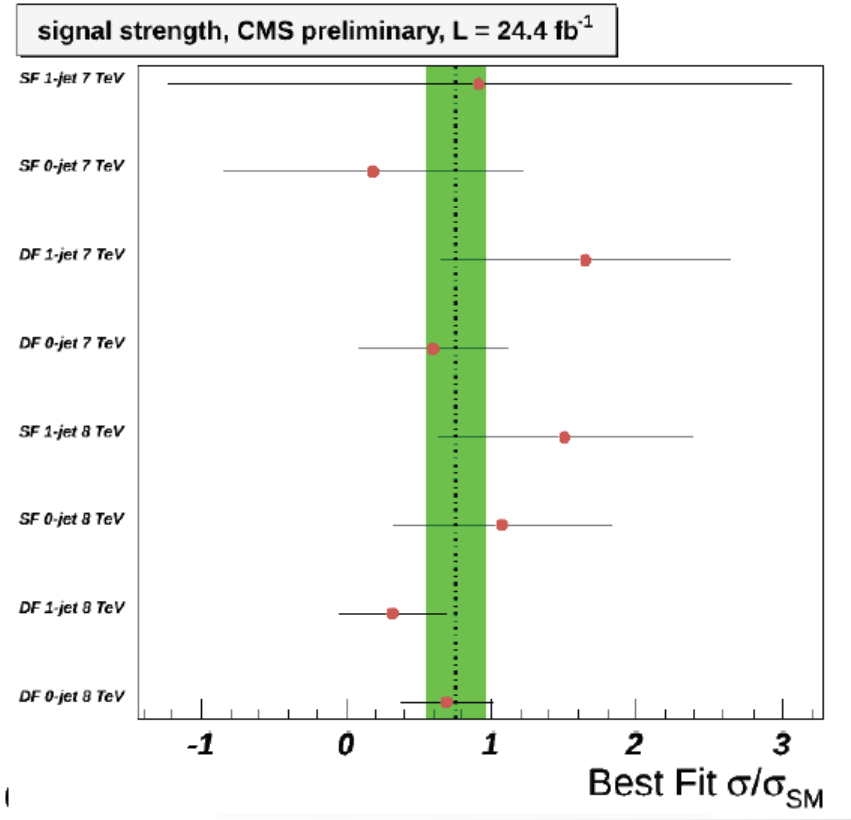


$H \rightarrow WW^*$

CMS HIG-13-003

Broad enhancement seen compared to backgd only hypothesis, consistent with SM Higss @4σ (5.1 σ expected)





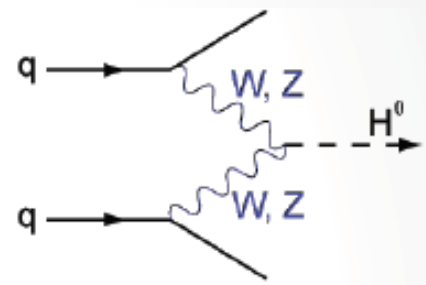
Significance: 4.0σ (5.1σ expected)

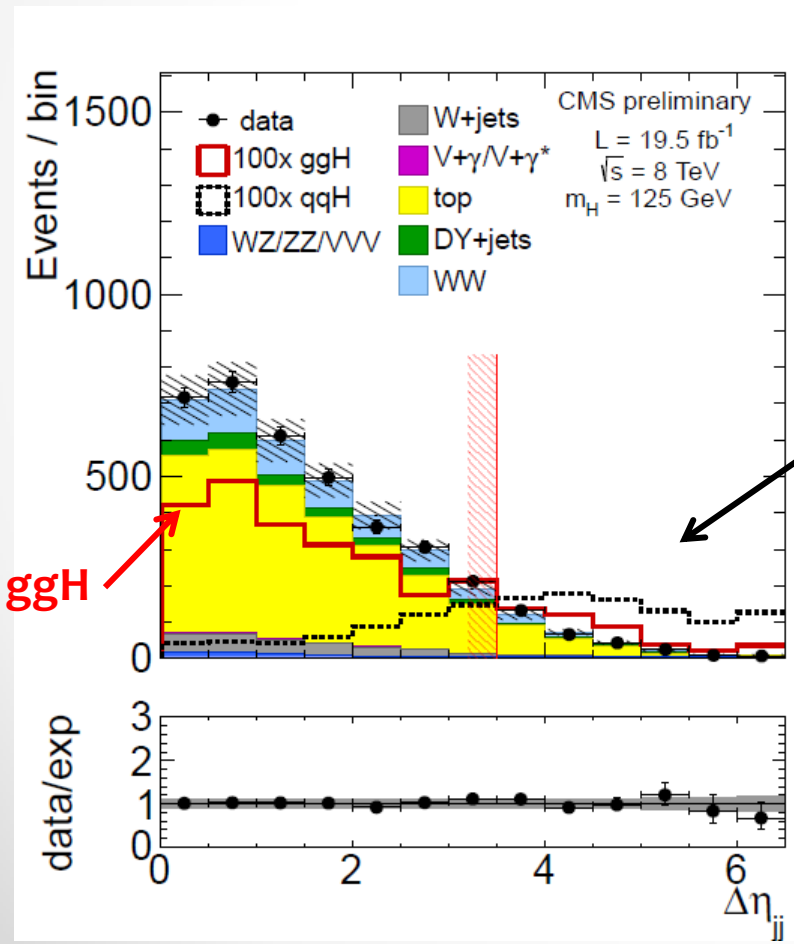
Signal Strength:
$\sigma / \sigma_{SM} = 0.76 \pm 0.21$

H→WW (VBF)

CMS HIG-13-022

- VBF production enhanced requiring 2 jets in forward direction, high pT, well separated in pseudorapidity
- Additional value → test of vector bosons scattering





qqH ➔ 2 jets well separated in pseudorapidity

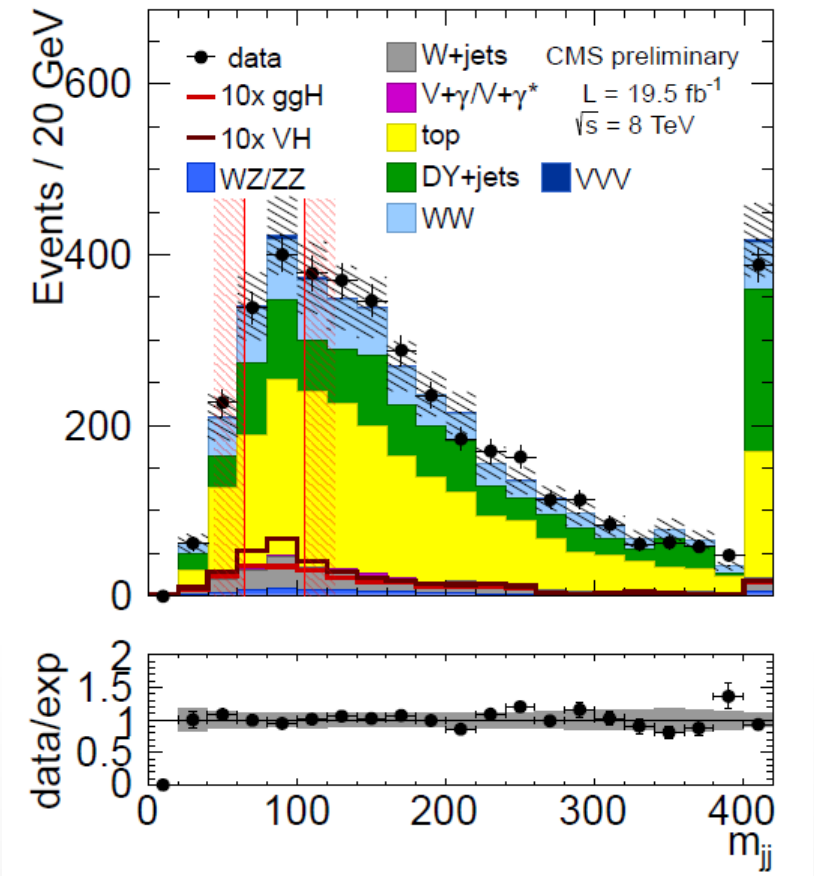
Significance: 1.3σ (2.1σ expected) for SM m_H = 125 GeV

VH, H→WW* & V →jj

CMS HIG-13-017

Interesting test of production of ggH vs VH

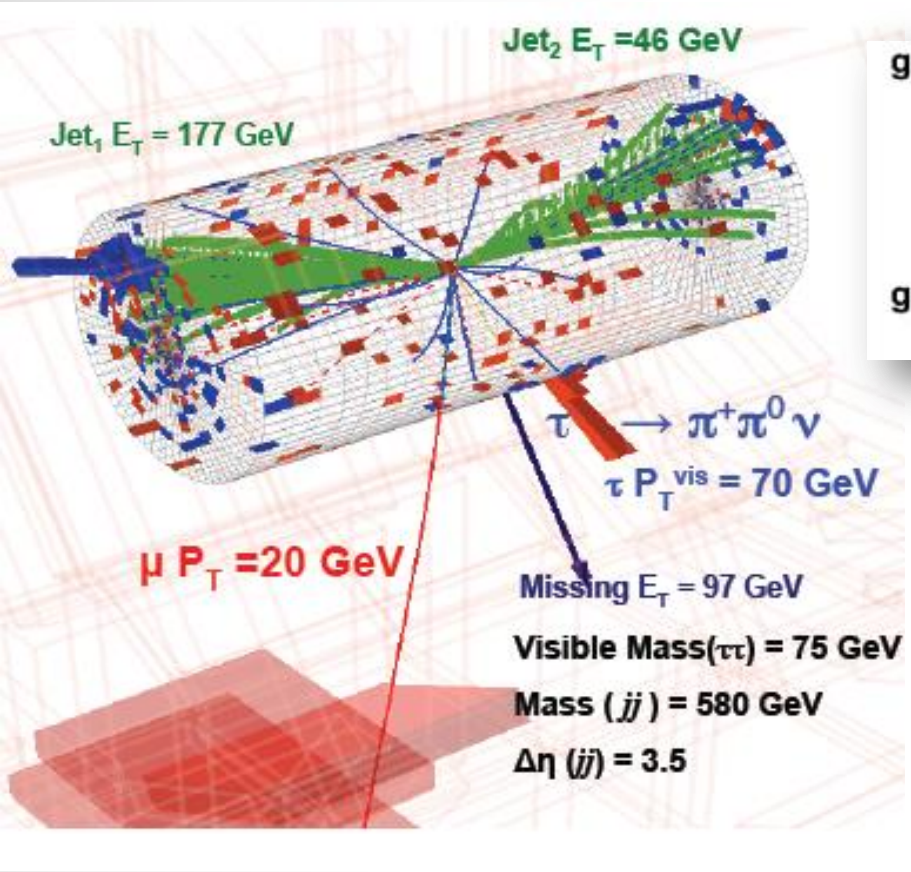
- M_{jj} compatible with coming from W or Z ($65 < m_{jj} < 105$ GeV)
- Reaching sensitivity to expected SM level ➔ expectations for Run2

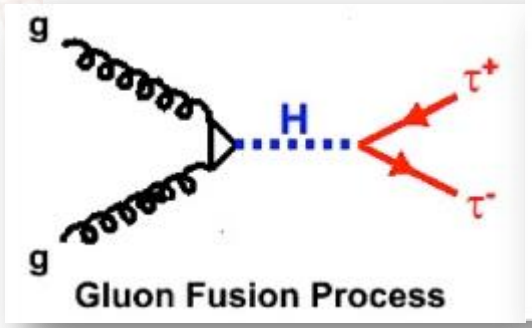


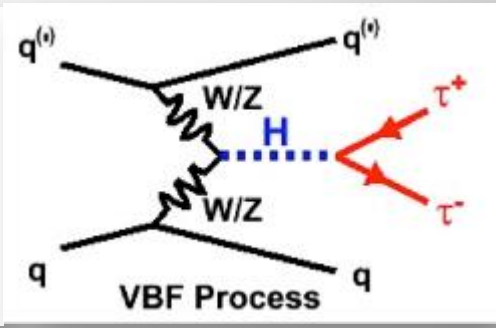
Higgs Couplings to Fermions

Indications of mass generation in fermion sector

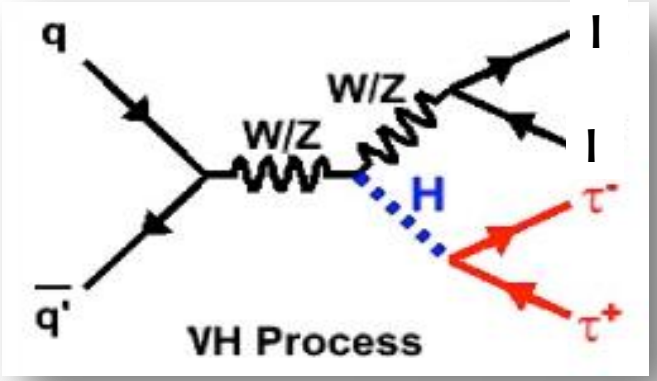
$H \rightarrow \tau\tau$







gg & VBF production: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$



VH production: $l\tau_h\tau_h$, $ll\tau_h\tau_h$, $ll\tau_h$

Number of jets categories

0 jets: only to constrain the background

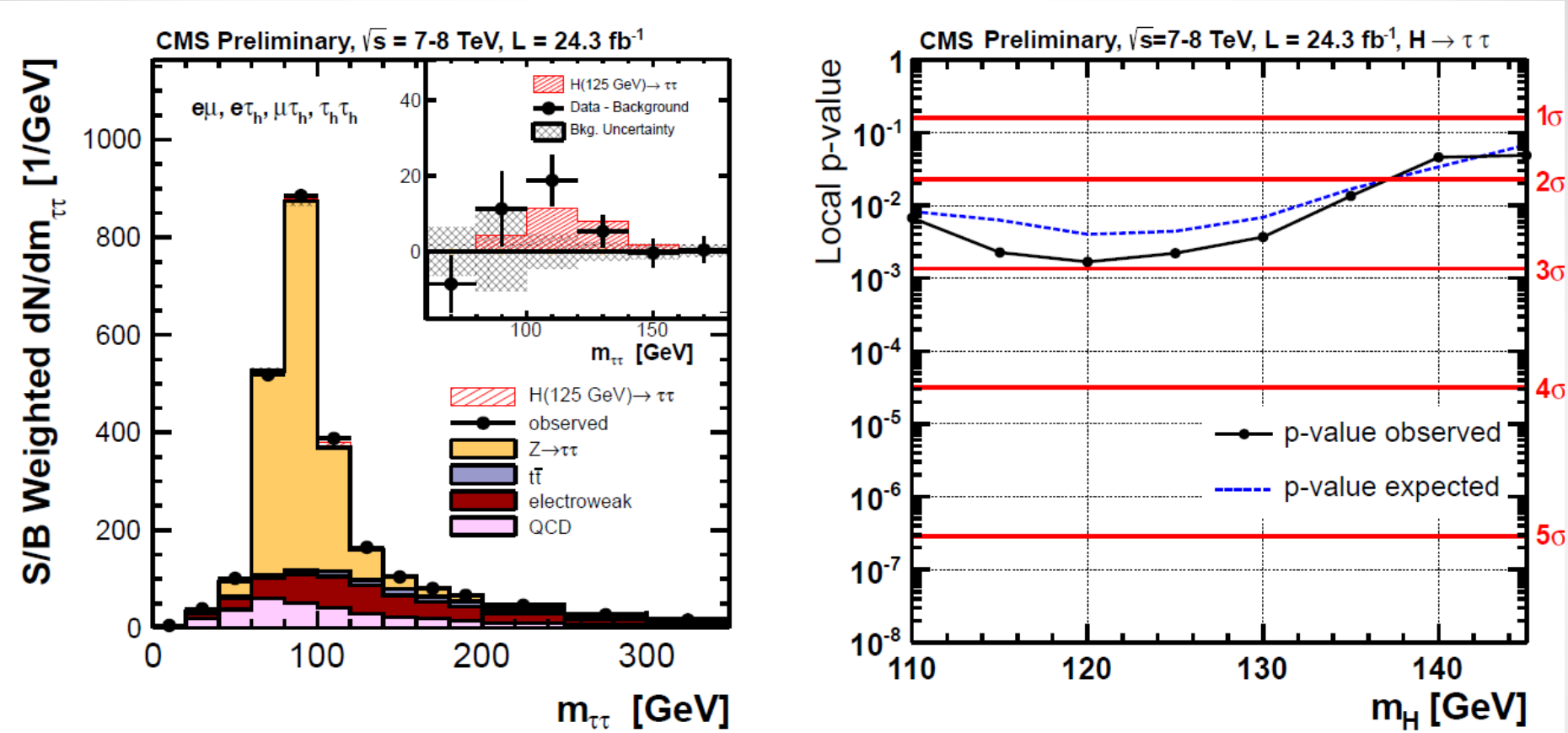
1 jet: low / high pT

2 jets : VBF process

τ reconstruction is very challenging

$H \rightarrow \tau\tau$

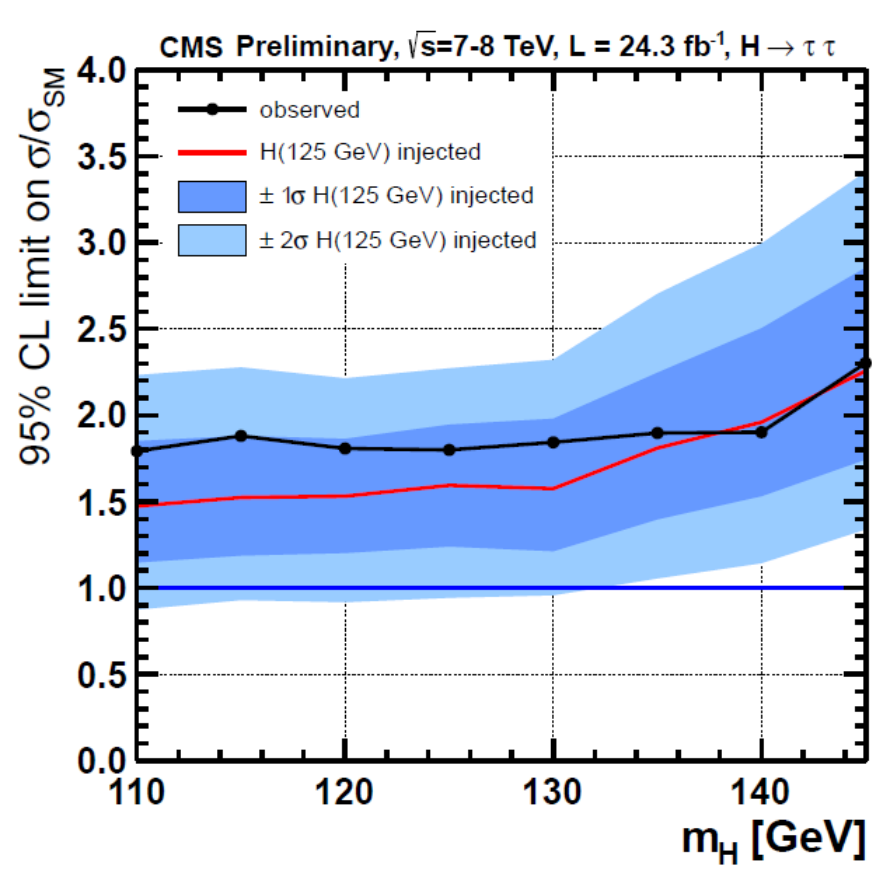
CMS HIG-13-004

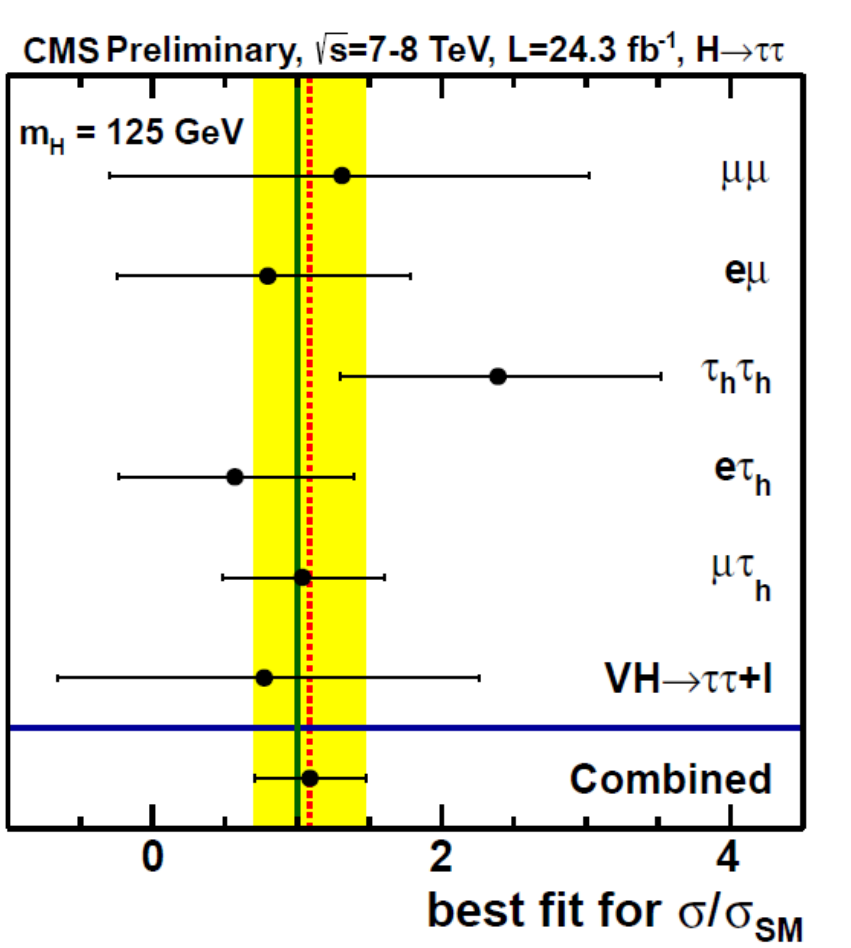


A 2.9σ signal at m_H = 125 GeV is emerging (expected 2.6σ)

$H \rightarrow \tau\tau$

CMS HIG-13-004





Compatible with the signal + background hypothesis for a m_H = 125 GeV

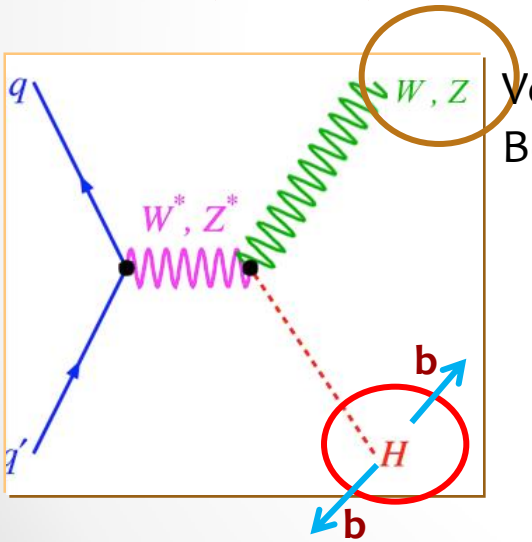
$\sigma/\sigma_{SM} = 1.1 \pm 0.4$

H→bb (VH)

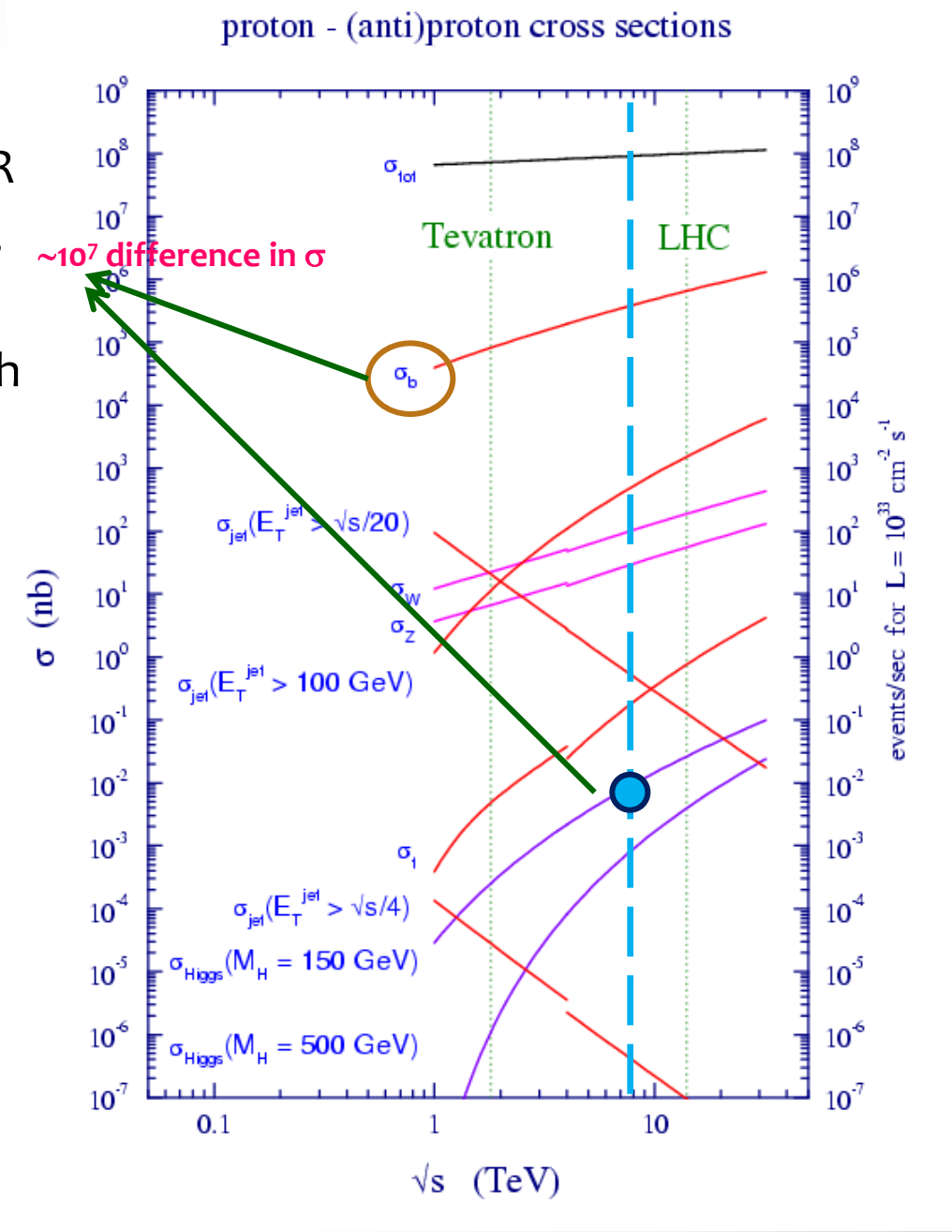
- If SM Higgs ➔ bb has the highest BR
- But very high levels of backgrounds looking for b-pairs alone.
- Look for Associated Production with a Vector Boson (W,Z)

Z➔ ll (l = e, μ, ν)
W➔ lν (l = e, μ)

5 different final states



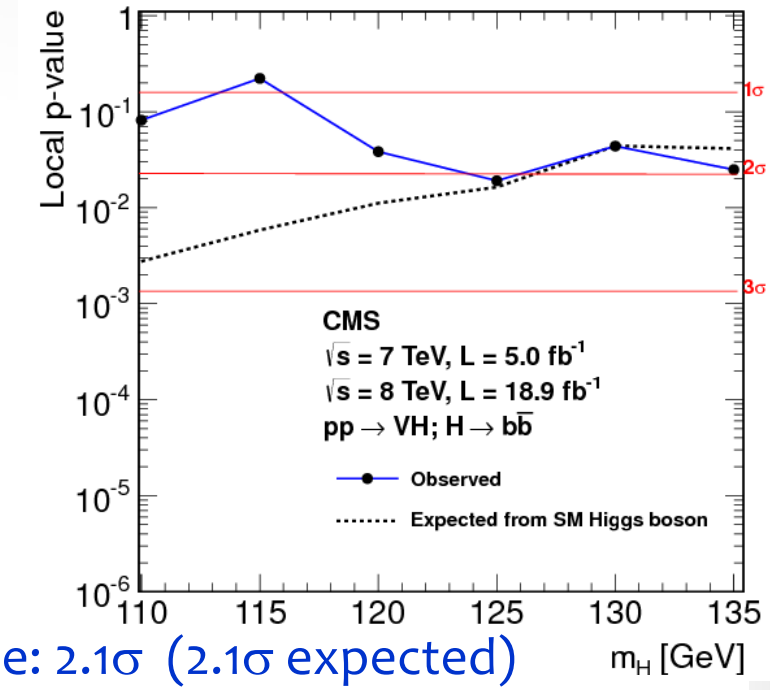
Vector Boson



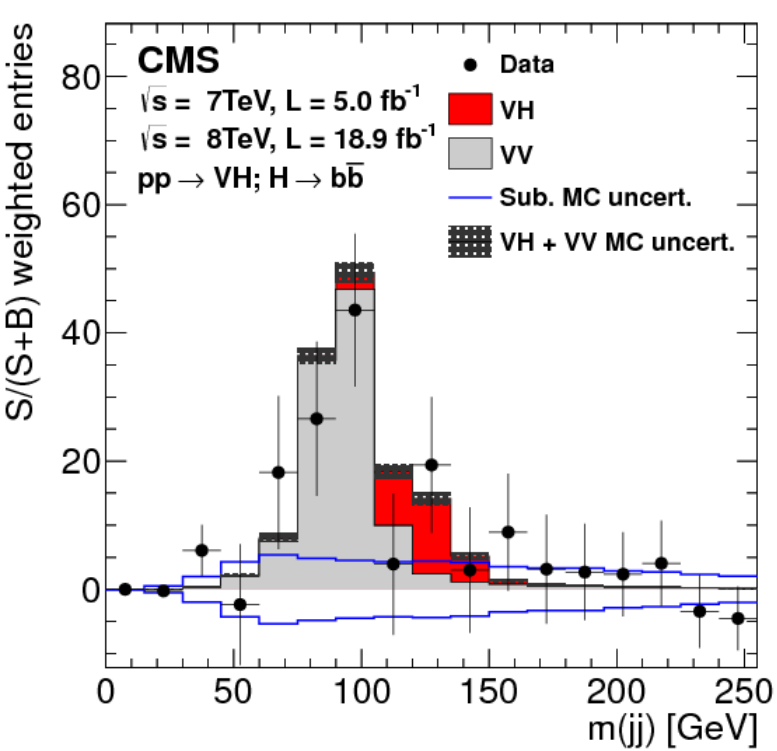
CMS HIG-13-012

H→bb (VH)

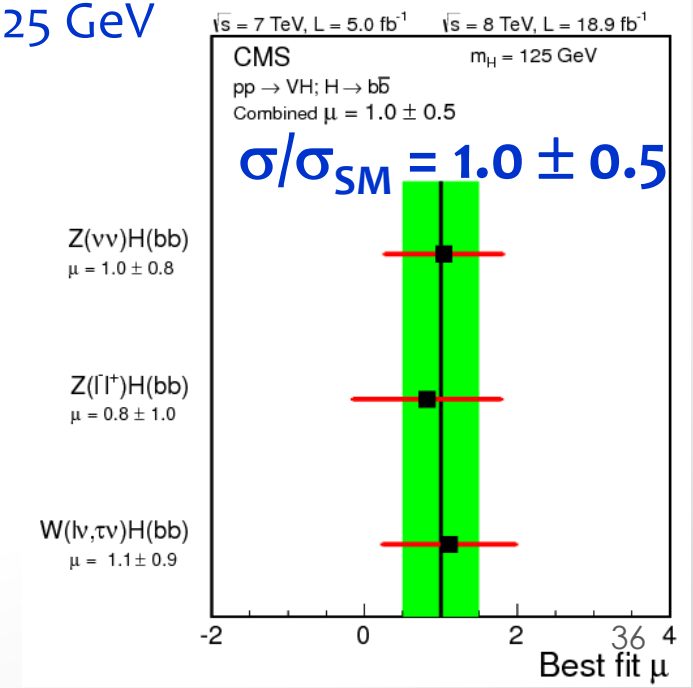
- Gluon-gluon fusion signal overwhelmed by QCD
- Associated production with W(lν), Z(ll, νν) is probed
- Observe a broad excess compatible with signal



Significance: 2.1σ (2.1σ expected) for SM m_H = 125 GeV



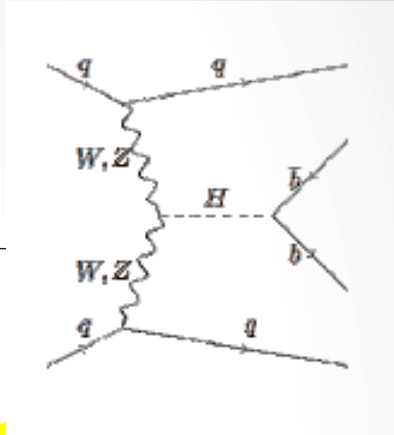
MVA analysis + cut based one, as a cross-check

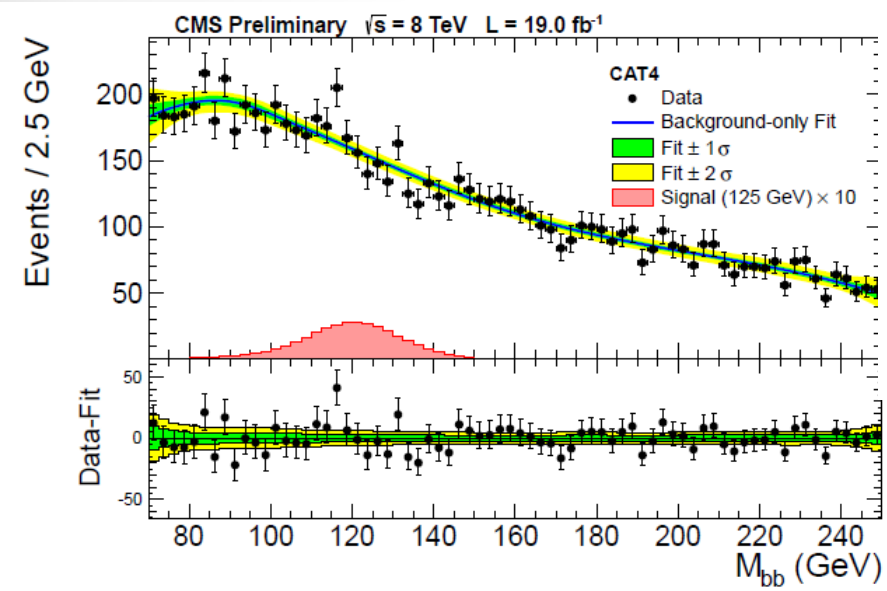


H→bb (VBF)

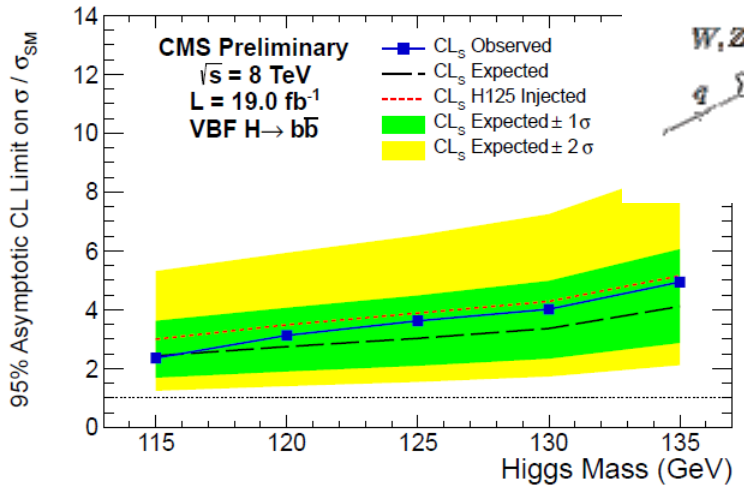
CMS HIG-13-011

- Vector Boson fusion production with 2 tagged forward jets
- 2 b-jets in central rapidity region
- Special trigger developped

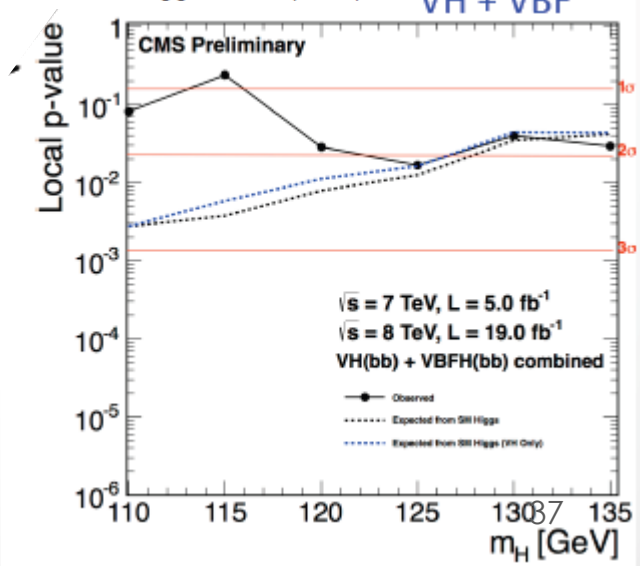




M_{bb} for the most sensitive category



VH + VBF



3.4σ evidence of Higgs to fermion coupling, combining H→bb & H→ττ channels

Higgs Properties

CMS HIG-13-005

Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
$\tau\tau$	2.6	2.8

- Mass
- Signal strength (μ)
- Couplings
- Spin-parity

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

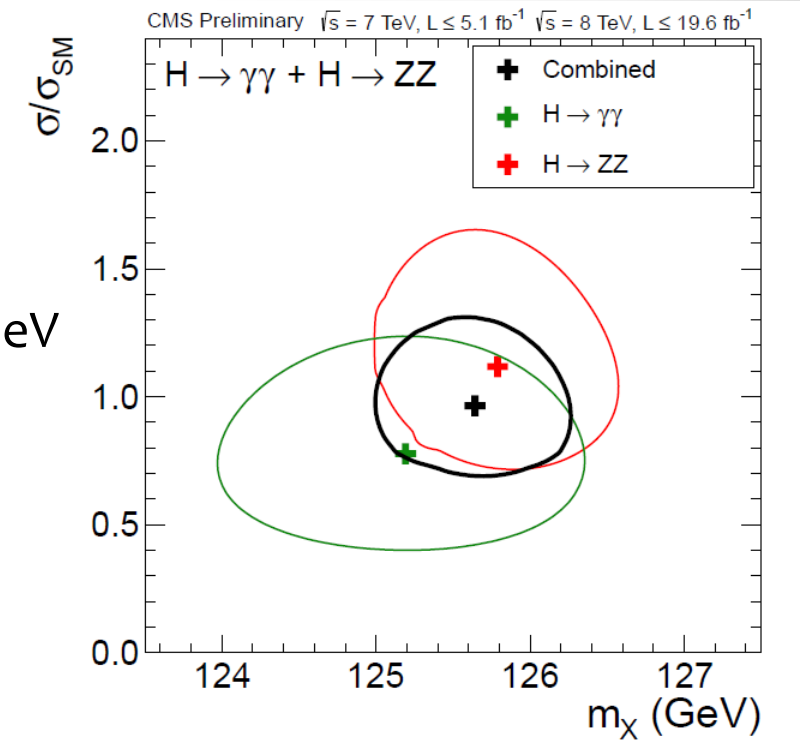
Last combination performed with Moriond'13 dataset, around spring 2013,

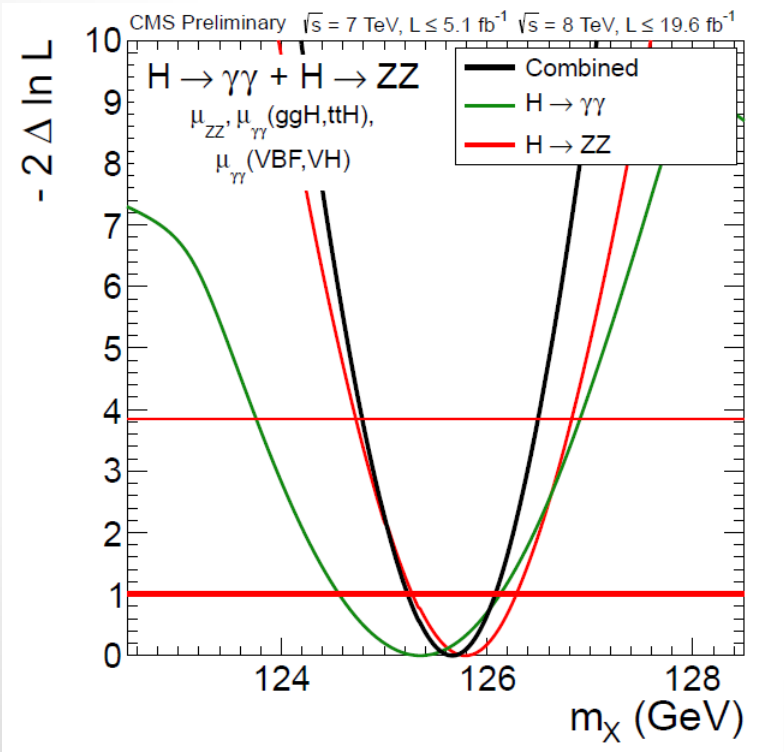
Higgs mass

CMS HIG-13-005

Higgs mas determination driven by the channels with better momentum precision: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$

CMS	$\gamma\gamma$	125.4±0.5±0.6 GeV
CMS	$ZZ \to 4l$	125.8±0.5±0.2 GeV
CMS	comb.	125.7±0.3±0.3 GeV = 125.7 ±0.4 GeV



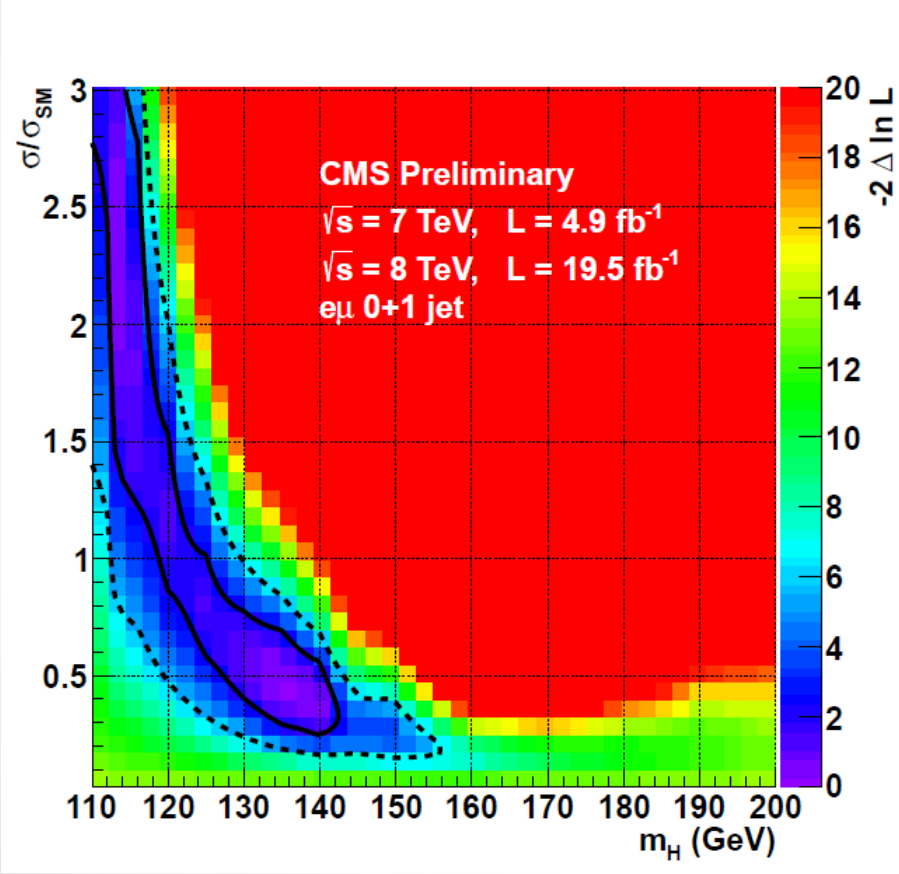


$H \to ZZ \to 4l$: small systematics due to good control of lepton scale and resolution.

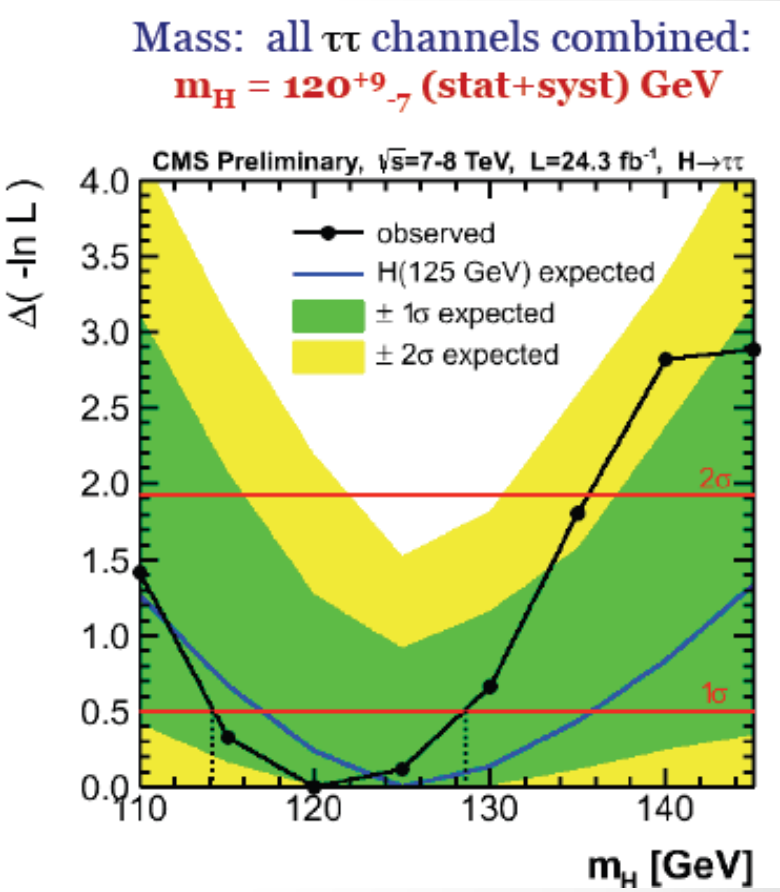
$H \to \gamma\gamma$: systematic on extrapolation from $Z \to ee$ to $H \to \gamma\gamma$ (0.25% from e to γ, 0.4% from $Z \to H$).

Higgs mass

H→ WW



H→ ττ

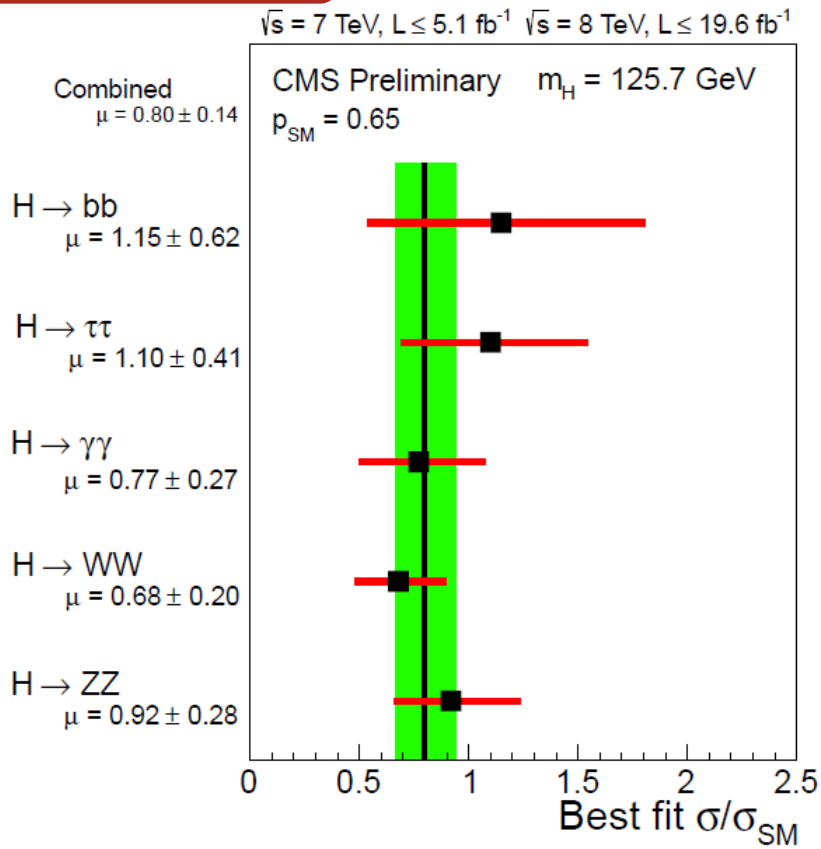


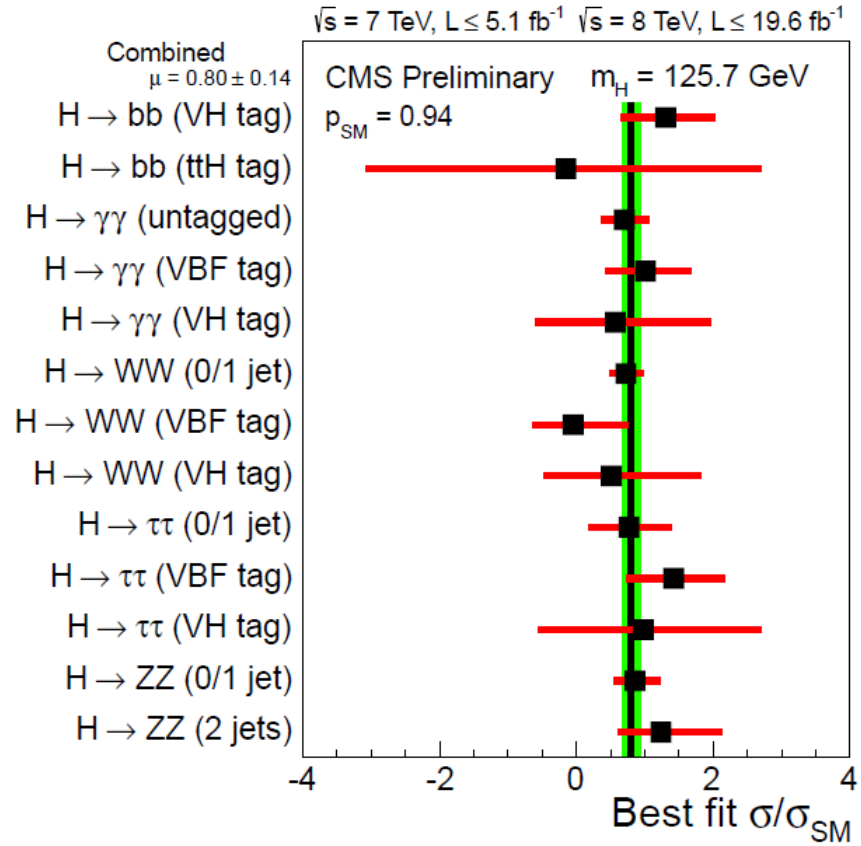
SM Higgs Signal Strength: Consistency

Using the 5 decay channels (with great variety of subchannels)

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

CMS HIG-13-005





$\mu = 0.80 \pm 0.14$ for $m_H = 125.7$ GeV

Compatible with SM Higgs

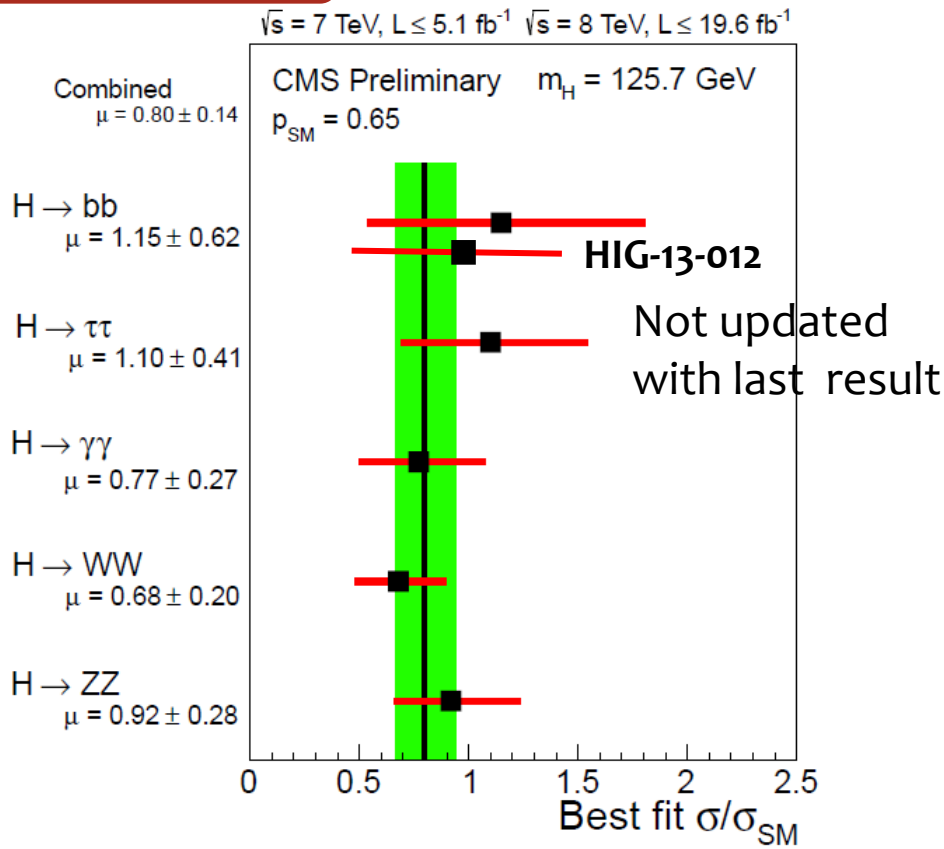
- Theory uncertainty (QCD scale ±8%@NNLO and PDF+α_s ±8%) is comparable to experimental.

SM Higgs Signal Strength: Consistency

Using the 5 decay channels (with great variety of subchannels)

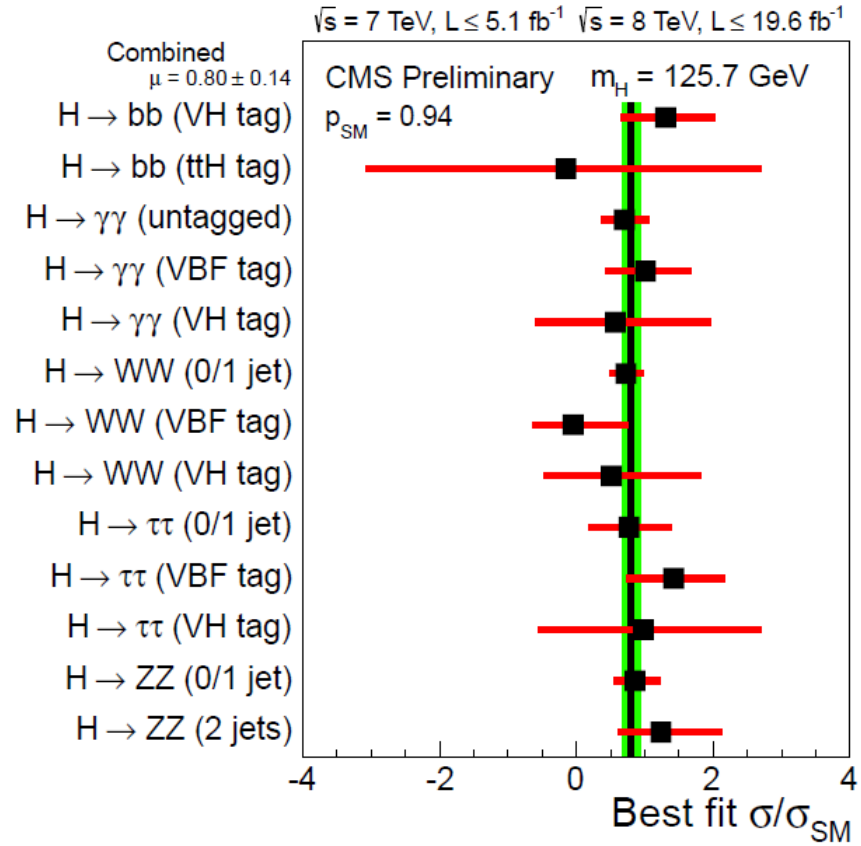
$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

CMS HIG-13-005



HIG-13-012

Not updated with last result



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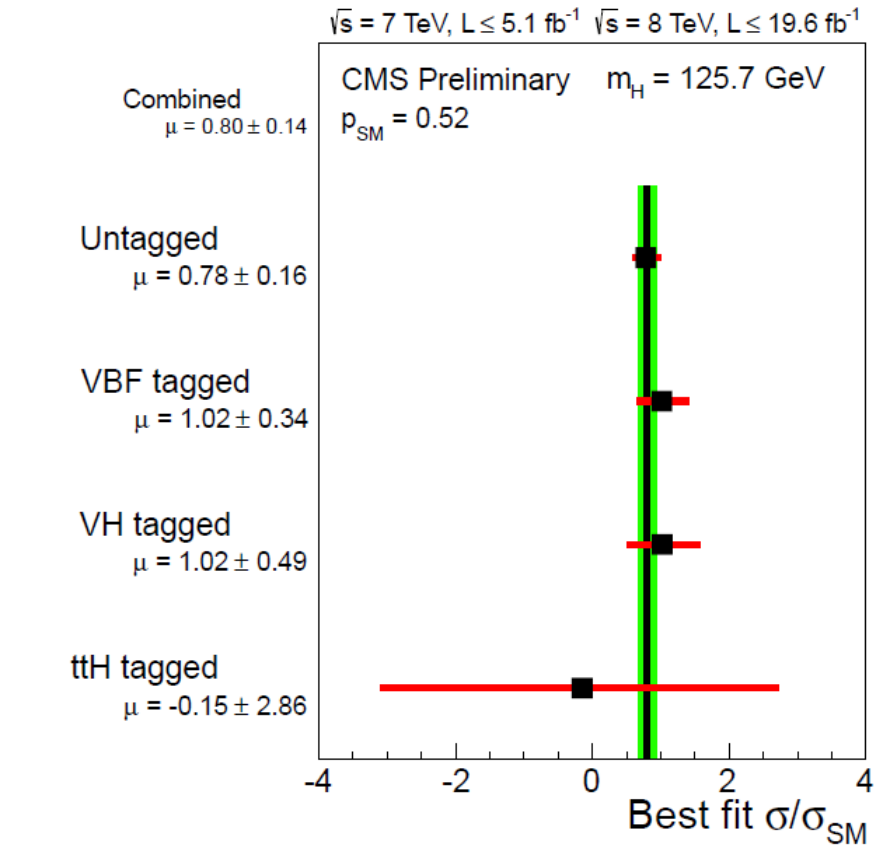
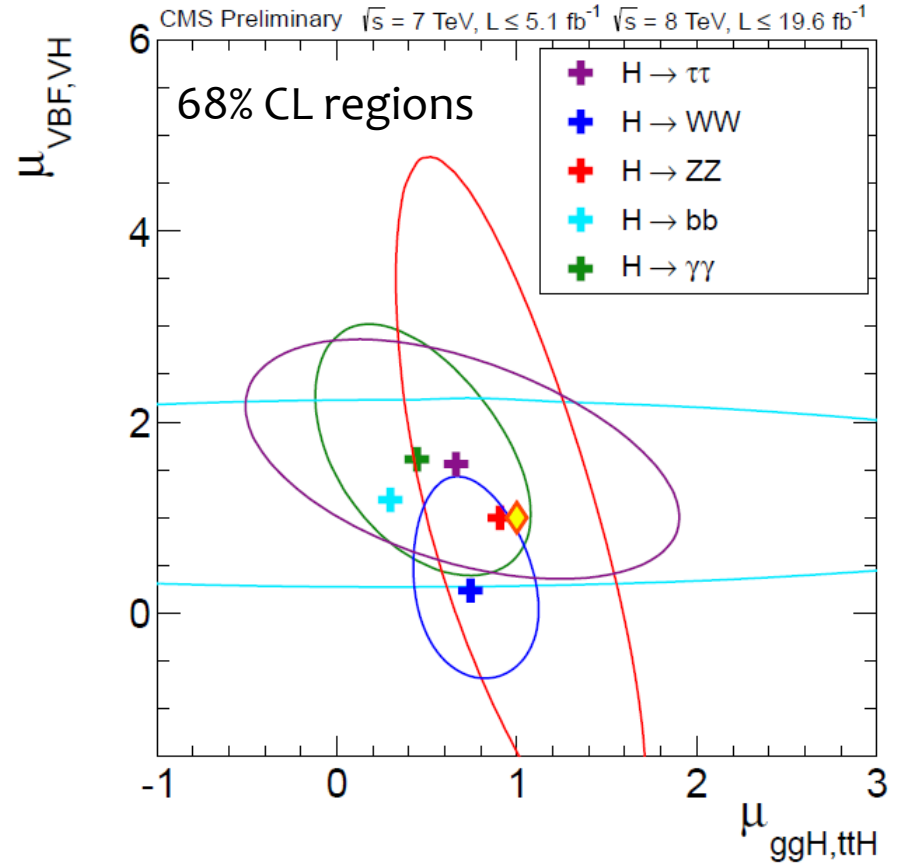
SM Higgs Signal Strength: Consistency

CMS HIG-13-005

Production modes
(not completely pure modes)



Test of quark/gluon production modes



$\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.4 \pm 0.4\text{-}0.3(stat)+0.6\text{-}0.4(sys)$

Independent of BRs

(Deviations of) Couplings

- Event yield in any final state, related to (at LO in EWK & NLO QCD)

$$\sigma(H) \times BR(ii \rightarrow H \rightarrow xx) = \sigma_{ii} \times \Gamma_{xx} / \Gamma_H$$

- Measure deviations from SM couplings by measuring ratios w.r.t. SM cross sections and partial widths predictions
- Introduce set of parameters

- Example: $gg \rightarrow H \rightarrow \gamma\gamma$ process

$$(\sigma \times BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H)\, BR(H \rightarrow \gamma\gamma) \bullet \kappa_g^2 \ \kappa_\gamma^2 / \kappa_H^2$$

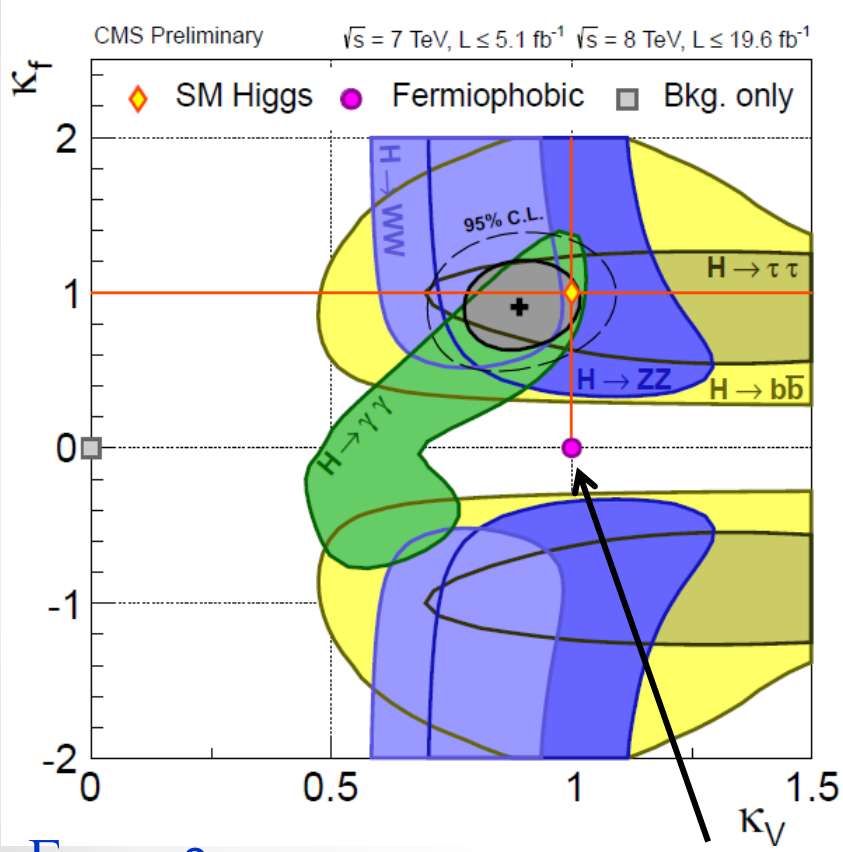
LHC XS WG benchmark models (arXiv:1209.0040):

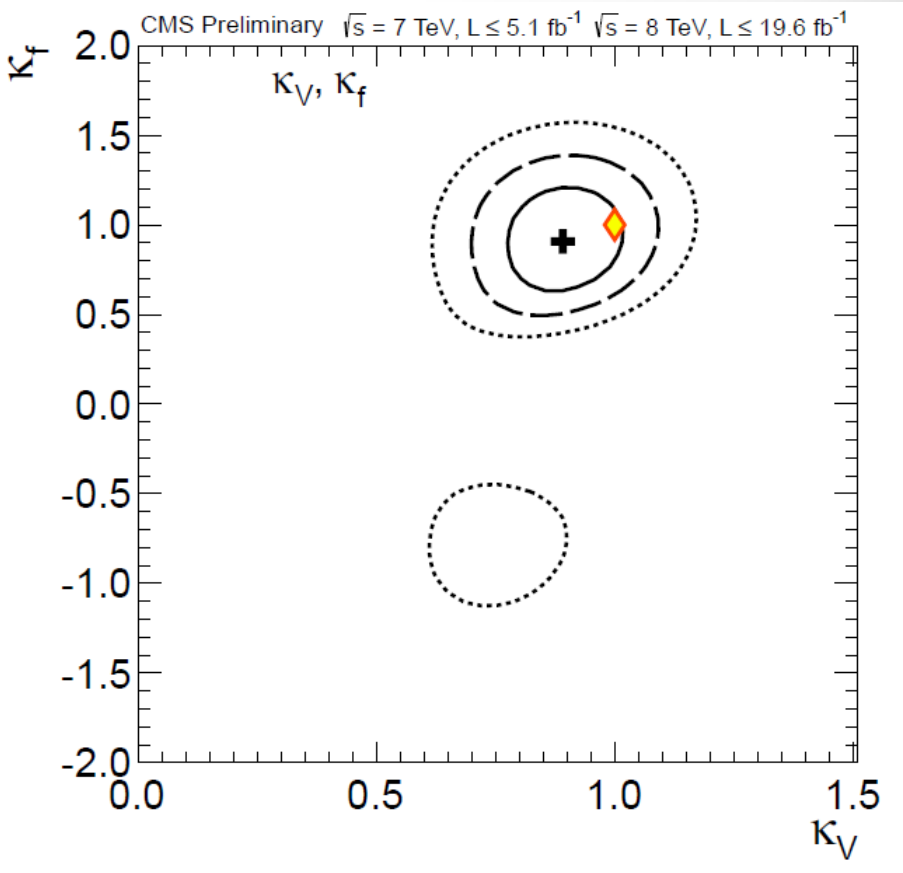
- Fermionic vs Bosonic couplings: k_V, k_f
- Search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq}
- Search for new physics in loops: k_g, k_γ, BR_{BSM}

Simultaneous fit of all couplings (also fixing some of them)

Fermionic vs Bosonic Coupling

Assume all fermion couplings scale with k_f, while all vector boson couplings scale as k_V





$\Gamma_{BSM} = 0$

$\Gamma(H\rightarrow\gamma\gamma) \sim |\alpha k_V + \beta k_f|^2$

W & top main loop contributors

α, β from SM predictions

Fermiophobic Higgs excluded (m_H~126 GeV)

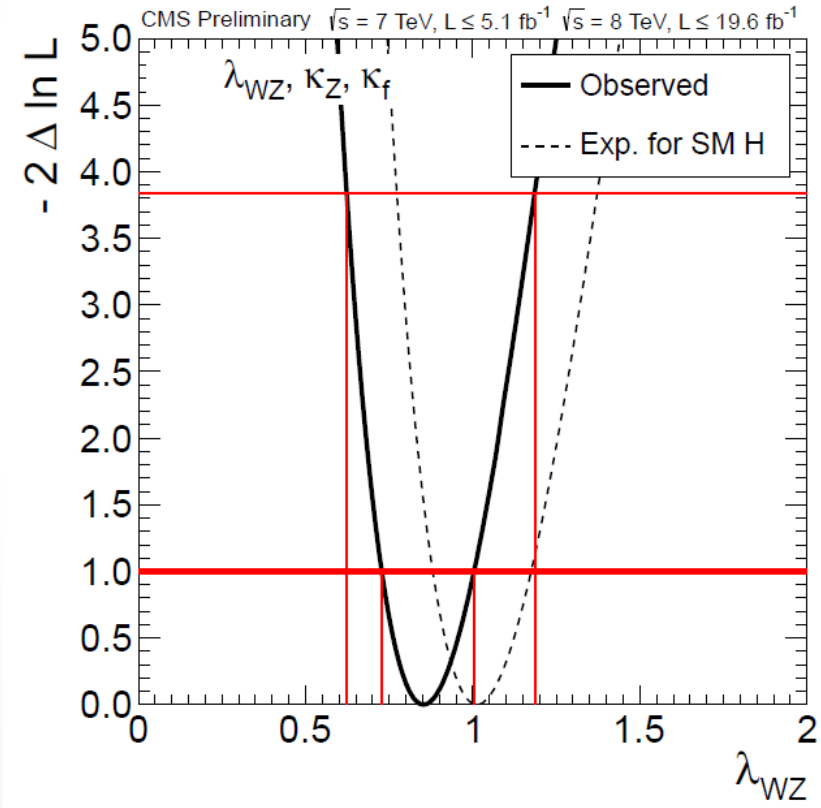
95% CL intervals

k_V :[0.74, 1.06] for k_f =1

k_f :[0.61, 1.33] for k_V =1

Custodial Symmetry

- SM predict very similar higgs couplings to W and Z bosons ➔ Test HWW (k_W) & HZZ (k_Z) couplings, through $\lambda_{WZ} = k_W / k_Z$
- If new physics exist, violations of custodial symmetry are possible



All channels combined, k_Z & k_W profiled $\Gamma_{BSM} = 0$

λ_{WZ} :[0.62, 1.19] 95%CL

Fermion Universality

- Test Up- vs Down-type fermion couplings & lepton vs quarks couplings
- Motivated by 2HDM models, where these couplings can be modified (decoupled from boson couplings)

lepton vs quarks couplings $\lambda_{lq} := \kappa_l/\kappa_q$, coupling to τ [0.89,1.62] @ 68% CL [0.57,2.05] @ 95% CL

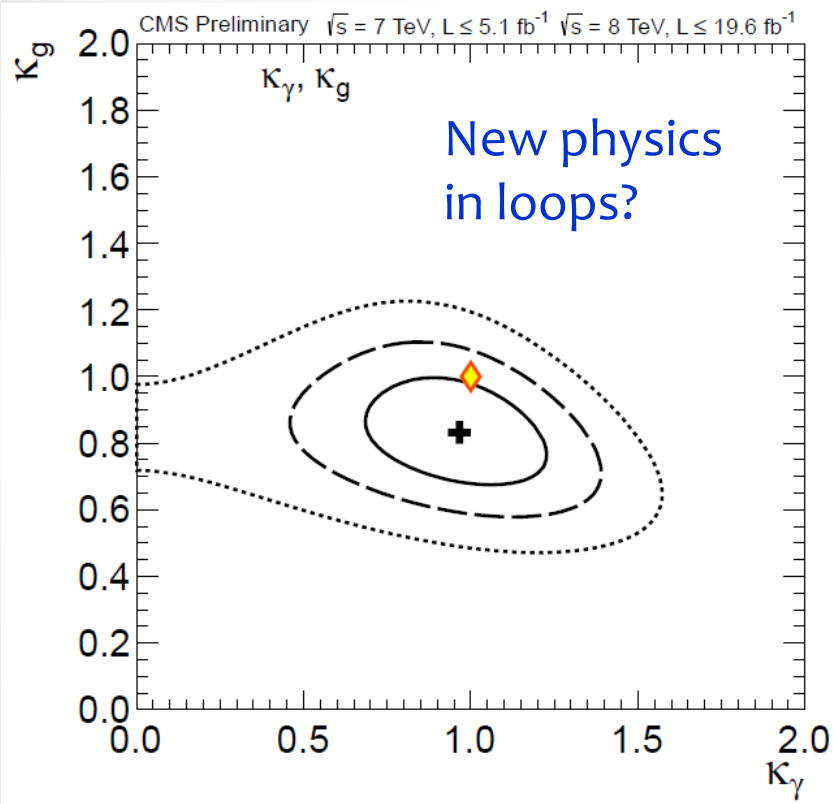
Driven by $\mu_{\tau\tau}$, larger than average

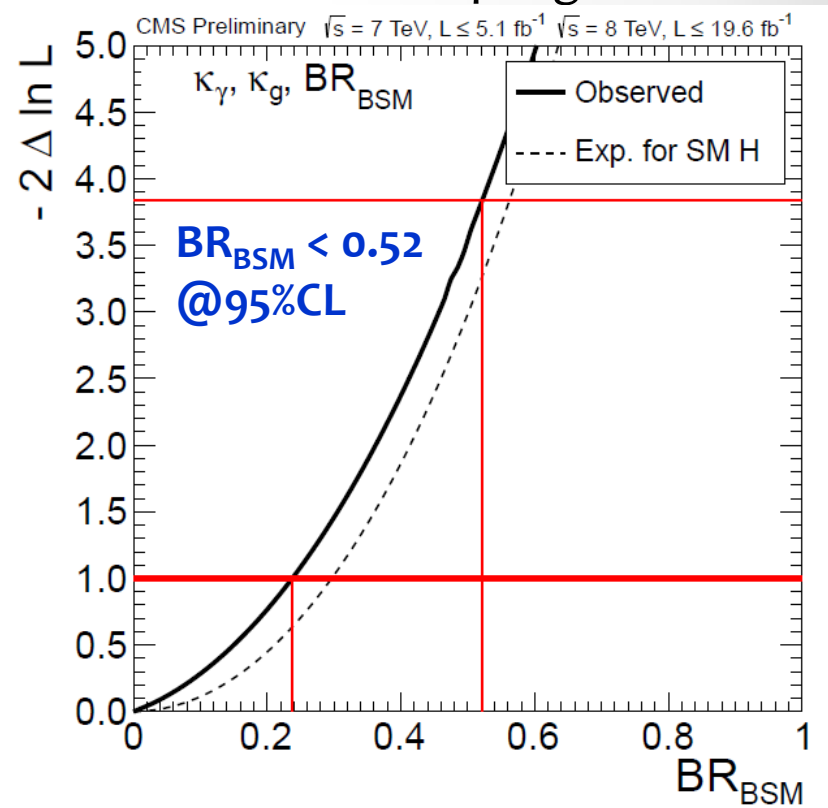
Up- vs Down-type fermion $\lambda_{du} := \kappa_d/\kappa_u$, Coupling to b and τ [1.00,1.60] @ 68% CL [0.74,1.95] @ 95% CL

Driven by low VV, $\gamma\gamma$ yields, compared to bb, $\tau\tau$

Searches for new physics (BR_{BSM})

Extra particles in loops or decays can generate deviations in couplings



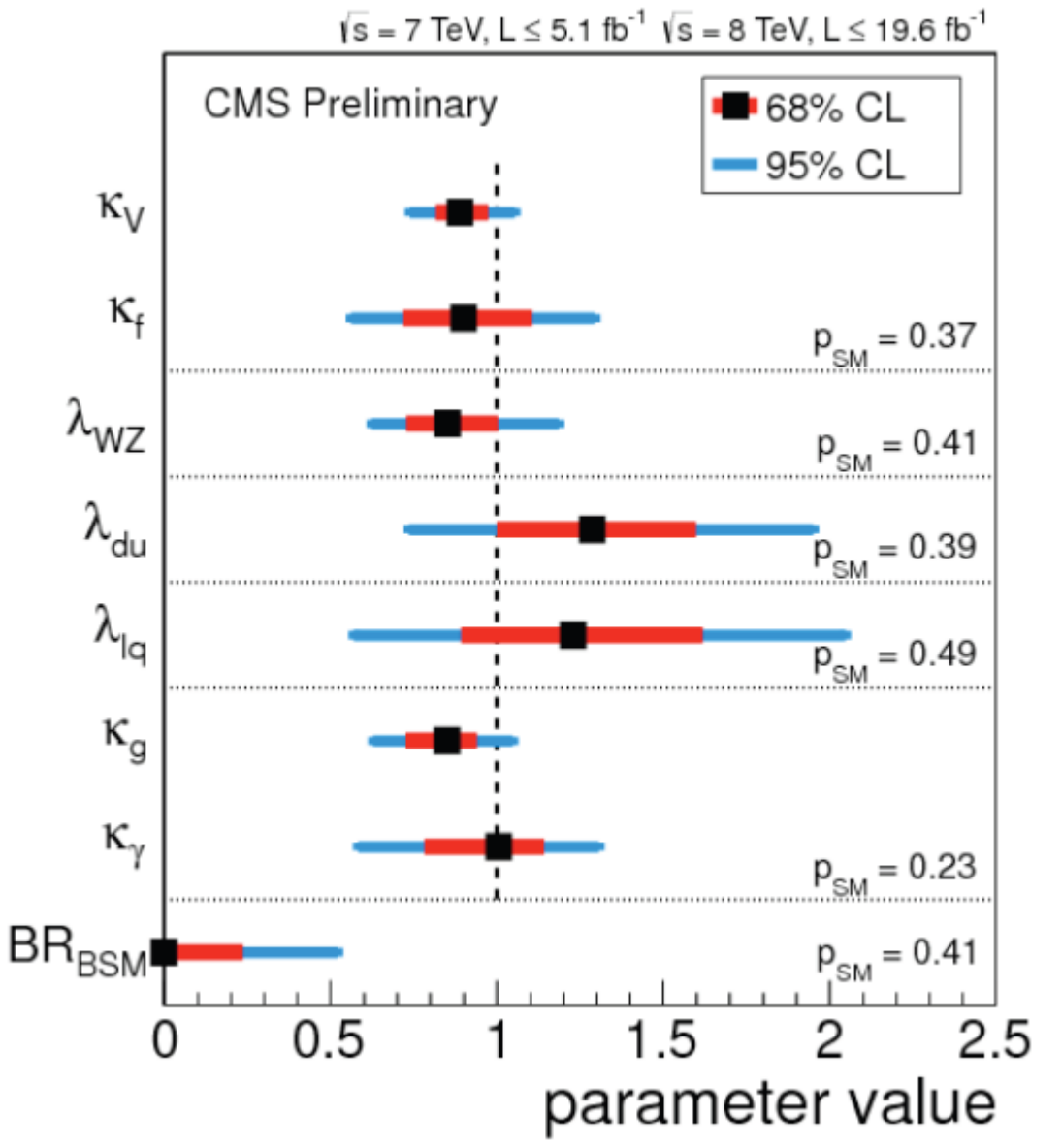


Effective couplings to gluons & photons

$\Gamma_{BSM} = 0$

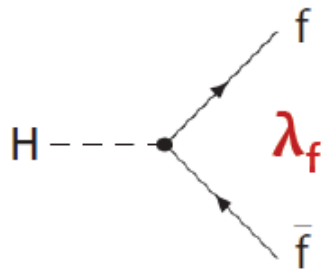
Loop-induced couplings free (kγ, kg profiled)
Allowed for extra particles in loops
Not using direct search for H→ invisible

Summary of coupling results

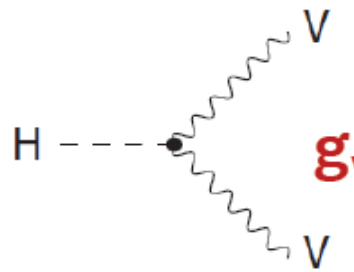


Coupling vs mass

Expressing Higgs couplings as a function of mass



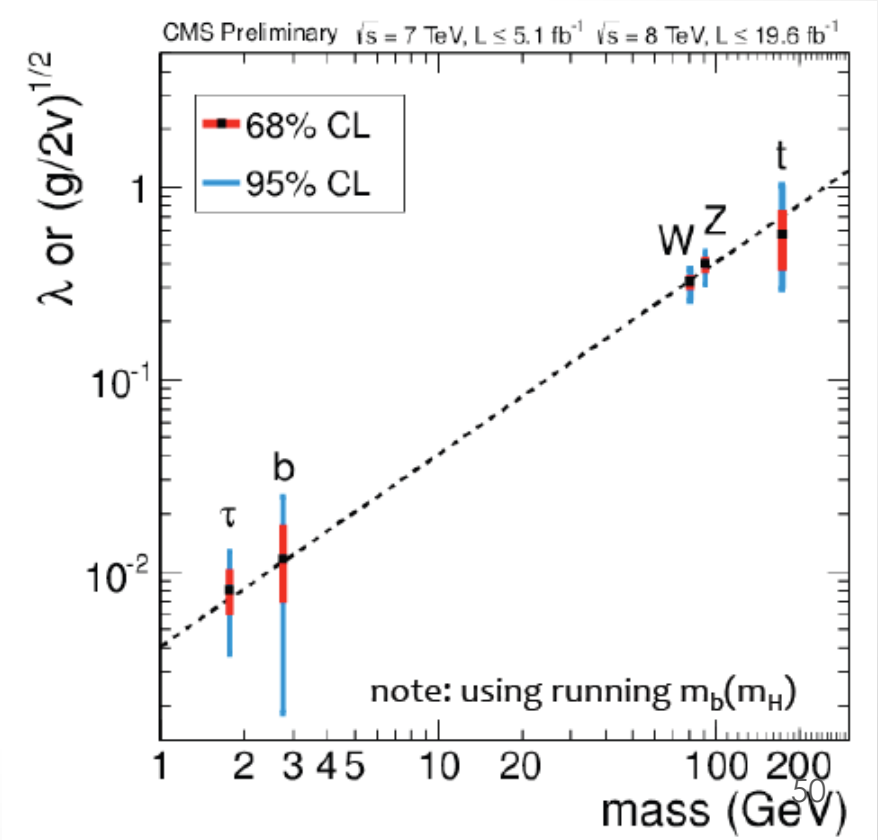
$\lambda_f = m_f / v$



$g_V = 2\, m_V^2 / v$

[e.g. Giardino et al, arXiv:1303.3570]

$$\lambda_f = \kappa_f\, m_f / v$$
$$g_v = 2\, \kappa_V\, m_V^2 / v$$

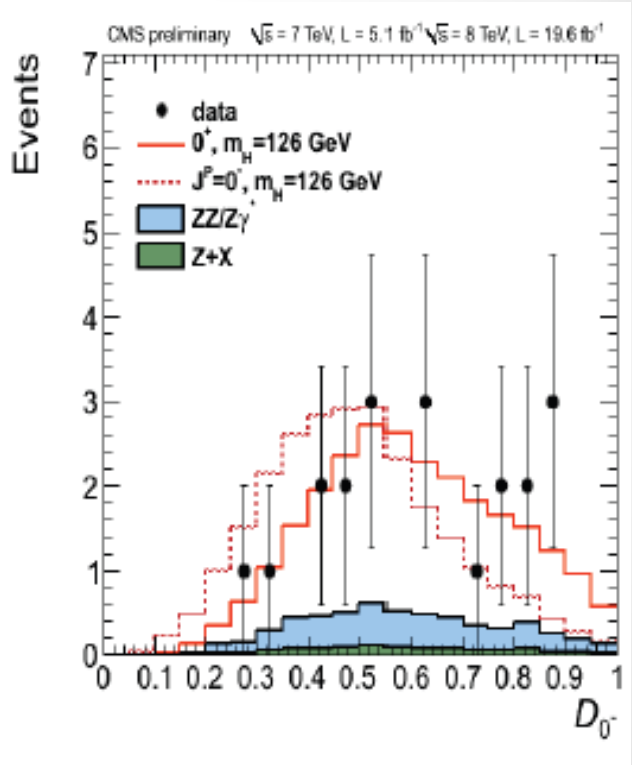


Spin

- Spin 0 is required if SM Higgs
- Spin 1 is excluded by $H \rightarrow \gamma\gamma$ decay (Landau-Yang theorem)
- Spin 2 induced by KK-graviton couplings

Parity:

- SM CP-even Higgs
- BSM CP-odd HIggs



Exploit kinematical variables distributed differently for one or other hypothesis of J^P

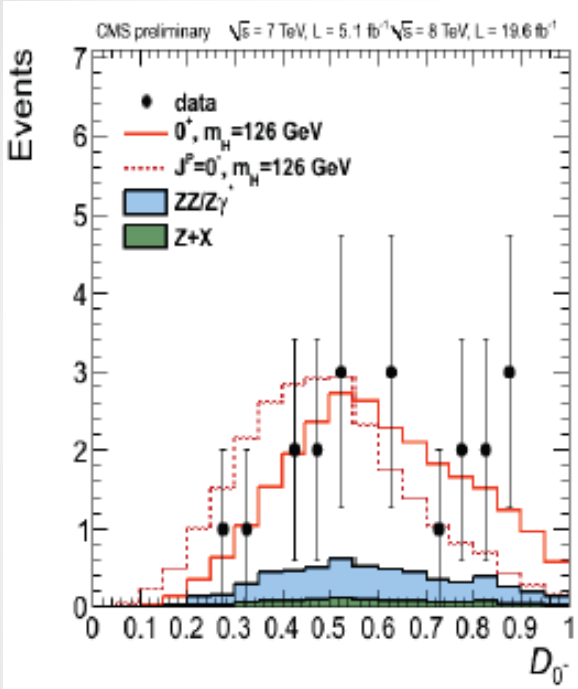
Using mainly $ZZ \rightarrow 4l$, but also $H \rightarrow WW$ and $H \rightarrow \gamma\gamma$ data samples

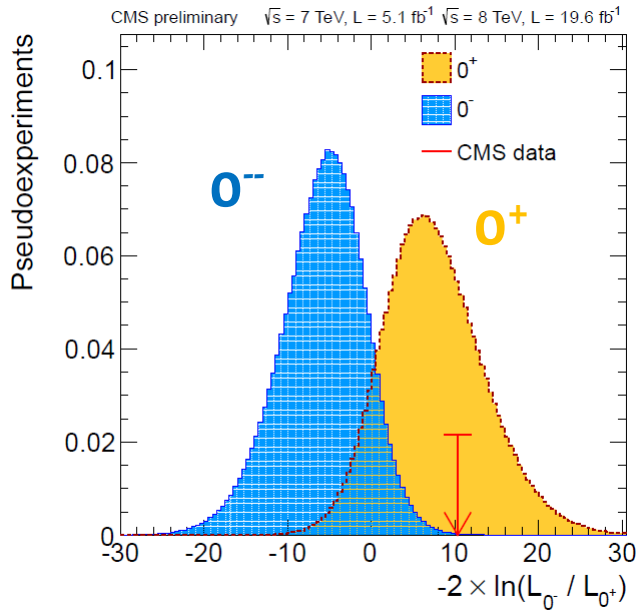
Several alternative models tested: 0^-, 0^+_h, 1^+, 1^-, $2^+_m(gg)$, $2^+_m(qq)$

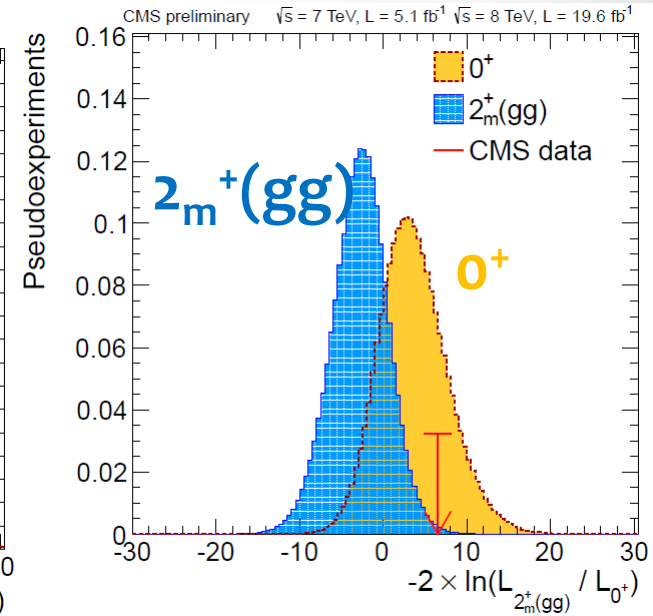
State $J^P = 0^+$ preferred.

Spin

Exploit kinematical variables distributed differently for one or other hypothesis of J^P







$$CLs\left(0^-/0^+\right)=0.16\%, CLs\left(2^+/0^+\right)=1.5\%$$

J^P	CL_s
0^-	0.16%
0^+_h	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

Using ZZ→4l and H →WW data samples

Several alternative models tested: 0-, 0^+_h, 1^+, 1^-, 2^+_m(gg), 2^+_m(qq)

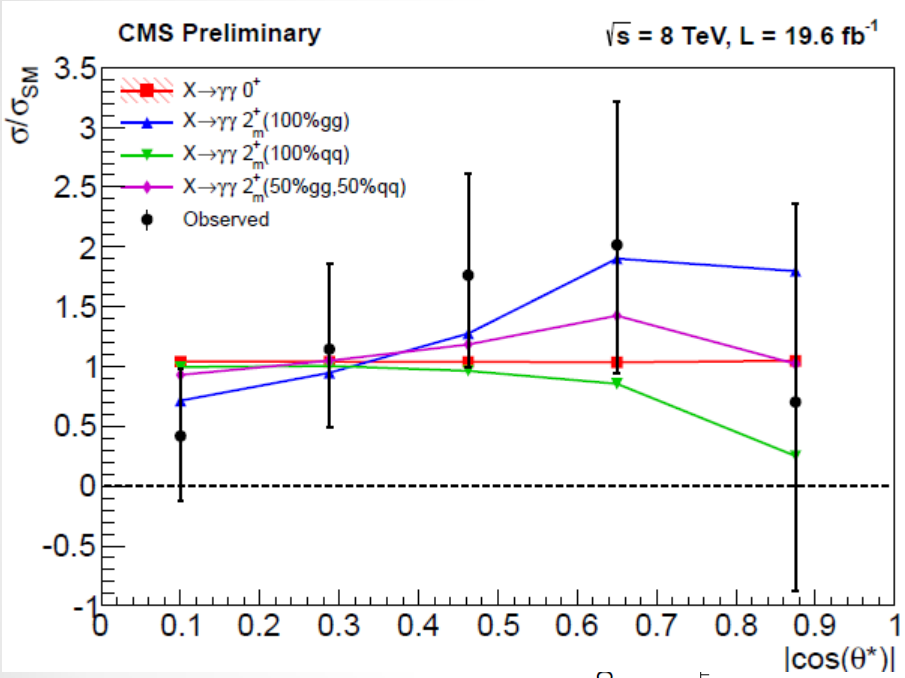
State $J^P = 0^+$ preferred.

Spin from H→γγ

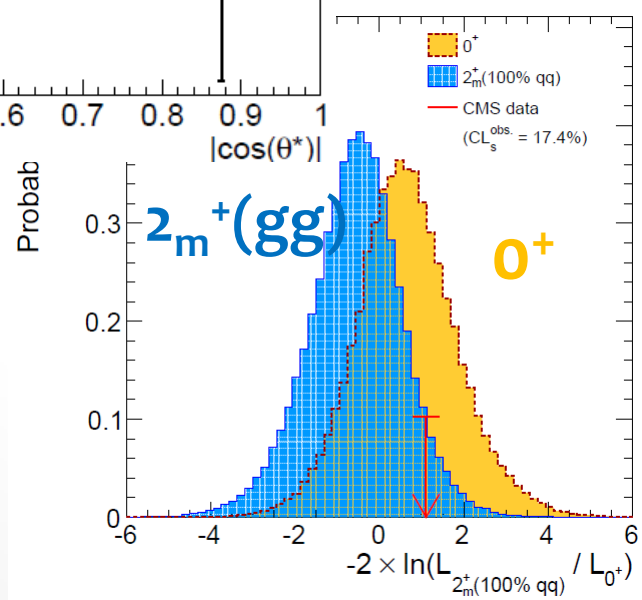
CMS HIG-13-016

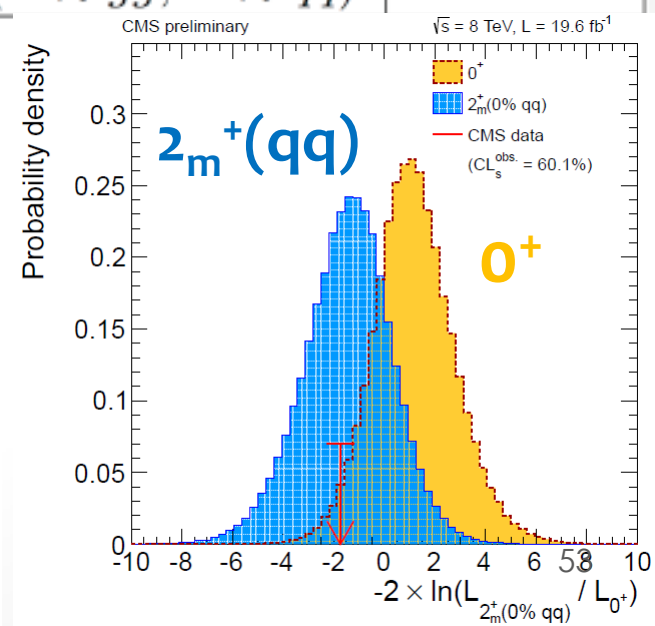
- Spin 0^+ or 2^+_m (graviton-like) (from gg or qq interactions) tested
- Decay angle $\cos\theta^*$ in diphoton rest frame

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



Compatibility results from Spin-Parity analysis	
Source	χ^2 p-value
Data vs. 0^+	0.68
Data vs. 2^+_m (100% gg)	0.91
Data vs. 2^+_m (100% $q\bar{q}$)	0.51
Data vs. 2^+_m (50% gg, 50% $q\bar{q}$)	0.81





Data compatible with 0^+ state, but 2^+_m cannot be ruled out.

Other channels

Search for high mass Higgs

CMS HIG-12-024, 13-014

- Models predict Higgs doublets (2HDM) or other Higgs-like resonances at higher mass (EWK singlets).
- Use SM Higgs as a benchmark (similar gg/qq contributions to total production)
- Scan different relative widths and BR
- ZZ and WW decay modes dominant at high mass

95% CL limits on SM Higgs

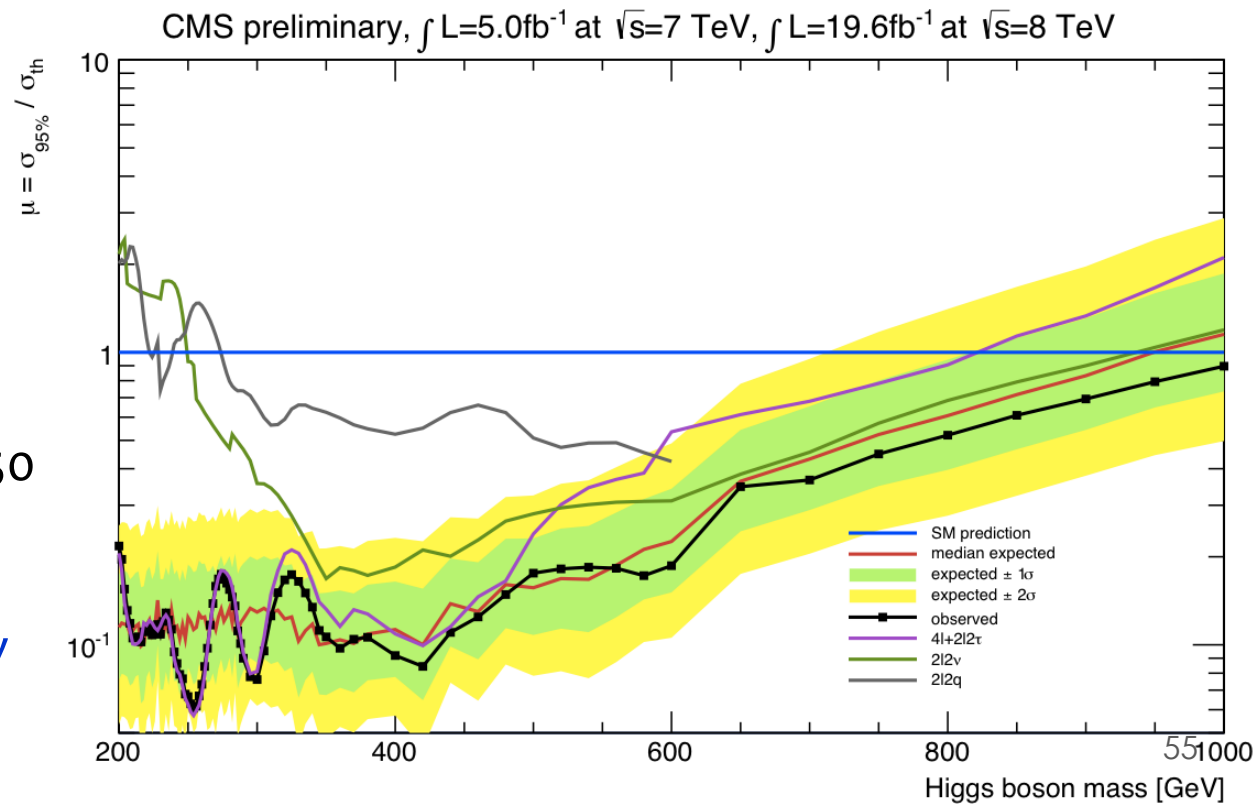
- WW channel:

$128<m_H<600$ GeV (115-575 expected)

- ZZ channel

$200<m_H<1000$GeV (200-950 exp.)

ZZ excludes m_H up to 1 TeV



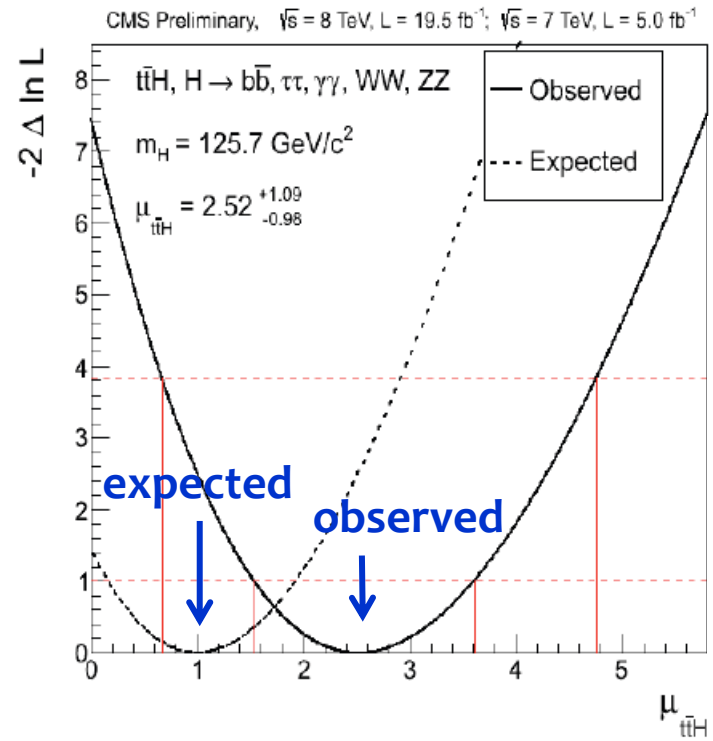
Couplings to top quark, ttH

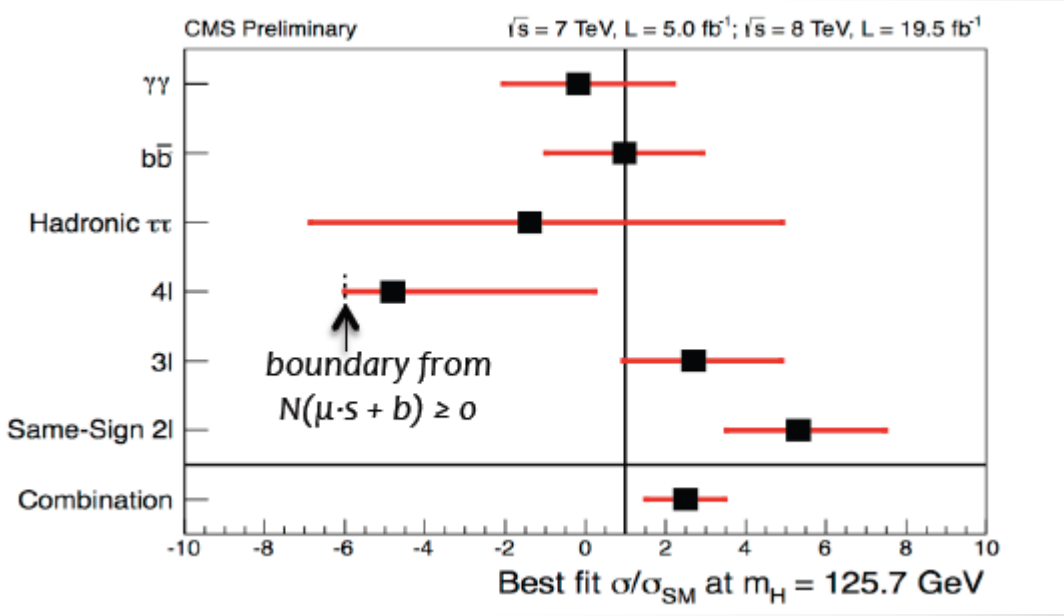
CMS HIG-13-019, 020, 015

Important to measure ttH coupling, any special role in EWKSB due to top mass?

Combination of several decay channels analysed

- tt→W bWb →lν b qq'b (l+jets), lνlν bb (dilepton)
- H →bb, $\tau_h\tau_h$, γγ, ZZ*,WW* (into leptons)



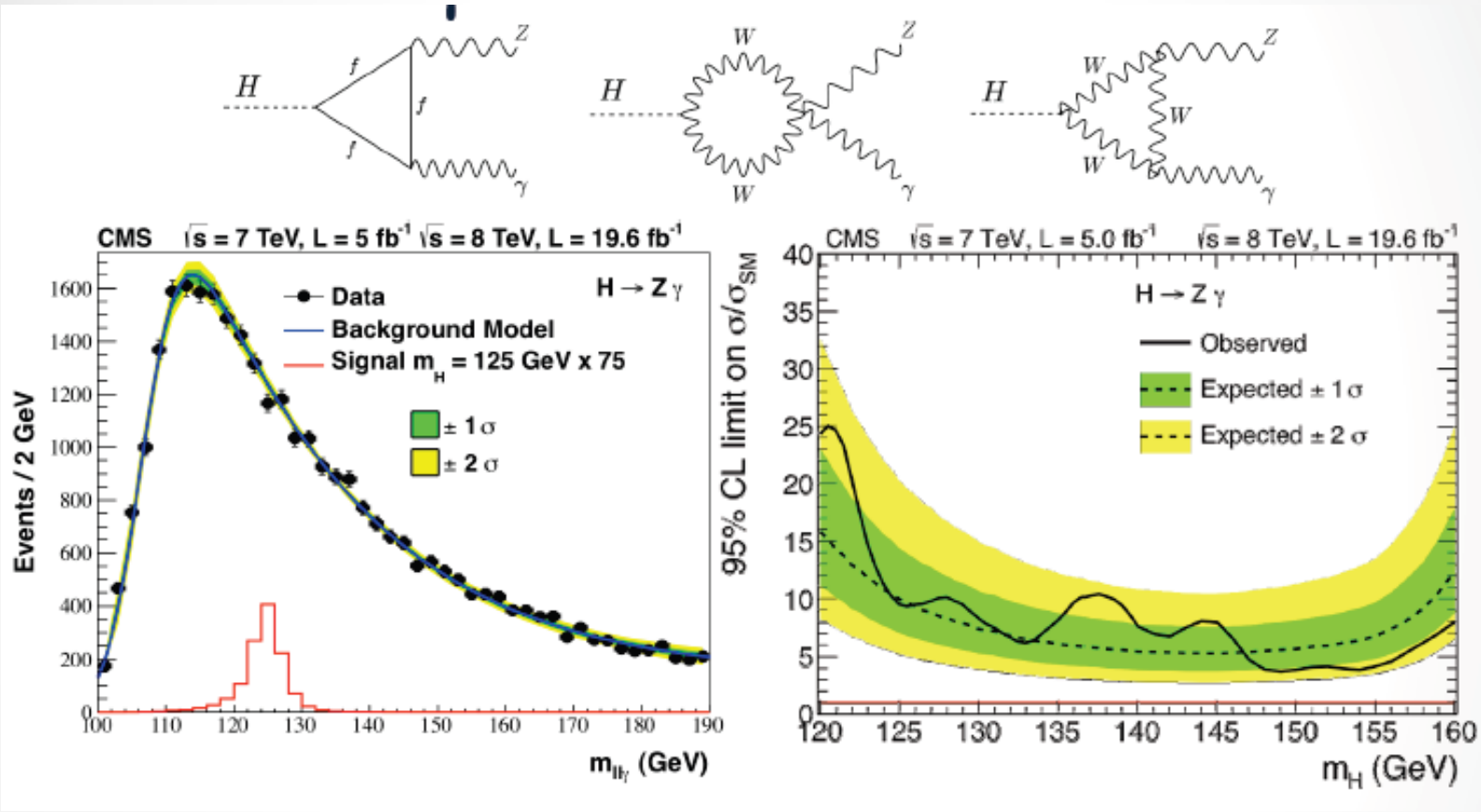


Already at SM sensitivity on μ(ttH)!! (was 2.6xSM at Moriond'13)

Run2 data needed to asses accurately the nature of the coupling ttH

H→Zγ (Z → e, μ)

CMS HIG-13-006
arXiv: 1307.5515



Not yet sensitive at SM level

- Search motivated by potential new physics contribution (loops of heavy charged particles)
- Includes VBF process (increases 15% in sensitivity)

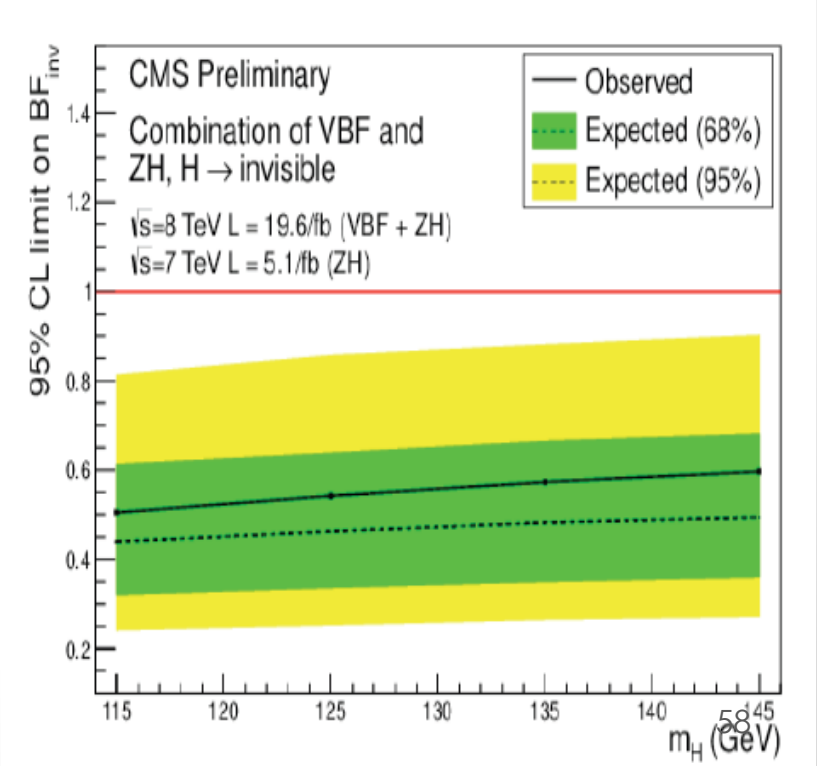
H to invisible (VH & VBF)

CMS HIG-13-018, 013, 028

- In SM, H $\rightarrow$ inv proceeds through H $\rightarrow$ ZZ $\rightarrow$ 4ν (BR ~0.1%)
- Possible sign of new physics, like
  - H decays to LSP (➔ relation with DM), or
  - decay particles into extra-dimensions (undetected decay mode).
- Studied
  - Higgs$\rightarrow$ inv recoiling against a visible system (Z $\rightarrow$ ll, bb) New
  - Higgs $\rightarrow$ inv from VBF, accompanied by 2 jets with large rapidity gap and invariant mass and high MET.

Combining ZH(Z $\rightarrow$ ll) and VBF,
95% upper limit on BR(H $\rightarrow$ inv)
Observed: 54%
Expected: 46%

To be included in couplings fit, assuming
BR_{BSM} = BR(H $\rightarrow$ inv)
Next combination with H $\rightarrow$ inv, Z $\rightarrow$bb



$H \rightarrow \mu\mu$

CMS HIG-13-007

- Search for $H \rightarrow \mu\mu$ in the context of SM Higgs and MSSM
- Interesting measurement 2nd generation fermion-Higgs coupling, g_μ
- Extremely small BR (~2.2 x 10-4)
- Inclusive (ggF) and VBF
- Results: ~4xSM sensitivity on $\mu=\sigma/\sigma_{SM}$

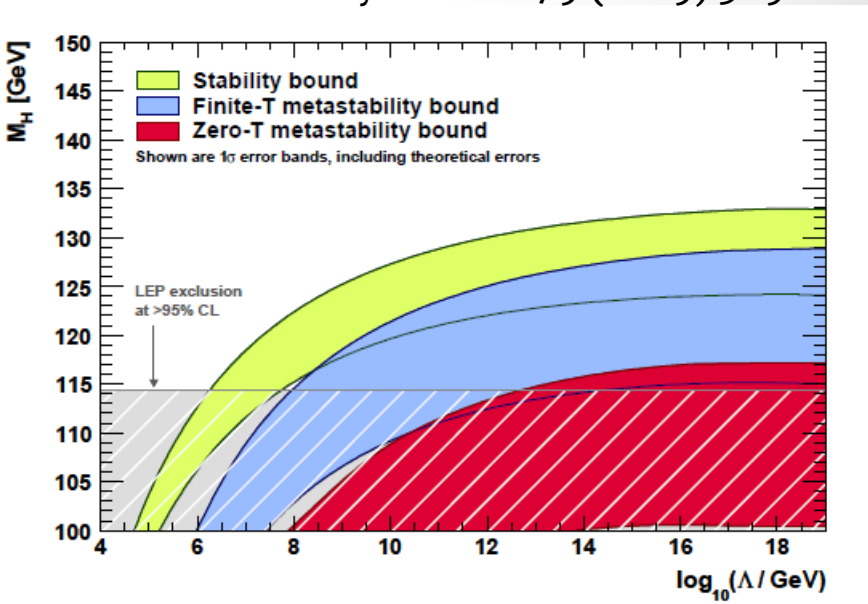
- In the future, test Hcc couplings measuring $H \rightarrow J/\psi\gamma$ (BR ~10^{-6}) once probed excellent CMS reconstruction of quarkonia.

So, where are we today?

- The boson found at 125 GeV looks rather "standard" scalar from all checks done up to now ➔ SM Higgs boson

- That brings implications on which kind of vacuum we live in
  - Check vacuum stability up to Planck scale M_{Pl}~10^{19} GeV

Ellis et al. Phys Lett B679 (2009) 369.



- Values of m_H and m_T seem to indicate we are in a highly fine-tuned situation of stability/metastability ➔ important to measure this masses with high precision!

- Look for BSM Physics
  - Dark Matter
  - Search for SUSY
  - Other Exotica
  - Neutrino mass

SUSY Higgs sector

- Simple extention: Two Higgs-doublet model (2HDM) (7 free parameters)
- Types distinguished based on how they couple to fermions.
  - Type I 2HDM, only one doublet couples to fermions.
  - Type II 2HDM, a symmetry is imposed so that one doublet couples to up-type fermions and the other couples to down-type fermions.
  - Type III and IV couplings to leptons and quark-types differ.
- Two neutral CP-even (h, H), one neutral CP-odd (A) and charged CP-even (H+, H-).

In MSSM (Minimal Supersymmetric Model)

2 scalars Higgs doublets, Hu, Hd

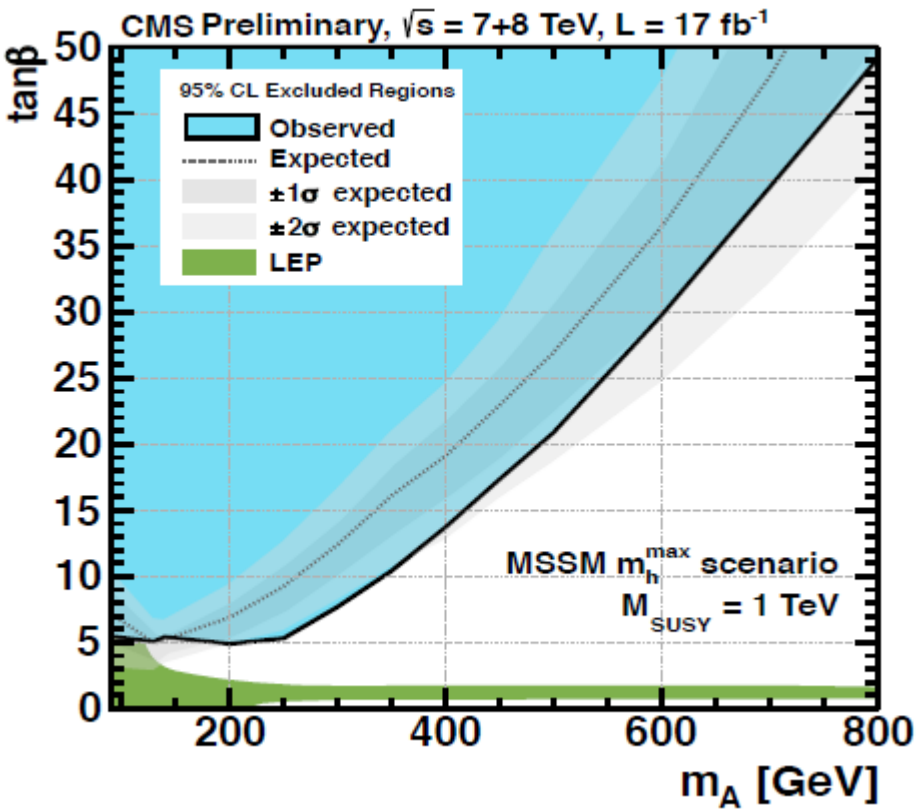
- **5 physical scalars**
  - **3 neutral** $\Phi = h, H(CP-even)/A(CP-odd)$
  - **2 charged** $(H^{\pm})$
- Determined by two parameters at tree level
  - $tan\beta = < H_u > / < H_d >$
  - M_A
- *h* boson
  - behavior as the **SM** Higgs boson

SUSY Higgs sector

Searches performed for

- $\Phi \rightarrow \tau\tau$, bb, $\mu\mu$
- $H\pm$

Eg: $\Phi \rightarrow \tau\tau$ exclusion limits

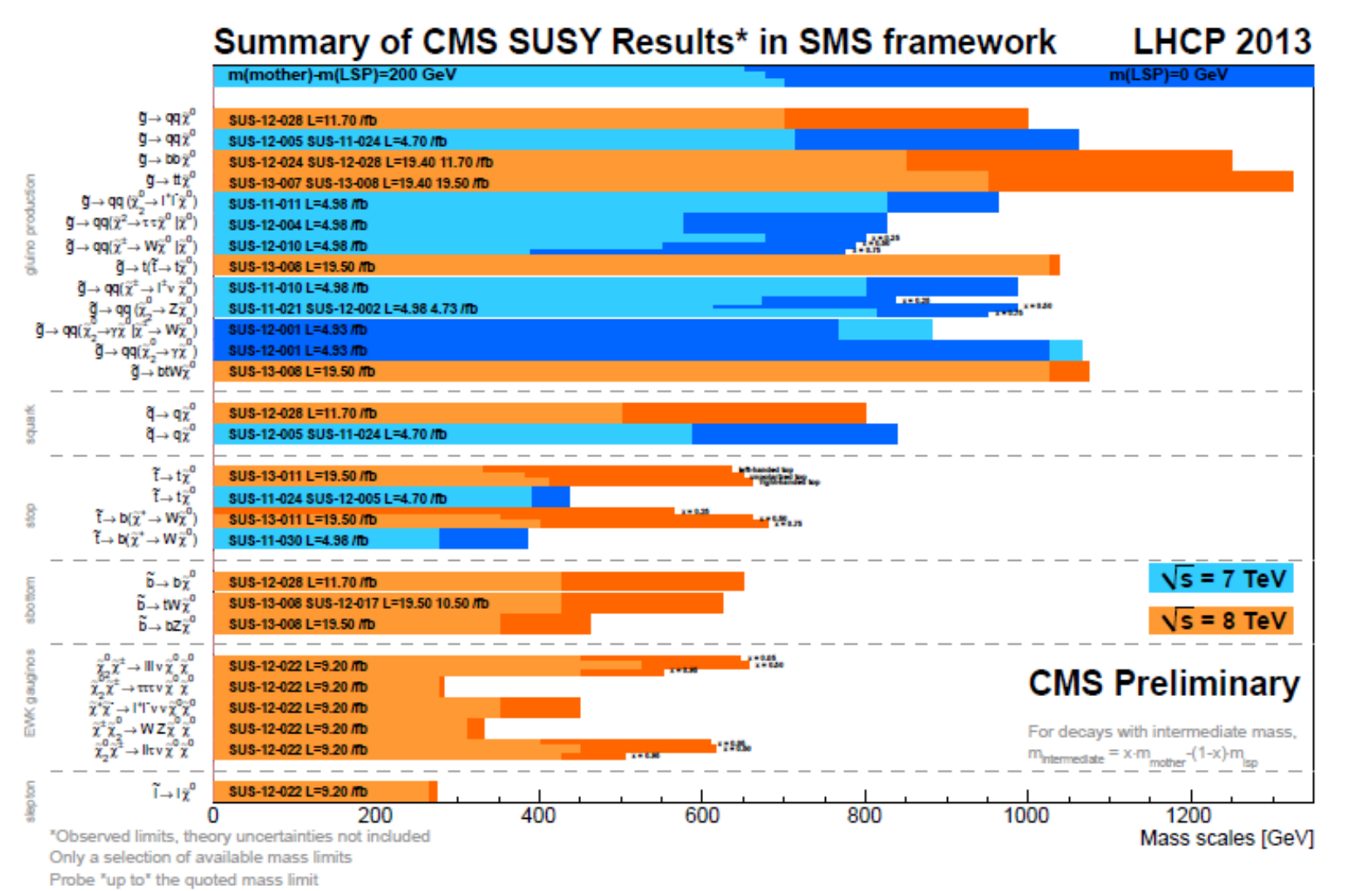


No evidence of a BSM Higgs boson

➔ Limits have been set on the MSSM parameters

SUSY Summary

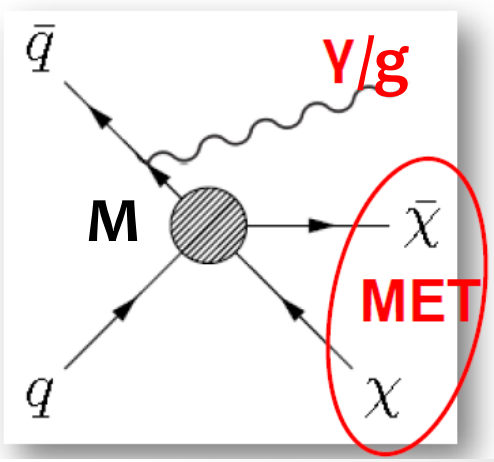
Up to now, no sign of SUSY!

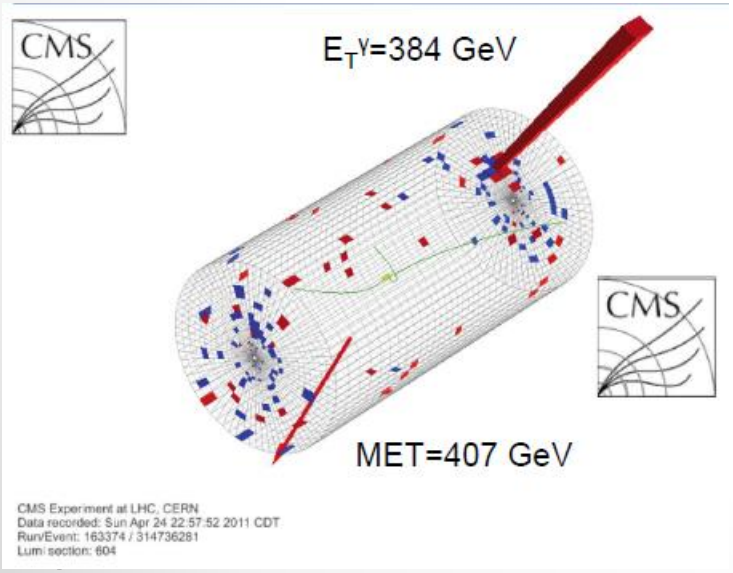


Dark Matter?

- Dark Matter existence is well established based on gravitational effects
  - Neutral and stable massive particle
  - No SM candidate, but can interact with SM particles

- LHC can provide alternative, complementary way to search for DM
  - Direct detection (DM-nucleon scattering)
  - Indirect detection (DM annihilation)





- Undetectable (as neutrinos)
- Signature: monophoton/monojet + MET

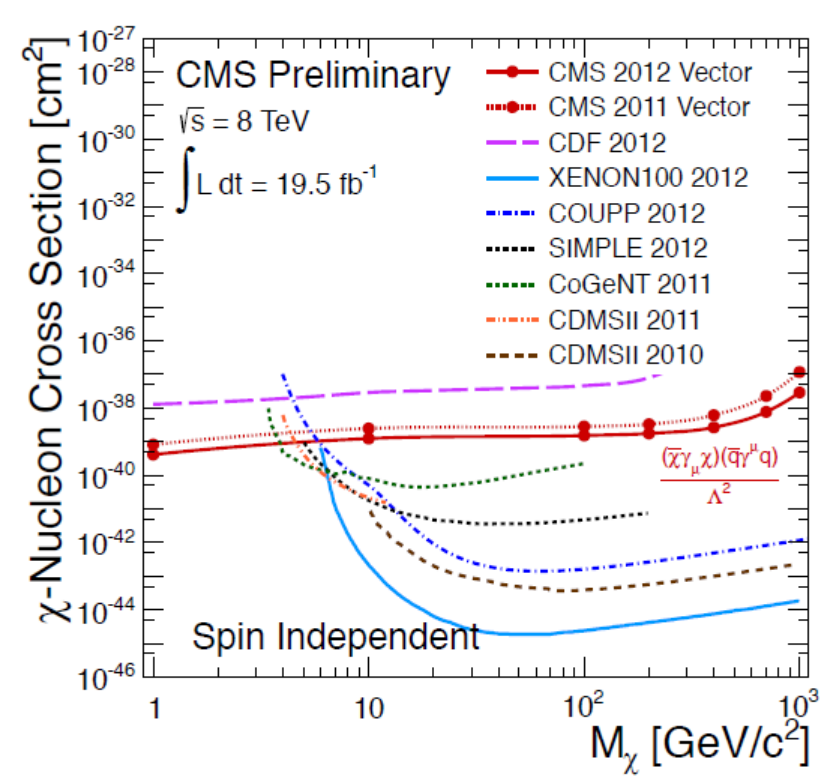
Dark Matter?

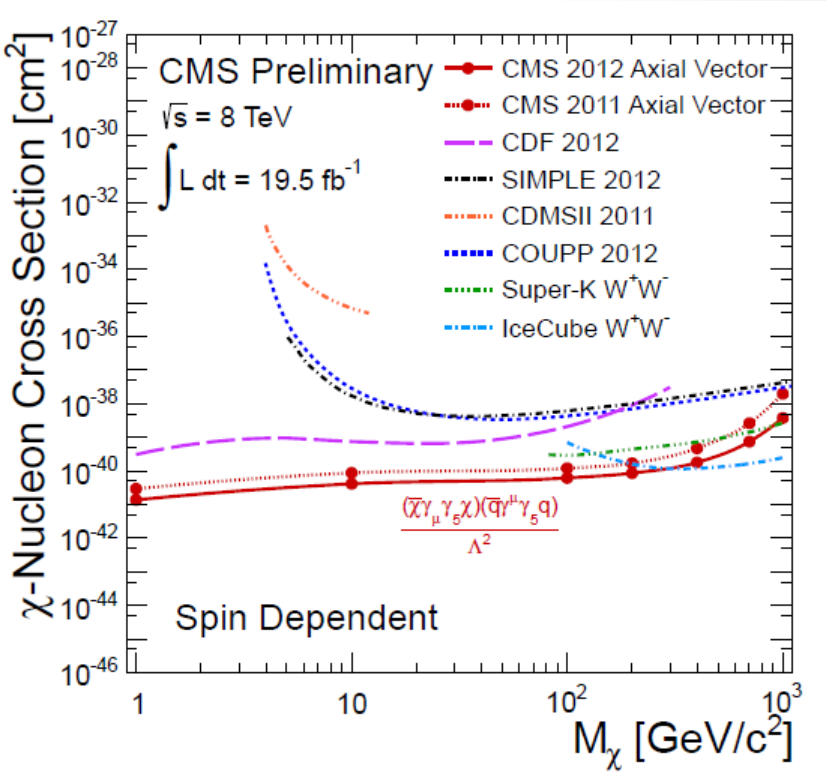
CMS EXO-12-048

In effective theory, mediator M can be

- Vector mediator ➔ spin dependent
- Axial-vector mediator ➔ spin independent

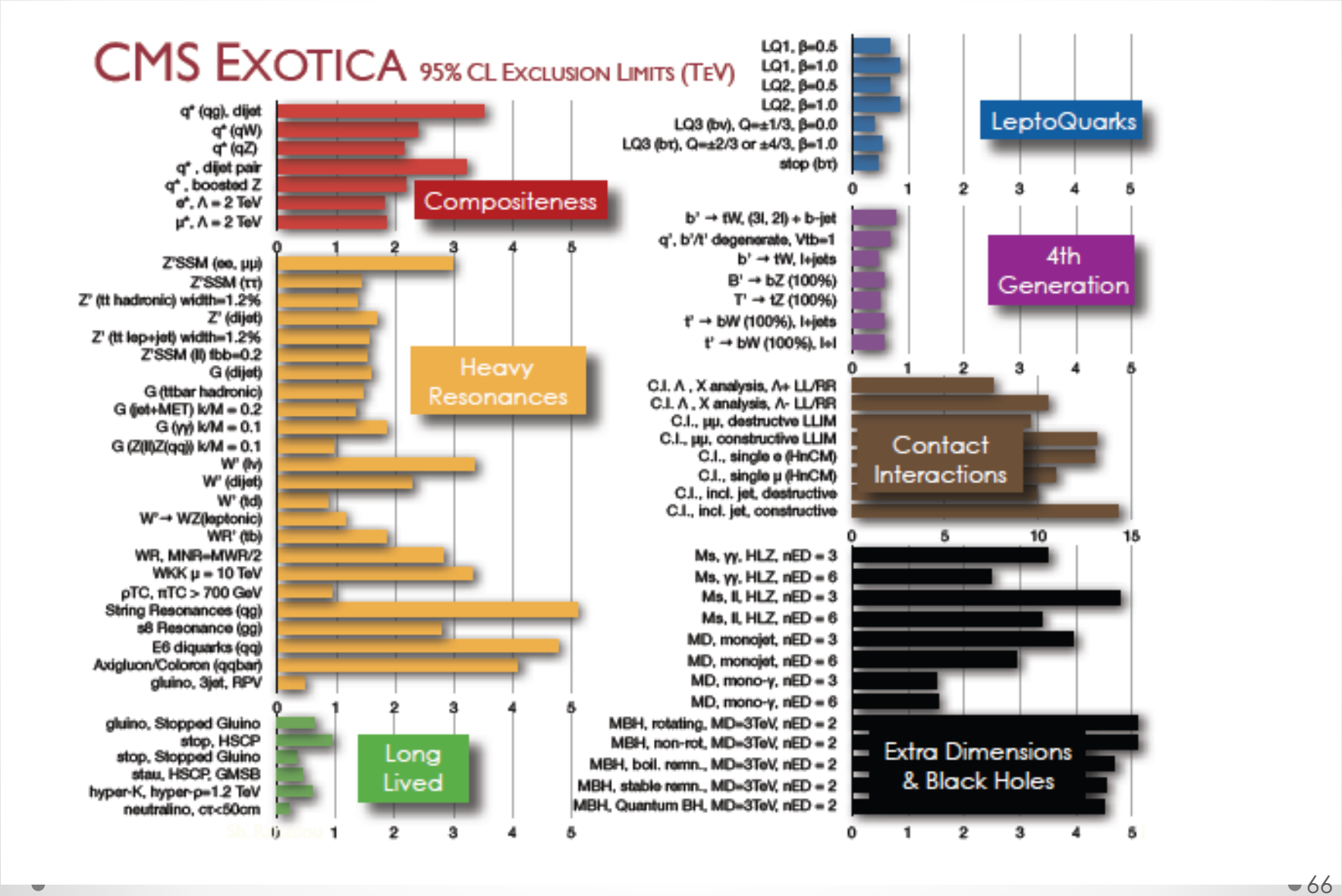
No excess of data over SM prediction ➔ limits on DM production cross section





- Assumption: DM are Dirac fermions

Seaches for Exotica



Summary/Outlook

- CMS is carrying a whole program of precision measurements and searches, yielding a major discovery.
- Properties of the Higgs bosons discovered already being established ➔ SM Higgs boson
  - rare decays channels, couplings: need Run2 data (~100 fb^{-1}, ~2016)
  - Higgs self-coupling will require longer, O(1ab^{-1}) at HL-LHC

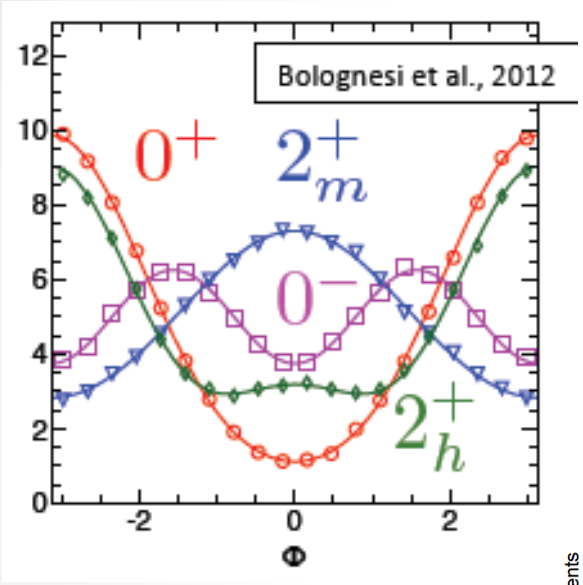
- LHC is currently taking a short break, till 2015, to come back at ~13 TeV
- Already looking forward for what the 13-TeV-LHC will bring us!

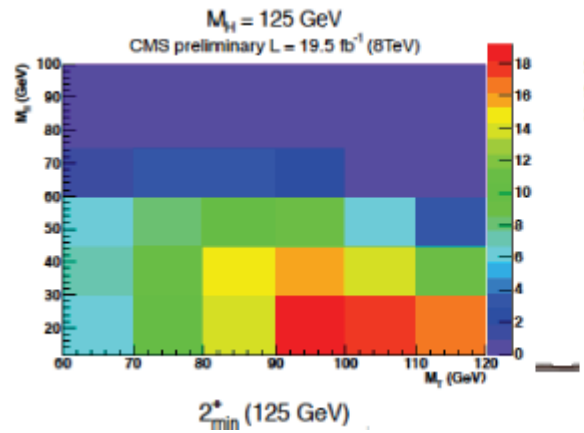
Backup

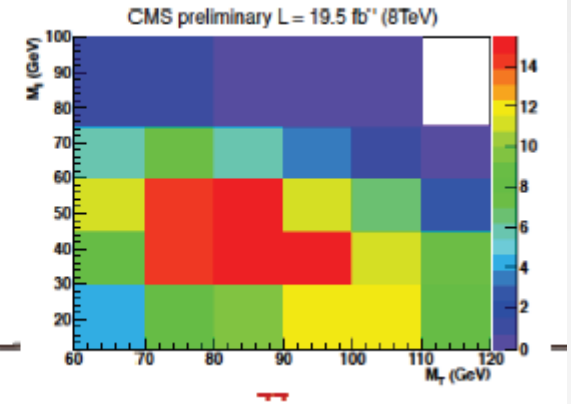
Spin from H→WW

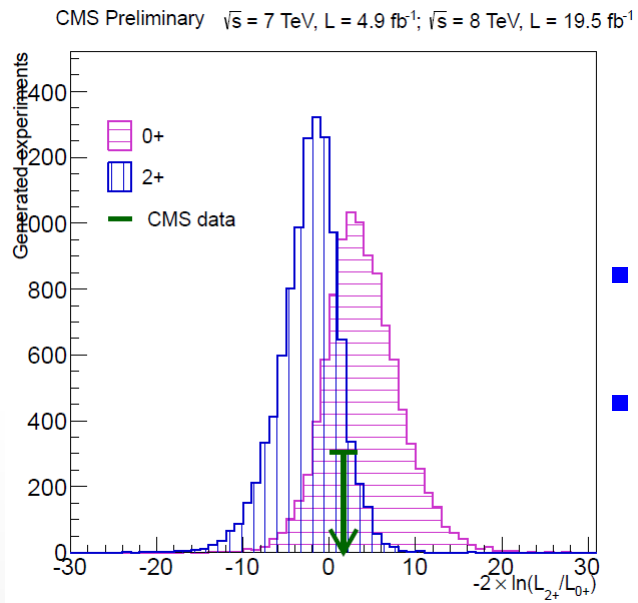
Kinematical variables sensitive to J^P: $\Delta\phi_{ll}$, M_{ll}, m_T ...

Make use of spin correlation in $H \to WW^* \to l\nu l\nu$ decay.









$CL_S(2_m^+/0^+)$ =14%

- SM H includes gg,VBF, VH processes
- 2_m^+ only gg (JHUGen)