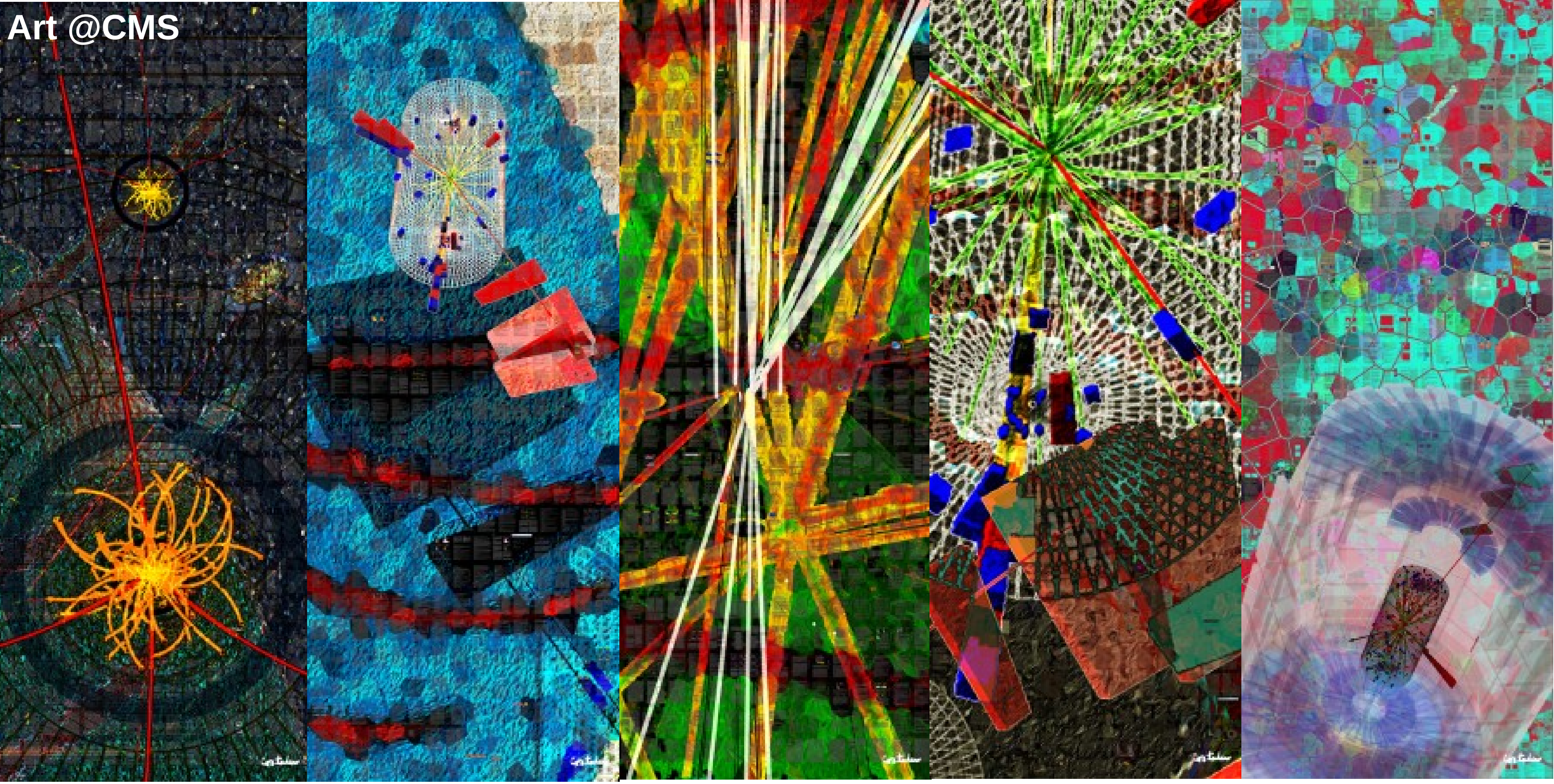
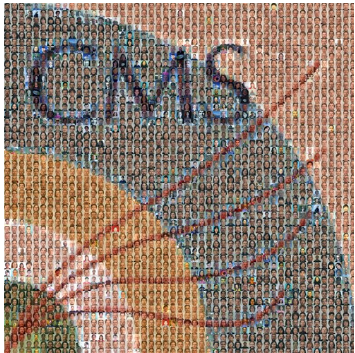


Latest Higgs results from CMS

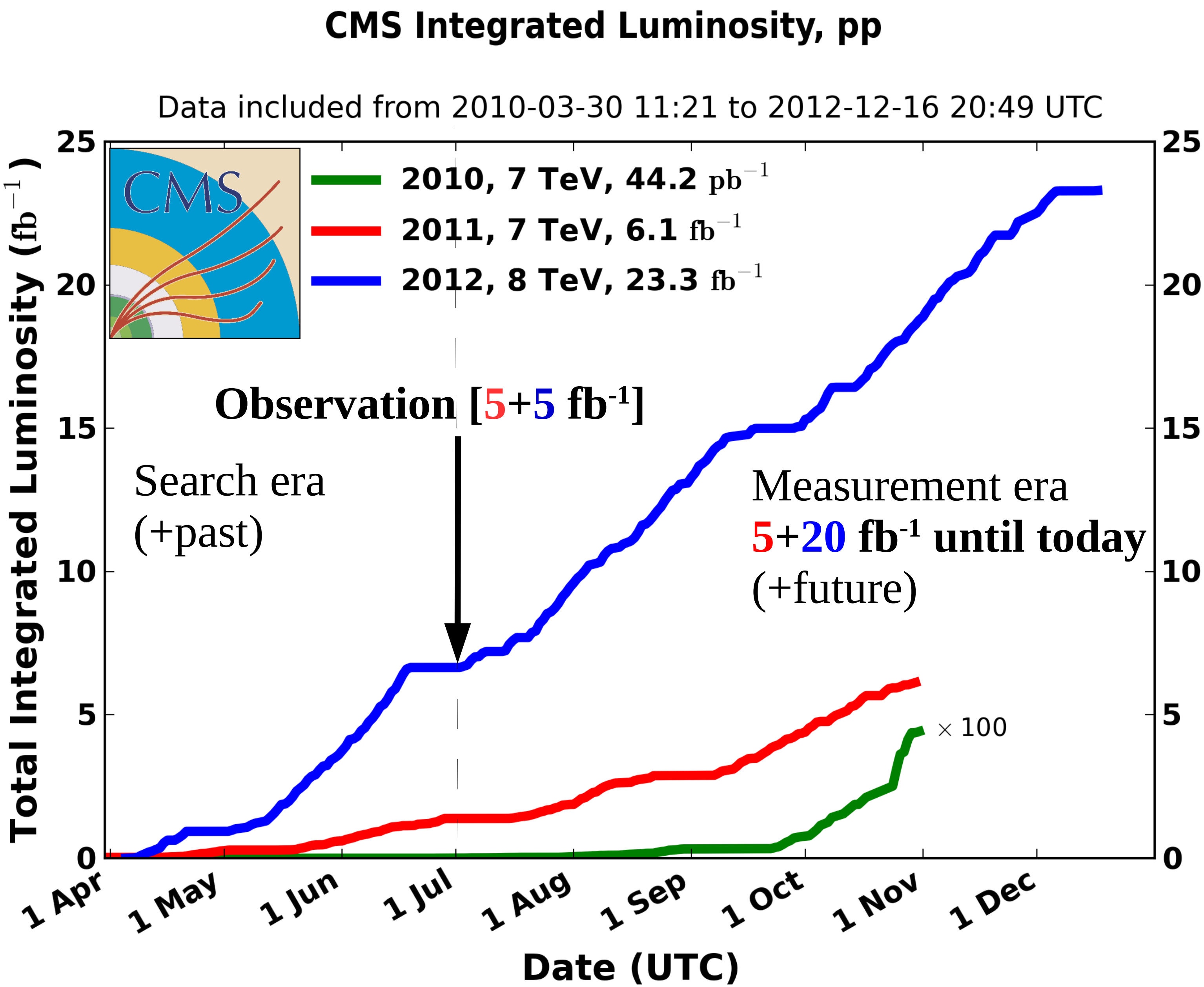


M.Bachtis (CERN)
on behalf of the CMS Collaboration

Introduction

- The observation of a new boson at the LHC started an era of precision measurements for the characterization of the new state
- Today, two years later, CMS closes chapter on Higgs measurements with the final harvest of results from the full Run I dataset

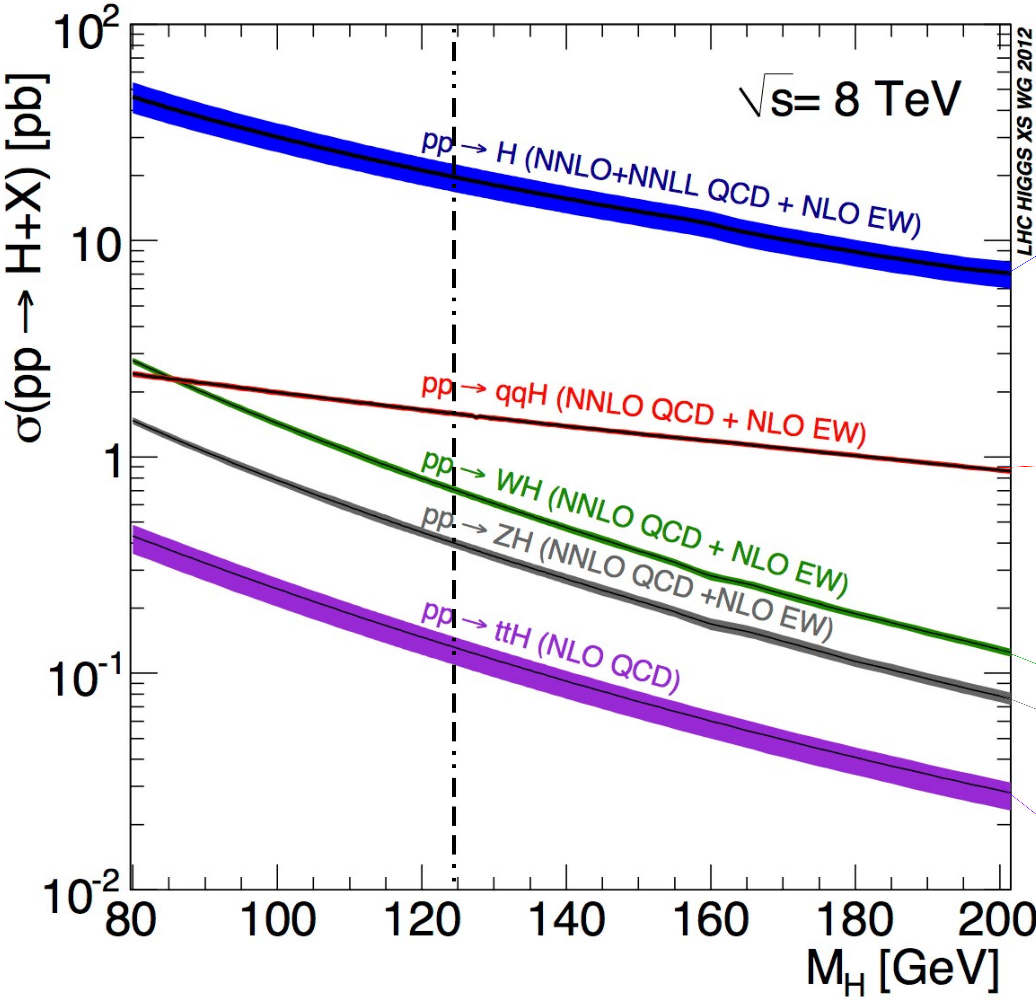
Data sample



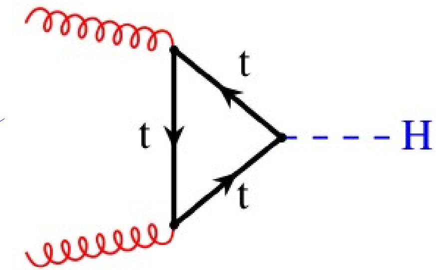
CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
Observation [5+5 fb⁻¹]
Search era
(+past)
Measurement era
5+20 fb⁻¹ until today
(+future)
× 100
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
0
5
10
15
20
25

Higgs production @ the LHC

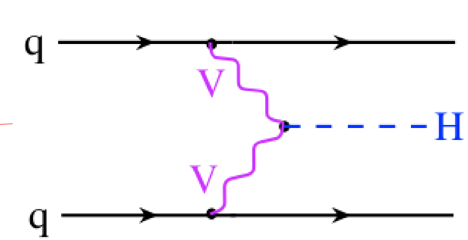
we are here



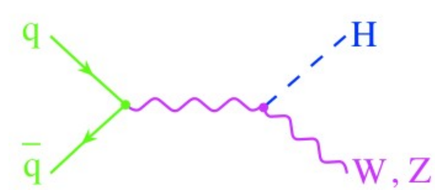
gluon fusion



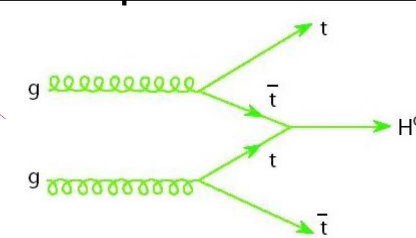
vector boson fusion



Assoc. production with W,Z

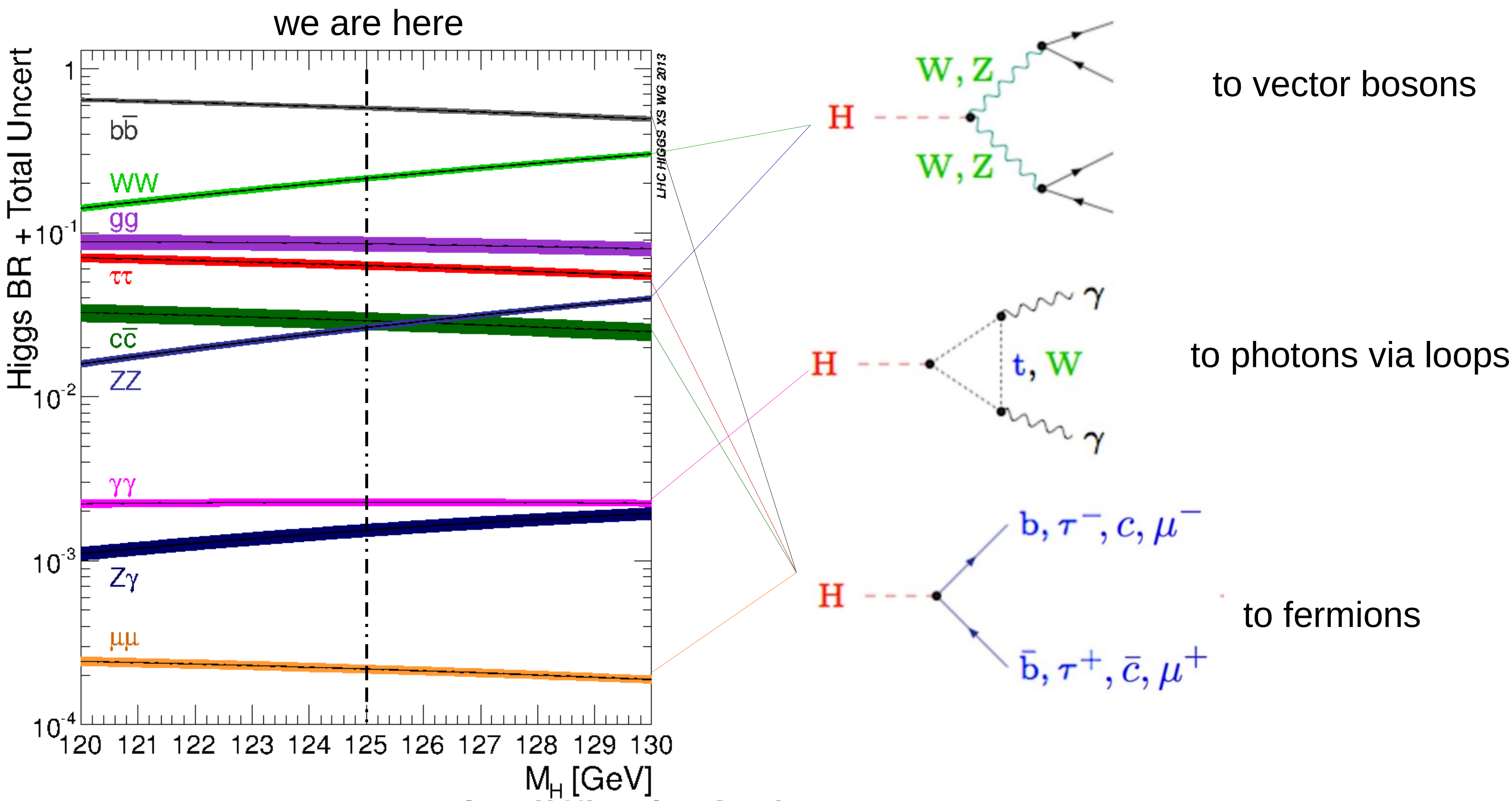


Assoc. production with tops



- Many production modes with distinct signatures

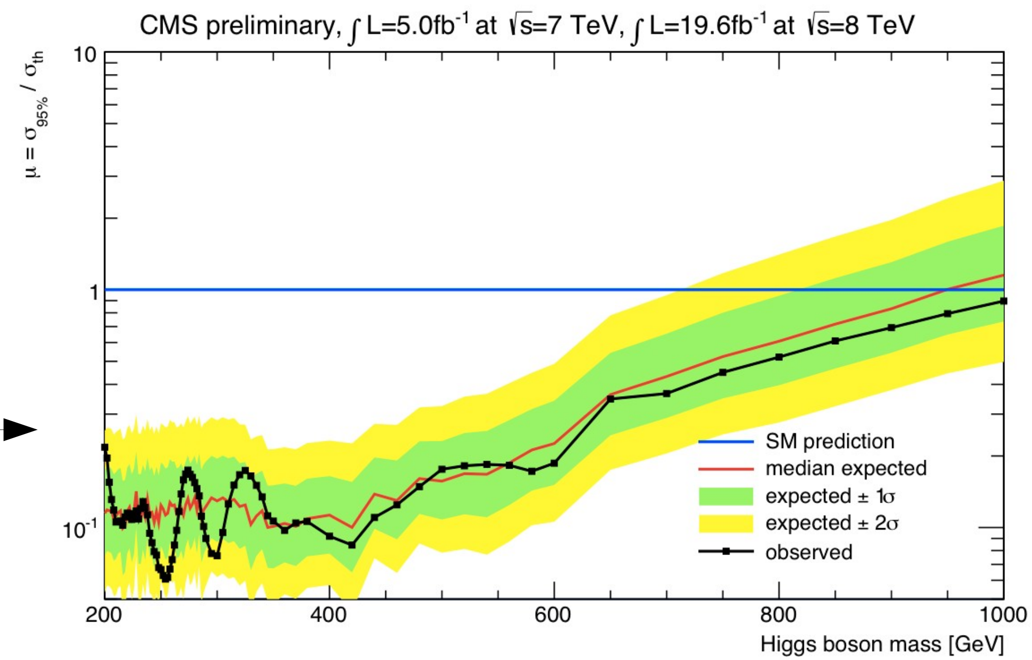
Higgs decay modes



- H → gg extremely difficult @ the LHC
- Probably expected to see Zγ and μμ with very high luminosity

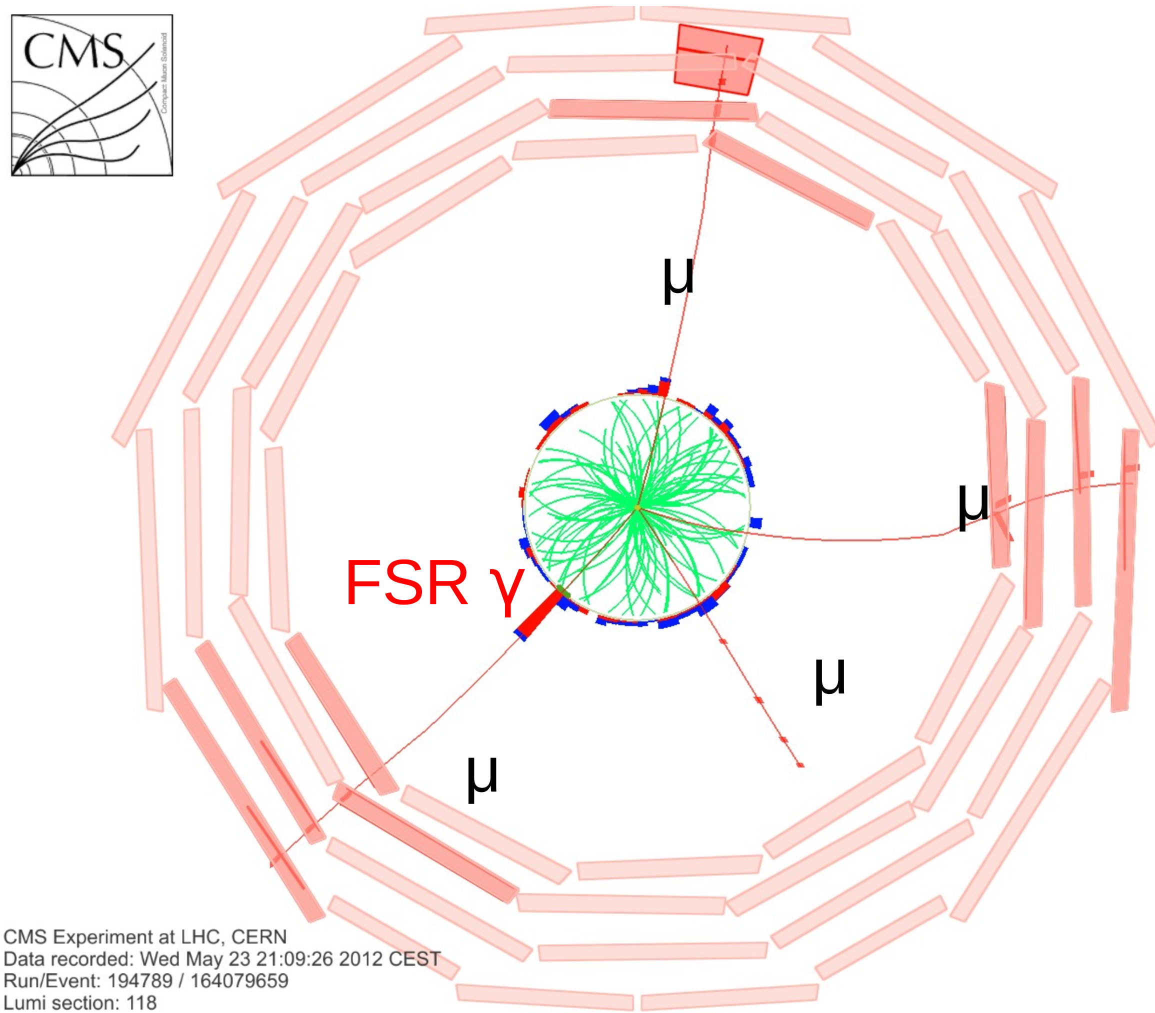
Summary of CMS searches

- First of all, we have found only one Higgs boson around 125 GeV
- Even if we would find it had it been elsewhere...



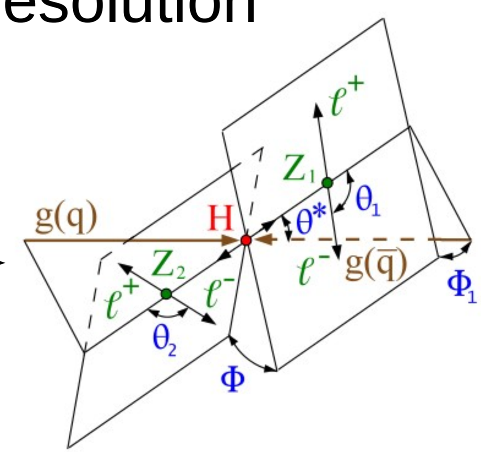
★ "seen" ☆ "tried"	H→bb̄	H→ττ	H→WW*	H→ZZ*	H→γγ	H→Zγ	H→inv.	H→μμ
ggH		★	★	★	★	☆		☆
VBF	☆	★	★	☆	★	☆	☆	☆
VH	★	☆	☆	☆	☆		☆	
ttH	☆	☆	☆	☆	☆			

H → ZZ* → 4 charged leptons



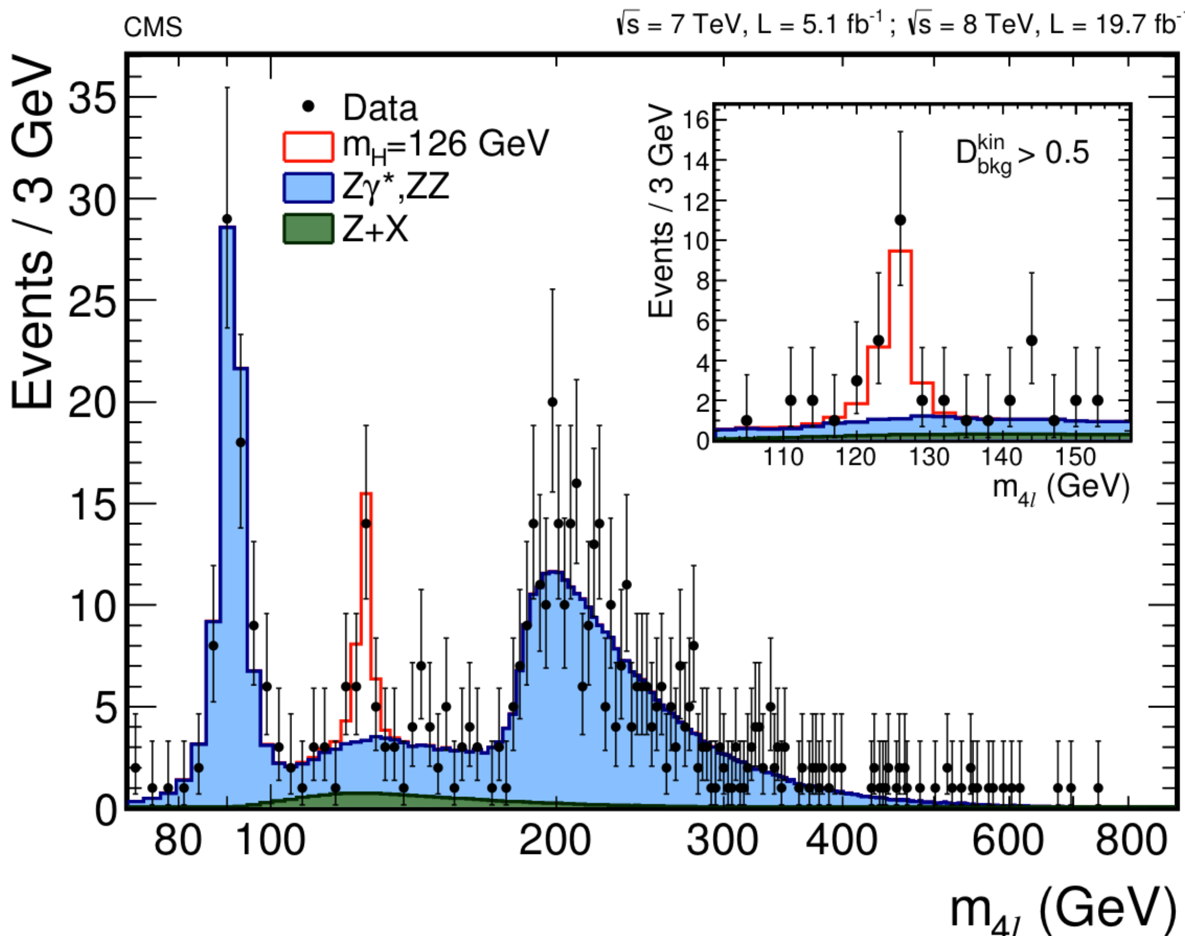
- Signature of 4 high quality leptons
  - add tagged photons from FSR
- Small and flat (in mass) backgrounds
  - SM qq/gg → ZZ → 4l
  - Z+ bb/cc , top pairs
- Excellent mass resolution

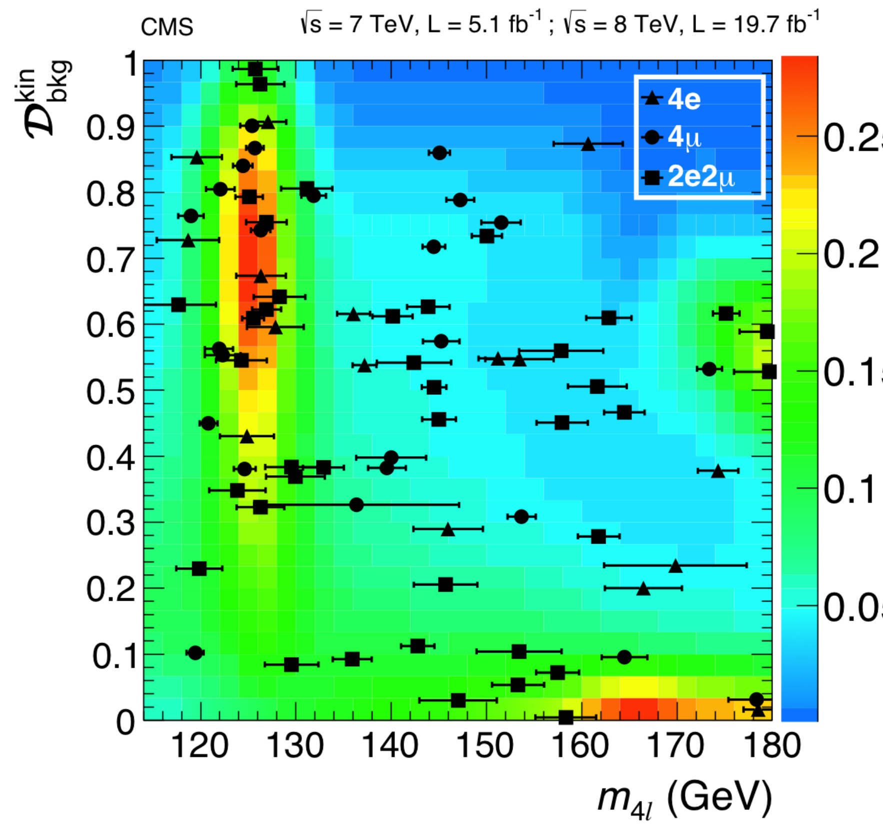
- Fully reconstructed final state
- Exploit angular information to reject background and measure spin-parity properties



Phys.Rev.D 89, 092007

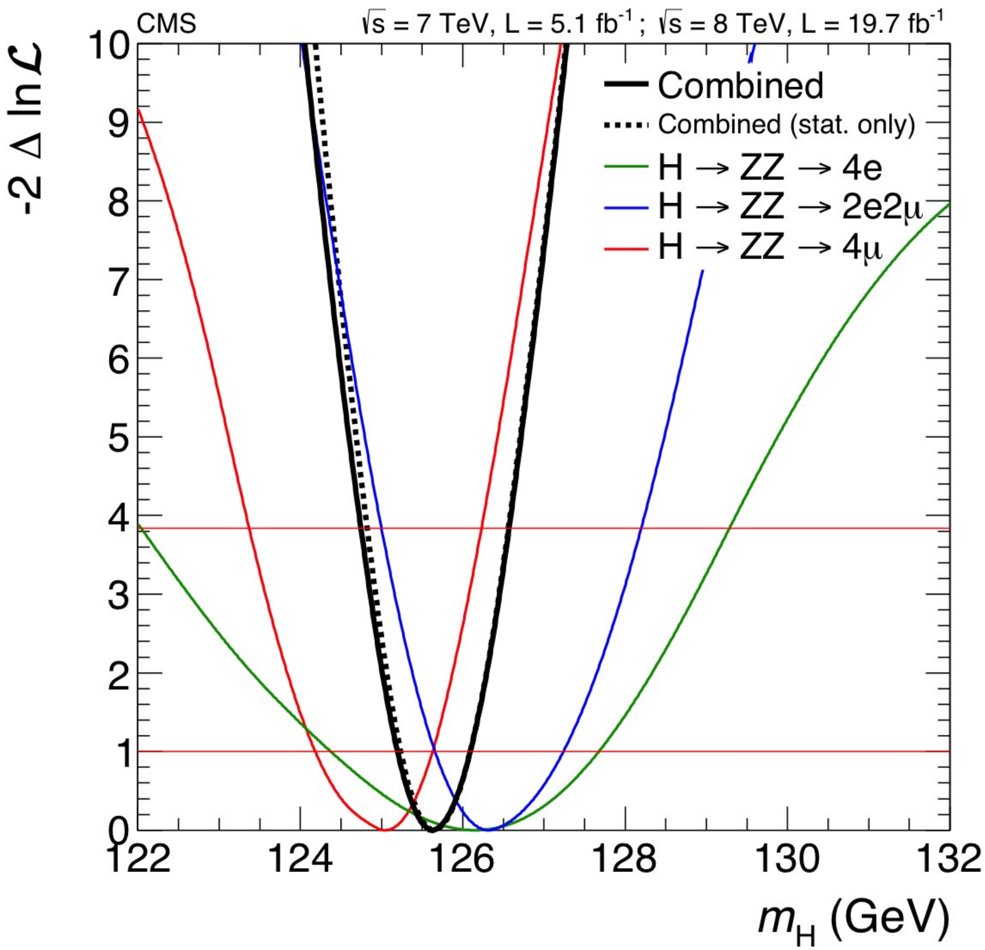
H → ZZ* → 4l distributions

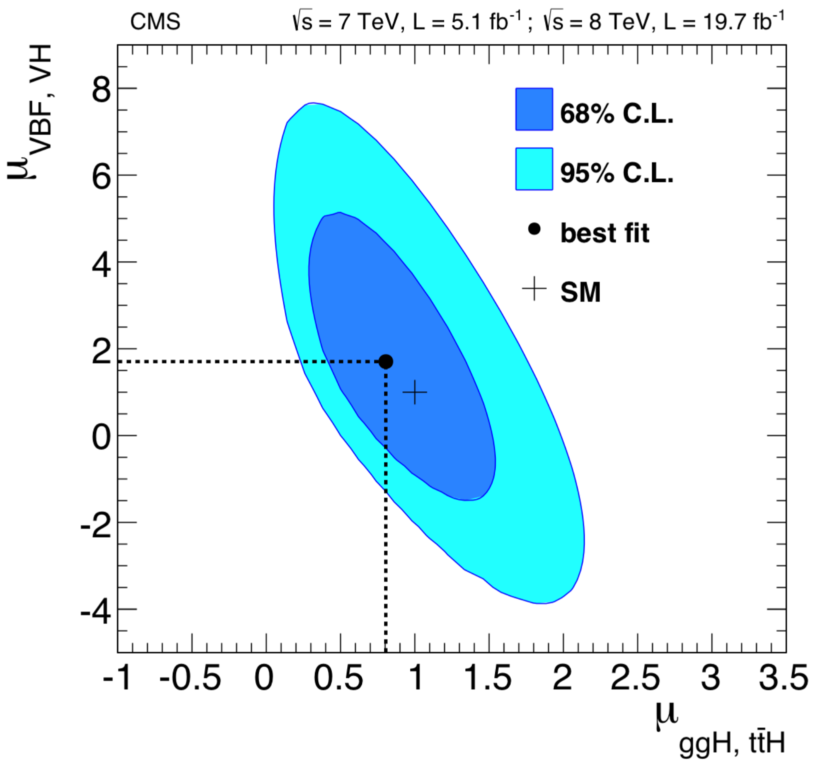




- Fold angular information in a kinematic discriminant to separate Higgs and SM qq → ZZ background
- Data distributions in agreement with expected SM Higgs signal
- Expected significance of 6.7σ (obs. 6.8 σ)

$H \rightarrow ZZ^*$ mass and signal strength





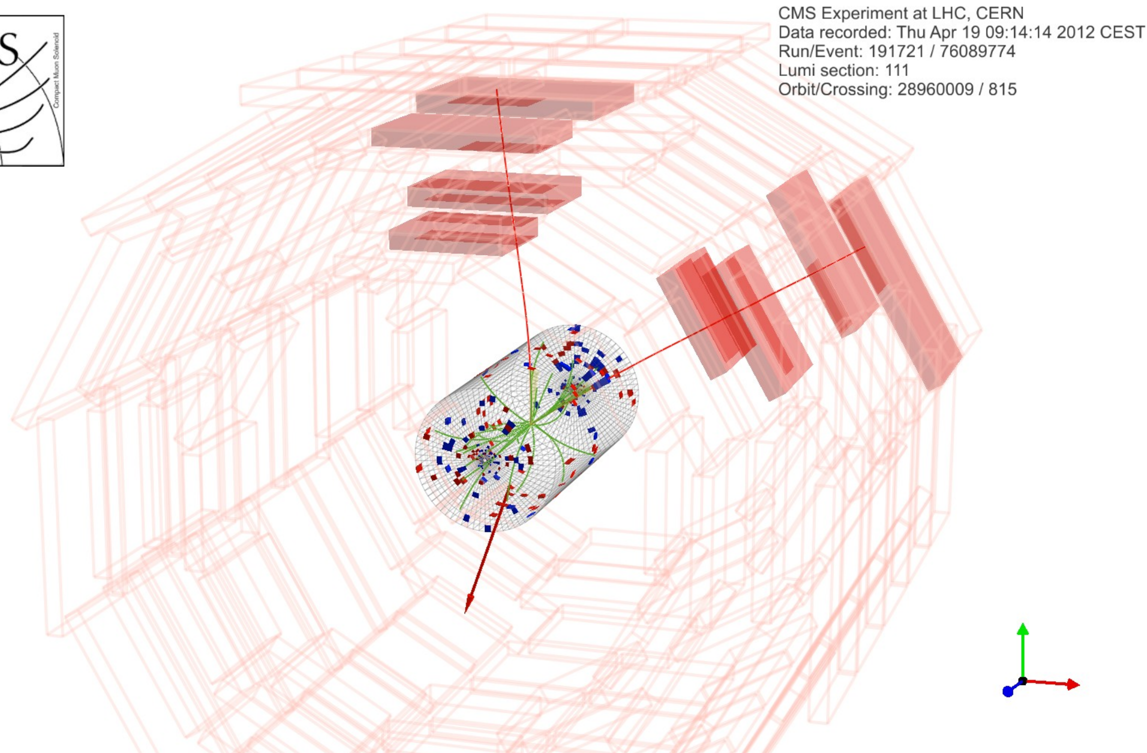
- $M_H = 125.6 \pm 0.4$ (stat) ± 0.2 (syst) GeV
- Consistency between the different four lepton final states

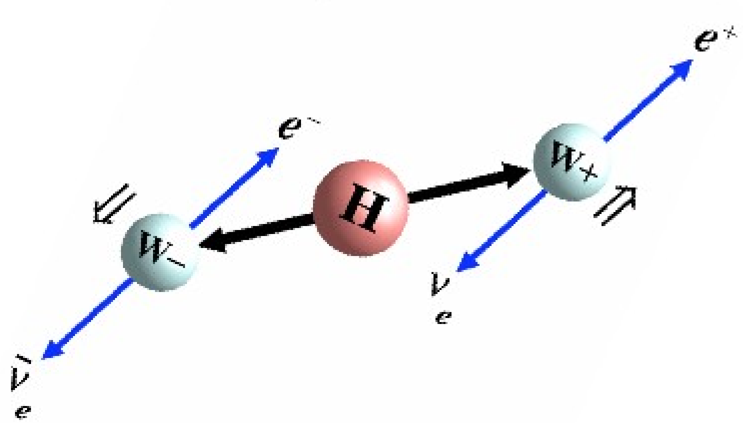
- $\mu = 0.93^{+0.26}_{-0.23}$
- Global signal strength and strength by production mode in agreement with SM

Phys.Rev.D 89, 092007

$H \rightarrow WW^* \rightarrow 2l2\nu$

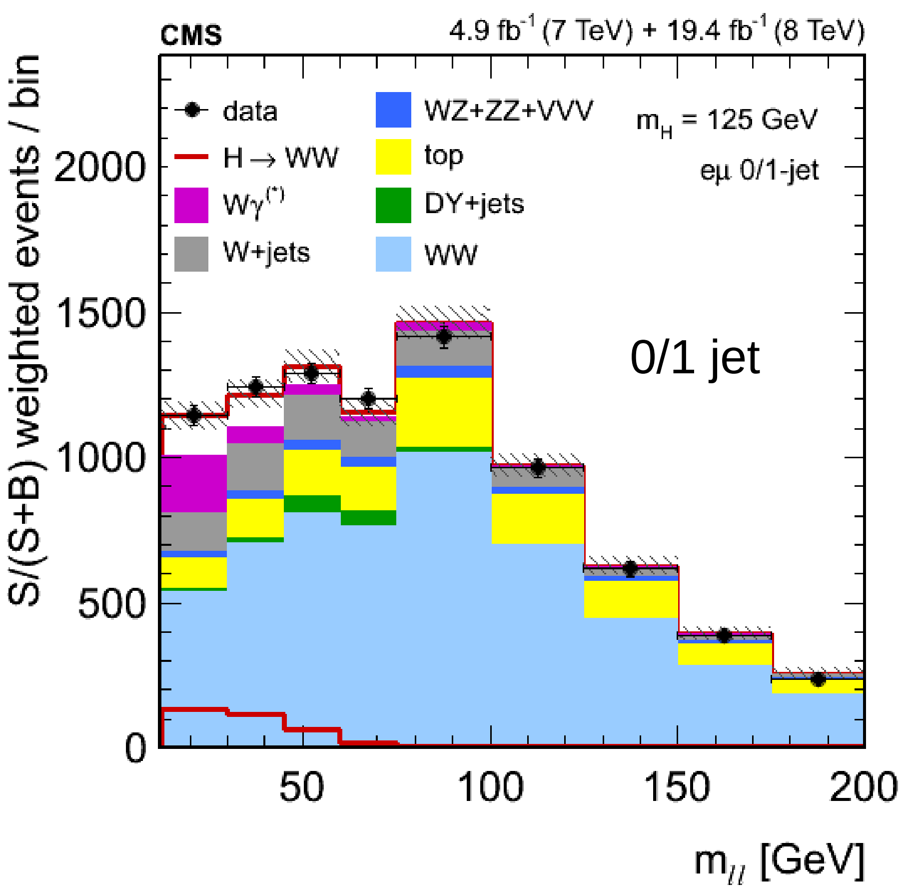
- Two high quality OS leptons+ ME_T
- Final state not fully reconstructed
  - Broad signal peak
- **Large expected yield** for properties measurements
  - once the mass is known
- Exploit angular correlations to reject background

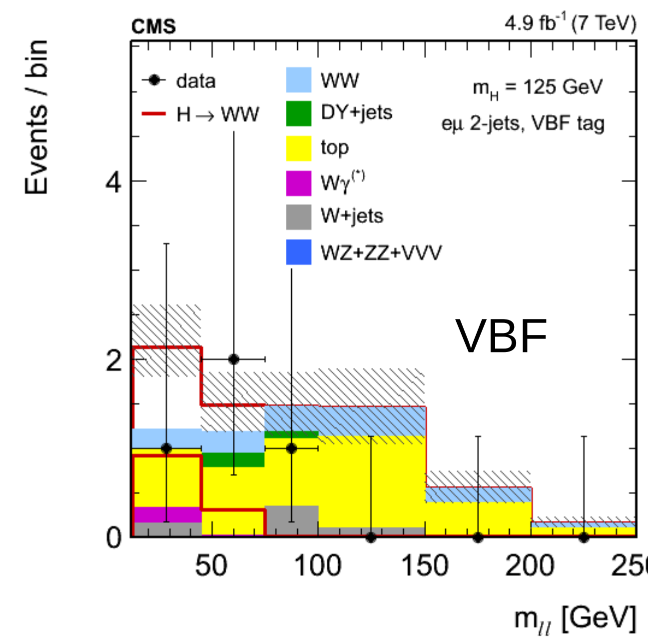


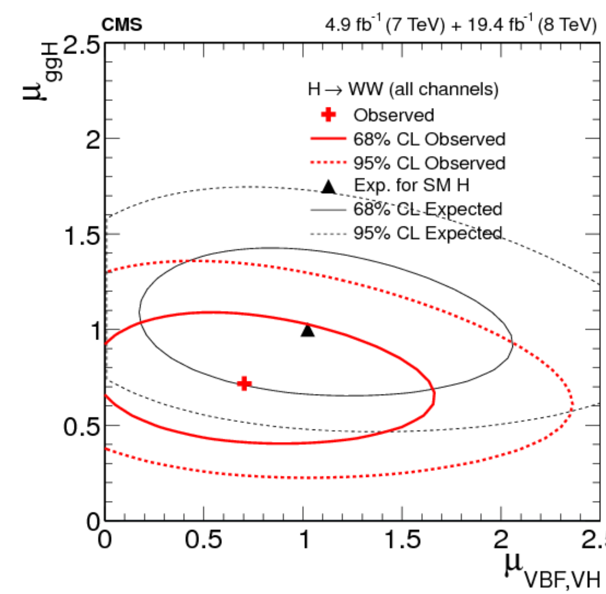


- Analysis performed in categories
  - Based on # jets including exclusive VBF tagging (di-jet)
  - Based on di-lepton signature
  - Using also tri-lepton events to probe VH

H → WW* results



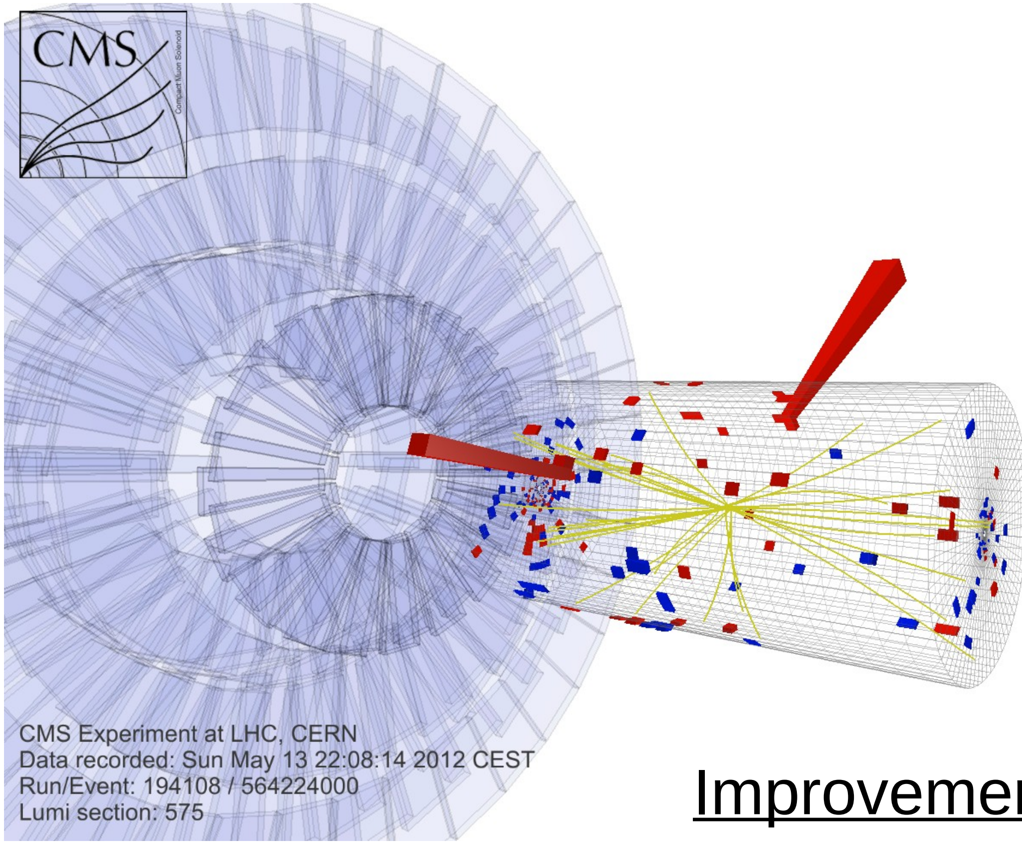




- Excess observed on top of the broad backgrounds
- Expected significance of 5.8σ (obs. 4.3σ)
- Signal strength @ 125.6 GeV = $0.72^{+0.20}_{-0.18}$

H → γγ

NEW!



- Reconstruct a pair of high quality photons
- Smooth falling background spectra
  - Direct di-photon production
  - Events with fake photons
- Excellent mass resolution required!

Expected sensitivity

Improved resolution
→ +9%
Improved selection
→ +9%
Background model
→ +7%

Improvements to the analysis

- Latest ECAL calibration
- Run dependent MC
- Better modeling of out of time PU
- New background model

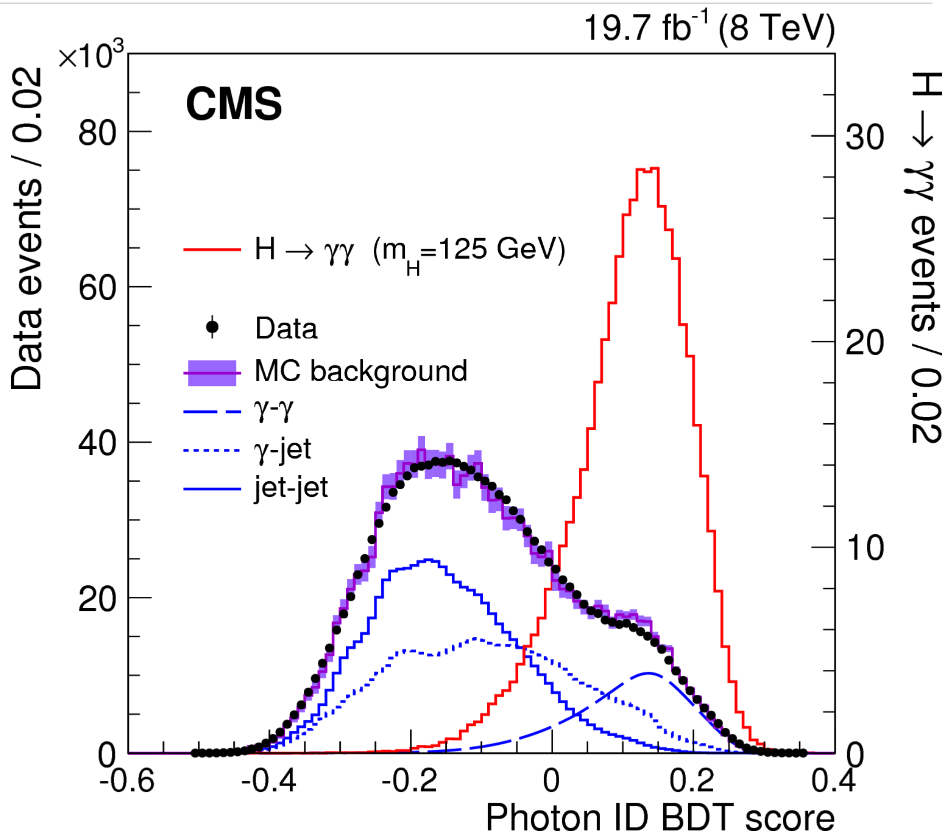
- Analysis chain re-optimized
- Additional exclusive categories
- Improvement on energy scale systematics

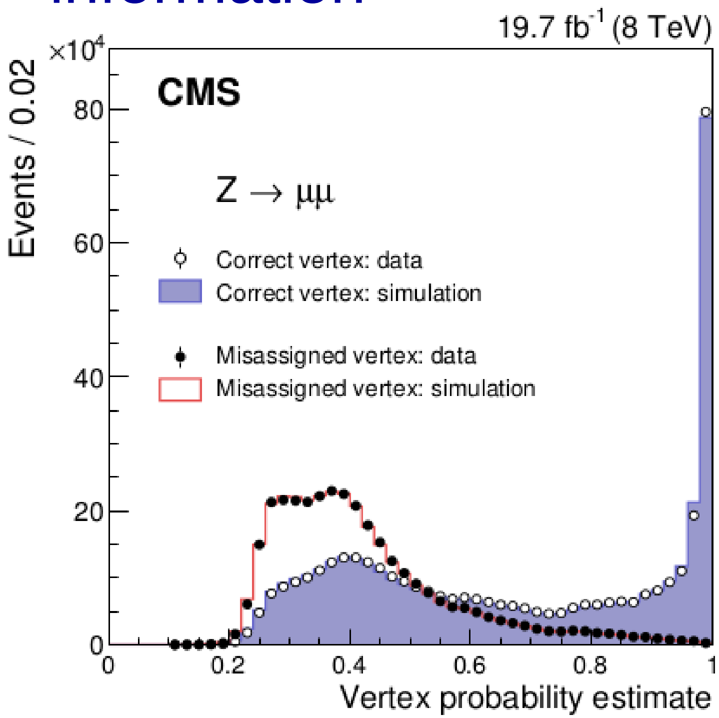
arXiv 1407.2856

H → γγ photon and vertex ID

NEW!

- Built out of ECAL clusters expanding on the bending plane
  - Same clusters used for electrons
  - Conversion pairs also tagged
- Deploy a multivariate discriminant
  - using shower shape and isolation information

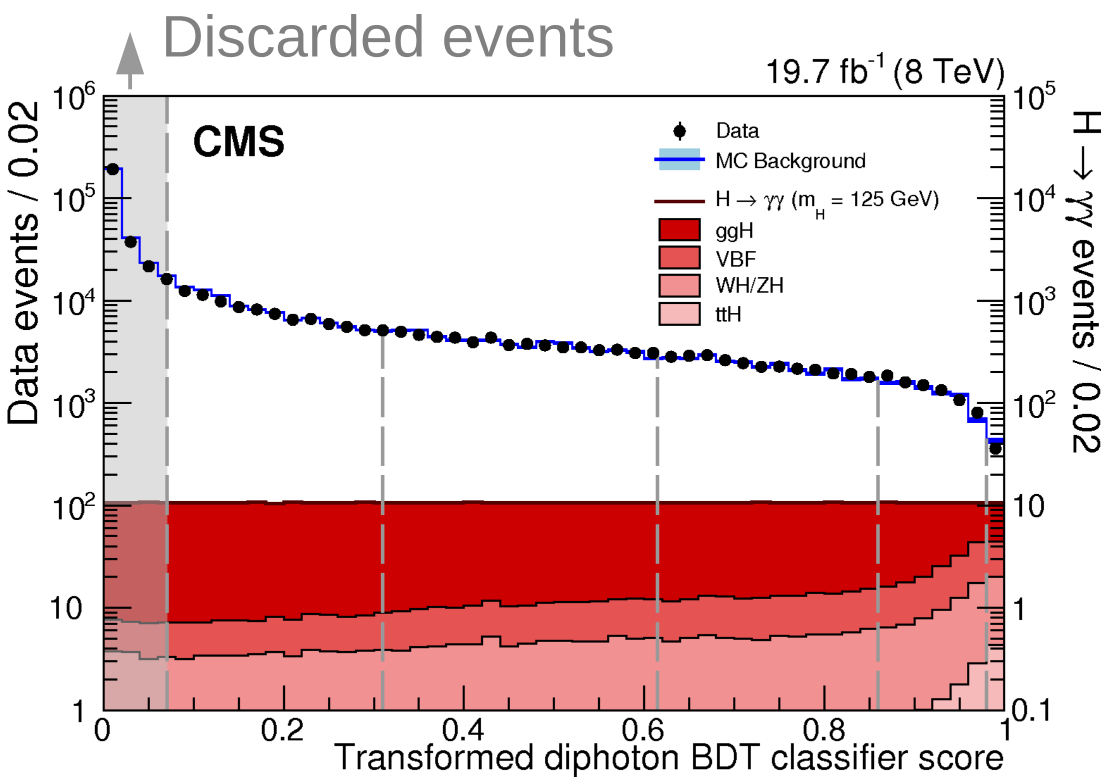




- MVA vertex selection using di-photon kinematics and vertex information
- Validated with Z → μμ after removing muon tracks
  - And re-reconstructing vertices

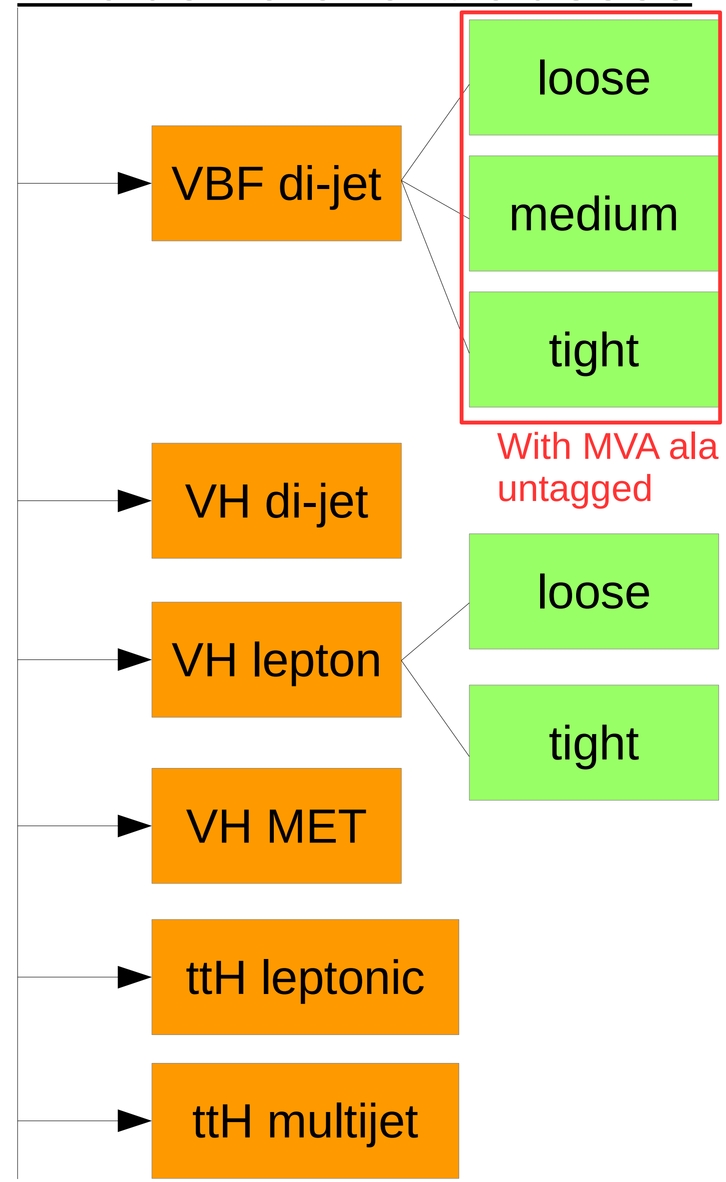
H → γγ event categorization

NEW!



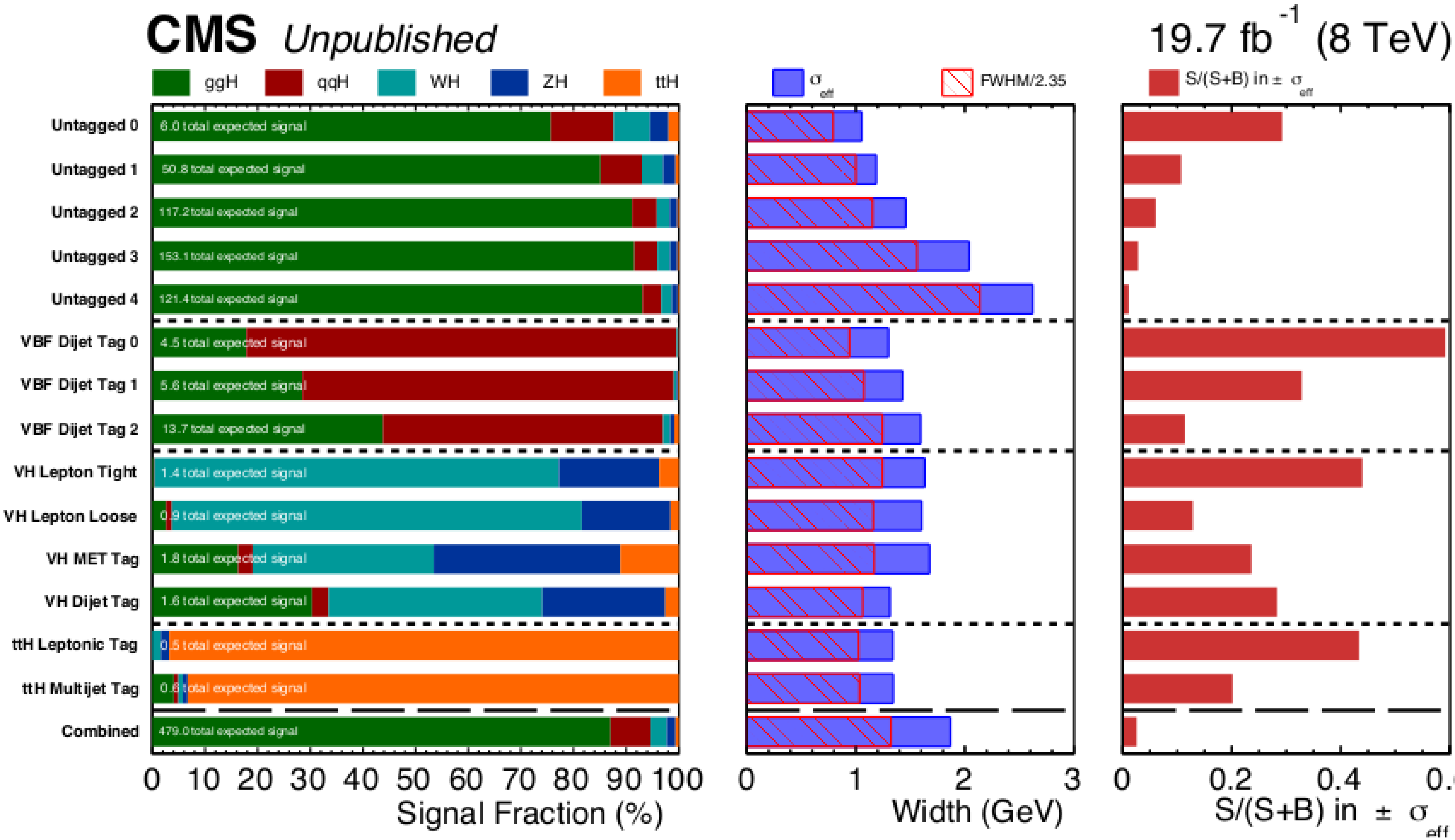
- Di-photon discriminant defines categorization
  - for non-exclusive categories
  - based on kinematics and mass resolution

Exclusive event classes



$H \rightarrow \gamma\gamma$ category composition

NEW!

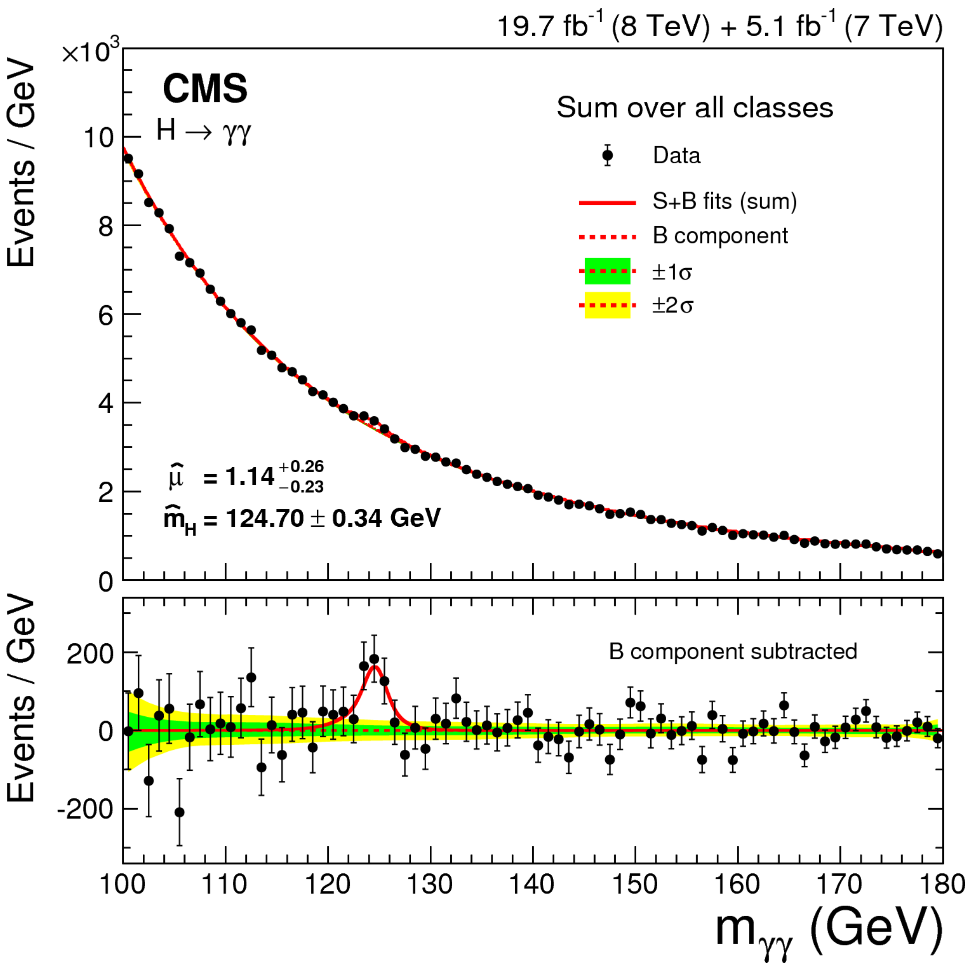


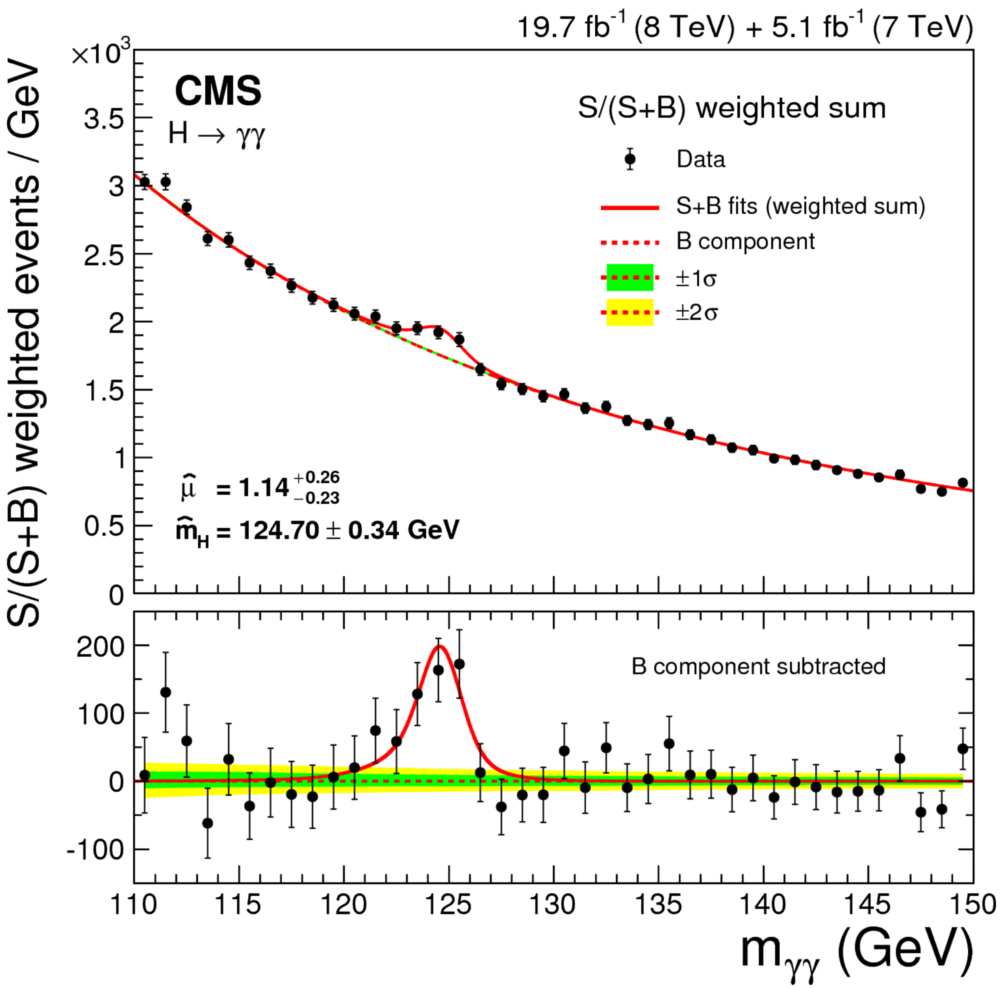
- Untagged and di-jet categories split based on output of multivariate discriminants
- Resolution varies from 1.0-2.6 GeV in categories

arXiv 1407.2856

H → γγ combined mass spectra

NEW!

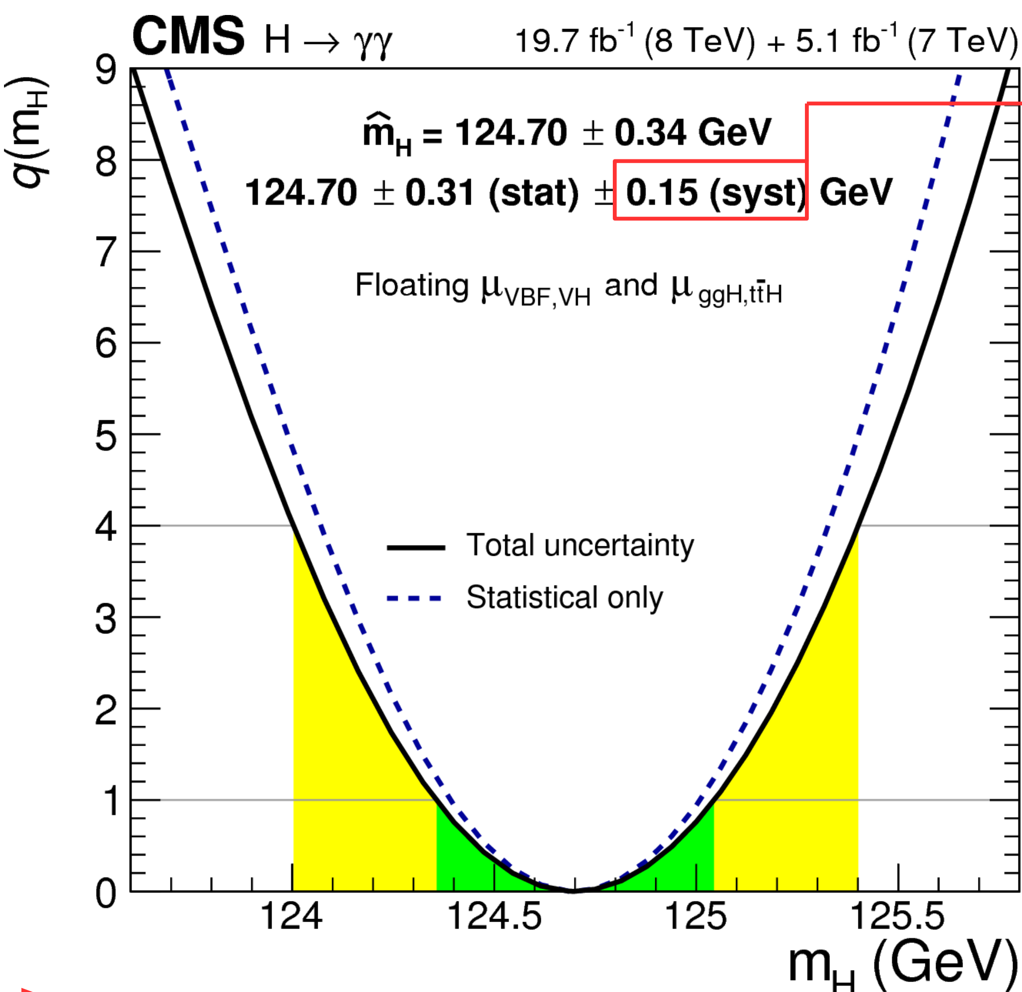




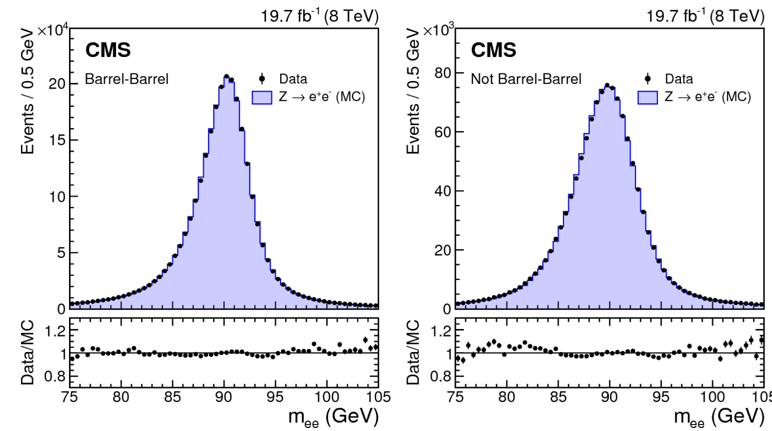
- Visible excess at ~ 125 GeV
  - Even unweighted
- Expected Significance of 5.2σ(Obs 5.7σ)

H → γγ mass measurement

NEW!

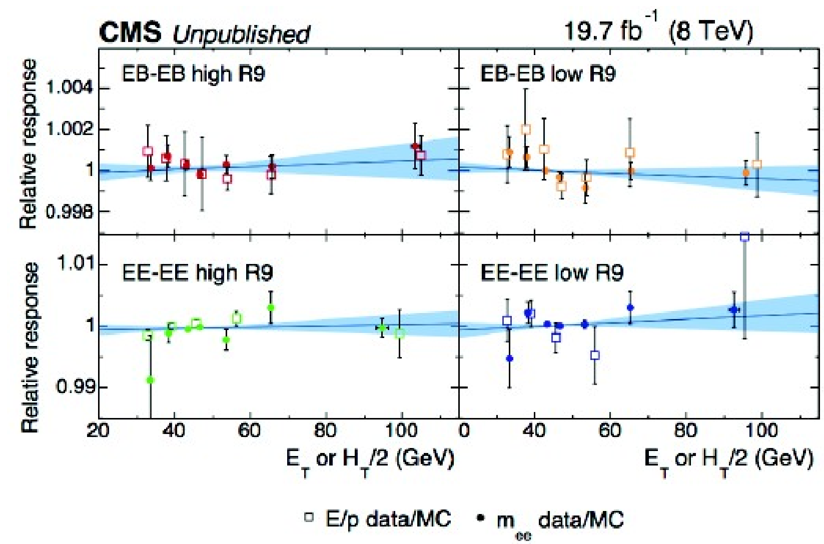


Photon Calibration @ ~ 45 GeV with Z → e$^+$e$^-$



±0.05 GeV

Boosted Zs: Higher ET



±0.10 GeV

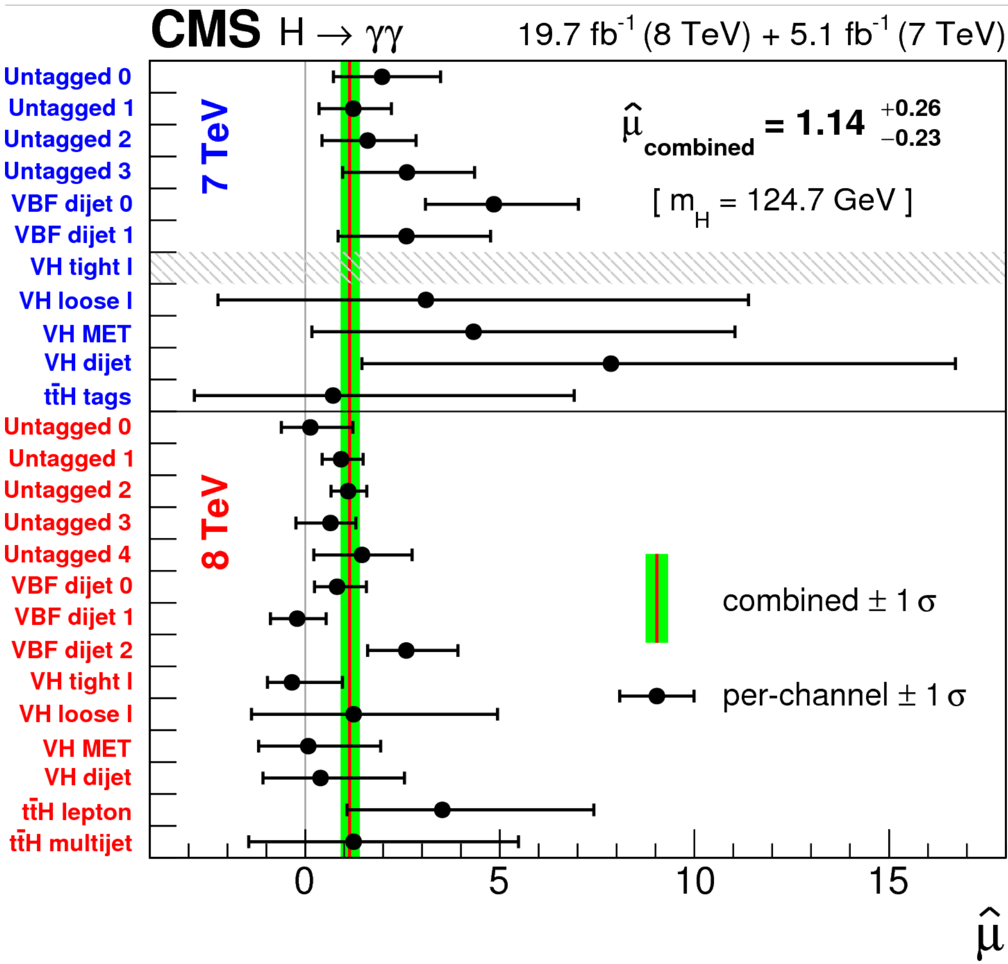
Data to MC Photon/ Electron differences based on knowledge on the material, scintillation light peak in the crystal and imperfections in the shower simulation

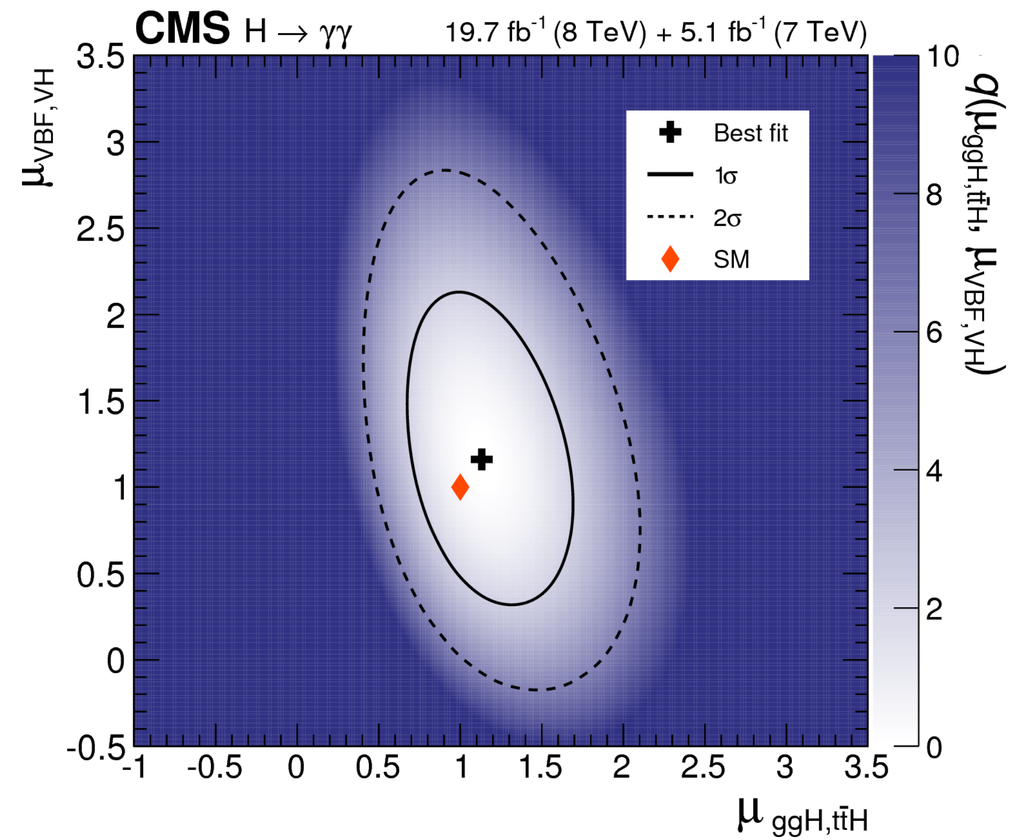
±0.10 GeV

arXiv 1407.2856

H → γγ signal strength

NEW!

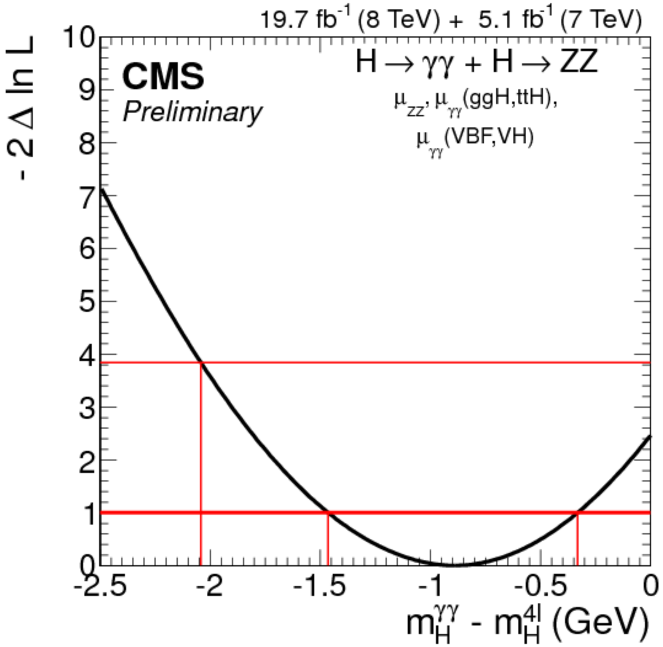


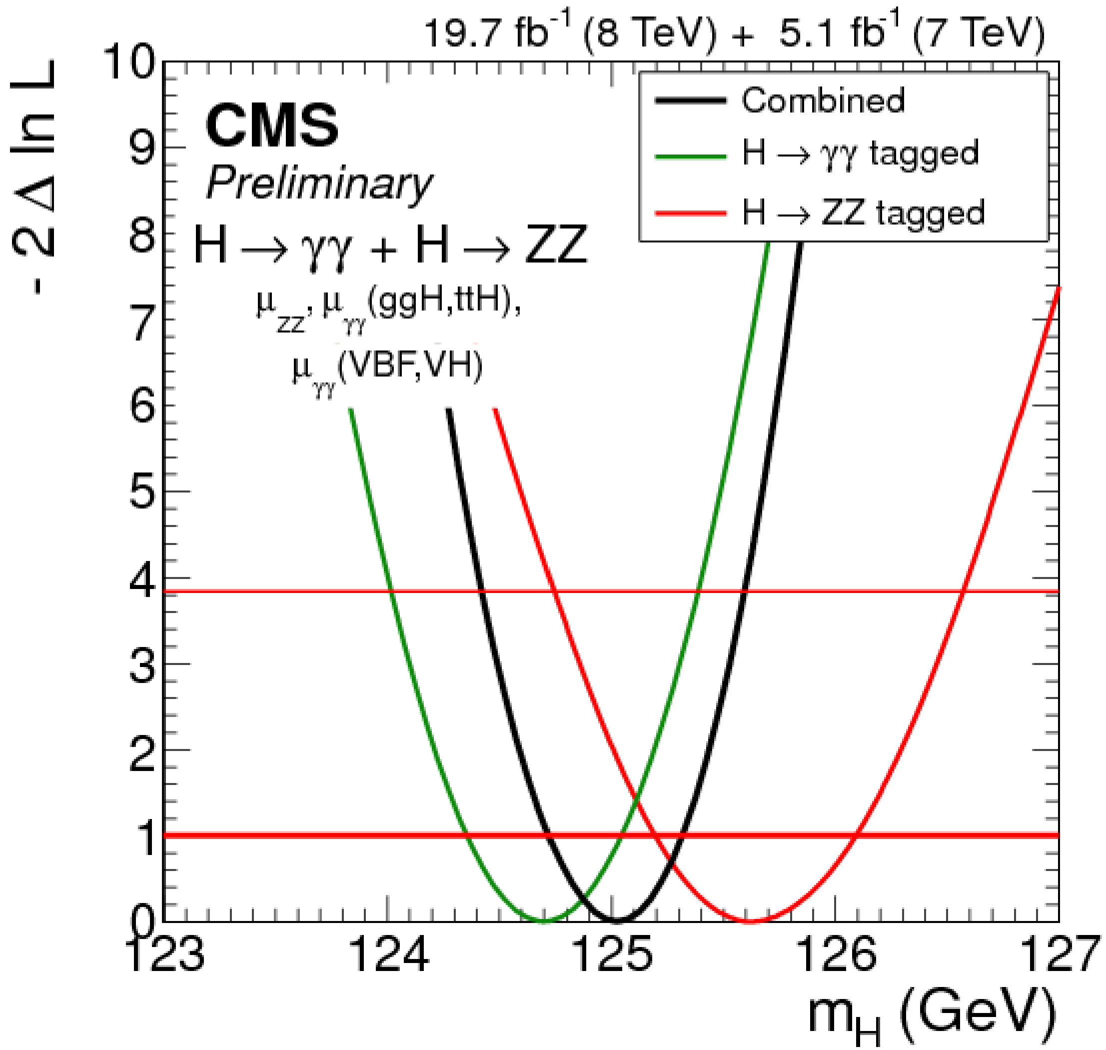


- Signal strength of 1.14 $^{+0.26}_{-0.23}$
- Compatibility between categories, production modes and with the SM

Mass combination

- Combination of H → γγ and H → ZZ
  - Floating yields for production and decay
- Individual final states compatible @ 1.6σ level

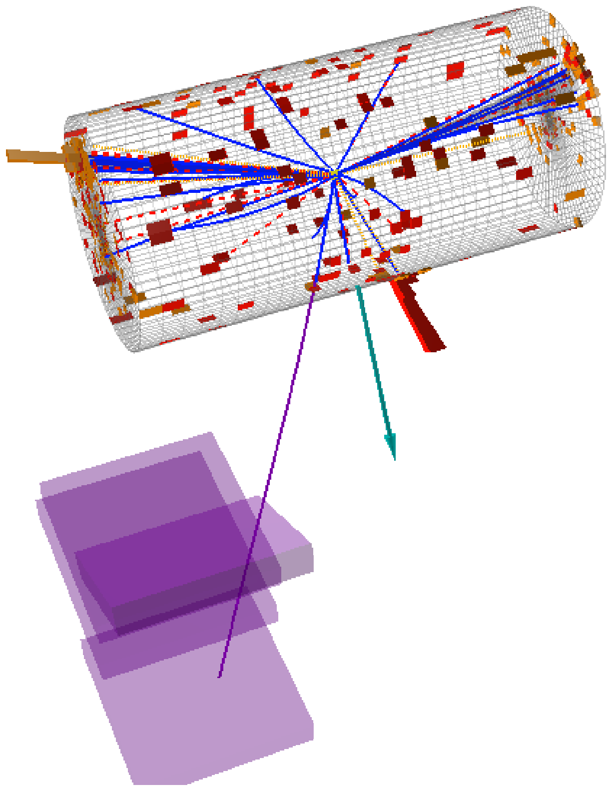


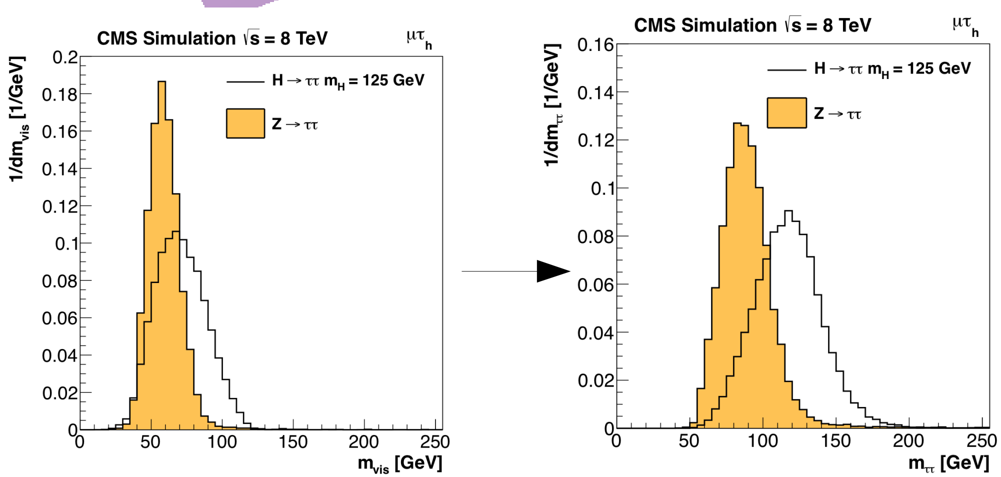


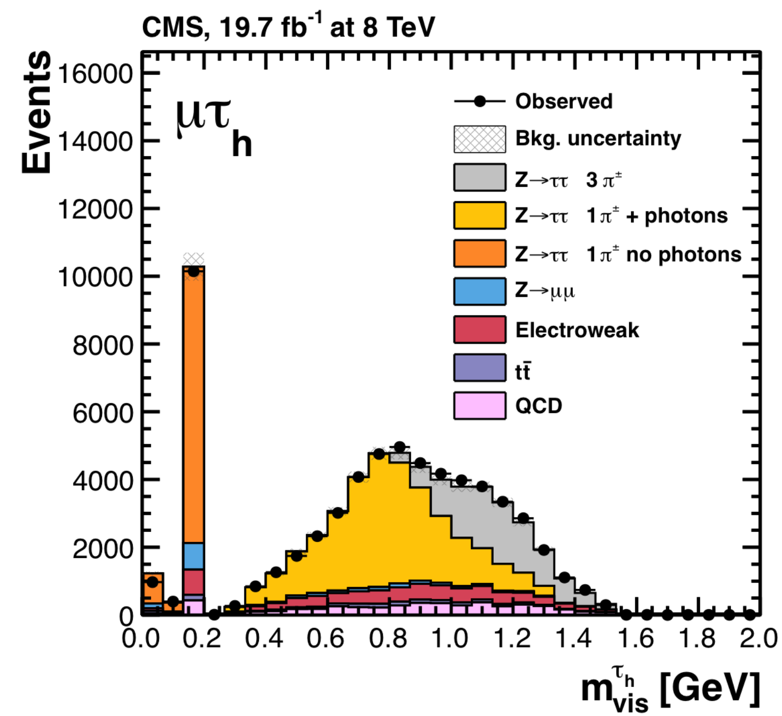
$$m_H = 125.03 \pm 0.30 \left[^{+0.26}_{-0.27}(\mathrm{stat.})^{+0.13}_{-0.15}(\mathrm{syst.}) \right] \mathrm{GeV}$$

H → ττ

- Reconstruct a tau pair
  - Plethora of final states based on tau decay modes
- Experimental challenges
  - Hadronic tau identification
  - Di-tau mass reconstruction



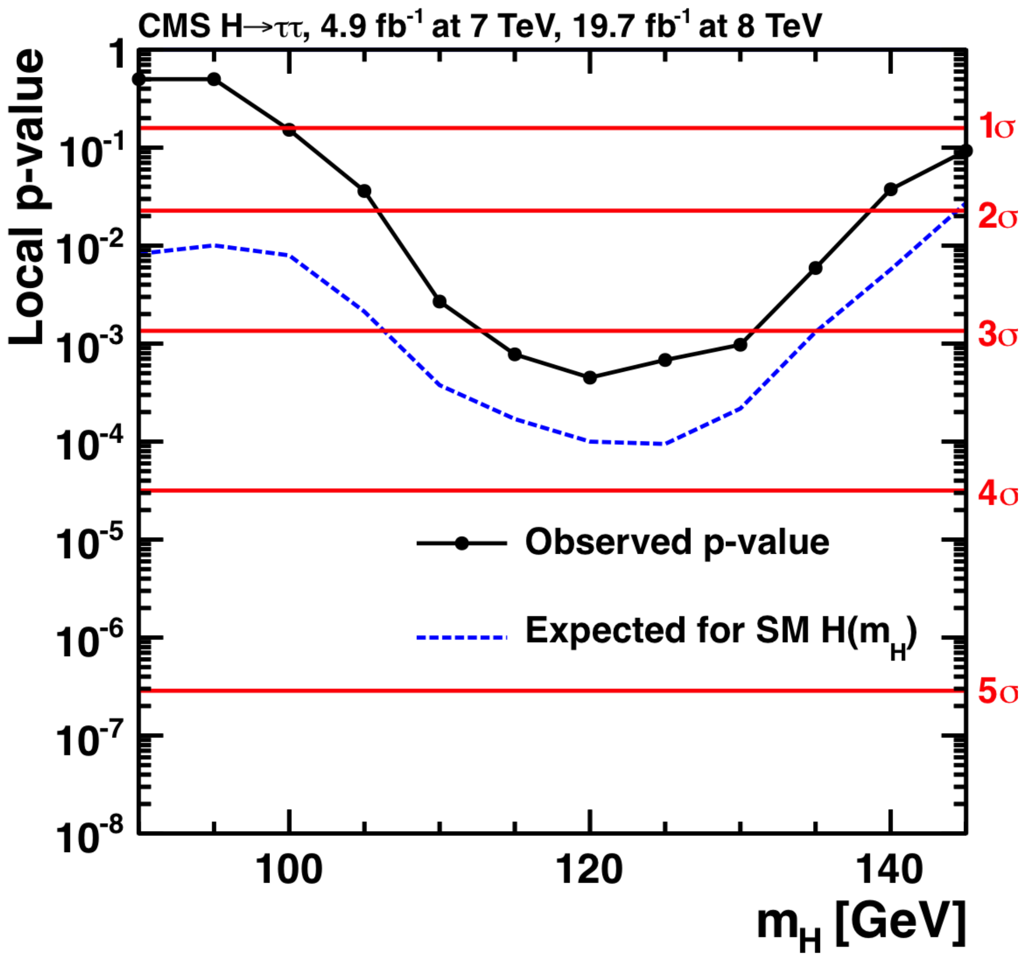


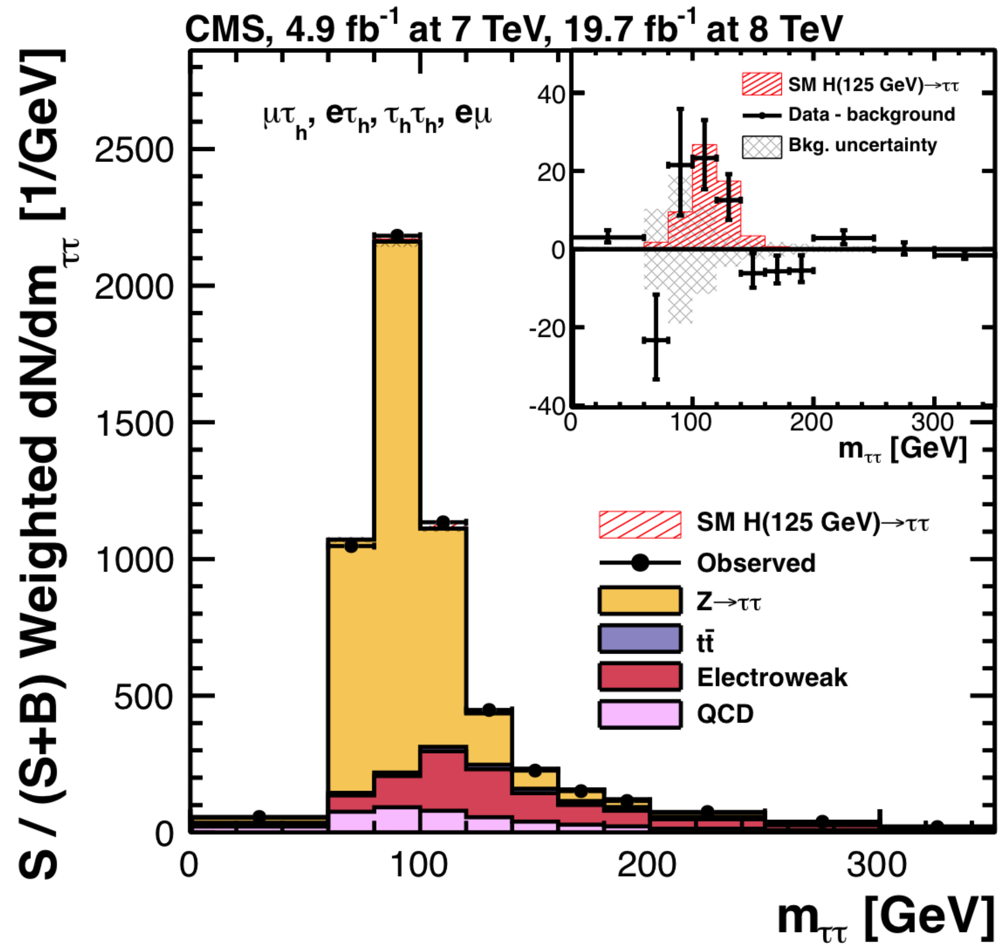


JHEP 1405 (2014) 104

H → ττ results

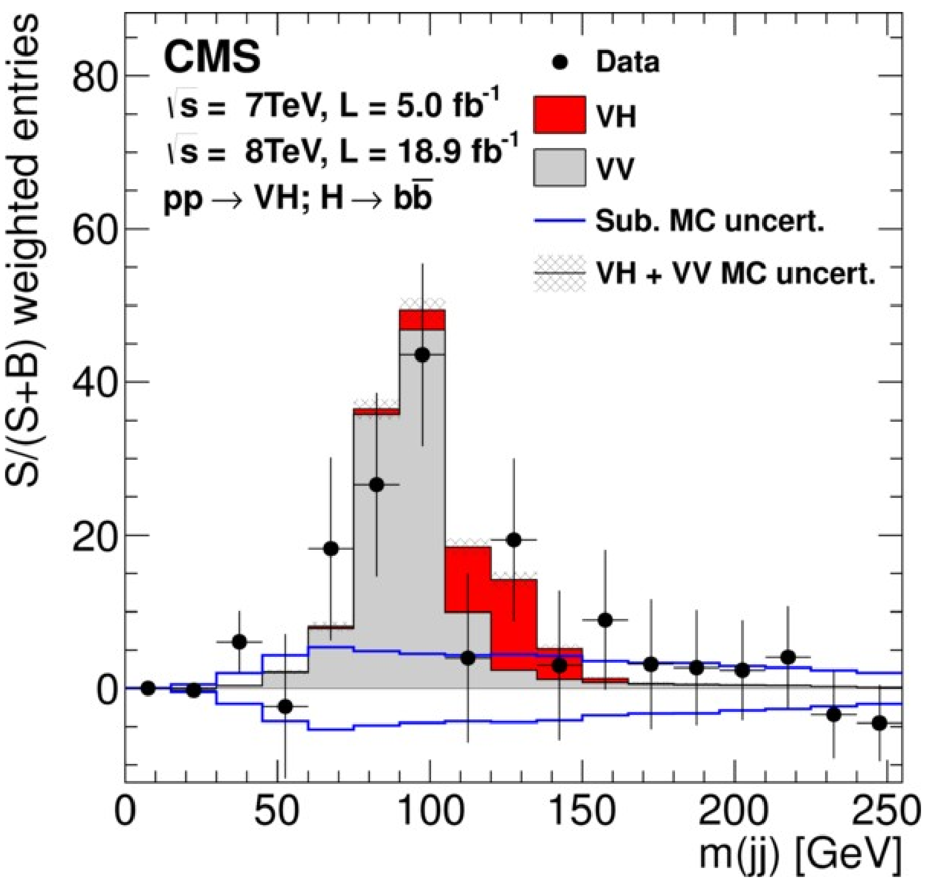
- Expected 3.7σ (obs 3.2σ)
- Signal strength =0.78 ±0.27 @125.6 GeV

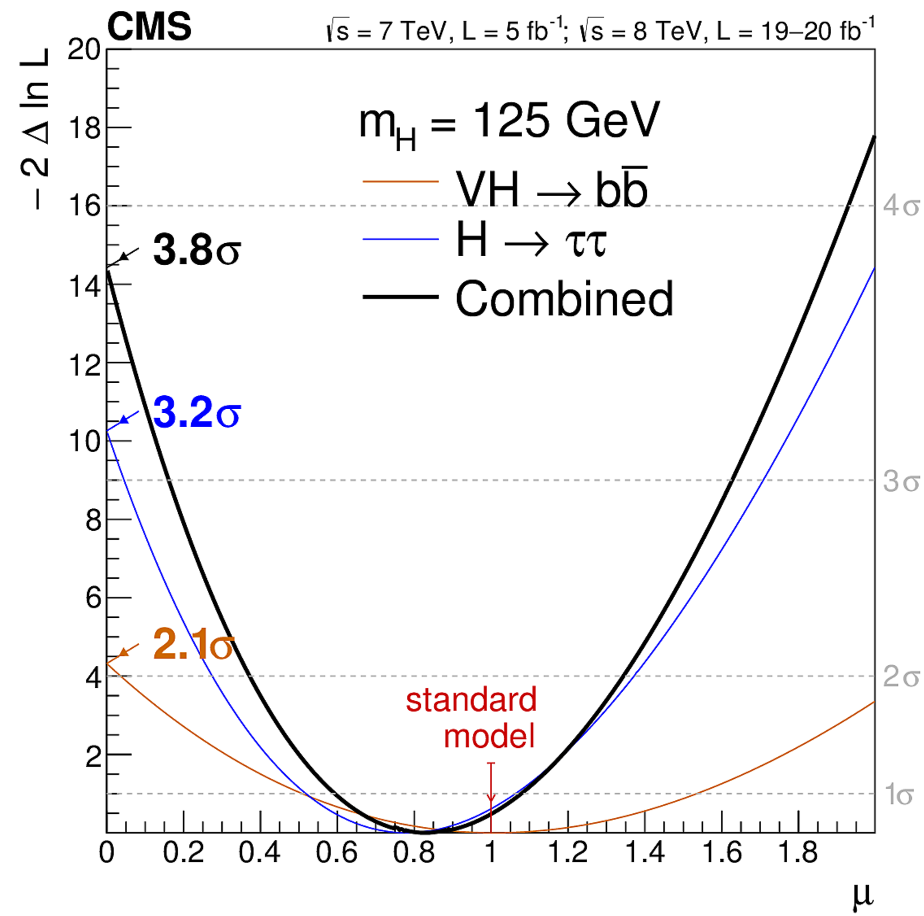




JHEP 1405 (2014) 104

H → bb and fermion combination





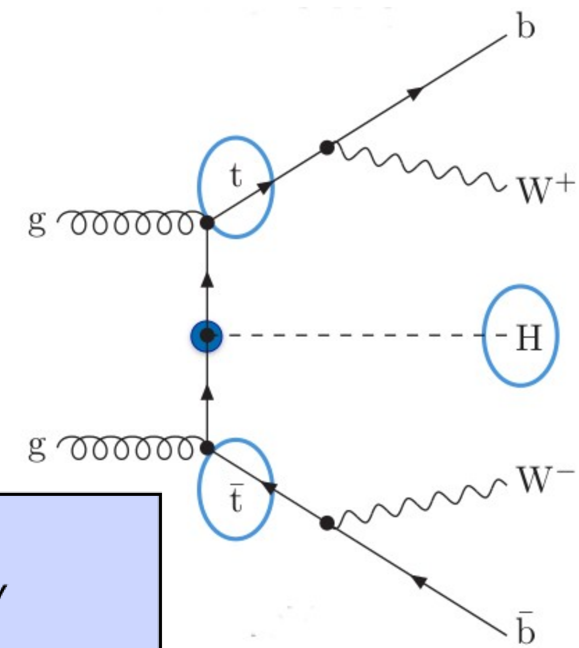
- Obs.(Exp) Significance of ~2σ @ 125 GeV
- Diboson(VZ) peak extracted as cross check >6σ

- Combination with di-tau final state provides solid evidence for fermionic decays of the Higgs boson

 Phys.Rev.D 89, 012003 **Nature Phys. 10 (2014)**

Probing directly the top coupling

- Top coupling can be probed at tree level via ttH production
  - Very low cross section but unique experimental signature → bbWWH



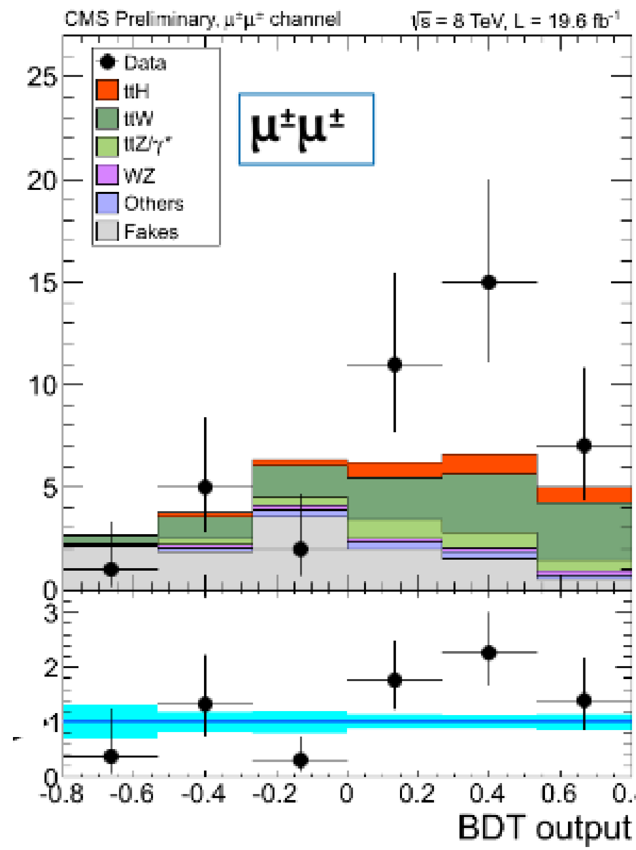
CMS ttH analyses as of today

	$H\to bb$	$H\to\tau\tau$: $\tau_{had}\tau_{had}$	$H\to\tau\tau$: $\ell\tau_{had}$	$H\to WW^*/ZZ^*$	$H\to\gamma\gamma$
ttH	H→hadrons 7+8 TeV CMS-PAS-HIG-12-035 JHEP 1305 (2013) 145 CMS-PAS-HIG-13-019 CMS-PAS-HIG-14-010			H→leptons ($\ell^\pm\ell^\pm$, 3ℓ, 4ℓ) 8 TeV CMS-PAS-HIG-13-020	H→photons 7+8 TeV CERN-PH-EP-2014-117
tH	8 TeV *in progress*				8 TeV CMS-PAS-HIG-14-001

ttH combined results

NEW!

Channel	μ^{fit}	$\Delta\mu^{fit}$
ttH, H→bb	0.7	-1.8/+1.8
ttH, H→$\tau_{had}\tau_{had}$	-1.3	-3.6/+6.1
ttH, H→leptons	3.9	-1.4/+1.7
ttH, H→γγ	2.7	-1.7/+2.4
ttH tagged	2.76	-0.92/+1.05



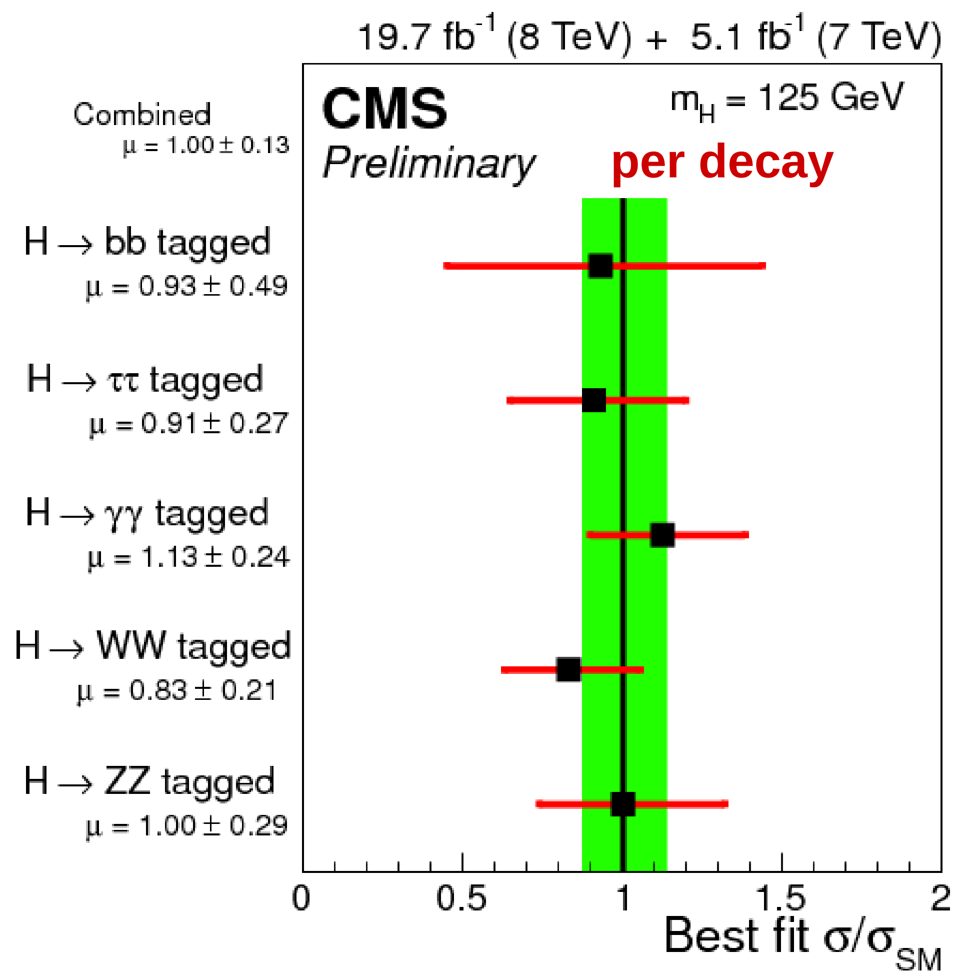
- Expected uncertainty on signal strength ~ 100%
  - Mild excess observed in SS di muon events
  - Within two standard deviations wrt SM expectation

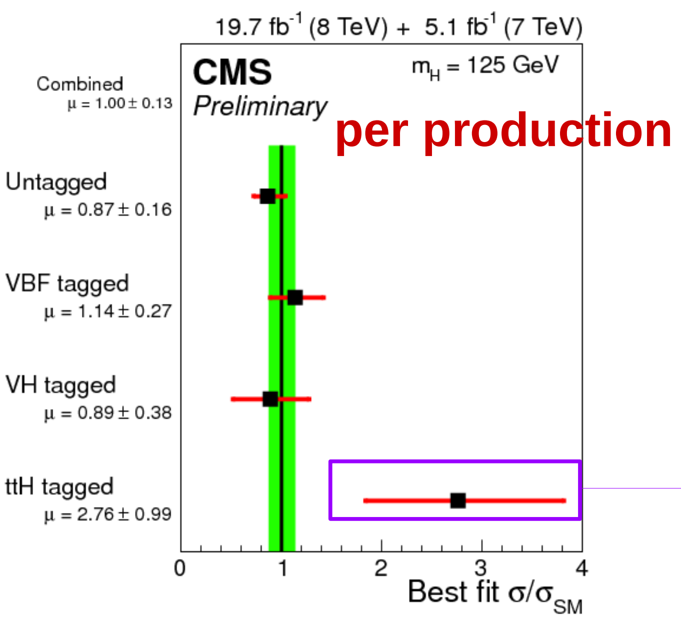
Combined signal strength

NEW!

$$\mu = 1.00 \pm 0.13[\pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst})]$$

- Uncertainty at 15% level
- Theoretical systematics start to become important
- Compatibility between measurements and with SM





ttH → multileptons and diphotons

Measurement of the couplings (I)

In each analysis we measure:

$$\sigma(XX \to H) \times BR(H \to YY) \approx \frac{g_x^2 g_y^2}{\Gamma_{tot}}$$

Defining deviations from the SM couplings of the form: $\kappa_x = \frac{g_X}{g_X^{\mathrm{SM}}}$

the signal strength is $\mu \approx \frac{\kappa_X^2 \kappa_Y^2}{\frac{\Gamma_{tot}}{\Gamma_{tot}^{\mathrm{SM}}}}$

The total width deviation in principle depends on all couplings

$$\frac{\Gamma_{tot}}{\Gamma_{tot}^{\mathrm{SM}}} \approx \sum_i \kappa_i^2 BR(H \to Y_i Y_i)^{\mathrm{SM}}$$ + BSM contribution

For a given set of coupling deviations,a fit is performed in all final states

Measurement of the couplings(II)

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} :$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

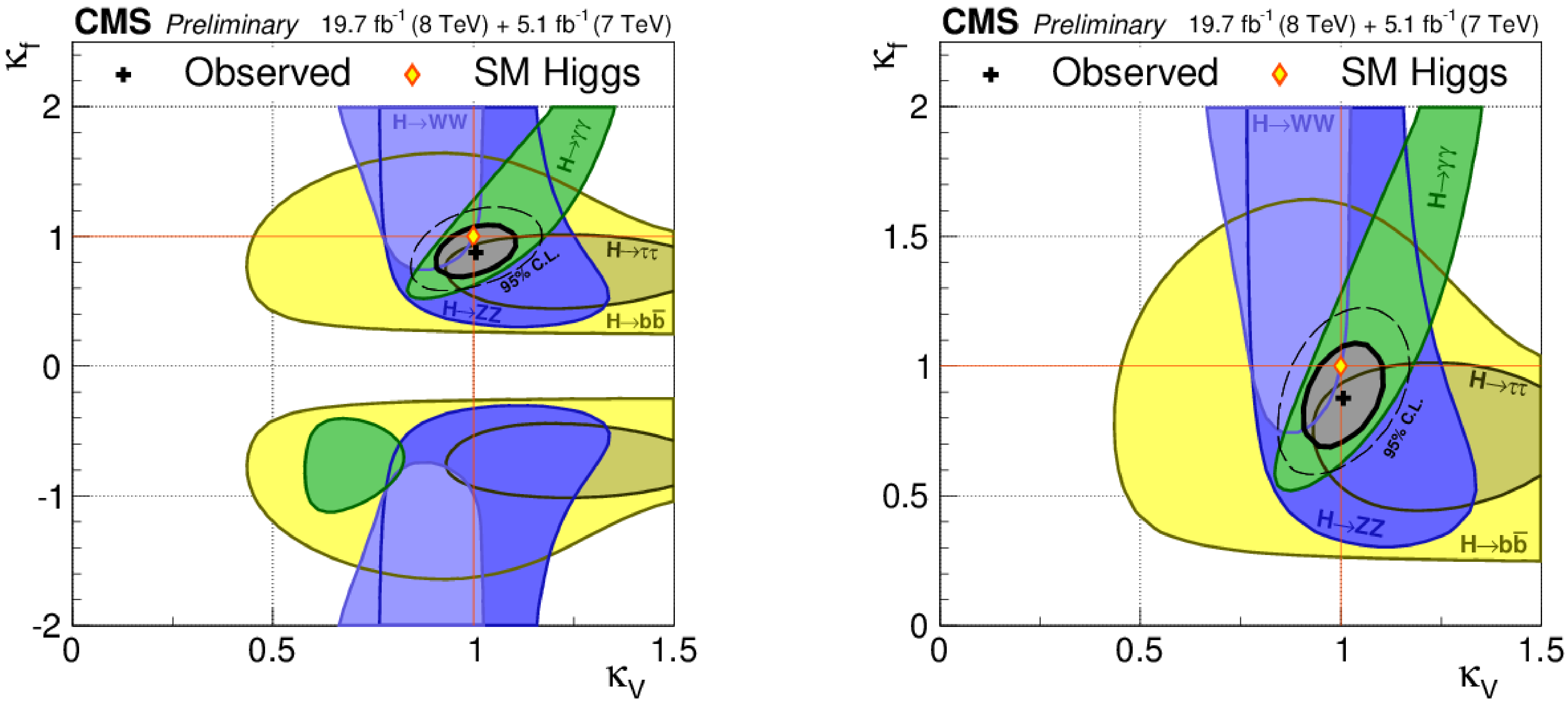
$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Loops can be resolved (at NLO QCD and LO EWK)
  - Or assume effective couplings [model independent]
- Assume undetected states 100% correlated with similar detected

Simplest model [$\kappa_V \kappa_F$] NEW!

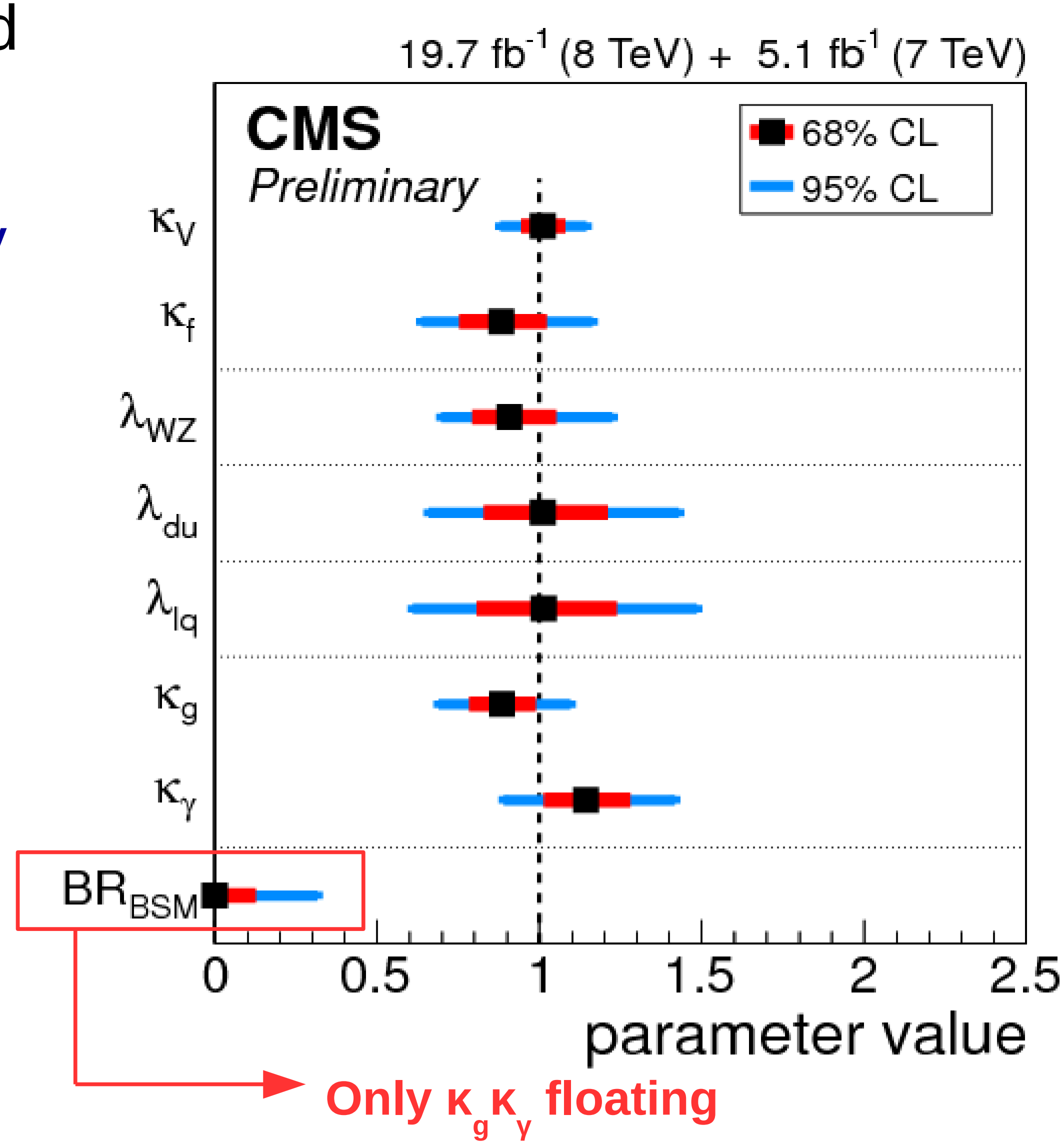


- Scale all fermions couplings by the same factor and all vector boson couplings by the same factor
  - Negative sign allowed due to destructive interference in di-photon loop
- **Compatibile with the SM**

Other models

NEW!

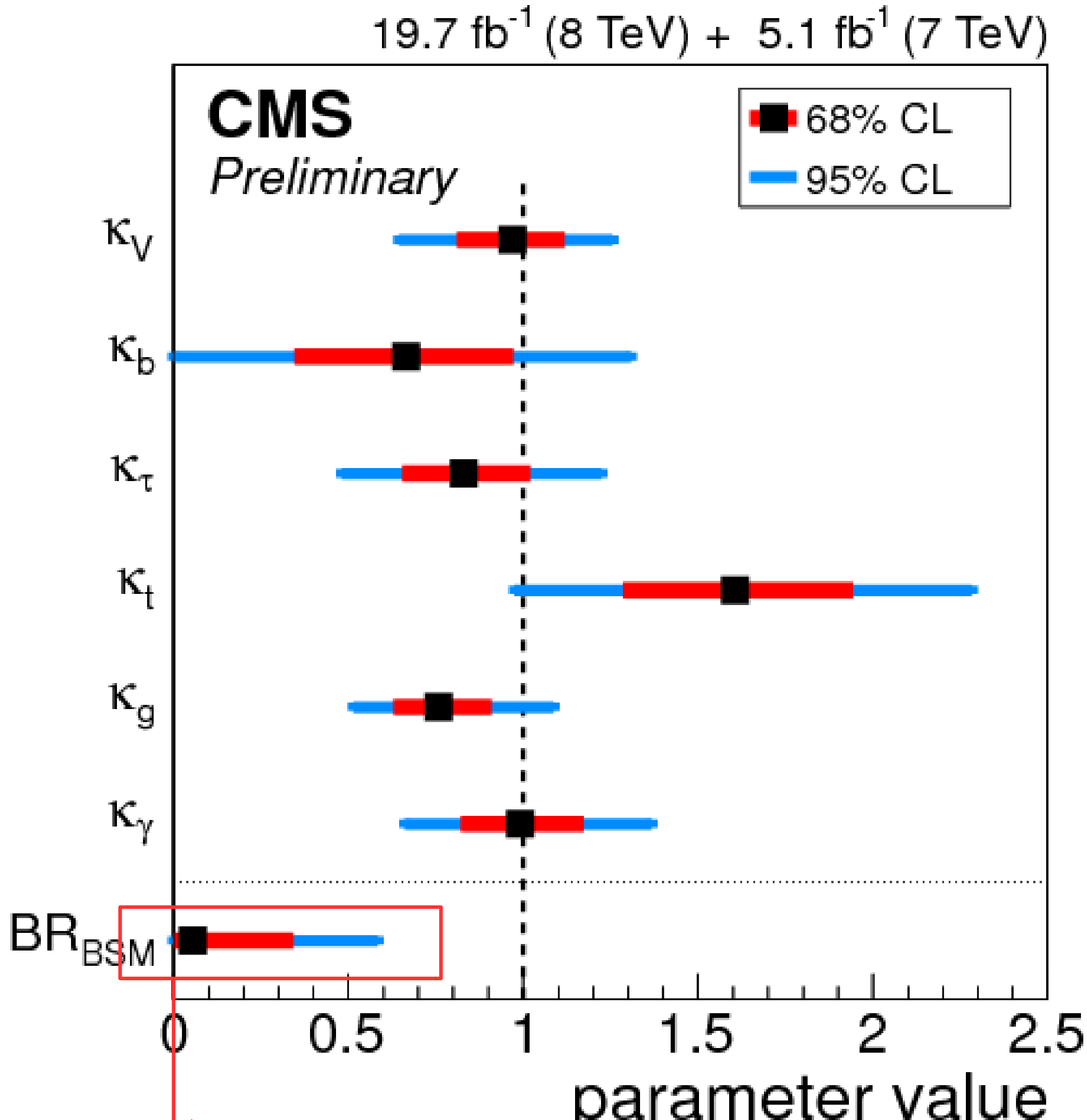
- Six benchmark models studied
  - Fermions vs bosons
  - Test of Custodial symmetry (W vs Z)
  - Up vs down fermions
    - Interesting for 2HDMs
  - Quarks vs leptons
    - Common (Yukawa) structure?
  - Physics in the loops
    - New physics at nearby scales?
  - Extra width to BSM?
- **No significant deviations**



More general model

NEW!

- Assuming effective loop couplings for quarks and gluons
    - Top coupling from ttH
    - Gluon coupling from gluon fusion
- Top coupling directly from ttH
- Gluon coupling from gluon fusion production
- Compatibility with the SM
- **With larger statistics, will start looking at deviations...**



All parameters floating and $\kappa_V \leq 1$

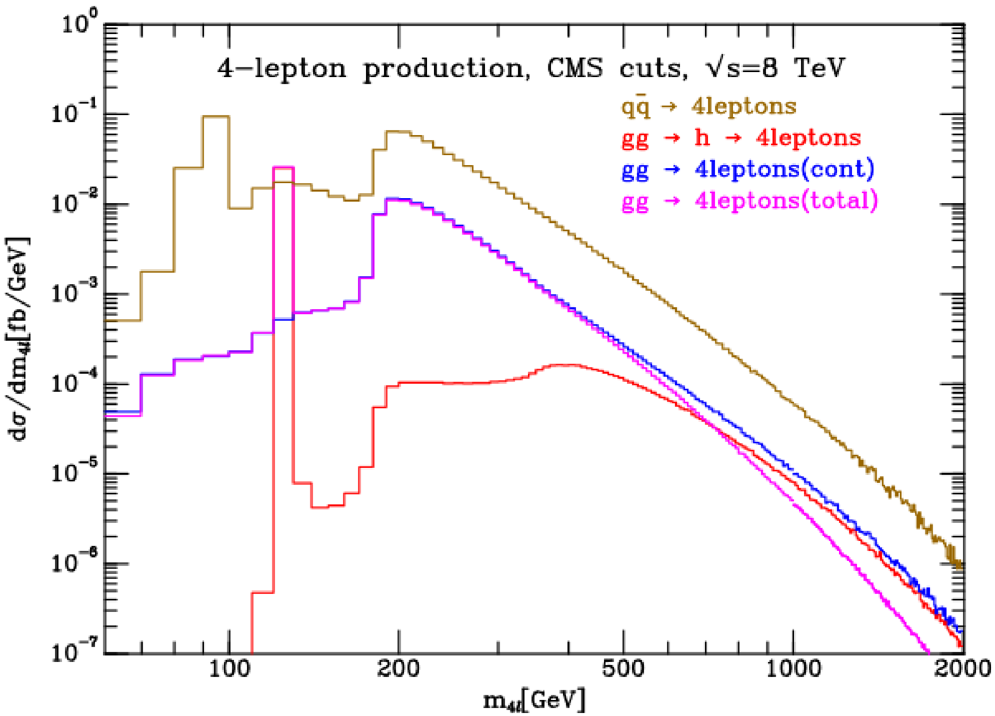
Higgs width from off-shell ZZ

- Off-shell production sizeable at high mass
  - ~7.6% of the total cross section > 2Mz
  - Destructive interference between H and gg → ZZ

On-shell and off-shell production comparison constrains the width:

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

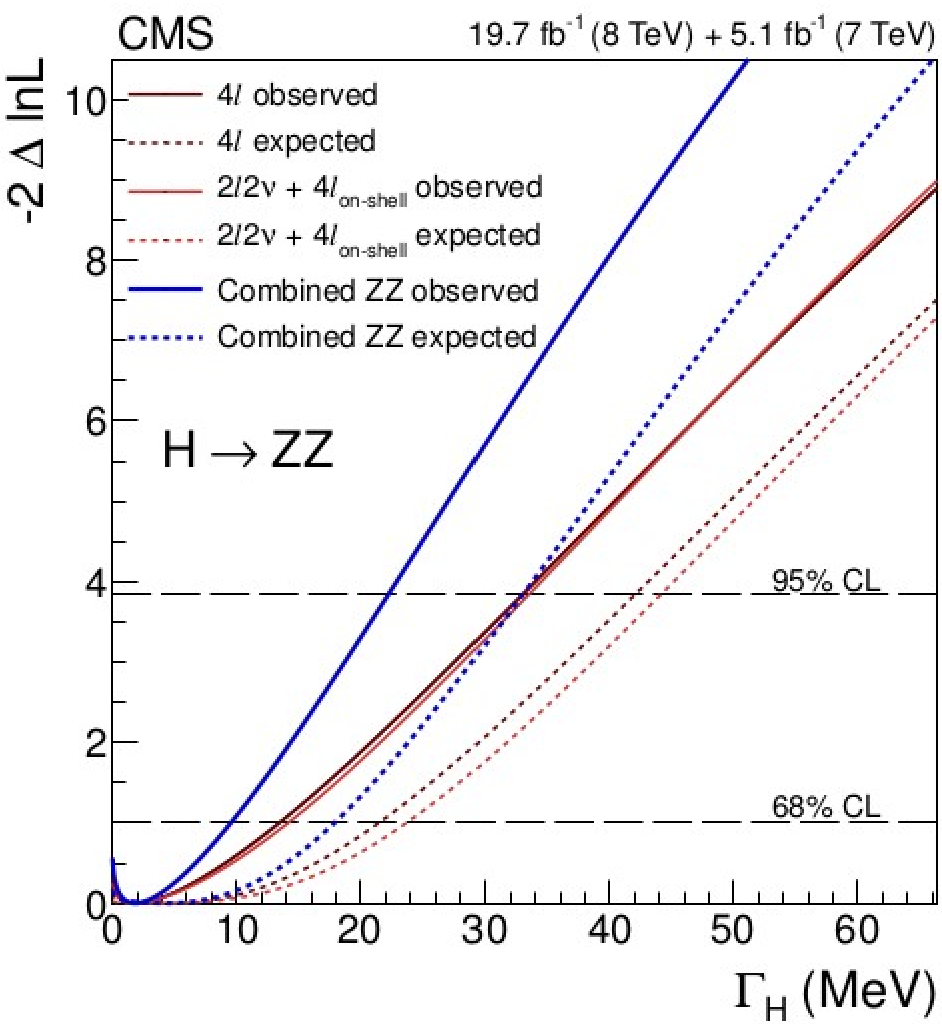
- Mild model dependence
  - No new physics at high M_{ZZ}
  - Gluon fusion production and ZZ decay

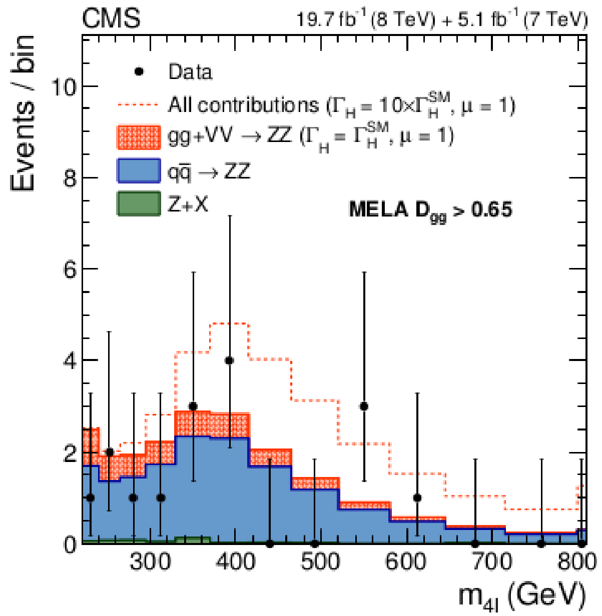


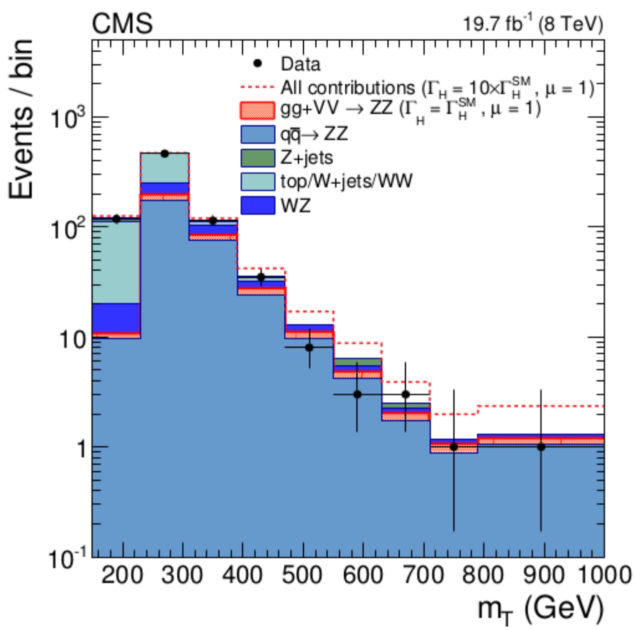
Final states

- Four lepton final state
  - 2D fit in mass and gluon fusion discriminant
- 2l2ν final state
  - 1D fit in transverse mass

Results on bounds on Γ_{tot}







- Expected width < 30 MeV @95%CL
  - Observed width<22 MeV
  - SM Width of 4.15 MeV

Anomalous couplings in spin 0

NEW!

Generic decay amplitude in H → VV defined in terms of complex and momentum dependent couplings (up to q^2)

SM tree level + leading momentum expansion

$$A(X_{J=0} \to V_1 V_2) = v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2}\right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu}\right)$$

} VV couplings

} $Z\gamma^*$ couplings

} $\gamma^*\gamma^*$ couplings

a_2 terms: CP-even scalar

a_3 terms: CP-odd pseudo-scalar

- $Z\gamma^*$ and $\gamma^*\gamma^*$ only present in the ZZ* case
- Λ_1 → scale of new physics affecting tree level VV* coupling
- **goal → extract the α_i parameters!**

Analysis strategy in ZZ* and WW*

- Instead of the couplings themselves define ratios of cross sections:

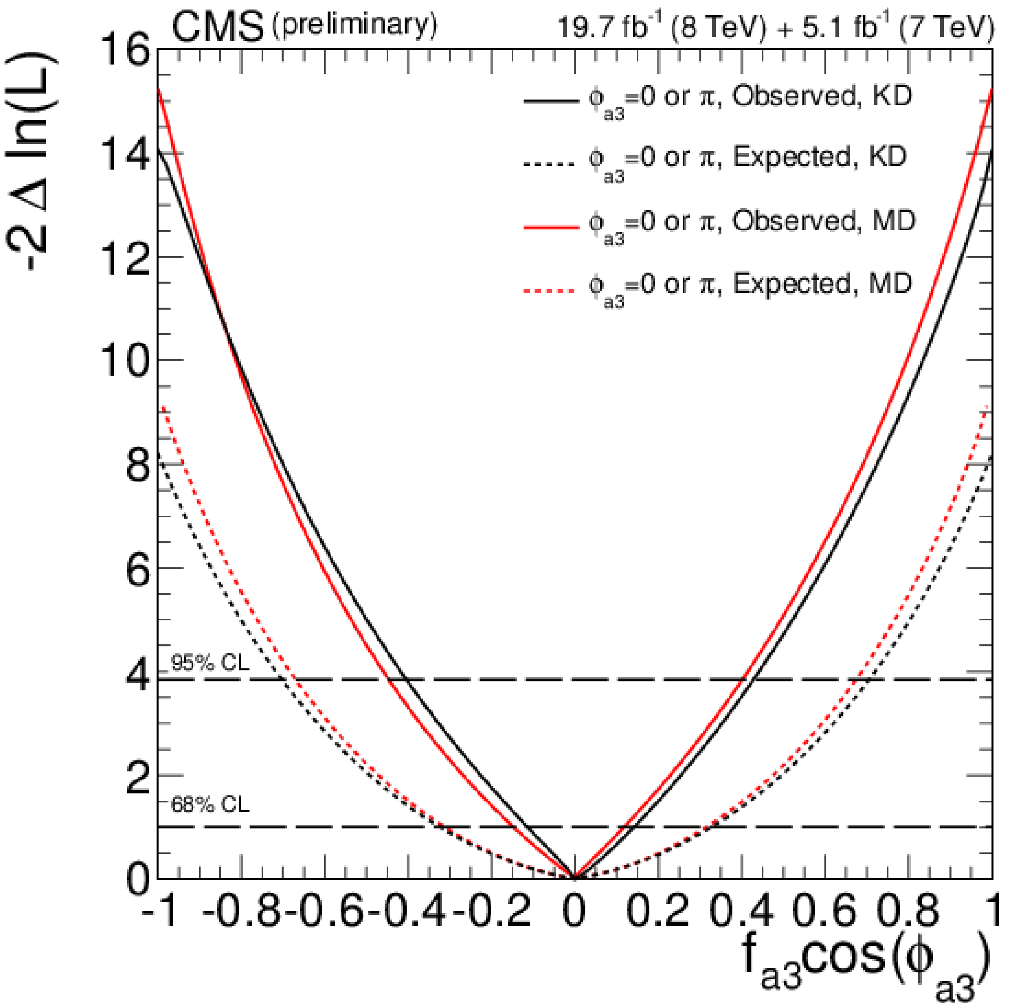
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

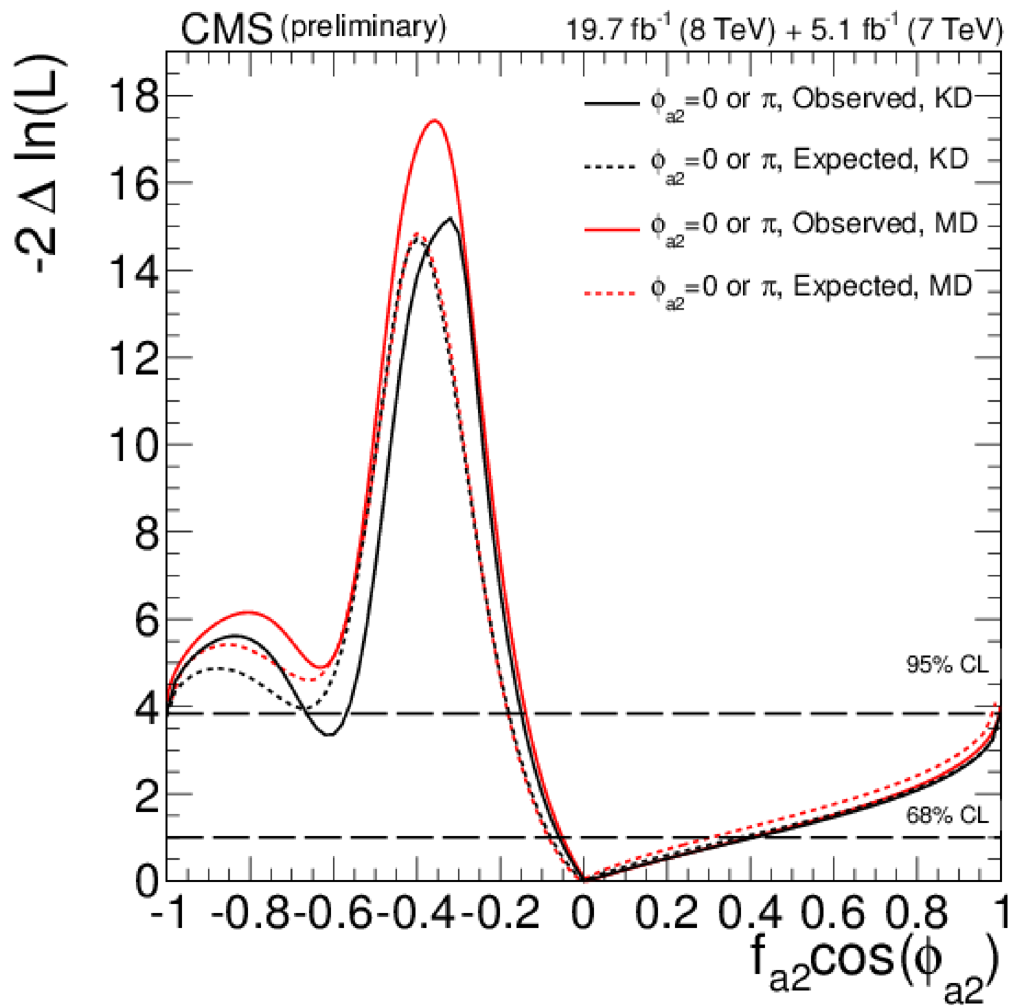
- In the ZZ* final state possible to perform 8D fit to extract the results
  - Dimensionality can be reduced to 2D /3D by exploiting kinematic discriminants
- Both real and complex couplings are studied

- In the WW* final state, angular information is packed in the transverse mass and the dilepton mass distributions
  - Use 2D templates
  - Only real couplings studied

NEW!

Probing a single coupling in ZZ*

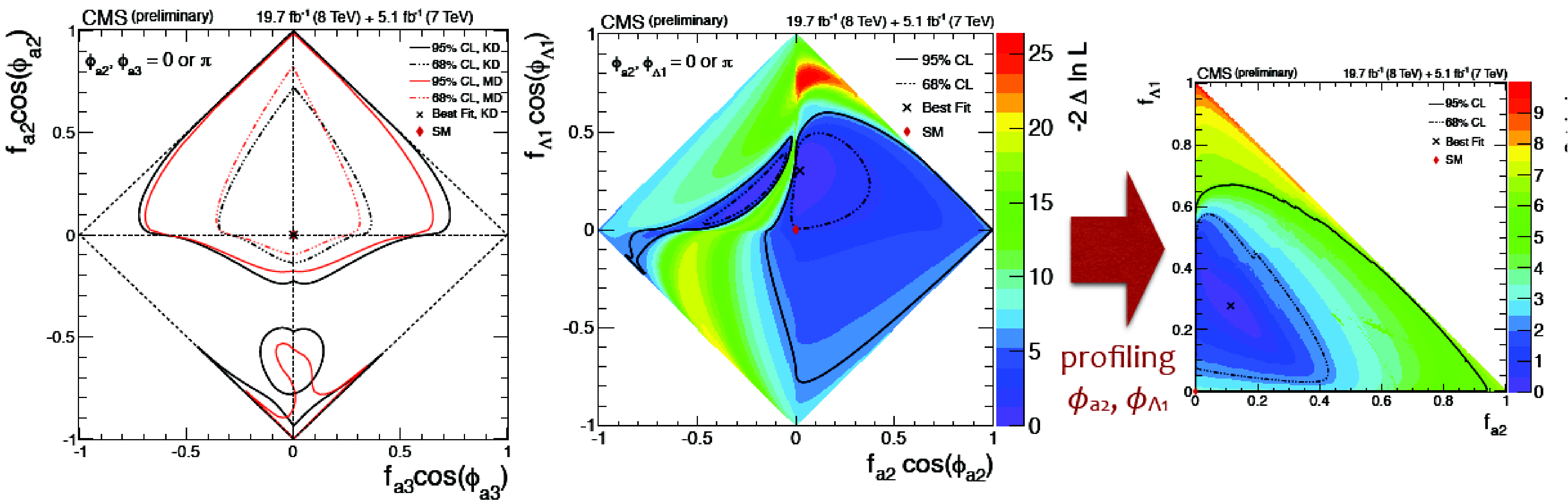




- Real phases (0 or π)
- Good agreement between different techniques
- Better observed exclusion in fa3

NEW!

Probing 2D couplings

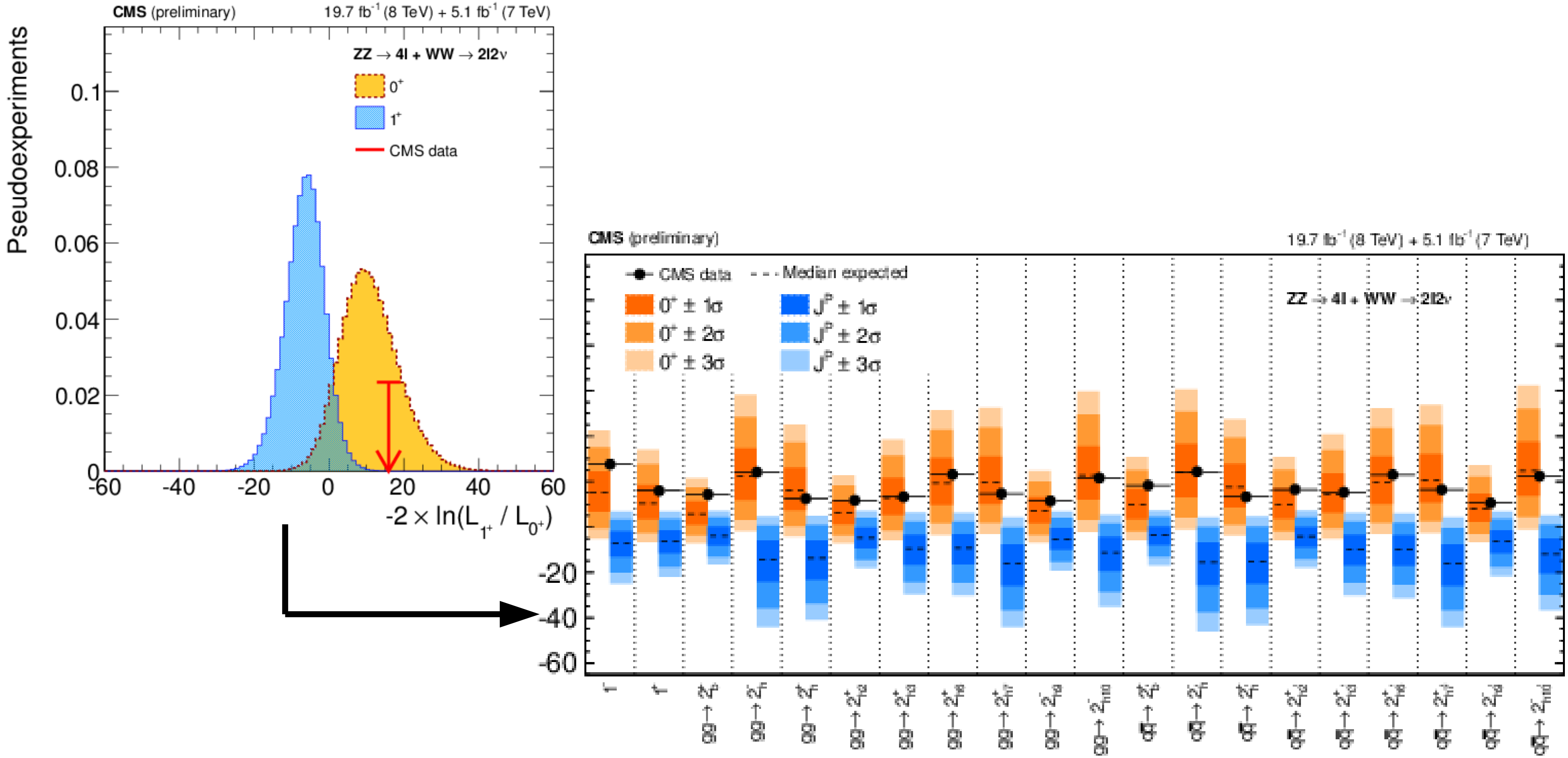


- 2D fit of fa_2 vs fa_3 with real phases
  - Good agreement between discriminants and multidimensional fit
- 2D fit of fa2 vs $f\Lambda_1$ using the kinematic discriminant method
  - For real phases and after profiling the phases
  - As expected lower sensitivity when profiling
- Observation consistent with the SM

NEW!

Hypotheses tests for J=1,2

Combining ZZ* and WW* final states



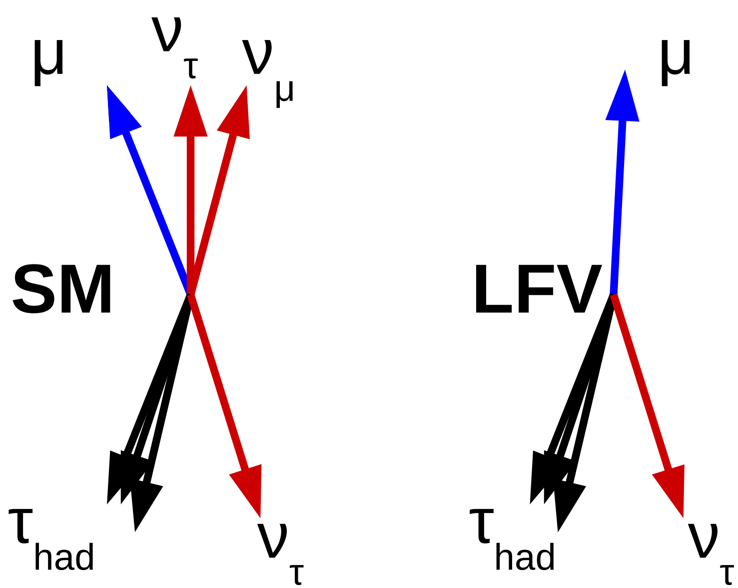
Several pure states have been considered

All alternative hypotheses excluded > 99% CL

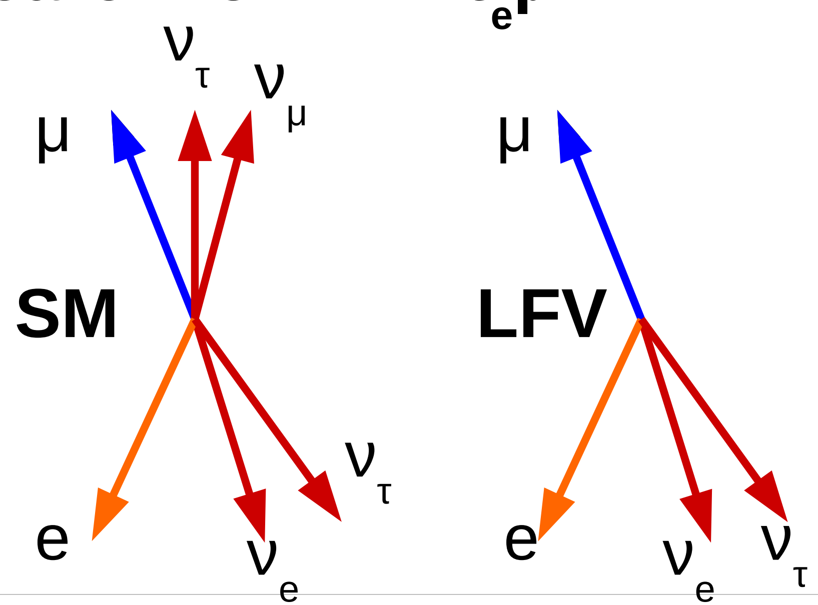
Search for LFV Higgs decays

NEW!

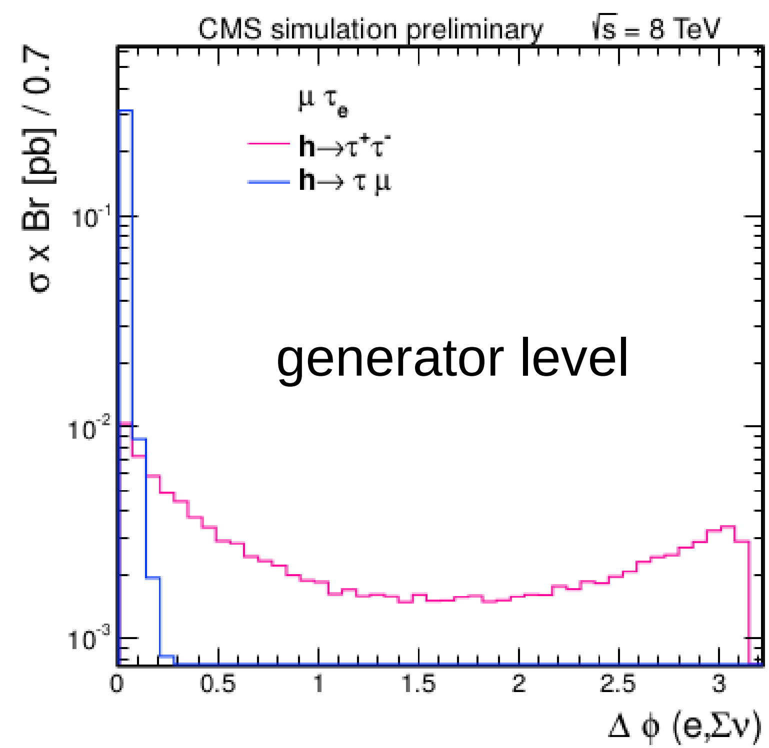
Search for H → $\tau_{had}\mu$



Search for H → $\tau_e\mu$



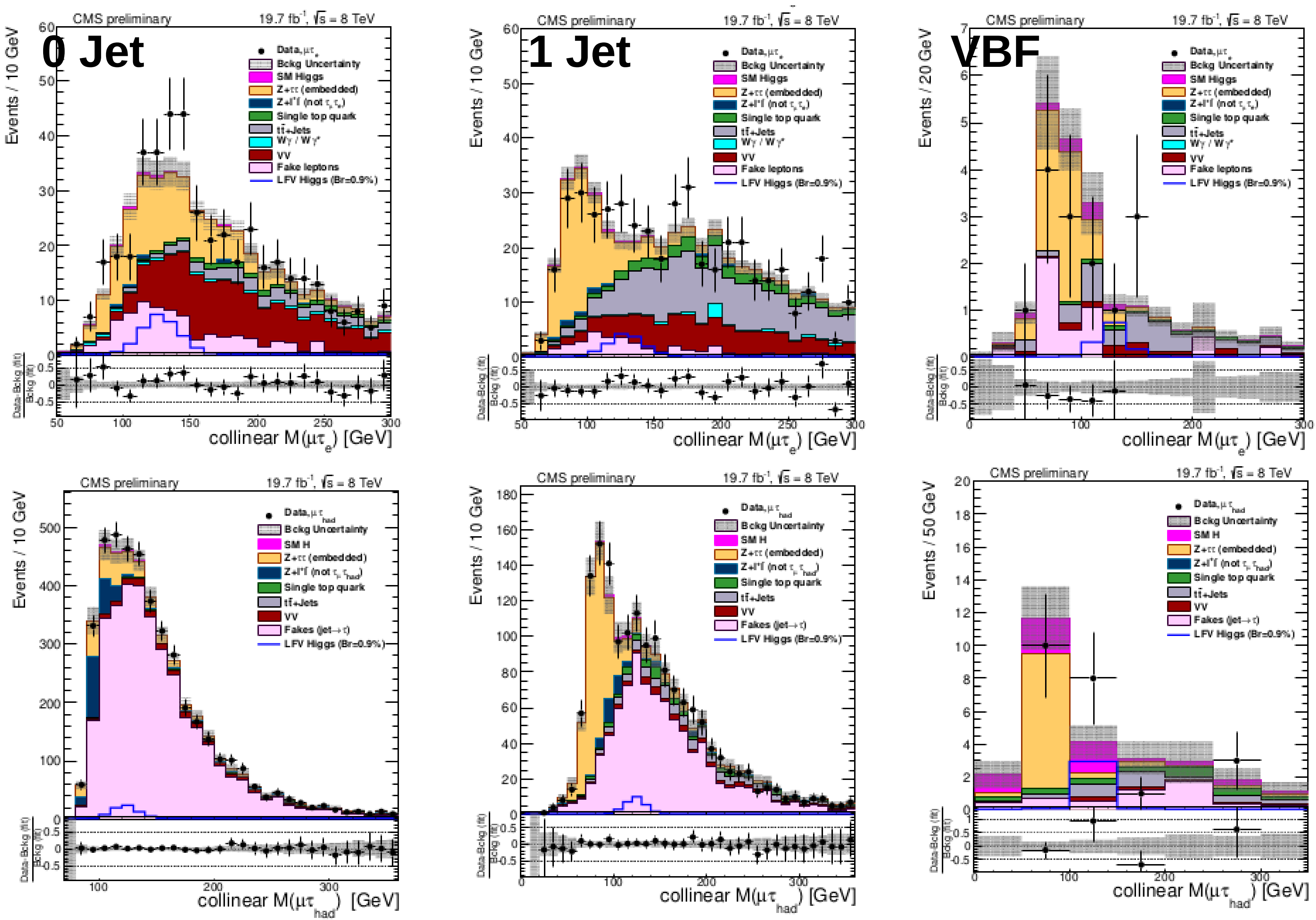
- Main backgrounds: Z/H → ττ
- Similar strategy as in the di-tau analysis
- Exploit collinearity between tau and MET
  - Use collinear approximation



CMS PAS HIG-14-005

LFV Higgs mass distributions

NEW!

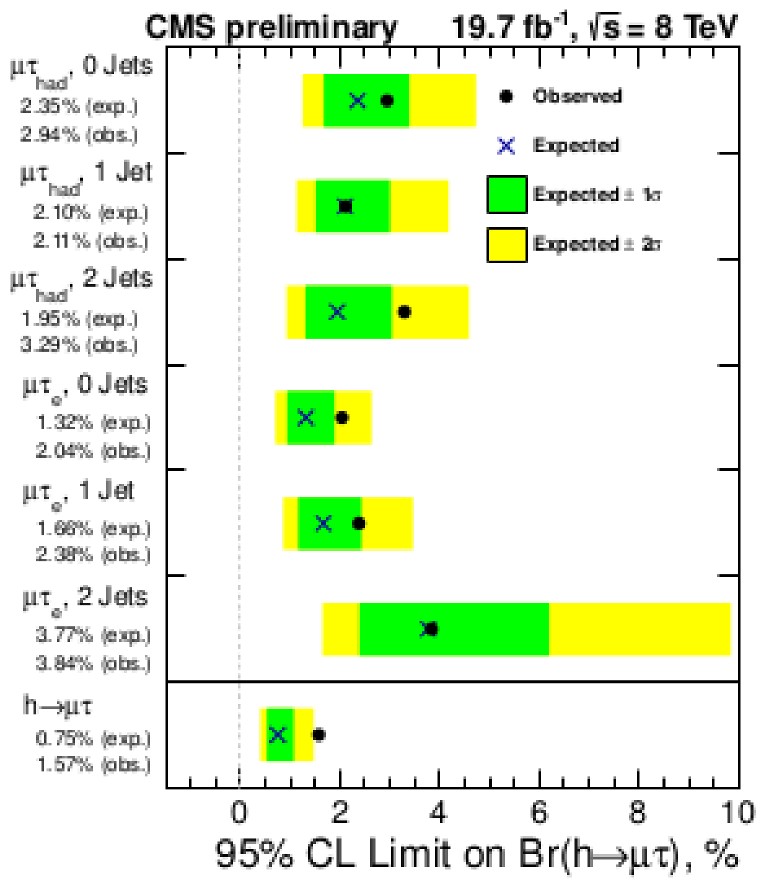


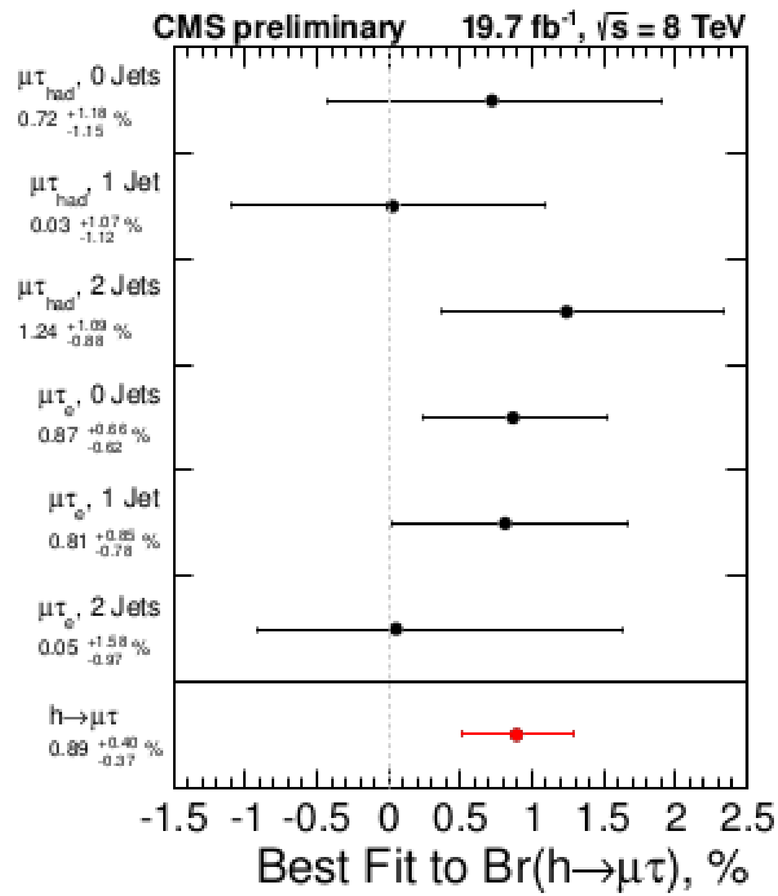
$\tau_e\mu$

$\tau_{had}\mu$

Limits on BR(H → τμ)

NEW!

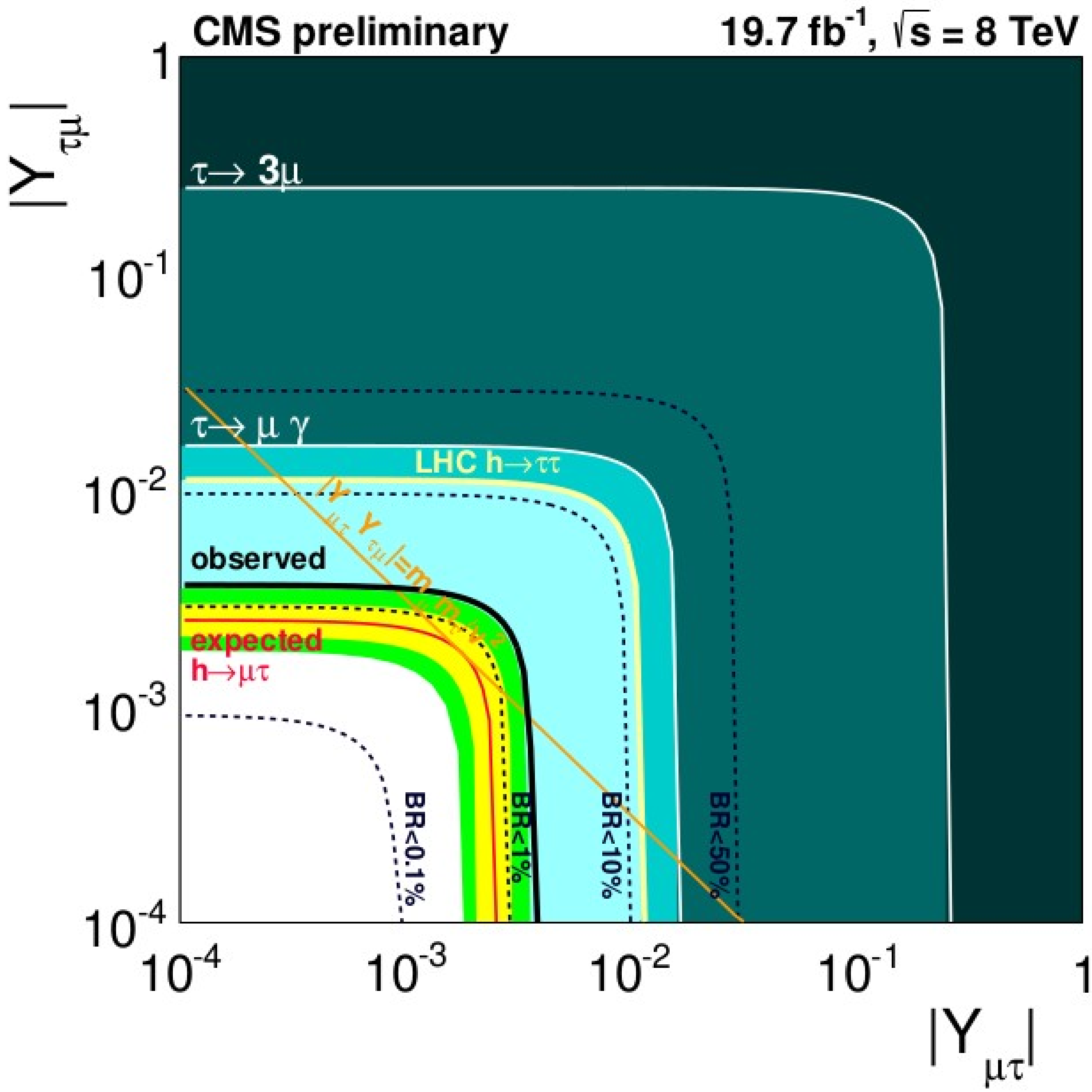




- Expected limit on BR(H → μτ) = 0.75% @ 95% CL
  - Observed limit=1.57% @95% CL
- Mild excess on data at the level of 2.5σ

FV Yukawa couplings

NEW!



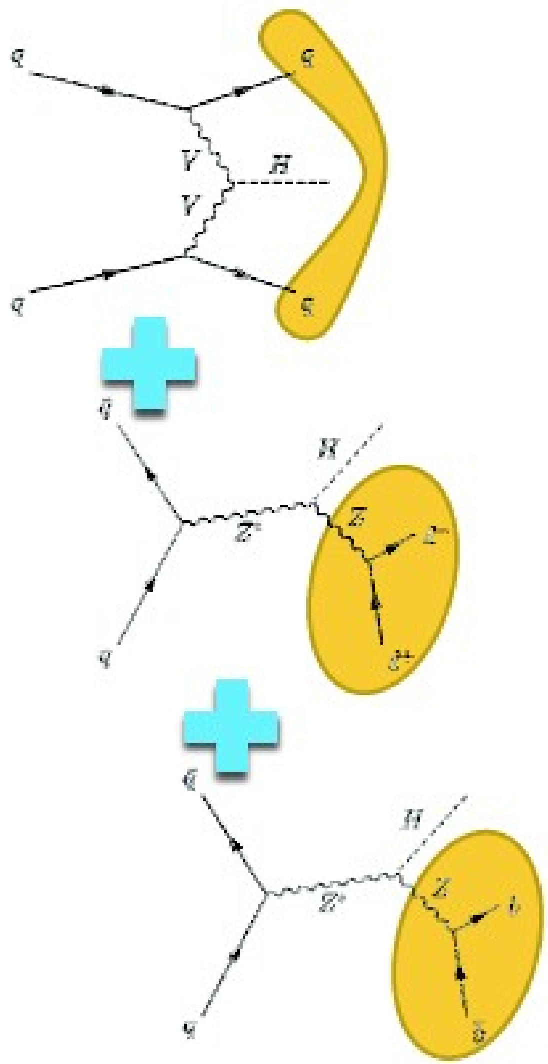
- Promising future in the LFV Yukawa sector

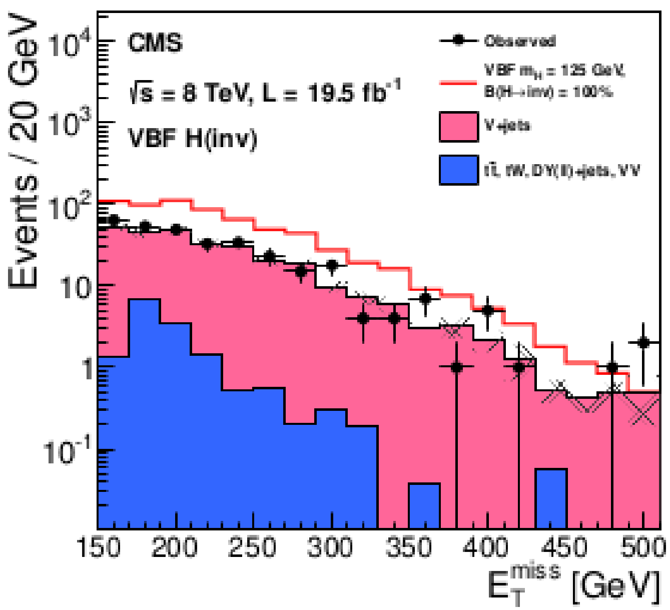
Invisible Decays

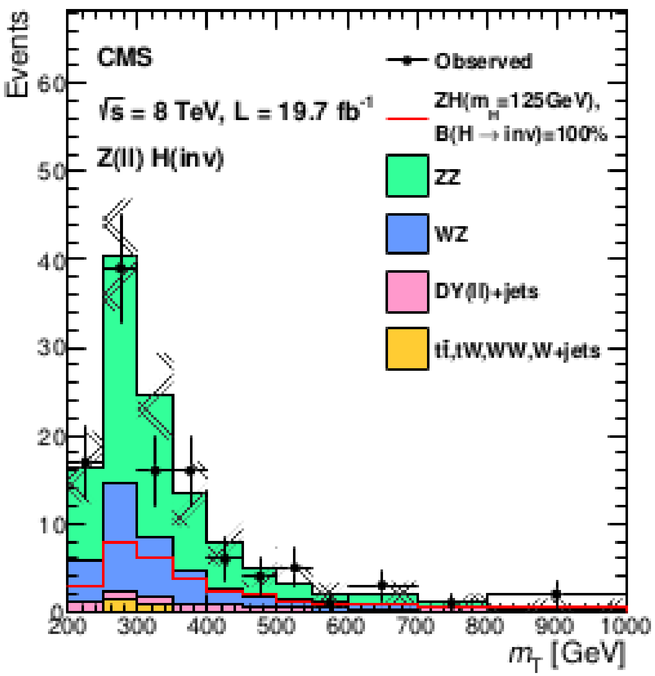
- Higgs → a portal to dark matter searches

  CMS searches in VBF and ZH

  - Z → l^+l^- /bb

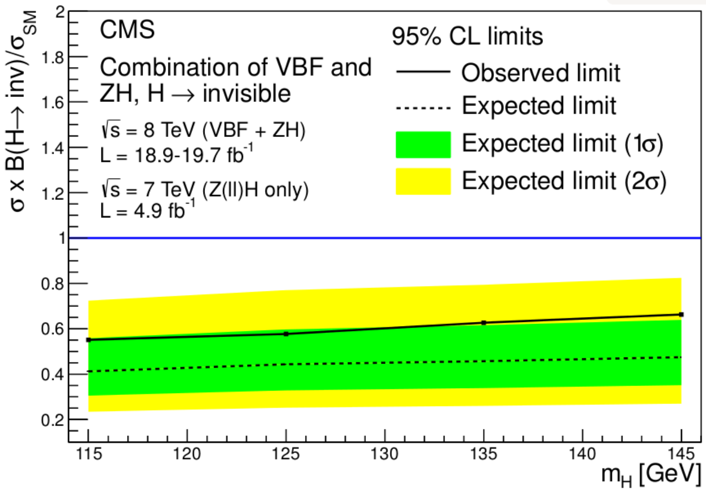




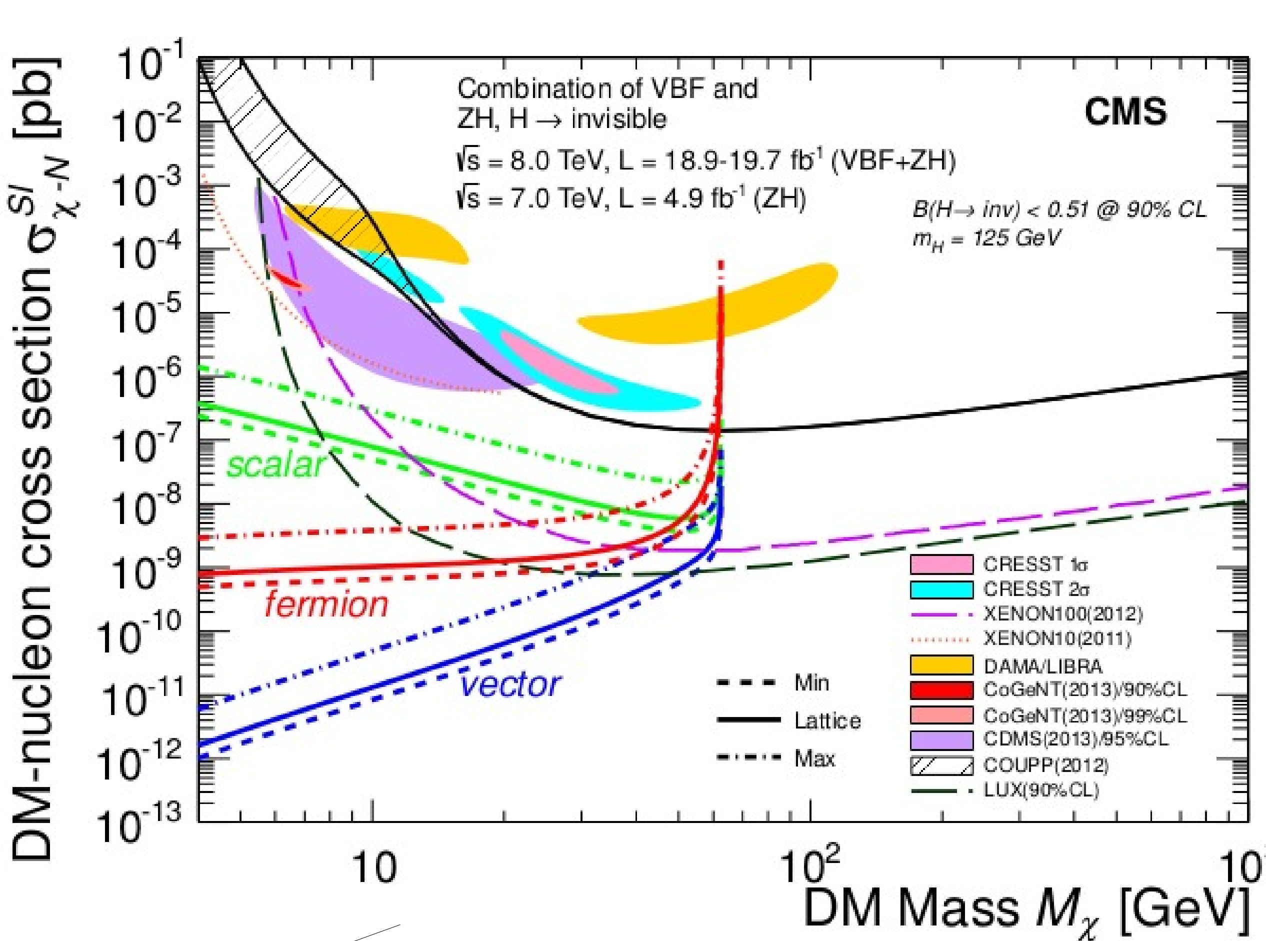


arXiv 1404.1344

Invisible Decays: Results



- Expected limit of 44% in the invisible BR @ 95% CL
  - Observed limit 51%

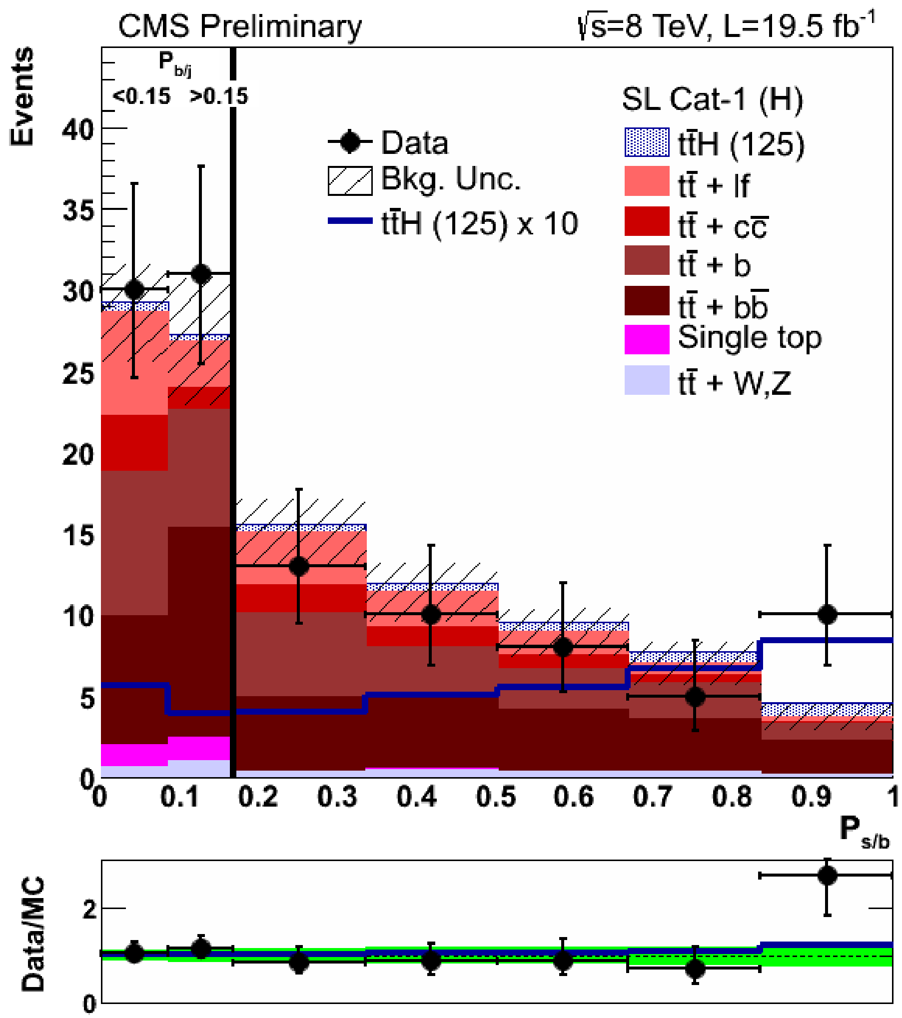


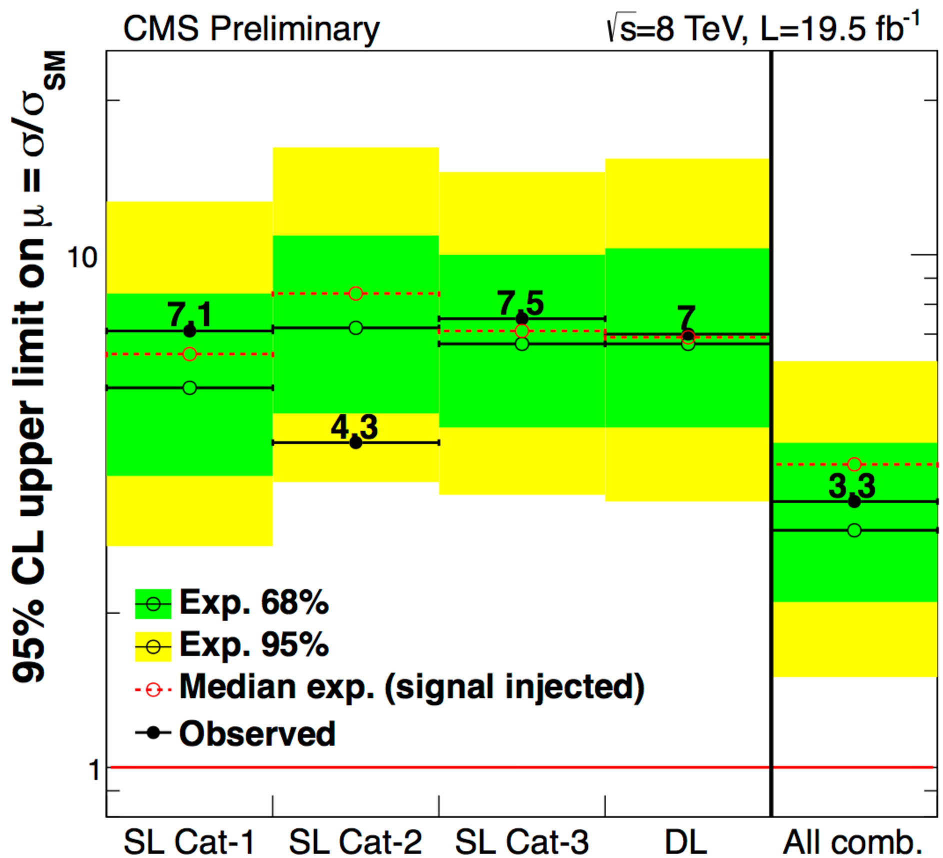
- BR results reinterpreted in the context of Higgs portal of DM interactions
- LHC Higgs search improves reach at low DM mass

Improving ttH with H → bb

NEW!

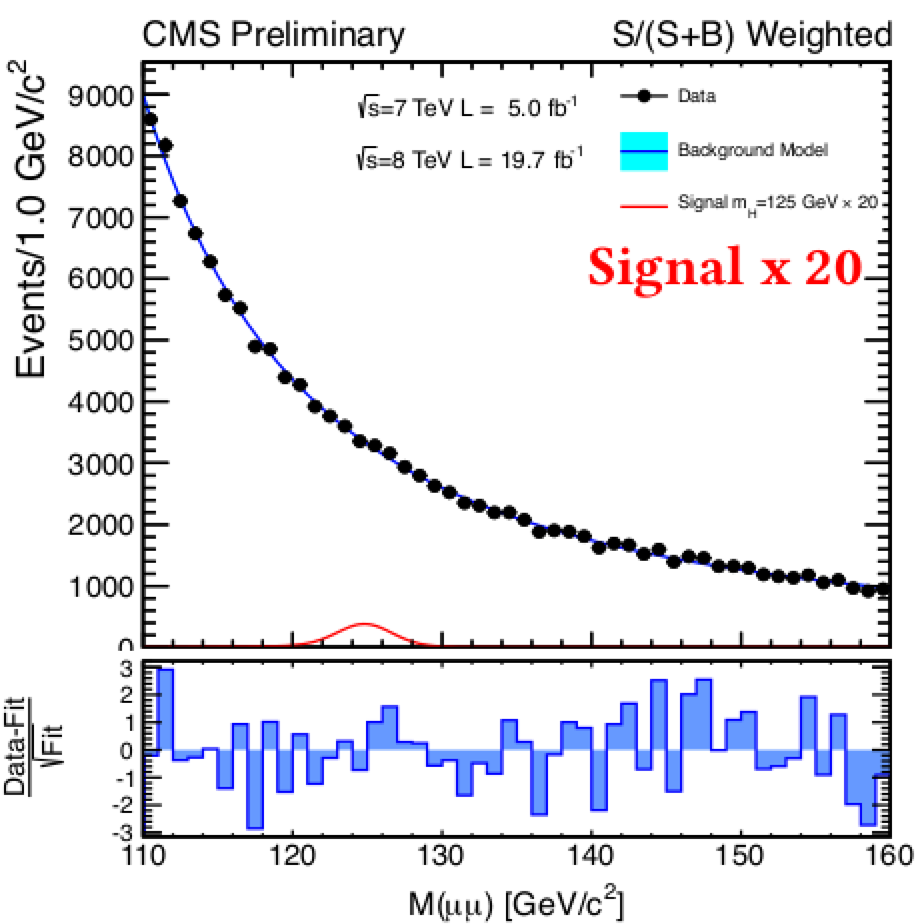
- Improved sensitivity by introducing event probability
  - Based on ME probabilities

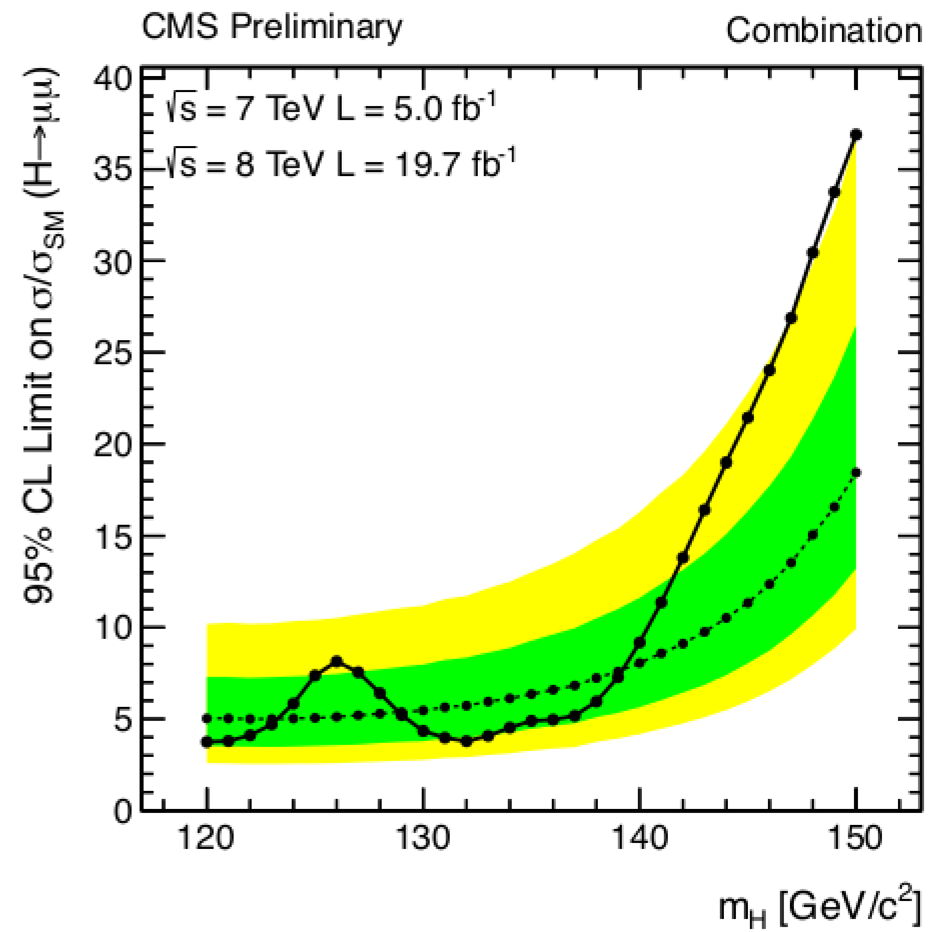




- 30% improvement in the expected limit wrt previous CMS result!

Prospects for H → $\mu\mu$





- Analysis a la di-photon
- Expected limit of 5.1 x SM [25x more data to probe it]
- Leptons not universal regarding Higgs decays !

Conclusions

- CMS closes chapter of Higgs measurements
  - After the publication of the combination paper the main Run I analyses will be finished
  - Focus on preparation for data taking next year
- Excellent results with many measurements in many final states and production modes
- With the current statistical precision **we observe a Higgs boson fully consistent with the SM**
  - Regarding couplings and spin-parity properties
- Focus on using the new particle as tool to probe new physics (directly or indirectly)

Additional material

Challenges of *in situ* operations

Light yield variations:

- scintillation light → temperature dependence: $\Delta S/S \sim -2\%/^\circ\mathrm{C}$ @ 18 °C
- crystal transparency → radiation dose-rate dependence

Photo-detector response:

- APD →
  - gain temperature dependence: $\Delta G/G \sim -2\%/^\circ\mathrm{C}$
  - gain High-Voltage dependence: $\Delta G/G \sim 3\%/\mathrm{V}$
  - direct ionization effects, a.k.a. "spikes"
- VPT → response dependence on the incremental charge at the cathode

Tracker material in front of ECAL:

- photon conversions
- bremsstrahlung losses for electrons

3.8 T solenoidal magnetic field:

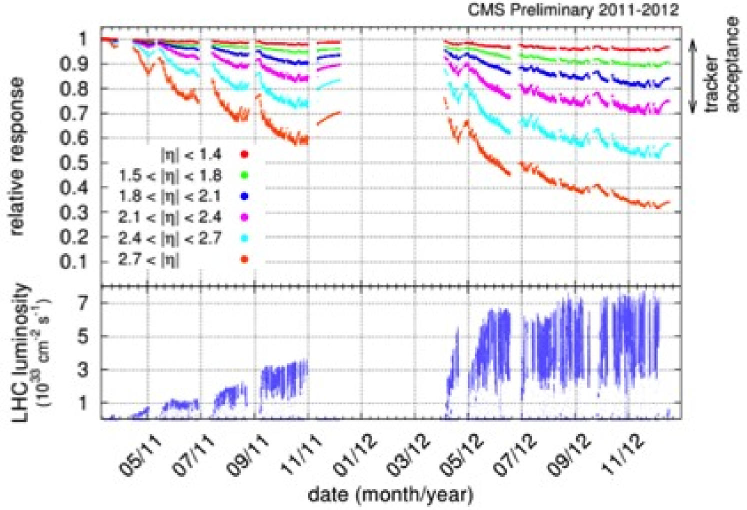
- spread of the e, γ energy along φ, at ≈ constant η

→ **Excellent environmental stability** (×2 to ×3 better than required) [3]
→ **Dedicated monitoring system and calibration techniques** [4, 5]
→ **Specific energy reconstruction algorithms and corrections**

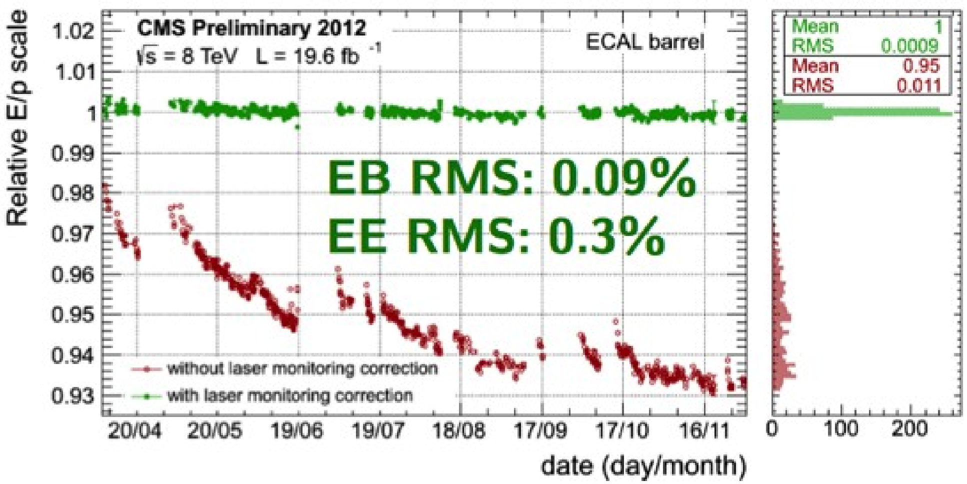
[http://cern.ch/go/PT9c]

Monitoring and calibration signals

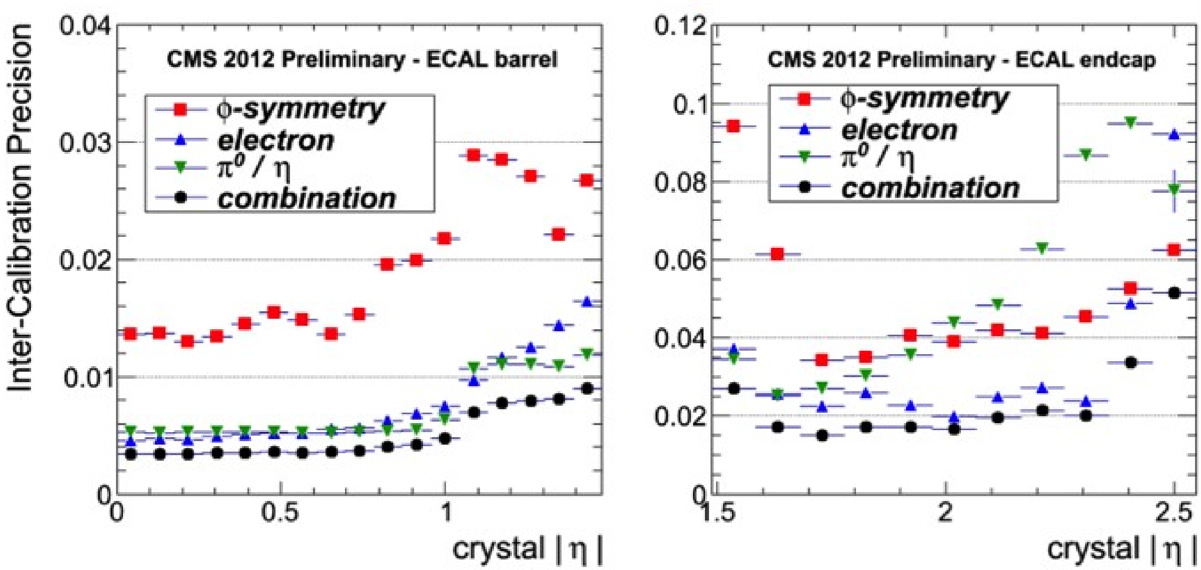
Laser monitoring measurements



Validation of the corrections with E/p



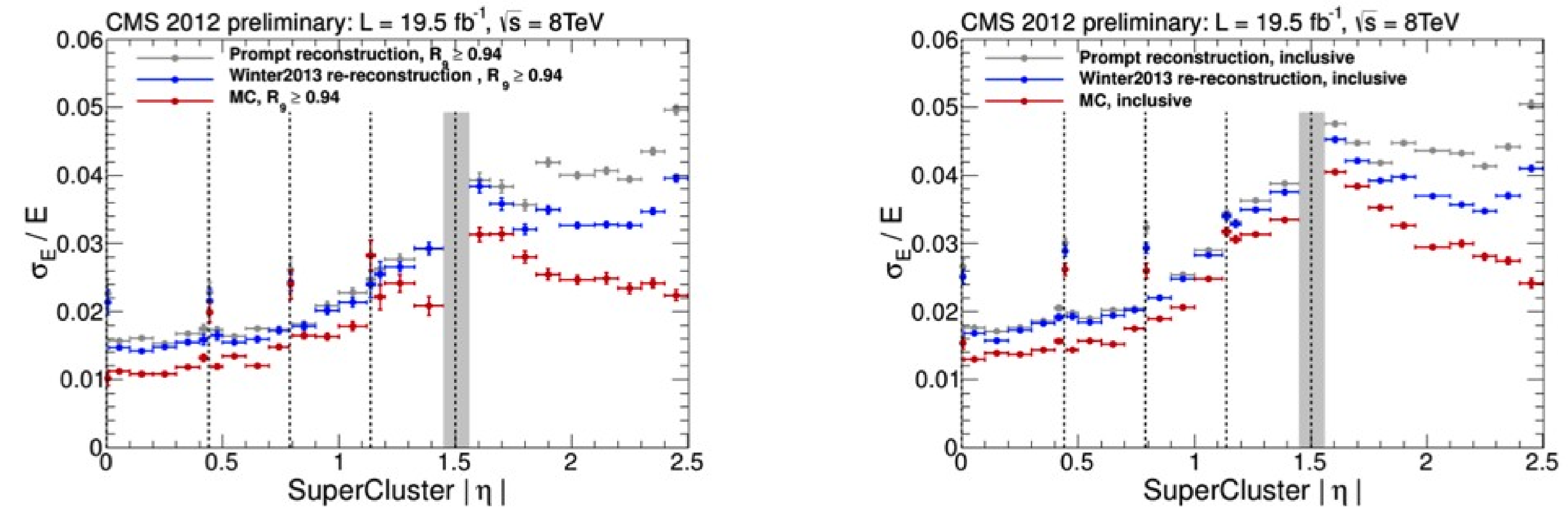
Inter-calibration precision



[F. De Guio's talk]

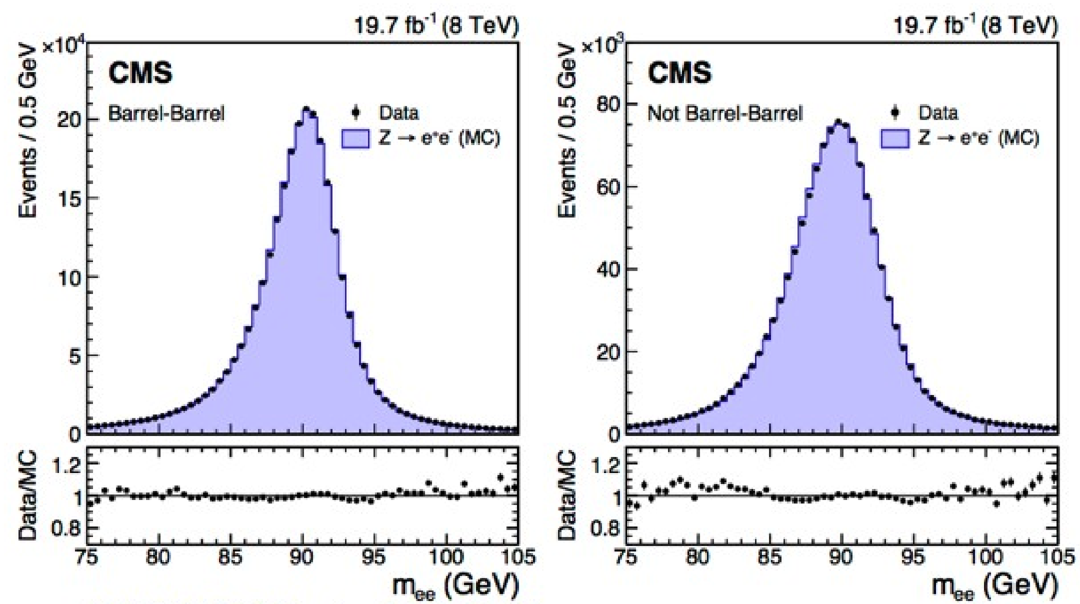
Performance: energy resolution

With electrons from Z



↑ Fit to $Z \to ee$ of a Breit-Wigner convolved with a Gaussian function [4]

→ Simulation tuned to match performance observed *in situ* with $Z \to ee$ events



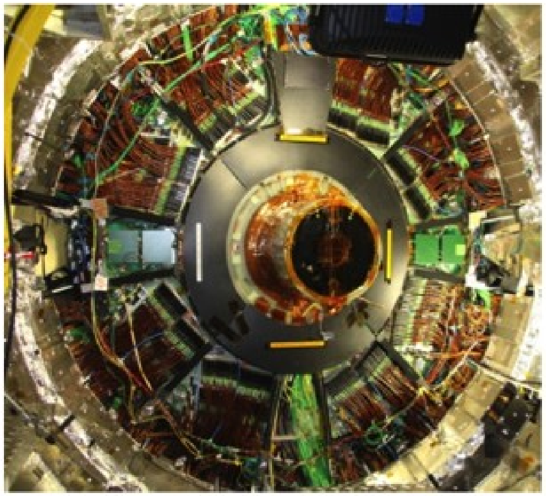
Accurate simulation

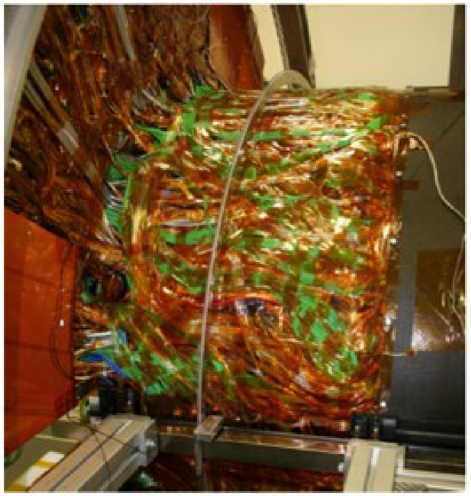
Noise model:

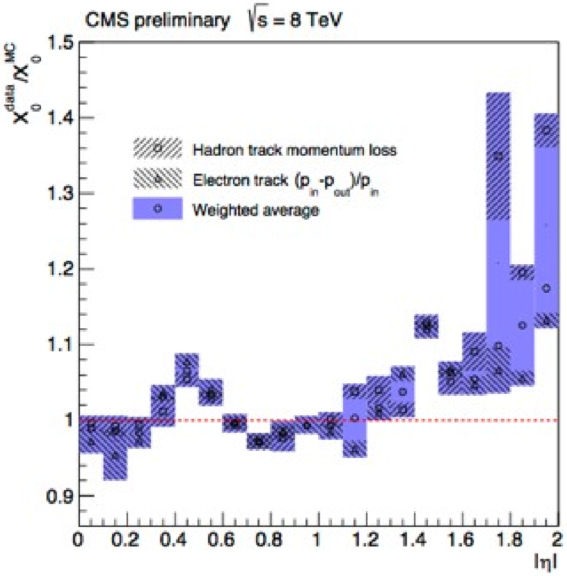
- realistic noise with sample-correlations and channel-to-channel variations
- increase of the APD dark current (expected)
- transparency variations for realistic light-yield (and corresponding photo-statistics)

Material description:

- including in-homogeneities in φ of services in front of the endcaps
- for systematic uncertainties, being implemented in current simulation







Light propagation effects in the crystals (only relevant for upgrade studies)

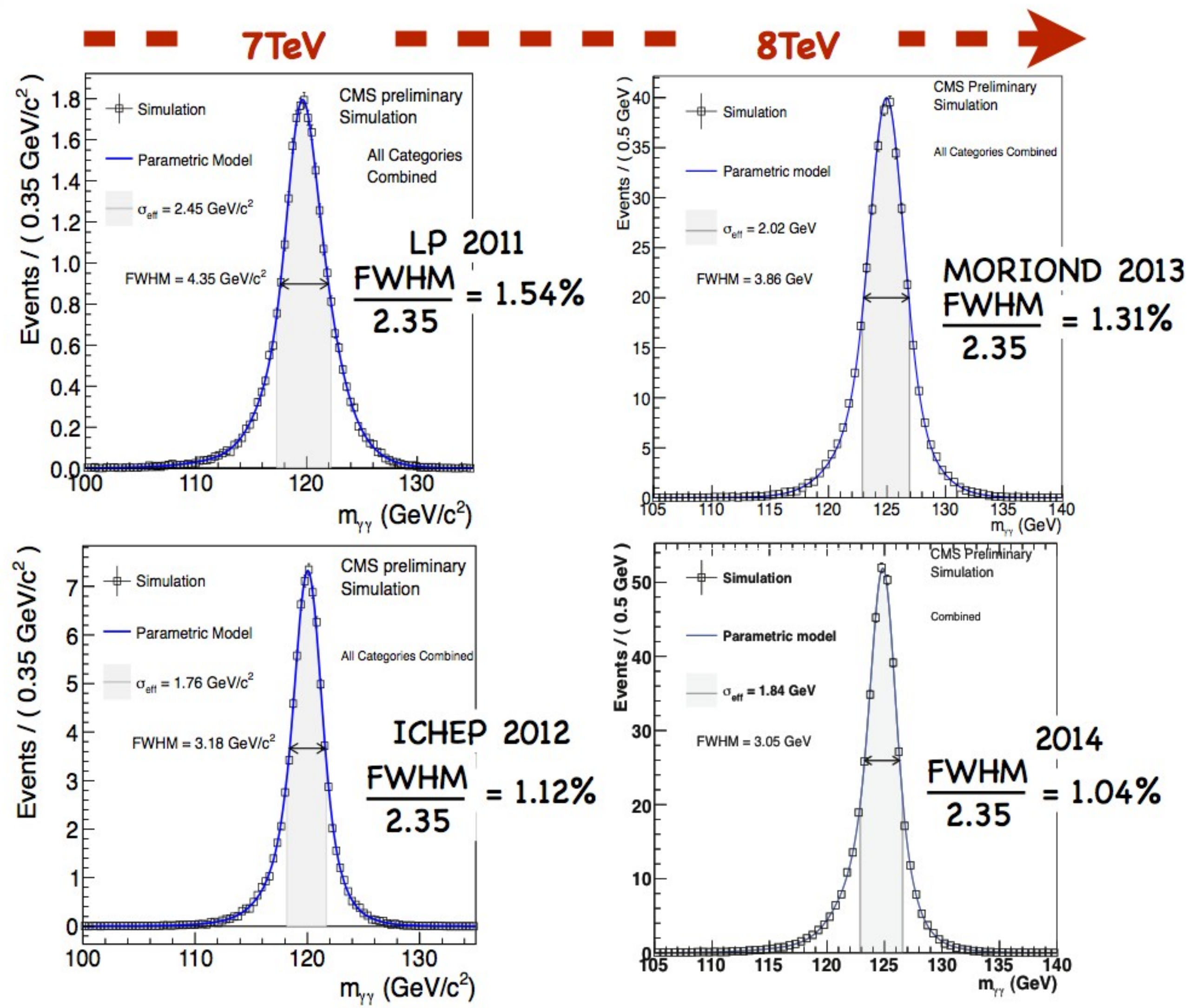
Varying conditions used for a "run-dependent" simulation [N. Marinelli's talk]

Performance evolution

- The energy resolution measured in data with $Z \to ee$ is used to model the expected $H \to \gamma\gamma$ signal in the simulation
- **Steady progress and excellent results**

PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions



ECAL-related systematic uncertainties on m_H

From $H \to \gamma\gamma$:

$$m_H = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})\ \text{GeV}$$

- Electron/photon differencies in the simulation . . . . 0.10 GeV
  - material distribution . . . . 0.07 GeV
  - **longitudinal light-yield non-uniformity . . . . 0.02 GeV**
  - Geant4 . . . . 0.06 GeV
  - ★ uncertainty on the single contribution: ≈ 10 MeV

  N.B.: the detector response to electrons and photons shows differences at the level of 0.5%. What matters is the *difference of these differences* between data and simulation.
- **Residual non-linearity in scale . . . . 0.10 GeV**
- Photon energy scale corrections . . . . 0.05 GeV
- Z line shape . . . . 0.01 GeV
- Checked and negligible contribution: gain switch of the electronics

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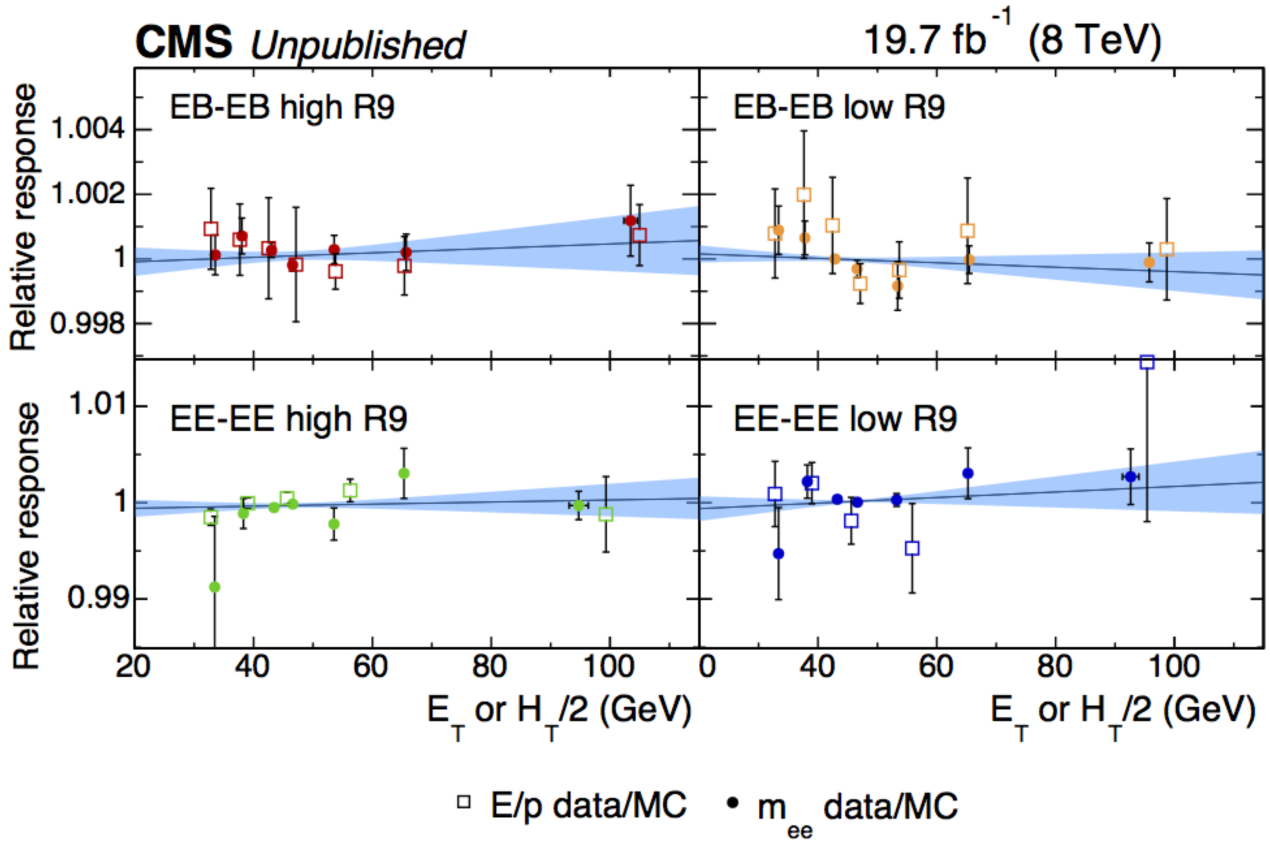
[http://cern.ch/go/PT9c]

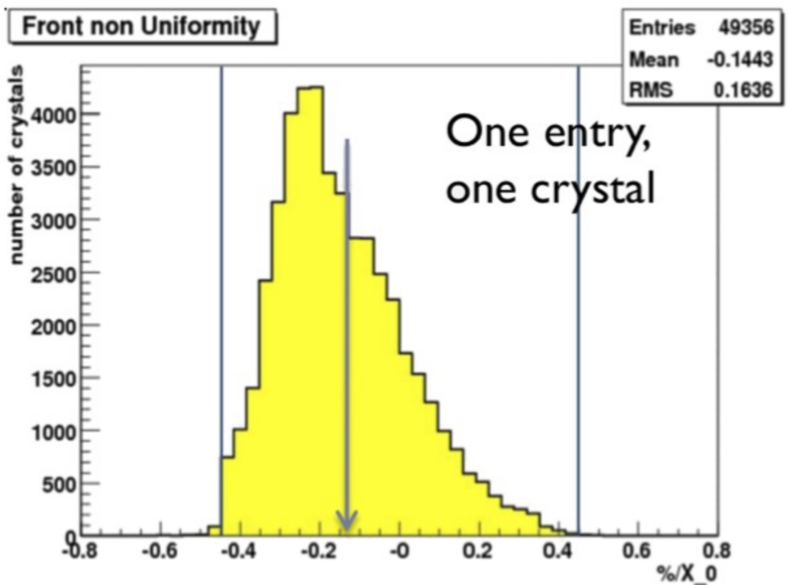
More detail: residual non-linearity in scale

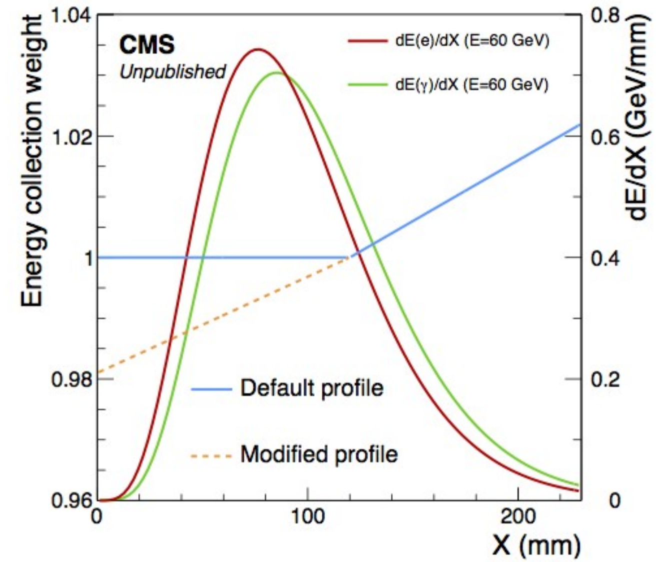


- Residual non-linearity of the energy response in data relative to simulation, relevant in the extrapolation from the energy scale measured at the Z peak ($\approx$ 90 GeV) to the Higgs boson mass ($\approx$ 125 GeV)
  1. electron E/p vs. E_T with electrons from Z and W decays
  2. di-electron invariant mass vs. $H_T = E_T^1 + E_T^2$ in $Z \to ee$ events
- **0.08% effect on the Higgs boson mass**

More detail: longitudinal non-uniformity (NUF)

- **R&D achievements: adequate uniformity of longitudinal light yield**
  - one face of each barrel crystal depolished





- Simulation: rear non-uniformity of 0.15%, front part assumed uniform
- Ionizing radiation found to induce additional NUF of 30% of its initial value (worst case scenario) at the end of Run1 [6]

→ simulation modified to account for these effects

- at most **0.06% effect on the energy scale**, anti-correlated between converted and un-converted photons → **0.015% effect on the mass**

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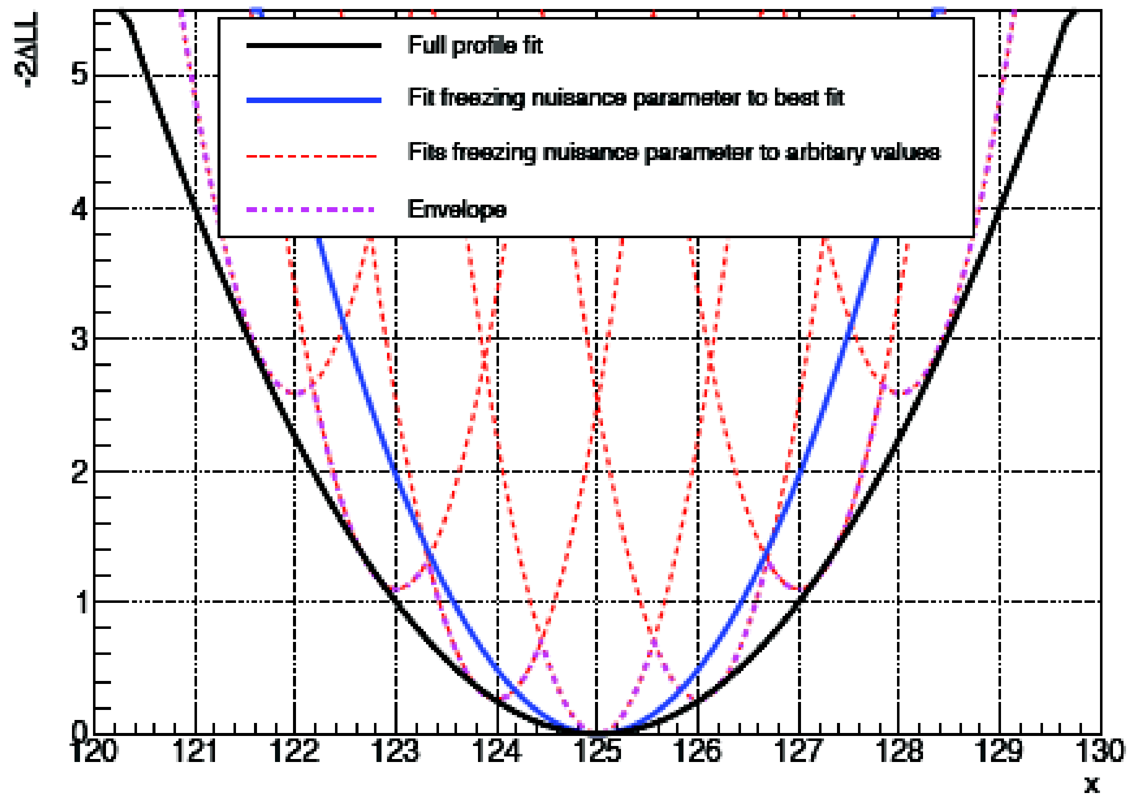
Diphoton background model

- Imagine a simple case with one POI, x, and one nuisance parameter, θ
  - Black line – standard likelihood scan of x profiling θ
  - Blue line – standard likelihood scan of x freezing θ (stat. only)
  - Red lines – standard likelihood scans of freezing θ to different values
  - Pink line – Envelope around this

- If you sample enough of the infinite θ phase-space eventually you can reproduce the black curve with the pink "envelope".



Di-photon background model

- In principle **would like to sample the "infinite" phase space of all possible functions.**
  - In practice this is impossible.
- Instead, **choose from four classes** which we expect ca reasonably cover the phase-space:
  - Power law sum.
  - Exponential sum.
  - Laurent series.
  - Bernstein polynomials.
- **Lowest order** selected by loose G.O.F test.
- **Highest order** selected by loose variant of the F-test.

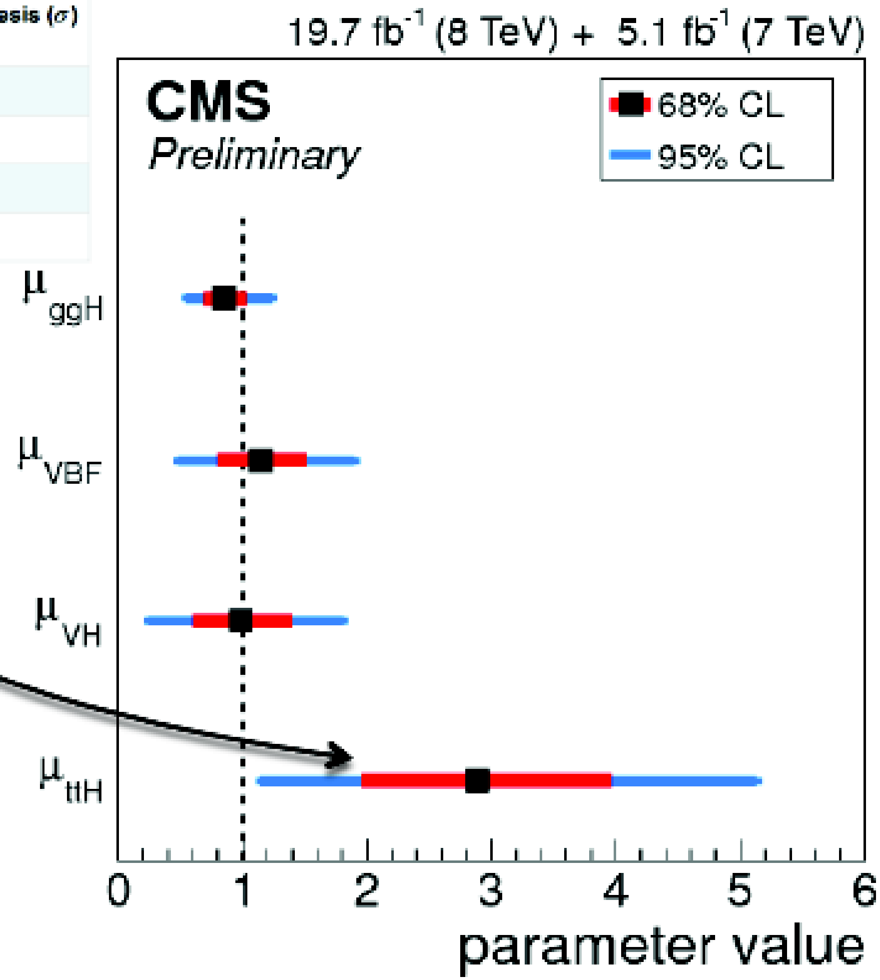
Summary of couplings

Model Parameters	Table in Ref. [27]	Best-fit result Parameter	68% CL	95% CL	Comment
κ_Z, λ_{WZ} ($\kappa_f = 1$)	-	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61,1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.91^{+0.14}_{-0.12}$	[0.70,1.22]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.88,1.15]	κ_V scales couplings to W and Z bosons.
		κ_f	$0.89^{+0.14}_{-0.13}$	[0.64,1.16]	κ_f scales couplings to all fermions.
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.10}_{-0.10}$	[0.69,1.10]	Effective couplings to gluons (g) and photons (γ).
		κ_γ	$1.15^{+0.13}_{-0.13}$	[0.89,1.42]	
$\kappa_g, \kappa_\gamma, BR_{BSM}$	48 (middle)	BR_{BSM}	≤ 0.13	[0.00,0.32]	Branching fraction for BSM decays.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$1.01^{+0.20}_{-0.19}$	[0.66,1.43]	$\lambda_{du} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	[0.61,1.49]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.
$\kappa_g, \kappa_\gamma, \kappa_V,$ $\kappa_b, \kappa_\tau, \kappa_t$	Similar to 50 (top)	κ_g	$0.76^{+0.15}_{-0.13}$	[0.51,1.09]	
		κ_γ	$0.99^{+0.18}_{-0.17}$	[0.66,1.37]	
		κ_V	$0.97^{+0.15}_{-0.16}$	[0.64,1.26]	
		κ_b	$0.67^{+0.31}_{-0.32}$	[0.00,1.31]	Down-type quarks (via b).
		κ_τ	$0.83^{+0.19}_{-0.18}$	[0.48,1.22]	Charged leptons (via τ).
		κ_t	$1.61^{+0.33}_{-0.32}$	[0.97,2.28]	Up-type quarks (via t).
as above plus BR_{BSM} and $\kappa_V \leq 1$	-	BR_{BSM}	≤ 0.34	[0.00,0.58]	

Production mode scaling

- $\mu_{ggH} = 0.85\,^{+0.11}_{-0.09}\,(\text{stat.})\,^{+0.11}_{-0.08}\,(\text{theo.})\,^{+0.10}_{-0.09}\,(\text{syst.})$

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1



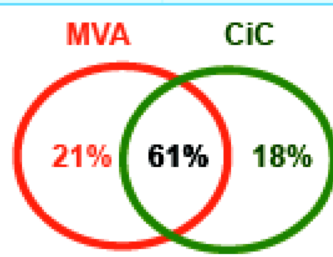
Parameter	Best fit result (68% CL) for 7 TeV data	Best fit result (68% CL) for 8 TeV data
μ_{ggH}	$1.00^{+0.36}_{-0.32}$	$0.80^{+0.19}_{-0.17}$
μ_{VBF}	$1.78^{+0.97}_{-0.91}$	$1.02^{+0.39}_{-0.36}$
μ_{VH}	$0.69^{+0.98}_{-0.66}$	$1.06^{+0.45}_{-0.43}$
μ_{ttH}	$0.00^{+2.13}_{-0.00}$	$3.22^{+1.14}_{-1.00}$

Di-photon analyses Compatibility

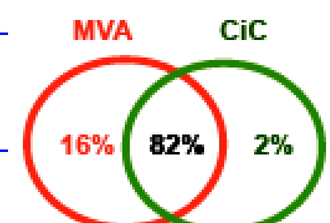
- Jack-knife provides estimate of expected width, σ(δμ), between two correlated analyses using sub-samples of each dataset.
  - Used Bernstein polynomial background model for simplicity.

Analysis 1	Analysis 2	σ(δμ)	δμ (obs)	Linear correlation
Final MVA 8 TeV	Final CiC 8 TeV	0.20	0.19	74%
Final MVA 7 TeV	Final CiC 7 TeV	0.42	0.17	72%
Final MVA 8 TeV	Moriond MVA 8 TeV	0.21	0.22	71%
Final CiC 8 TeV	Moriond CiC 8 TeV	0.21	0.03	76%
Final MVA (Envelope) 8 TeV	Final MVA (Bernsteins) 8 TeV	0.22	0.35	-

CiC – MVA Overlap
(Final **Data** 8 TeV)



CiC – MVA Overlap
(Final **Signal** 8 TeV)



Production modes

Channel grouping	Best fit $(\mu_{ggH,t\bar{t}H}, \mu_{VBF,VH})$
$H \to ZZ$ tagged	(0.88, 1.75)
$H \to \gamma\gamma$ tagged	(1.07, 1.24)
$H \to WW$ tagged	(0.87, 0.66)
$H \to \tau\tau$ tagged	(0.52, 1.21)
$H \to bb$ tagged	(0.57, 0.96)
Combined best fit $\mu_{VBF,VH}/\mu_{ggH,t\bar{t}H}$	
	Observed (expected)
	$1.25^{+0.63}_{-0.45}$ $(1.00^{+0.49}_{-0.35})$