Combined mass and couplings of the Higgs boson at CMS

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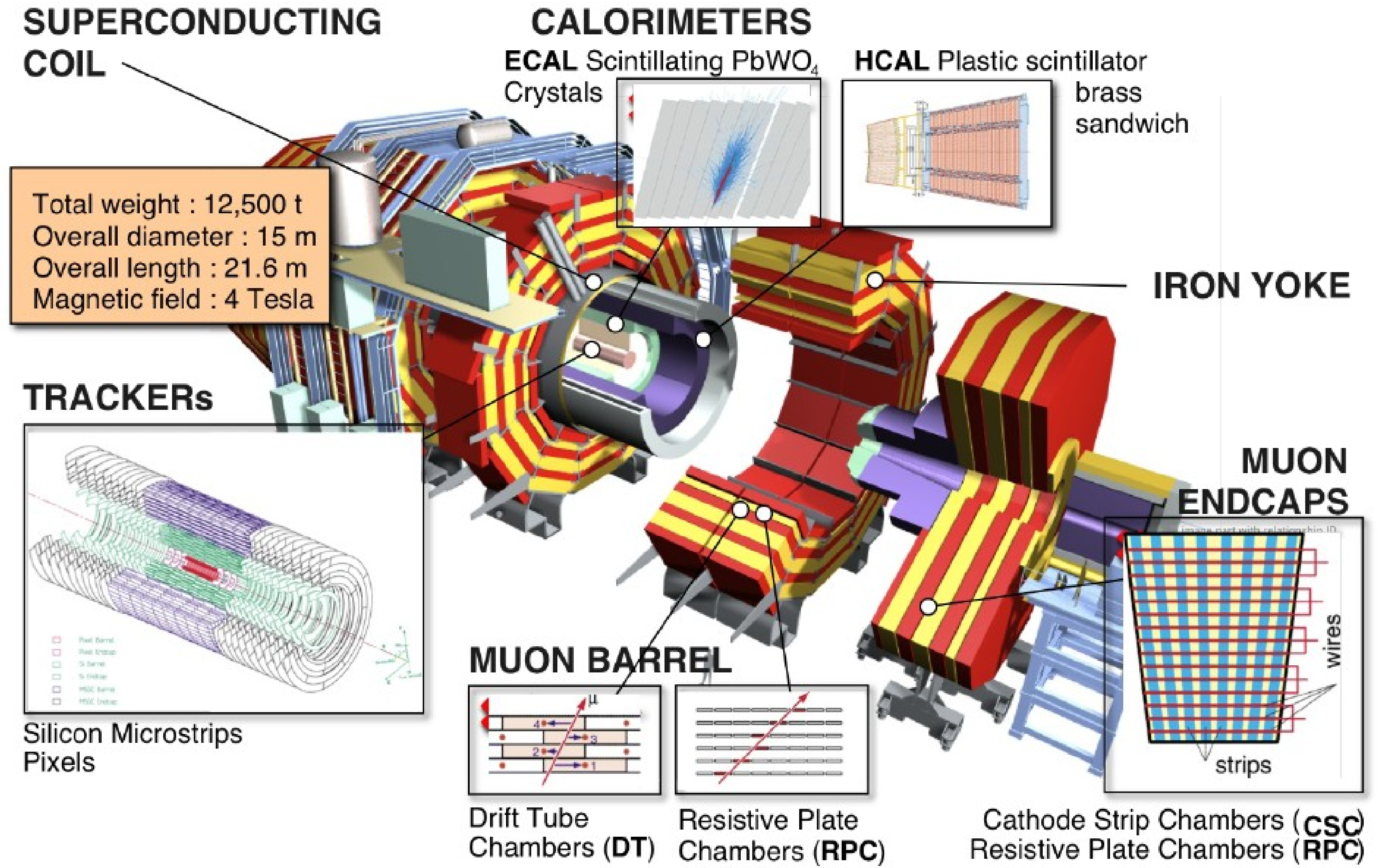
On Behalf of the CMS collaboration

ETH Institute for Particle Physics

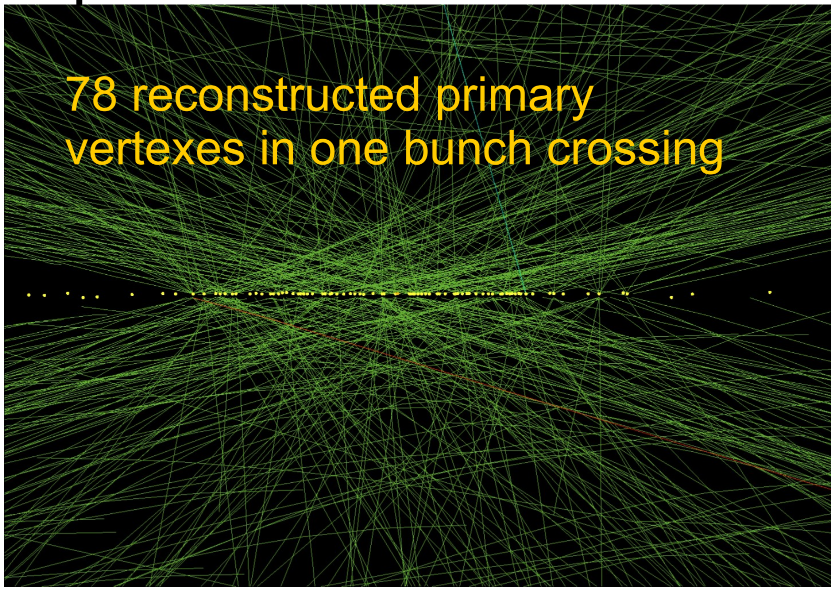
CMS

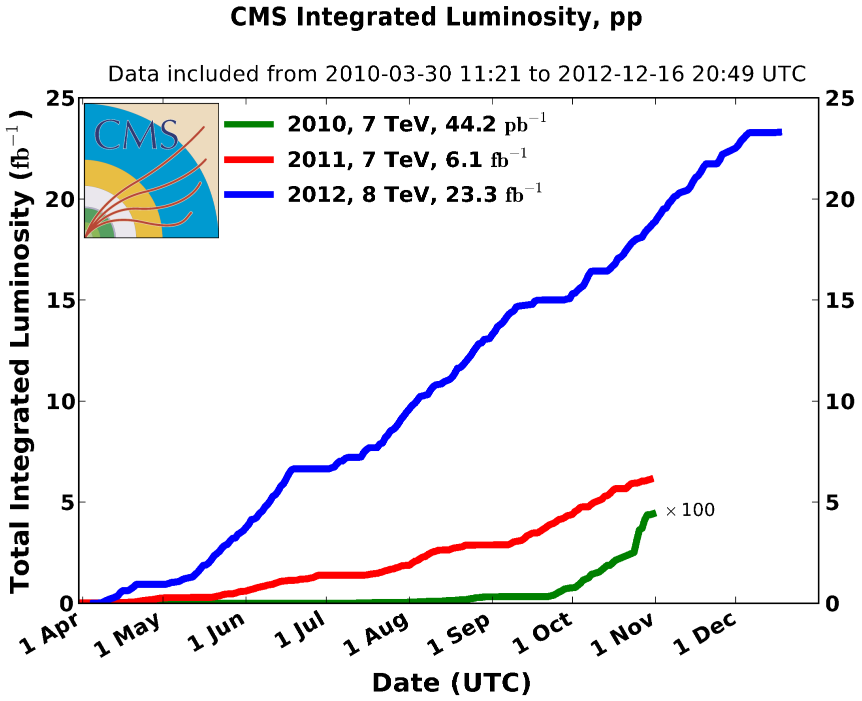
The CMS detector

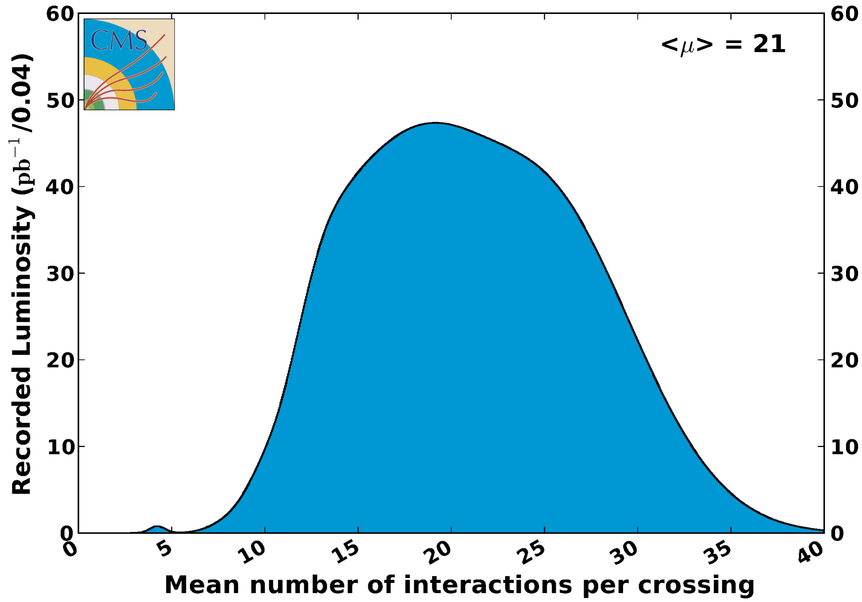


LHC Run I

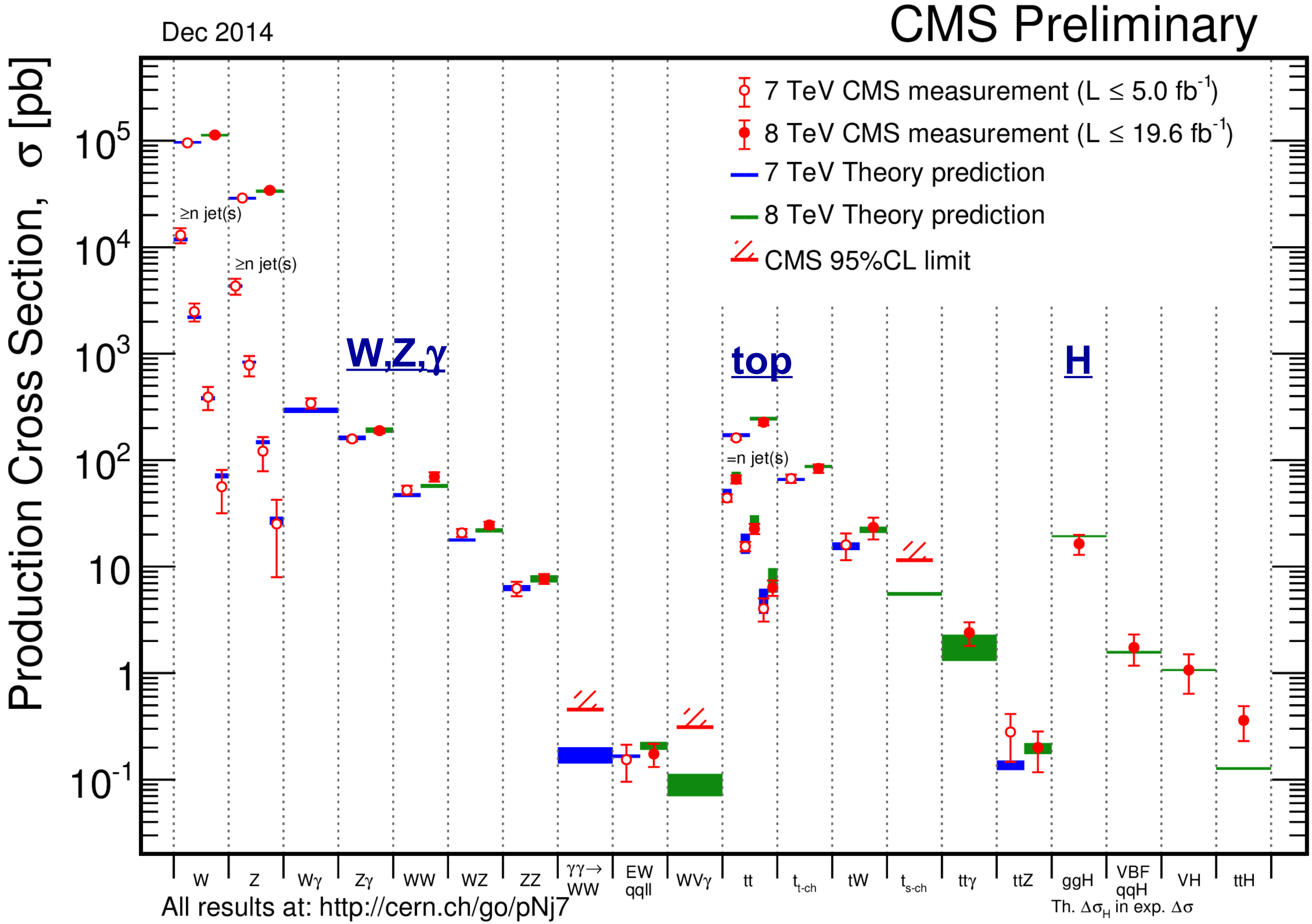
- Thanks to the excellent performance of the LHC, a high quality dataset of 25 fb^{-1} is available for data analysis.
  - Environmental conditions pose challenging problems to the ingeniousness of the experiments.







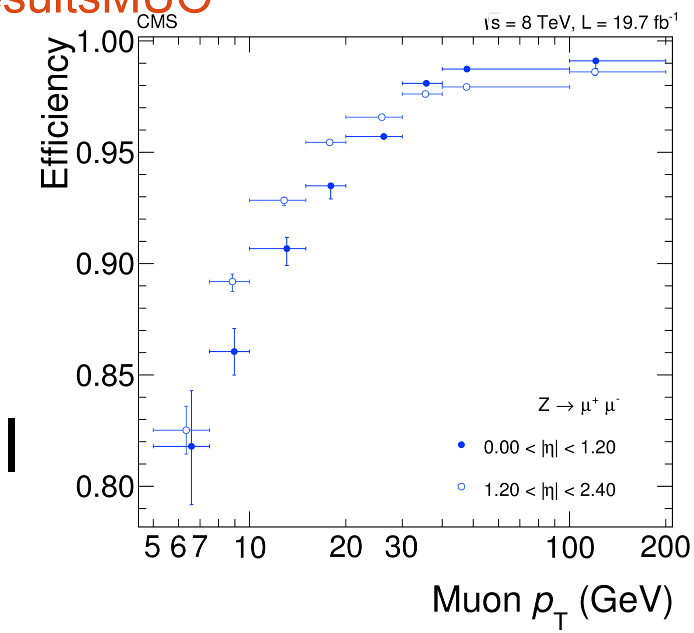
Solid foundations

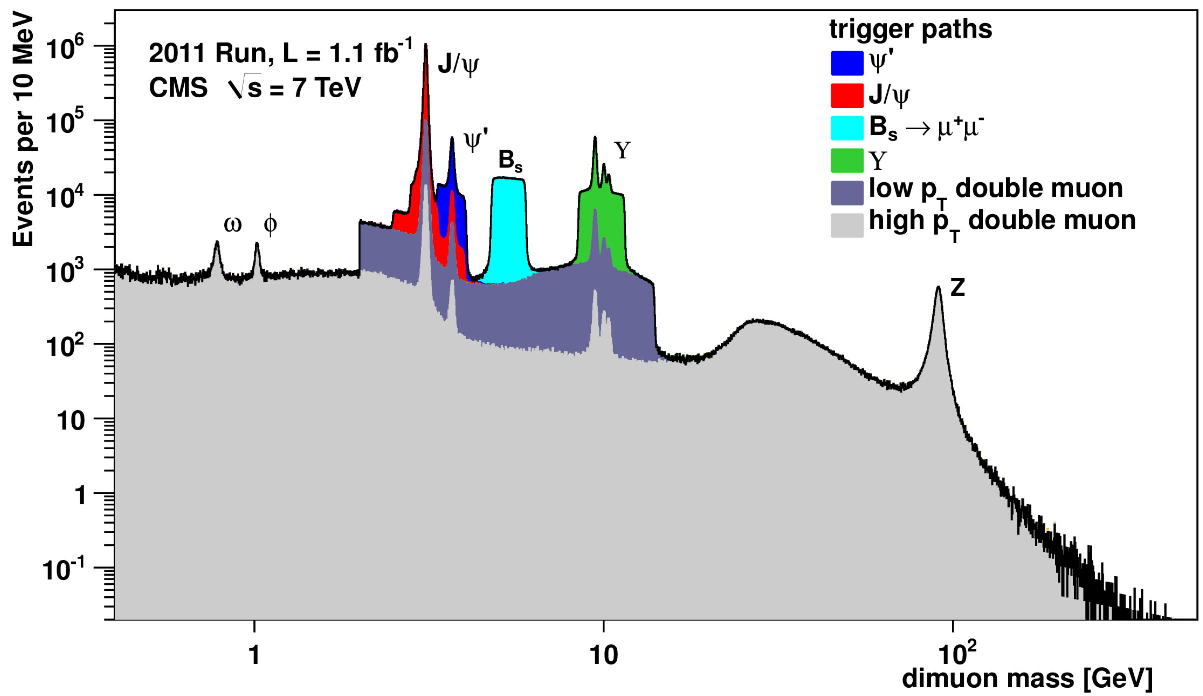


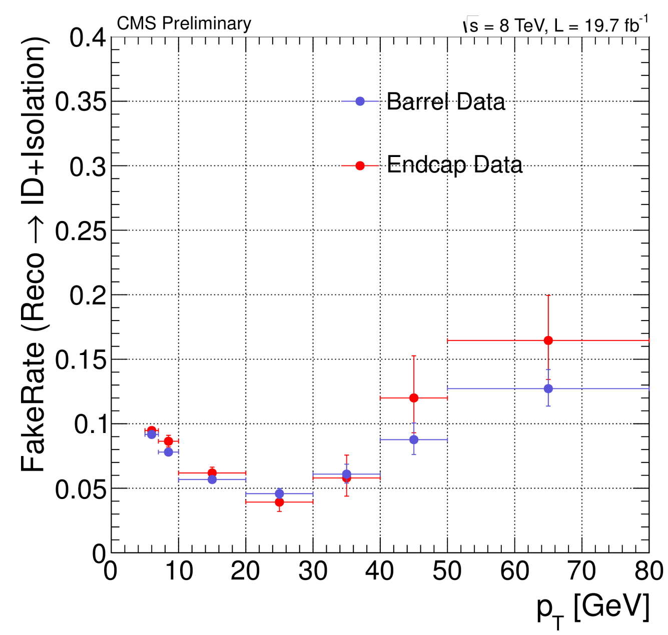
… through always improving algorithms

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO

- Excellent momentum resolution.
- High identification efficiency down to low transverse momenta.
  - While keeping fake rate under control



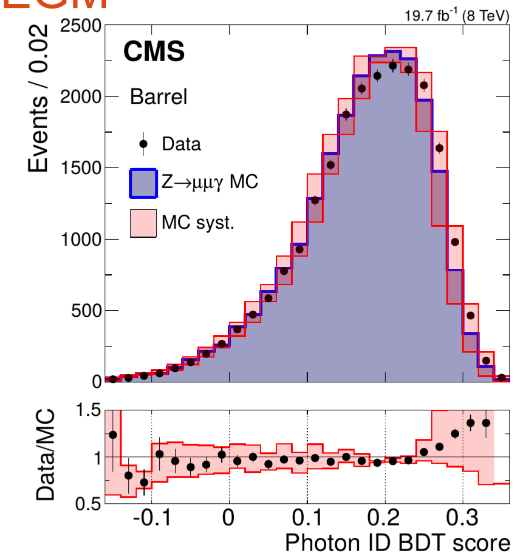


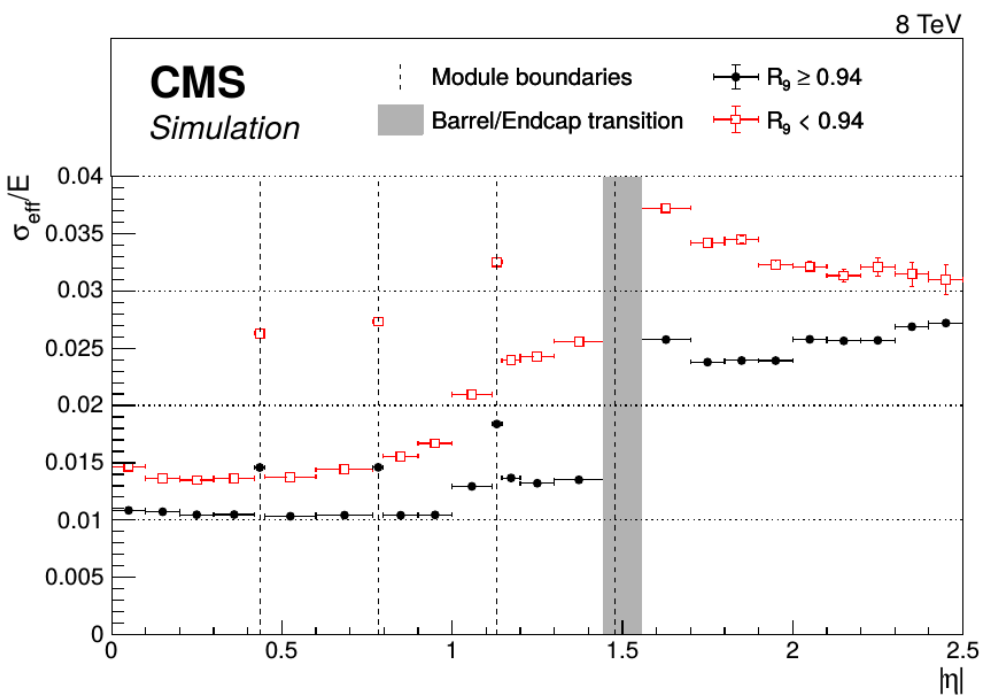


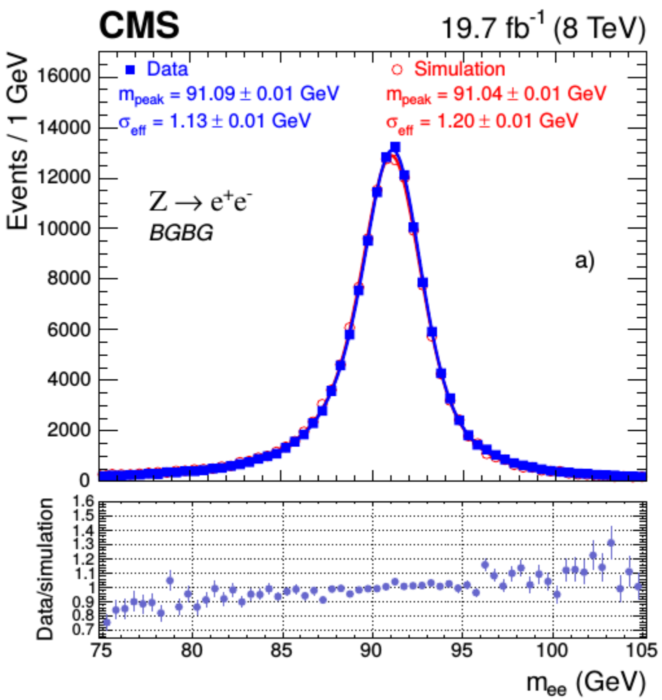
Electrons/Photons

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEGM

- Electron and photon energy resolutions 1-3%.
  - Thanks to the meticulous calibration of the ECAL.
  - Modeling of detector response fine tuned with Z → ee events.
- Shape of electromagnetic clusters well predicted by simulation.



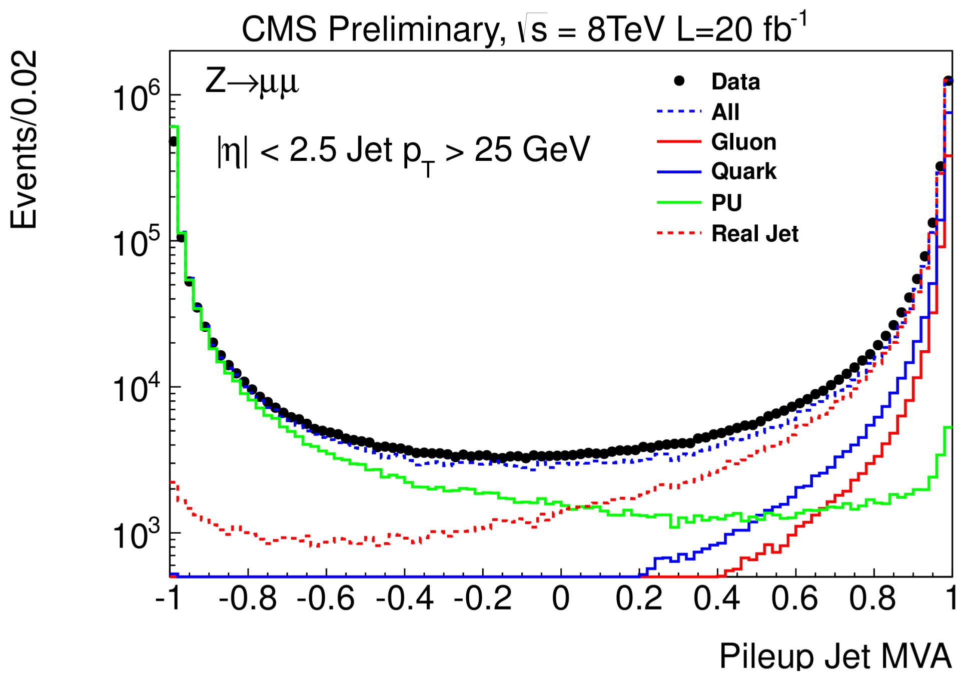


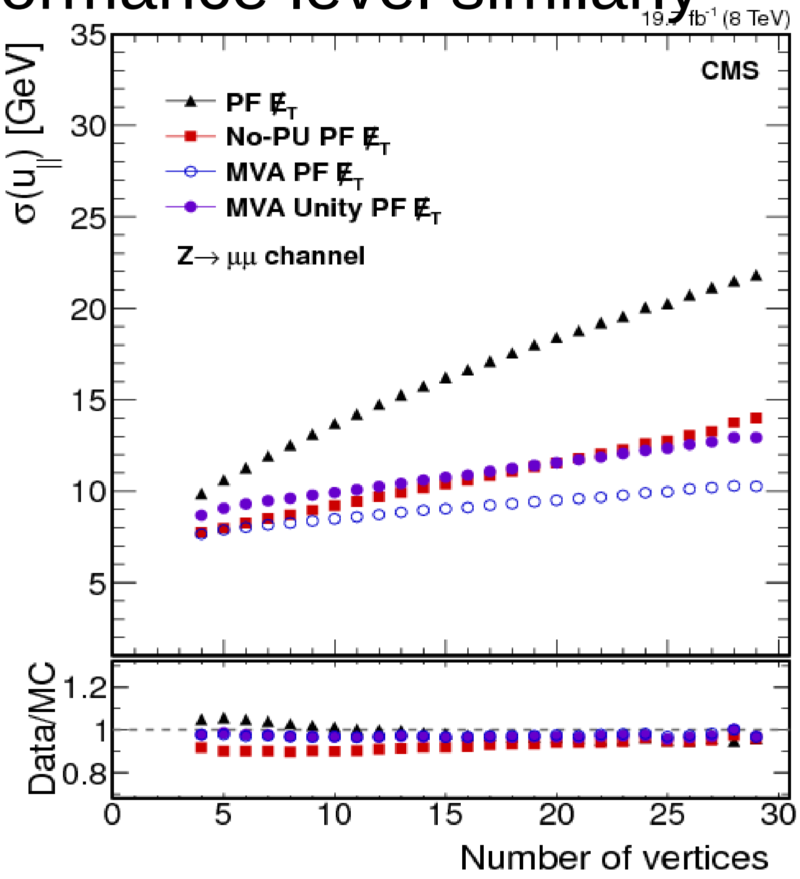


Jets and MET

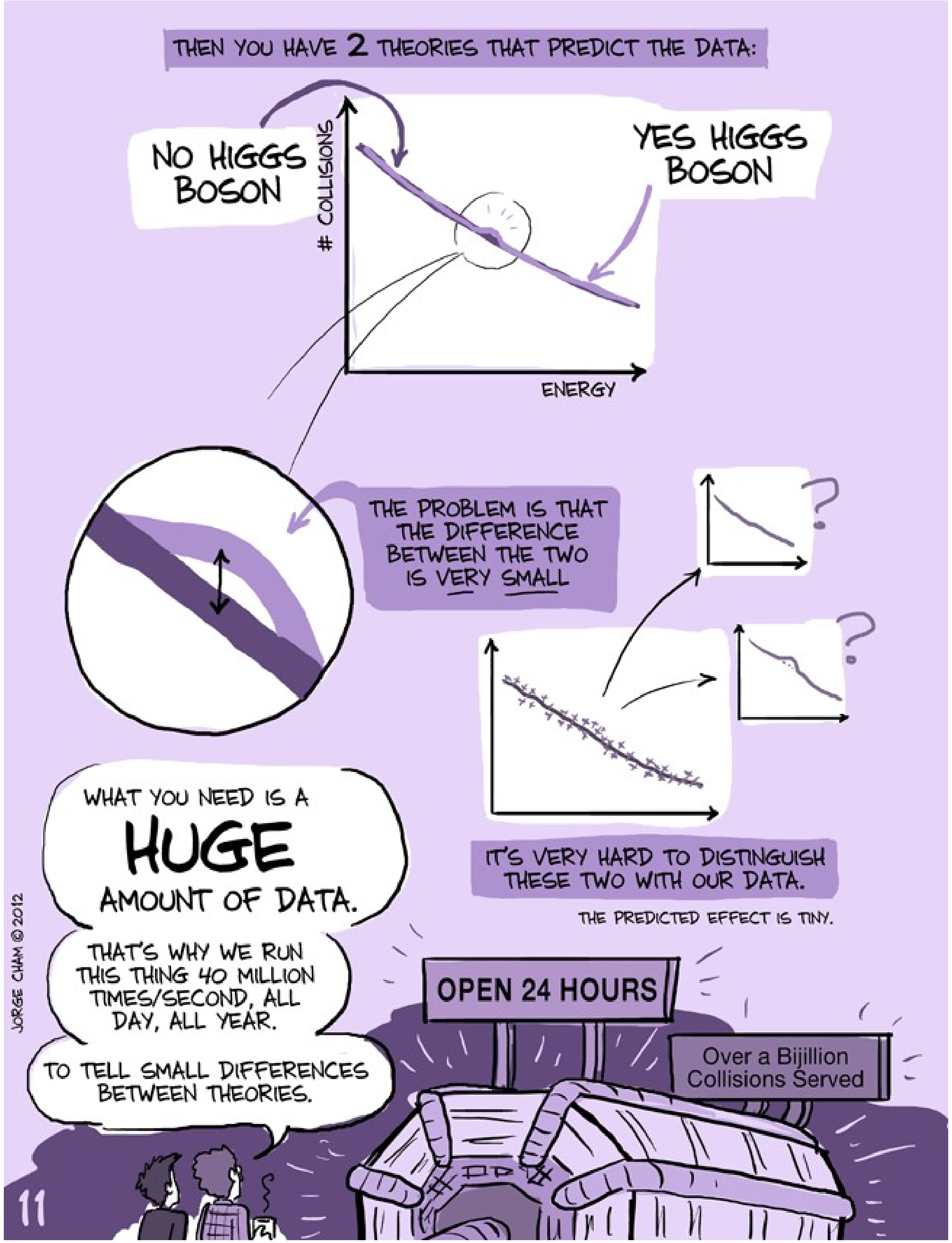
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME

- Pile-up interactions produce challenging environment.
  - Big effort went into tuning algorithms for pile-up mitigation on jets and MET.
  - Successfully managed to kept performance level similarly high in all pile-up conditions.

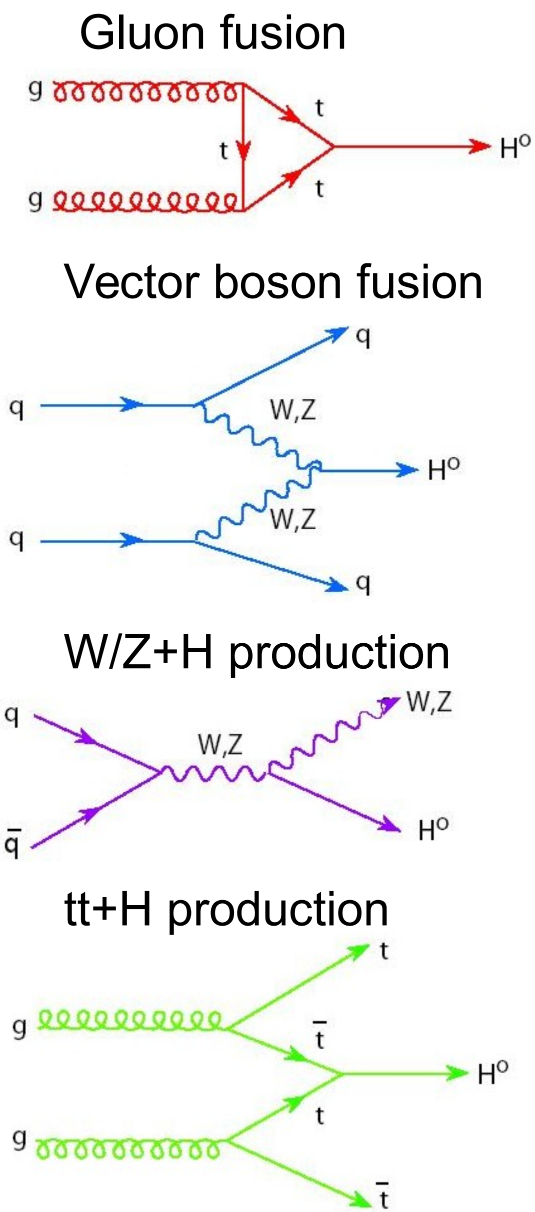


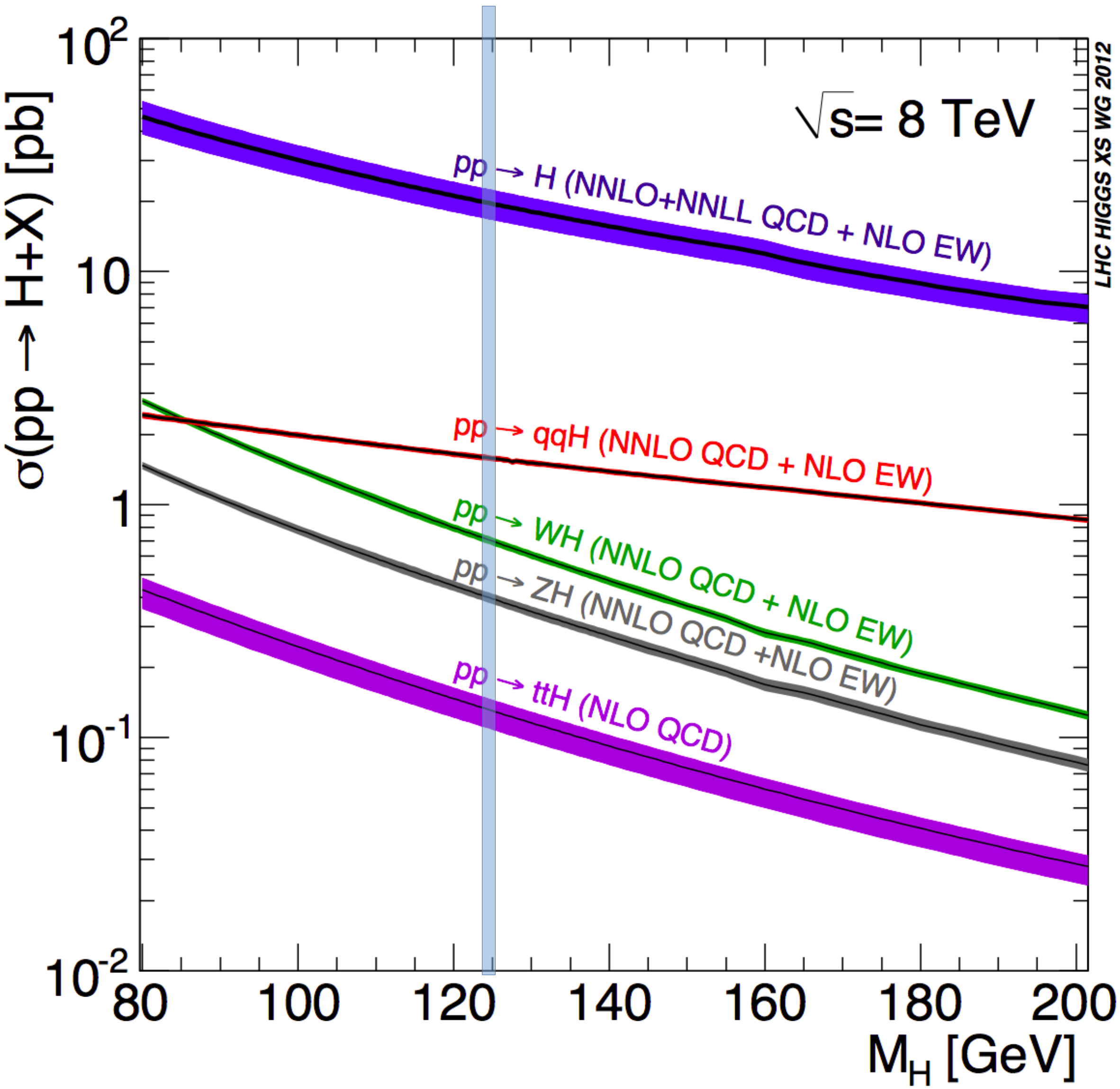


The quest for the Higgs boson

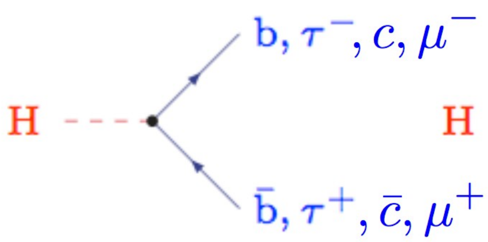


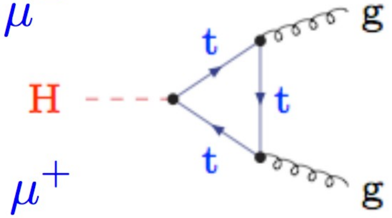
Higgs production at the LHC

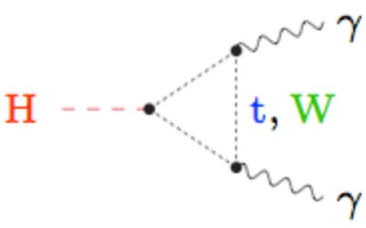


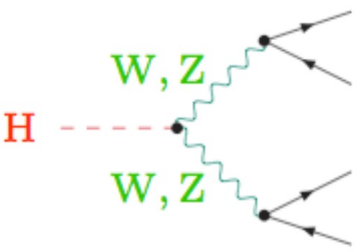


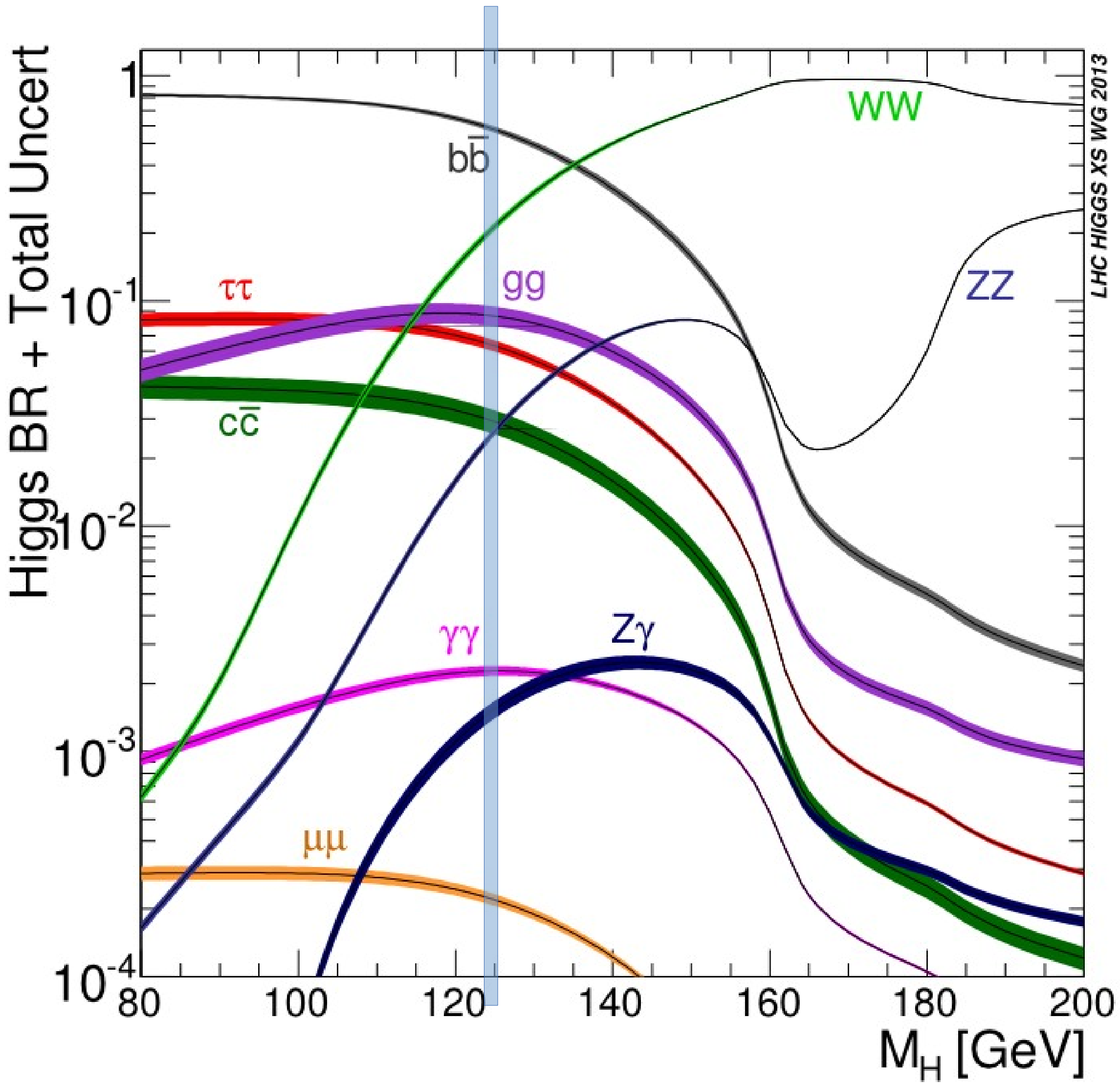
… and decays


H
b, τ⁻, c, μ⁻
b̄, τ⁺, c̄, μ⁺


H
t
t
t
g
g


H
t, W
γ
γ

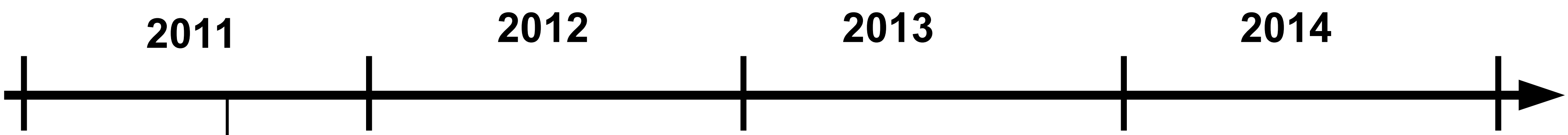

H
W, Z
W, Z

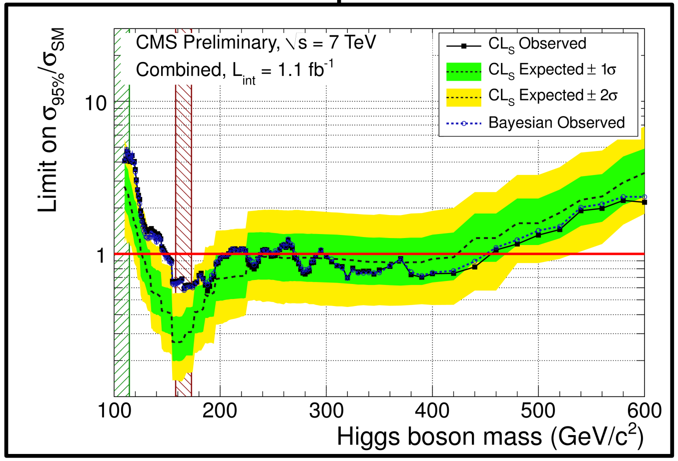

Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
bb̄
WW
gg
ττ
cc̄
ZZ
γγ
Zγ
μμ
M_H [GeV]

Brief historical interlude

- Or:
  "how a discovery that was expected to take 10years was compressed into just 2….
  "

First combined exclusion limits





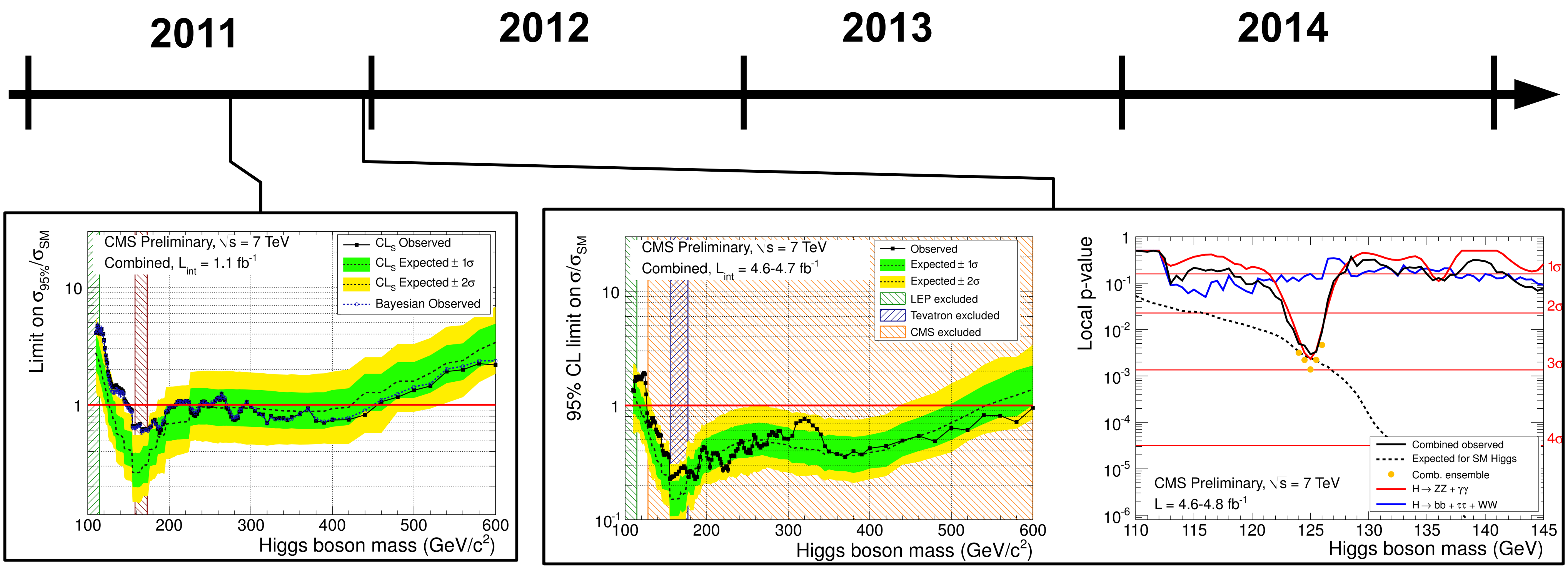
First $1fb^{-1}$ (7TeV):

no Higgs boson between 160 and 500GeV

EPS-HEP '11 [CMS-PAS-HIG-11-011]

Lepton-Photon '11 [CMS-PAS-HIG-11-022]

First hints

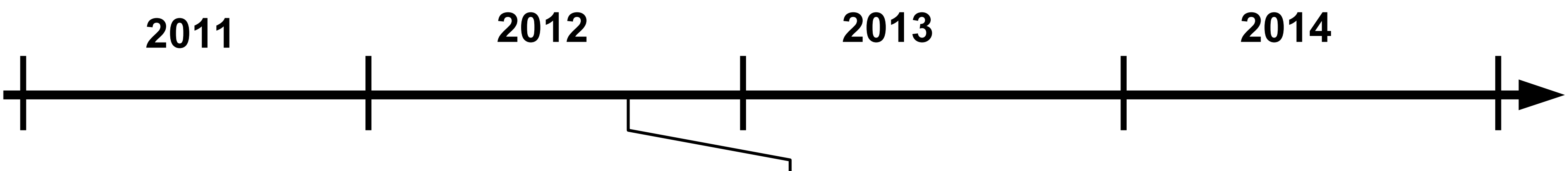


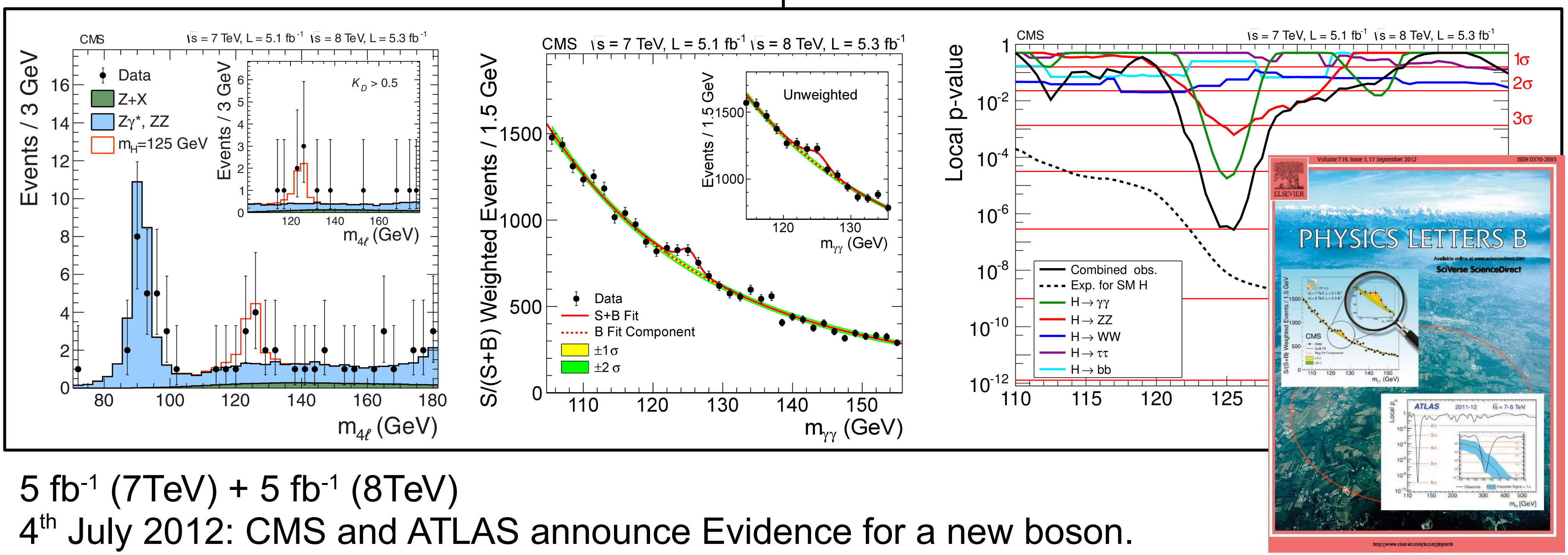
First 5fb^{-1} (7TeV):

- SM Higgs boson excluded for 127 < m_H < 600GeV
- Excess (local significance 2.8σ) for m_H~125GeV

CMS/ATLAS Higgs Jamboree [CMS-PAS-HIG-11-032]
Moriond 2012 [CMS-PAS-HIG-12-008]

A new boson





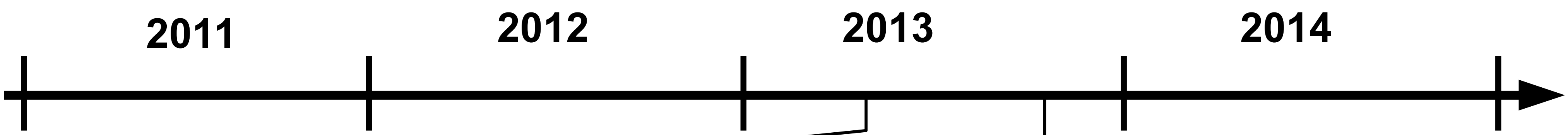
$5\ fb^{-1}$ (7TeV) + $5\ fb^{-1}$ (8TeV)

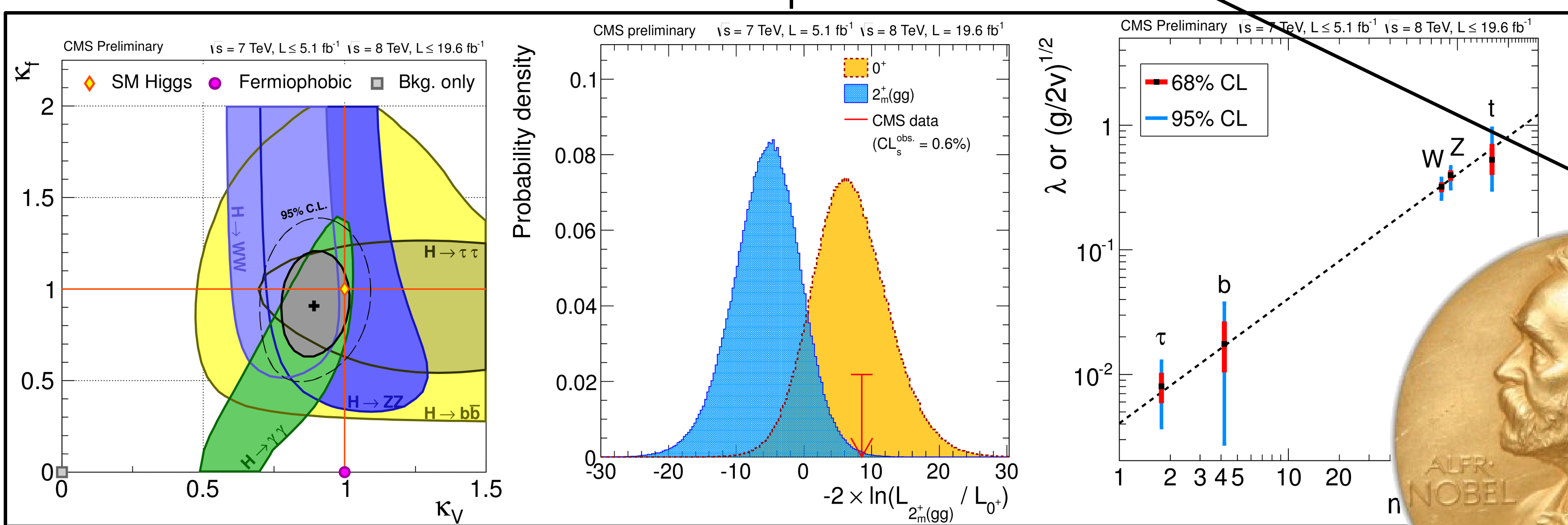
4th July 2012: CMS and ATLAS announce Evidence for a new boson.

[Phys. Lett. B 716 (2012)] 1-29 (ATLAS)

[Phys. Lett. B 716 (2012)] 30 (CMS)

A ~~new~~ Higgs boson





$5fb^{-1}$ (7TeV) + $20fb^{-1}$(8TeV)

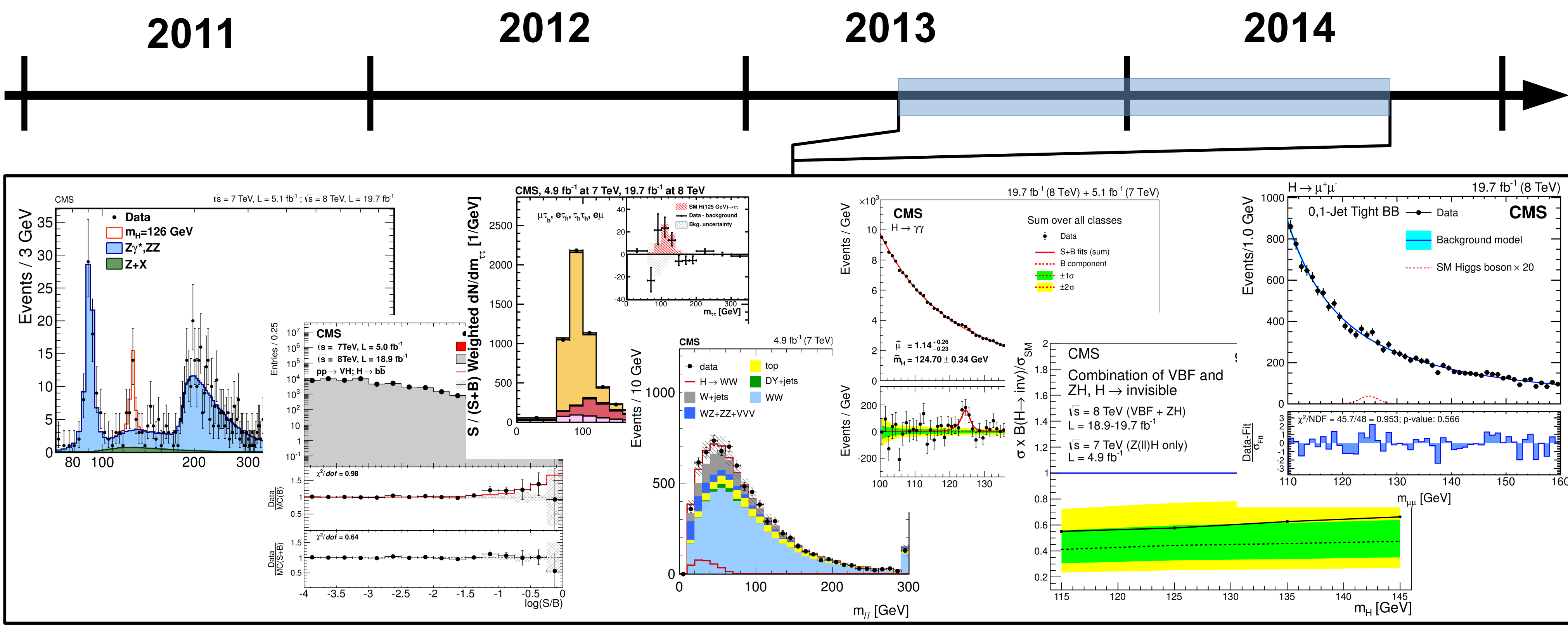
Characterization of the new state with full Run I dataset:

- Production and decays rates consistent with SM Higgs
- 0^+ spin parity favoured by data.

[CMS-PAS-HIG-13-005]

8th October 2013: Nobel Prize for Physics awarded to prof. Higgs and Englert.

Run I legacy



$5 fb^{-1}$ (7TeV) + $20 fb^{-1}$(8TeV)

Final results on Run I full dataset published 1-2 years after the discovery of the new boson.

Ultimate precision for this dataset attained.

Preliminary combined analysis of all channels presented in July 2014.

Today: combined analysis

2011 | 2012 | 2013 | 2014

Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV

CMS Collaboration

(Submitted on 30 Dec 2014)

Properties of the Higgs boson with mass near 125 GeV are measured in proton-proton collisions with the CMS experiment at the LHC. Comprehensive sets of production and decay measurements are combined. The decay channels include gamma gamma, ZZ, WW, tau tau, bb, and mu mu pairs. The data samples were collected in 2011 and 2012 and correspond to integrated luminosities of up to 5.1 inverse femtobarns at 7 TeV and up to 19.7 inverse femtobarns at 8 TeV. From the high-resolution gamma gamma and ZZ channels, the mass of the Higgs boson is determined to be 125.02 +0.26 -0.27 (stat) +0.14 -0.15 (syst) GeV. For this mass value, the event yields obtained in the different analyses tagging specific decay channels and production mechanisms are consistent with those expected for the standard model Higgs boson. The combined best-fit signal relative to the standard model expectation is 1.00 +/- 0.09 (stat) +0.08 -0.07 (theo) +/- 0.07 (syst) at the measured mass. The couplings of the Higgs boson are probed for deviations in magnitude from the standard model predictions in multiple ways, including searches for invisible and undetected decays. No significant deviations are found.

Comments: Submitted to Eur. Phys. J. C

Subjects: **High Energy Physics - Experiment (hep-ex)**

Report number: CMS-HIG-14-009, CERN-PH-EP-2014-288

Cite as: **arXiv:1412.8662 [hep-ex]**

(or **arXiv:1412.8662v1 [hep-ex]** for this version)

What is included

Production →

Decay ↓

	ggH	qqH	VH	ttH	Observed (Expected) **Significance (m_H=125GeV)**	σ_m/m
H → ZZ(4l)	✓	✓	✓		6.5 (6.3) σ	1-2%
H → WW(2l2ν)	✓	✓	✓	✓	4.7 (5.4) σ	15%
H → γγ	✓	✓	✓	✓	5.6 (5.3) σ	1-2%
H → ττ	✓	✓	✓	✓	3.8 (3.9) σ	10-20%
H → bb			✓	✓	2.0 (2.6) σ	10%
H → μμ	✓	✓			<0.1 (0.4) σ	1-2%
H → invisible		✓	✓		- -	

Precise determination of the mass of the Higgs boson

and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV

Production →

↓ Decay

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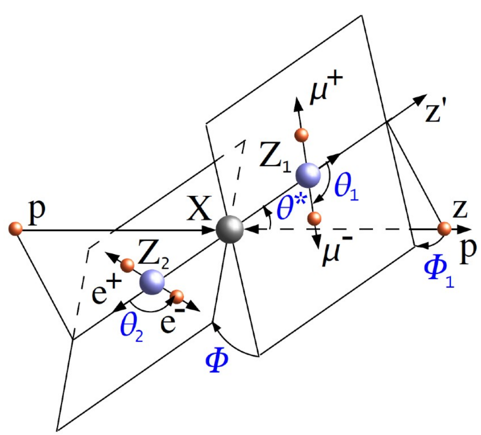
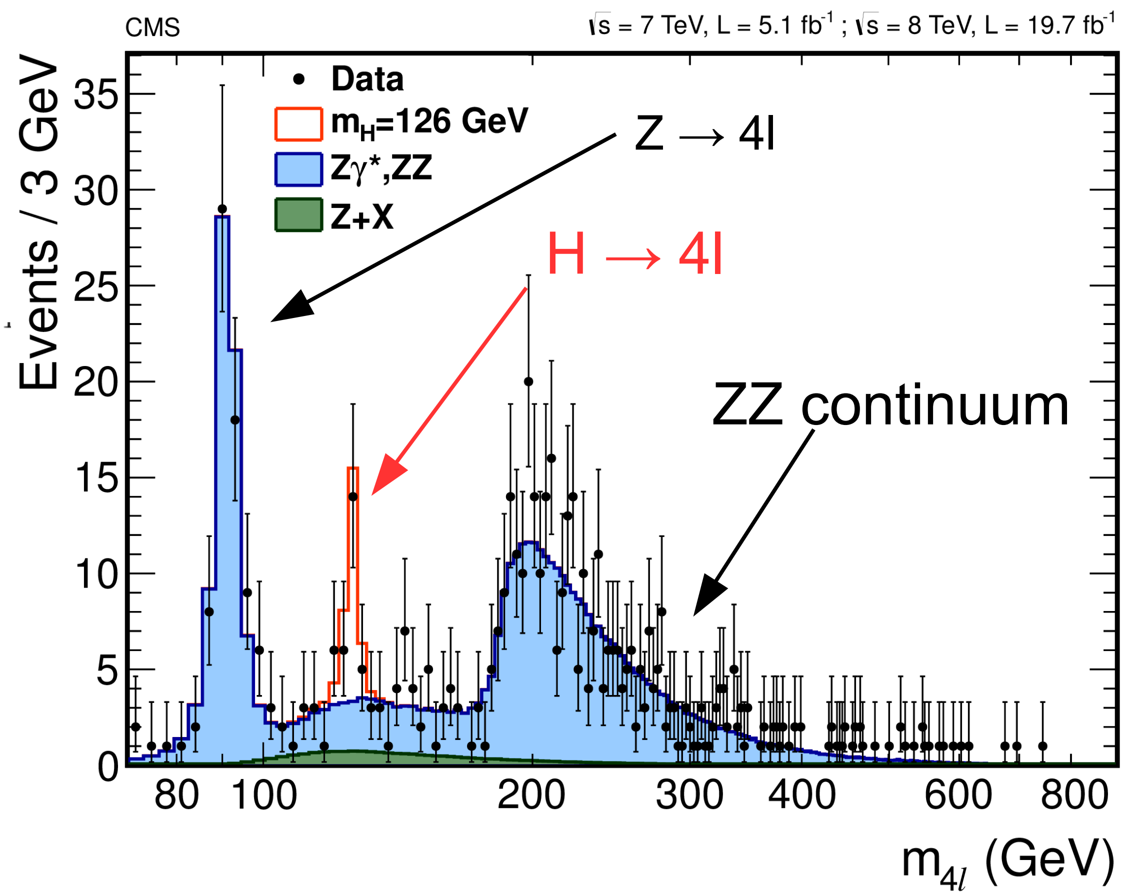
H → bb			✓	✓	2.0 (2.6) σ	10%
H → μμ	✓	✓			<0.1 (0.4) σ	1-2%
H → MET		✓	✓		- -	

H → ZZ(4l)

- Golden channel: 4 isolated leptons.
  - Very high S/B ratio, fully reconstructed final state, excellent mass resolution (1-2%)
  - Low event yield. Demanding requirements in terms of efficiency down to leptons' p_T of 5-10GeV.
  - Background rejection improved through kinematic discriminant

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

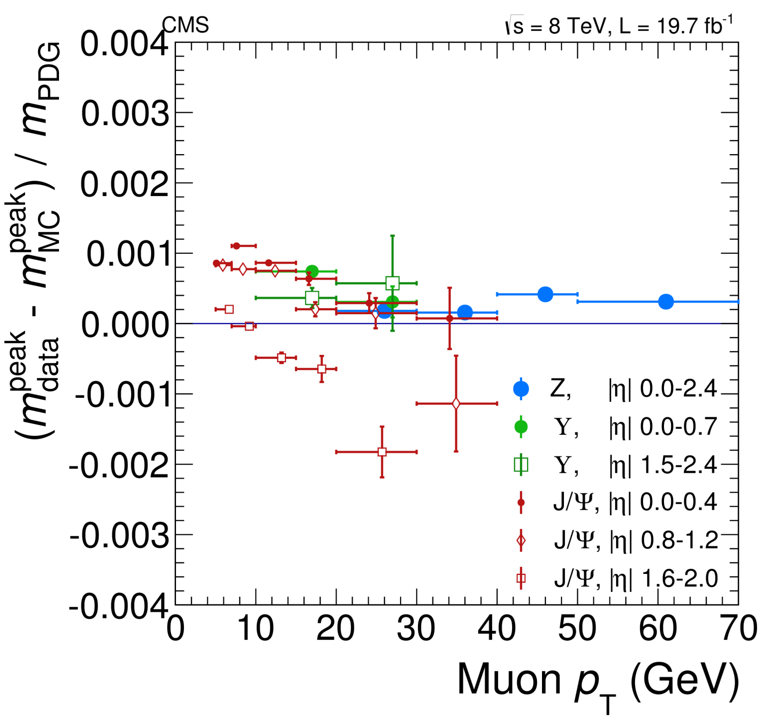


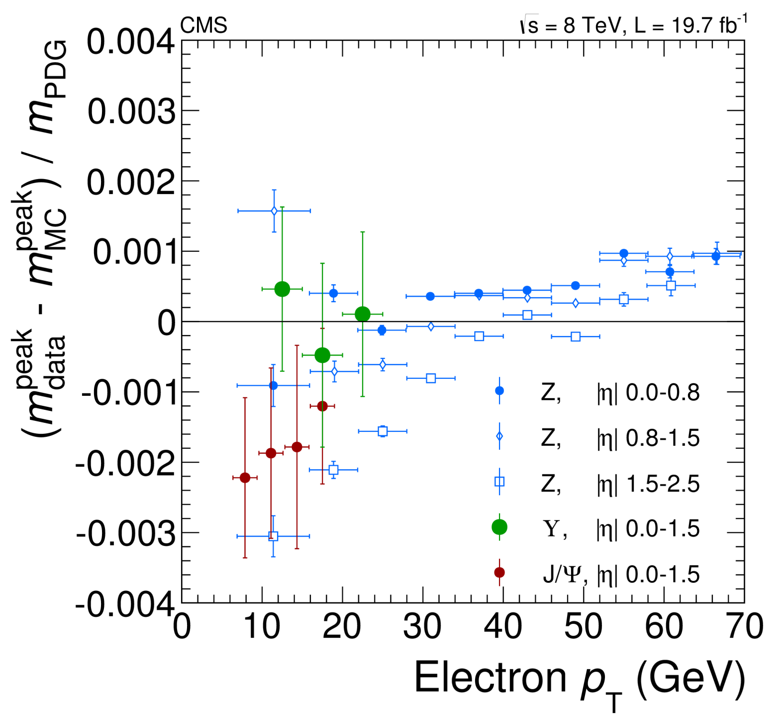


Lepton energy/momentum scale

- Energy and momentum scale and resolution for both electrons and muons calibrated using J/ϕ, Υ and Z → ll decays.
  - Systematic uncertainty derived from residual data/MC differences
  - m_H measurement completely dominated by stat. uncertainty

Source	δm_H / m_H
Muon p-scale	0.1% (H → 4μ)
Electron E/p-scale	0.3% (H → 4e)

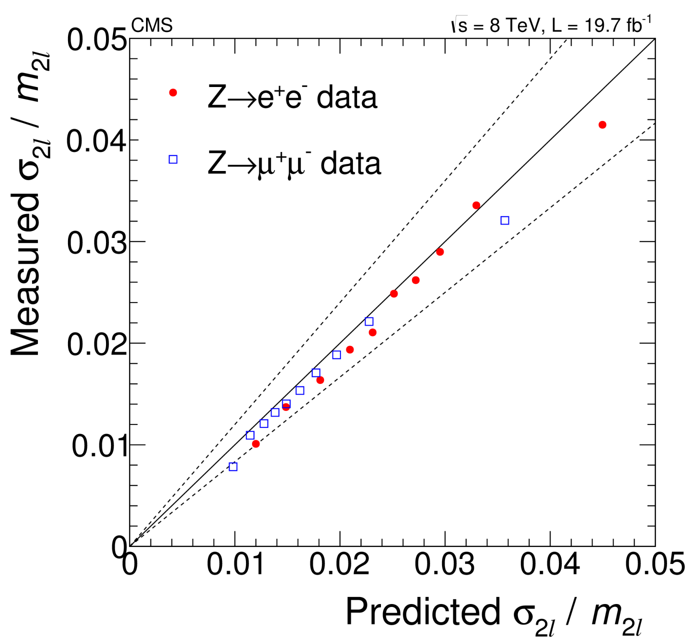


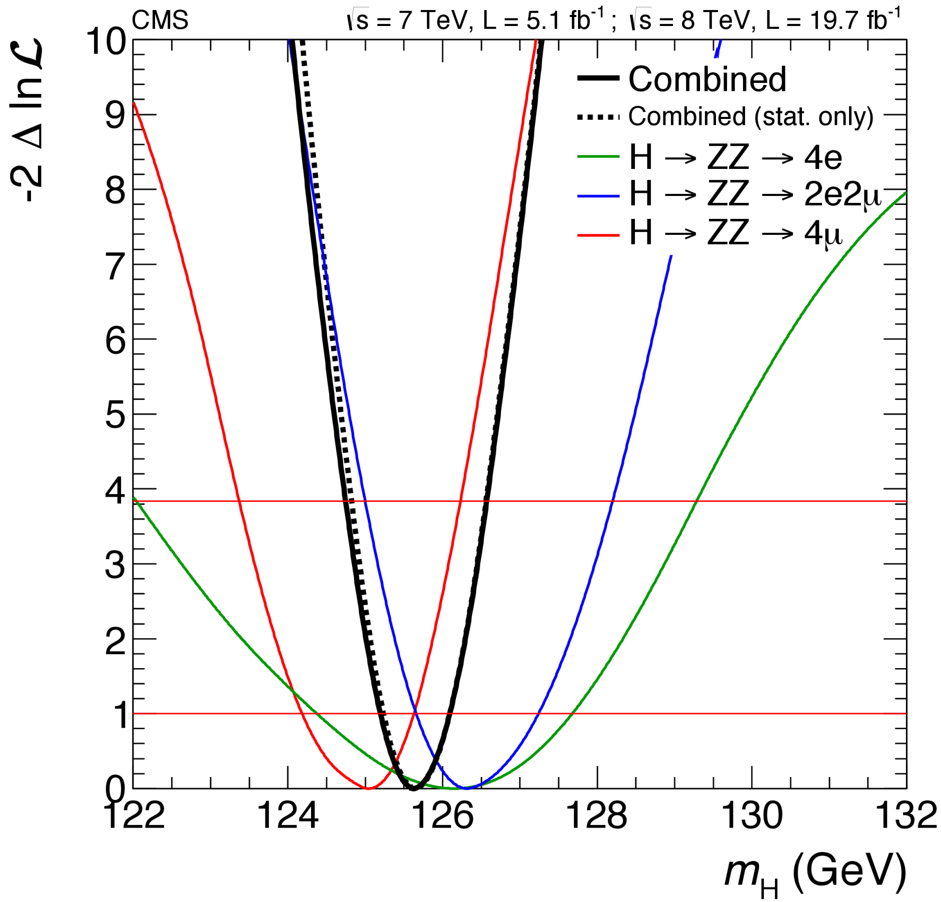


m_H from H → ZZ(4l)

- Mass measured through 3D fit to m_{4l}, mass-resolution estimator σ_{m4l}/m_{4l} and $\mathcal{K}_{\mathcal{D}}$

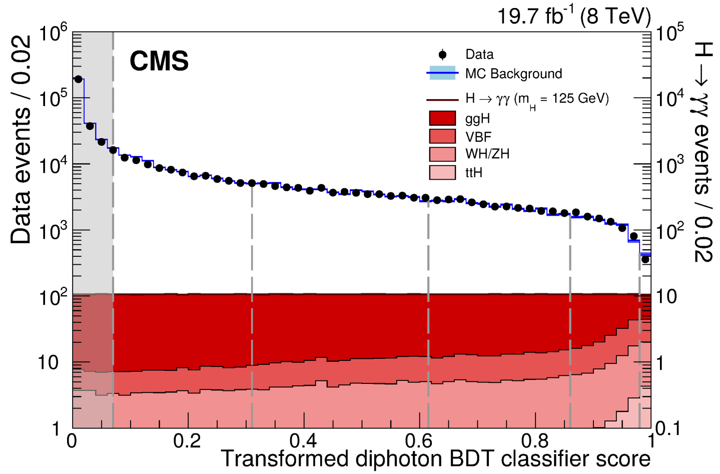
$$m_H^{H\to 4l} = 125.6 \pm 0.4(stat) \pm 0.2(syst)\,GeV$$

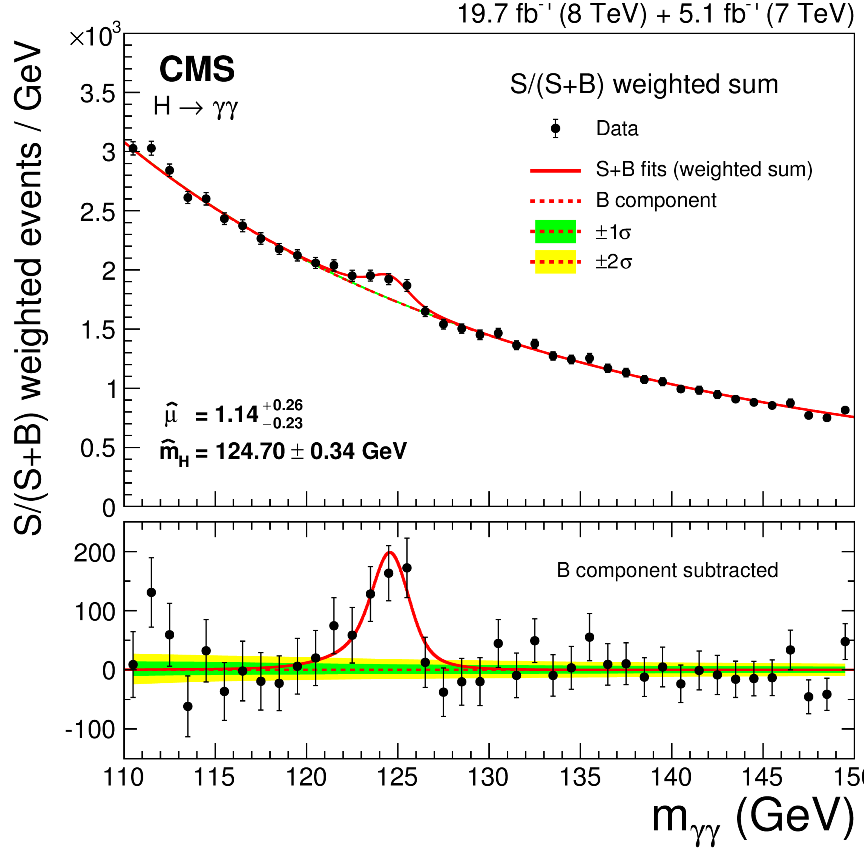




H → γγ

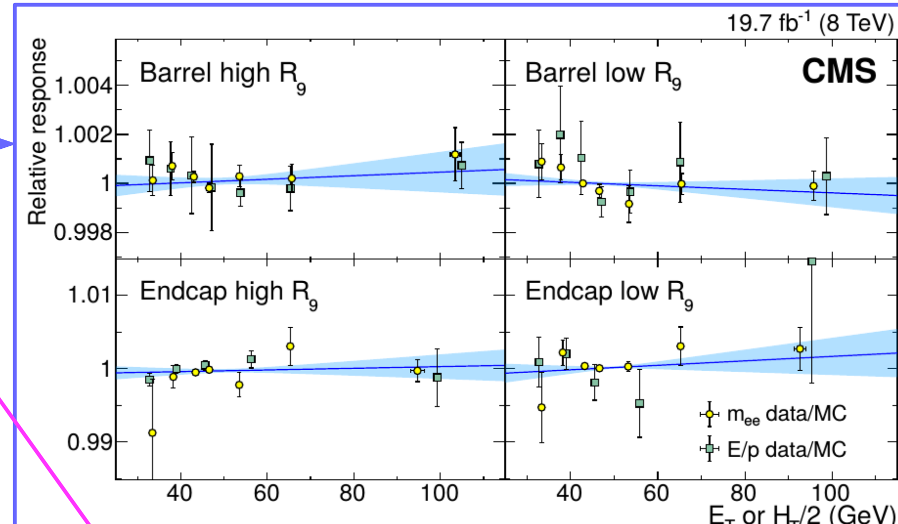
- Search for a narrow peak on a smoothly falling background.
  - Excellent mass resolution (1-2%). (Energy resolution and vertex identification).
  - Rejection of reducible background also crucial.
- Background estimated using $m_{\gamma\gamma}$ side-bands.
- Data driven corrections from $Z \rightarrow ee$, $Z \rightarrow \mu\mu\gamma$ and $Z \rightarrow \mu\mu$ control samples.
- All production modes analyzed.
  - BDT discriminants enhance sensitivity to VBF and ggH.





Photon energy scale

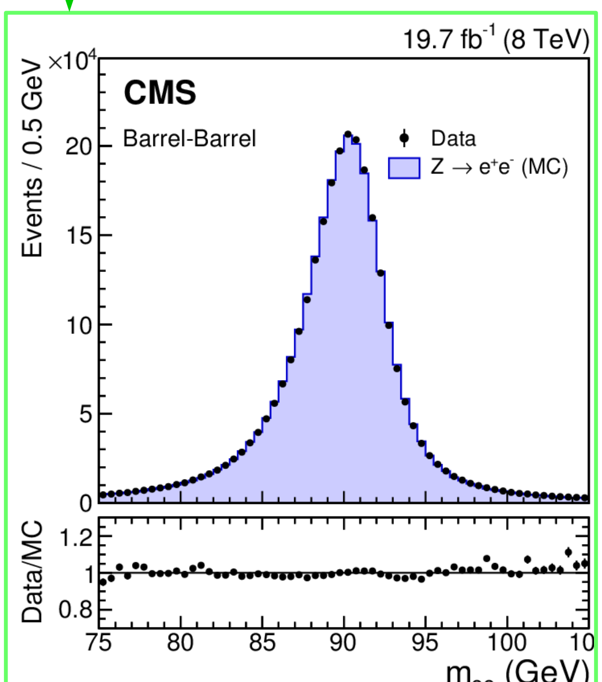
- Photon energy scale and resolution corrections derived from $Z \rightarrow ee$ events.
  - Extrapolation to higher p_T through boosted Z production.
  - Extrapolation from electrons to photons through MC simulation ($Z \rightarrow ll\gamma$ low-E_T cross-check)



$Z \rightarrow ee$

E

$e \rightarrow \gamma$



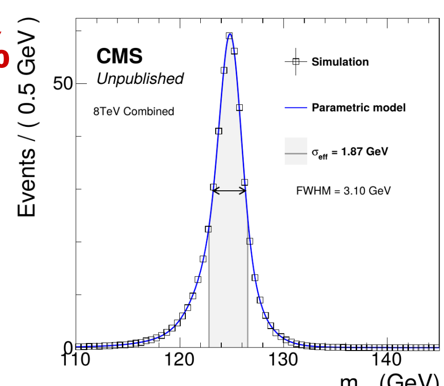
$\delta m_H/m_H \sim 0.05\%$

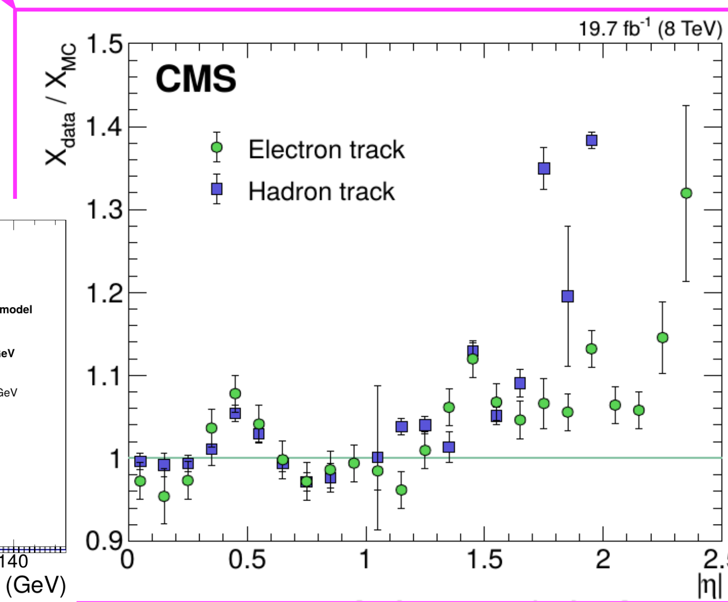
$\oplus\ \delta m_H/m_H \sim 0.08\%$

$\oplus\ \delta m_H/m_H \sim 0.08\%$

$= \delta m_H/m_H \sim 0.13\%$

$H \rightarrow \gamma\gamma$

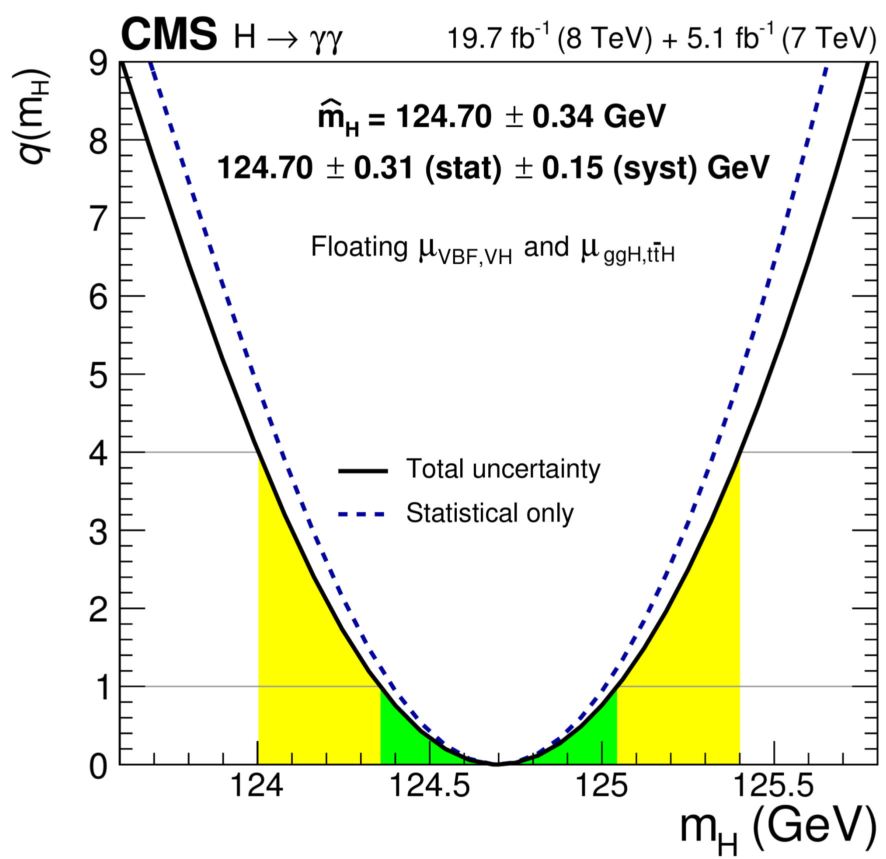




m_H from H → γγ

- m_H extracted from simultaneous fit to $m_{\gamma\gamma}$ in 25 event categories.
  - Normalization of ggH,ttH and VBF,VH production floated independently.

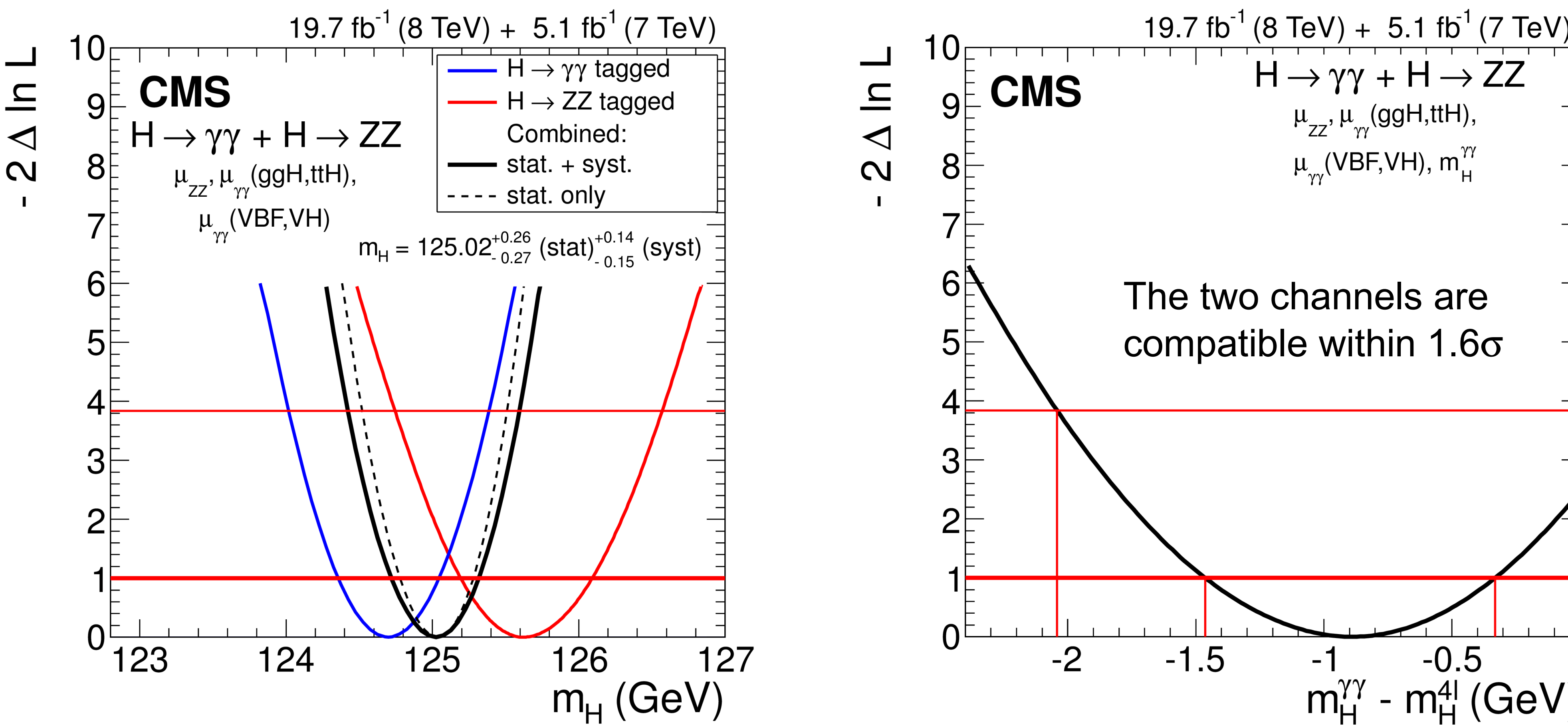
$$m_H^{H\rightarrow\gamma\gamma} = 124.70 \pm 0.31\,(stat) \pm 0.15\,(syst)\,GeV$$



Combined mass measurement

- Obtained through simultaneous fit to H→4l and H→γγ datasets.
  - Same modelling as for individual measurements.

$$m_H = 125.02^{+0.26}_{-0.27}(stat)^{+0.14}_{-0.15}(syst)\,GeV$$



Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV

Production →

Decay ↓

	ggH	qqH	VH	ttH	Observed (Expected) **Significance (m_H=125GeV)**	σ_m/m
H → ZZ(4l)	✓	✓	✓		6.5 (6.3) σ	1-2%
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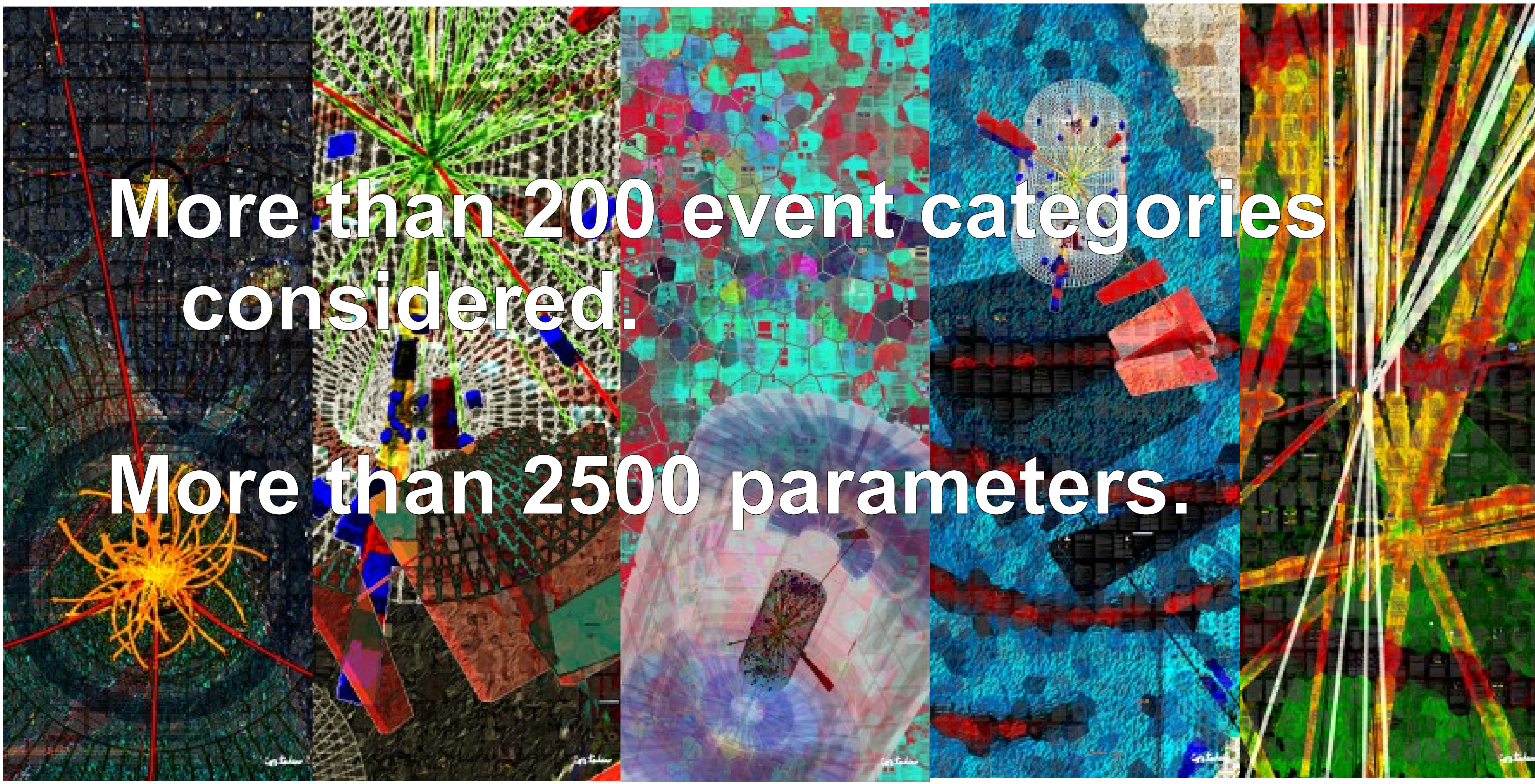
H → μμ	✓	✓			<0.1 (0.4) σ	1-2%
H → invisible		✓	✓		- -	

Putting everything together



More than 200 event categories considered.

More than 2500 parameters.

(Note: Will fix m_H to 125 GeV in the following.)

Characterizing the Higgs boson

- Properties of the Higgs boson can be inferred correlating the event rates measured in all the channels.

"Signal strength"

Measured

Estimated

$$N^{cat} = \mu^{cat} \cdot \sum_{p,d} \left[\left(\varepsilon \cdot A \right)^{ch}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{ch}$$

Predicted

Inference

Statistical model

$$q(\mu) = -\ln \left[\frac{\mathcal{L}(data|\mu;\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu};\hat{\theta})} \right]$$

Overall signal strength

- Simplest model: one overall signal strength ($\mu^{ch} = \mu$)

$$\hat{\mu} = 1.00^{+0.14}_{-0.13} \left[\pm 0.09(stat)^{+0.08}_{-0.07}(theo) \pm 0.07(syst) \right]$$

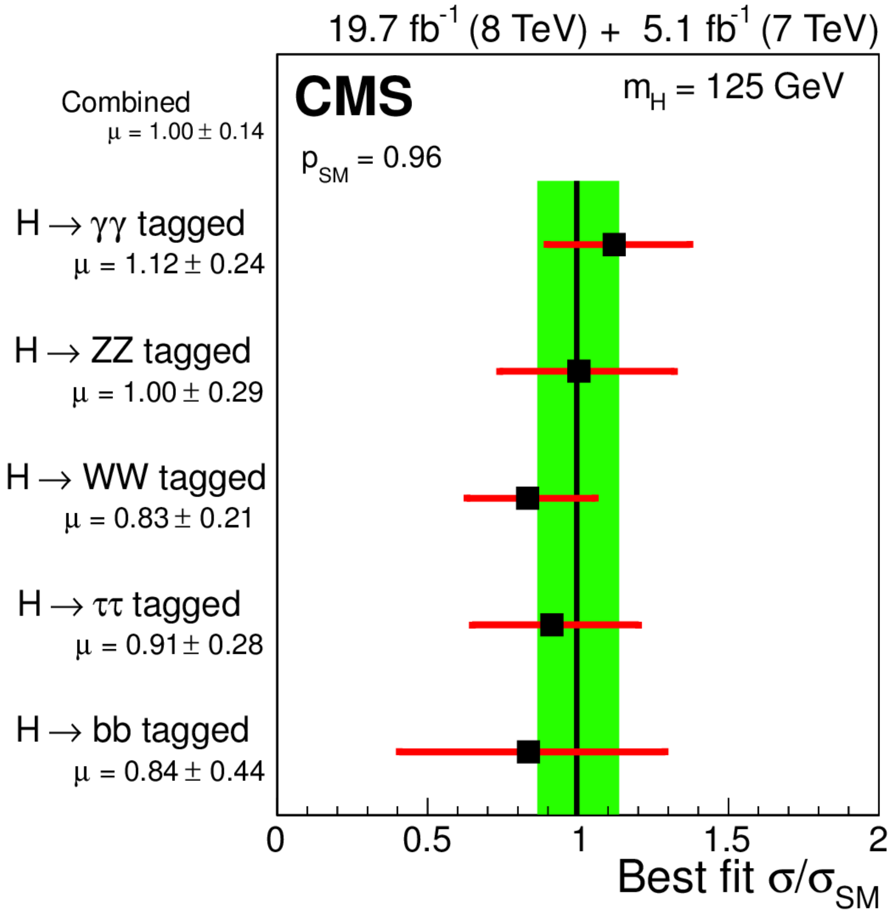
- Good agreement with theoretical predictions.
  - Theoretical and experimental uncertainties have similar size as the statistical ones.

Grouped by target decay mode

- Check consistency of different channels with SM hypotesis.

$$\hat{\mu} = 1.00^{+0.14}_{-0.13} \left[\pm 0.09 (stat)^{+0.08}_{-0.07} (theo) \pm 0.07 (syst) \right]$$

- Grouping channels by decay mode yields very good compatibility with SM Higgs predictions.

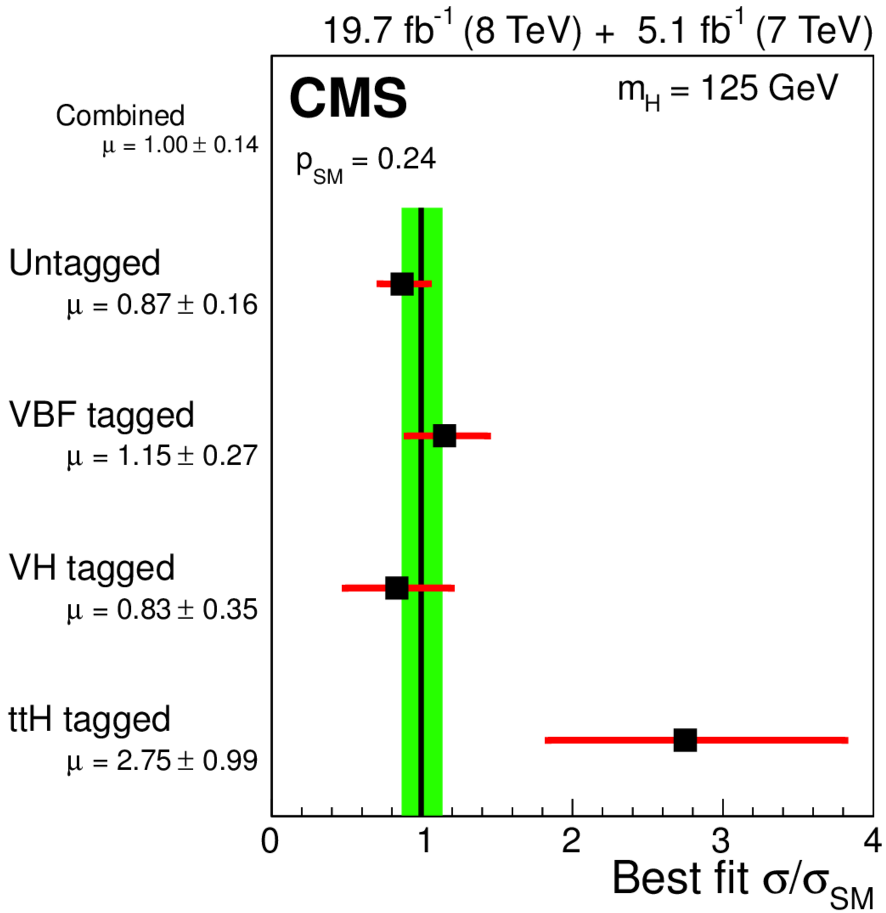


… by target production mechanism

- Another possible grouping is by target production mechanism.

$$\hat{\mu} = 1.00^{+0.14}_{-0.13}\left[\pm 0.09(stat)^{+0.08}_{-0.07}(theo) \pm 0.07(syst)\right]$$

- Signal strength for ttH tagged channels roughly 2σ higher than SM prediction.
  - Mostly driven by excess in same-sign di-lepton channel.

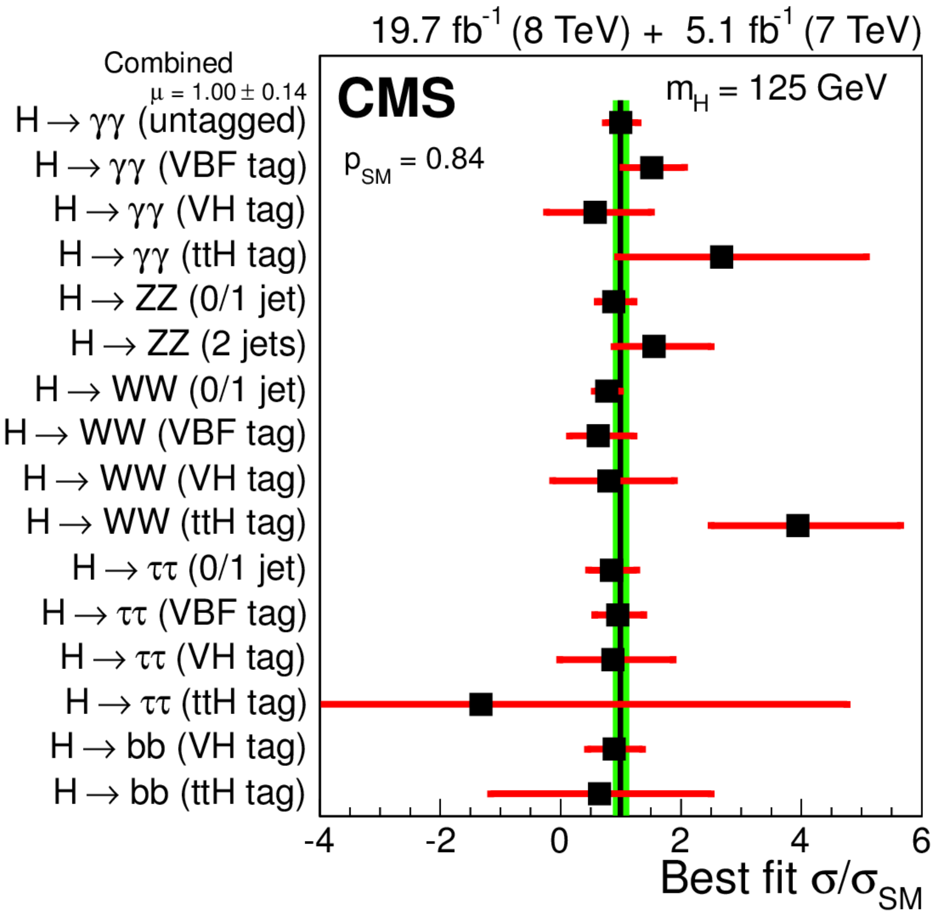


… or both

- Can also split more finely.

$$\hat{\mu} = 1.00^{+0.14}_{-0.13}\left[\pm 0.09\,(stat)^{+0.08}_{-0.07}\,(theo) \pm 0.07\,(syst)\right]$$

- Much reduced statistical precision.
  - Picture consistent with SM predictions.



Unfolding to production processes

- Search channels don't select exclusively one production/decay mode (εxA matrix is not diagonal).

- Account for this effect in the fit to extract specific production/decay signal strength.

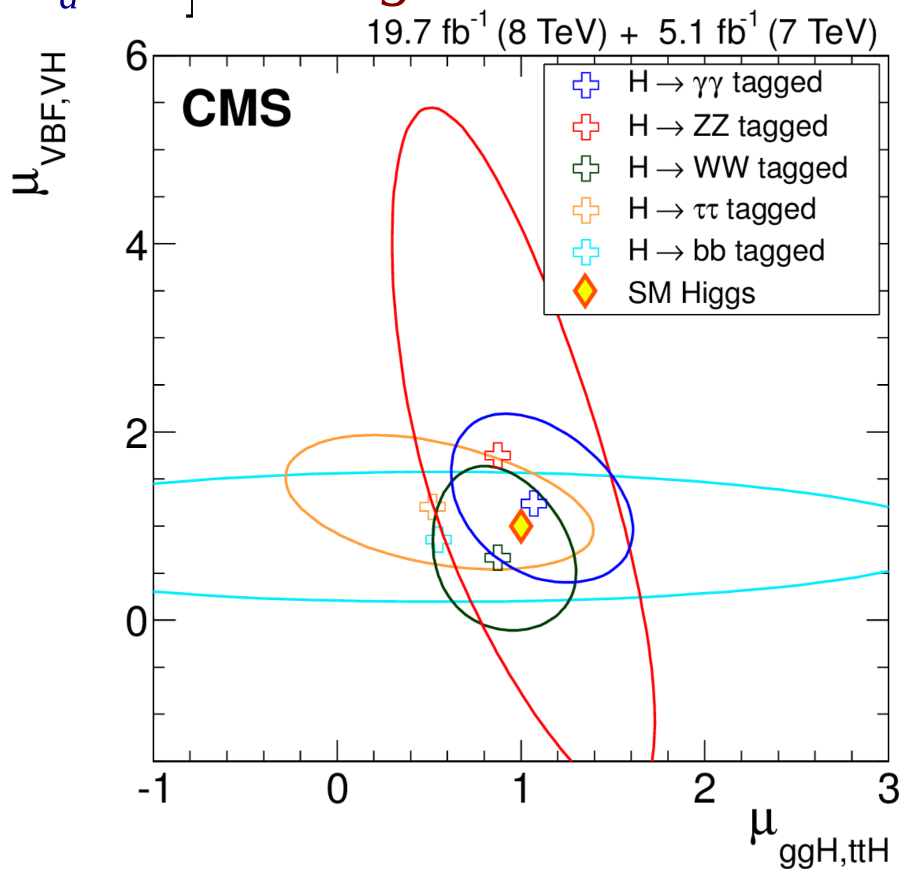
$$N^{ch} = \sum_{p,d} \left[\mu_{pd} \cdot (\varepsilon \cdot A)^{ch}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{ch}$$

- Group “bosonic” and “fermionic” modes to improve uncertainties.

p →

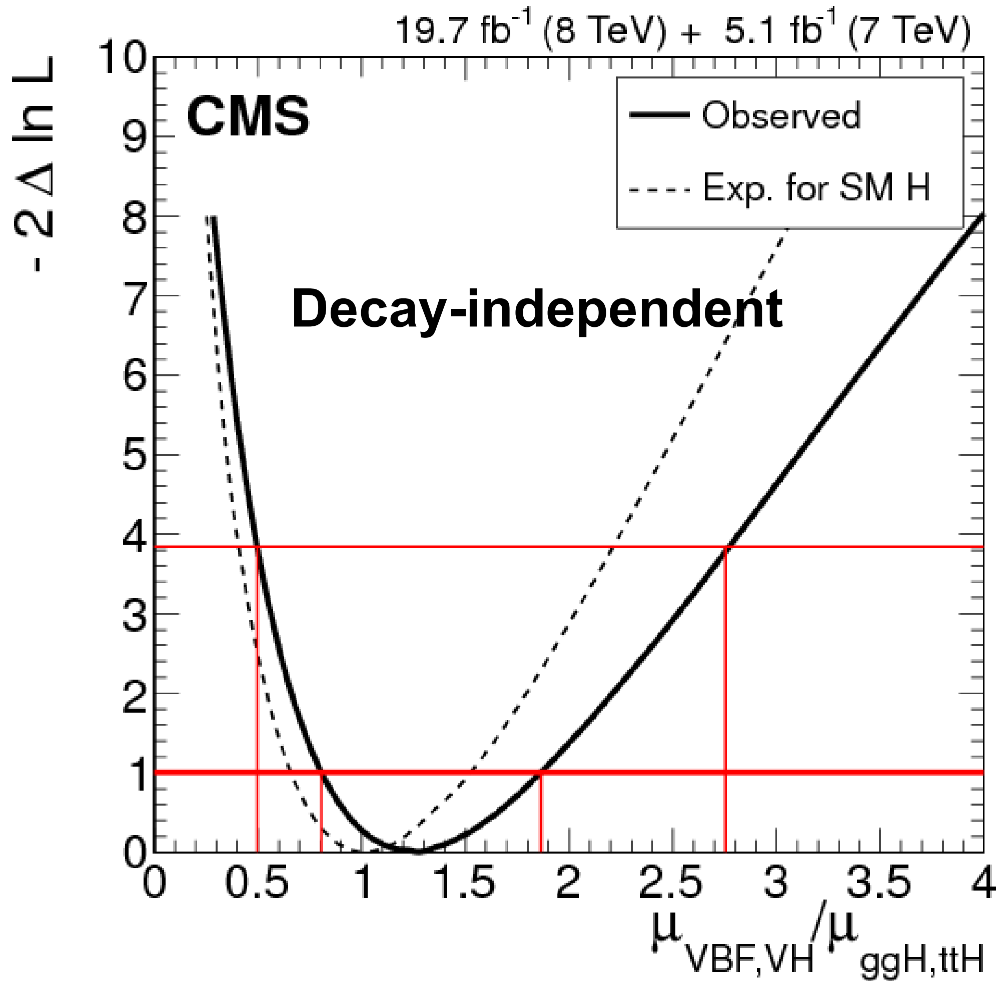
d ↓

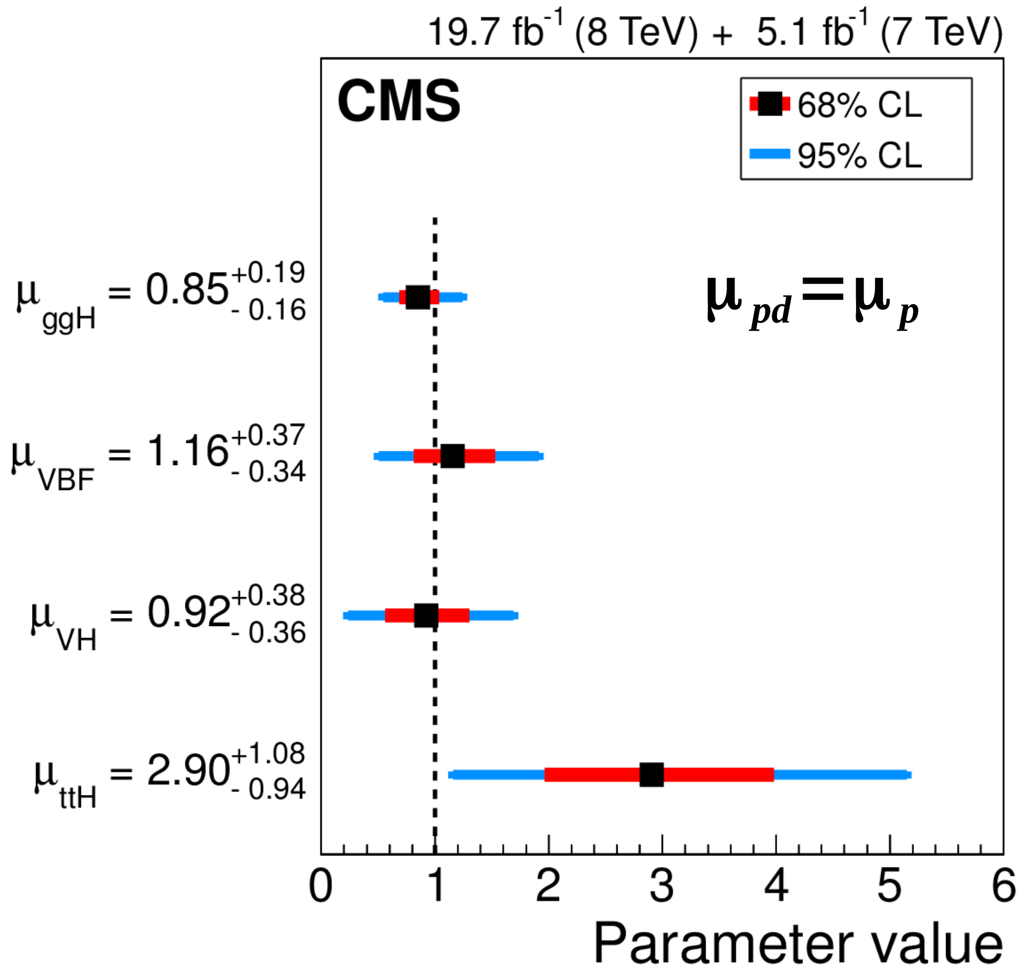
	ggH	ttH	qqH	VH
H → ZZ	✓		✓	✓
H → WW	✓	✓	✓	✓
H → γγ	✓	✓	✓	✓
H → ττ	✓	✓	✓	✓
H → bb		✓		✓



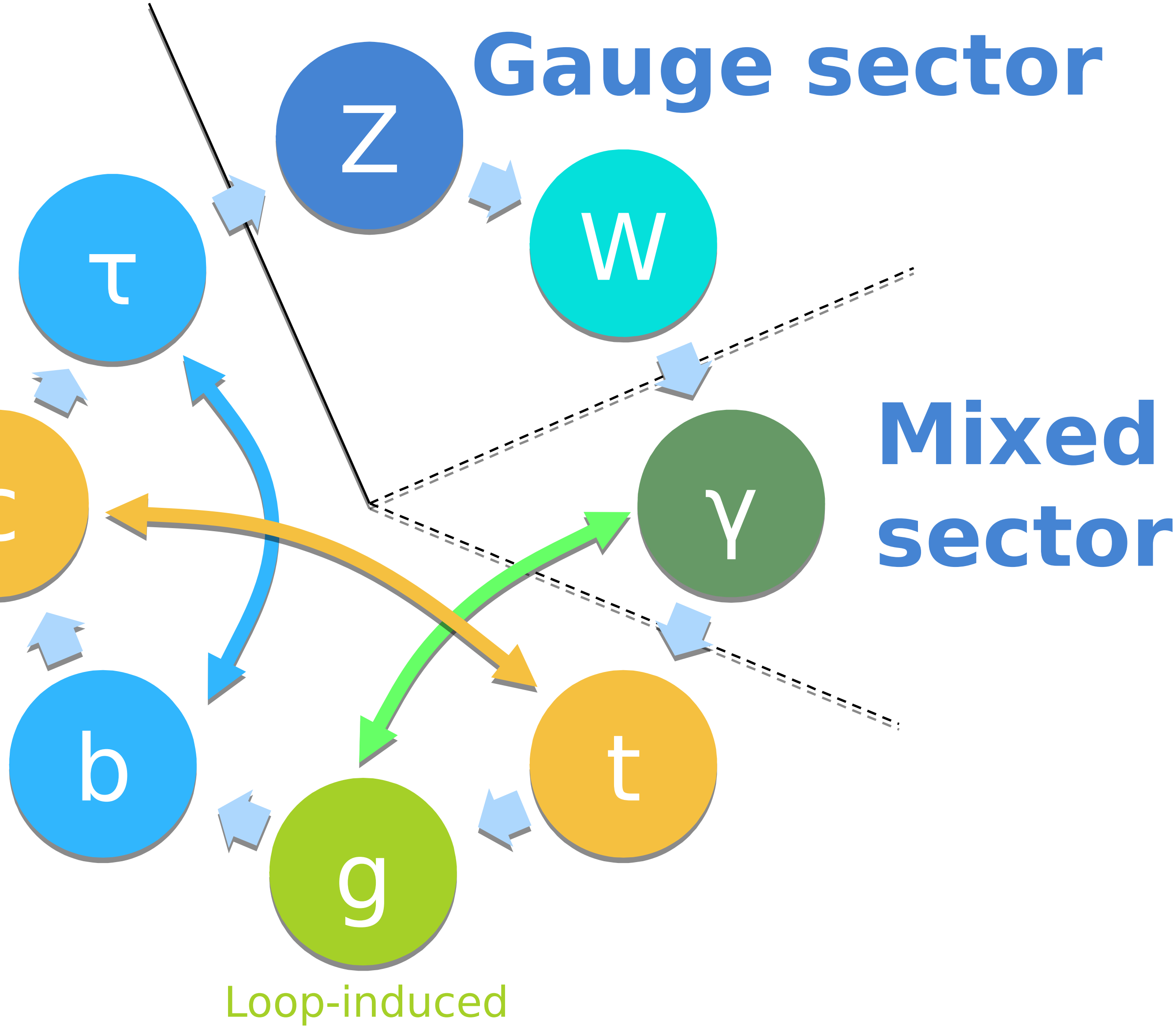
Unfolding to production processes

- Can also combine informations from all decay modes.
  - Fermionic-to-bosonic production ratio (decay independent).
  - Per production signal strengh (assuming SM BRs).





From signal strengths to coupling modifiers



What are the coupling modifiers?

- Simplest parametrization of Higgs-couplings deviations from SM values.
  - Strengths modifications from SM amplitudes (LO EWK, NLO QCD).
  - Assume kinematics unmodified.
  - Motivated only for small deviations from SM.

$$\sigma_p \cdot BR_d = \sigma_p \cdot \frac{\Gamma_d}{\Gamma_{tot}} = \frac{k_p^2 \cdot k_d^2}{k_H^2} \cdot \sigma_p^{SM} \cdot \frac{\Gamma_d^{SM}}{\Gamma_{tot}^{SM}}$$

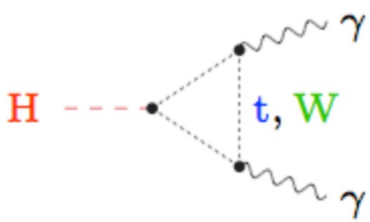
- Parametrise μ's in terms of k's
  - Can test different assumptions on relation between k's.

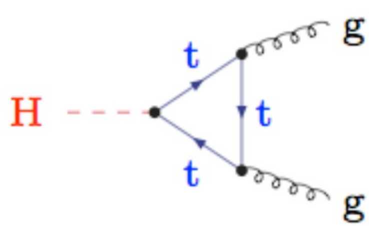
$$\mu_{pd} = \frac{k_p^2 \cdot k_d^2}{k_H^2}$$

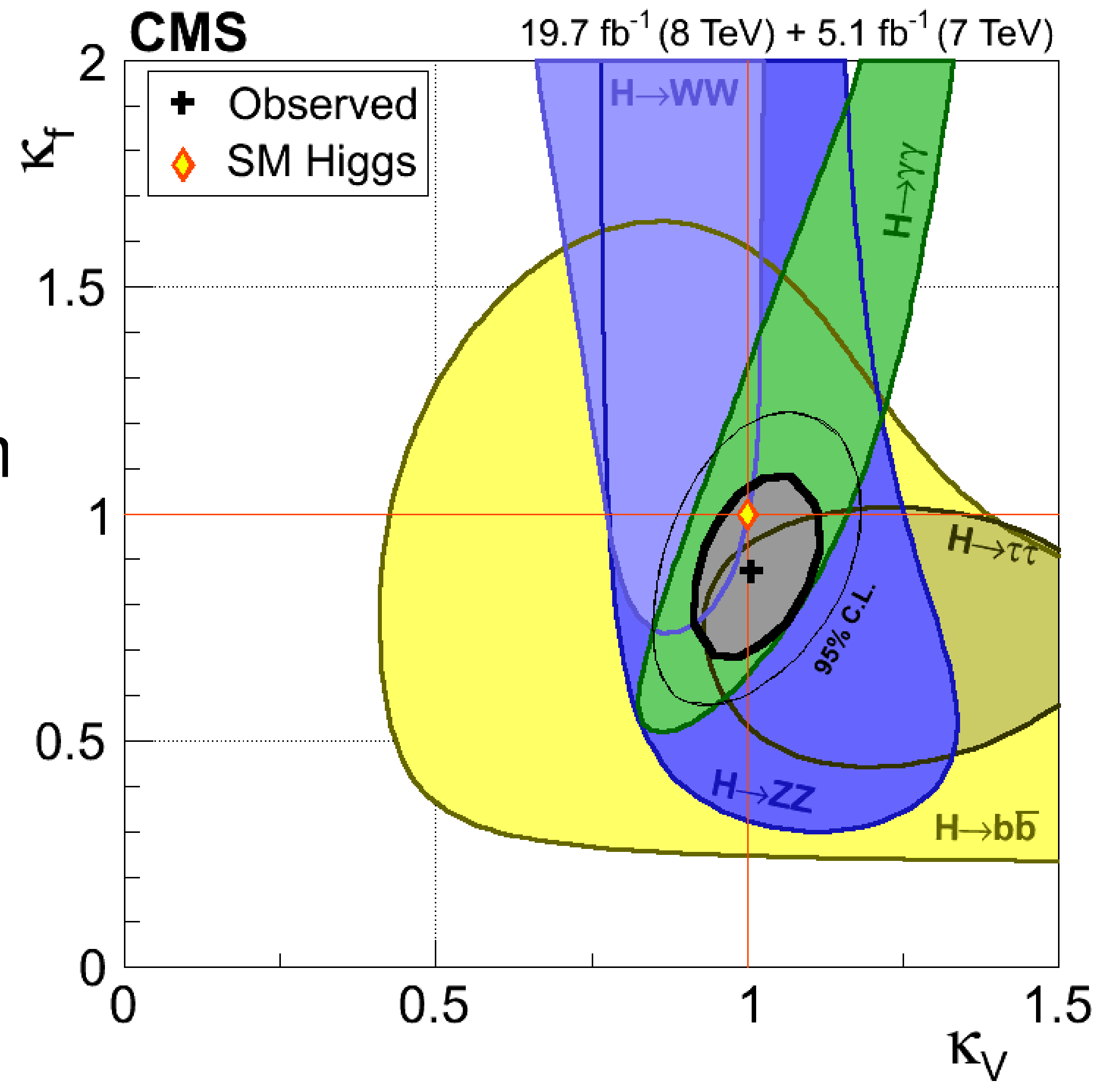
- k_H paramatrises change in total width:
  - As an independent parameter or as a function of the other k's

Simple models

- Common modifier for fermion couplings: k_f
- Another one for boson couplings: k_V
- Parametrize loop-mediated couplings as in SM.

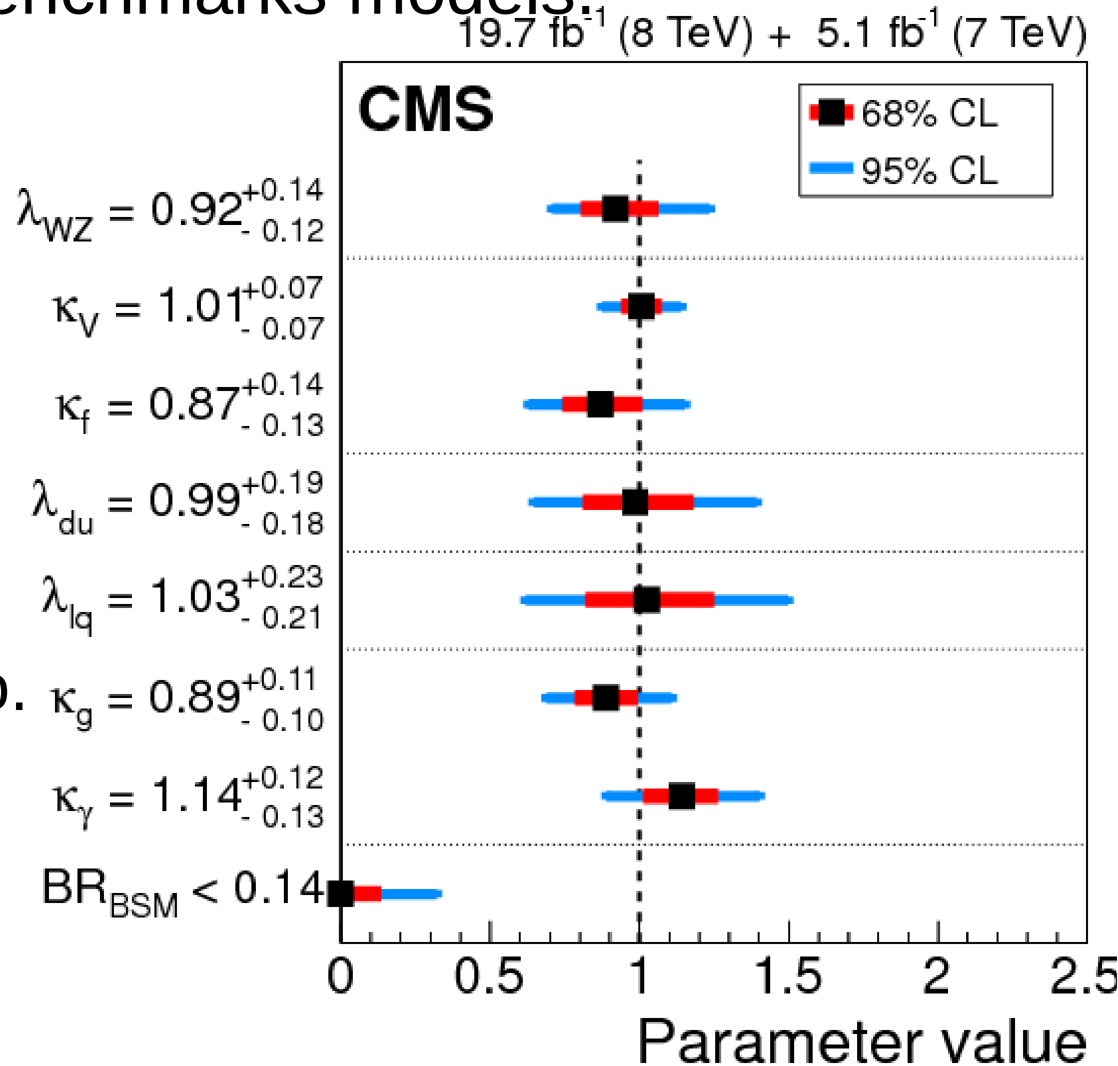






Simple models: summary.

- Summary of the fits of six benchmarks models. Probing:
  - Custodial symmetry.
  - Fermions and vector bosons
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: BR_{BSM}.
- **No significant deviations from SM.**



$$\lambda_{ab} :\stackrel{*}{=} \frac{k_a}{k_b}$$

Do the Higgs couplings scale with the mass?

- Parametrize k's as

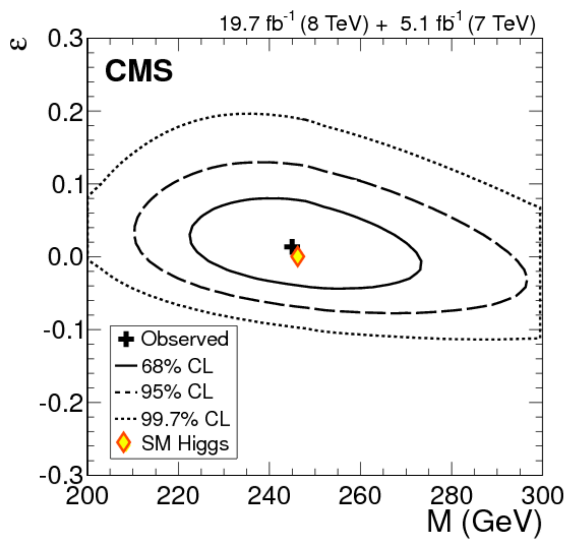
  $k_{W,Z} = vev \times m^{2\varepsilon}_{W,Z} \;/\; M^{1+2\varepsilon}$

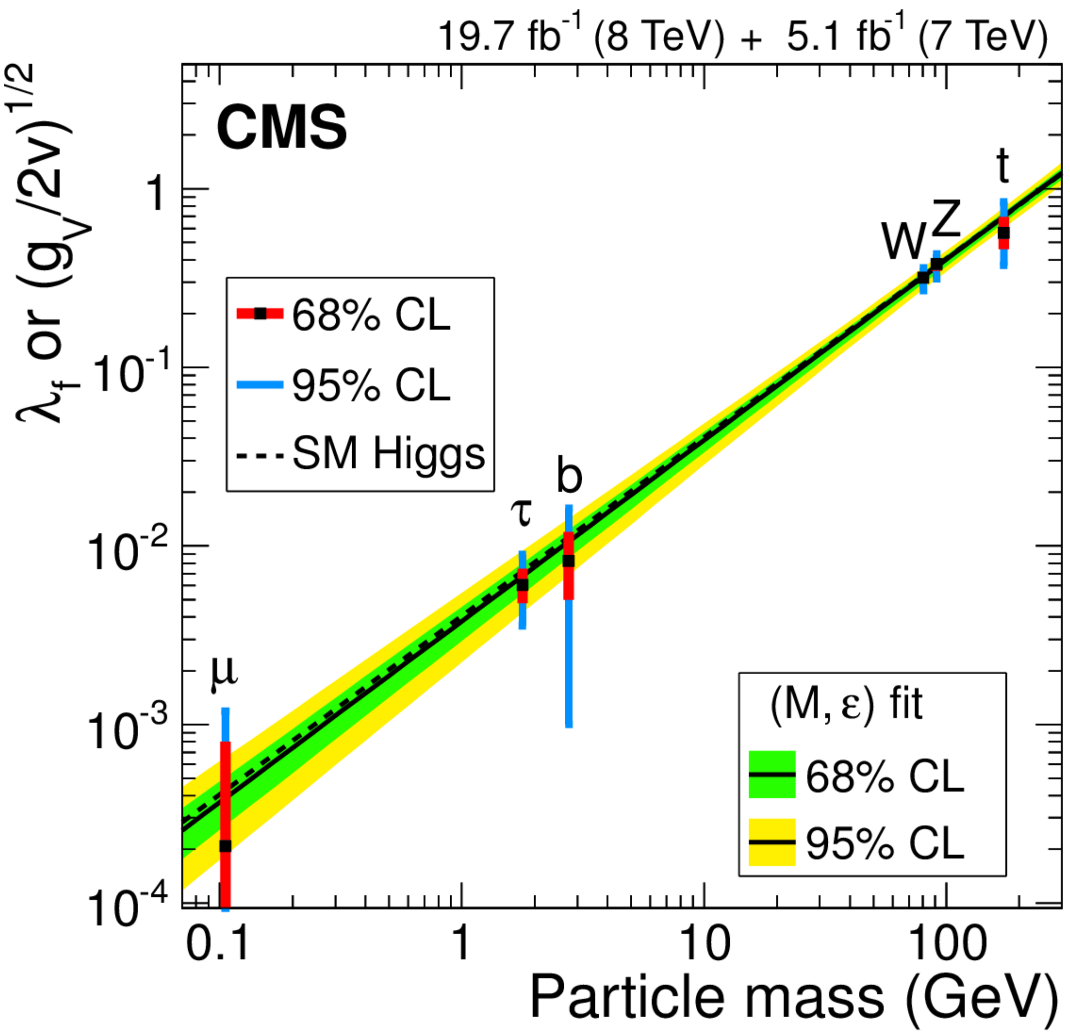
  $k_{\mu,b,t,\tau} = vev \times m^{\varepsilon}_{\mu,b,t,\tau} \;/\; M^{1+\varepsilon}$

- SM:

  M = *vev* = 246.22 GeV

  ε = 0.





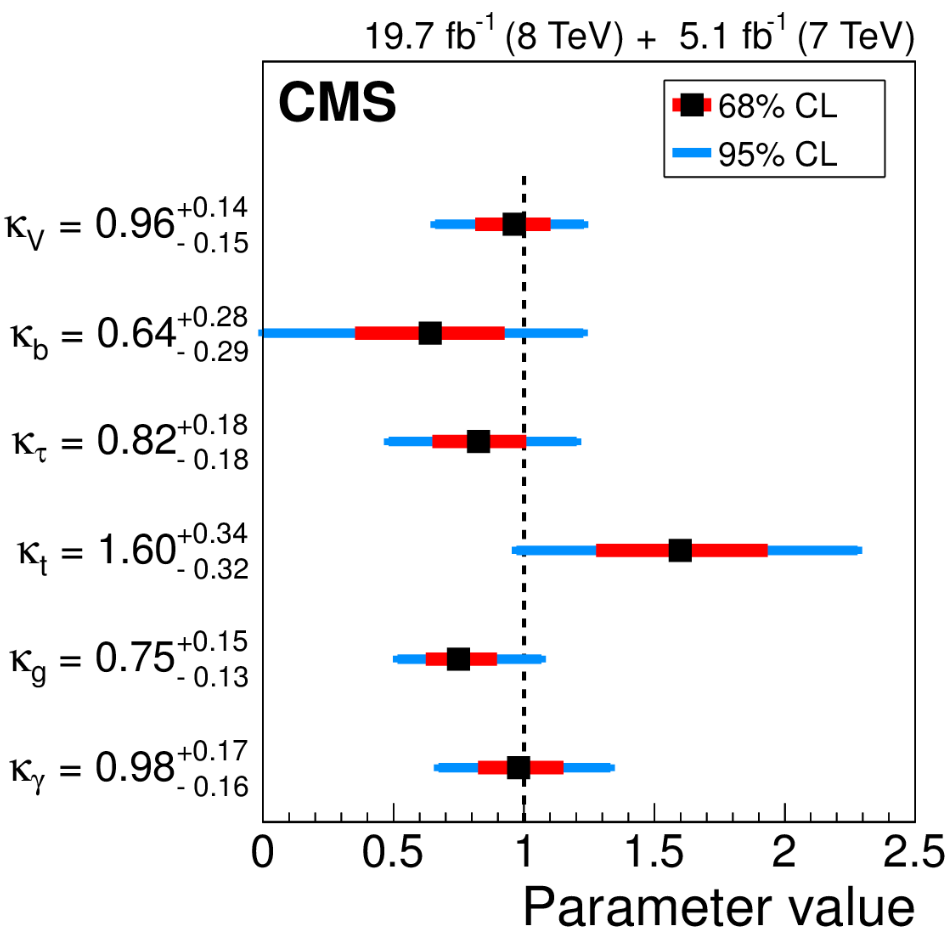
More general models

- Again no significant deviations.

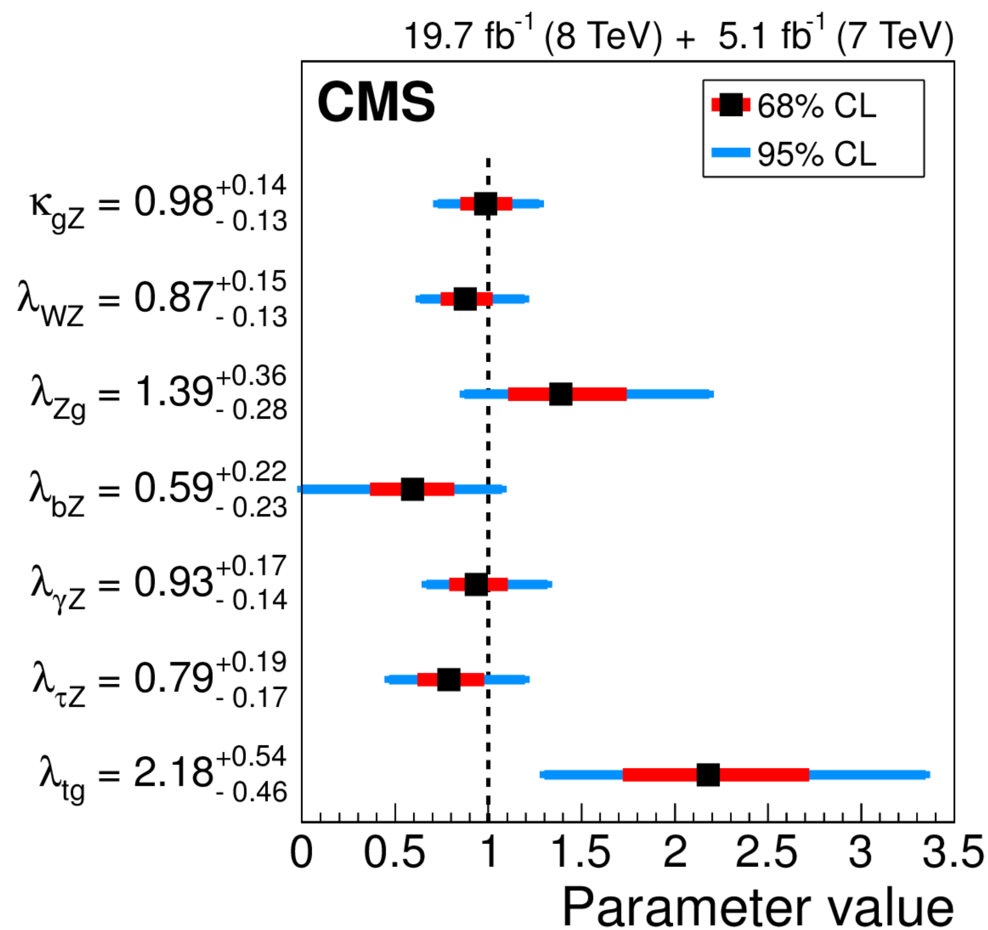
* $\lambda_{ab} := \frac{k_a}{k_b}$

$k_{xy} := \frac{k_x \cdot k_y}{k_H}$

Decouple k_γ and k_g from k_t, and k_V



Float total width and ratio of coupling modifiers.



Room for BSM decays?

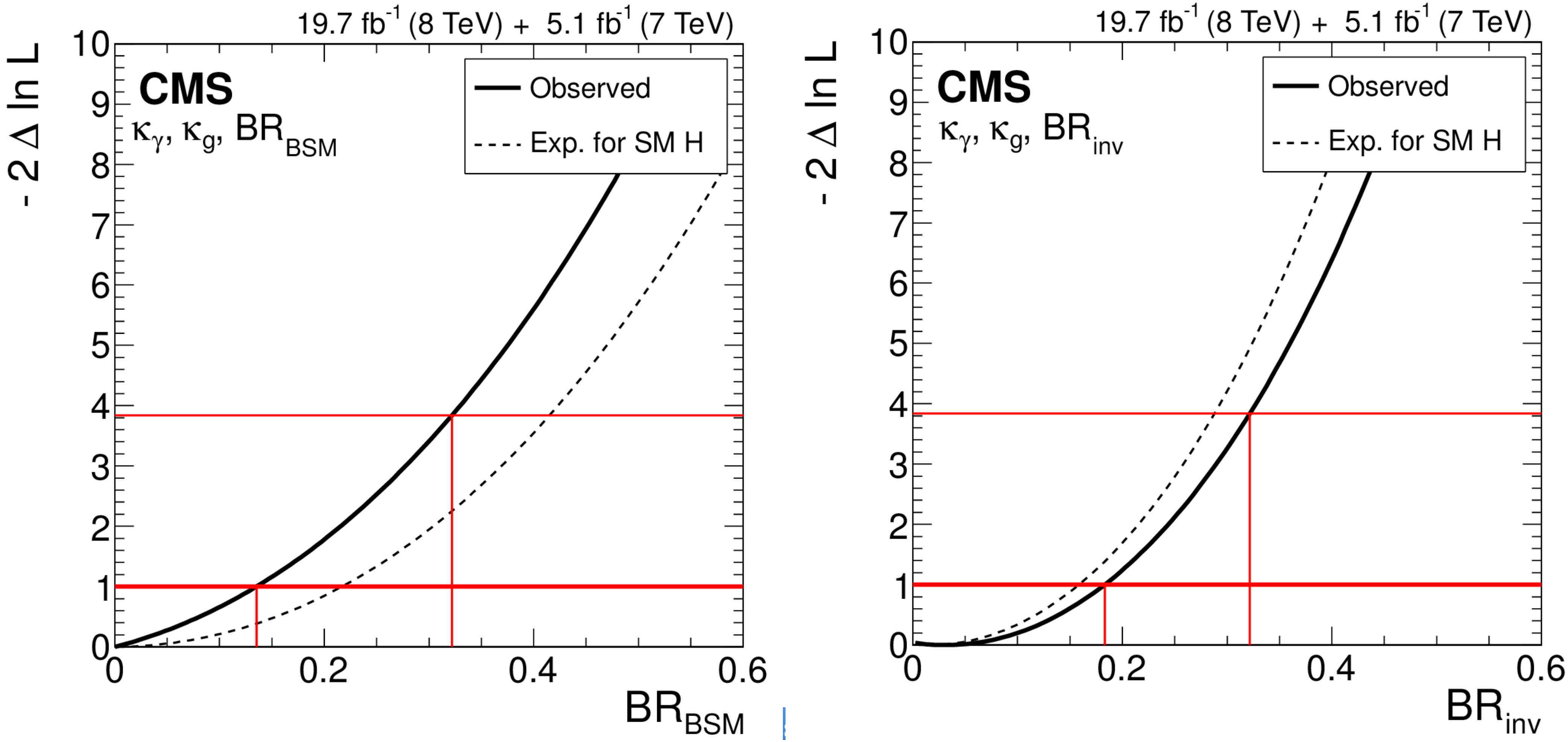
- Strength of observed channels can be used to infer the one of unobserved ones.
  - The inferred constraints depend on the assumptions being made.
  - In these parameterizations, contributions to the total with can be classified as:

$$\Gamma_{tot} = \sum_{fix} \Gamma_d + \sum_{float} \Gamma_d\left(k_j\right) + \overbrace{\Gamma_{inv} + \Gamma_{undet}}^{\Gamma_{BSM}}$$

- $\sum_{fix} \Gamma_d$: Decay widths fxied to SM value.
- $\sum_{float} \Gamma_d(k_j)$: Decays widths associated to floating coupling modifiers.
- Γ_{inv}: Decays to weakly interactive particles.
- Γ_{undet}: Undetected decays not predicted by SM.

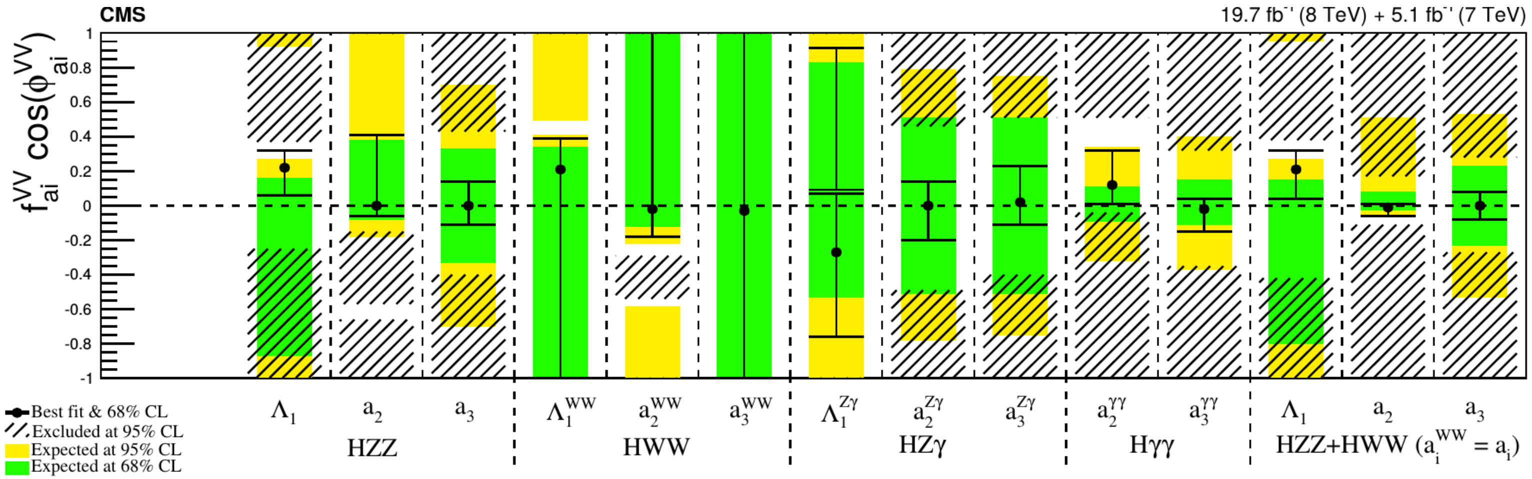
Room for BSM ?

- Two particular models:
  - Float only loop-mediated couplings and total decay with to BSM (left).
  - Or, in addition, also assume all BSM decays are invisible (right). Combine with results from direct searches.



… and more ...

- “Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV” [arXiv:1411.3441v1 (Submitted to PRD)].
  - Constraints on HVV anomalous couplings.



- “Constraints on the Higgs boson width from off-shell production and decay to ZZ→4l or 2l2ν” [PLB 736 (2014) 64]

- Several searches for BSM in Higgs sector and rare H decays. Full list at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Conclusions

- A Higgs boson was discovered by the CMS and ATLAS collaborations in 2012.
- Two years after the discovery CMS has completed the final analysis of the Run I dataset.
  - The mass of the Higgs boson has been measured to be.

$$m_H = 125.02^{+0.26}_{-0.27}(stat)^{+0.14}_{-0.15}(syst)\,GeV$$

  - Combination of several channels allows to infer properties of the new particle, in particular on the structure of the Higgs field couplings.
  - Precision attained on signal strength/coupling modifiers is in the 10-30% range.
  - Results are consistent with SM expectations.
- Looking forward to LHC Run II.
  - Increased precision will allow for more stringent tests of SM predictions.
  - Stay tuned.

Thank you for your attention!

“Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV” [arXiv:1412.6886, submitted to EPJC]

and references therein:

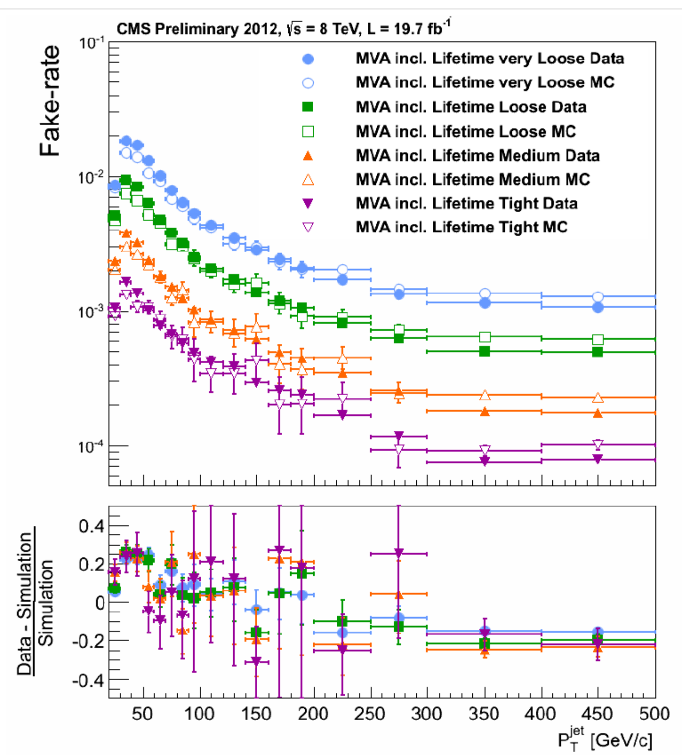
“Measurement of the properties of a Higgs boson in the four-lepton final state”	PRD 89 (2014) 092007
“Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties”	EPJC 74 (2014) 3076
“Search for the standard model Higgs boson produced in association with a top-quark pair in pp collisions at the LHC”	JHEP 05 (2013) 145
“Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks”	PRD 89 (2014) 012003
“Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states”	JHEP 01 (2014) 096
“Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons”	JHEP 05 (2014) 104
“Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs”	PLB 736 (2014) 64
“Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes”	EPJC 74 (2014) 2980
“Search for the associated production of the Higgs boson with a top-quark pair”	JHEP 09 (2014) 087
“Search for a standard model-like Higgs boson in the $\mu+\mu-$ and $e+e-$ decay channels at the LHC”	arXiv:1410.6679 Submitted to PLB.

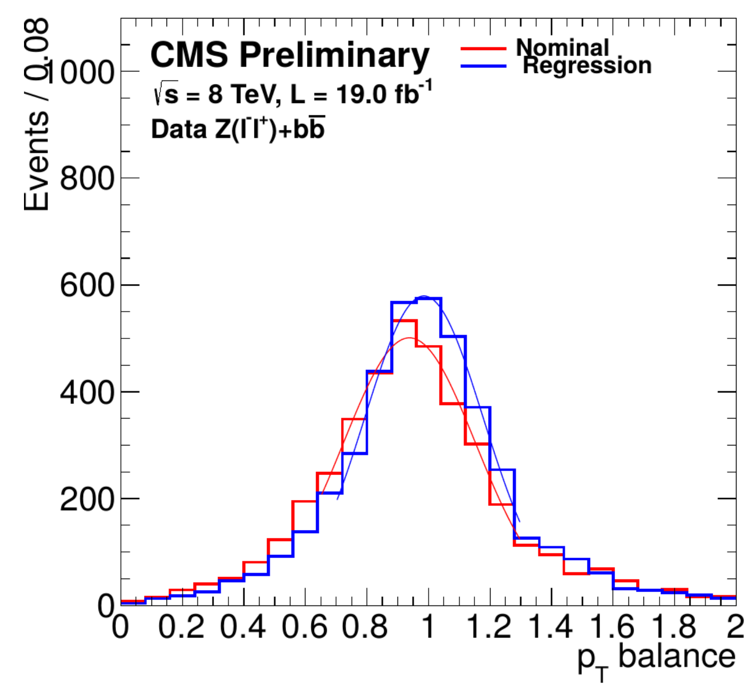
Additional material

Tau's and b-jets

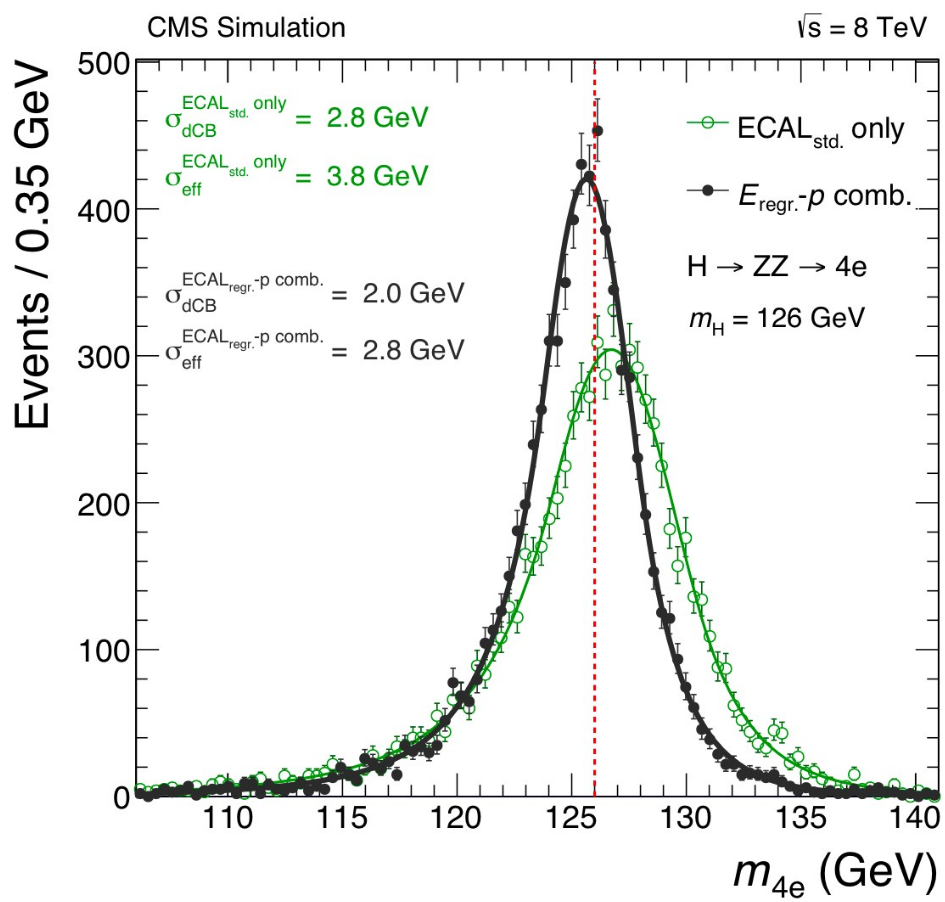
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsPFT
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBTV

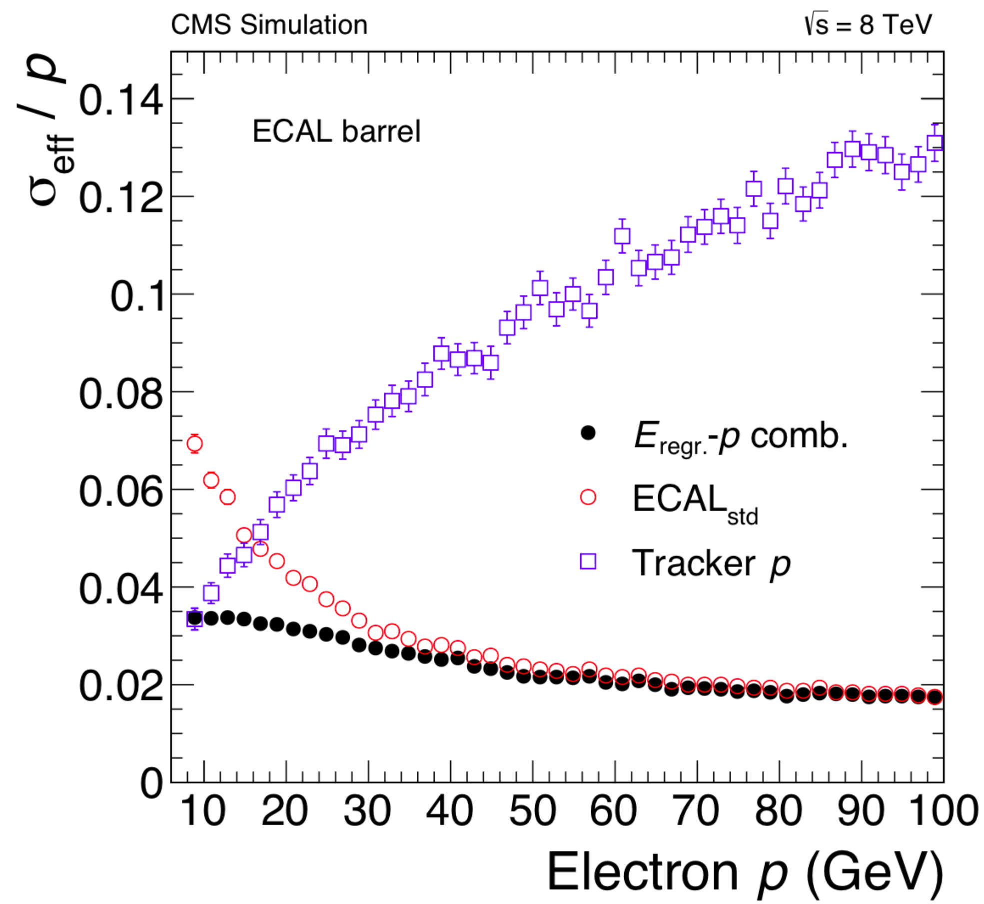
- Tau identification crucial for $H \to \tau\tau$ searches.
  - Tau fake rate at 0.1-1% level with 50-70% identification efficiency.
- Besides b-tagging, b-jet energy resolution very important to $H \to bb$ searches.
  - With BDT regression technique <10% resolution on m_{bb}.
- Performances predicted by simulation nicely validated on data.



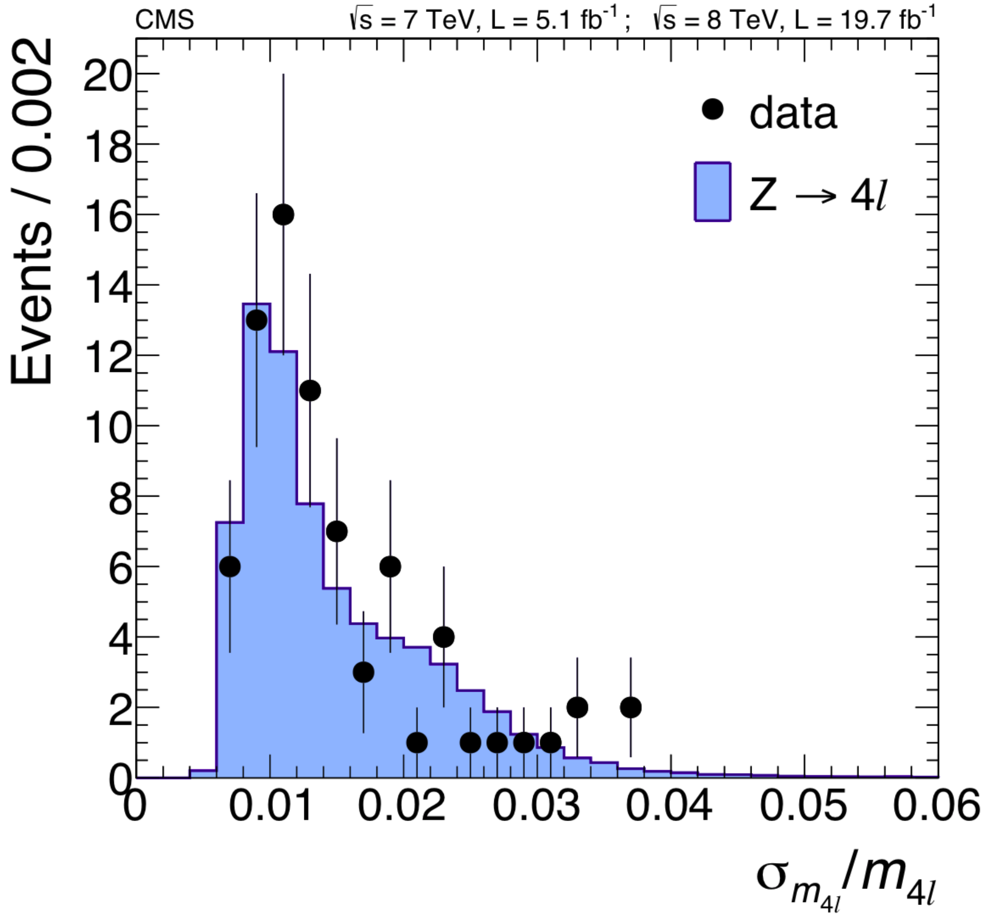


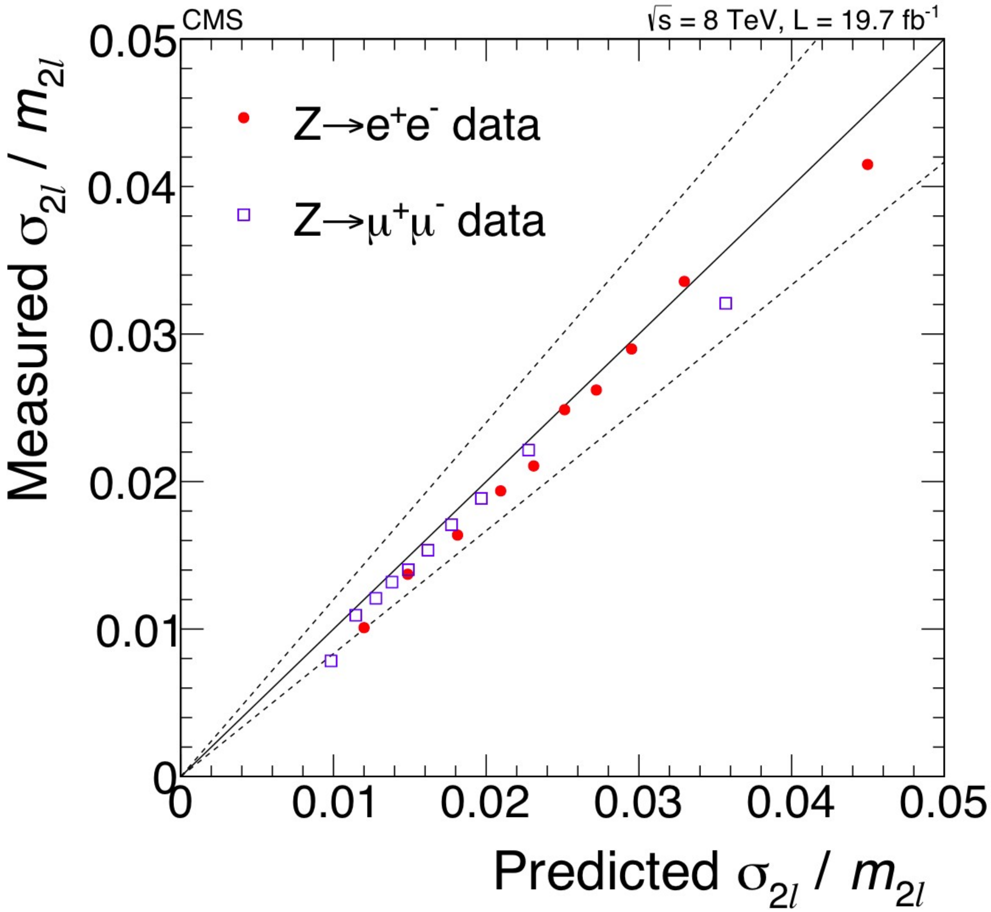
H → 4l : electron E/p corrections



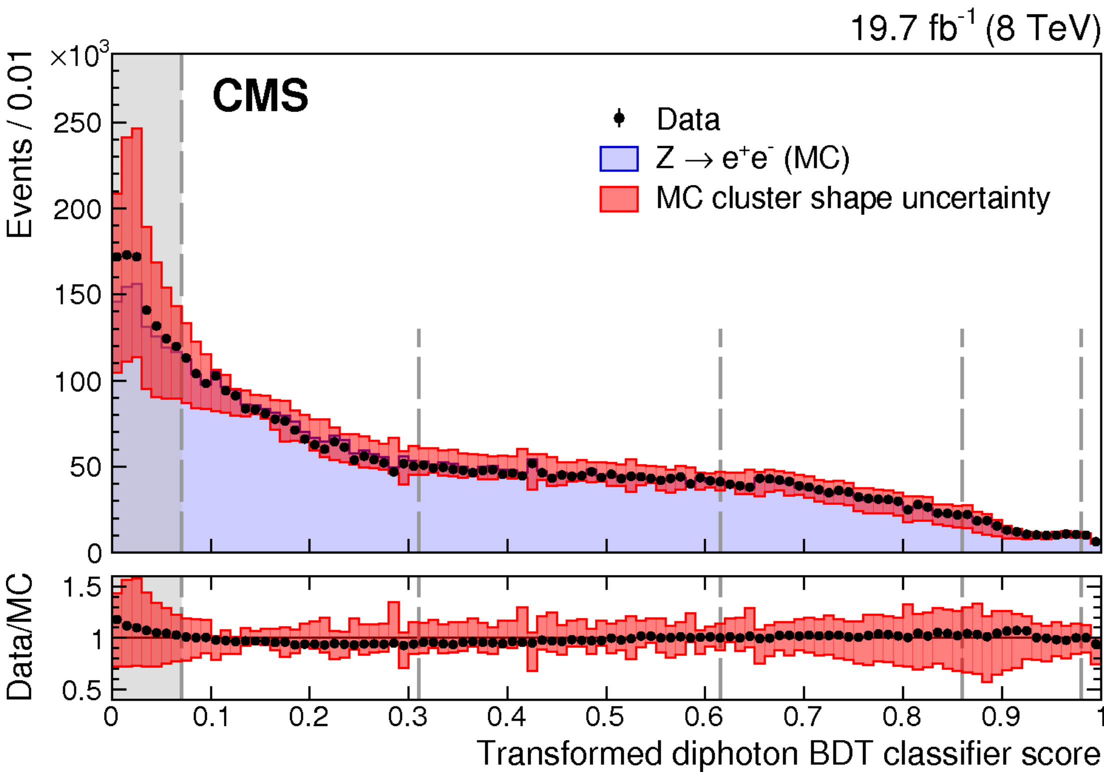


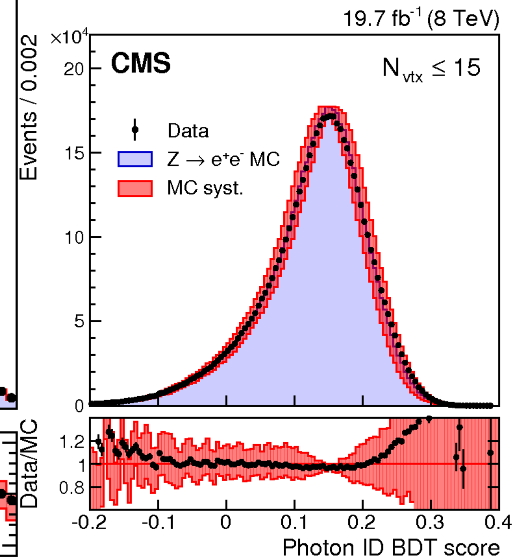
H → 4l mass resolution estimator

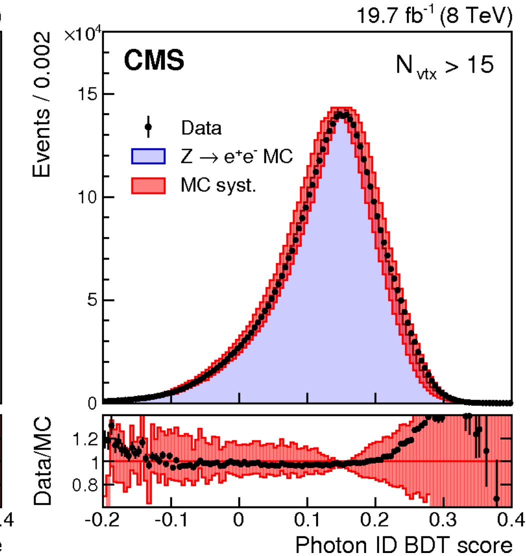




$H \rightarrow \gamma\gamma$: BDT discriminants





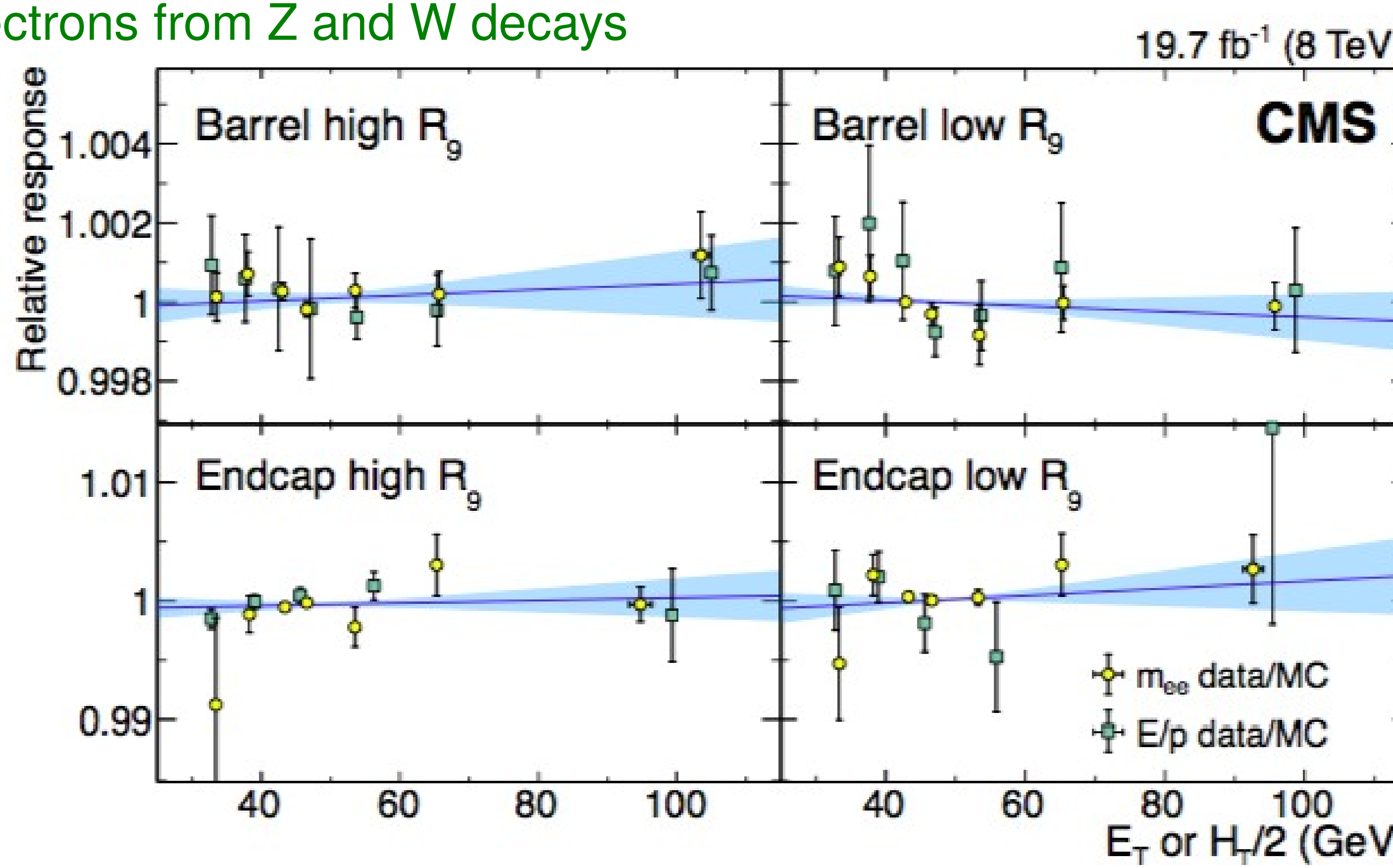


Energy corrections (at m_Z) and linearity

- **Photon energy corrections : *δm_H = 0.05 GeV***
  - Method stability against R9 reweighting, selections, fit range
- **Residual non linearity : *δm_H = 0.10 GeV***
  - Dielectron invariant mass vs $H_T = ½ (E_{T,1} + E_{T,2})$ in boosted $Z \rightarrow ee$
  - E/p vs E_T with electrons from Z and W decays

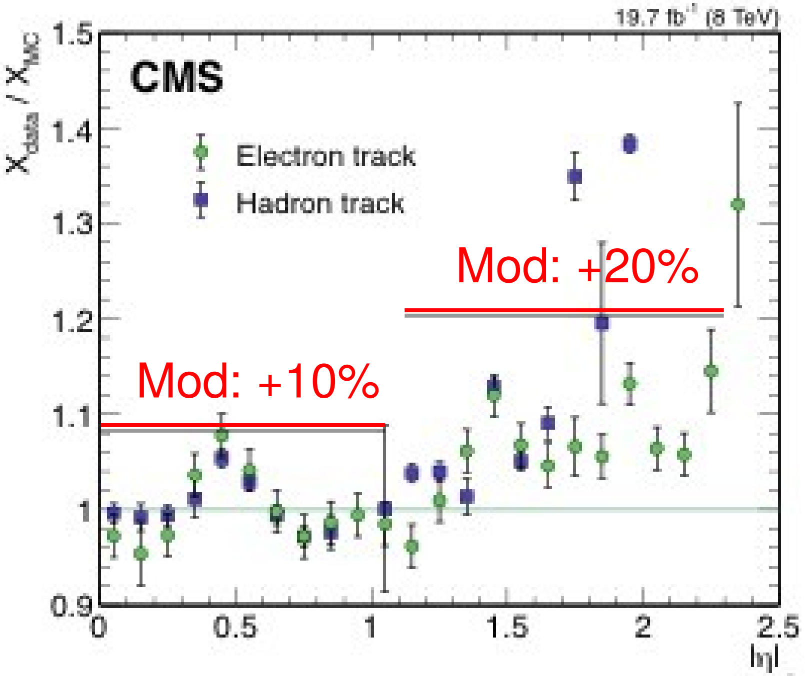
- Error band scaled to get X^2/dof =1
- Also verified with parabola

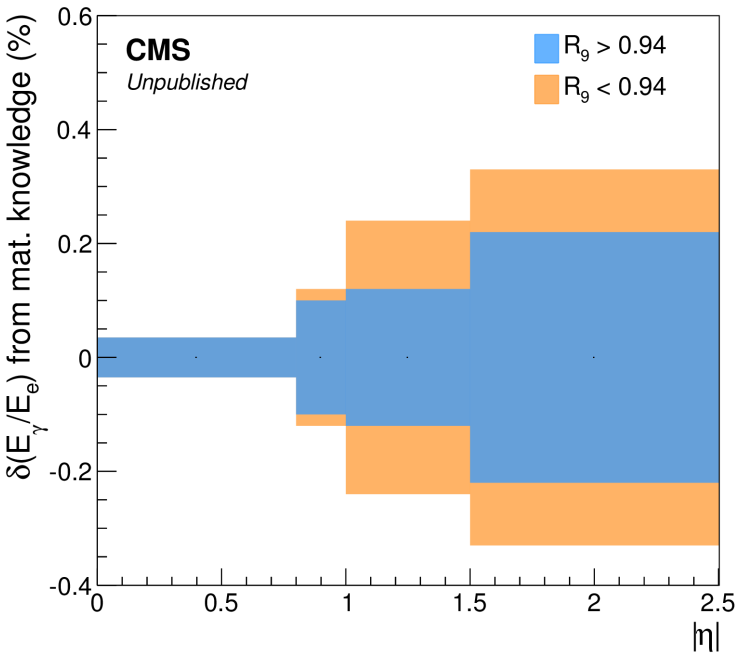
Additional checks
- Gain switch of electronics in < 2% of events negligible



Photon/ electron response difference

- **Imperfect simulation of e/γ difference : *δm_H = 0.10 GeV***
  - Per-photon effect from ***double ratio of e/γ response difference*** in ***modified*** and ***default*** simulation
- *Longitudinal non-uniformity of light collection : 0.02 GeV (next)*
- **Imperfect EM shower simulation : 0.05 GeV**
  - *G4 modified with Seltzer-Berger model*
- **Imperfect description of material : 0.07 GeV**

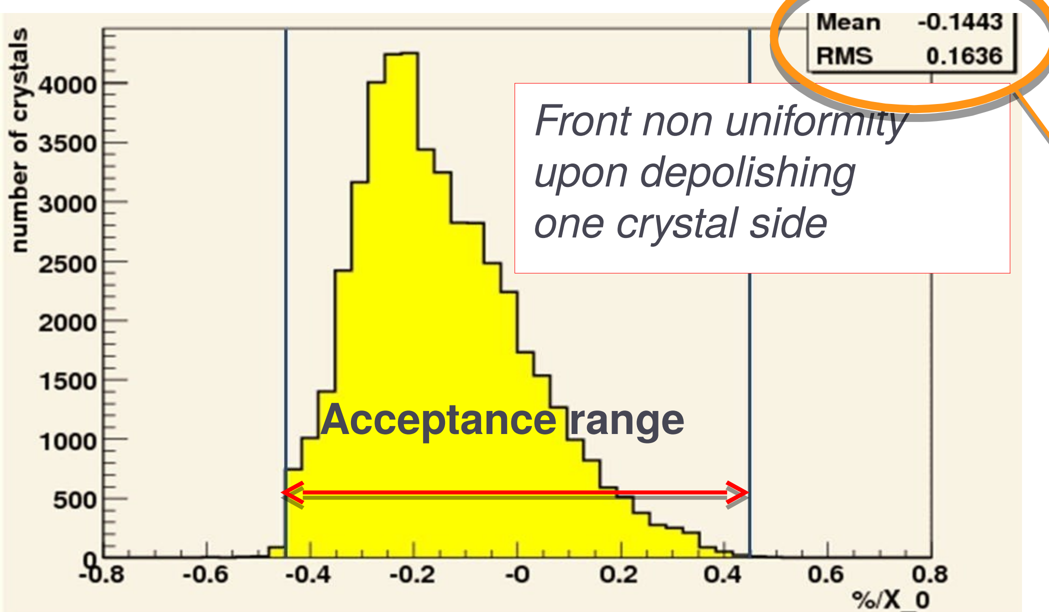




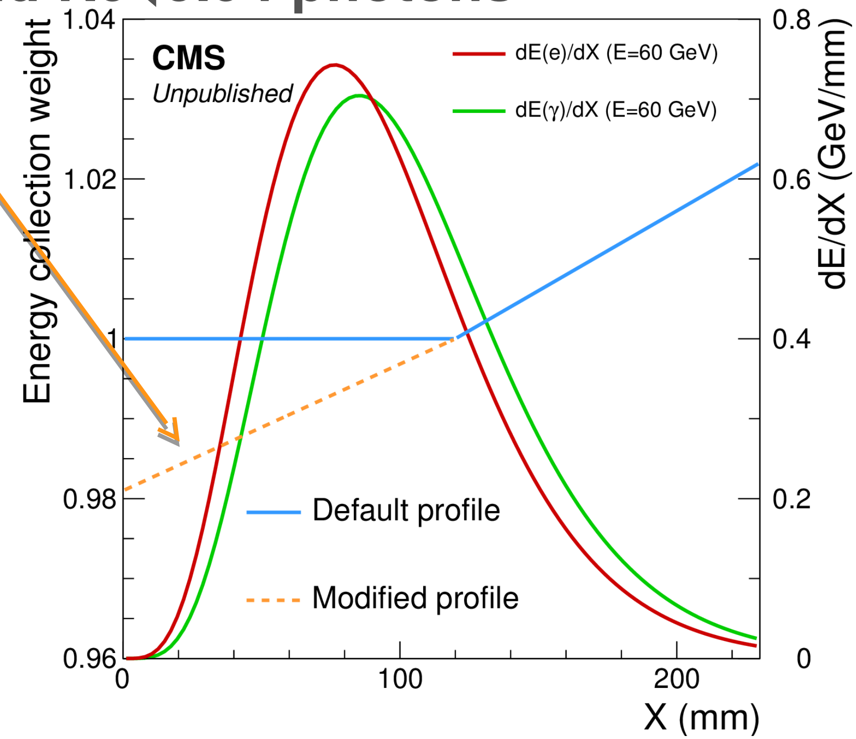
Photon/ electron response difference (2)

- **Imperfect simulation of e/γ difference : δm_H = 0.10 GeV (cont'd)**
  - **Longitudinal non-uniformity of light collection : 0.02 GeV**
    - Residual non-uniformity from lab tests (all crystals!): 0.14%/X_0
    - e/γ response difference from difference in shower depth

→Per-photon scale change (including radiation effects): ~**0.05%** **anti-correlated between R9>0.94 and R9<0.94 photons**

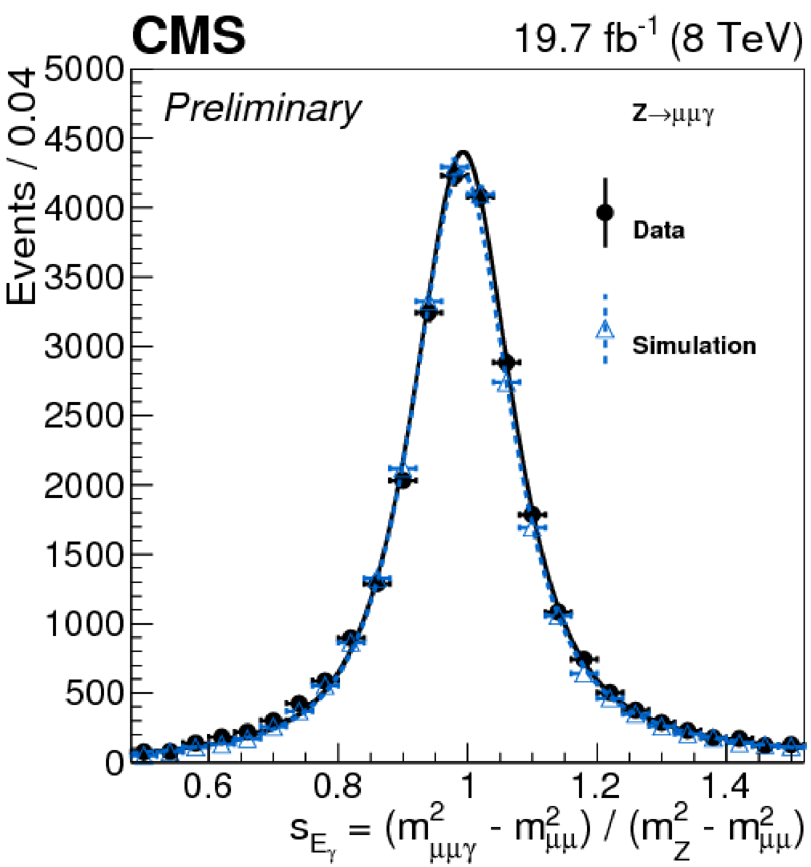


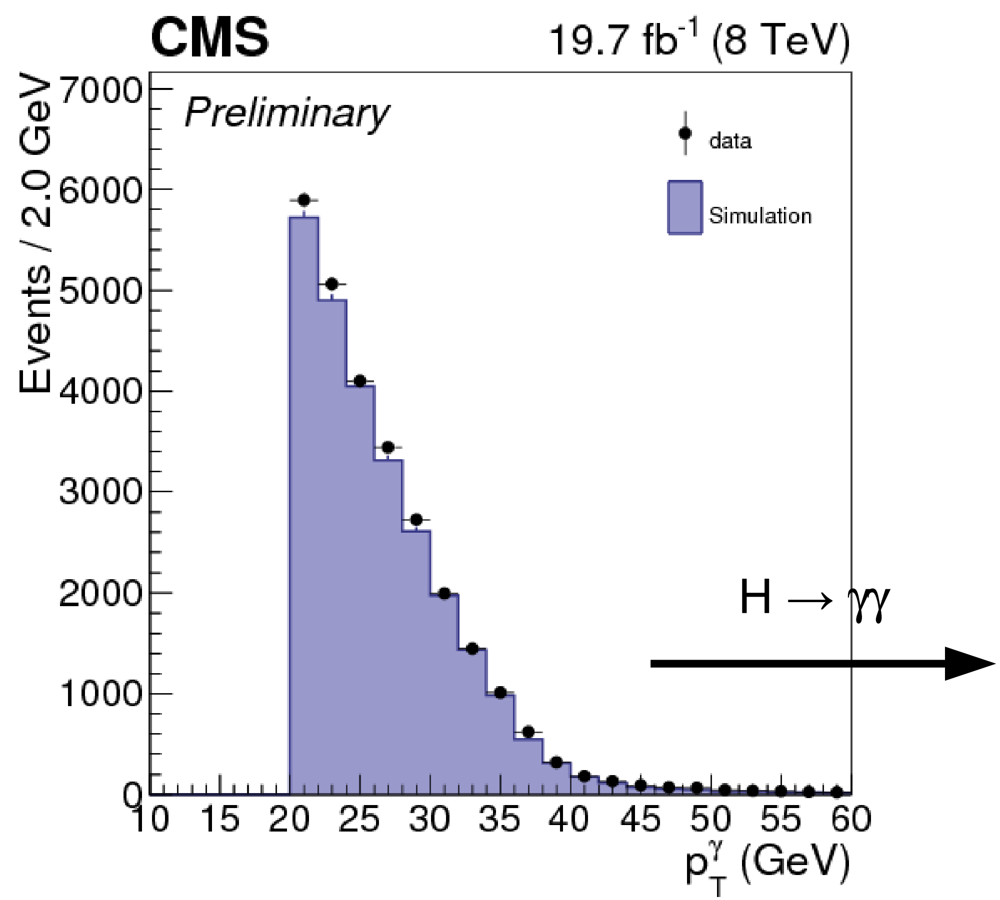
Dependence on radiation damage also studied in R&D



Z → μμγ cross check

- Use of Z→μμγ has limited usefulness to constrain H → γγ photon energy scale, due different kinematic regime.
  - Still a valuable cross-check. $\delta E_\gamma / E_\gamma$ = 0.25 +- 0.20 [0.11(stat)+0.17(syst)] %



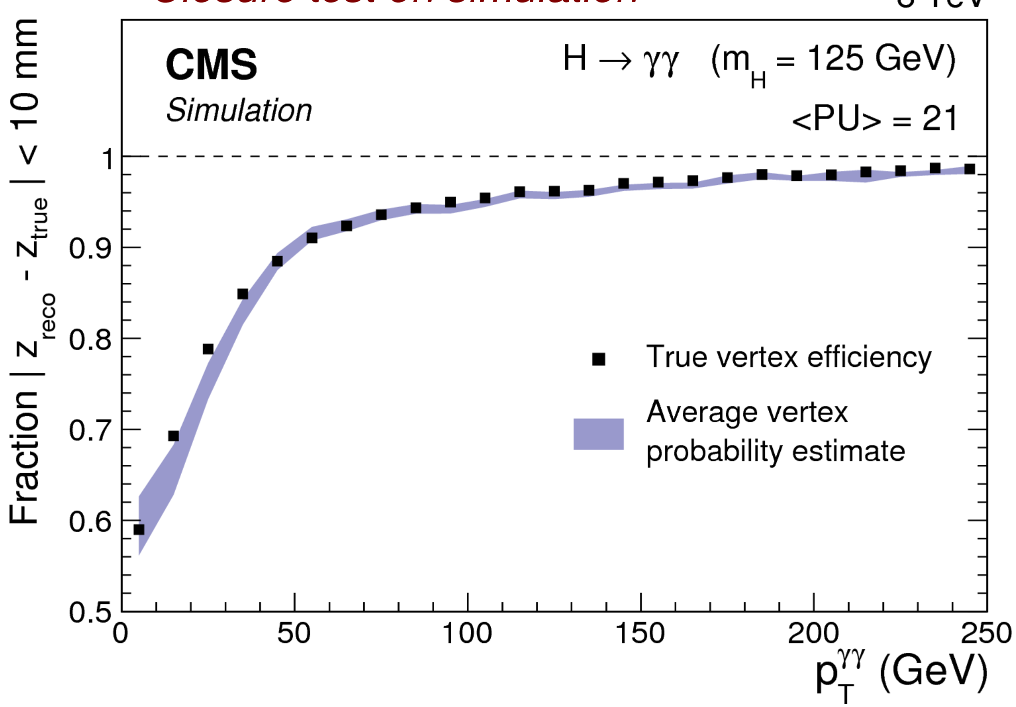


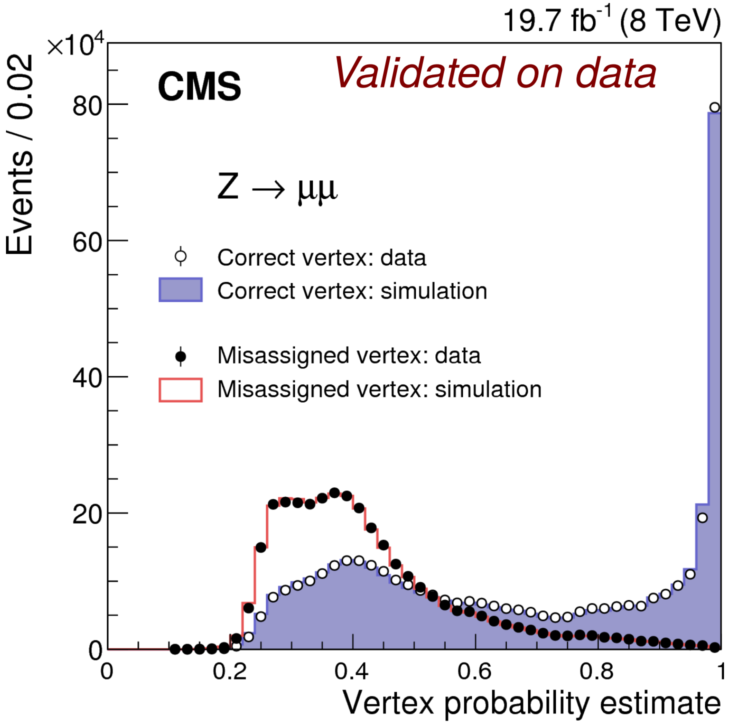
Vertex identification in $H \to \gamma\gamma$

- Resolution unaffected if vertex within 10 mm of true position

1. **BDT to identify vertex**
   - Hardness of interactions p_T
   - Balance of diphoton system and charged tracks
   - Conversion information
2. **BDT to assign per-event probability of correct vertex id**
   - BDT score and distance of three most likely vertices
   - Number of vertices in the event
   - Number of conversion tracks

Closure test on simulation



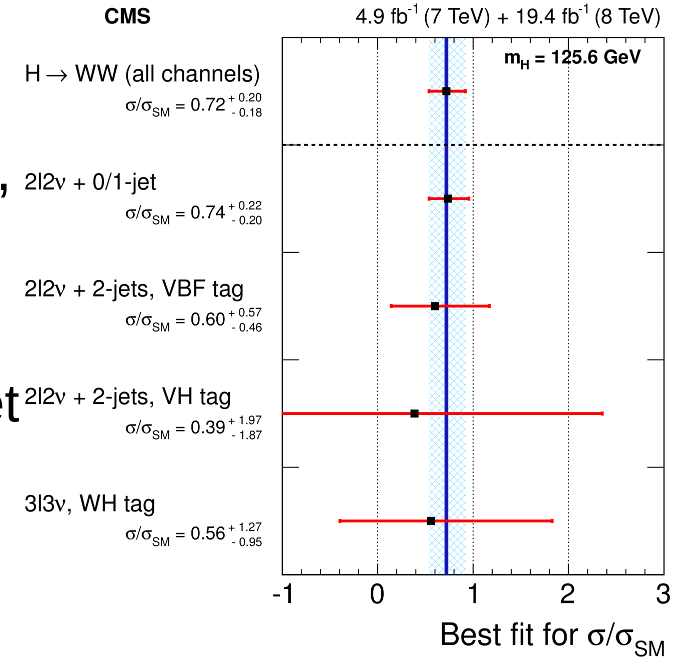


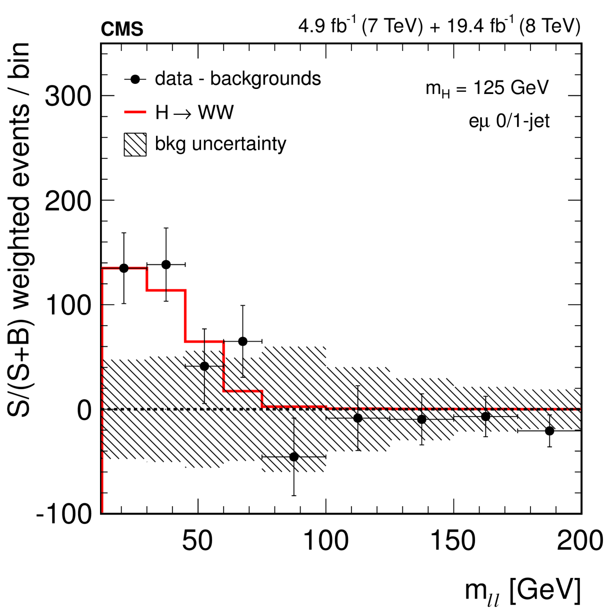
>> **Input to diphoton BDT**

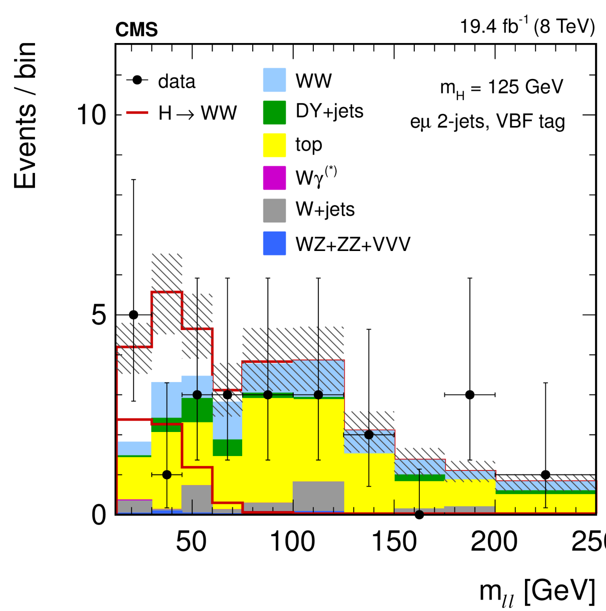
H → WW (2l2ν)

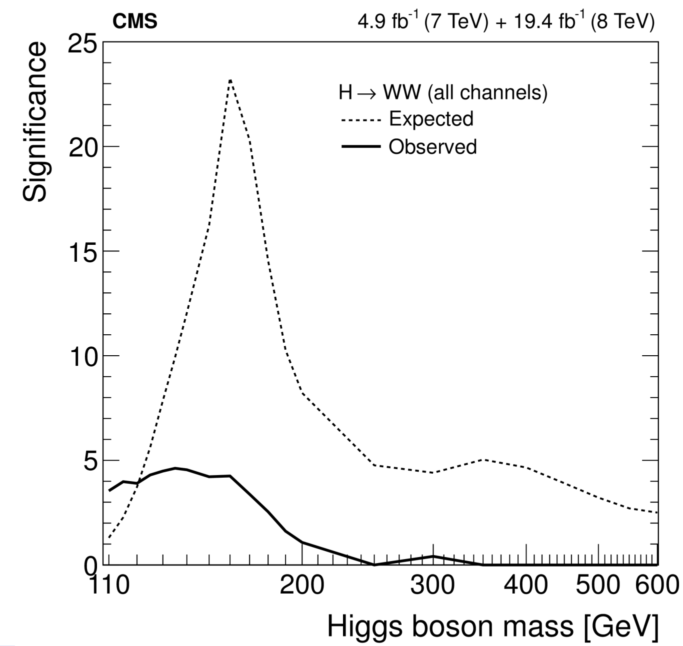
- BR(H → WW → 2l2ν)~ 1%.
- Clean signature:
  - Isolated high p_T leptons.
  - Missing transverse energy
- Mass resolution ~15%.

- Main backgrounds:
  - Non resonant WW, ttbar
- Sensitivity enhanced by categorization in 0jet,1jet and VBF categories.
  - WH → 3l3n channel also analyzed.



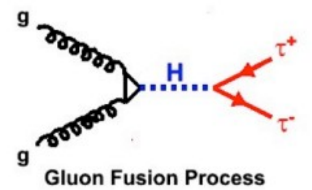


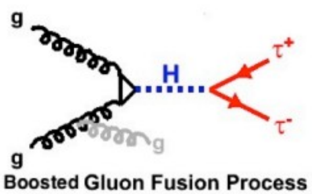


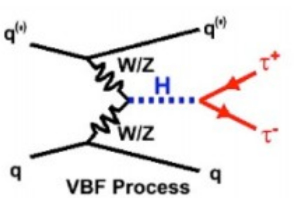


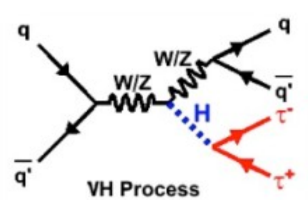
H → ττ

- Complex analysis, combining many different sub-channels









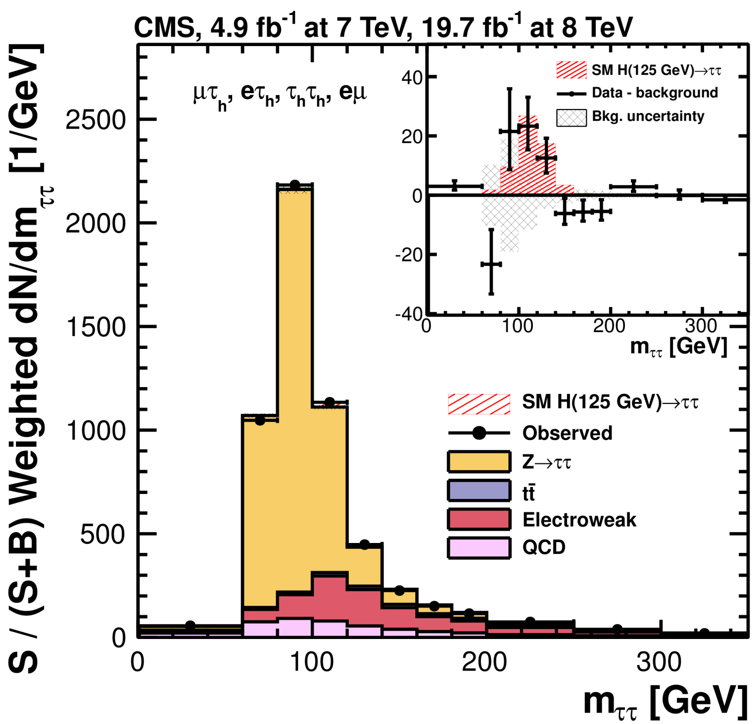
Production/signature

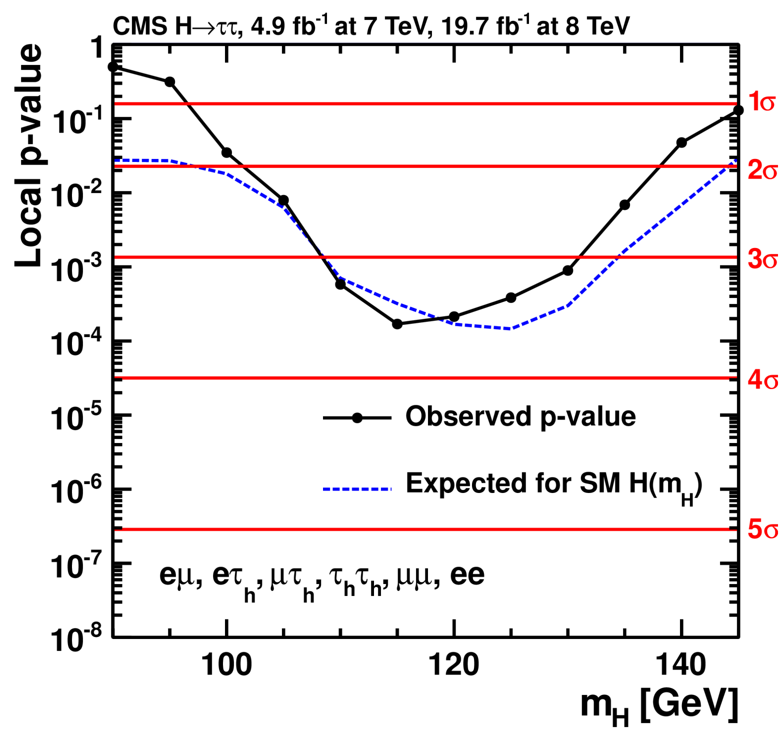
0-jet
1-jet boosted
2-jet VBF
VH (use leptonic decays of V)

$\otimes$

Decay

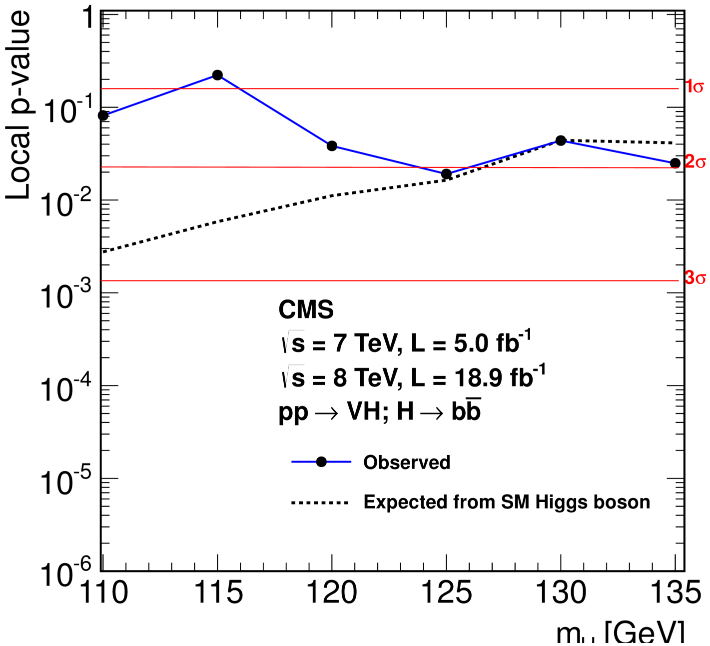
$$H \to \tau\tau \to \ell\ell + 4\nu \;\; (12\%)$$
$$H \to \tau\tau \to \ell\tau_h + 3\nu \;\; (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \;\; (42\%)$$

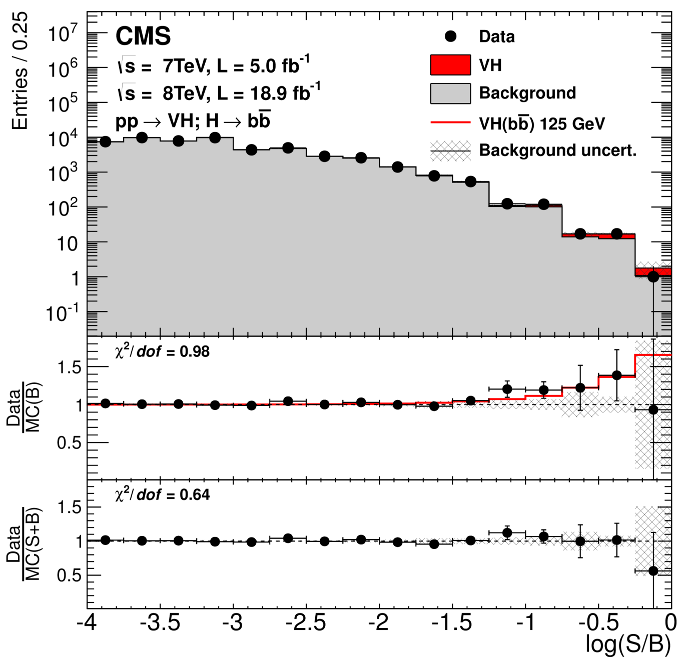




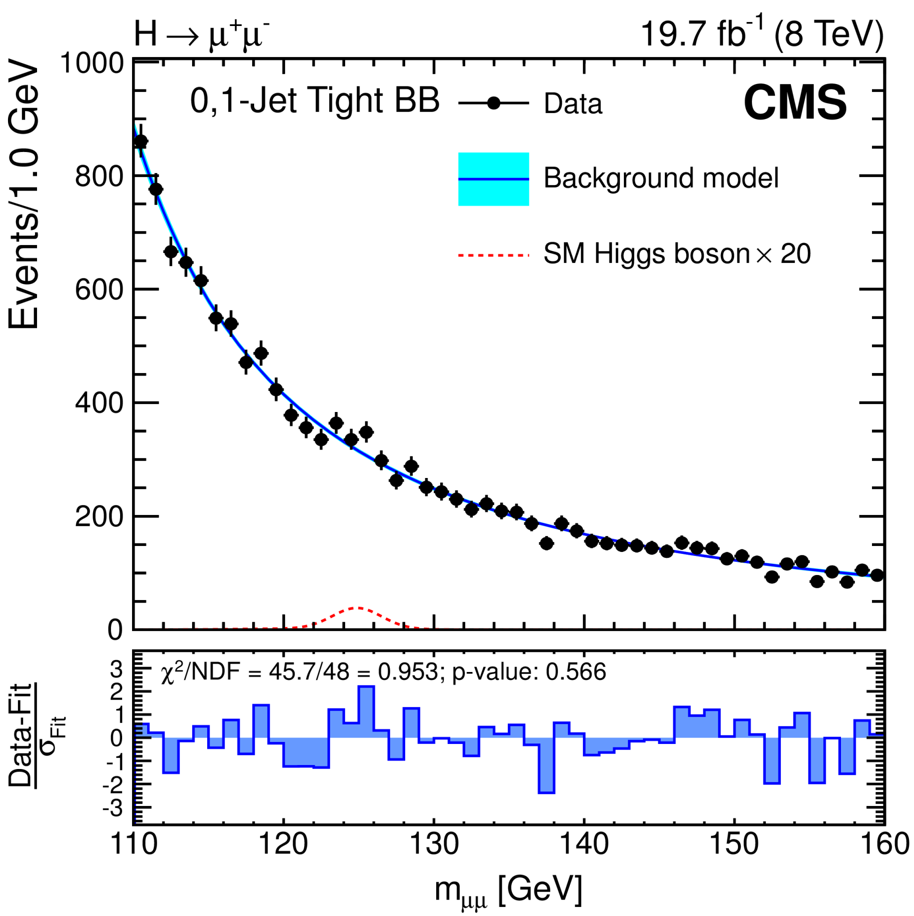
H → bb

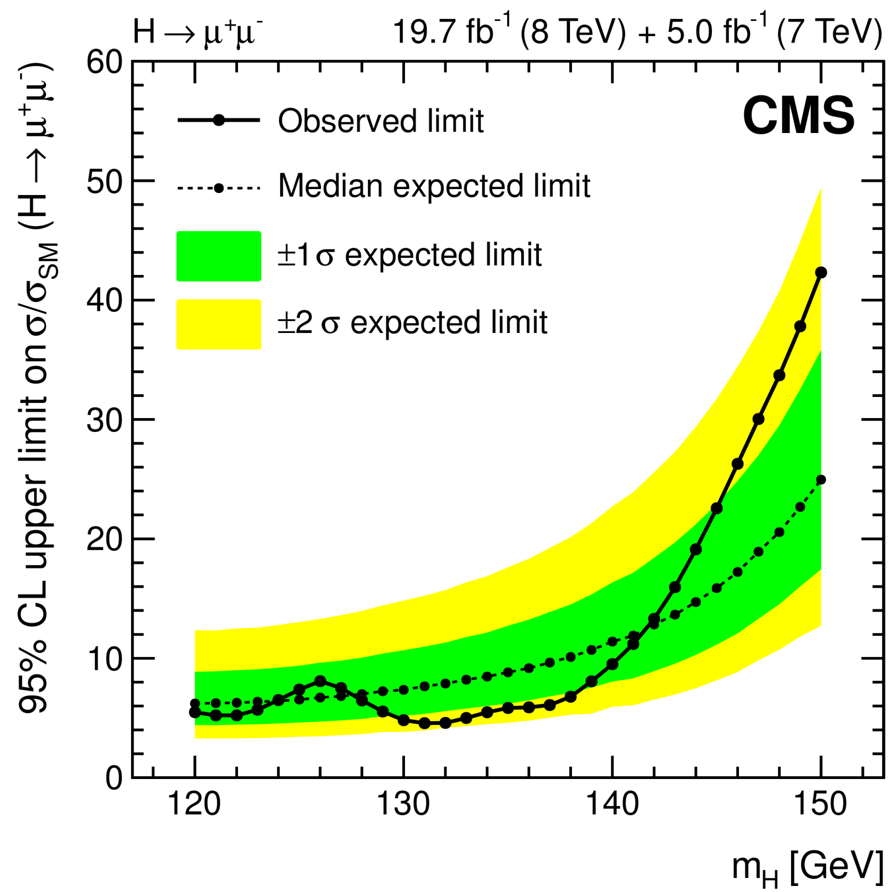
- QCD BG too large for gg fusion, needs additional tag
  - Most sensitive is VH (but also use ttH)
- Common features:
  - B-tagging
  - bb mass reconstruction, use BDT regression ($\sigma_M/_M$ = 8-9%)
- MVA based analyses to enhance the sensitivity





- Search for di-muon decay mode very similar to di-photon one.
  - Much smaller branching ratio make the analysis even more challenging.
  - Exclusion sensitivity at 7.5 x σ_{SM}

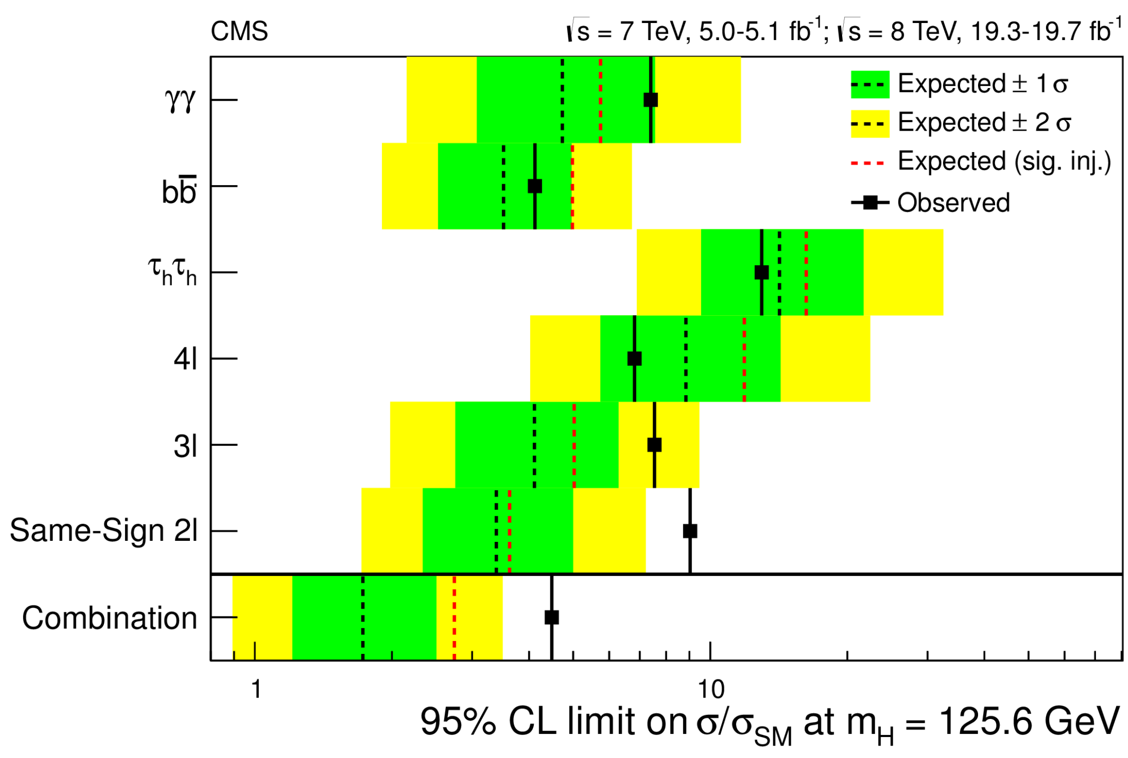


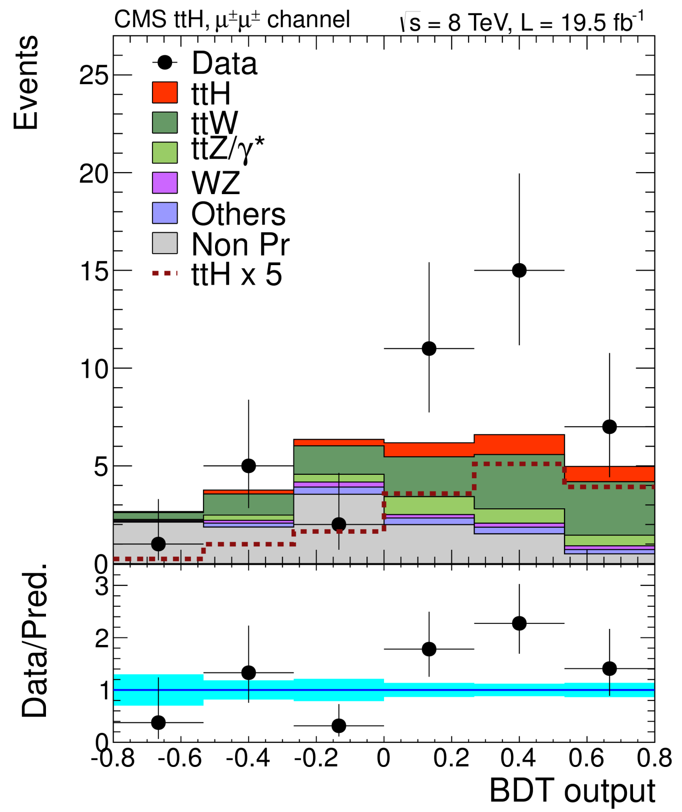


ttH

- Search for ttH production in H→bb,γγ, multileptons
- Some excess of events near 125 GeV (~2σ above SM expectation)
  - expected significance: 1.1 σ
  - observed significance: 3.4 σ

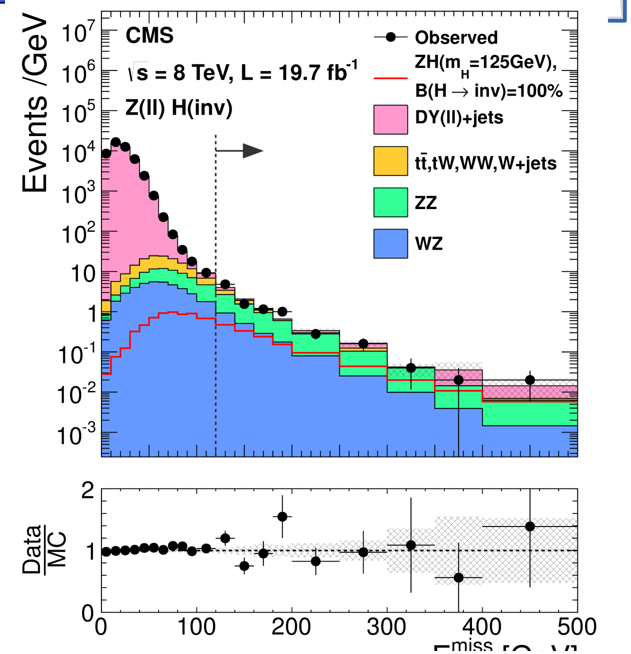
Excess driven by the same sign di-lepton search

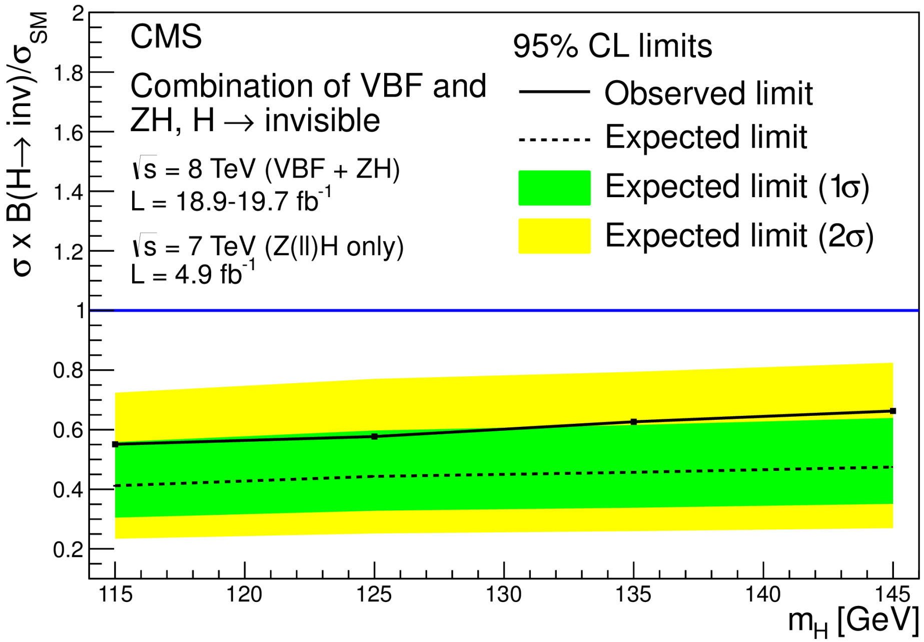


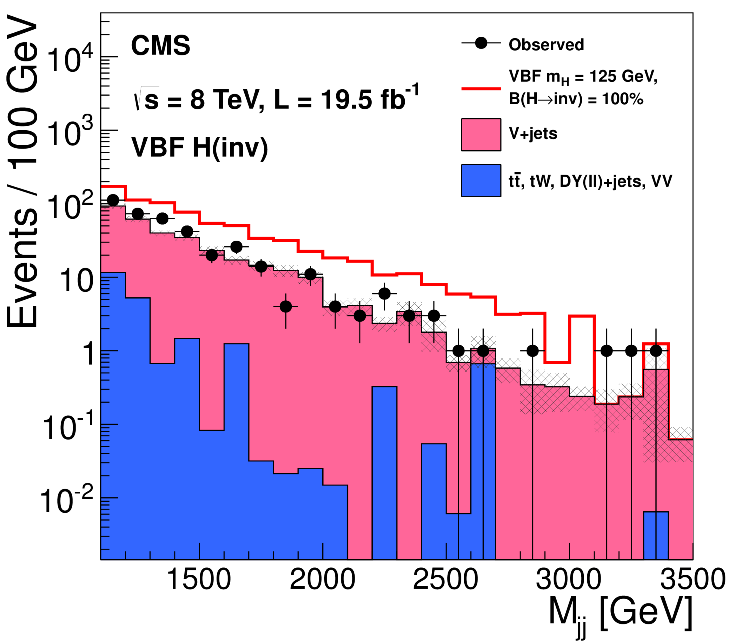


H → invisible

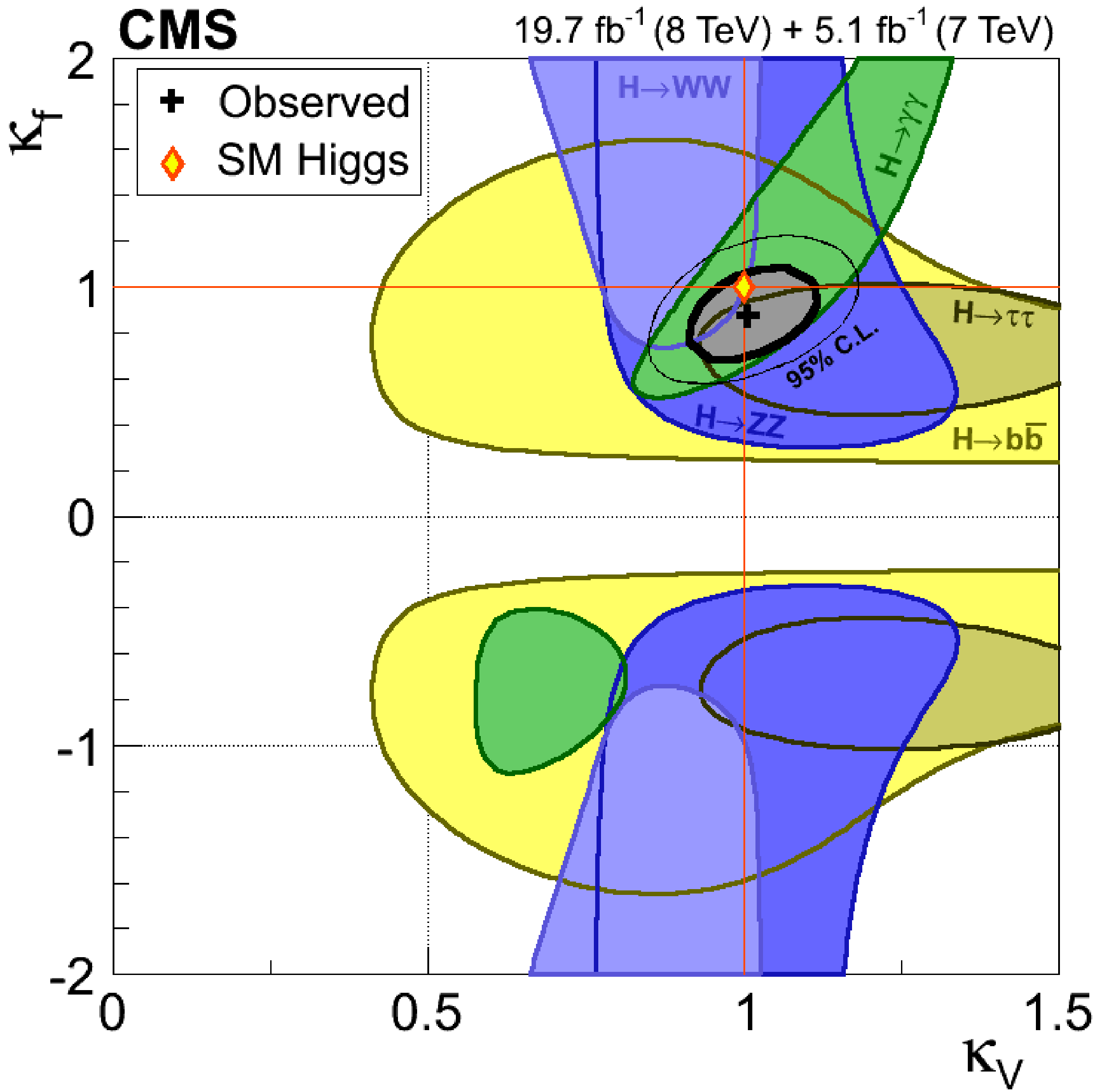
- Search for Higgs boson decays into weakly interacting particles.
  - Tagged by VBF or VH production.
  - Large MET required.
- Combination of both channels gives exclusion sensitivity of $\sigma \times BR_{inv} / \sigma_{SM} \sim 40\%$







Two-quadrant kV,kF



BR_{BSM} fit with free couplings