THE HIGGS BOSON

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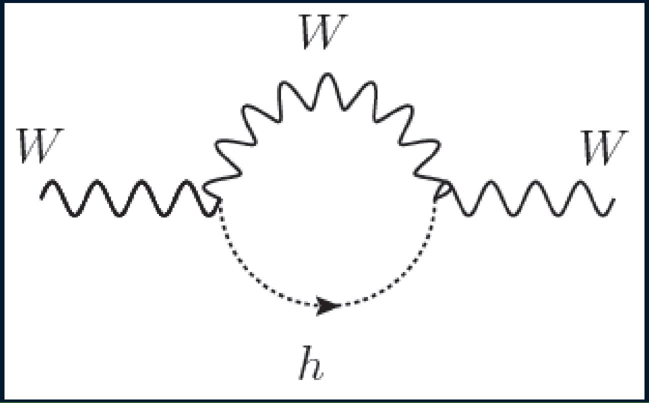
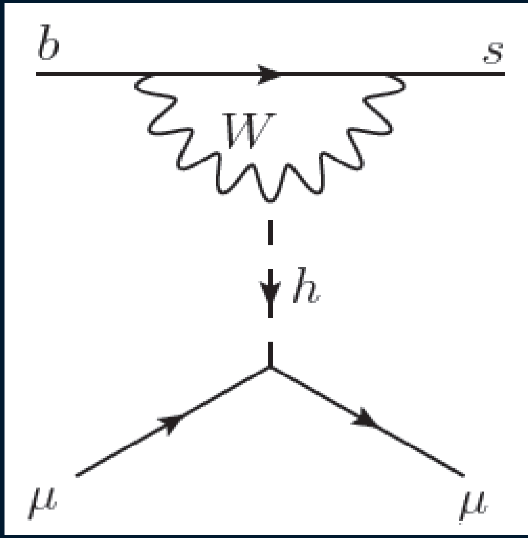
Purdue University & University of Oxford

Higgs Physics

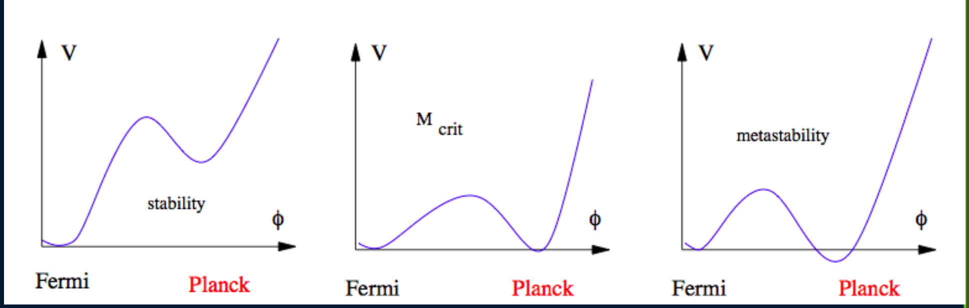
- Indirect precision EW



- Indirect flavor (Higgs Penguin)



- Cosmology (the first scalar)
  - Vacuum stability
  - Higgs inflation



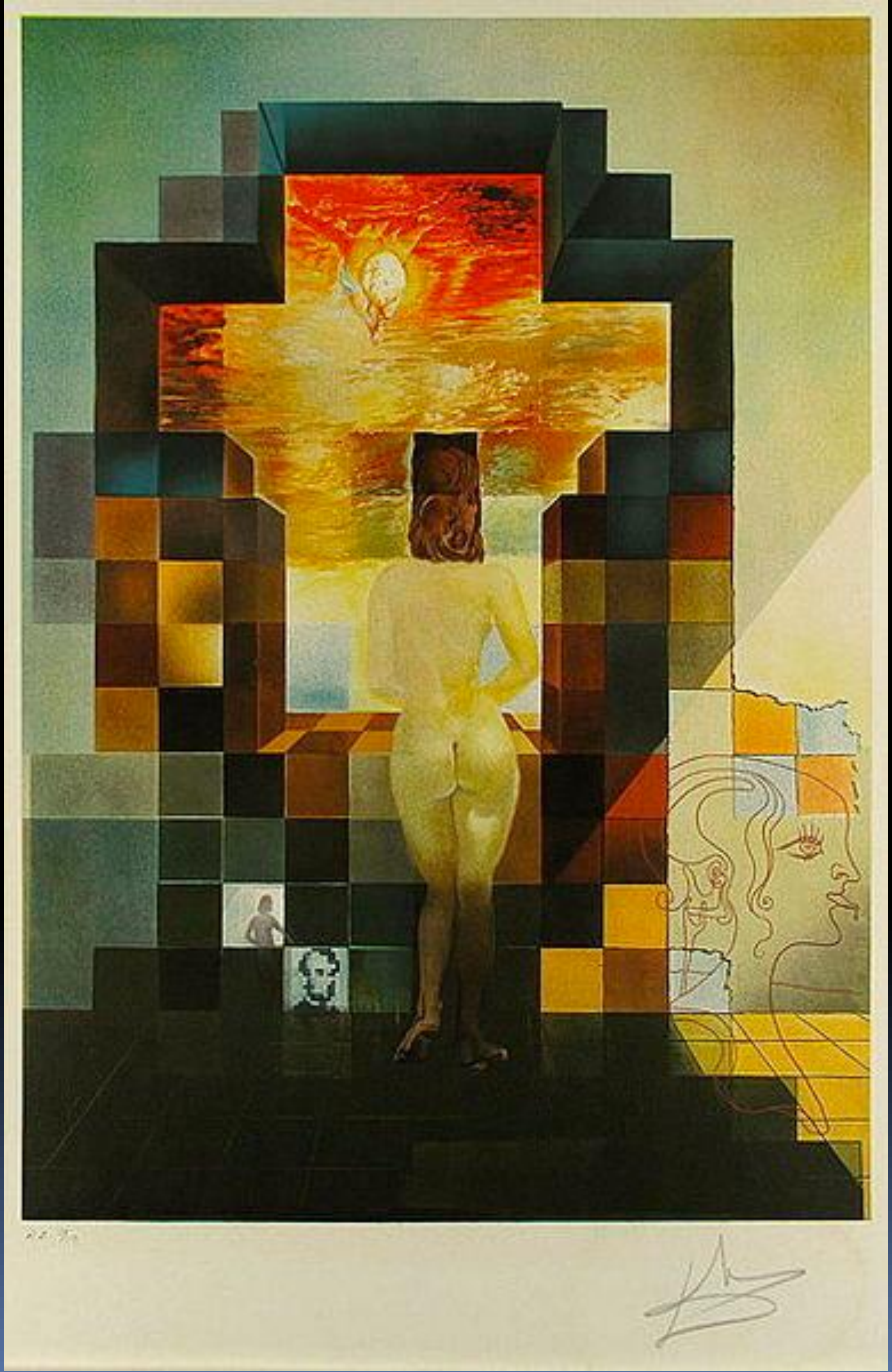
- Direct studies at the LHC

The LHC Higgs Physics Program

H^0

Now in the PDG

- Precision Measurements
  - Mass
  - Width
  - Couplings
  - Quantum numbers (Spin, CP)
  - Differential cross section
  - Off shell couplings and width
  - Interferometry
- Rare decays
  - $Z\gamma$, $\mu\mu$
  - Lepton Flavor Violation $\mu\tau$, $e\tau$
  - J/ψ, $Z\Upsilon$
- Higgs as a tool of discovery
  - Portal to DM (invisible Higgs)
  - Portal to hidden sectors
  - Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)
- Is the SM minimal?
  - 2HDM searches
  - MSSM, NMSSM Searches
  - Doubly charged Higgs
- And even more:
  - FCNC Top decays
  - Di-Higgs production
  - Trilinear couplings prospects
  - Etc…



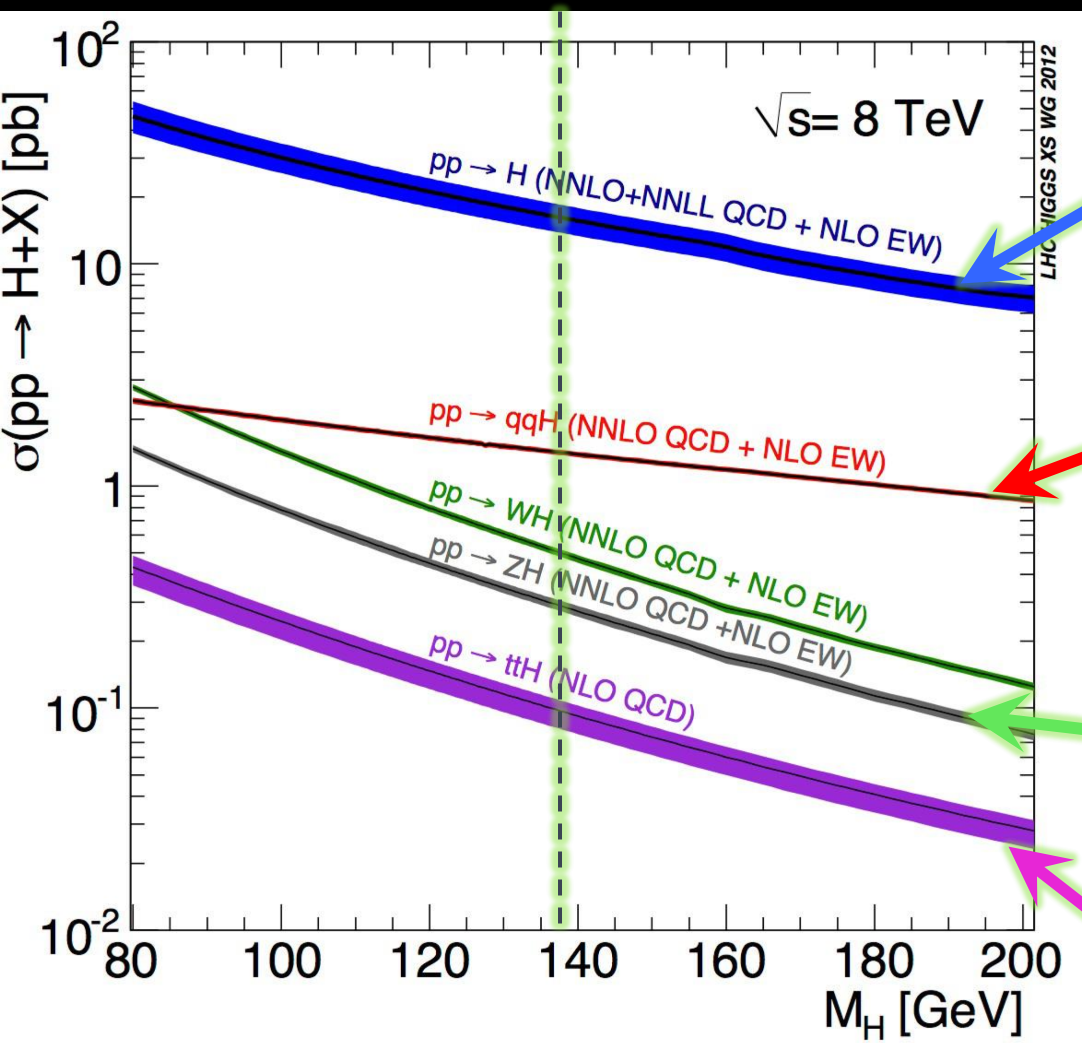
Is it really Lincoln?

Can the study of the properties of the Higgs boson reveal cracks in the SM?

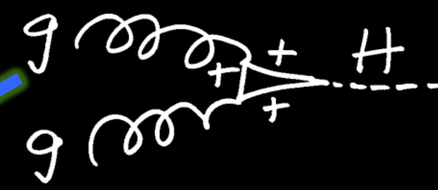
Higgs boson mass, width, and spin, couplings

…the future

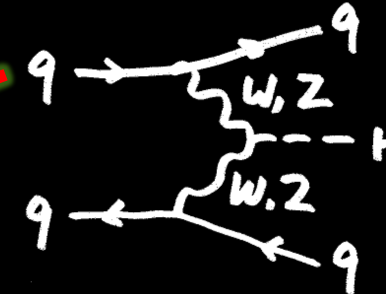
Higgs production at the LHC



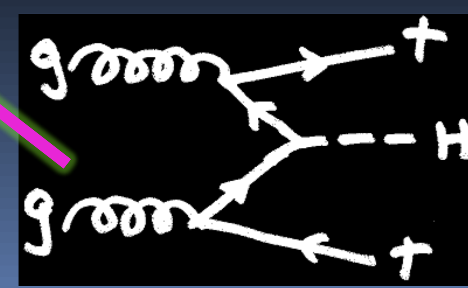
Gluon fusion NNnLO ~O(10%)



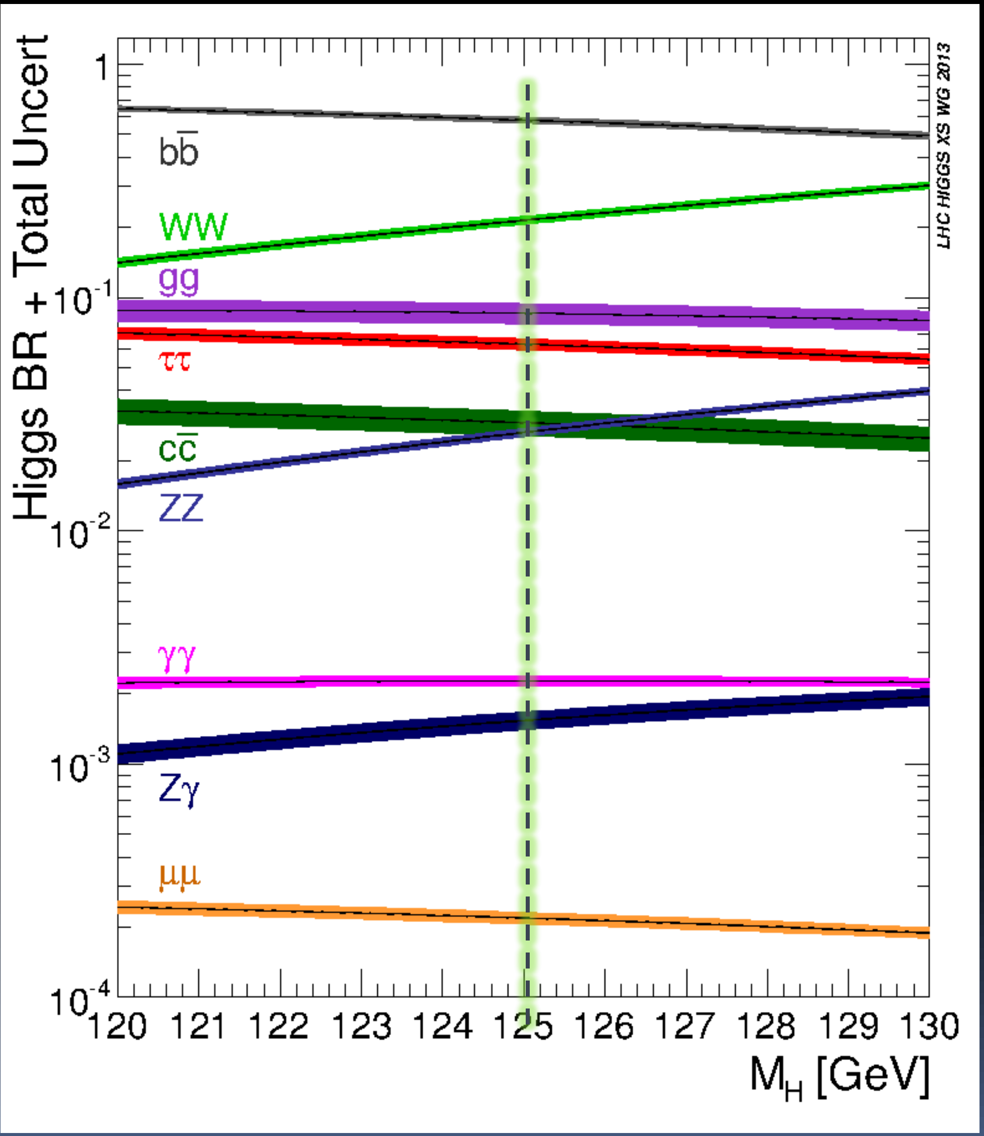
Vector Boson Fusion NNLO ~O(3%)

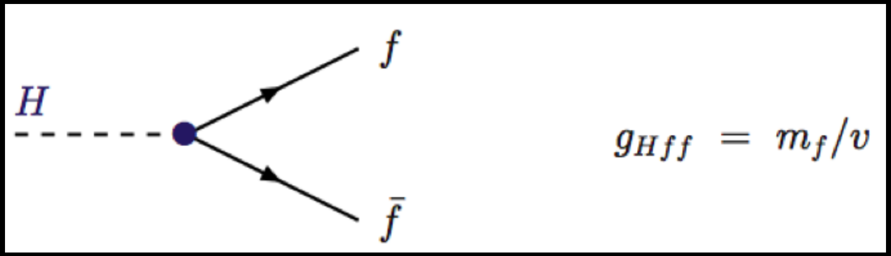


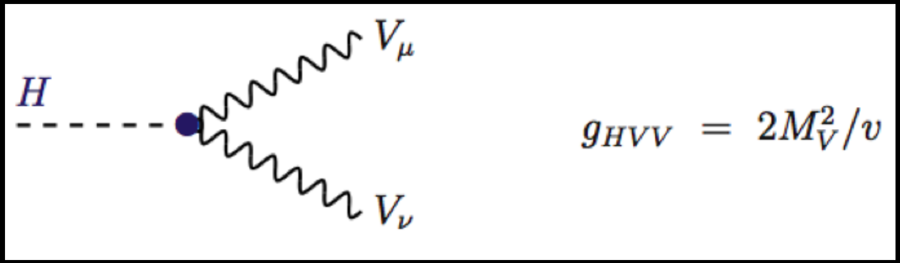
Associated production NNLO ~O(5%)

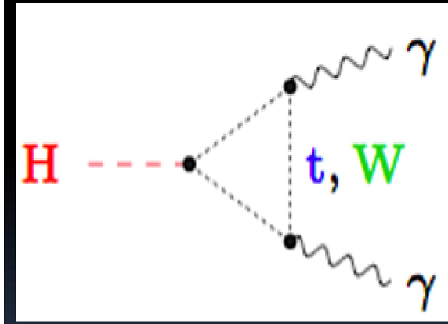


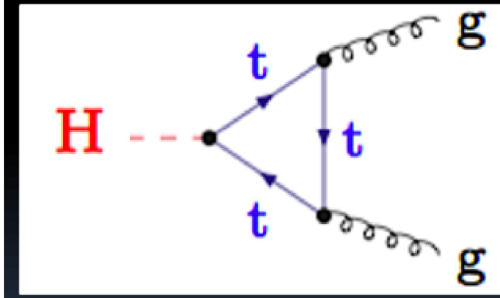
Higgs decay modes









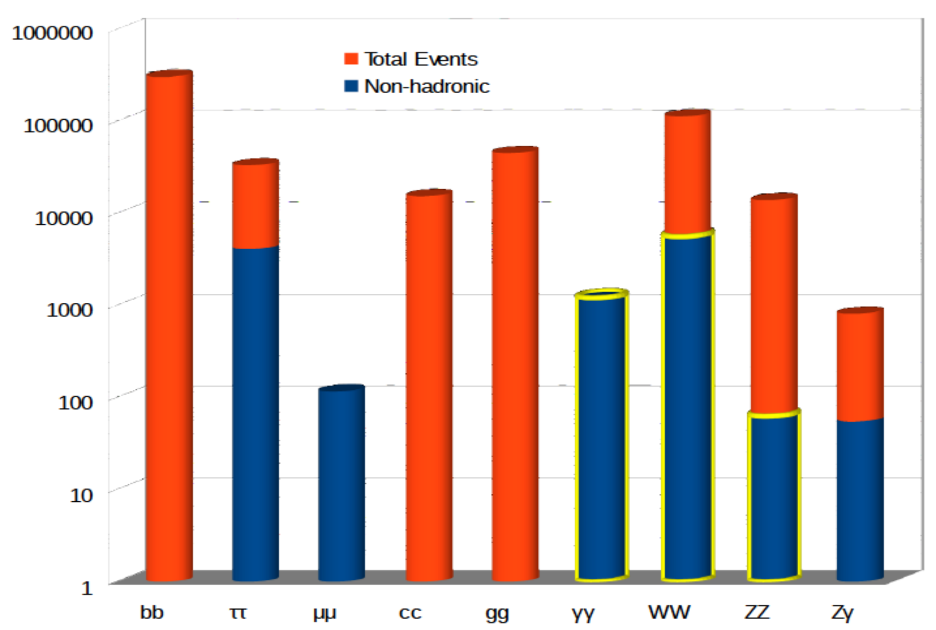


- H→ cc extremely difficult @ the LHC
- Expect to see Zγ and μμ with very high luminosity

LHC Rates by decay mode

- Run1/experiment: 100 to 300000 events per channel out of 2×10^{15} pp events

Every event at a lepton collider is physics; every event at a hadron collider is background
Sam Ting



DECAY

PRODUCTION

⦿ Seen ○ Tried	bb	ττ	WW	ZZ	γγ	Zγ	μμ	INV	cc	HH
ggH		⦿	⦿	⦿	⦿	○	○			
VBF	○	⦿	⦿	○	⦿	○	○	○		
VH	⦿	○	○	○	○			○		
ttH	○	○	○		○					

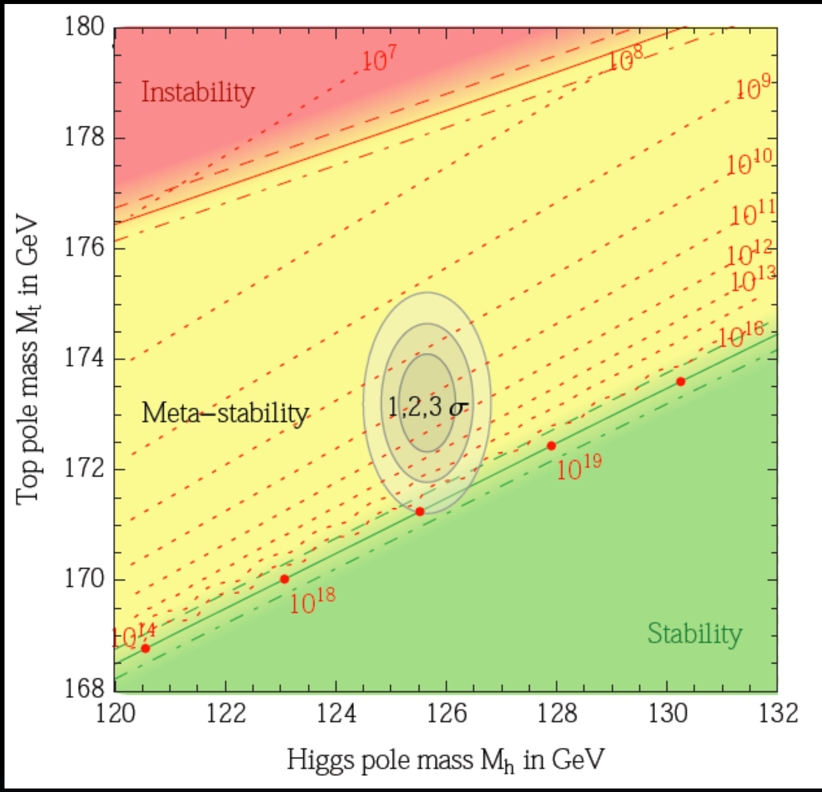
Higgs mass measurement

- M_H is a fundamental parameter not predicted by the SM
- Precision measurements of the Higgs mass provide important constraints.
- In the SM

$$\mathbf{M}^2_H = 2\lambda_{SM}\mathbf{v}^2$$

We must check this relation by measuring LHS and RHS independently

- Implication on the stability of the Higgs potential



Buttazzo, Degrassi, Giardino, Giudice, Salab, Salvio, Strumia

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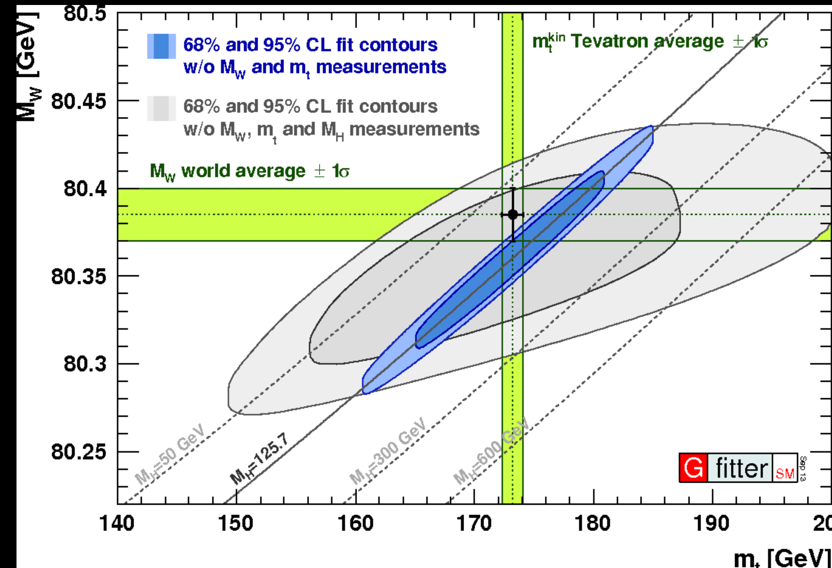
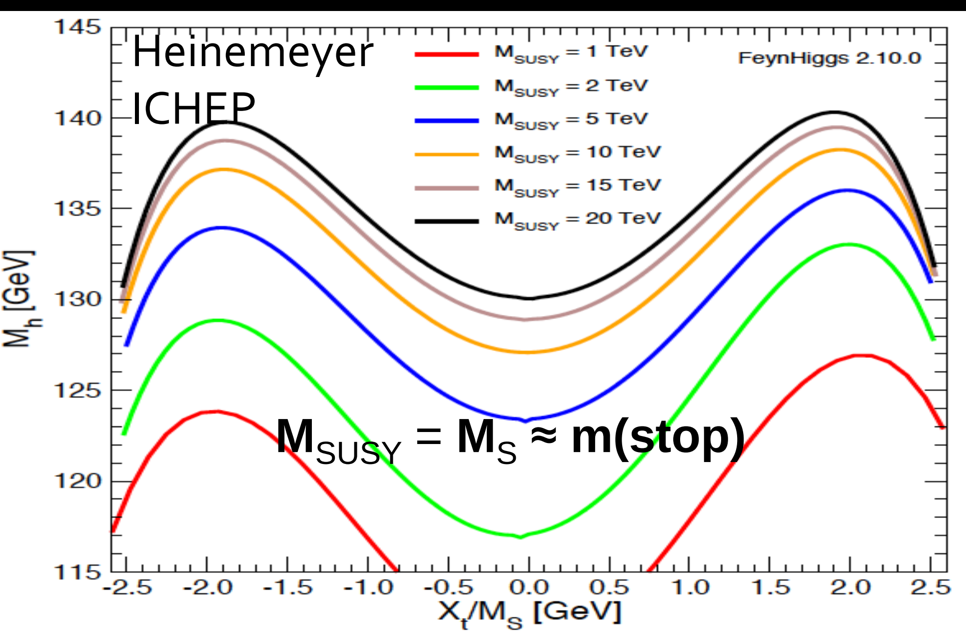




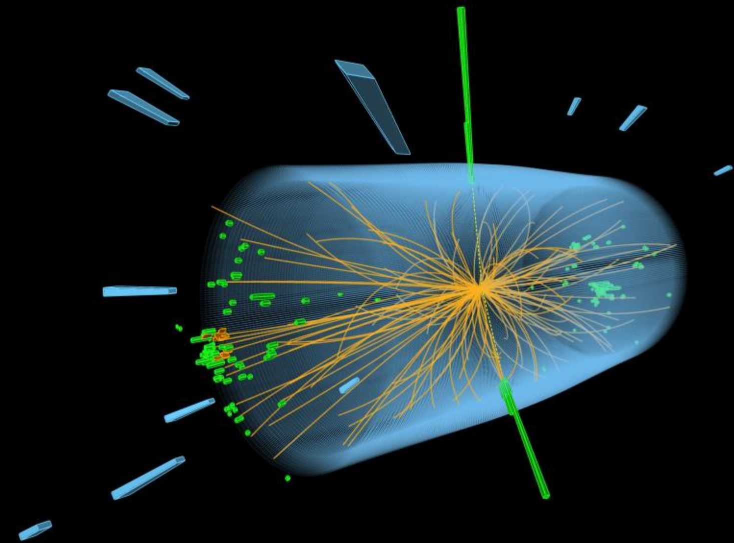
- Over constraining the EW fits
- In SUSY

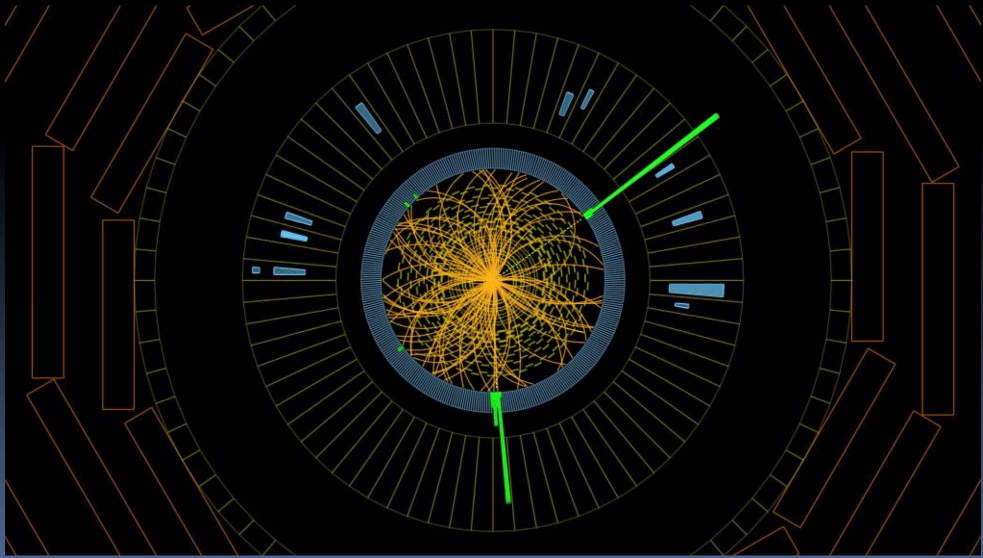
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2},$$

- Theoretical error improving but still $\delta M_{h,theory} \sim 1.5$ GeV

$H \rightarrow \gamma\gamma$

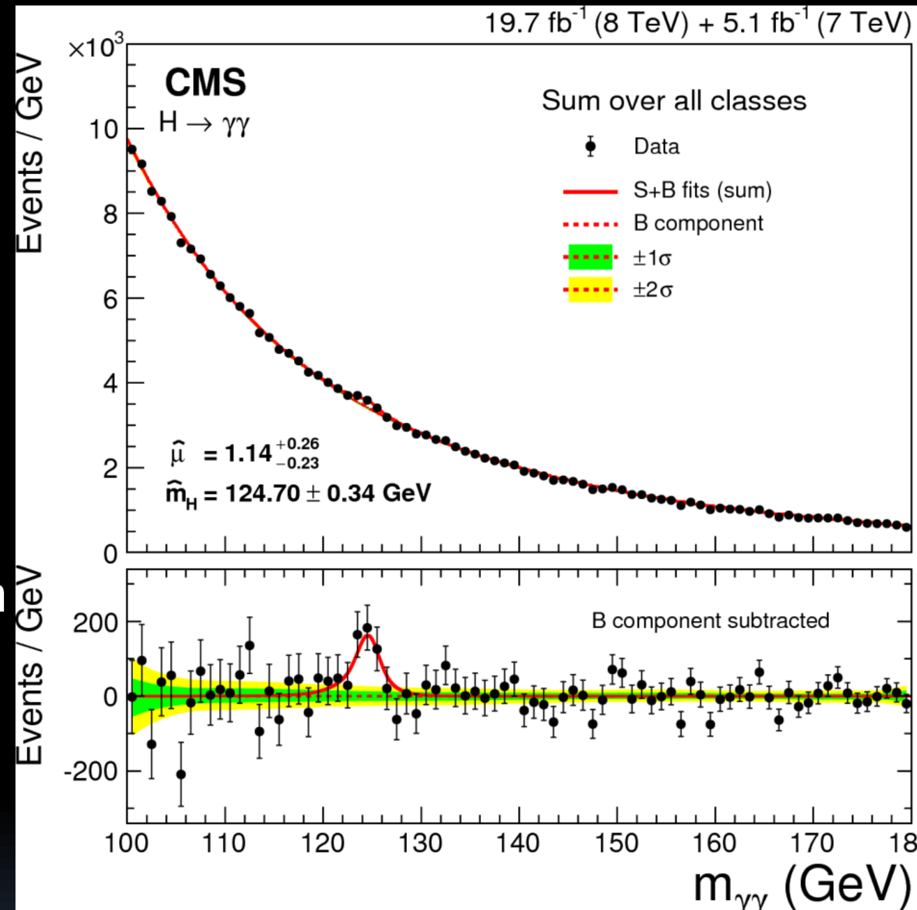
- Clean signature:
  - Two isolated, high p_T photons.
  - Small branching-fraction: ~0.2%.
  - Excellent mass resolution: 1-2%.
  - Large background from QCD processes: S/B ~ 1/1 □ 1/20
- Strategy for analysis
  - Events categorized according to photon resolution and kinematics.
  - Exclusive channels targeting VBF and associated production.
  - Background modeled with polynomials or falling power-law or exponentials





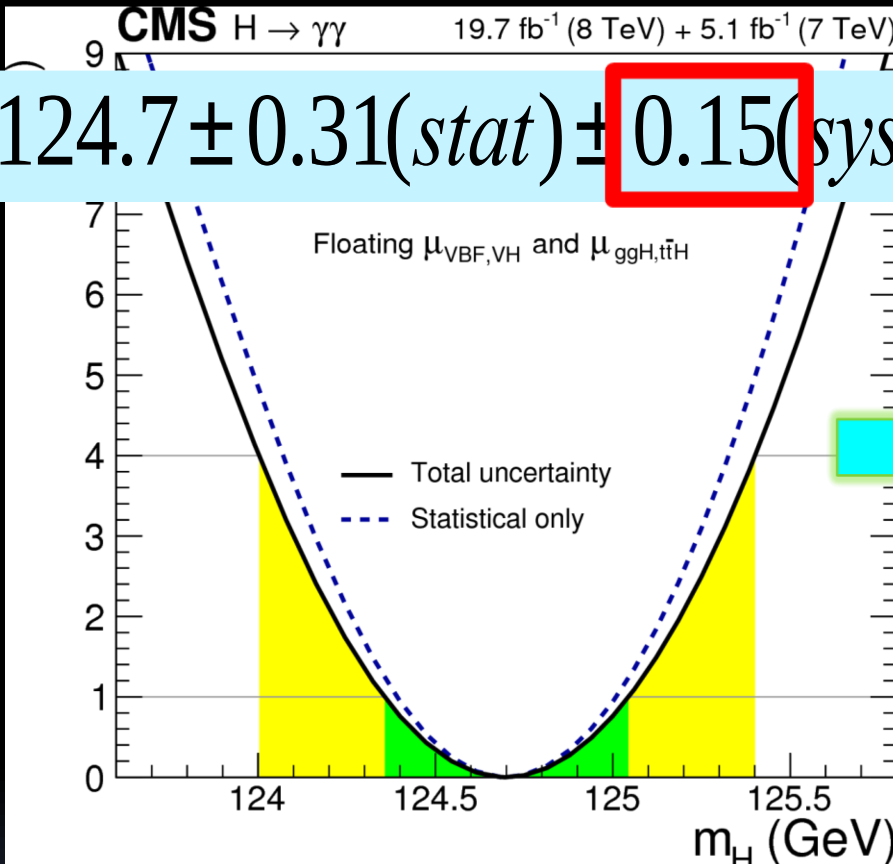
$H\to\gamma\gamma$ Mass Measurement

- "Final calibration" of the CMS ECAL for Run 1 data.
- Improved simulation/understanding:
  - ECAL noise evolution with time.
  - Effect of out-of-time collisions.
  - Amount and distribution of material in front of ECAL
- Improved description of energy scale uncertainties.
- New event categorization:
  25 categories targeting all production modes.
- New background modeling considers multiple functional forms simultaneously.



	Improved Energy resolution	Improved Event Selection	New Background Model
Improvement on Expected Sensitivity	9%	8%	7%

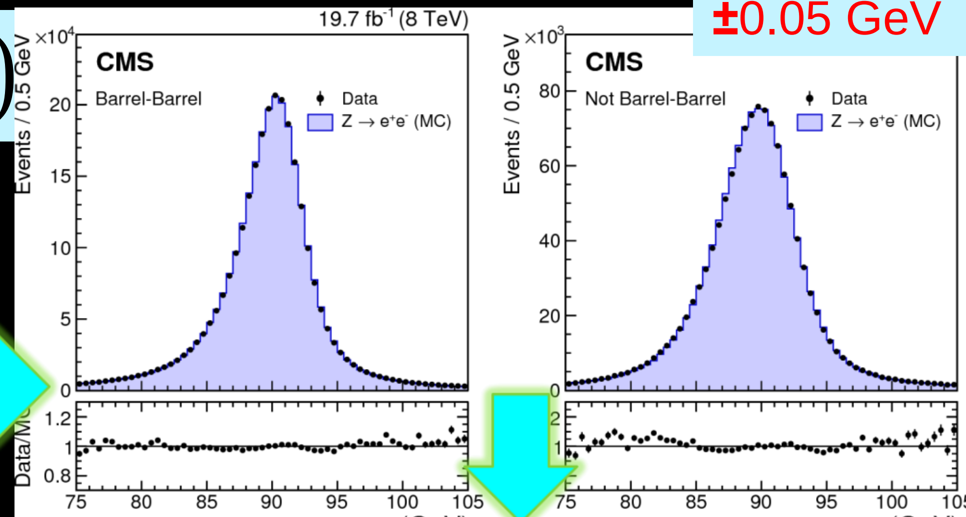
H→γγ Mass Measurement



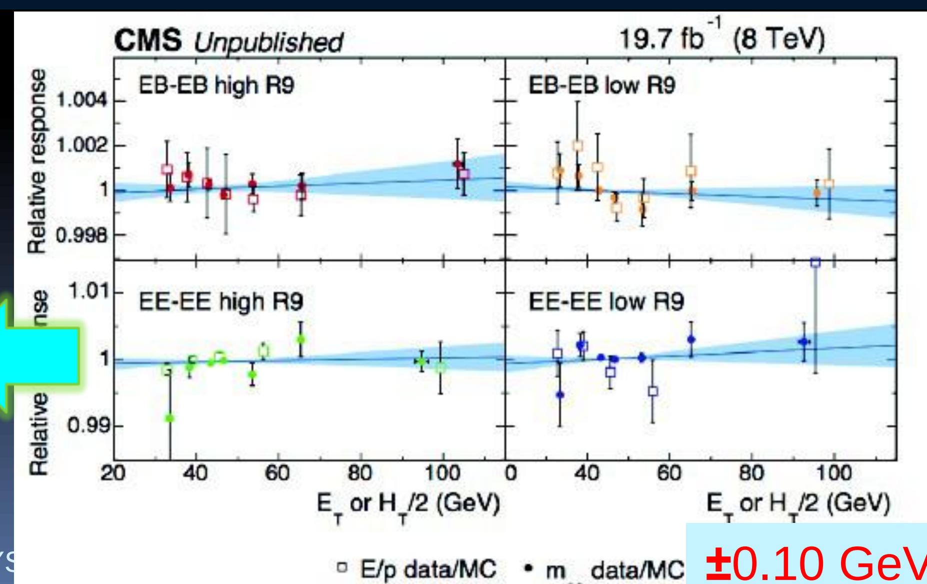
$$124.7 \pm 0.31(stat) \pm 0.15(sys)$$

Photon Calibration @ ~ 45 GeV ($Z \rightarrow e^+e^-$)

±0.05 GeV



Non linearity in extrapolation of energy scale **(Z)**

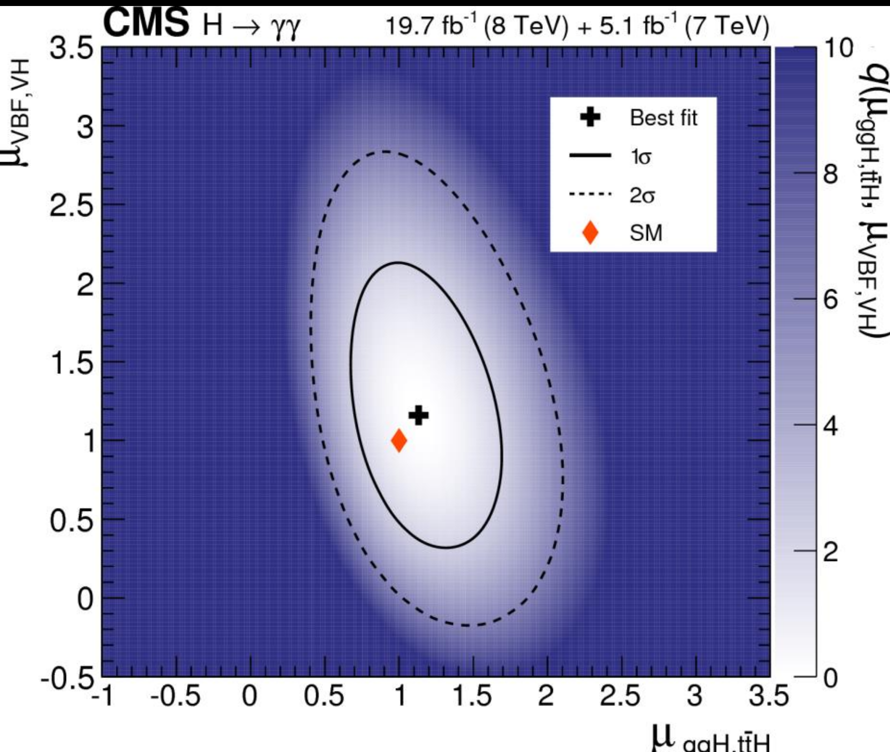


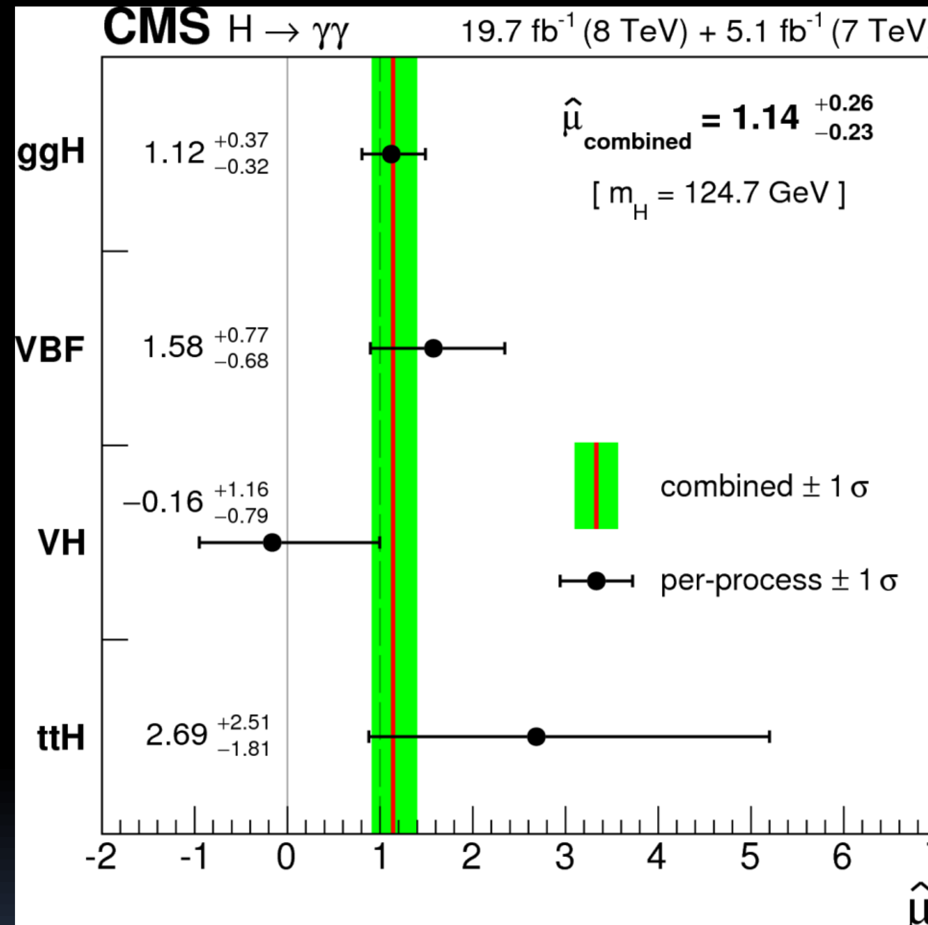
±0.10 GeV

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

±0.10 GeV

H→γγ Signal Strength



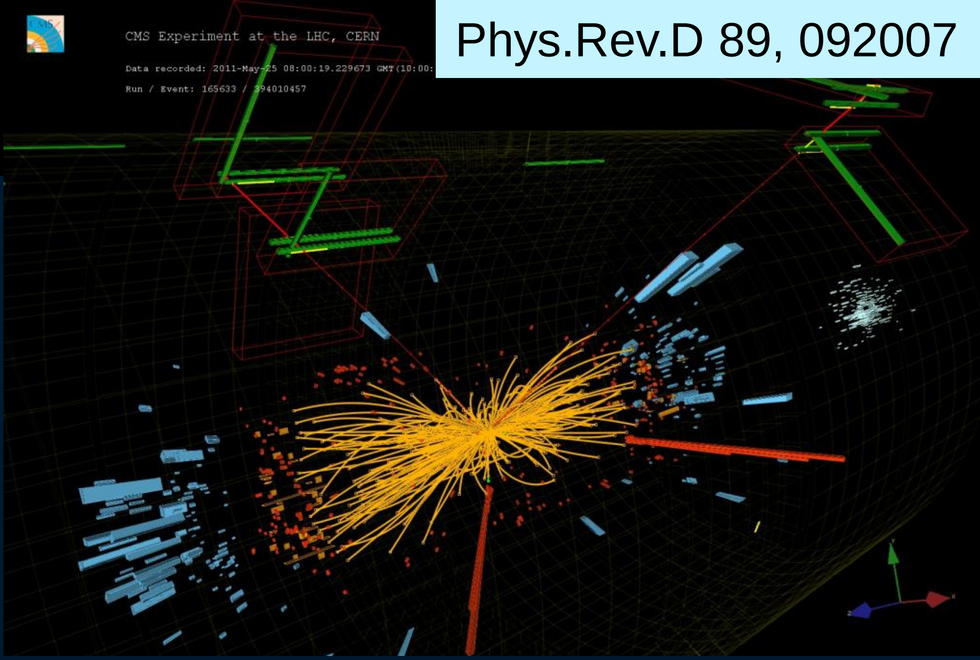


$$m = 1.14^{+0.26}_{-0.23}$$

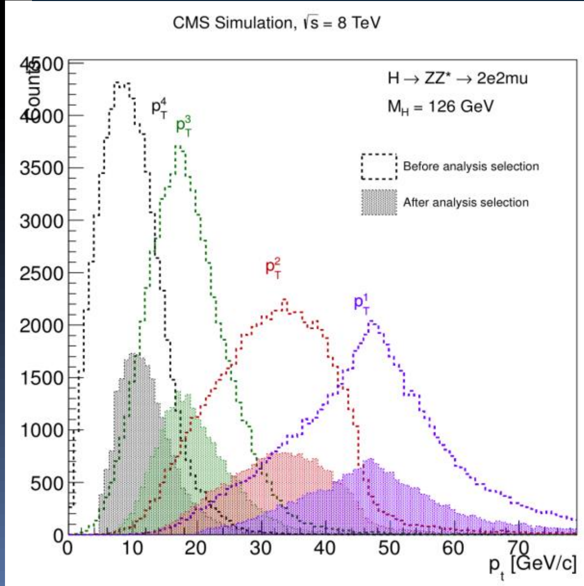
Agreement between production modes and with SM

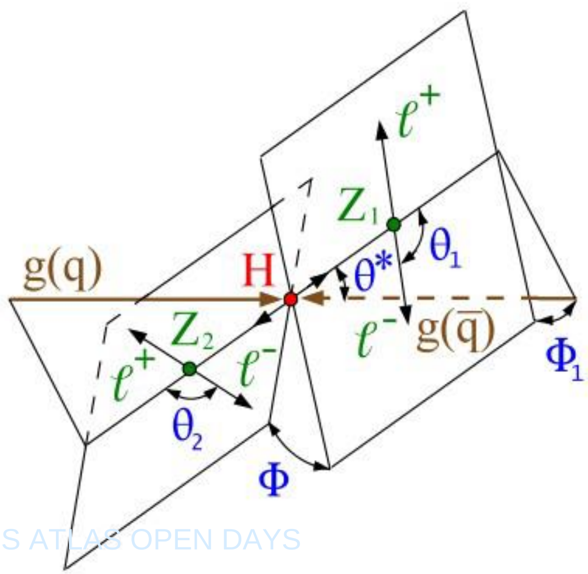
H→4l

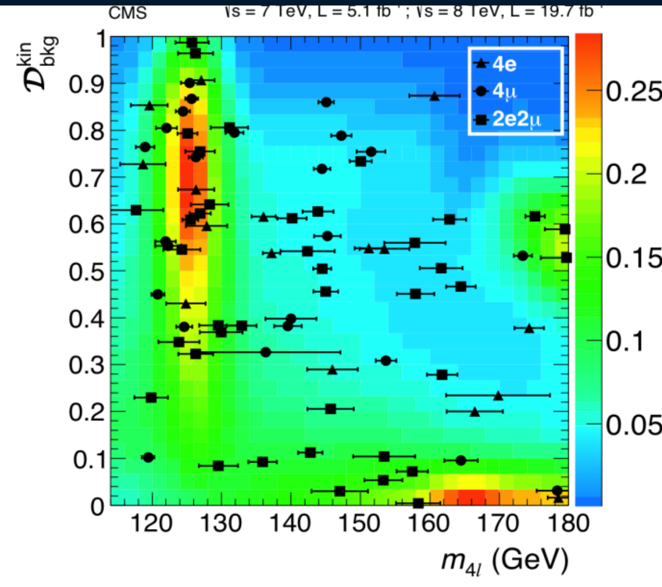
Phys.Rev.D 89, 092007



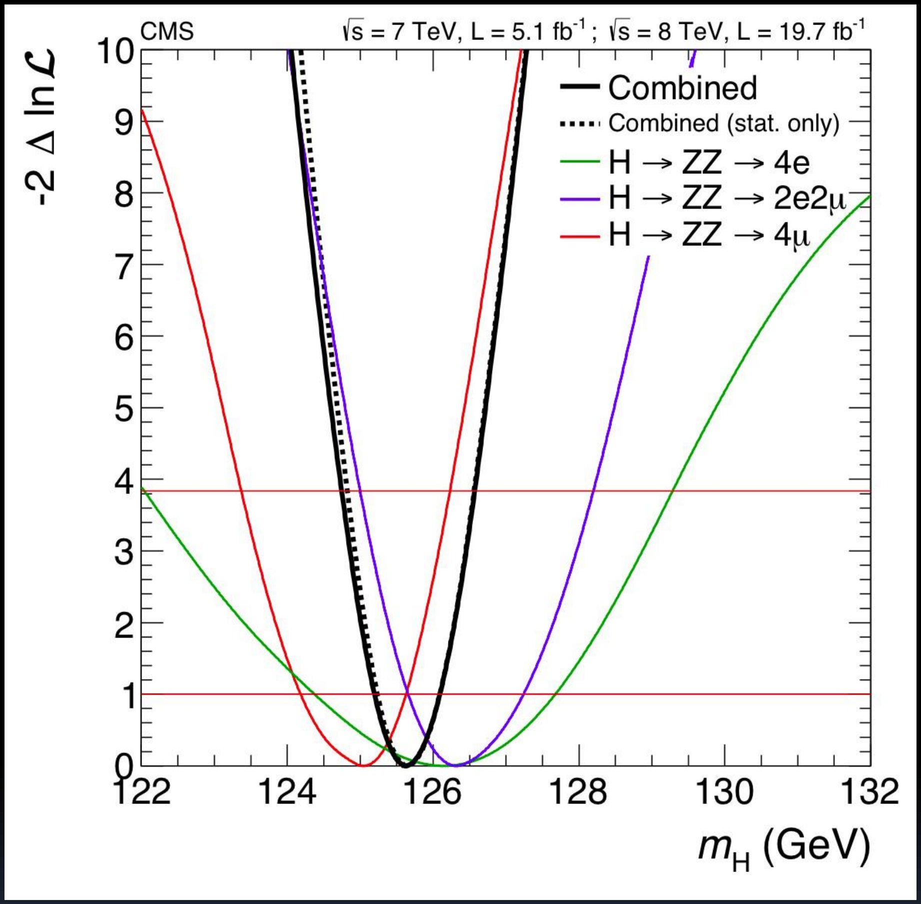
- Golden channel:
  - Four isolated leptons.
  - Small branching fraction: ~10^{-4}
- Extremely pure: S/B ~ 2:1
- Challenges :
  - Maximize acceptance for low p_T leptons
- Precise calibration of lepton p_T scale
- Analysis strategy:
  - Use m(4l) vs kin. discriminant (KD) for S/B separation and event-by-event mass errors (estimated from lepton momentum errors)

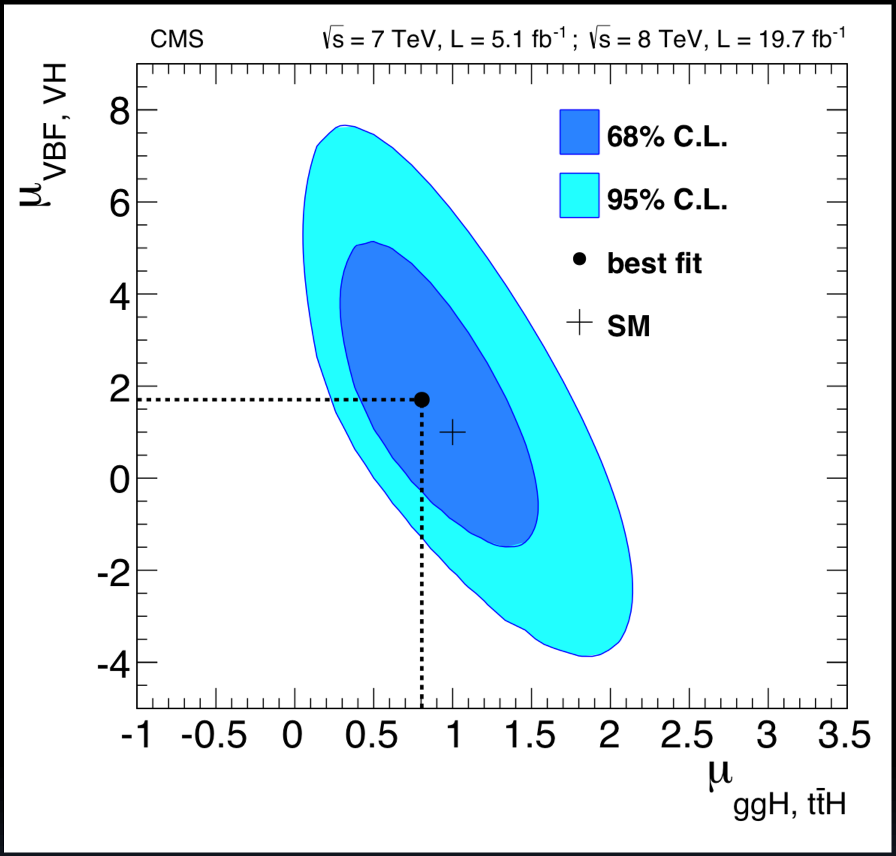






H→4l Mass and signal strength





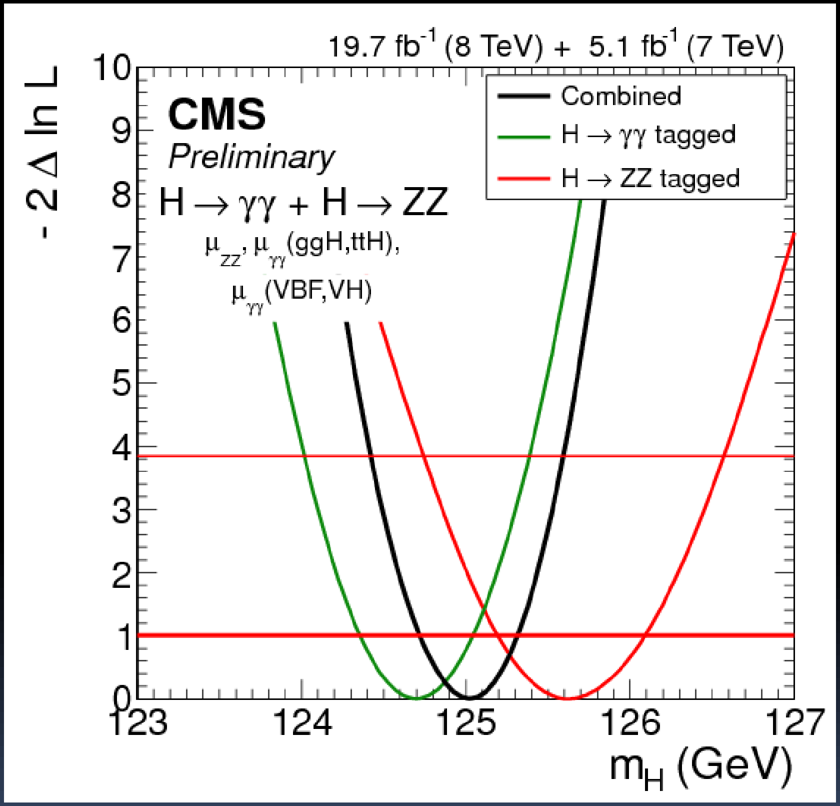
$$125.6 \pm 0.4(stat) \pm 0.2(sys)$$

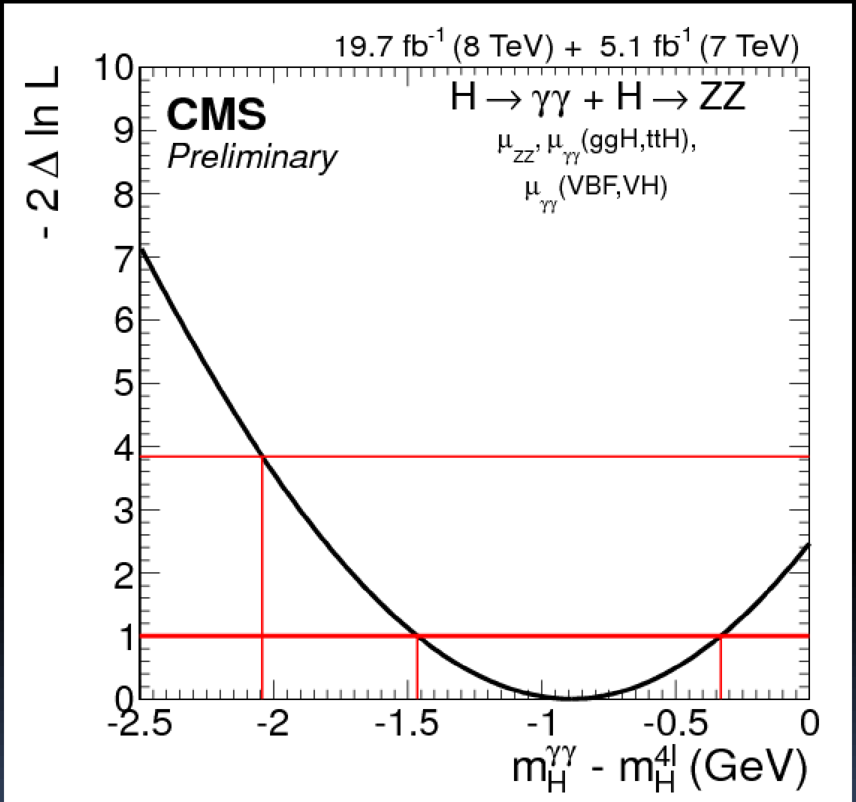
$$m = 0.93 \,^{+0.26}_{-0.23}\,(\mathrm{stat})\,^{+0.13}_{-0.09}(sys)$$

3D fit to m4l, KD, and □(m4l)/m

Mass combination H → γγ and H → ZZ*

- Floating yields for production and decay
- Individual final states compatible @ 1.6σ level

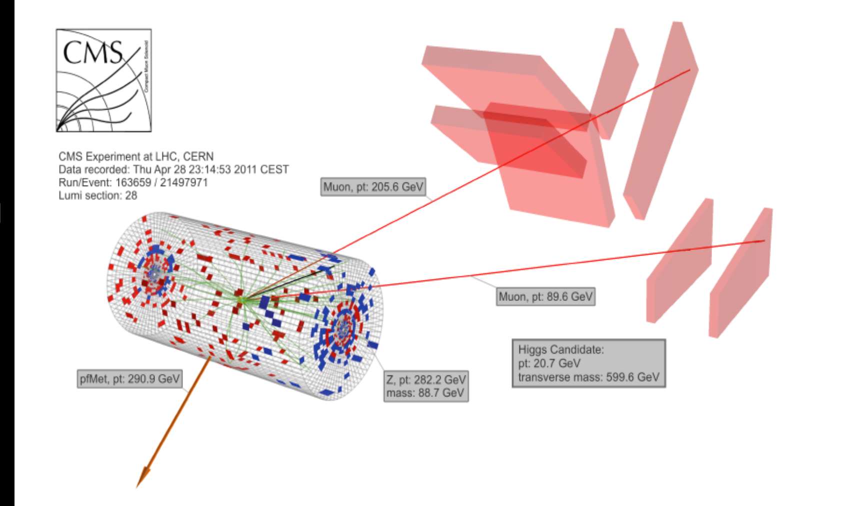




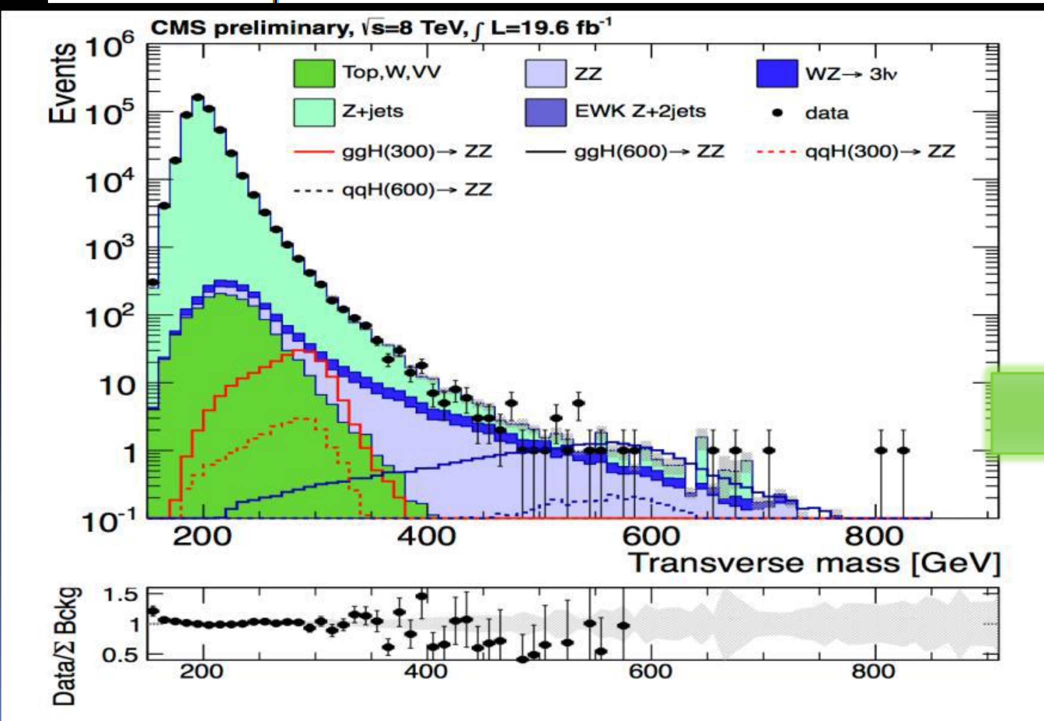
$$m_H = 125.03 \pm {}^{+0.26}_{-0.27}(stat)^{+0.13}_{-0.15}(sys)GeV$$

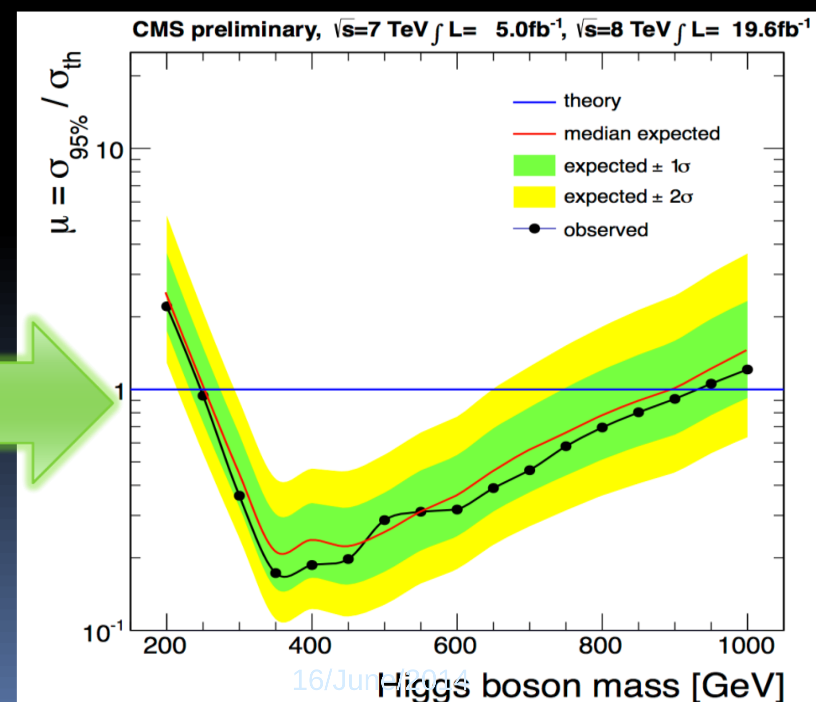
H→ZZ→2l2ν

- Analysis optimized separately for Gluon Fusion (0+1 jets) and VBF (2 jets)
- Boosted Z topology (MET>80 GeV)
- Two variables chosen for final selection MET and Transverse Mass of Higgs (MT)



$$M_T^2 = \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{miss,2} + m_{\ell\ell}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\text{miss}}\right]^2$$





H→ZZ→2l2ν

CMS-PAS-HIG-13-014

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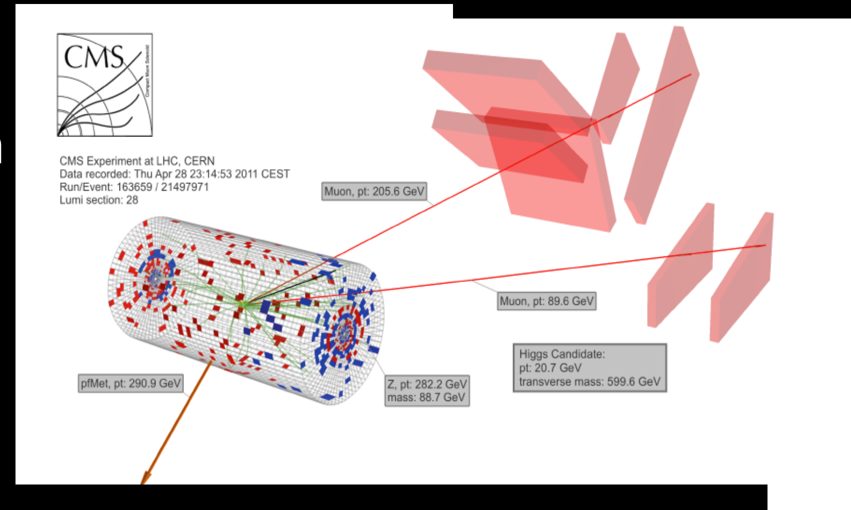
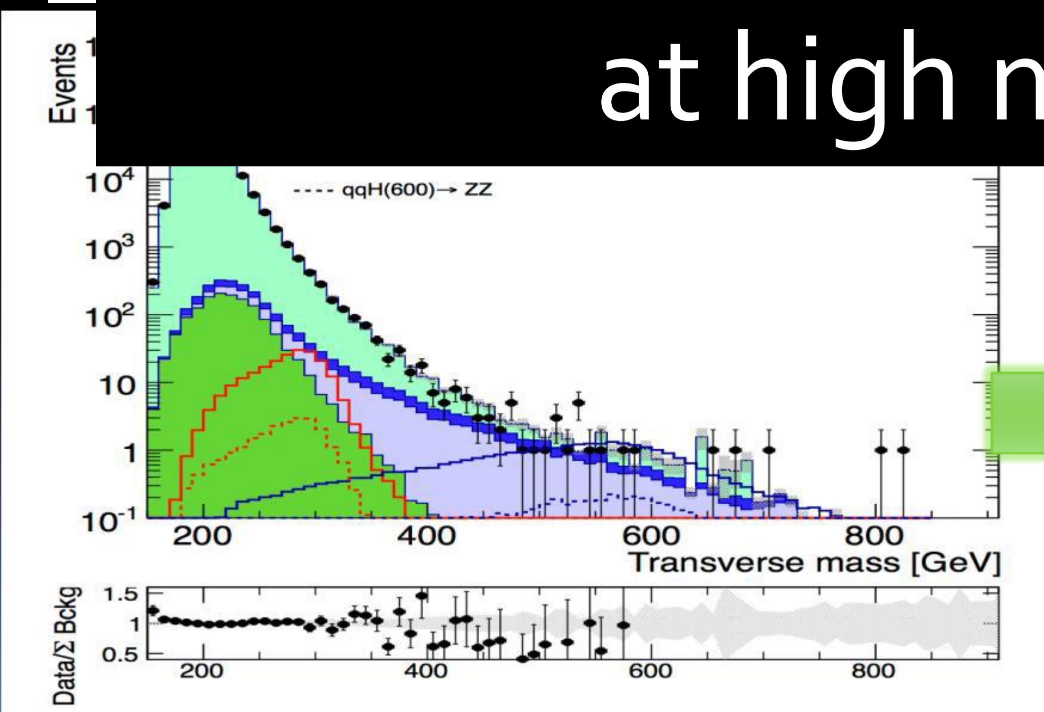
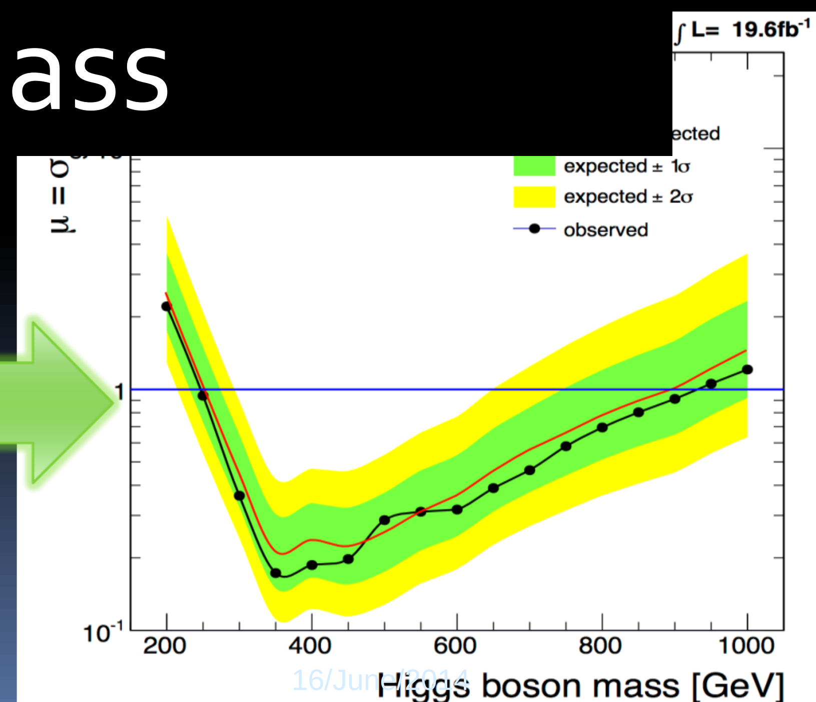


Most sensitive channel at high mass





Electroweak Singlet Model

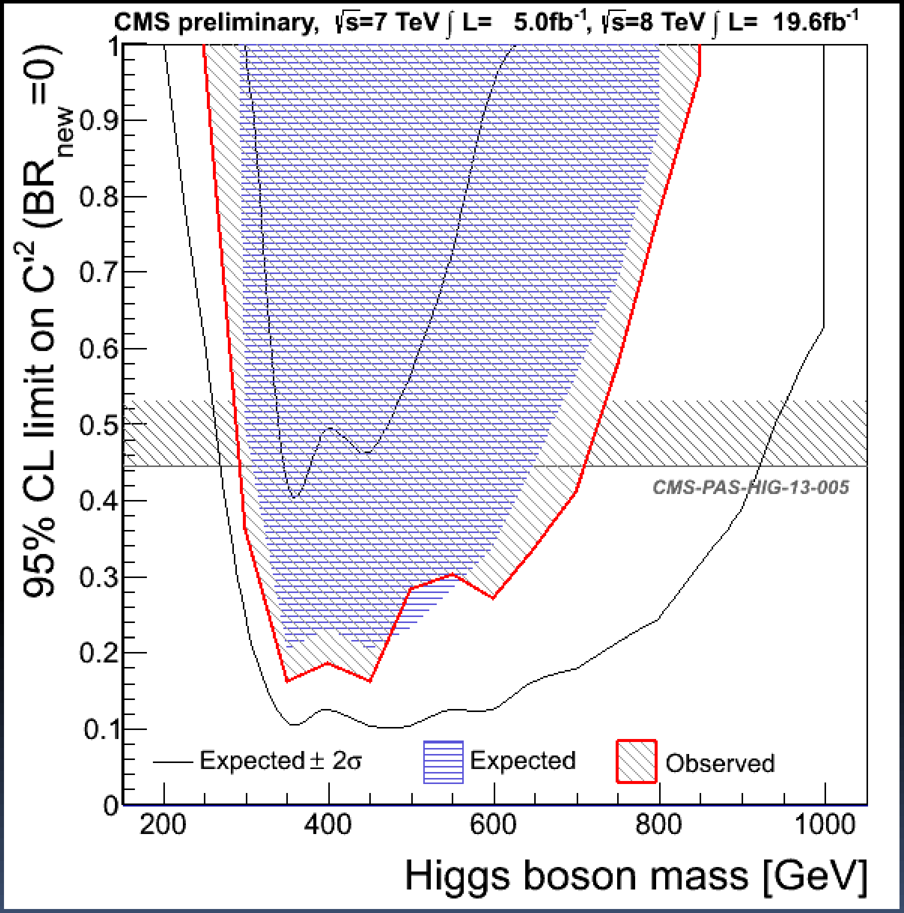
Bowen, Cui, Wells,: arxiv:hep-ph/0701035v1

- Addition of an EW singlet field to the SM scalar sector, acquiring a non-zero vacuum expectation value and providing a hidden sector
- Two CP even state can mix :
  - Light state = h(126)
  - Heavy state (still to be discovered)
- Higgs properties are modified

LIGHT (h)	HEAVY (H)
$\mu_h = C^2$	$\mu_h = C'^2(1-BR_{new})$
$\Gamma_h = C^2 \times \Gamma_{SM}$	$\Gamma_H = C'^2 \times \Gamma_{SM}/(1-BR_{new})$
$\sigma_h \times BR_h = C^2 \times \sigma_{SM} \times BR_{SM}$	$\sigma_H \times BR_H = C'^2 \times \sigma_{SM} \times (1-BR_{new})$

- BR_{new} accounts for possible new decays of H (e.g. H→ hh).

Run 2 data necessary to extend reach to multi-TeV bosons.



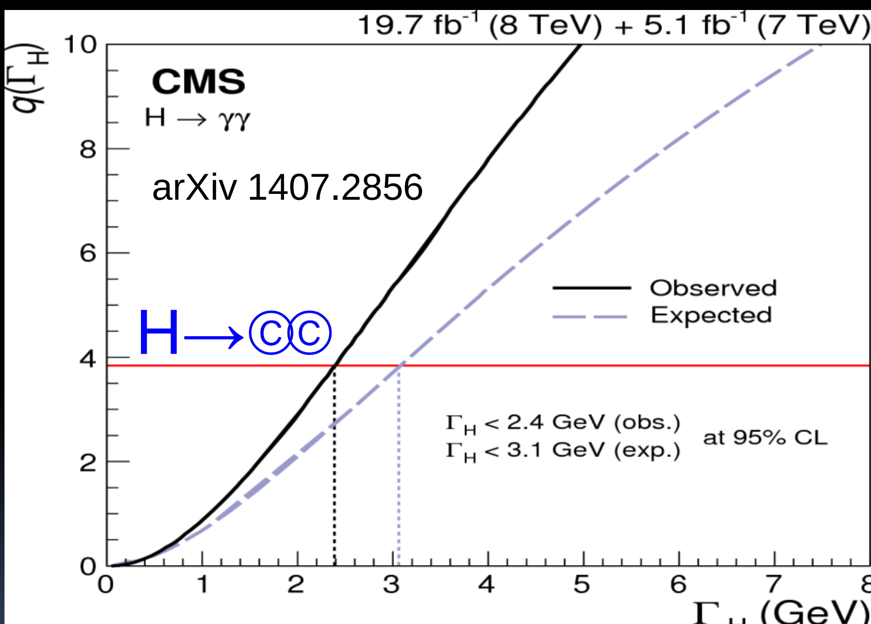
Also scanned $BR_{new} \neq 0$ cases: limit on C' gets weaker with $Br_{new}>0$

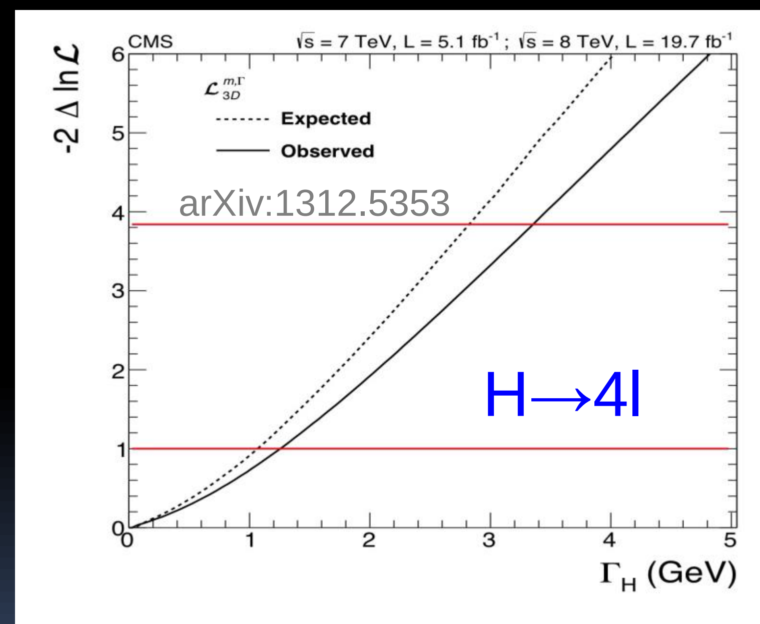
Higgs boson width

- Lack of knowledge of Γ_H introduces degeneracy in the knowledge of the Higgs couplings

$$\sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

- In the SM $□_H$ (125 GeV)~ 4MeV
- Direct measurements limited by experimental resolution (≈ GeV).
  - Current upper limits 3.4(2.4) GeV from 4l (□□) decay modes.





New: Use interference between Higgs resonance in gluon fusion and the continuum back-ground to measure the Higgs width

- Complements more direct measurements possible at lepton colliders

Higgs width from off-shell production

- Off-shell H* → VV (V = W, Z) enhances the H(125) cross-section at high mass [~7.6% of $\sigma(H\to ZZ)$ found in $m_{ZZ} > 2m_Z$]

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

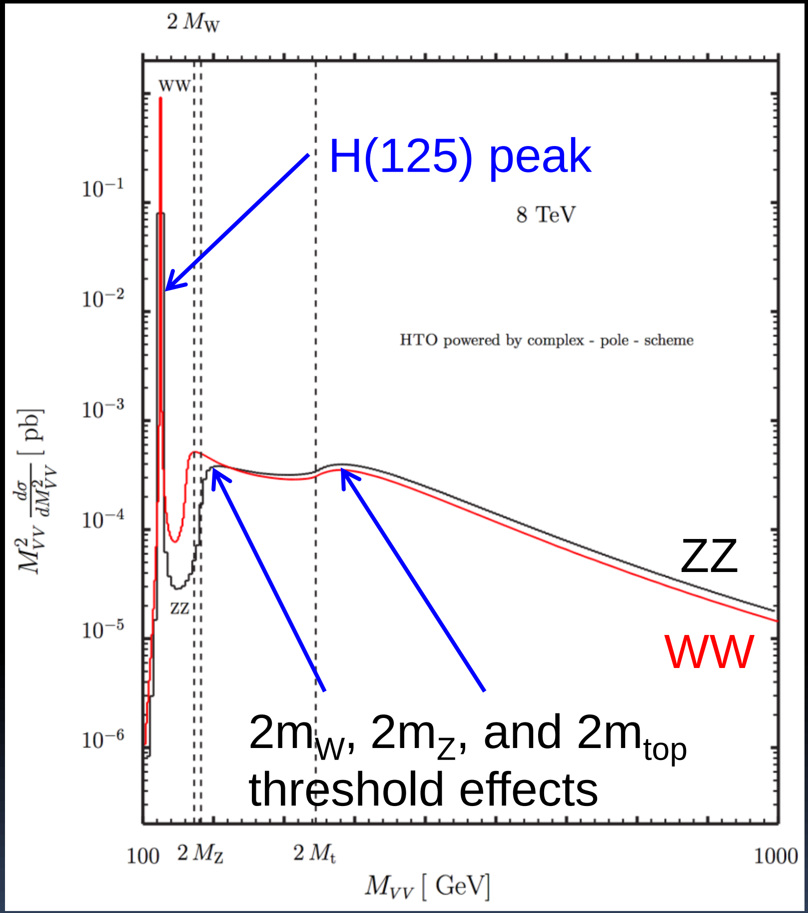
$M_{4l} \approx m_H$

$$\sigma_{gg\to H\to ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$M_{4l} - m_H >> \Gamma_H$

$$\sigma_{gg\to H\to ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

$$\frac{\sigma_{gg\to H\to ZZ}^{\text{off-shell}}}{\sigma_{gg\to H\to ZZ}^{\text{on-shell}}} \sim \Gamma_H$$

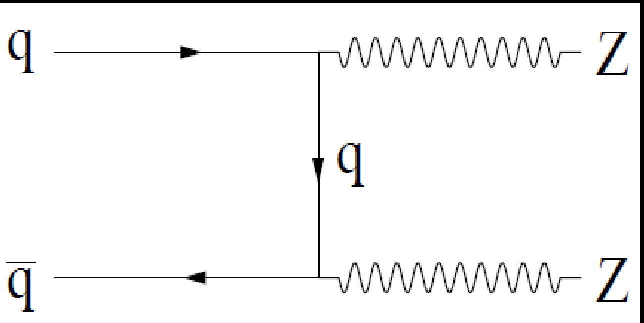


- Mild model dependence: The method works for BSM models if this ratio is not modified by new physics (i.e. top loop still dominates in ggF)

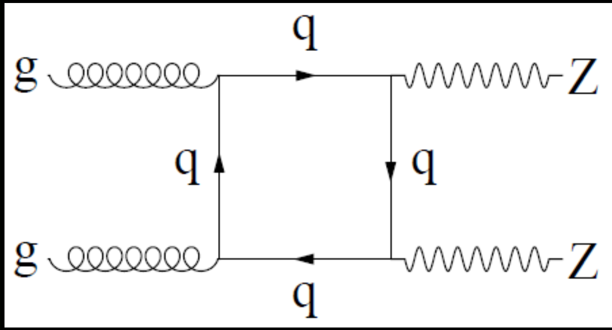
F. Caola, K. Melnikov, Phys. Rev. D88 (2013) 054024
J. Campbell et al. arXiv:1311.3589

ZZ production and K-Factors

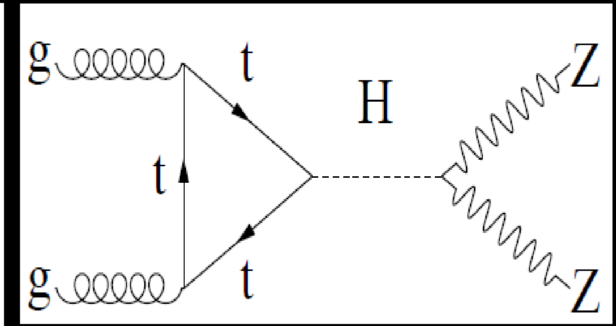
Background (qq)



Backgrounds (gg)

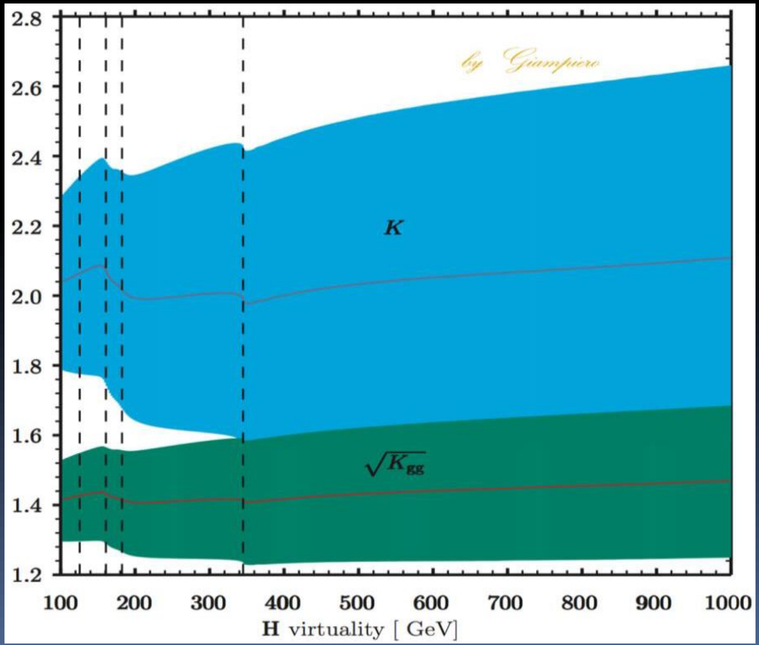


Signal



Interference

- Signal / background / interference
- NNLO/LO kFactors depend on m_{ZZ} G. Passarino (arXiv:1312.2397)
- Use the same kFactors for signal and gg continuum M. Bonvini et al.(Phys.Rev.D 88 2013)
- NLO EWK corrections
  - qq→ZZ/WZ (5% decrease @700GeV) up to 10% uncertainty

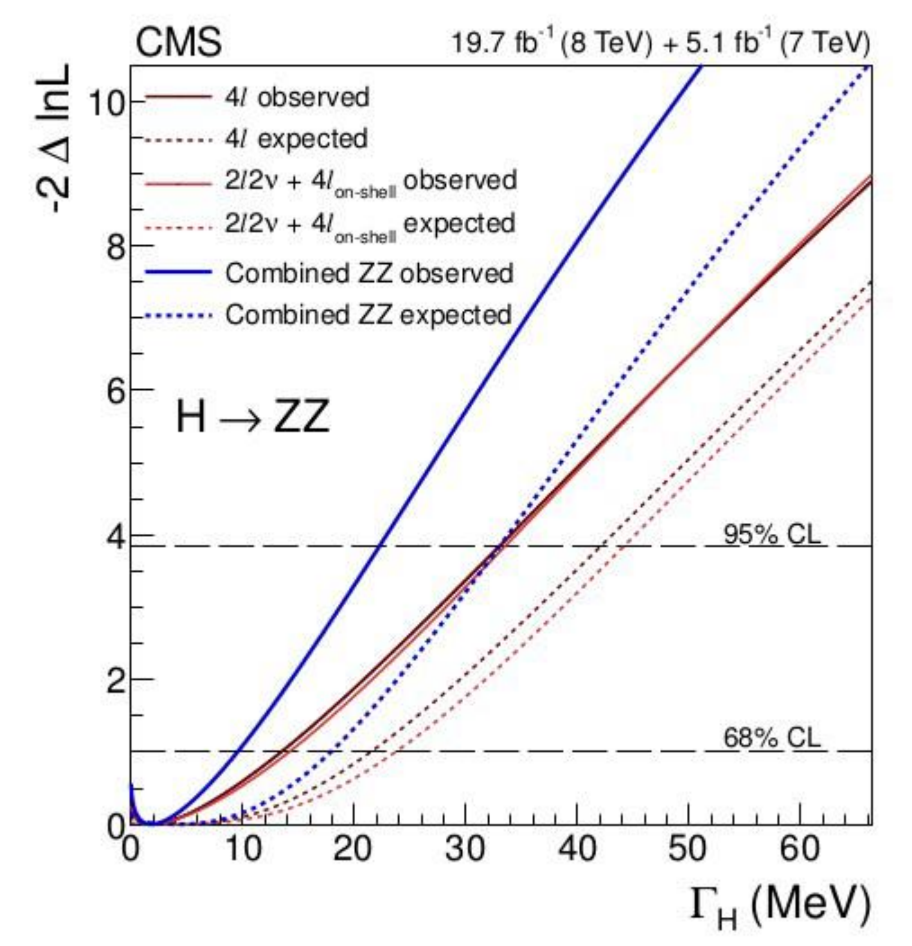


Bounds on Γ_T

doi:10.1016/j.physletb.2014.06.077

- Four lepton final state
  - 2D fit in mass and gluon fusion discriminant (distinguish gg → ZZ vs qq → ZZ)
- 2l2ν final state
  - 1D fit in transverse mass

$$m_T^2 = \left[\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_T^{miss\,2} + m_{\ell\ell}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{miss}\right]^2$$



- Observed limit lower than expected

Expected width < 33 MeV @95%CL
Observed width <22 MeV @95%CL
Γ_H Measurement 1.8 + 7.7-1.8 MeV
SM Width = 4.15 MeV

Spin, Parity, and anomalous coupling

- In the Standard Model the Higgs boson is a 0^+ state.
  - This must be verified experimentally
- Tests of alternative hypothesis against SMH (0^+) have been presented
- CMS has extended these tests to probe anomalous couplings (Phys.Rev. D89, **2014, 035007;** ATL-PHYS-PUB-2013-013**)**
- The goal is to test the full tensor structure

J=0

SM tree level + leading momentum expansion

$$A(X_{J=0} \to V_1 V_2) = v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2}\right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right.$$

$$+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \quad \} \text{ VV couplings}$$

$$+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \quad \} \; Z\gamma^* \text{ couplings}$$

$$\left. + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu}\right) \quad \} \; \gamma^*\gamma^* \text{ couplings}$$

a_2 terms: CP-even scalar

a_3 terms: CP-odd pseudo-scalar

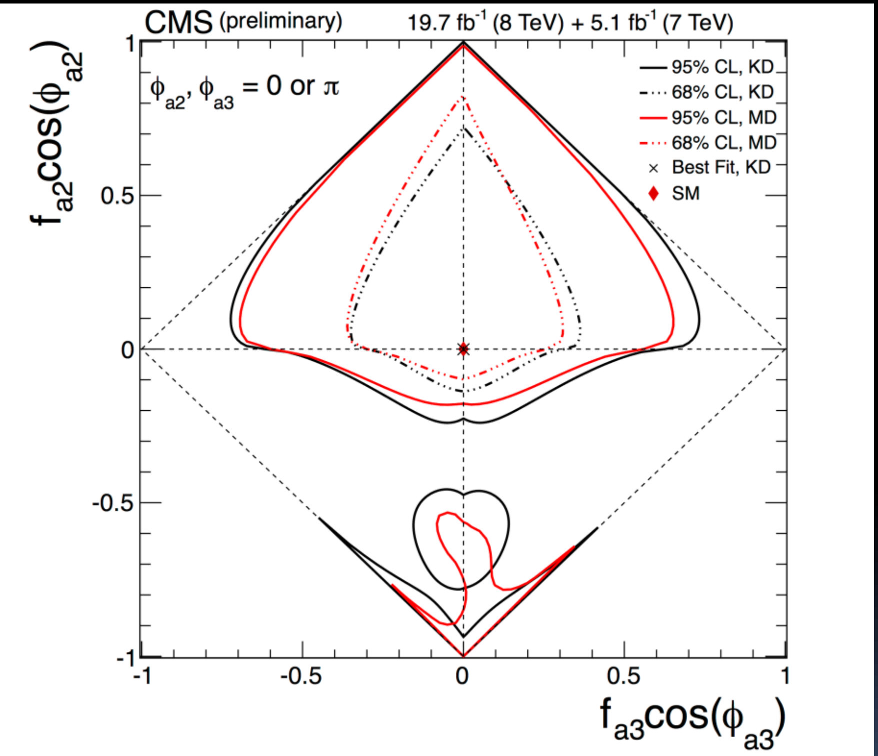
- Parameterisation of a_i in term of fractions of cross sections

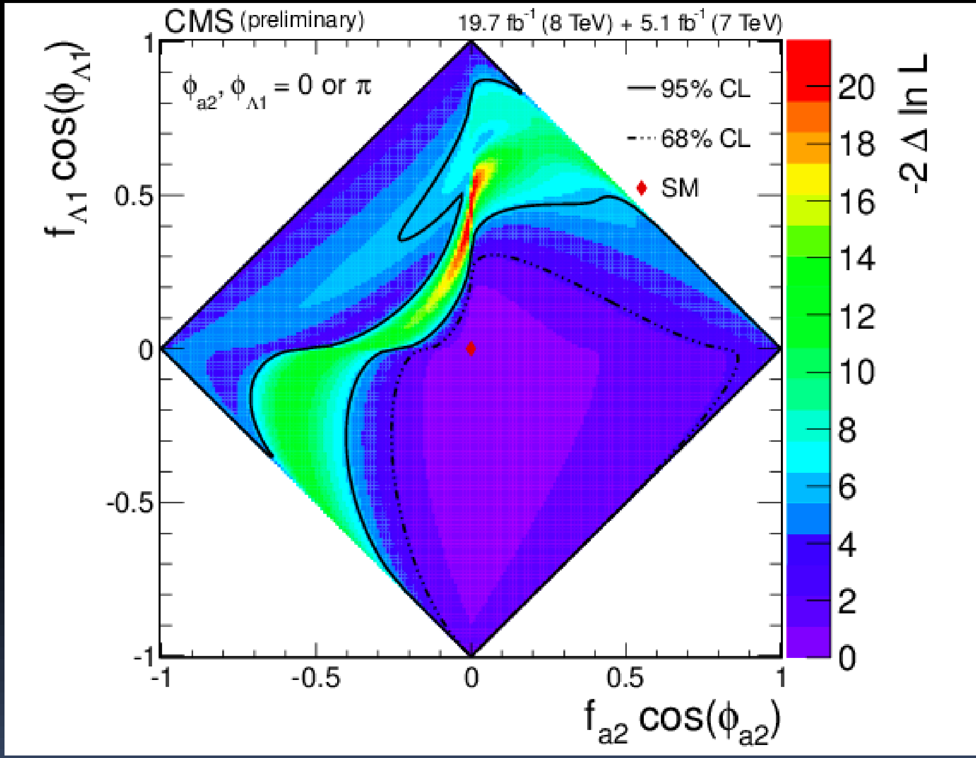
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

J=0 anomalous couplings

CMS PAS HIG-14-014

- Fit for the simultaneous presence of 2 anomalous ZZ amplitudes
  - N-2 couplings fixed to the SM; a_2/a_1 real; a_3/a_1 real
  - **a_2 and a_3 control the CP-even and CP-odd amplitudes**
  - **Λ_1 is a higher-term of an expansion in momentum**





Best fit ≡SM!

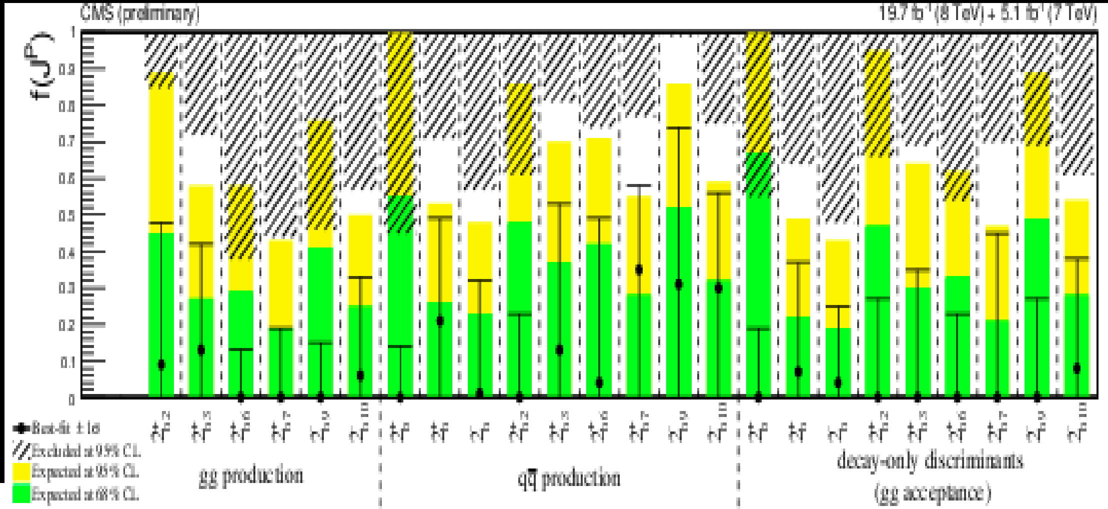
Best fit within 1 σ of SM

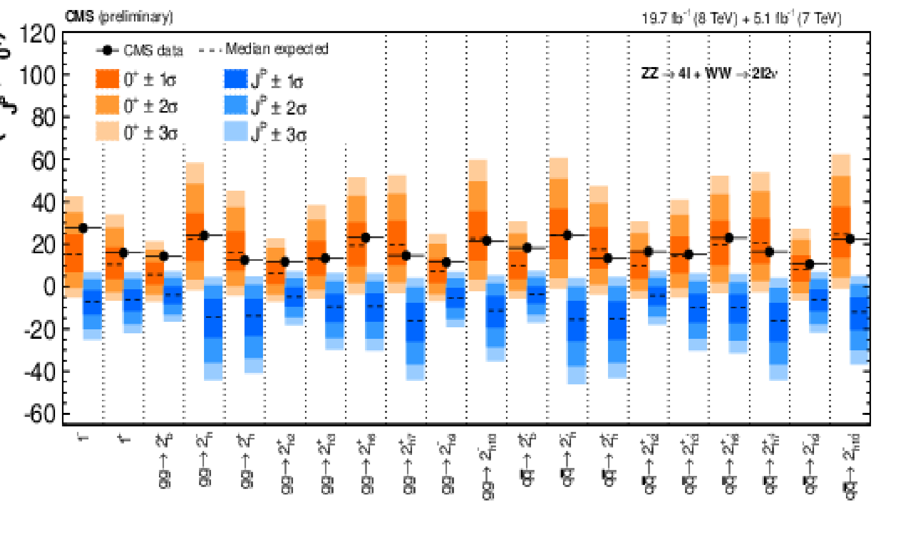
J = 2

CMS PAS HIG-14-014

- Several pure states have been considered
- Combine ZZ* and WW* final states

$$CL_s(J^P_{alt}) = \frac{p_0(J^P_{alt})}{1 - p_0(0^+)}$$





- Probe for a second resonance with J^{CP} different from 0^+ near SM Higgs-like state.
- Assume
  - $\delta M < \sigma_M$ but large enough so that they do not interfere.
- For all the models, fraction f(2P) consistent with 0
- Analysis ZZ only

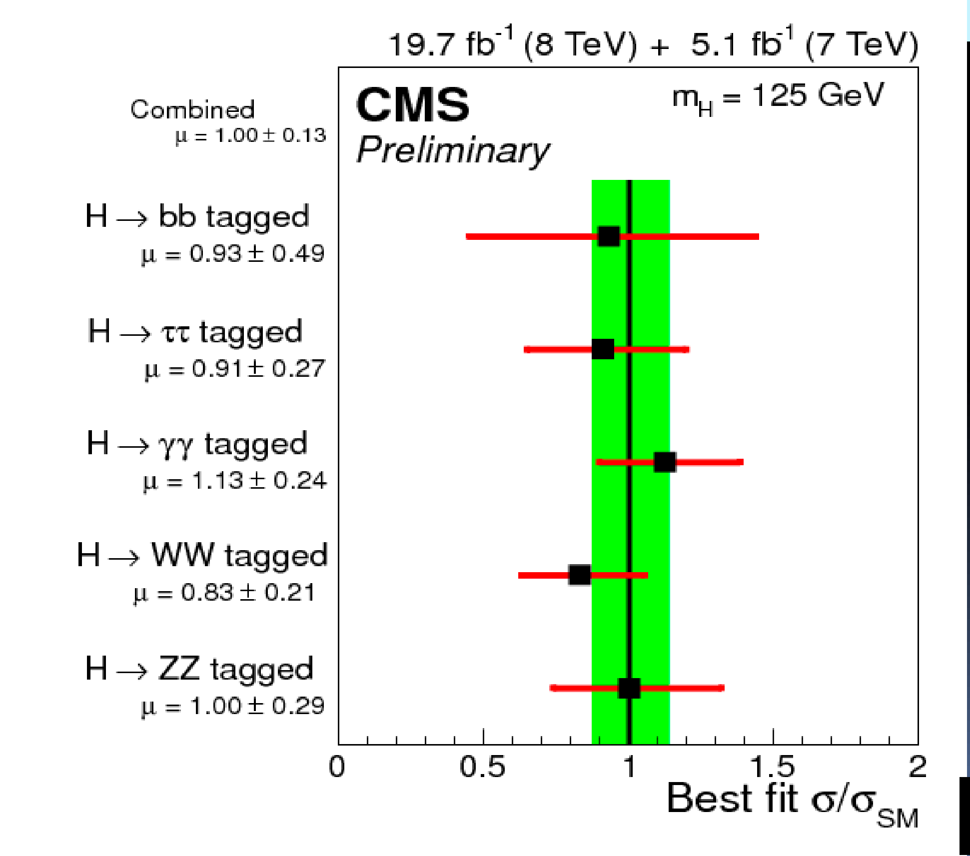
- All alternative hypotheses excluded > 99% CL

Combination of final Higgs results

> 200 channels

> 2'500 floating parameters

$$\frac{s}{s_{SM}} = 1.00 \pm 0.09(stat)^{+0.08}_{-0.07}(sys) GeV$$



Grouped by dominant decay

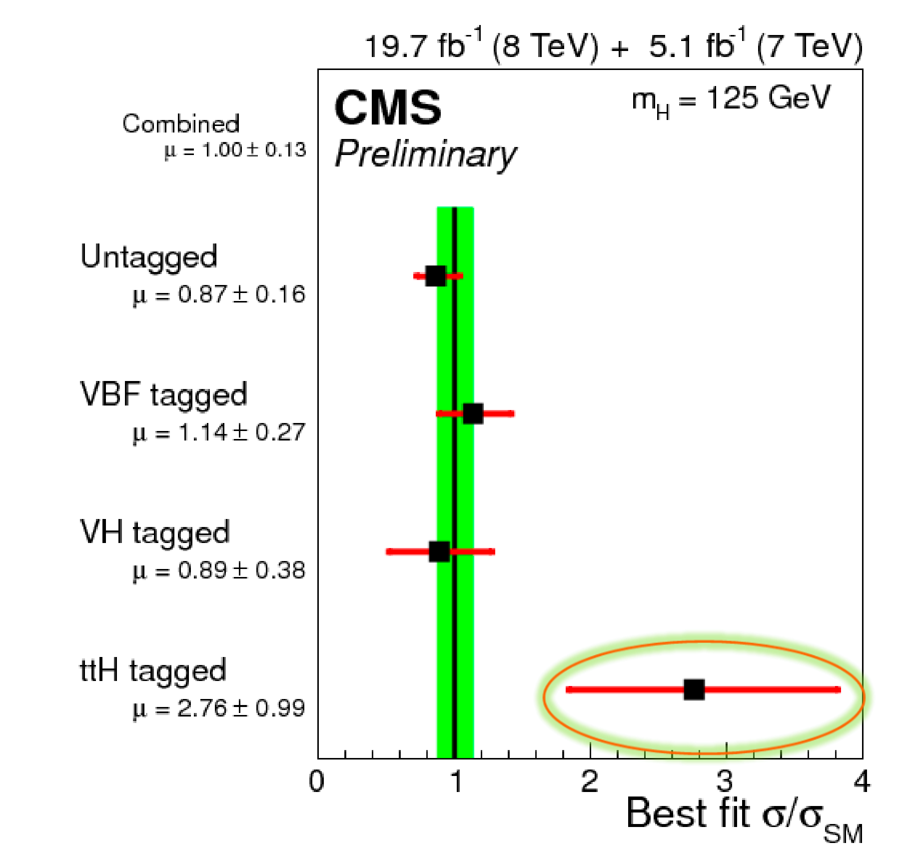
CMS-PAS-HIG-14-009

Combination of final Higgs results

> 200 channels

> 2'500 floating parameters

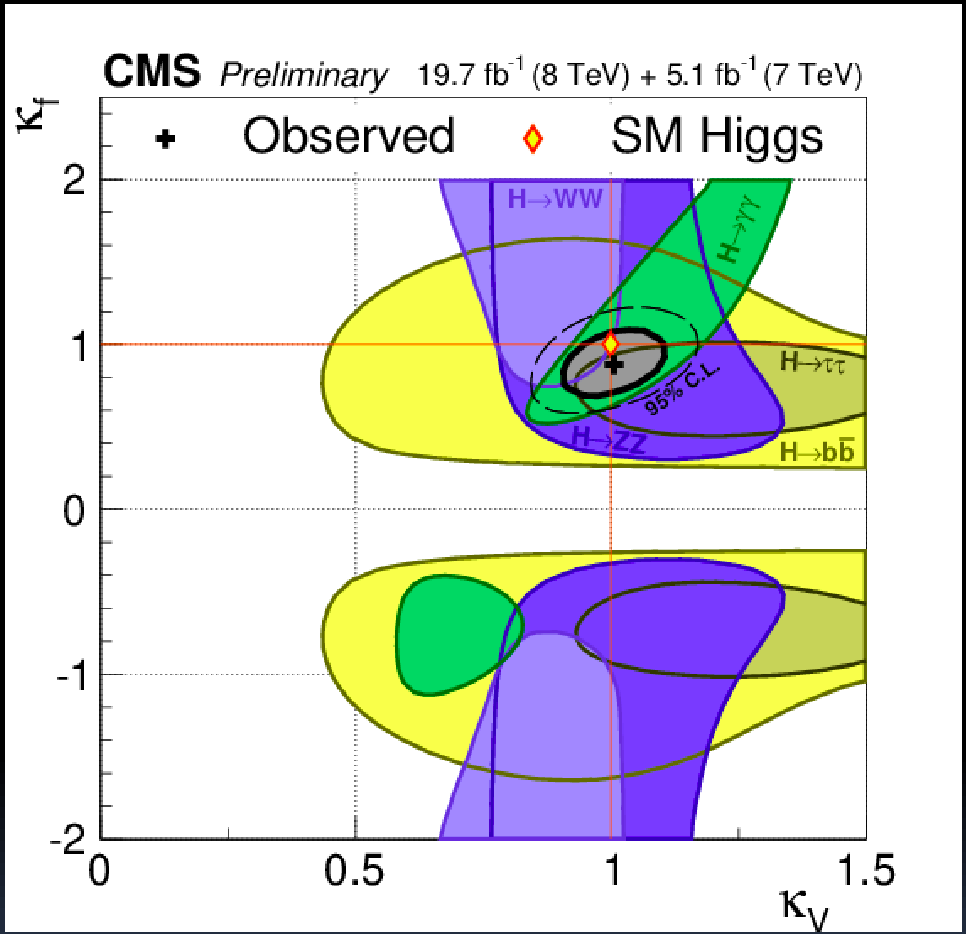
$$\frac{s}{s_{SM}} = 1.00 \pm 0.09(stat)^{+0.08}_{-0.07}(sys)GeV$$

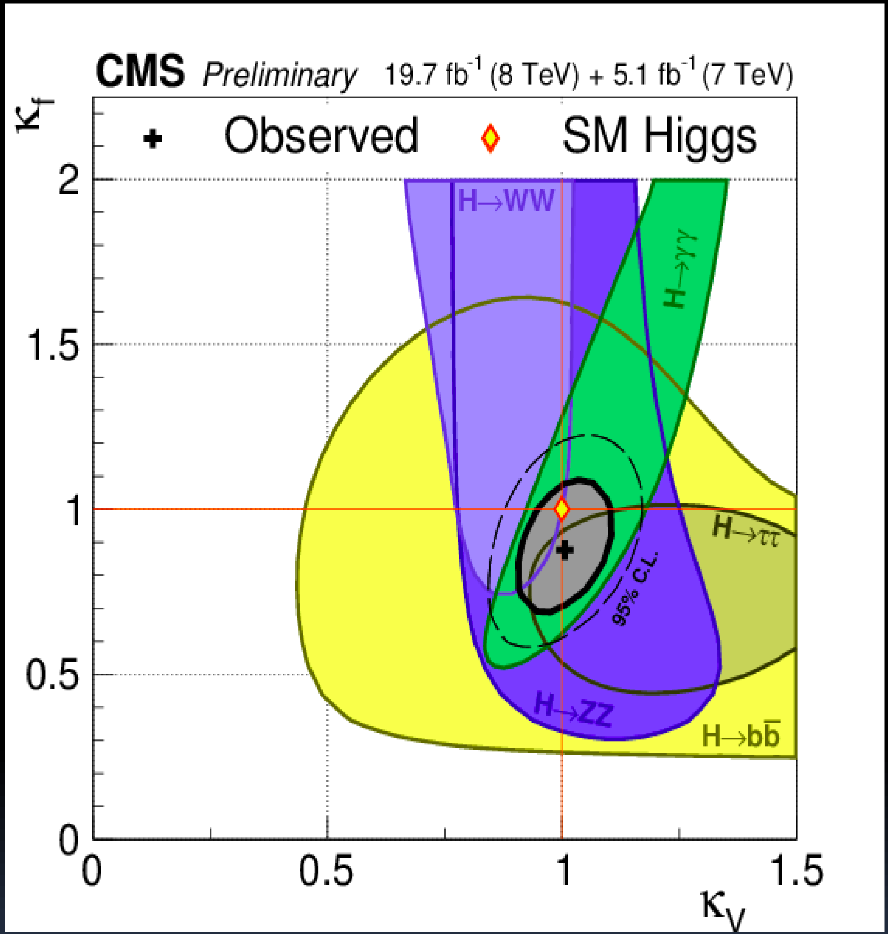


Grouped by production

ttH-tagged 2.0σ above SM.

Couplings





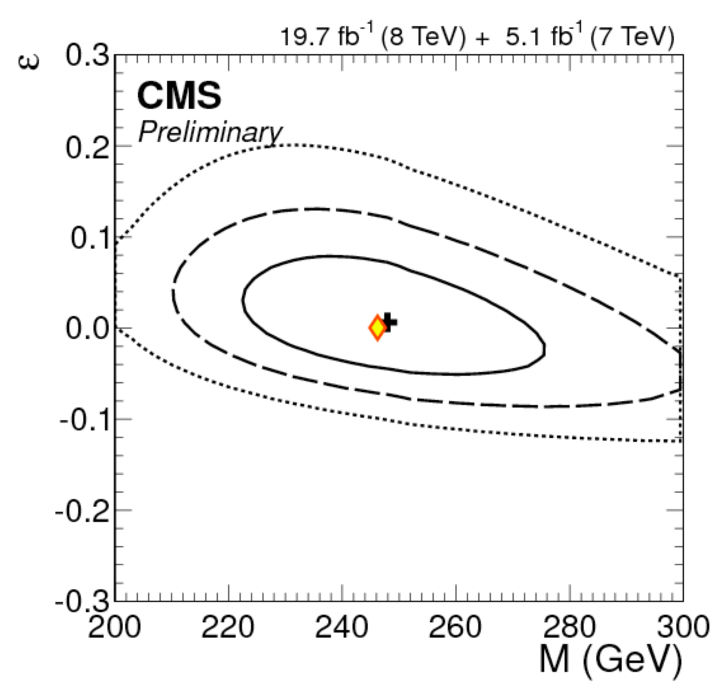
- Scaling the couplings to fermions (**κ_f**) and vector bosons (**κ_V**).
- Destructive interference in **H→ γγ** decay loop breaks degeneracy

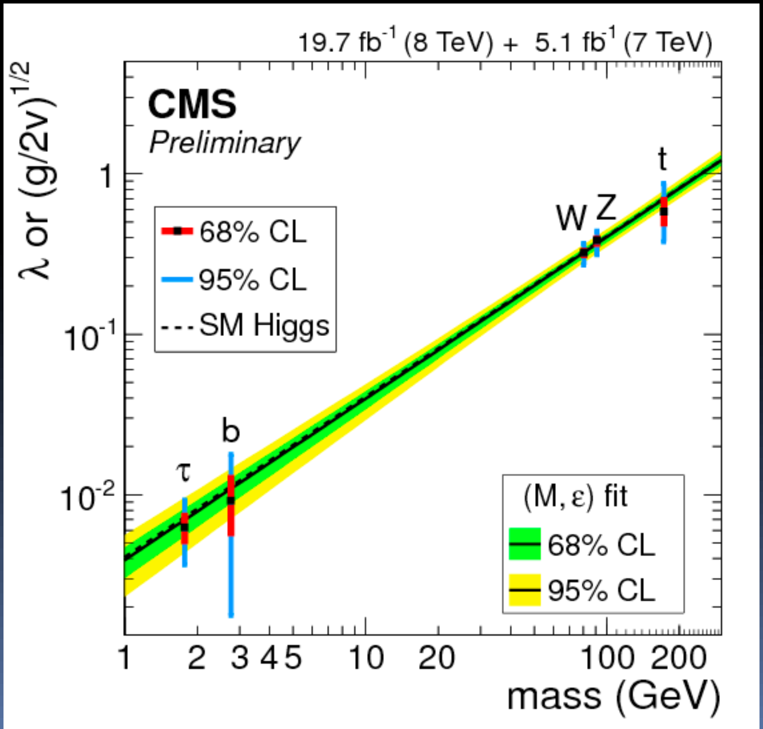
Couplings

- Parameterize coupling scale factor in terms of vev modifier (**M**) and power of coupling to mass (**ε**) [J. Ellis and T. You,arXiv:1207.1693]
- For SMH, M=vev=246.22 GeV and ε =0.

$$Bosons: k_V = vev \times \frac{m_V^{2e}}{M^{1+e}}$$

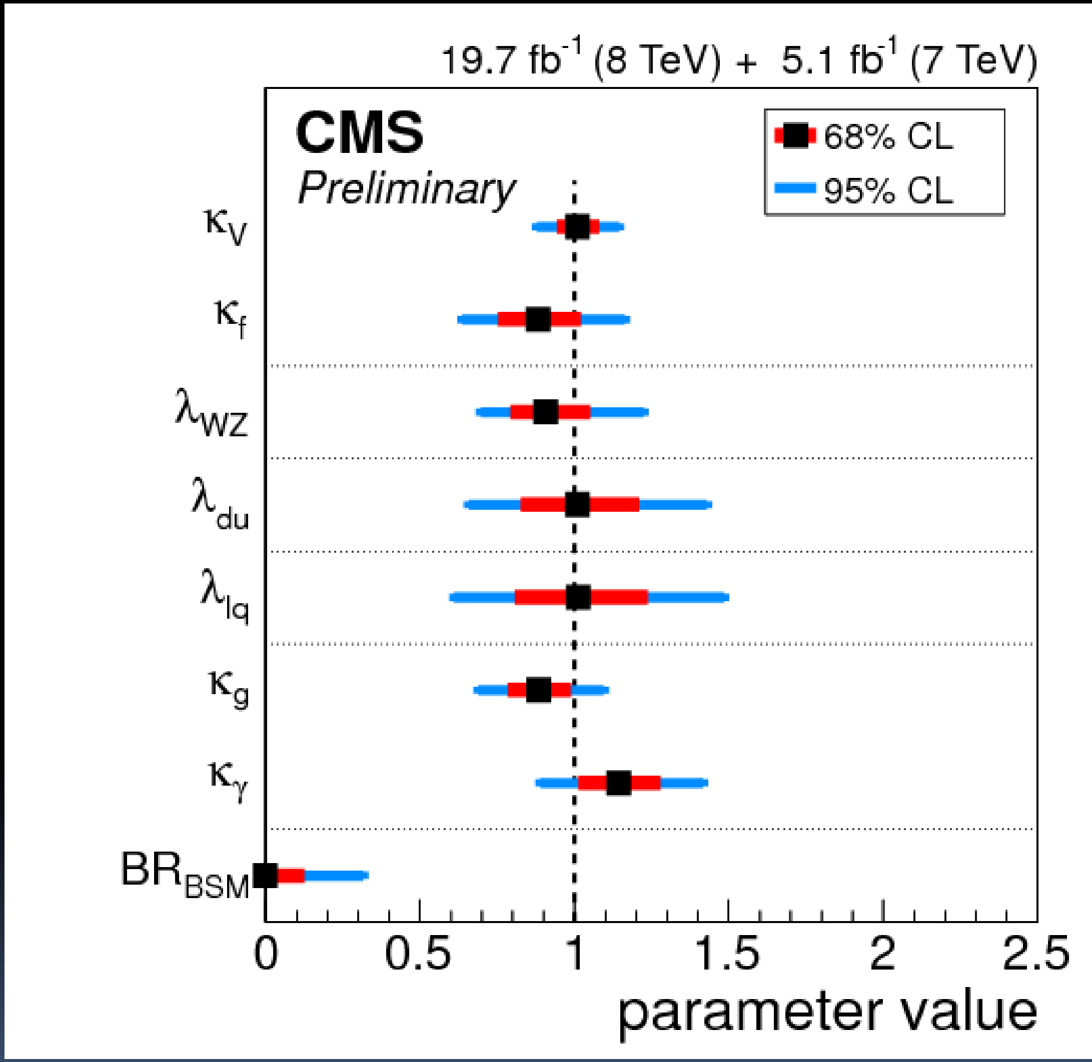
$$Fermions: k_F = vev \times \frac{m_f^{e}}{M^{1+e}}$$





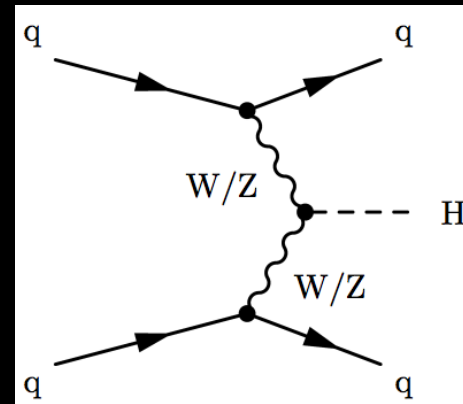
Couplings

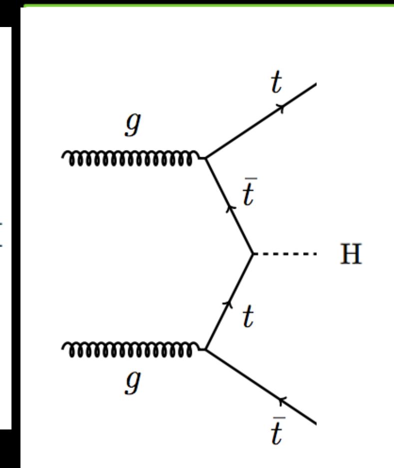
- Six benchmark models studied
  - Fermions vs bosons
  - W vs Z
    - Test of Custodial symmetry
  - Up vs down fermions
    - Interesting for 2HDMs
  - Quarks vs leptons
    - Test common (Yukawa) structure
  - Physics in the loops
    - Probe new physics at nearby Scales
  - Extra width to BSM

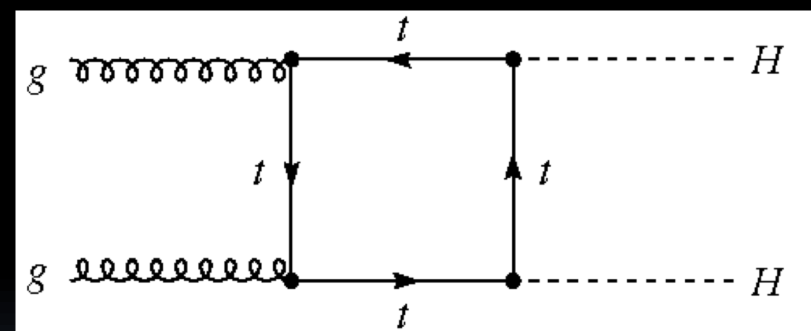


…and the future

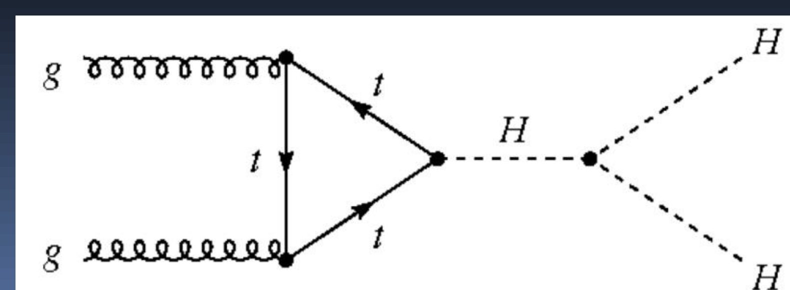
	Total Higgs Bosons
LHC Run 1	660k
HL-LHC, 3000 fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
$H \to \gamma\gamma$	390k
$H \to Z\gamma$	260k
$H \to \mu\mu$	37k
HH (all)	99000
$HH \to WWWW$	9200
$HH \to bb\gamma\gamma$	260
$HH \to \gamma\gamma\gamma\gamma$	1







Destructive interference!



$$\sigma(gg \to HH) \sim 34 \text{ fb}$$

Fundamental to BEH Mechanism!

Extrapolation: Methodology

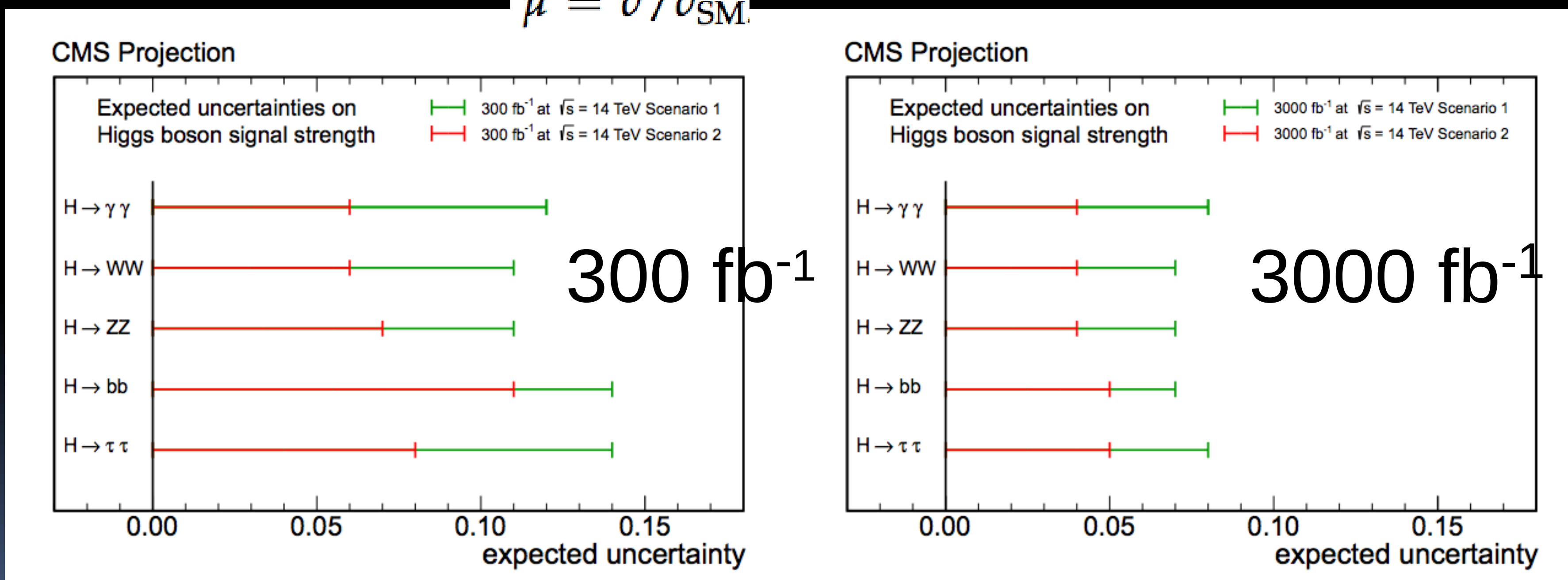
- Estimate of CMS performance at HL-LHC: extrapolate from numbers of S and B events in current analyses, scale with statistics
- Two scenarios for systematic uncertainties:
  - All remain the same as Run I
  - Appropriate experimental systematics as 1/√L , theory scaled to ½
- Procedure assumes that resolution on physics objects can be maintained despite pileup

H decay	prod. tag	exclusive final states	cat.	res.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{\text{VBF}}$	2	<1.5%
	VH-tag	$\gamma\gamma + (\text{e}, \mu, \text{MET})$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
$\text{ZZ} \to 4\ell$	$N_{\text{jet}} < 2$	4e, 4μ, $2e2\mu$	3	1-2%
	$N_{\text{jet}} \geq 2$		3	
$\text{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4	20%
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\text{VBF}}$ (DF or SF dileptons)	2	20%
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2	
$\tau\tau$	0/1-jet	$(\text{e}\tau_h, \mu\tau_h, \text{e}\mu, \mu\mu)\times$ (low or high p_T^τ)	16	15%
	1-jet	$\tau_h\tau_h$	1	
	VBF-tag	$(\text{e}\tau_h, \mu\tau_h, \text{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\text{VBF}}$	5	
	ZH-tag	$(\text{ee}, \mu\mu) \times (\tau_h\tau_h, \text{e}\tau_h, \mu\tau_h, \text{e}\mu)$	8	
	WH-tag	$\tau_h\mu\mu, \tau_h\text{e}\mu, \text{e}\tau_h\tau_h, \mu\tau_h\tau_h$	4	
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets$)\times$x	13	10%
	ttH-tag	(ℓ with 4, 5 or ≥6 jets) × (3 or ≥4 b-tags);	6	
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or ≥3 b-jets)	3	
$\text{Z}\gamma$	inclusive	$(\text{ee}, \mu\mu) \times (\gamma)$	2	
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{\text{VBF}}$	3	
invisible	ZH-tag	$(\text{ee}, \mu\mu) \times (\text{MET})$	2	

Signal Strength

- Estimate of CMS performance at HL-LHC: extrapolate from numbers of signal and background events in current analyses, scale statistics
- Two scenarios for systematic uncertainties:
  - All remain the same as Run I
  - Appropriate experimental systematics as 1/√L , theory scaled to 1/2

$$\mu = \sigma / \sigma_{SM}$$

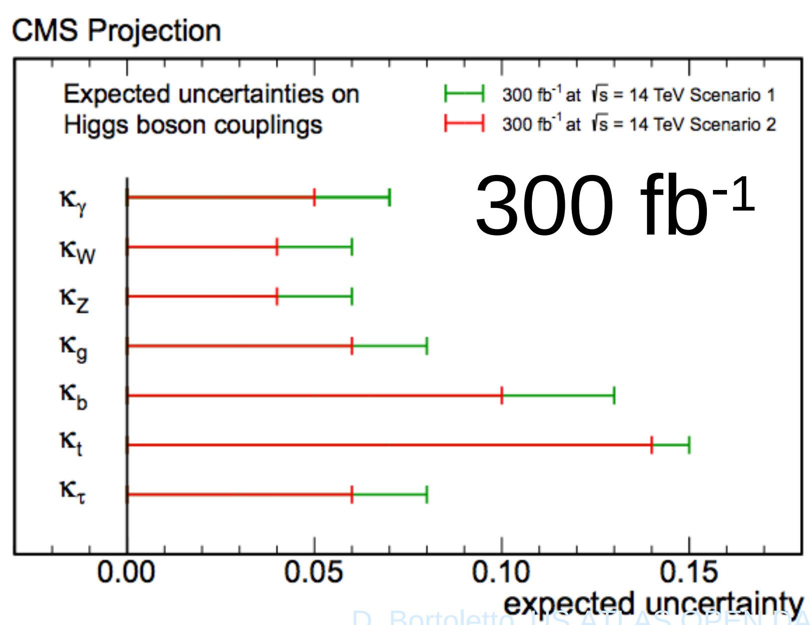


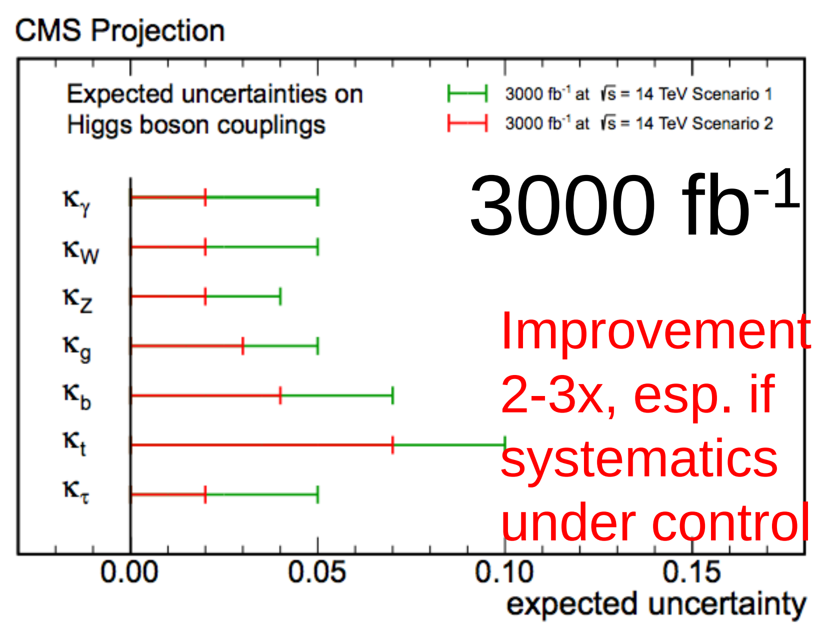
Couplings

- Estimate of CMS performance at HL-LHC: extrapolate from numbers of signal and background events in current analyses, scale statistics
- Two scenarios for systematic uncertainties:
  - All remain the same as Run I
  - Appropriate experimental systematics as $1/\sqrt{L}$, theory scaled to 1/2
- Coupling modifiers κ_i defined s.t. relevant production/decay rate scales with κ_i^2

E.g. $$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2 \qquad \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

LHC Higgs XSWG arXiv:1209.0040



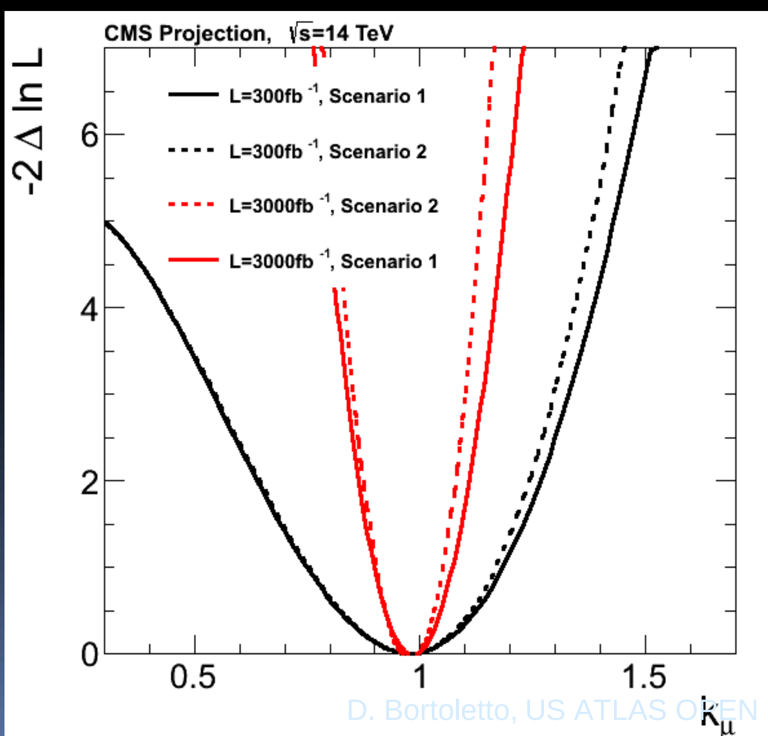


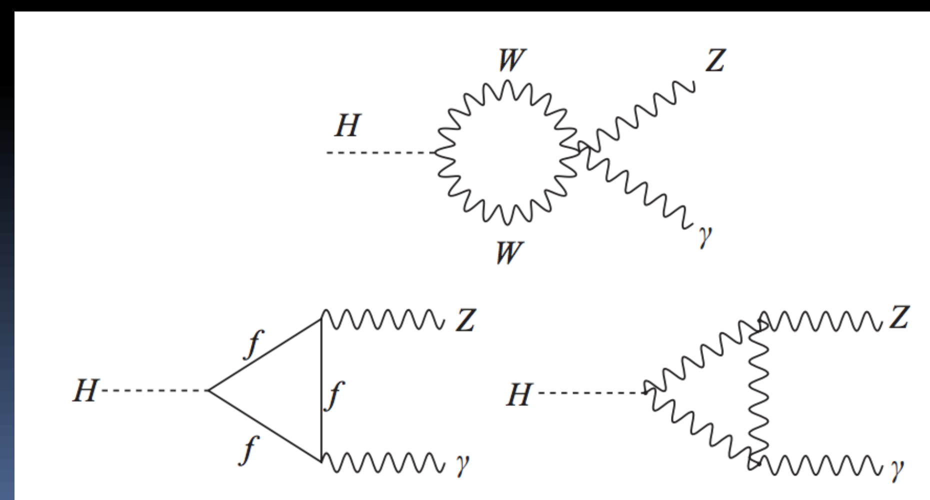
Improvement of: 2-3x, esp. if systematics under control

Rare Decays

- Observe and measure rare decays
  - $H \to \mu\mu$ probes coupling to second generation
  - $H \to Z\gamma$ probes multi-boson loop interactions for non-SM contributions
- Direct search for $H \to$ invisible
  - ZH- or VBF-tagged

	$300\ fb^{-1}$	$3000\ fb^{-1}$
κ_μ uncertainty	23%	8%
$\kappa_{Z\gamma}$ uncertainty	40%	10%
Invisible BR (95% CL limit)	17%	6%



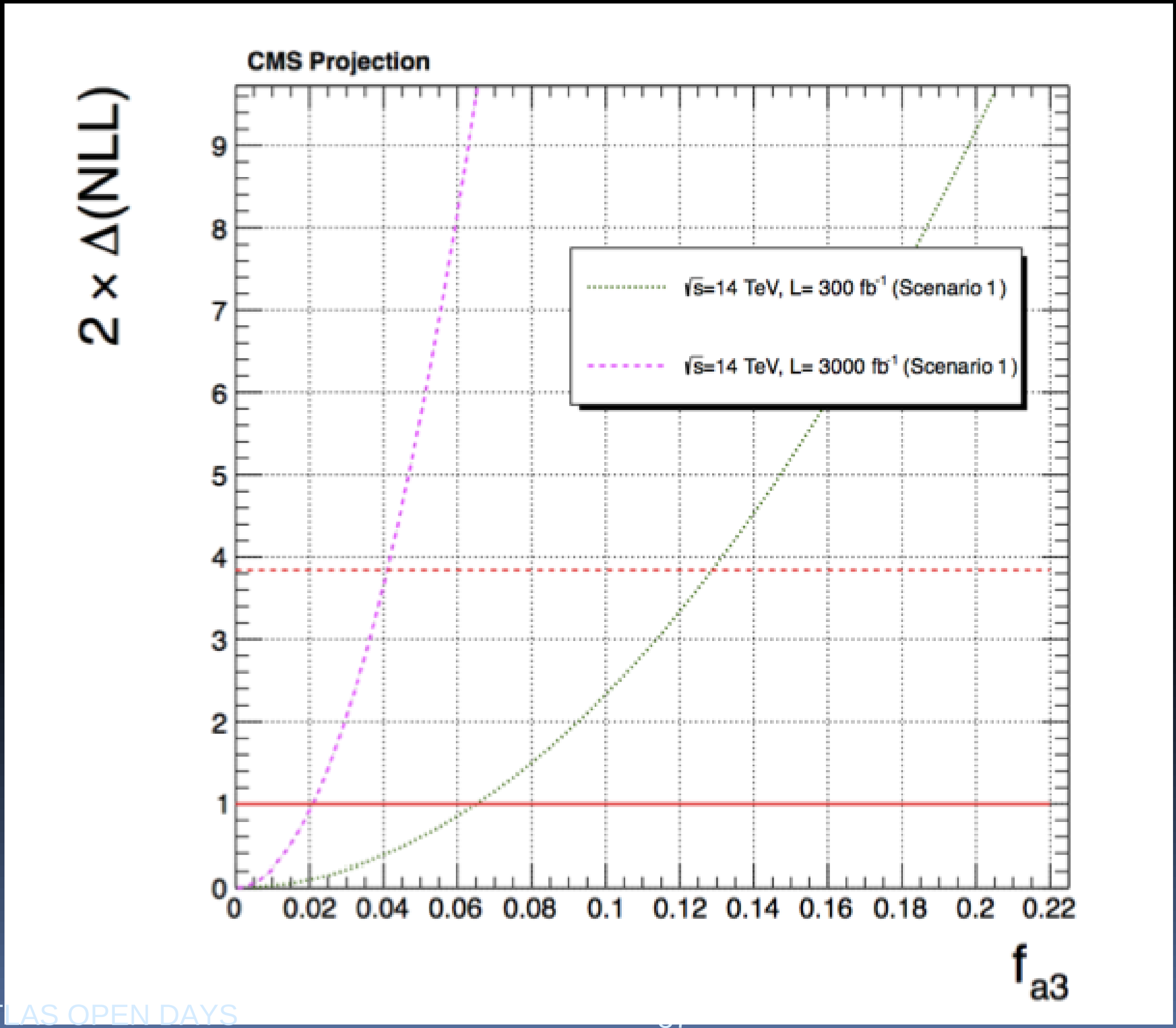


Spin-Parity

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$$

- Measure f_{a3} from simultaneous fit to m(H) and kinematics of 4-lepton system
- Increasingly precise limits on CP-odd contribution to Higgs boson
- 95% CL limit at 3000 fb^{-1}: $f_{a3} < 0.04$



Conclusions

- Run1 of the LHC has brought the discovery of the new boson and the first measurements of its properties
  - Measurements of m_H at 0.24% from combination of 4l and 2γ
  - J^{PC} consistent with 0^+
  - A new technique to constrain the Higgs boson width from off-shell ZZ production has emerged
- High Luminosity LHC → high-precision Higgs physics
  - Uncertainties on couplings 2-5% will provide important tests of Standard Model
  - Precise measurements of rare SM decays
  - Improved limits on CP-odd, additional Higgs bosons, invisible decays
- Realizing full HL-LHC potential demands significant detector improvements to cope with radiation damage and high pileup
- CMS Phase II Upgrade Technical Proposal in preparation
- Work will be required to bring down the theory uncertainties as well

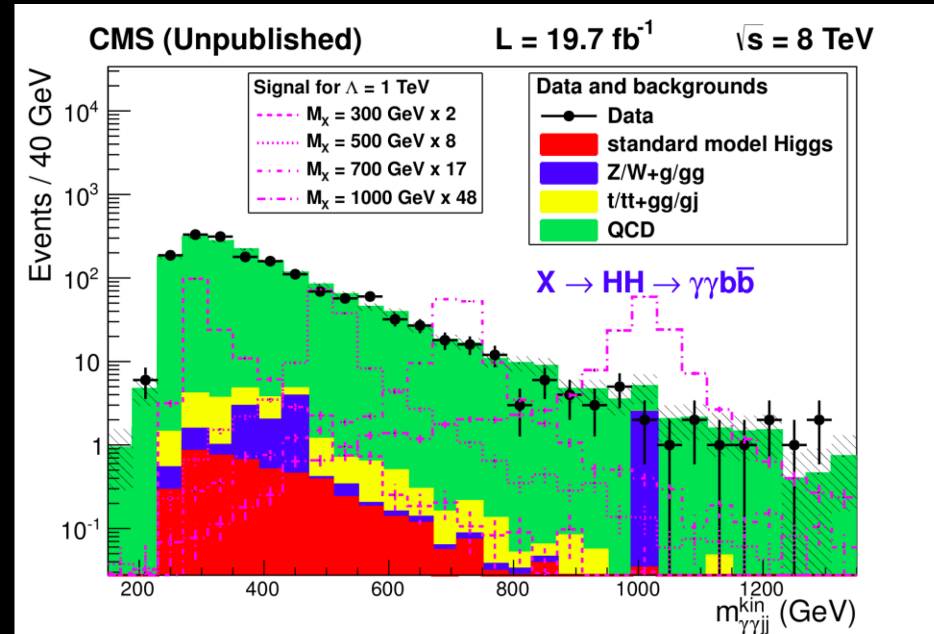
Conclusions

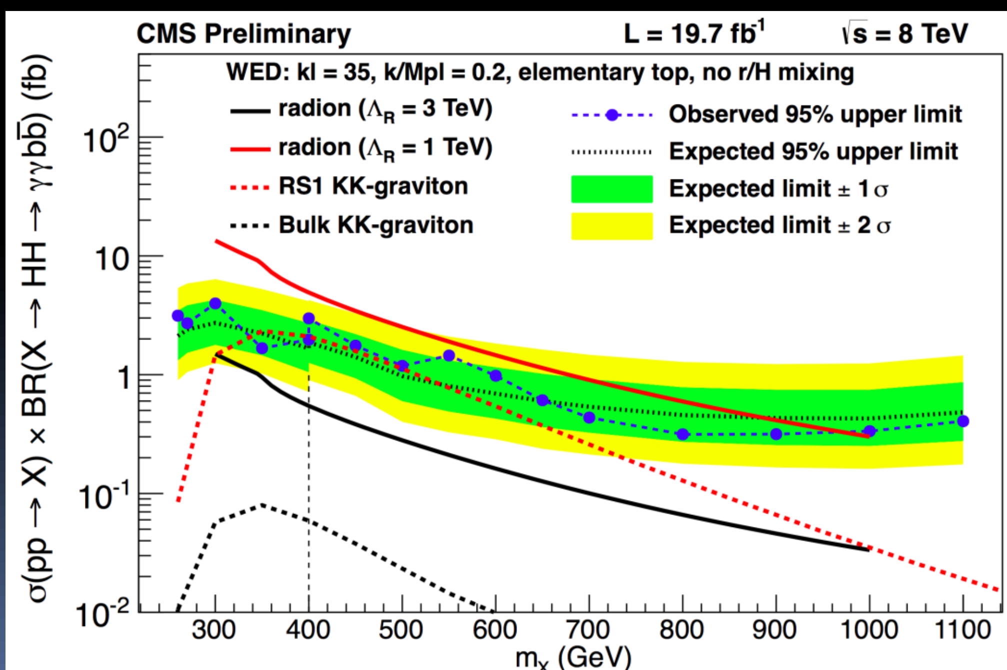
- Run1 of the … boson and the first mea…
  - Measurem… 2γ
  - J^{PC} consis…
  - A new tech… ff-shell ZZ production…
- High Lumin…
  - Uncertaint… s of Standard Model
  - Precise m…
  - Improved … ble decays
- Realizing fu… etector improveme… pileup
- CMS Phase… tion
- Work will be… inties as well

BACKUP

X→HH→b$\bar{b}$γγ

- First step towards two-Higgs measurements at the HL-LHC.





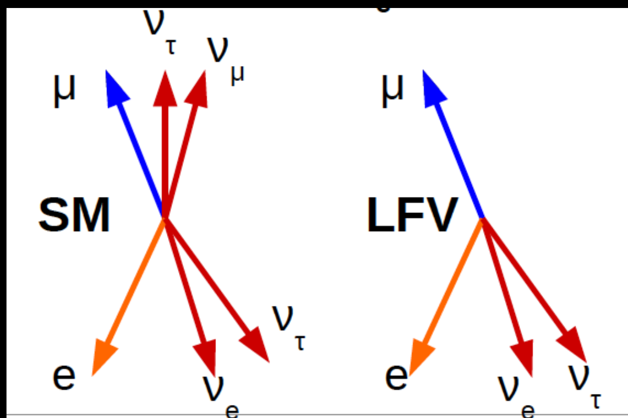
- Limits on radion production from warped extra dimensions

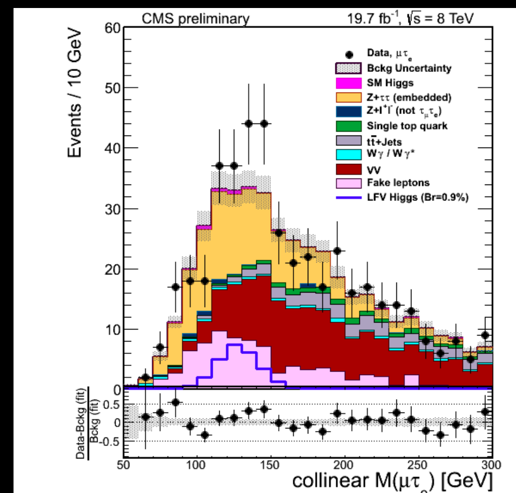
Search for H→μτ

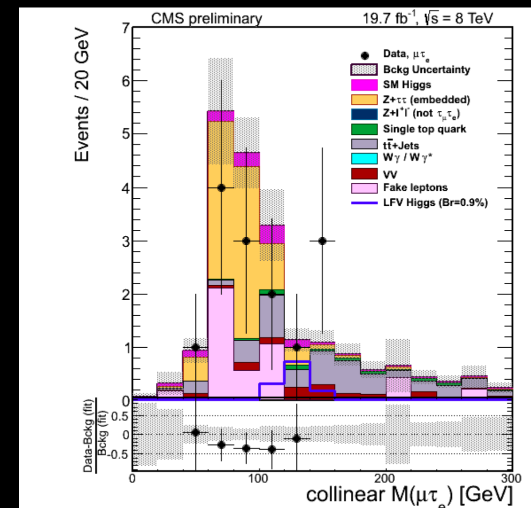
CMS PAS HIG-14-005

- | lepton flavor violation not as well constrained as ⌠e (MEG).
- Based on SM **H→**| | analysis. Different kinematics allows good SM H rejection.
- BR(H→⌠ |) < 1.57% at 95%CL (expected limit of 0.75%)

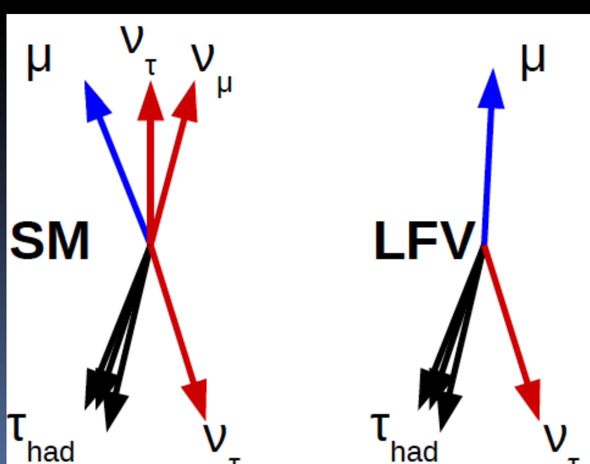
$\mu\tau_e$

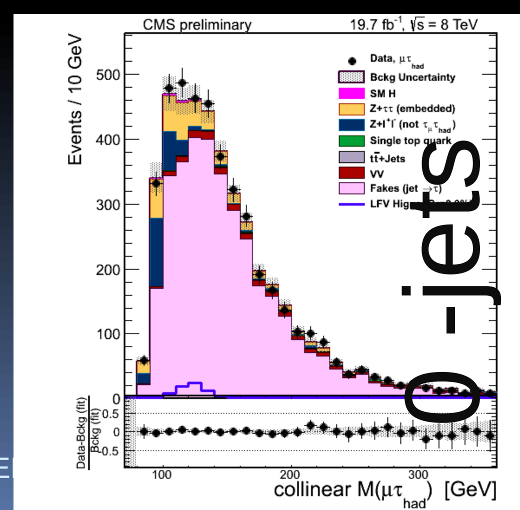


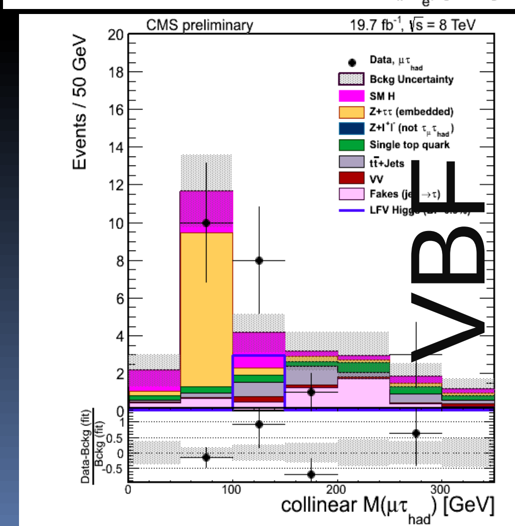




$\mu\tau_{had}$

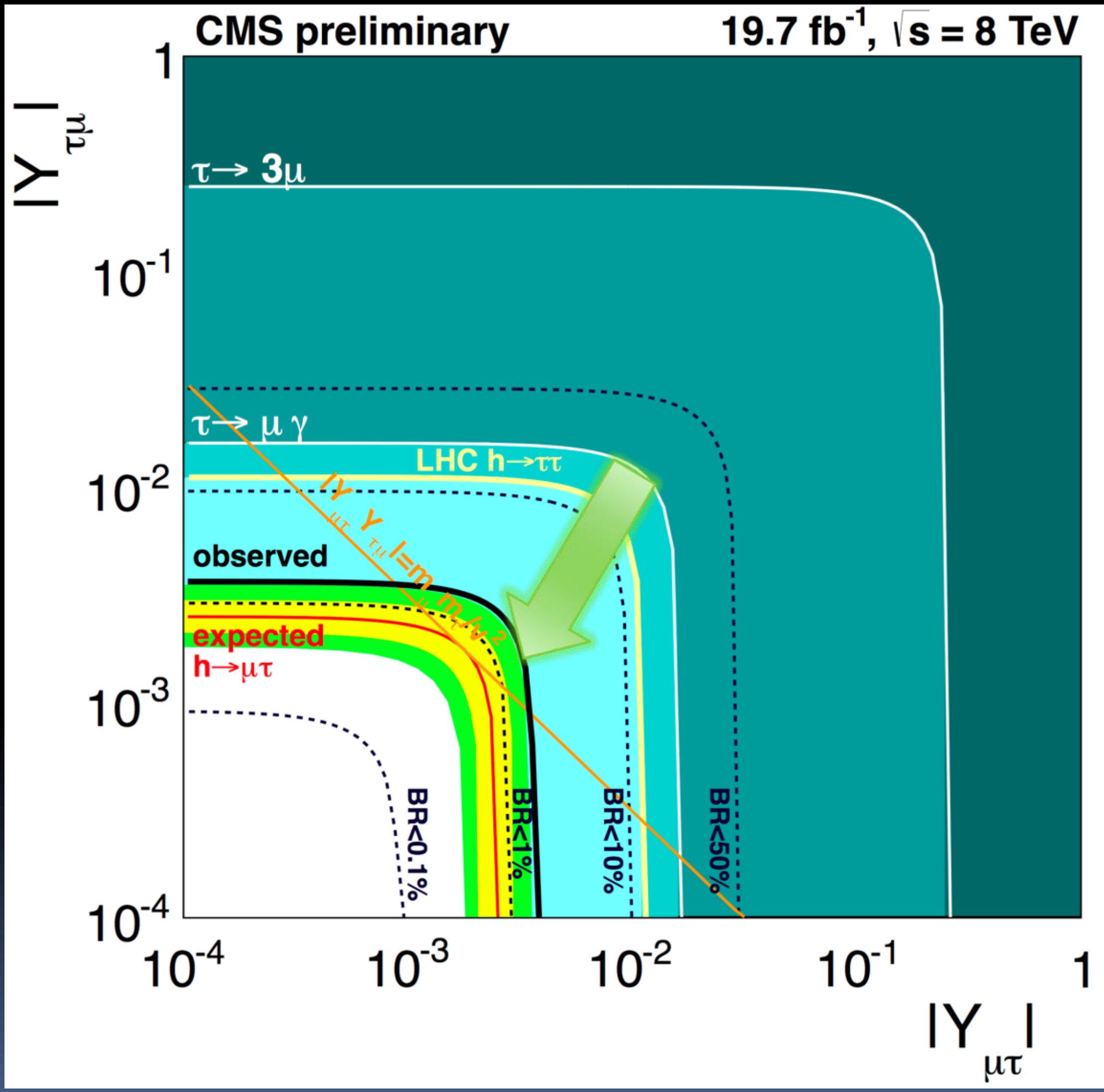






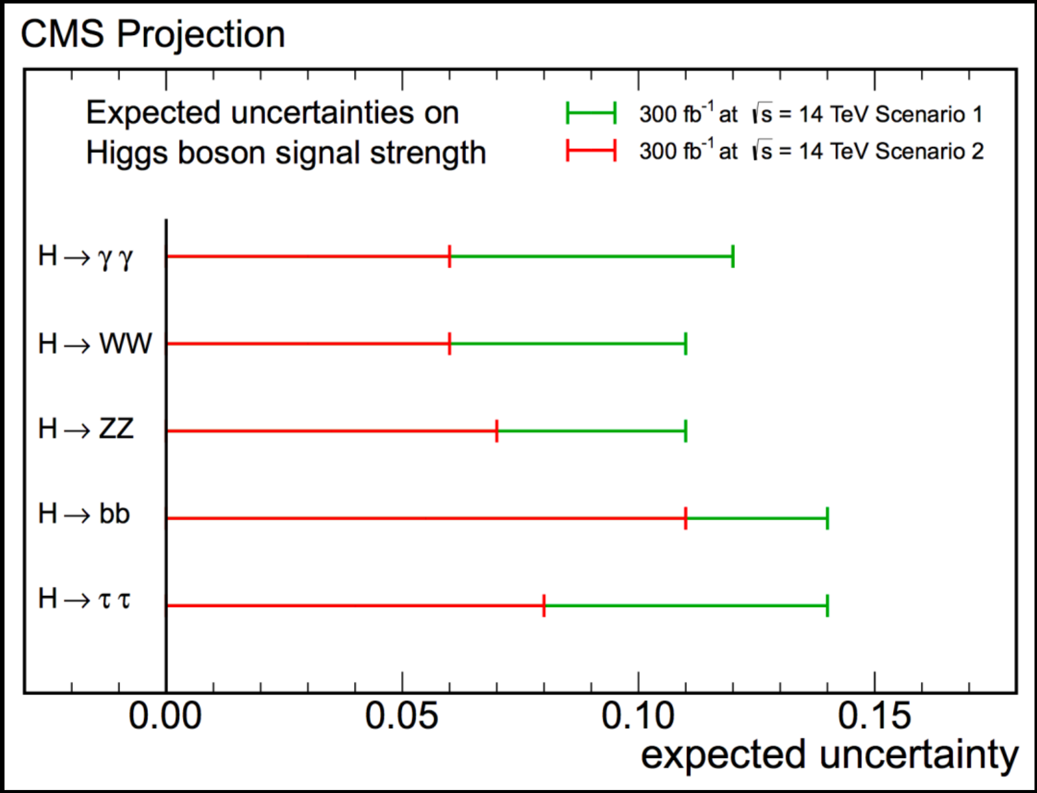
Search for H→

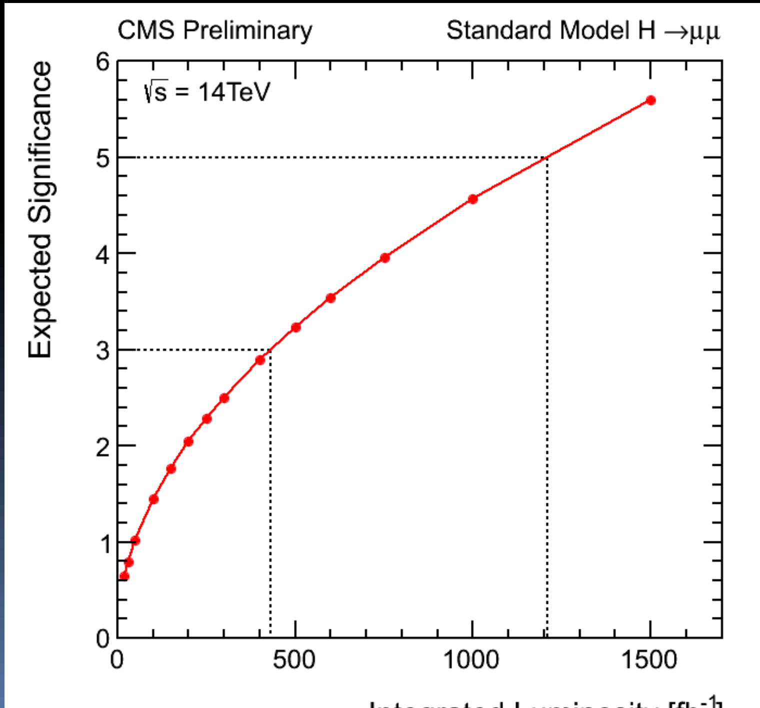
- Best limits on anomalous Yukawa couplings
- Improvement by a factor of 4.4



Higgs physics at the LHC

- Everything looks like the SM Higgs but all analysis are statistics limited
- 300 fb^{-1} at 14 TeV will bring a major improvement over present datasets.
- Room for theory improvements.

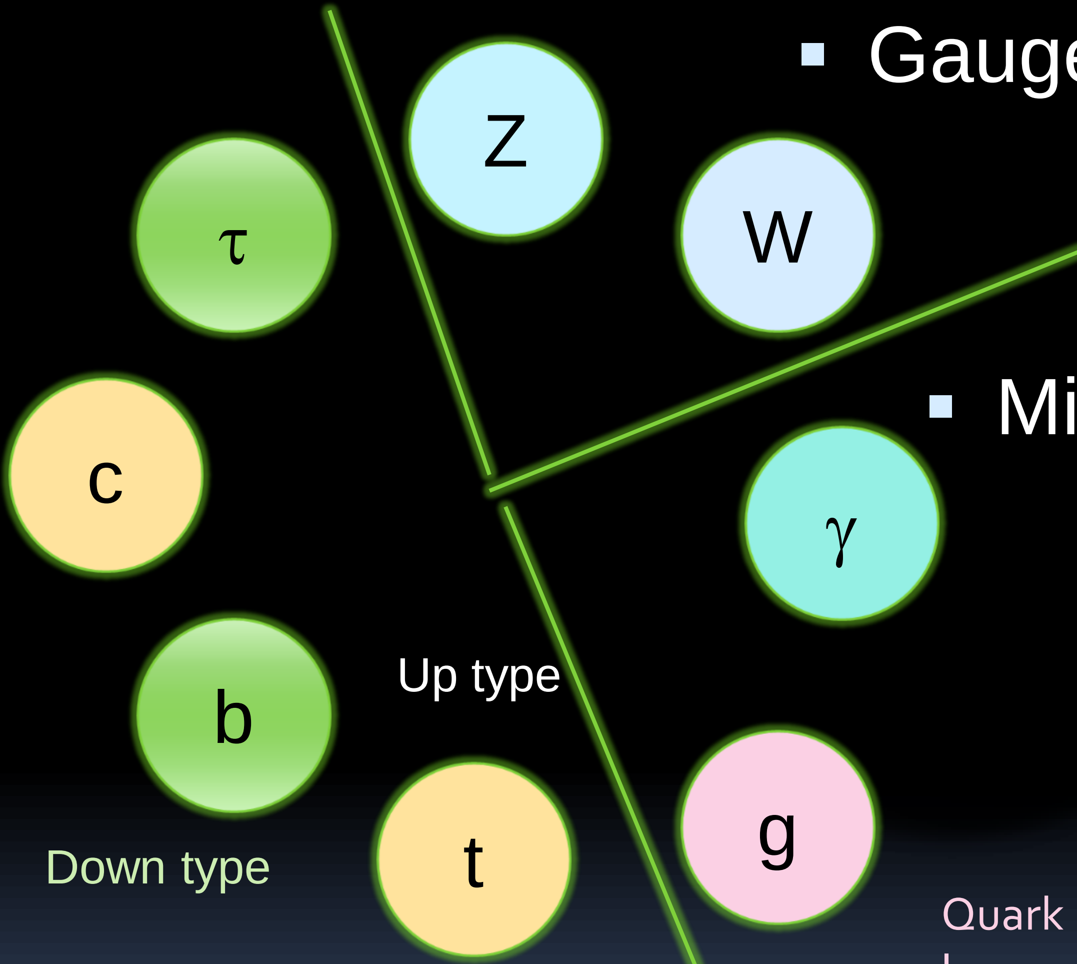




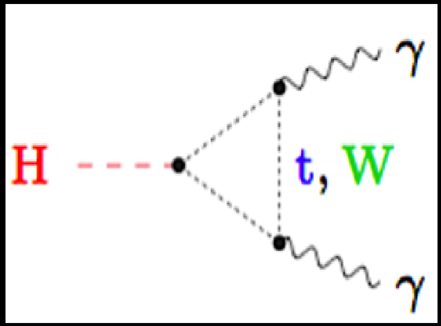
- For (HL-LHC) 3000 fb-1:
  - **H→μμ at > 5σ.**
  - Can we get to the Higgs self-coupling?

Couplings

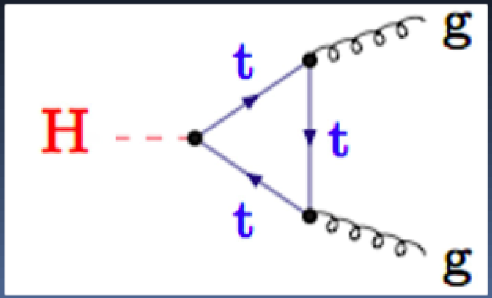
- Gauge sector



- Mixed sector



Quark loop



- Yukawa sector

Couplings

- Single state, spin 0, and CP-even.
- Narrow-width approximation: (**σx**BR) =**σ·Γ/Γ**$_H$

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

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

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

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

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

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

Total width

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

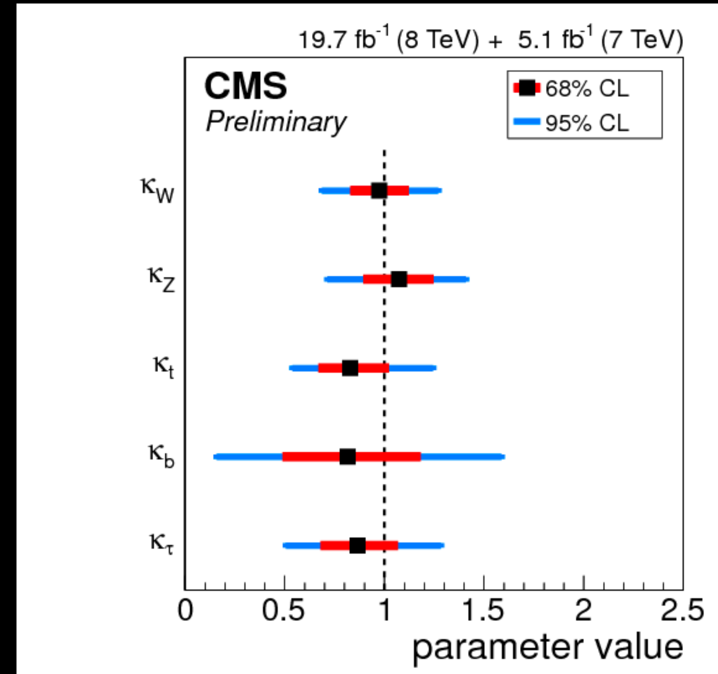
- Loops resolved at NLO QCD and LO EWK accuracy
- Use related info if necessery (cc, ss etc.)

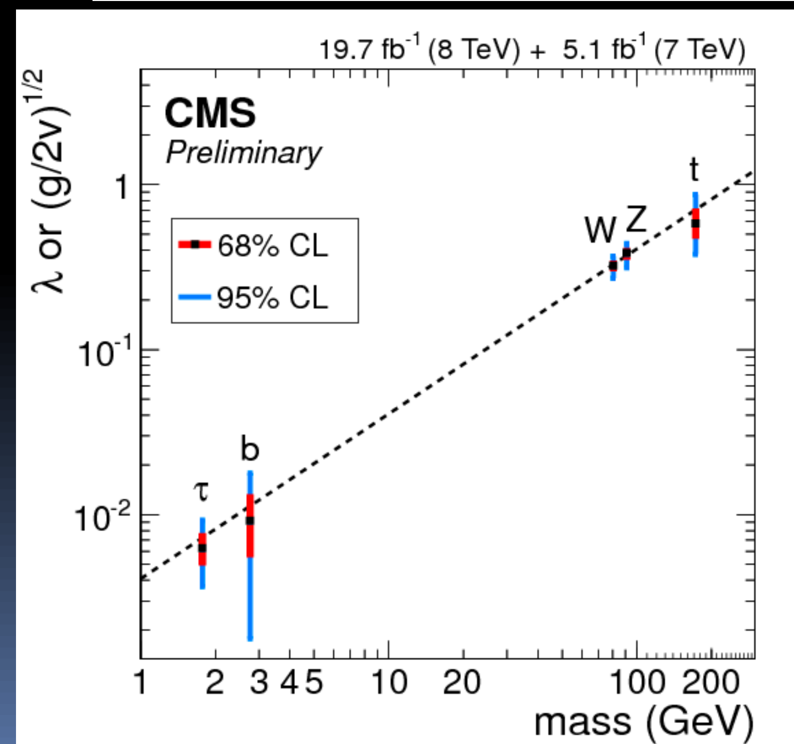
Couplings

- Test of generic model, assuming SM structure for loops
  - i.e., VBF is resolved into W and Z, ggH is resolved into top and bottom, etc
- One parameter per tree-level coupling

$$k_W, k_Z : \left(\frac{g_V}{2v}\right)^{1/2} = k_V^{1/2} \frac{m_V}{vev}$$

$$k_t, k_b, k_t : \lambda = k_F \frac{m_f}{vev}$$

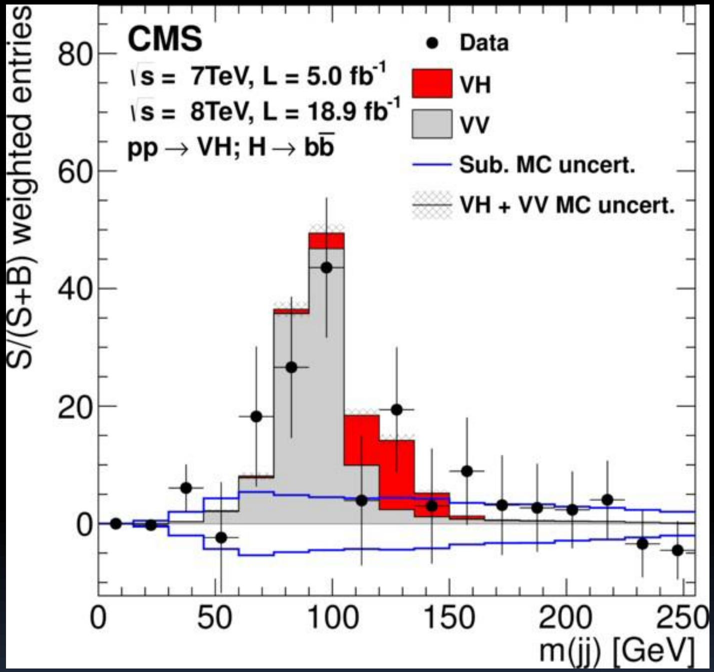


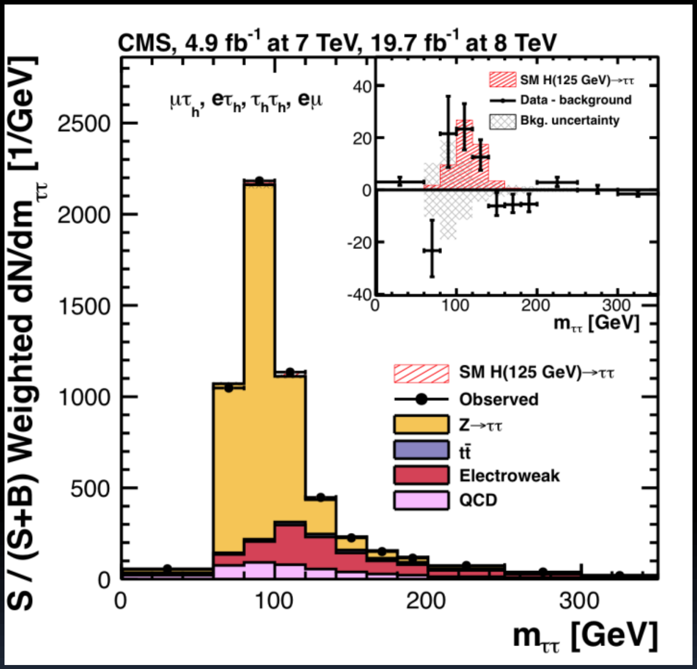


H→bb & H→ττ combination

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

- Reconstruct a tau pair in many final states based on tau decay modes
- Expected 3.7σ (obs 3.2σ)

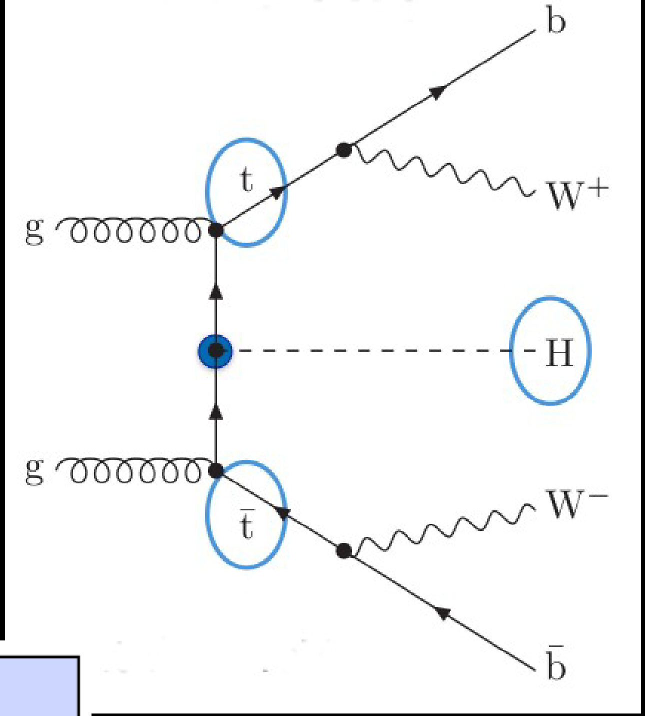




Combination bb and di-tau final state provide solid evident (3.8 σ) for fermionic decays of the Higgs boson (Nature Phys. 10 (2014))

ttH

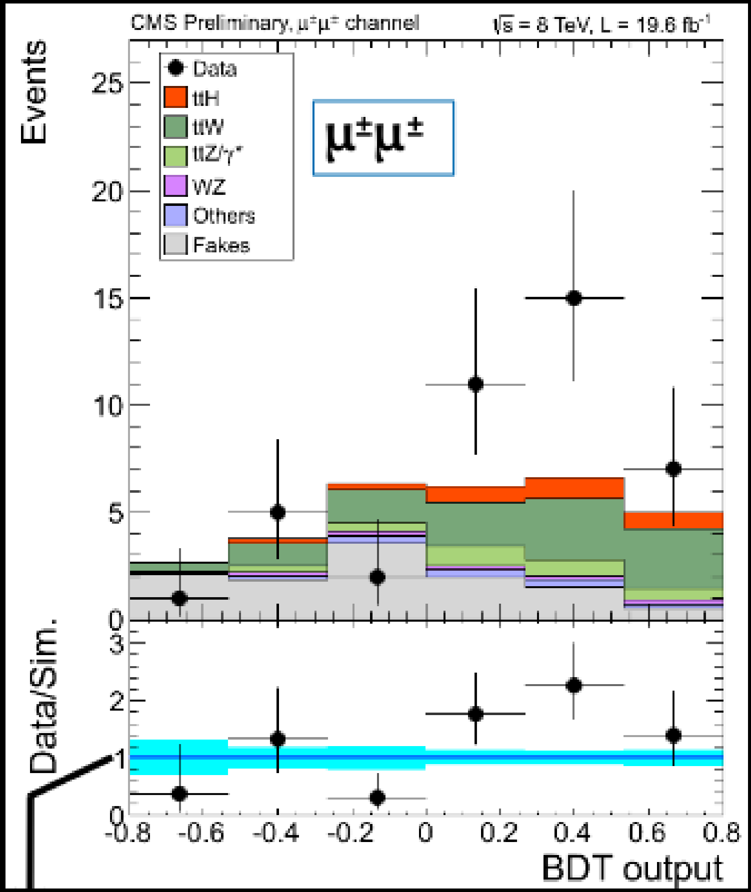
- Top coupling can be probed at tree level via ttH production
- Very low cross section but unique experimental signature → bbWWH



	$H\to bb$	$H\to\tau\tau$: $\tau_{had}\tau_{had}$	$H\to\tau\tau$: $l\tau_{had}$	$H\to WW^*/ZZ^*$	$H\to\gamma\gamma$
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

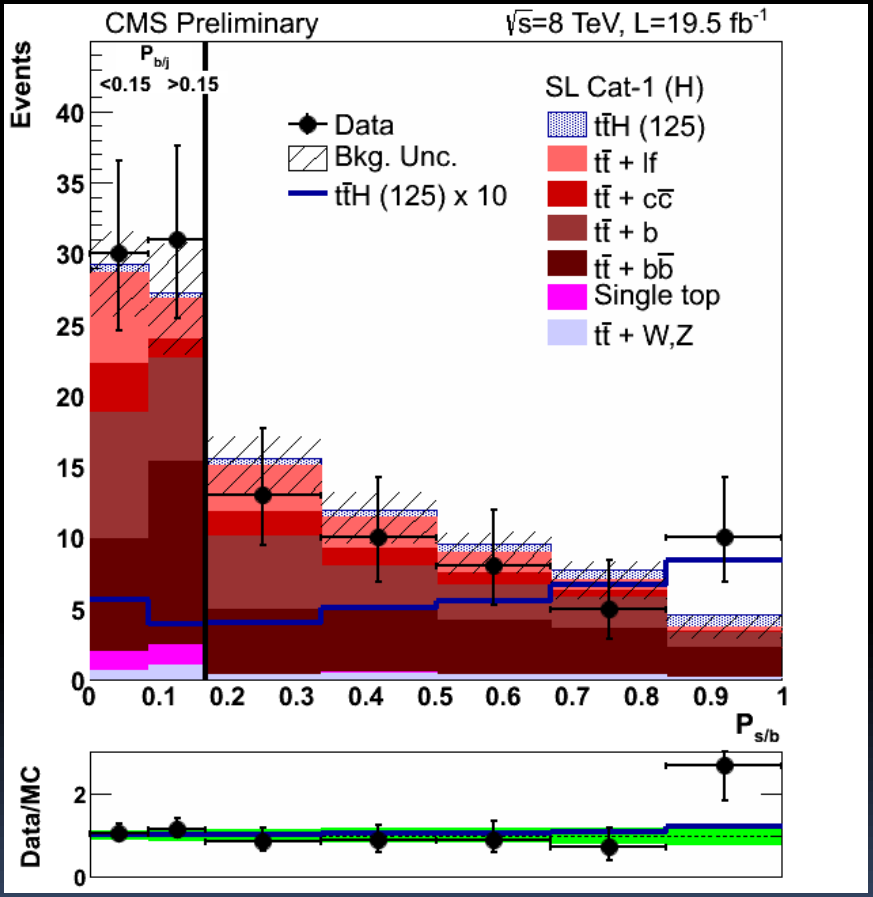
Channel	μ^{fit}	$\Delta\mu^{fit}$
ttH, $H \to bb$	0.65	-1.8/+1.8
ttH, $H \to \tau_{had}\tau_{had}$	-1.3	-3.6/+6.1
ttH, $H \to$ leptons	3.9	-1.4/+1.7
ttH, $H \to \gamma\gamma$	2.7	-1.7/+2.4
ttH tagged	2.76	-0.92/+1.05

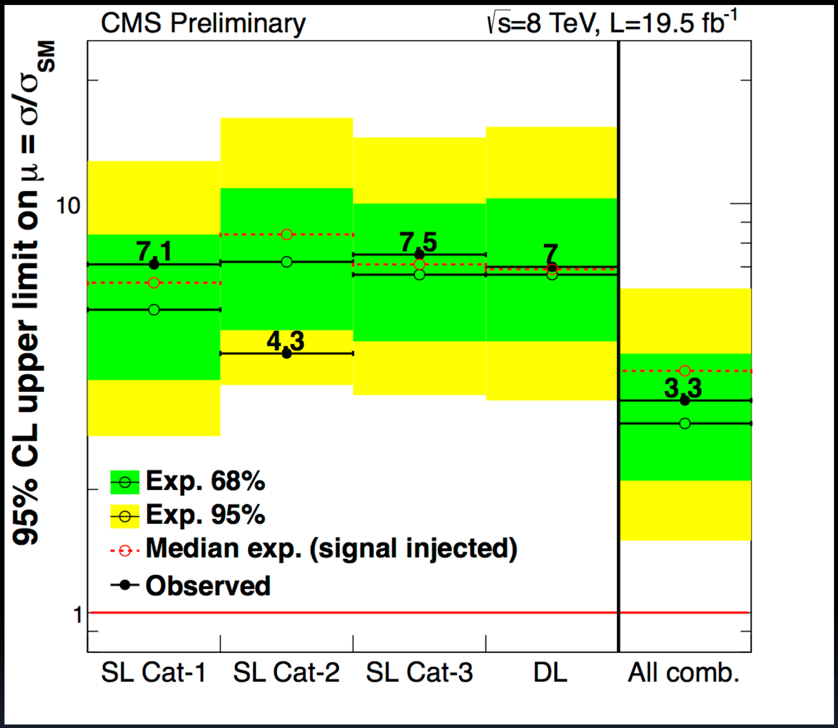


- Expected uncertainty on signal strength ~ 100%
- Mild excess observed in SS di muon events
- Within two standard deviations wrt SM expectation

Improving ttH with H→ bb

- Improved sensitivity with matrix element





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

Spin 2

- J=2 tested in all the channels for different production modes

$$A(X_{J=2}\to V_1V_2)\sim\Lambda^{-1}\Big[2c_1t_{\mu\nu}f^{*1,\mu\alpha}f^{*2,\nu\alpha}+2c_2t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2}f^{*1,\mu\alpha}f^{*2,\nu,\beta}$$
$$+c_3\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2}t_{\beta\nu}(f^{*1,\mu\nu}f^{*2}_{\mu\alpha}+f^{*2,\mu\nu}f^{*1}_{\mu\alpha})+c_4\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}f^{*(2)}_{\alpha\beta}$$
$$+m_V^2\left(2c_5t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu}+2c_6\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha}-\epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right)+c_7\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+c_8\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2}t_{\mu\nu}f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta}+c_9t^{\mu\alpha}\tilde{q}_\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho}q^\sigma$$
$$+\frac{c_{10}t^{\mu\alpha}\tilde{q}_\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*)+\epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]$$

Dictionary:

A. c_1,c_5: minimal couplings (a.k.a. 2_m)
B. other c_is: higher orders
C. All couplings: assumed momentum-independent

Anomalous couplings in S=0

- Decay amplitude in H → VV can be pararetized in terms of complex and momentum dependent couplings (up to q^2)
  - **a_1 is the SM amplitude.**
  - **Λ_1 is a higher-term of an expansion in momentum.**
  - **a_2 and a_3 control the CP-even and CP-odd amplitudes**

SM tree level + leading momentum expansion

$$A(X_{J=0} \to V_1 V_2) = v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right.$$

$$+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \quad \} \text{VV couplings}$$

$$+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \quad \} Z\gamma^* \text{ couplings}$$

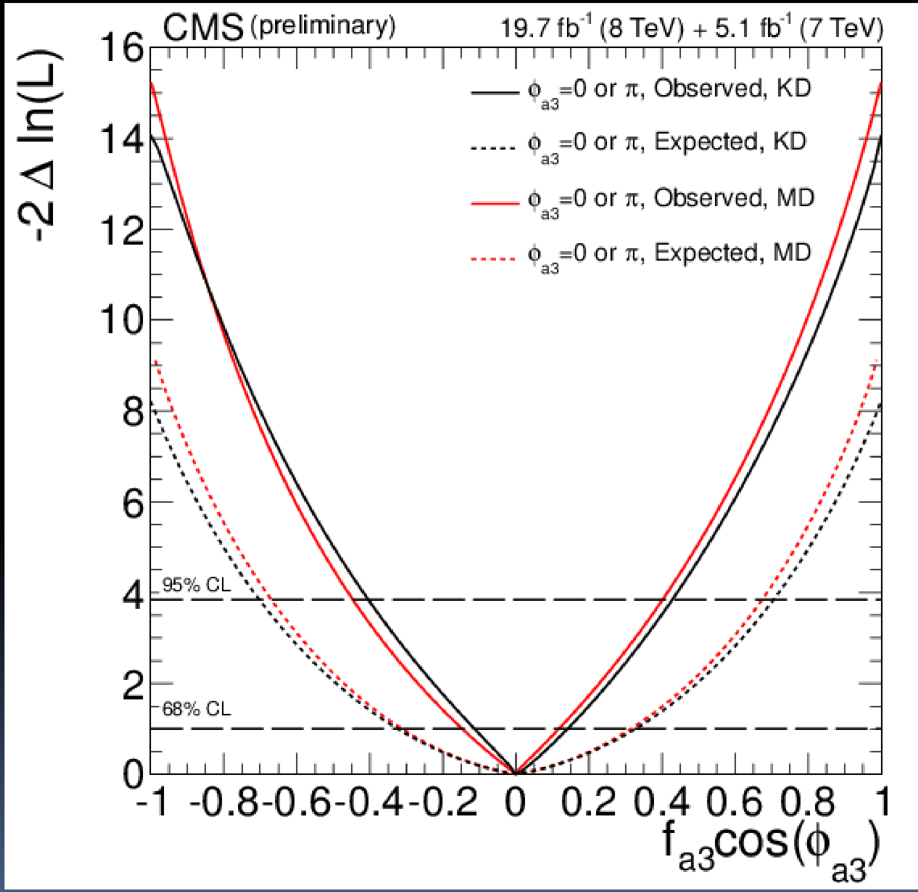
$$\left. + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \quad \} \gamma^*\gamma^* \text{ couplings}$$

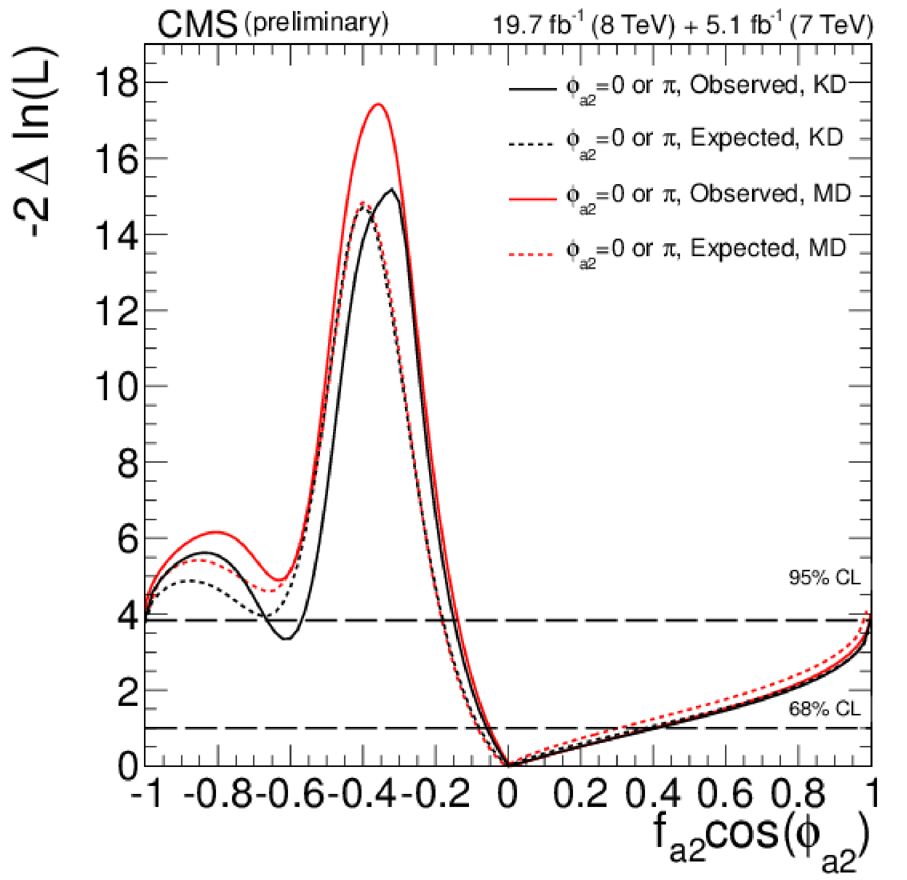
a_2 terms: CP-even scalar

a_3 terms: CP-odd pseudo-scalar

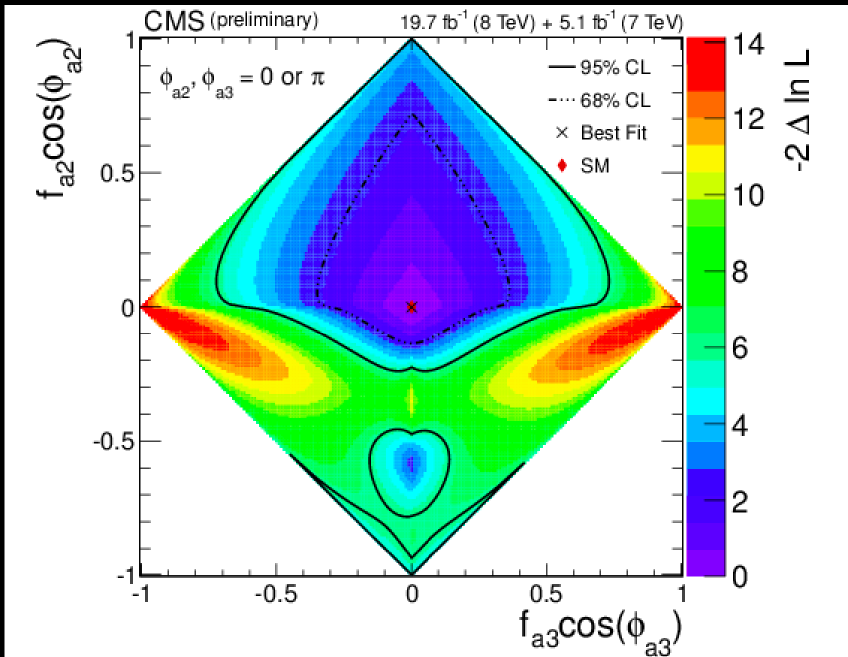
Probing a single coupling in ZZ*

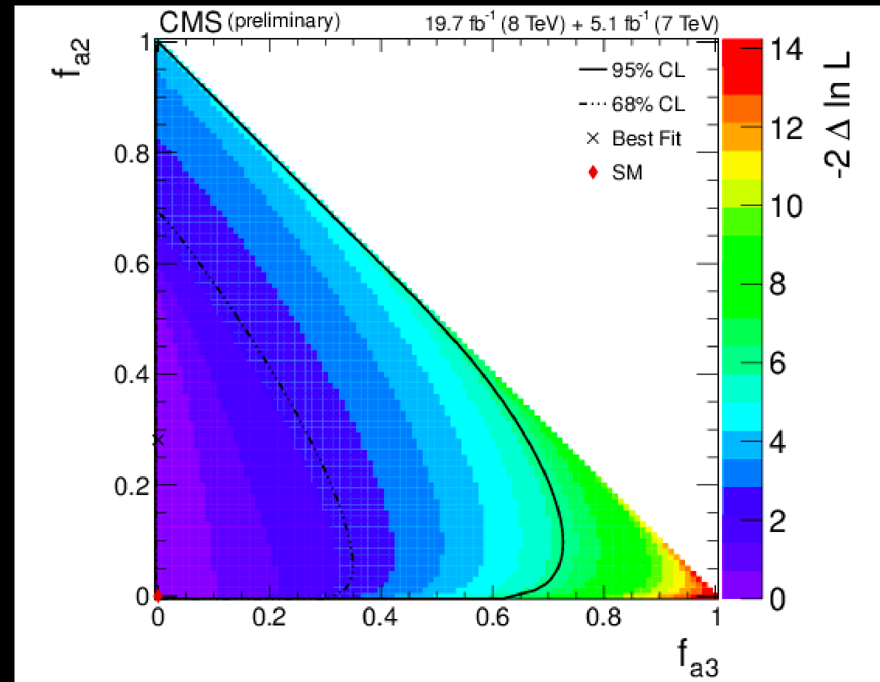
- Real phases (0 or π)
  - Good agreement between different techniques
  - Better observed exclusion in $_{fa3}$





Probing 2D couplings

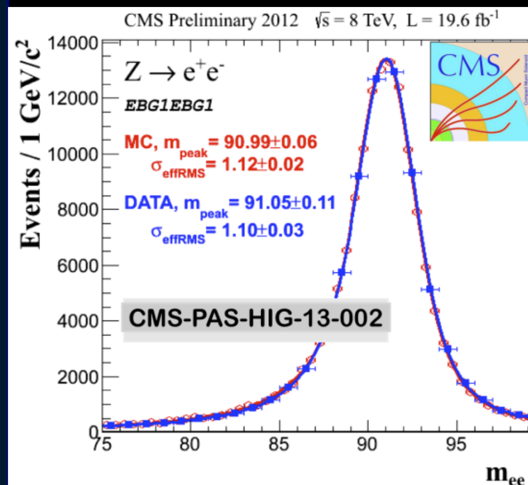


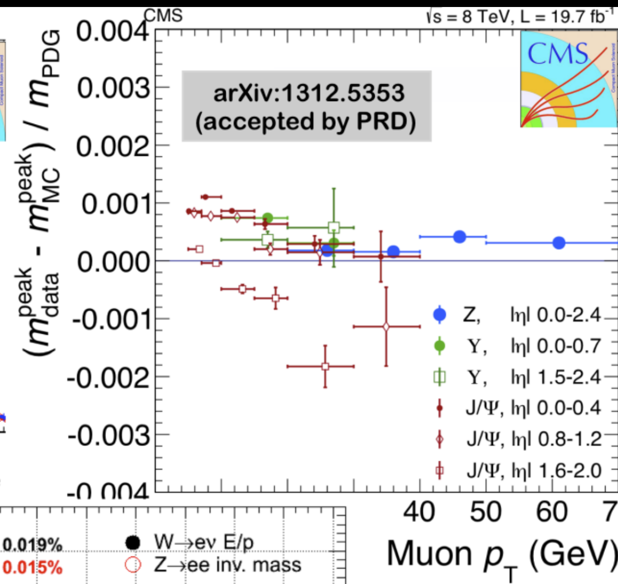


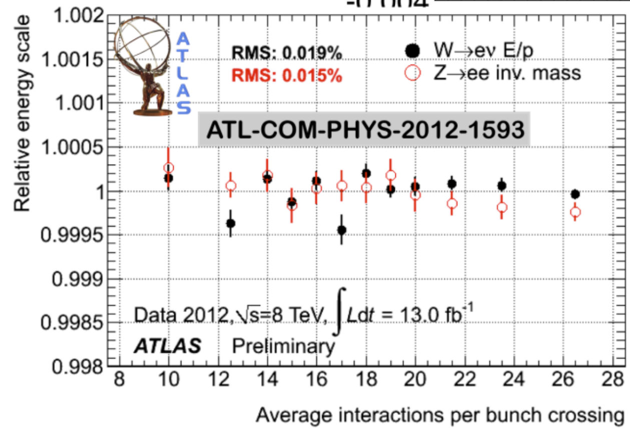
- 2D fit of f_{a2} vs f_{a3} with real phases
  - Good agreement between discriminants and multidimensional fit
- 2D fit of f_{a2} vs $f_{\Lambda 1}$ using the kinematic discriminant method
  - For real phases and after profiling the phases
  - Observations consistent with the SM

Mass resolution and scale uncertainties

- CMS: **e/γ** energy estimated using multivariate regression
- ATLAS: weighted sum of energy deposits in the different calorimeter layers
- Scale and resolution is obtained from **W; Z; J/psi** and Upsilon resonances
- Additional smearing is applied to MC to match the resolution in data
- Resulting systematic uncertainty on mass measurements is 0.5% per channel (H → γγ and H→ 4**l**)







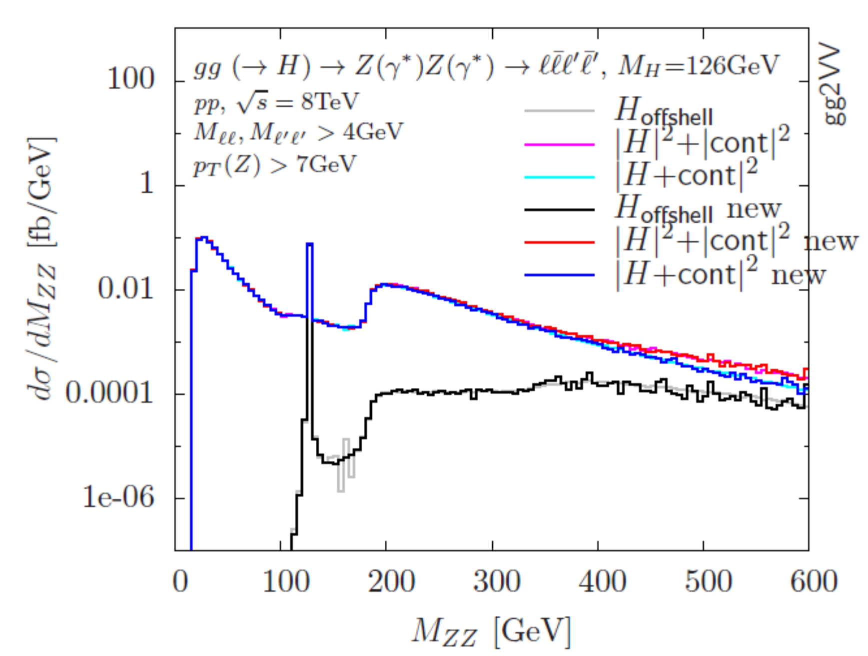
H→4l Mass Measurement

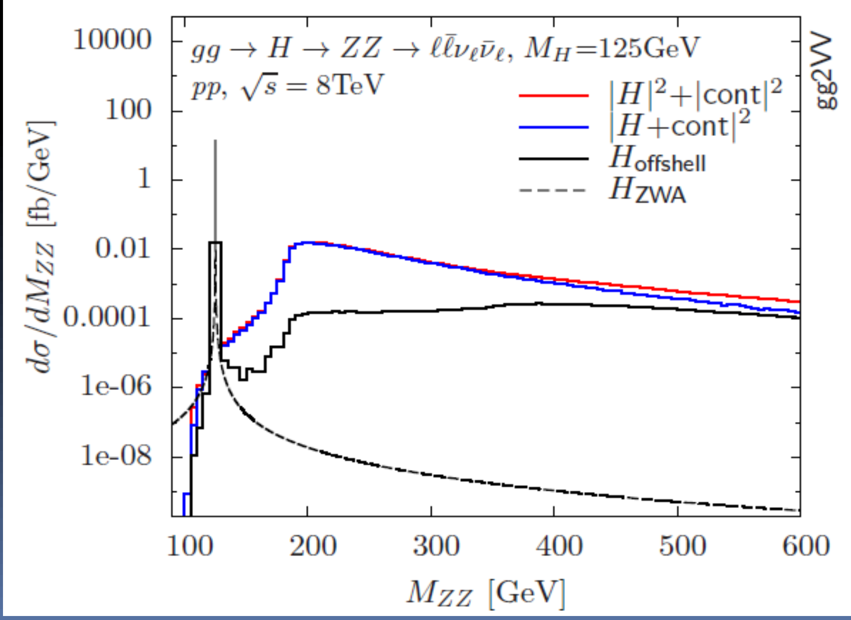
- Systematics
  - Electron energy corrections.
    - MC correction using multivariate regression (CMS) or weighted sum of energy deposits.
    - Data/MC corrections derived on $Z \rightarrow ee$ and checked with $Z \rightarrow ee$ and low-mass resonances.
  - Muon momentum scale corrections.
    - Data/MC corrections from Z → □□ + check w/ low-mass resonances.

	ATLAS PLB 726 (2013), 88-119		**CMS** arXiv:1312.5353	
Mass [GeV]	$124.3^{+0.6}_{-0.5}(stat) \pm 0.7^{+0.5}_{-0.3}(sys)$		$125.6 \pm 0.4(stat) \pm 0.2(sys)$	
Sys. Uncertainty	Electron e/p scale	0.2-0.4%	Electron e/p scale	0.1-0.3%
	Muon p-scale	0.1-0.2%	Muon p-scale	0.1%

The 4l and 2l2ν final states

- 4l final state (l = e, μ)
  - At high mass, basically only background is qq → ZZ (known at NLO, QCD uncertainties at the level of %)
  - Fully reconstructed state →can use matrix element probabilities of lepton 4-vectors to distinguish between gg and qq production
- 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller acceptance (tight p_T selection)
  - Rely on transverse mass distributions



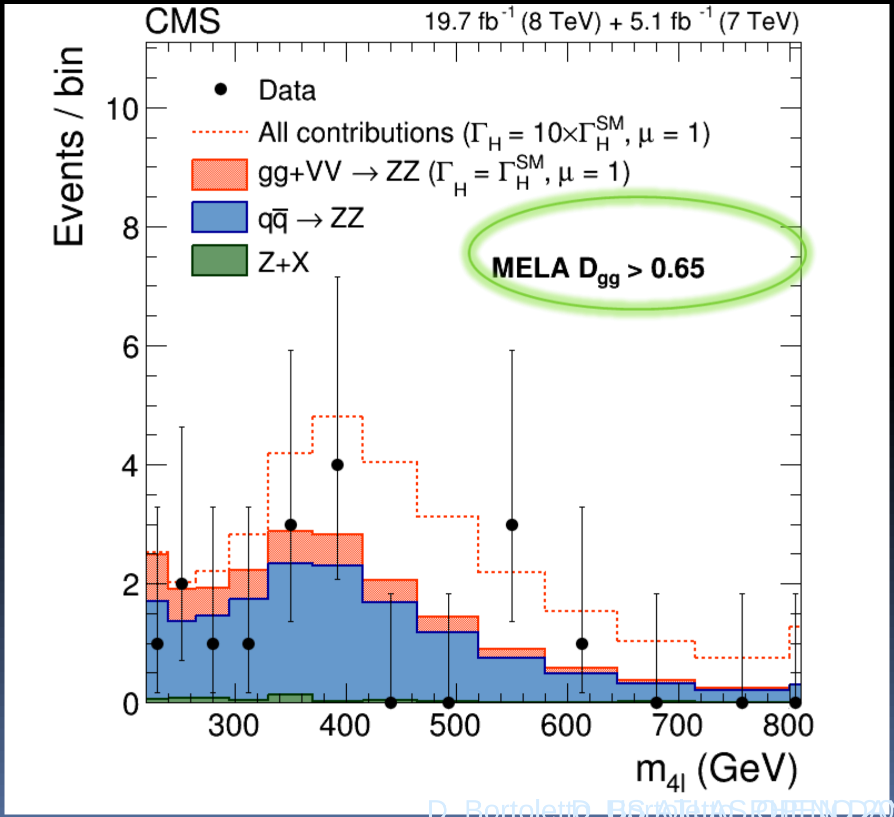


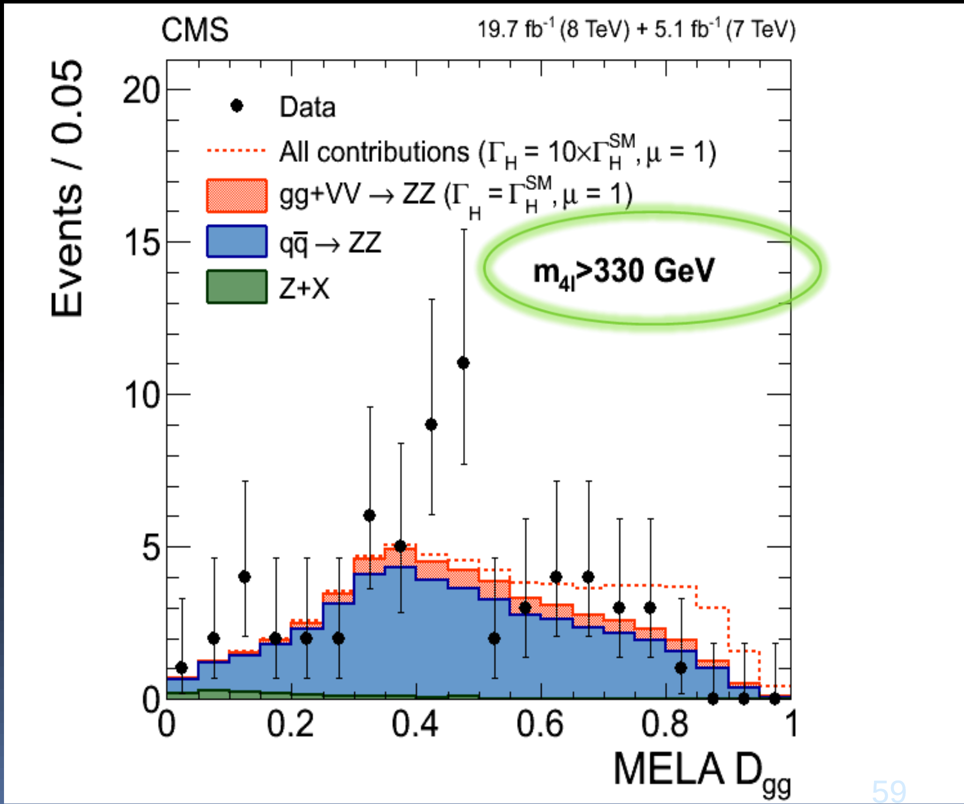
Width in H→ZZ→4l

- H→ZZ→4l analysis (arXiv:1312.5333)
- Off-shell
  - Require m(4l) >220GeV
  - NEW MELA discriminant using with 7 kinematics variables (m_{Z1}, m_{Z2}, five angles) to distinguish between gg → ZZ production (signal background and interference) vs qq → ZZ

$$\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}}$$

a=10 [a=1 for SM]

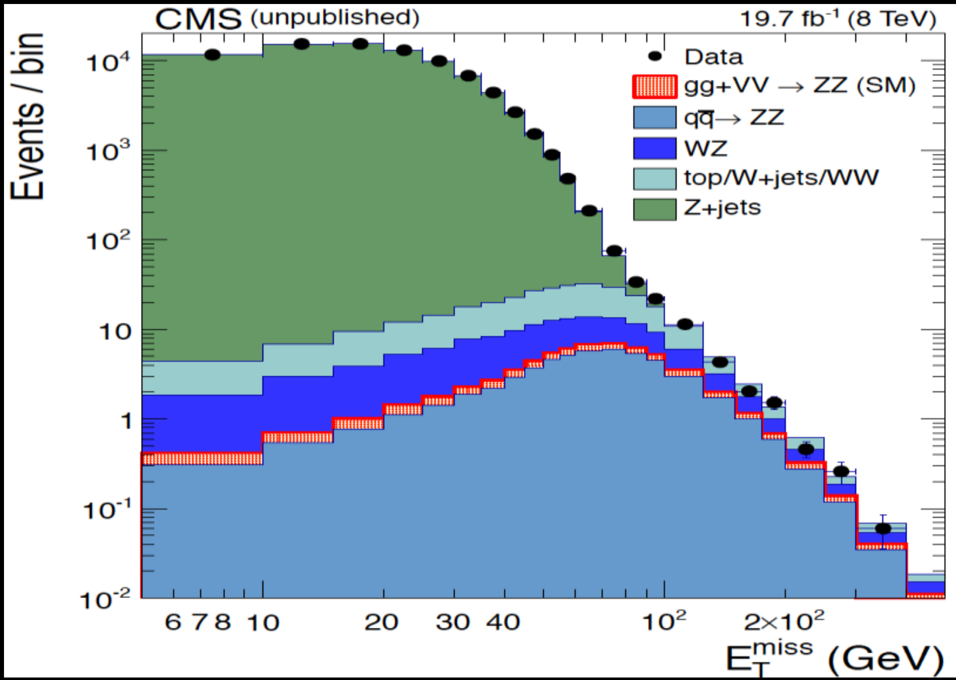


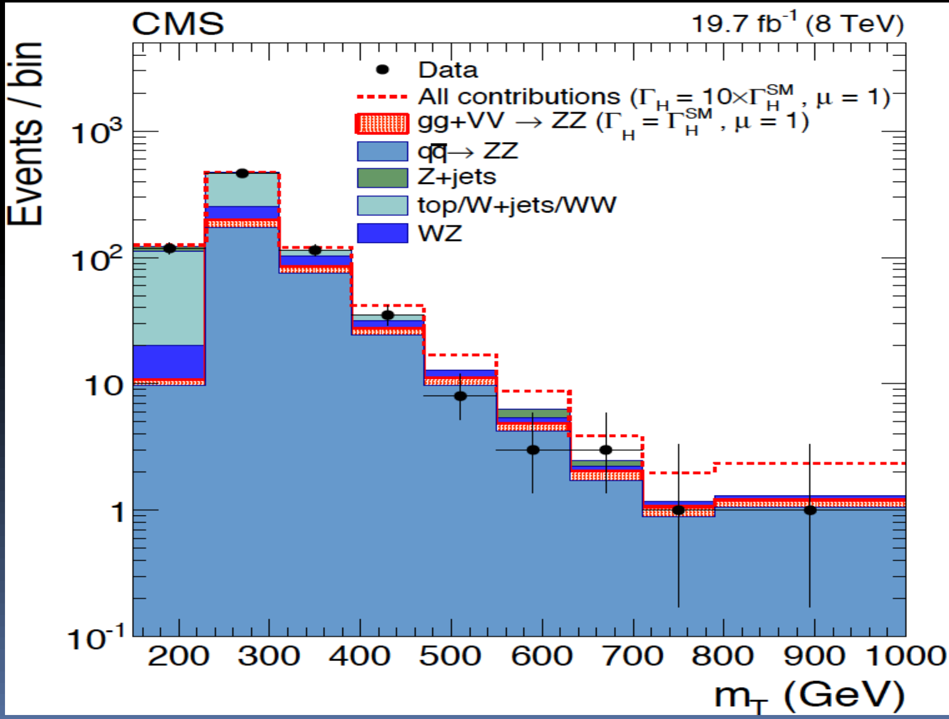


ZZ→2l2nu off-shell

- Analysis technique as in high mass Higgs search (CMS-PAS-HIG-13-014)
- BR(ZZ→2l2nu) = ~6x BR(ZZ→4l)
- Larger backgrounds compared to 4l channel → Data-driven estimation
- Selection
  - isolated leptons (p_T>20GeV)
  - OS / SF lepton pair (compatible with a Z)
  - $E_{T,miss}$ > 80 GEV (from neutrinos)
  - Transverse mass : m_T>180 GeV
- m_T distribution (inclusive in #Jets) is used as the final variable entering the likelihood fit

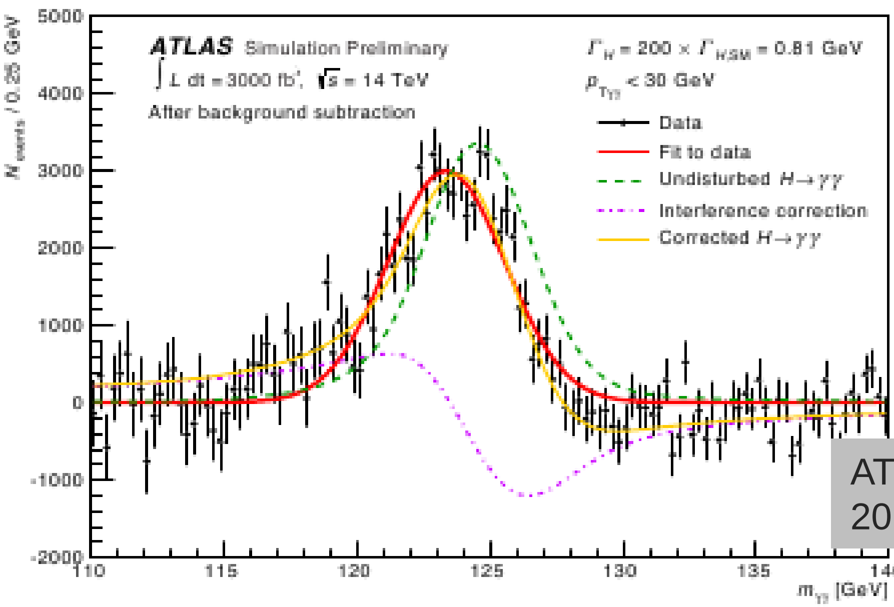
$$m_T^2 = \left[\sqrt{p_{T,2\ell}{}^2 + m_{2\ell}{}^2} + \sqrt{E_T^{miss\,2} + m_{2\ell}{}^2}\right]^2 - \left[\vec{p}_{T,2\ell} + \vec{E}_T^{miss}\right]^2$$

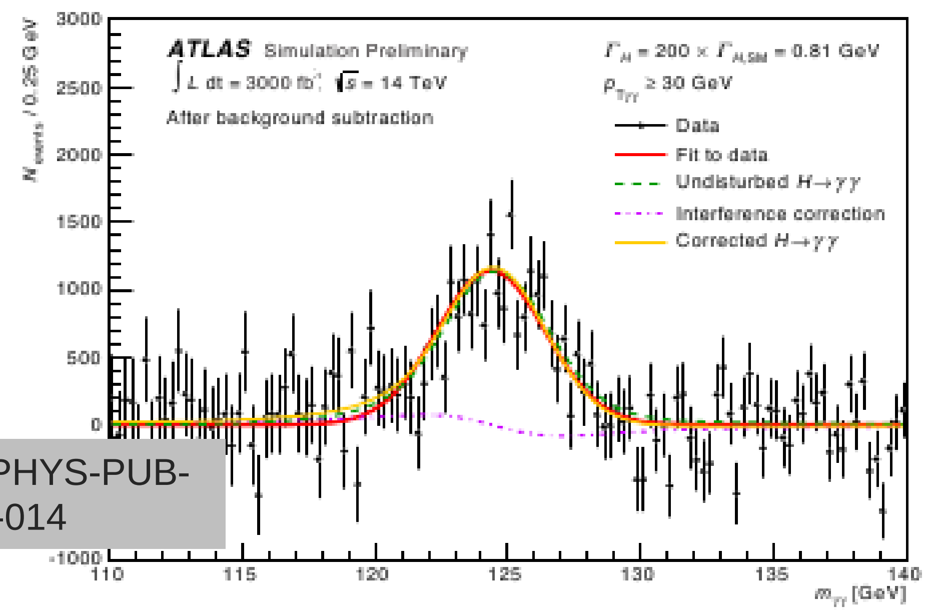




Interferometry - di-photon

- Can also exploit destructive interference between gg → □□ and gg → H → □□.
- Generate effective mass shift, which magnitude varies as a function of the boson p_T.
- Constraint of the width from measurement of m_H vs p_{TH}.
- Projected sensitivity for $3ab^{-1}$ □ < 30 $□_{SM}$ (95% CL).

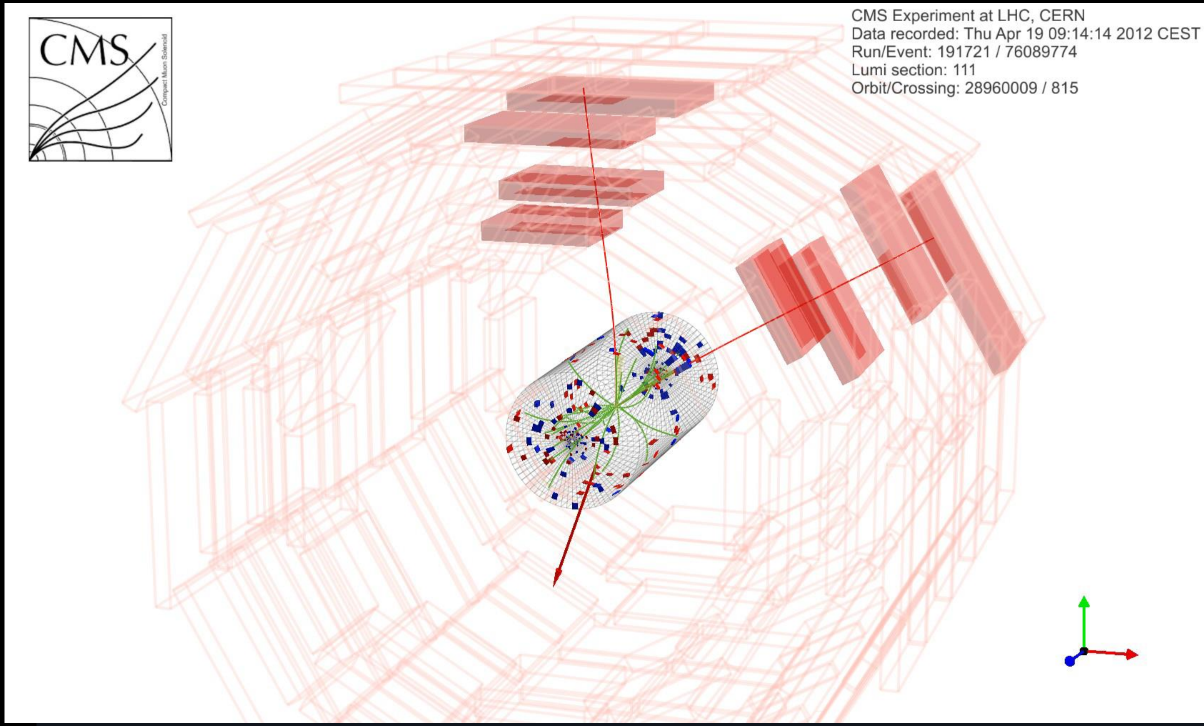




ATL-PHYS-PUB-2013-014

J^P in $H \rightarrow WW \rightarrow l\nu l\nu$

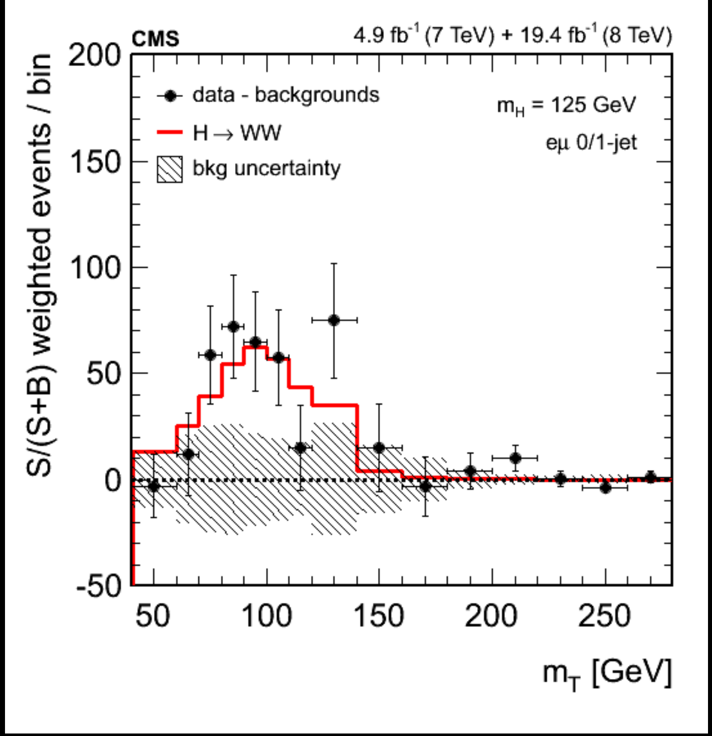
- Distinct signature:
  - Two high p_T leptons
  - Missing transverse energy.
- Large branching fraction.
- Poor mass resolution.
- Large backgrounds.
- Angular correlation between final state leptons provides information on the polarization of the resonance.

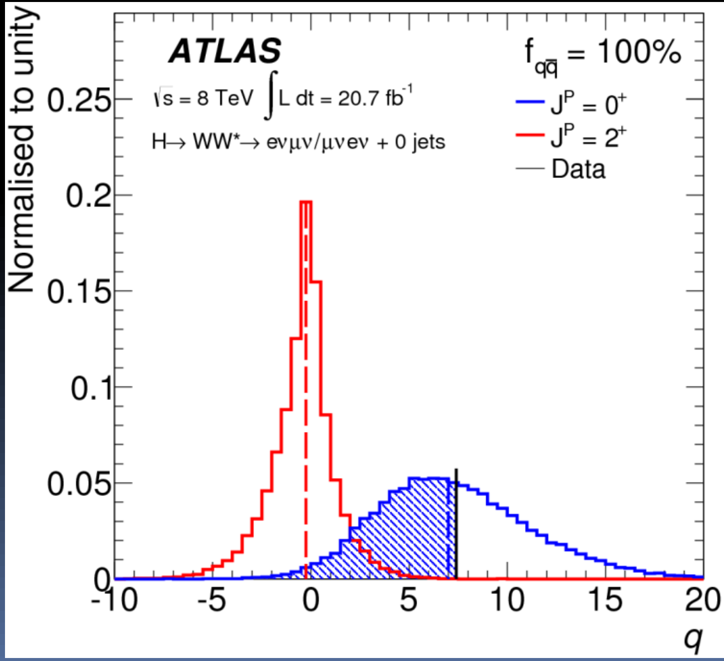


- Challenges:
  - Missing energy resolution.
  - Background modeling

J^P in $H \rightarrow WW \rightarrow l\nu l\nu$

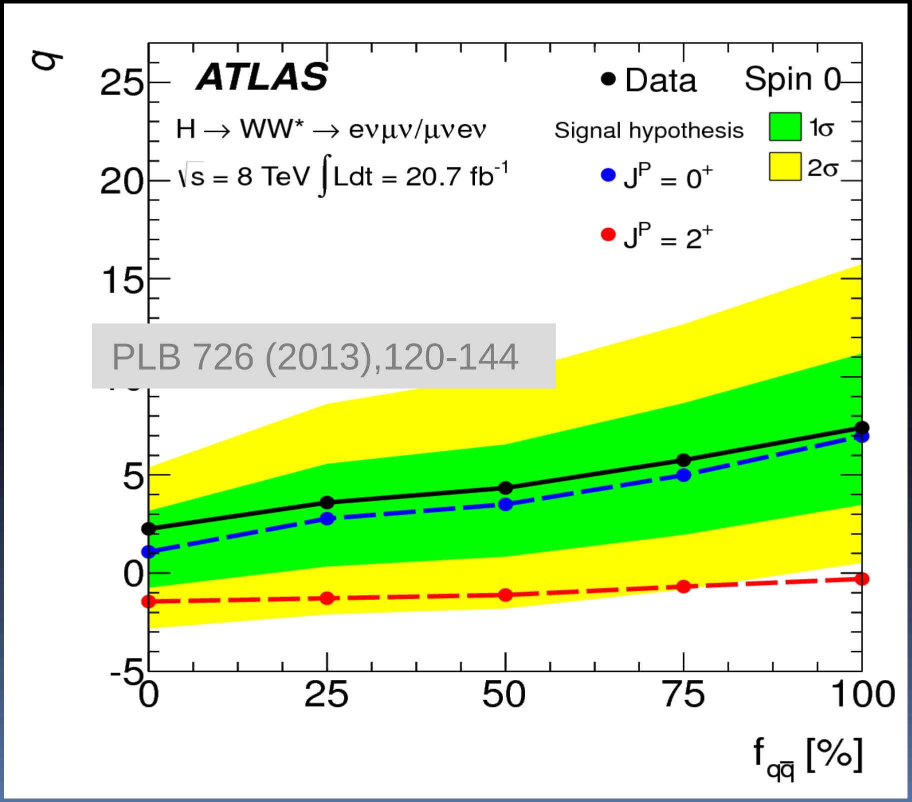
- Analysis strategy:
- Select two high p_T, different flavor leptons plus missing E_T.
  - CMS: categorize events in 0 and 1 jet bins
  - ATLAS: no categorization in number of jets.
- Hypothesis test from 2D template fit to data:
- CMS: m_{ll} vs m_T
- ATLAS: use two BDT discriminants (□□$_{ll}$, m_{ll}, m_T)
  - DT0 (discriminate SM from background)
  - BDTalt (discriminate alternative hyp from background).
- Tested alternative models:
  - CMS: 2+m "graviton-like" and 0^-.
  - ATLAS: 2+ m "graviton-like".
  - For 2+ m model both qq, gg production modes (and mixtures) are considered.

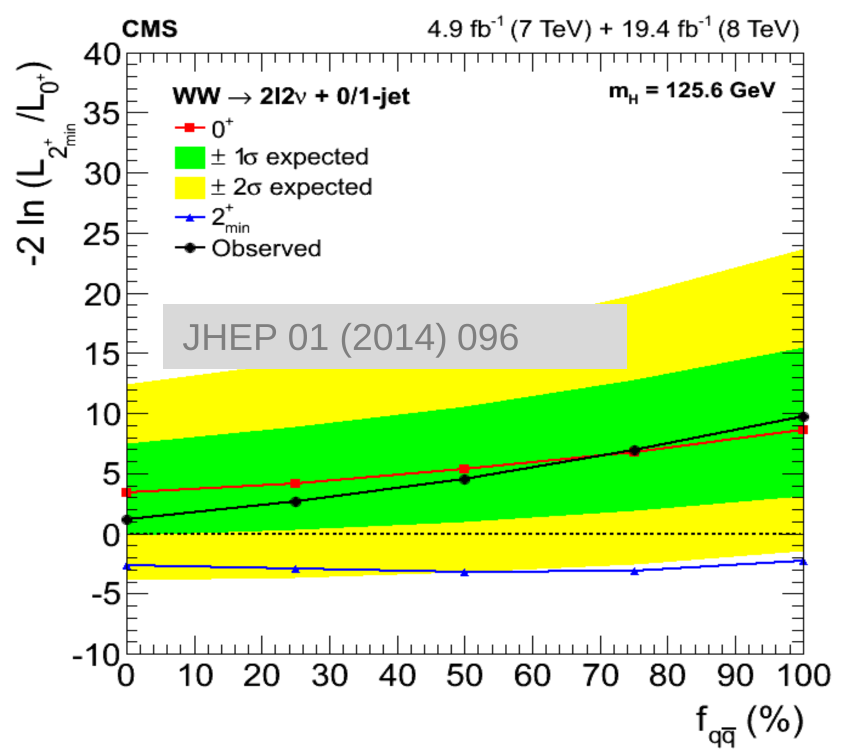




J^P in H→WW→lνlν

- Expected (post-fit) exclusion for 2+m model 1-CLs > 0.94.
- In CMS, 0- expected (post-fit) exclusion 1-CLs = 0.72.
- Observed results favor SM hypothesis.





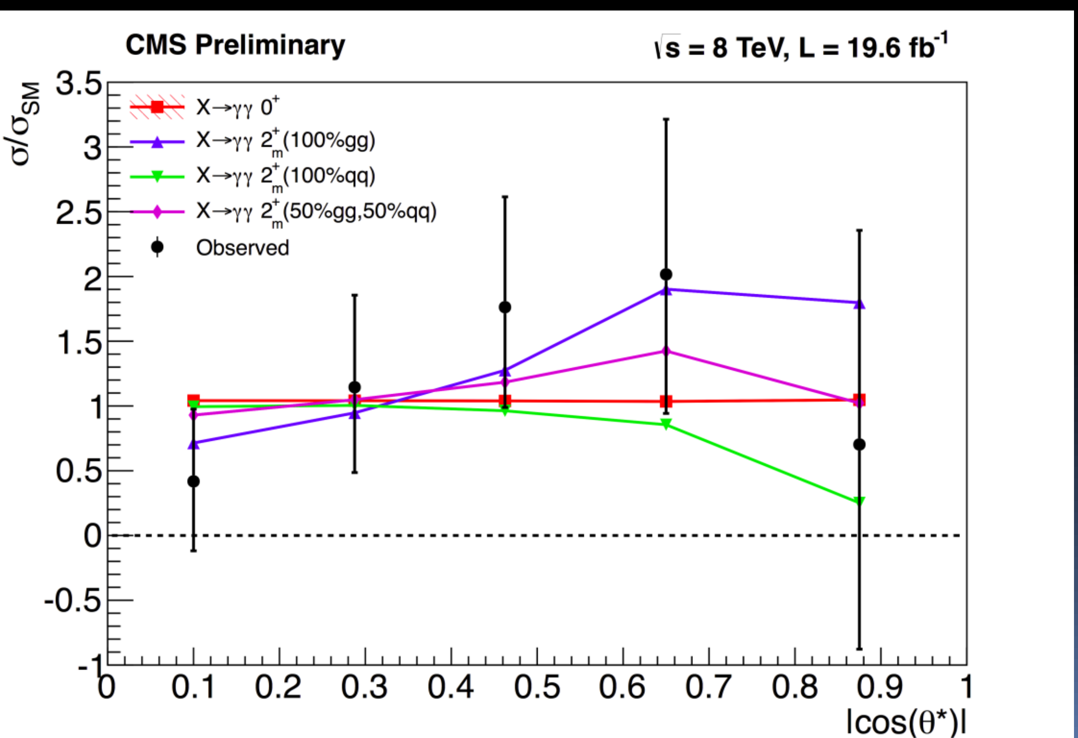
J^P in H→γγ

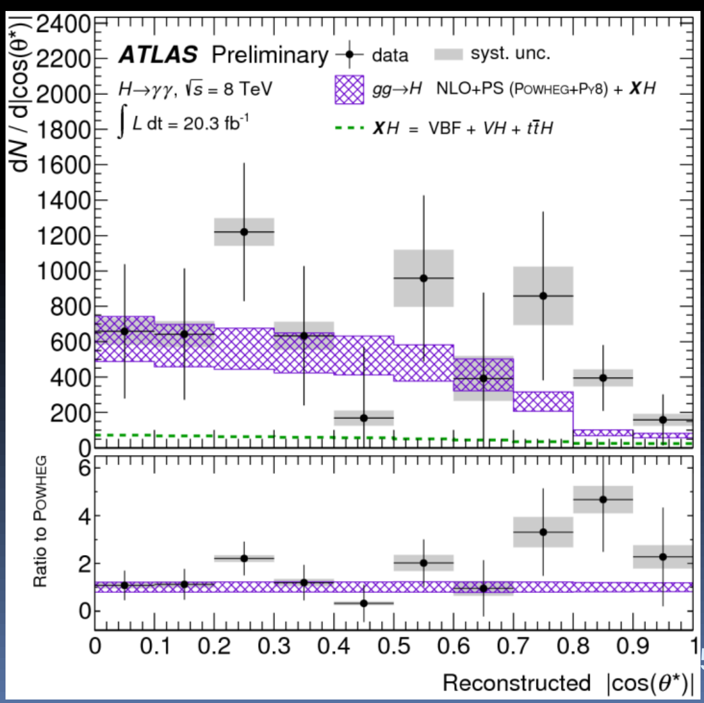
- Distribution of production angle sensitive to spin/parity.
- Event selection similar to mass analysis.
- ATLAS: no categorization in photon kin. or resolution
- CMS: simple 4 categories cut-based categorization
- Hypothesis test:

$$\cos\theta^* = 2\frac{E_2 p_{z_1} - E_1 p_{z_2}}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + p_{T\gamma\gamma}^2}}$$

- CMS: simultaneous fit to m□□ in 5 cos(□*) bins

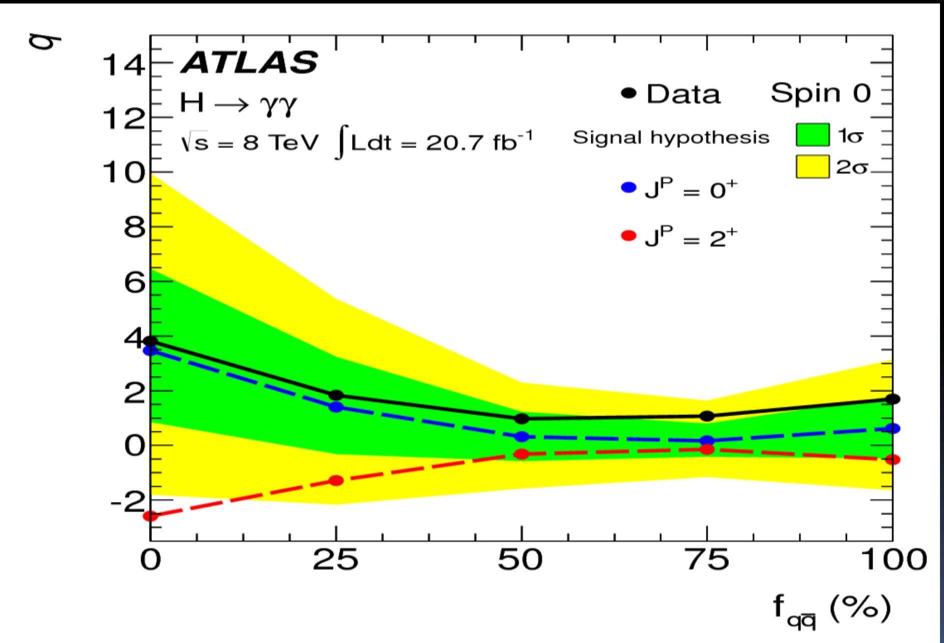
- ATLAS: 2D fit of cos(□*) vs m□□

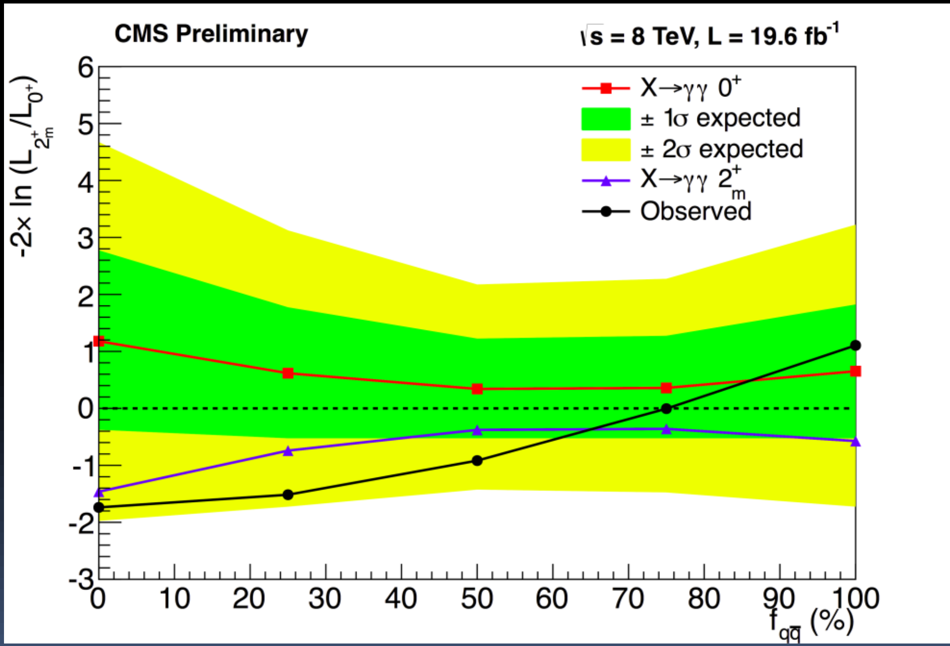




J^P in $H\to\gamma\gamma$

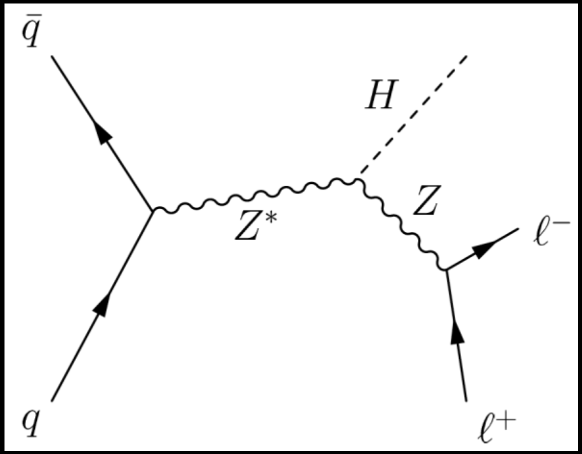
- Post-fit) Expected separation: 1-CLs > 17(55)-60(99)% for CMS
- (ATLAS).
- Better sensitivity for ATLAS analysis partially driven by higher observed excess.
- SM hypothesis generally favored in data.

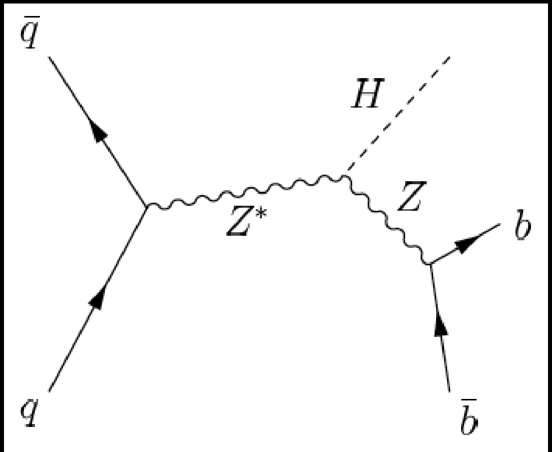


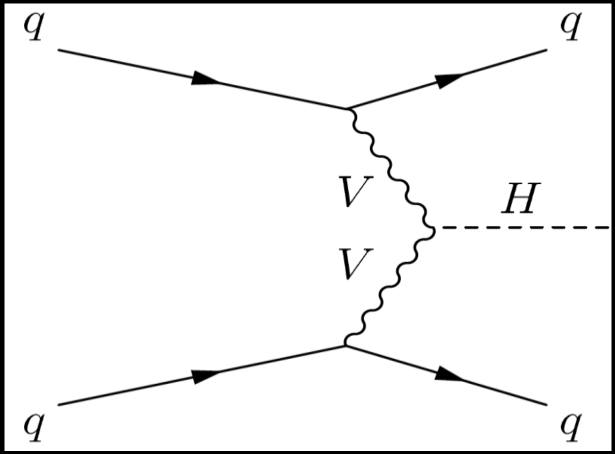


Invisible Higgs decays

- Look for decays of Higgs boson to weakly interacting particles B(H→inv**)** using VBF and ZH production.



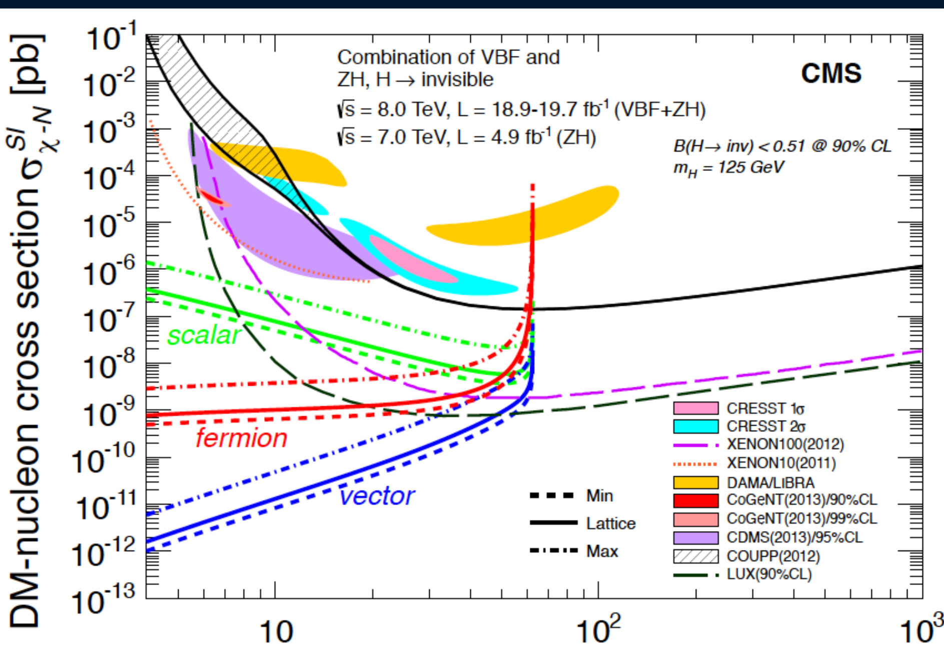




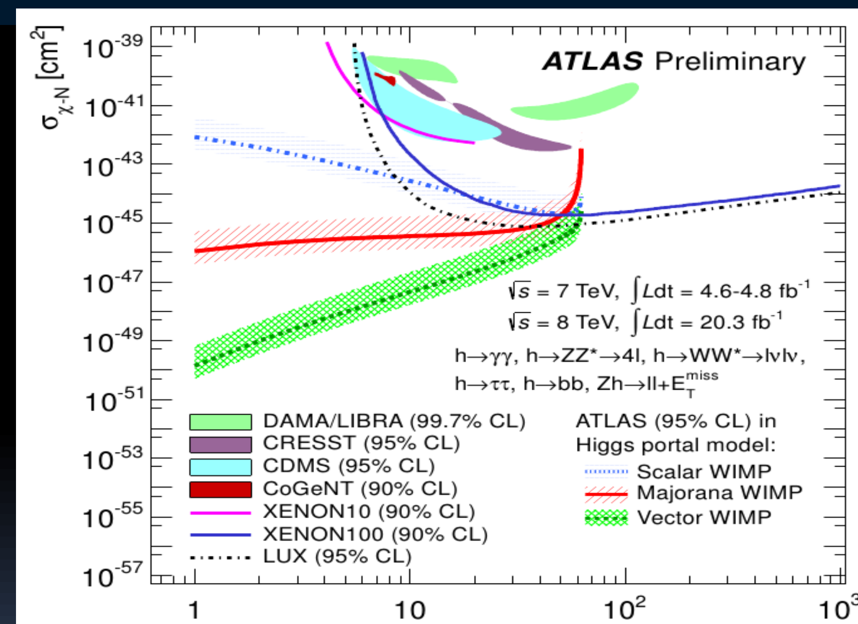
- Complementary to direct searches for dark matter.
  - Exploited channels:
    - ATLAS: Z(ll) + MET
    - CMS: Z(ll,bb) + MET, VBF + MET
- Direct constraint on B(H→inv**)** can also be obtained from global fit of measured decay modes

Invisible Higgs Decay

- CMS:
  - combination of Z(ll)+ MET, Z(bb)+MET and VBF + MET searches yields
  - Observed (expected) **B(**H→inv**)/**□$_{SM}$ <0.58 (< 0.44) @ 95% CL
- ATLAS:
  - Combination of direct and indirect results
  - Observed (expected) limit B(H→inv**)** <0.41(0.55) at 95% CL



CMS-HIG-13-030



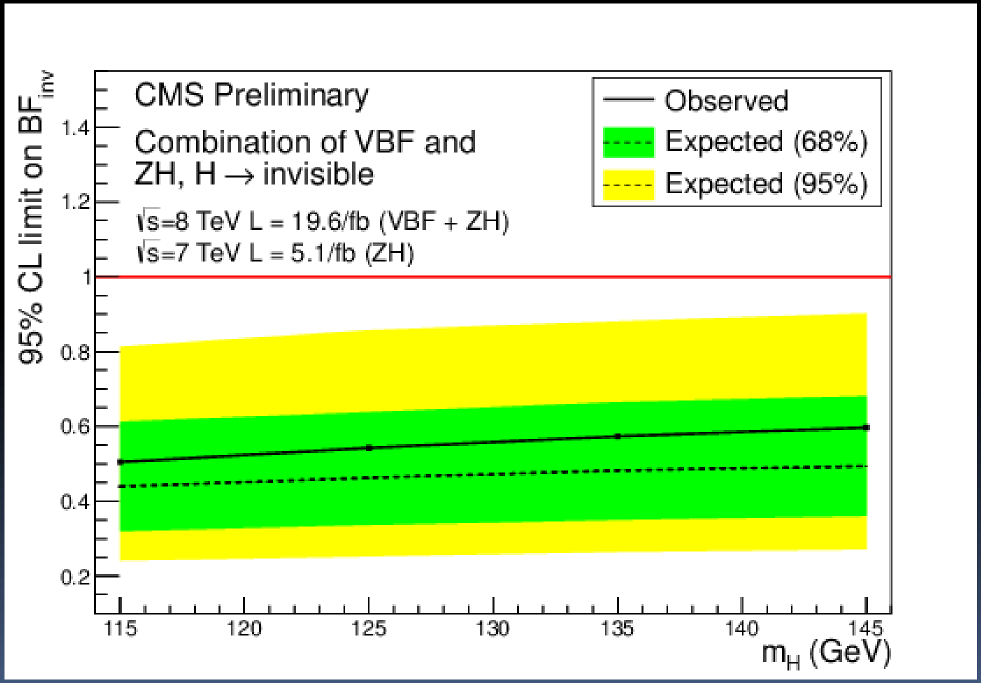
ATLAS-CONF-2014-010

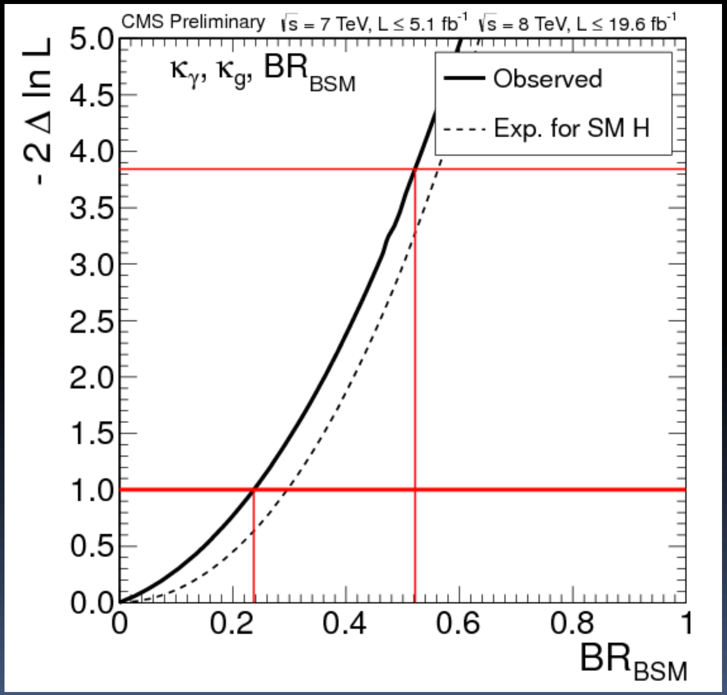
- Re-Interpret B(H→inv**)** limit in Higgs-portal model:
  - DM sector decoupled from SM, except for Higgs-mediated interactions with mχ < $m_{H/2}$

- Djouadi, A. Falkowski, Y. Mambrini, and J. Quevillon
- B. Patt and F. Wilczek

Direct and indirect constraints

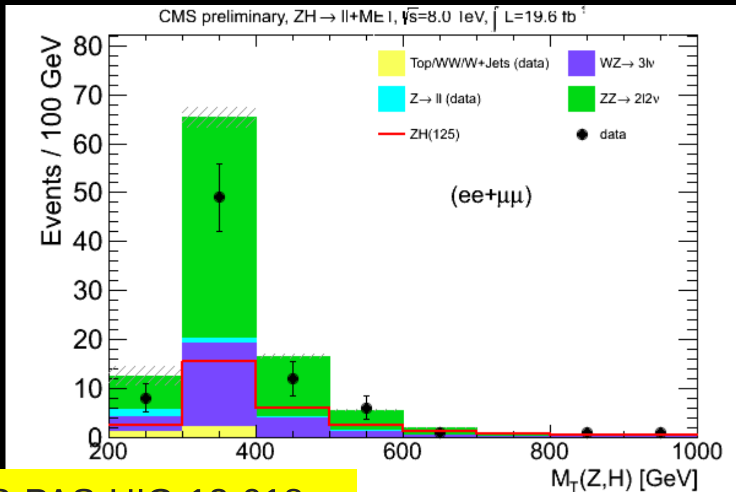
- Indirect constraint on BRinv can also be obtained from global fit of measured decay modes.
- Fixing unmeasured modes to SM predictions and assuming k_V<1.
- Direct and indirect limits have comparable magnitudes

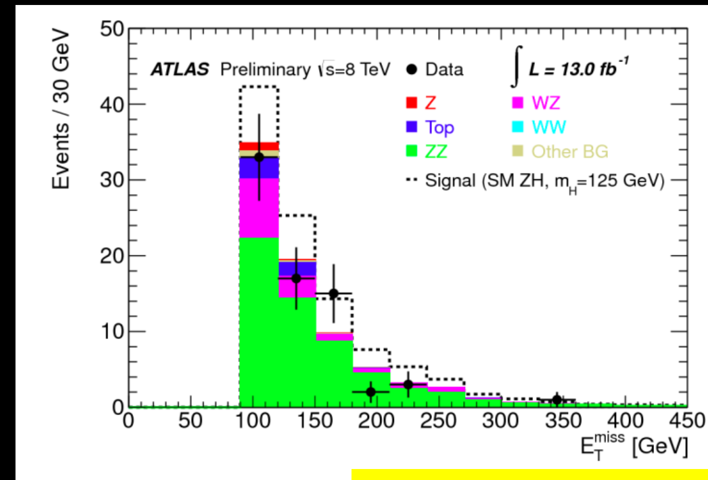




CMS-PAS-HIG-13-005

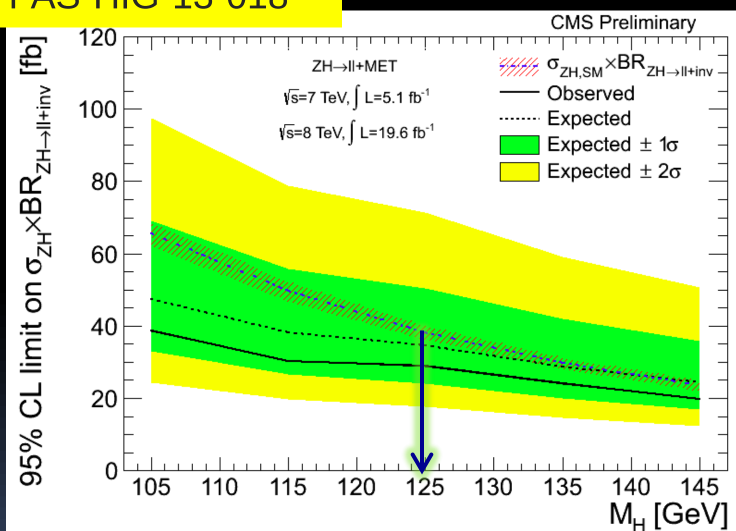
ZH →ll+invisible

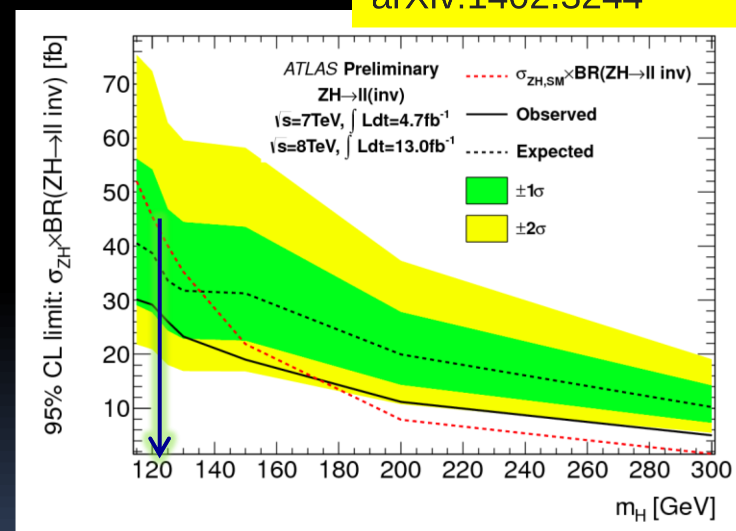




CMS-PAS-HIG-13-018

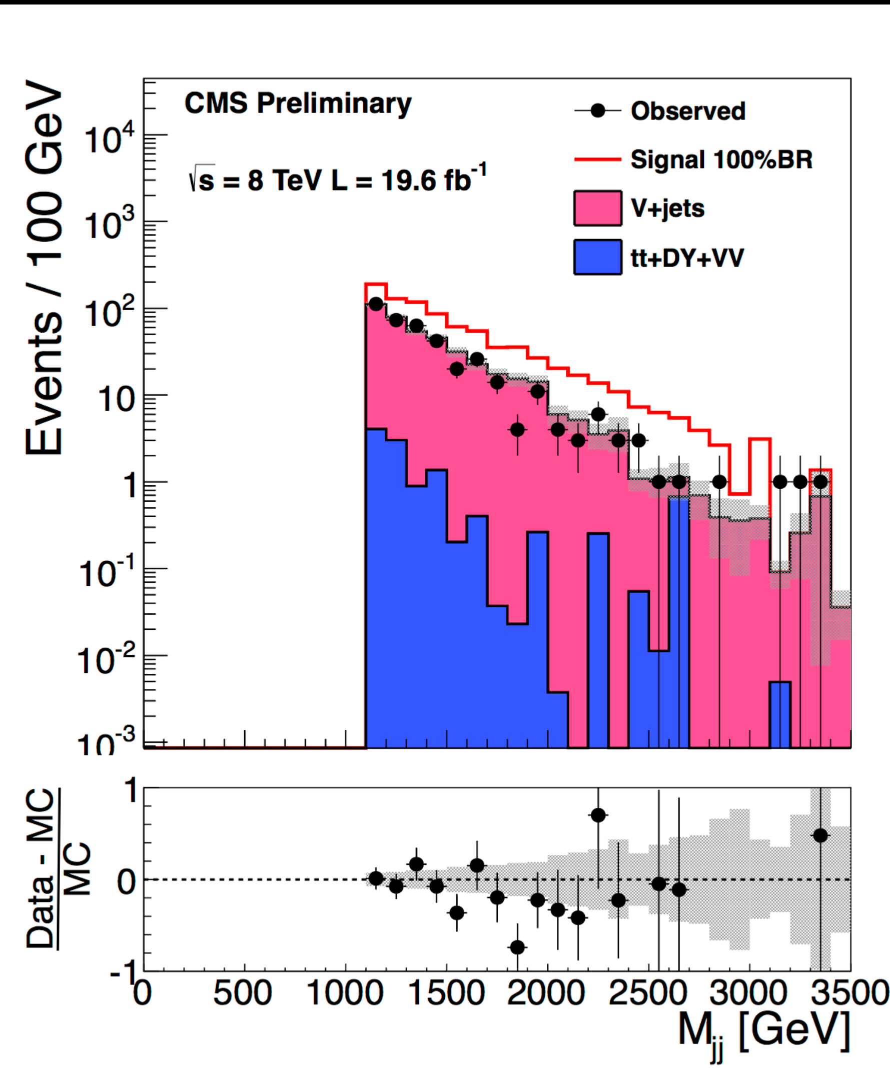
arXiv:1402.3244



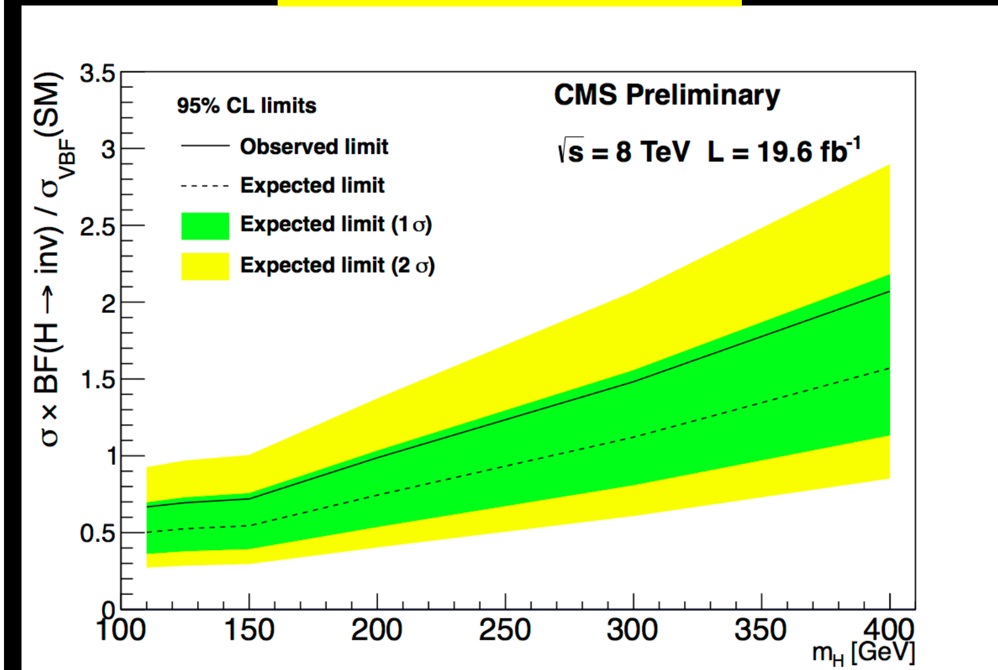


Observed (expected)	**CMS**	**ATLAS**
B(H→inv) at 125 GeV @95% CL	< 0.75 (0.91)	< 0.65 (0.84)

VBF H →Invisible

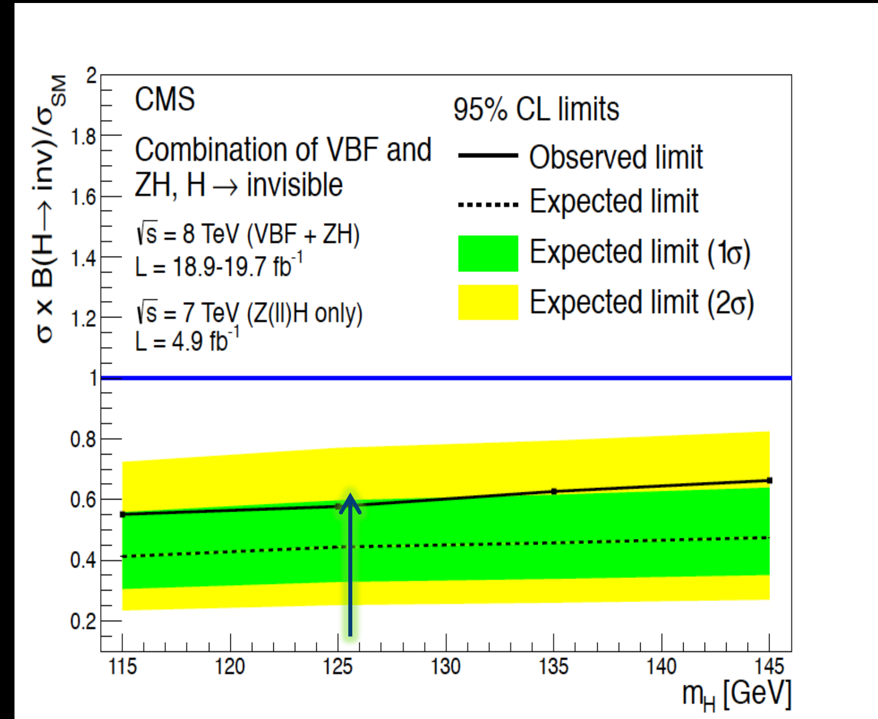


CMS-PAS-HIG-13-013

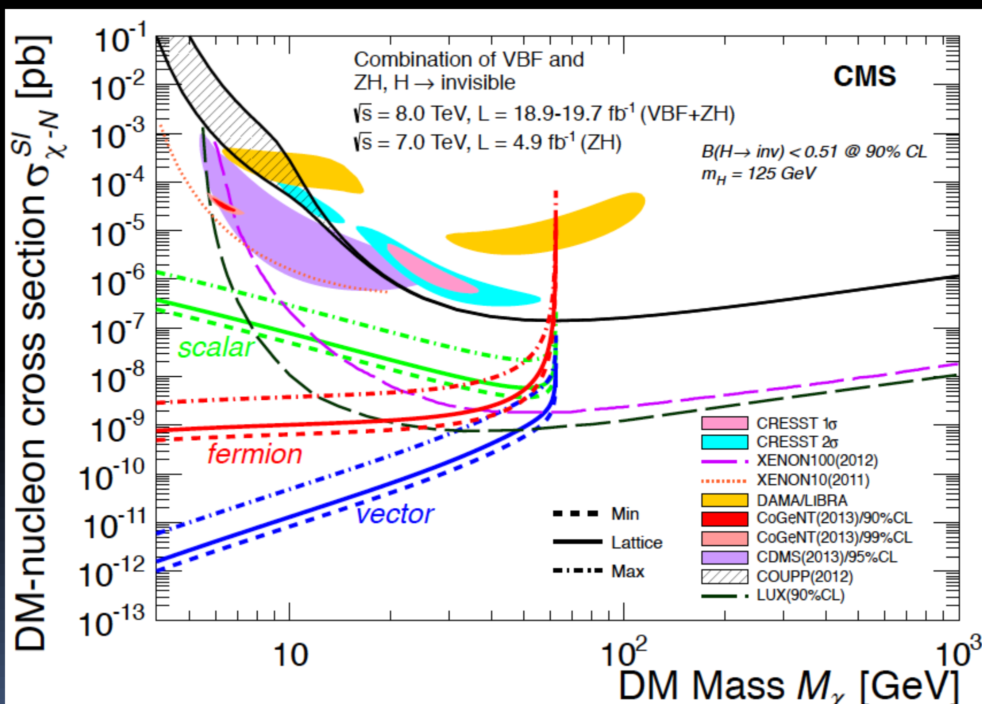


- At m_H=125 GeV observed (expected) limits at 95% CL on □ x **B(**H→inv**)** / $□_{SM}$ < 0.69 (0.53) at 95%CLs

CMS combination



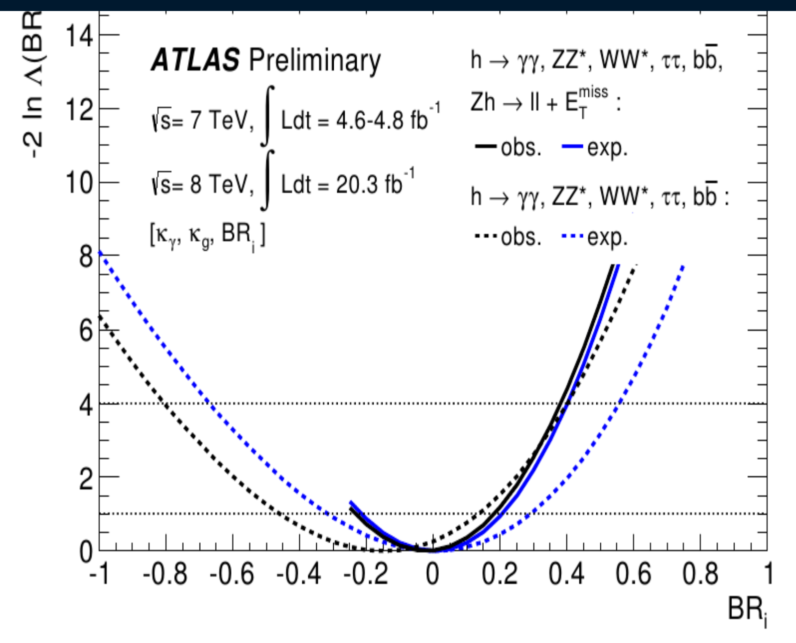
- Three individuals CMS searches combined assuming the SM production cross section and acceptance
- **B(**H→inv**)/** $\square_{SM}$ <0.58 (< 0.44) observed (expected) @ 95% CL



- **B(**H→inv**)** for **m_H =** 125 GeV used to obtain upper limits at 90% CL on the DM-nucleon cross section as a function of the DM mass in Higgs-portal models of DM interactions
  - Djouadi, A. Falkowski, Y. Mambrini, and J. Quevillon
  - B. Patt and F. Wilczek

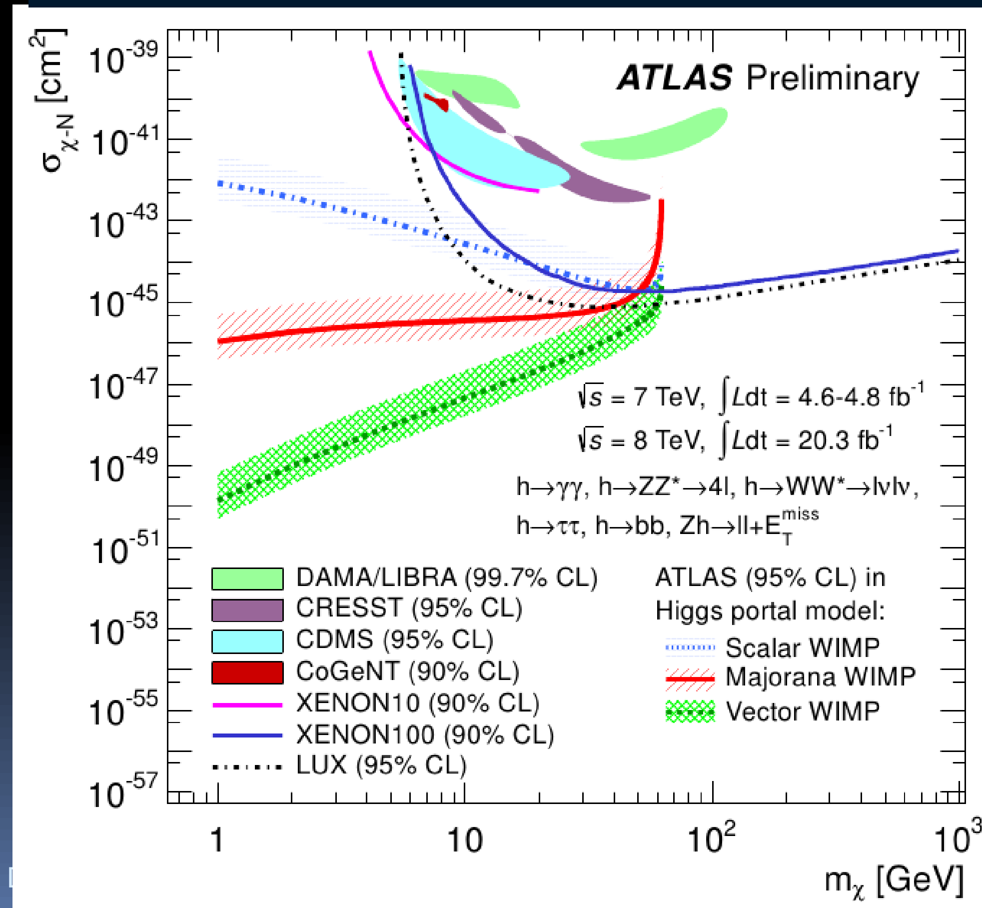
Invisible decays and dark matter

- Indirect constraint on B(H→inv) can also be obtained from global fit of measured decay modes.
- Combination of direct and indirect results
- Observed (expected) limit B(H→inv) <0.41(0.55) at 95% CL



ATLAS-CONF-2014-011

- Interpret limit on B(H→inv) as direct bounds on massive dark particles with $m_\chi < m_{H/2}$ coupling to the Higgs
- Interpretation in Higgs-portal model:
  - DM sector decoupled from SM, except for Higgs-mediated interactions

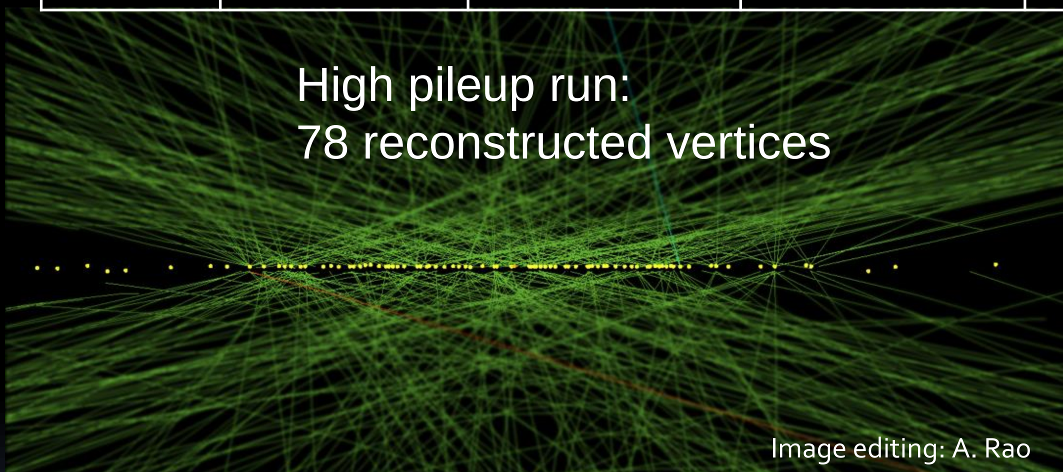


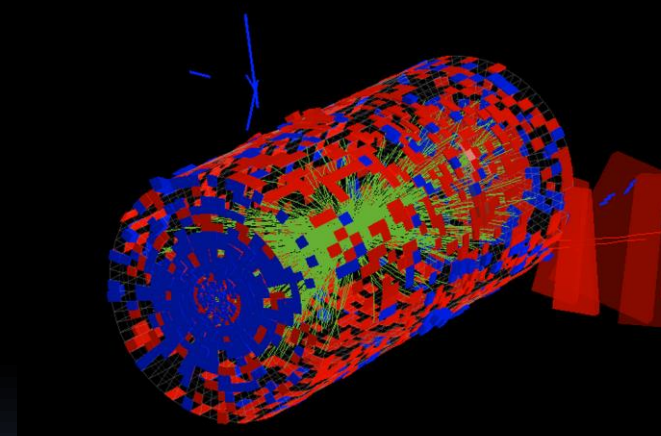
…and the future

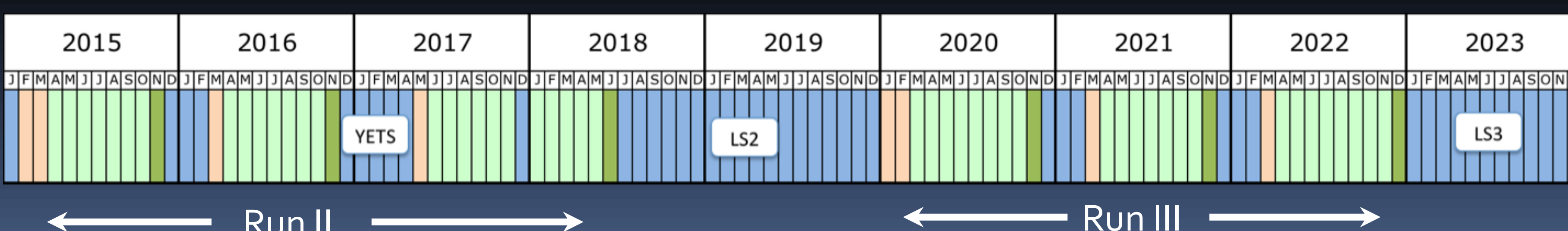
- Precision measurements of Higgs boson properties are a major goal for experimental particle physics and the Large Hadron Collider program
- LHC plans for collecting 300 fb^{-1} or more through 2022
- HL-LHC could deliver 3000 fb^{-1} by end of 2035
- Strong potential for precise studies of Higgs boson properties
- Precision signal strength and coupling measurements
- Higgs self-coupling
- Rare decays: $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$
- BSM Higgs searches
  - Undetectable in SM: $H \rightarrow$ inv.
  - Additional heavy Higgs bosons

LHC: Now through Run III

	CM Energy	Peak $\langle N_{PU} \rangle$	Bunch spacing	Peak inst. lumi.	Cumulative int. lumi.
Run I	7-8 TeV	up to 35	50 ns	7.7×10^{33} cm^{-2} s^{-1}	29.5 fb^{-1}
Run II	13-14 TeV	~40	25 ns	1.5×10^{34} cm^{-2} s^{-1}	~100 fb^{-1}
Run III	14 TeV	~60	25 ns	$\sim 2.0 \times 10^{34}$ cm^{-2} s^{-1}	~300 fb^{-1}

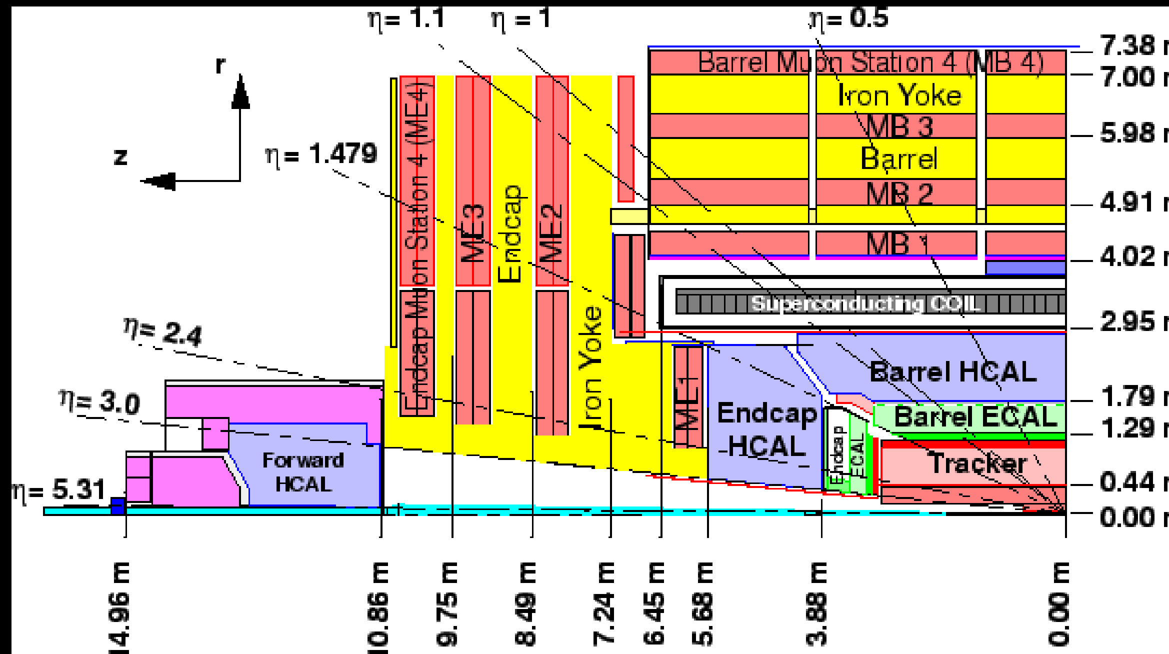






CMS: Phase I and Phase 2 Upgrades

Phase I Upgrades



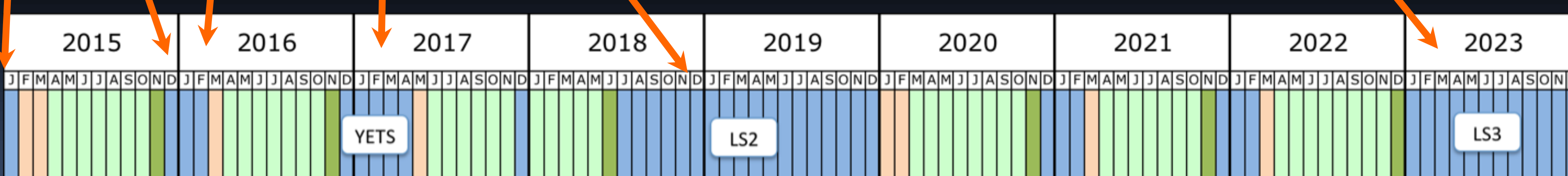
"Slices" of later upgrades already being installed

HCAL photodetector/ electronics upgrades Forward Barrel/Endcap

New L1 Trigger Systems

Replace Pixel Detector

Phase II Upgrades



Run II

Run III

HL-LHC

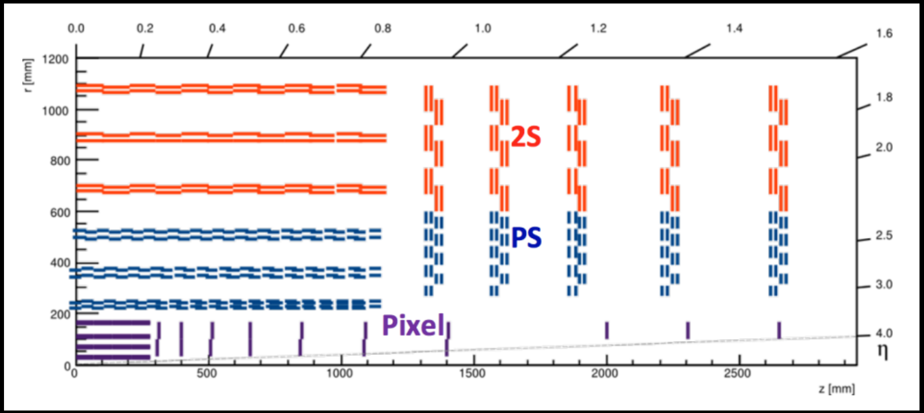
- Upgrade of LHC and injectors to achieve luminosity of 5 $\times 10^{34}$ cm^{-2} s^{-1}
- $\langle N_{PU} \rangle \sim 130$, 25 ns spacing, luminosity leveling and interaction region

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

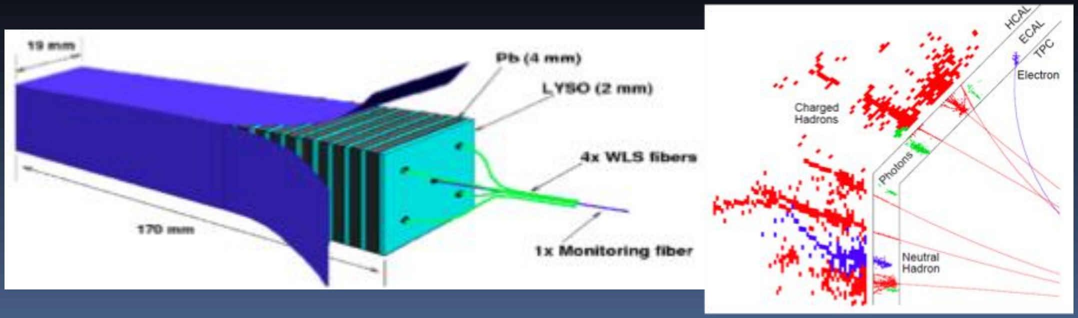
CMS Phase II Upgrade

- Overall goals
  - Replace detector components with significant radiation damage
  - Maintain good performance with high luminosity
- Tracker upgrade
  - Triggering capability
  - Extend to |η| < 4.0
- Replace Forward Calorimeter
  - Shashlik (crystal scintillator) + HE with more fibers, rad-hard tiles
  - HGCAL - high-granularity calorimeter building on ILC R&D

Tracker upgrade



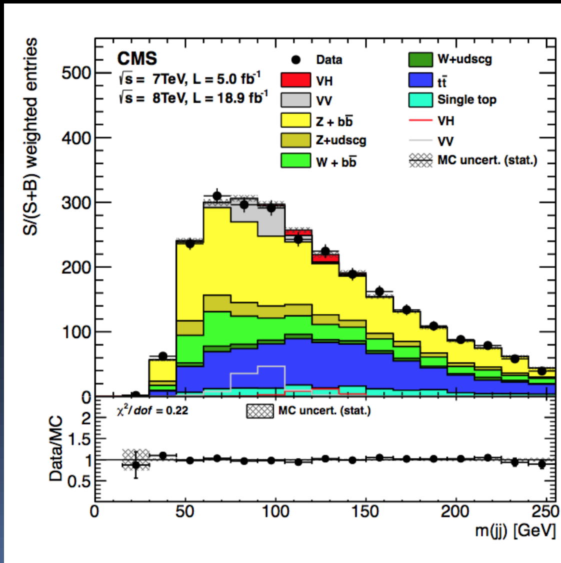
- Muon system extension

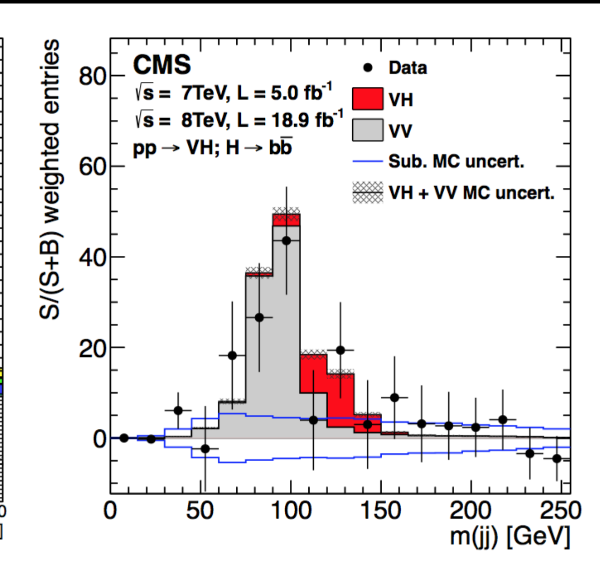


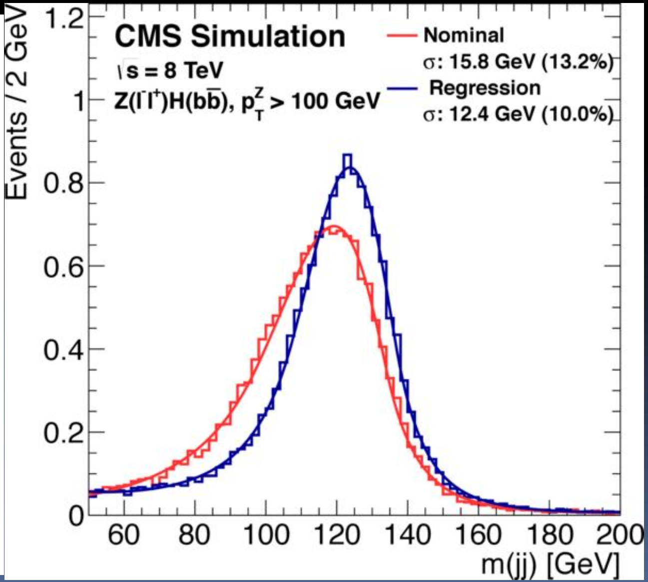
Calorimeter upgrade options:

Extrapolation: Caveats

- Estimate of CMS performance at HL-LHC: extrapolate from numbers of signal and background events in current analyses, scale statistics
- Two scenarios for systematic uncertainties:
  - All remain the same as Run I
  - Appropriate experimental systematics as $1/\sqrt{L}$, theory scaled to 1/2
- Procedure assumes that object resolutions can be maintained
  - *Example*: $H \to bb$ relies on narrow m(bb) to maximize S/B
  - Extrapolated performance can only be achieved in the LH-LHC environment through <u>combination</u> of upgraded detectors and new reconstruction techniques
- New channels or optimizations for high luminosity are neglected

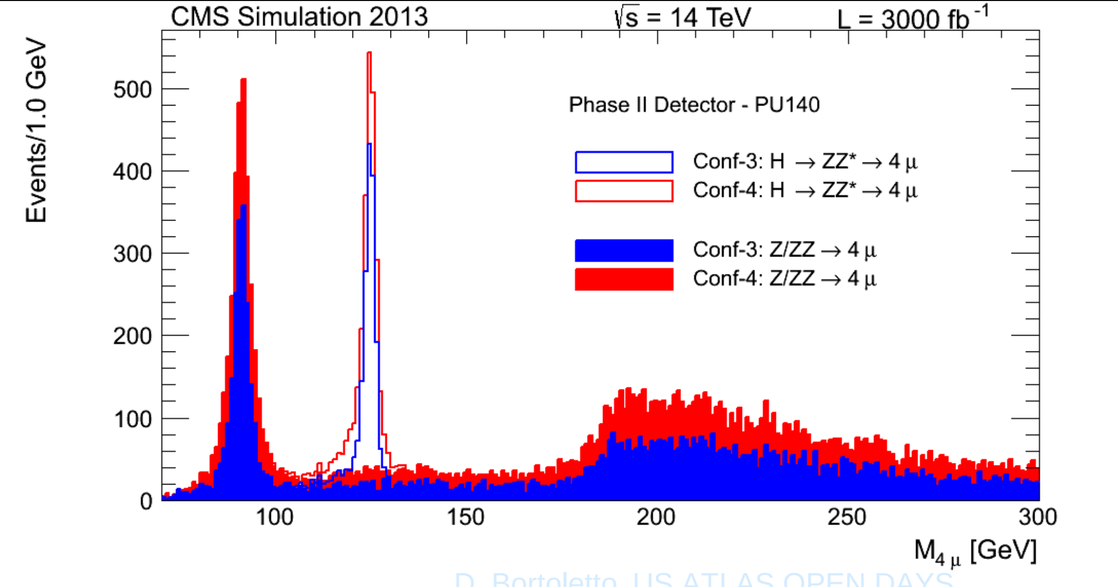


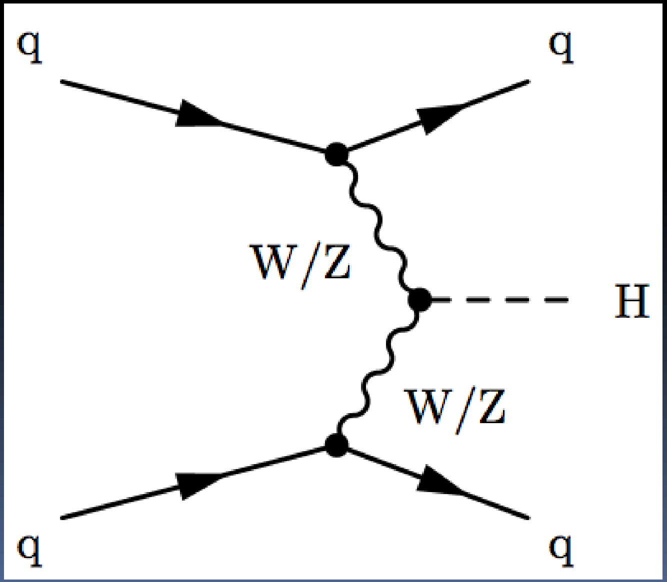




Tracker/Muon Extension

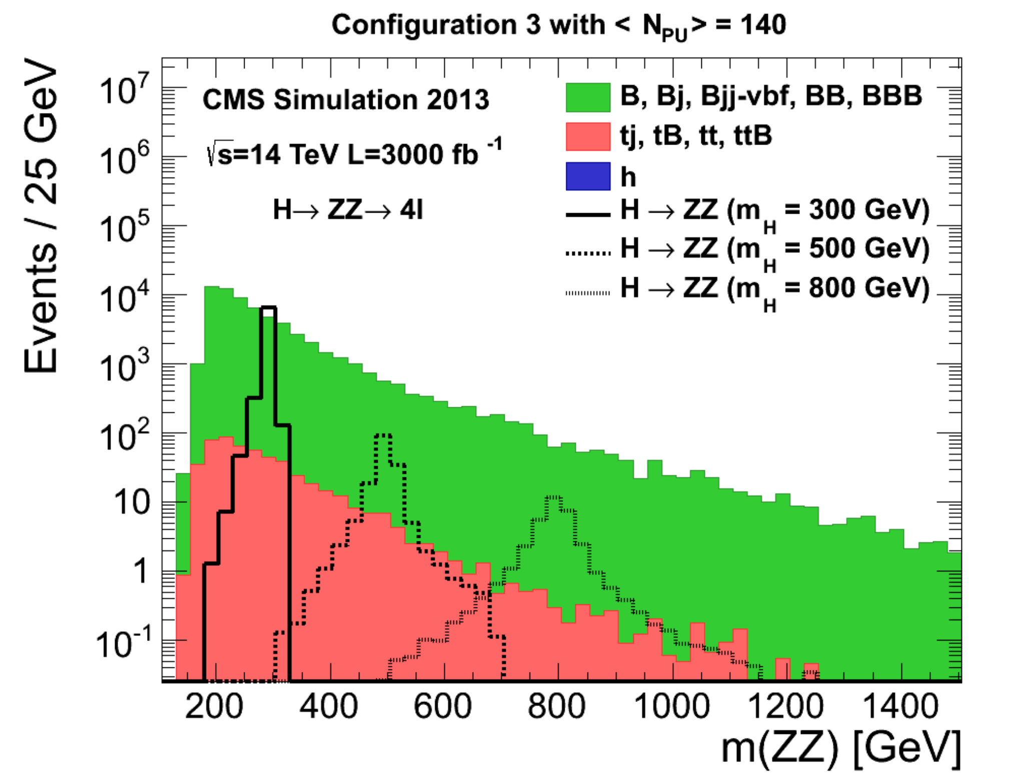
- Extension of tracker and muon system to |η| up to 4.0 under consideration
- Provides critical benefits for Higgs program
  - Lepton acceptance, e.g. for $H \rightarrow ZZ \rightarrow 4\mu$
  - Pileup mitigation: correcting/removing jets with tracks from pileup vertices
  - Vector Boson Fusion:
    - Remove pileup jets leading to wrongly-calculated rapidity gap
    - Improved q/g identification

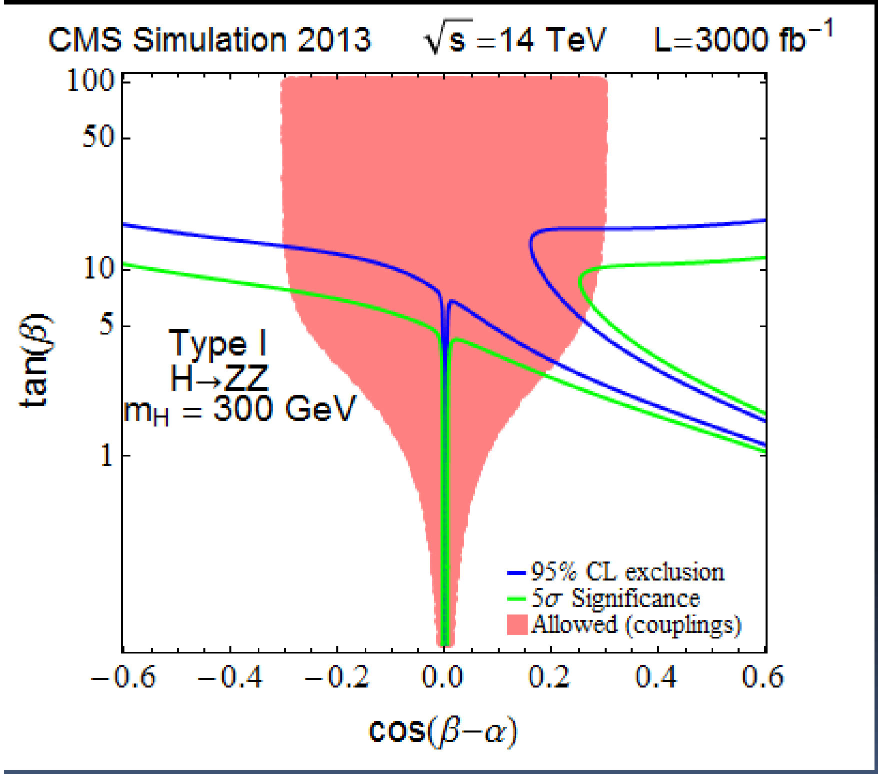




2HDM Higgs

- Beyond-the-Standard Model BEH physics: possibility of additional heavy Higgs bosons, e.g. in 2 Higgs Doublet Models
- Significant discovery potential in large areas of parameter space





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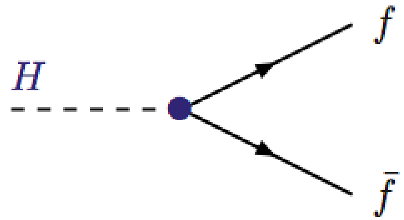
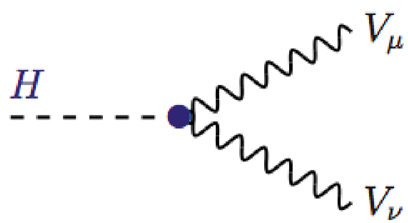
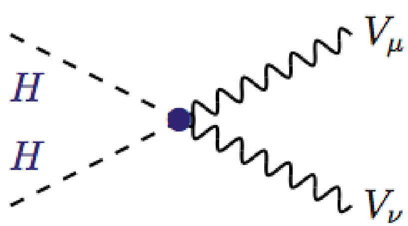


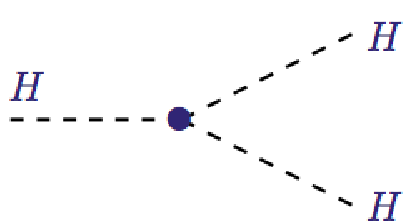
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \qquad \times\ (i)$$



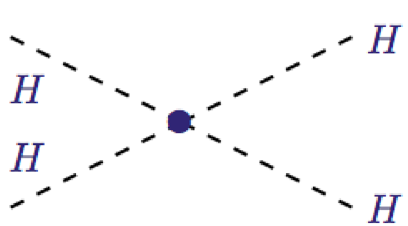
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



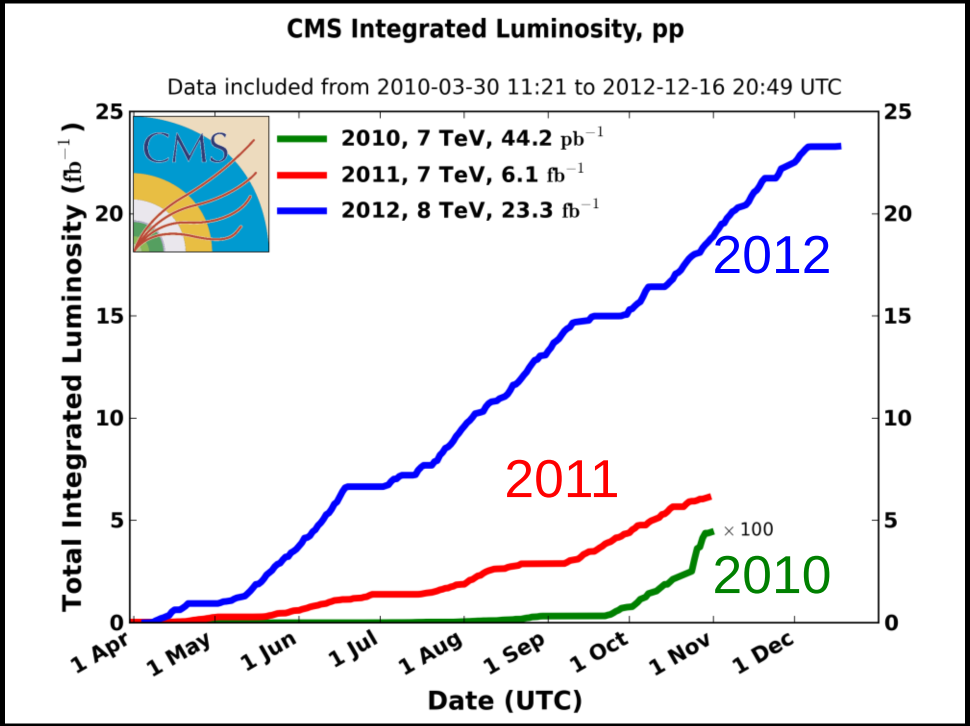
$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2}\, M_H^2 \qquad \times\ (i)$$

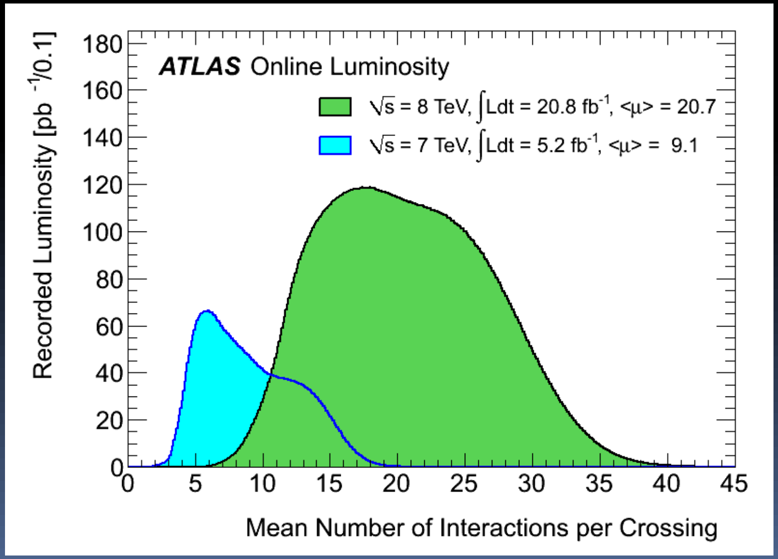


$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu\, M_H^2 \qquad \times\ (i)$$

LHC Run 1 data set

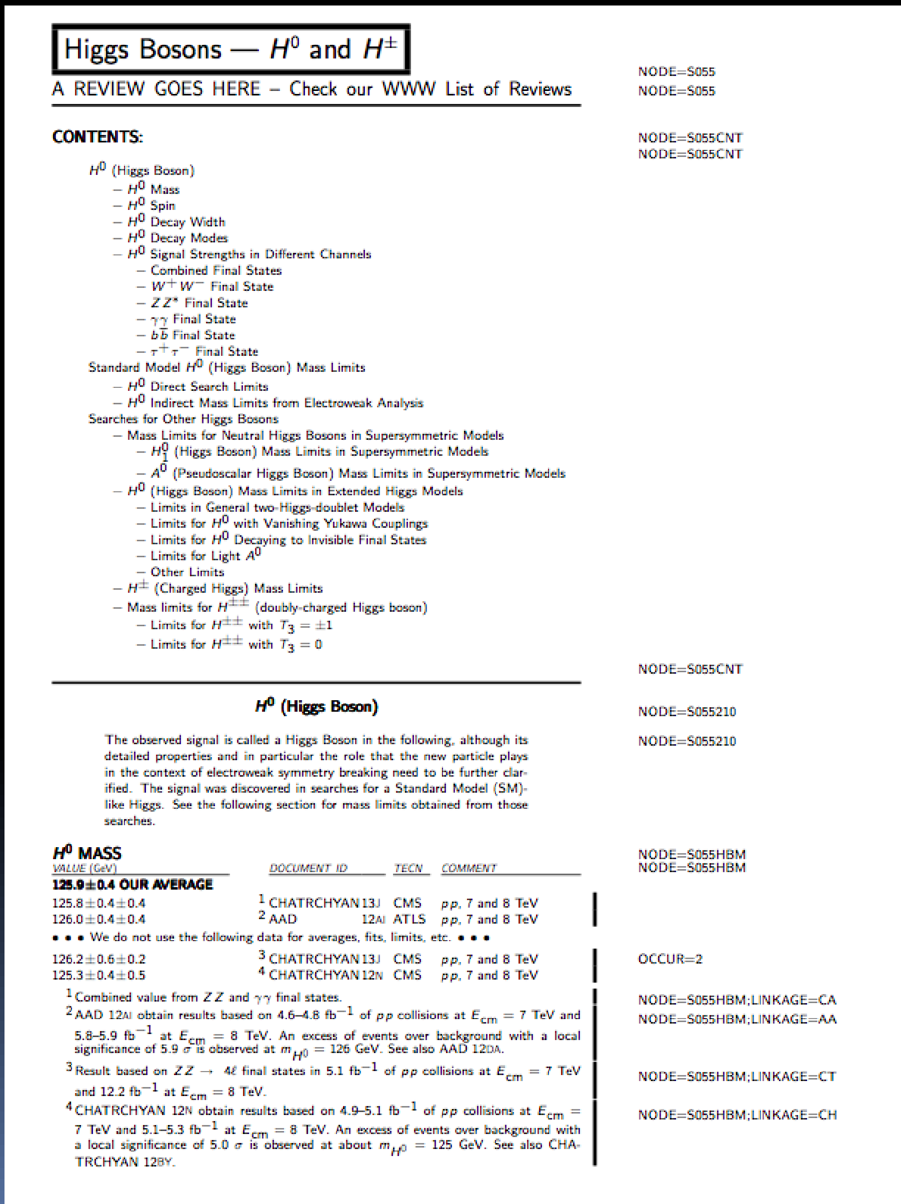
- Spectacular performance of the machine and the detectors
- ~90% of the delivered data available for offline analysis.
- Available dataset: ~5fb^{-1} √s = 7TeV + ~20fb^{-1} √s = 8TeV





- Challenging pile-up conditions.
  - Up to 30 average interactions per bunch-crossing.
  - Development of pile-up safe analysis techniques

H^0 in the PDG



Higgs Bosons — H^0 and $H^{\pm}$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

H^0 (Higgs Boson)
– H^0 Mass
– H^0 Spin
– H^0 Decay Width
– H^0 Decay Modes
– H^0 Signal Strengths in Different Channels
– Combined Final States
– W^+W^- Final State
– ZZ^* Final State
– $\gamma\gamma$ Final State
– $b\bar{b}$ Final State
– $\tau^+\tau^-$ Final State
Standard Model H^0 (Higgs Boson) Mass Limits
– H^0 Direct Search Limits
– H^0 Indirect Mass Limits from Electroweak Analysis
Searches for Other Higgs Bosons
– Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
– H_1^0 (Higgs Boson) Mass Limits in Supersymmetric Models
– A^0 (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
– H^0 (Higgs Boson) Mass Limits in Extended Higgs Models
– Limits in General two-Higgs-doublet Models
– Limits for H^0 with Vanishing Yukawa Couplings
– Limits for H^0 Decaying to Invisible Final States
– Limits for Light A^0
– Other Limits
– $H^{\pm}$ (Charged Higgs) Mass Limits
– Mass limits for $H^{\pm\pm}$ (doubly-charged Higgs boson)
– Limits for $H^{\pm\pm}$ with $T_3 = \pm 1$
– Limits for $H^{\pm\pm}$ with $T_3 = 0$

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT	
125.9±0.4 OUR AVERAGE					
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV	
126.0±0.4±0.4	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV	OCCUR=2
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV	

[1] Combined value from ZZ and $\gamma\gamma$ final states. NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA. NODE=S055HBM;LINKAGE=AA

[3] Result based on $ZZ \to 4\ell$ final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV. NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY. NODE=S055HBM;LINKAGE=CH

- Inaugural entrance in 2013

H^0

Conferences on Higgs Physics

- Task: *We are not looking for a usual overview talk but an inspirational 30min talk (with additional 15min discussion) containing exciting subjects which may be overlooked by the ATLAS/CMS or in general the current LHC program.*

- Non complete list of recent conferences with Higgs in their title
  - **The 2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck**
  - **Workshop on Multi-Higgs Models**
  - **Unification and Cosmology after Higgs Discovery and BICEP**
  - **Higgs Hunting 2014**
  - **After the Discovery: Hunting for a Non-Standard Higgs Sector**
  - **Tohoku Forum for Creativity: Particle Physics and Cosmology after the discovery of Higgs boson**
  - **Electroweak Symmetry Breaking, Flavour and Dark Matter after the Higgs Discovery : One Solution for Three Mysteries**
  - **Higgs Days at Santander: Theory meets Experiment (HDays 2013)**
  - **Higgs and Beyond 2013**