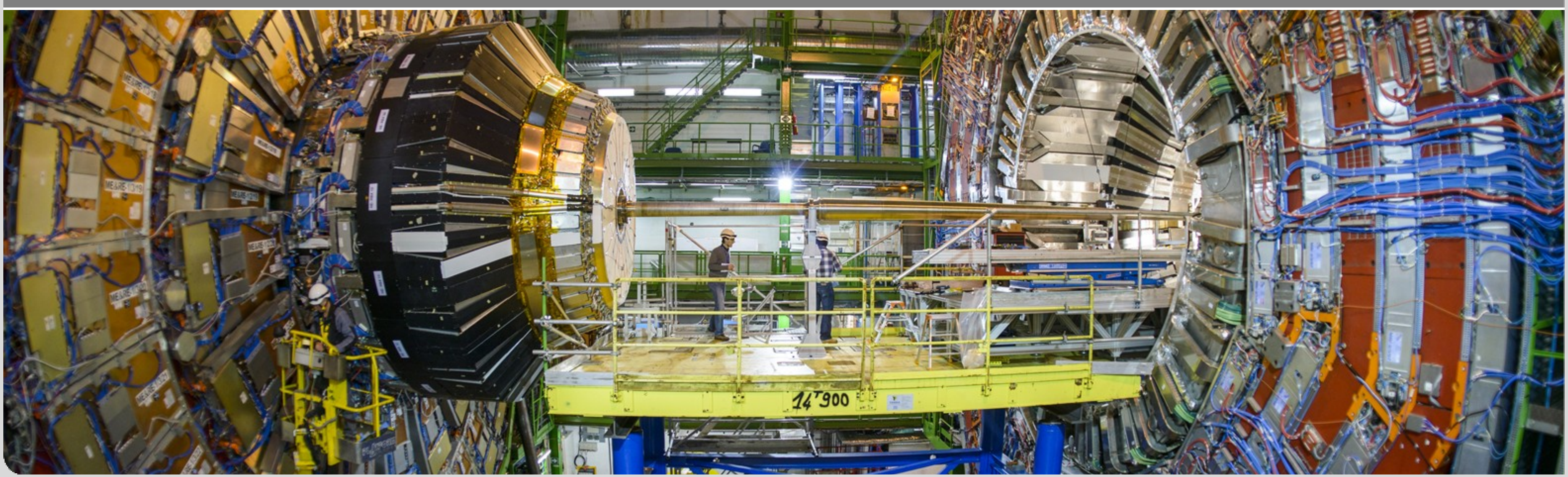
Karlsruhe Institute of Technology

Properties of the Higgs Boson
(Status Summer 2014)

Roger Wolf
24. June 2014

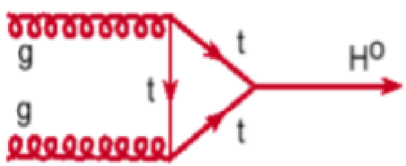
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



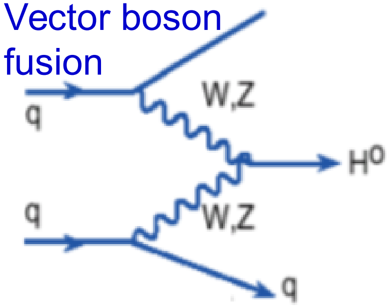
Higgs Boson Production & Decay

If m_H is given all properties of the (SM) Higgs boson are known:

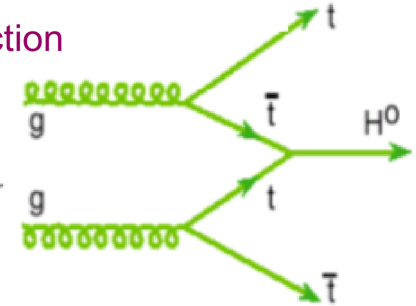
Gluon fusion



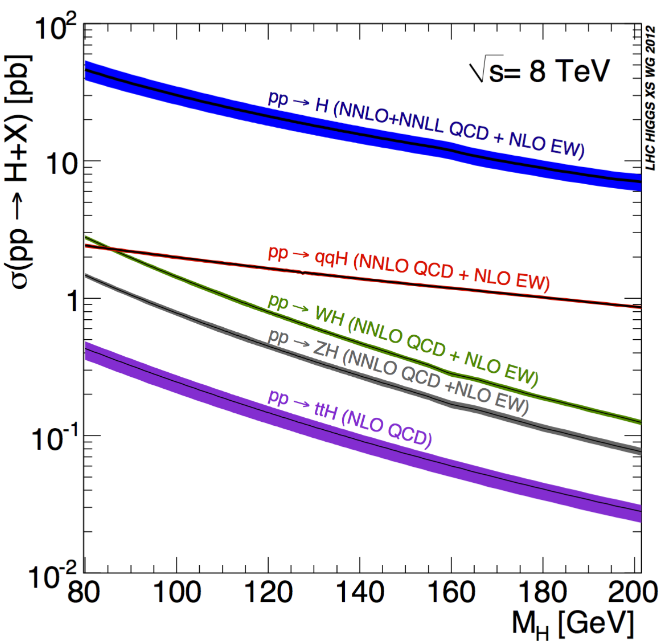
Vector boson fusion



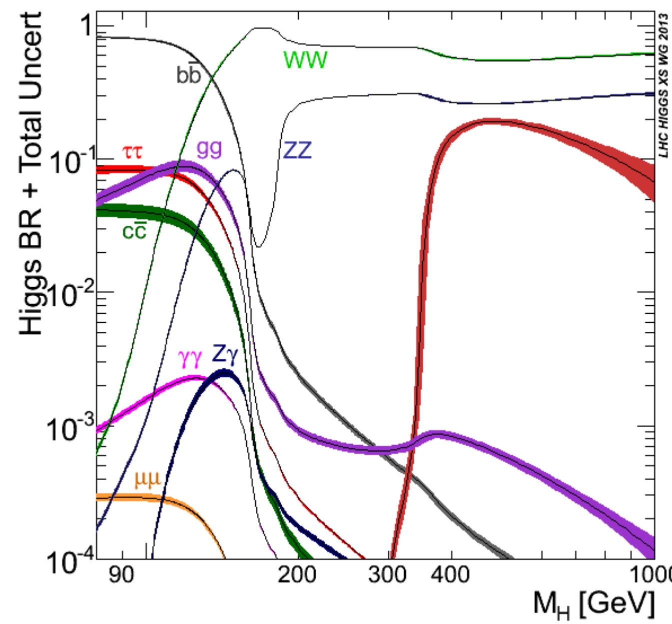
Associated production



Production (in proton proton collisions)

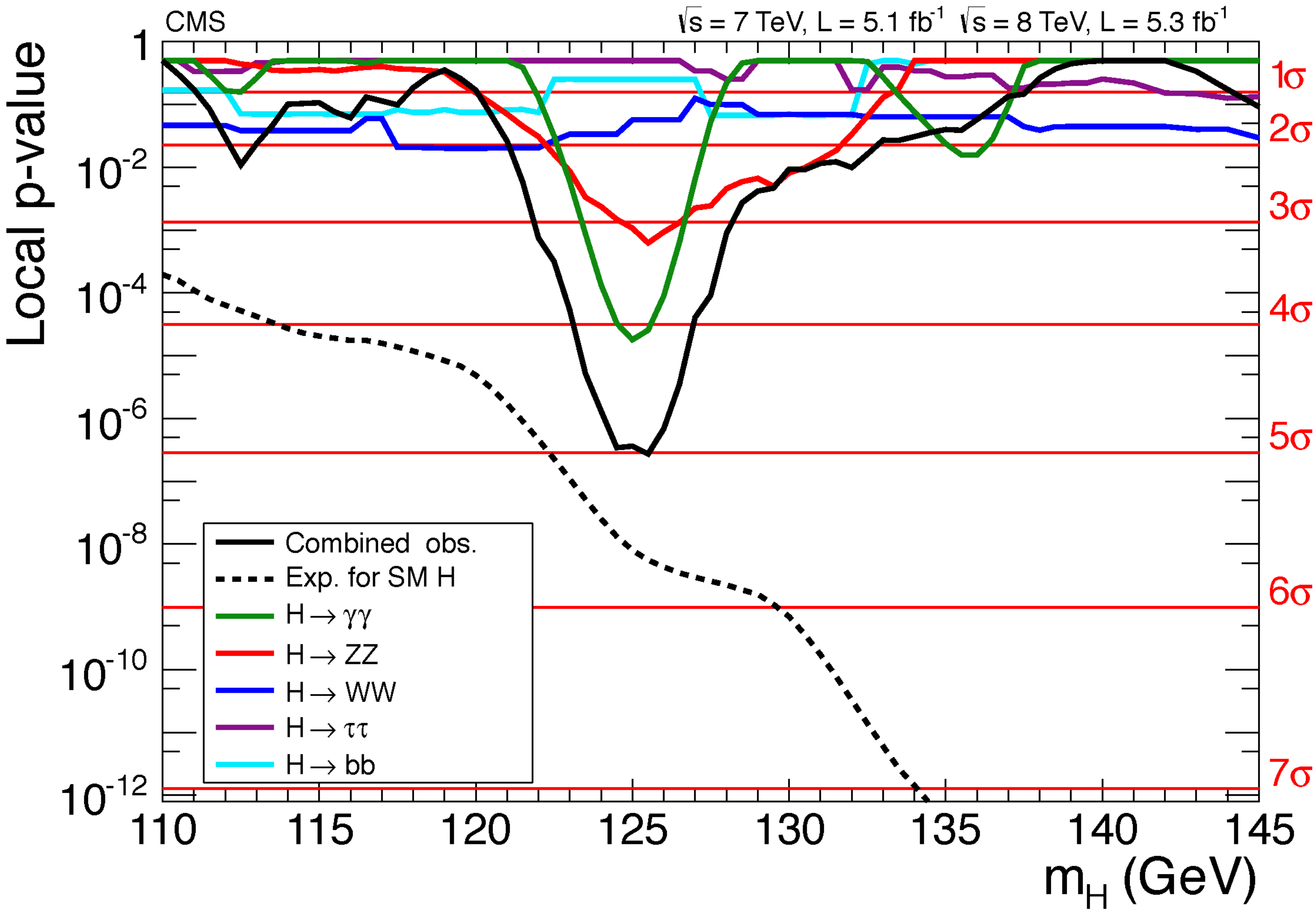


Decay



Reminder: Discovery on 4th July 2012

- Scratching magic 5σ boundary.
- Discovery driven by $H \to \gamma\gamma$ and $H \to ZZ$ (high resolution channels).
- Broad moderate excesses for $H \to WW$ and $H \to bb$.
- No signal seen in $H \to \tau\tau$.



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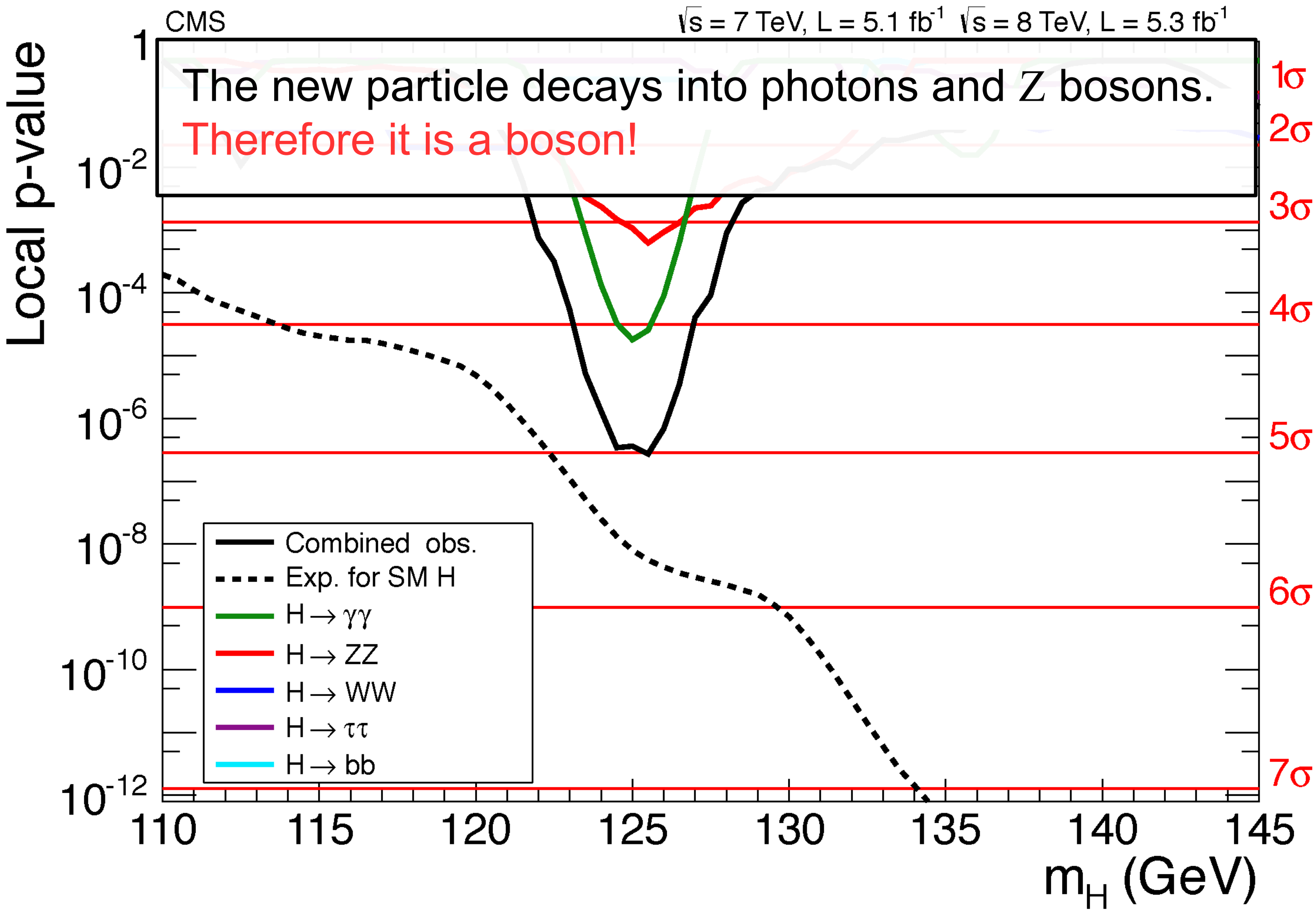


The new particle decays into photons and Z bosons.
Therefore it is a boson!

- Mass
- Decay Width
- Signal Strength
- Couplings
- Spin and CP

Analyzed Datasets

- Status: Summer 2014.
- Final states:

$H \rightarrow \gamma\gamma$ $\quad H \rightarrow bb$

$H \rightarrow ZZ$ $\quad H \rightarrow \tau\tau$

$H \rightarrow WW$

- Production modes:

$gg \rightarrow H$ $\quad qq \rightarrow VH$

$qq \rightarrow qqH$ $\quad gg \rightarrow ttH$

- 207 event categories.
- 2519 nuisance parameters.
- ~20 MB binary file of statistic model, ~50 MB human readable *txt* tile.

Decay tag and production tag		Expected signal composition	σ_{eff}/m_H	Luminosity (fb^{-1}) / No. of categories 7 TeV	8 TeV
$H \rightarrow \gamma\gamma$ [20], Section 2.1				5.1	19.7
$\gamma\gamma$	Untagged	76-93% ggH	0.8-2.1%	4	5
	2-jet VBF	50-80% VBF	1.0-1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70-80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0-1.3%	1	1
	Leptonic $t\bar{t}$H	≈95% $t\bar{t}$H	1.1%	1†	1
	Multijet $t\bar{t}$H	>90% $t\bar{t}$H	1.1%		1
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ [18], Section 2.2				5.1	19.7
4μ, $2e2\mu$, $4e$	2-jet	42% VBF + VH	1.3, 1.8, 2.2%‡	3	3
	Other	≈90% ggH		3	3
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ [17], Section 2.3				4.9	19.4
$ee + \mu\mu$, $e\mu$	0-jet	96-98% ggH	$e\mu$ 16%‡	2	2
	1-jet	82-84% ggH	$e\mu$ 17%‡	2	2
	2-jet VBF	78-86% VBF		2	2
	2-jet VH	31-40% VH		2	2
$3\ell3\nu$ WH	SF-SS, SF-OS	≈100% WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu jj$ ZH	eee, $ee\mu$, $\mu\mu\mu$, $\mu\mu e$	≈100% ZH		4	4
$H \rightarrow \tau\tau$ [19], Section 2.4				4.9	19.7
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70-80% ggH	12–16%	5	5
	2-jet VBF	75-83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67-70% ggH	10–12%	-	2
	2-jet VBF	80% VBF	11%	-	1
$e\mu$	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75-80% ggH, 31-38% WW	18–19%	2	2
	2-jet VBF	79-94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h$, $\ell\tau_h$, $e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ ($e\mu$)		8	8
$\ell + \tau_h\tau_h$ WH		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ WH		ZH/WH ≈ 5%, 9–11% WW		2	4
VH with $H \rightarrow bb$ [16], Section 2.5				5.1	18.9
W($\ell\nu$)bb	p_T(V) bins	≈100% VH, 96–98% WH	≈10%	4	6
W($\tau_h\nu$)bb		93% WH		-	1
Z($\ell\ell$)bb	p_T(V) bins	≈100% ZH		4	4
Z($\nu\nu$)bb	p_T(V) bins	≈100% VH, 62–76% ZH		2	3
$t\bar{t}$H with $H \rightarrow$ hadrons [14, 28], Section 2.6				5.0	19.3
$H \rightarrow bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% $\tau\tau$		2	3
$H \rightarrow \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% $\tau\tau$, 13–22% WW, 5–13% bb		-	6
$t\bar{t}$H with $H \rightarrow$ leptons [29], Section 2.6				-	19.6
2ℓ-SS		WW/$\tau\tau$ ≈ 3		-	6
3ℓ		WW/$\tau\tau$ ≈ 3		-	2
4ℓ		WW : $\tau\tau$: ZZ ≈ 3 : 2 : 1		-	1

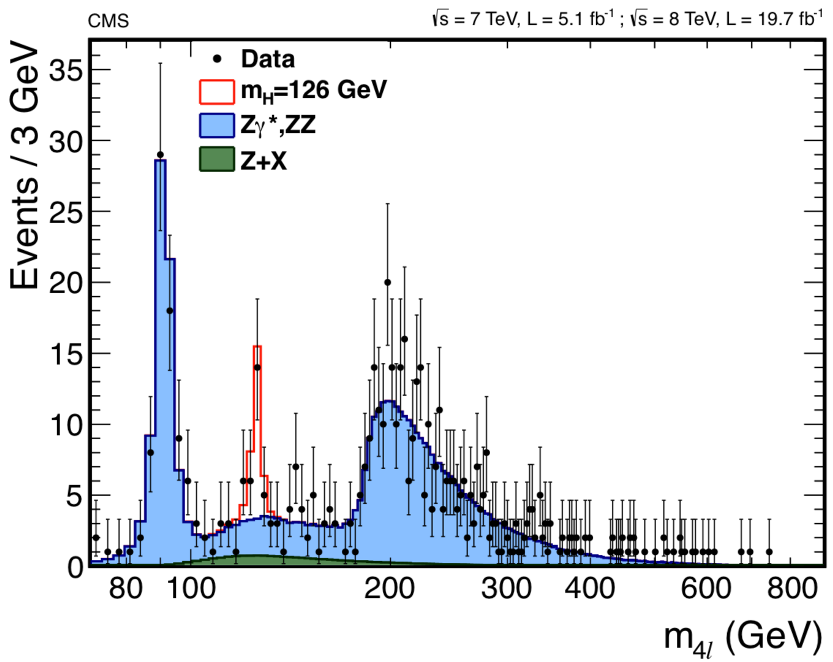
† Events fulfilling the requirements of either selection are combined into one category.

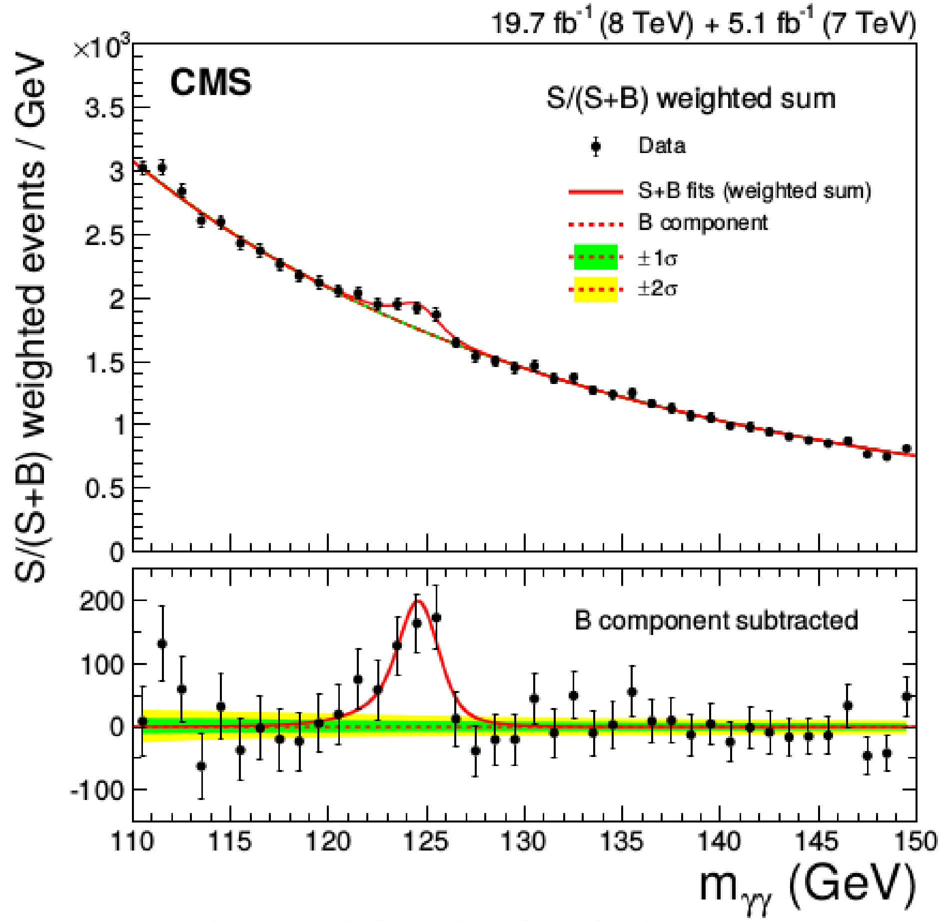
‡ Values for analyses dedicated to the measurement of the mass that do not use the same categories and/or observables.

* Composition in the regions for which the ratio between signal and background $s/(s+b) > 0.05$.

Mass Measurement & Decay Width

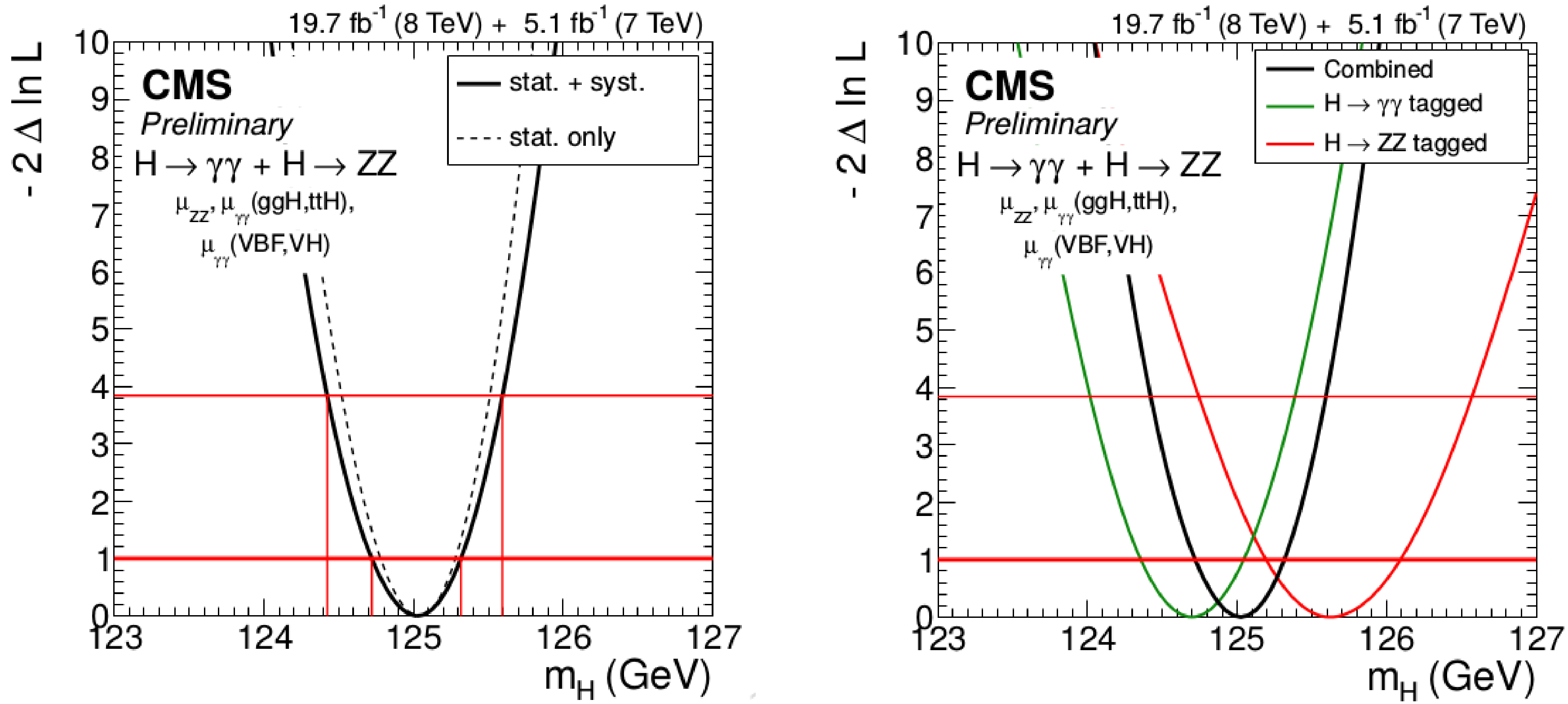
Mass Measurement





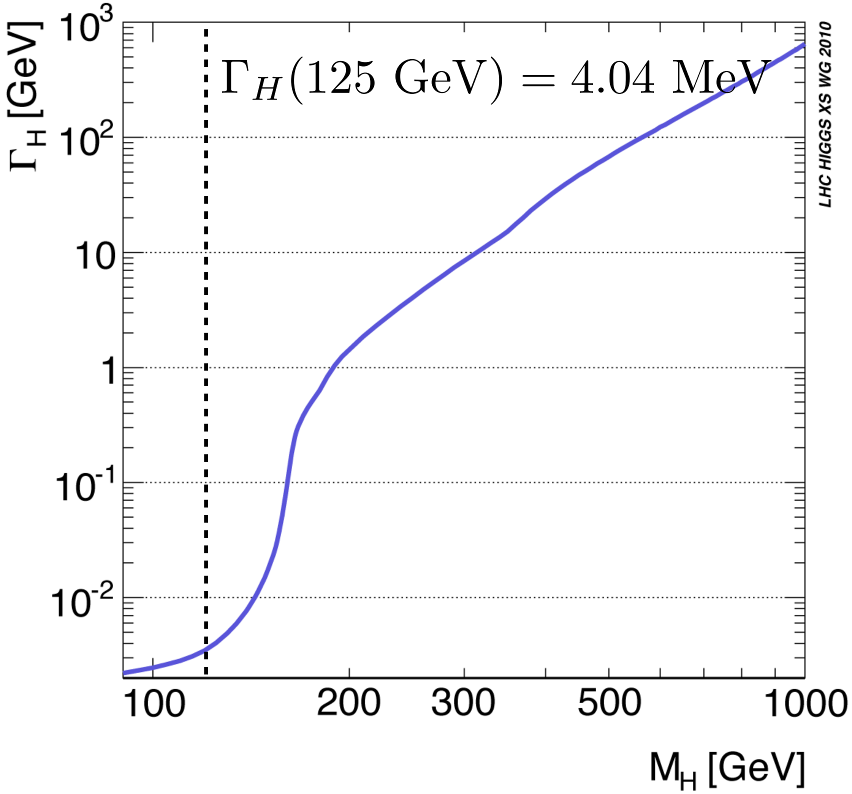
- Only “free parameter” in the SM.
- Can be directly measured in high resolution channels ($H \to \gamma\gamma$, $H \to ZZ$).

Mass: Best Estimate



- Four fee parameters in fit: $m_H\ (POI)$, μ_{ZZ}, $\mu_{\gamma\gamma}(ggH, ttH)$, $\mu_{\gamma\gamma}(qqH, VH)$ (profiled)
- Best estimate: $m_H = 125.03 \pm^{0.26}_{0.27}\ (\text{stat.}) \pm^{0.13}_{0.15}\ (\text{syst.})\ \text{GeV}$

Decay Width



- Cannot be measured directly from mass peak (experimental resolution).
- But accessible in $H \to ZZ$ via line shape analysis of (non-)resonant $gg \to ZZ, H \to 4\ell$ production:

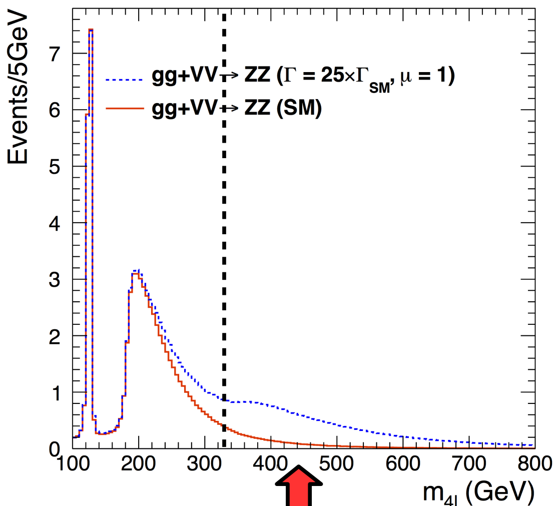
$$\frac{\mathrm{d}\sigma(gg\to H\to ZZ)}{\mathrm{d}m_{4\ell}^2} \propto \frac{\kappa_g^2\kappa_Z^2}{(m_{4\ell}^2-m_H^2)^2+m_H^2\Gamma_H^2}$$

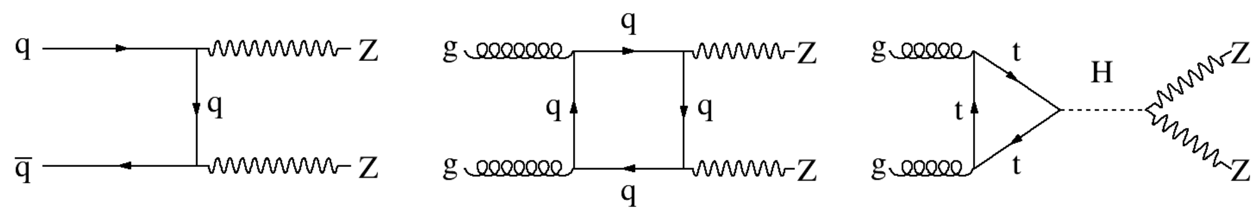
$$\sigma^{\mathrm{on-shell}} \propto \left.\frac{\kappa_{ggH}^2\kappa_{HZZ}^2}{m_H\Gamma_H}\right|_{m_{4\ell}\approx m_H}$$

$$\sigma^{\mathrm{off-shell}} \propto \left.\frac{\kappa_{ggH}^2\kappa_{HZZ}^2}{(m_{4\ell})^2}\right|_{m_{4\ell}\approx 2m_Z}$$

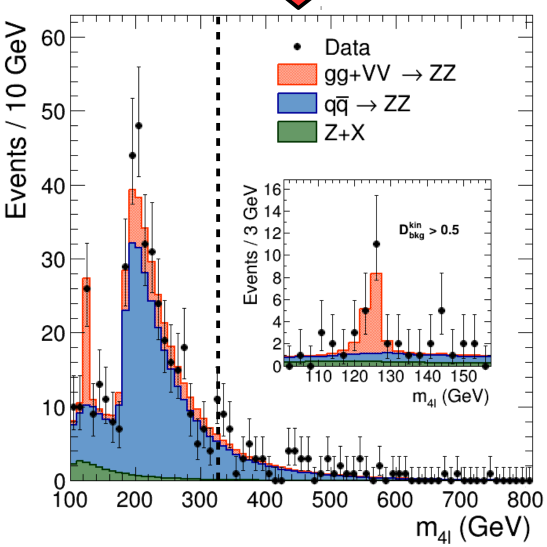
- Off-shell cross sections enhanced close to ZZ production threshold.
- Best estimate: $m_H = 125.03 \pm^{0.26}_{0.27}\,(\mathrm{stat.}) \pm^{0.13}_{0.15}\,(\mathrm{syst.})\ \mathrm{GeV}$

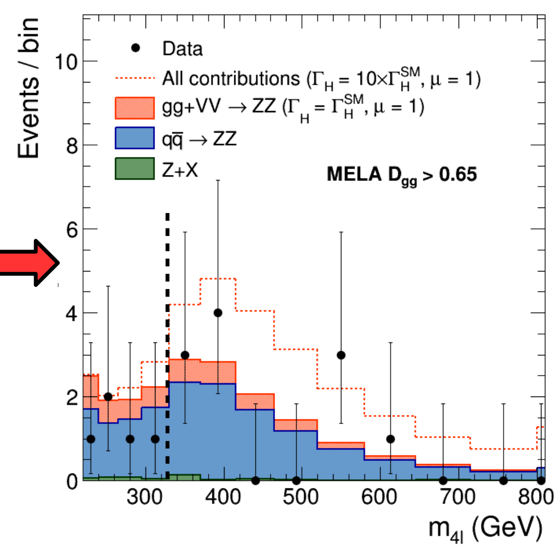
Decay Width

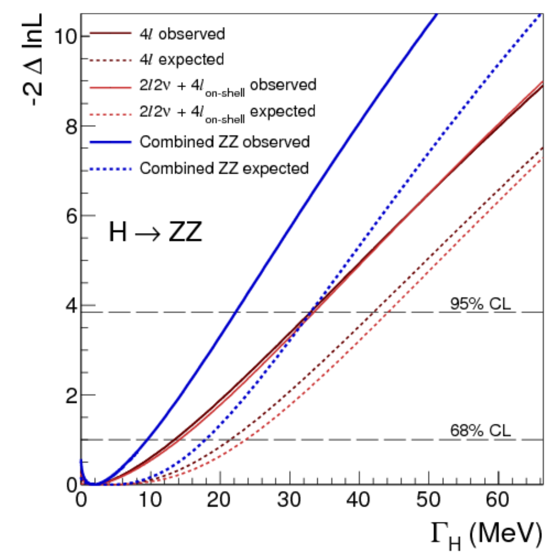




- Count ratio of off-shell over on-shell events.
- Use 4ℓ (on- and off-shell) & $2\ell 2\nu$ (off-shell only).
- 95% CL upper limit $\Gamma_H < 22$ MeV (obs), 33 MeV (exp).





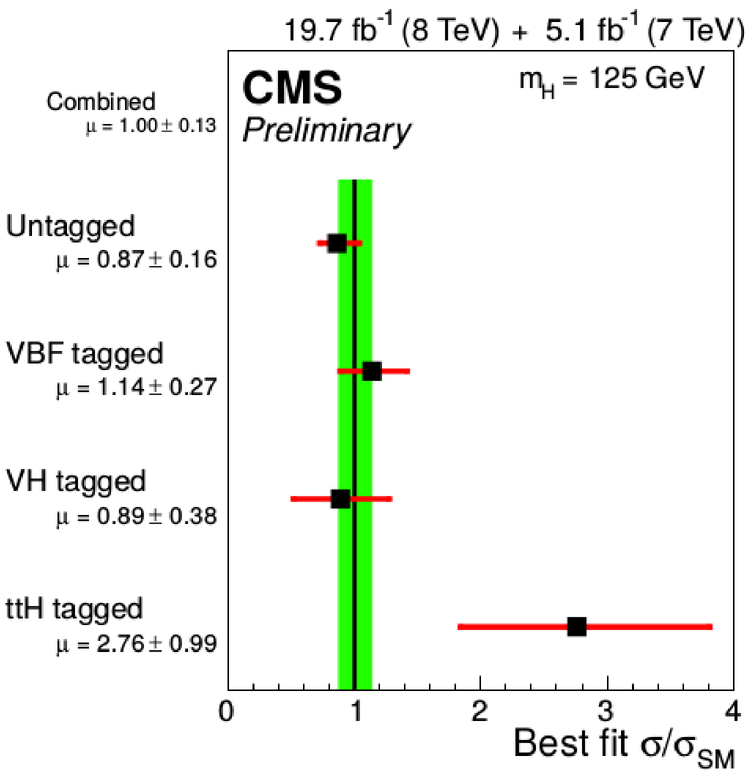


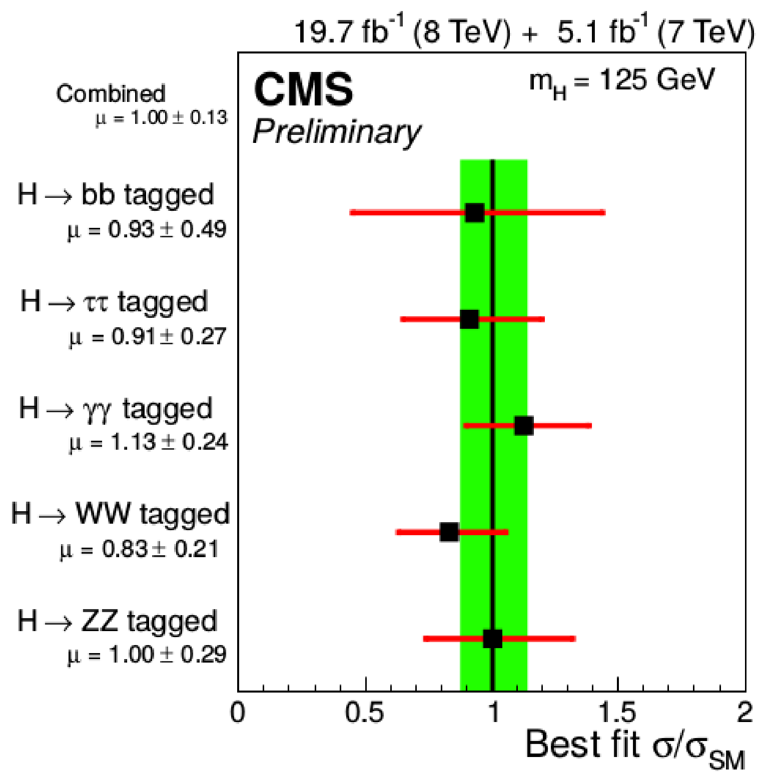
Compatibility of Couplings the SM

8			4		6			7
						4		
	1					6	5	
5		9		3		7	8	
				7				
	4	8		2		1		3
	5	2					9	
		1						
3			9		2			5

Compatibility of Couplings the SM

- Fix mass to best fit value from $H \to ZZ$ and $H \to \gamma\gamma$ (125 GeV).
- Introduce signal strength modifier μ_X for each production mode or decay channel.
- Apply separate fit for each production mode or decay channel.



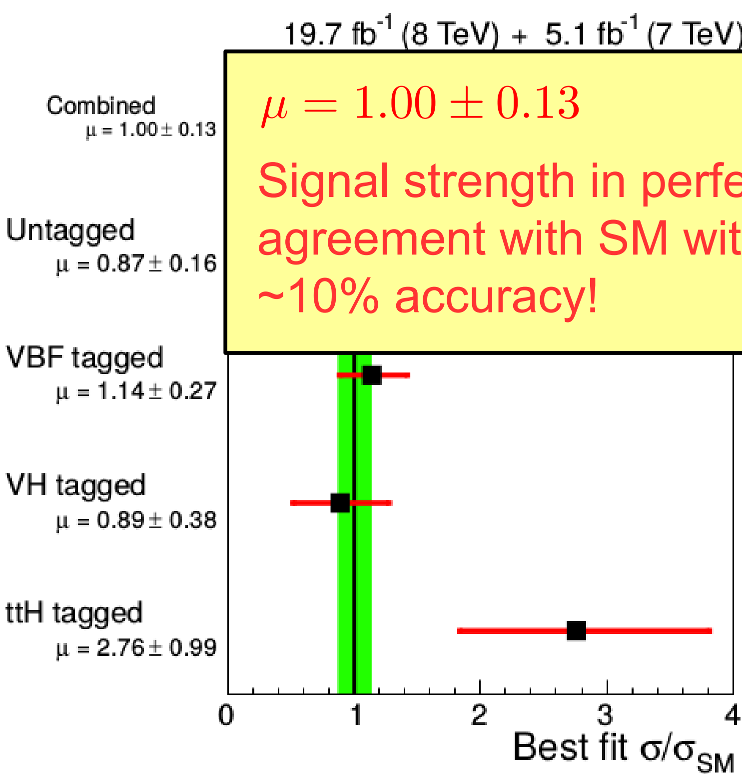


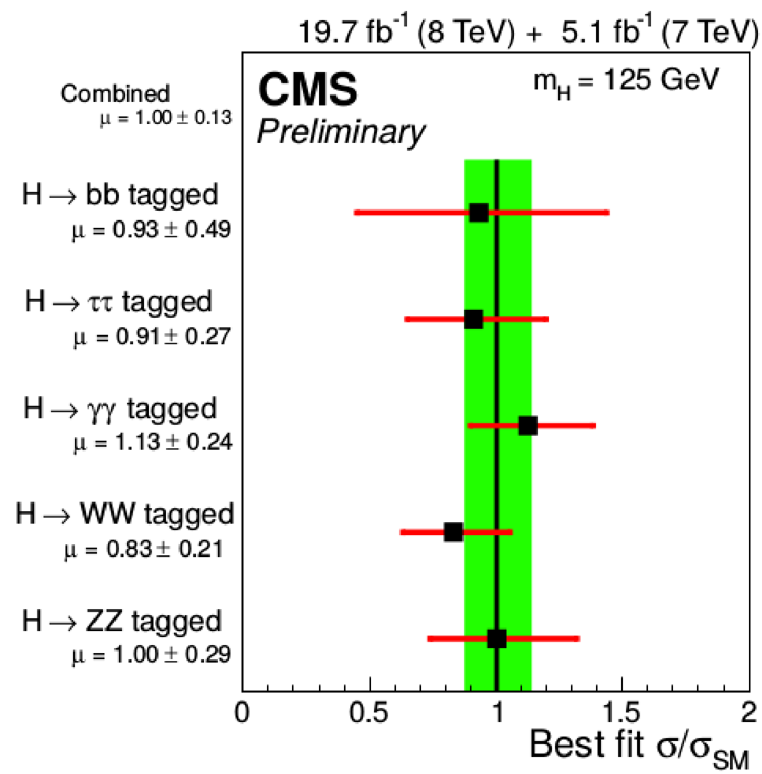
Compatibility of Couplings the SM

- Fix mass to best fit value from $H \to ZZ$ and $H \to \gamma\gamma$ (125 GeV).
- Introduce signal strength modifier μ_X for each production mode or decay channel.
- Apply separate fit for each production mode or decay channel.

$\mu = 1.00 \pm 0.13$

Signal strength in perfect agreement with SM within ~10% accuracy!

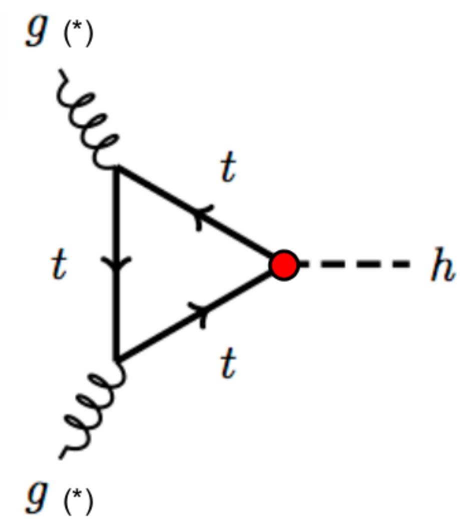




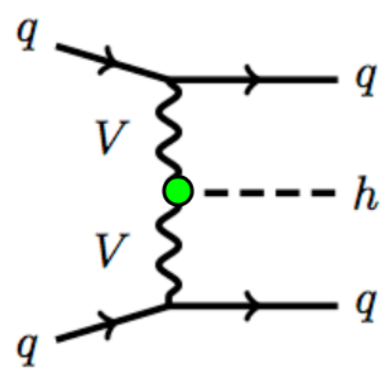
Coupling Estimates

- Determine couplings from production mode and decay channel:

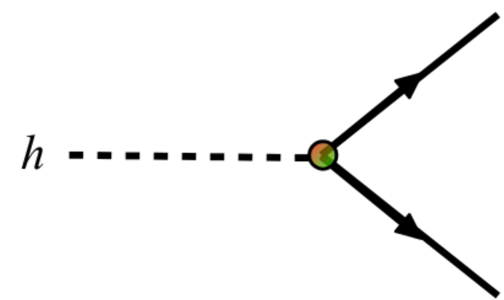
$gg \to H$ production:



$qq \to qqH$ production:



Decay to f or V:



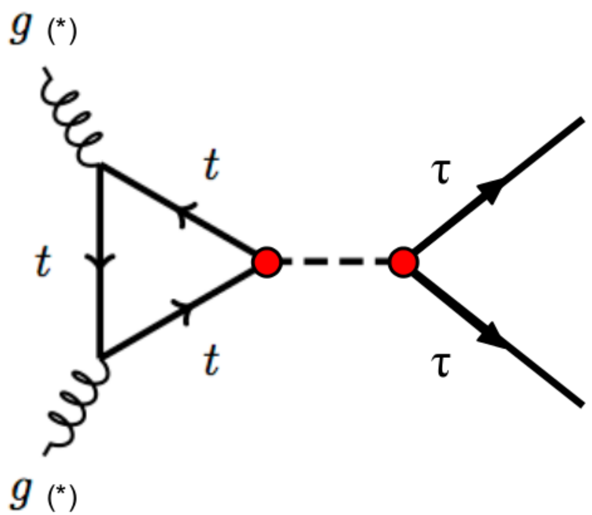
- (red) f : $\kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}}$
- (green) V : $\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

- Coupling to gluon can be f or effective (*).
- Coupling to γ can be effective or a mixture of $f + V$.

- Direct measurement not possible since κ_i appear in nominator and denominator of $\mathrm{BR}_i = \frac{\kappa_i}{\Gamma_h} = \frac{\kappa_i}{\sum \kappa}$

Narrow Width Approximation

- Assume $\Gamma_H \ll m_H$, which is well justified by $\Gamma_H = 4.04\ \mathrm{MeV}$ and $m_H = 125\ \mathrm{GeV}$.
- Propagator: $\frac{1}{(q^2 - m^2 + m^2\Gamma^2)} \rightarrow \frac{\pi}{m\Gamma}\delta(q^2 - m^2)$ for $\Gamma \rightarrow 0$.

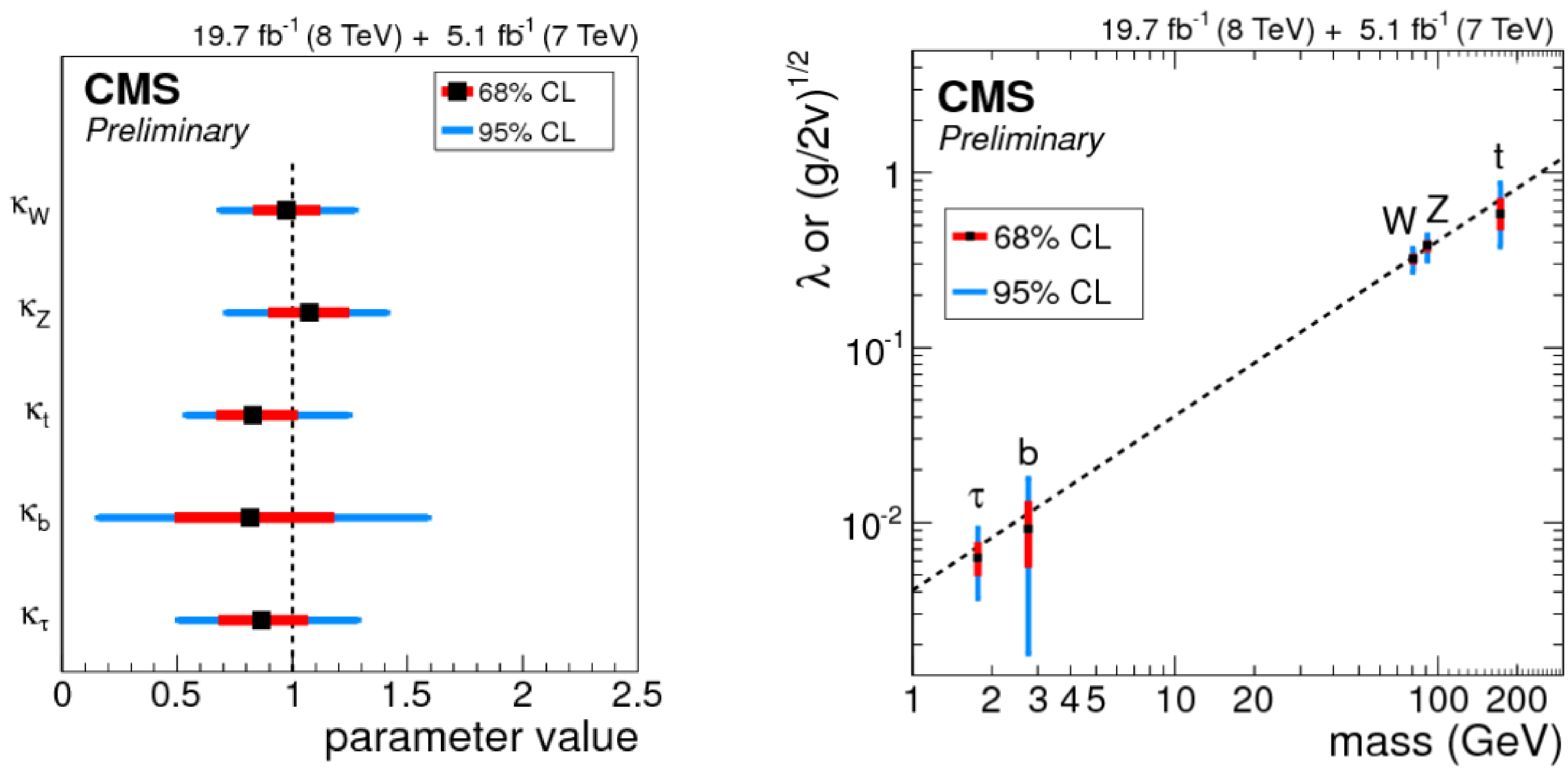


- i.e. put propagating particle on shell.
- Calculate cross section as $\sigma \times \mathrm{BR}$.
- $\mathrm{BR}_X = \frac{\Gamma_X}{\Gamma_H}, \quad \Gamma_H = \sum_i \Gamma_i$.
- $\sigma \propto (\kappa_t \kappa_\tau)^2 \propto (\kappa_u \kappa_d)^2 \propto (\kappa_q \kappa_f)^2 \propto (\kappa_g \kappa_f)^2$.

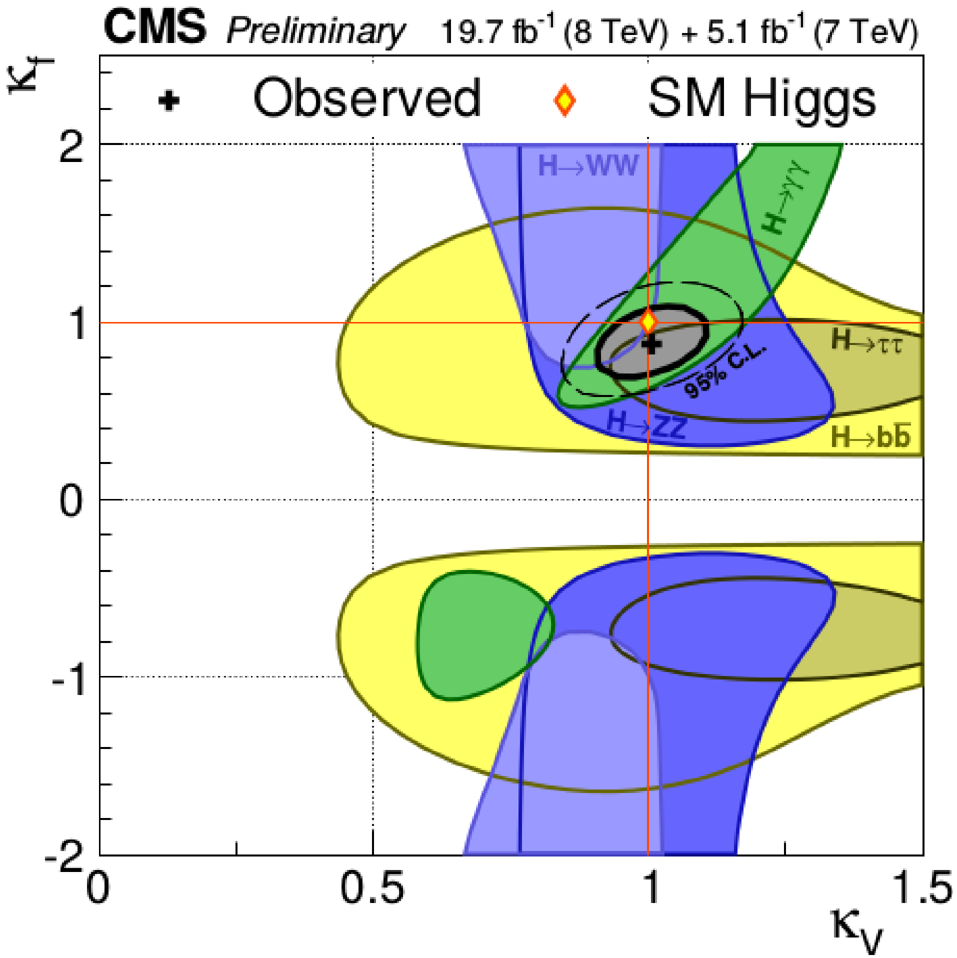
- For each production mode and decay channel collect κ_i and express Γ_H as sum of individual κ_i .

General Fitting model with 5 POI's

- Five free parameters for each tree-level coupling, m_H fixed to best fit value, κ_γ resolved in W, Z and t contributions, κ_g resolved in t and b contribution.



Fermion versus Vector Boson Couplings



- Cross section $H \to VV$:

  $\sigma \propto (\kappa_f \kappa_V)^2 + (\kappa_V \kappa_V)^2$

  $gg \to H$ $\quad qq \to qqH$

- Cross section $H \to ff$:

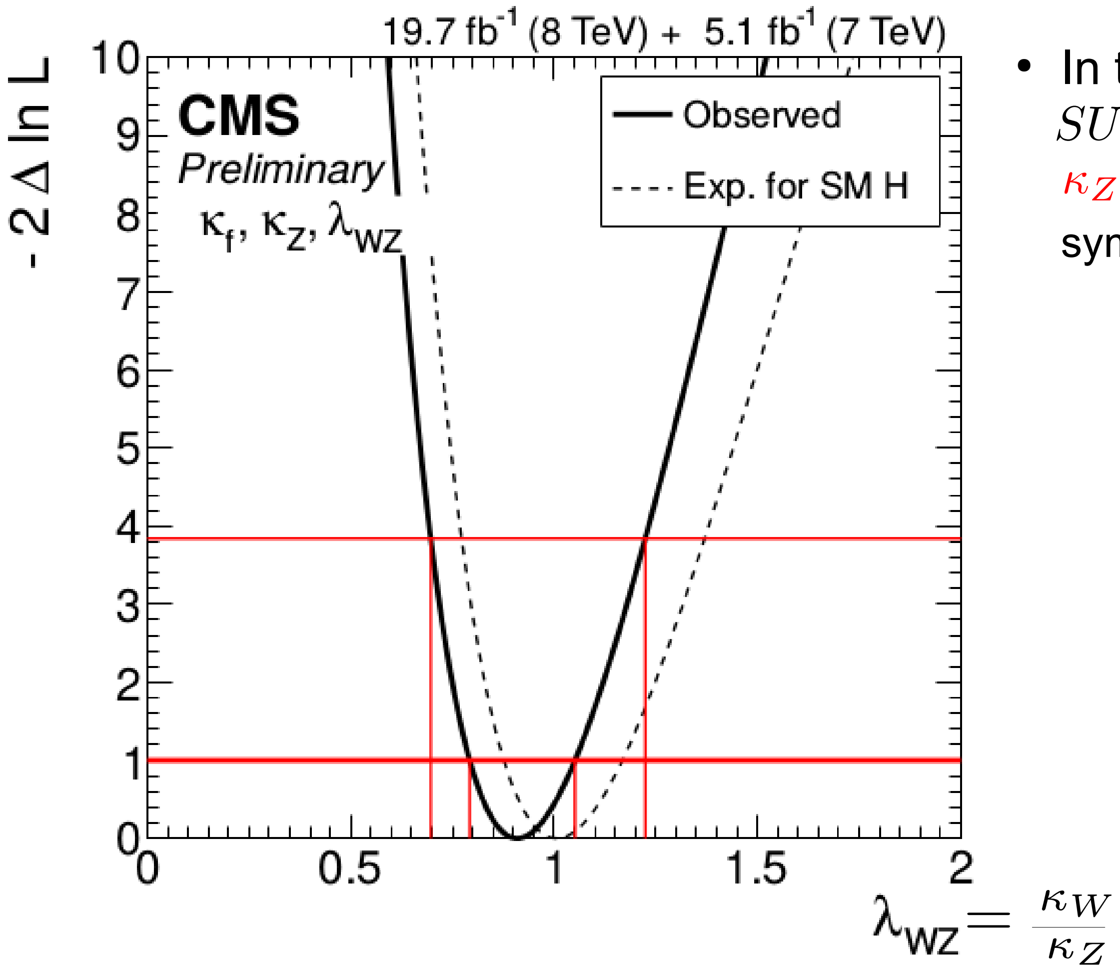
  $\sigma \propto (\kappa_f \kappa_f)^2 + (\kappa_V \kappa_f)^2$

- Cross section $H \to \gamma\gamma$:

  $\sigma \propto (\kappa_f^2 - \kappa_f \kappa_V)^2 + (\kappa_V \kappa_f - \kappa_V^2)^2$

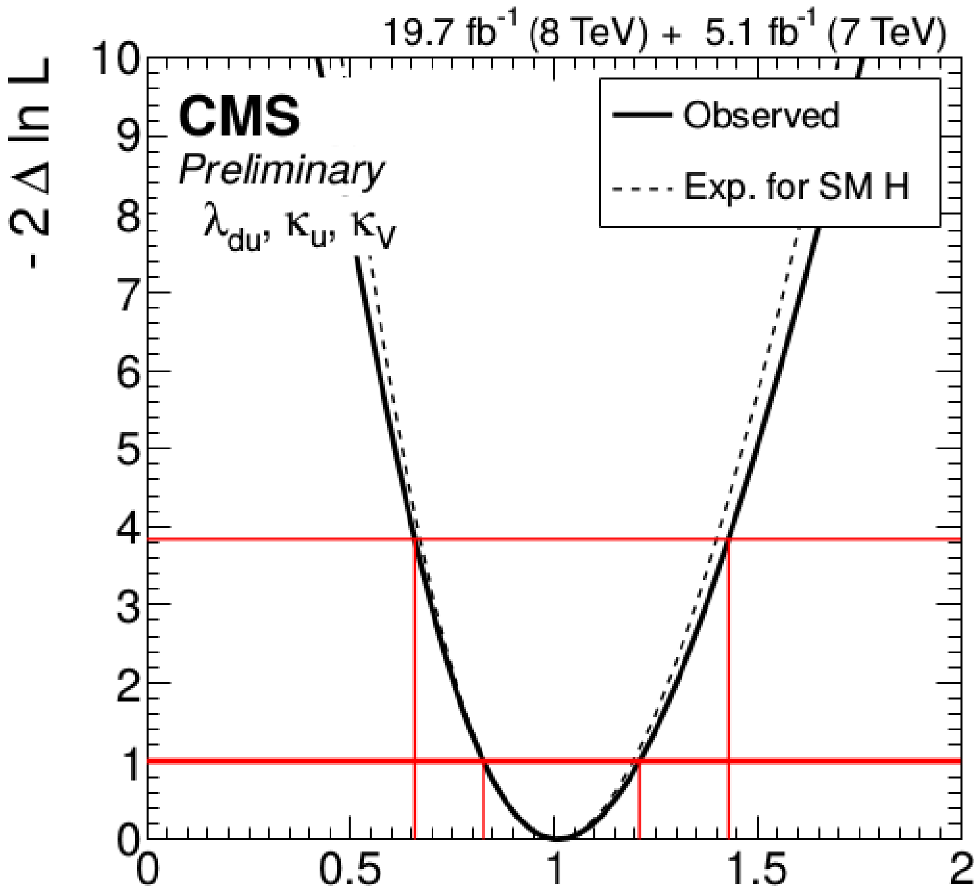
- $H \to \gamma\gamma$ only channel to distinguish sign ambiguities due to interference terms.

Custodial Symmetry



- In the SM an additional $SU(2)_L \times SU(2)_R$ symmetry protects κ_W & κ_Z to be the same (→ custodial symmetry).

Up-type versus Down-type Fermion Couplings



$\lambda_{du} = \frac{\kappa_d}{\kappa_u}$

- In the SM fermion masses can be obtained via only one Higgs doublet field.
- In Two Higgs Doublet Models (2HDM) the coupling to *up-* and *down-type* fermions can differ significantly.

New Physics in Loops

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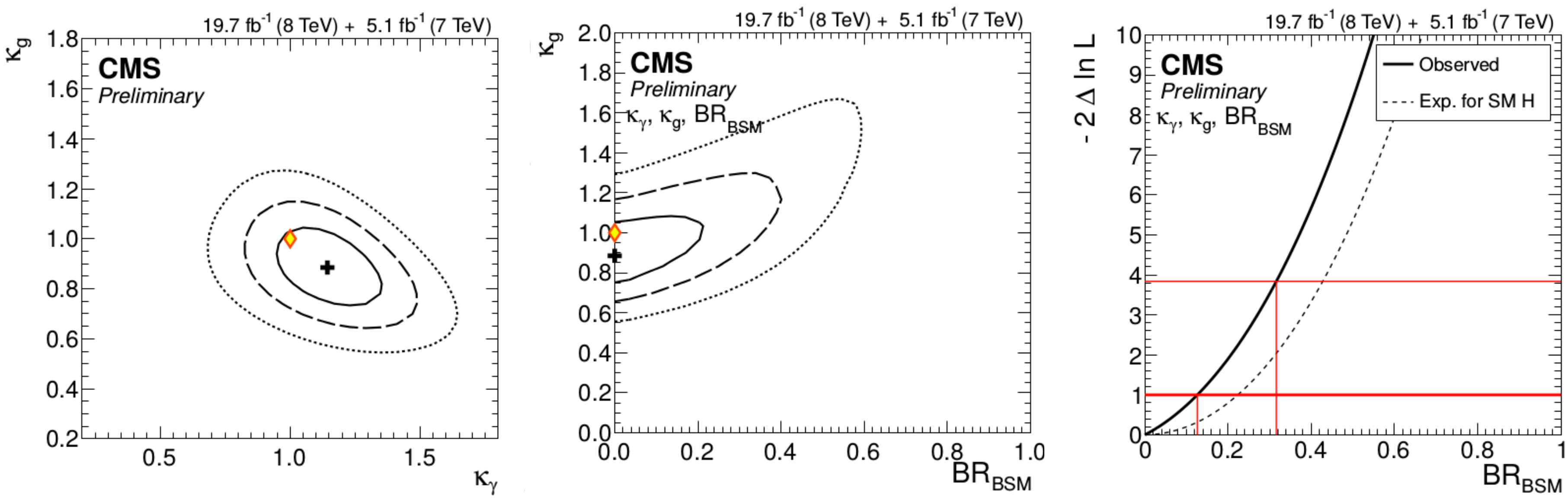
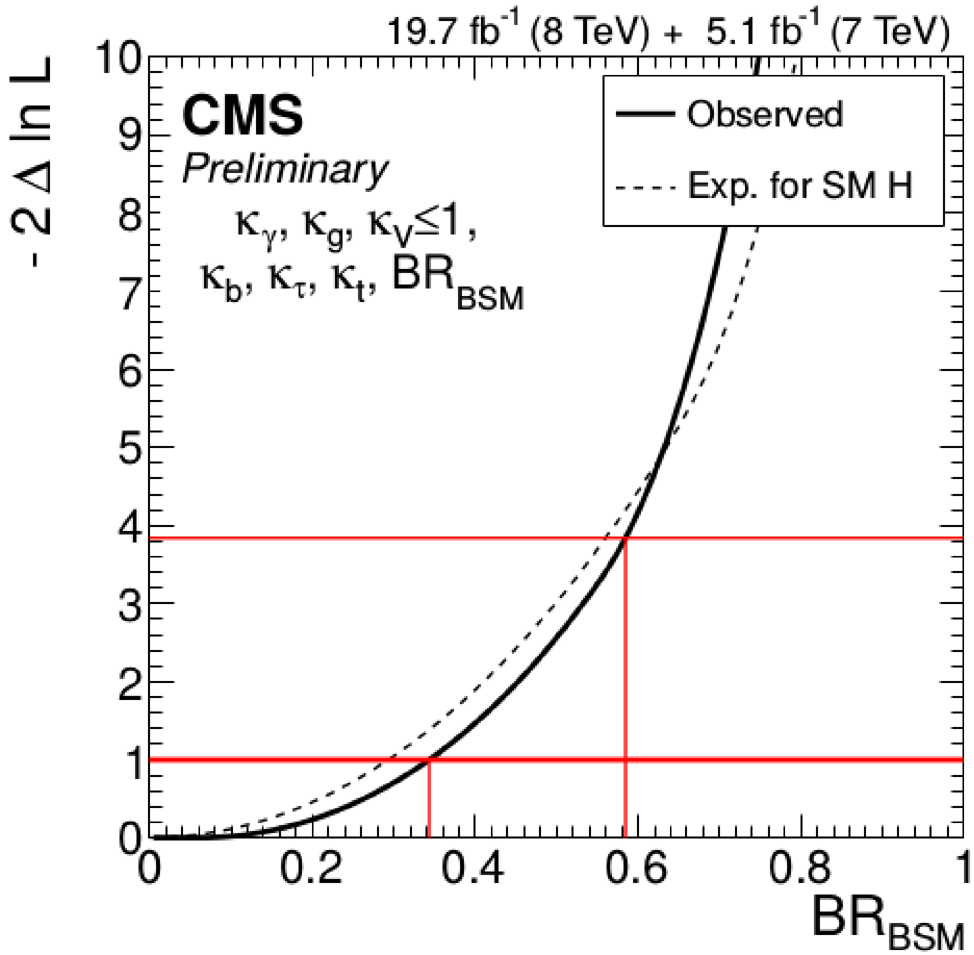
- New particles in loops can lead to deviations of the effective couplings to gluons and photons from the SM expectation.
- Such deviations can be expressed by a BR to new particles, which have not been observed, yet.



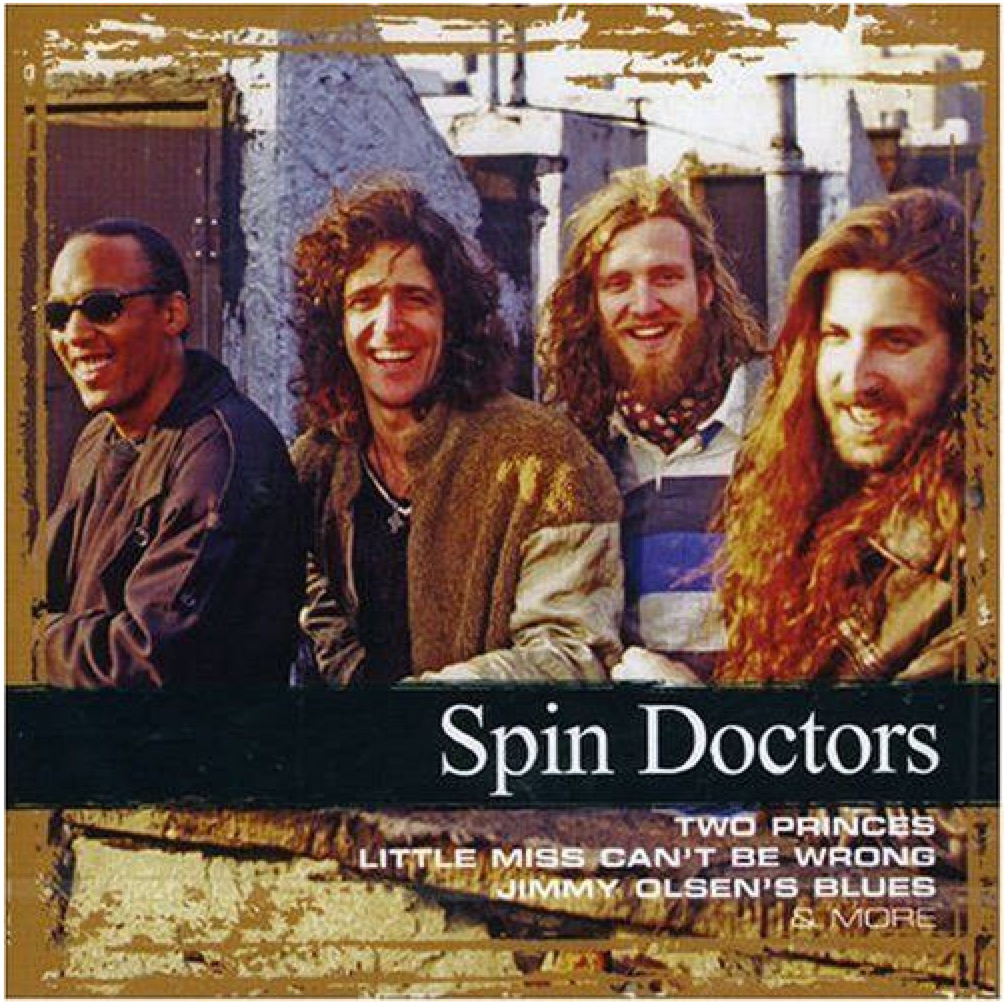
- Assuming SM values for tree-level couplings.

Search for the Invisible



- Most model independent (inclusive) search for the decay, which has not been observed, yet, via deviation of $\sum \kappa_i$ from one.

Spin & Parity Estimates



Spin & Parity Estimates

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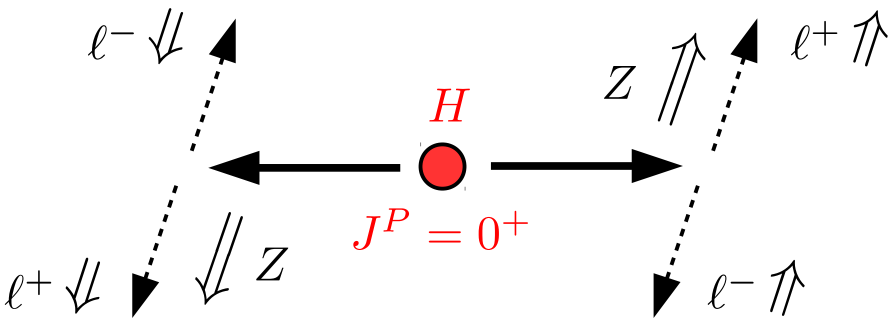
- Spin and CP studies need something to make spin of particles visible → spin analyzer.
- Principle: angular momentum conservation in 2-body decay (best high energetic or with ν's).
- Examples for $H \to ZZ \to 4\ell$:



$$Z: \quad P = -1$$
$$f: \quad P = +1$$
$$\bar{f}: \quad P = -1$$
$$P = (-1)^L \prod_i (-1)$$

→ Intrinsic parities

- Both longitudinal and transverse polarization states of Z bosons are Spin and Parity sensitive.

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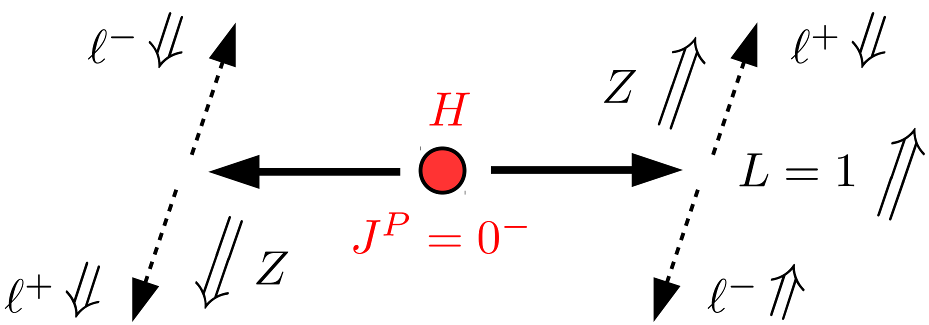

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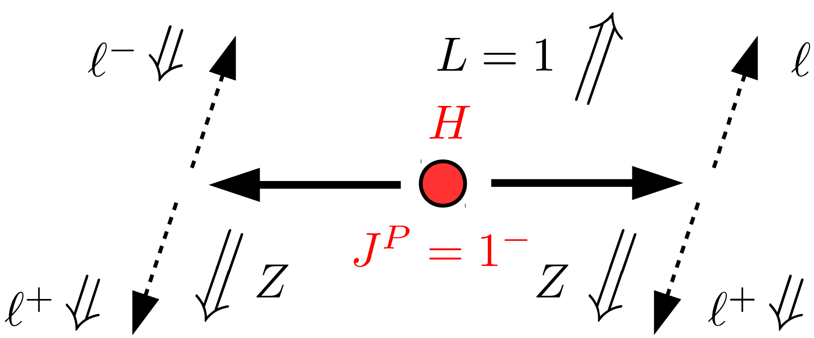

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The $H \to ZZ$ System

- System described by m_{Z1}, m_{Z2} and five more variables:

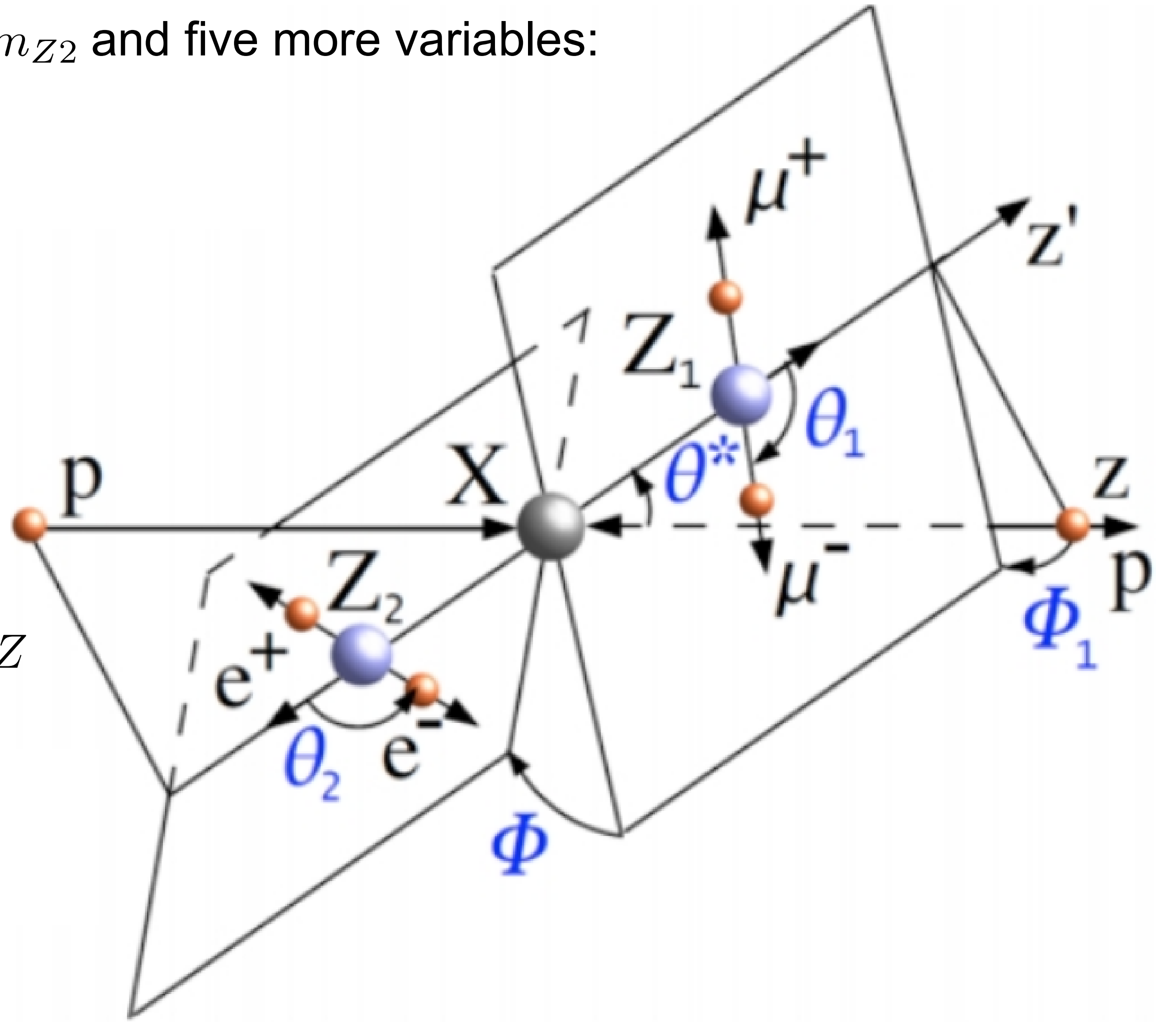
θ_1 decay angle $Z_1 \to \ell\ell$

θ_2 decay angle $Z_2 \to \ell\ell$

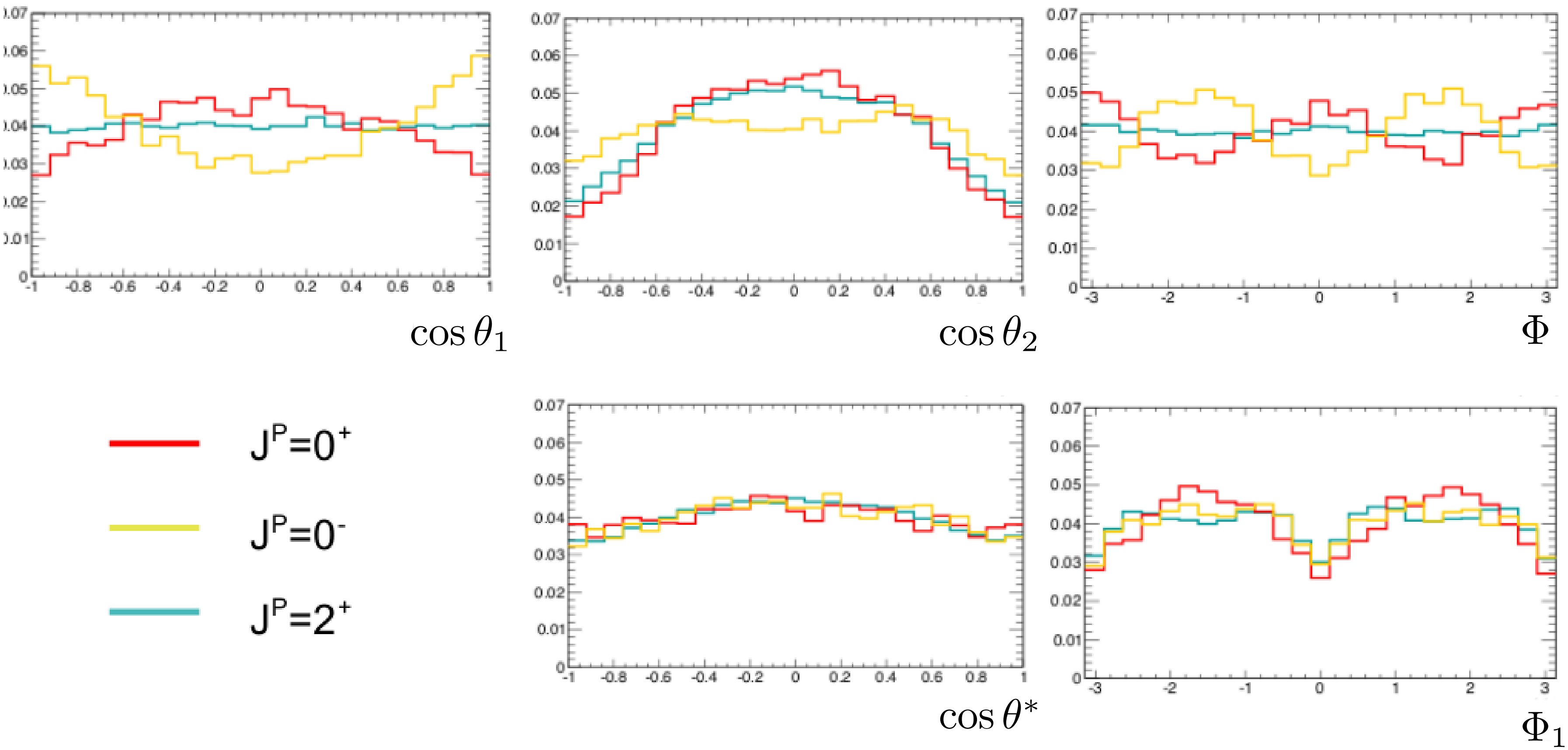
θ^* decay angle $H \to ZZ$

Φ azimuthal angle $H \to ZZ$

Φ_1 azimuthal angle $Z_1 \to \ell\ell$



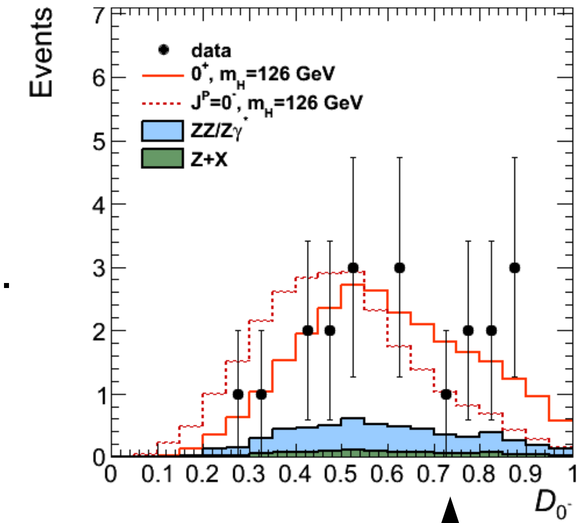
Discriminating Variables

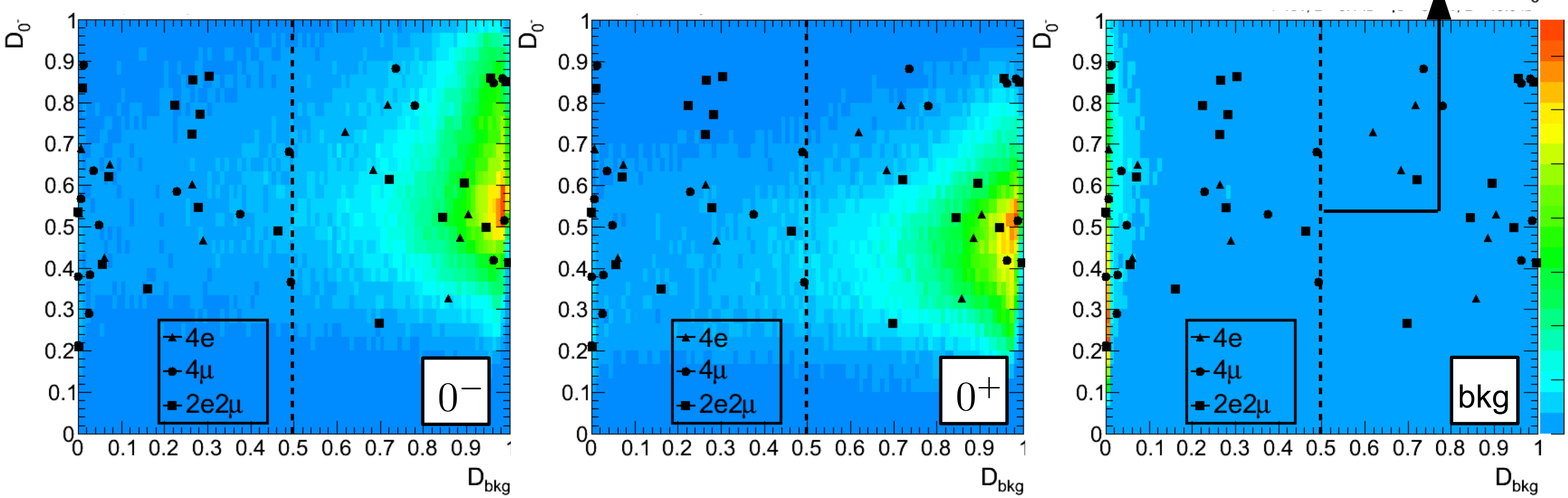


- As obtained from MC simulation (http://www.pha.jhu.edu/spin/).
- Taking acceptance and resolution effects into account.

Combination into a Single Discriminating Variable

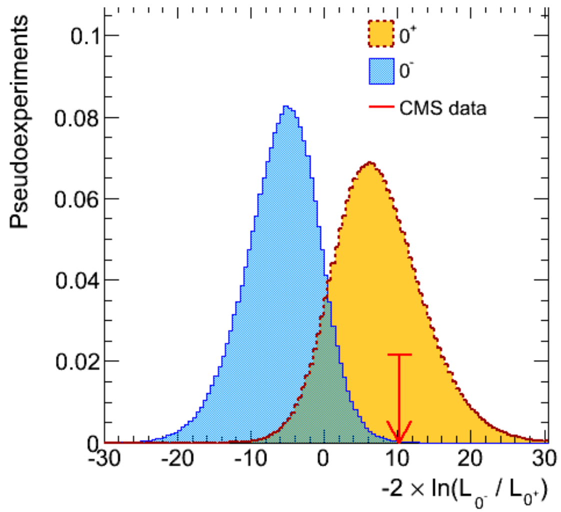
- Events with $106\ \mathrm{GeV} < m_{4\ell} < 141\ \mathrm{GeV}$ (49 events).
- Example given for 0^{-} hypothesis.
- For 1d projection a cut has been applied of $\mathrm{D_{bkg}} > 0.5$.
- Statistical assessment based on hypothesis tests.

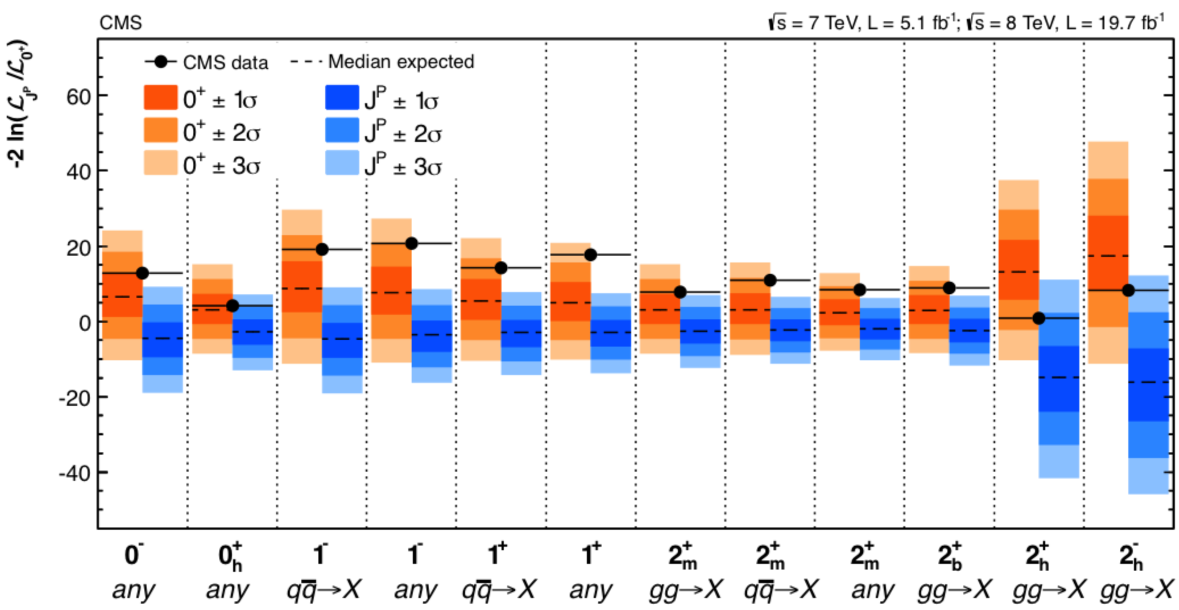




Combination into a Single Discriminating Variable

- Test statistic: $q = -2\ln\left(\frac{\mathcal{L}(0^+ + BG)}{\mathcal{L}(J^P + BG)}\right)$.
- Expectation for given hypothesis 0^+ or J^P obtained from toy experiments.
- SM hypothesis (0^+) tested against large number of alternative hypotheses. SM favored in each case.





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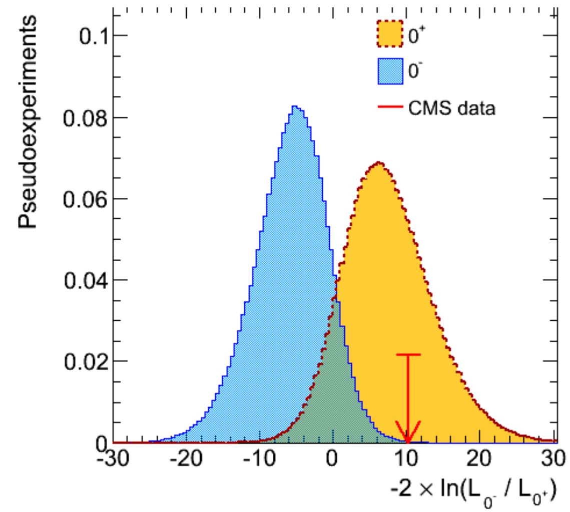
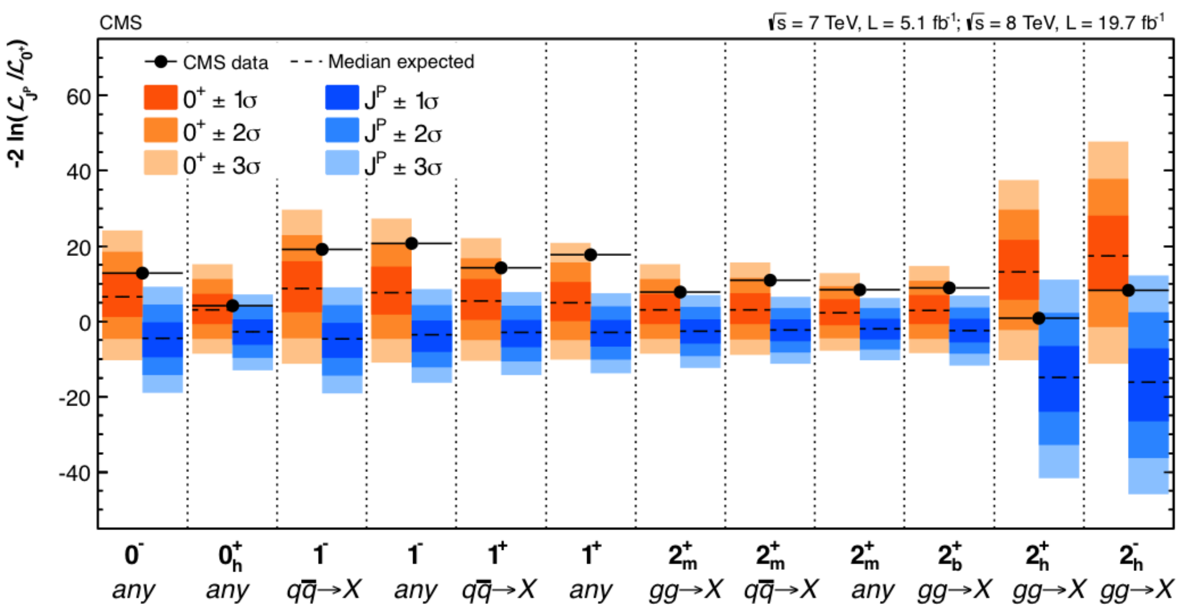


0^+ hypothesis favored.



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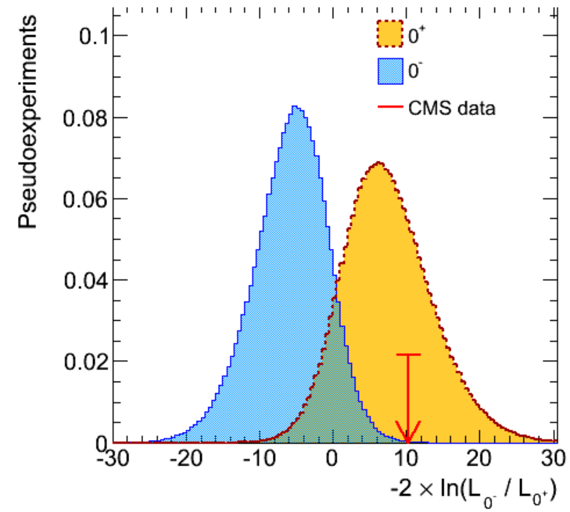

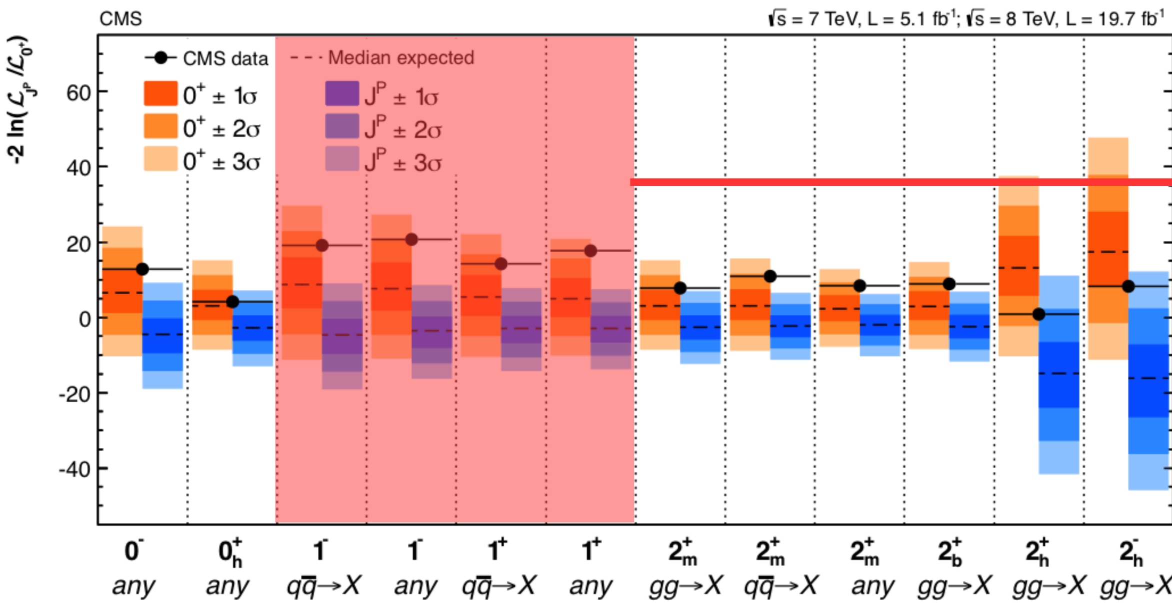

Spin 1 already excluded from $H \to \gamma\gamma$.

Combination into a Single Discriminating Variable

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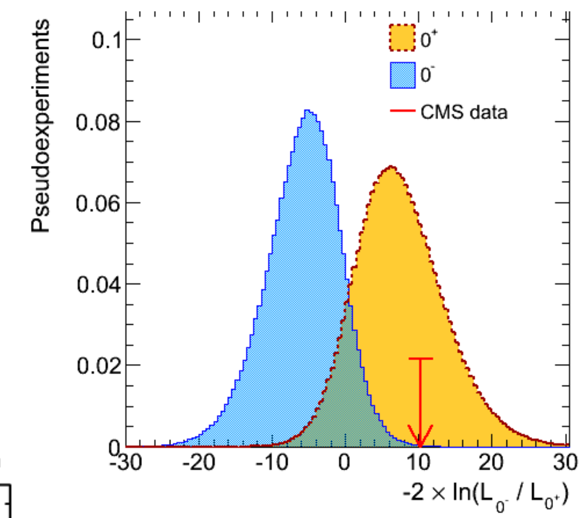
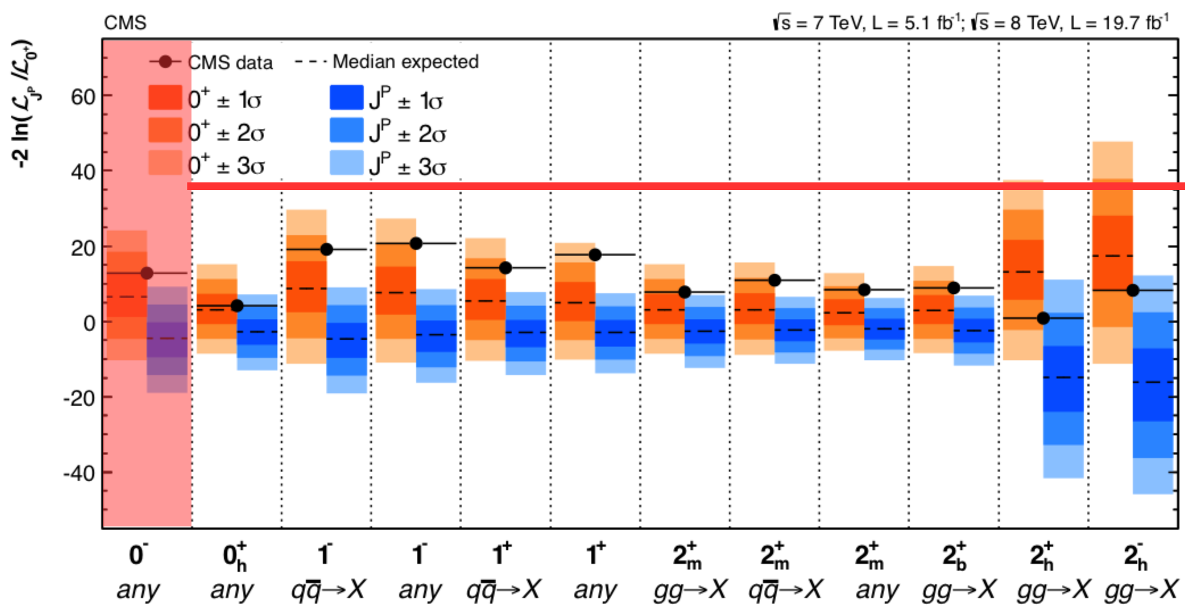
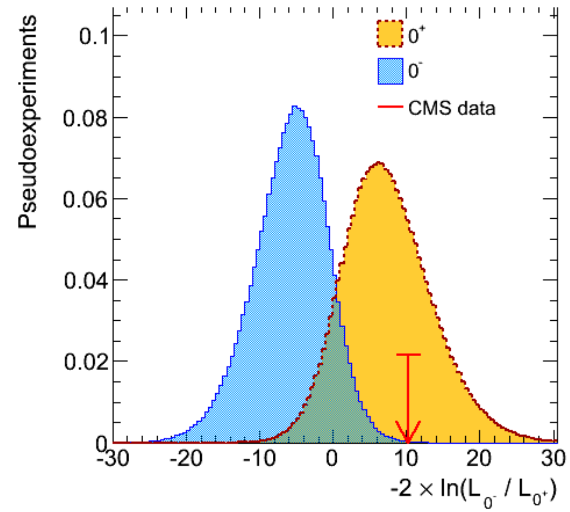


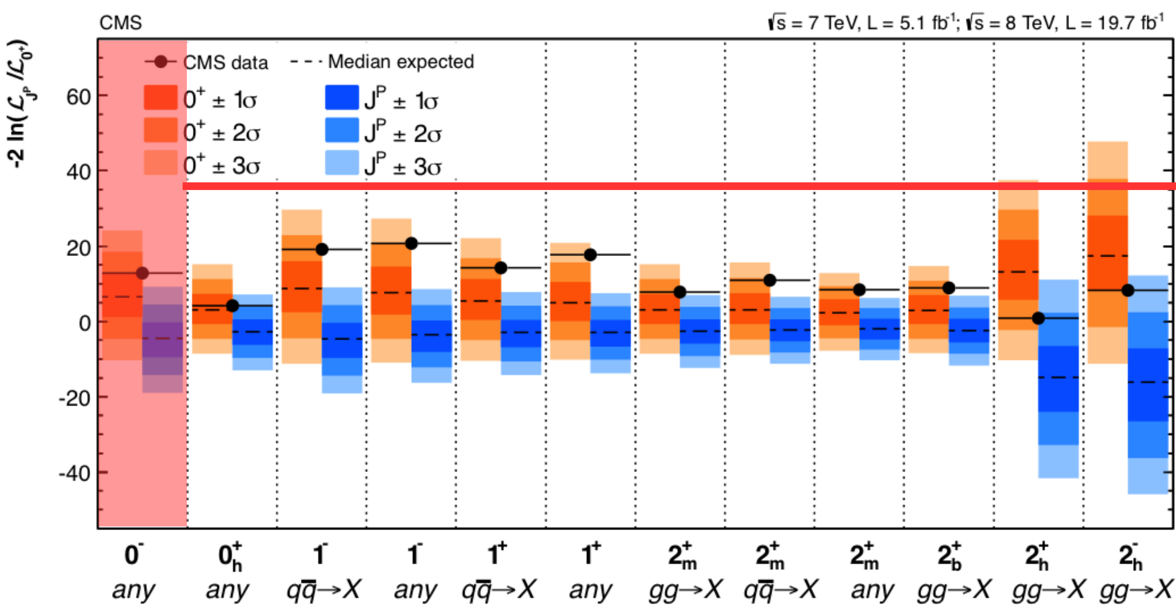


Implies anomalous coupling since no 0^- couplings at tree level in the SM.

Combination into a Single Discriminating Variable

- 0^- most interesting hypothesis, since predicted in many extensions of the SM (e.g. MSSM).
- Only realistic decay channel to study this hypothesis: $H \to \tau\tau$





Implies anomalous coupling since no 0^- couplings at tree level in the SM.

Properties Summary

- New particle is a boson. ✓
- Mass: $m_H = 125.03 \pm^{0.26}_{0.27} \, (\text{stat.}) \pm^{0.13}_{0.15} \, (\text{syst.}) \text{ GeV}$ ✓
- Decay width: $\Gamma_H < 22 \text{ MeV}$ ✓
- Spin: 0 favored ✓
- Parity: +1 favored ✓
- CP: ???

Sneak Preview for Next Week

- Remaining questions:
  - Is this **A** Higgs bosons?
  - Is this **THE** Higgs bosons?
  - Is there **MORE THAN ONE** Higgs bosons?

- Last lecture will be given by Günter Quast, I will be at CERN. Topics will be:
  - Search for additional Higgs bosons (compulsory program).
  - Search for additional Higgs bosons (dedicated searches: $H \to \tau\tau$).
  - Decay to invisible.
  - Other dedicated searches (?).

Backup & Homework Solutions