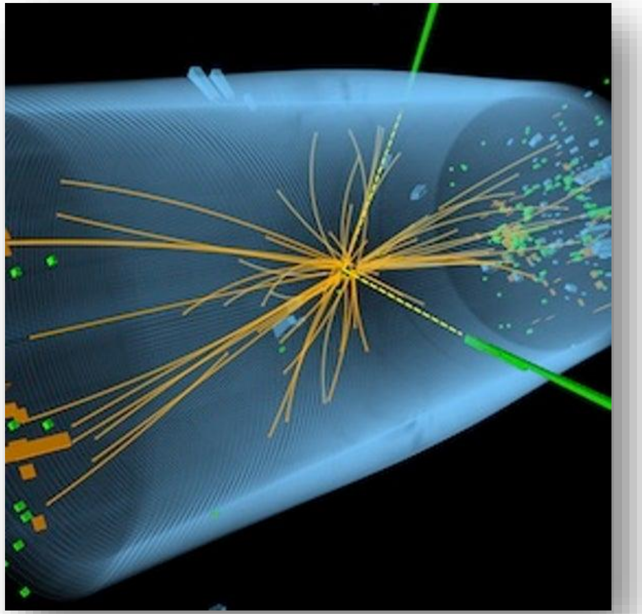
Higgs Boson Discovery



Hyunwoo Oh

게이지 대칭성

디락 라그랑지안 $\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$

에 대한 국소 게이지 변환(local gauge transformation)을 생각해 보자

국소 게이지 변환: $\psi(x) \to \psi'(x) = e^{i\varepsilon(x)q}\psi(x)$

$$\bar{\psi}(x) \to \bar{\psi}'(x) = e^{-i\varepsilon(x)q}\bar{\psi}(x)$$

국소 게이지 변환을 한 후의 라그랑지안은

$$\mathcal{L}' = ie^{-i\varepsilon q}\bar{\psi}\gamma^{\mu}\left(e^{i\varepsilon q}\partial_{\mu}\psi + iq(\partial_{\mu}\varepsilon)e^{i\varepsilon q}\psi\right) - me^{-i\varepsilon q}\bar{\psi}e^{i\varepsilon q}\psi$$

$$= \mathcal{L} - q\bar{\psi}\gamma^{\mu}(\partial_{\mu}\varepsilon)\psi \neq \mathcal{L}$$

따라서 디락 라그랑지안은 U(1) 국소 게이지 변환에 대해 대칭이 아니다.

게이지 대칭성

공변미분(covariant derivative) D_μ 를 도입

$$\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu$$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - m\bar{\psi}\psi = i\bar{\psi}\gamma^\mu(\partial_\mu \psi + iqA_\mu \psi) - m\bar{\psi}\psi$$

벡터장은 게이지 변환에 대해 다음과 같이 변환

$$A_\mu \to A'_\mu = A_\mu - \partial_\mu \varepsilon$$

국소 게이지 변환을 한 후의 라그랑지안은

$$\mathcal{L}' = ie^{-i\varepsilon q}\bar{\psi}\gamma^\mu\left(e^{i\varepsilon q}\partial_\mu \psi + iq(\partial_\mu \varepsilon)e^{i\varepsilon q}\psi + iqA_\mu e^{i\varepsilon q}\psi - iq(\partial_\mu \varepsilon)e^{i\varepsilon q}\psi\right) - me^{-i\varepsilon q}\bar{\psi}e^{i\varepsilon q}\psi$$

$$= i\bar{\psi}\gamma^\mu\left(\partial_\mu \psi + iqA_\mu \psi\right) - m\bar{\psi}\psi = \mathcal{L}$$

디락 라그랑지안이 U(1) 국소 게이지 변환에 대해 대칭성을 가지려면 벡터장을 도입해야 한다.

이 벡터장은 광자의 장으로 볼 수 있으며 전자기작용을 자연스럽게 포함하게 된다.

게이지 대칭성

따라서 U(1) 국소 게이지 변환에 대해 불변인 디락 라그랑지안은

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi - q\bar{\psi}\gamma^{\mu}\psi A_{\mu}$$
$$= \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi - j^{\mu}A_{\mu} \qquad j^{\mu} = q\bar{\psi}\gamma^{\mu}\psi$$

로 주어지며 광자와 결합하는 항을 자연스럽게 포함하게 된다.

여기에 광자를 기술하는 벡터 보존의 장을 같이 포함하면 라그랑지안이 완성된다.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A^{\mu}A_{\mu}$$

$$\frac{1}{2}m^2 A^{\mu}A_{\mu} \rightarrow \frac{1}{2}m^2(A^{\mu} - \partial^{\mu}\varepsilon)(A_{\mu} - \partial_{\mu}\varepsilon) \neq \frac{1}{2}m^2 A^{\mu}A_{\mu}$$

즉 국소게이지대칭성을 만족하려면 벡터보존은 질량을 가질 수 없게 된다.

게이지 대칭성

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi - j^{\mu}A_{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

자발적 대칭성 깨짐(Spontaneous Symmetry Breaking)

다음과 같은 스칼라 장을 고려해 보자

$$\mathscr{L} = T - V = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 \qquad \lambda > 0$$

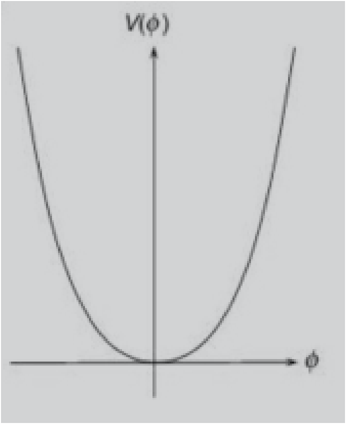
$$V = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

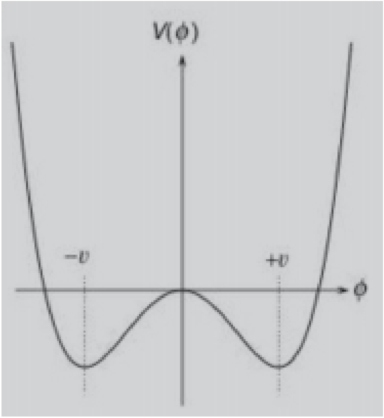
$\mu^2 > 0$ 일 경우 양의 질량을 가지는 평범한 스칼라 장. $\phi = 0$ 일 때가 바닥 상태

$\mu^2 < 0$ 일 경우 음의 질량

이 포텐셜 에너지는 $\phi = 0$ 이 바닥상태가 아니다. 최소값인 곳은 $\phi = \pm v$ $\quad v = \sqrt{-\mu^2/\lambda}$

$\mu^2 > 0$





$\mu^2 < 0$

자발적 대칭성 깨짐(Spontaneous Symmetry Breaking)

새로운 장변수를 도입 $\phi = v + \eta$ η 는 최소점에 대한 요동에 해당

원래 라그랑지안 $\mathscr{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2}\mu^2 \phi^2 - \frac{1}{4}\lambda \phi^4$ 다시 쓰면 $\mu^2 = -\lambda v^2$

$$\mathscr{L} = \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \lambda v^2 \eta^2 - \lambda v \eta^3 \cdots$$

양의 질량을 가지는 질량항을 얻었다.

$$m = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}$$

두 라그랑지안은 같은 계를 기술하지만 원래 라그랑지안은 대칭인데 반해 새로운 라그랑지안은 대칭이 깨져 있다.

이 과정을 자발적 대칭성 깨짐(spontaneous symmetry breaking)이라 부른다.

Higgs mechanism

복소 스칼라 장을 고려해 보자 $\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$

$$\mathcal{L} = (\partial_\mu\phi)^*(\partial^\mu\phi) - \mu^2\phi^*\phi - \lambda(\phi^*\phi)^2 \qquad \mu^2 < 0$$

이 라그랑지안은 U(1) global gauge 변환에 대해 대칭 $\phi \to \phi' = e^{i\alpha}\phi$

또는 두 개의 실수 스칼라장으로 나타내면

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) - \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2$$

이 포텐셜 에너지는 $\phi_1 = \phi_2 = 0$ 인 지점이 바닥상태가 아니다.
최소값인 곳은

$$\phi_1^2 + \phi_2^2 = v^2 = \frac{-\mu^2}{\lambda}$$

Higgs mechanism

최소인 곳을 $(\phi_1, \phi_2) = (\upsilon, 0)$ 로 정하고 새로운 장을 도입

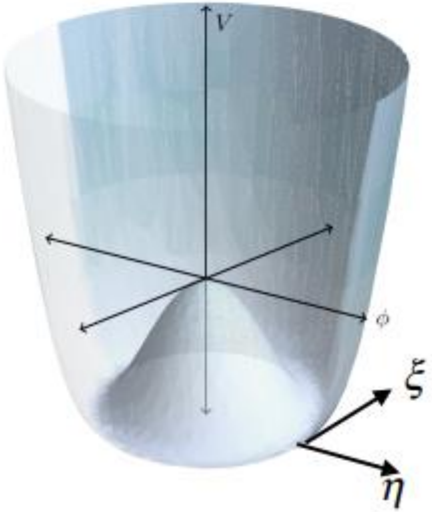
$$\phi_1 = \eta + \upsilon, \quad \phi_2 = \xi$$

$$\phi = \frac{1}{\sqrt{2}}(\eta + \upsilon + i\xi)$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \eta \partial^\mu \eta + \frac{1}{2}\partial_\mu \xi \partial^\mu \xi + \frac{1}{2}\lambda \upsilon^2 \{(\eta+\upsilon)^2 + \xi^2)\} - \frac{1}{4}\lambda\{(\eta+\upsilon)^2 + \xi^2)\}^2$$

$$= \underline{\frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \lambda \upsilon^2 \eta^2} + \underline{\frac{1}{2}\partial_\mu \xi \partial^\mu \xi} - V_{\text{int}}$$

$$V_{\text{int}} = \lambda \upsilon \eta^3 + \frac{1}{4}\lambda \eta^4 + \frac{1}{4}\lambda \xi^4 + \lambda \upsilon \eta \xi^3 + \frac{1}{2}\lambda \eta^2 \xi^2$$



질량이 있는 스칼라 장(η)과 질량이 없는 스칼라 장(ξ)이 나타난다. 질량이 있는 장이 들뜨는 방향은 포텐셜이 변하는 방향이고 질량이 없는 장이 들뜨는 방향은 등포텐셜원의 접선 방향으로 힘이 작용하지 않는 방향이다. 질량이 없는 장을 **Goldstone 보존**이라 부른다.

Higgs mechanism

복소스칼라장의 경우에 U(1) 국소 게이지 변환을 적용하여 보자

$$\mathscr{L} = (\partial_\mu \phi)^*(\partial^\mu \phi) - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2$$

$$\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu \qquad \phi \to \phi' = e^{iq\varepsilon(x)}\phi \quad A_\mu \to A'_\mu = A_\mu - \partial_\mu \varepsilon$$

$$\mathscr{L} = (\partial_\mu - iqA^\mu)\phi^*(\partial^\mu - iqA_\mu)\phi - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2$$

앞의 경우와 같이 스칼라장의 대칭성을 깨면 $\phi = \frac{1}{\sqrt{2}}(\eta + \upsilon + i\xi)$

$$\mathscr{L} = \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \lambda \upsilon^2 \eta^2 + \frac{1}{2}\partial_\mu \xi \partial^\mu \xi + \frac{1}{2}q^2 \upsilon^2 A_\mu A^\mu + q\upsilon A_\mu \partial^\mu \xi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V_{int}$$

앞의 경우와 같이 질량이 있는 스칼라 장과 질량이 없는 스칼라 장이 나타나며 추가로 게이지 장의 질량항이 나타나는 것을 알 수 있다 !

$$m_\eta = \sqrt{2\lambda\upsilon^2}, m_A = q\upsilon$$

Higgs mechanism

$$\mathscr{L} = \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \lambda\upsilon^2\eta^2 + \frac{1}{2}\partial_\mu\xi\partial^\mu\xi + \frac{1}{2}q^2\upsilon^2A_\mu A^\mu + q\upsilon A_\mu\partial^\mu\xi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V_{int}$$

적당한 게이지의 선택을 통해 골드스톤 보존을 제거할 수 있을까?

$$\frac{1}{2}\partial_\mu\xi\partial^\mu\xi + \frac{1}{2}q^2\upsilon^2A_\mu A^\mu + q\upsilon A_\mu\partial^\mu\xi = \frac{1}{2}q^2\upsilon^2\left(A_\mu + \frac{1}{q\upsilon}\partial^\mu\xi\right)^2$$

게이지 변환 $A_\mu \to A'_\mu = A_\mu + \frac{1}{q\upsilon}\partial^\mu\xi$

$$\frac{1}{2}q^2\upsilon^2\left(A_\mu + \frac{1}{q\upsilon}\partial^\mu\xi\right)^2 \to \frac{1}{2}q^2\upsilon^2A'_\mu A'^\mu$$

라그랑지안은 $\mathcal{L} = \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \lambda\upsilon^2\eta^2 + \frac{1}{2}q^2\upsilon^2A_\mu A^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V_{\text{int}}$

즉 $A_\mu \to A'_\mu = A_\mu - \partial_\mu\varepsilon$ 에서 $\varepsilon(x) = -\frac{1}{q\upsilon}\xi(x)$

로 택하면 라그랑지안에 골드스톤보존 항이 없어진다.

Higgs mechanism

원래 스칼라장의 게이지 변환은 $\phi \rightarrow \phi' = e^{iq\varepsilon(x)}$ $\varepsilon(x) = -\frac{1}{q\upsilon}\xi(x)$ 를 대입하면

$$\phi \rightarrow \phi' = e^{-iq\frac{1}{q\upsilon}\xi(x)}\phi = e^{-i\frac{1}{\upsilon}\xi(x)}\phi$$

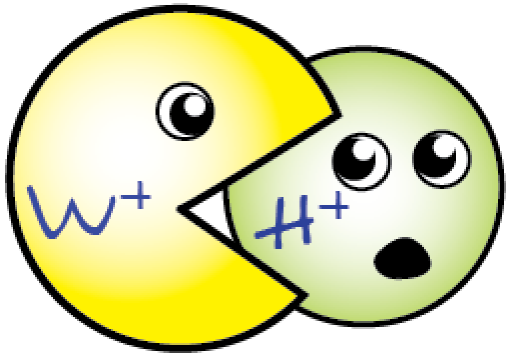
$$\phi = \frac{1}{\sqrt{2}}(\eta + \upsilon + i\xi) \approx \frac{1}{\sqrt{2}}(\eta + \upsilon)e^{i\frac{\xi}{\upsilon}}$$ (장의 1차항으로 근사하면)

$$\phi' = e^{iq\frac{1}{q\upsilon}\xi(x)}\phi = e^{-i\frac{1}{\upsilon}\xi(x)}\frac{1}{\sqrt{2}}(\eta + \upsilon)e^{i\frac{1}{\upsilon}\xi(x)} = \frac{1}{\sqrt{2}}(\eta + \upsilon)$$

따라서 이 게이지 변환은 복소 스칼라장이 실수 스칼라장이 되도록 취하는 것이다.
이 게이지를 하나게이지(unitary gauge)라고 부른다. 실수 스칼라장은 힉스장이라고 한다.

$$\phi = \frac{1}{\sqrt{2}}(H + \upsilon)$$

원래 있던 스칼라장의 2 개의 자유도 중 하나는 질량이 있는 힉스입자가 되고 골드스톤 보존은 질량이 있는 게이지보존에 필요한 길이방향의 편극(longitudinal polarization)을 제공한다.
(게이지 보존에게 먹혔다!)



Nambu-Goldstone bosons

- Spontaneous breaking of a continuous symmetry $\Rightarrow$ existence of massless spin-0 ***Nambu-Goldstone bosons***.
- e.g. Goldstone model $\mathrm{L} = \partial_\mu \phi^* \partial^\mu \phi - \mathrm{V}$

$$\mathrm{V} = \tfrac{1}{2}\lambda(\phi^*\phi - \tfrac{1}{2}\eta^2)^2$$

— vacuum breaks symmetry:

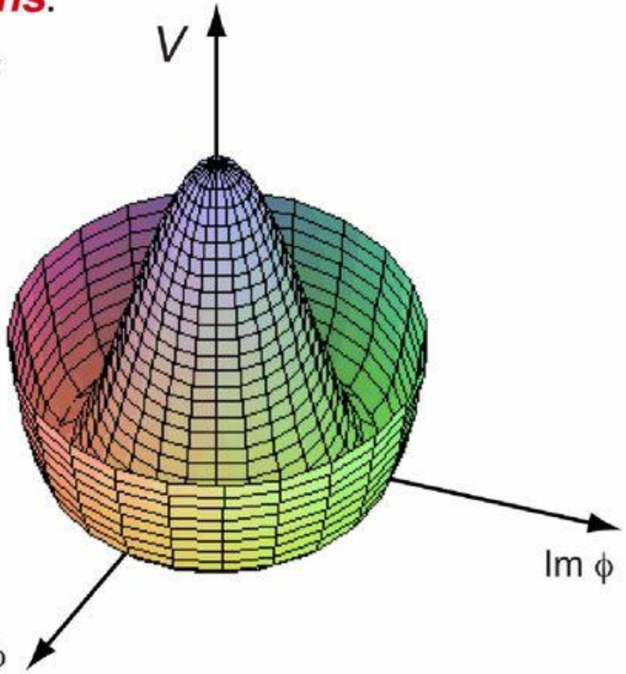
$$\langle 0|\phi|0\rangle = \frac{\eta}{\sqrt{2}} e^{i\alpha} \quad \text{— choose} \quad \alpha = 0$$

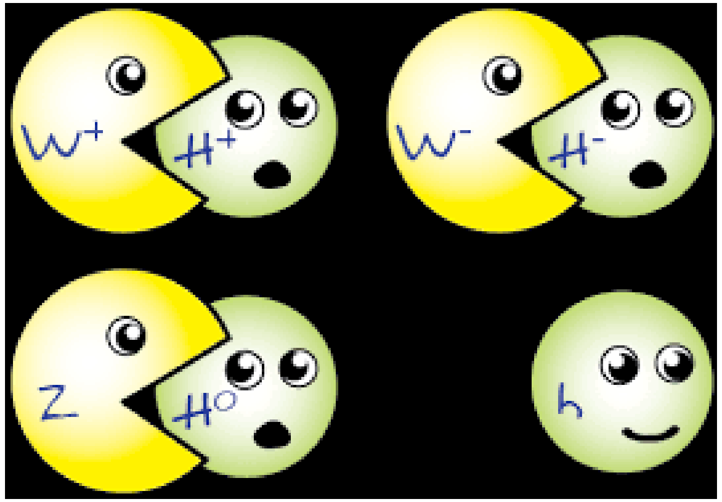
and set $\phi = \frac{1}{\sqrt{2}}(\eta + \varphi_1 + i\varphi_2)$

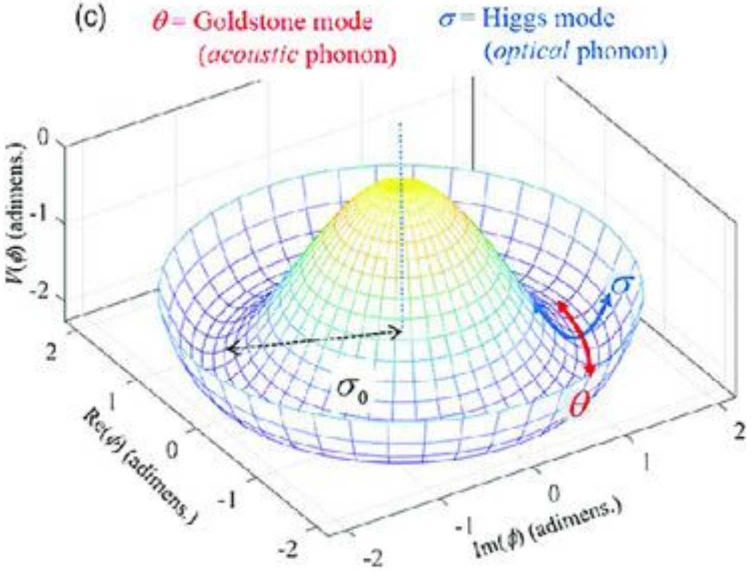
$$\mathrm{V} = \tfrac{1}{2}\lambda\eta^2\varphi_1^2 + \text{ cubic and quartic terms}$$

So $m_1^2 = \lambda\eta^2, \quad m_2^2 = 0$ (Goldstone boson)

- This was believed **inevitable** in a relativistic theory

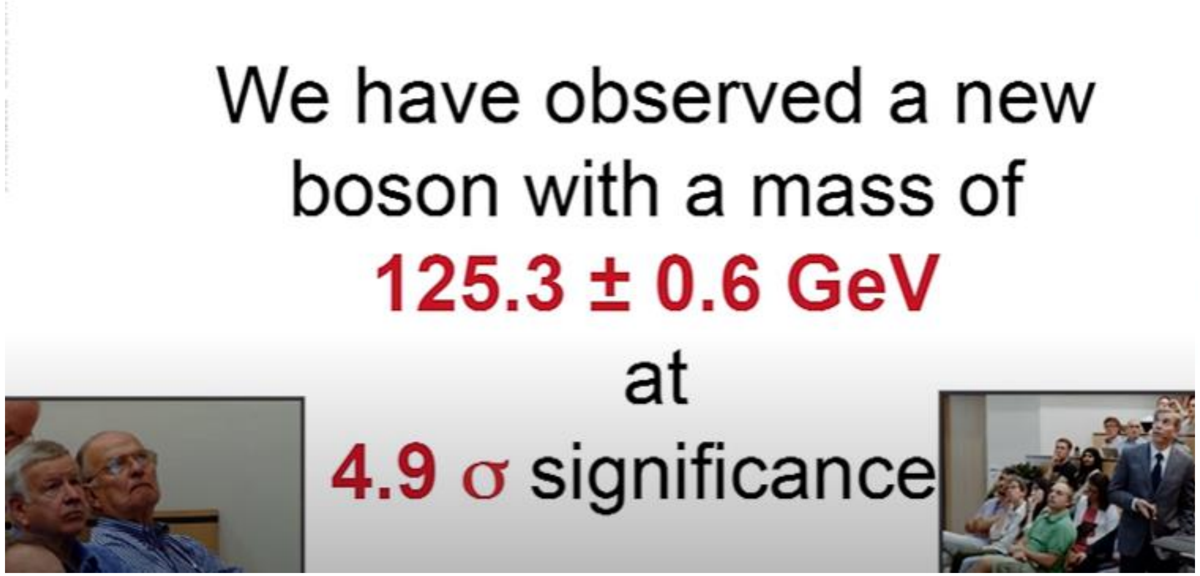


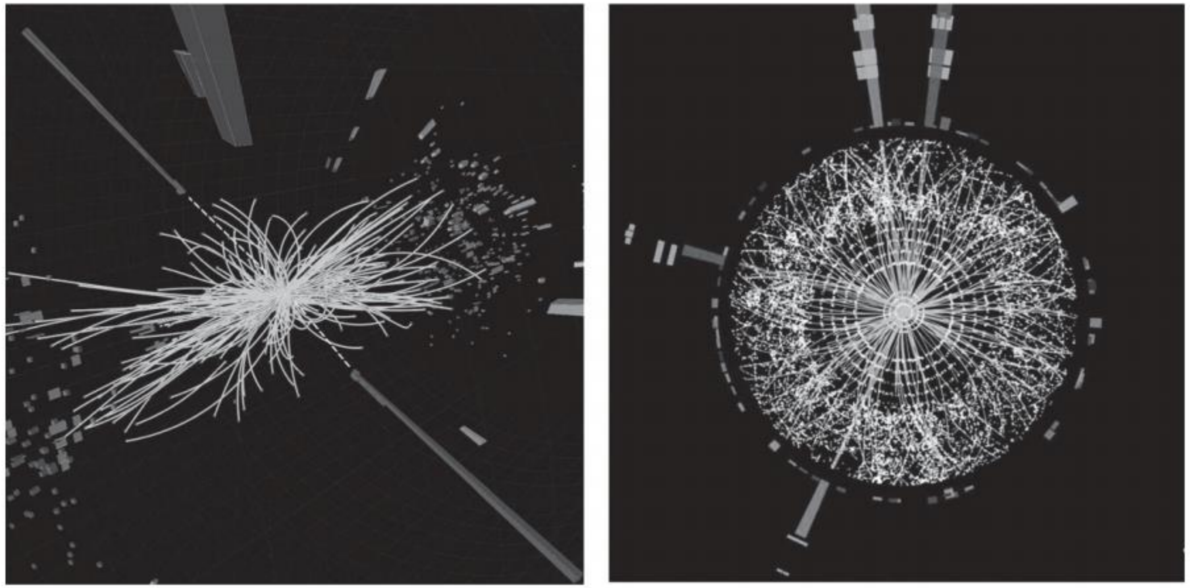




Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *





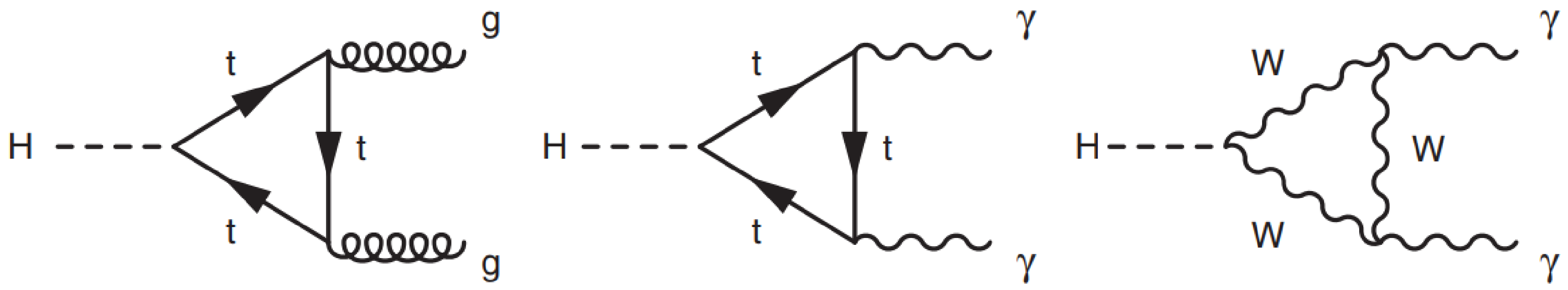
Left: a candidate $H \to \gamma\gamma$ event in the CMS detector. Right: a candidate $H \to ZZ^* \to e^+e^-e^+e^-$ in the ATLAS detector. Reproduced with kind permission from the ATLAS and CMS collaborations, © 2012 CERN.

The **Higgs boson**, sometimes called the **Higgs particle**,[9][10] is an elementary particle in the Standard Model of particle physics produced by the quantum excitation of the **Higgs field**,[11][12] one of the fields in particle physics theory.[12] In the Standard Model, the Higgs particle is a massive scalar boson with zero spin, even (positive) parity, no electric charge, and no colour charge, that couples to (interacts with) mass.[13] It is also very unstable, decaying into other particles almost immediately.

Nearly fifty years ago it was proposed [1–6] that spontaneous symmetry breaking in gauge theories could be achieved through the introduction of a scalar field. Applying this mechanism to the electroweak theory [7–9] through a complex scalar doublet field leads to the generation of the W and Z masses, and to the prediction of the existence of the SM Higgs boson (H). The scalar field also gives mass to the fundamental fermions through the Yukawa interaction. The mass m_H of the SM Higgs boson is not predicted by theory. However, general considerations [10–13] suggest that m_H should be smaller than $\sim$1 TeV, while precision electroweak measurements imply that $m_H < 152$ GeV at 95% confidence level (CL) [14]. Over the past twenty years, direct searches for the Higgs boson have been carried out at the LEP collider, leading to a lower bound of $m_H > 114.4$ GeV at 95% CL [15], and at the Tevatron proton–antiproton collider, excluding the mass range 162–166 GeV at 95% CL [16] and detecting an excess of events, recently reported in [17–19], in the range 120–135 GeV.

Table 1
Summary of the subchannels, or categories, used in the analysis of each decay mode.

Decay mode	Production tagging	No. of subchannels	m_H range (GeV)	Int. Lum. (fb^{-1})	
				7 TeV	8 TeV
$\gamma\gamma$	untagged	4	110–150	5.1	5.3
	dijet (VBF)	1 or 2			
ZZ	untagged	3	110–160	5.1	5.3
WW	untagged	4	110–160	4.9	5.1
	dijet (VBF)	1 or 2			
$\tau\tau$	untagged	16	110–145	4.9	5.1
	dijet (VBF)	4			
bb	lepton, E_T^{miss} (VH)	10	110–135	5.0	5.1



The Feynman diagrams for the decays H $\rightarrow$ gg and H $\rightarrow$ $\gamma\gamma$.

The excess is most significant in the two decay modes with the best mass resolution, γγ and ZZ

6. Decay modes with low mass resolution

6.1. H → WW

6.2. H → ττ

6.3. H → bb

5. Decay modes with high mass resolution

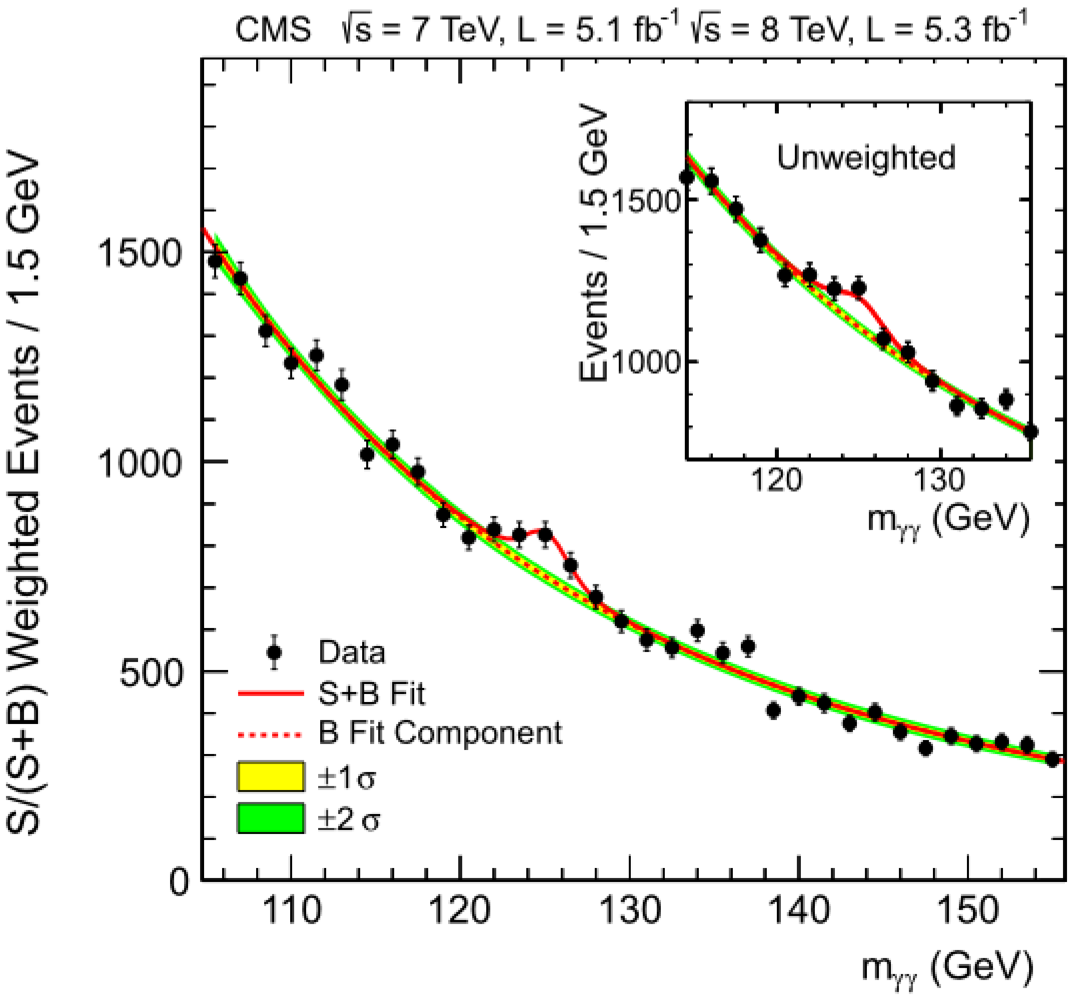
5.1. H → γγ

5.2. H → ZZ

Table 17.1 The predicted branching ratios of the Higgs boson for $m_H = 125$ GeV.

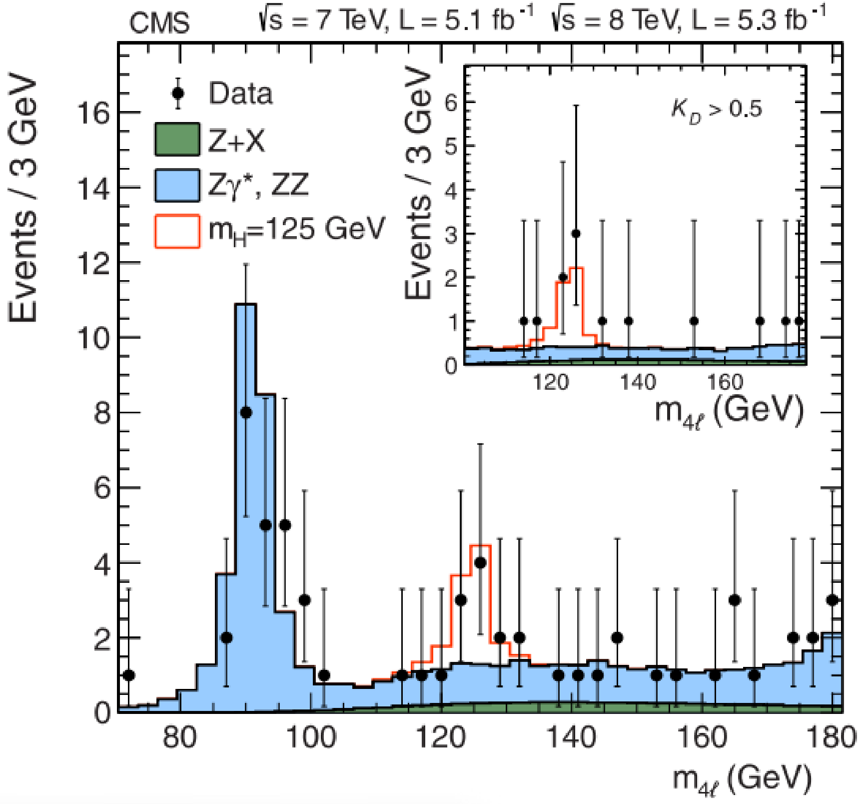
Decay mode	Branching ratio
$H \to b\bar{b}$	57.8%
$H \to WW^*$	21.6%
$H \to \tau^+\tau^-$	6.4%
$H \to gg$	8.6%
$H \to c\bar{c}$	2.9%
$H \to ZZ^*$	2.7%
$H \to \gamma\gamma$	0.2%

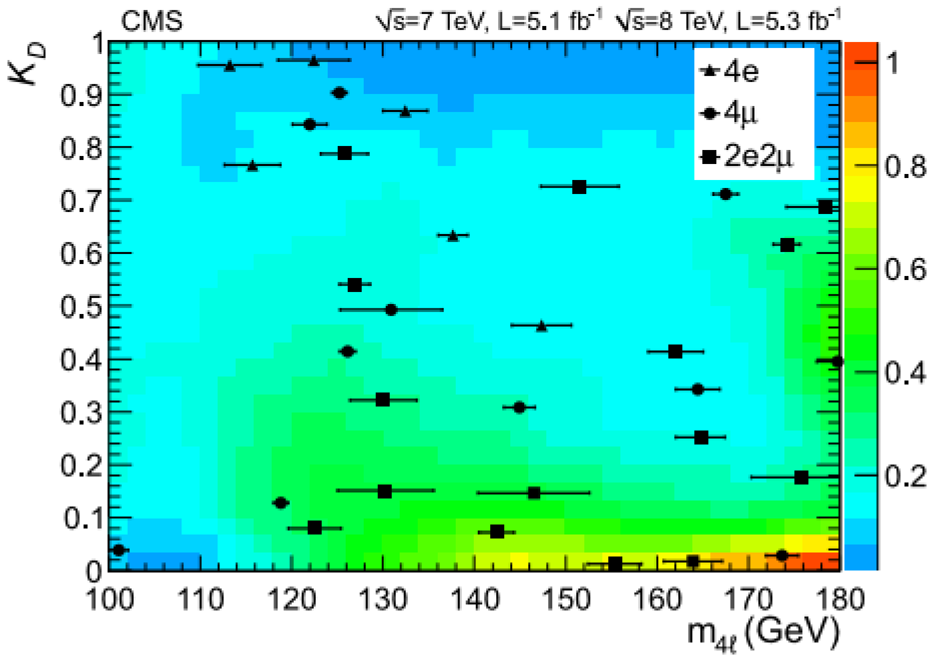
π^0 입자는 두 개의 광자로 붕괴한다. 두 광자의 에너지 E_1, E_2와 두 광자 사이의 각 θ 를 측정하였을 경우 이를 이용하여 π^0 입자의 질량을 결정하라.

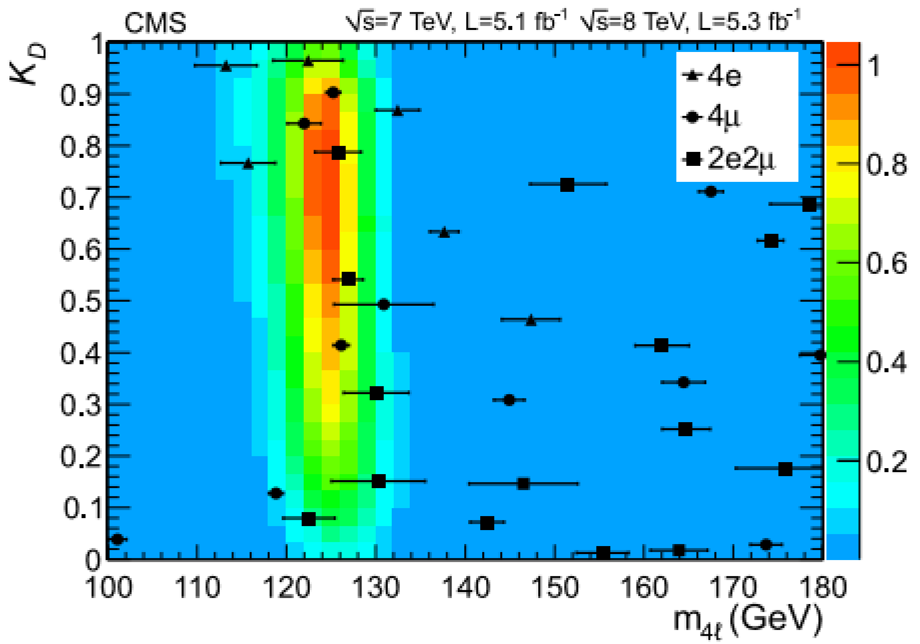


CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
m_γγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2 σ
Unweighted
Events / 1.5 GeV
m_γγ (GeV)

arises from Z + jets and WZ + jets events where jets are misidentified as leptons. Compared to the analysis reported in Ref. [25], the present analysis employs improved muon reconstruction, improved lepton identification and isolation, and a kinematic discriminant exploiting the decay kinematics expected for the signal events. An algorithm to recover final-state radiation (FSR) photons has also been deployed.







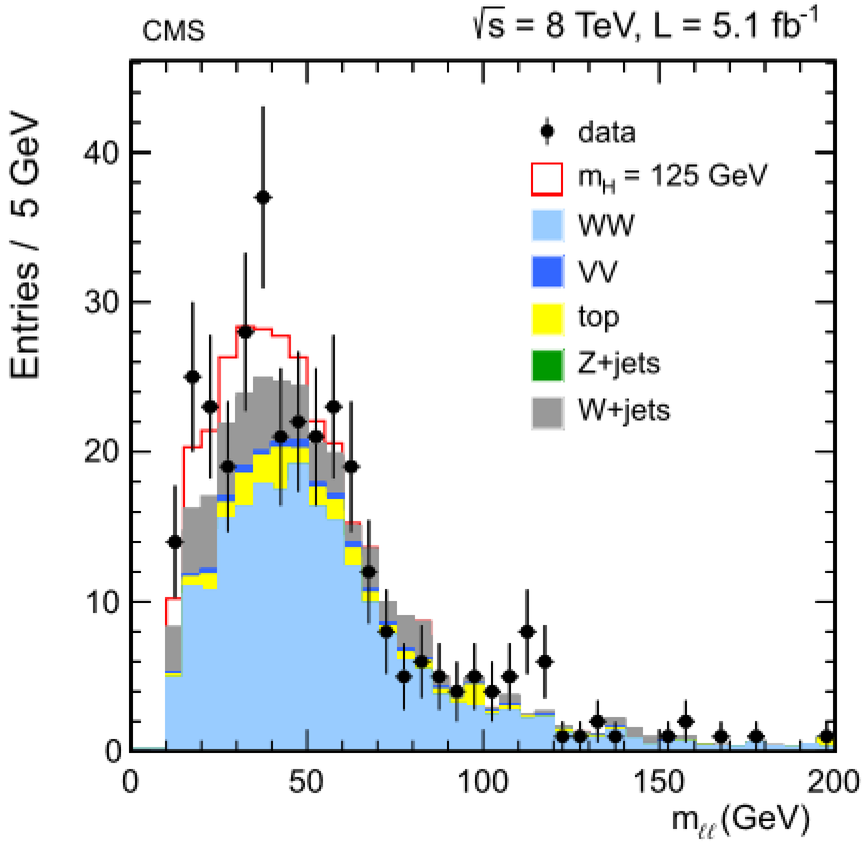


Fig. 7. Distribution of $m_{\ell\ell}$ for the zero-jet eμ category in the H → WW search at 8 TeV. The signal expected from a Higgs boson with a mass $m_{\mathrm{H}} = 125$ GeV is shown added to the background.

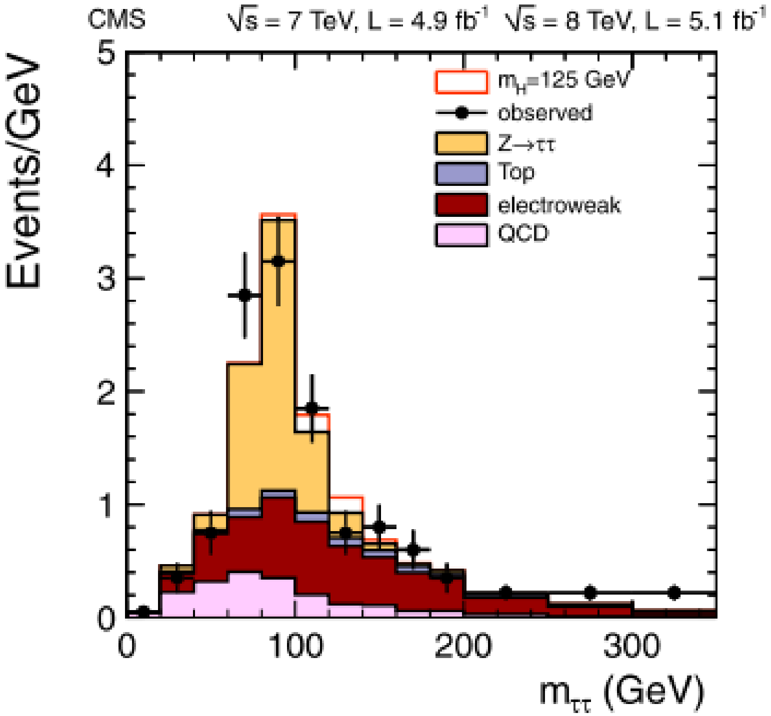
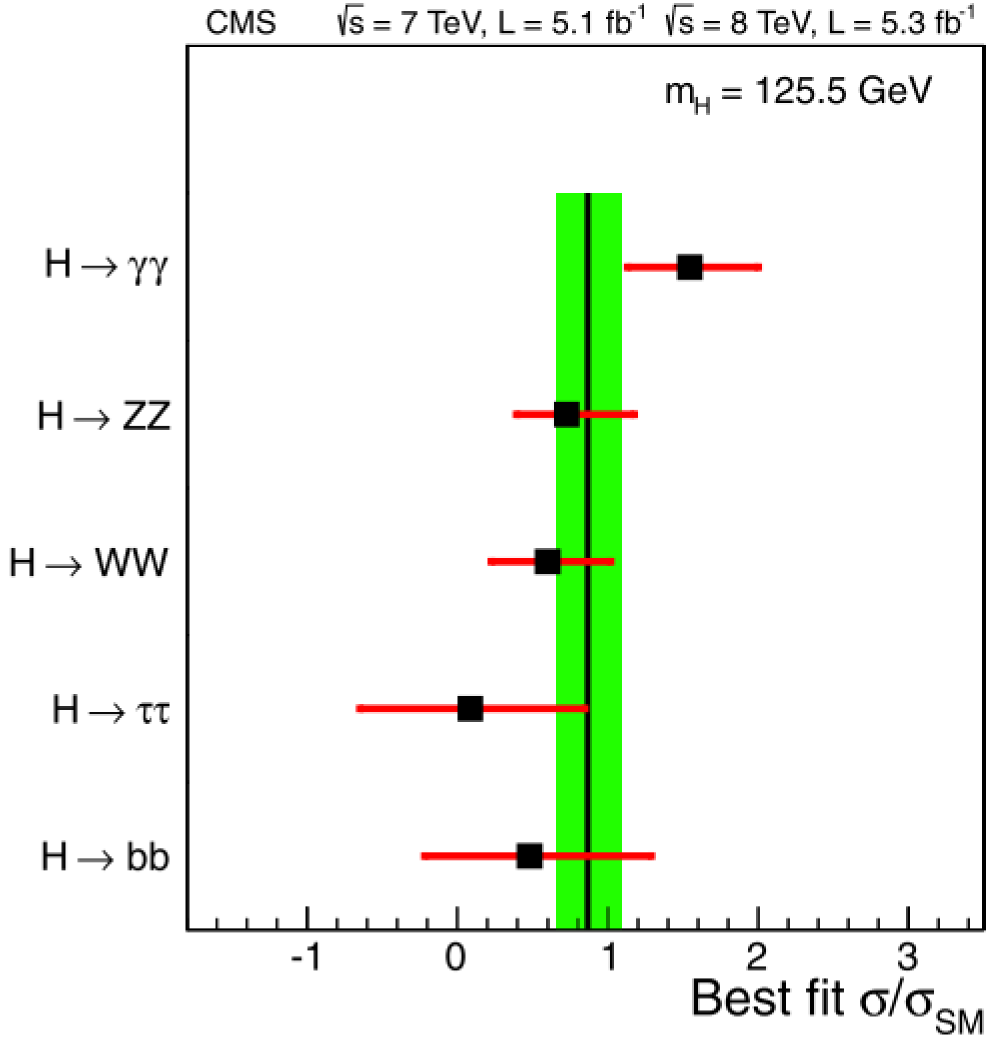


Fig. 9. Distribution of $m_{\tau\tau}$ in the combined 7 and 8 TeV data sets for the $\mu\tau_{\mathrm{h}}$ VBF category of the H → $\tau\tau$ search. The signal expected from a SM Higgs boson ($m_{\mathrm{H}} = 125$ GeV) is added to the background.



CMS
√s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
m_H = 125.5 GeV
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
-1
0
1
2
3
Best fit σ/σ_SM

0.87+-0.2