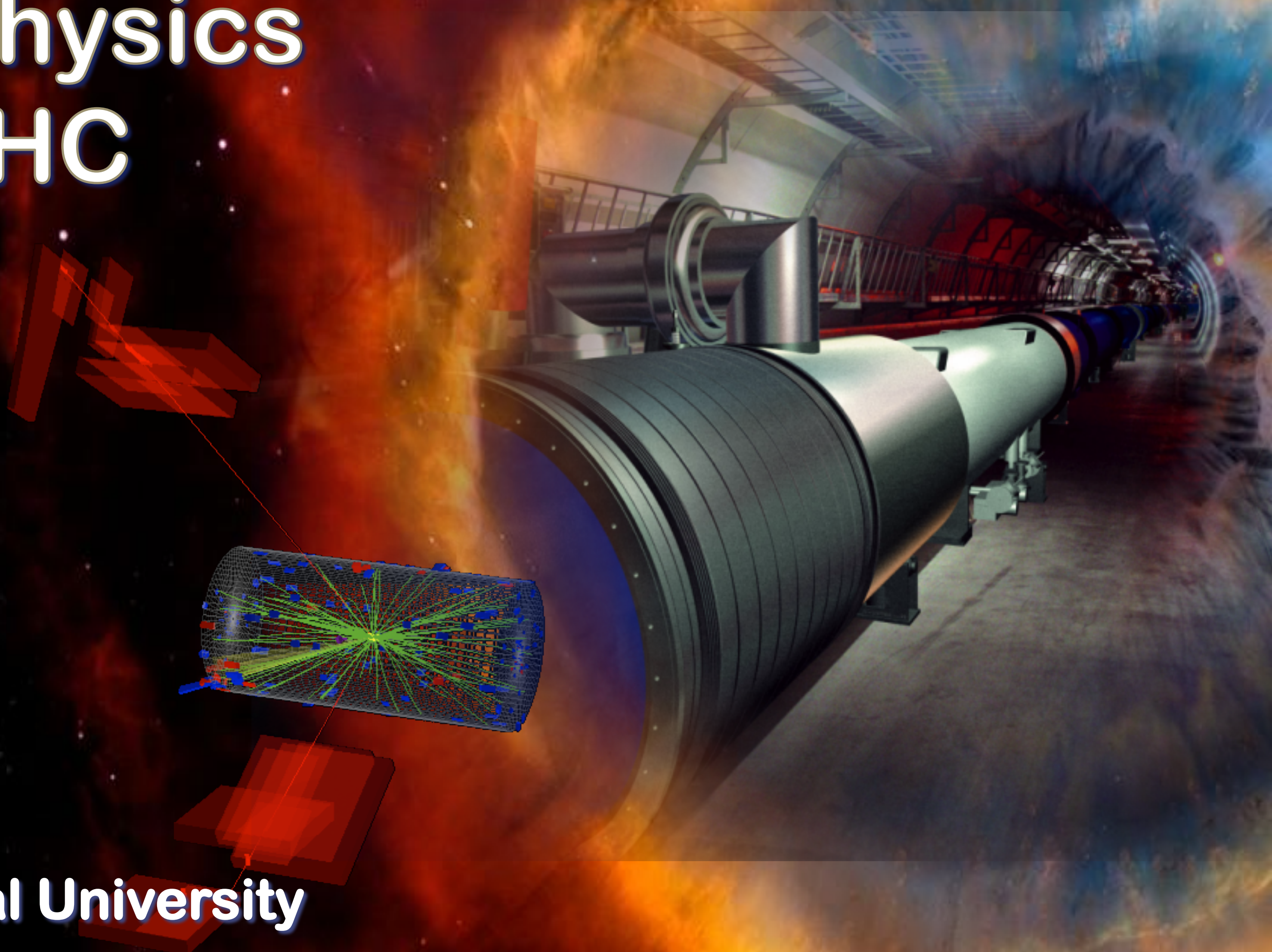
Higgs Physics at the LHC



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KCMS Collider Lecture Series, May 10, 2022

HIGGS THEORY OVERVIEW

- Slides from 3 to 20 pages
- You may skip them

Higgs Mechanism

- A few basics on Lagrangians

$$\mathcal{L} = \mathrm{T(kinetic)} - \mathrm{V(potential)}$$

- The Euler-Lagrange equation brings the equation of motion

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2 \rightarrow \text{Euler-Lagrange} \rightarrow \underbrace{(\partial_\mu \partial^\mu + m^2)\phi = 0}_{\text{Klein-Gordon equation}}$$

In general, the Lagrangian for a real scalar particle (ϕ) is given by:

$$\mathcal{L} = \underbrace{(\partial_\mu \phi)^2}_{\text{kinetic term}} + \underbrace{\beta\phi^2}_{\text{mass term}} + \underbrace{\gamma\phi^3}_{\text{3-point int.}} + \underbrace{\delta\phi^4}_{\text{4-point int.}}$$

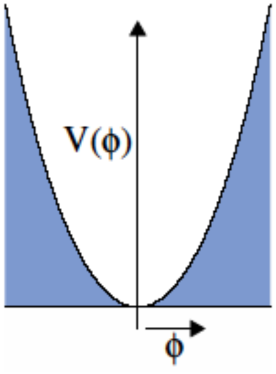
Higgs Mechanism

- A real scalar field

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu \phi)^2 - \mathrm{V}(\phi) \\ &= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4\end{aligned}$$

$\mathcal{L}$ is symmetric under $\phi \to -\phi$

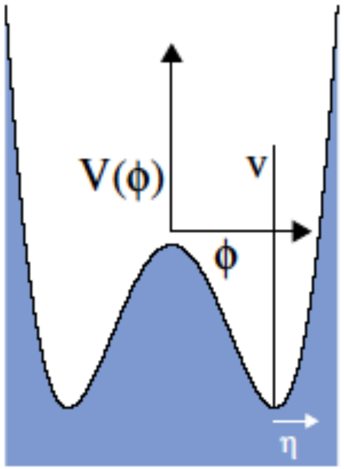
- For $\mu^2 > 0$, the minimum (vacuum) is at $\phi = 0$



$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2}_{\text{free particle, mass } \mu} \quad \underbrace{-\frac{1}{4}\lambda\phi^4}_{\text{interaction}}$$

Higgs Mechanism

- For $\mu^2 < 0$, introducing a particle with imaginary mass?



$$\phi_0 = \sqrt{-\frac{\mu^2}{\lambda}} = v \quad \text{or} \quad \mu^2 = -\lambda v^2$$

- To study a particle spectrum, we look at an excited state (near ground state), $\eta = \phi - v.$

Higgs Mechanism

- Rewriting the Lagrangian in terms of η

$$
\begin{aligned}
\text{Kinetic term:} \quad \mathcal{L}_{\text{kin}}(\eta) &= \frac{1}{2}(\partial_\mu(\eta+v)\partial^\mu(\eta+v)) \\
&= \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) \qquad \text{, since } \partial_\mu v = 0.
\end{aligned}
$$

$$
\begin{aligned}
\text{Potential term:} \quad \mathrm{V}(\eta) &= +\frac{1}{2}\mu^2(\eta+v)^2 + \frac{1}{4}\lambda(\eta+v)^4 \\
&= \lambda v^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4 - \frac{1}{4}\lambda v^4,
\end{aligned}
$$

we used $\mu^2 = -\lambda v^2$

- Symmetry is broken→ spontaneous symmetry breaking.

$$\mathrm{V}(-\eta) \neq \mathrm{V}(\eta)$$

Higgs Mechanism

- Full Lagrangian

$$\mathcal{L}(\eta) \;=\; \frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \lambda v^2 \eta^2 - \lambda v \eta^3 - \frac{1}{4}\lambda \eta^4 - \frac{1}{4}\lambda v^4$$

- This describe the kinematics for a massive scalar particle

$$\frac{1}{2}m_\eta^2 = \lambda v^2 \to m_\eta = \sqrt{2\lambda v^2} \quad \left(= \sqrt{-2\mu^2}\right) \qquad \text{Note: } m_\eta > 0.$$

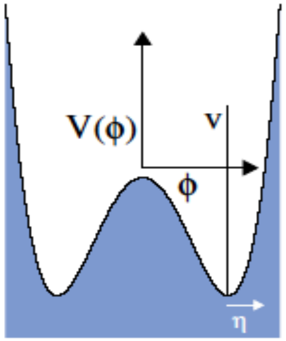
- Adding a particle with imaginary mass with a four-point self-interaction, thus we examine the particle spectrum using perturbation around the vacuum
  - We find that it actually describes a massive scalar particle (real, positive mass) with three- and four-point self interactions.
  - The vacuum is not symmetric in the field η though the Lagrangian is symmetric in ϕ ➔ spontaneous symmetry breaking.

Higgs Mechanism

- The Universe is filled with a spin-zero field, a Higgs field that is a doublet in the SU(2) space and carries non-zero U(1) hypercharge but a singlet in color space
- Spontaneous Symmetry Breaking
- A real scalar field

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi)^2 - \mathrm{V}(\phi) \\ &= \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4\end{aligned}$$

$\mathcal{L}$ is symmetric under $\phi \to -\phi$



$$\mathcal{L}(\eta) = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \lambda v^2\eta^2 - \lambda v\eta^3 - \frac{1}{4}\lambda\eta^4 - \frac{1}{4}\lambda v^4$$

$$m_\eta = \sqrt{2\lambda v^2}$$

$$\phi_0 = \sqrt{-\frac{\mu^2}{\lambda}} = v$$

vacuum is not symmetric in the field η: spontaneous symmetry breaking.

Complex Scalar Field

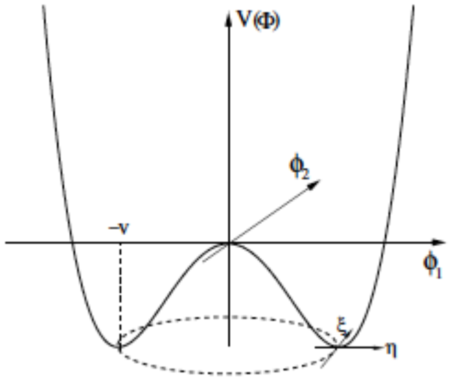
- A global symmetry

$$\mathcal{L} = (\partial_\mu \phi)^* (\partial^\mu \phi) - \mathrm{V}(\phi) \qquad \text{, with } \mathrm{V}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$

$$\phi = \tfrac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \qquad \text{U(1) global symmetry, i.e. under } \phi' \to e^{i\alpha}\phi$$

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

$$\sqrt{\phi_1^2 + \phi_2^2} = \sqrt{\frac{-\mu^2}{\lambda}} = v \qquad \phi_0 = \frac{1}{\sqrt{2}}(\eta + v + i\xi)$$



$\mu^2 < 0$

$$\begin{aligned} \mathcal{L}_{\text{kin}}(\eta, \xi) &= \frac{1}{2}\partial_\mu(\eta + v - i\xi)\partial^\mu(\eta + v + i\xi) \\ &= \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}(\partial_\mu \xi)^2 \quad \text{, since } \partial_\mu v = 0. \end{aligned}$$

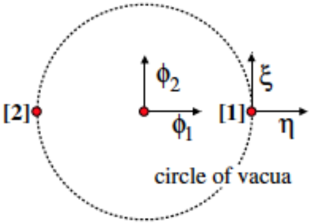
$$\begin{aligned} \mathrm{V}(\eta, \xi) &= \mu^2\phi^2 + \lambda\phi^4 \\ &= -\frac{1}{2}\lambda v^2[(v+\eta)^2 + \xi^2] + \frac{1}{4}\lambda[(v+\eta)^2 + \xi^2]^2 \\ &= -\frac{1}{4}\lambda v^4 + \lambda v^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4 + \frac{1}{4}\lambda\xi^4 + \lambda v\eta\xi^2 + \frac{1}{2}\lambda\eta^2\xi^2 \end{aligned}$$

Complex Scalar Field

- A global symmetry

$$\mathcal{L}(\eta,\xi) = \underbrace{\frac{1}{2}(\partial_\mu\eta)^2 - (\lambda v^2)\eta^2}_{\text{massive scalar particle } \eta} + \underbrace{\frac{1}{2}(\partial_\mu\xi)^2 + 0\cdot\xi^2}_{\text{massless scalar particle } \xi} + \text{higher order terms}$$

$$-\lambda v\eta^3 - \frac{1}{4}\lambda\eta^4 \text{ -}$$



no 'force' acting on oscillations along the ξ-field.

- This Lagrangian describes a massive scalar particle and a massless particle (Goldstone boson) by spontaneous symmetry breaking

Complex Scalar Field

- A local symmetry

$$\mathcal{L} = (\partial_\mu \phi)^*(\partial^\mu \phi) - \mathrm{V}(\phi) \qquad , \text{with } \mathrm{V}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$

$$\phi = \tfrac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \qquad \phi' \to e^{i\alpha(x)}\phi$$

$$\begin{aligned} \partial_\mu &\to D_\mu = \partial_\mu - ieA_\mu \\ A'_\mu &= A_\mu + \frac{1}{e}\partial_\mu \alpha \end{aligned} \qquad \mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - V(\phi)$$

$$\begin{aligned} \mathcal{L}_{\rm kin}(\eta,\xi) &= (D^\mu \phi)^\dagger (D_\mu \phi) \\ &= (\partial^\mu + ieA^\mu)\phi^*(\partial_\mu - ieA_\mu)\phi \end{aligned} \qquad \phi_0 = \frac{1}{\sqrt{2}}(\eta + v + i\xi)$$

$$\mathcal{L}(\eta,\xi) = \underbrace{\frac{1}{2}(\partial_\mu\eta)^2 - \lambda v^2\eta^2}_{\eta\text{-particle}} + \underbrace{\frac{1}{2}(\partial_\mu\xi)^2}_{\xi\text{-particle}} \underbrace{- \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}e^2v^2A_\mu^2}_{\text{photon field}} - \underbrace{evA_\mu(\partial^\mu\xi)}_{?} + \text{int.-terms}$$

Complex Scalar Field

$$\frac{1}{2}(\partial_\mu \xi)^2 - evA^\mu(\partial_\mu \xi) + \frac{1}{2}e^2v^2A_\mu^2 \;=\; \frac{1}{2}e^2v^2\left[A_\mu - \frac{1}{ev}(\partial_\mu \xi)\right]^2 \;=\; \frac{1}{2}e^2v^2(A'_\mu)^2$$

$$\phi' \to e^{-i\,\xi/v}\phi \;=\; e^{-i\,\xi/v}\frac{1}{\sqrt{2}}(v+\eta+i\xi) \;=\; e^{-i\,\xi/v}\frac{1}{\sqrt{2}}(v+\eta)e^{+i\,\xi/v} \;=\; \frac{1}{\sqrt{2}}(v+h)$$

$$\mathcal{L}_{\text{scalar}} \;=\; \underbrace{\frac{1}{2}(\partial_\mu h)^2 - \lambda v^2 h^2}_{\substack{\text{massive scalar} \\ \text{particle h}}} + \underbrace{\frac{1}{2}e^2v^2A_\mu^2}_{\substack{\text{gauge field } (\gamma) \\ \text{with mass}}} \underbrace{+ e^2vA_\mu^2h + \frac{1}{2}e^2A_\mu^2h^2}_{\substack{\text{interaction Higgs} \\ \text{and gauge fields}}} \underbrace{- \lambda v h^3 - \frac{1}{4}\lambda h^4}_{\substack{\text{Higgs self-} \\ \text{interactions}}}$$

- A mass term for the gauge boson and a massive scalar particle.
- Goldstone boson of the previous section has become the longitudinal polarization state of the gauge boson

The Higgs Mechanism

Breaking the local gauge invariant $\mathrm{SU(2)_L \times U(1)_Y}$ symmetry

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$\mathcal{L}_{\text{scalar}} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi), \qquad D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}YB_\mu$$

$$\text{Vacuum} = \phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \begin{matrix} \phi_1 = \phi_2 = \phi_4 = 0 \\ \phi_3 = v \end{matrix}$$

$$\begin{aligned}
\mathrm{SU(2)_L}: \quad \tau_1\phi_0 &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} = +\frac{1}{\sqrt{2}} \begin{pmatrix} v+h \\ 0 \end{pmatrix} \neq 0 \rightarrow \text{broken} \\
\tau_2\phi_0 &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} = -\frac{i}{\sqrt{2}} \begin{pmatrix} v+h \\ 0 \end{pmatrix} \neq 0 \rightarrow \text{broken} \\
\tau_3\phi_0 &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} = -\frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \neq 0 \rightarrow \text{broken} \\
\mathrm{U(1)_Y}: \quad Y\phi_0 &= Y_{\phi_0} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} = +\frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \neq 0 \rightarrow \text{broken}
\end{aligned}$$

The Higgs Mechanism

$$\underbrace{W_1 \quad W_2}_{\text{W}^+ \text{ and W}^- \text{ bosons}} \qquad \underbrace{W_3 \quad B}_{\text{Z-boson and } \gamma}$$

$$\text{U(1)}_{\text{EM}}: \quad Q\phi_0 \; = \; \frac{1}{2}(\tau_3 + Y)\phi_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} = 0 \rightarrow \text{unbroken}$$

1) W_1 and W_2 mix and will form the massive a W^+ and W^- bosons.
2) W_3 and B mix to form massive Z and massless γ.
3) Remaining degree of freedom will form the mass of the scalar particle (Higgs boson)

$$\mathcal{L}_{\text{scalar}} = (D^\mu\phi)^\dagger(D_\mu\phi) - V(\phi)$$

$$D_\mu\phi = \left[\partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}YB_\mu\right] \; \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

The Higgs Mechanism

1) Masses for the gauge bosons ($\propto v^2$)
2) Interactions gauge bosons and the Higgs ($\propto vh$) and ($\propto h^2$)

$$(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{1}{8}v^2\left[g^2(W_1^2 + W_2^2) + (-gW_3 + g'Y_{\phi_0}B_\mu)^2\right]$$

$$g^2(W_1^2 + W_2^2) = g^2(W^{+2} + W^{-2})$$

$$(-gW_3 + g'Y_{\phi_0}B_\mu)^2 = (g^2 + g'^2)Z_\mu^2 + 0 \cdot A_\mu^2$$

$$M_{W^+} = M_{W^-} = \frac{1}{2}vg$$

$$M_Z = \frac{1}{2}v\sqrt{(g^2 + g'^2)}$$

$$\frac{M_W}{M_Z} = \frac{\frac{1}{2}vg}{\frac{1}{2}v\sqrt{g^2 + g'^2}} = \cos(\theta_W)$$

$$M_\gamma = 0$$

$$m_h = \sqrt{2\lambda v^2}$$

- V~246 GeV, but λ is a free parameter

Fermion masses

A term like $-m\bar{\psi}\psi = -m[\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L]$ is <u>not</u> gauge invariant

$$\begin{aligned} \text{left handed doublet} &= \chi_L \to \chi_L' = \chi_L e^{i\vec{W}\cdot\vec{T}+i\alpha Y} \\ \text{right handed singlet} &= \psi_R \to \psi_R' = \psi_R e^{i\alpha Y} \end{aligned}$$

- a term: $\propto \bar{\psi}_L\psi_R$ is **not** invariant under $\mathrm{SU(2)_L \times U(1)_Y}$
- a term: $\propto \bar{\psi}_L\phi\psi_R$ is invariant under $\mathrm{SU(2)_L \times U(1)_Y}$

using the complex (Higgs) doublet

$$\mathcal{L}_{\text{fermion-mass}} = -\lambda_f[\bar{\psi}_L\phi\psi_R + \bar{\psi}_R\bar{\phi}\psi_L]$$

Lepton masses

$$\mathcal{L}_e = -\lambda_e \frac{1}{\sqrt{2}} \left[(\bar{\nu}, \bar{e})_L \begin{pmatrix} 0 \\ v+h \end{pmatrix} e_R + \bar{e}_R (0, v+h) \begin{pmatrix} \nu \\ e \end{pmatrix}_L \right]$$

$$= -\frac{\lambda_e (v+h)}{\sqrt{2}} [\bar{e}_L e_R + \bar{e}_R e_L]$$

$$= -\frac{\lambda_e (v+h)}{\sqrt{2}} \bar{e}e$$

$$= -\underbrace{\frac{\lambda_e v}{\sqrt{2}} \bar{e}e}_{\text{electron mass term}} - \underbrace{\frac{\lambda_e}{\sqrt{2}} h\bar{e}e}_{\text{electron-higgs interaction}}$$

$$m_e = \frac{\lambda_e v}{\sqrt{2}} \qquad \frac{\lambda_e}{\sqrt{2}} \propto m_e$$

1) The Yukawa coupling is often expressed as $\lambda_f = \sqrt{2} \left(\frac{m_f}{v} \right)$

2) The mass of the electron is **not** predicted since λ_e is a free parameter.

$$\frac{\Gamma(h \to ee)}{\Gamma(h \to WW)} \propto \frac{\lambda_{eeh}^2}{\lambda_{WWh}^2} = \left(\frac{g m_e / 2M_W}{g M_W} \right)^2 = \frac{m_e^2}{4M_W^4} \approx 1.5 \cdot 10^{-21}$$

Quark masses

The fermion mass term $\mathcal{L}_{\rm down} = \lambda_f \bar{\psi}_L \phi \psi_R$ (leaving out the hermitian conjugate term $\bar{\psi}_R \bar{\phi} \psi_L$ for clarity) only gives mass to 'down' type fermions, i.e. only to one of the isospin doublet

$$\mathcal{L}_{\rm up} = \bar{\chi}_L \tilde{\phi}^c \phi_R + \text{h.c., with}$$

$$\tilde{\phi}^c = -i\tau_2 \phi^* = -\frac{1}{\sqrt{2}} \begin{pmatrix} (v+h) \\ 0 \end{pmatrix}$$

$$\begin{aligned}
\text{down-type:} \quad \lambda_d(\bar{u}_L, \bar{d}_L)\phi d_R &= \lambda_d(\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ v \end{pmatrix} d_R = \lambda_d v \; \bar{d}_L d_R \\
\text{up-type:} \quad \lambda_u(\bar{u}_L, \bar{d}_L)\tilde{\phi}^c d_R &= \lambda_u(\bar{u}_L, \bar{d}_L) \begin{pmatrix} v \\ 0 \end{pmatrix} u_R = \lambda_u v \; \bar{u}_L u_R
\end{aligned}$$

Higgs Mechanism Summary

Slide from Prof. I. Park

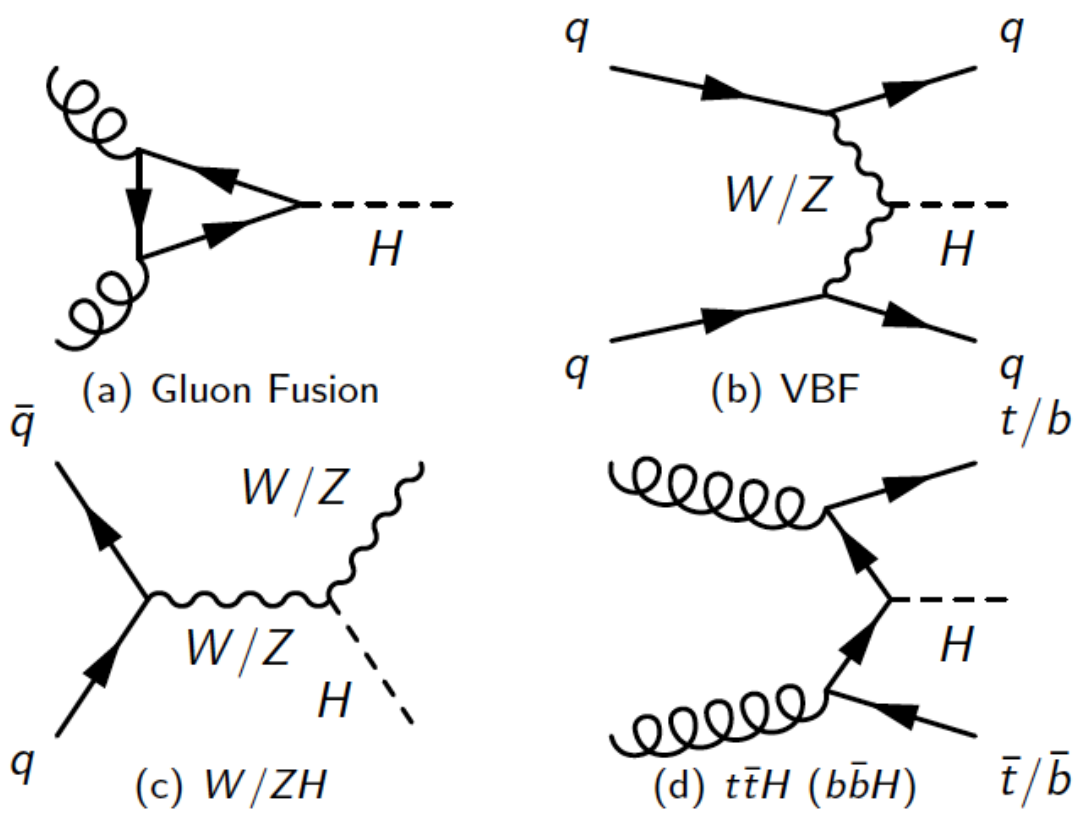
	스칼라 장	U(1)	SU(2)
라그랑지안	$\mathscr{L} = (\partial_\mu \phi)^2 - V(\phi)$	$\mathscr{L} = \lvert(i\partial_\mu - q\vec{A}_\mu)\phi\rvert^2 - V(\phi)$	$\mathscr{L} = \lvert(i\partial_\mu - g\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu)\phi\rvert^2 - V(\phi)$
포텐셜	$\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$	$\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$	$\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$
스칼라 장	$\phi = \phi_1 + i\phi_2$	$\phi = \phi_1 + i\phi_2$	$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \psi_3 + i\phi_4 \end{pmatrix}$
최저점	$\phi^*\phi = \frac{1}{2}(\phi_1^2 + \phi_2^2) = v^2$ $v \equiv \sqrt{-\mu^2/\lambda}$	$\phi^*\phi = \frac{1}{2}(\phi_1^2 + \phi_2^2) = v^2$ $v \equiv \sqrt{-\mu^2/\lambda}$	$\phi^*\phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = v^2$ $v \equiv \sqrt{-\mu^2/\lambda}$
진공	$\phi_1 = v, \phi_2 = 0$	$\phi_1 = v, \phi_2 = 0$	$\phi_1 = \phi_2 = \phi_4 = 0, \phi_3 = v$
좌표 이동	$\phi = \frac{1}{\sqrt{2}}(v + \eta(x) + i\xi(x))$	$\phi = \frac{1}{\sqrt{2}}(v + h(x))e^{i\theta(x)/v}$	$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} e^{i\vec{\tau}\cdot\vec{\theta}(x)/v}$
질량	$m_\xi = 0$ $m_\eta = \sqrt{2\lambda v^2}$	$m_h = \sqrt{2\lambda v^2}$ $m_A = qv$	$m_\eta = \sqrt{2\lambda v^2}$ $m_W = \frac{1}{2}gv$

Higgs Mechanism Summary

Slide from Prof. I. Park

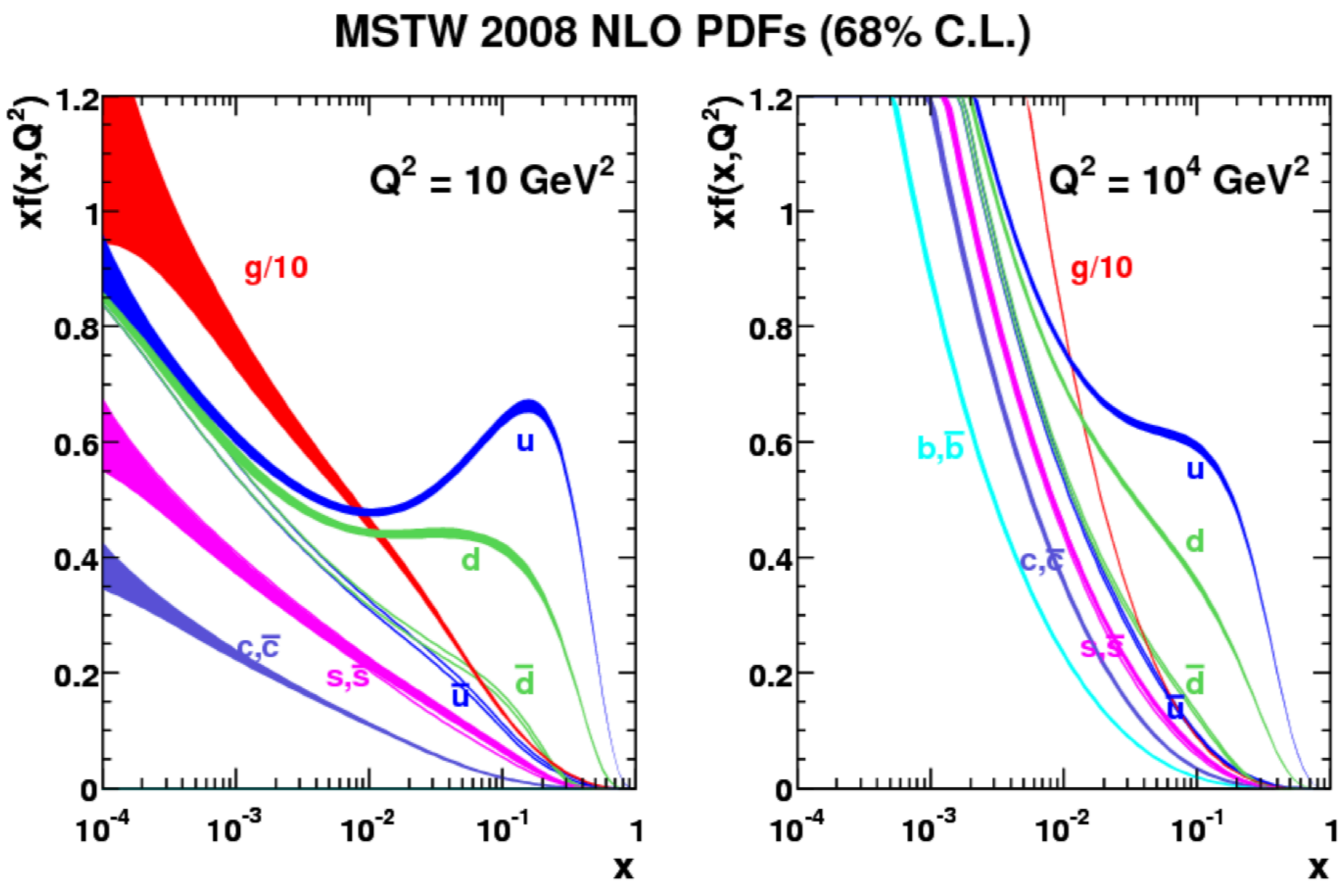
	SU(2) x U(1)
라그랑지안	$\mathscr{L} = \lvert(i\partial_\mu - g\frac{\vec{\tau}}{2}\cdot\vec{W}_\mu - g'\frac{Y}{2}B_\mu)\phi\rvert^2 - V(\phi)$
포텐셜	$\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$
스칼라 장	$\phi = \begin{pmatrix}\phi_1 + i\phi_2 \\ \psi_3 + i\phi_4\end{pmatrix}$
최저점	$\phi^*\phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = v^2$ $v \equiv \sqrt{-\mu^2/\lambda}$
진공	$\phi_1 = \phi_2 = \phi_4 = 0, \phi_3 = v$
좌표 이동	$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + h(x)\end{pmatrix}e^{i\vec{\tau}\cdot\vec{\theta}(x)/v}$
질량	$m_h = \sqrt{2\lambda v^2}$ $m_W = \frac{1}{2}gv$ $m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}v$ $m_A = 0$

Higgs Production at LHC



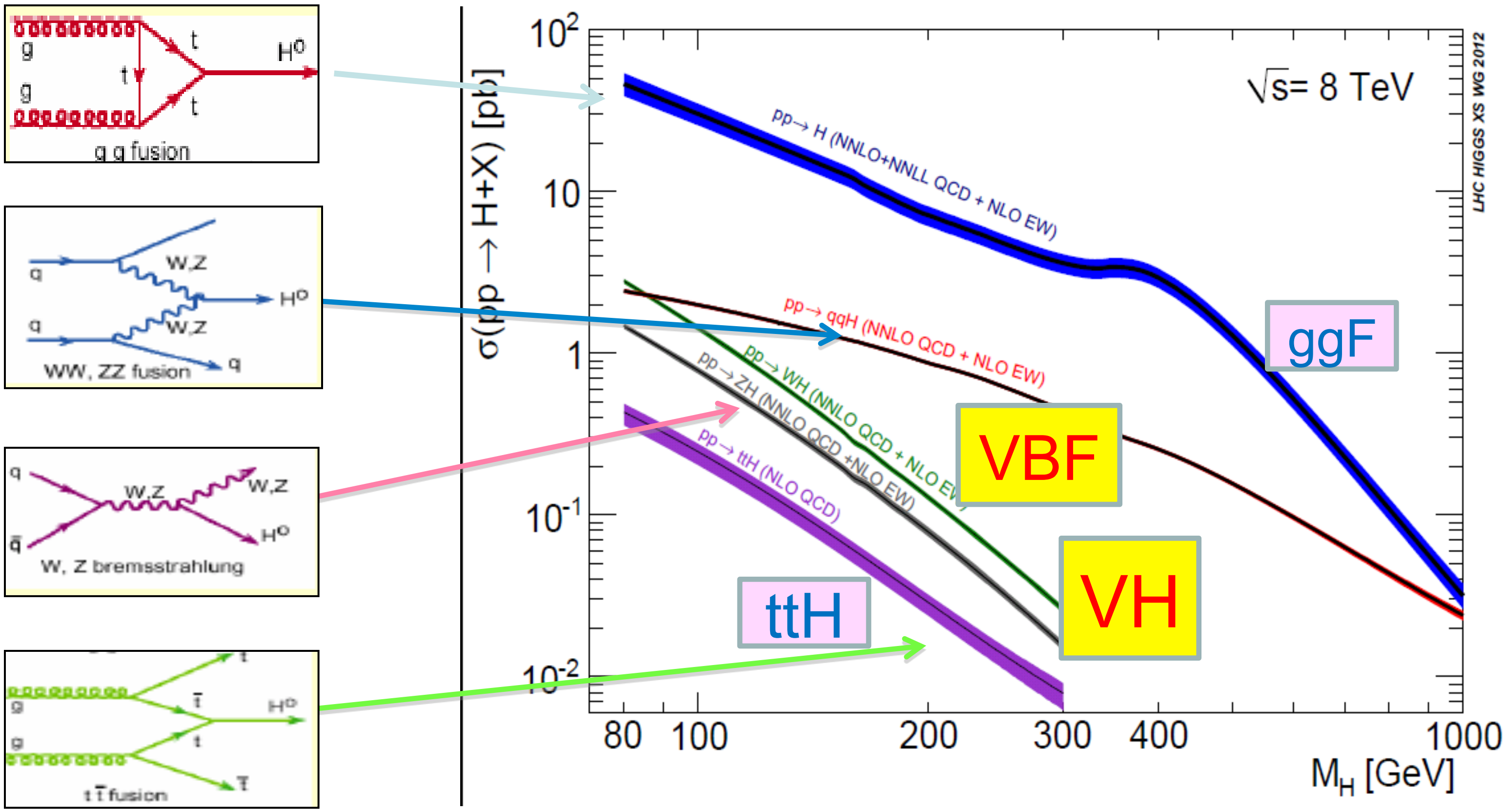
- What process dominates?
  - depending on Higgs mass?

Parton Distributions Functions



$$< x >= \frac{Q}{\sqrt{S}} \approx 0.06\ \text{(Tevatron)}, 0.015\ \text{(LHC) for } m_H = 125\ \text{GeV}$$

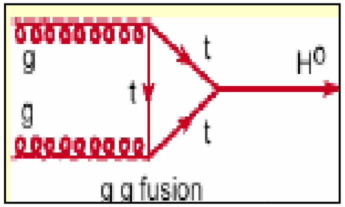
Higgs productions at the LHC



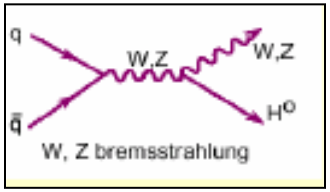
- ggF: a dominant process through the top quark loop → indirect probe of Higgs-fermion coupling
- VBF: two forward jets → direct probe of vector boson coupling
- VH: signature with hi-pt leptons → direct probe of vector boson coupling
- ttH: direct probe of Higgs-top quark coupling

Higgs Production at Tevatron

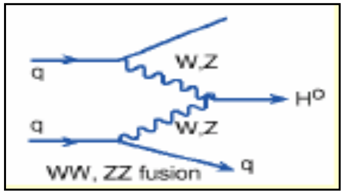
Primary production modes:



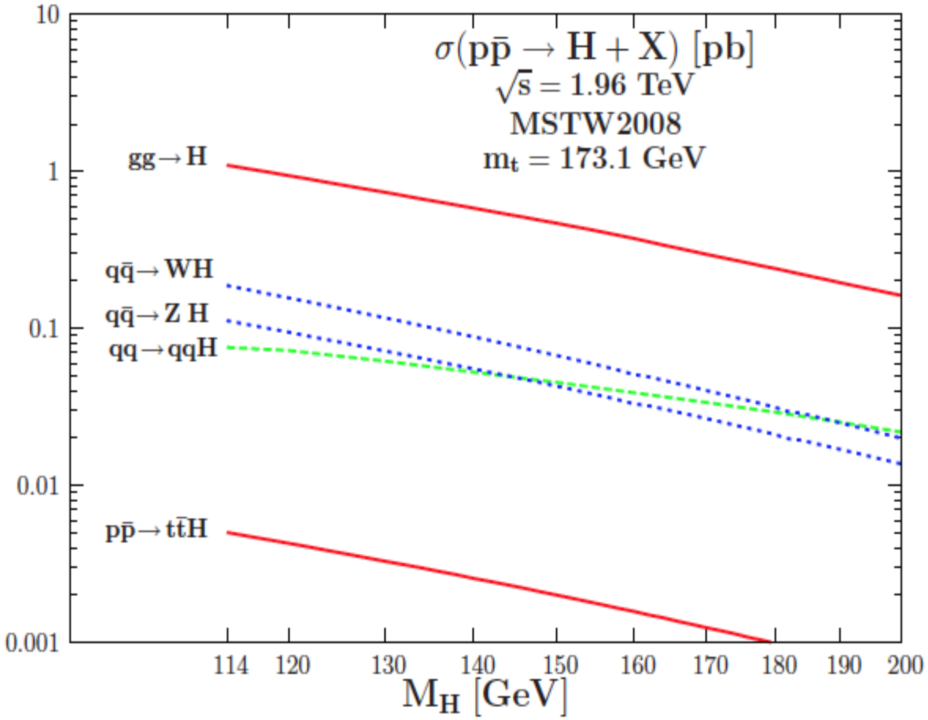
1.8~0.2 pb



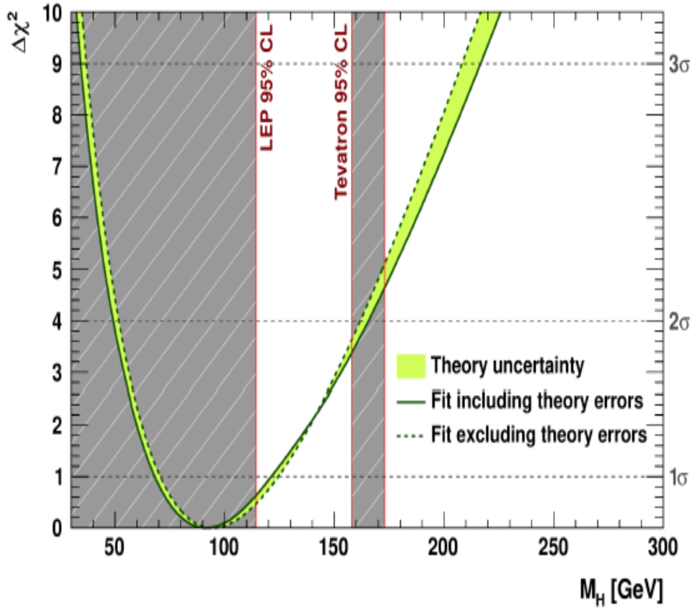
0.5~0.03 pb

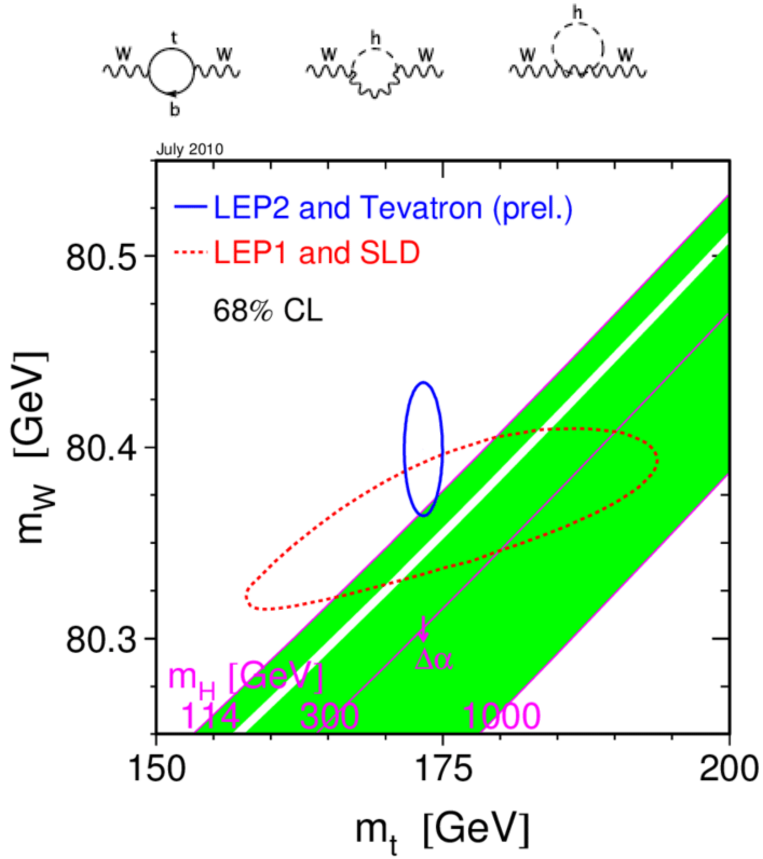


0.1~0.02 pb



Constraints on Higgs Before Discovery



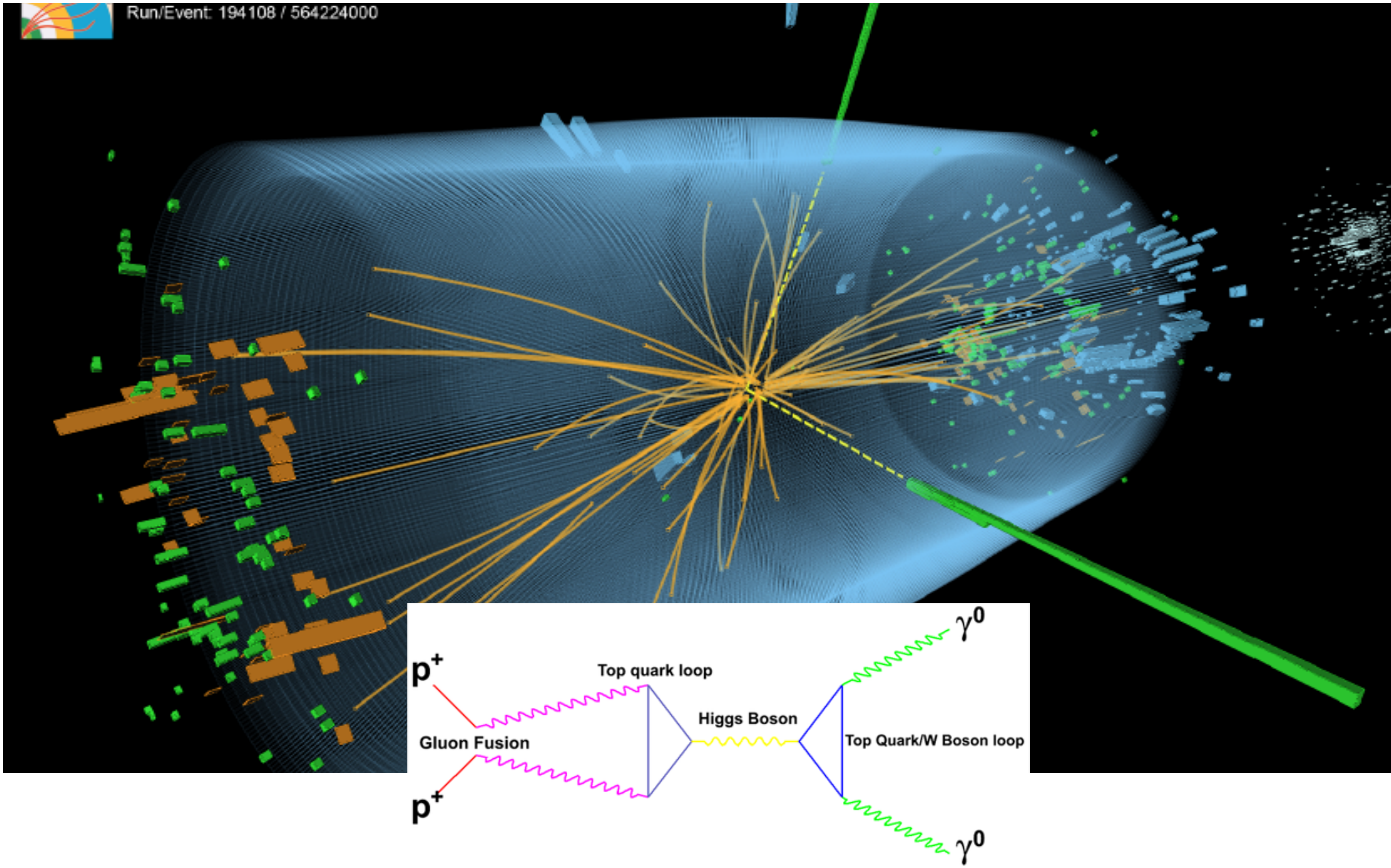


$$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W}\left[1 + \Delta_\rho^{\mathrm{quarks}} + \Delta_\rho^{\mathrm{higgs}} + \ldots\right]$$

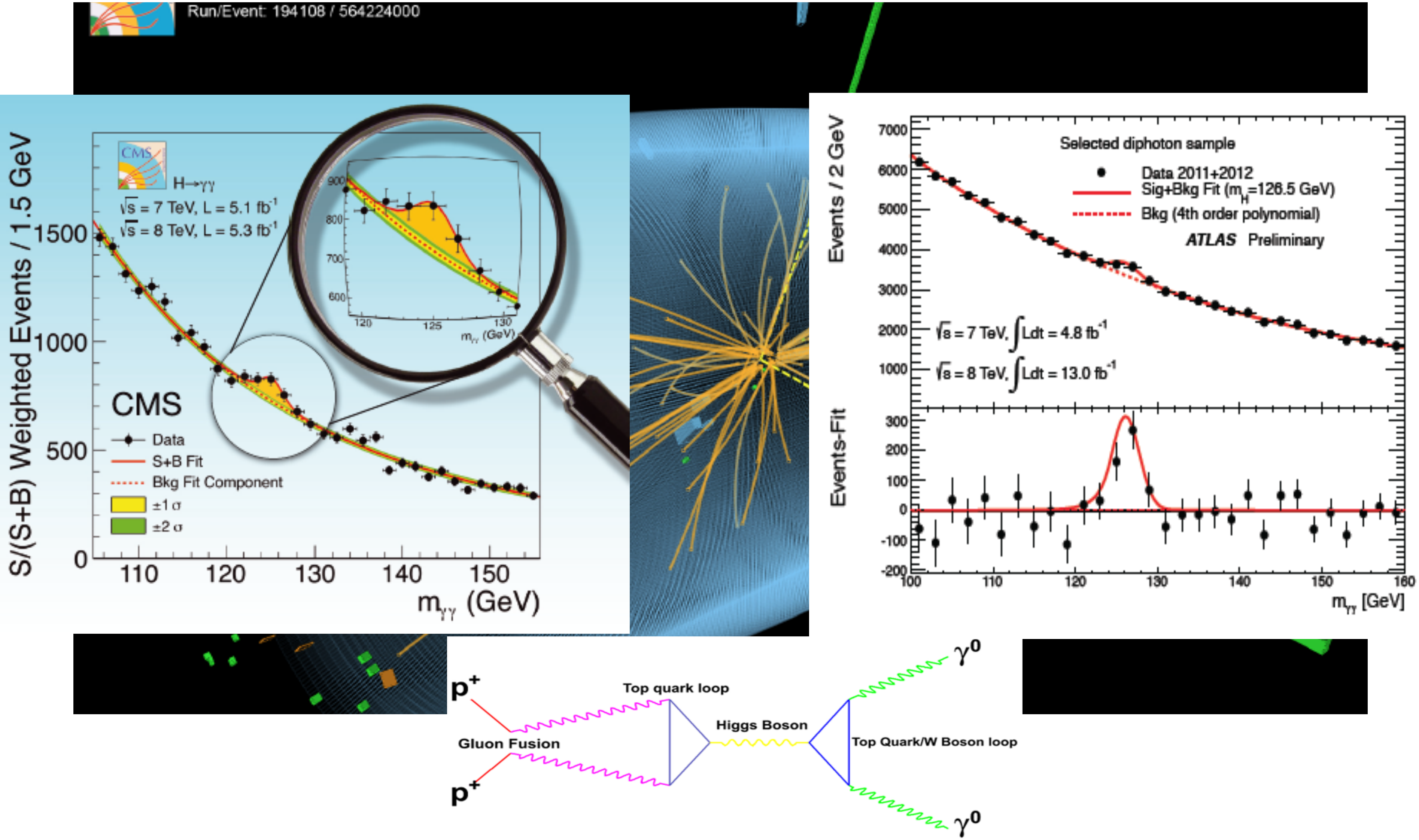
$$= \frac{M_W^2}{M_Z^2 \cos\theta_W}\left[1 + \frac{3}{16\pi^2}\left(\frac{m_t}{v}\right)^2 + 1 - \frac{11\tan\theta_W}{96\pi^2} g^2 \ln\left(\frac{m_h}{M_W}\right) + \ldots\right]$$

- Global EWK fits: preferred a light Higgs with large uncertainty
- LEP and Tevatron exclusions

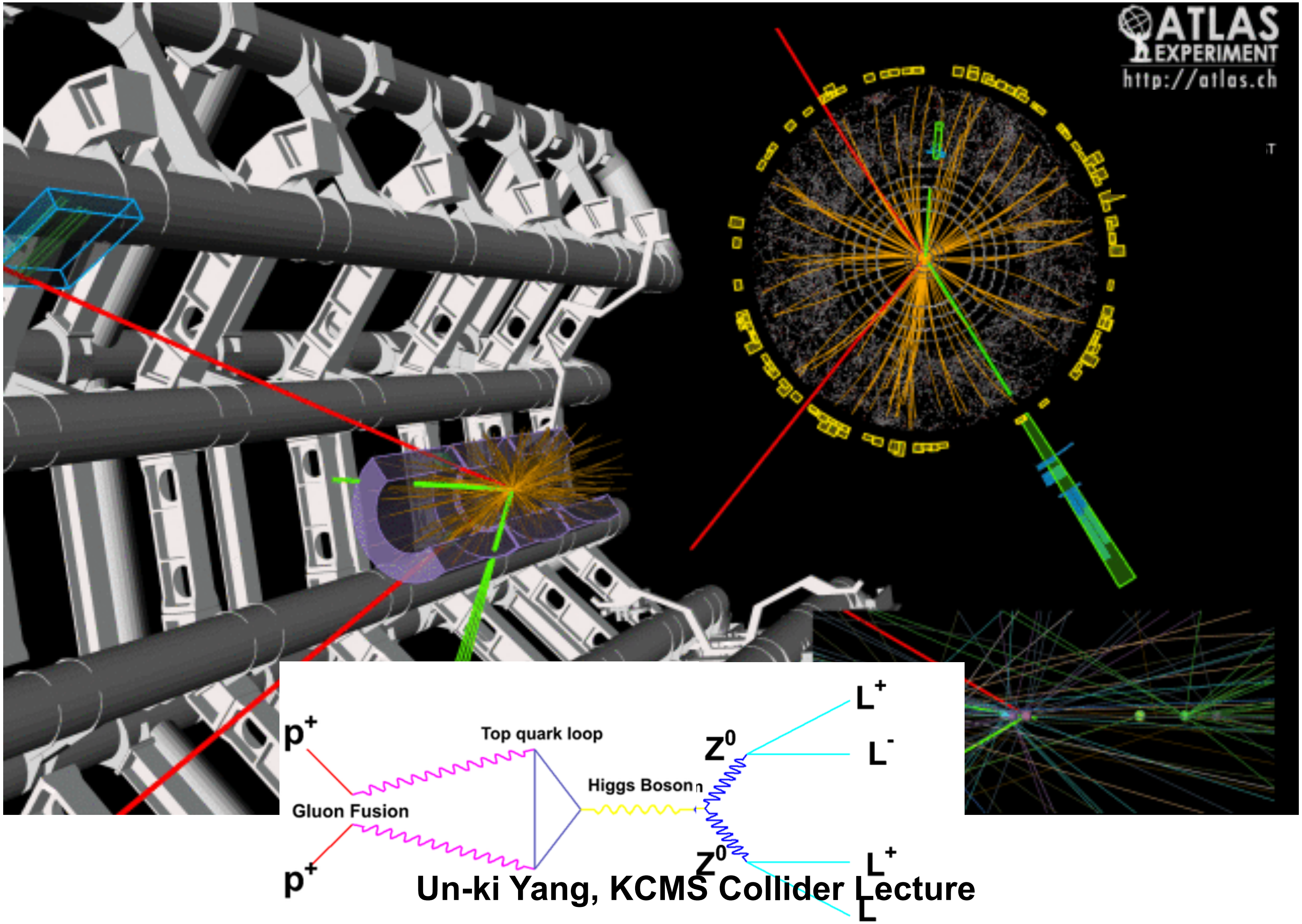
Discovery of a Higgs boson (2012)



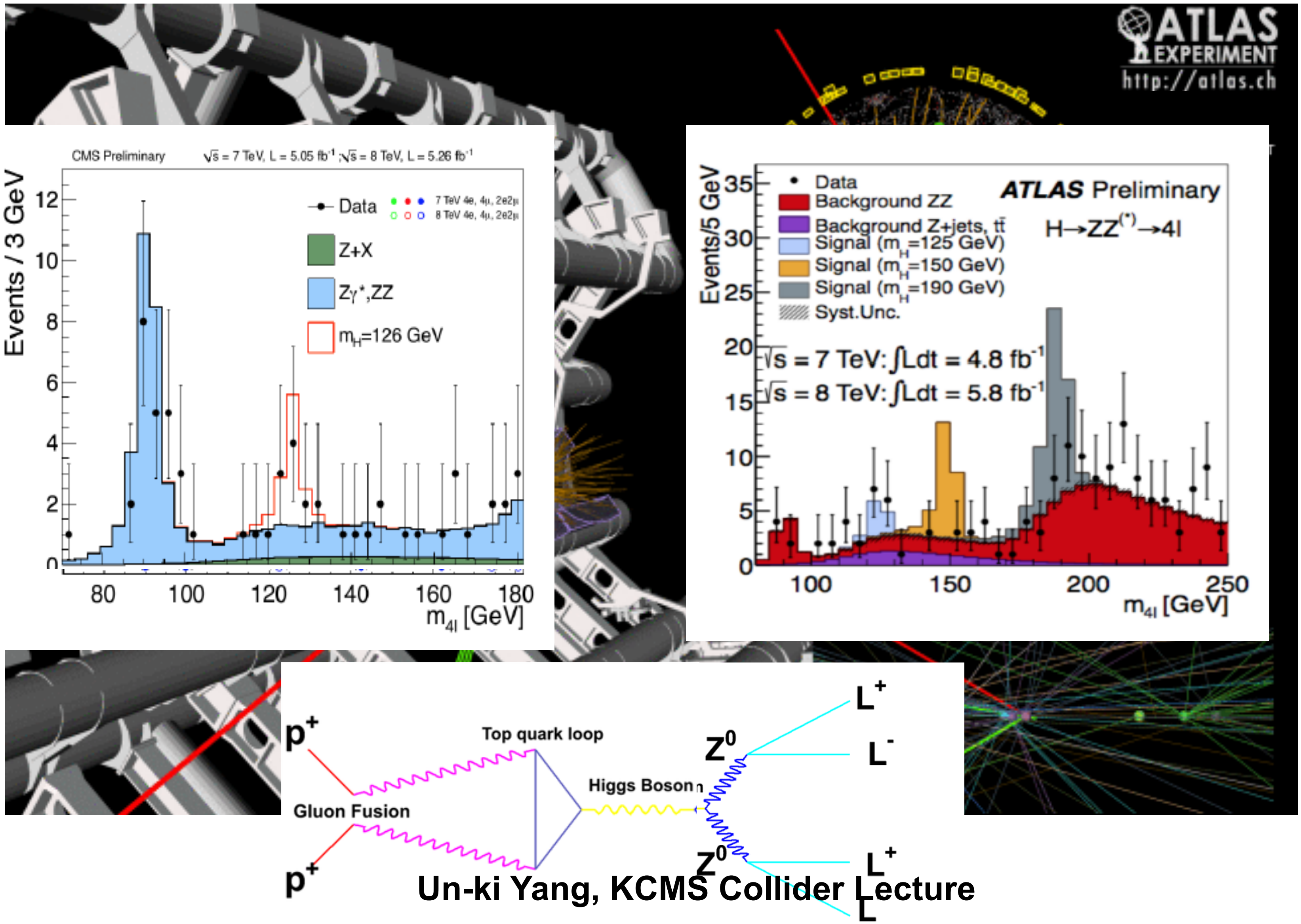
Discovery of a Higgs boson



Discovery of a Higgs boson



Discovery of a Higgs boson



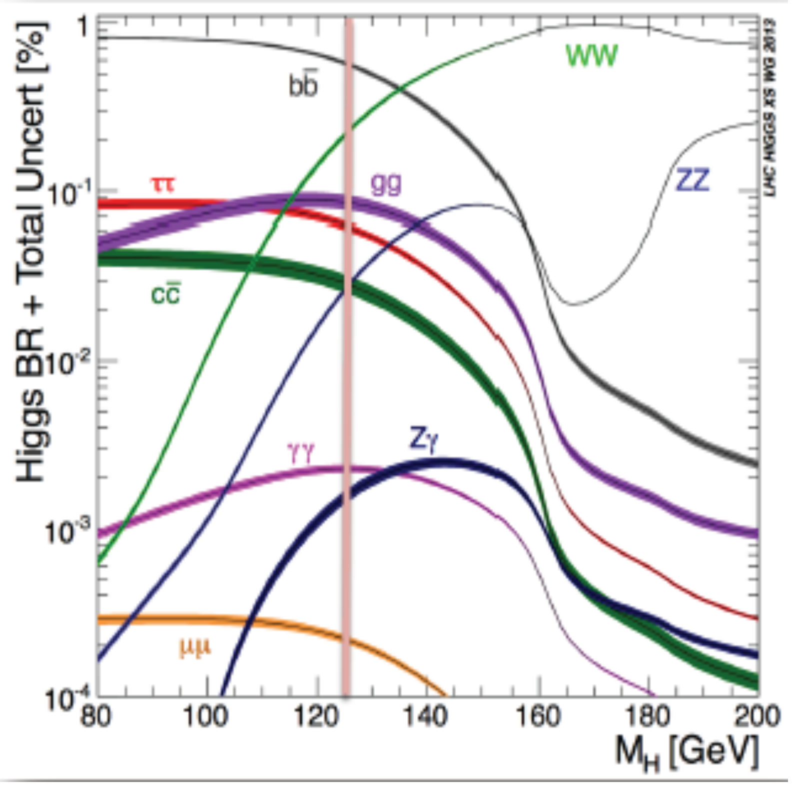
Two of these 10,000 people presented results…

Fabiola Gianotti
ATLAS Spokesperson

Joe Incandela
CMS Spokesperson

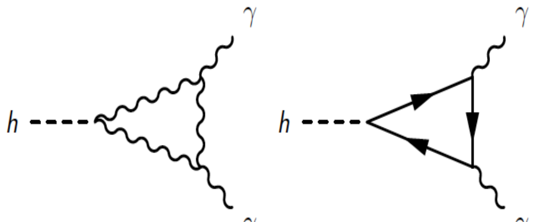
Higgs decays at the LHC

Discovery channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$



m_H=125.5GeV	BR(%)
$H \rightarrow \gamma\gamma$	0.23
$H \rightarrow ZZ$	2.8
$H \rightarrow WW$	22
$H \rightarrow \tau\tau$	6.2
$H \rightarrow bb$	57

- **$H \rightarrow \gamma\gamma$: decays via W or t loop: negative interference → indirect measurement on couplings**

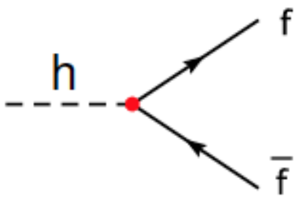


(a) W loop (b) t loop

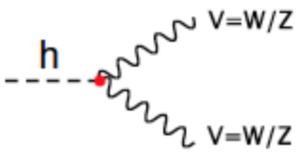
$$\kappa_\gamma^2 \sim= 1.6\kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$$

Rich decay modes at $m_H \sim 125$ GeV

Higgs Decays

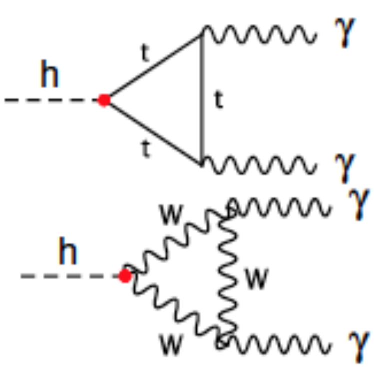


$$\Gamma(h \to f\bar{f}) = \frac{N_c}{8\pi v^2}\, m_f^2\, m_h\, \sqrt{1-x} \qquad \text{, with } \; x = \frac{4m_f^2}{m_h^2}$$



$$\Gamma(h \to VV) = \frac{g^2}{64\pi M_W^2}\, m_h^3\, \mathcal{S}_{VV}\, (1 - x + \tfrac{3}{4}x^2)\sqrt{1-x}$$

, with $x = \frac{4M_V^2}{m_h^2}$ and $\mathcal{S}_{WW,ZZ} = 1, \frac{1}{2}$.



$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2}{256\pi^3 v^2}\, m_h^3\, \left| \frac{4}{3}\sum_f N_c^{(f)} e_f^2 - 7 \right|^2$$

, where e_f is the fermion's electromagnetic charge.

Note: - WW contribution ≈ 5 times top contribution
- Some computation also gives $h \to \gamma Z$

Higgs Searches

- Two special channels in the search
  - $H \to ZZ^* \to 4l$ ($l = e, \mu$), $H \to \gamma\gamma$
  - Fully reconstructed final state (no neutrinos):

    a special role in mass determination
  - Well reconstructed objects with excellent energy/momentum resolutions (only tracking and EM calorimeters)
- $H \to ZZ^* \to 4l$ ($l = e, \mu$)
  - So small branching fraction: ~ 10^{-5}
  - But extremely small bkgds.:

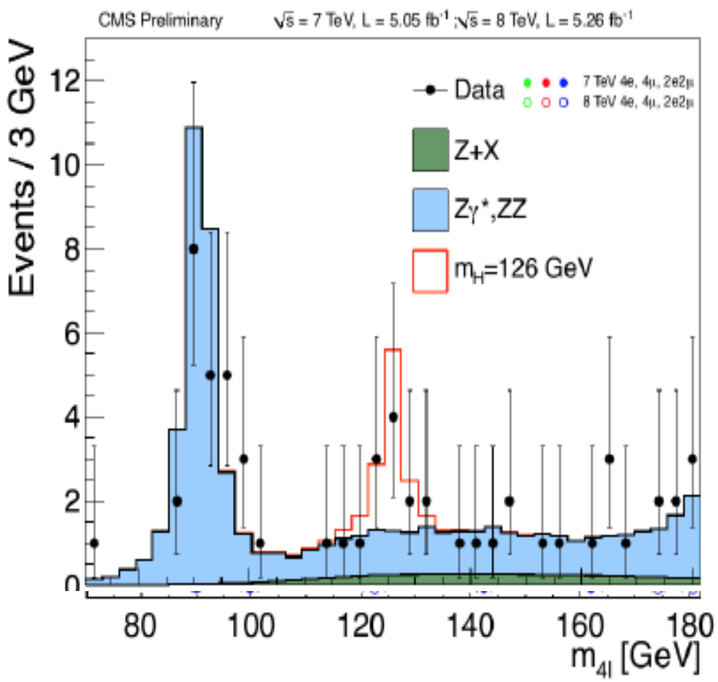
    - irreducible: $ZZ \to 4l$

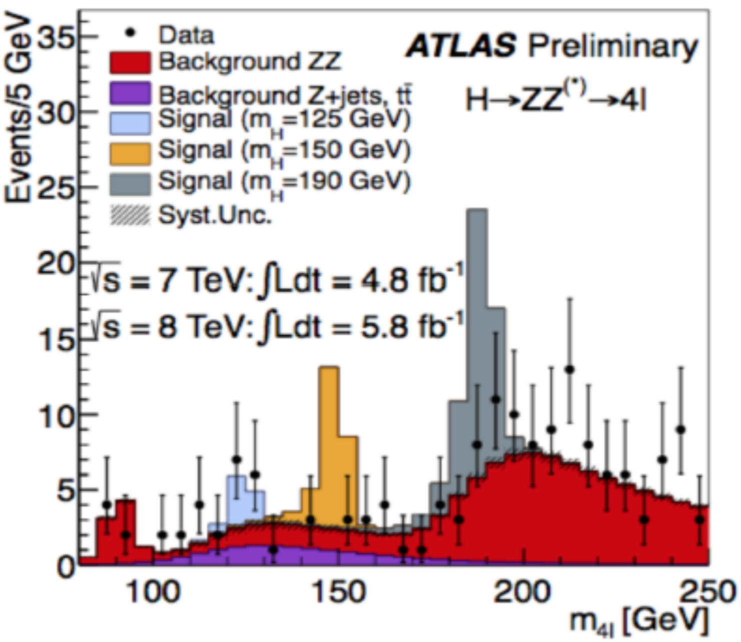
    - reducible: mis-identified leptons (mostly 2 real + 2 mis-id)
  - Challenges:

    - Maximize lepton eff. & acceptance, down to low pt, 5 GeV

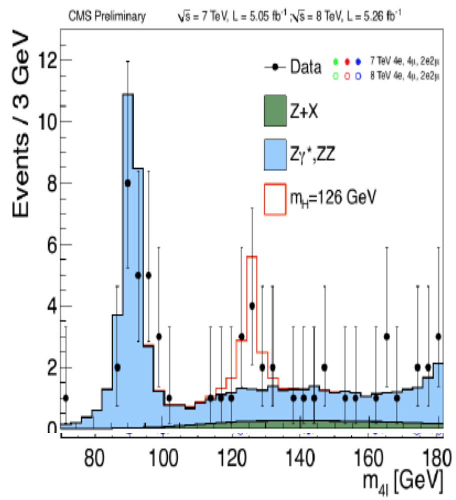
    - Optimize lepton resolution and estimation of mis-ID

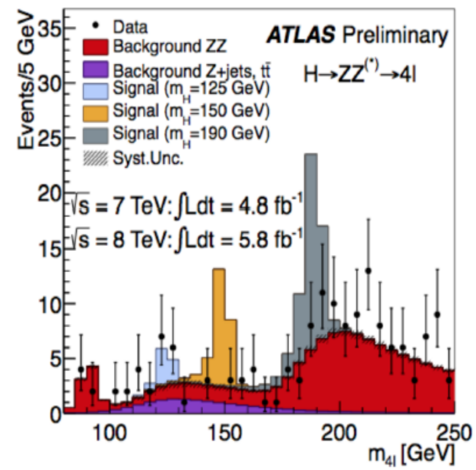
H→ZZ*→4l (Discovery)

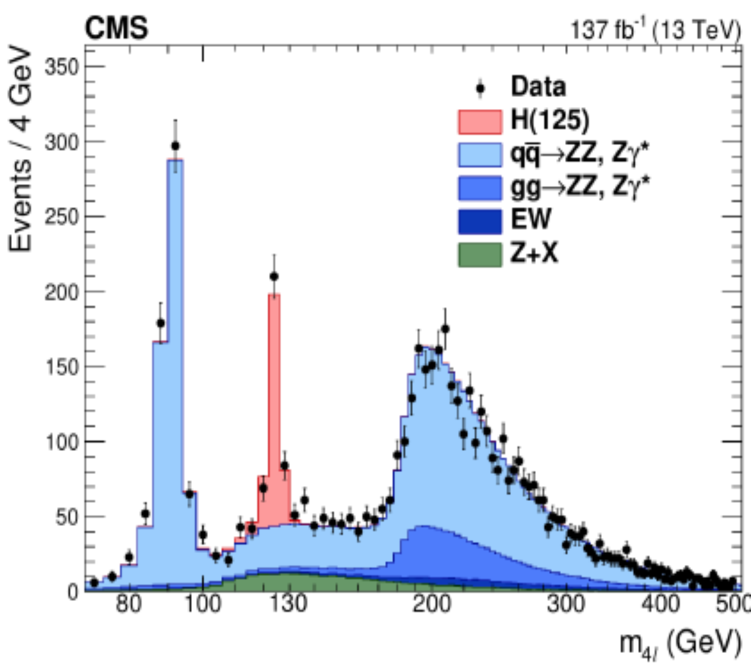


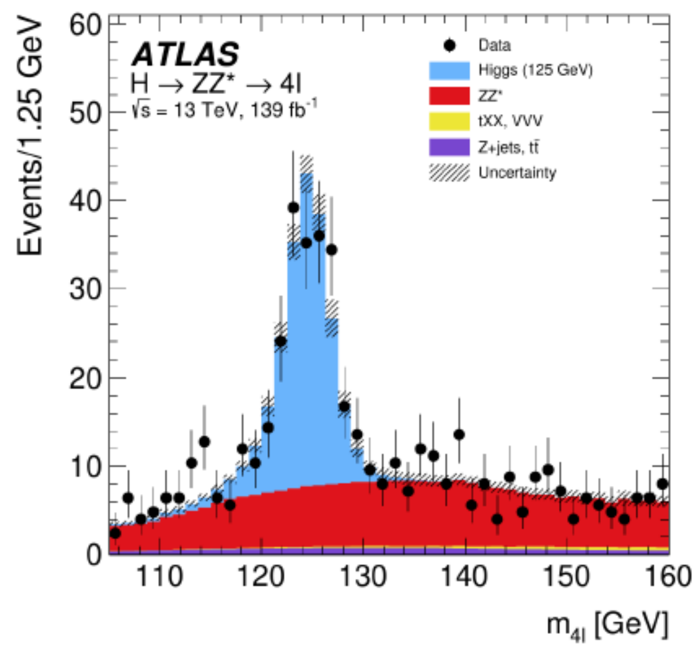


H→ZZ*→4l (Full Run II)



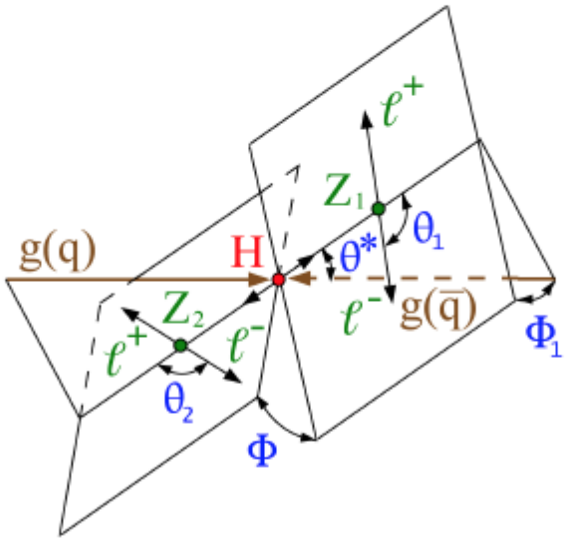


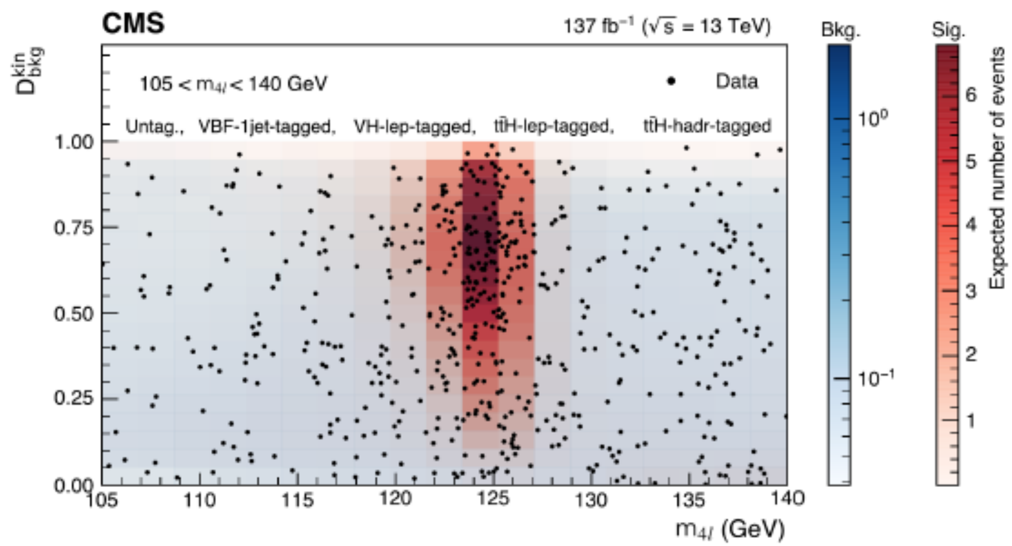


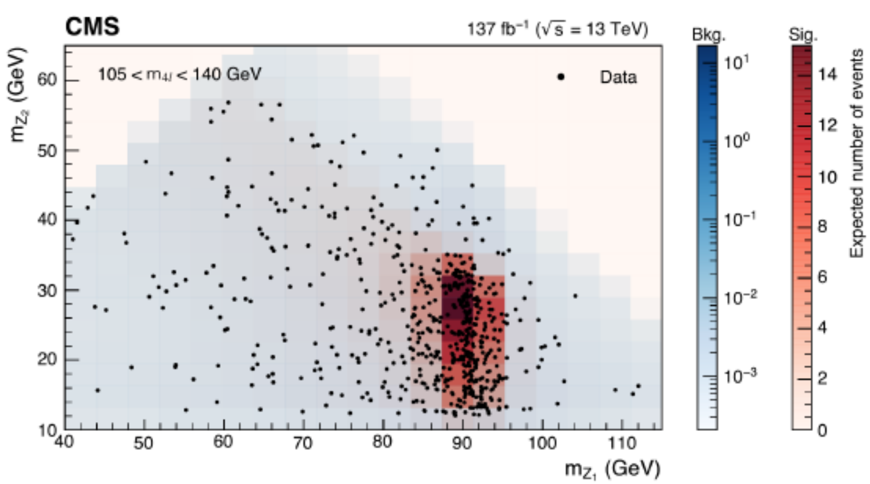


H→ZZ*→4l (Kinematics)

- Masses of lepton pairs and decays angles: additional information

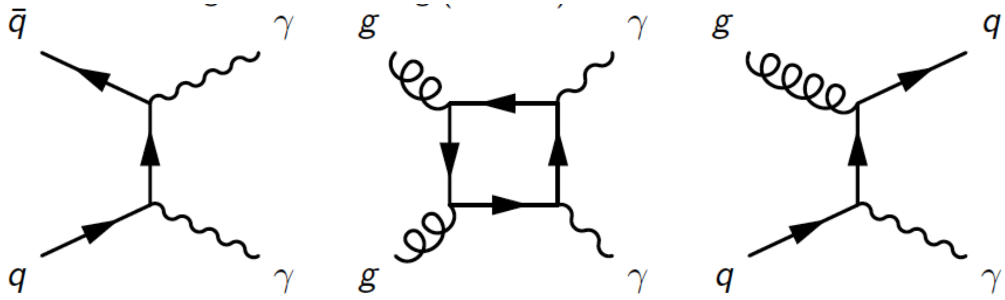




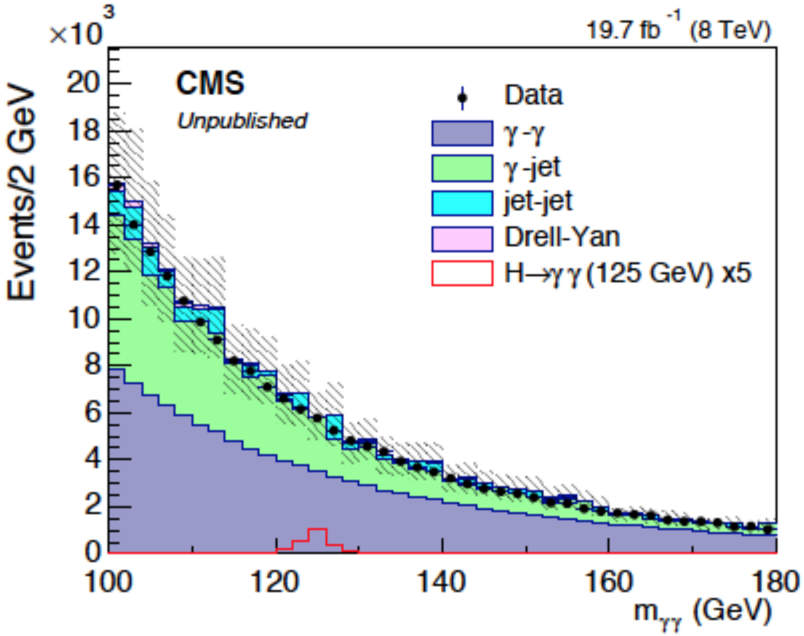


$H \rightarrow \gamma\gamma$

- Small branching fraction: ~ 2 x10^{-3} (larger than $H \rightarrow ZZ^* \rightarrow 4l$)
- Significant bkgds.:
  - Irreducible: $pp \rightarrow \gamma\gamma$ (relatively large cross section)
  - reducible: γ + jet with one mis-ID and multijet with two mis-IDs
  - Challenges:
    - Maximize lepton eff. & acceptance, down to low pt, 5 GeV
    - Optimize diphoton mass resolution
    - Photon ID efficiency
    - Background modelling (mass fit)



Search for H → γγ

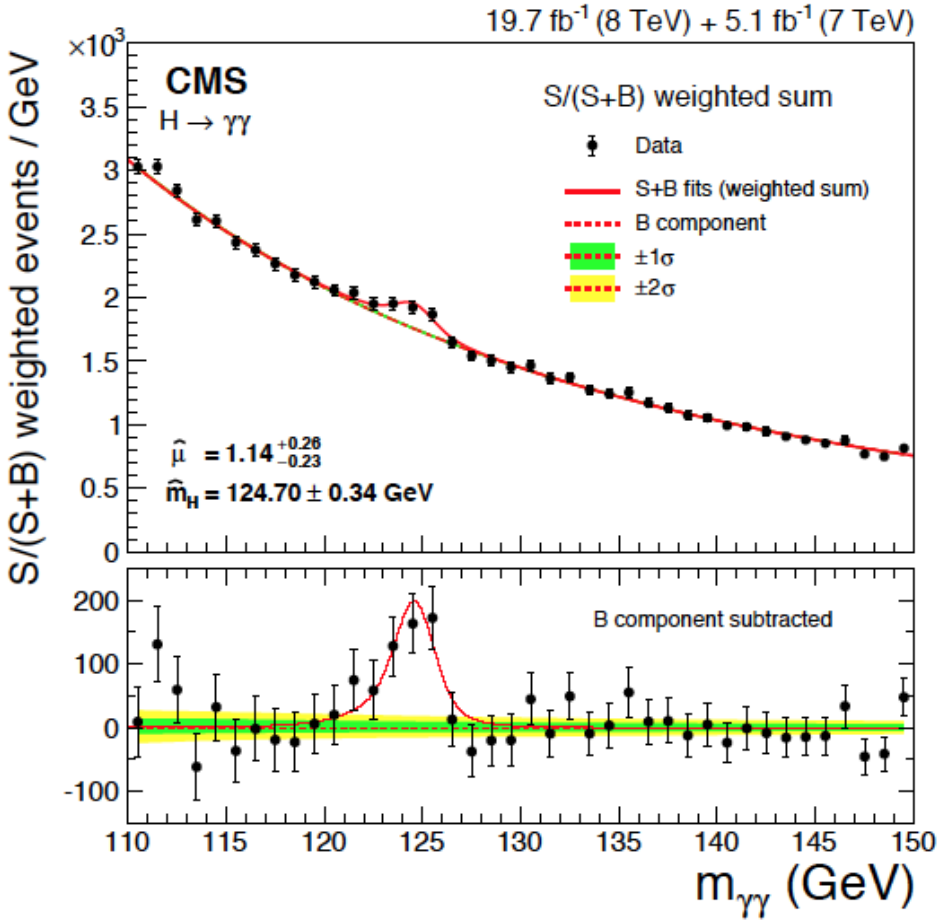


$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$$

$$\frac{\sigma_m}{m_{\gamma\gamma}} = \frac{1}{2}\sqrt{\frac{\sigma_{E1}^2}{E_1^2} + \frac{\sigma_{E2}^2}{E_2^2}}$$

- Search for a small narrow mass peak on top of a large smoothly falling background
- Take an advantage of multivariate techniques to optimize the sensiti vity, but basically, “bump hunt”

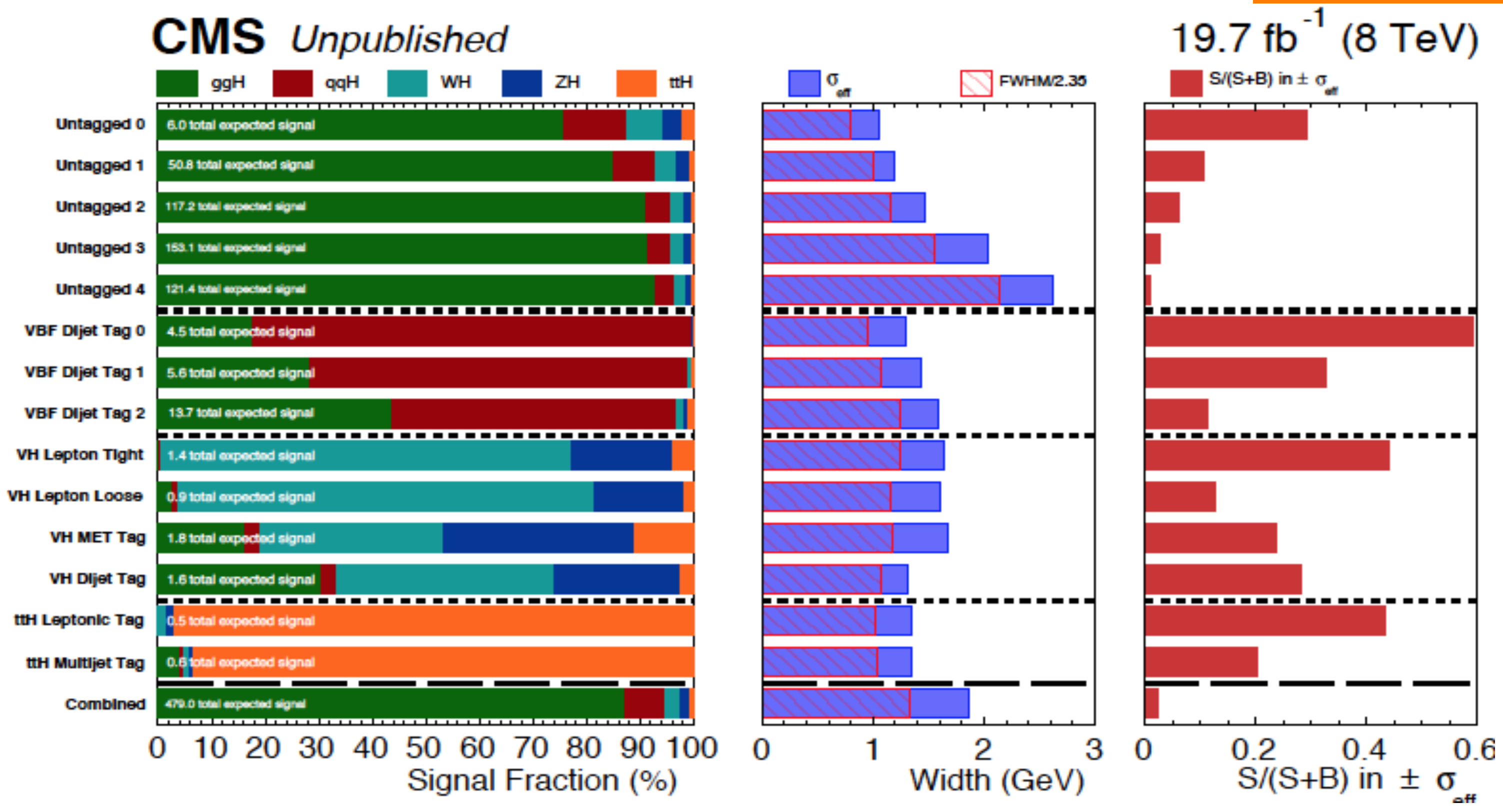
Search for H → γγ



- Results extracted from simultaneous fit to 25 event classes, but combined mass spectrum useful for visualisation
- Combination of all 25 event classes, weighted by $S/(S+B)$ for a $\pm\sigma_{eff}$ window in each event class
- Weights are normalised to preserve the fitted number of signal events

H → γγ: event classification

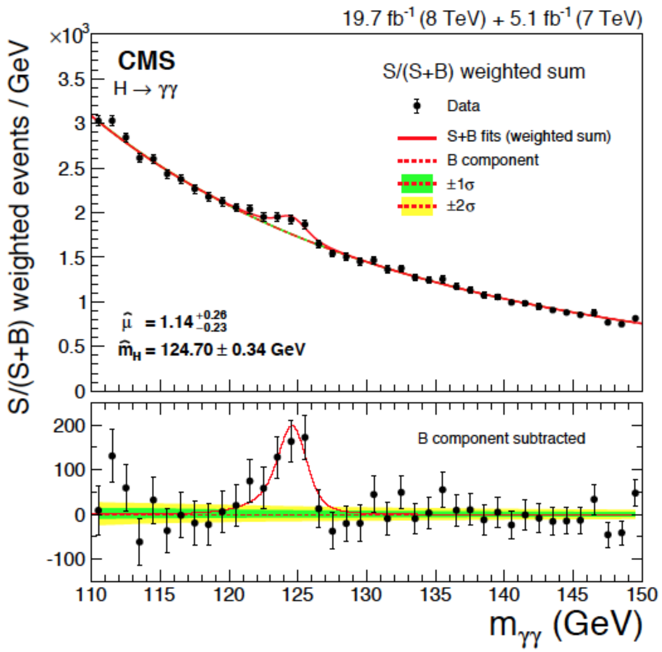
Slide from J. Bendavid

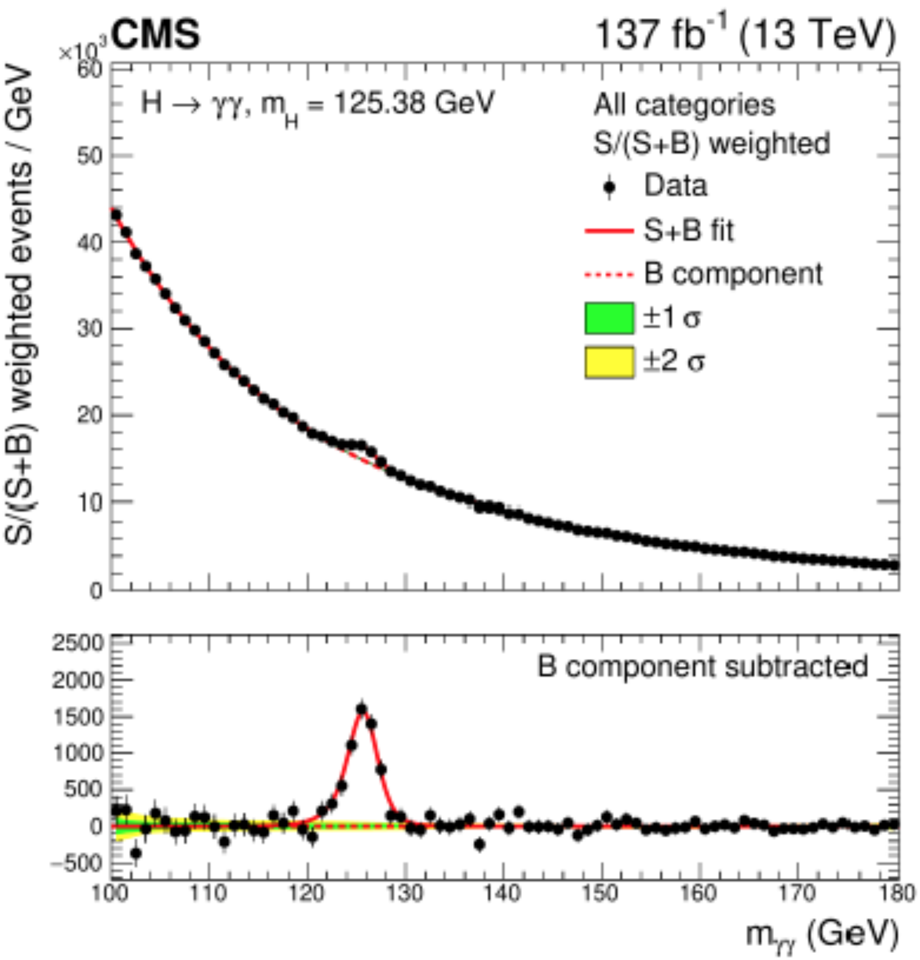


Events classified according to di-photon MVA output plus tagging of additional objects

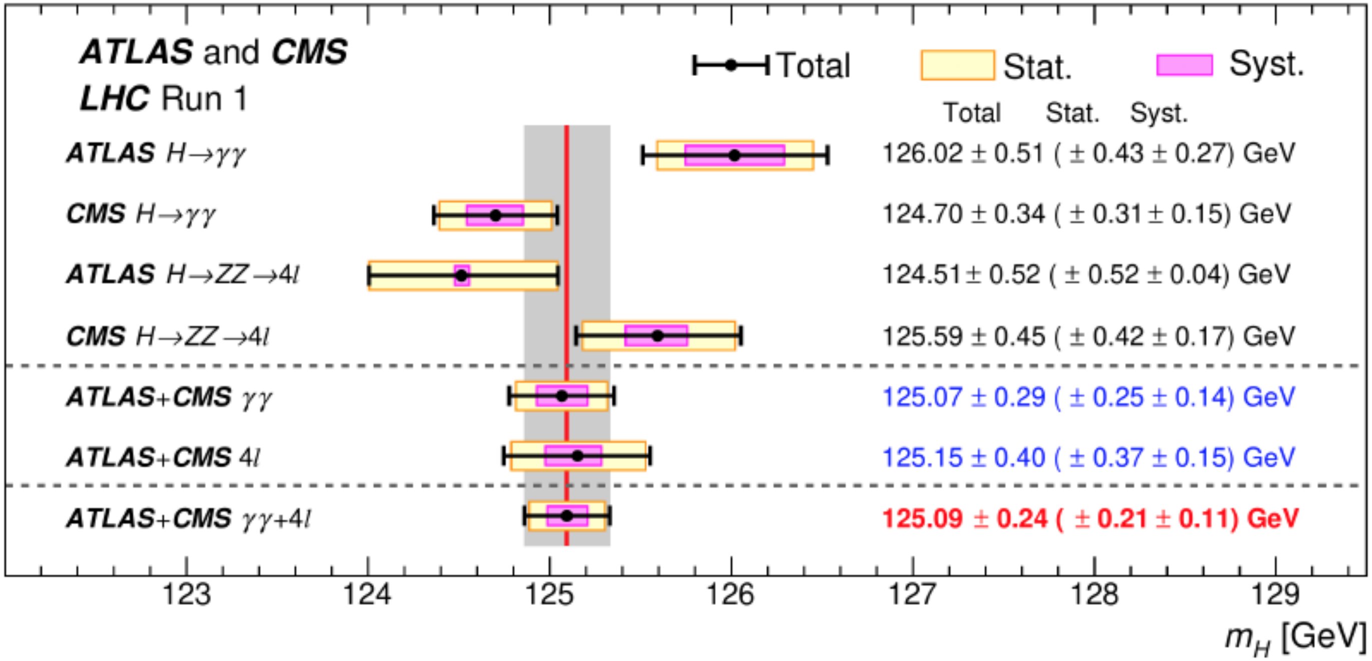
Large variation in resolution and S/B across categories

Search for H → γγ (full Run II)





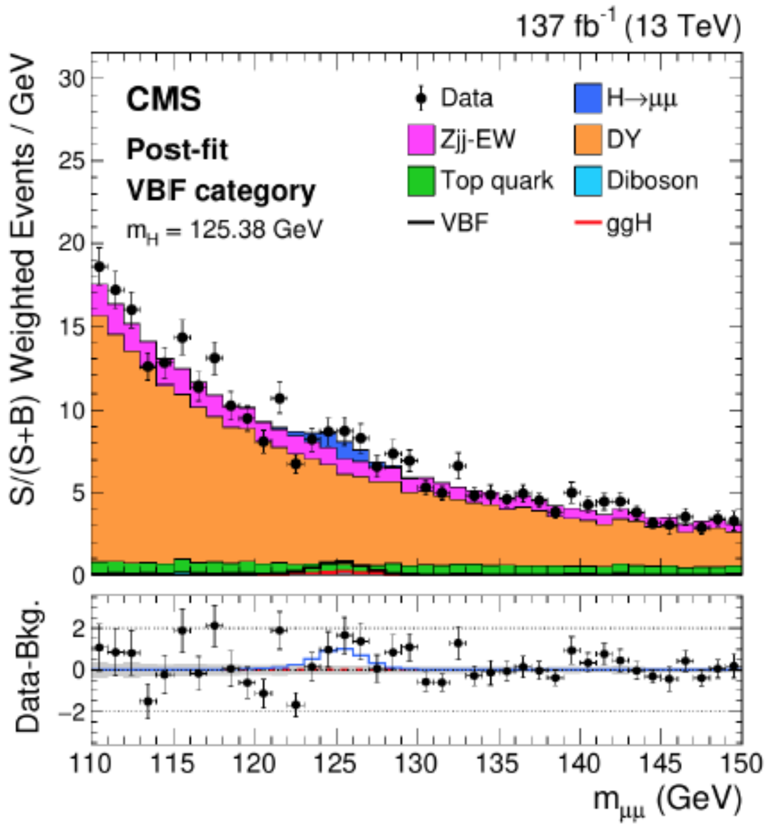
Higgs Mass

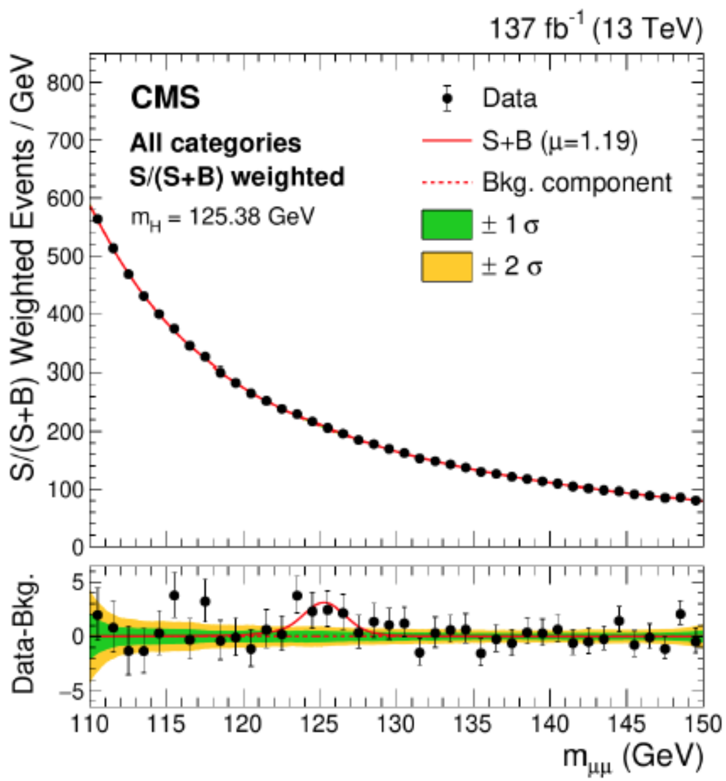


- Higgs mass is measured from the peak position in γγ and 4l
- Calibration of the photon, electron, and muon, mainly using the Z peak
- γγ channel has small statistical error, but larger systematics due to e→ photon extrapolation

Search for H → μμ

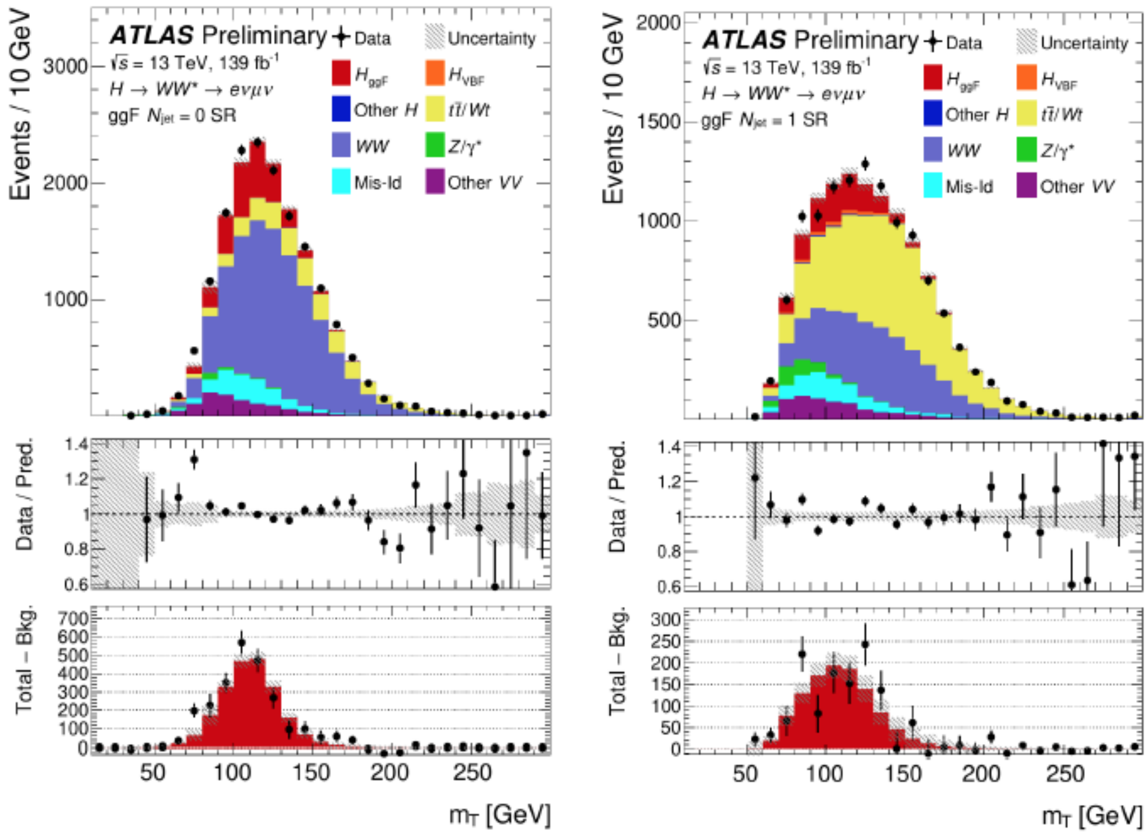
- Tiny branching fraction and larger DY→μμ bkgd
- Bump hunting





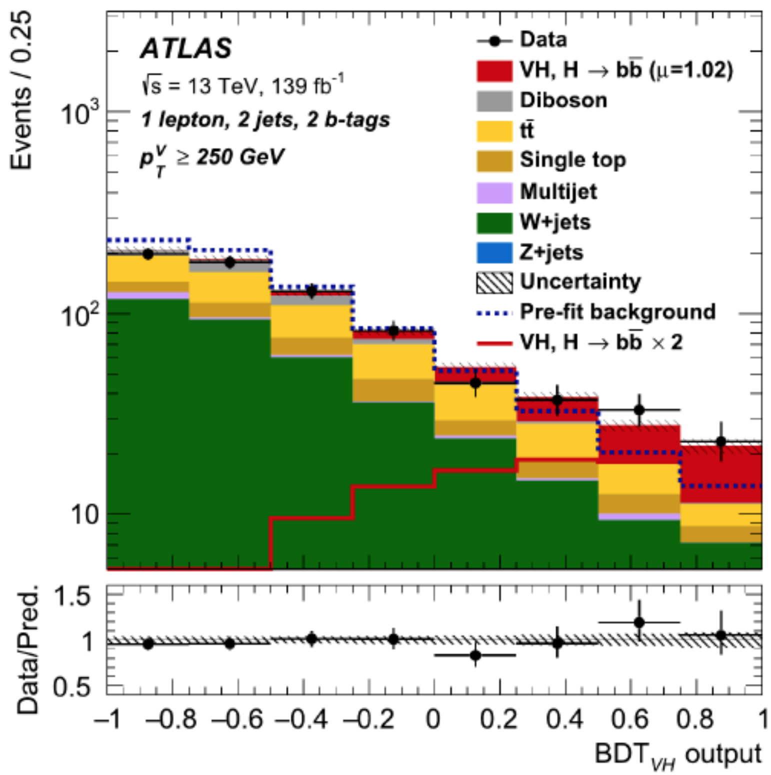
H →WW*→ 2l2ν

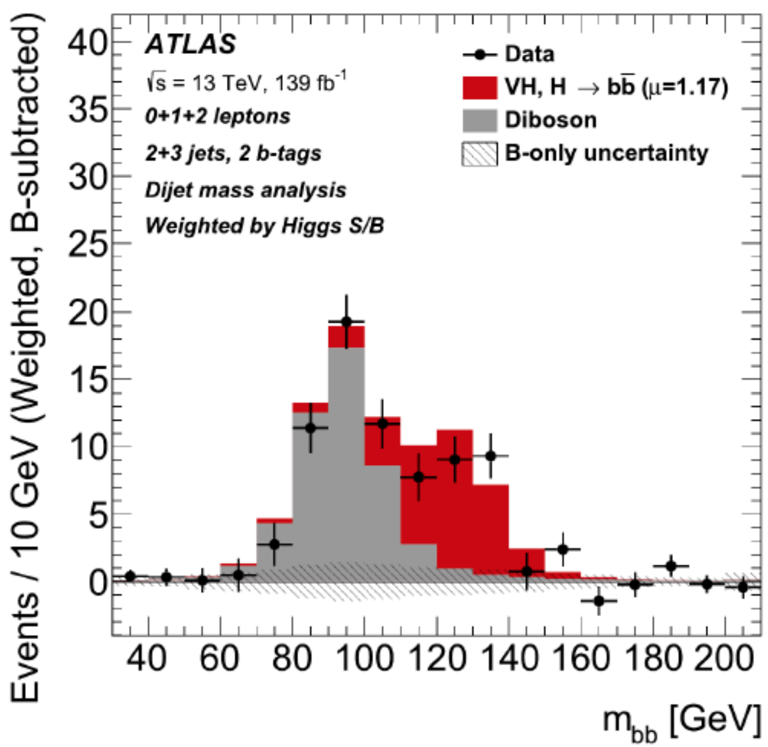
- Relatively large branching ratio and significant bkgds from WW, ttand W+jets with mis-ID
- Bkgds with two real leptons from control regions (WW, tt with b-tag, DY with Z mass)



H→bb

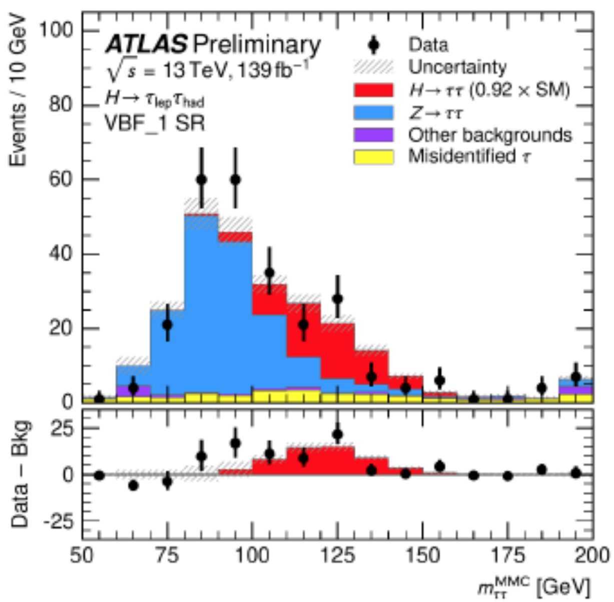
- Large branching ratio, but huge QCD bkgds
- Strategically, use V+H→ ll, lν, νν + bb with large W/Z Pt

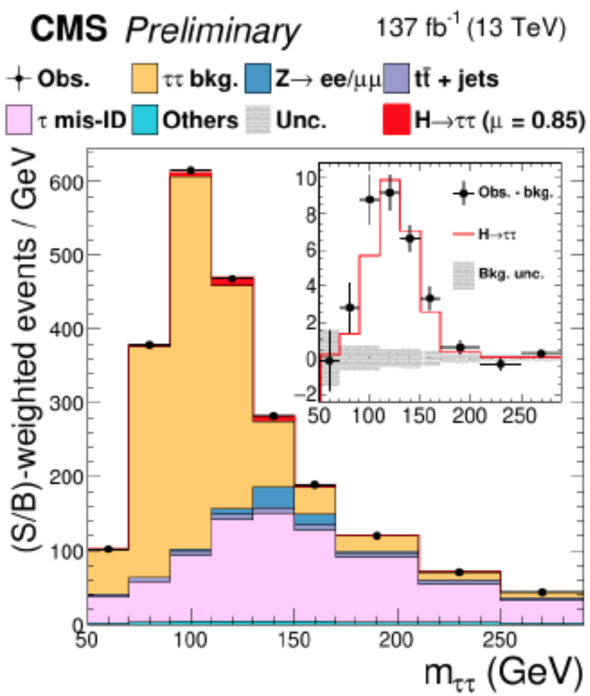




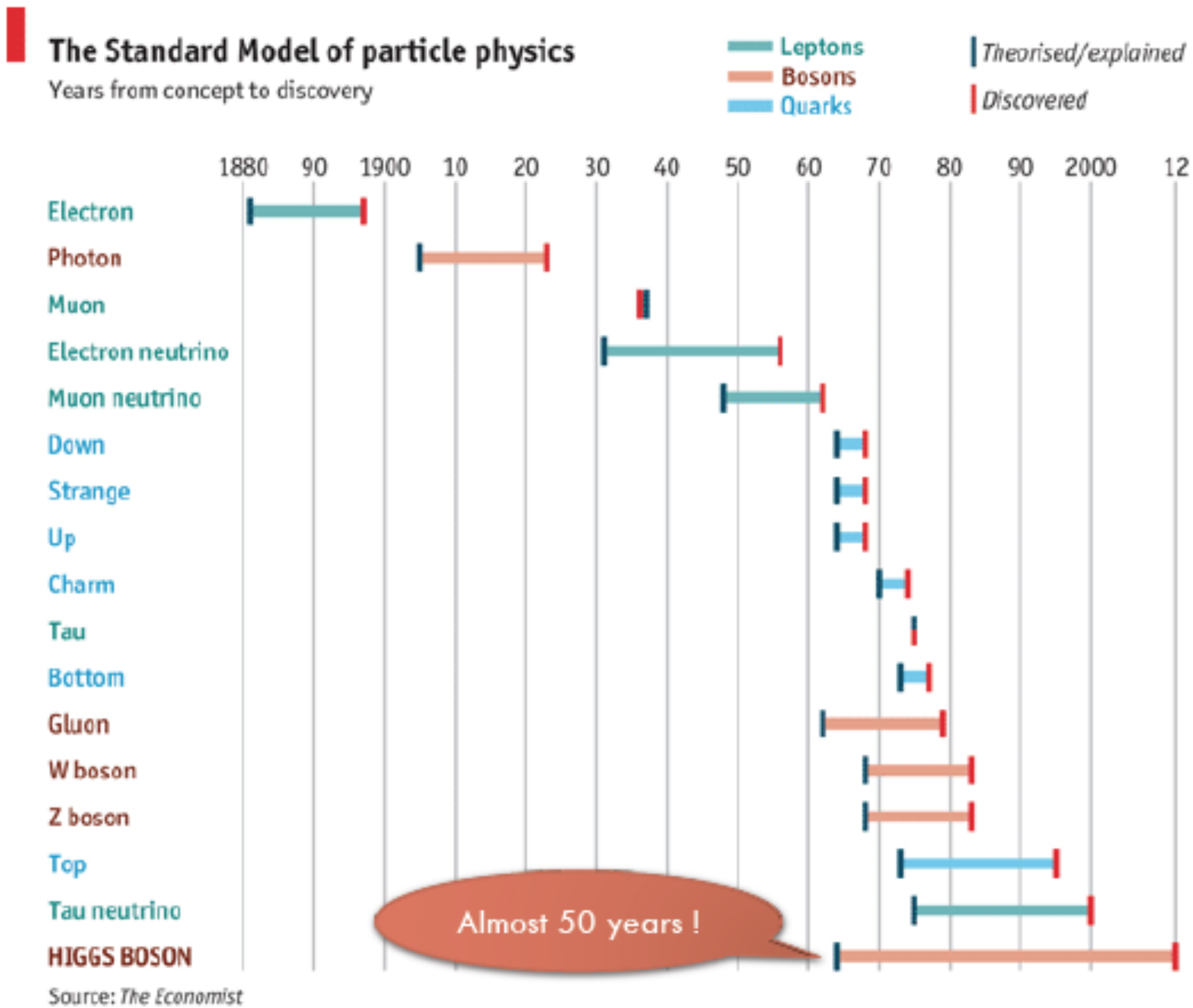
H →ττ

- Select events in eμ, eτ(h) μτ(h) τ(h)τ(h) final states.
- ττ mass reconstruction using various techniques (kinematic fit, and constraints on decay kinematics etc)
- Categorized with lepton, VBF tagged, boosted, jets





Discovery to Higgs



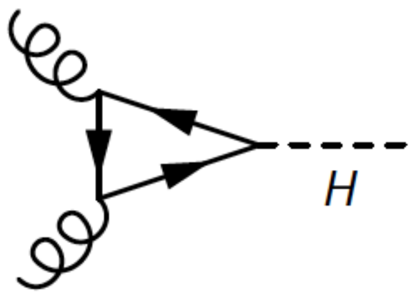
Higgs Couplings

- Parameterizing compatibility with the SM (or small deviations)

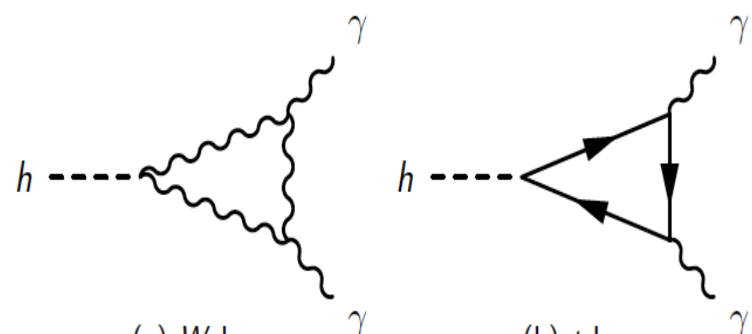
$$\mu \equiv (\sigma \times \text{BR})_{\text{observed}} / (\sigma \times \text{BR})_{\text{expected}}$$

κ parameterize the ratio of the **coupling** of the Higgs to a given particle as a ratio to the SM prediction

- Loop-induced couplings



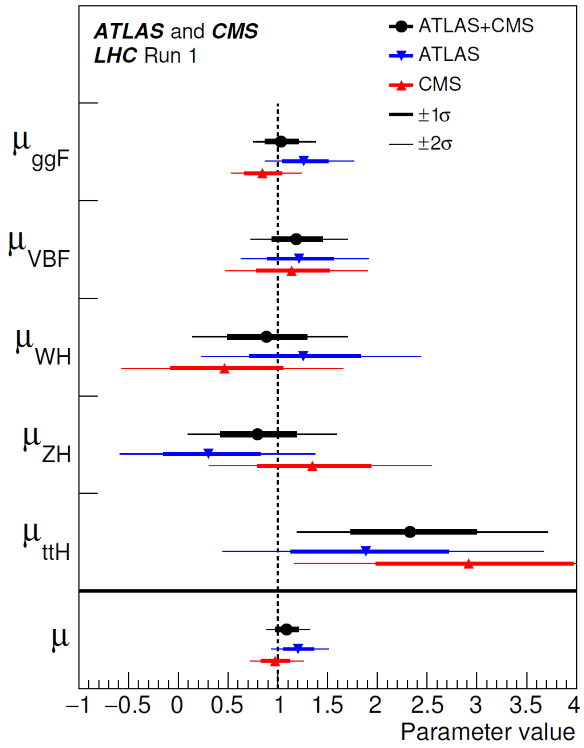
$$\kappa_g^2 \sim= 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$

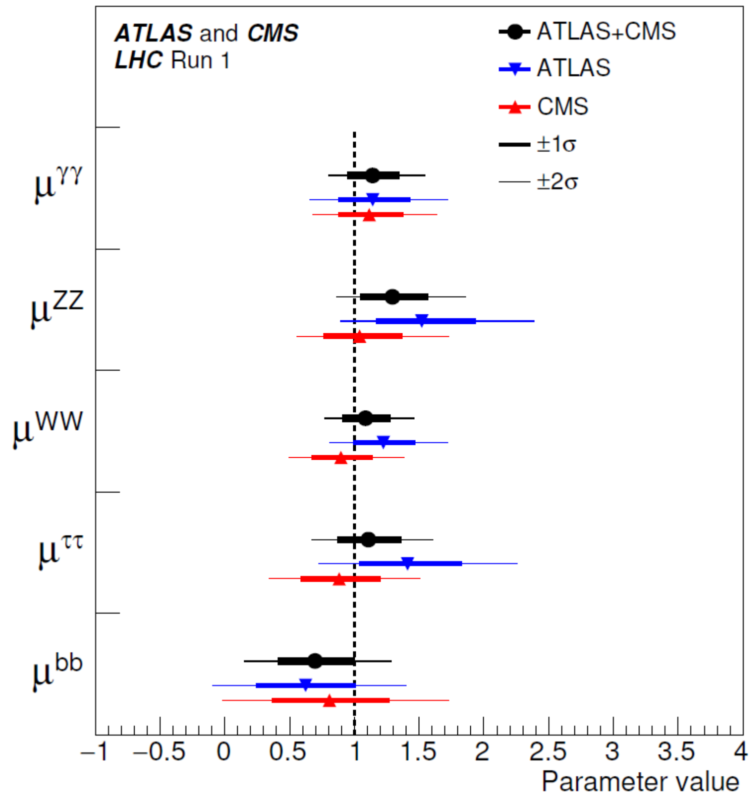


(a) W loop (b) t loop

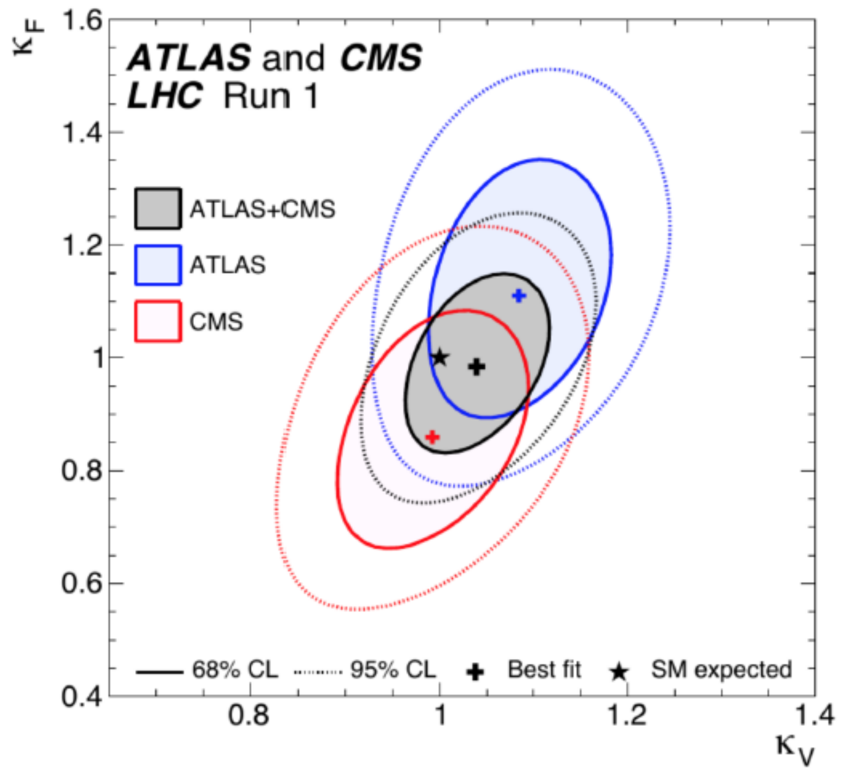
$$\kappa_\gamma^2 \sim= 1.6\kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$$

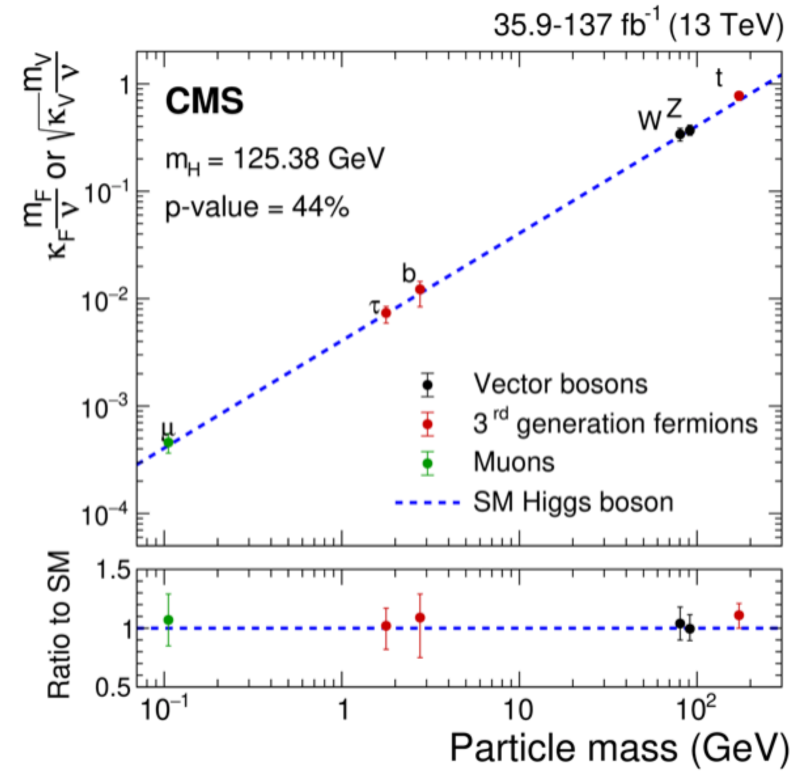
Higgs Couplings





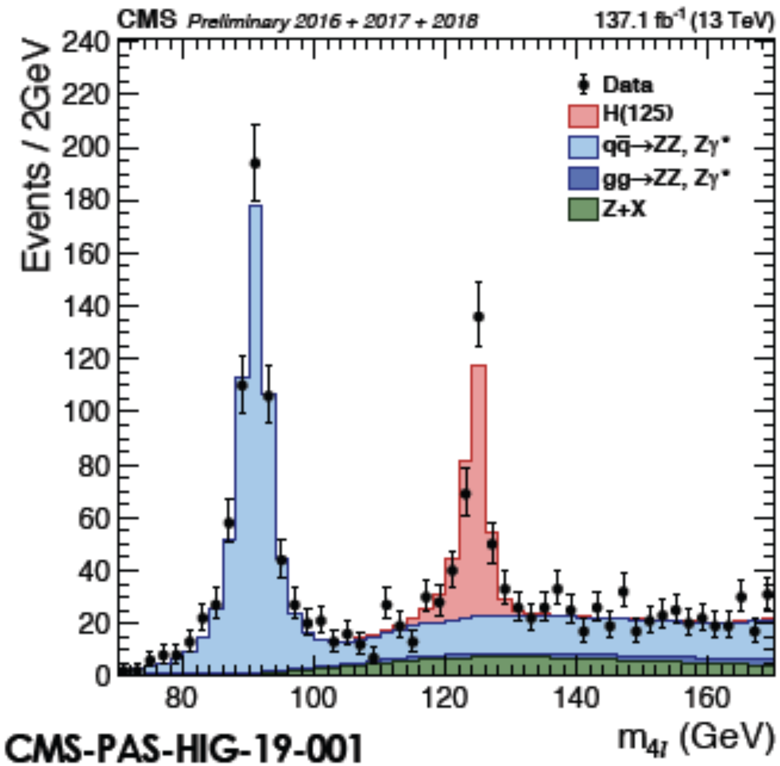
Higgs Couplings

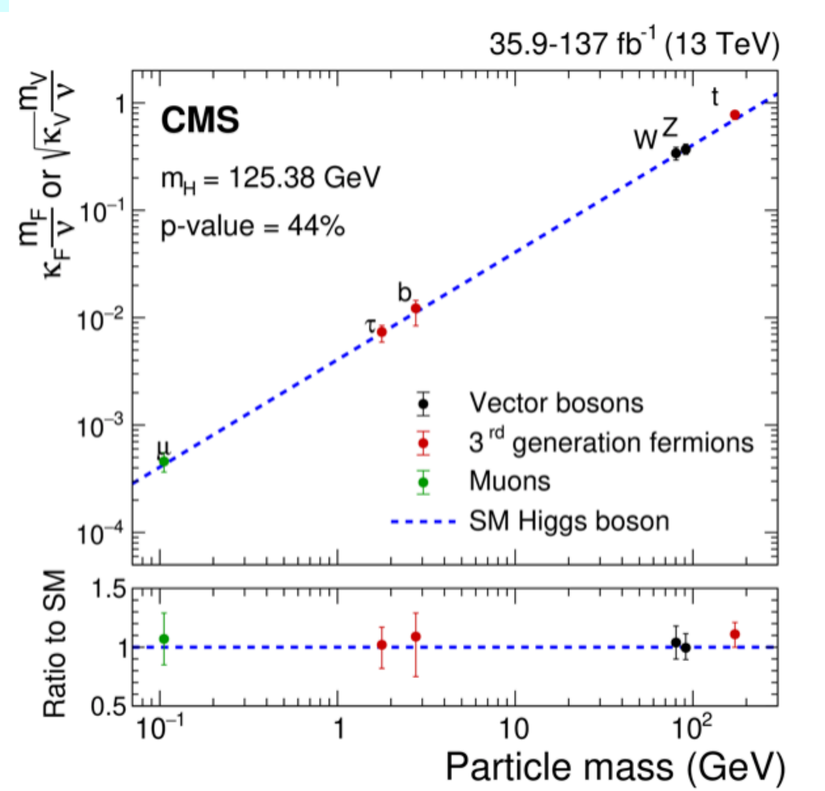




- Consistent with the SM predictions

Higgs Physics





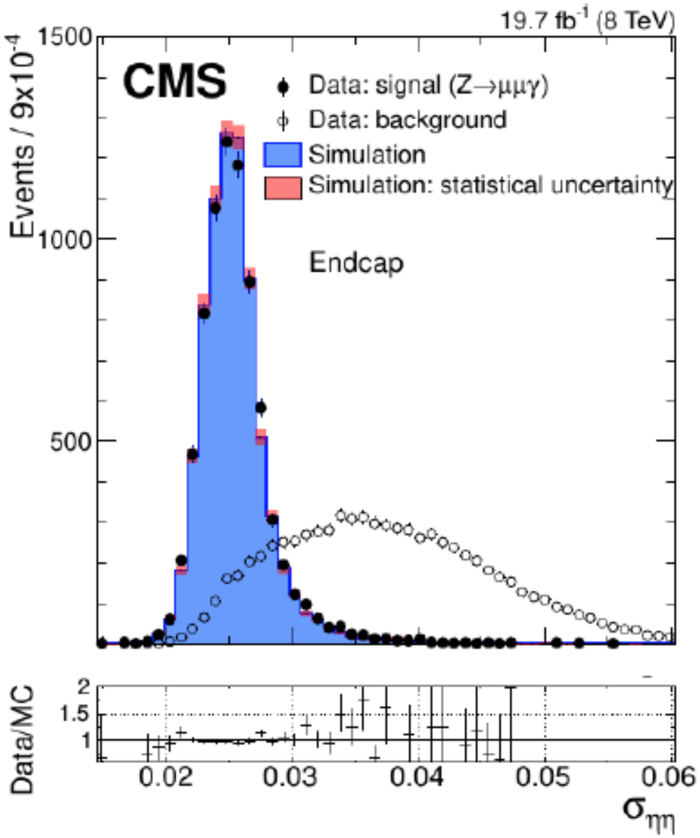
- ➢ Higgs mass: 125.38 GeV with 0.1% precision
- ➢ Couplings to the SM particles: consistent with the SM predictions
- ➢ All consistent with the SM Higgs world

Backup Slides

Photon ID

Main sources of Misidentified Prompt Photons:

- $\pi^0 \rightarrow \gamma\gamma$ (at high energies, the decay is collimated and tends to merge into a single shower)
- **Electrons** where primary track is not reconstructed, or misidentified as belonging to a conversion

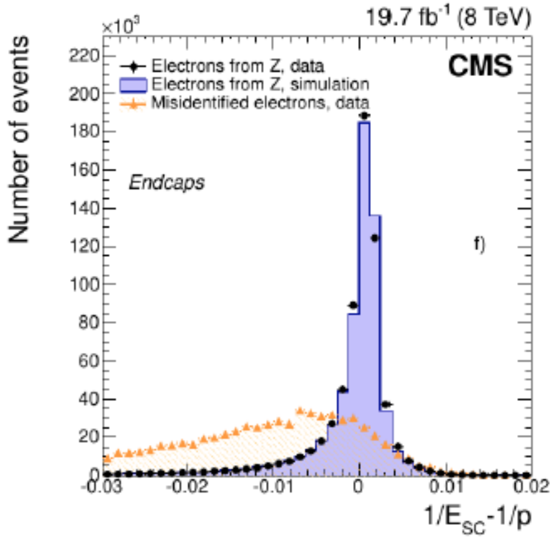


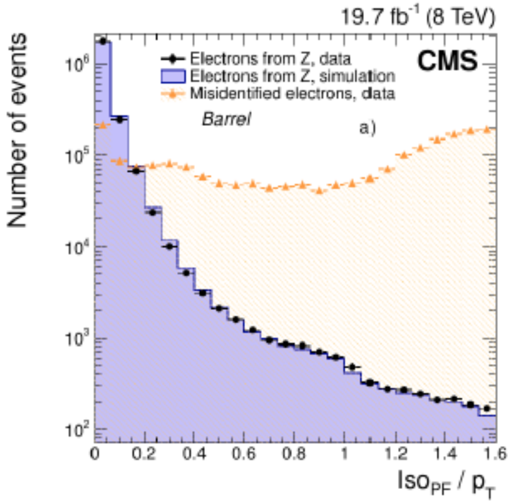
Transverse shower width (parallel to B-field)

Electron ID

Main sources of Misidentified Prompt Electrons:

- **Heavy flavour** decays (e.g. B and D hadrons) producing displaced electrons
- **Photon conversions** (attempt to reconstruct or identify them, but difficult to do efficiently)
- Early showering of **charged hadrons** in EM calorimeter (e.g. via inelastic charge exchange $\pi^+ p \to \pi^0 n$)



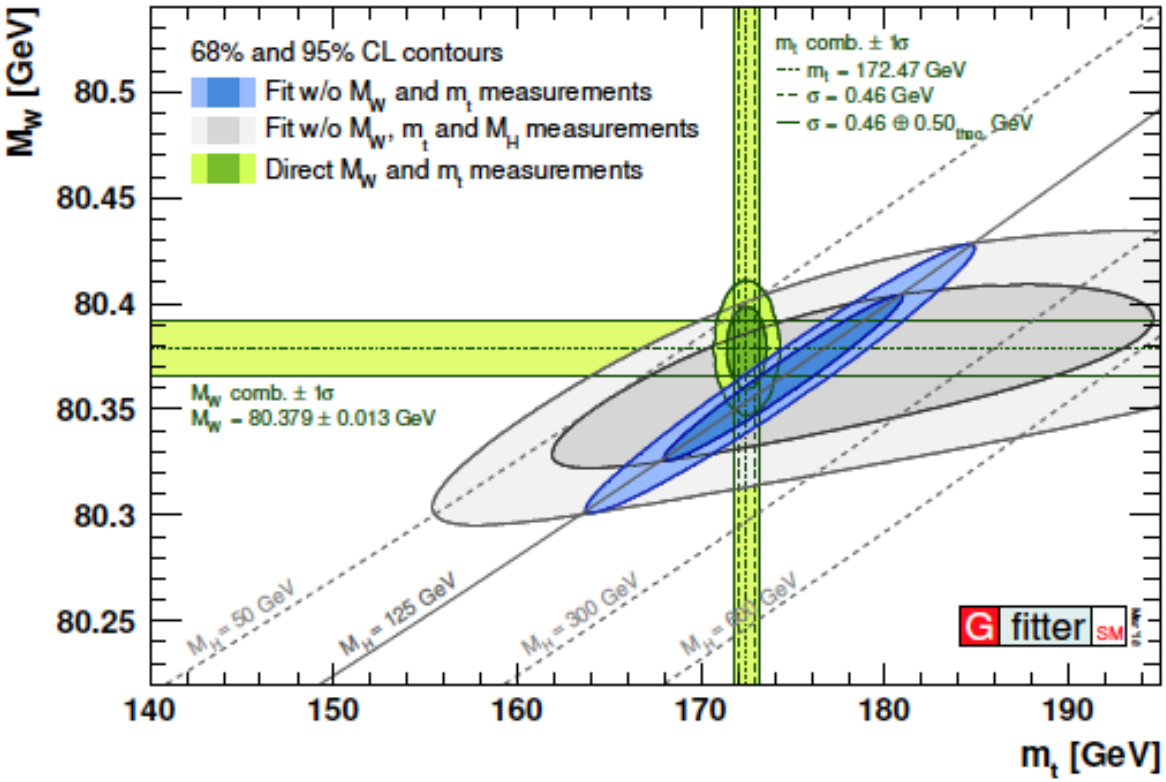


Muon ID

Main sources of Misidentified Prompt Muons:

- **Heavy flavour** decays (e.g. B and D hadrons) producing displaced muons
- **Decay in flight** of charged hadrons (e.g. $\pi^+/K^+ \rightarrow \mu^+\nu$), can be supressed with track quality, "kink-finding"
- **"Punch through"** of charged hadrons (negligible with enough hadronic interaction lengths upstream)

EWK Fit



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