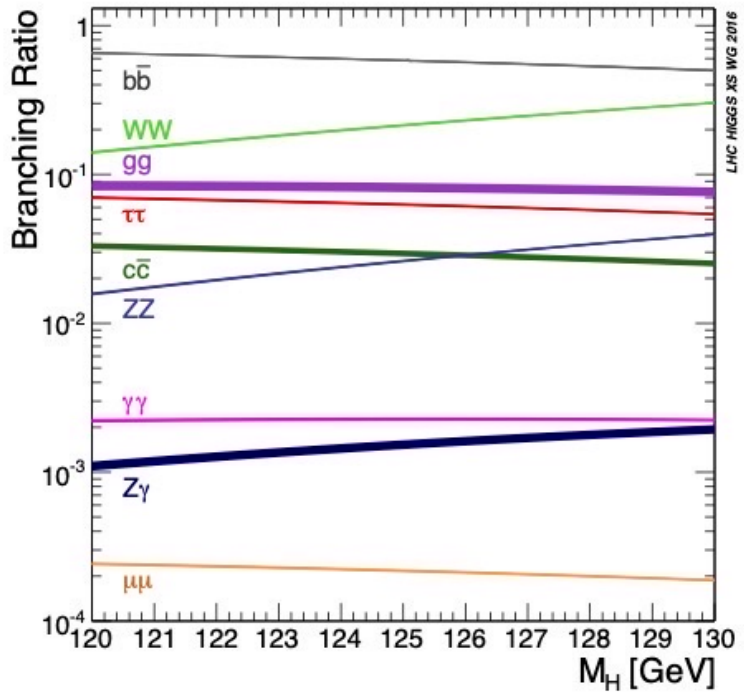
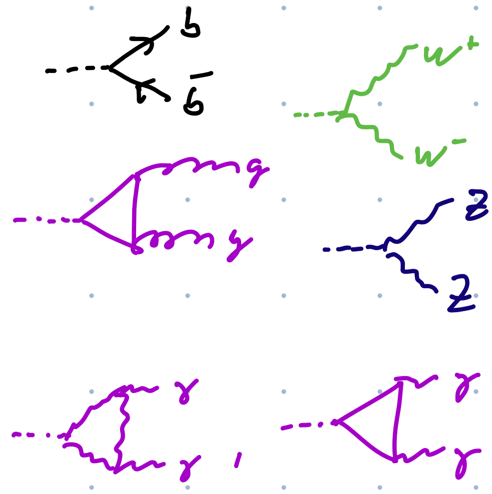
Lecture 19:

Higgs decays





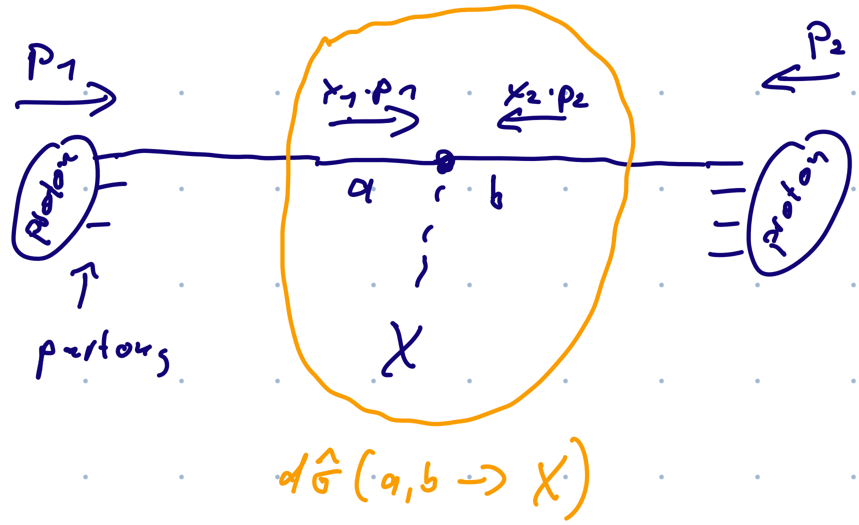
V.2 Higgs production at the LHC

The LHC collides protons with a center-of-mass energy of (currently) $\sqrt{s} = 13.6$ TeV

Cross sections obtained via collinear factorization

$$d\sigma(pp \to X) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \; f_a(x_1, \mu_F)\, f_b(x_2, \mu_F)\, d\hat{\sigma}(a, b \to X)$$

from cross section of underlying partonic process



$f_a(x, \mu_F)$: parton density function

$\to$ "probability" to find parton a with momentum $x \cdot p$ in the proton

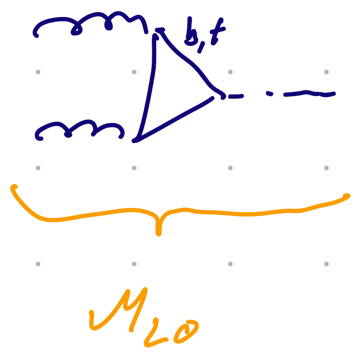
$a \in \{ g, u, \bar{u}, d, \bar{d}, s, \ldots \}$

μ_F : factorization scale

(similar to renormalization scale of running coupling $\to$ IV.2)

gluon fusion

dominant production mode for Higgs at LHC

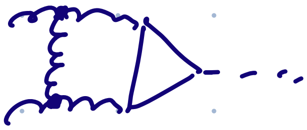
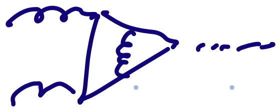


$$\hat{\sigma}(gg \to H) = \frac{G_F \, \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q A(\tau_Q) \right|^2$$

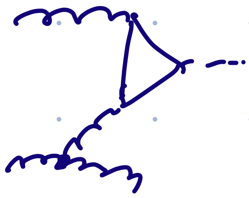
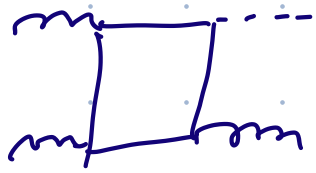
same as for $H \to gg$ decay

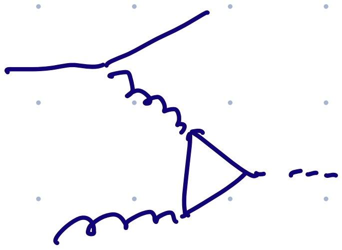
next-to-leading order corrections:

- virtual corrections

$\mathcal{M}_V =$  $+$  $+ \ldots$

- real corrections:

$\mathcal{M}_R^{gg} =$  $+$ 

$\mathcal{M}_R^{qg} =$ 

Need to be included, since $H+g$ and $H+q$ final state indistinguishable with H final state if the q/g momentum is small or collinear to initial state.

→ "inclusive cross section" $\sigma(pp \to H + X)$

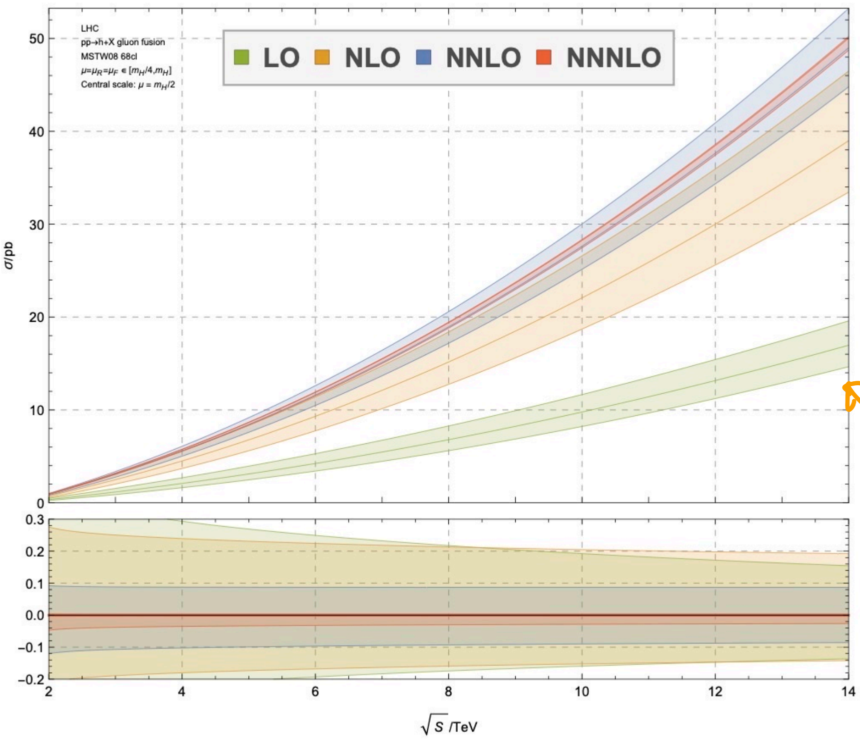
$$\Rightarrow \hat{\sigma}_{NLO} = \hat{\sigma}_{LO} + \hat{\sigma}_V + \hat{\sigma}_R$$

$$= \int d\Phi_1 \, \underbrace{|\mathcal{M}_{LO}|^2}_{(\alpha_s)^2} + \int d\Phi_1 \left(\underbrace{\mathcal{M}_V^* \cdot \mathcal{M}_{LO}}_{\alpha_s^2 \cdot \alpha_s} + \mathcal{M}_{LO}^* \mathcal{M}_V \right) + \int d\Phi_2 \left(\underbrace{|\mathcal{M}_R^{gg}|^2}_{(\alpha_s^{3/2})^2} + |\mathcal{M}_R^{qg}|^2 \right)$$

The NLO corrections increase the cross section by ~100%

→ not sufficient for accurate description of process.

The corrections up to N^3LO in α_s are known (using the HTL) arXiv: 1503.06056



N^3LO ~ 3%

$NNLO$ ~ 20%

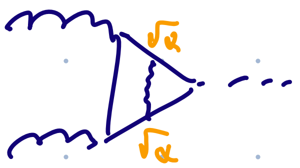
NLO ~ 100% correction

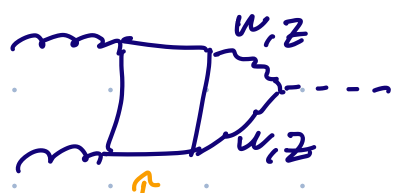
LO $\sigma_{LO} \approx 18\,pb$

uncertainty estimates via variation of μ_R, μ_F, unreliable at LO due to new partonic channels appearing at NLO.

further corrections:

- NLO EW + 5%

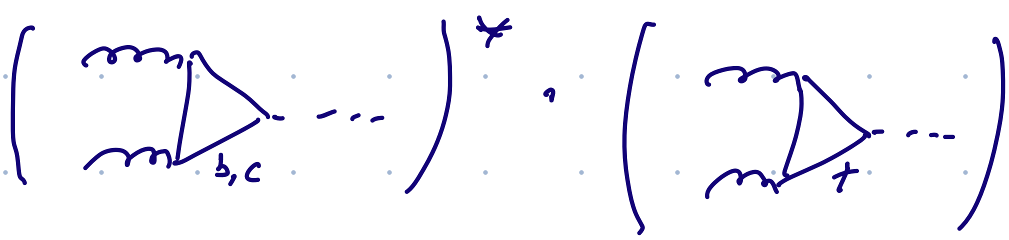




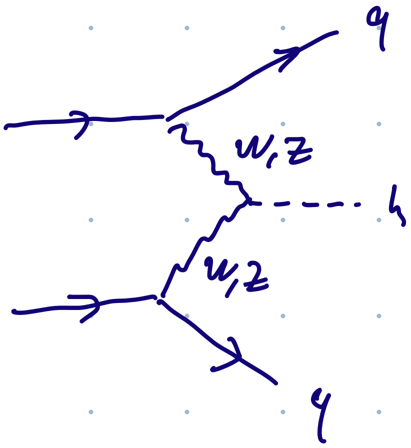
also light quarks contribute

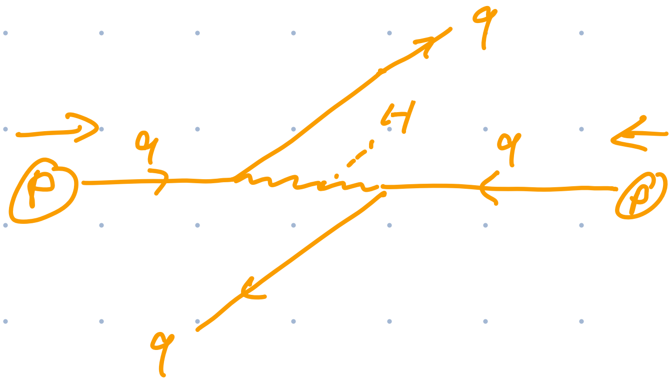
- light quarks −4%

negative interference with top-quark loop



vector boson fusion





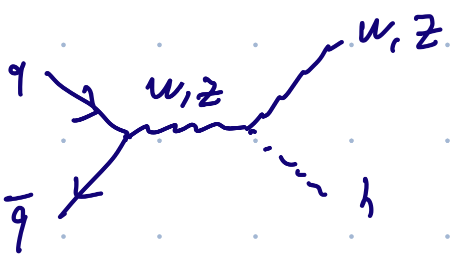
$pp \to W^*W^* / Z^*Z^* \to H$

$\Rightarrow$ characteristic detector signature:
- 2 jets with large separation
- Higgs boson in central region

NLO QCD corrections : $\sim 1-10\%$ (depending on phase-space cuts)

also NNLO QCD and NLO EW corrections known
↳ N^3LO QCD in some approximation

Higgs strahlung



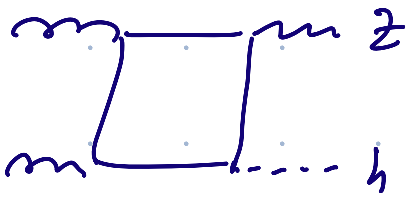
$pp \to W^*/Z^* \to W, Z + h$

NLO QCD $+30\%$
NNLO QCD $+3\%$

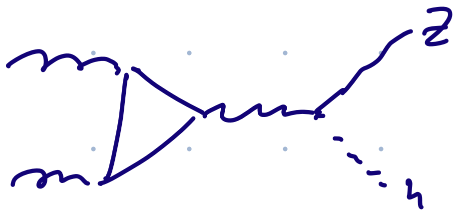
also N^3LO QCD and NNLO EW known.

additional contributions for ZH production

$gg \to ZH$ $+10\%$

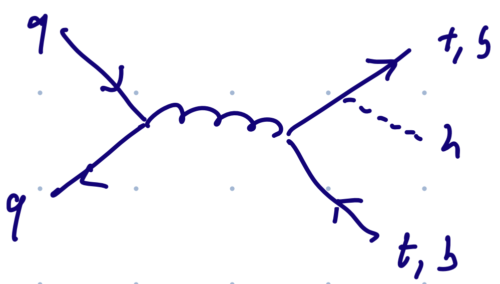


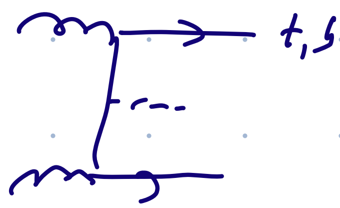
+



Associate production

$pp \to t\bar{t}H \;/\; b\bar{b}H$





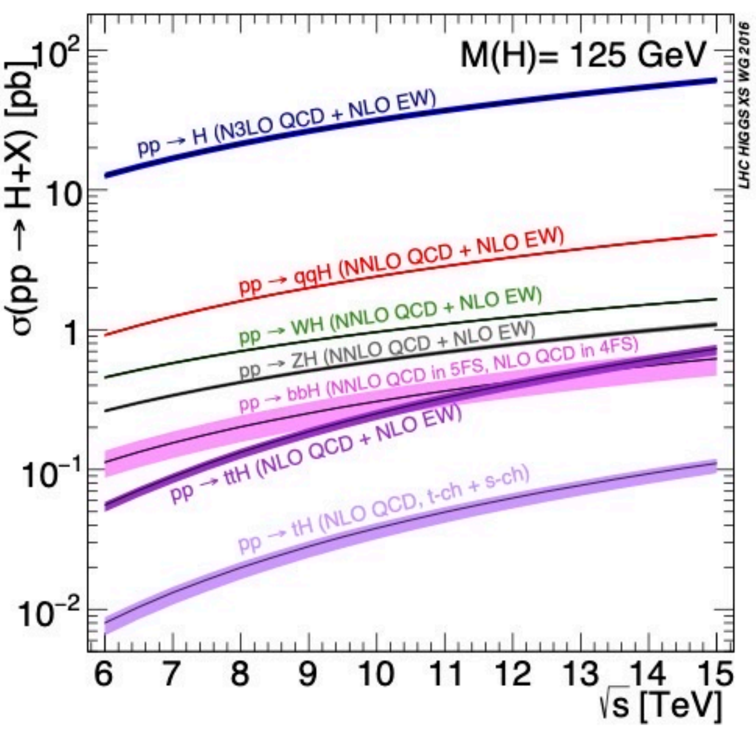
NLO QCD +20%

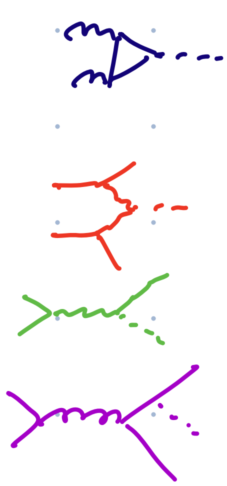
→ direct measurement of top-quark Yukawa coupling.

complicated final state for ttH due to subsequent decays $t \to b + W^{\pm}$

$\hookrightarrow q\bar{q}\,,\ \ell^{\pm}\nu$

summary of production cross sections





V 3. Higgs discovery and quantum numbers

discovery in july 2012 during LHC run 1:

2011: $\sqrt{s} = 7$ TeV $\qquad \int L = 5.6\ fb^{-1}$

2012: $\sqrt{s} = 8$ TeV $\qquad \int L = 6.6\ fb^{-1}$

c.f. run 2 2015-18 $\sqrt{s} = 13$ TeV $\qquad \int L \approx 130\ fb^{-1}$

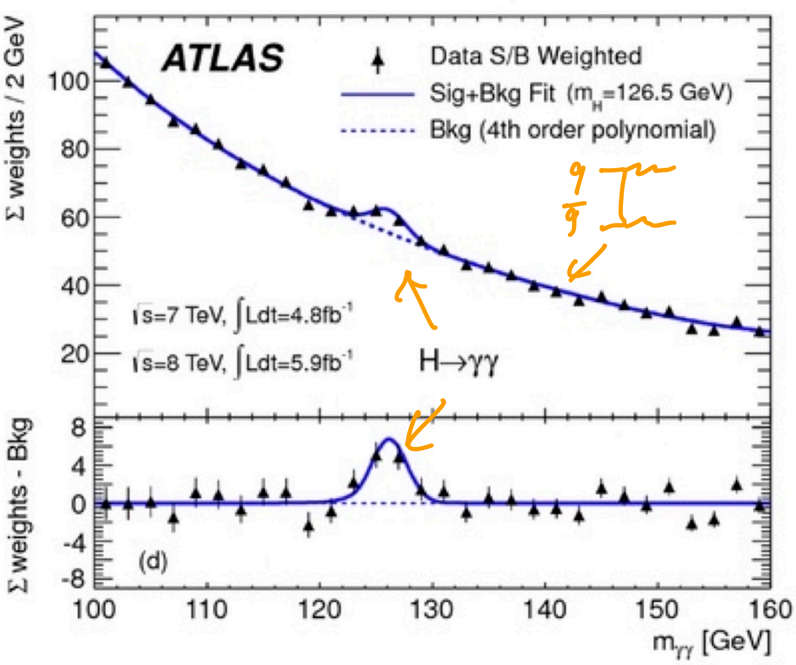
run 3 2022-24 $\sqrt{s} = 13.6$ TeV $\qquad \int L \approx 300\ fb^{-1}$

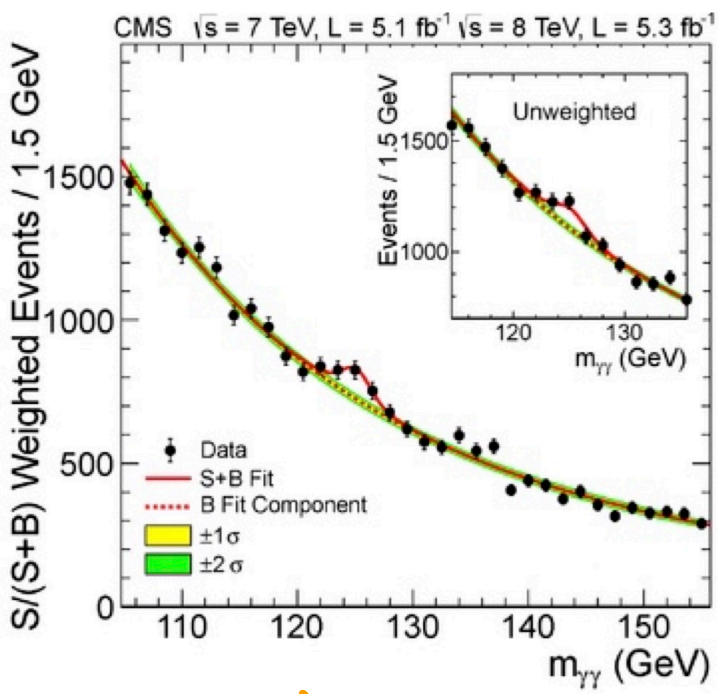
main decay channels for discovery:

$$H \to \gamma\gamma \ , \qquad H \to ZZ^* \to 4\ell$$

$\Rightarrow$ small BR, but distinct detector signal

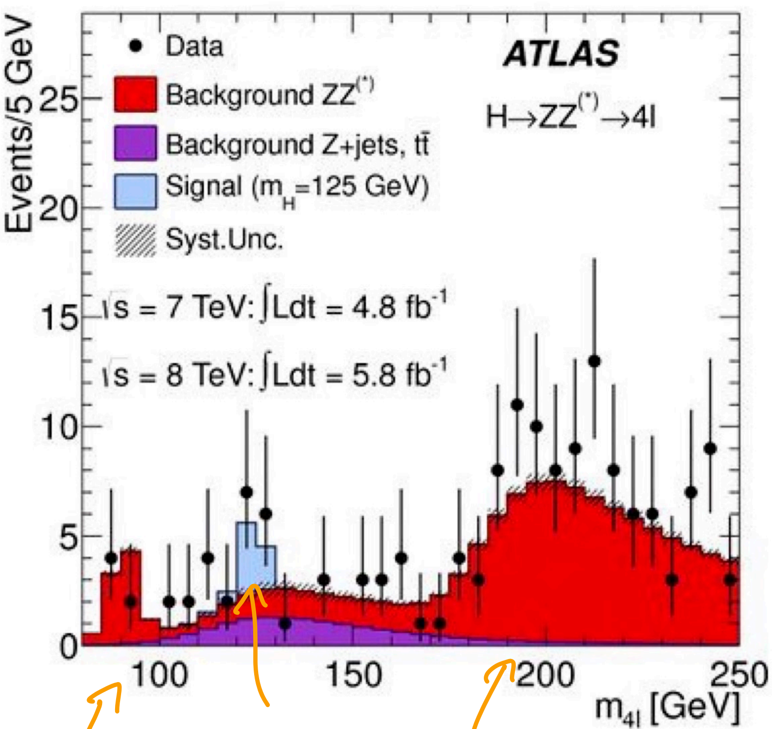
$H \to \gamma\gamma$:

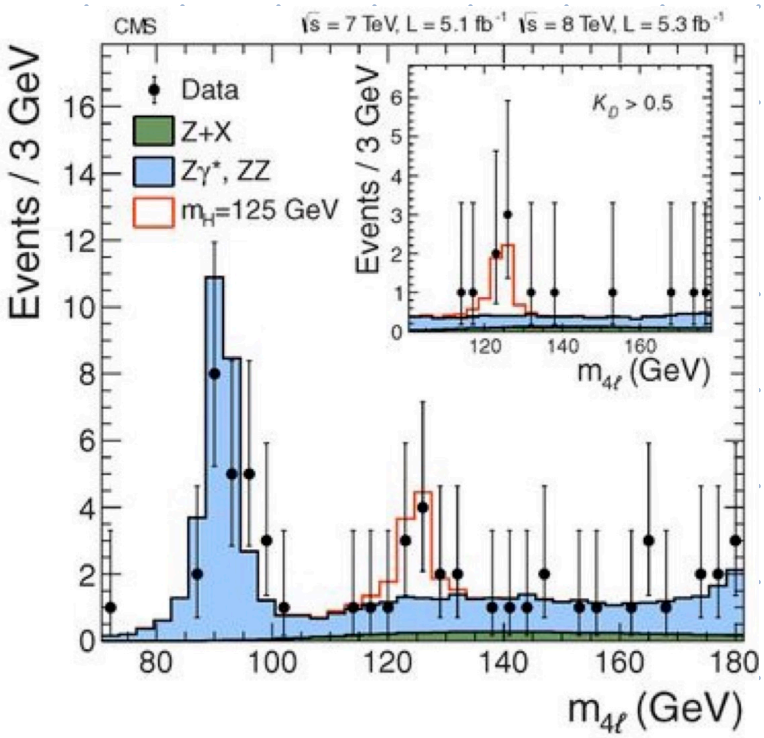


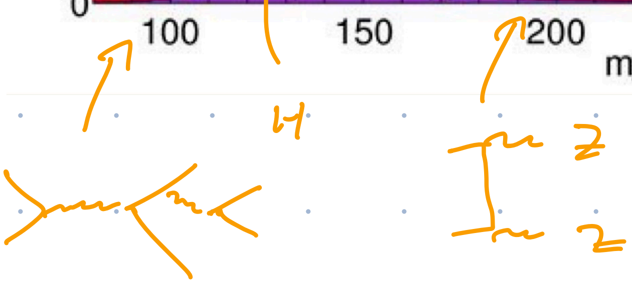


$\hookrightarrow \quad m_{\gamma\gamma}^2 = (p_{\gamma_1} + p_{\gamma_2})^2$

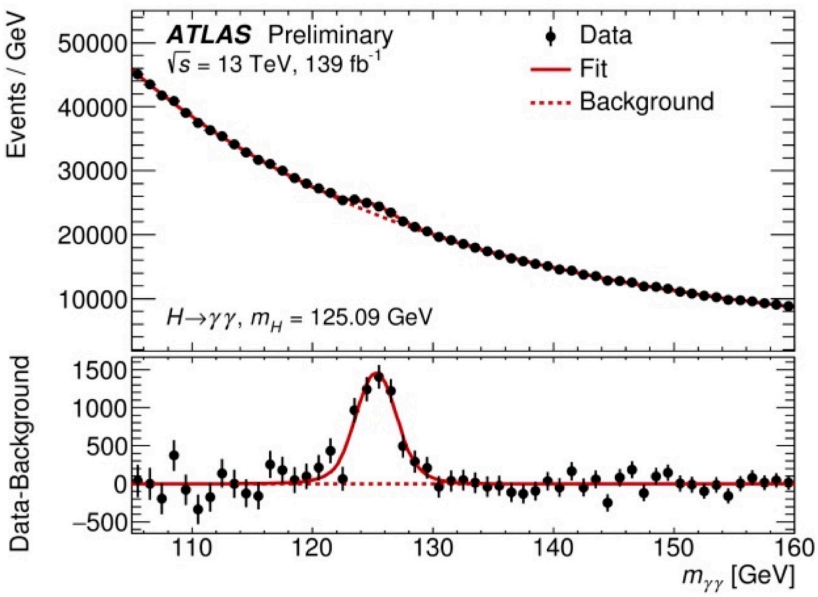
H → ZZ

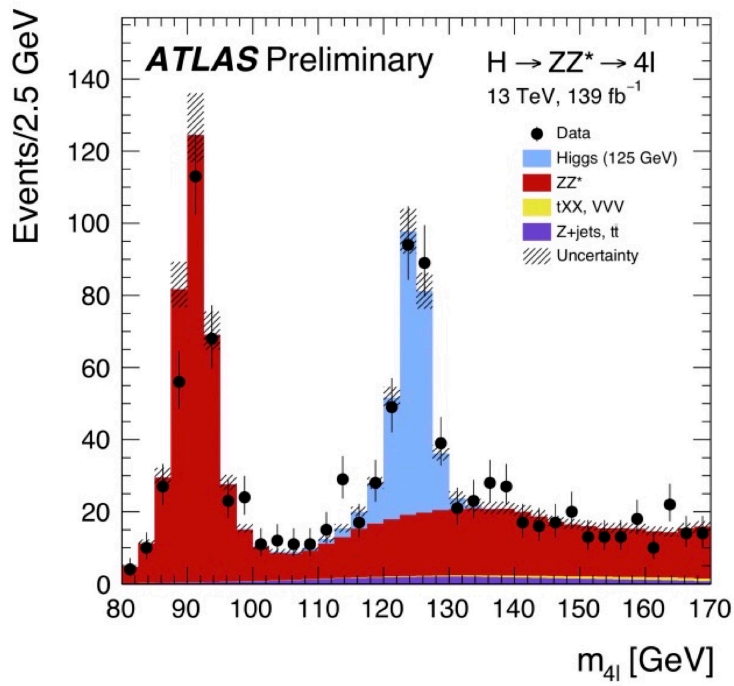






updated results with full run 2 statistics





spin and parity quantum numbers

The Higgs boson in the SM is CP even, with couplings

$$\mathcal{L} \supset \frac{h}{v} \left(m_W^2 \, W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu + m_f \bar{\psi} \psi \right)$$

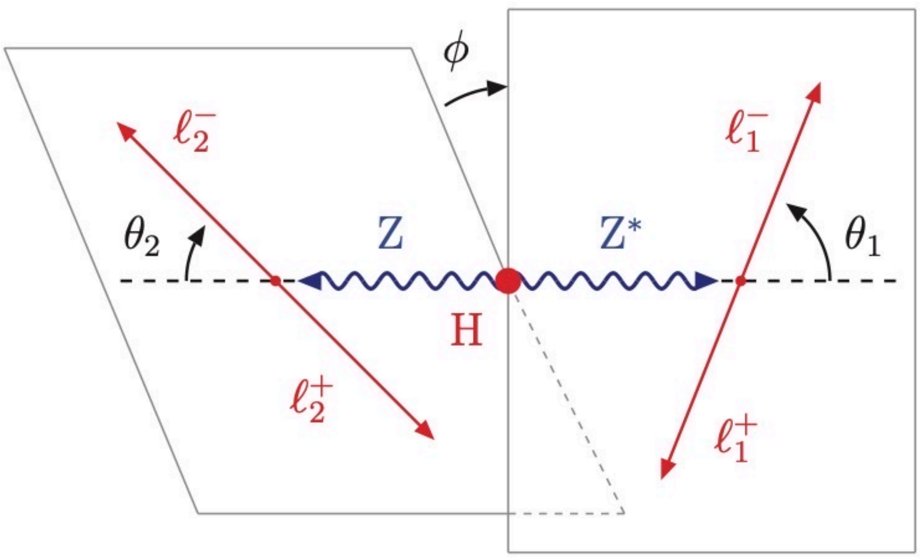
The corresponding CP-odd coupling structures would be

$$\sim \quad h \, W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \quad , \quad \frac{1}{2} h \, Z_{\mu\nu} \tilde{Z}^{\mu\nu} \quad , \quad h \bar{\psi} \gamma_5 \psi$$

with $\tilde{F}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$

$\Rightarrow$ modification of angular distributions, e.g. in

$H \to Z Z^* \longrightarrow 4\ell$ decay

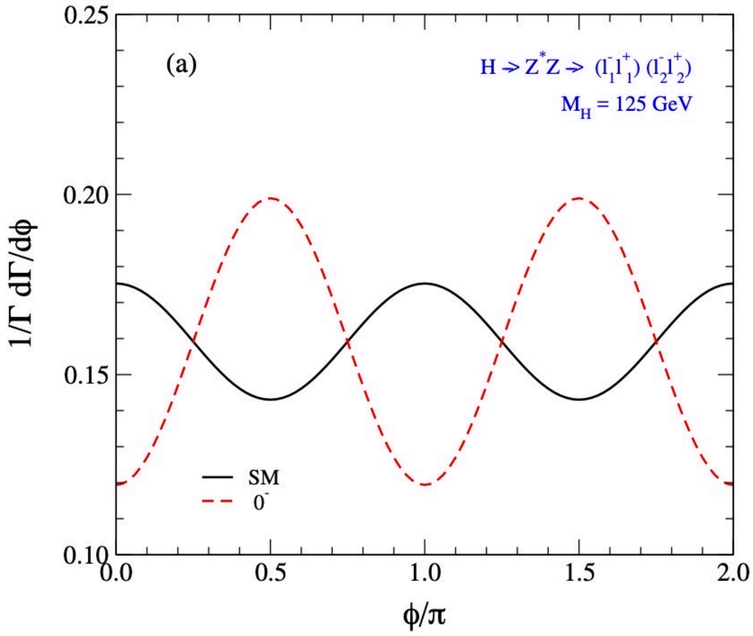


arXiv 1307.1347

for CP-even: $\quad \frac{d\Gamma}{d\phi} \sim 1 + \frac{1}{2\gamma^4 + 4} \cos 2\phi$

CP-odd: $\quad \frac{d\Gamma}{d\phi} \sim 1 - \frac{1}{4} \cdot \cos 2\phi$

$$\gamma^2 = \frac{m_h^2 - m_Z^2 - m_{Z^*}^2}{2\, m_{Z^*}\, m_Z}$$



arXiv 1307.1347

→ Experimental confirmation that Higgs is CP even by ATLAS, CMS in 2012/13

Also confirmed spin = 0:

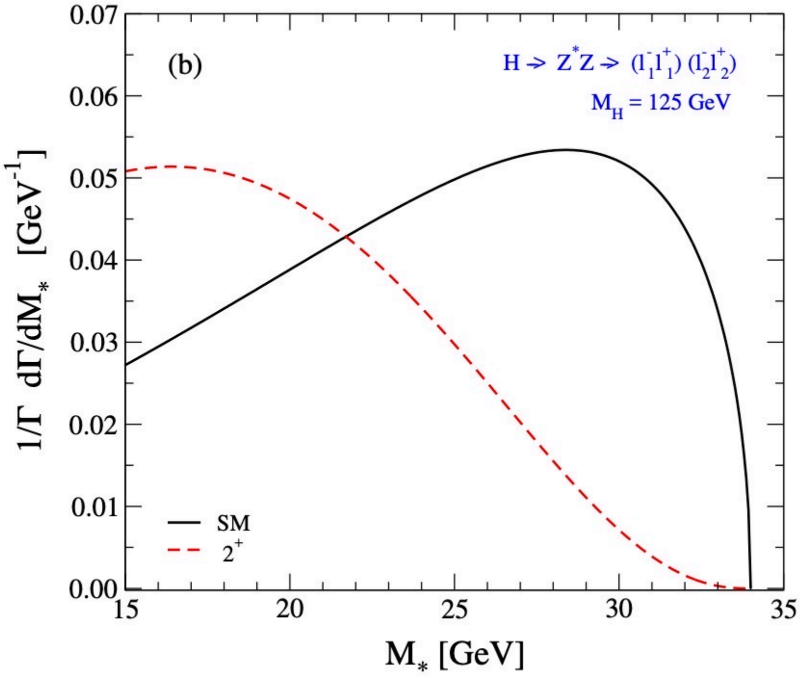
- spin = 1 excluded, since decay $H \to \gamma\gamma$ would be forbidden by angular momentum conservation and parity

  → Landau, Yang theorem, 1948/50

- spin = 2 would lead to different partial decay width for $H \to ZZ^*$

  spin 0: $\frac{d\Gamma}{dm_{Z^*}} \sim \beta = \sqrt{(m_h - m_Z)^2 - m_{Z^*}^2}\,/m_h$

  spin 2: $\frac{d\Gamma}{dm_{Z^*}} \sim \beta^3$



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