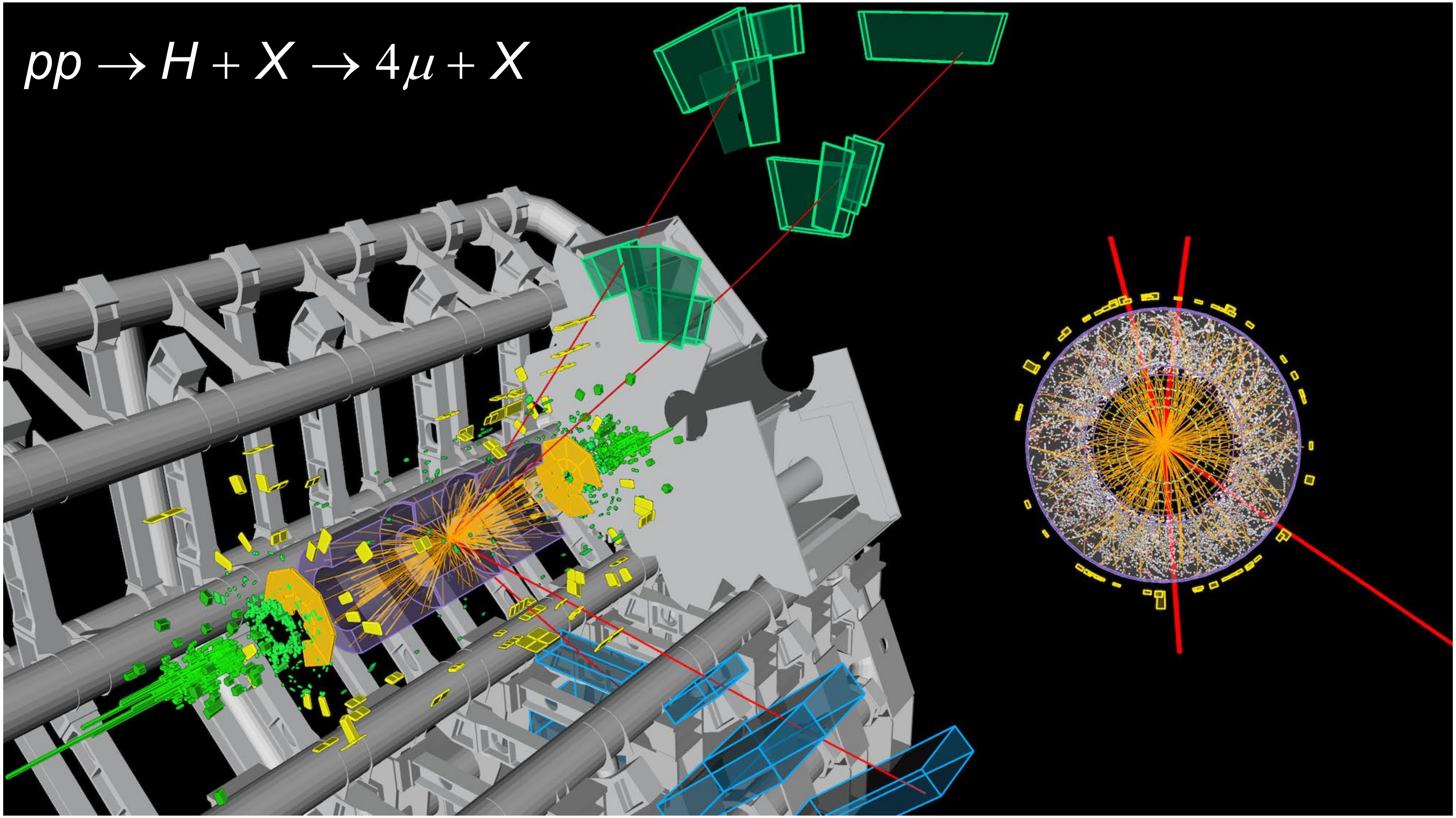
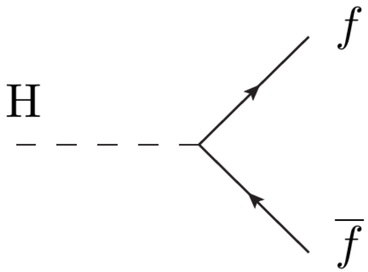
4. Discovery of the Higgs boson and its properties



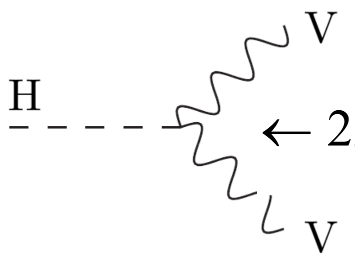
Recap: Higgs couplings

$$\upsilon^2 = \frac{1}{\sqrt{2}G_F} = \frac{4m_W^2}{g^2} = (246.22\,\text{GeV})^2$$



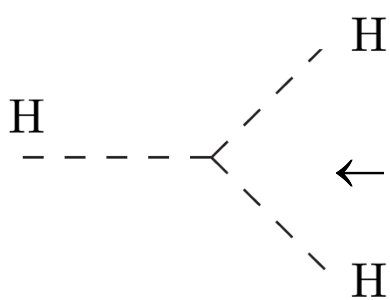
$$\frac{m_f}{v}$$

$$\Gamma(H \to f\bar{f}) = \frac{C G_F m_f^2 M_H}{4\pi\sqrt{2}}\left(1 - 4\frac{m_f^2}{M_H^2}\right)^{\frac{3}{2}}$$

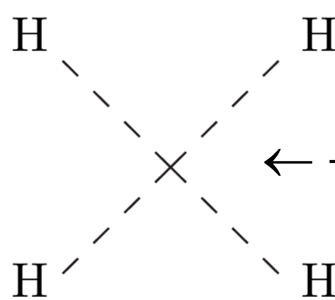


$$\leftarrow 2i\frac{m_V^2}{\upsilon}g_{\mu\nu}$$

$$\Gamma(H \to WW) = \frac{G_F M_H^3}{8\pi\sqrt{2}}\left(1 - 4\frac{M_W^2}{M_H^2} + 12\frac{M_W^4}{M_H^4}\right)\sqrt{1 - 4\frac{M_W^2}{M_H^2}}$$

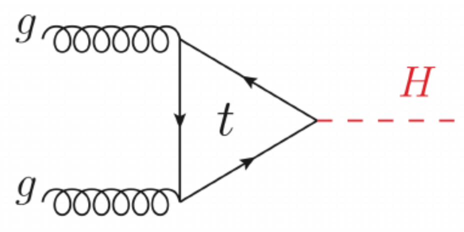


$$\leftarrow -3i\frac{m_H^2}{\upsilon}$$



$$\leftarrow -3i\frac{m_H^3}{\upsilon}$$

Two additional effective couplings:



$$\sim \frac{\alpha_s m_f}{v} \cdot \frac{1}{M}$$

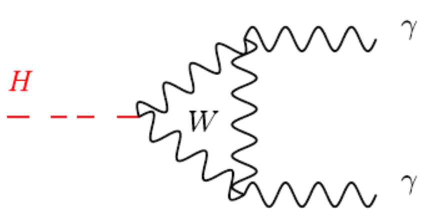
M is momentum flowing in loop:

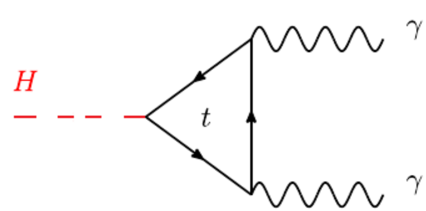
Important for production

Two cases:

- $2m_f < m_H$
  Diagram suppressed by factor $2m_f / m_H$
- $2m_f > m_H$
  Factor m_f cancels and diagram at full strength independent of m_f

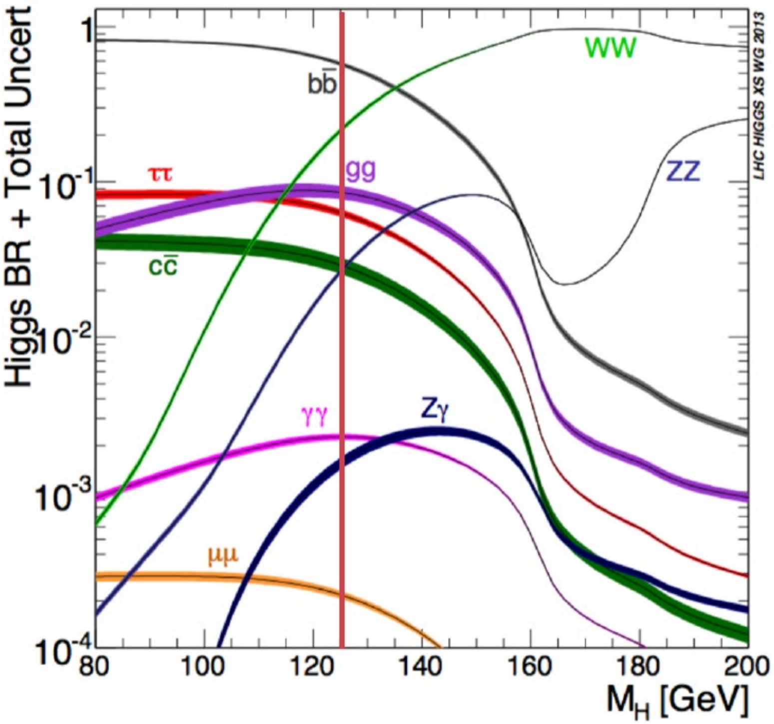
$$m_h^2 \ll 4m_t^2 \qquad \Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^2} \frac{m_h^3}{m_W^2}$$

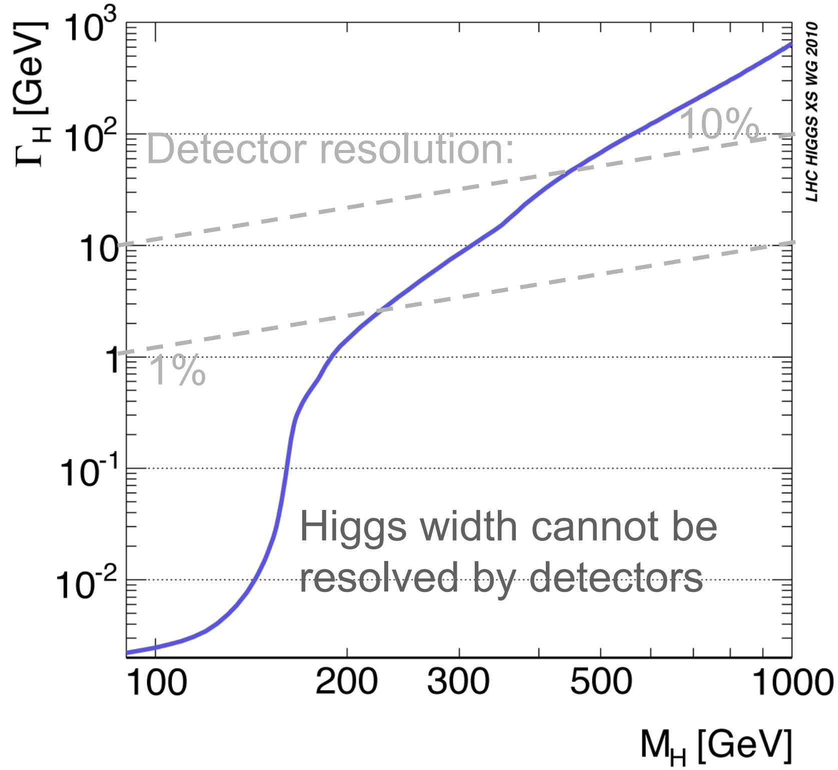




$$m_h \ll (2m_W, 2m_t) \qquad \Gamma(h \to \gamma\gamma) = \frac{\alpha_w \alpha^2}{144\pi^2} \frac{m_h^3}{m_W^2} \left| \frac{21}{4} - \frac{4}{3} \right|^2$$

The decay widths of the Higgs boson will depend on the Higgs boson mass, but, once this is known, the widths can be computed precisely.



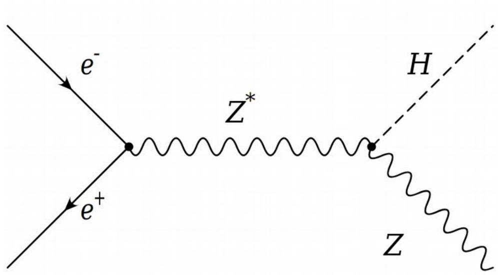


$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

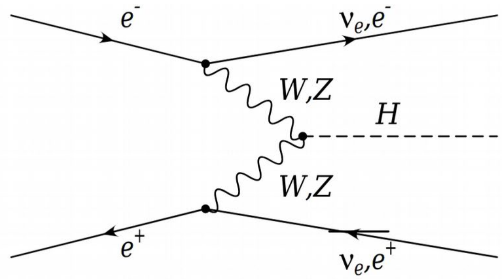
Higgs boson mass of 125 GeV, the prediction for the total width is Γ_{Higgs} = 4.1 MeV

F. Gianotti: “Thank you, Nature.”

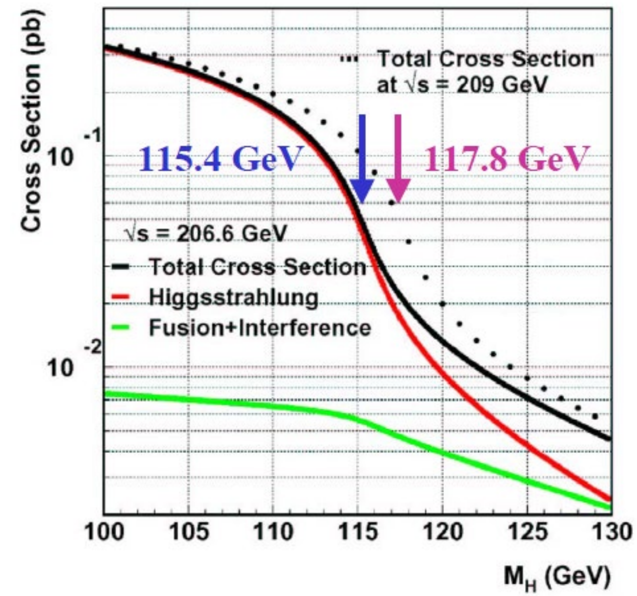
Direct Higgs searches at LEP



Higgs bremsstrahlung



Vector boson fusion (suppressed)



CERN-EP/2003-011
13 March 2003

Mass sensitivity limited by center-of-mass energy:

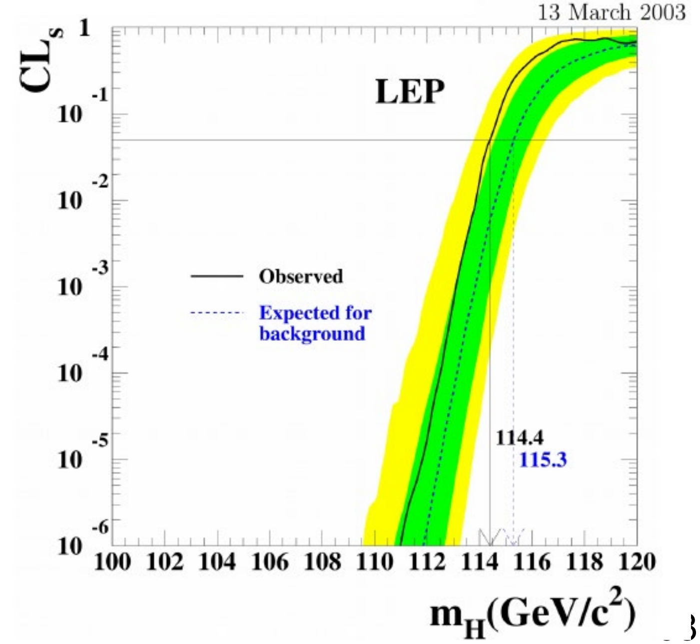
$$m_H \approx \sqrt{s_{\max}} - m_Z \approx 205\,\text{GeV} - m_Z \approx 114\,\text{GeV}$$

Higgs decay channels analyzed: H→bb

Some interesting events but at the end nothing seen!

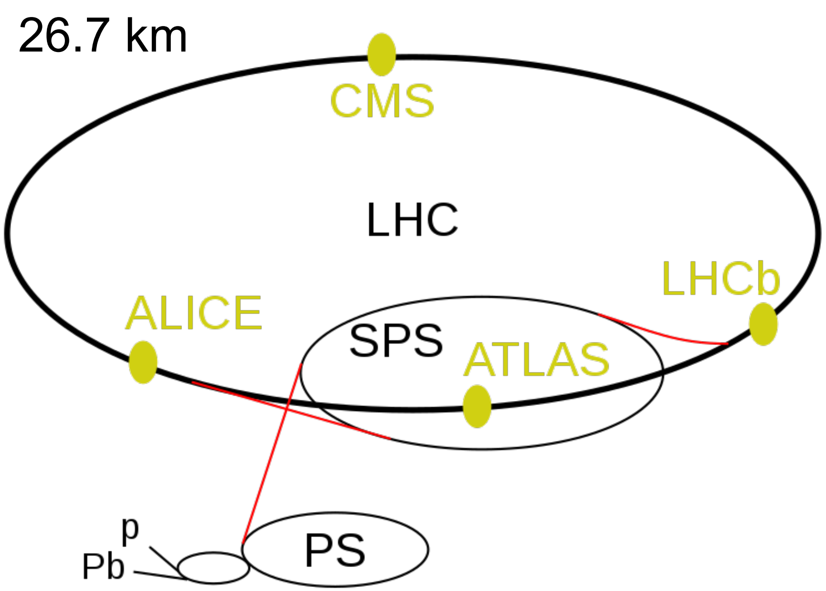
Confidence level for lower limit for signal:

At 95% CL (0.05): m_H > 114,4 GeV



Searches at Tevatron: no significant signal.

Large Hadron Collider



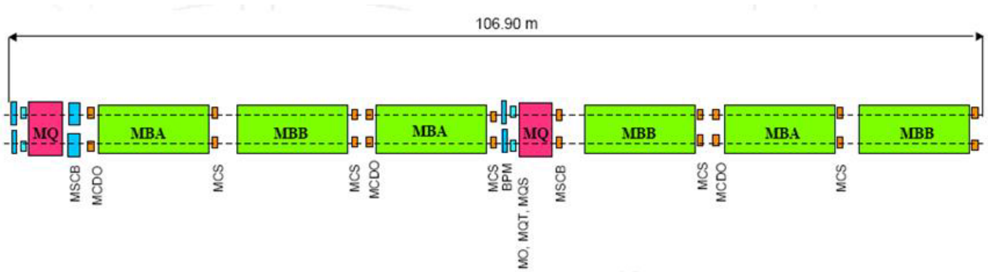
Beam parameters:

$C = 26659$ m
$n_b = 2808$ / beam
$N_b = 1{,}15 \cdot 10^{11}$
$I_B = 0{,}54$ A / beam
$\pi\varepsilon = 1.68 \times 10^{-9}$ rad m
$\beta^* = 0.55\ (0.33)$ m
$L = 10^{34}$ cm^{-2} s^{-1}

RF Cavities: 8 per beam
400.8 MHz
2 MV per cavity (5 MV/m field)
→ 16 MV in total

8 arcs (octants,2450 m): **23 arc cells (FODO)**

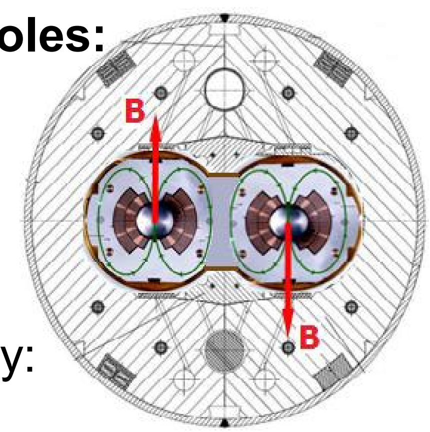
FODO: 2 Quadrupoles + 6 dipoles + multipoles



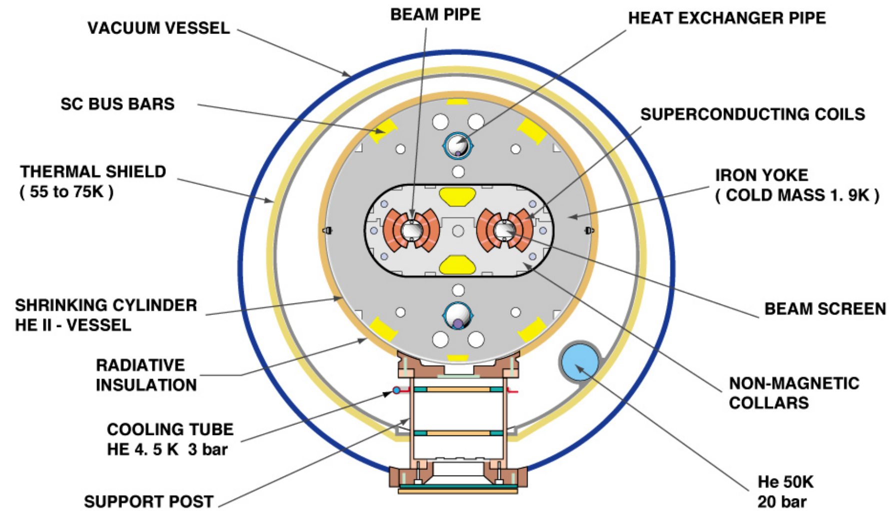
1232 SC dipoles:

$I = 11800$ A
$B = 8.33$ T
$R = 2804$ m
$L = 14.3$ m

Stored energy:
7 MJ / dipole

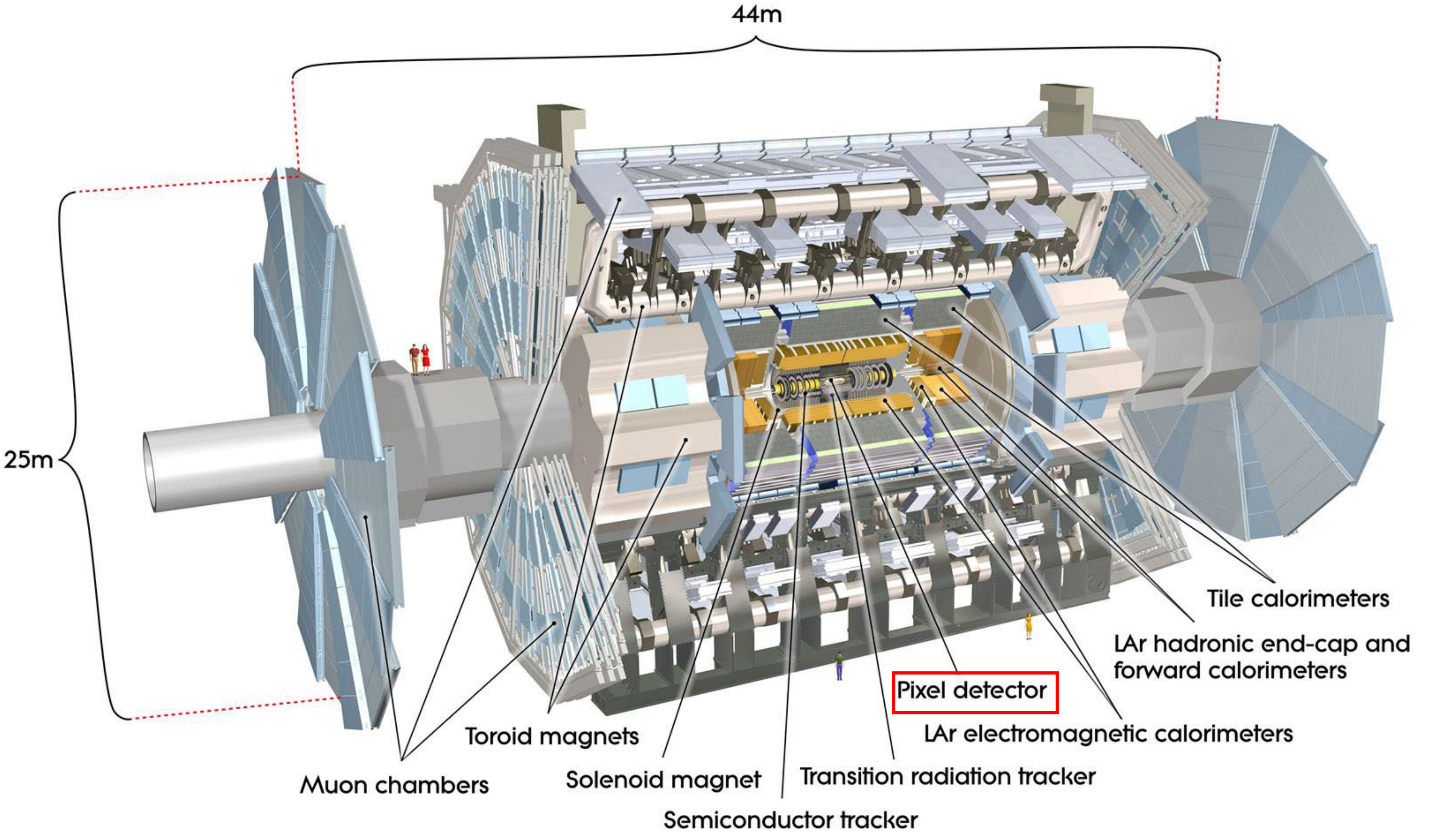


LHC tunnel:



Live display of machine status: https://op-webtools.web.cern.ch/vistar/

ATLAS Detector

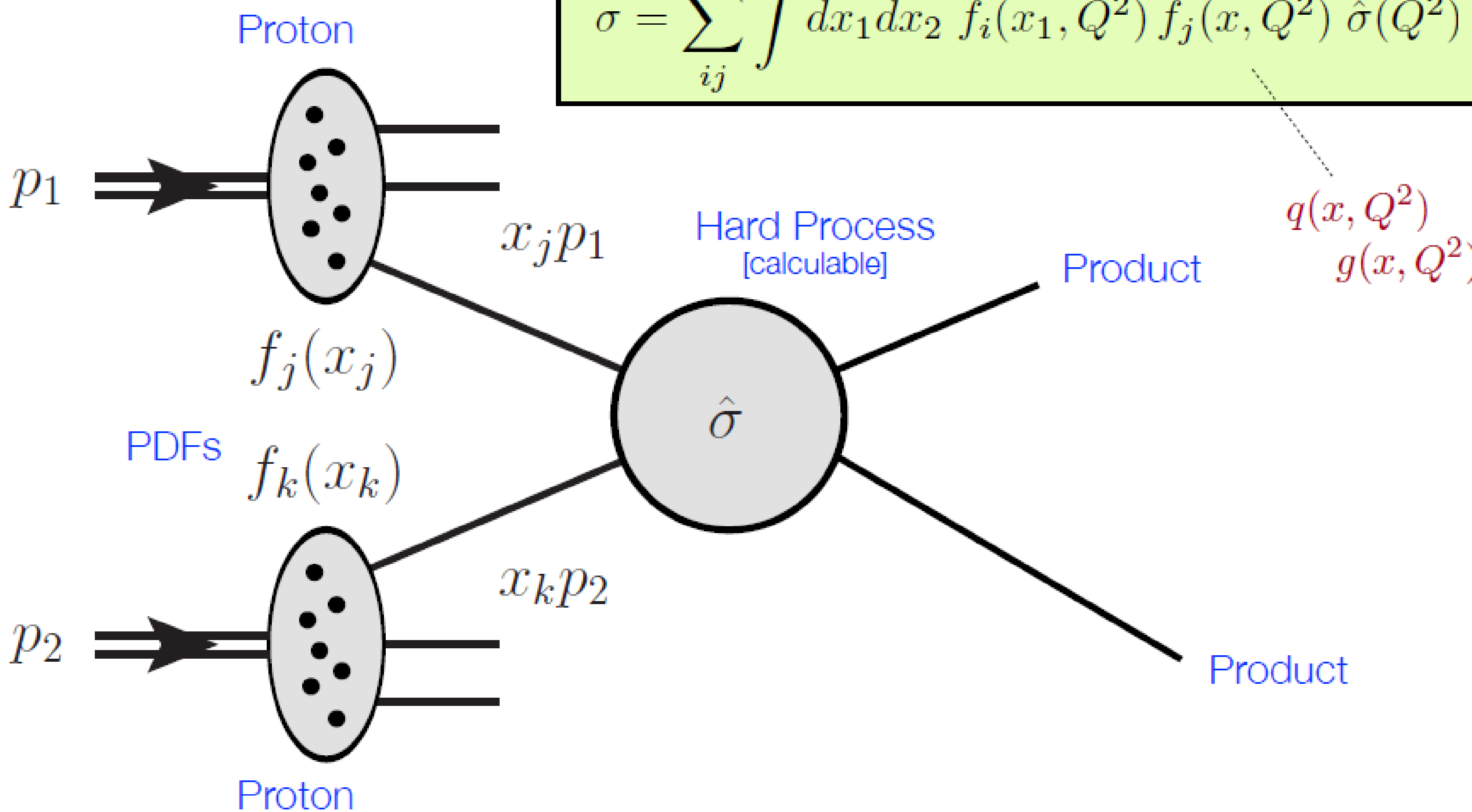


e.g. 90M channels

Proton-proton scattering

Slide: H.C Schultz-Coulon

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\; \hat{\sigma}(Q^2)$$

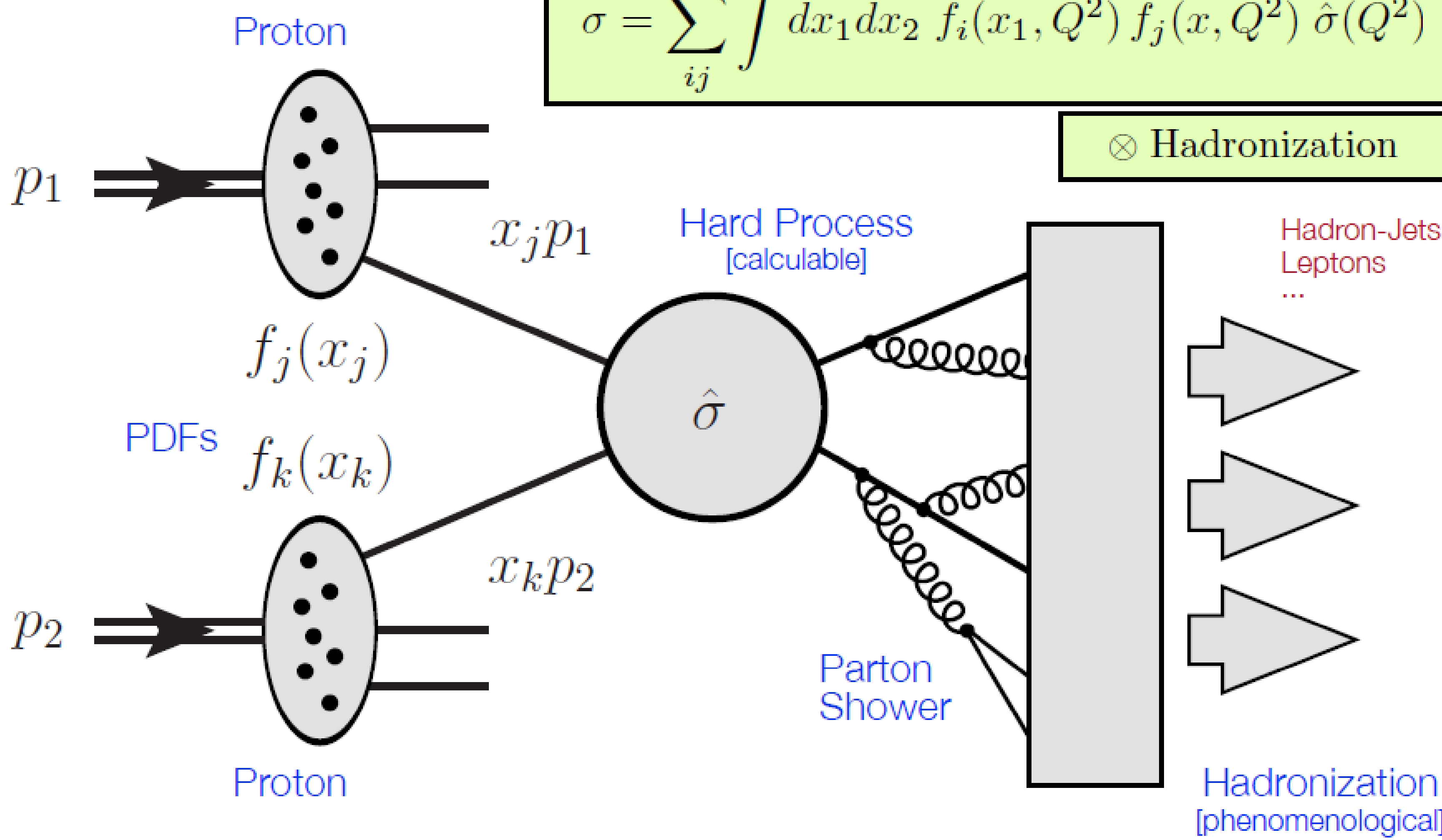


Proton-proton scattering

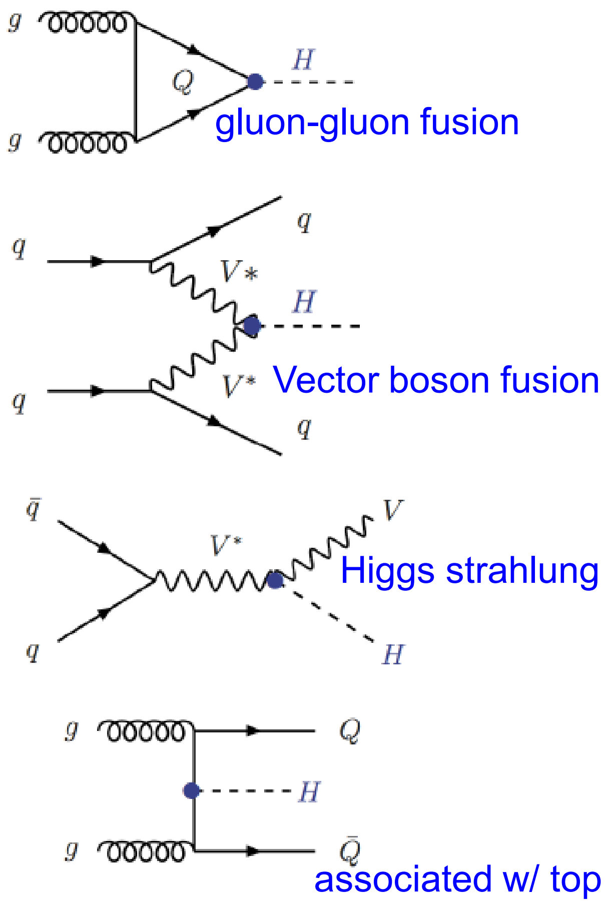
Slide: H.C Schultz-Coulon

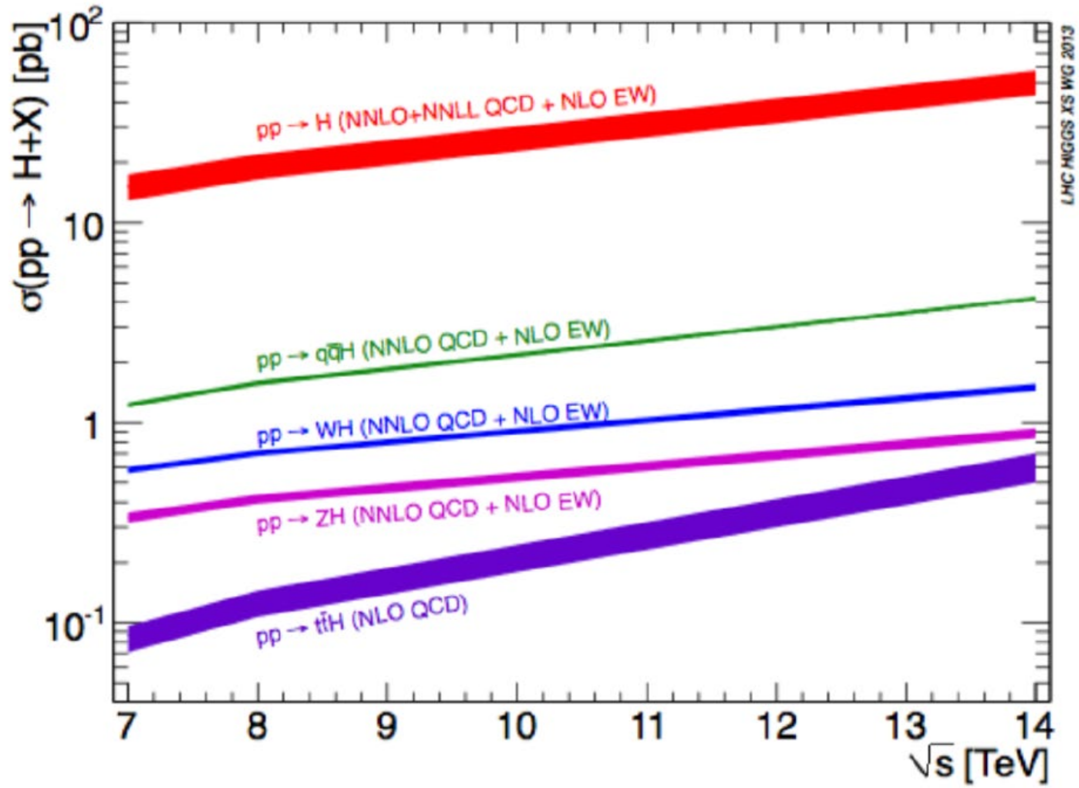
$$\sigma = \sum_{ij} \int dx_1 dx_2\ f_i(x_1, Q^2)\ f_j(x, Q^2)\ \hat{\sigma}(Q^2)$$

$\otimes$ Hadronization



Higgs production at LHC: pp @ 7 and 13.6 TeV

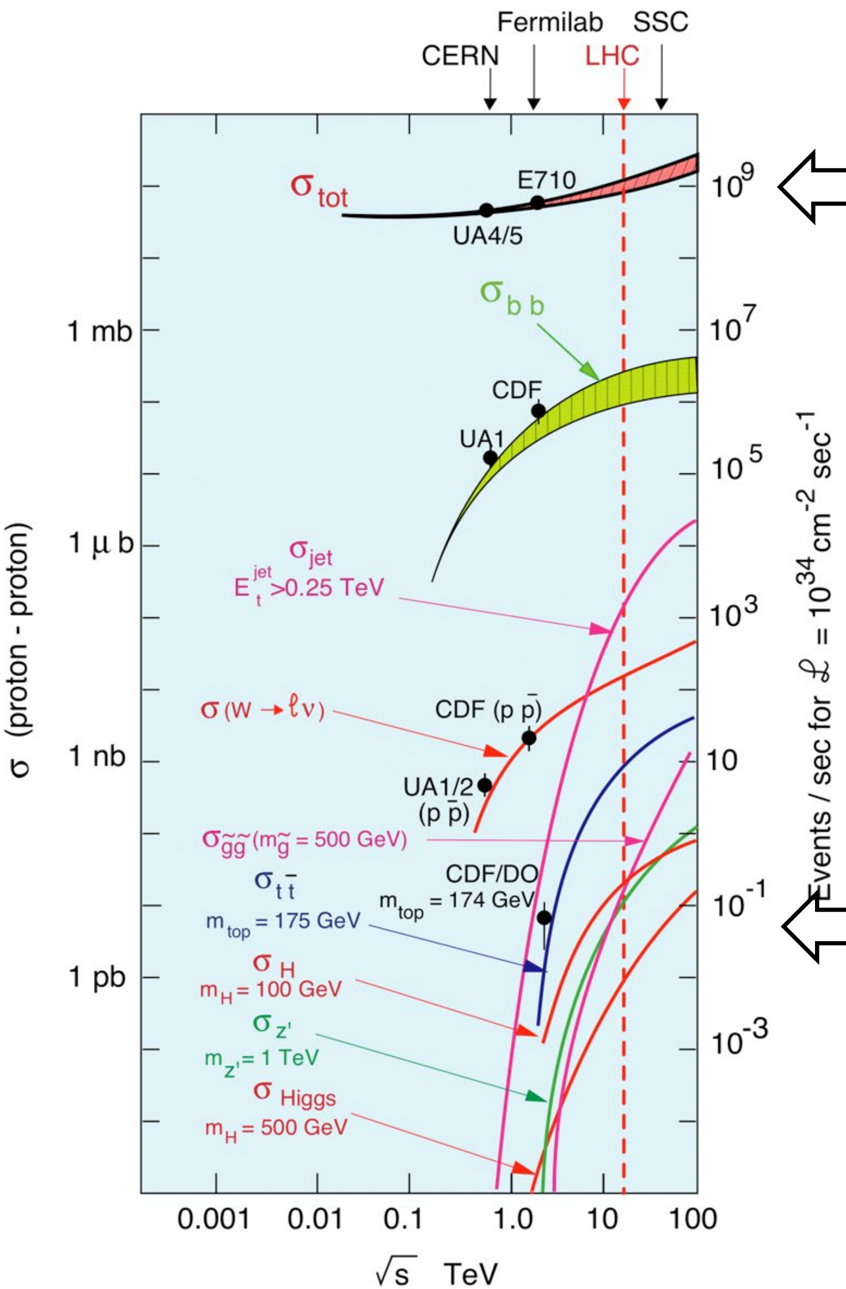




Strongest contribution from gluon-gluon fusion:

The other production processes can be important to search for Higgs decays with large background: associated signatures → background reduction

Higgs cross section in comparison



LHC luminosity: $>10^{34}\ \mathrm{cm^{-2}\,s^{-1}}$

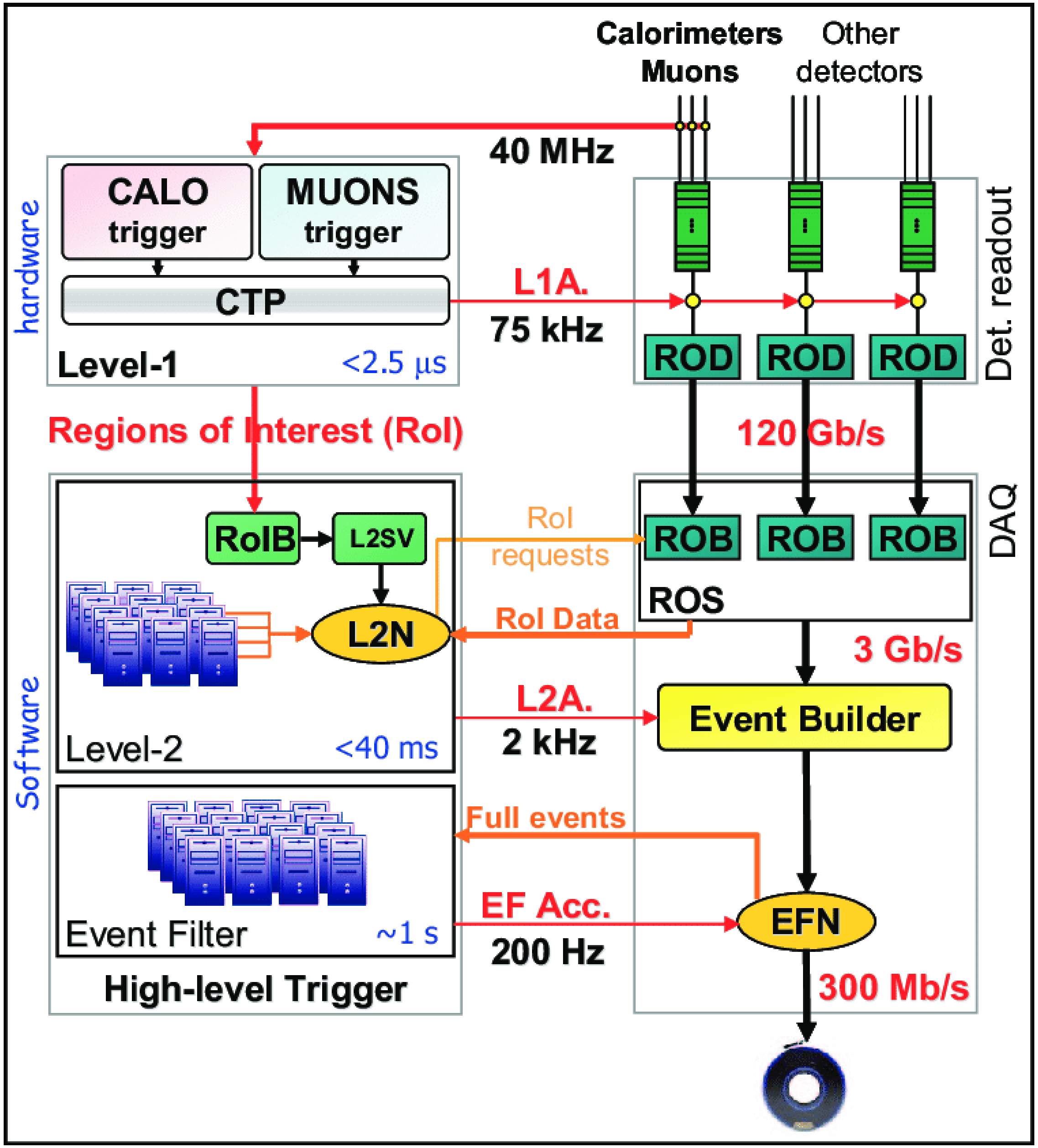
Total pp cross section ~ 100 mb
Interaction rate: 10^9 IA / sec
Events per bunch crossing: >35

$\times 10^{-10}$

Data reduction:
Trigger & event filter

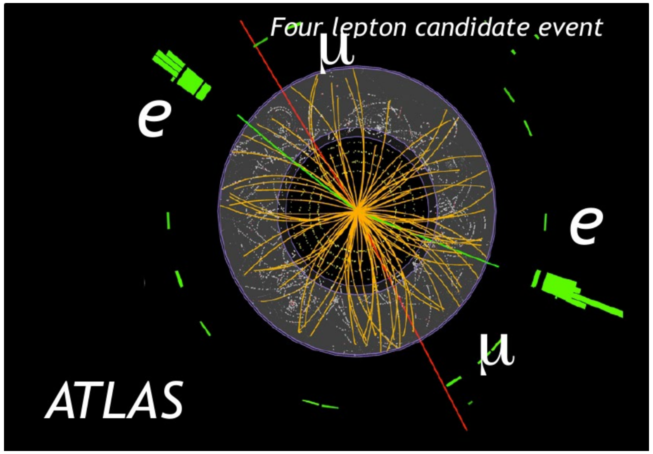
Higgs cross section ~ 10 pb
~ 1 Higgs pro 2min (produziert)

e.g.: ATLAS Trigger (Run 1)

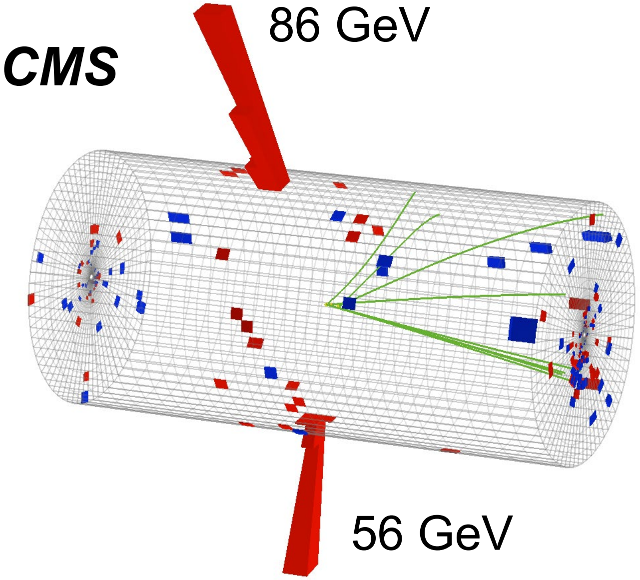


The "easy" Higgs decay channels

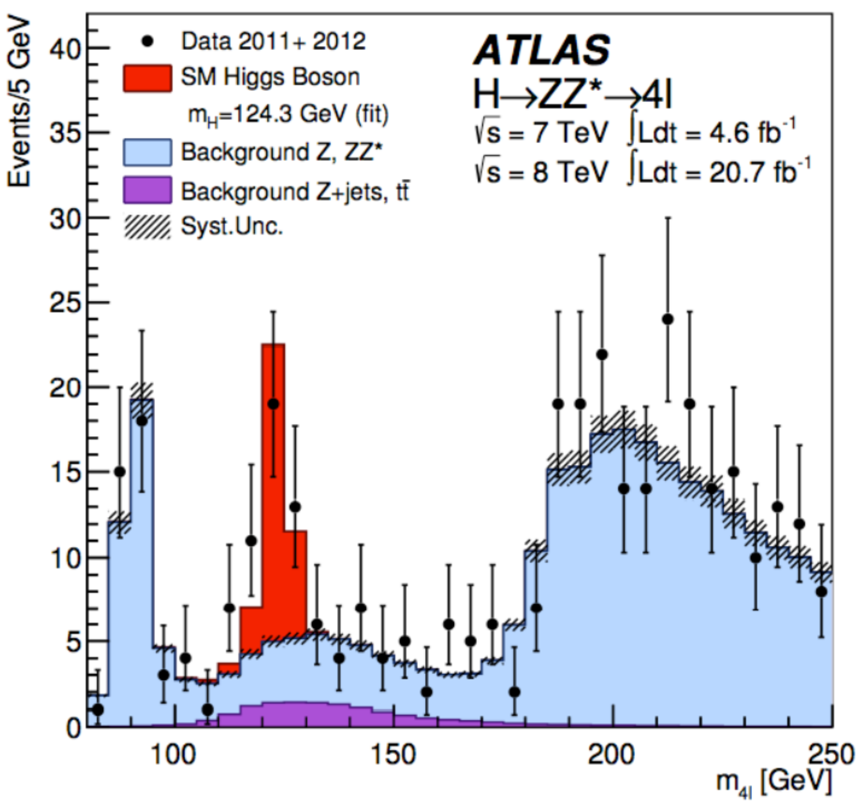
$$H \to ZZ^* \to 4\ell$$

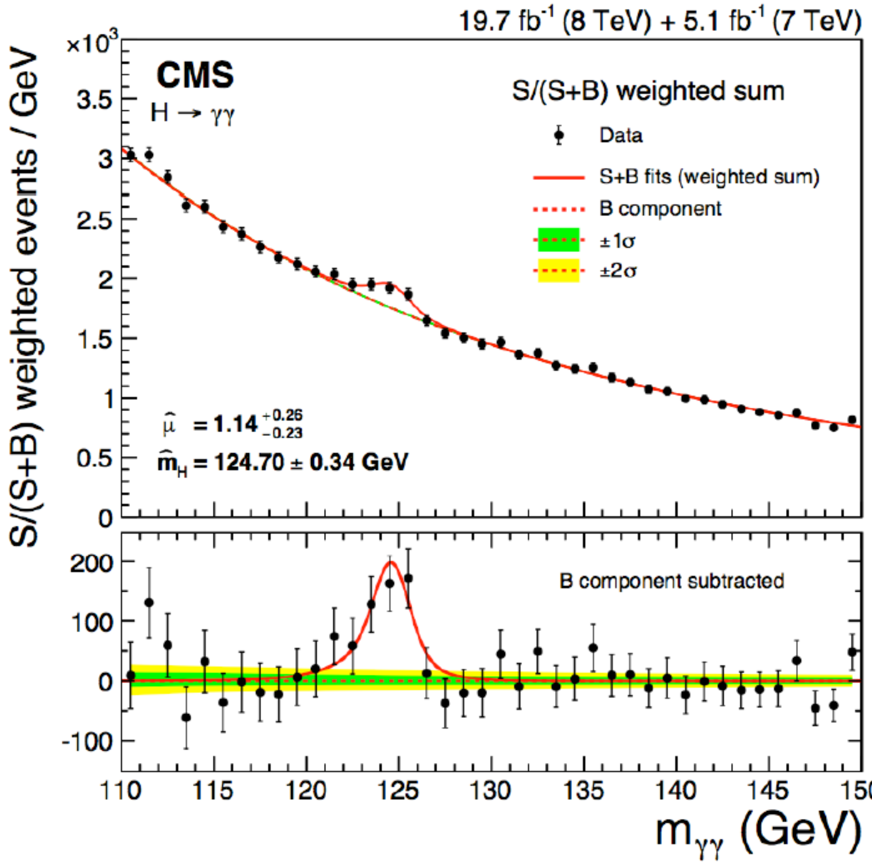


$$H \to \gamma\gamma$$

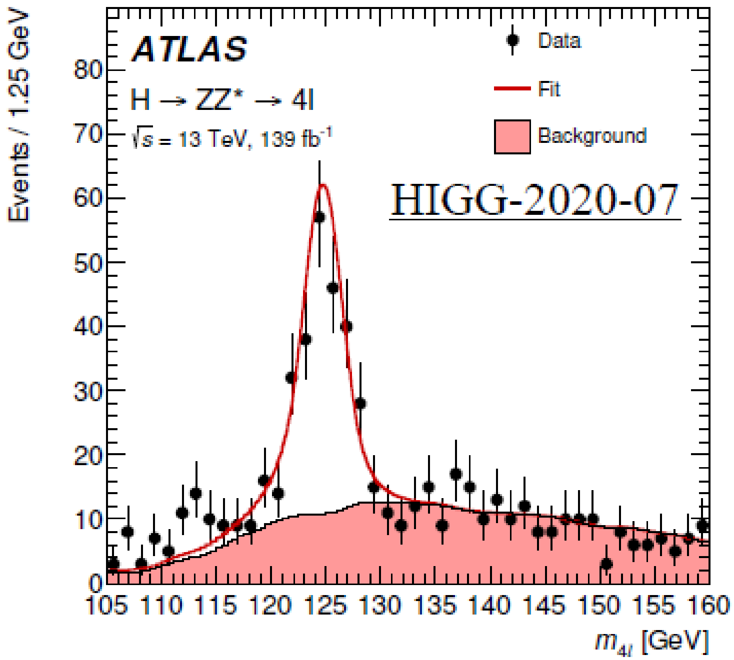


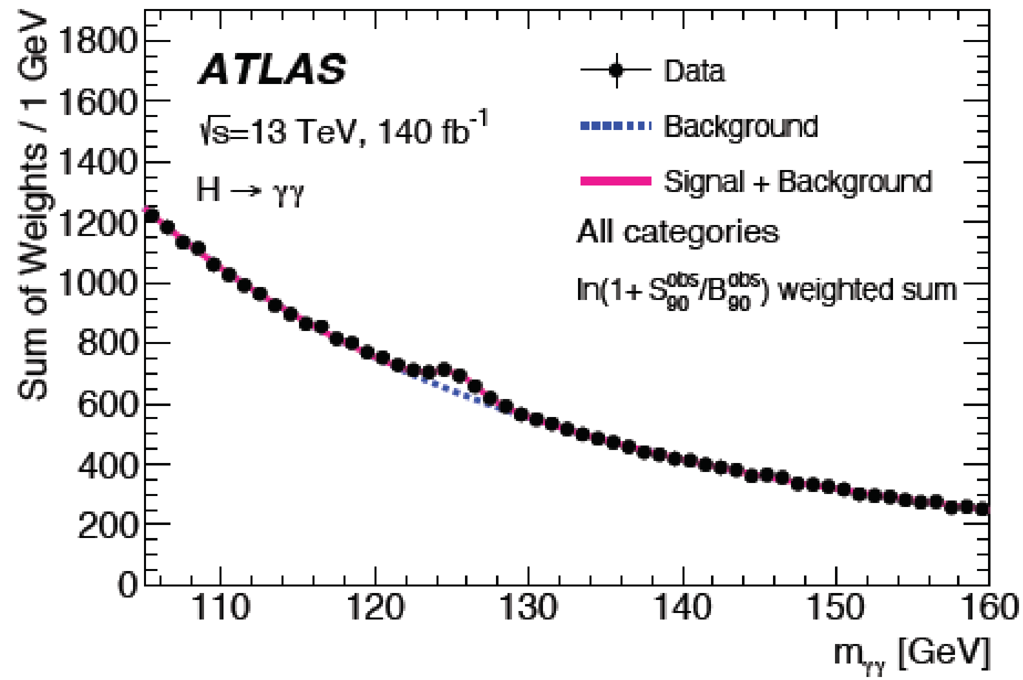
Higgs signals in 2012



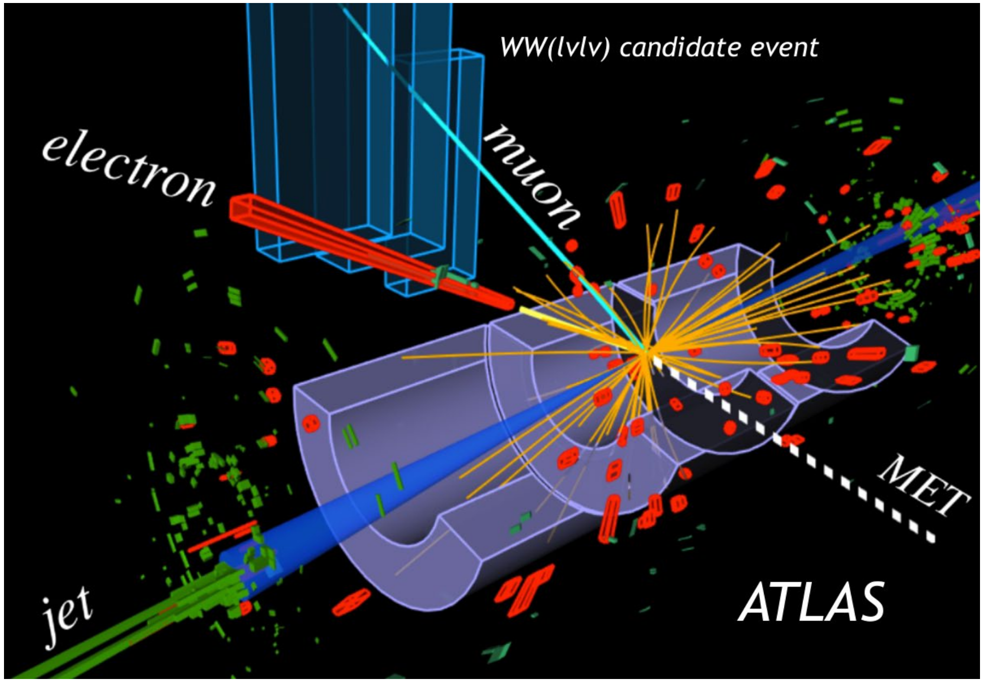


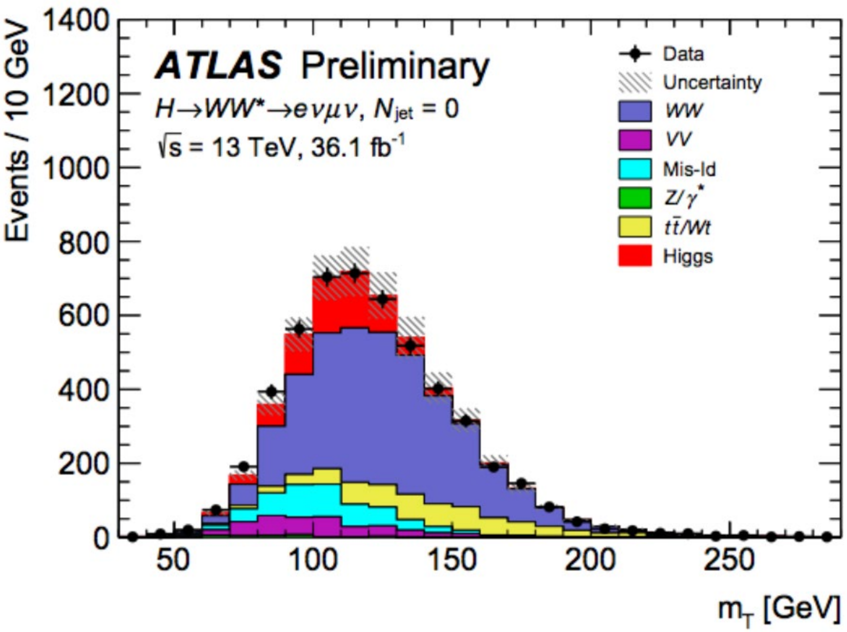
Higgs signals as presented in Moriond 2024

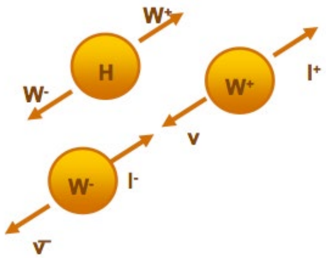




For discovery also important: H → WW → lν lν

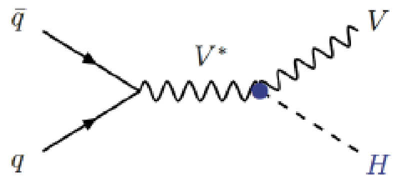




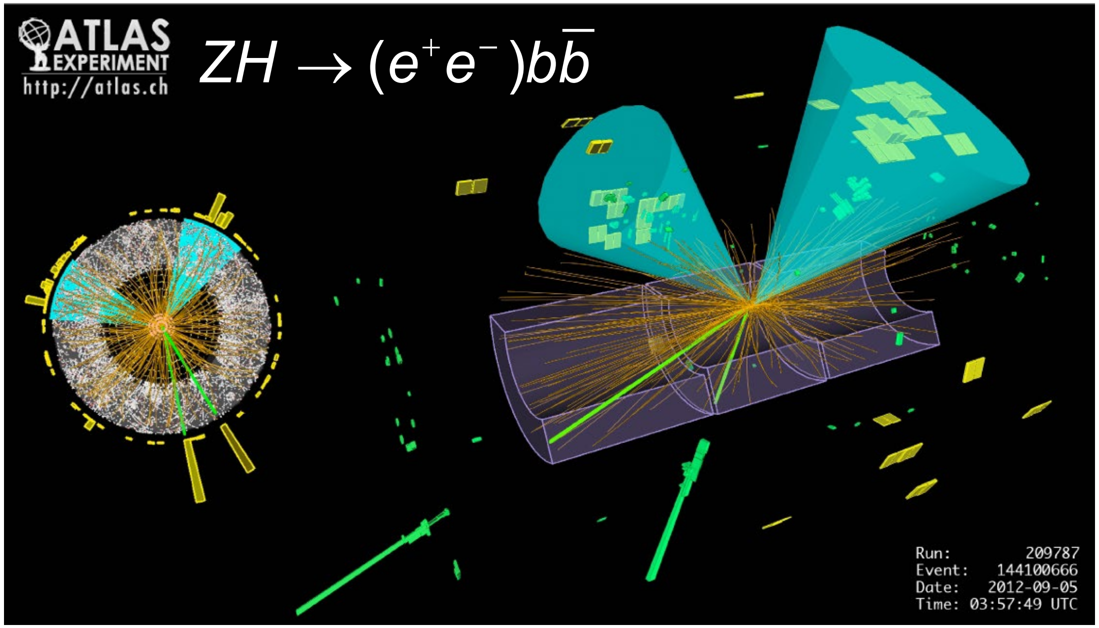


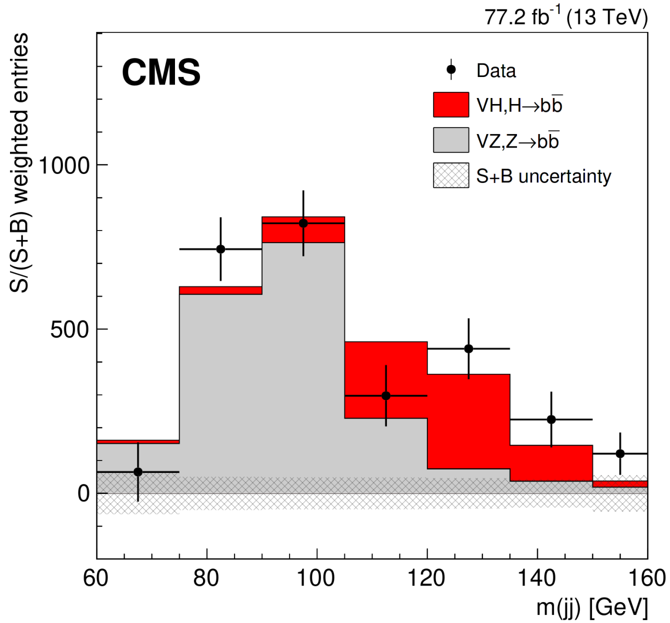
Huge background from pp→WW.
Interesting experimental detail to reduce backgrounds:
Higgs is a scalar → 2 leptons are very close.

H→bb: large signal but extremely large background



Use associated VH production:
Reconstruct V: W→lν, Z→ll, and Zνν
Use b-jet-tagging (displaced 2nd vertex)





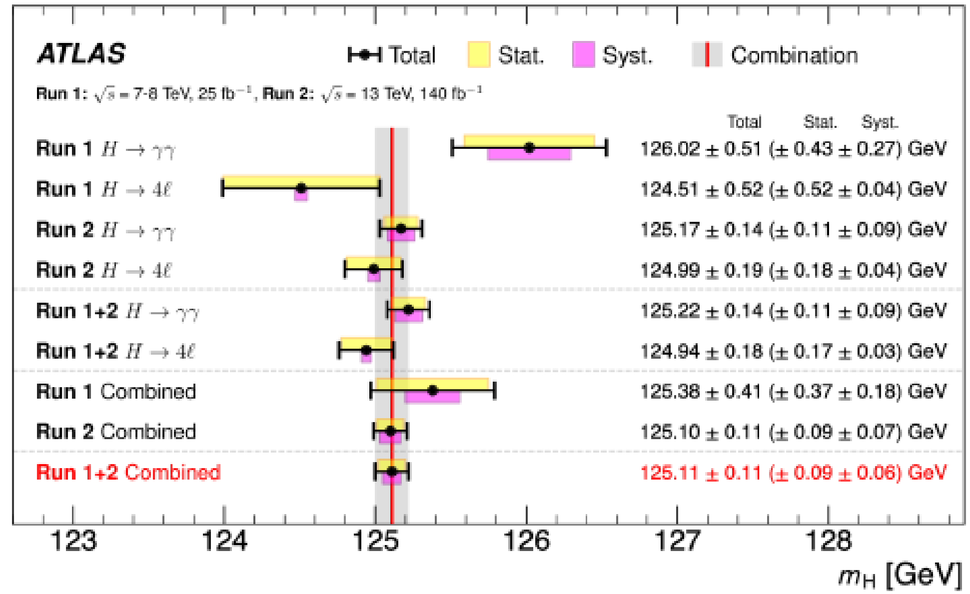
Higgs mass:

Reference: see J.-B. de Vivie, Moriond 2024

Resolution (%) of reconstructed Higgs mass:

$H \to ZZ \to 4l$	1-2
$H \to gg$	1-2
$H \to WW \to 2l2\nu$	20
$H \to$ tau tau	15
$H \to bb$	10

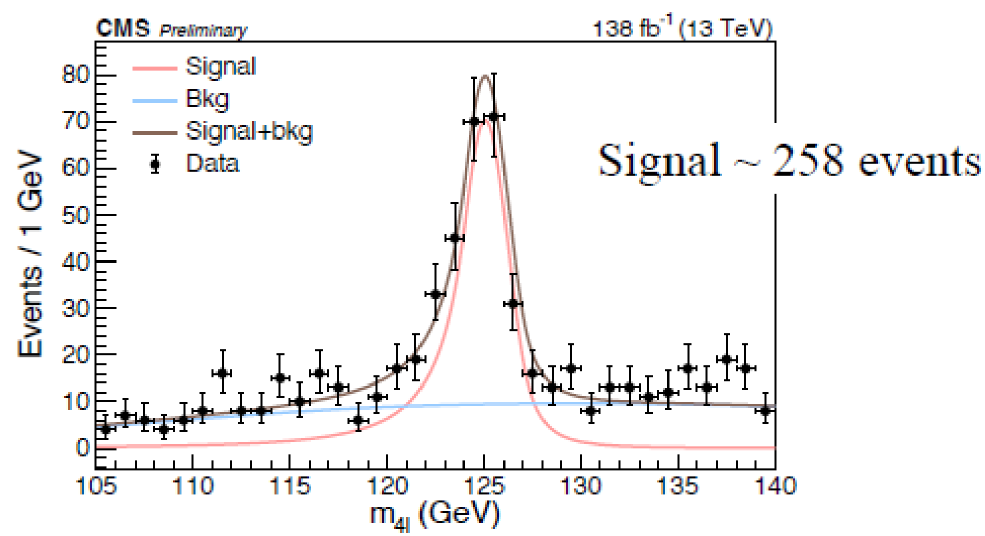
(taken from C. Paus)



Recent 4l measurement from CMS:

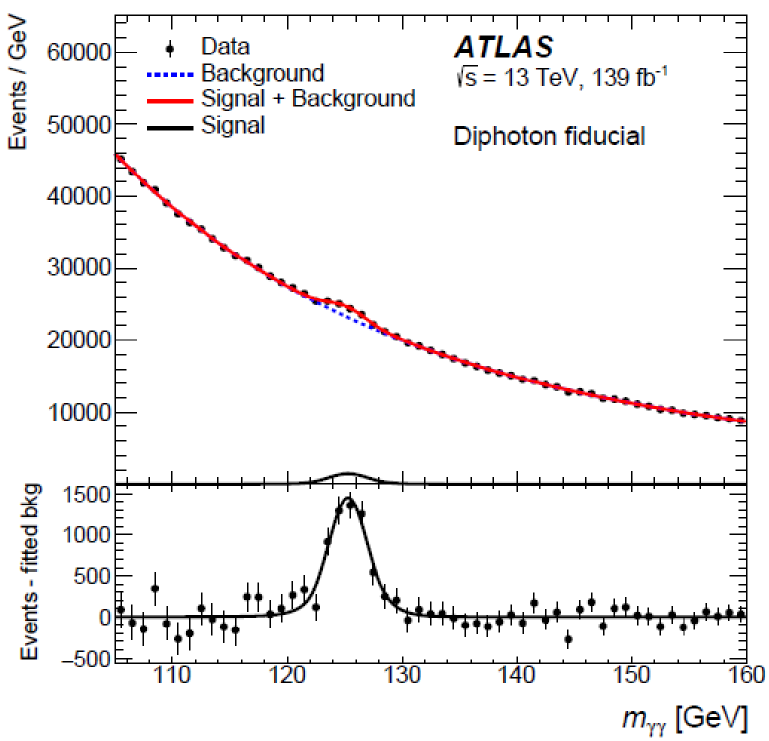
$m_H = 125.04 \pm 0.11_{stat} \pm 0.05_{syst}$ GeV

(most precise single measurement)

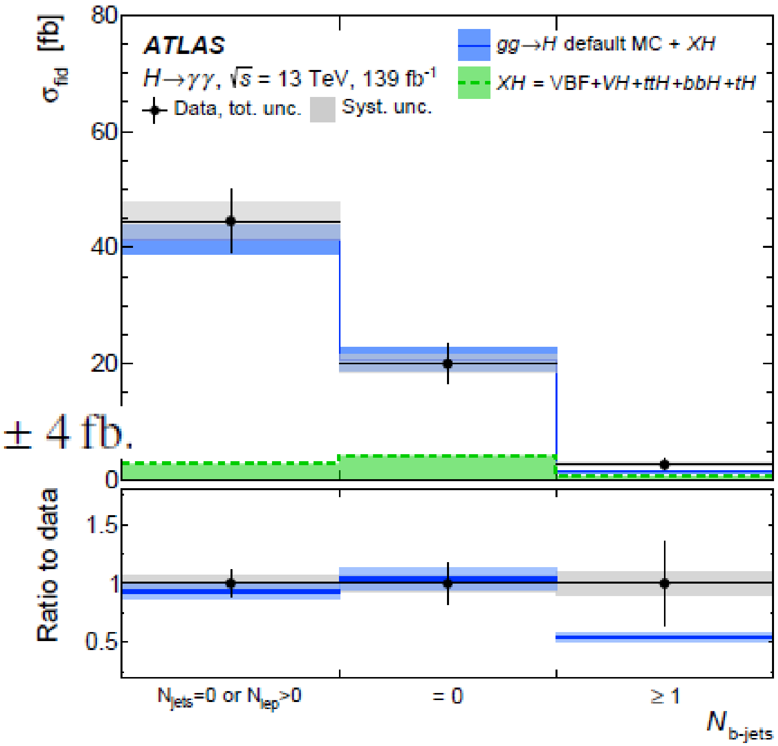


Higgs production cross section: H→γγ

ATLAS, 10.1007/JHEP08(2022)027



64 ± 4 fb.

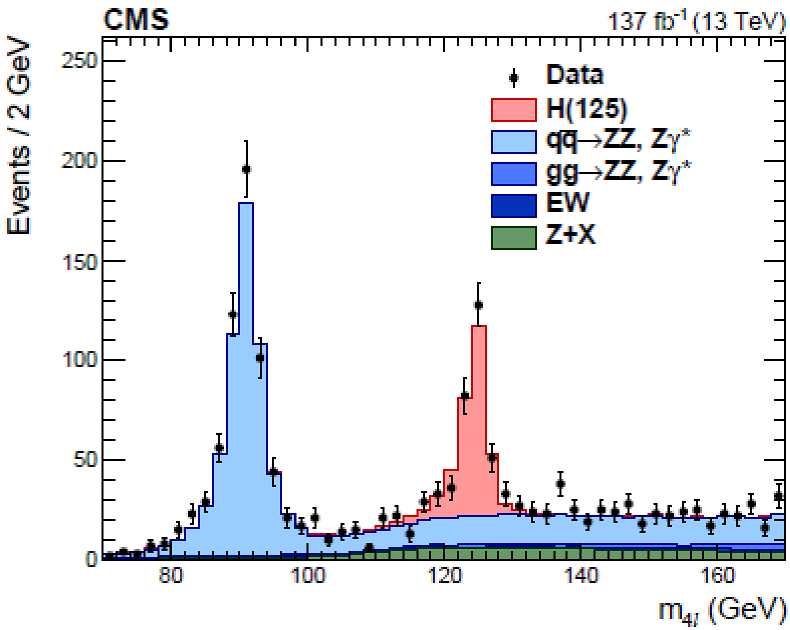


$\sigma_{\text{fid}} = 67 \pm 5\ (\text{stat.}) \pm 4\ (\text{sys.})\ \text{fb}$

SM: 64±5 fb

$$\sigma(pp \to H) = (58 \pm 4_{stat} \pm 4_{syst})\text{pb}$$
$$\sigma(pp \to H)_{SM} = (55.6 \pm 2.7)\text{pb}$$

Higgs production cross section pp→H→ZZ→4l



CMS, arXiv:2103.04956v

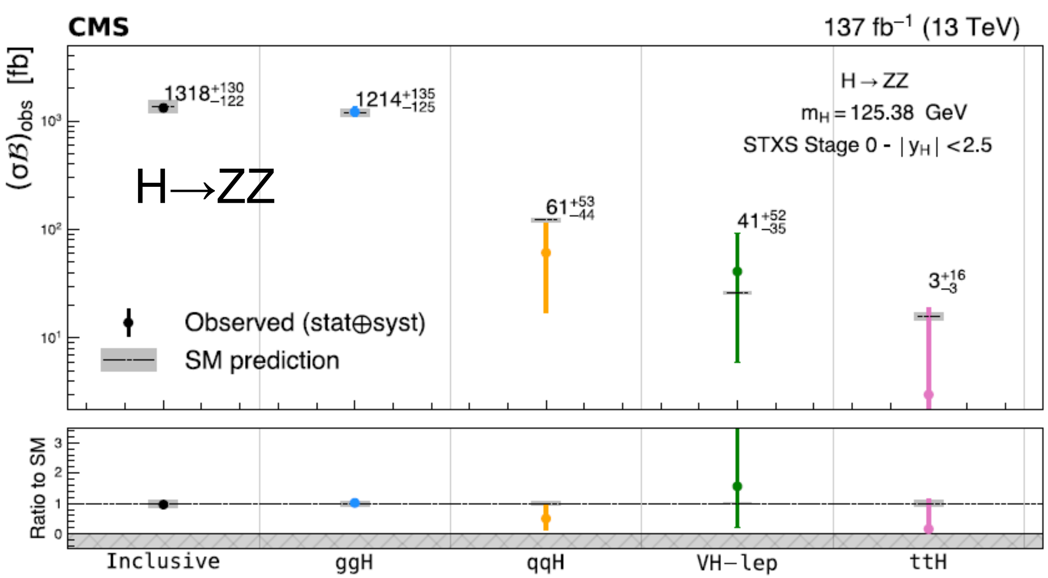
$$\sigma_{\rm fid} = 2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}\,(\text{stat})^{+0.26}_{-0.21}\,(\text{syst})\ \text{fb}$$

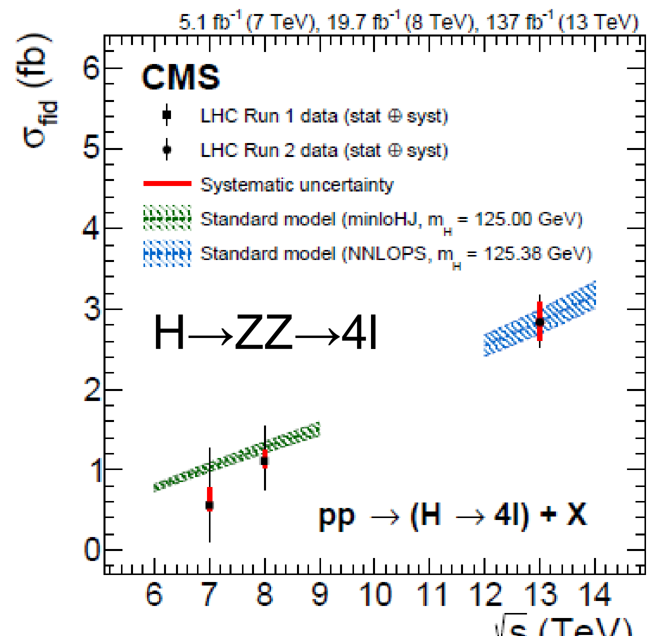
$$\sigma^{\rm SM}_{\rm fid} = 2.84 \pm 0.15\ \text{fb}.$$

U.Uwer

$$\sigma(pp \to H) = (52.3 \pm 6.7)\,\text{pb}$$

$$\sigma(pp \to H)_{SM} = (55.6 \pm 2.7)\,\text{pb}$$





Measurement of Higgs total widths Γ_H

Direct measurement difficult because of experimental errors of many contributions. Also need assumptions on invisible decay witdhs Γ_{inv}..

→ Instead study "off-shell" Higgs production, i.e.

$$\frac{d\sigma(i \to H^{(*)} \to f)}{d\hat{s}} \sim \underbrace{\frac{g_i^2 g_f^2}{(\hat{s} - m_H^2) + m_H^2 \Gamma_H^2}} \quad \text{with} \quad \hat{s} \gg m_H$$

Breit-Wigner Resonanz

Higgs cross section "on-shell"

$$\sigma(i \to H^{(*)} \to f) \sim \frac{g_i^2 g_f^2}{\Gamma_H} \sim \mu_{on}$$

Higgs cross section "off-shell", i.e. $\hat{s} \gg m_H$

$$\sigma(i \to H^{(*)} \to f) \sim g_i^2 g_f^2 \sim \mu_{on} \Gamma_{Higgs}$$

Often used parameter: production strength

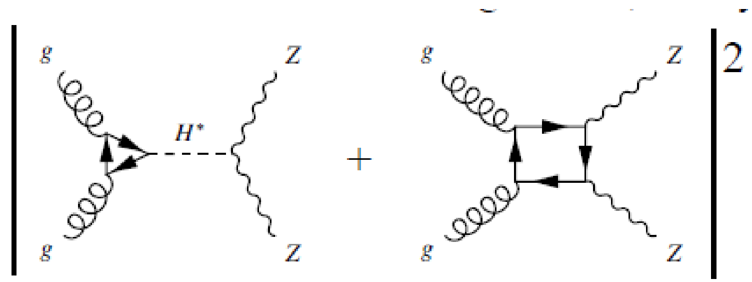
$$\mu_{on,off} = \frac{\sigma(i \to H^{(*)} \to f)}{\sigma(i \to H^{(*)} \to f)_{SM}}$$

Measurement of on- and off-shell contribution allows determination of Γ_{higss}

Studied Higgs decay: Vector boson pair production $H \to ZZ$

But: in addition to Higgs amplitudes, there are electroweak background processes which need to be considered, e.g.

$gg \to ZZ$:

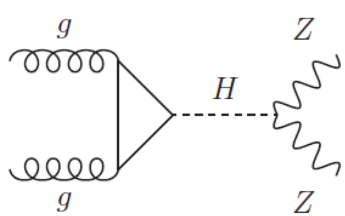


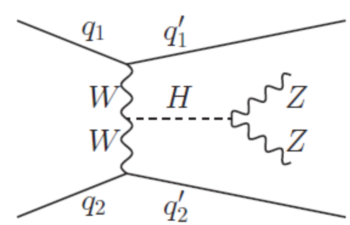
H^2 + interference + C^2

Experimentally studies Z-decays: (1) $ZZ \to \ell^+\ell^-\ell^+\ell^-$

(2) $ZZ \to \ell^+\ell^-\nu\bar{\nu}$

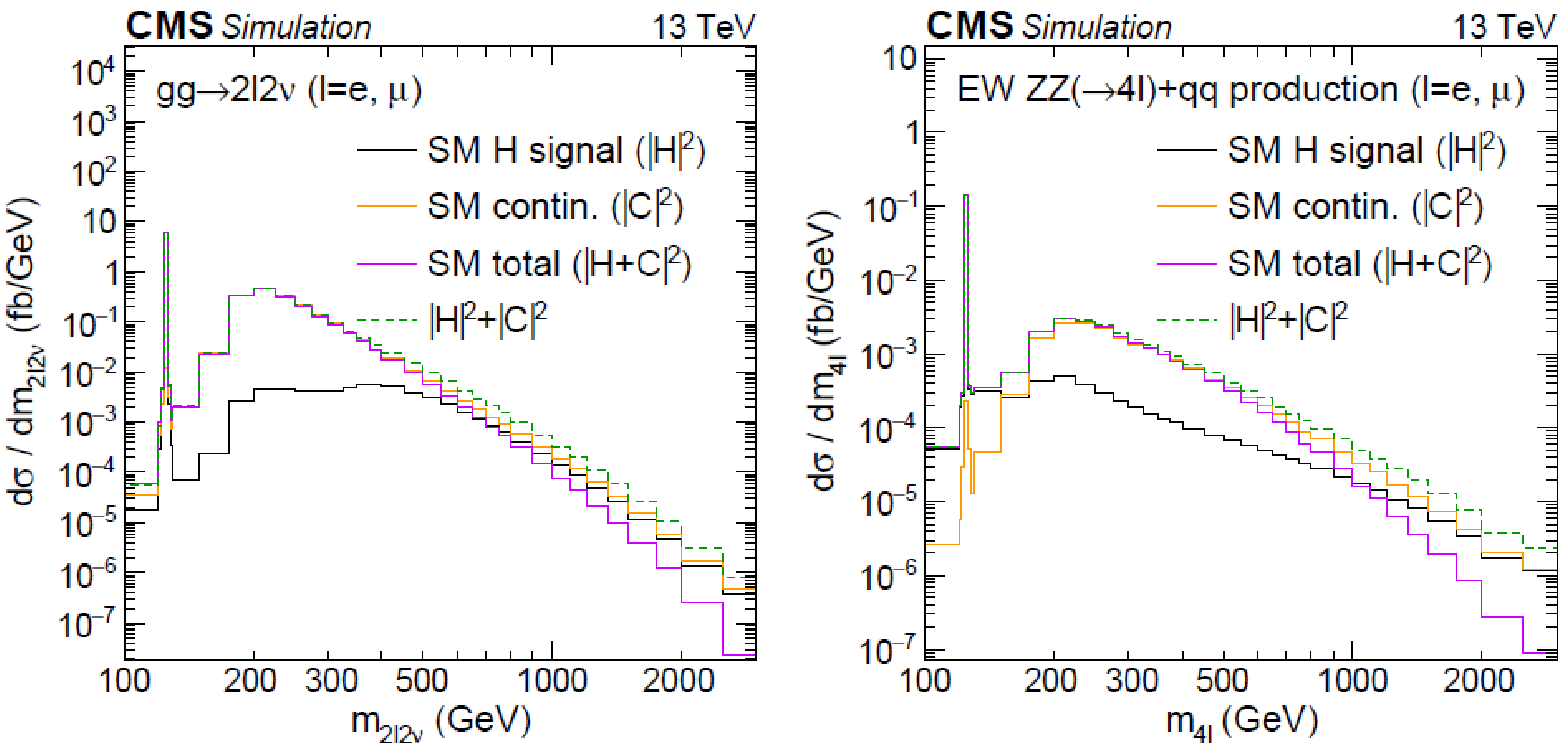
Additional complication: Beside gluon fusion there is also vector boson fusion.





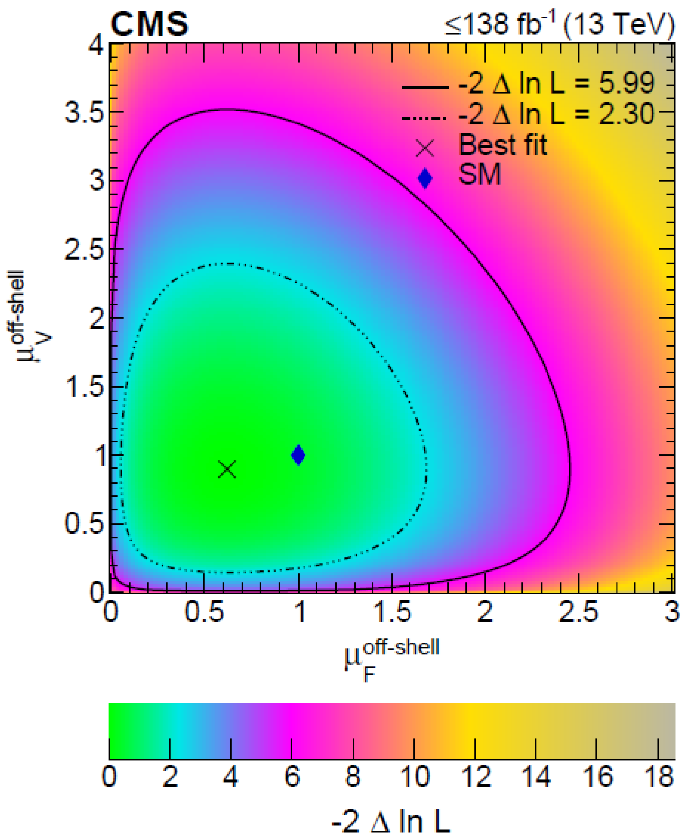
Theoretical predictions:

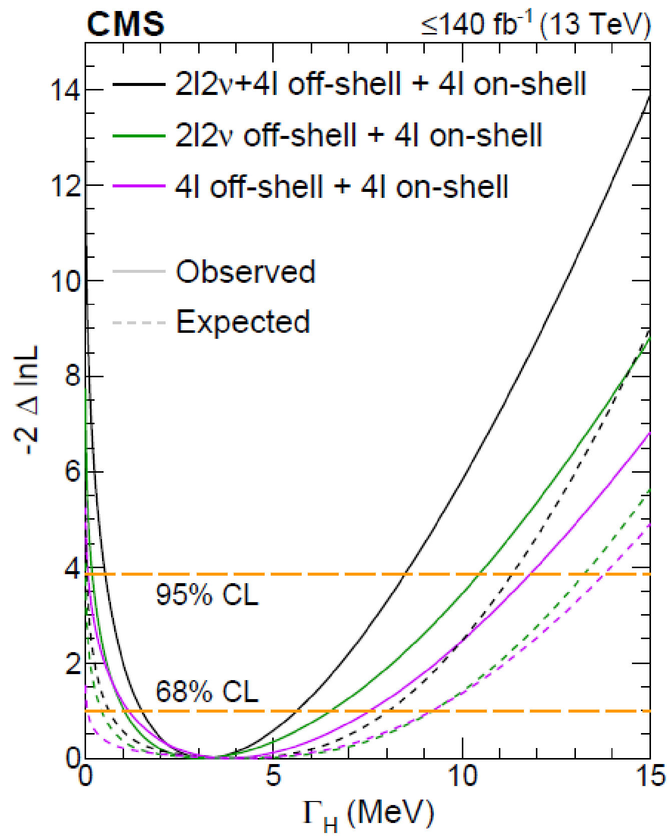
CMS; Nature Physics 2022, arXiv:2202.06923



Extraction of Γ_{Higgs}

CMS; Nature Physics 2022, arXiv:2202.06923





CMS 2023: $\Gamma = 2.9\ ^{+1.9}_{-1.4}$ MeV

ATLAS 2018: $\Gamma = 4.5^{+3.0}_{-2.5}$ MeV

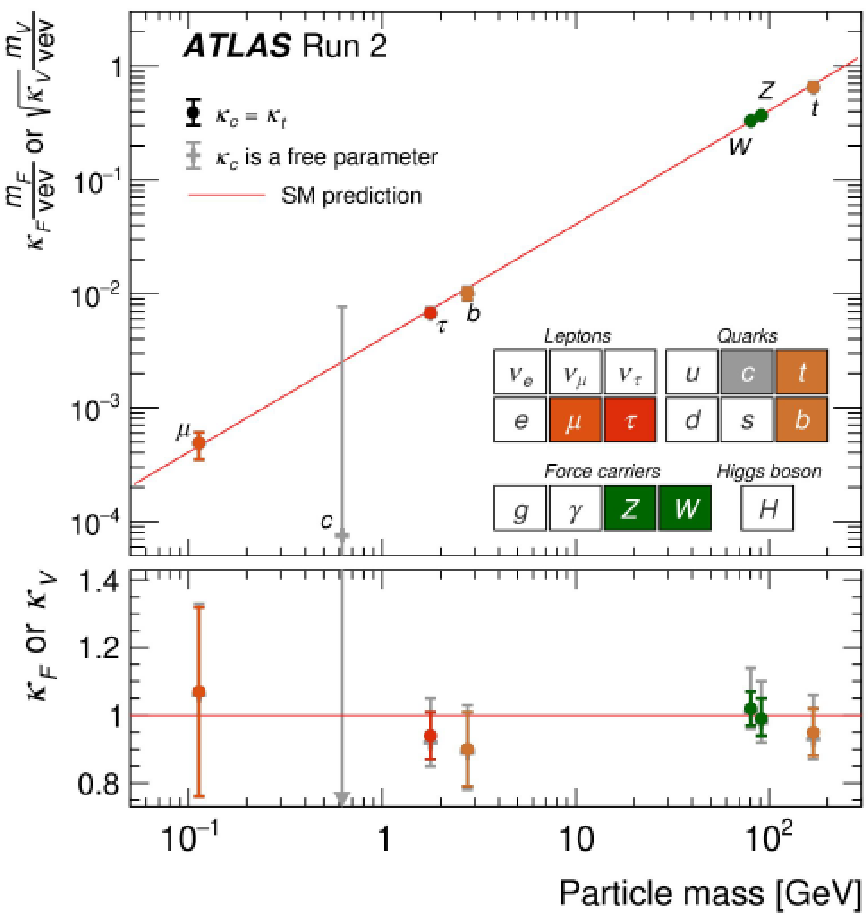
Constraints from Higgs production on 4th generation:

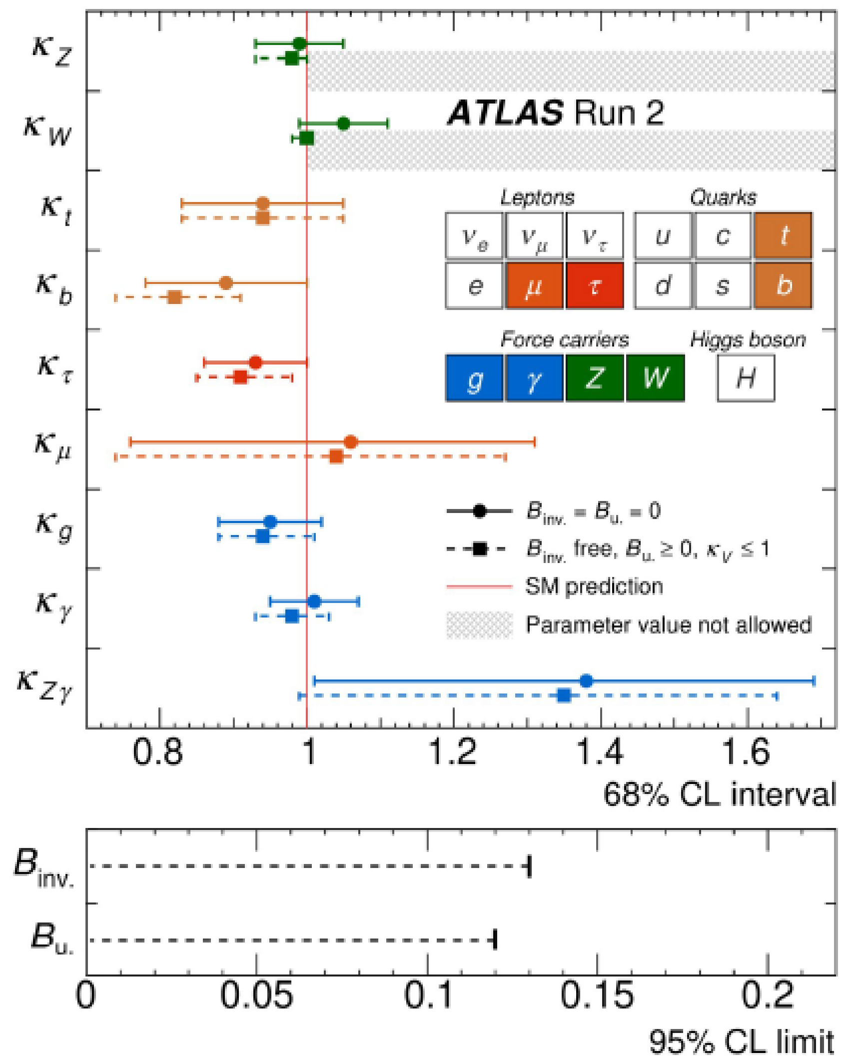
Presence of additional heavy quarks will increase the effective ggH coupling by a large factor, i.e. we would expect an enhanced Higgs production rate at the LHC w/r to the Standard Model rate.

Observed Higgs rate excludes the existence of a heavy 4th generation of quarks. Cancellation of triangle anomalies requires the same number of lepton and quark families:

Higgs results establish the existence of only four sequential generations of fermion.

Higgs Couplings to Fermions and Bosons





e.g. H → μμ coupling

Measurement of Higgs couplings to light Fermions is most difficult.

Categorization based on special selection for each production mode: CMS used Neural Network to enhance signal / background ratio.

CMS:

Signal strength H→μμ

$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat.})\ ^{+0.15}_{-0.14}(\text{syst.})$$

Branching fraction:

$0.8 \times 10^{-4} < BR(H\to\mu\mu) < 4.5 \times 10^{-4}$ (95%CL)

SM BR = 2.18×10^{-4}

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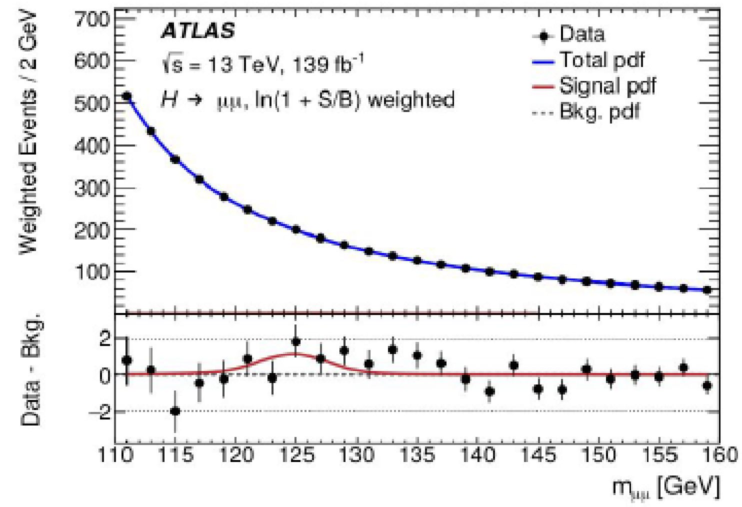

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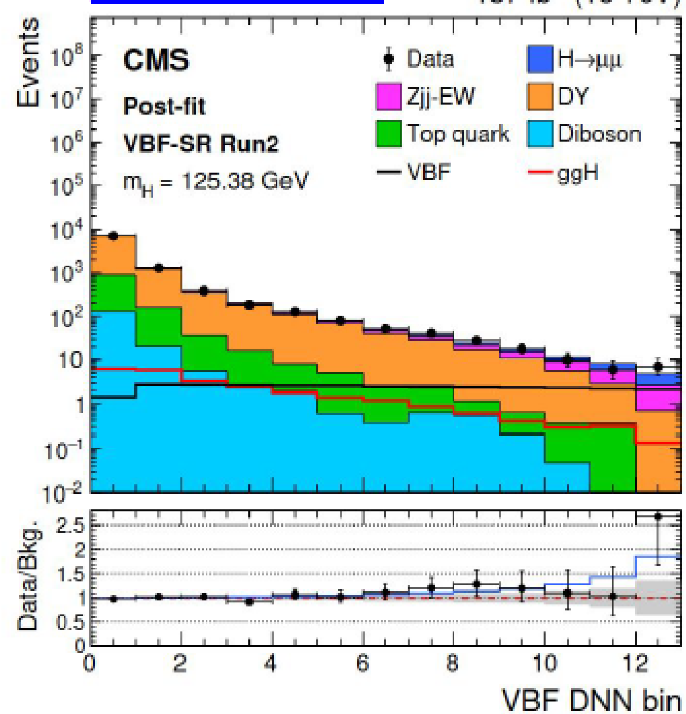
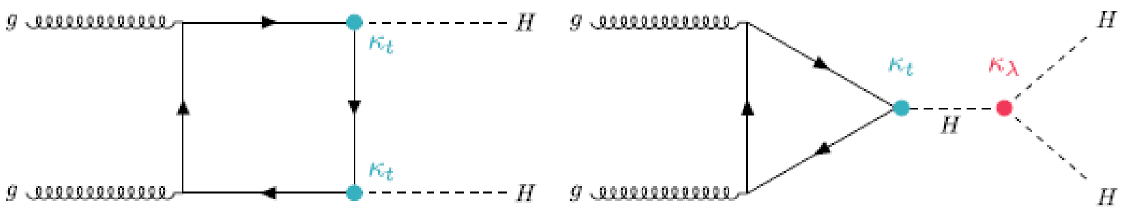


Triple Higgs Coupling and Double Higgs Production

Higgs self coupling relevant for the form of Higgs potential:

$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 \qquad \lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} = \frac{m_h^2}{2v^2} \qquad \kappa_\lambda = \lambda_3 / \lambda_{3,SM}$$

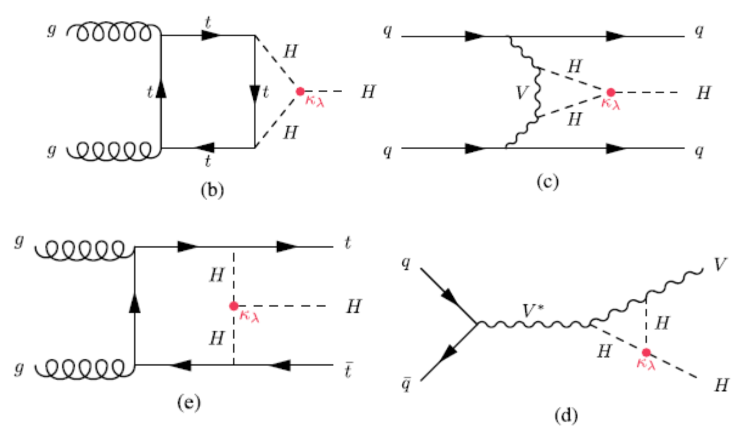
Triple Higgs coupling can be tested in double Higgs production:



Beside the gluon fusion contribution also contributions from associated production.

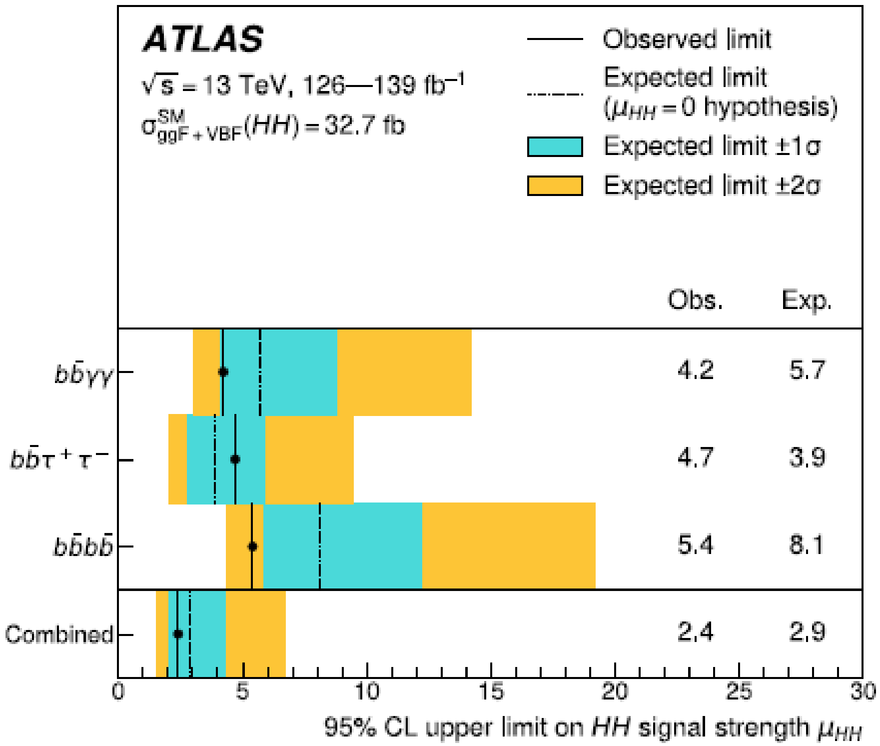
The following HH final-states are considered: bbbb, bb$\tau\tau$, bbWW, $\gamma\gamma$bb, $\gamma\gamma\gamma$WW, and WWWW, where bbbb has largest branching fraction

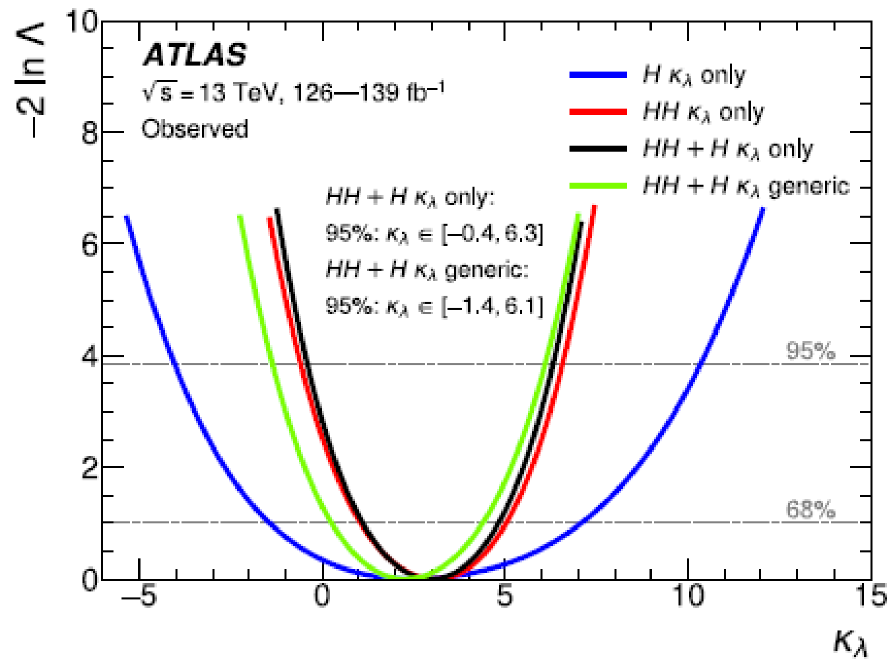
However, through loop corrections there is also dependency of the single Higgs production on the triple Higgs vertex:



ATLAS results on triple Higgs couplings

ATLAS, Physics Letters B 843 (2023) 137745





Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Hardly any sensitivity yet.

Triple Higgs Coupling at High-Lumi LHC

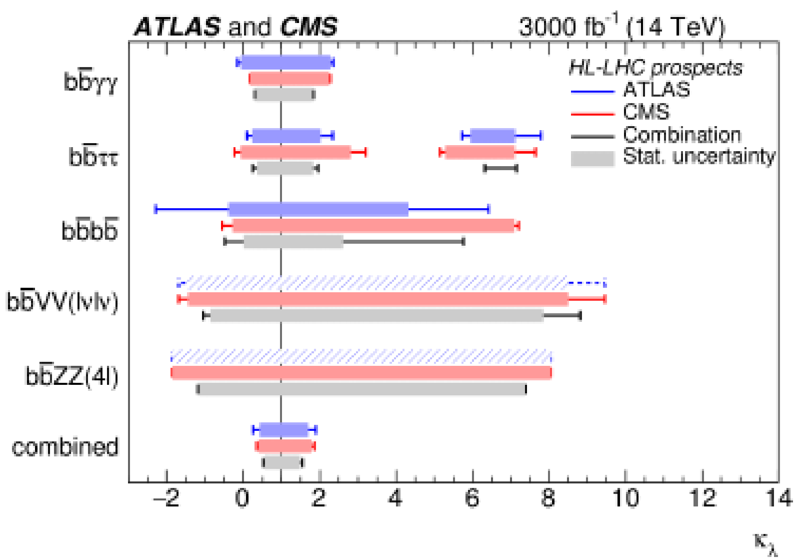
3000 fb^{-1} (Run 1+2: ~190 fb^{-1})

Oberservation of double Higgs productuion

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

Significance in "standard deviations"

Hoping for some analysis improvements an observation seems possible



Expected error at 68% CL:
$0.57 < \kappa_\lambda < 1{:}5$

Higgs factory (FCCee) discussed to improve H coupling measurements.