Karlsruhe Institute of Technology

Particle Physics 1

Lecture 12: Higgs

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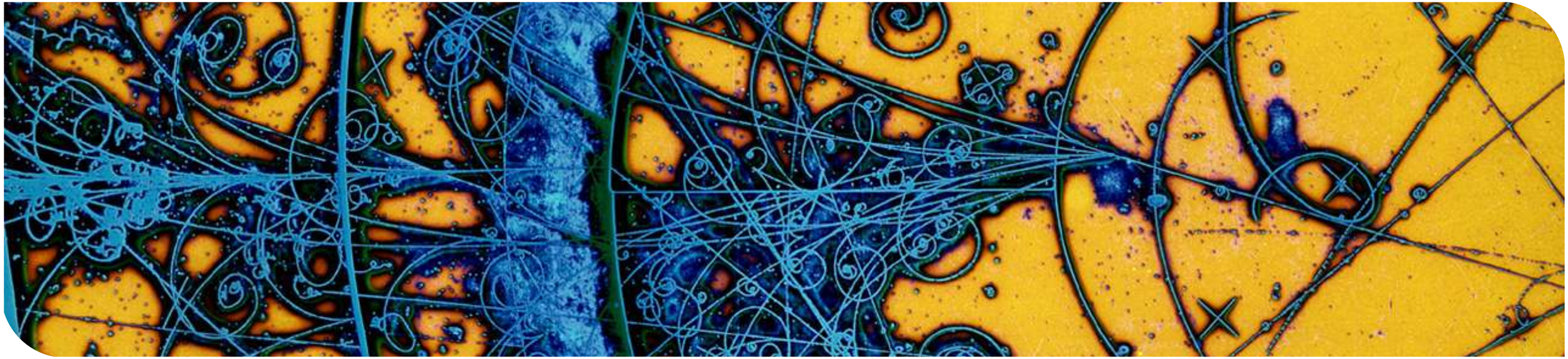
Winter 2024/2025



Credit: CERN

Recap: Higgs Mechanism

- $\mathcal{L}_{SM}$ should retain all gauge symmetries: add Higgs field ϕ as **left-chiral weak-isospin doublet of two complex fields**

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

- Lagrangian for the Higgs field

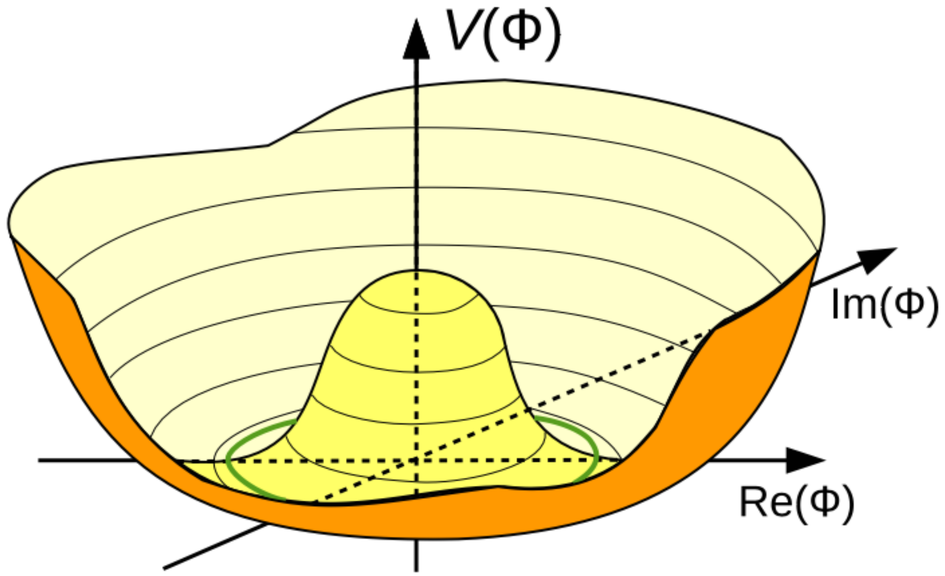
$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi^\dagger)(\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

with $\mu^2 < 0$ (SSB!)

- The Standard-Model Lagrangian becomes

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{CC} + \mathcal{L}_{NC} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$



Recap: Higgs Mechanism

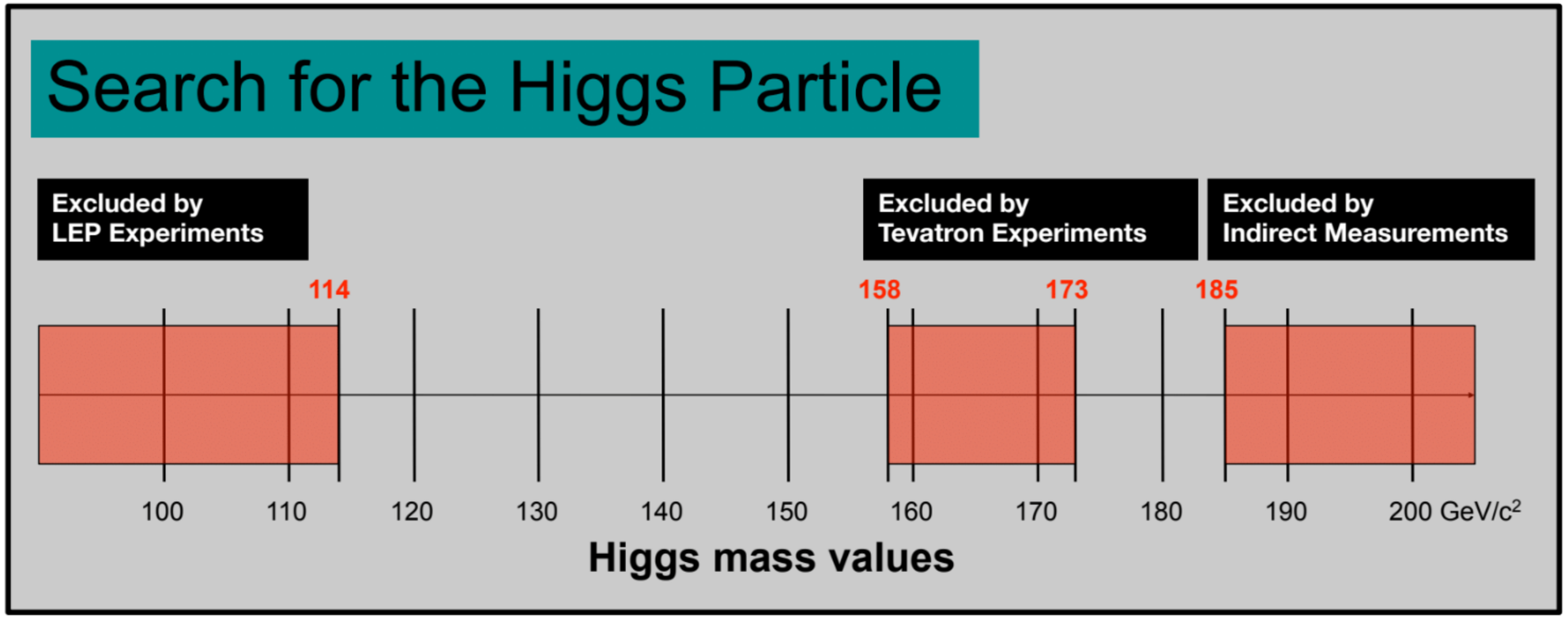
- Adding ϕ as $SU(2)_L$ doublet with specific non-zero ground-state

$$\begin{aligned}\mathcal{L}_{\text{Higgs}} = &\tfrac{1}{2}\left(\partial_\mu \mathrm{H}\right)\left(\partial^\mu \mathrm{H}\right) - \lambda v^2 \mathrm{H}^2 + \lambda v \mathrm{H}^3 - \tfrac{1}{4}\lambda \mathrm{H}^4 \\ &+ \tfrac{1}{2} m_{\mathrm{Z}}^2 \mathrm{Z}_\mu \mathrm{Z}^\mu + \frac{m_{\mathrm{Z}}^2}{v} \mathrm{H} \mathrm{Z}_\mu \mathrm{Z}^\mu + \tfrac{1}{2}\frac{m_{\mathrm{Z}}^2}{v^2} \mathrm{H}^2 \mathrm{Z}_\mu \mathrm{Z}^\mu \\ &+ m_{\mathrm{W}}^2 \mathrm{W}_\mu^+ \mathrm{W}^{-,\mu} + 2\frac{m_{\mathrm{W}}^2}{v} \mathrm{H} \mathrm{W}_\mu^+ \mathrm{W}^{-,\mu} + \frac{m_{\mathrm{W}}^2}{v^2} \mathrm{H}^2 \mathrm{W}_\mu^+ \mathrm{W}^{-,\mu}\end{aligned}$$

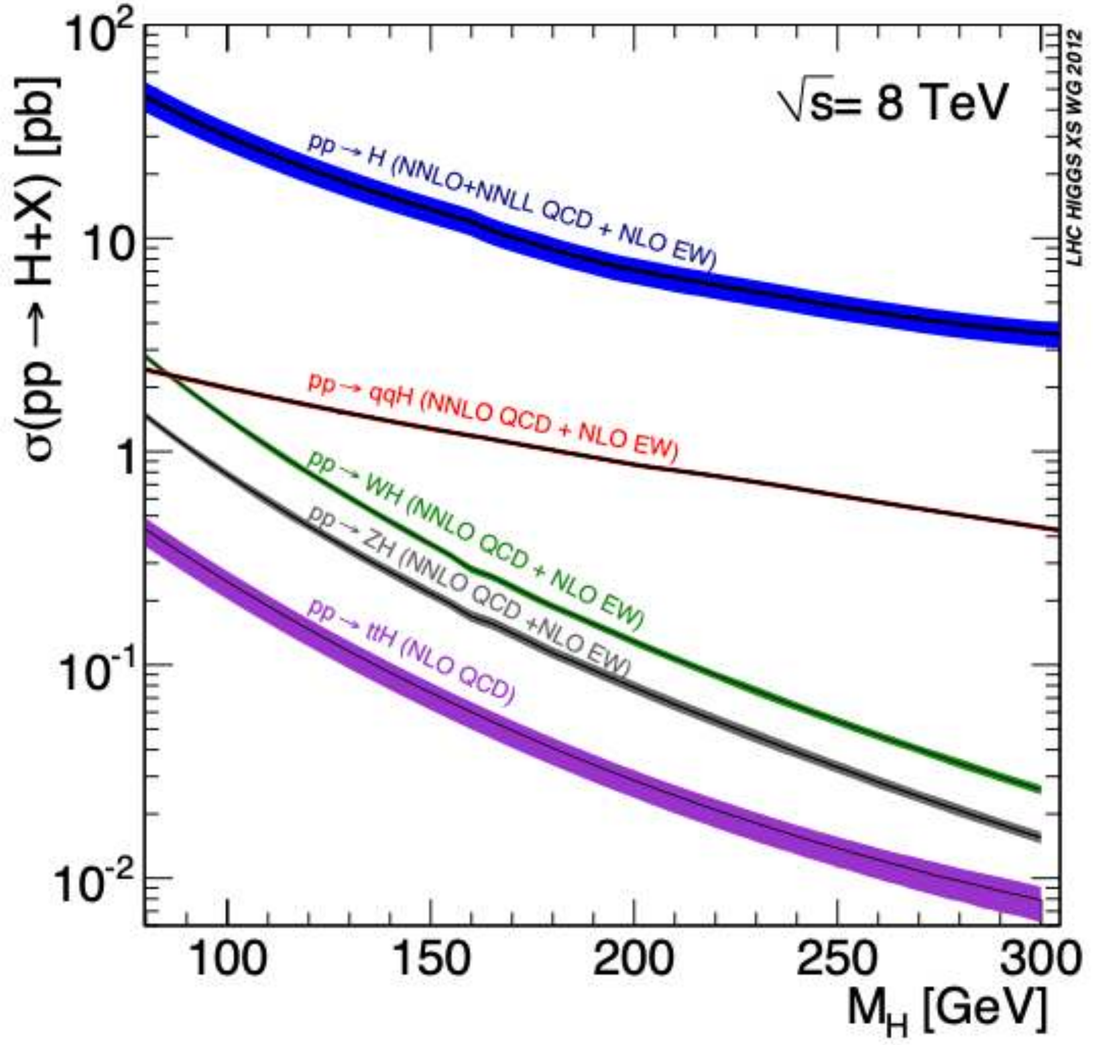
- Masses (mass terms) for the gauge bosons $\mathrm{W}^\pm$ and Z

w/o ϕ-W/Z interaction: d.o.f.		with ϕ-W/Z interaction: d.o.f.	
4 massless vector fields W^a, B:	8	3 massive vector fields $\mathrm{W}^\pm$, Z:	9
2 complex Higgs fields:	4	1 massless vector field A:	2
		1 massive scalar:	1
total number d.o.f.:	12	total number d.o.f.:	12

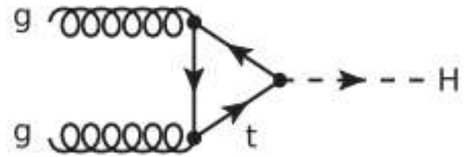
Status of Higgs Searches before the LHC



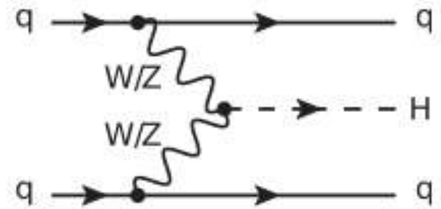
Higgs production at the LHC



Gluon-Gluon Fusion

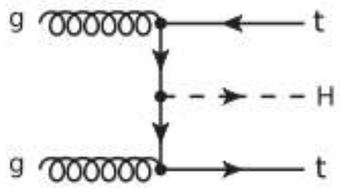


Vector Boson Fusion

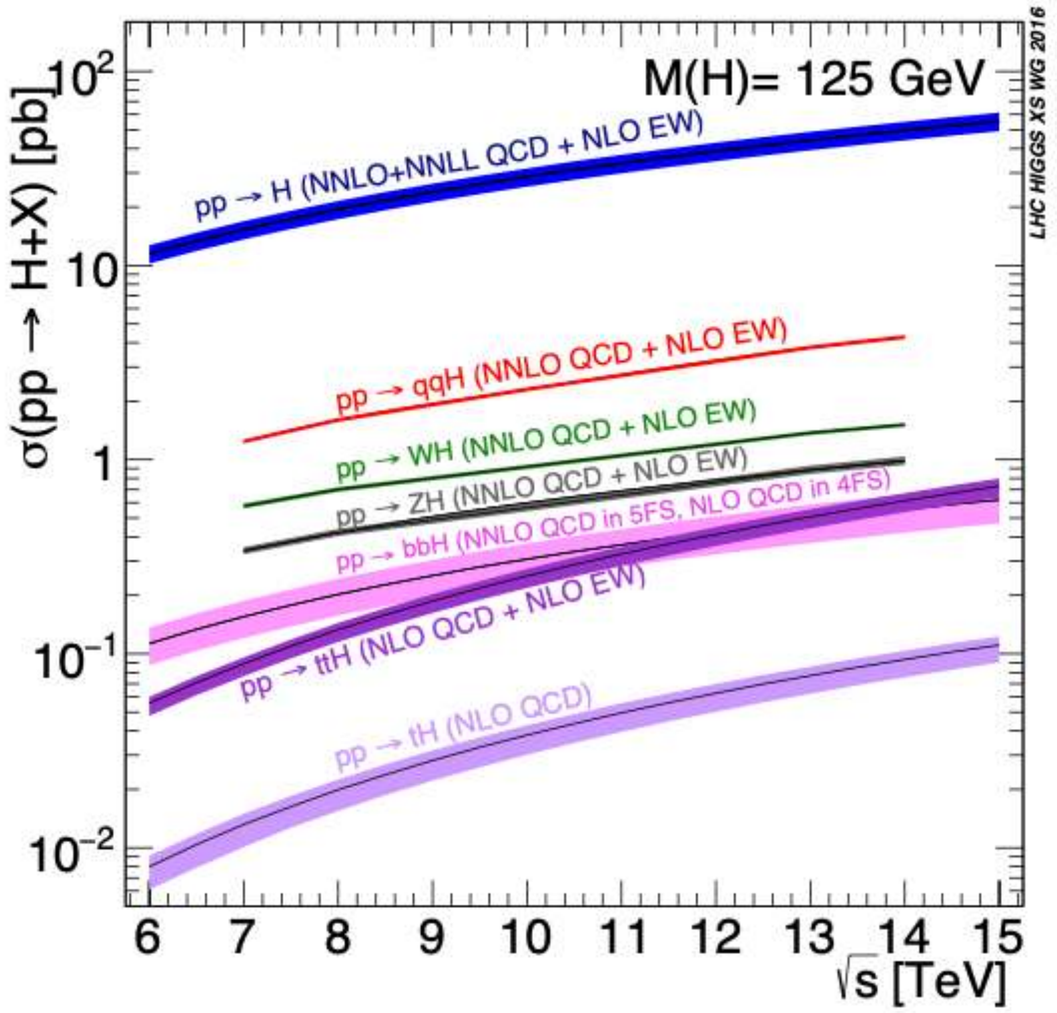


Associated Production with W and Z

Associated Production with t



Higgs production at the LHC



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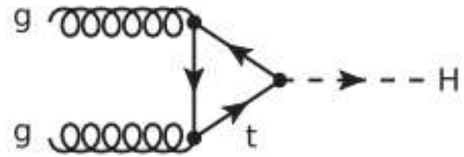

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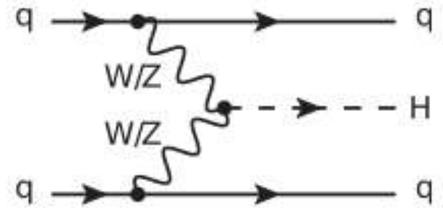

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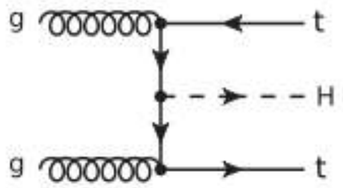
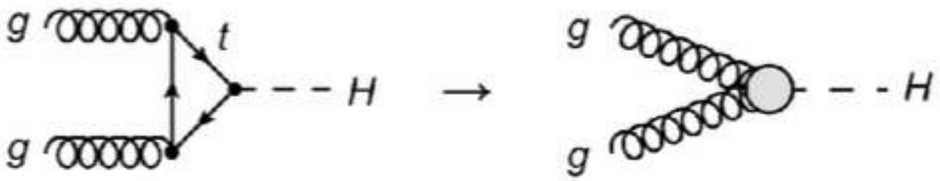
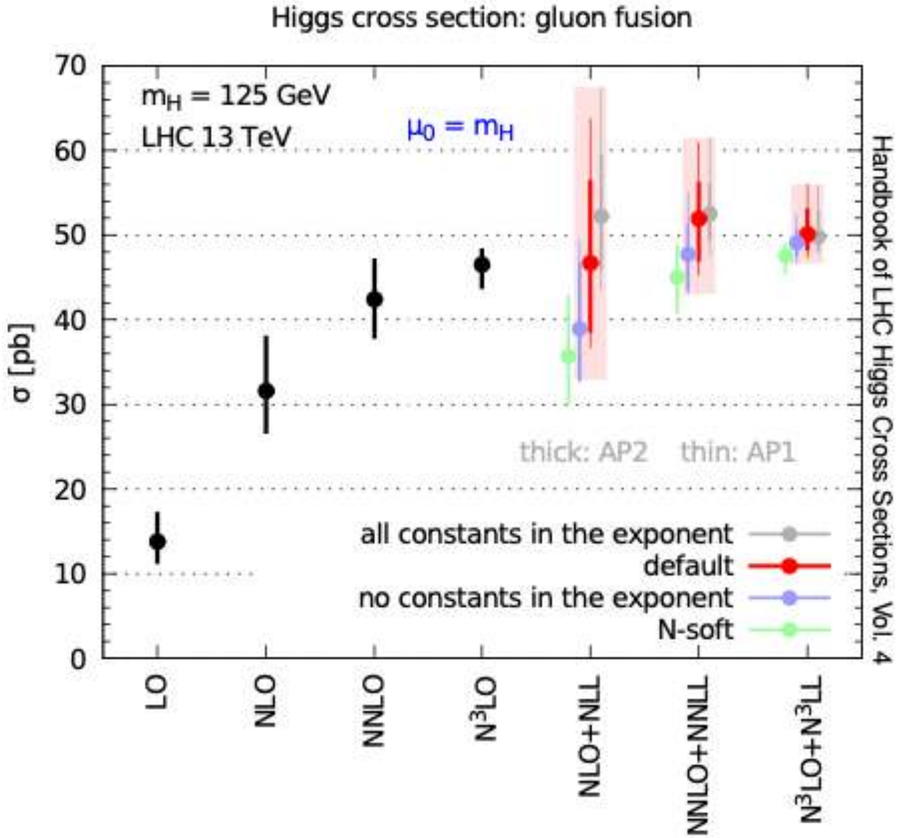


Higgs production at the LHC

- State-of-the-art for gg → H inclusive cross section: NNNLO QCD and NLO electroweak (EWK) corrections[1]
  - **NNNLO** in effective field theory (EFT) with $m_t \to \infty$, rescaled to exact LO result ($\sigma^{\text{LO}}_{\text{ex}} / \sigma^{\text{LO}}_{\text{EFT}}$)



  - Corrections: massive quarks, EWK $\mathcal{O}(\alpha^3)$, mixed QCD-EWK $\mathcal{O}(\alpha\alpha_s^3)$
  - Result for $m_H = 125\,\text{GeV}$ at 13 TeV



$$\sigma(\text{gg} \to \text{H}) = 48.58\,^{+2.22}_{-3.27}\ (\text{theory}) \pm 1.56\ (\text{PDF} + \alpha_s)\ \text{pb} \ \to\ \text{about } \mathbf{6\,\%\ uncertainty}$$

Most important analysis channels

Rationale: favourable combination of cross section times branching ratio,selection efficiency, signal-to-background ratio, resolution, . . .

Production	Decay	Remark
$gg \to H$	$H \to ZZ(*) \to 4\ell$	excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to \gamma\gamma$	small branching fraction but excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to WW(*) \to \ell\nu\ell\nu$	large production cross section but poor mass resolution (two neutrinos)
$gg \to H$ $qq \to qqH$	$H \to \tau\tau$	decay into fermions with large branching fraction but large QCD background
$qq \to VH$	$H \to bb$	large QCD background → additional tag through (leptonic) vector-boson decay
$gg \to ttH$ $gg \to tHq/tHW$	$H \to bb, \gamma\gamma,$ multi-leptons	access to top-quark Yukawa coupling

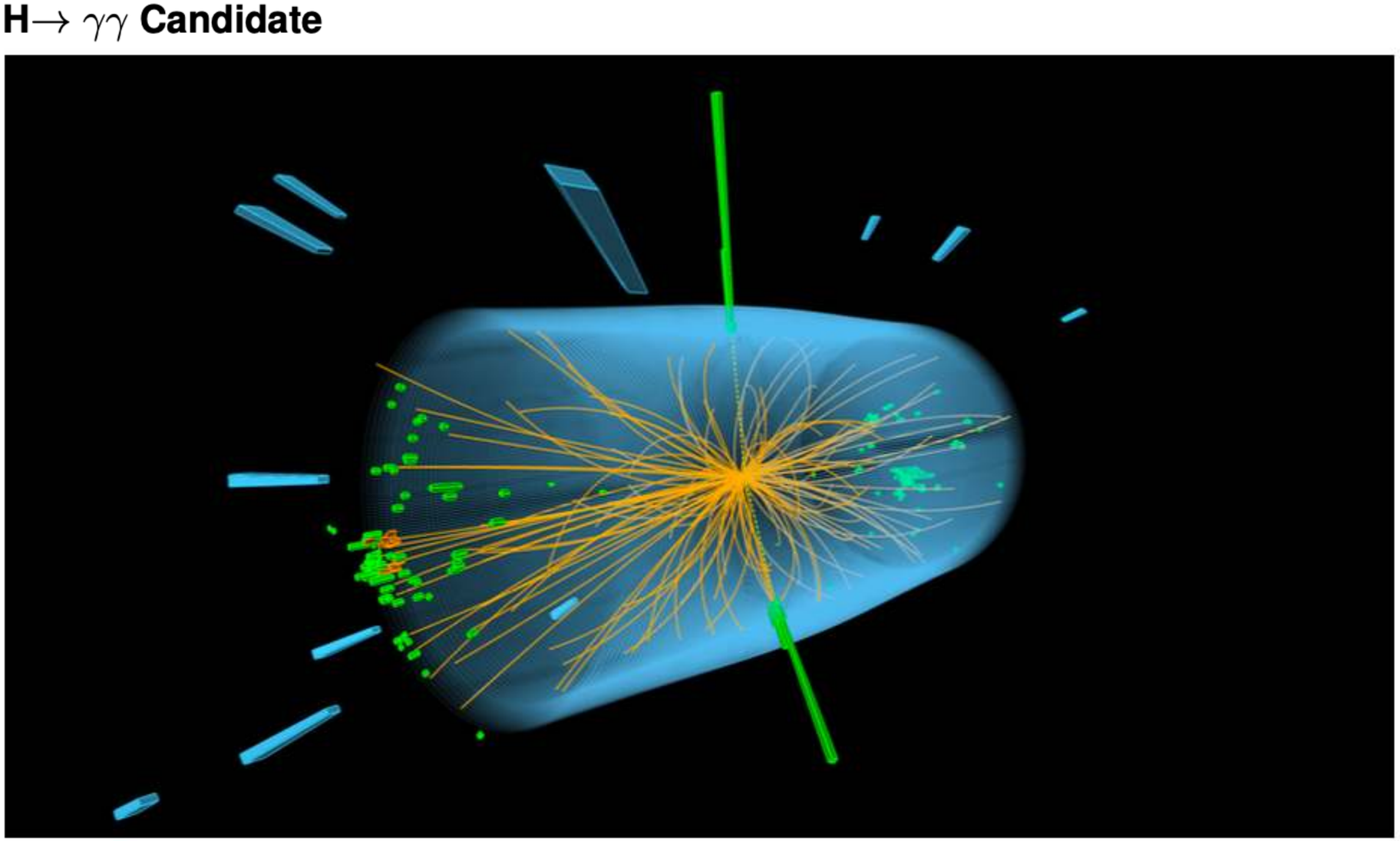
Discovery Timeline

- First serious Higgs searches at the LHC: **2011 dataset** ($5\,\mathrm{fb}^{-1}$ @ 7 TeV)
- CERN public seminar (December 13, 2011)
  - **Excess** at $m_H \approx 125\,\mathrm{GeV}$, **both** in ATLAS and CMS
  - $\approx 3\,\sigma$ ($\approx 2\,\sigma$) local (global) significance
- Update with 2011 data + first part of 2012 data (July 4, 2012):
  - Significance: **5.0 σ/4.9 σ** in ATLAS/CMS on $5 + 5\,\mathrm{fb}^{-1}$ per experiment
- CERN DG R. Heuer:

  "As a layman I would say: 'I think we have it!'"

Discovery Timeline

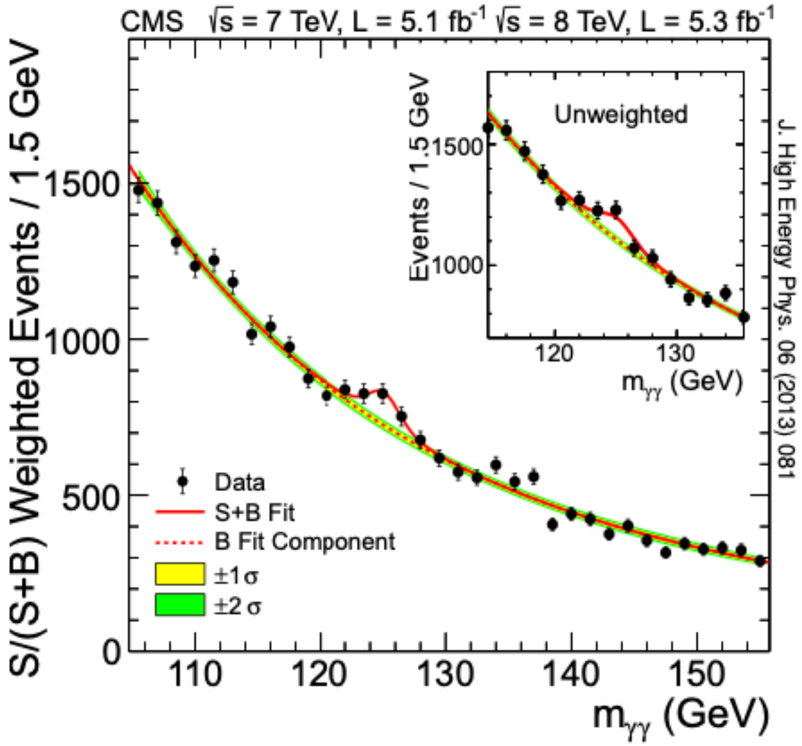
Observation of a new particle with mass of 125 GeV



Observation of a new particle with mass of 125 GeV

$H \to \gamma\gamma$ Candidate

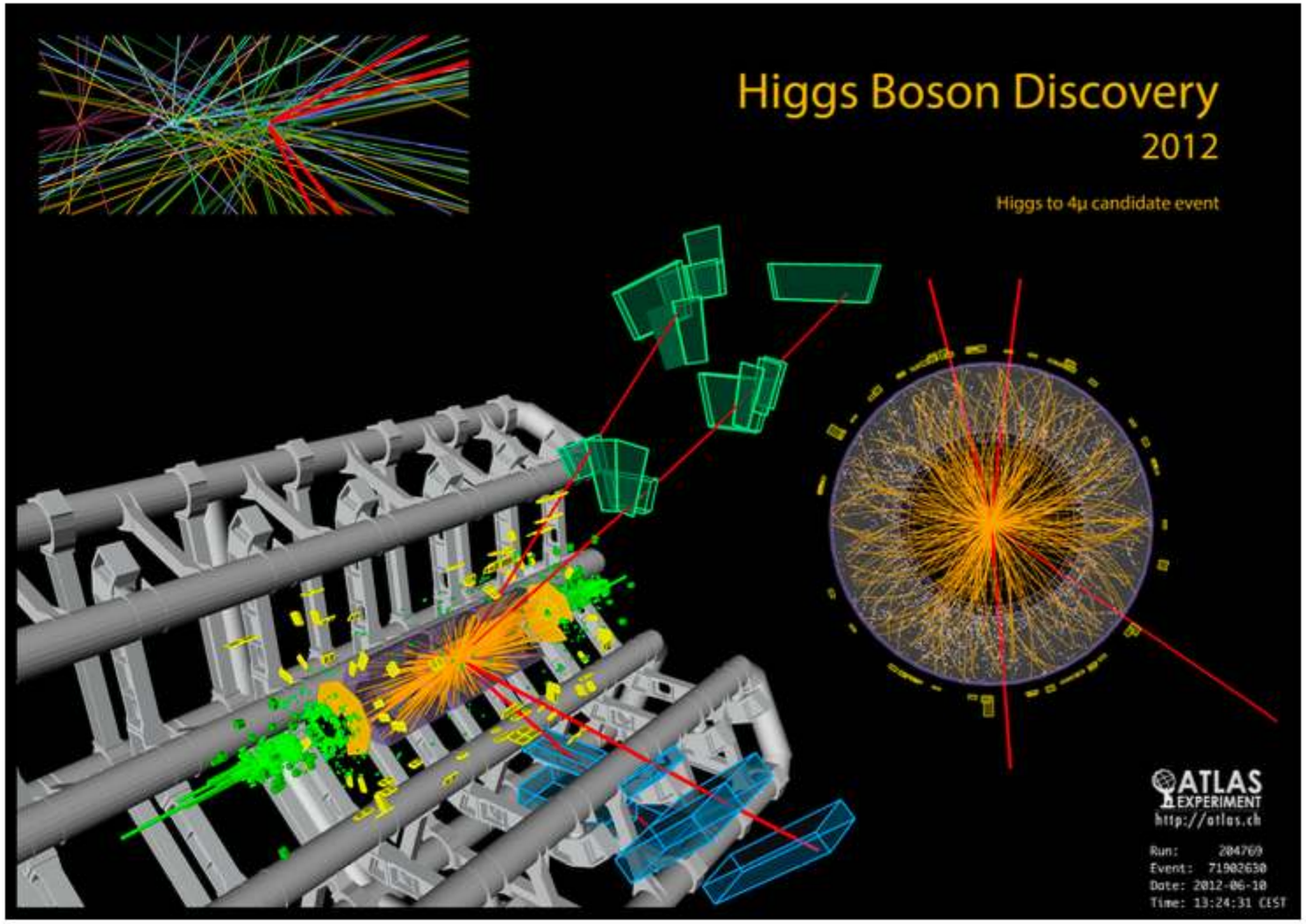
- Signature: **small narrow peak** on huge **combinatorial** background
- Detect **photons** (ECAL) and e^+e^- pairs from **photon conversion** before ECAL
- **Dijet tag** for VBF Higgs production
- Background: QCD **diphoton** production + **jets misidentified as photons**
- Background **estimated from data**: fit empirical function outside signal region



- Signal and background separation: **cut-based** or **boosted decision trees** (ECAL cluster shape, object kinematics, consistency with primary vertex)
- Experimental challenge: excellent calibration of **photon energy scale**

Observation of a new particle with mass of 125 GeV

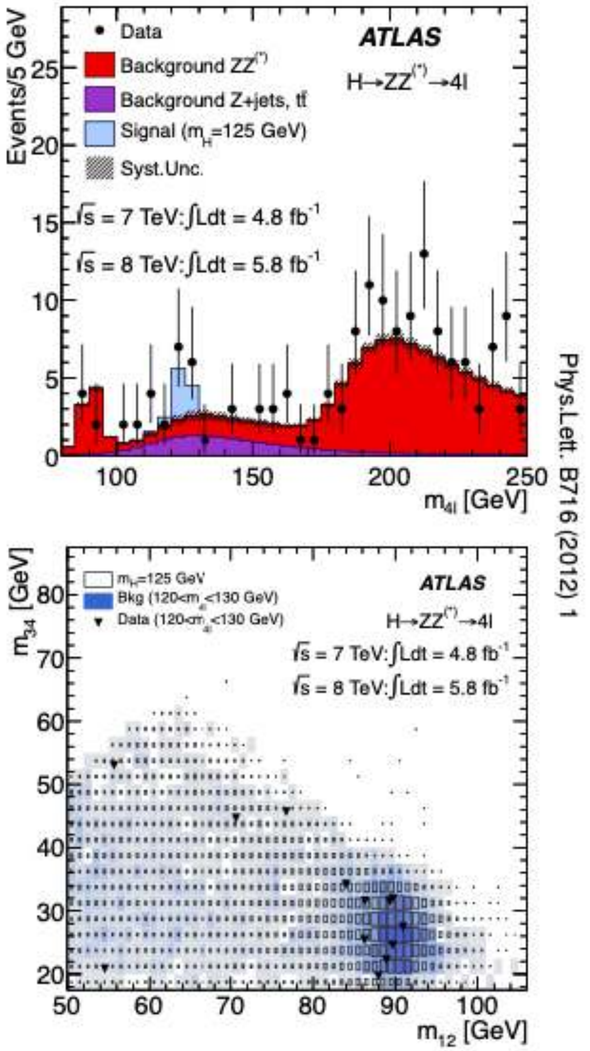
H→ZZ→ 4ℓ Candidate



Observation of a new particle with mass of 125 GeV

$H \to ZZ \to 4\ell$ Candidate

- Signature: **4 isolated high-p_T leptons** (e, μ), invariant mass of one pair compatible with Z boson
- Sensitive over **wide Higgs-boson mass range** (100–600 GeV)
- Excellent Higgs mass resolution **1–2 %**
- Background:
  - **ZZ* continuum**: estimated from MC simulation
  - Z + jets, $t\bar{t}$: estimated from control regions in data
- Selection: kinematics of 4-lepton system (5 angles, 2 pair masses)



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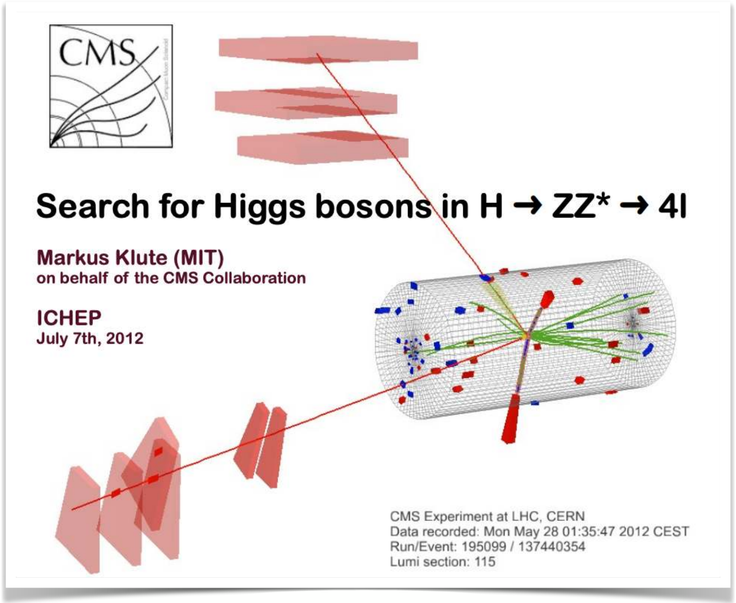

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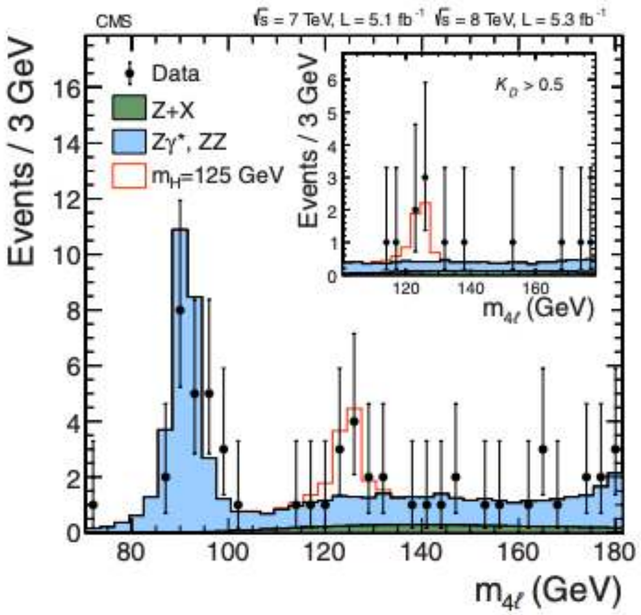

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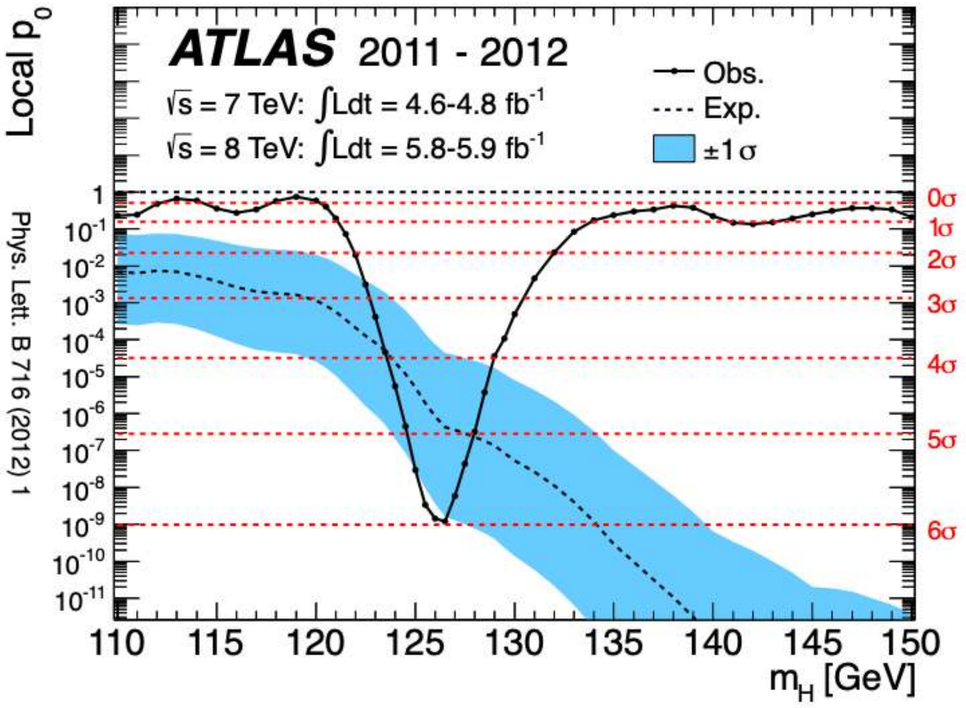
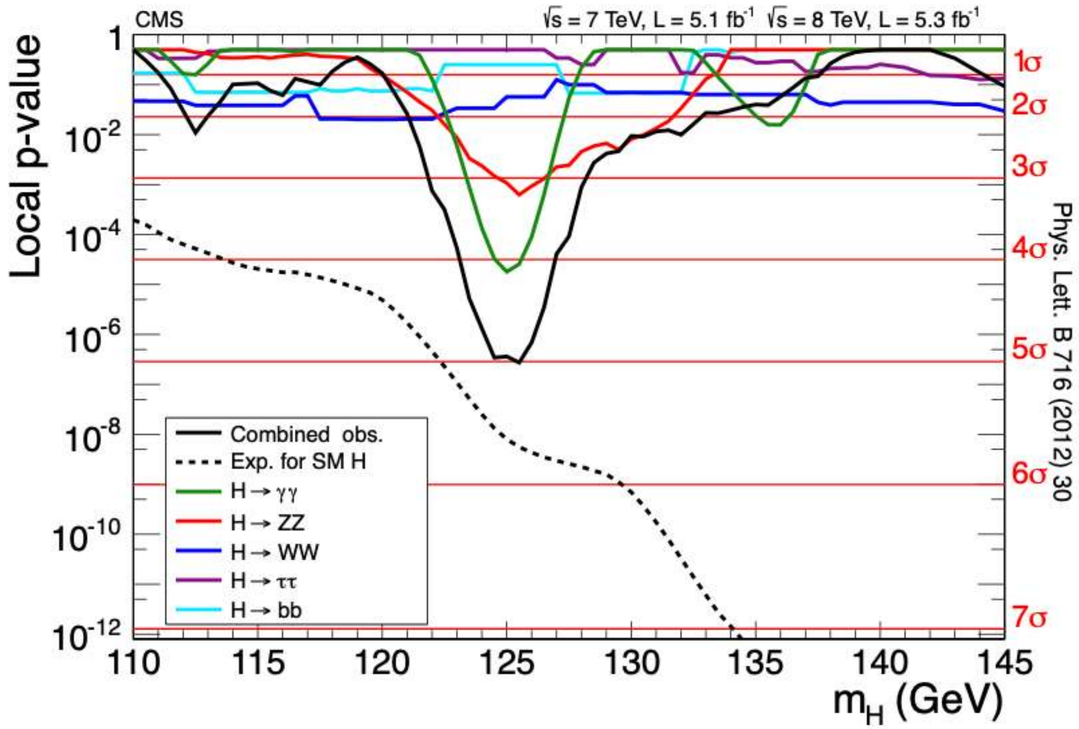
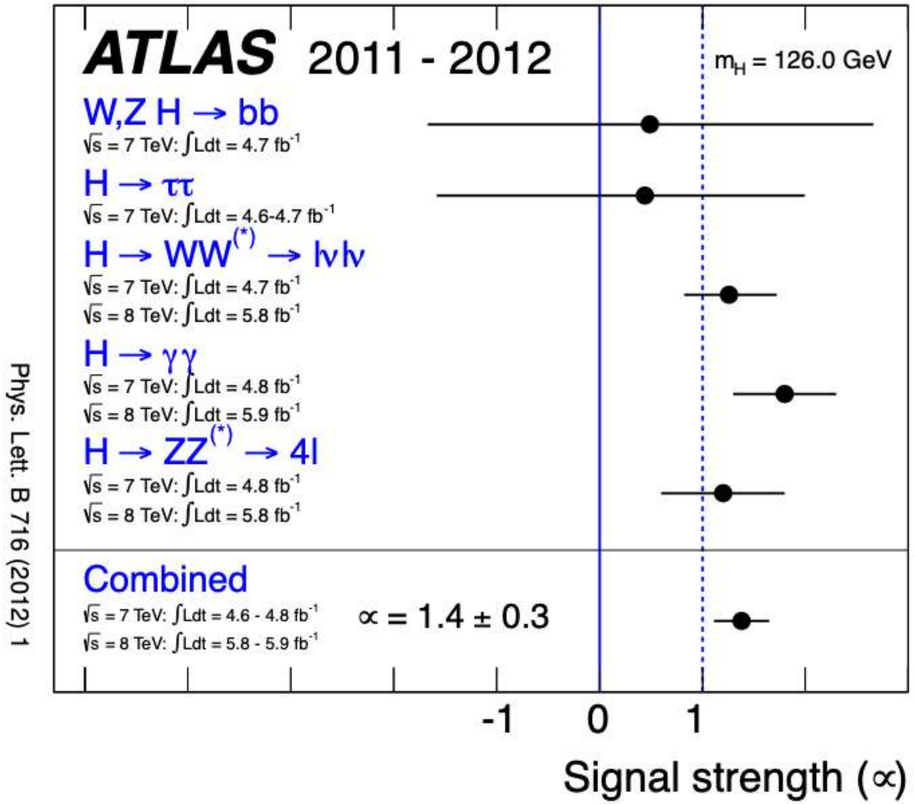
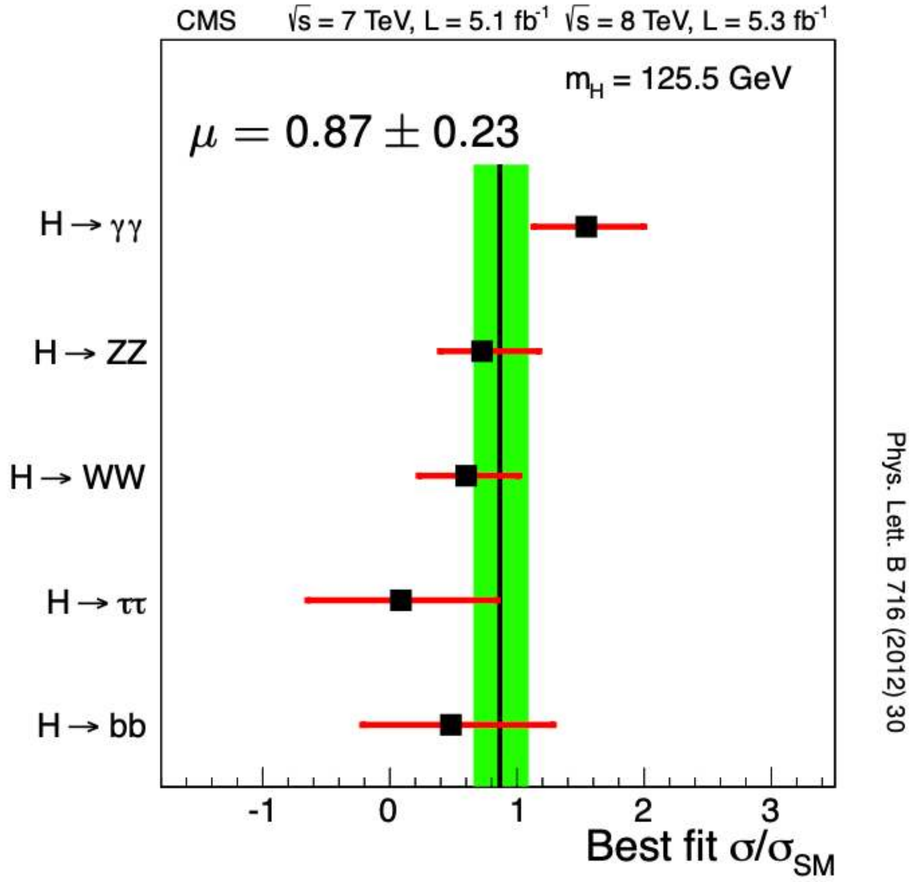




- Best sensitivity: **combination** of all decay channels $\mathbf{H \to \gamma\gamma}$, $\mathbf{H \to ZZ^{(*)} \to 4\ell}$, $H \to WW^{(*)} \to \ell\nu\ell\nu$, $H \to \tau\tau$, $H \to b\bar{b}$
- Local p values for combination: $\geq \mathbf{5\,\sigma}$ **excess** around $m_H = 125\,\text{GeV}$

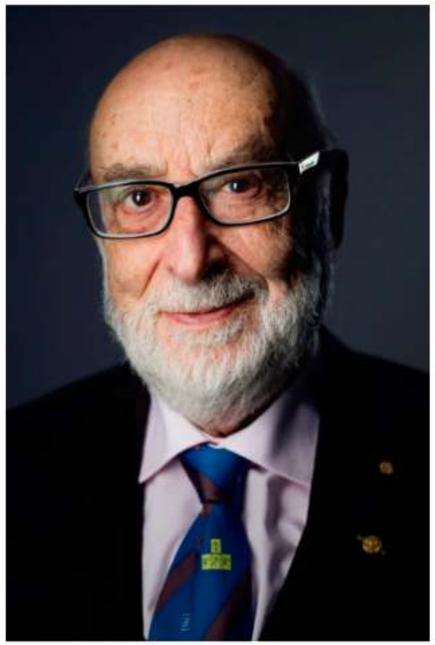
Observation of a new particle with mass of 125 GeV





- All decay channels **compatible with SM** ($\mu = 1$)
- First measurement of m_H: 126.0 ± 0.6 GeV (**ATLAS**) 125.3 ± 0.6 GeV (**CMS**)

The Nobel Prize in Physics 2013



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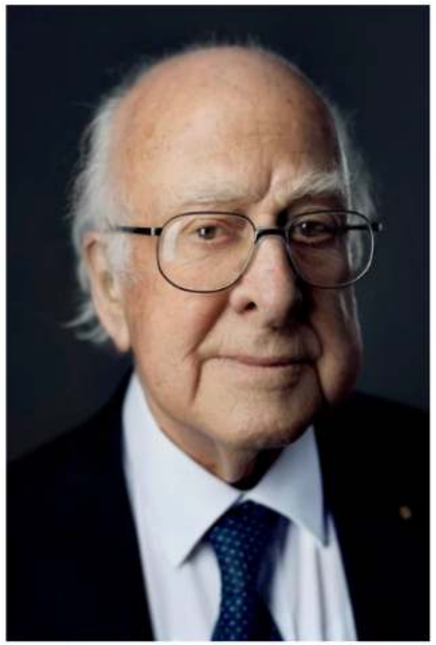
François Englert

Prize share: 1/2



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Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Break

Summary: Higgs Discovery

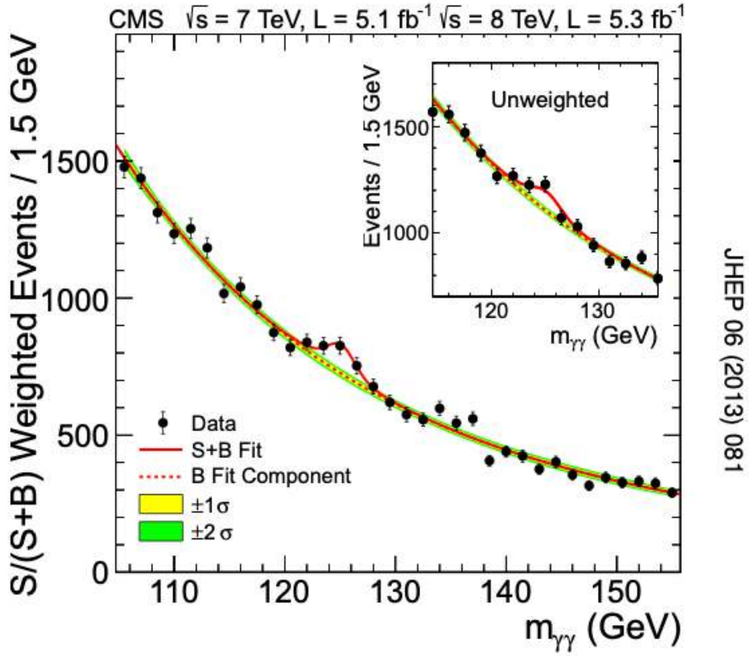
- Coupling structure of the Higgs boson well-defined
  - Coupling strength determined by the Higgs boson mass
  - But Higgs boson mass unknown from theory, many signatures to cover experimentally
- Long-lasting **search for the Higgs boson** at LEP, Tevatron and LHC
- Finally observed by ATLAS and CMS at the LHC in 2012
  - Main discovery channels: $\mathbf{H \to \gamma\gamma}$, $\mathbf{H \to ZZ^{(*)} \to 4\ell}$ (mass peaks)
  - Other channels contributing: $H \to WW^{(*)} \to l\nu l\nu$, $H \to \tau\tau$, $H \to b\bar{b}$
- Measurements of Higgs boson properties become feasible with more data
- Higgs boson mass already known up to a level of 0.1 %

High-Resolution Channels: Now and Then

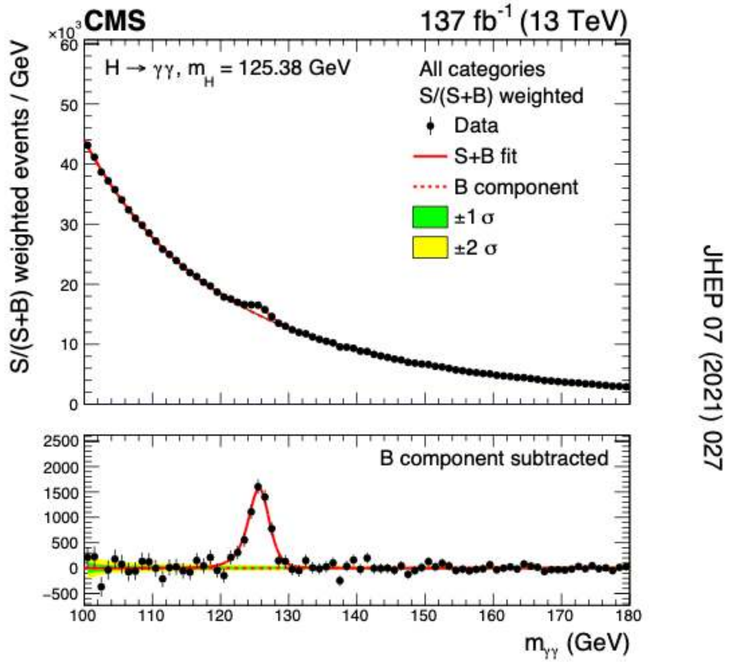
- Decay channels with **best resolution**:
  - $H \to \gamma\gamma$ (low signal purity)
  - $H \to ZZ \to 4\ell$ (small signal rate)

$\to$ typically **first choice for property measurements**

At discovery (part of Run 1 data)



today (full Run 2 dataset)



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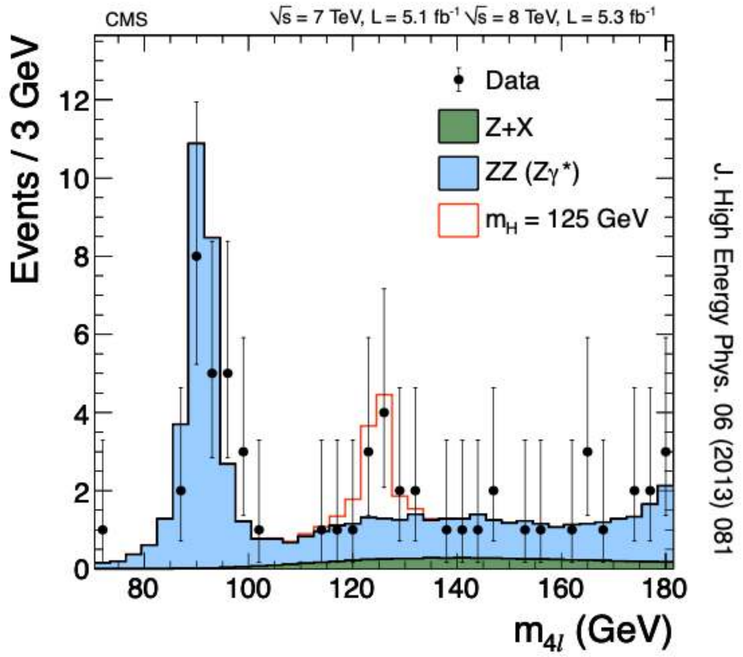

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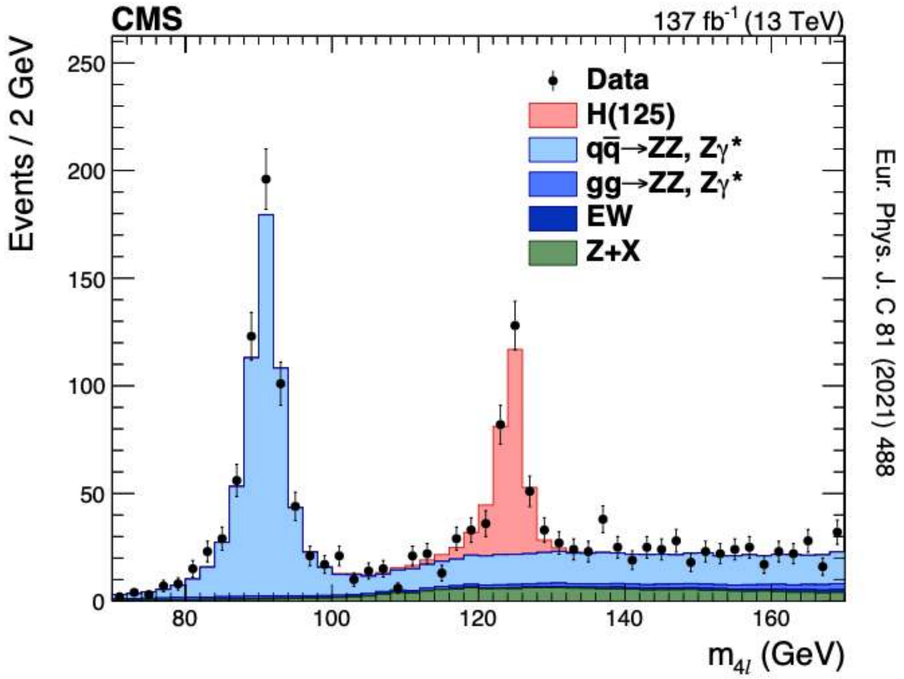
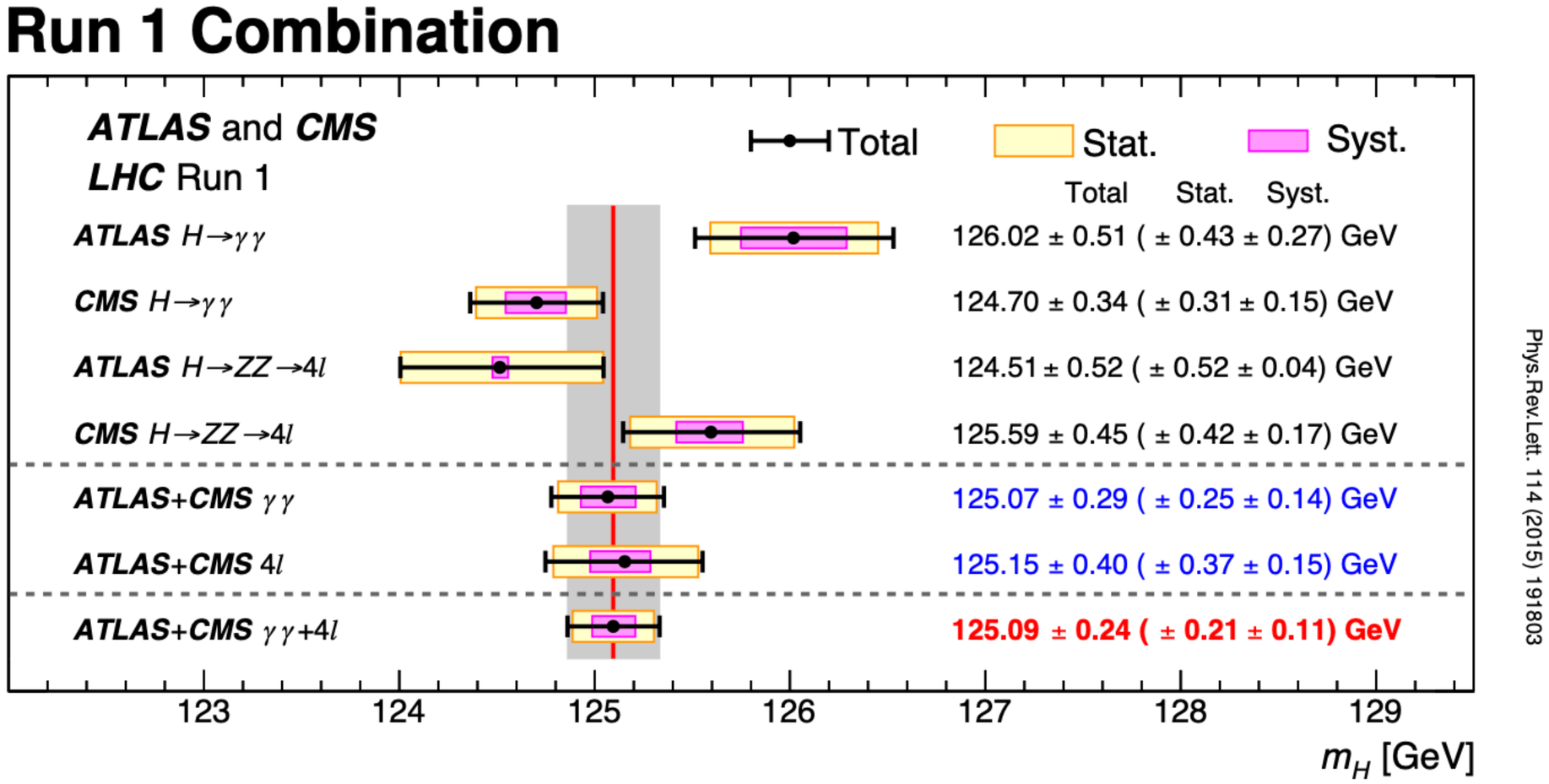


Higgs-Boson Mass

- Reminder: importance of the Higgs-boson mass
  - m_H **only free parameter of SM Higgs sector**: consistency check of SM (relation to m_t and m_W through quantum corrections)
  - Improved knowledge on m_H $\rightarrow$ more precise predictions of other Higgs properties
  - Decay channels with **best mass resolution**: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$

Higgs-Boson Mass



- Measurement precision: $2 \cdot 10^{-3}$ → one of **most precisely known** SM parameters, still limited by **statistics**, i.e., the amount of data recorded

Higgs-Boson Mass

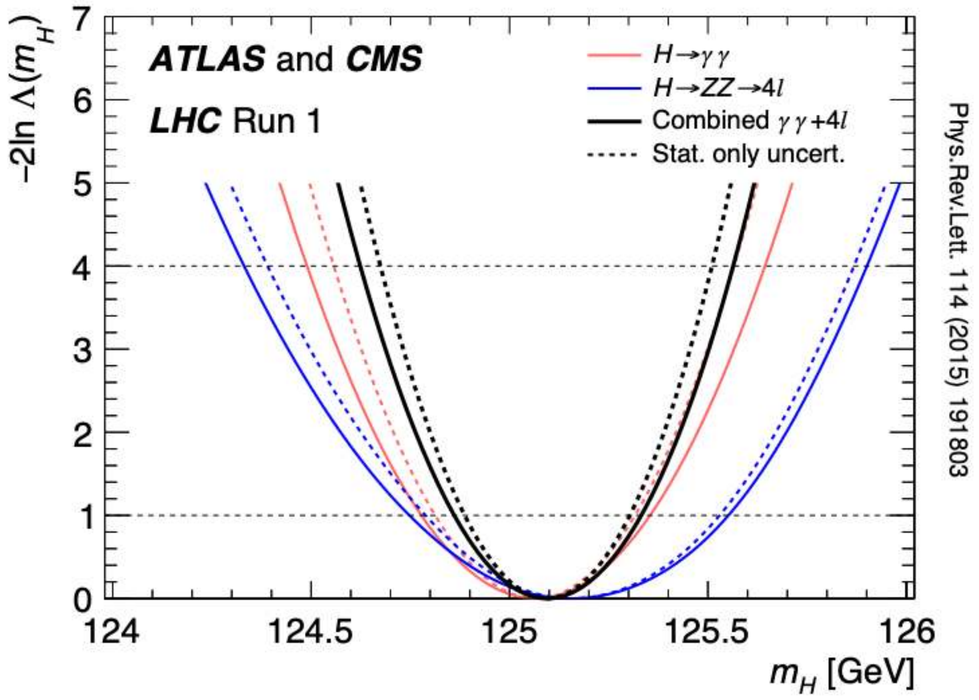
- Combination at level of **likelihoods**: minimise negative logartihm of **profile-likelihood ratio**

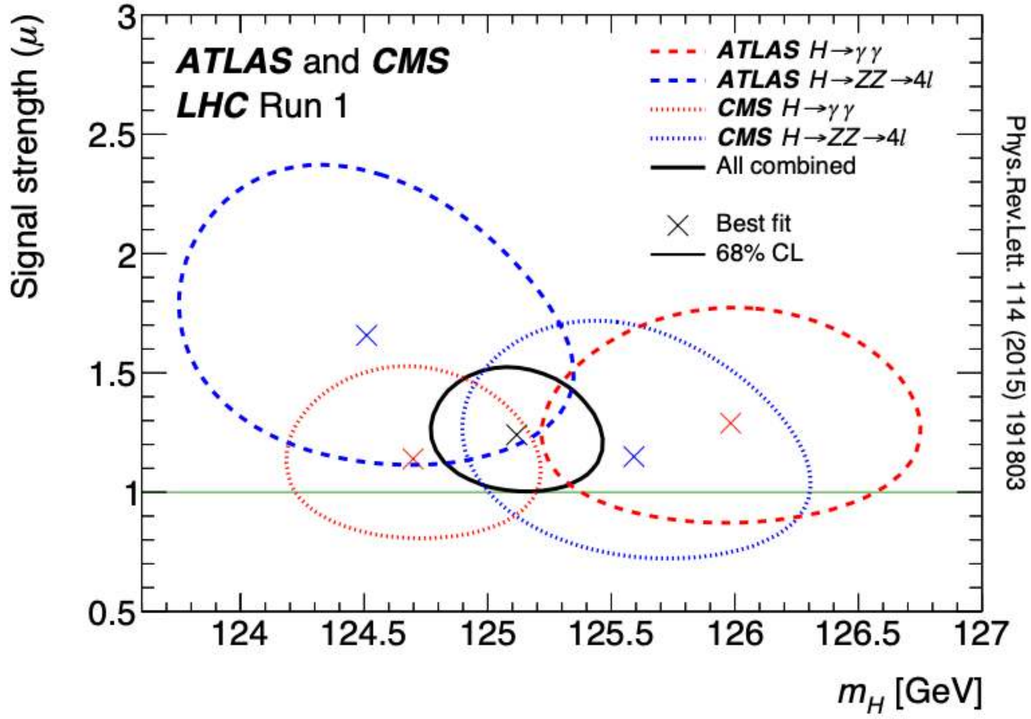
$$\Lambda(m_{\mathrm{H}}) = \frac{\mathcal{L}(m_{\mathrm{H}}, \hat{\hat{\theta}}(m_{\mathrm{H}}))}{\mathcal{L}(\hat{m}_{\mathrm{H}}, \hat{\theta})}$$

$\hat{\hat{\theta}}(m_{\mathrm{H}})$: values that maximise $\mathcal{L}$ for given m_{H}

$\hat{m}_{\mathrm{H}}, \hat{\theta}$: values that maximise $\mathcal{L}$ globally

  - Λ function of mass-dependent $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ signal strengths

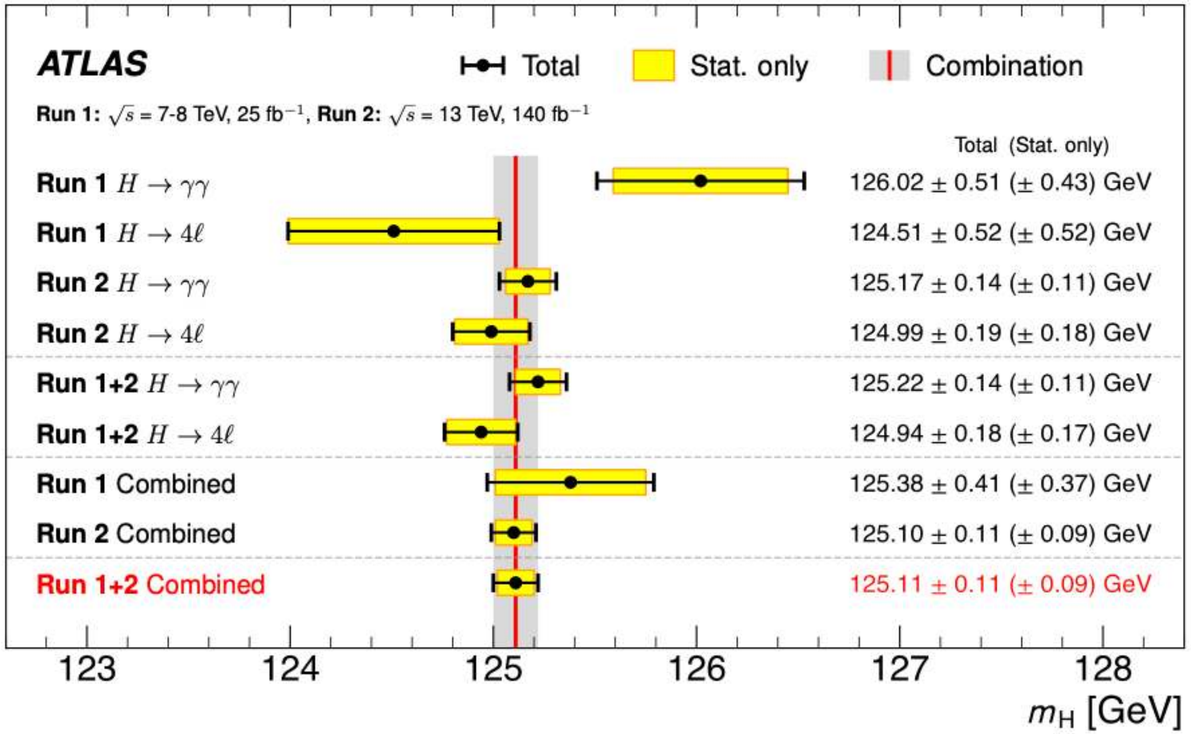




Higgs-Boson Mass

- Most precise measurement in $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ decay channels by the ATLAS Collaboration
  - Combined measurements at 7, 8 and 13 TeV
  - Main systematic uncertainty from photon energy calibration
  - $m_H = 125.11 \pm 0.09\ (\text{stat}) \pm 0.06\ (\text{syst})$ GeV
  - **Precision: $< 0.1\,\%$ level**

Status Summer 2024



Phys. Rev. Lett. 131 (2023) 251802

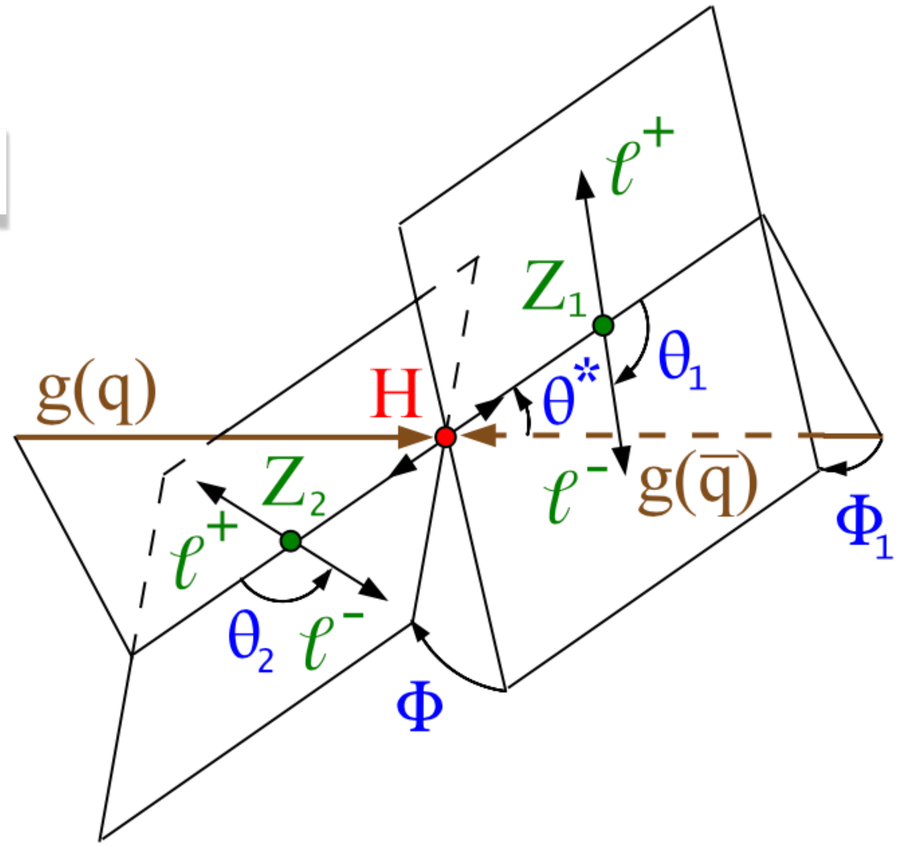
Higgs-Boson Spin and Parity

- SM prediction for the Higgs boson are $J^P = 0^+$
  - Spin 1 forbidden by Landau–Yang theorem (observed decay into photons)
  - Spin 2 scenario not excluded from discovery
- Can be measured from angular analysis of decay products in $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$
  - Probes CP in HVV couplings
  - First measurements in Yukawa sector from $t\bar{t}H$ with $H \to \gamma\gamma$

$$\mathbf{H \to ZZ \to 4\ell}$$

- Kinematics fully determined by
  - 2 masses $\boxed{m_{Z_1}, m_{Z_2}}$
  - Decay planes of $Z_{1,2}$:

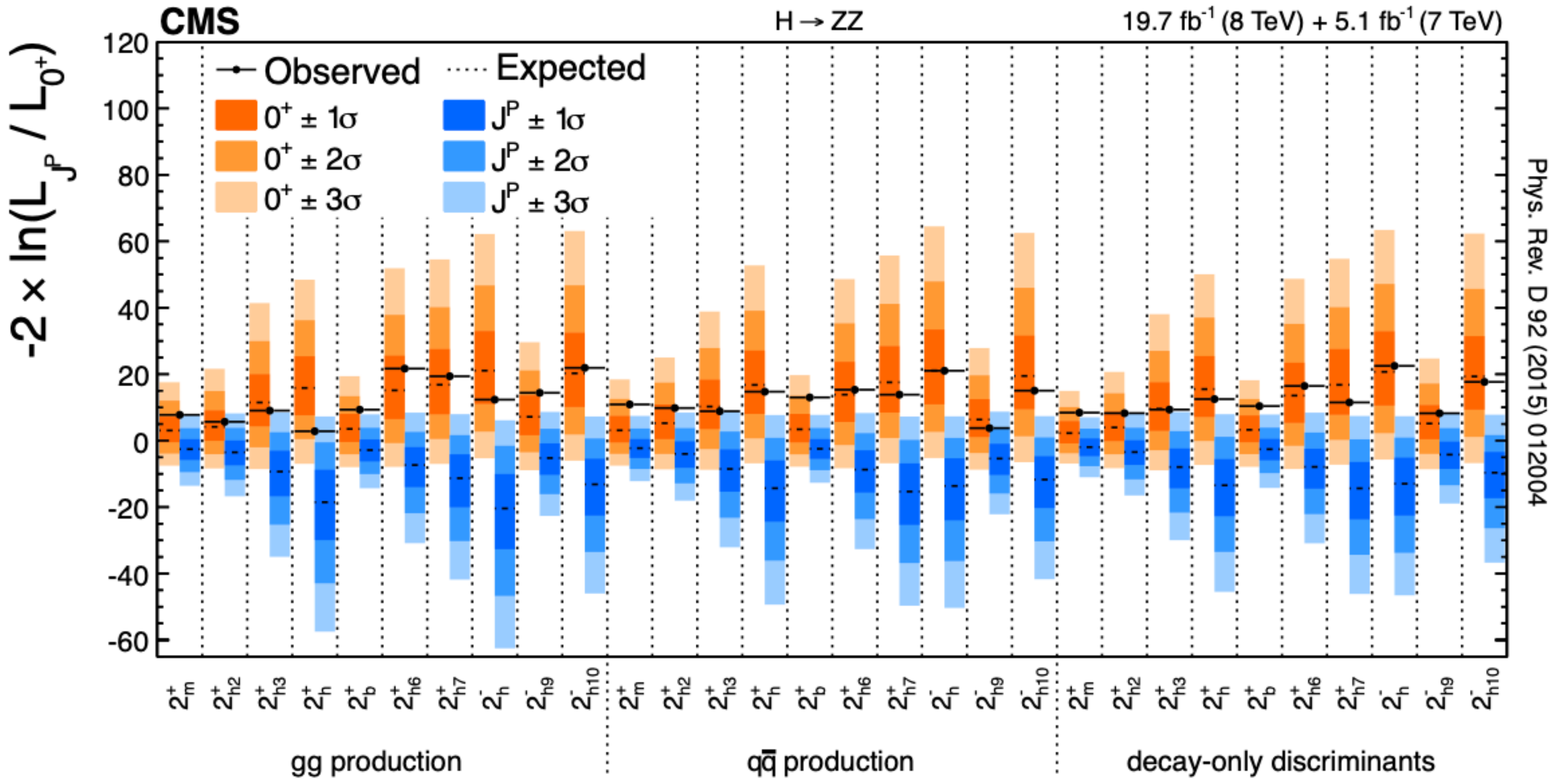
    5 angles $\boxed{\vec{\Omega} = (\theta^*, \phi_1, \phi, \theta_1, \theta_2)}$
    - Polar angle of Z bosons (θ^*)
    - Azimuthal angle of Z_1 plane (ϕ_1)
    - Azimuthal angle of Z_2 plane relative to Z_1 plane (ϕ)
    - Polar angles of leptons relative to $Z_{1,2}$ ($\theta_{1,2}$)



Handbook of LHC Higgs Cross Sections: 3. Higgs Properties

Higgs-Boson Spin and Parity

$$H \rightarrow ZZ \rightarrow 4\ell$$

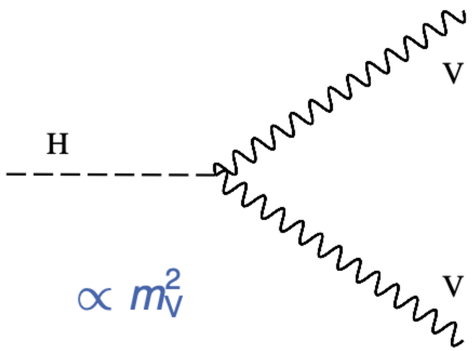


- Measurements favour $J^P = 0^+$ hypothesis (i. e. SM) with high confidence level
- Admixtures of other states still well possible

Higgs-Boson Properties

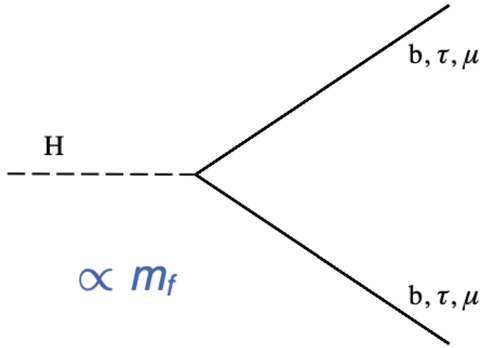
The Standard Model Higgs Boson:

Coupling to gauge bosons



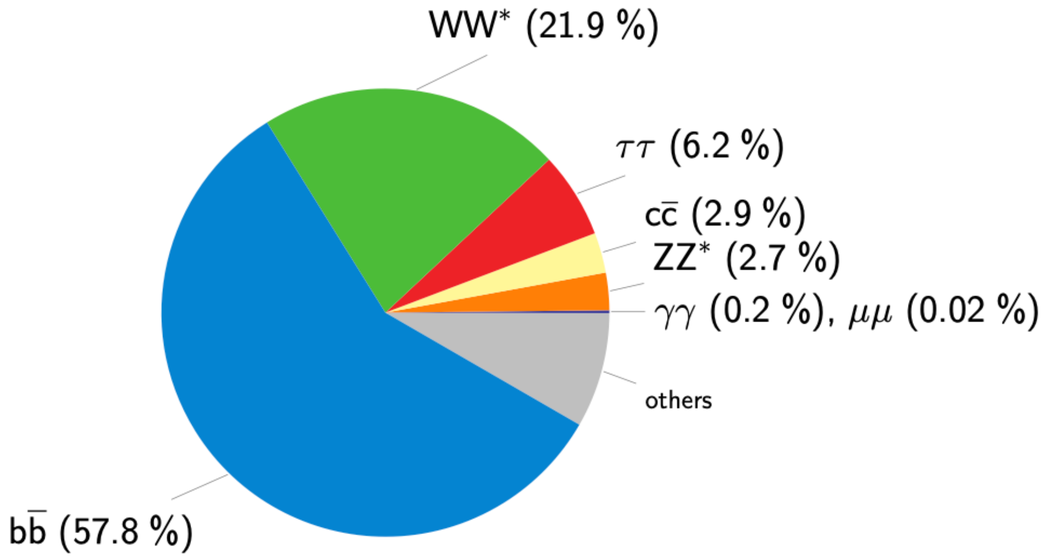
$\propto m_V^2$

Yukawa coupling to fermions



$\propto m_f$

Branching ratios



Measure properties as precisely as possible!

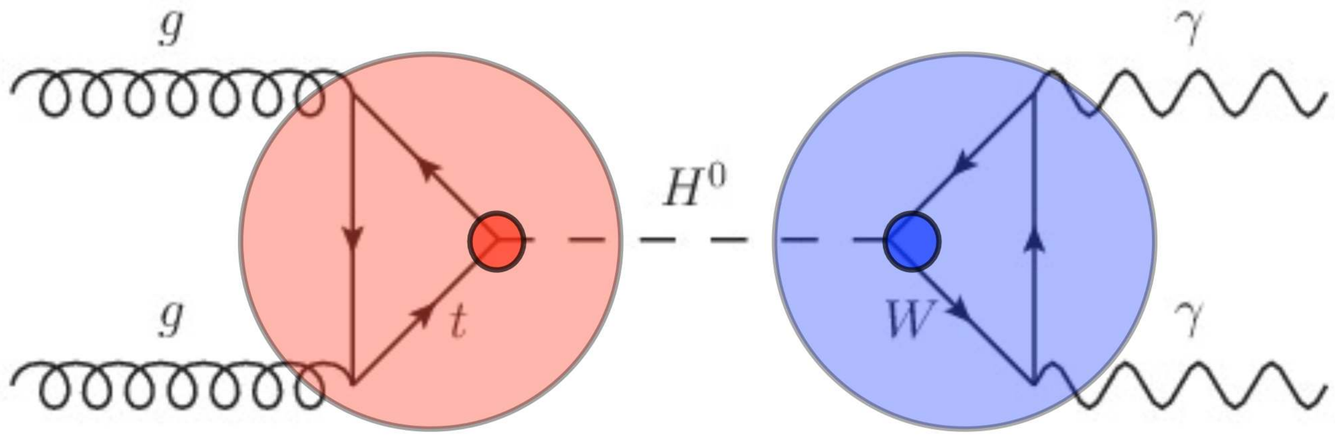
Probe all possible couplings

→ Test of the SM and probe of new physics

Higgs-Boson Properties

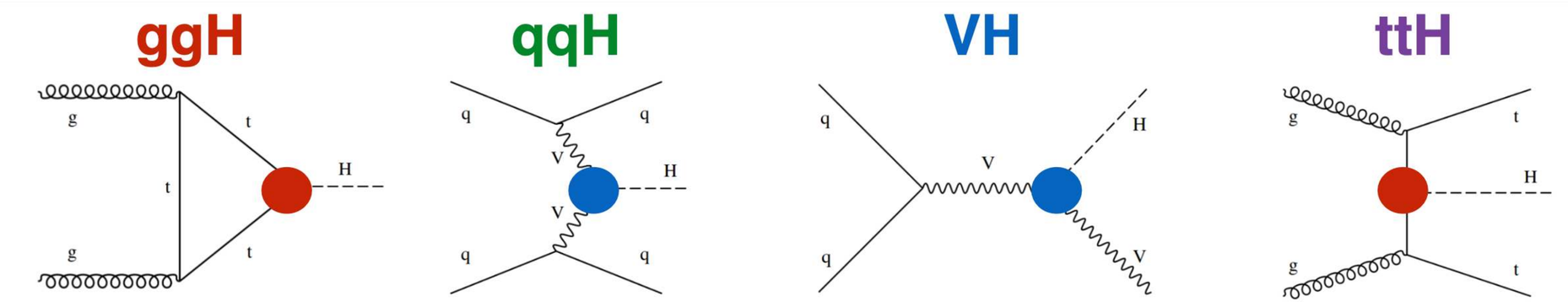
- Higgs-boson signal **firmly established**
  - Main discovery channels: $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to 4l$ (mass peaks)
  - Other channels contributing: $H \to WW^{(*)} \to l\nu l\nu$, $H \to \tau\tau$, $H \to b\bar{b}$
  - Full dataset of LHC Run 1 (2010–2012) analysed
  - Many results from LHC Run 2 (2015–2018) published, still a few more to come
  - LHC Run 3 (2022–2025) currently ongoing, first results published
  - **Observation** ($5\,\sigma$) or **evidence** ($3\,\sigma$) in many **individual decay channels**, often combining **several production modes**

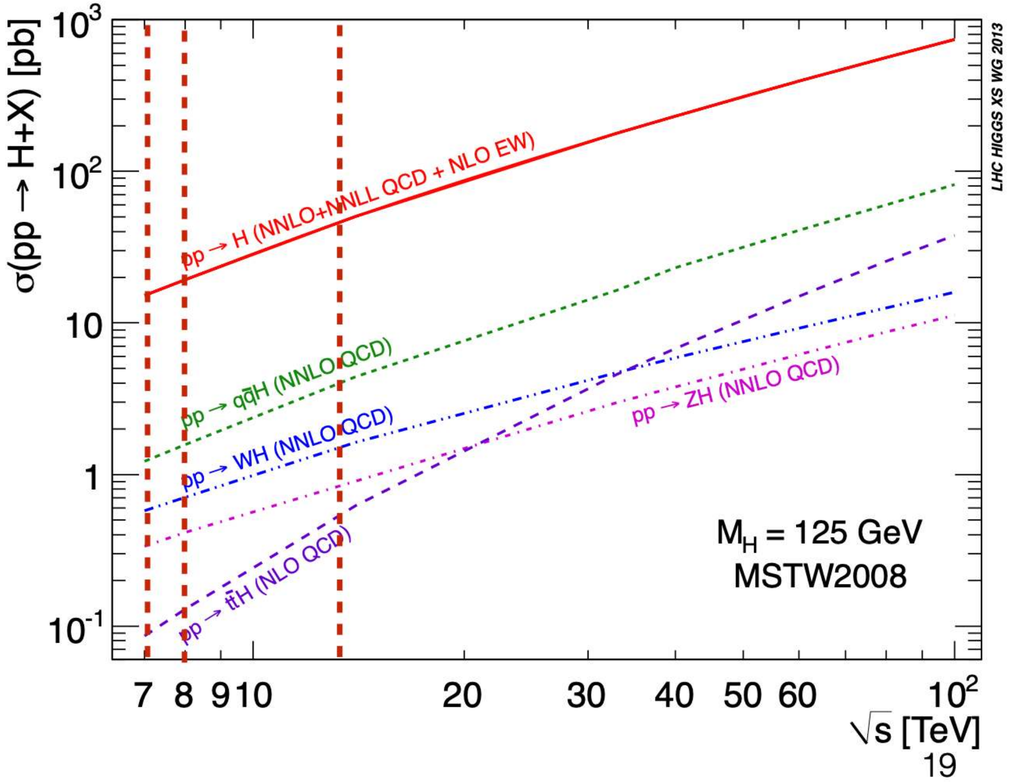
Higgs-Boson Properties

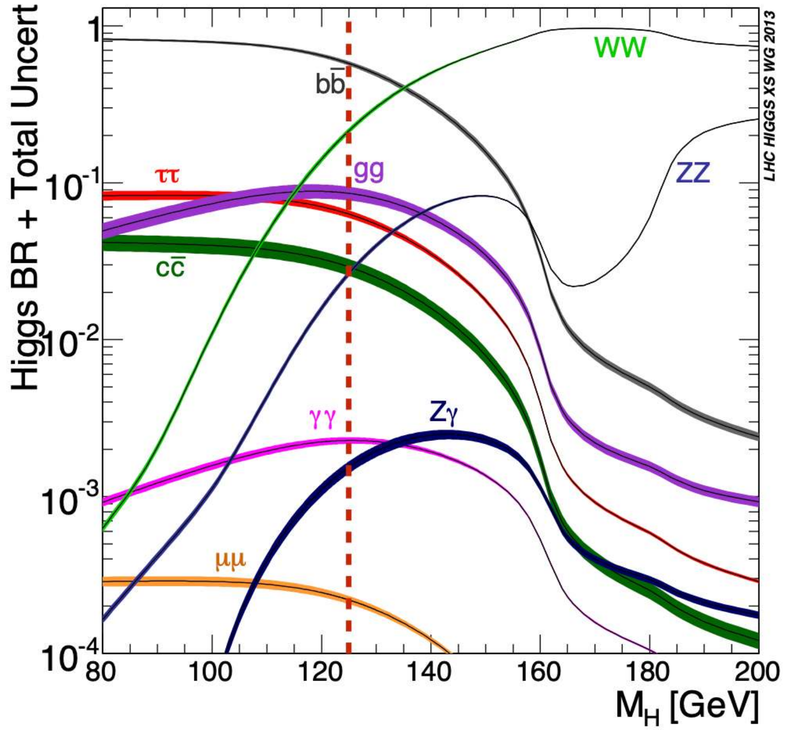


$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Higgs-Boson Properties







Higgs-Boson Properties - status today

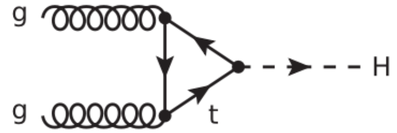
rate ←

	ggH	VBF	VH	$t\bar{t}H$
$H \to b\bar{b}$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to c\bar{c}$	✓		✓	
$H \to WW^* \to 2l2\nu$	✓	✓	✓	✓
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to Z\gamma$	✓	✓	✓	✓
$H \to \mu\mu$	✓	✓	✓	✓
$H \to ZZ^* \to 4l$	✓	✓	✓	✓

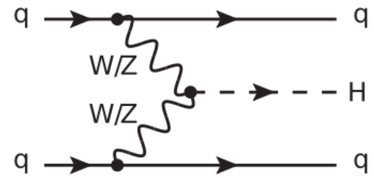
purity ↓

rate ↑

Gluon-Gluon Fusion

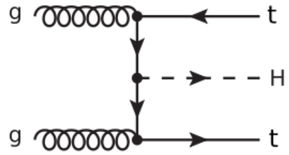


Vector Boson Fusion



Associated Production with W and Z

Associated Production with t



Break

Higgs-Boson Properties - signal-strength modifier

- Simplest measure of SM compatibility with **product $\sigma \cdot \mathcal{B}$: signal-strength modifier μ**
- **Narrow-width approximation**: production and decay **factorise**
  (good assumption for SM Higgs boson: total width $\Gamma_H = 4.1$ MeV)

$$\mu(i \to H \to f) = \frac{\sigma(i \to H)}{\sigma_{SM}(i \to H)} \cdot \frac{\mathcal{B}(H \to f)}{\mathcal{B}_{SM}(H \to f)} \equiv \mu_i \cdot \mu^f$$

- Reminder: branching fraction = fraction of total width, i. e.

$$\mathcal{B}(H \to f) \equiv \mathcal{B}^f \equiv \Gamma^f / \Gamma_H$$

Higgs-Boson Properties - couplings

- Consistency check with SM in **leading-order** framework [(Handbook of LHC Higgs Cross Sections: 3. Higgs Properties)]
  - Assumption 1: **single** Higgs boson with **narrow width**
  - Assumption 2: deviations from SM **only affect production rates** and **branching fractions**, but not kinematic distributions
- **Coupling modifiers** κ for Higgs-boson coupling vertex to SM particles

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \kappa_f^2 = \frac{\Gamma^f}{\Gamma_{\mathrm{SM}}^f}$$

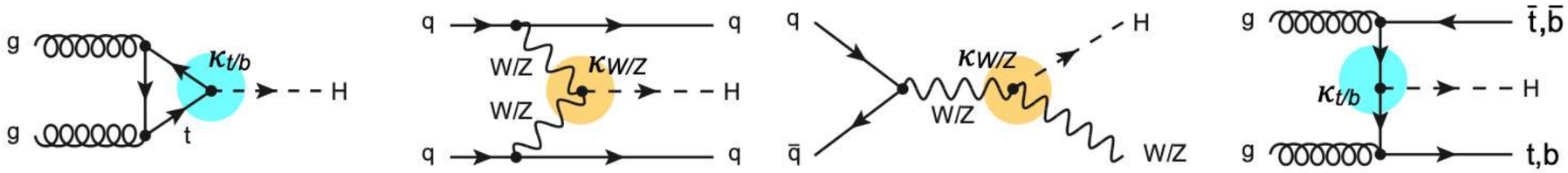
  - $\kappa_{i,f} = 1$: coupling as predicted by SM
- **Combine** all available production and decay channels
  - Each channel depends on **one or more coupling modifiers**
  - Processes with same final state **interfere**

$$\sigma_i \cdot \mathcal{B}^f = \frac{\sigma_i(\kappa_i) \cdot \Gamma^f(\kappa^f)}{\Gamma_{\mathrm{H}}}$$

Higgs-Boson Properties - couplings

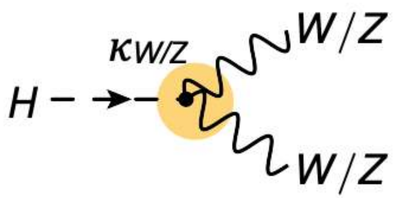
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	—	numerically insignificant		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	—	—		κ_W^2
$\sigma(qq/qg \to ZH)$	—	—		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	—	—		κ_t^2
$\sigma(gb \to tHW)$	—	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	—	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	—	—		κ_b^2

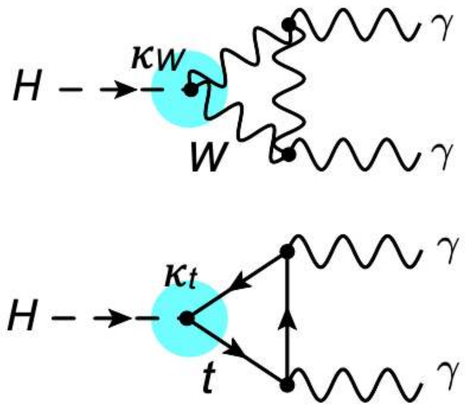
JHEP 08 (2016) 045

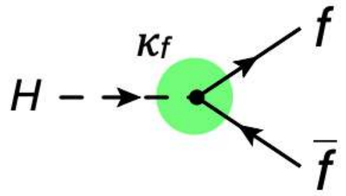


Higgs-Boson Properties - couplings

Partial decay width	Loops	Interference	Effective scaling factor	Resolved scaling factor
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2







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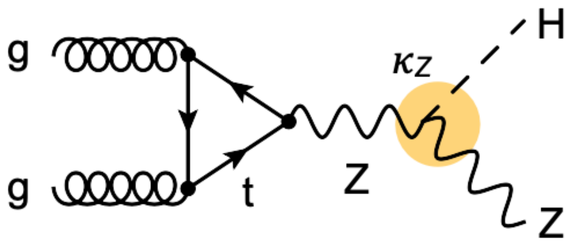
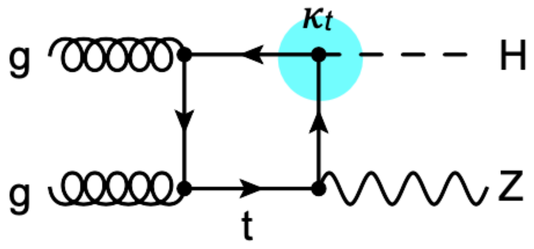
Higgs-Boson Properties - couplings

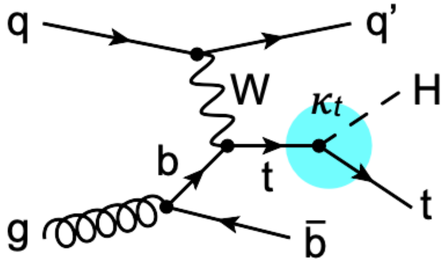
- **Interference** of couplings in Higgs-boson **production**
  - $gg \rightarrow ZH$

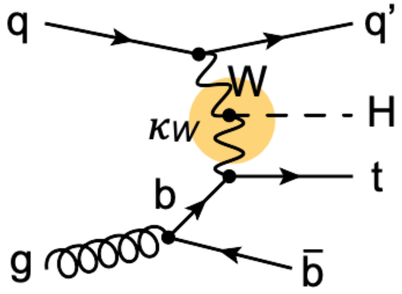




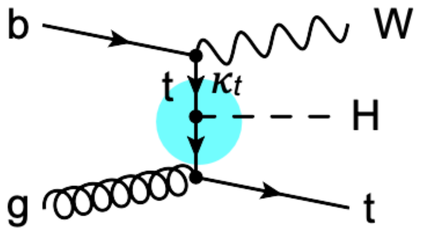
$$\sim 2.27\kappa_Z^2 + 0.37\kappa_t^2 - 1.64\kappa_Z\kappa_t$$

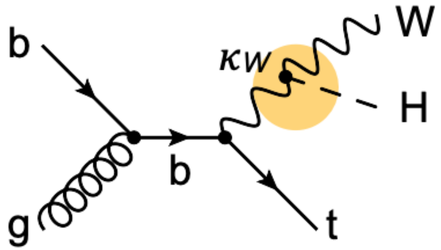
  - $gq \rightarrow tHq$ and $gb \rightarrow tHq$





$$\sim 3.40\kappa_t^2 + 3.65\kappa_W^2 - 5.96\kappa_t\kappa_W$$





$$\sim 1.84\kappa_t^2 + 1.57\kappa_W^2 - 2.41\kappa_t\kappa_W$$

Higgs-Boson Properties - couplings

- **Effective coupling modifiers** may be used for loop-induced couplings to gluons κ_g and photons κ_γ (loops not resolved)
- LHC data so far:
  - insensitive to couplings to light quarks
  - little sensitivity to couplings to μ
- Usually assume:
  - $\kappa_c = \kappa_t$
  - $\kappa_s = \kappa_b$
  - $\kappa_\mu = \kappa_\tau$
  - $\kappa_u = \kappa_d = \kappa_{e^-} = 1$
- Changes of couplings cause change of the **total width**
  - **Most general** case: introduce additional modifier for the total width:

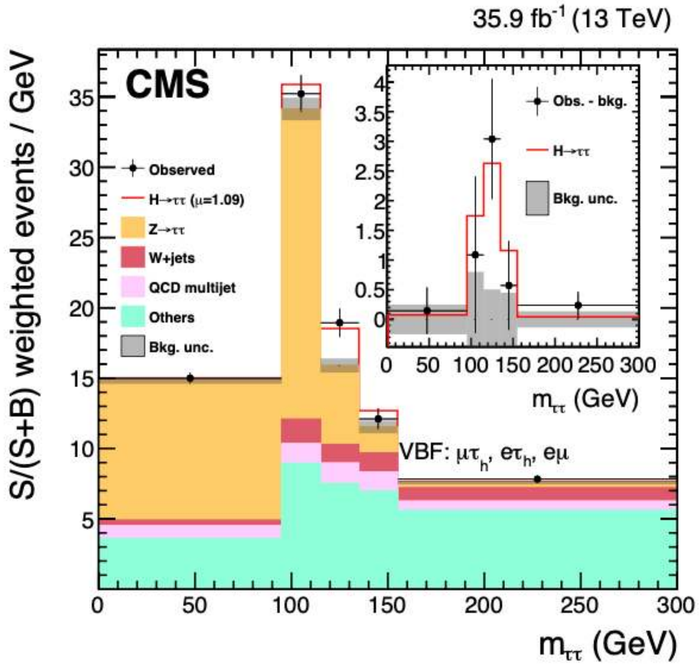
$$\kappa_H^2 \equiv \sum_j \kappa_j^2 \mathcal{B}_{SM}^j = \begin{cases} \frac{\sum_j \kappa_j^2 \Gamma^j}{\Gamma_H^{SM}} = \frac{\Gamma_H}{\Gamma_H^{SM}} : & \text{SM decays only} \\ \frac{\Gamma_H}{\Gamma_H^{SM}} (1 - \mathcal{B}_{BSM}) : & \text{SM+BSM decays} \end{cases}$$

Higgs-Boson Properties - status today

- Couplings to bosons observed with 5 σ significance during Run 1
- Run 2: direct measurement of Higgs-fermion couplings
- **Observation of couplings to 3rd-generation fermions**

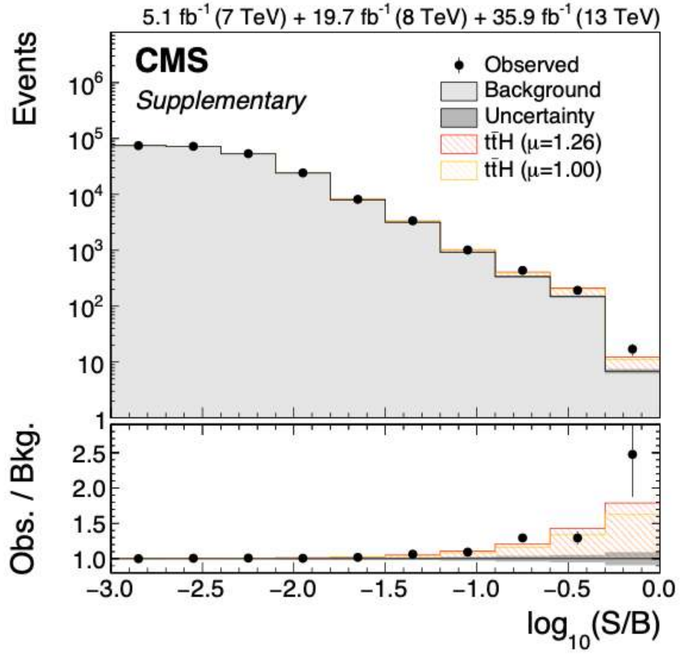
$H \to \tau\tau$ (2017)

[PLB 779 (2018) 283]



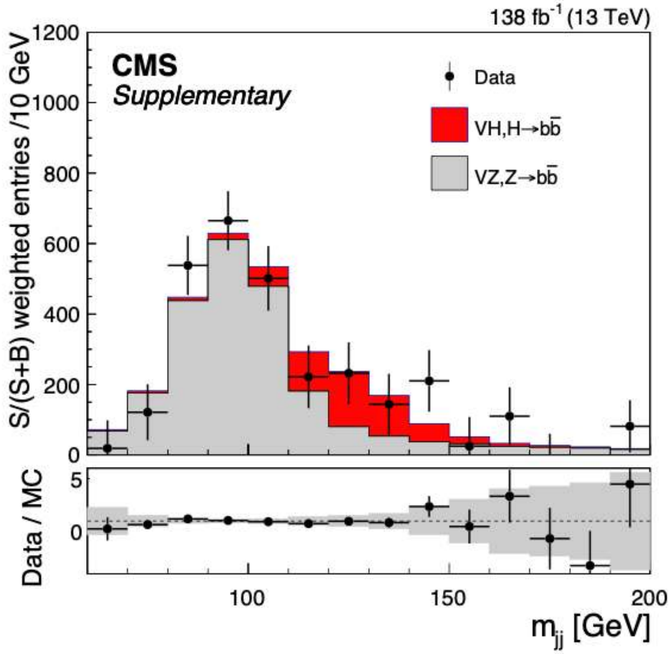
$t\bar{t}H$ (2018)

[PRL 120 (2018) 231801]



$H \to b\bar{b}$ (2024)

[Phys. Rev. D 109 (2024) 092011]

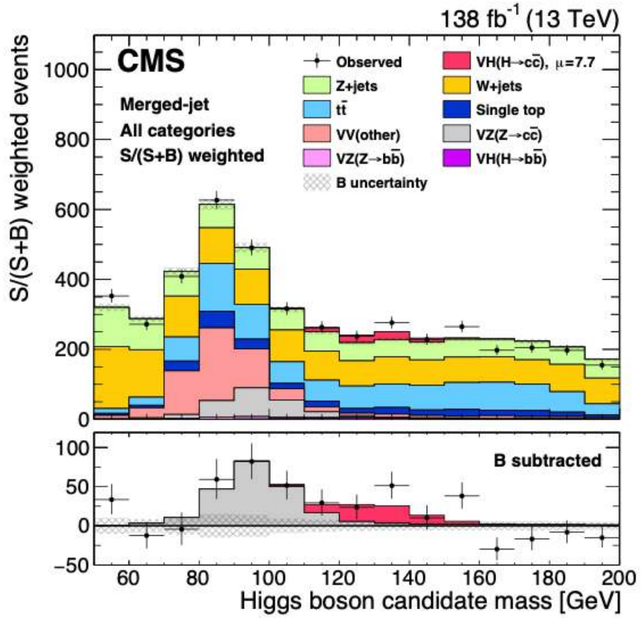


Higgs-Boson Properties - status today

- Couplings to bosons observed with 5 σ significance during Run 1
- Run 2: direct measurement of Higgs-fermion couplings
- **First sensitivity to 2nd-generation fermions**

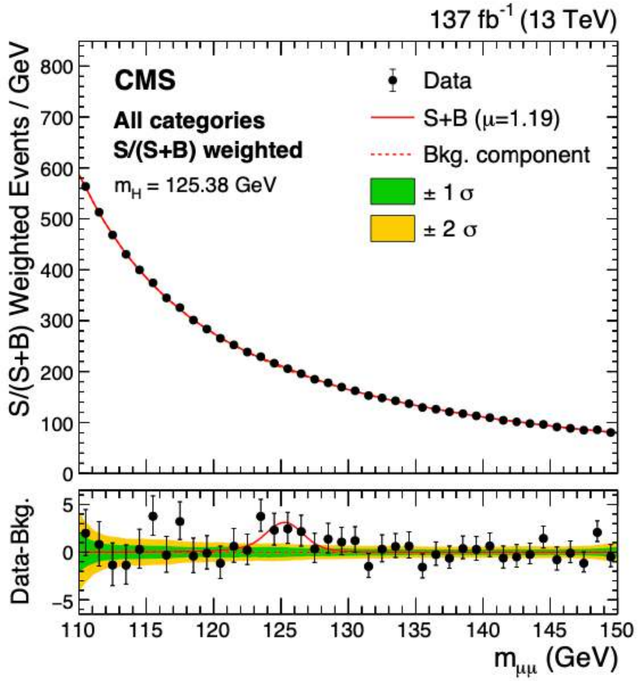
$H \to c\bar{c}$ ($\mu < 14$, 2022)

[PRL 131 (2023) 061801]

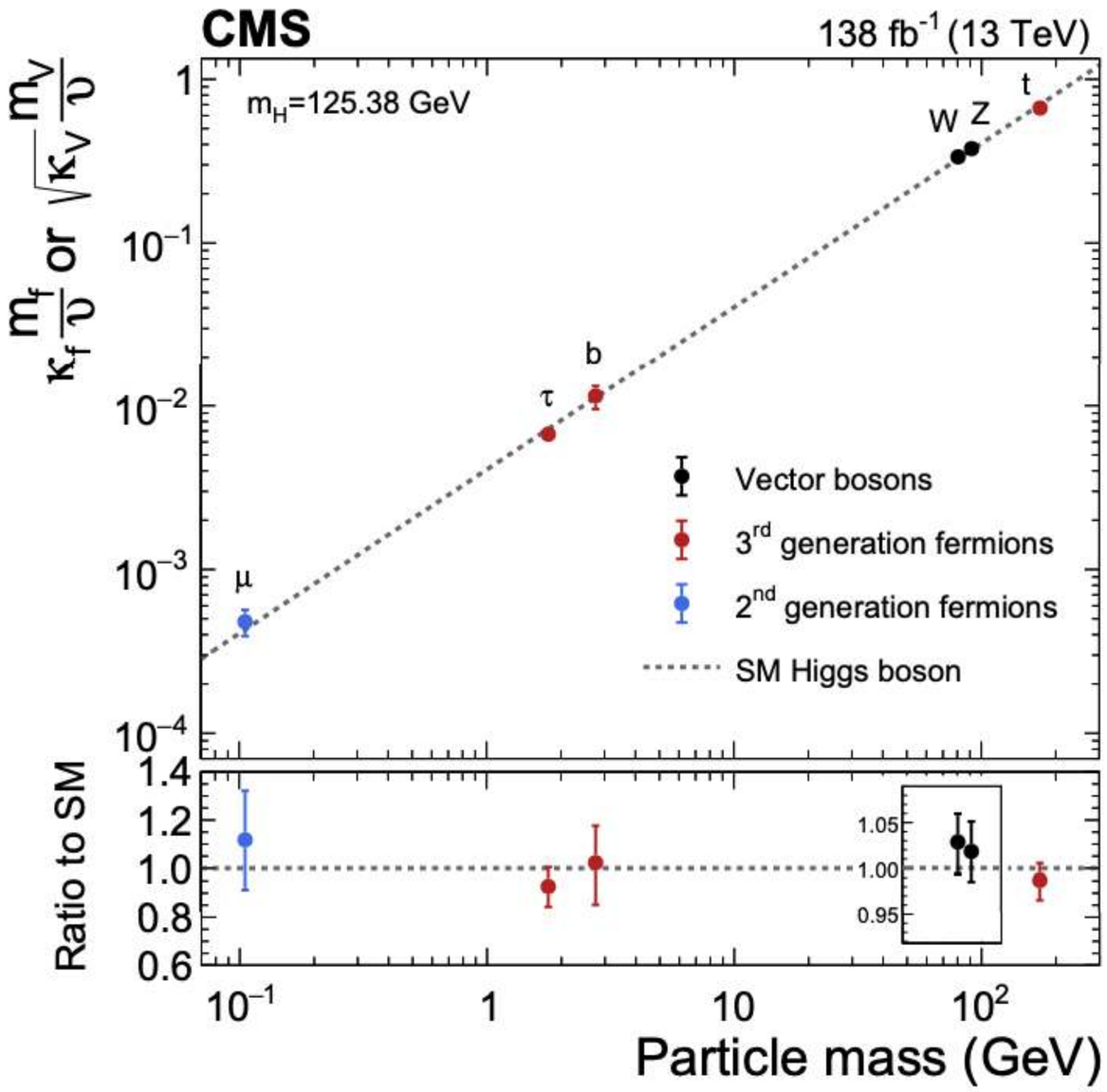


$H \to \mu\mu$ (first evidence, 2020)

[JHEP 01 (2021) 148]



Higgs-Boson Properties - status today



Summary

- After the discovery of the Higgs boson in 2012: **extensive measurements of its properties** at the LHC
  - Mass, width, spin, parity, couplings
- New analysis techniques such as the matrix-element method and neural networks allow to pursue difficult channels or observables
- Global combination of different coupling measurements allows to derive a consistent and uniform picture of the Higgs boson
  - So far, everything looks like a **SM Higgs boson**

What questions do you have?