Teilchenphysik II - W, Z, Higgs am Collider

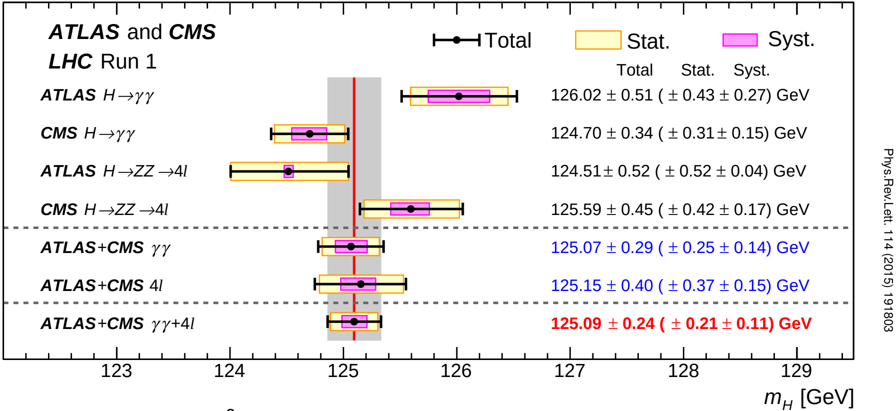
Lecture 12: Higgs Boson Properties

PD Dr. K. Rabbertz, **Dr. Nils Faltermann** | 14. Juli 2023

Recap

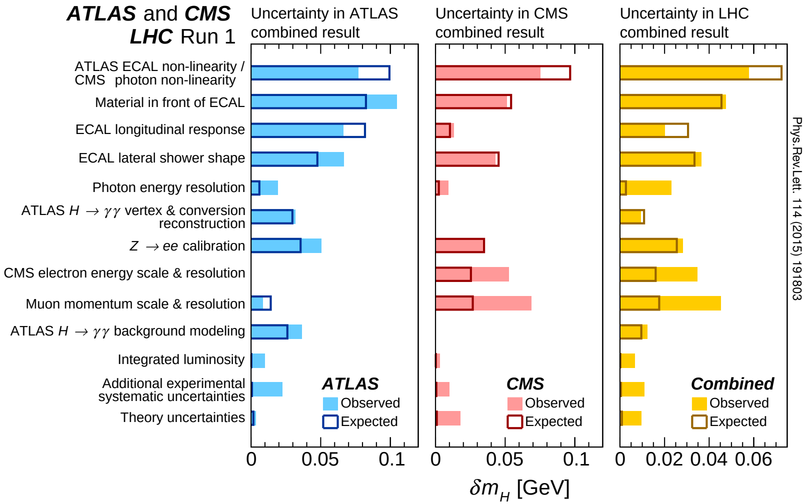
- Long-lasting **search for the Higgs boson** at LEP, Tevatron and LHC
- Last missing particle predicted by the Standard Model
  - W and Z boson @ Sp$\bar{\text{p}}$S in 1983
  - Top quark @ Tevatron in 1995
  - Tau neutrino @ DONUT in 2000
- Finally observed by the ATLAS and CMS collaborations at the LHC in 2012
  - Main discovery channels: $\mathbf{H \to \gamma\gamma}$, $\mathbf{H \to ZZ^{(*)} \to 4\ell}$ (mass peaks)
  - Other channels contributing: $\text{H} \to \text{WW}^{(*)} \to l\nu l\nu$, $\text{H} \to \tau\tau$, $\text{H} \to \text{b}\bar{\text{b}}$

Higgs-Boson Mass m_H: Run 1 Combination



- Measurement precision: $2 \cdot 10^{-3}$ → one of **most precisely known** SM parameters, still **statistics limited**
- Breakdown of systematic uncertainties: ± 0.11 (scale) $\pm$ 0.02 (others) $\pm$ 0.01 (theory) GeV
  → **energy scale** uncertainties dominant

Higgs-Boson Mass m_H: Uncertainties



Higgs-Boson Mass m_H: Combination

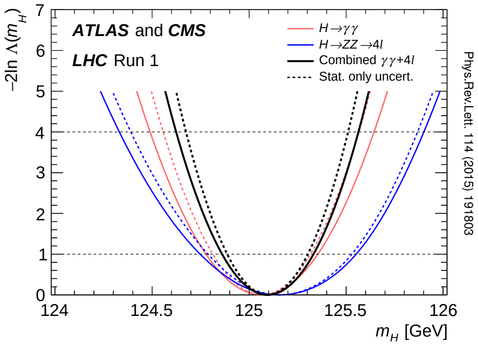
- Combination at level of **likelihoods**: minimise negative logartihm of **profile-likelihood ratio**

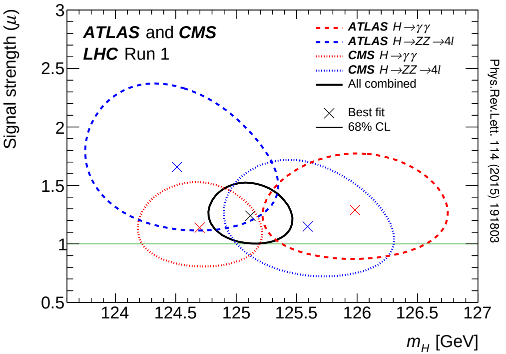
$$\Lambda(m_\mathrm{H}) = \frac{\mathcal{L}(m_\mathrm{H}, \hat{\hat{\theta}}(m_\mathrm{H}))}{\mathcal{L}(\hat{m}_\mathrm{H}, \hat{\theta})}$$

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

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

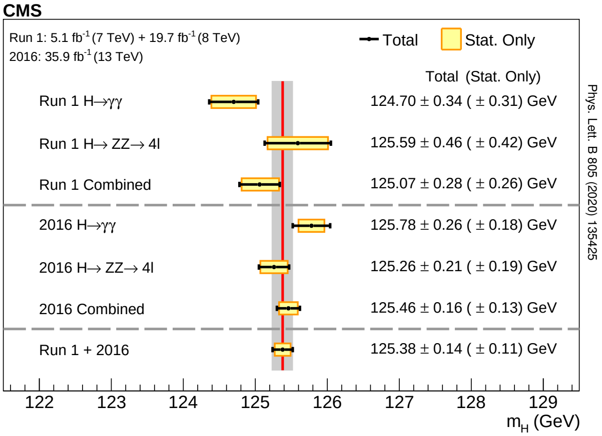
- Λ function of mass-dependent $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ signal strengths





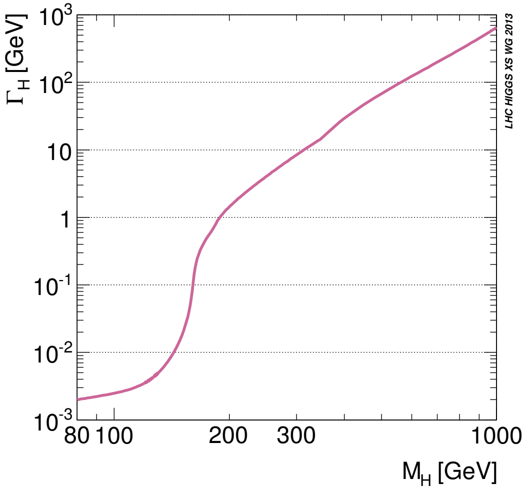
Higgs-Boson Mass m_H: Status Summer 2023

- Most precise measurement in $H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$ decay channels by the CMS Collaboration
- $m_H = 125.38 \pm 0.11\ (\text{stat}) \pm 0.08\ (\text{syst})$ GeV
- **Precision: $< 0.1\ \%$ level**



Higgs-Boson Width Γ_H

- Reminder: natural **total decay width Γ_H** of Higgs boson in SM **only 4 MeV**
  - Typical mass resolution in $H \rightarrow \gamma\gamma/4\ell$: **1–2.5 %** (1–3 GeV)
  - Measured Higgs line shape entirely **resolution dominated**



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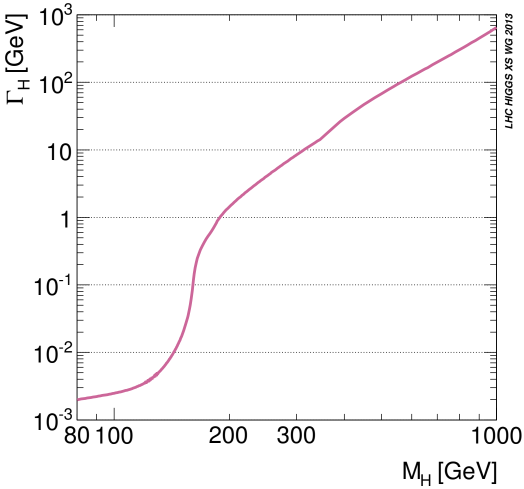
  - Typical mass resolution in $H \to \gamma\gamma/4\ell$: **1–2.5 %** (1–3 GeV)
  - Measured Higgs line shape entirely **resolution dominated**
- Ideas for Higgs-boson width **measurement**
  - **Direct** (model-independent): fit of Higgs line shape
  - **Indirect** (model-dependent): **off-shell effects**



Higgs-Boson Width Γ_H: Direct Measurement

- Invariant mass distribution of unstable particles with decay width Γ: **Breit–Wigner distribution**

$$\frac{d\sigma}{dm^2} \propto \frac{1}{(q^2 - m^2)^2 + m^2\Gamma^2} \quad \xrightarrow{\Gamma\to 0} \quad \frac{\pi}{m\Gamma}\delta(q^2 - m^2)$$

  - q: momentum transfer
  - $\Gamma \to 0$: **narrow-width approximation**
    $\to$ production and decay factorize

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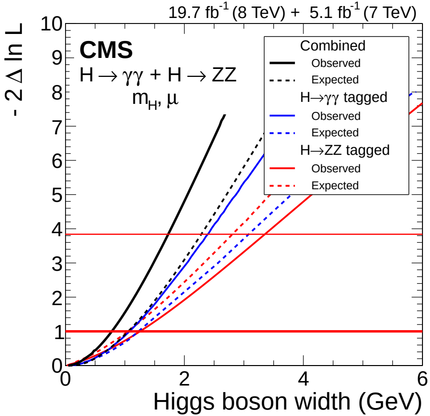
  - q: momentum transfer
  - $\Gamma \to 0$: **narrow-width approximation**
    $\to$ production and decay factorize
- Experimentally accessible: **convolution** of decay width and **detector resolution**
  - Decay channels: $H \to \gamma\gamma$, $H \to 4\ell$
  - Likelihood fit to signal model: consistent with $\Gamma_H = 0$
  - Upper 95 % CL limit (Run 1):
    $\Gamma_H <$ **1.7 GeV** (2.3 GeV expected)



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Higgs-Boson Width Γ_H: Indirect Measurement

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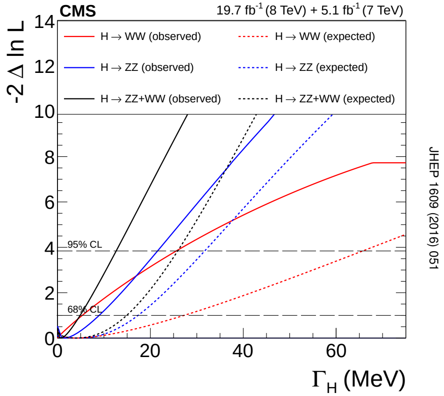
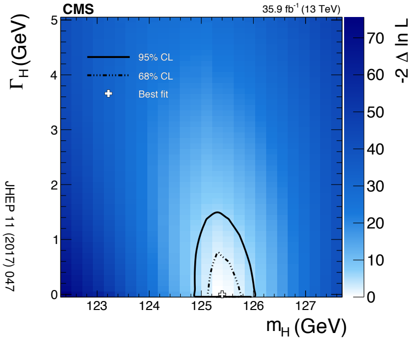
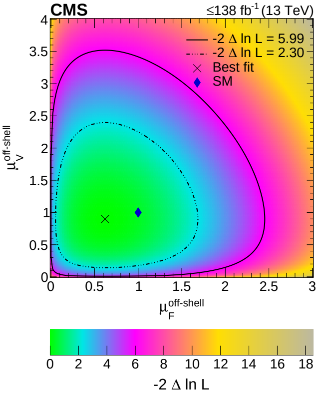
- Idea: **ratio of on-shell and off-shell Higgs-boson production** sensitive to Higgs-boson width

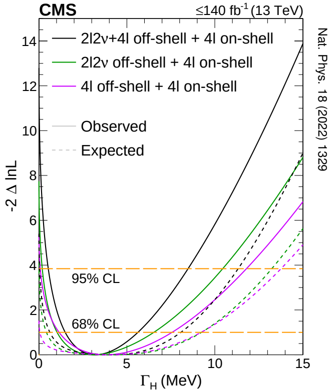
- $H \rightarrow ZZ \rightarrow 4\ell$:
  - On-shell: $105.6 < m_{4\ell} < 140.6\,\text{GeV}$
  - Off-shell: $220 < m_{4\ell} < 1600\,\text{GeV}$
- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$:
  - On-shell: $m_{\ell\ell} < 70\,\text{GeV}$
  - Off-shell: $m_{\ell\ell} > 70\,\text{GeV}$
- Combined 95 % CL limit: $\Gamma_H <$ **13 MeV** (26 MeV expected)



Higgs-Boson Width Γ_H: Status Summer 2023







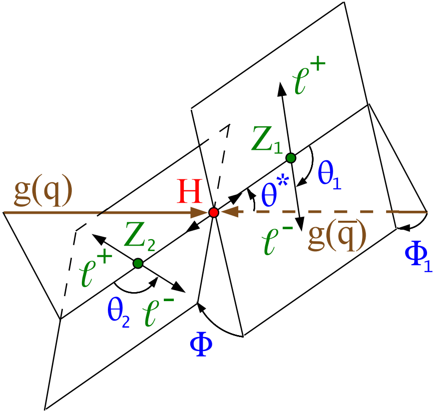
- Direct measurement: $\Gamma_H < 1.10\,\text{GeV}$ (95 % C.L.)
- From on-shell/off-shell ratio: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV, first evidence (3.6σ) for off-shell contribution
  - Assuming same couplings at high ZZ mass, no BSM particles, ...

Higgs-Boson Spin and Parity

- SM prediction for the Higgs boson are $J^P = 0^+$
- 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 $H \to \gamma\gamma$

Higgs-Boson Spin and Parity ($H \to ZZ \to 4\ell$)

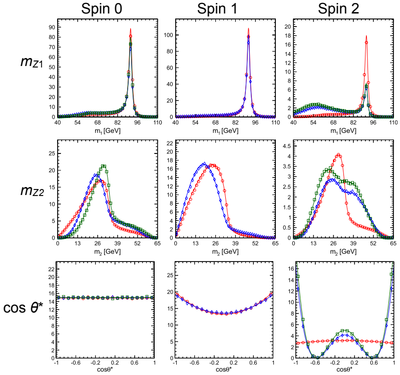
- Kinematics fully determined by
  - 2 masses m_{Z_1}, m_{Z_2}
  - Decay planes of $Z_{1,2}$:
    5 angles $\vec{\Omega} = (\theta^*, \phi_1, \phi, \theta_1, \theta_2)$
    - Polar angle of Z bosons (θ^*)
    - Azimuthal angle of Z_1 plane (ϕ_1)
    - Azimuthal angle of Z_2 plane relative to Z_1 plane (ϕ)
    - Polar angles of leptons relative to $Z_{1,2}$ ($\theta_{1,2}$)

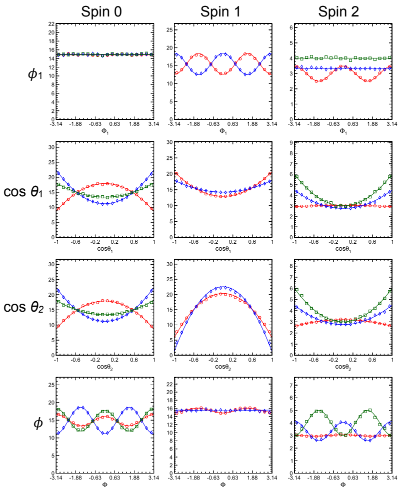


Handbook of LHC Higgs Cross Sections: 3. Higgs Properties

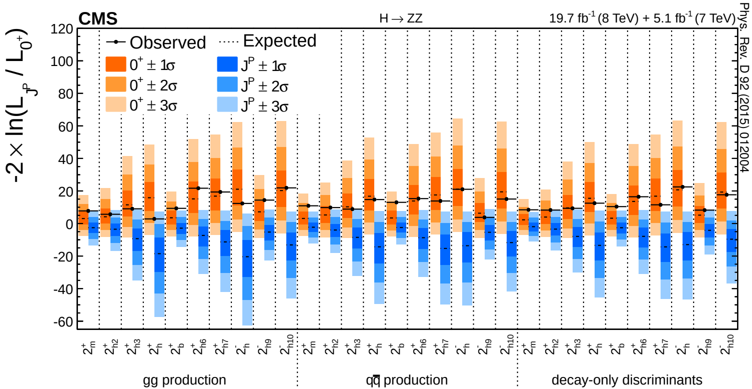
Higgs-Boson Spin and Parity (H $\rightarrow$ ZZ $\rightarrow 4\ell$)

- Prediction of angular distributions for decay of spin 0/1/2 particles to ZZ: hypothesis test:
  - J^+
  - J^+ with higher-dim. operators
  - J^-





Higgs-Boson Spin and Parity ($H \to ZZ \to 4\ell$)



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

Matrix-Element Method (MEM)

- Entire parton-level kinematics of a process contained in squared **scattering amplitude**
  $\rightarrow$ **"matrix element"** (ME)
- **Matrix-element method** (MEM): construct **event-based likelihood discriminant** that fully exploits all information from matrix element
  - Likelihood function for a given process contains **hard-scattering ME** for that process (see next slides)
  - For each event: ratio of likelihood functions for **observed set of kinematic variables $\vec{x}$** under signal hypothesis S and background hypothesis B_i

$$R(\vec{x}) = \frac{L(\vec{x}|S)}{L(\vec{x}|S) + \sum_i c_i L(\vec{x}|B_i)}$$

Matrix Element and Phase Space

- Main ingredient of event-based likelihood: **parton-level cross sections** for signal and (main) backgrounds

1. Consider cross section for all processes pp $\to y$ under hypothesis H with parton-level kinematics $\vec{y}$ that could have led to the reconstruction-level final state x with kinematics $\vec{x}$

$$\sigma_H(\mathrm{pp} \to y) = \sum_{jk}^{\text{partons}} \int \frac{\mathrm{d}z_j \mathrm{d}z_k}{z_j z_k s} \underbrace{f_j(z_j) f_k(z_k)}_{\text{PDFs}} \underbrace{|\mathcal{M}_H(jk \to y)|^2}_{\text{matrix element}} \underbrace{(2\pi)^4 \mathrm{d}\Phi_H}_{\text{phase space}}$$

- Approach uses **QCD factorisation** theorem:
  - PDFs f_j, f_k
  - Hard-scattering matrix element $\mathcal{M}_H$
  - Lorentz-invariant phase-space volume element $\mathrm{d}\Phi_H$

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- Current implementations: **LO** ME, first attempts at NLO
- **Integration** over all unobserved variables in the event: parton momentum fractions, phase-space element $\rightarrow$ often **numerically expensive** (limiting factor)

Transfer Functions

2. **Transfer functions $W(\vec{x}|\vec{y})$**: translation from parton-level final-state to **reconstruction level**
   - Account for limited **detector resolution** and **combinatorics** in matching parton-level and reconstruction-level objects (esp. quarks/gluons $\rightarrow$ jets)

$$\sigma_H(\mathrm{pp} \rightarrow x) = \int \mathrm{d}\vec{y}\ \sigma_H(\mathrm{pp} \rightarrow y)\ \boxed{W(\vec{x}|\vec{y})}$$

   - Transfer functions determined from MC simulation

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3. **Normalisation** to (fiducial) cross section σ_H^α

$$\sigma_H^\alpha = \int \mathrm{d}\vec{x}\mathrm{d}\vec{y}\ \sigma_H(\mathrm{pp} \rightarrow y) \boxed{W(\vec{x}|\vec{y})}\ \boxed{\alpha(\vec{x})}$$

with acceptance $\alpha(\vec{x}) \in [0, 1]$ for single event with kinematics $\vec{x}$

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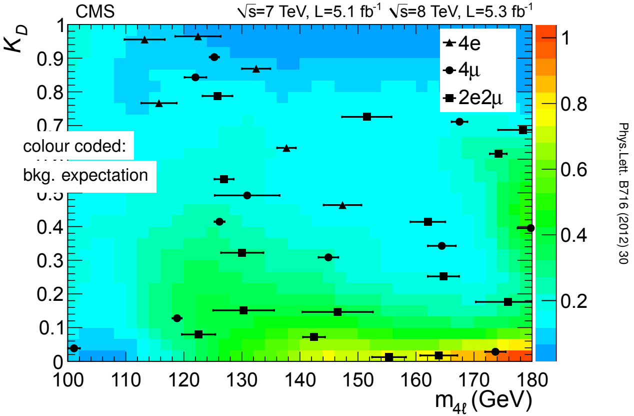
   with acceptance $\alpha(\vec{x}) \in [0, 1]$ for single event with kinematics $\vec{x}$
4. **Likelihood** of event under hypothesis $H = S, B_i$

$$\boxed{L(\vec{x}|H) = \frac{\sigma_H(\mathrm{pp} \rightarrow x)}{\sigma_H^\alpha}}$$

MEM Application: MELA

- Application of MEM to angular analysis of $H \to ZZ \to 4l$
- **MELA**: Matrix Element Likelihood Analysis $\to$ already applied for CMS Higgs boson discovery analysis
- **Purely leptonic** final state: **no phase space intergration and transfer functions** required



- MELA discriminant

$$K_D = \frac{L(m_{Z_1}, m_{Z_2}, \vec{\Omega}; m_{4l}|H_S)}{L(m_{Z_1}, m_{Z_2}, \vec{\Omega}; m_{4l}|H_S) + L(m_{Z_1}, m_{Z_2}, \vec{\Omega}; m_{4l}|H_B)}$$

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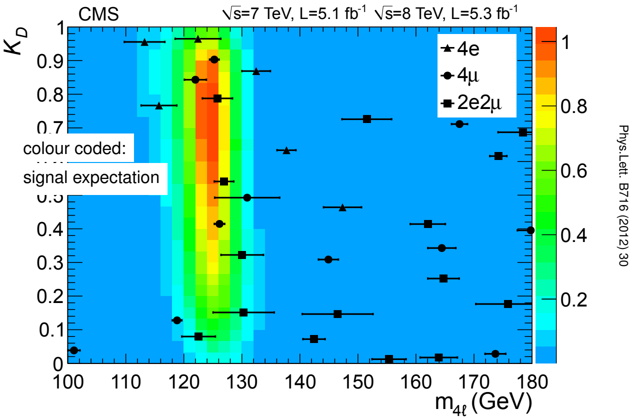

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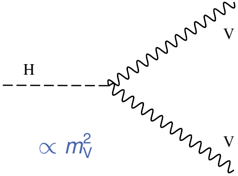
What Should We Do With the Higgs Boson?

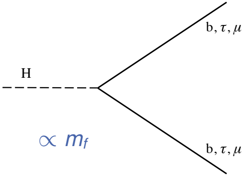
The Standard Model Higgs Boson:

Coupling to gauge bosons



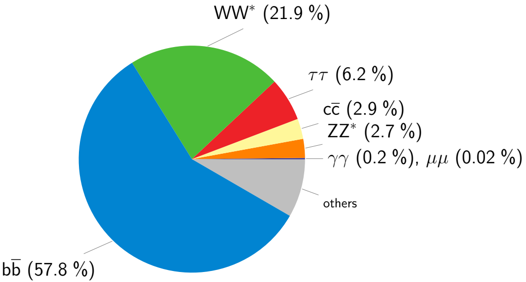
$\propto m_V^2$

Yukawa coupling to fermions



$\propto m_f$

Branching ratios



Measure properties as precisely as possible!

Probe all possible couplings

$\rightarrow$ Test of the SM and probe of new physics

Higgs Boson: Status Summer 2023

- Higgs-boson signal **firmly established**
  - Main discovery channels: H $\rightarrow \gamma\gamma$, H $\rightarrow$ ZZ$(^*) \rightarrow 4l$ (mass peaks)
  - Other channels contributing: H $\rightarrow$ WW$(^*) \rightarrow l\nu l\nu$, H $\rightarrow \tau\tau$, H $\rightarrow b\bar{b}$
  - 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
  - **Observation** ($5\,\sigma$) or **evidence** ($3\,\sigma$) in many **individual decay channels**, often combining **several production modes**

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- In the following: **recent Higgs-boson production results** and current topics

Production and Decay Modes Studied

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rate ← (increasing toward ggH)

purity ↓ / rate ↑

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

Direct Coupling Measurements

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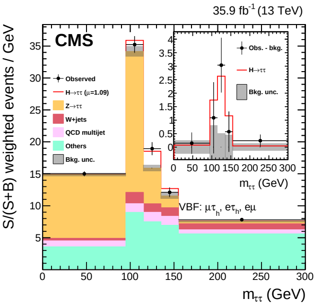
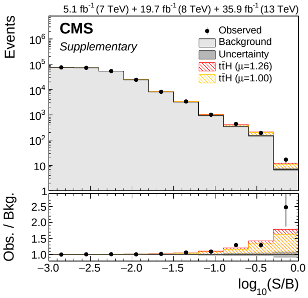
- Couplings to bosons observed with 5 σ significance during Run 1
- Run 2: direct measurement of Higgs-fermion couplings
- **Observation of couplings to 3rd-generation fermions**

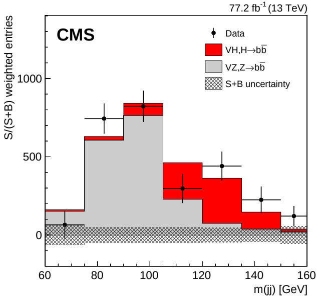
$H \to \tau\tau$ (2017)
[PLB 779 (2018) 283]



$t\bar{t}H$ (2018)
[PRL 120 (2018) 231801]



$H \to b\bar{b}$ (2018)
[PRL 121 (2018) 121801]

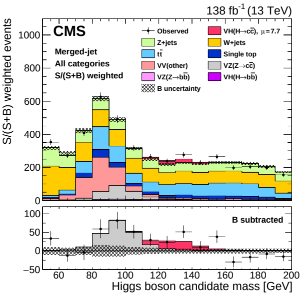


Direct Coupling Measurements

- 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**

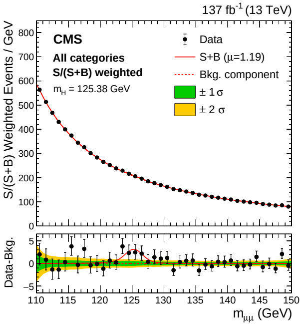
H $\rightarrow$ c$\bar{c}$ ($\mu < 14$, 2022)

[CMS-HIG-21-008, Submitted to PRL]



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

[JHEP 01 (2021) 148]



Probing Yukawa Couplings

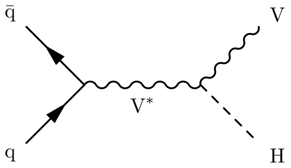
- Entirely new sector of the SM:
  - Higgs boson is the **only** fundamental boson of the SM to exhibit Yukawa couplings
- Fermion interactions illuminate nature of Higgs sector independently from gauge bosons
- Measuring Higgs-fermion couplings probes the mechanism that generates the masses of the fundamental fermions, including the electron

  $\rightarrow$ Responsible for the stability of atoms!

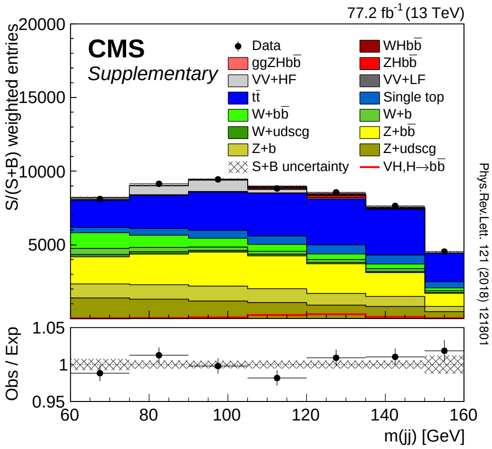
Example: Bottom-Higgs Coupling

- Measured in $H \to b\bar{b}$ decays
- $H \to b\bar{b}$ dominant decay channel but huge QCD background at the LHC

$\to$ **Most sensitive channel: associated W/Z production**



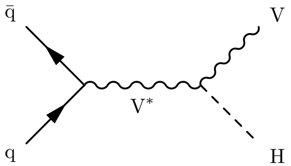
- Background reduced by requiring high-p_T V boson



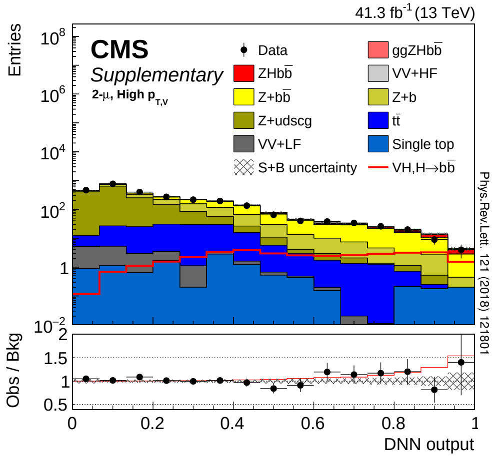
Example: Bottom-Higgs Coupling

- Measured in $H \rightarrow b\bar{b}$ decays
- $H \rightarrow b\bar{b}$ dominant decay channel but huge QCD background at the LHC

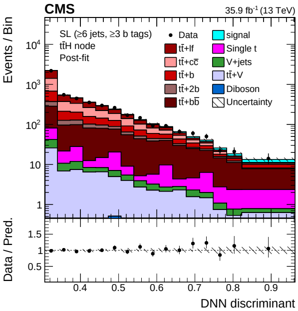
$\rightarrow$ **Most sensitive channel: associated W/Z production**



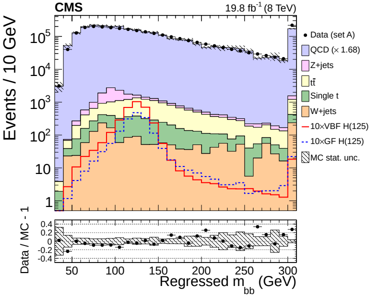
- Background reduced by requiring high-p_T V boson
- Signal extraction using MVA-based observable:
  - $4.4\,\sigma$ ($4.2\,\sigma$) observed (expected) significance



Further Channels Sensitive to H $\rightarrow b\bar{b}$



JHEP 1903 (2019) 026



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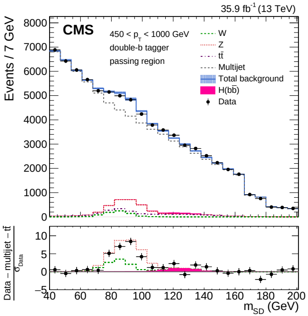
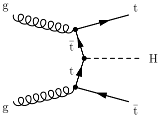
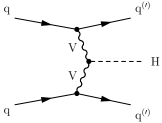
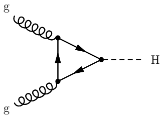


Phys.Rev.Lett. 120 (2018) 7



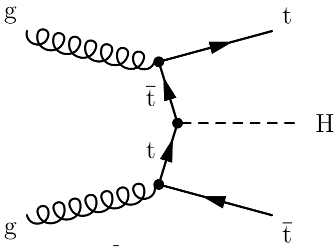




Common approach: **Higgs boson recoiling against other objects**

Example: Top-Higgs Coupling

- **Important property of the Higgs boson**
  - By far the largest Yukawa coupling
    $\rightarrow$ Strong impact on SM and BSM physics
- Indirect constraints from gluon-fusion production and $H \rightarrow \gamma\gamma$ decays ($\rightarrow$ later)
  - Model dependent: assuming only SM contributions in loops



$t\bar{t}H$ production

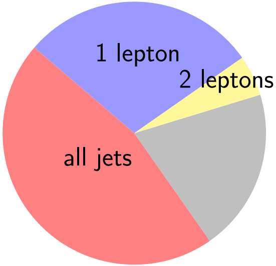
$t\bar{t}$ associated Higgs boson production ($t\bar{t}H$):
best direct probe of top-Higgs coupling

$t\bar{t}H$ Measurements at the LHC

Karlsruhe Institute of Technology

- Small production cross-section: **0.5 pb at 13 TeV/13.6 TeV**
- **Multitude of possible final states with many objects**

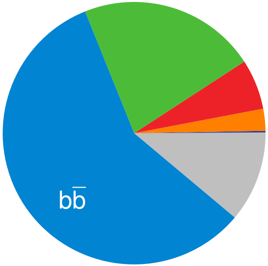
$t\bar{t}$ decay channels



lepton: electron, muon

×

Higgs boson decay channels



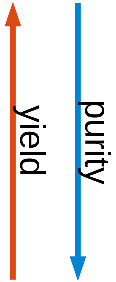
$H \rightarrow b\bar{b}$

$H \rightarrow WW^{*}/\tau\tau/ZZ^{*}$

"multi-lepton analysis"

$H \rightarrow \gamma\gamma$

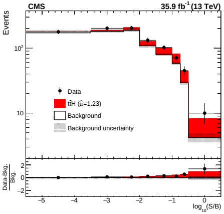
$H \rightarrow ZZ^{*} \rightarrow 4l$



Different challenges → dedicated analysis techniques per channel

Combination of $t\bar{t}H$ Searches

- Analyses with 2016 data



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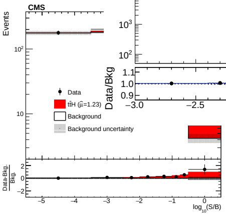

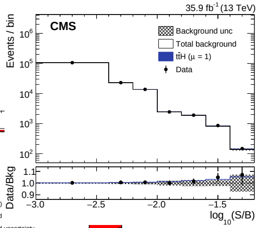

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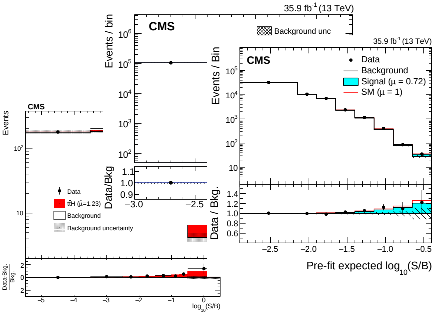

Combination of $t\bar{t}H$ Searches

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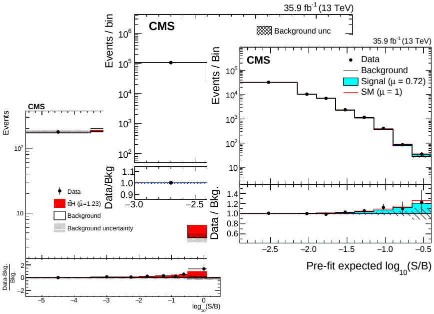
  - $+$ Run 1 $b\bar{b}$, multi-lepton, $\gamma\gamma$ analyses



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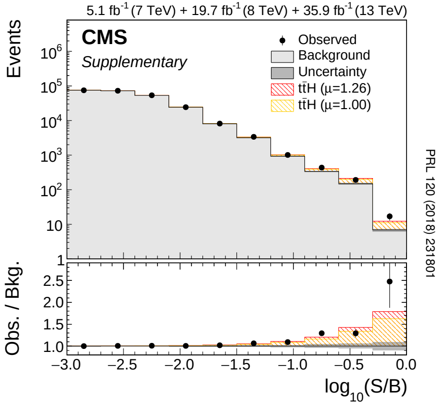

- Experimental uncertainties largely uncorrelated between Run 1 and 2
- Signal and some background theory uncertainties correlated

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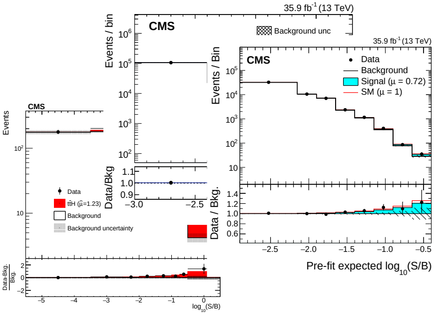

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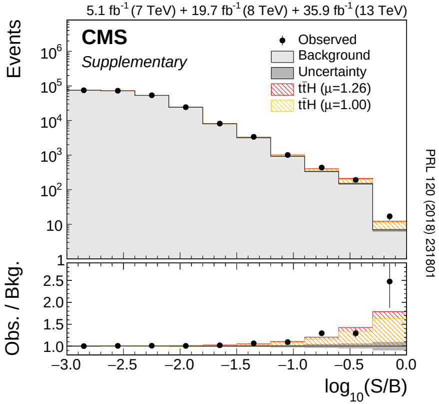
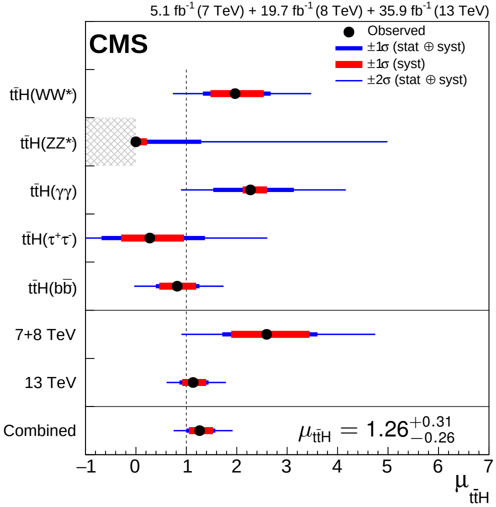


- Experimental uncertainties largely uncorrelated between Run 1 and 2
- Signal and

5.2 σ (4.2 σ) observed (expected) significance

Observation of $t\bar{t}H$ production process

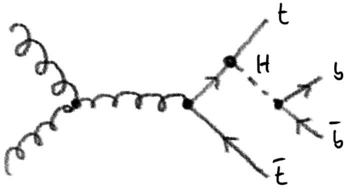
Combination of $t\bar{t}H$ Searches

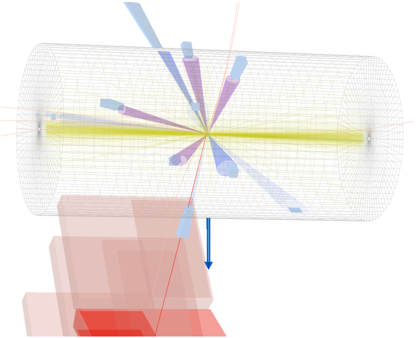


PRL 120 (2018) 231801

Example: $t\bar{t}H$ with $H \rightarrow b\bar{b}$

- **Among the most sensitive channels**
- Large branching ratio of 58 % $\rightarrow$ **large rate** ($\sigma \cdot \mathcal{B} \approx 295$ fb)





Example: $t\bar{t}H$ with $H \to b\bar{b}$

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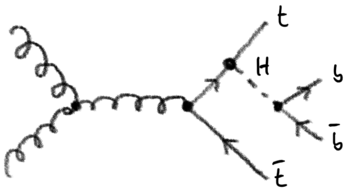
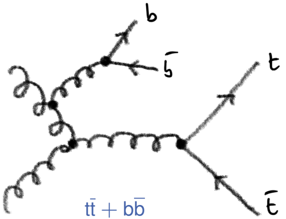
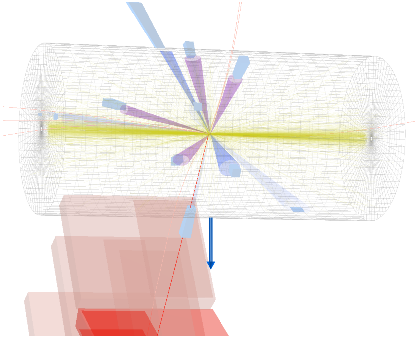




$t\bar{t} + b\bar{b}$
(10–20 × signal)



- But **challenging final state**:
  - Large (irreducible) background due to $t\bar{t} + b\bar{b}$ with **large uncertainties**
  - Many jets: no unambiguous event reconstruction

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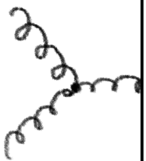

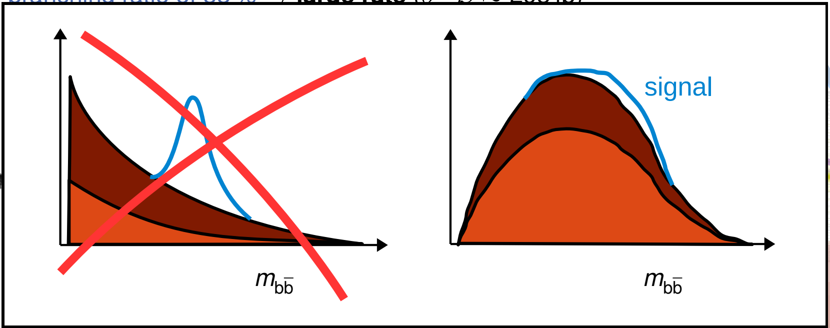

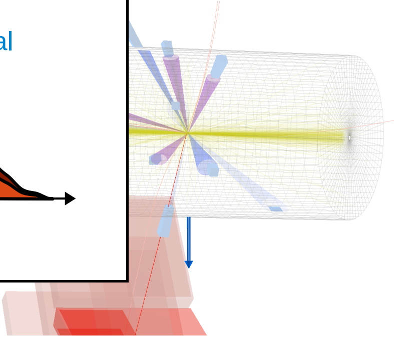

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Example: $t\bar{t}H$ with $H \rightarrow b\bar{b}$

- Prime example of machine learning in LHC analysis
  - Discriminating observable $\rightarrow$ separate signal from background
  - Categorisation $\rightarrow$ background control regions to constrain uncertainties
- Many other applications:
  - Object identification
  - Jet-flavour tagging
  - B-jet energy regression
  - Event reconstruction

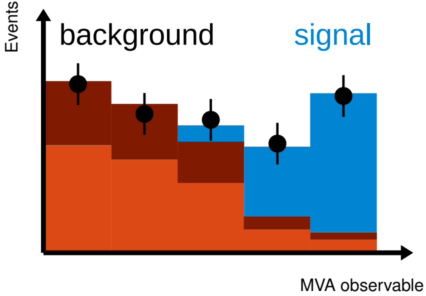
Much progress since first $t\bar{t}H$ analysis

e. g. binary-classification BDT $\longrightarrow$ multi-classification Neural Network

Active development testing more advanced concepts

Typical Multivariate Analysis

- Various input variables → single discriminating observable
  - Kinematics of jets and leptons, b-tagging information, event topology. . .
  - Additional information from correlations



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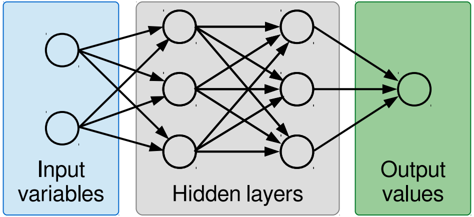
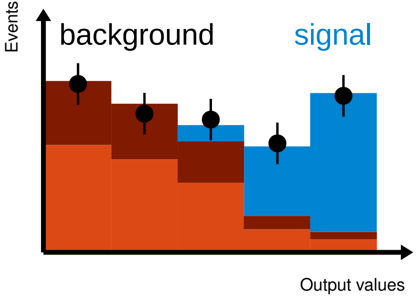
Example: Artificial Neural Network
(feed forward fully-connected network)





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$$f\left(\sum w_i \cdot y_{\text{in},i} + b\right) = y_{\text{out}}$$

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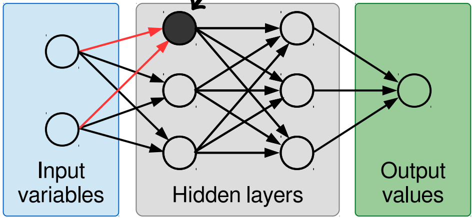

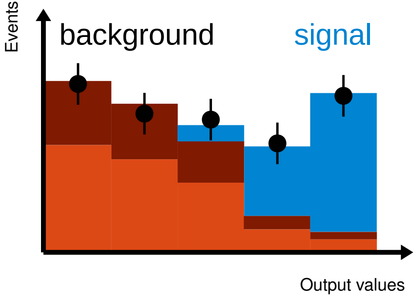

Typically *supervised learning* with simulated data to find optimal values for w_i, b

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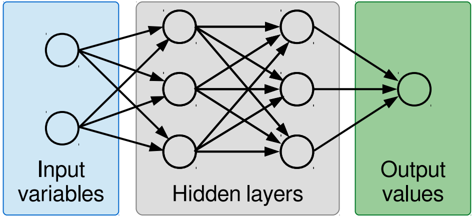
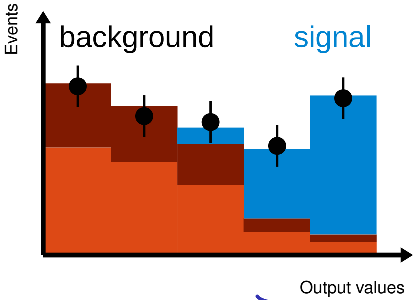
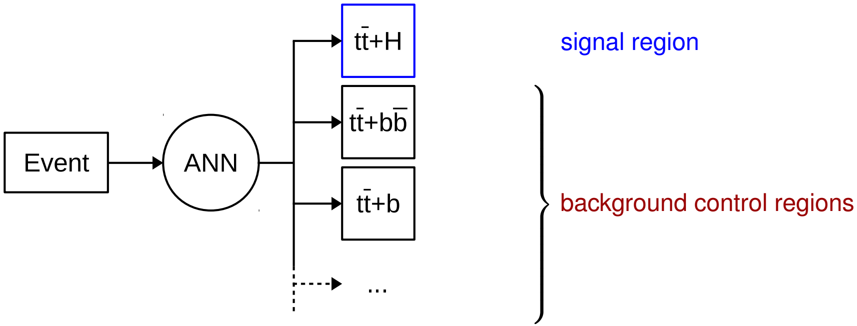


Function
$\mathbb{R}^n \rightarrow \mathbb{R}: \; g(\text{input variables})$



Application in $t\bar{t}$ Single-Lepton Channel

Events preselected by lepton and jet multiplicity



Artificial Neural Network (ANN) for **multi-classification**:

Several output values: *how compatible is event with certain process?*

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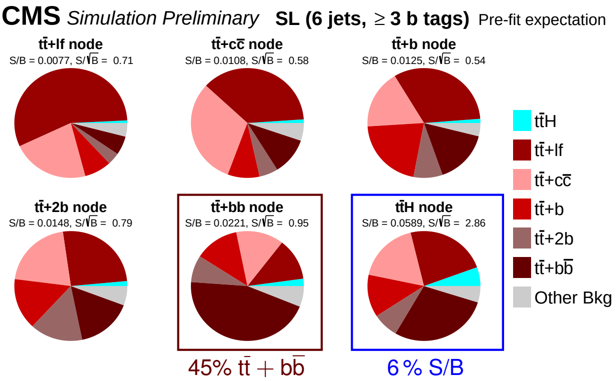

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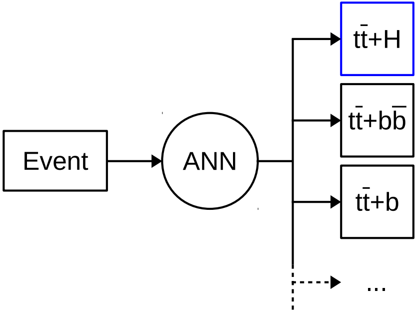

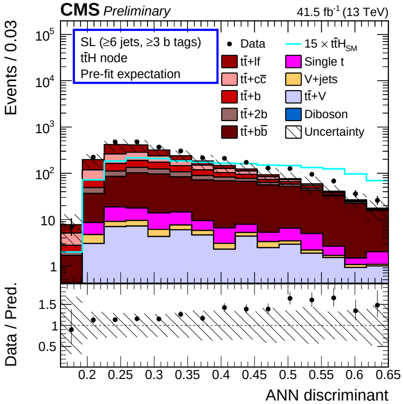

Artificial Neural Network (ANN) for **multi-classification**:

Final discriminant: ANN output in chosen process category

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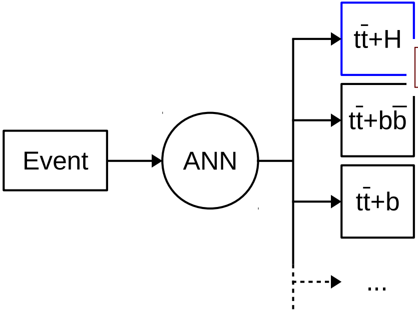

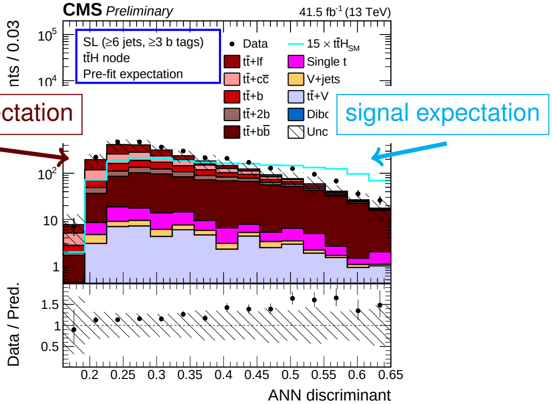

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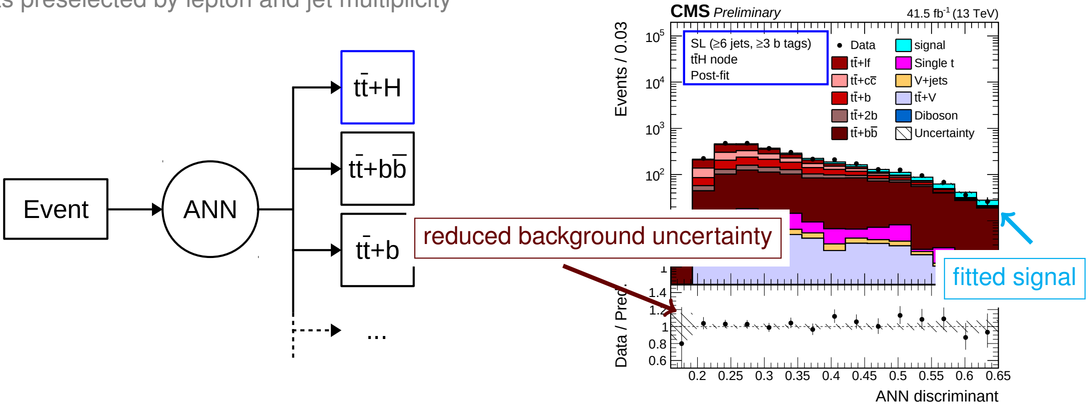

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Signal-Strength Modifier

- 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 $\Gamma_\mathrm{H} = 4.1\,\mathrm{MeV}$)

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

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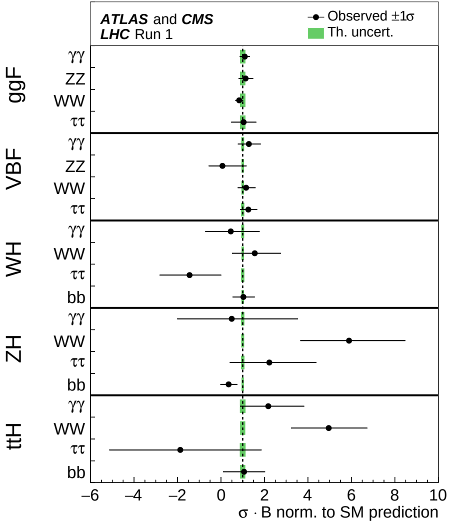
- Reminder: branching fraction = fraction of total width, i. e.

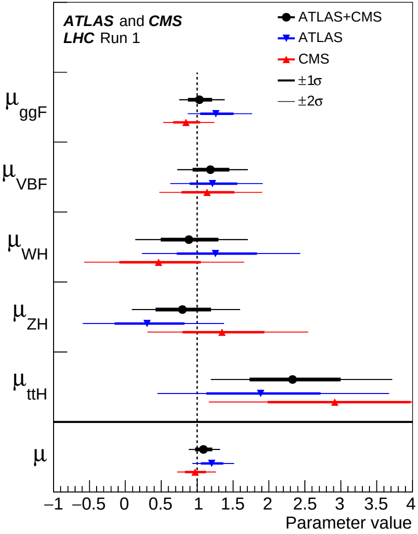
$$\mathcal{B}(\mathrm{H} \to f) \equiv \mathcal{B}^f \equiv \Gamma^f / \Gamma_\mathrm{H}$$

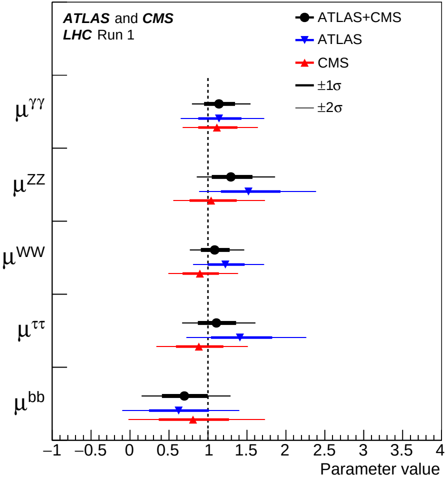
Independent Production × Decay Results

- **Independent products** of cross sections and branching fractions
- **Most sensitive** combinations of production mode and decay channel:
  - gg fusion (ggF): $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$
  - Vector boson fusion (VBF): $H \to \gamma\gamma$, $H \to WW$, $H \to \tau\tau$



Combined Signal Strengths





Kappa Framework

- 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

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- **Coupling modifiers** $\boldsymbol{\kappa}$ for Higgs-boson coupling vertex to SM particles

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

  - $\kappa_{i,f} = 1$: coupling as predicted by SM

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  - $\kappa_{i,f} = 1$: 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**

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

Kappa Framework: Production

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	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

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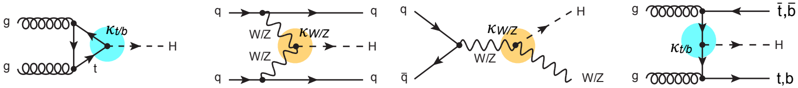
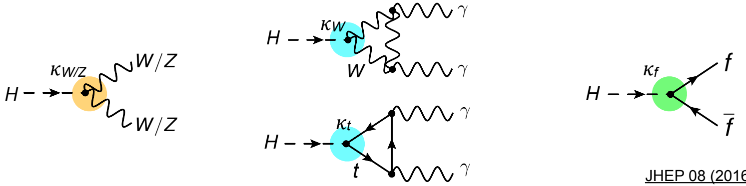


Kappa Framework: Decay

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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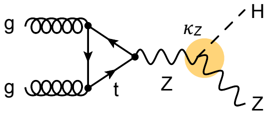
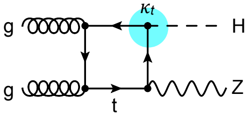
Kappa Framework: Interference Effects

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





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

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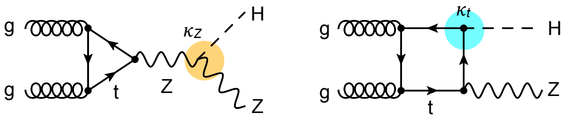
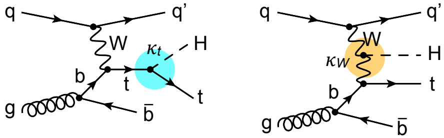


$\sim 2.27\kappa_Z^2 + 0.37\kappa_t^2 - 1.64\kappa_Z\kappa_t$

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



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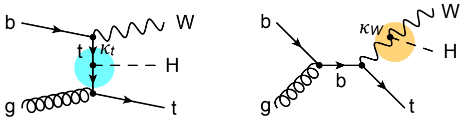

$\sim 1.84\kappa_t^2 + 1.57\kappa_W^2 - 2.41\kappa_t\kappa_W$

Kappa Framework

- **Effective coupling modifiers** may be used for loop-induced couplings to gluons κ_g and photons κ_γ (loops not resolved)

Kappa Framework

- **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:
  - $\kappa_{\mathrm{c}} = \kappa_{\mathrm{t}}$
  - $\kappa_{\mathrm{s}} = \kappa_{\mathrm{b}}$
  - $\kappa_\mu = \kappa_\tau$
  - $\kappa_{\mathrm{u}} = \kappa_{\mathrm{d}} = \kappa_{\mathrm{e}^-} = 1$

Kappa Framework

- Changes of couplings cause change of the **total width**
  - **Most general** case: introduce additional modifier for the total width:

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

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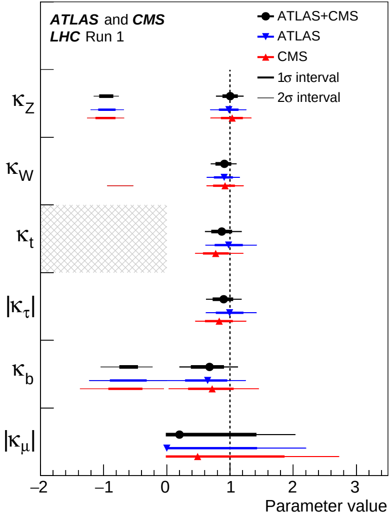
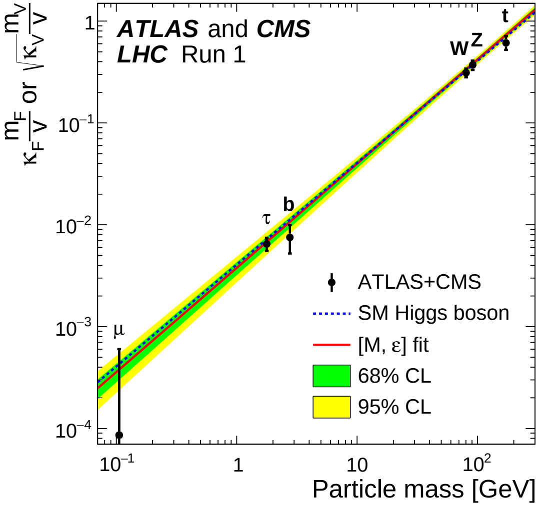
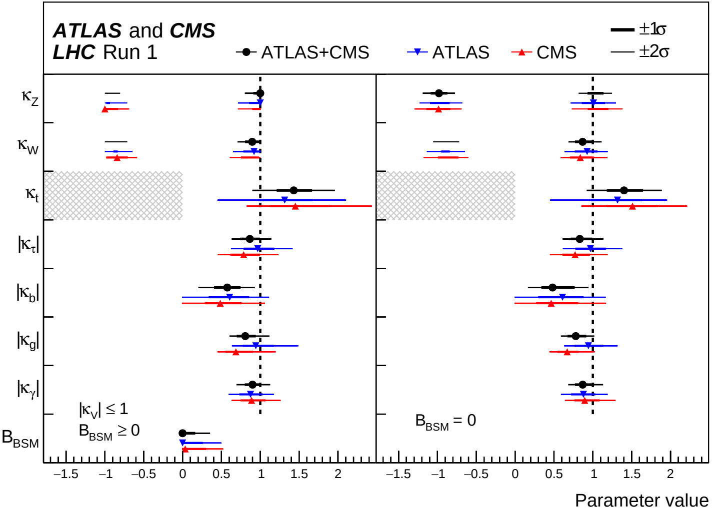
  - Currently: **total width not constrained** at LHC in model-independent way
    → only **ratios of coupling modifiers** accessible
  - Total width accessible only **indirectly** at the LHC, directly at **future ee colliders** in $e^+e^- \to ZH$ (later)

κ (Resolved Loops)





κ (Loops $\rightarrow$ Effective Couplings)

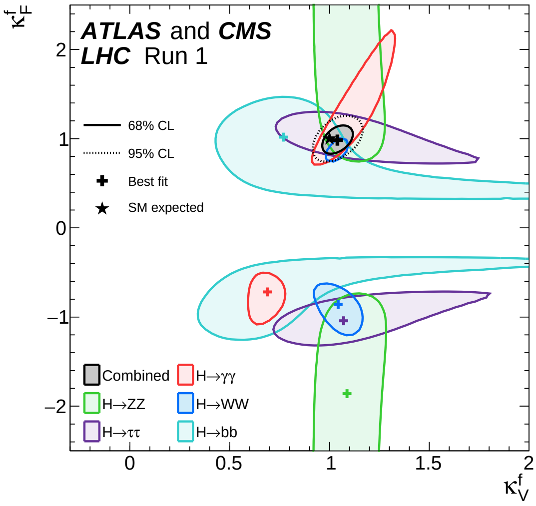


- Effectively allows contributions from BSM particles in the loops
- Case $\mathcal{B}_{\text{BSM}} \geq 0$: BSM contributions allowed also in decays

κ: Fermion/Boson Coupling

Karlsruhe Institute of Technology

- Sensitivity to **relative sign** of fermion and boson coupling from **interference** terms in H $\rightarrow \gamma\gamma$ decays
- Opposite sign of fermion and boson couplings **excluded** at almost 5 σ



Beyond the Kappa Framework

- Kappa framework only allows modification of coupling strength, i. e. can modify rate but not kinematic of a process
- Effects of BSM physics may be more subtle
  $\rightarrow$ LHC Run 2 (and beyond): **more sophisticated** approaches

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Beyond the Kappa Framework

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- Effects of BSM physics may be more subtle
  $\rightarrow$ LHC Run 2 (and beyond): **more sophisticated** approaches
- Interpretation: effective field theory (EFT)
- Measurement:
  - Fiducial cross sections in easy-to-reproduce phase space
  - Simplified template cross sections (STXS): fiducial cross-sections in exclusive phase-space regions (“bins”), e. g. in p_T (H), separately per Higgs boson production channel
  - Differential cross-section measurements

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**