Karlsruhe Institute of Technology

Institut für Experimentelle Teilchenphysik

Teilchenphysik II - W, Z, Higgs am Collider

Lecture 13: Higgs Boson Properties and Beyond

PD Dr. K. Rabbertz, **Dr. Nils Faltermann** | 21. Juli 2023

Summary on Higgs Boson Properties

- Higgs boson discovered in 2012
  - Not much known about the “new boson” by that time
  - Situation drastically changed during the subsequent years
- Precision measurement of its properties
  - 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**

Differential Cross Section

- So far: **reconstructed** distributions of kinematic observables compared to expected distributions (from MC simulation and/or data)
  - All physics effects **forward-folded** with detector effects, e. g. resolution
  - Problem: distributions **cannot be compared** between experiments or with theory calculations

Differential Cross Section

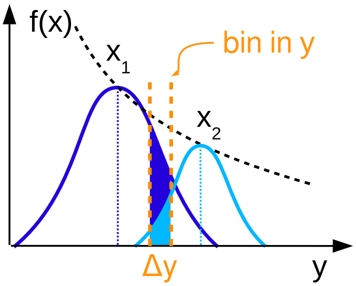
- So far: **reconstructed** distributions of kinematic observables compared to expected distributions (from MC simulation and/or data)
  - All physics effects **forward-folded** with detector effects, e. g. resolution
  - Problem: distributions **cannot be compared** between experiments or with theory calculations
- A solution: measurements presented as **differential** cross sections = cross sections as a function of one or more kinematic observable
  - Detector effects corrected by **unfolding** procedure
  - Typical result: **fiducial** differential cross section at level of **stable particles**
  - Differential distributions contain **more information** on physics processes than **inclusive** cross sections: more detailed **comparison with theory**
- Main channels: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$

Unfolding Techniques

- Determine true distribution $f(\vec{x})$ from reconstructed distribution $g(\vec{y})$
  - Relation: Fredholm integral equation

$$g(\vec{y}) = \int R(\vec{y}|\vec{x})\, f(\vec{x})\, \mathrm{d}\vec{x} + b(\vec{y}) = \int \alpha(\vec{y}|\vec{x})\epsilon(\vec{x})\, f(\vec{x})\, \mathrm{d}\vec{x} + b(\vec{y})$$

  - $\vec{y}$: observed (reconstruction level) kinematics, $\vec{x}$: "true" kinematics
  - $R(\vec{y}|\vec{x})$ **transfer function** = **acceptance** $\alpha(\vec{y}|\vec{x}) \times$ **efficiency** $\epsilon(\vec{x})$
  - $b(\vec{y})$: **background** distribution



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  - $b(\vec{y})$: **background** distribution

- Solving for $f(\vec{x})$: **ill-posed** mathematical problem, typical solution
  - First step: discretisation (=histogram) + response/migration matrix R

$$\boxed{g_i = \sum_{j=1}^{m} R_{ij} f_j + b_i}$$

i : bin observed distribution g
j : bin "true" distribution f

  - $R \approx$ diagonal: **bin-by-bin correction factors** c_i: $g_i = c_i f_i + b_i$
  - **Matrix inversion**: numerically unstable due to **statistical fluctuations**
    $\rightarrow$ additional assumption: **smooth** distributions ("regularisation")

Bin-by-Bin Unfolding (H → ZZ → 4l)

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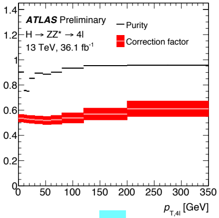
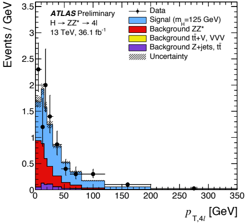
H → ZZ → 4ℓ:
clean signature, high **purity** (i.e. response matrix almost diagonal)
→ **bin-by-bin** unfolding

Correction Factors



Reconstructed $p_T(4\ell)$



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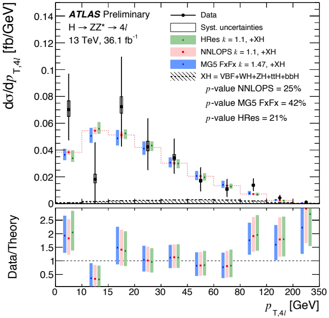
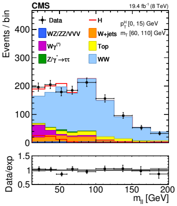
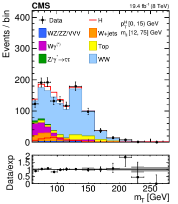


ATLAS-CONF-2017-032

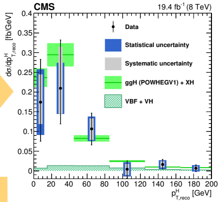
Matrix Unfolding (H $\rightarrow$ WW)

Fit to $m_{\ell\ell}$ and m_T in bins of $p_T(H)$

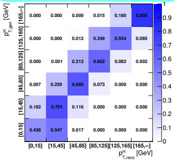




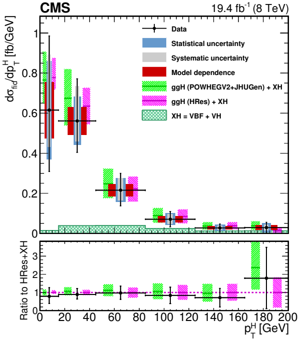
Reconstructed $p_T(H)$ distribution



Response matrix



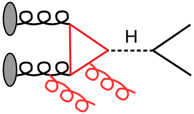
Unfolded $p_T(H)$ distribution

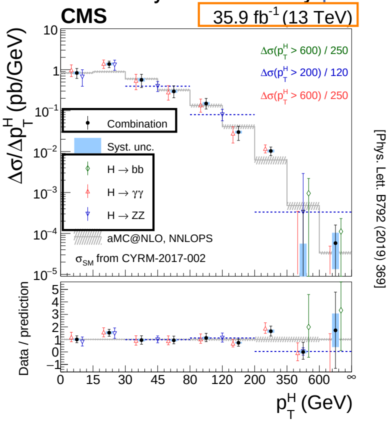


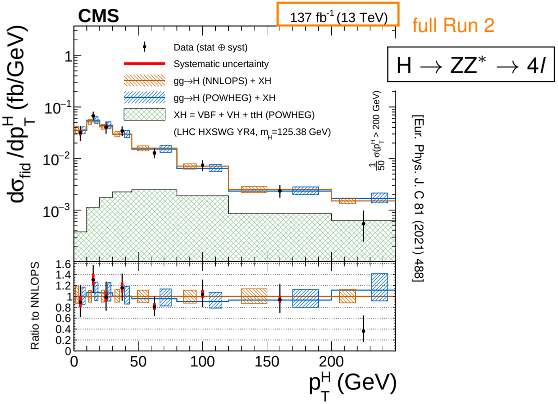
JHEP 03 (2017) 032

Example: Higgs-Boson p_T

- Probes modelling of dominant ggH production mode
- Sensitivity to new heavy particles in the loop







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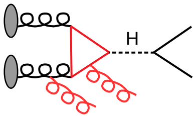

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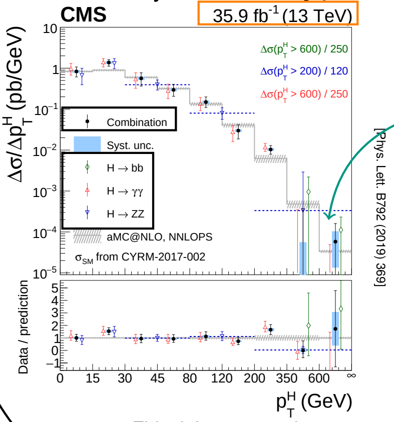
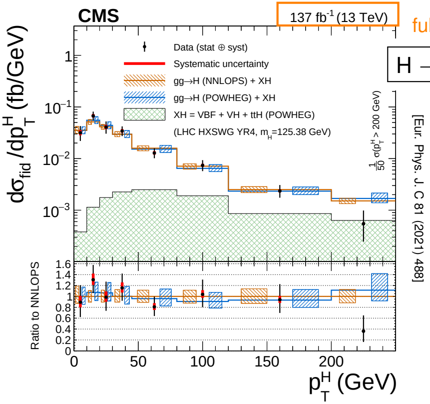


Boosted $H \to b\bar{b}$ improves sensitivity at high p_T



Fiducial cross-section measurements in each channel, extrapolated to full phase-space for combination

Example: Higgs-Boson p_T

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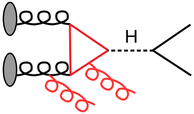
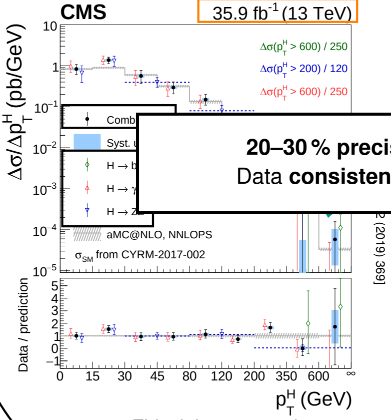
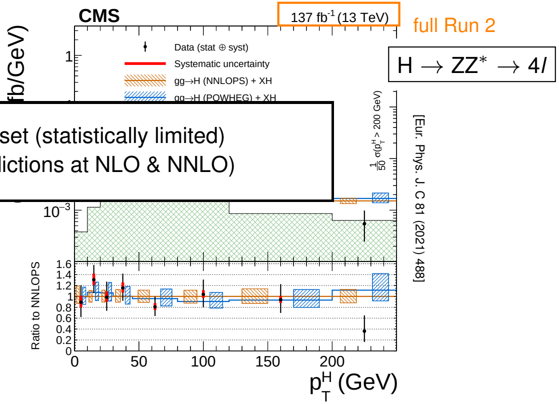


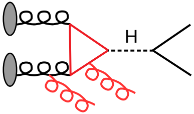




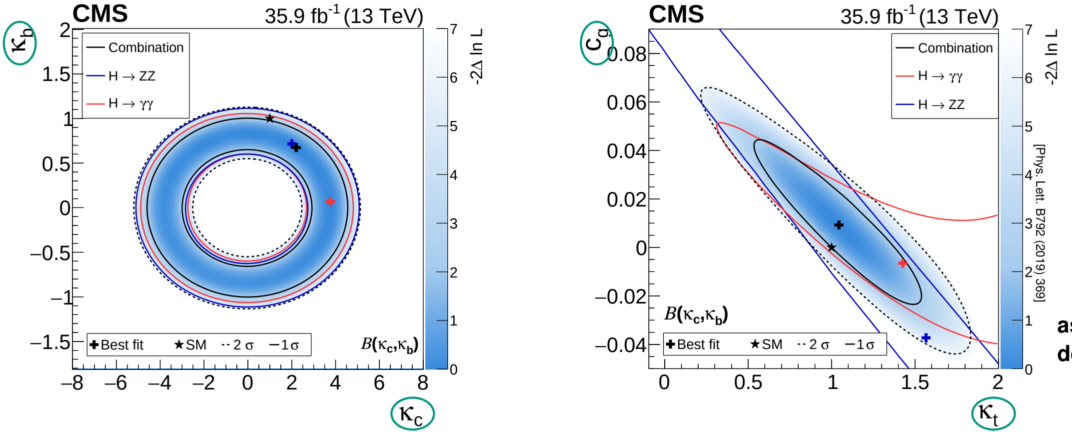
20–30 % precision with full Run 2 dataset (statistically limited)
Data **consistent with SM** (different predictions at NLO & NNLO)

Fiducial cross-section measurements in each channel, extrapolated to full phase-space for combination

Example: Higgs-Boson p_T



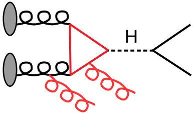
- Constraints on other Higgs-boson couplings
  - Yukawa couplings to top, bottom, charm quarks
  - Effective coupling to gluons (with higher dim. operator)

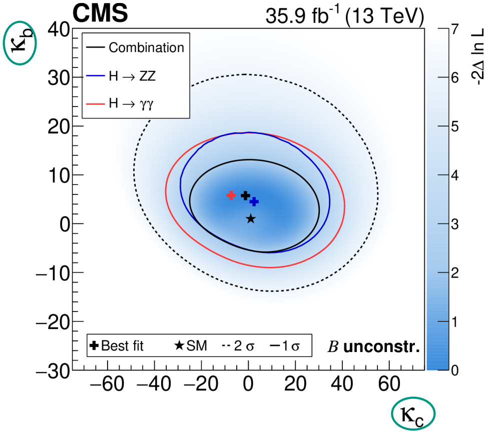


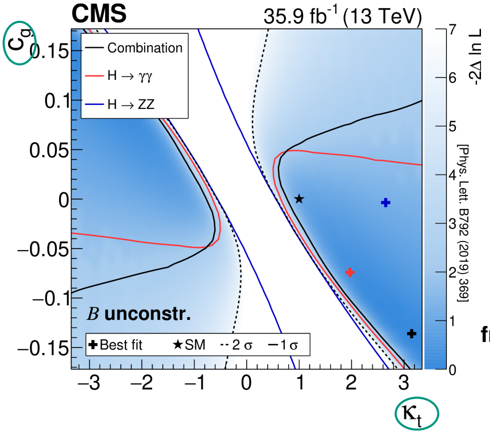
assuming $\mathcal{B}$s depend on κ

Example: Higgs-Boson p_T

- Constraints on other Higgs-boson couplings
  - Yukawa couplings to top, bottom, charm quarks
  - Effective coupling to gluons (with dim.-6 operator)







freely-floating $\mathcal{B}$s

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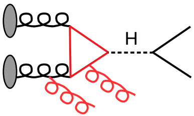
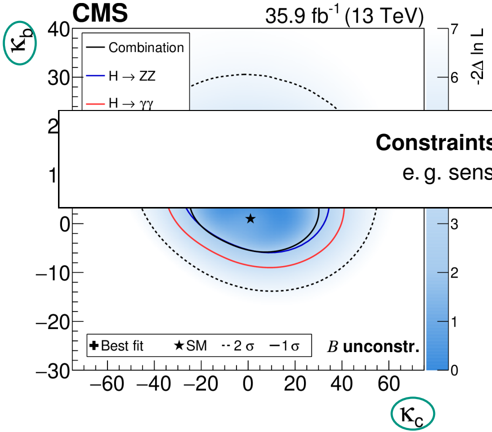
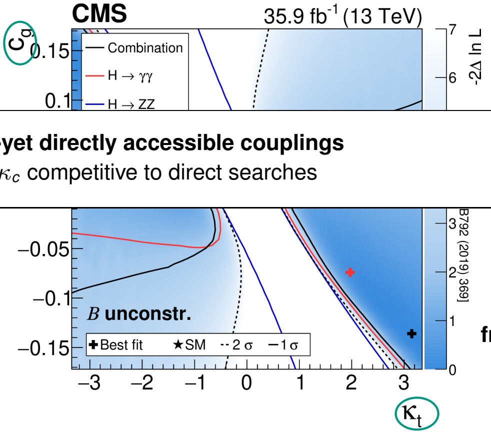






Constraints on not-yet directly accessible couplings

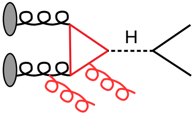
e. g. sensitivity to κ_c competitive to direct searches

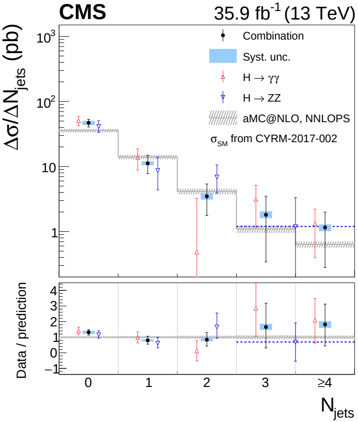
freely-floating $\mathcal{B}$s

Example: Jet Kinematics

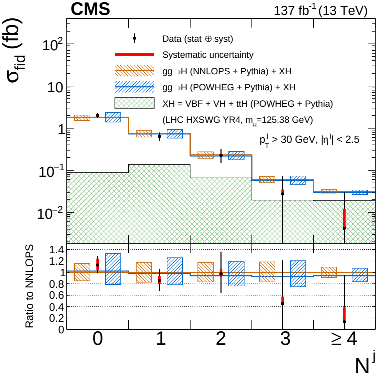
- Probes QCD radiation and Higgs production mode

Number of central jets





[Phys. Lett. B792 (2019) 369]



[Eur. Phys. J. C 81 (2021) 488]

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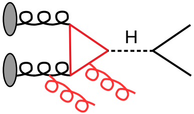
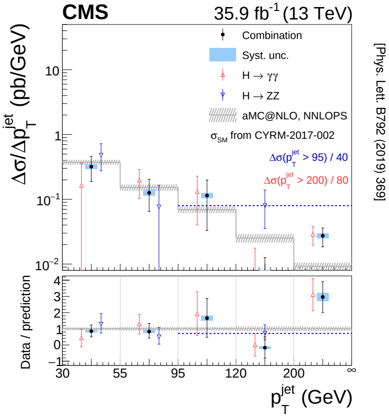
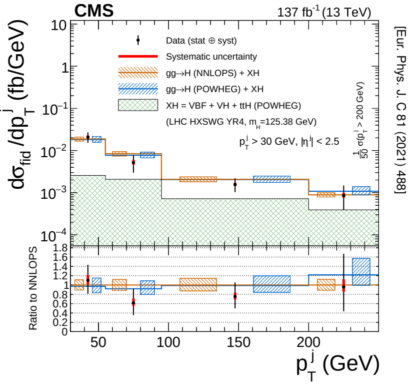


- Probes QCD radiation and Higgs production mode

p_T of central jets





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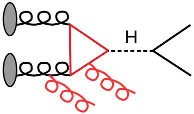
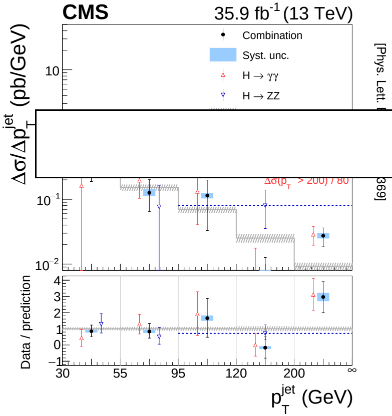
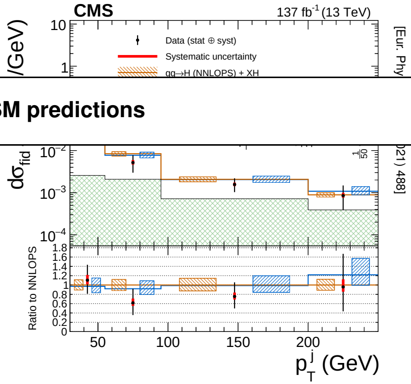


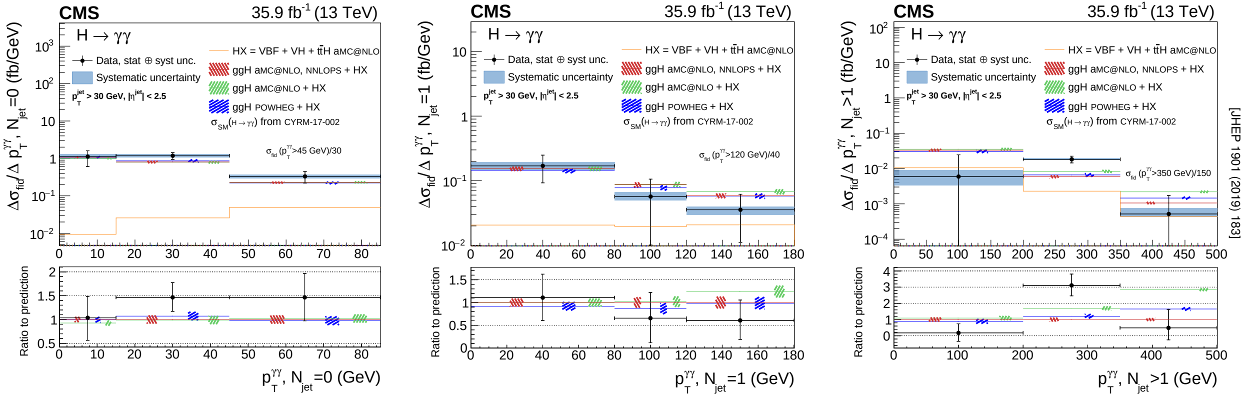




Consistent with SM predictions

Example: Double-Differential Cross-Section

$H \to \gamma\gamma$ channel, e. g. as function of p_T (H) $\times$ N(jets)



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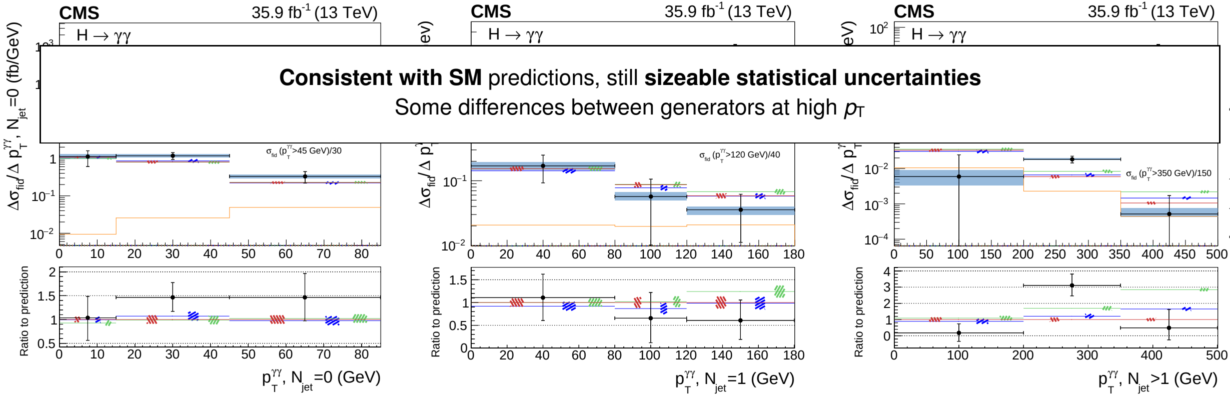

Consistent with SM predictions, still **sizeable statistical uncertainties**
Some differences between generators at high p_T

[JHEP 1901 (2019) 183]

Higgs Boson Self-Coupling at the LHC

- Higgs boson self-coupling: access to **shape of Higgs potential**

$$\mathcal{L}_H \supset -\lambda v^2 H^2 + \lambda v H^3 - \frac{1}{4}\lambda H^4 = \frac{1}{2} m_H H^2 + \boxed{\frac{m_H^2}{2v} H^3} - \frac{m_H^2}{8v^2} H^4$$

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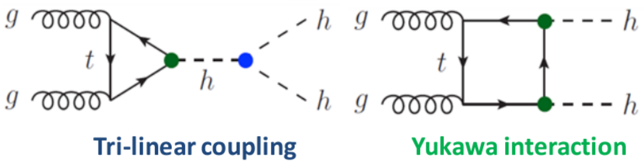
- **Tri-linear Higgs coupling** at hadron colliders: **di-Higgs production**



  - **Very small SM cross-section** due to destructive **interference** with diagrams with **Yukawa** coupling: $\sigma_\mathrm{SM}(\mathrm{HH}) = 33.5\,\mathrm{fb}$ at $13\,\mathrm{TeV}$ ($\approx 0.1\%\,\sigma_\mathrm{SM}(\mathrm{H})$)

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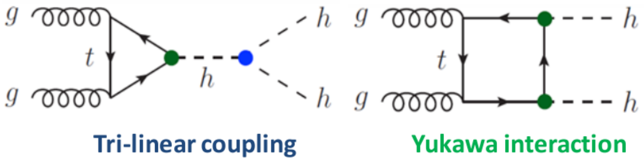

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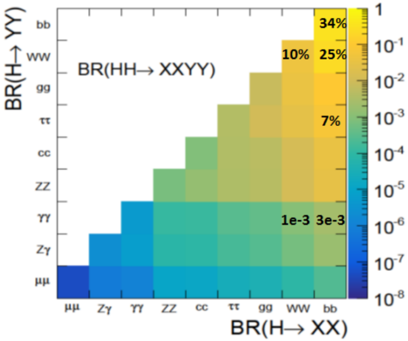
- In principle also **quartic Higgs self-coupling** (tri-Higgs production) but cross section even smaller: 0.1 fb at 13 TeV ($\rightarrow$ not feasible at LHC)

Searches for Di-Higgs Production

- Di-Higgs **searches performed in several different final-states**
- Often **final states with one H $\rightarrow$ b$\bar{\text{b}}$** decay to exploit high branching ratio

$\rightarrow$ compensate low cross-section



- Each channel
  - Upper limit on SM non-resonant production
  - Search for non-resonant hh BSM effects in m_{hh}
  - Model-independent search for narrow resonance in m_{hh} spectrum

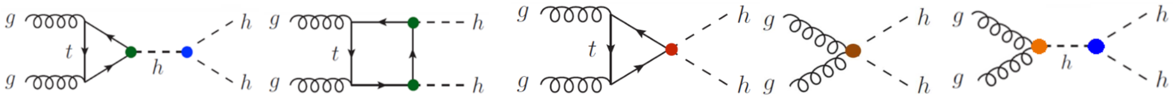
$\rightarrow$ same analysis results interpreted in different models

BSM Non-Resonant Di-Higgs Production?

- Resonant Higgs boson pair-production studied within **generic extension of SM** Lagrangian

$\longrightarrow$ EFT approach (JHEP 1604 (2016) 126)

M. Dall'Osso at EPS 2017

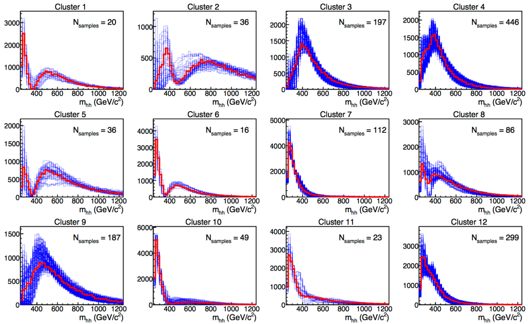


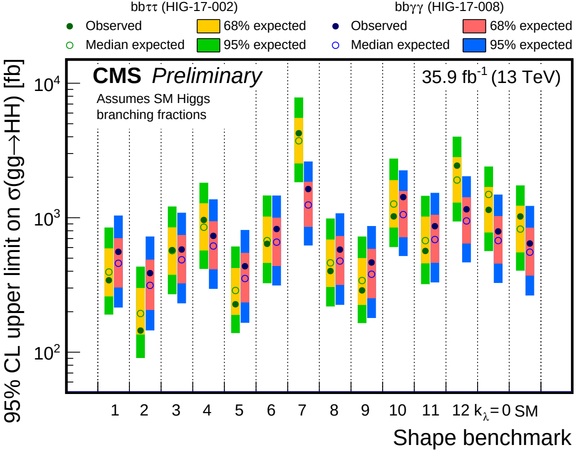
$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} hh\right)\left(\bar{t}_L t_R + h.c.\right) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} hh\right) G^{\mu\nu} G_{\mu\nu}$$

- **5 free parameters**: $\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{SM}$, $\kappa_t = \lambda_t/\lambda_t^{SM}$, c_2, c_g, c_{2g}

Di-Higgs Production: Early Run 2 Results

12 benchmarks for κ_λ, κ_t, c_2, c_g, c_{2g}





SummaryResultsHIG TWiki

- Non-resonant SM production not yet accessible, upper limit of $\approx 20 \times$ SM expectation
- No evidence of additional BSM contribution, but vast parameter space that is difficult to cover

Where are we now?

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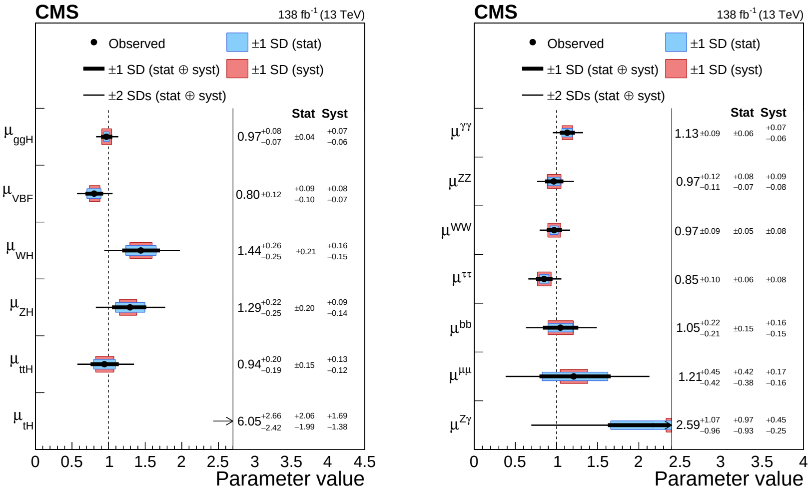
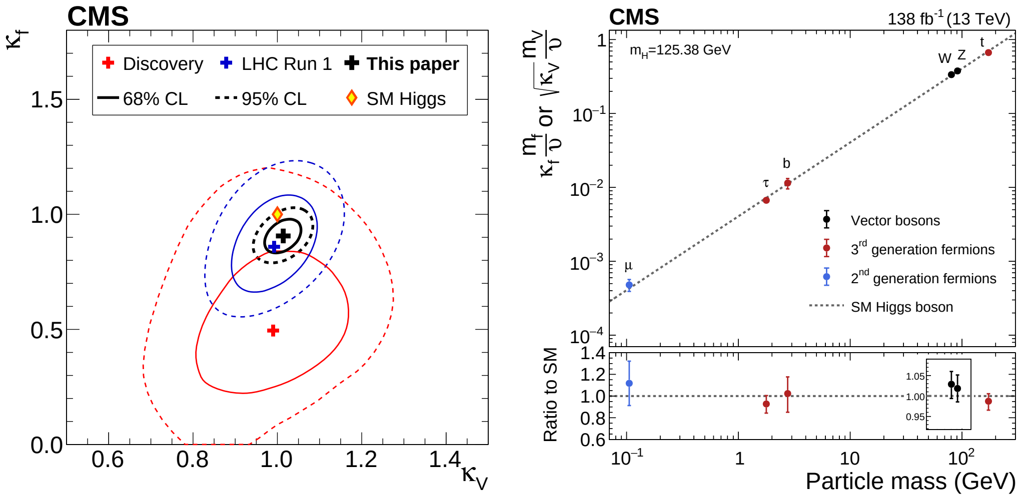
- Review paper by the CMS Collaboration ten years after the discovery of the Higgs Boson
- **A portrait of the Higgs boson by the CMS experiment ten years after the discovery** [Nature 607 (2022) 60-68]
- State-of-the-art results for couplings and Di-Higgs searches
- Similar paper from the ATLAS Collaboration

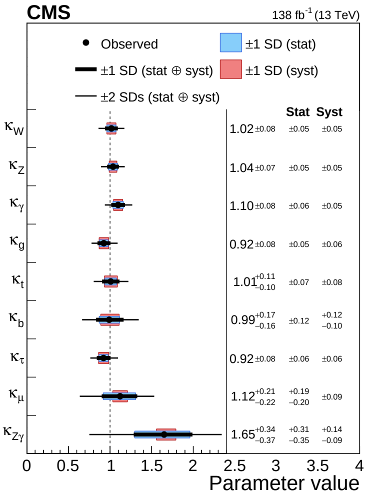
Signal Strengths: Production and Decay

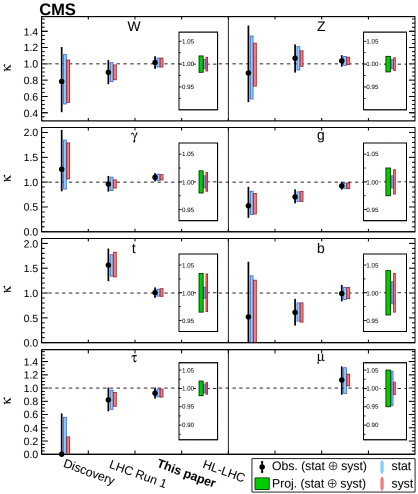


Couplings to Fermions and Bosons

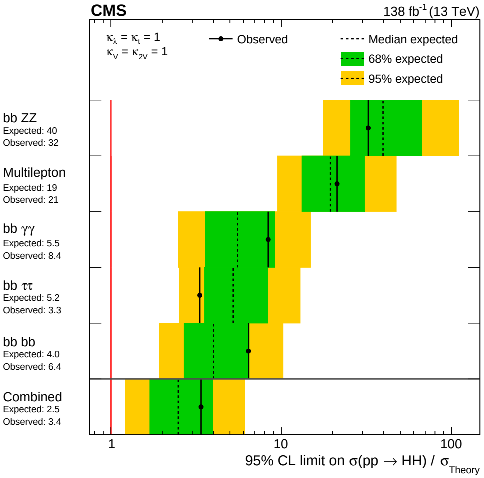


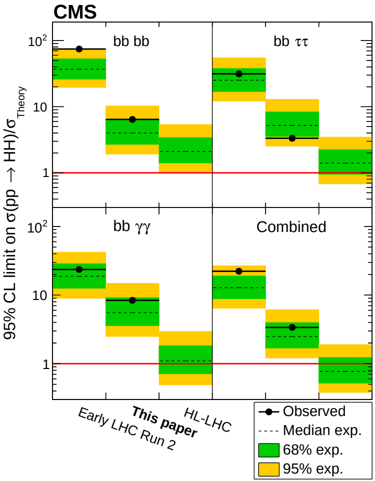
Individual Couplings



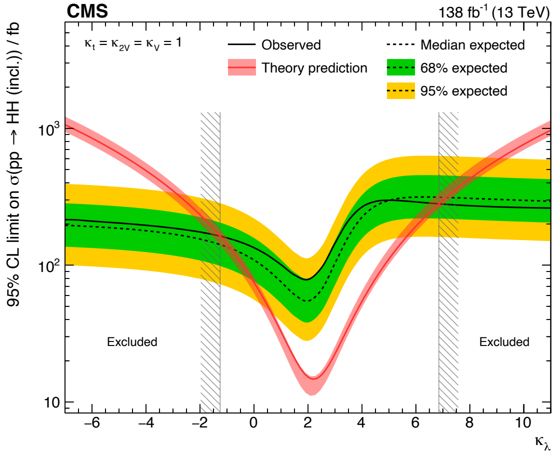


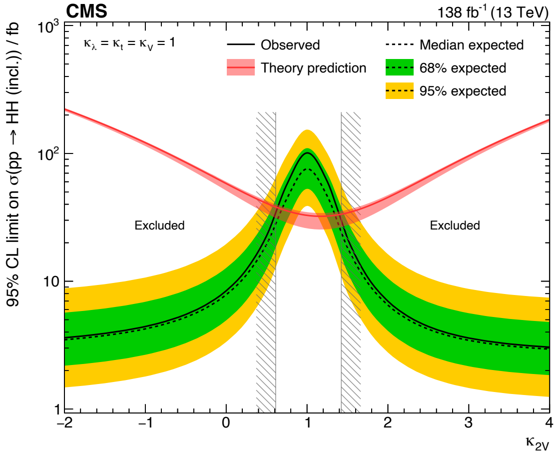
Di-Higgs Production





Self-Coupling and Quartic Coupling

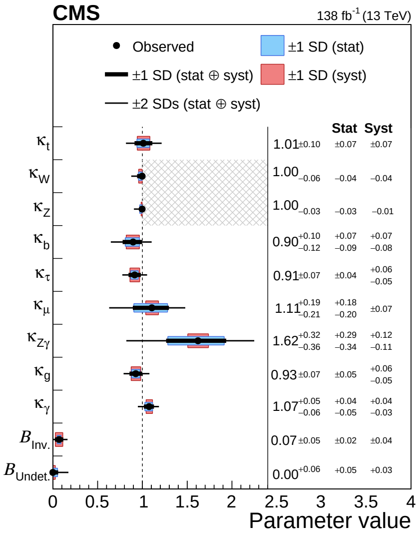




How SM-Like is H(125)?

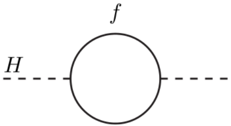
Karlsruhe Institute of Technology

- Couplings of the Higgs boson H(125) have been determined with an accuracy of around 10% or better
- **Non-SM couplings** at this order possible!



Hierarchy Problem in the SM Higgs Sector

- ‘Bare’ Higgs boson mass receives quantum corrections
- **Corrections to mass scale quadratically** with cut-off scale Λ
  - Λ: scale up to which SM is assumed to be valid
  - Quadratic corrections unique feature of scalar particles



quantum corrections

$$m_H^2 = m_0^2 - \frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \ldots$$

125 GeV

bare mass

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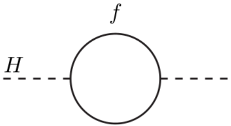

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bare mass

- SM: $\Lambda = \Lambda_{\text{Planck}} \approx 10^{16}$ GeV $\rightarrow$ natural scale for m_H

How can m_H be 125 GeV?

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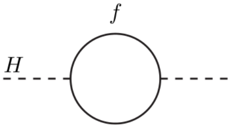

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Karlsruhe Institute of Technology

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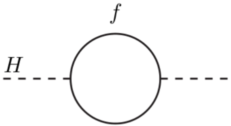

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How can m_H be 125 GeV?

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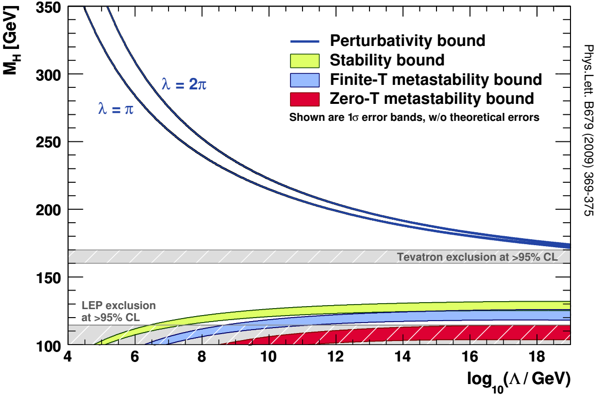
- Alternatively
  - New physics at a scale $\Lambda \ll \Lambda_{\text{Planck}}$?
  - Additional terms that cancel corrections (e. g. in Supersymmetry)?

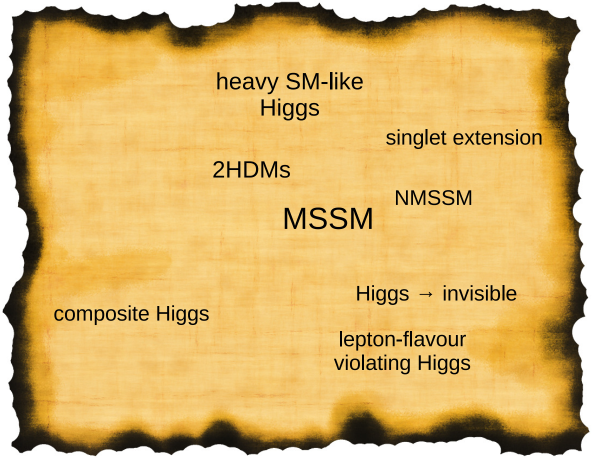
Pecularities of the SM Higgs Sector

- Standard Model self-consistent and renormalisable, but
  - **Metastable vacuum** when extrapolated to the Planck scale
  - Quadratically **divergent quantum corrections** to Higgs-boson mass



- Higgs mechanism **added somewhat ad-hoc** to achieve EWSB
- Yukawa couplings just **defer problem of fermion masses**

Out for the Unknown



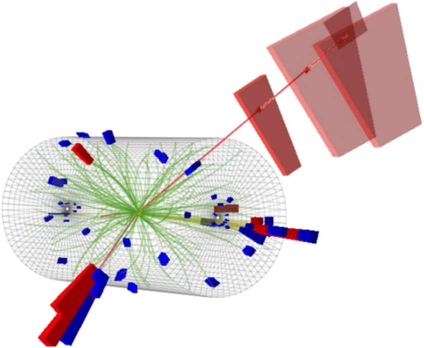
Non-SM-Higgs properties of the 125 GeV boson? Additional Higgs bosons?

Lepton-Flavour Violating Higgs Couplings

- In SM, no lepton-flavour violating (LFV) Higgs couplings
- But can occur in models with more than one Higgs doublet

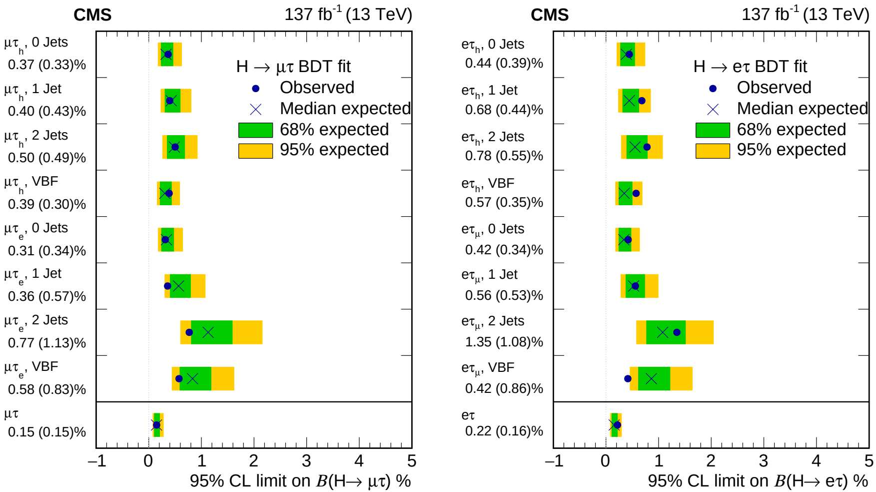
- **Indirect constraints**:
  - $\mathcal{B}(\mathrm{H} \to e\mu) < \mathcal{O}(10^{-8})$
  - $\mathcal{B}(\mathrm{H} \to \mu\tau) < \mathcal{O}(10\,\%)$
  - $\mathcal{B}(\mathrm{H} \to e\tau) < \mathcal{O}(10\,\%)$

  e. g. from virtual loop contributions of LFV Higgs couplings to
  $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$



$\mathrm{H} \to e\tau$ and $\mathrm{H} \to \mu\tau$ only weakly constrained
Perform direct measurements!

Lepton-Flavour Violating Higgs Couplings: $e\tau$ and $\mu\tau$



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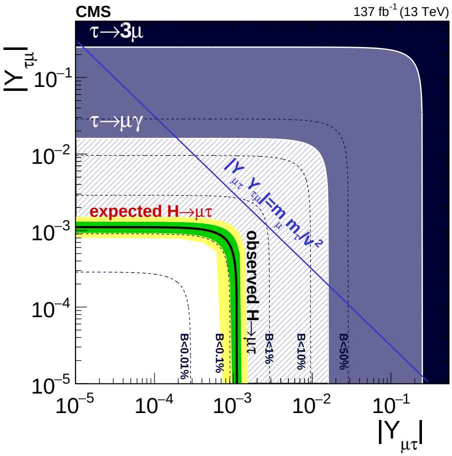

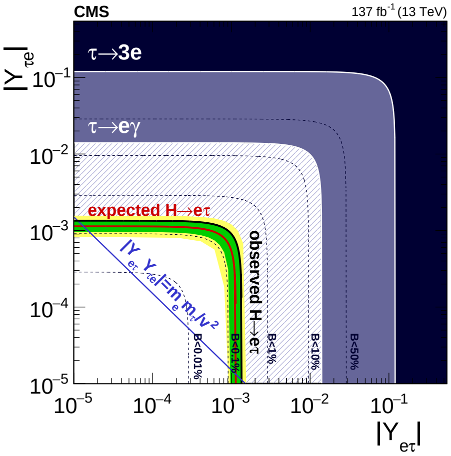

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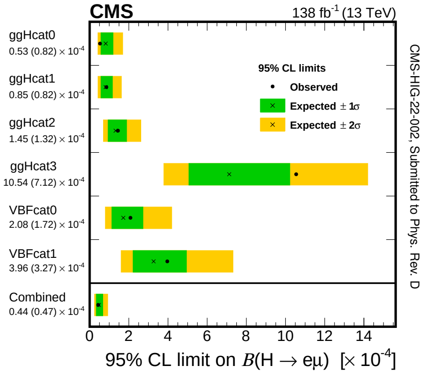
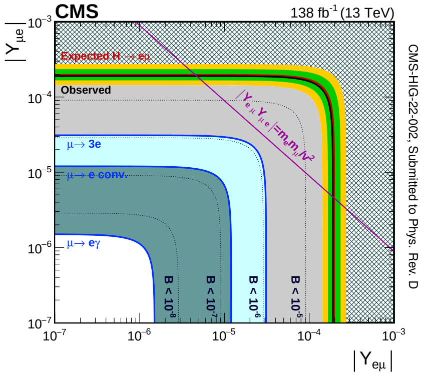
Interpreted as **limit on lepton-flavour violating Yukawa couplings**

Lepton-Flavour Violating Higgs Couplings: $e\mu$

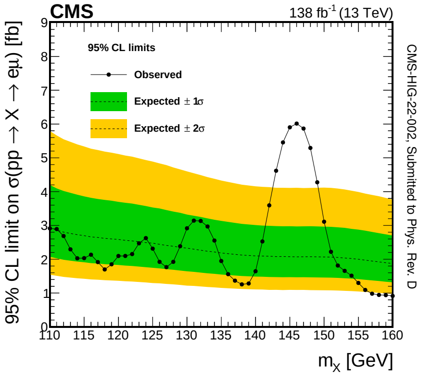
- Although the $e\mu$ channel has already higher constraints, a similar search has been carried out
- No signal found for decay of the SM Higgs boson into $e\mu$...

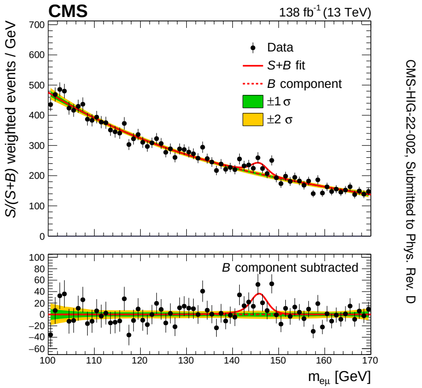




Lepton-Flavour Violating Higgs Couplings: $e\mu$

- However, the analysis covers not only SM Higgs boson decays, but also searches for a non-SM signal from the decay of a generic BSM boson decay ($m_X \neq 125$ GeV)
- Significant excess (3.8σ local, 2.8σ global) at around $m_X = 146$ GeV observed





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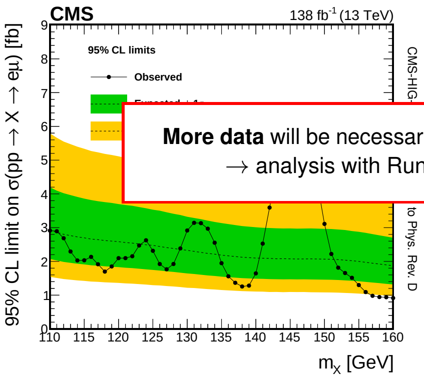

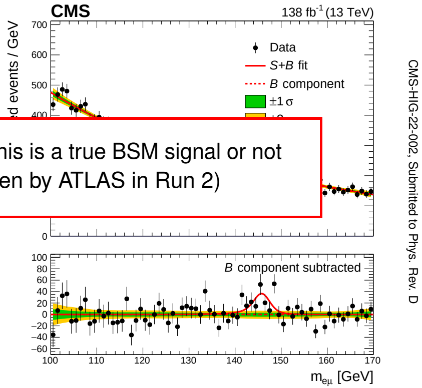

More data will be necessary to decide whether this is a true BSM signal or not
$\rightarrow$ analysis with Run 3 data (no signal seen by ATLAS in Run 2)

Searches for "Higgs $\to$ Invisible"

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- Very small branching ratio of $\approx 0.1\,\%$ in SM (mostly $H \to ZZ^* \to 4\nu$)
- But **possible at larger rate in new-physics models**, e. g. in Supersymmetry or extra-dimensions models
  - New invisible particle χ often Dark Matter candidate
- Constraints from combined coupling measurements

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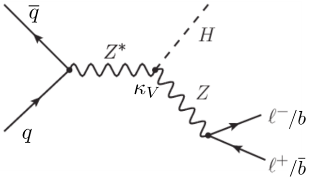
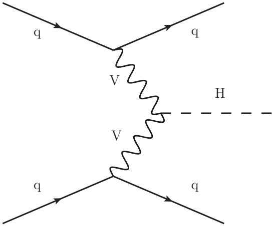
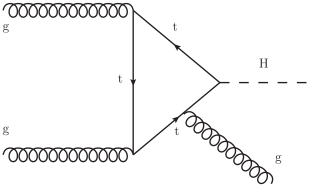


“VH”



vector-boson fusion

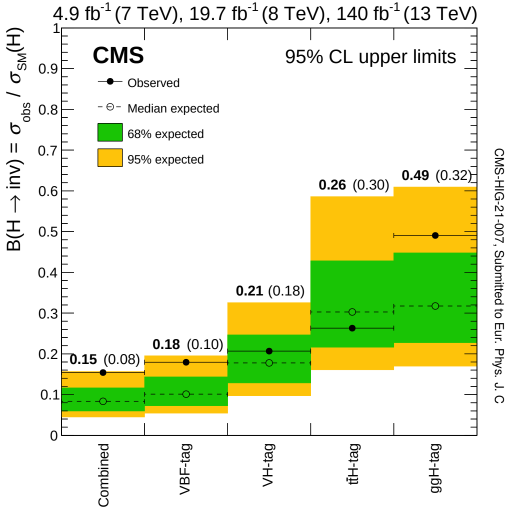


monojet

Direct searches in events where H recoils against visible objects

Signature: large $\not{E}_{\mathrm{T}}$ recoling against a distinctive visible system

Searches for "Higgs $\rightarrow$ Invisible"



- Combined upper limit at 95 % C.L.:

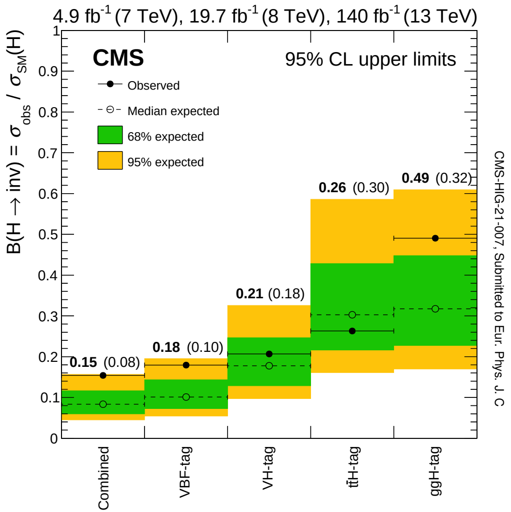
  $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{inv}) < 0.15$ (observed)

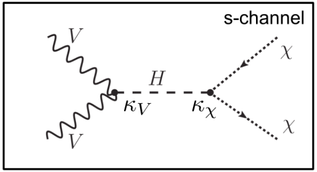
- Assuming SM production cross-sections of a H(125) boson

- How can we interpret this in terms of limits to BSM physics?

Searches for “Higgs → Invisible”

Karlsruhe Institute of Technology





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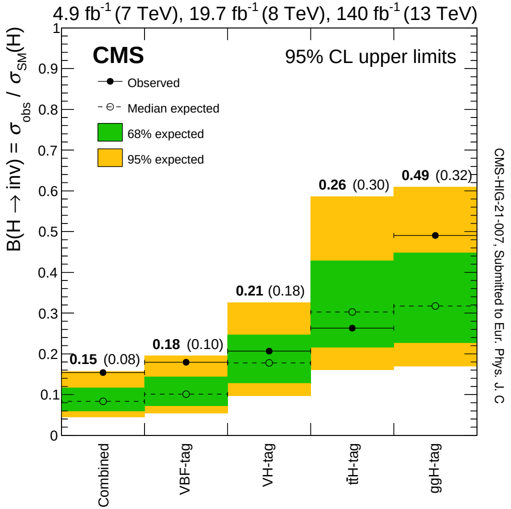

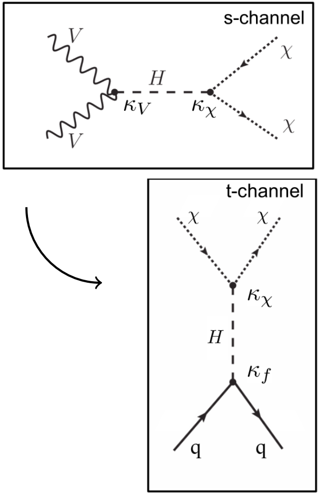

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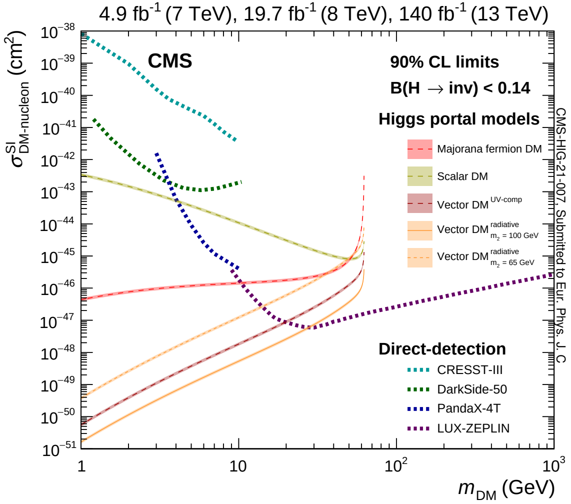

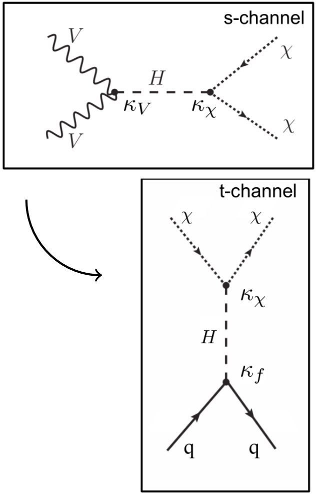

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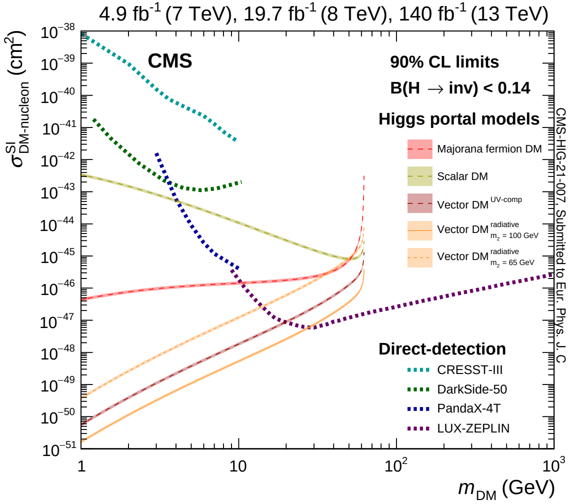

- Interpretation in Higgs-portal Dark Matter (DM) models
  - Hidden DM sector, only H couples to DM

→ **Limits on DM-nucleon scattering cross section**

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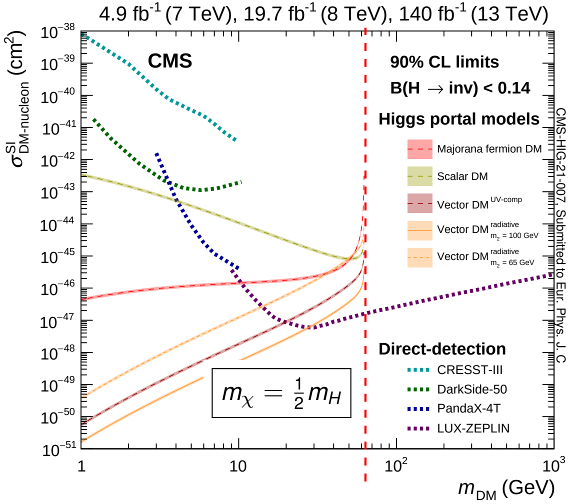

- Interpretation in Higgs-portal Dark Matter (DM) models
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→ **Limits on DM-nucleon scattering cross section**

→ **Complementary sensitivity to direct-detection DM experiments**

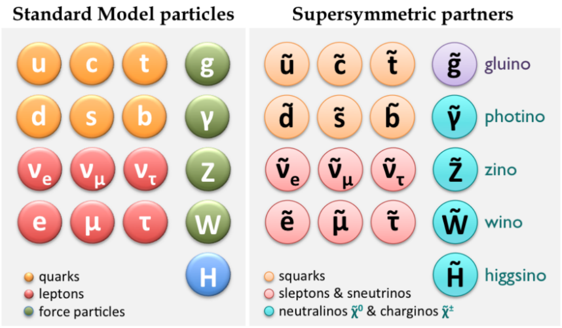
- No sensitivity for higher masses due to kinematic threshold

Supersymmetry

- In the SM two different kind of fundamental particles
  - **Bosons** with integer spin: mediate forces between particles and the Higgs boson
  - **Fermions** of half-integer spin: constituents of matter
- Is there a connection between both? Maybe a broken symmetry at higher energies similar to the EWSB?

$\rightarrow$ Concept of **Supersymmetry (SUSY)**: relate each fermion/boson to a corresponding superpartner called *sboson/sfermion* with $\Delta S = \frac{1}{2}$

- Many additional free parameters (>100) in general, focus on minimal extensions to the SM



ATLAS Silicon IFIC

Minimal Supersymmetric Standard Model

- MSSM requires **2 Higgs doublets** ϕ_u (ϕ_2) and ϕ_d (ϕ_1)

$$\phi_\mathrm{u} = \begin{pmatrix} \phi_\mathrm{u}^+ \\ \phi_\mathrm{u}^0 \end{pmatrix}, \; Y_{\phi_\mathrm{u}} = +1 \,, \; v_\mathrm{u} : \mathrm{VEV_u}$$

$$\phi_\mathrm{d} = \begin{pmatrix} \phi_\mathrm{d}^0 \\ \phi_\mathrm{d}^- \end{pmatrix}, \; Y_{\phi_\mathrm{d}} = -1 \,, \; v_\mathrm{d} : \mathrm{VEV_d}$$

  - SUSY invariance requires **different doublets for Yukawa-coupling terms of up- and down-type fermions**
  - Using instead conjugate Higgs field as in SM breaks SUSY invariance

- 8 d.o.f. since 2 complex Higgs doublets: 3 d.o.f. for $m_{\mathrm{W}^\pm}$, m_Z $\rightarrow$ **5 physical Higgs bosons**

2 CP-even neutral Higgs bosons h, H ($m_\mathrm{h} < m_\mathrm{H}$)

1 CP-odd neutral Higgs boson A

2 charged Higgs bosons $\mathrm{H}^\pm$

MSSM Higgs Sector

- **Two vacuum expectation values** v_u and v_d of the Higgs doublets

$$\boxed{\tan\beta = \frac{v_u}{v_d}} \quad v_u^2 + v_d^2 = v_{SM}^2 = (246\,\mathrm{GeV})^2 = \frac{4m_Z^2}{g^2 + g'^2}$$

Additional parameter α: angle between ϕ_u and ϕ_d in SU(2) isospace

- At LO, MSSM Higgs-sector entirely described by 2 parameters
  - Typical choice: $\boxed{\tan\beta \text{ and } m_A}$

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- Strict mass relation at LO

$$\boxed{\begin{aligned} m_{\mathrm{H}^\pm}^2 &= m_W^2 + m_{\mathrm{A}}^2 \\ m_{h,H}^2 &= \tfrac{1}{2}\left(m_{\mathrm{A}}^2 + m_Z^2 \mp \sqrt{(m_{\mathrm{A}}^2 - m_Z^2)^2 + 4m_Z^2 m_{\mathrm{A}}^2 \sin^2(2\beta)}\right) \end{aligned}}$$

  - In particular $\boxed{m_{\mathrm{h}} \leq m_Z \cdot |\cos 2\beta| \leq m_Z}$

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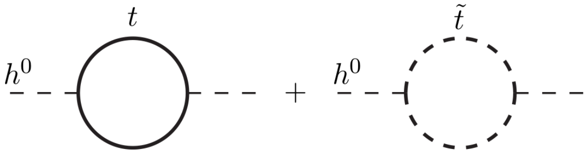
  - In particular $\boxed{m_h \leq m_Z \cdot |\cos 2\beta| \leq m_Z}$ **contradicts h(125) observation!**

MSSM Higgs Sector

- MSSM Higgs sector depends on other SUSY parameters than $\tan\beta$ and m_A via higher-order contributions
- Higgs boson masses receive **higher-order corrections**

$\Delta(m_{h^0}^2) =$



$\rightarrow$ $\boxed{m_h \lesssim \textbf{135 GeV}}$ **predicted** in MSSM!

Neutral MSSM Higgs Bosons

- Coupling strength relative to respective SM coupling

	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	—	$\gamma^5 \cot\beta$	$\gamma^5 \tan\beta$
H	$\cos(\beta-\alpha) \rightarrow 0$	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$
h	$\sin(\beta-\alpha) \rightarrow 1$	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$

- For $m_A \gg m_Z$ ('decoupling limit'): $\alpha \rightarrow \beta - \frac{\pi}{2}$
  - **h becomes SM-like**: cannot distinguish SM from MSSM via coupling measurements of h(125)

Neutral MSSM Higgs Bosons

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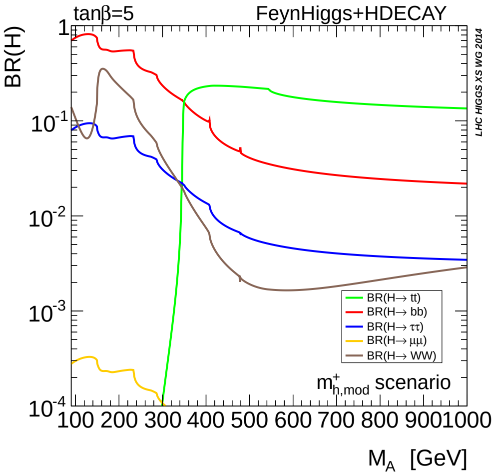
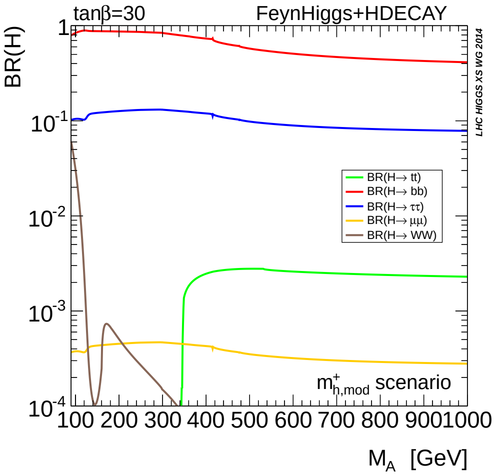
$\rightarrow$ Search for additional Higgs bosons!

Neutral MSSM Higgs Bosons

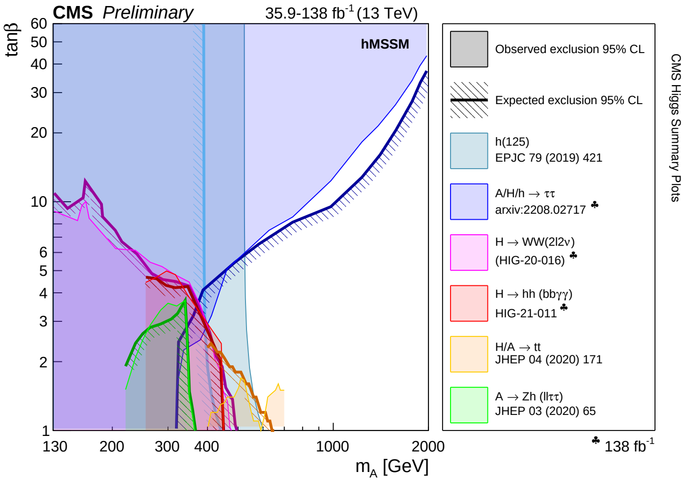




Cornering the MSSM Higgs Sector

$(m_A, \tan\beta)$ regions in **different scenarios** excluded by various direct searches

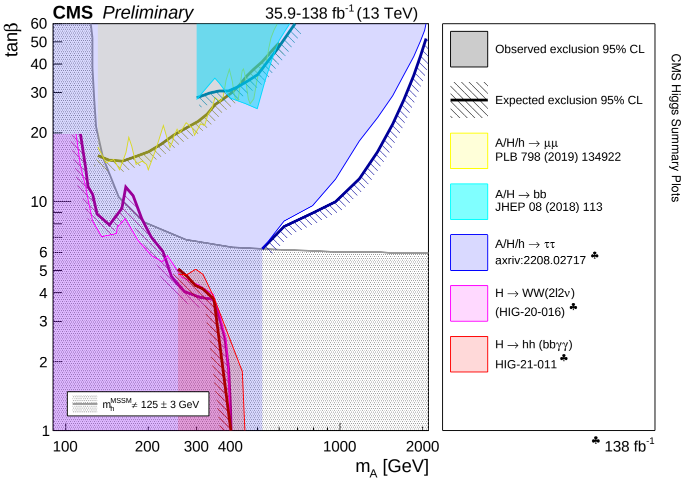
Assuming that h is the SM Higgs boson, low-m_A regions can be excluded by coupling measurement



hMSSM → modified version of the default MSSM to incorporate the observation of Higgs boson

Cornering the MSSM Higgs Sector

$(m_A, \tan\beta)$ regions in **different scenarios** excluded by various direct searches



If one requires a mass of 125 GeV for h in the default MSSM, also low $\tan\beta$ values are excluded

Summary on the (BSM) Higgs Sector

- H(125) with well-understood properties (SM-like "within less than 10%")
- SM self-consistent, but incomplete + theoretical deficits
  - Gravity, Dark Matter + hierarchy problem, ...
  - Why does EWSB occur?
- There must be **new physics** beyond the SM: (how) does it affect the Higgs sector?
  - Non-SM properties of the H(125) boson?
  - Extended Higgs sector with additional Higgs bosons, e. g. in SUSY?
- Vast number of searches **covering many of the expected signatures**
  - Generic "heavy SM Higgs" searches vs. model-inspired
  - Important inspiration for possible signatures: MSSM
  - Often interpretation of same results in different models
  - Goal is to **search for generic signatures of BSM Higgs physics**