Search for HH-Production and BSM Physics in the Higgs Sector

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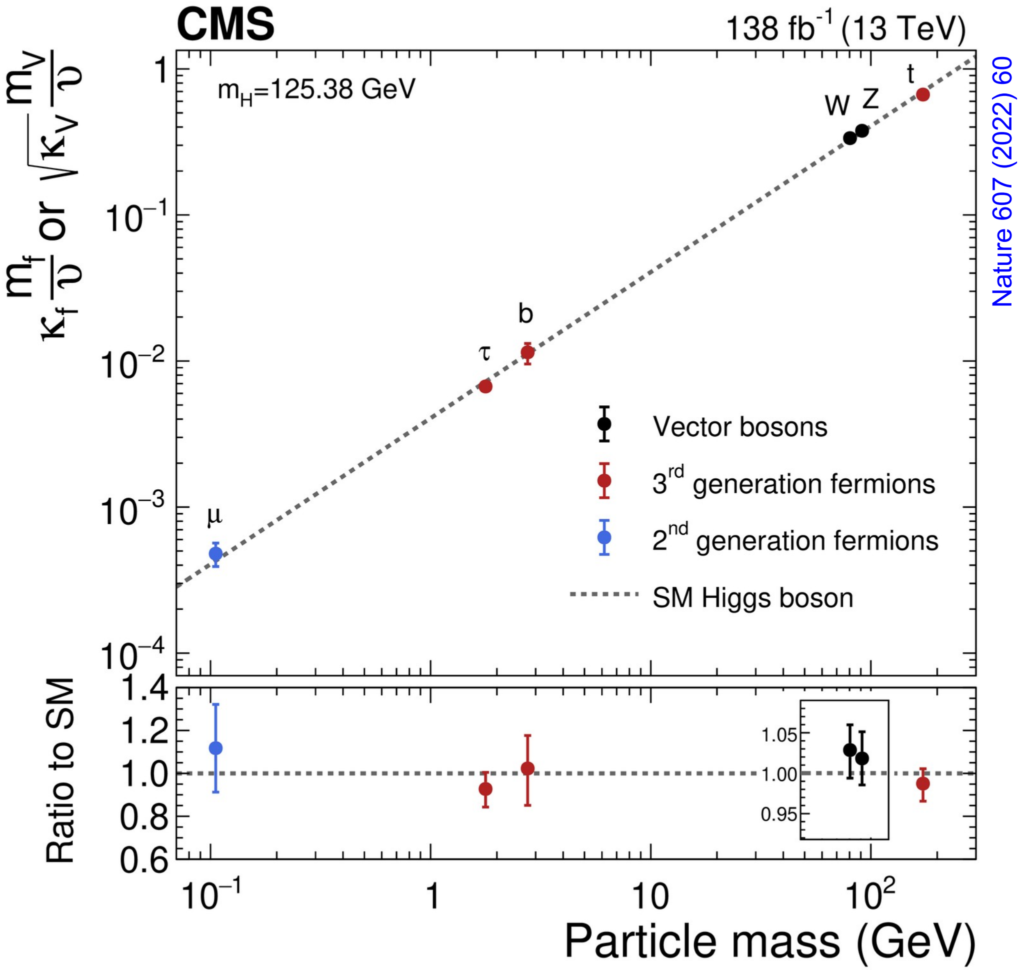
28. November 2023

What we know

- Observation of a new particle: Spin-0, coupling to fermions $(\mathrm{f}) \propto m_{\mathrm{f}}$, coupling to vector bosons $(\mathrm{V}) \propto m_{\mathrm{V}}^2$ → **Higgs boson** (H^0)
- Strong hints that **Higgs mechanism is realized in nature**



What we don’t know

„Is what we observe **THE Higgs** boson [of the SM], or is it just **A Higgs** boson?“

Facts (by Sven Heinemeyer)

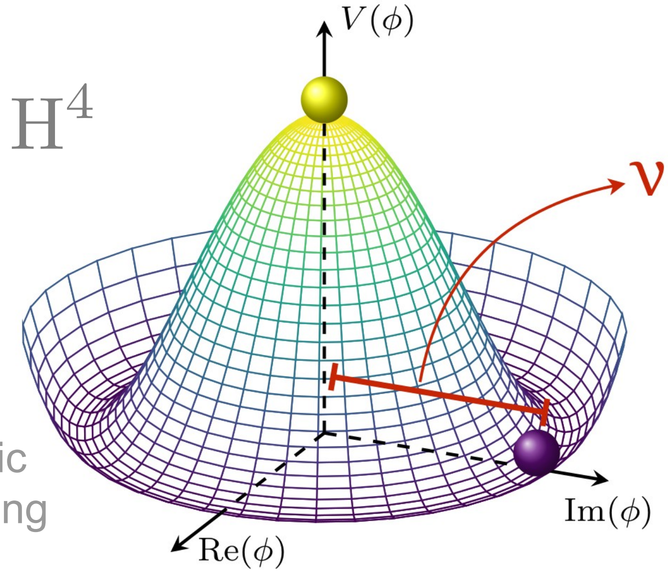
- Question: Is **NP observable** at the energy scales accessible to us?
- **There must be new physics** (NP) embracing the SM

- The SM is **NOT the ultimate** theory
- We do have the observation of H^0

To be presented here

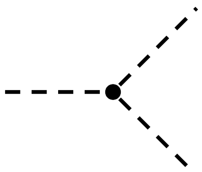
Higgs potential of the SM

$$V(\mathrm{H}) = \frac{1}{2} m_{\mathrm{H}}^{2}\,\mathrm{H}^{2} + \frac{1}{2}\lambda_{3}\,v\,\mathrm{H}^{3} + \frac{1}{4}\lambda_{4}\,\mathrm{H}^{4}$$

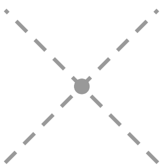


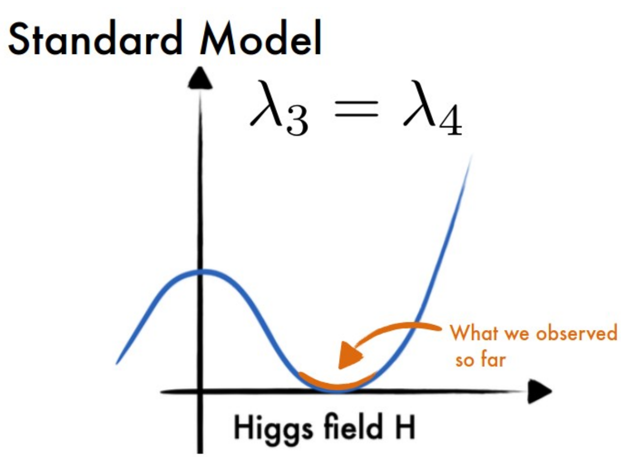
Mass term

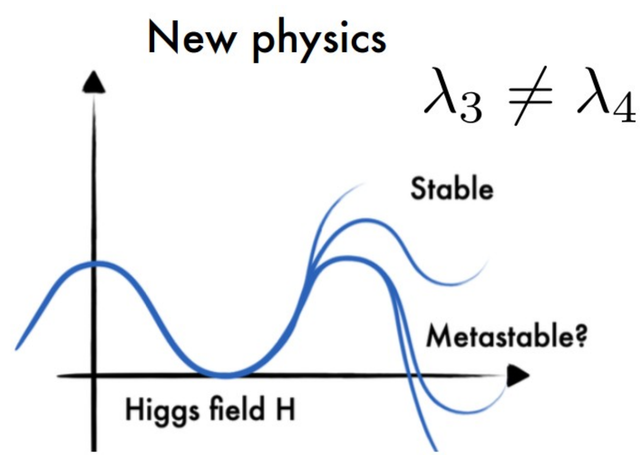
Trilinear coupling



Quartic coupling



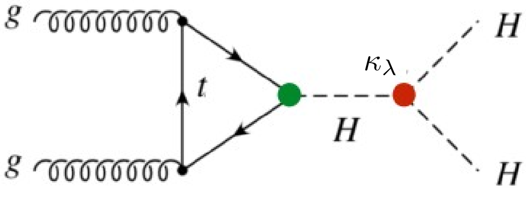


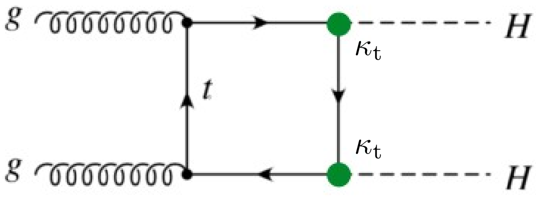


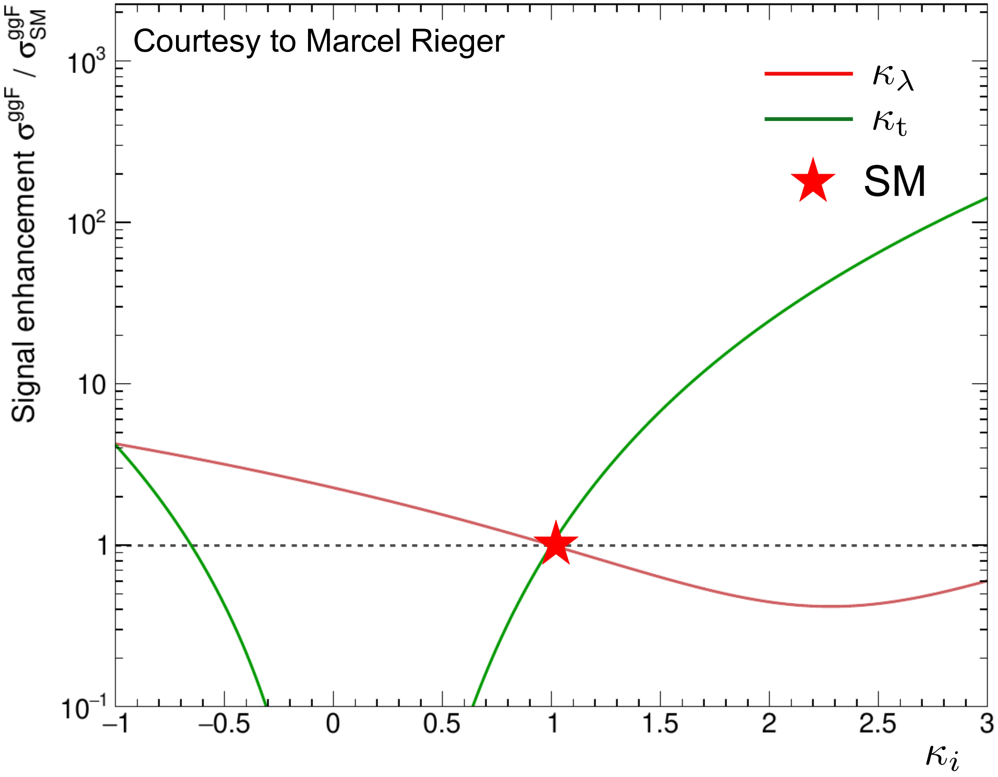
Convention that
$\lambda_3 = \lambda$

Key to λ

- **Di-Higgs (HH) production**
- Expect: $\sigma(\mathrm{gg}\rightarrow\mathrm{HH}) = 31\,\mathrm{fb}$
- 20x smaller than $\sigma(\mathrm{ttH})$
- Reduced by neg. interference between **box** and **triangle**



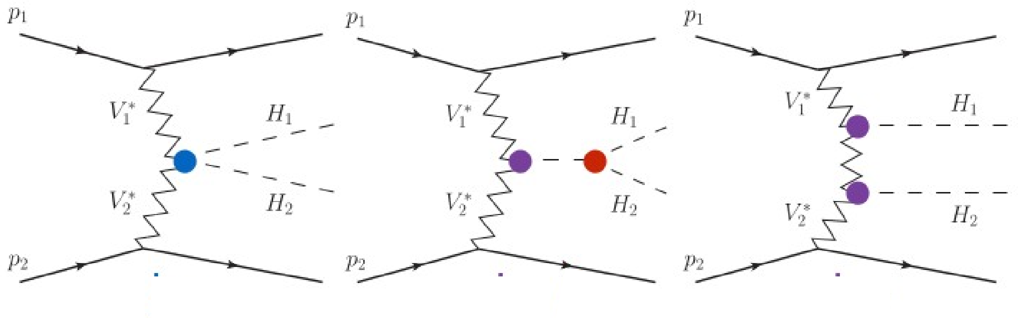


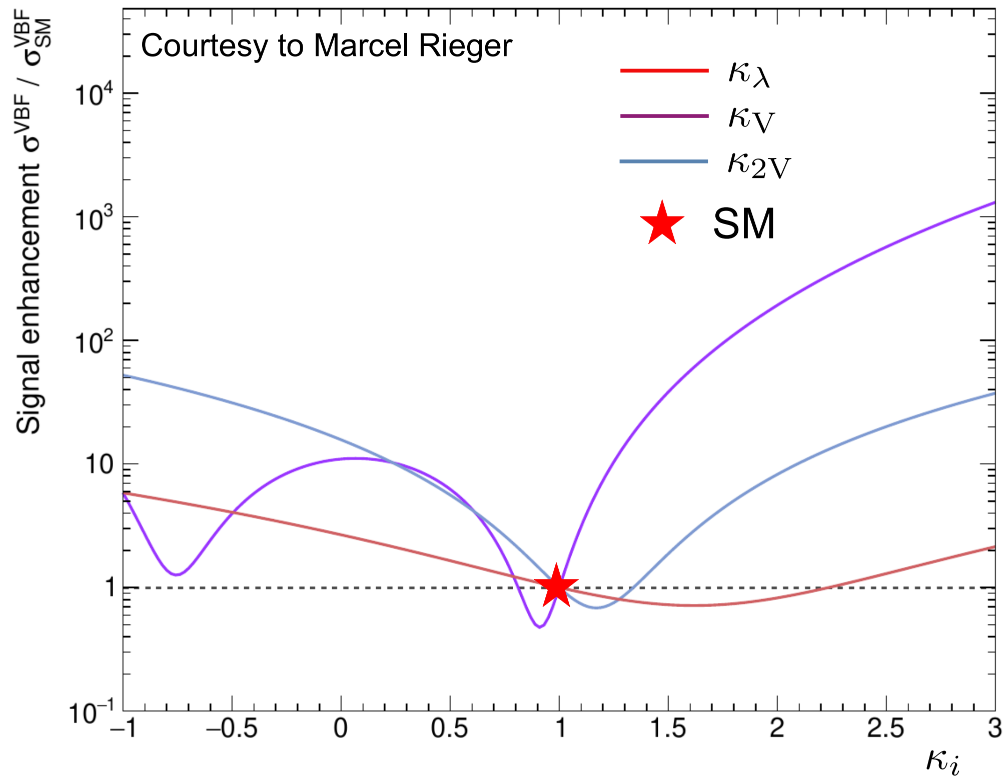


- **Expect sizeable deviations** if $\lambda \neq \lambda^{\mathrm{SM}}$

Additional interest in VBF

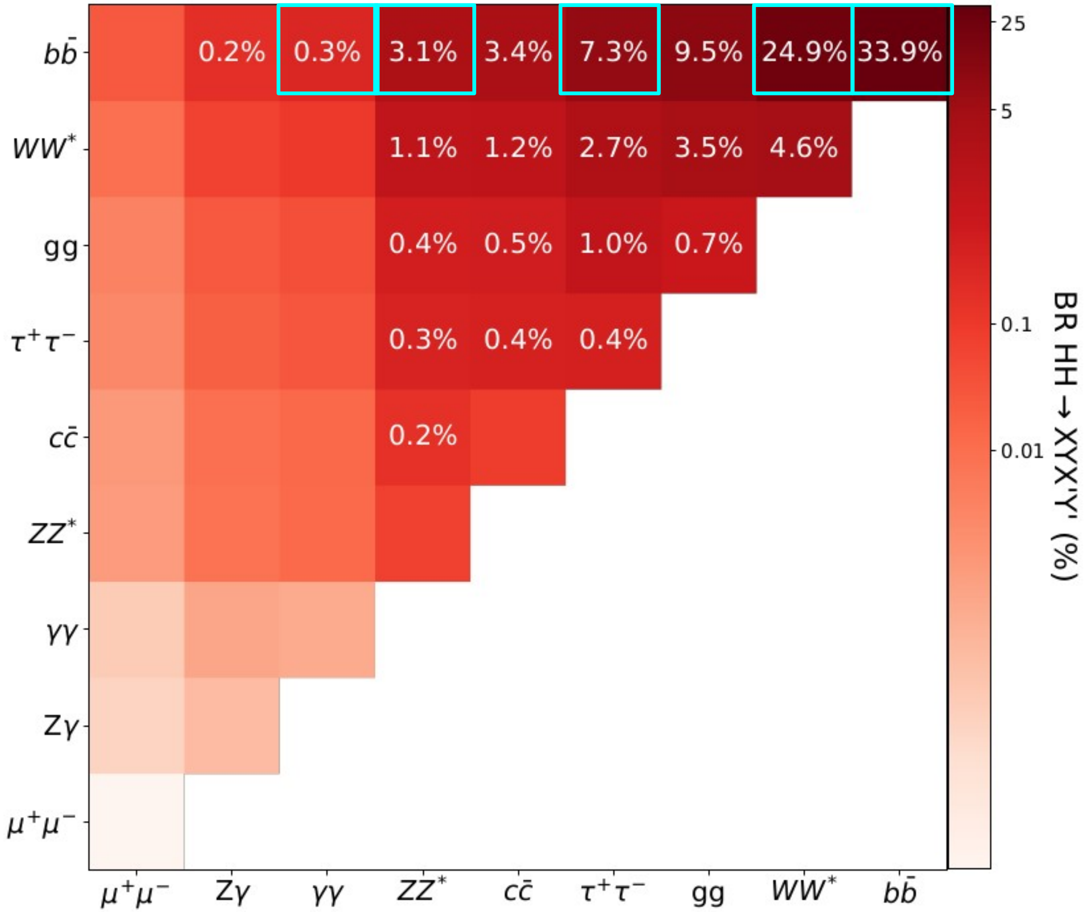
- Expect: $\sigma(\mathrm{VBFHH}) = 1.73\,\mathrm{fb}$
- 20x smaller than $\sigma(\mathrm{gg} \to \mathrm{HH})$
- **Three amplitudes contributing** ($\kappa_{\lambda},\, \kappa_{\mathrm{V}},\, \kappa_{2\mathrm{V}}$)





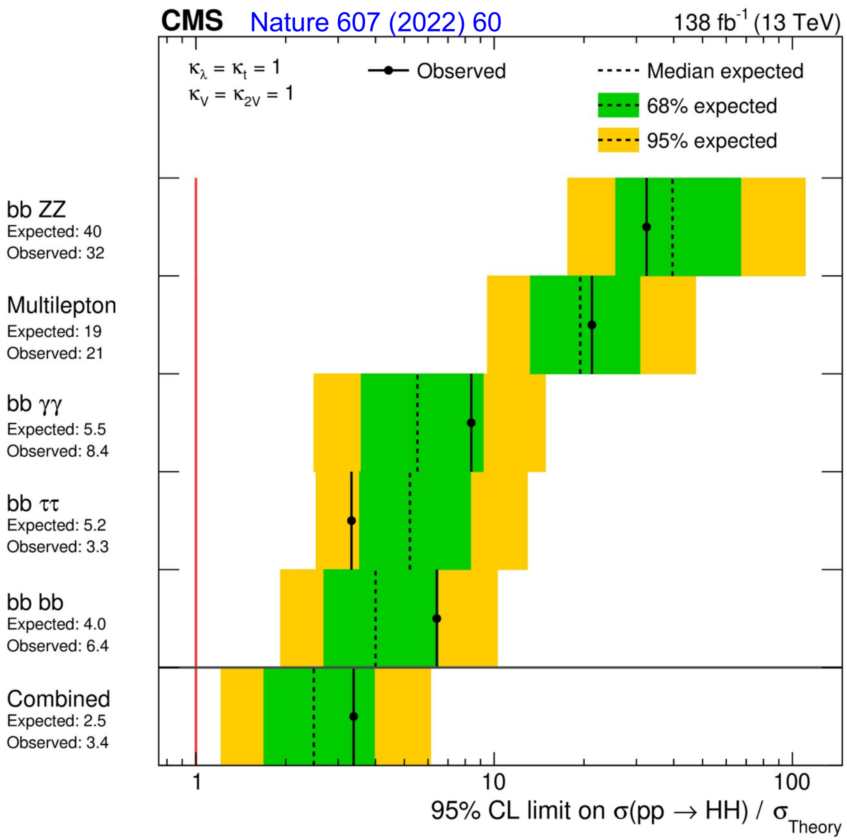
Most interesting final states

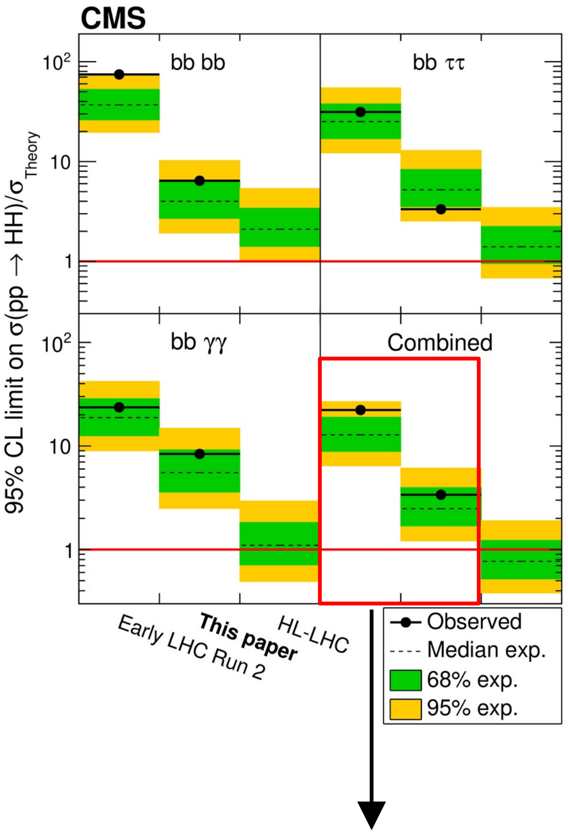
- Determined by $\mathcal{B}(\mathrm{H}\to\mathrm{XX}')$ and purity of final state



Sensitivity @ LHC

- Results based on full LHC Run-II[*]





Factor ~2.5 more sensitive than expected by luminosity-scaling of the previous partial Run-II result of PRL 122 (2019) 121803

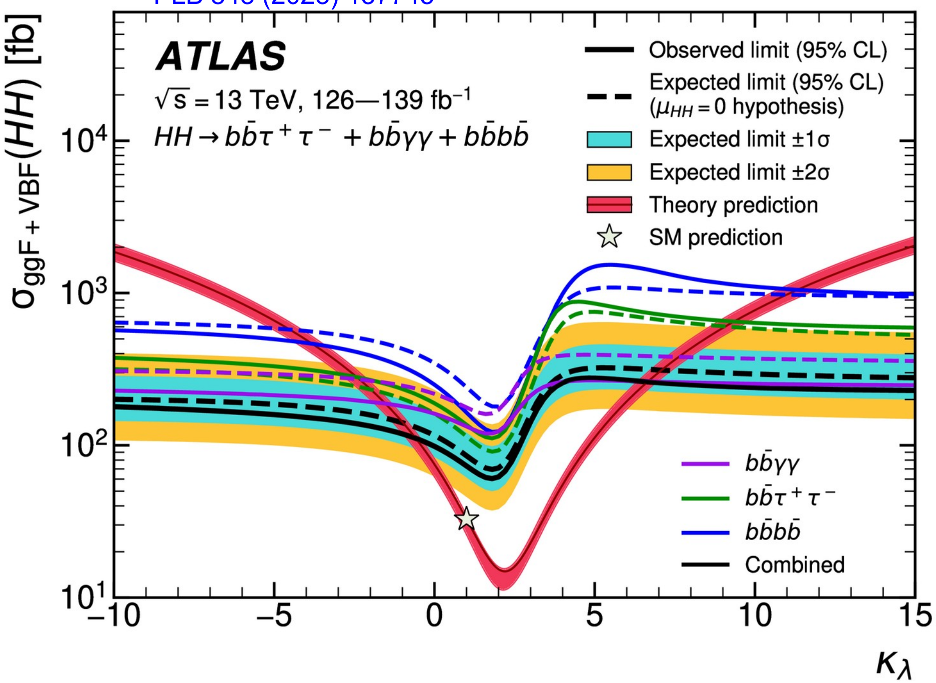
- Similar results from ATLAS (PLB 843 (2023) 137745)

[*] with small exceptions

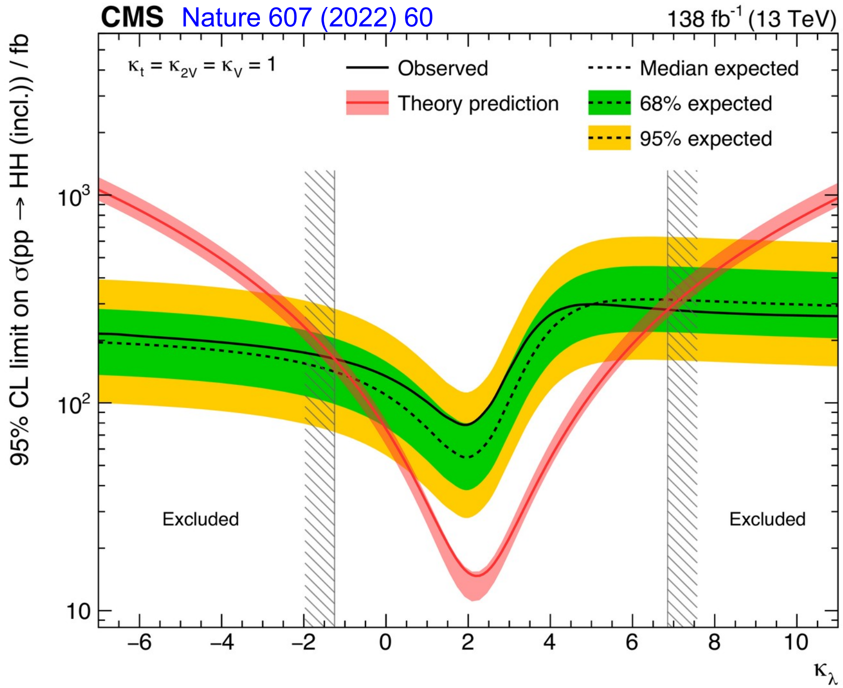
Constraint on κ_λ

- Obtained in κ-framework (1307.1347)

PLB 843 (2023) 137745



CMS Nature 607 (2022) 60

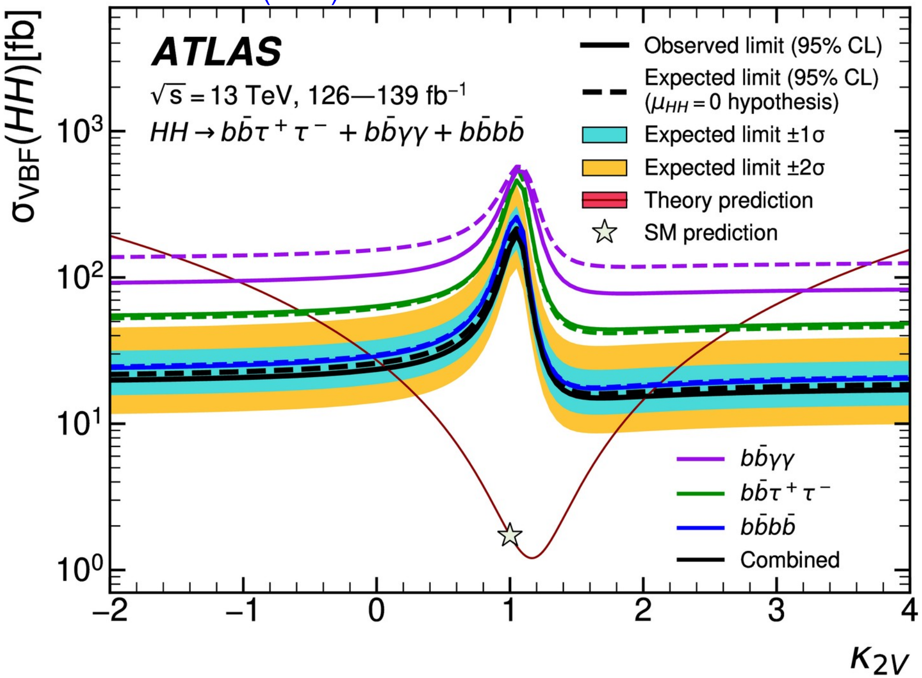


Observed: $-0.4 < \kappa_\lambda < 6.3 \quad (95\%\mathrm{CL})$ $\qquad$ $-1.24 < \kappa_\lambda < 6.49 \quad (95\%\mathrm{CL})$

Constraint on κ_{2V}

- Obtained in κ-framework (1307.1347)

PLB 843 (2023) 137745



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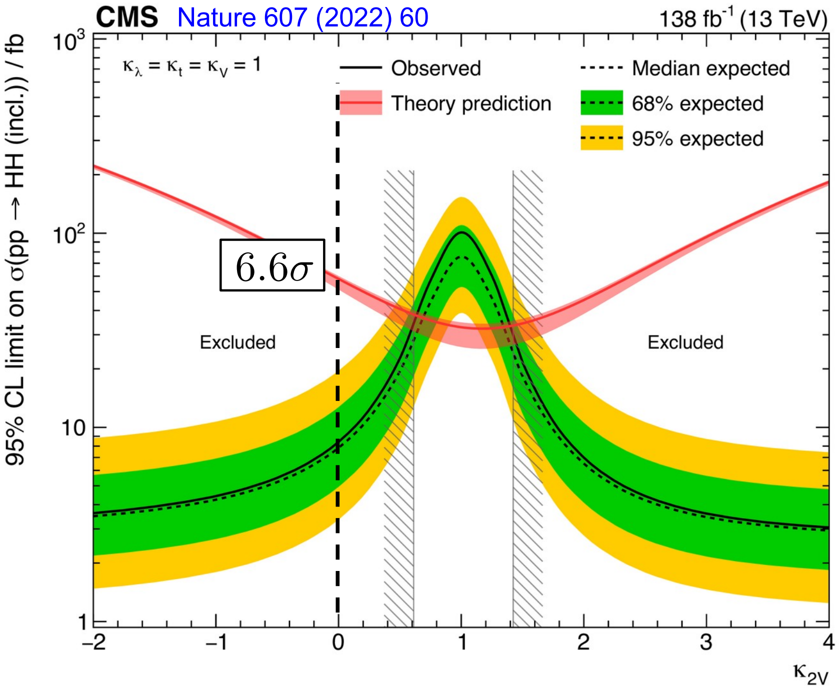
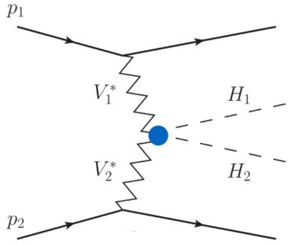
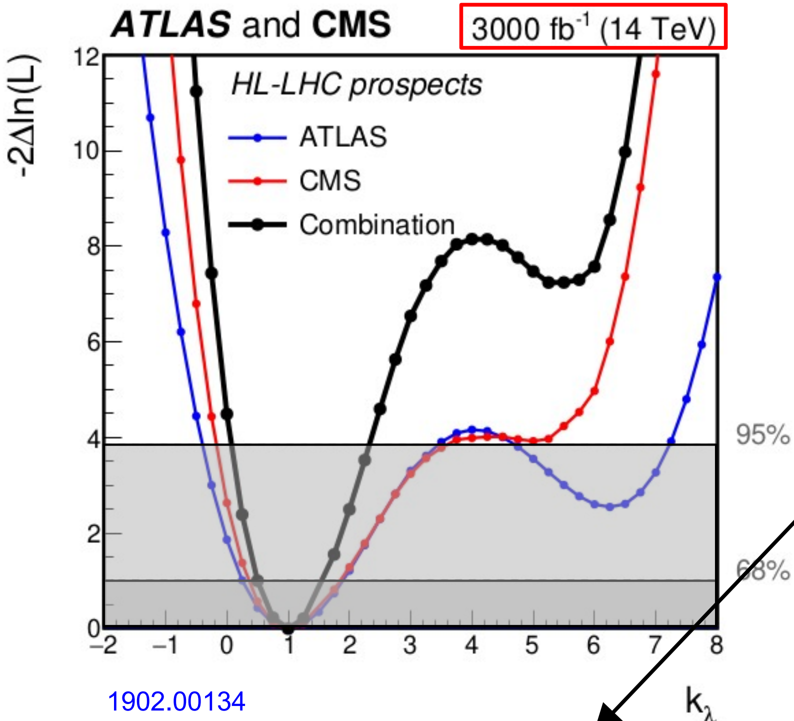


Observed: $\boxed{0.1 < \kappa_{2V} < 2.0 \quad (95\%\mathrm{CL})}$ $\boxed{0.67 < \kappa_{2V} < 1.38 \quad (95\%\mathrm{CL})}$

- Indirectly establishing quartic VVHH coupling (due to large increase of σ for $\kappa_{2V} \to 0$)



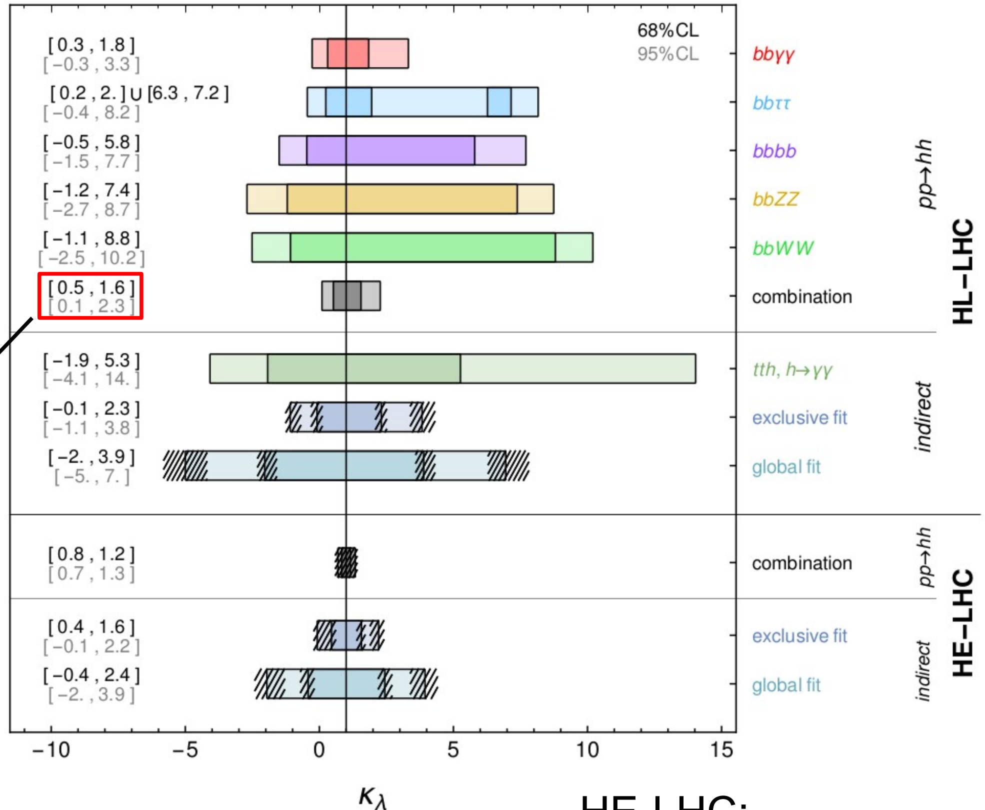
HL-LHC/HE-LHC projections



1902.00134

HL-LHC:
3 ab^{-1} @ 14 TeV

1902.00134



$$0.5 < \kappa_\lambda < 1.6 \quad (95\%\mathrm{CL})$$

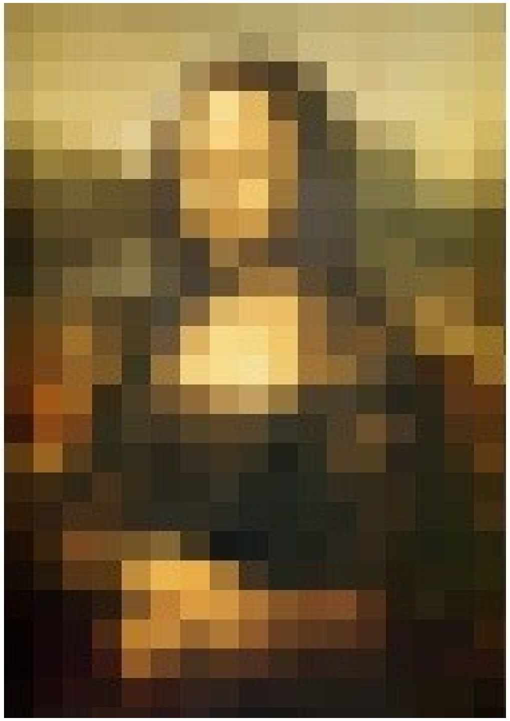
HE-LHC:
15 ab^{-1} @ 27 TeV

Meanwhile:

Same result **by only most sensitive ATLAS analyses**! (ATL-PHYS-PUB-2022-053)

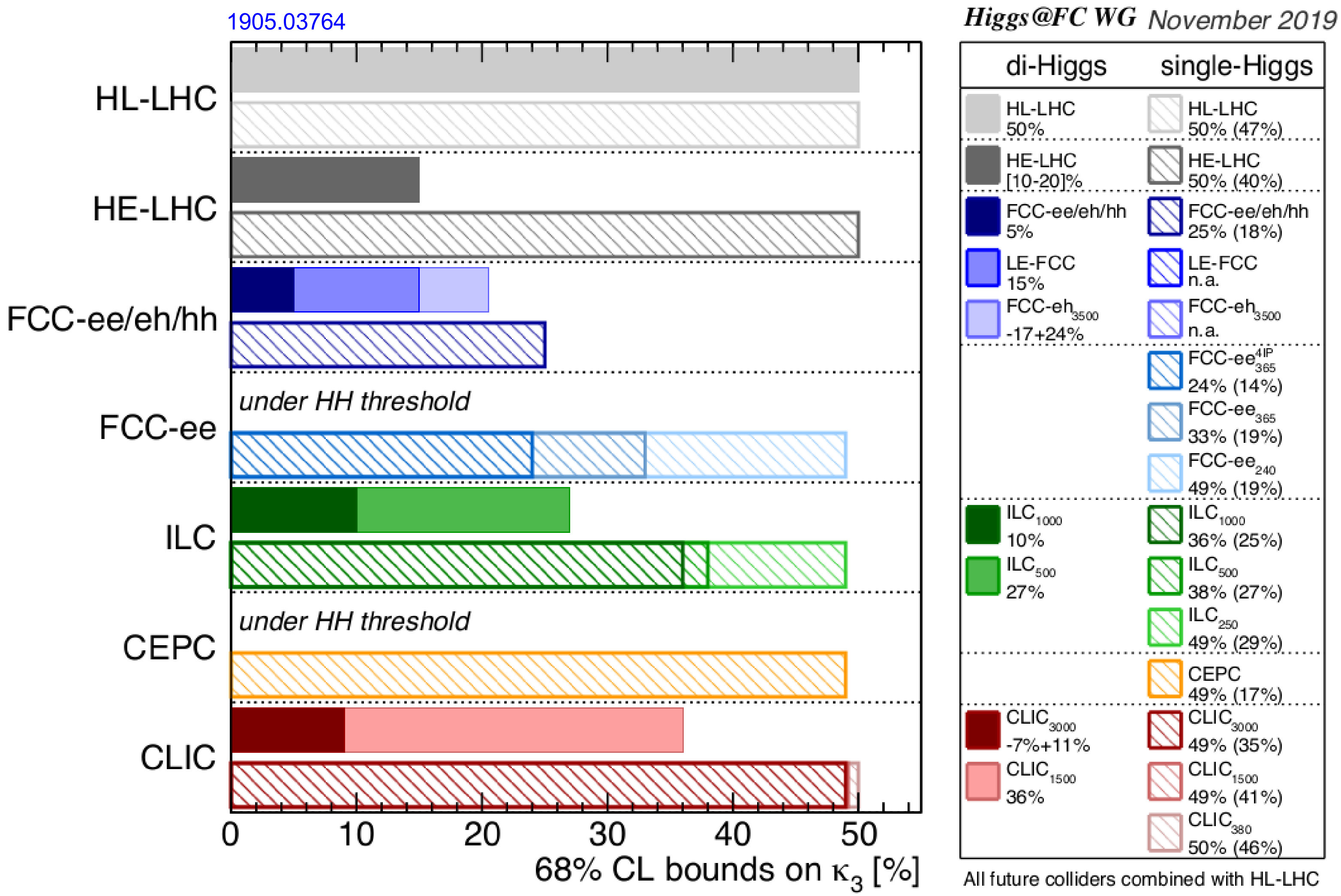
Source of improvements

- Better (i.e. more ambitious) object identification
- Better (i.e. more ambitious) separation between signal and backgrounds
- Use of modern ML models



- Only applicable due to **better understanding of data**!
- Implying experimental and theoretical understanding

Future colliders in perspective



where $\kappa_3 = \kappa_\lambda$

Quartic self coupling?

- Expect

$$\sigma(14\,\mathrm{TeV}) \approx 0.1\,\mathrm{fb}$$
$$\sigma(27\,\mathrm{TeV}) \approx 0.5\,\mathrm{fb}$$ (HE-LHC)
$$\sigma(100\,\mathrm{TeV}) \approx 5\,\mathrm{fb}$$ (FCC_{hh})

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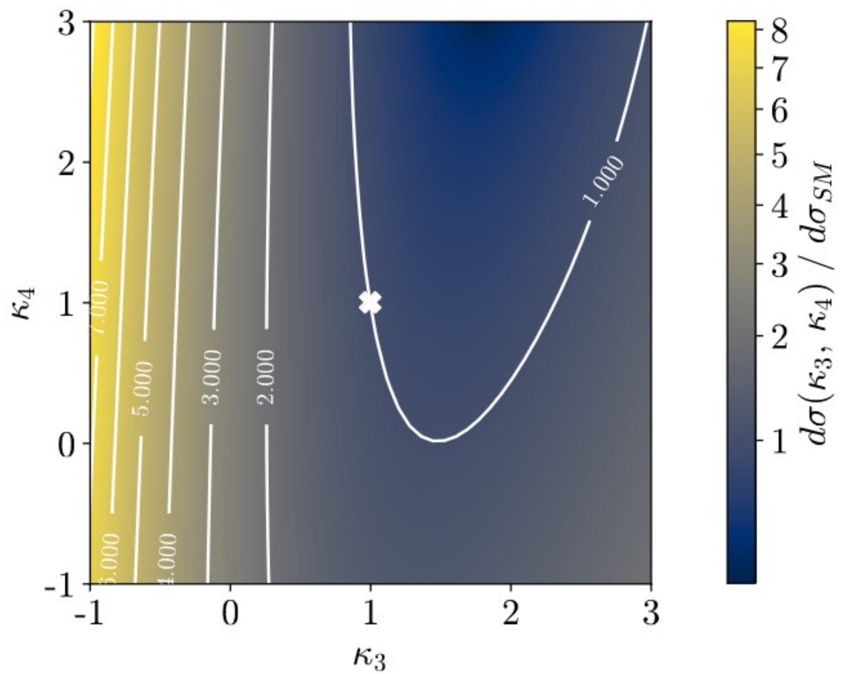
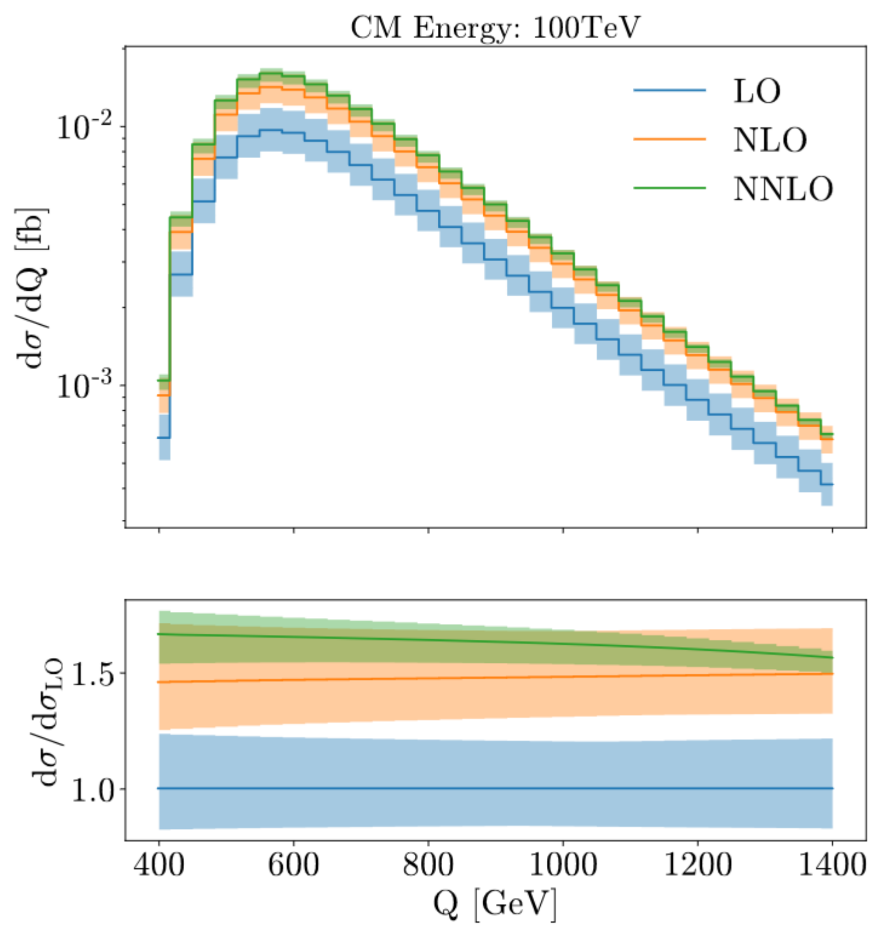




- Scale uncertainties @ NNLO accuracy 5–10%

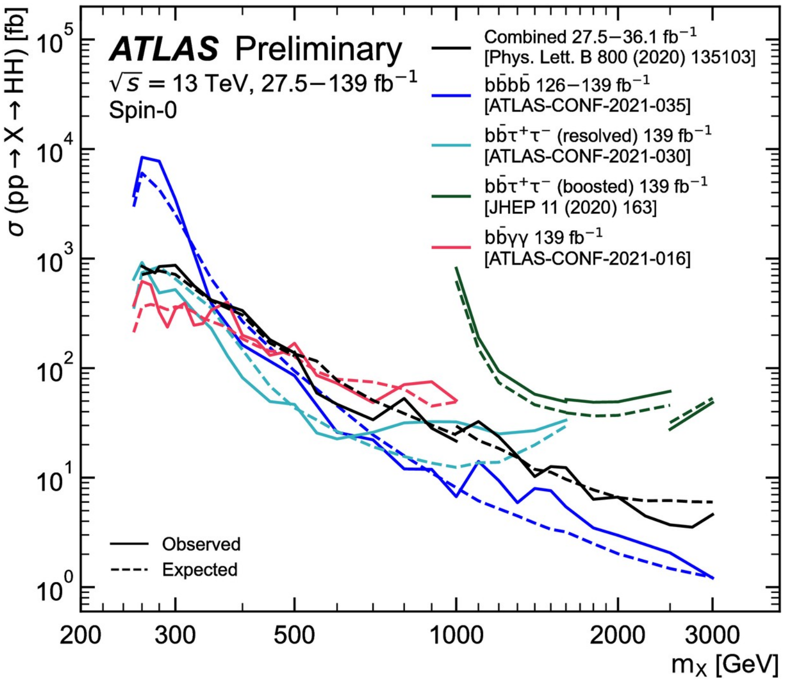
where $\kappa_3 = \kappa_\lambda,\ \kappa_4 = \kappa_{\lambda_4}$

Resonant $\mathrm{X} \rightarrow \mathrm{HH}$

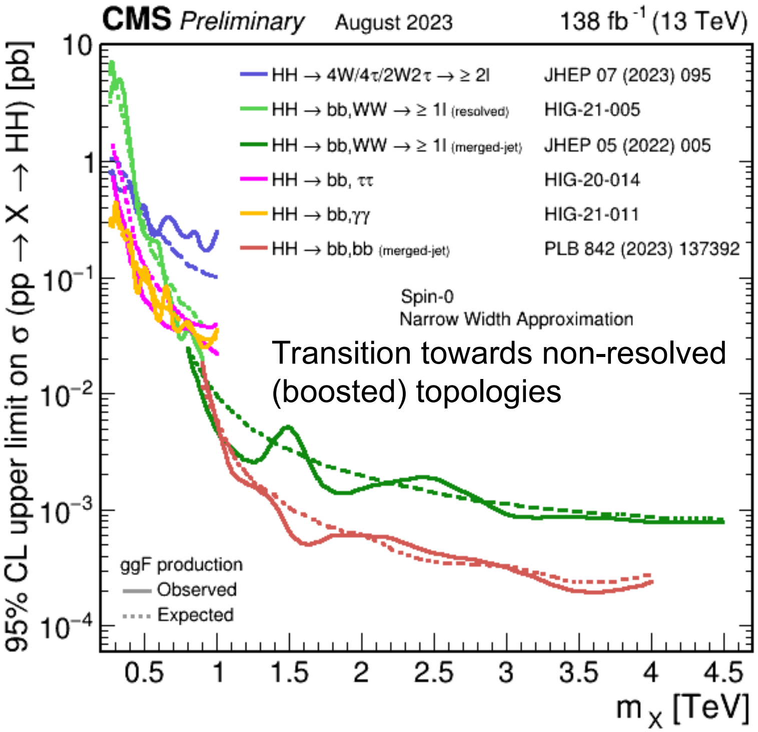
- **Most obvious influence of NP** on HH production $\mathrm{pp} \rightarrow \mathrm{X} \rightarrow \mathrm{HH}$
- Same final states as for non-resonant analyses
- Easy to distinguish from non-peaking backgrounds through m_{X}, m_{H}

Experimental reach

- Mostly **model-agnostic 95% CL upper limits** on $\sigma_{\mathrm{ppX}}\,\mathcal{B}(\mathrm{HH})$
- Provided in standard interpretations of **spin-0** (radion), spin-2 (graviton) models (see backup)
- Connected to more specific NP models e.g. 2HDM and MSSM (see later)



As obtained from ATL-PHYS-PUB-2021-031



As obtained from CMS Higgs summary pages

Prospects @ LHC and other accelerators

- More final states/topologies to chime in
- More ambitious exploration of **boosted topologies**
- More ambitious exploitation of **modern ML-methods**
- **Channel combinations**

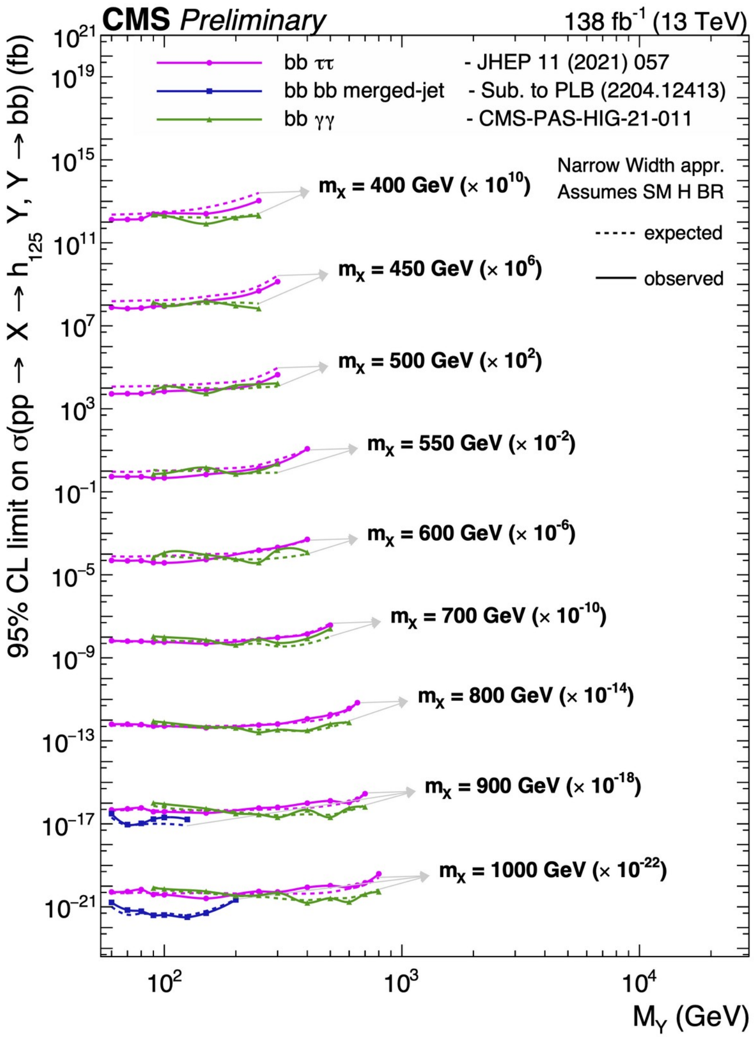
LHC Run2+3 and HL-LHC

Other accelerators

- No estimates for other accelerators
- Increases in $\sqrt{s}$ effectively lead to higher upper limits on $\sigma\,\mathcal{B}$
- Context btw accelerators requires model assumptions

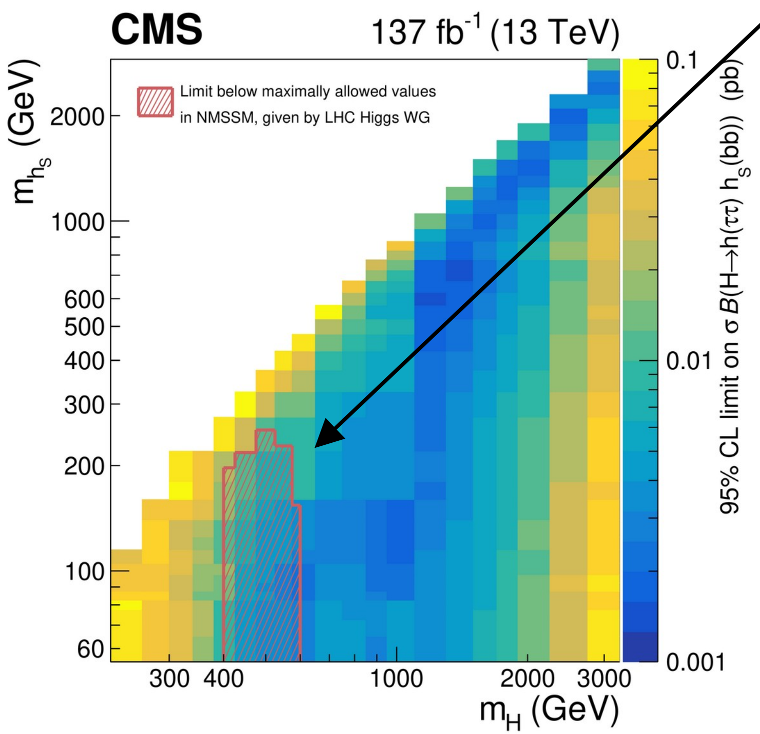
Resonant $\mathrm{X} \rightarrow \mathrm{YH}$

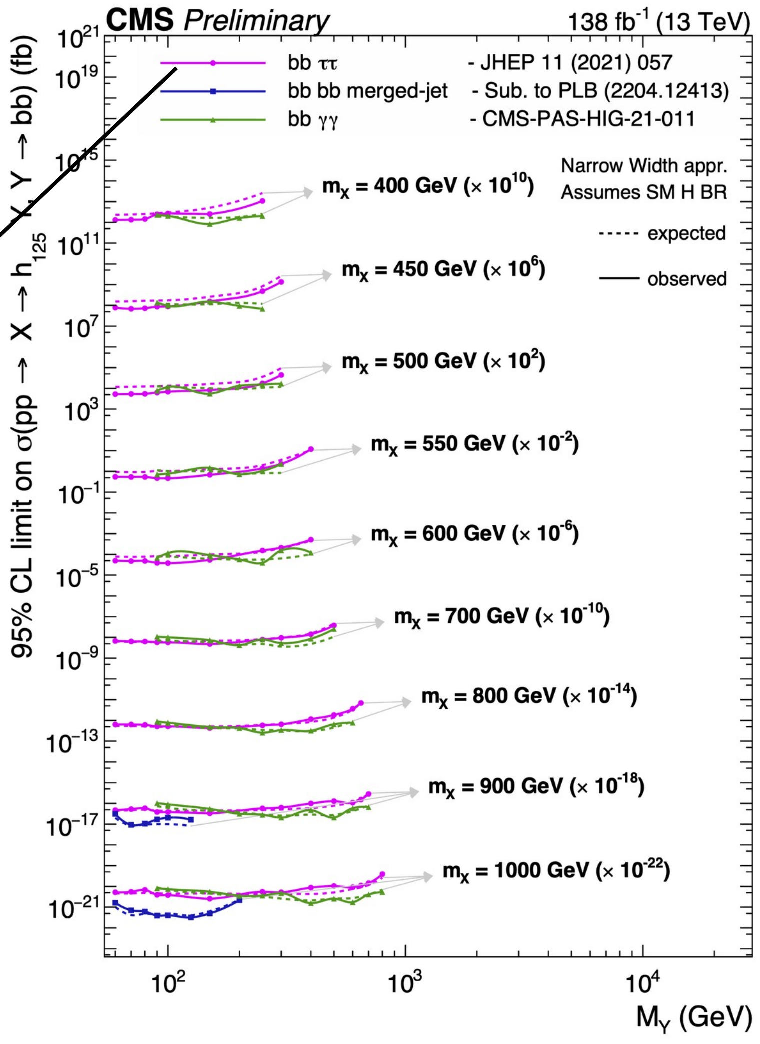
- Relaxed constraints on topology wrt $\mathrm{X} \rightarrow \mathrm{HH}$
- Mostly **model-agnostic 95% CL upper limits** on $\sigma_{\mathrm{ggX}}\,\mathcal{B}(\mathrm{YH})$
- Same final states of relevance, as before
- One more degree of freedom in constraints $m_{\mathrm{X}},\, m_{\mathrm{Y}},\, m_{\mathrm{H}}$
- Pandoras box in terms of limit setting information (→ scans with **hundreds of signal hypotheses**)



Relevance in terms of models

- Topology-based search
- Connection to (more) concrete models: **2HDM+S (e.g. NMSSM)**
- Sensitivity gauge on predictions of most optimistic models (with largest $\sigma\mathcal{B}$)





Also here **channel combinations** are thinkable while slightly more complicated

Search in more concrete models

Experiment-Theory Link
LHC HWG3
Annual Workshop

- 2HDM (e.g. MSSM)
- 2HDM+S (e.g. NMSSM)
- Searches for heavy or light additional scalar bosons

MSSM Higgs bosons

- MSSM predicts **five Higgs bosons**:

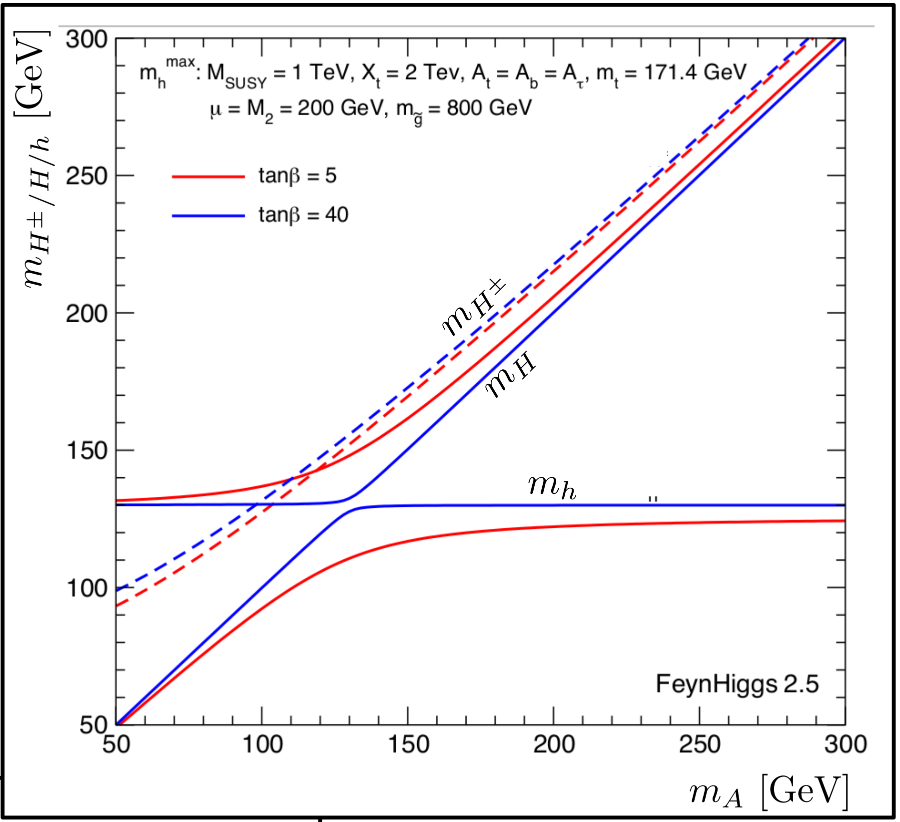
$$\phi_\mathrm{u} = \begin{pmatrix}\phi_\mathrm{u}^+ \\ \phi_\mathrm{u}^0\end{pmatrix}, \quad Y_{\phi_\mathrm{u}} = +1, \quad v_\mathrm{u}: \ \mathrm{VEV_u}$$

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

$$N_\mathrm{ndof} = 8 \ - \underbrace{3}_{\mathrm{W^\pm,\ Z}} = \underbrace{5}_{\mathrm{H^\pm,\ H,\ h,\ A}}$$

- Strict mass requirements lead to **2 free parameters** at tree-level:

$$m_\mathrm{A}, \quad \tan\beta = \frac{v_\mathrm{u}}{v_\mathrm{d}}$$



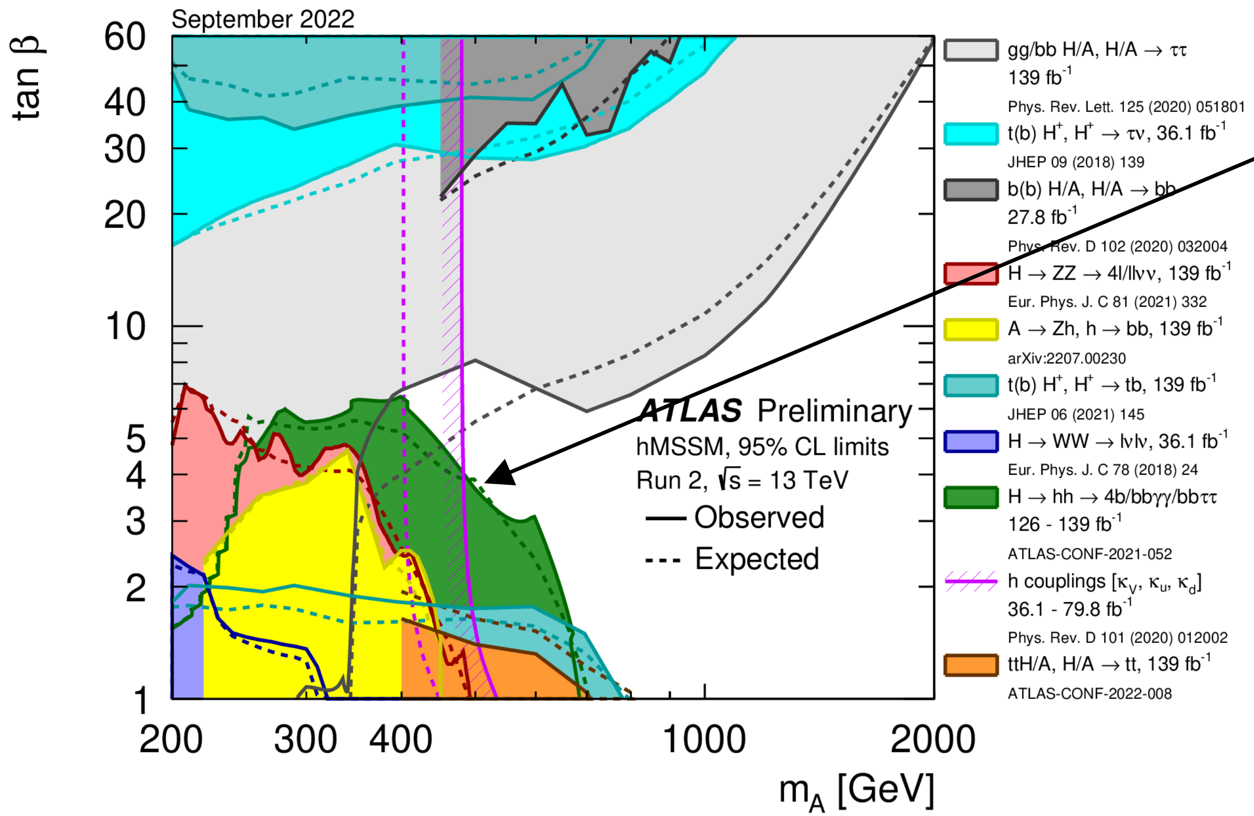
$$\boxed{\begin{aligned} m^2_{H^\pm} &= m^2_A + m^2_W \\ m^2_{H,\,h} &= \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}\right) \\ \tan\alpha^{(*)} &= \frac{-(m^2_A + m^2_Z)\sin 2\beta}{(m^2_Z - m^2_A)\cos 2\beta + \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}} \end{aligned}}$$

$\longrightarrow$ Determines couplings @ LO.

(*) angle btw. v_u & v_d in isospace.

MSSM searches

- Observed Higgs boson: $\mathrm{H}^0 \rightarrow \mathrm{h}$
- Look for H and A, preferred in down-type fermion final states



- $\boxed{\mathrm{X} \rightarrow \mathrm{HH} \text{ reappears as } \mathrm{H} \rightarrow \mathrm{hh}}$
- Flagship: $\mathrm{H/A/h} \rightarrow \tau\tau$
- New kid: $\mathrm{H/A/h} \rightarrow \mathrm{tt}$

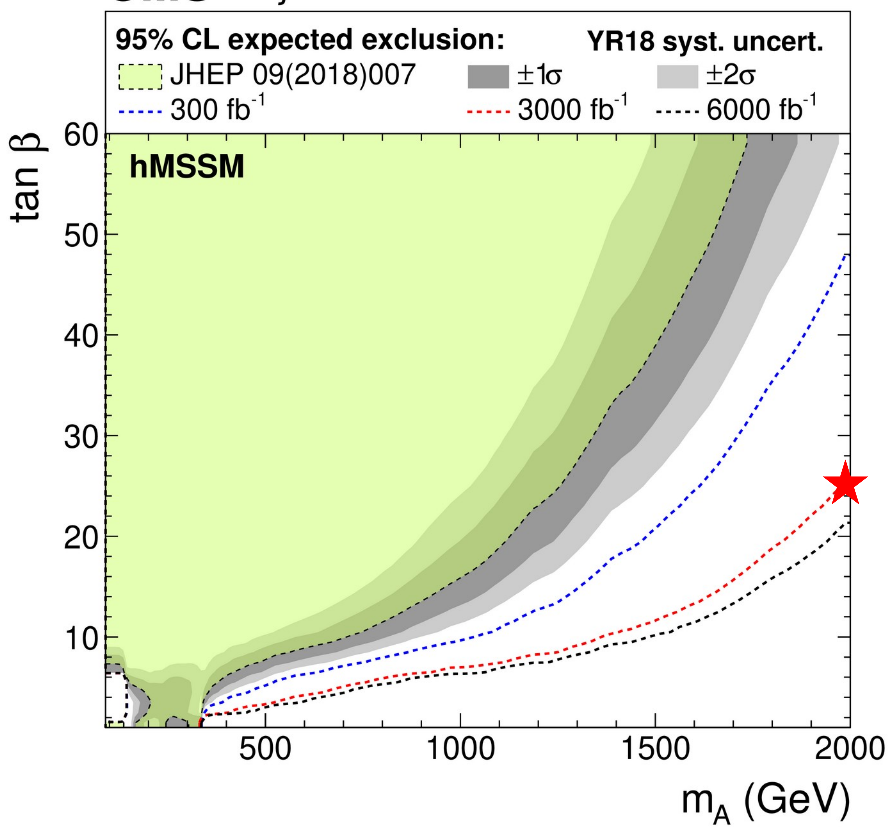
As obtained from ATL-PHYS-PUB-2022-043

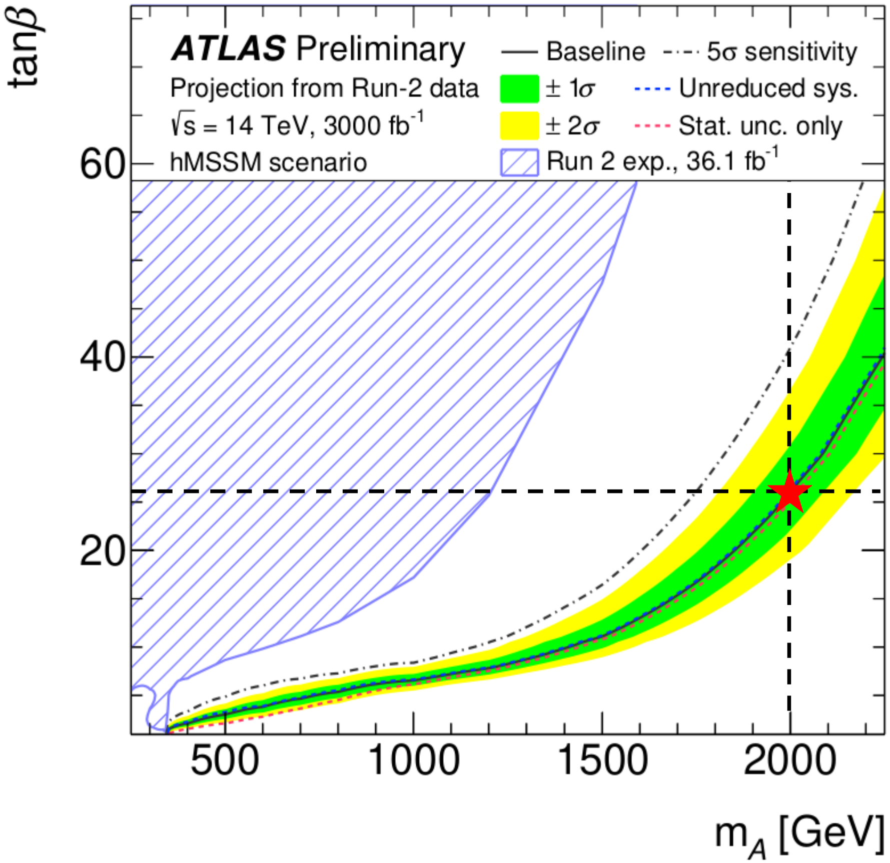
Similar results of CMS shown in backup

How far will the LHC carry us?

- 3 at^{-1} @ 14 TeV

CMS *Projection*

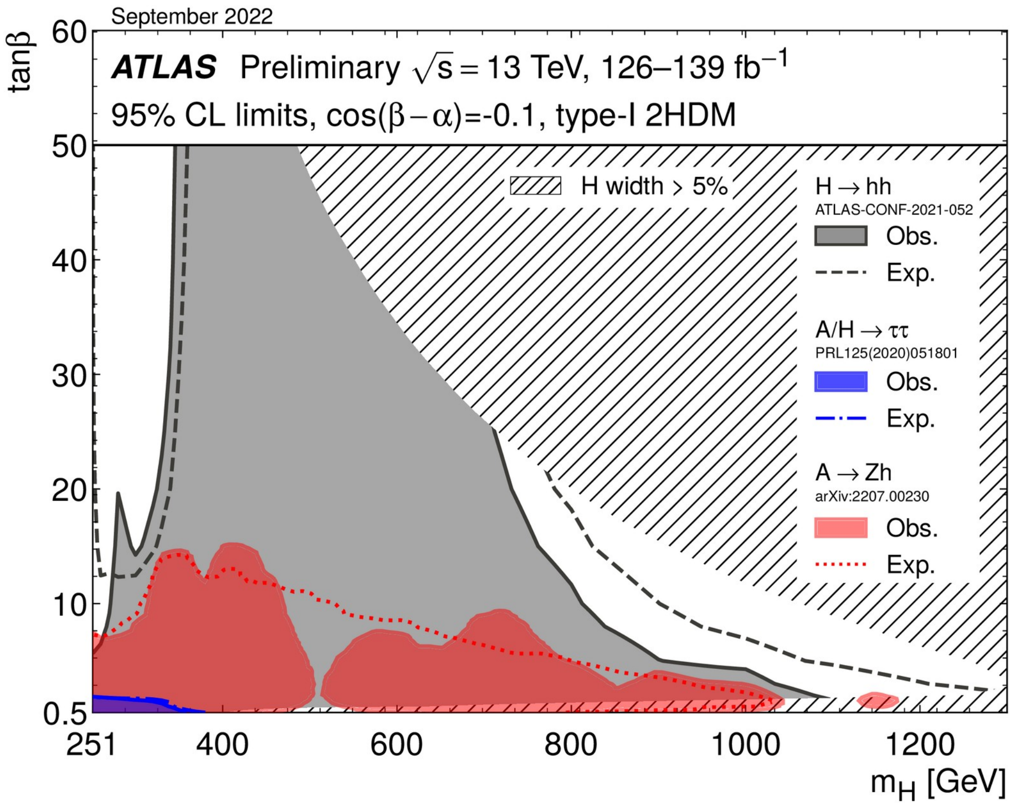




- Reach of LHC phase-1/2 → $m_{\mathrm{A}} \lesssim 2\,\mathrm{TeV}$
- **Real challenge for MSSM models** → to match h properties

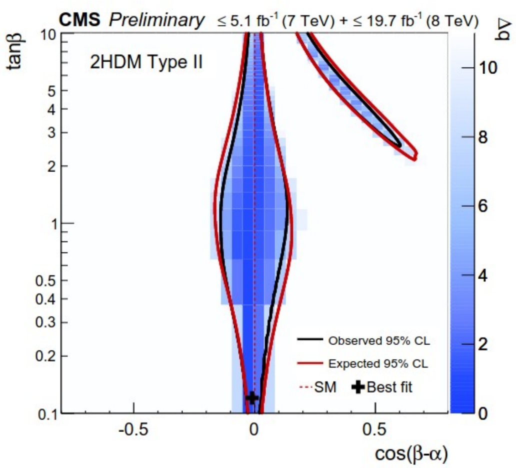
MSSM → 2HDM

- Keep 2 Higgs doublets
- Lift SUSY constraints: $m_\mathrm{A},\,\tan\beta\;\rightarrow m_\mathrm{h},\,m_\mathrm{H},\,m_\mathrm{A},\,m_{\mathrm{H}^\pm},\,\alpha,\,\tan\beta,\,m_{12}$ [1]
- Four types of CP-convserving 2HDM models w/o FCNC → MSSM concrete incarnation of a 2HDM of Type-2



As obtained from ATL-PHYS-PUB-2022-043

- Largely constrained by h properties (→ driving 2HDMs into alignment limit $\cos(\beta-\alpha)\rightarrow 0$)



Taken from CMS-PAS-HIG-16-007 for illustration purposes only

[1] Constrained by unitarity, perturbativity and vacuum stability

One more ghost at the attic

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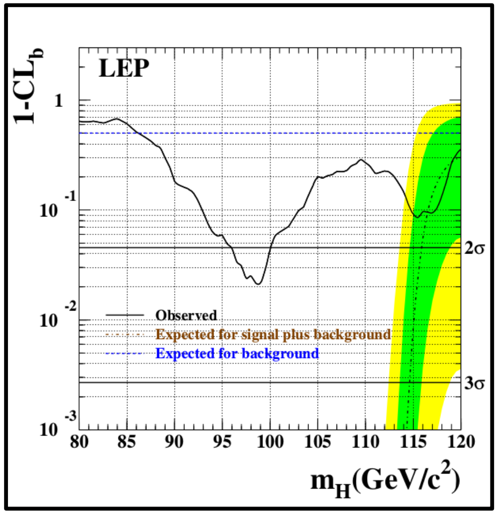
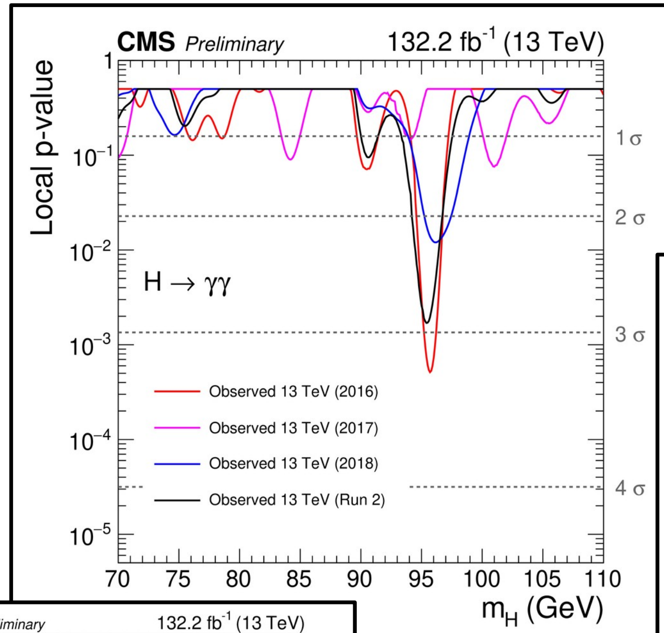


CMS-PAS-HIG-20-012



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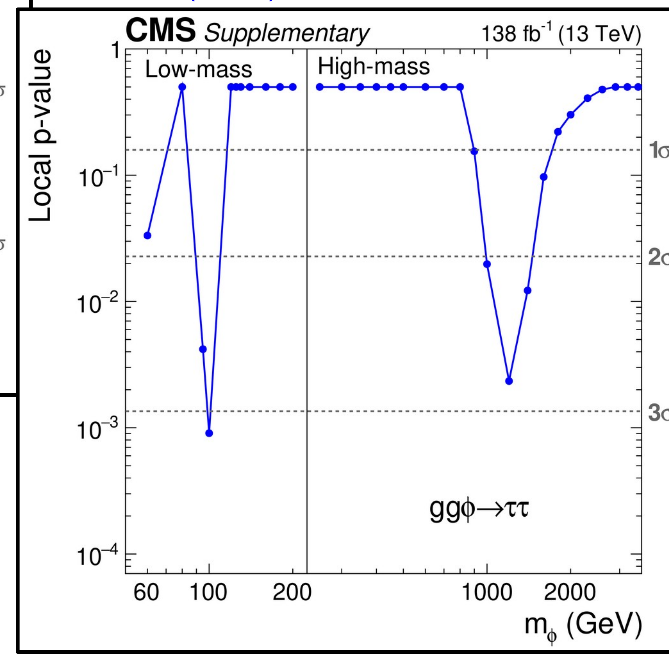
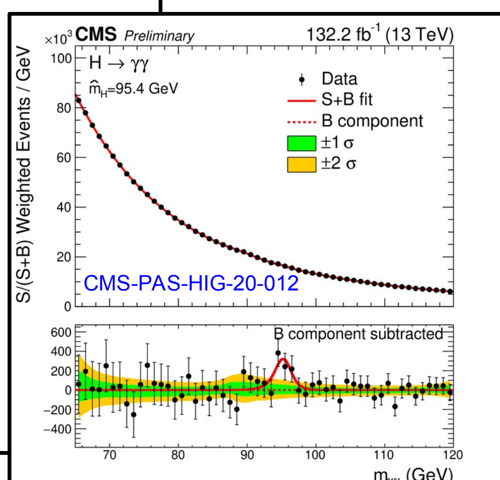
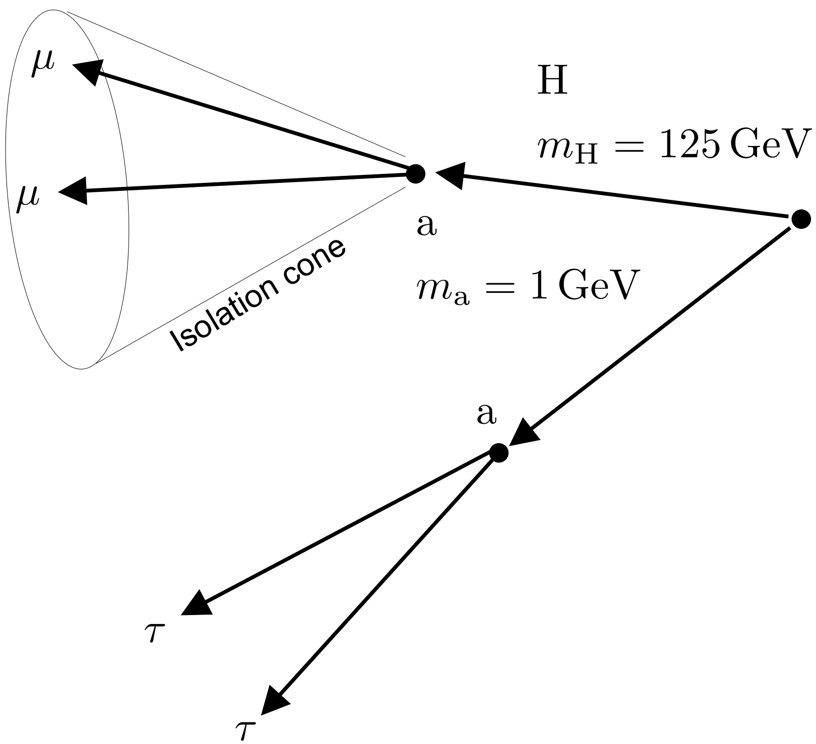


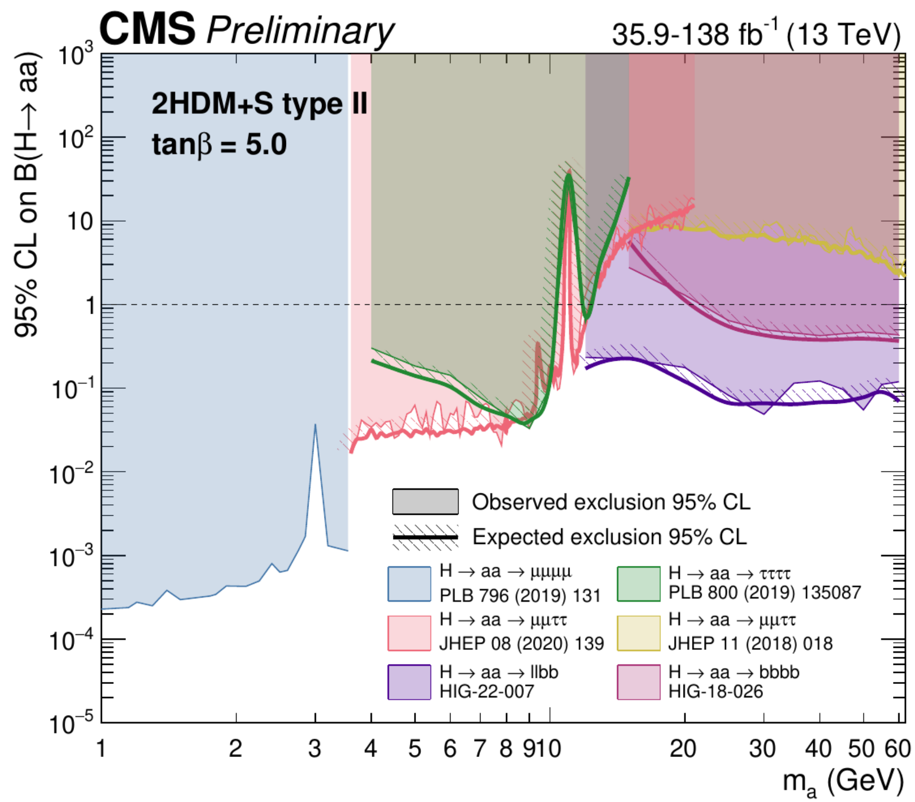


Corresp. ATLAS results in backup

Searches for (very) light Higgs bosons

- Motivated by 2HDM+S (e.g. NMSSM)
- Good example of how genuiously a multipurpose machine can be used
- Example: $\mathrm{H} \rightarrow \mathrm{a}(\mu\mu)\mathrm{a}(\tau\tau)$

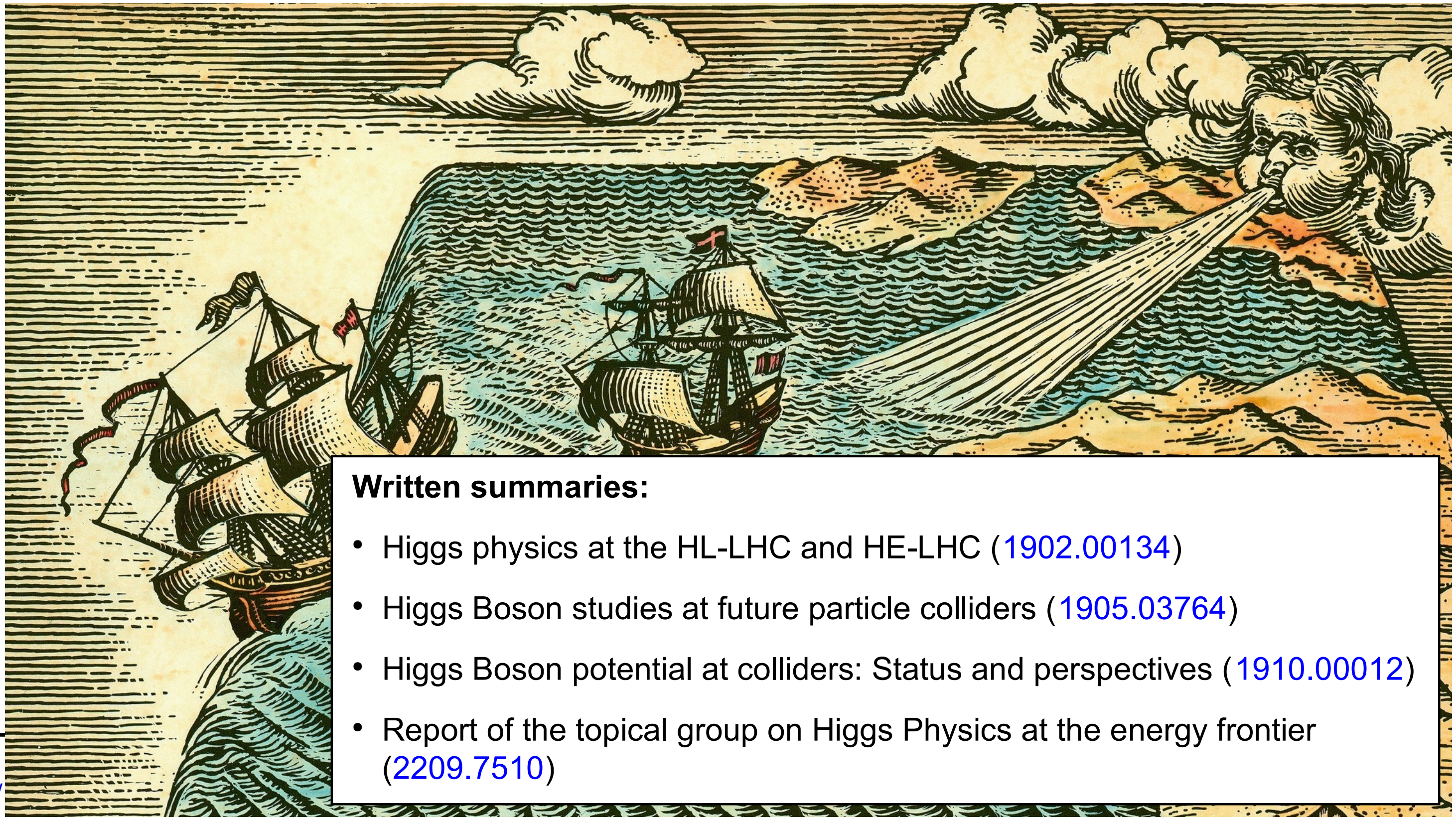




Summary

- LHC vastly explored newly opened Higgs sector (~300 papers)
- Search for NP at scales between 1 GeV – 4.5 TeV → no hints for NP, yet
- Direct searches will profit from **higher** $\sqrt{s}$, indirect hints through **precision**!
- Mapping out the Higgs potential will remain the next big challenge ($\Delta\kappa_{\lambda} \lesssim 0.20\,(0.05)$ possible at HE-LHC (FCC_{hh}))

Terra incognita



Written summaries:

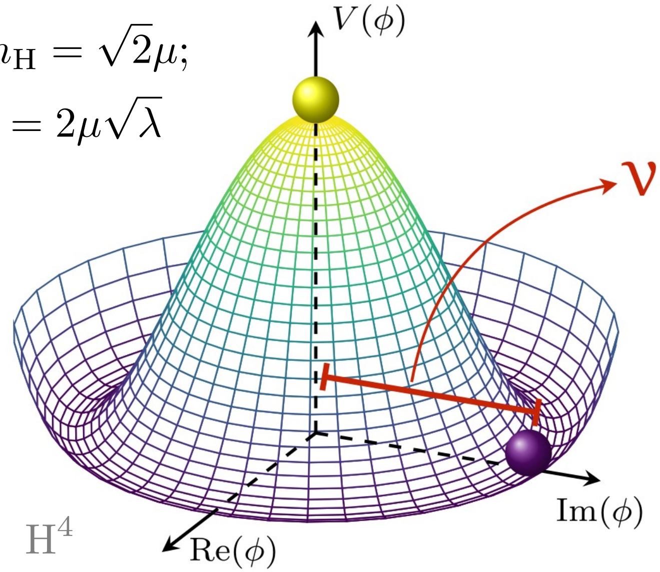
- Higgs physics at the HL-LHC and HE-LHC (1902.00134)
- Higgs Boson studies at future particle colliders (1905.03764)
- Higgs Boson potential at colliders: Status and perspectives (1910.00012)
- Report of the topical group on Higgs Physics at the energy frontier (2209.7510)

Backup

Higgs potential of the SM

$$\mathcal{L}^{\mathrm{SU(2)_L\times U(1)_Y}} = \mathcal{L}^{\mathrm{kin}} + \mathcal{L}^{\mathrm{CC}} + \mathcal{L}^{\mathrm{NC}} + \mathcal{L}^{\mathrm{gauge}} + \mathcal{L}^{\mathrm{Higgs}}$$

$$m_{\mathrm{H}} = \sqrt{2}\mu;$$
$$\nu = 2\mu\sqrt{\lambda}$$



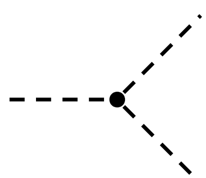
$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} \qquad \begin{aligned} \phi &\to \phi' = e^{i\vartheta'}G\phi \\ \phi^\dagger &\to \phi'^\dagger = \phi^\dagger G^\dagger e^{-i\vartheta'} \\ G &= e^{i\vartheta^a t^a} \in \mathrm{SU(2)_L} \quad \vartheta^a, \vartheta' \in \mathbb{R} \end{aligned}$$

$$\mathcal{L}^{\mathrm{Higgs}} = D_\mu\phi^\dagger D^\mu\phi - V(\phi)$$

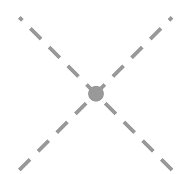
$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2 = -\frac{\mu^4}{4\lambda} + \mu^2\,\mathrm{H}^2 + \underbrace{\mu\sqrt{\lambda}}_{\equiv\lambda_3}\,\mathrm{H}^3 + \underbrace{\frac{\lambda}{4}}_{\equiv\lambda_4}\,\mathrm{H}^4$$

Mass term

Trilinear coupling



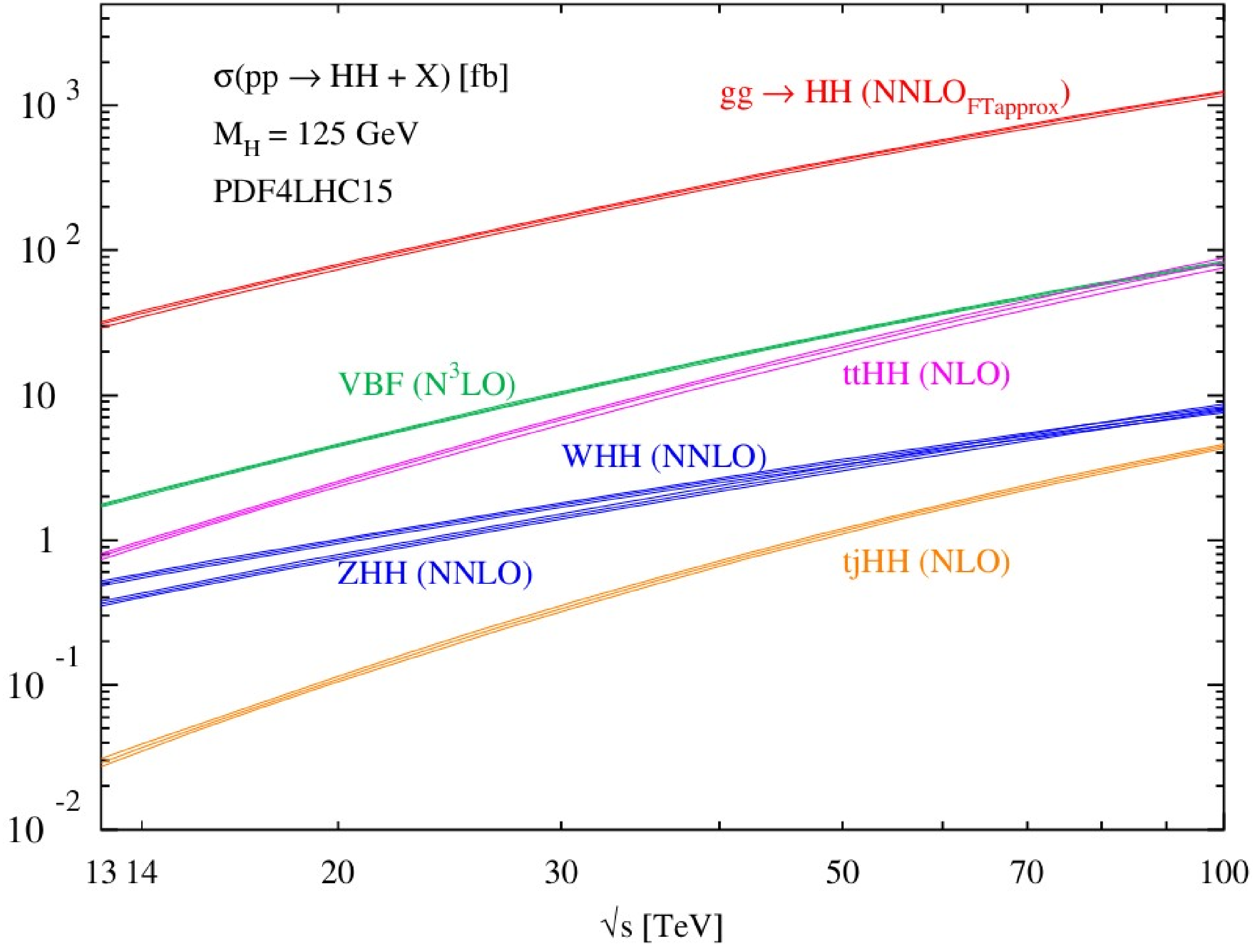
Quartic coupling



Priv.-Doz. Dr. Roger Wolf
https://etpwww.etp.kit.edu/~rwolf/

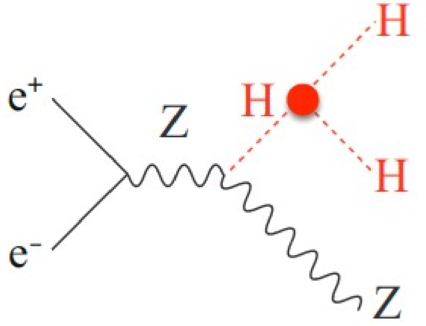
Cross sections for HH production

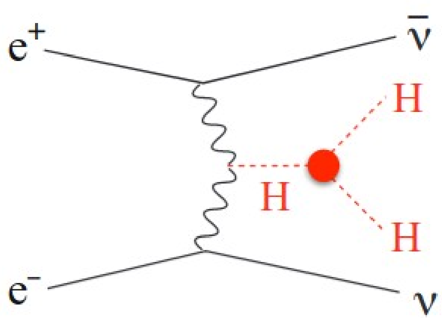
1910.00012



Direct vs. indirect hints on λ_3 @ e^+e^- colliders

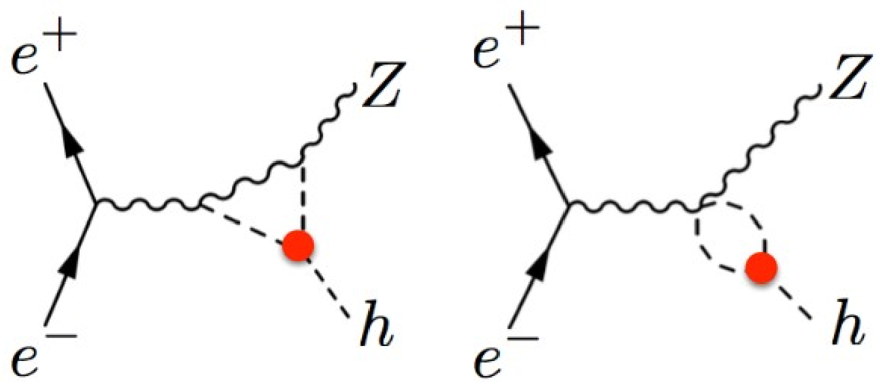
$\sqrt{s} \gtrsim 500$ GeV





$\sigma_{HH} \sim O(0.1)$ fb

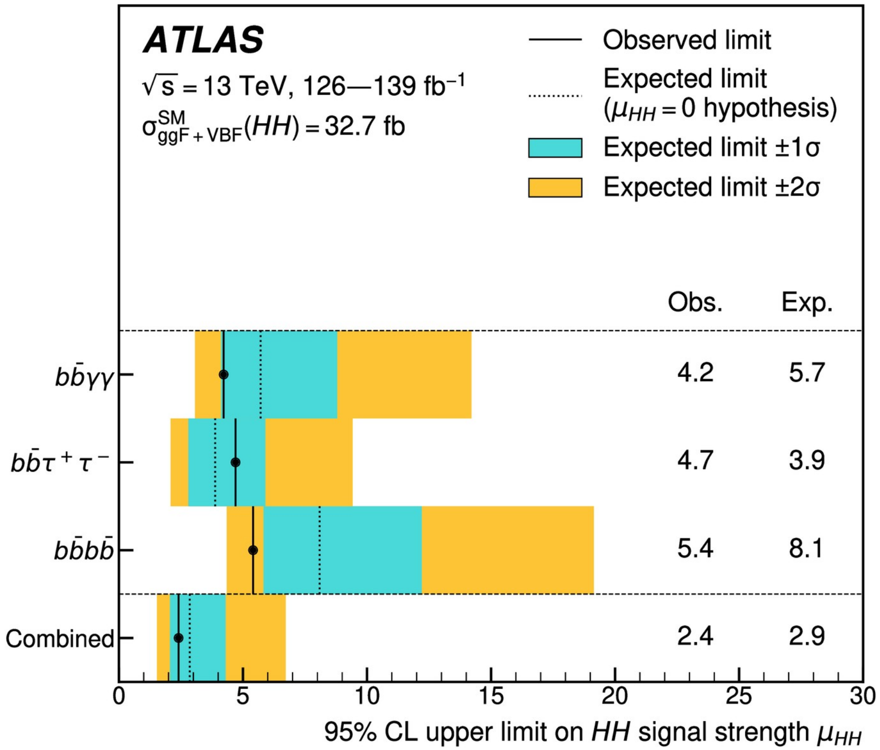
$\sqrt{s} \gtrsim 240\text{–}250$ GeV



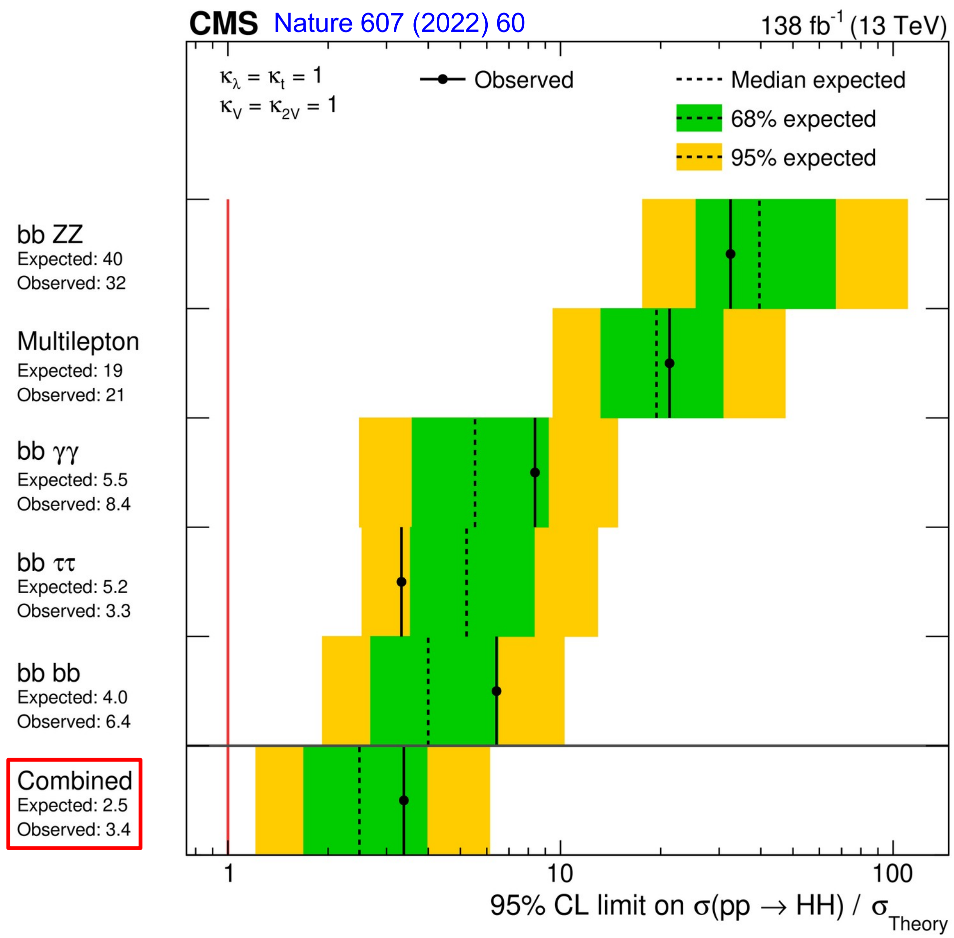
$\delta\sigma_{ZH} \sim O(1\%)$

Upper limits on SM HH production

PLB 843 (2023) 137745

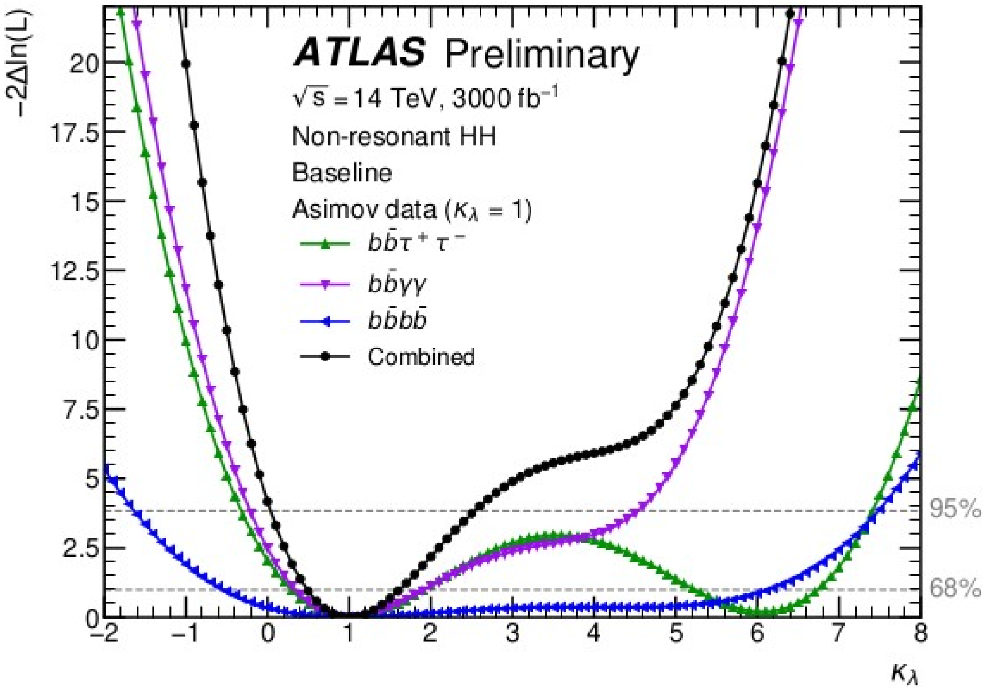


CMS Nature 607 (2022) 60

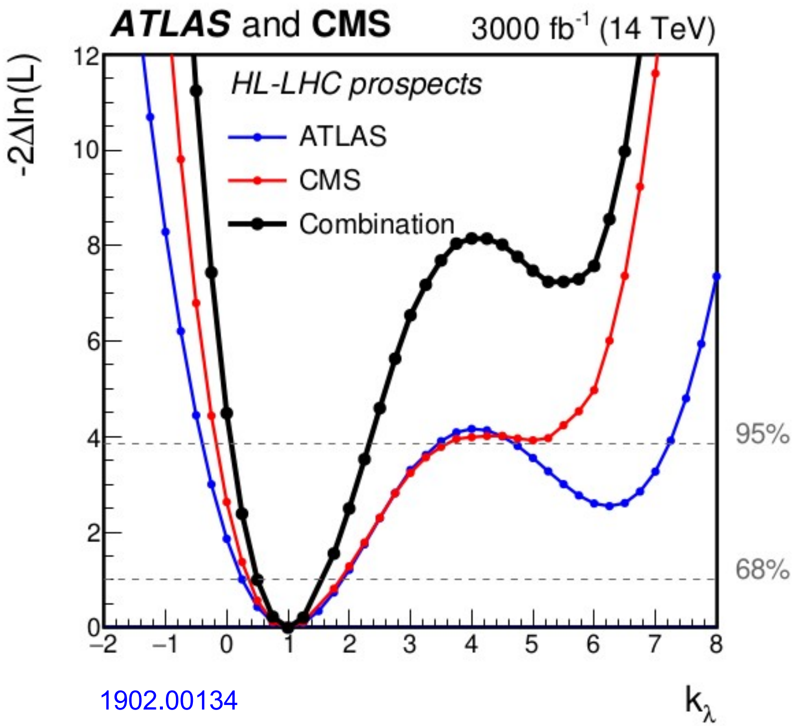


Newest projections of constraints on κ_λ by ATLAS

ATL-PHYS-PUB-2022-053



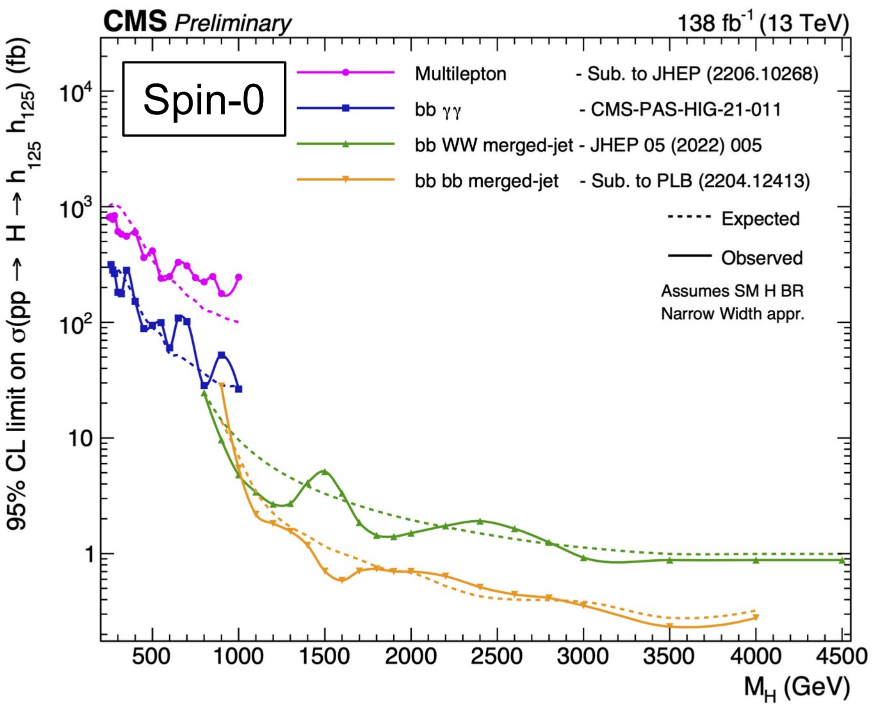
$$0.5 < \kappa_\lambda < 1.6 \quad (95\%\text{CL})$$

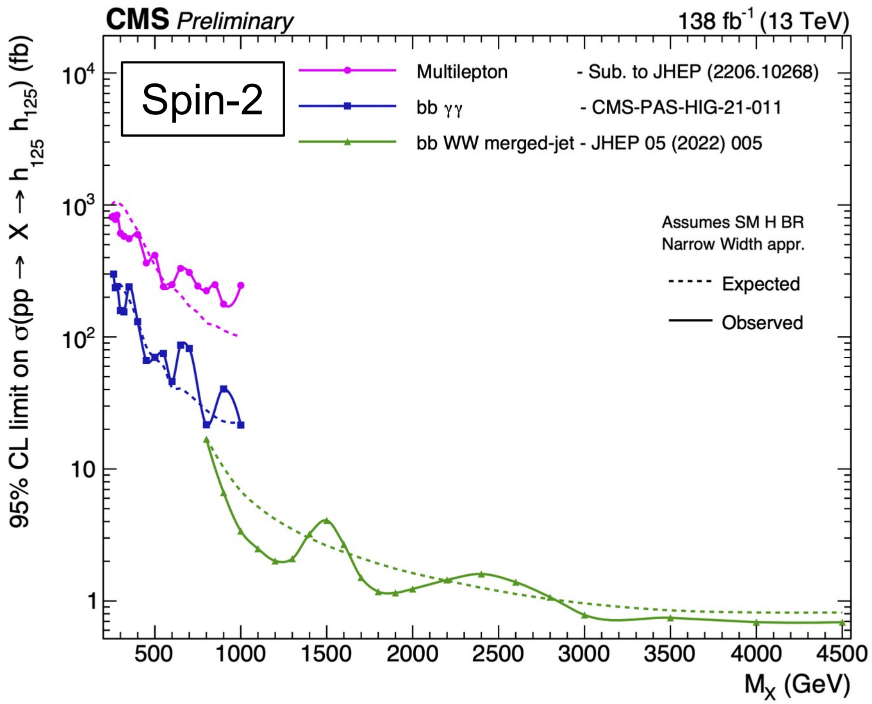


1902.00134

$$0.5 < \kappa_\lambda < 1.6 \quad (95\%\text{CL})$$

Upper limits on $\mathrm{X} \rightarrow \mathrm{HH}$ (Spin-2)

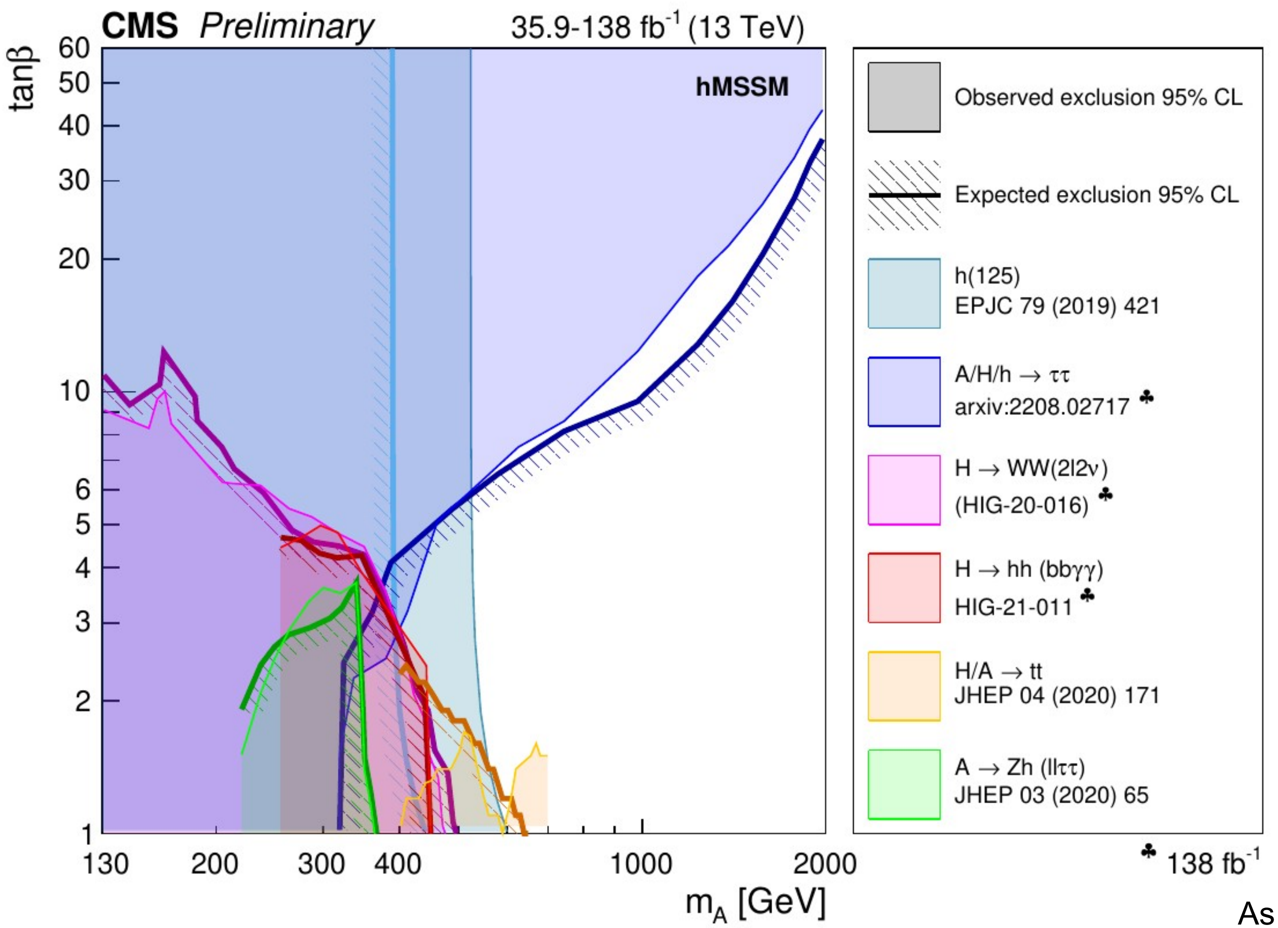




As obtained from CMS Higgs summary pages

MSSM searches @ CMS

- Observed Higgs boson: $\mathrm{H}^0 \rightarrow \mathrm{h}$
- Look for H and A, preferred in down-type fermion final states

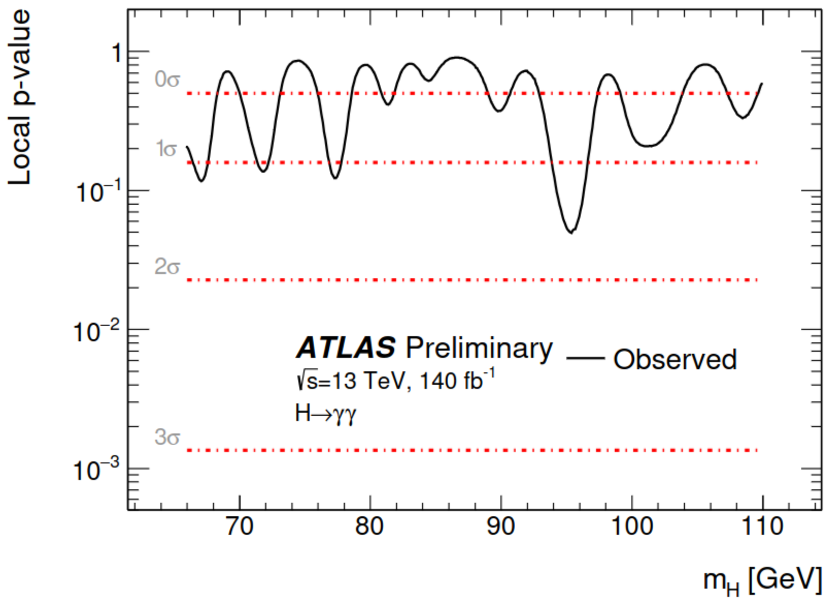


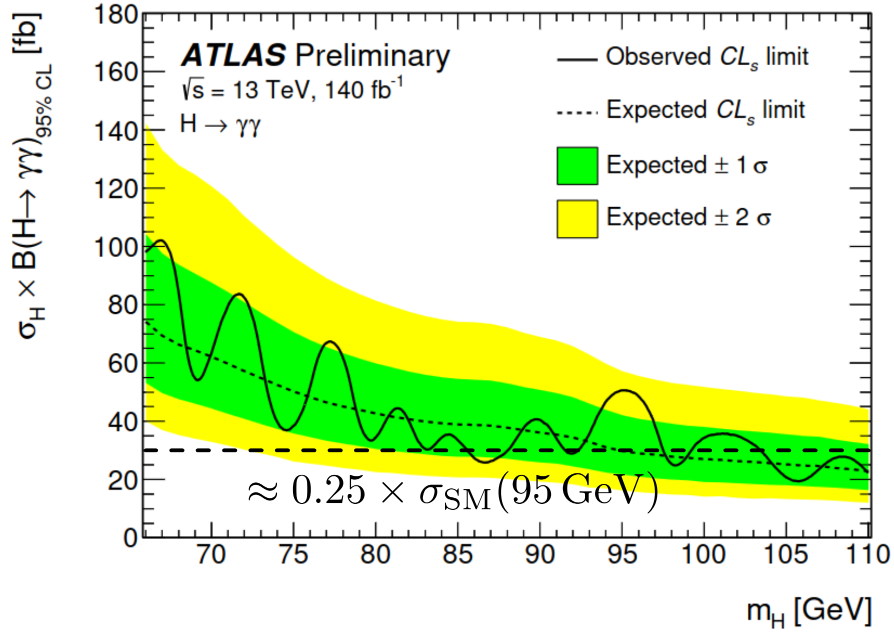
- $\mathrm{X} \rightarrow \mathrm{HH}$ reappears as $\mathrm{H} \rightarrow \mathrm{hh}$
- Flagship: $\mathrm{H/A/h} \rightarrow \tau\tau$
- New kid: $\mathrm{H/A/h} \rightarrow \mathrm{tt}$

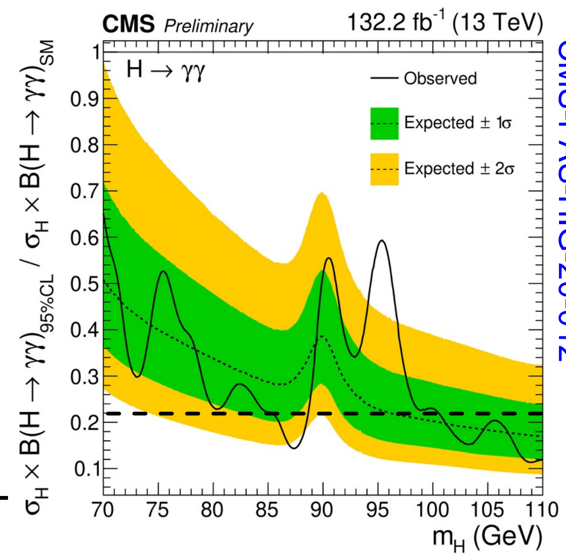
As obtained from
CMS Higgs summary pages

Excess at 95 GeV?

ATLAS-CONF-2023-035

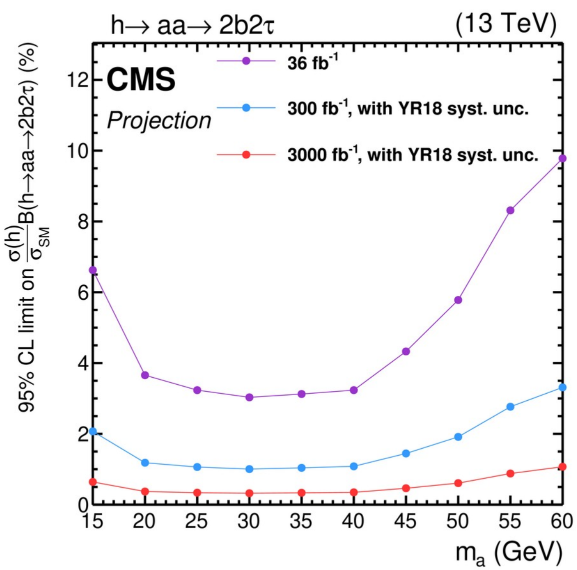


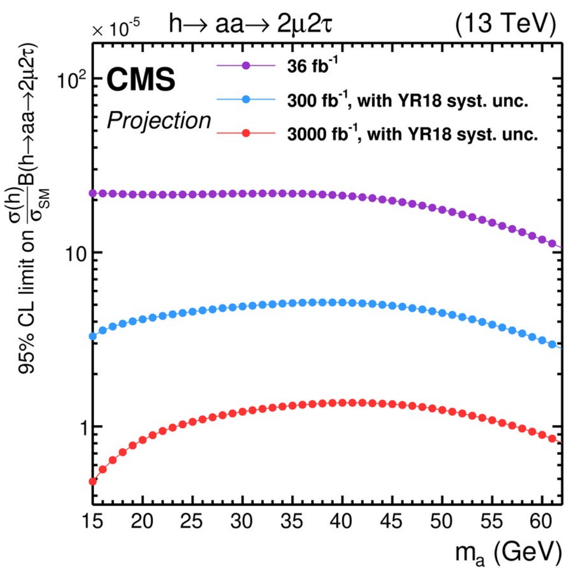




CMS-PAS-HIG-20-012

HL-LHC projections of





CMS-PAS-FTR-18-035

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