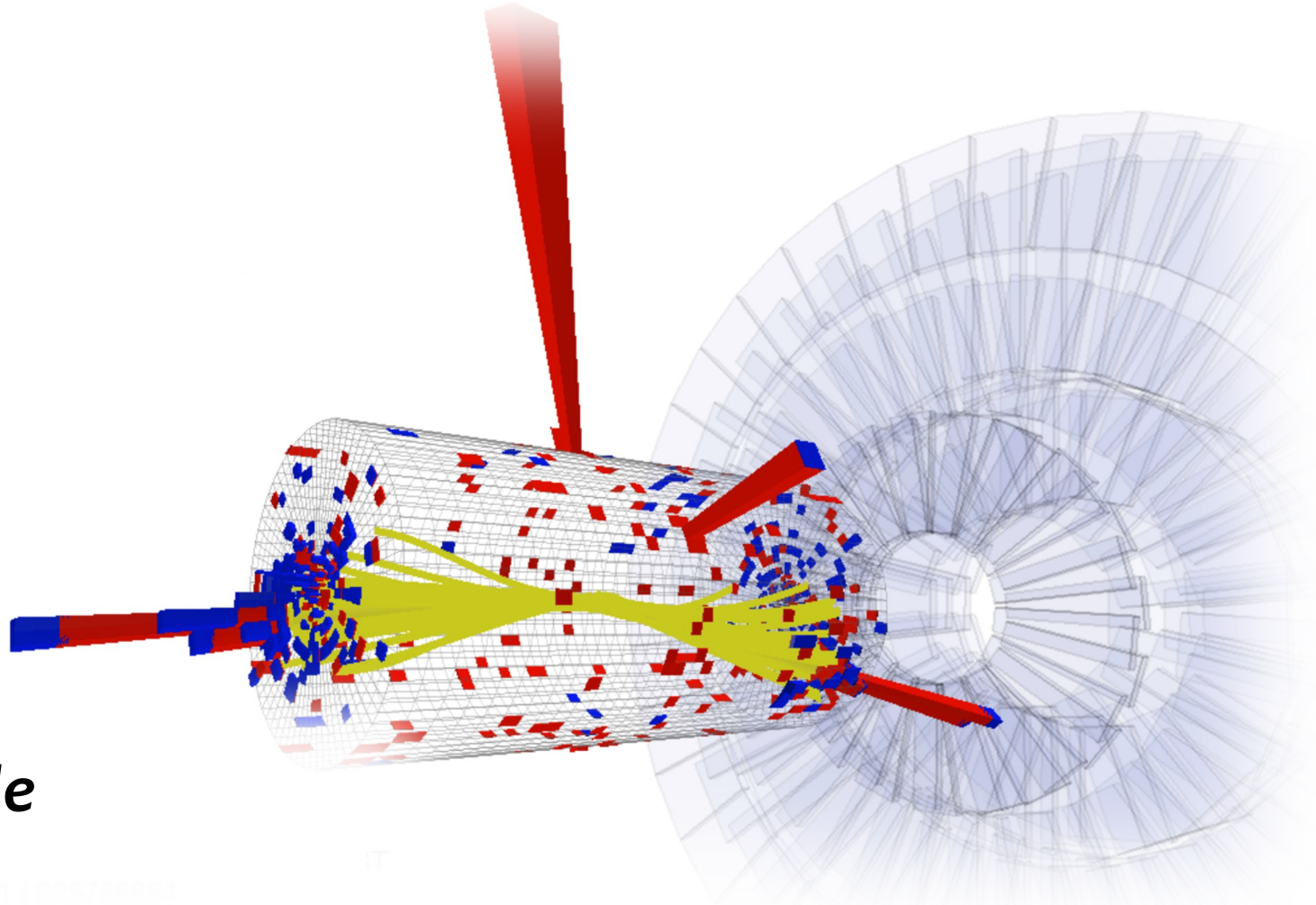
Imperial College London

Higgs @ CMS

Nicholas Wardle

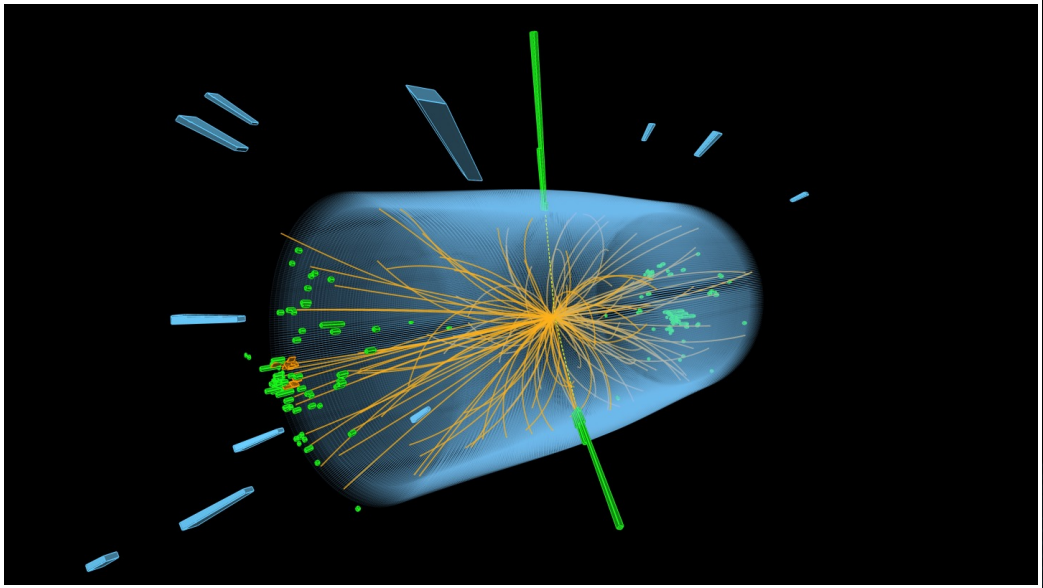


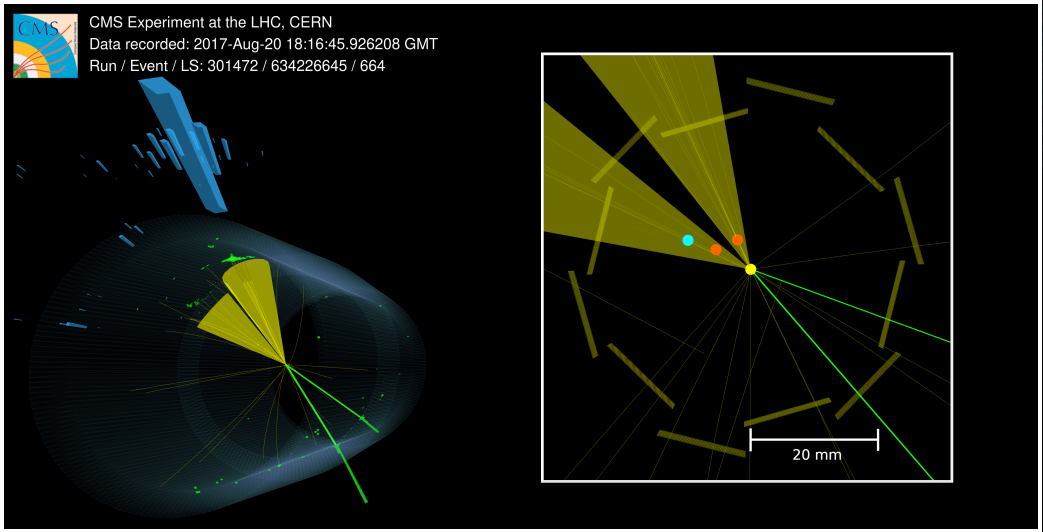
UK HEP Forum 2023:

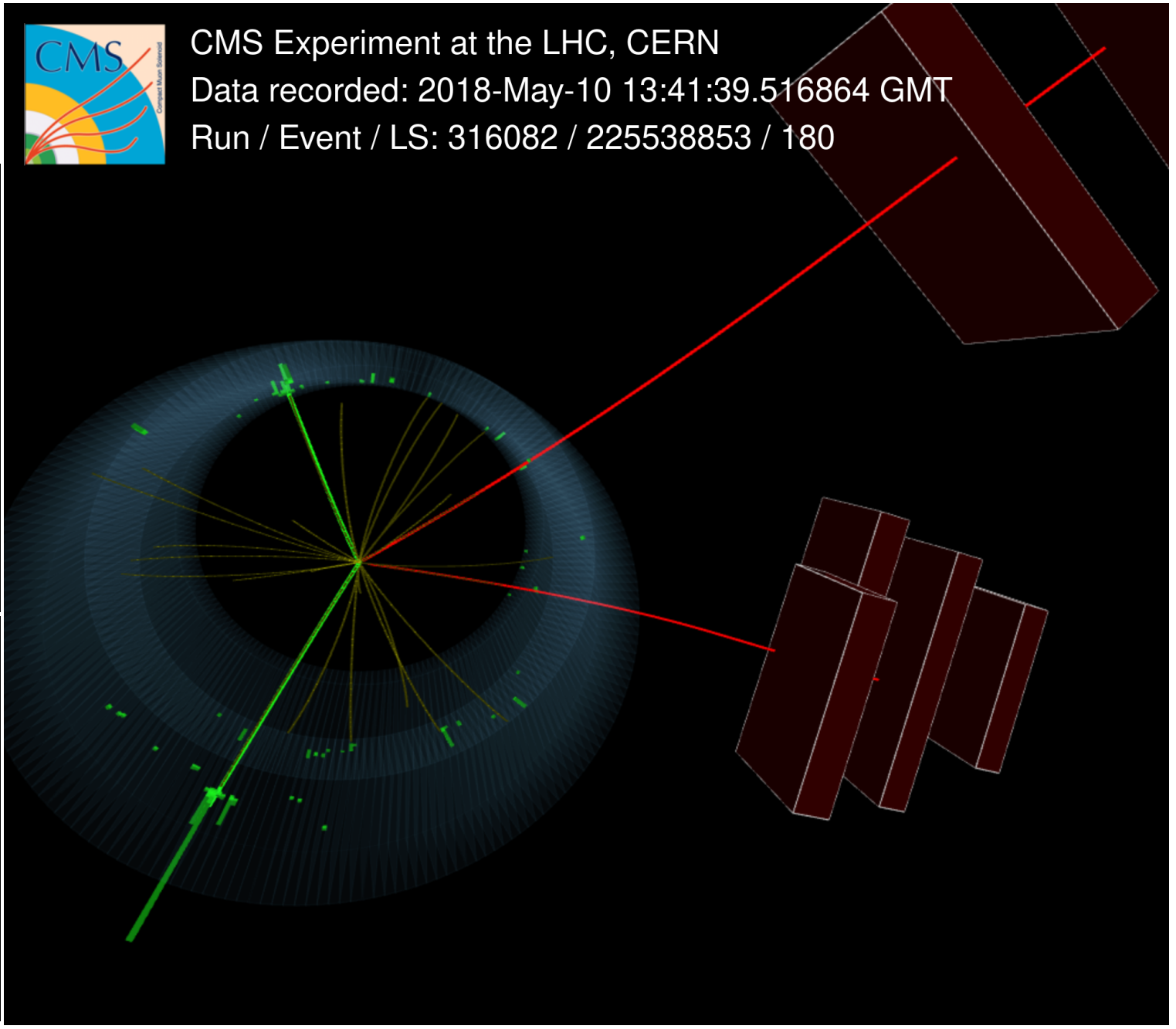
Completing the Higgs-saw Puzzle

21-22 November 2023

Higgs @ CMS

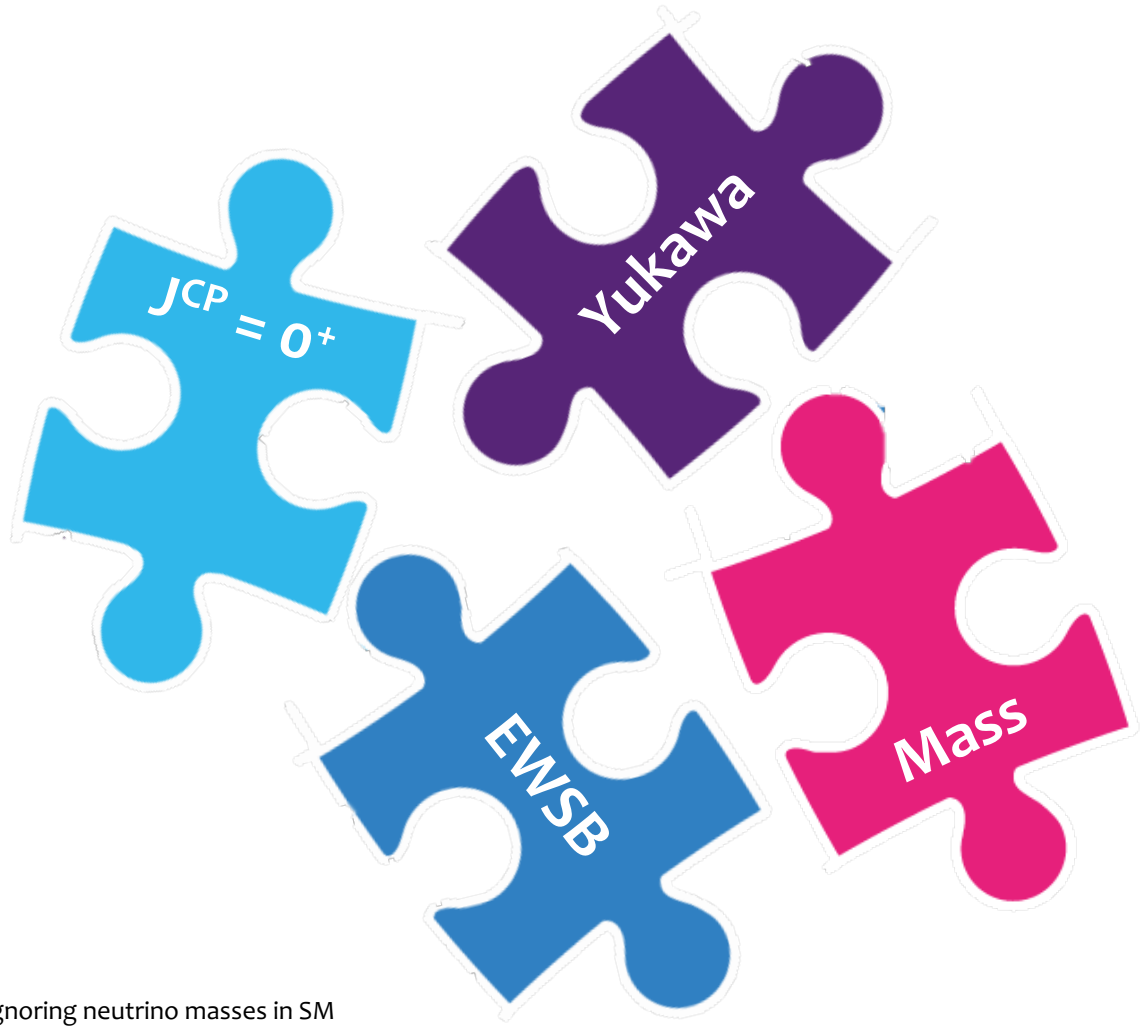


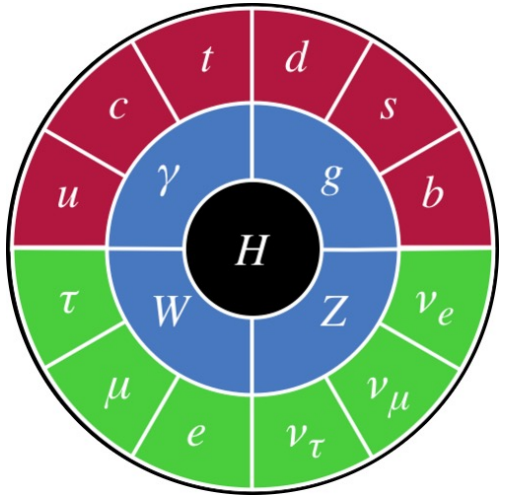

CMS Experiment at the LHC, CERN
Data recorded: 2017-Aug-20 18:16:45.926208 GMT
Run / Event / LS: 301472 / 634226645 / 664
20 mm


CMS Experiment at the LHC, CERN
Data recorded: 2018-May-10 13:41:39.516864 GMT
Run / Event / LS: 316082 / 225538853 / 180

Higgs potential plays a central role in the SM

→ Understanding Higgs boson properties is crucial to solving the Higgs-saw puzzle





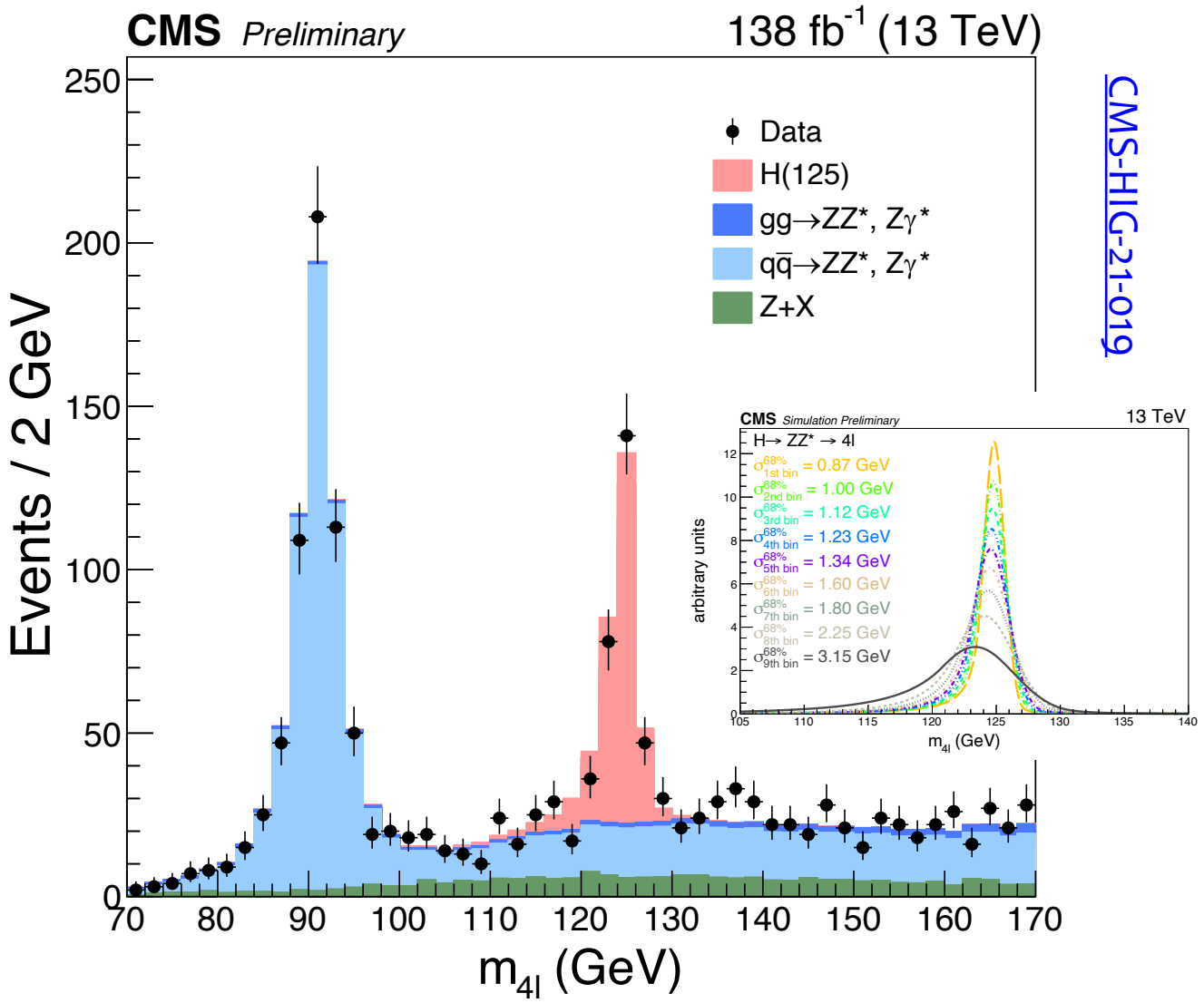
The Higgs boson is

- A **massive** fundamental **CP-even scalar** in SM
- Responsible for **masses of W/Z bosons** (EWSB)
- Gives rise to **fermion masses***

I will cover a few important CMS results → **personal highlights** from CMS Higgs physics measurements!

*ignoring neutrino masses in SM

Higgs mass and Width

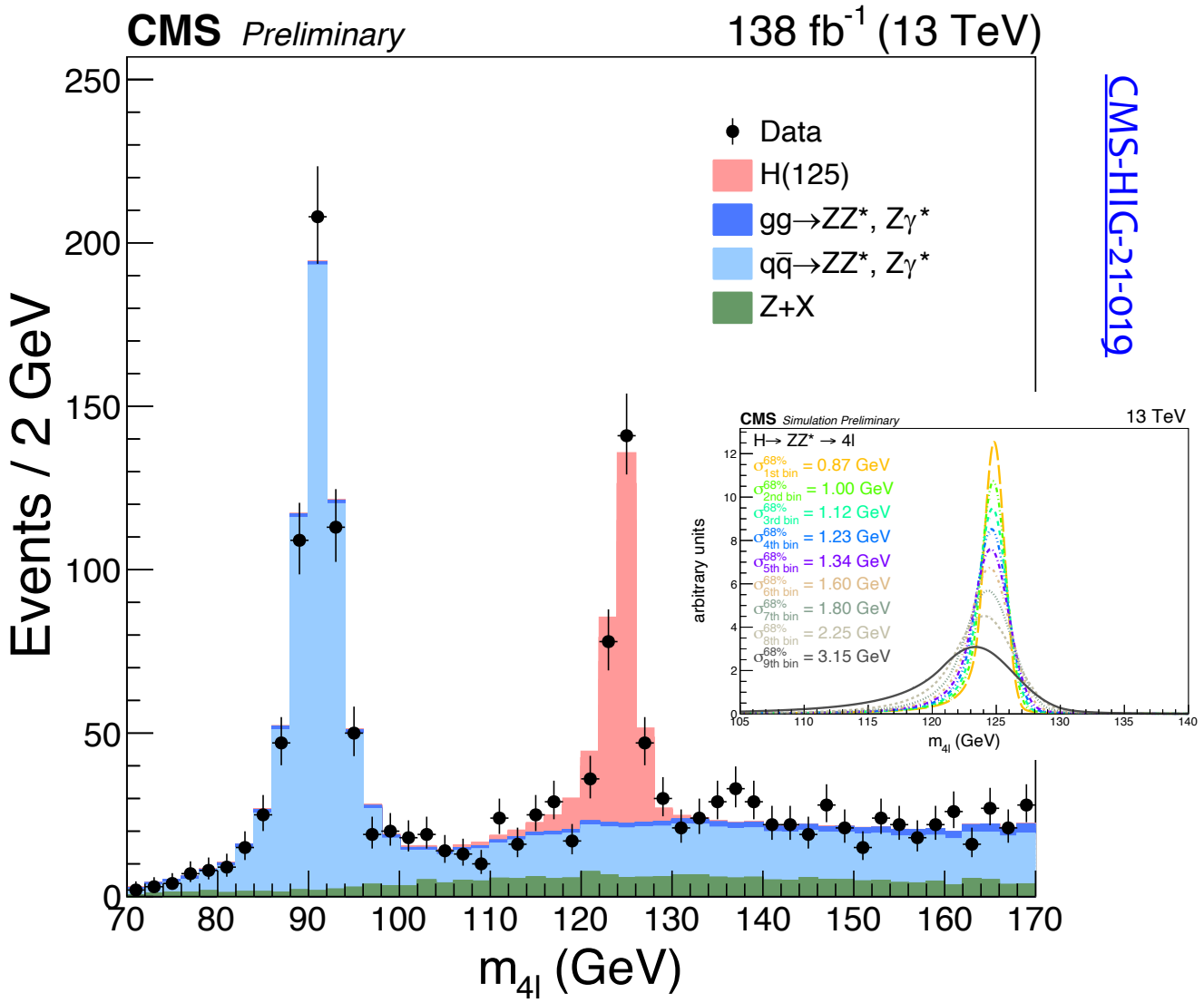


CMS-HIG-21-019

Best single-channel mass measurement from CMS in the H→4l channel

- Events classified in **9 classes** with **improving mass resolution**
- Mass resolution (1-2%) improved from Run-1 due to **beam-spot constraint in muon p_T** reconstruction

Higgs mass and Width



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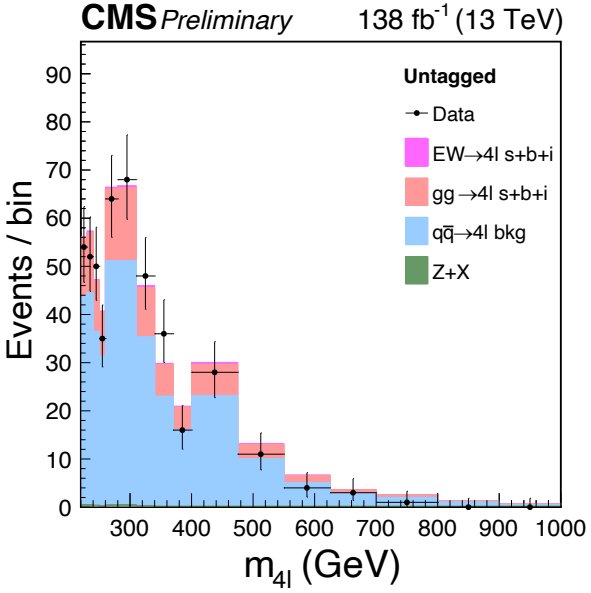
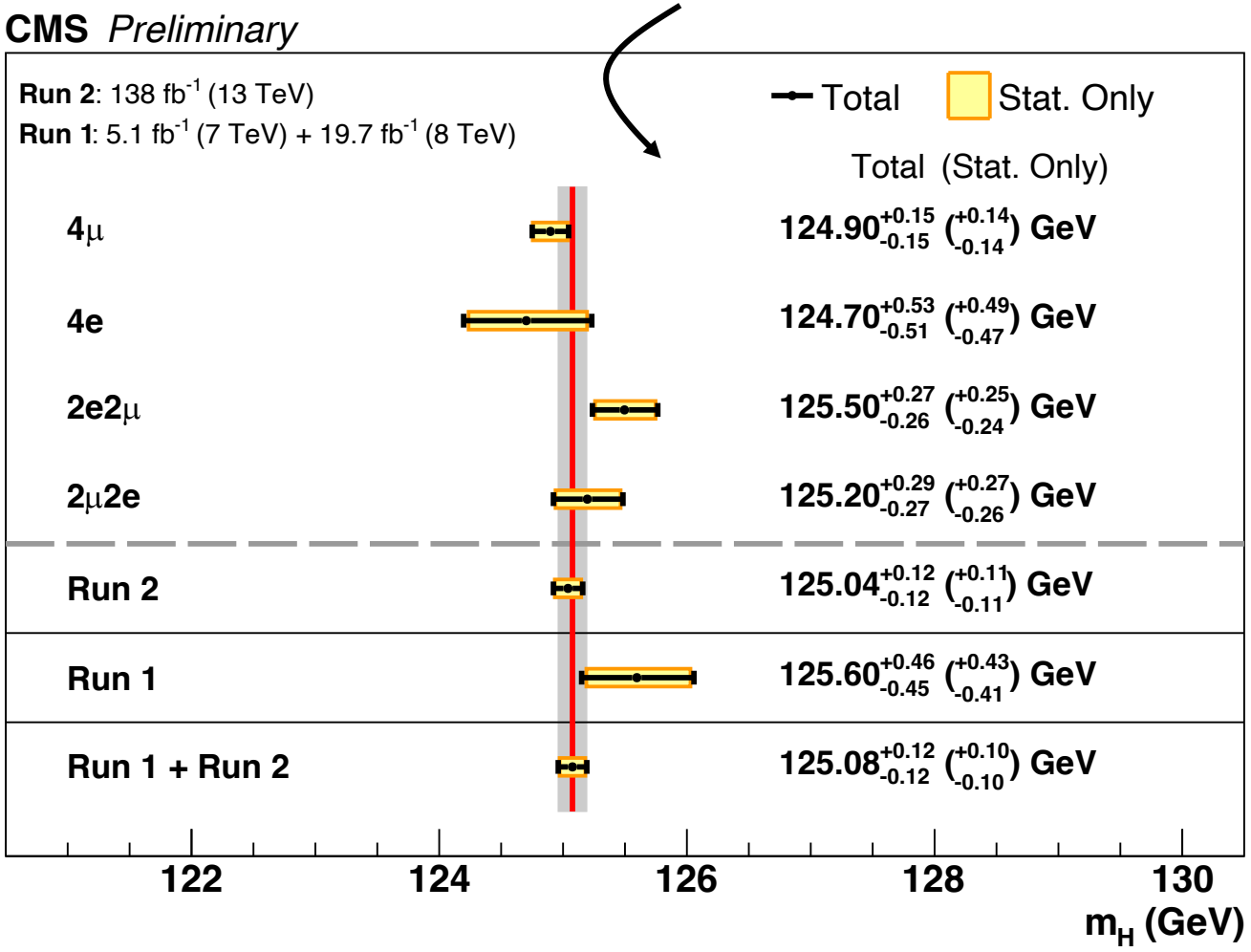


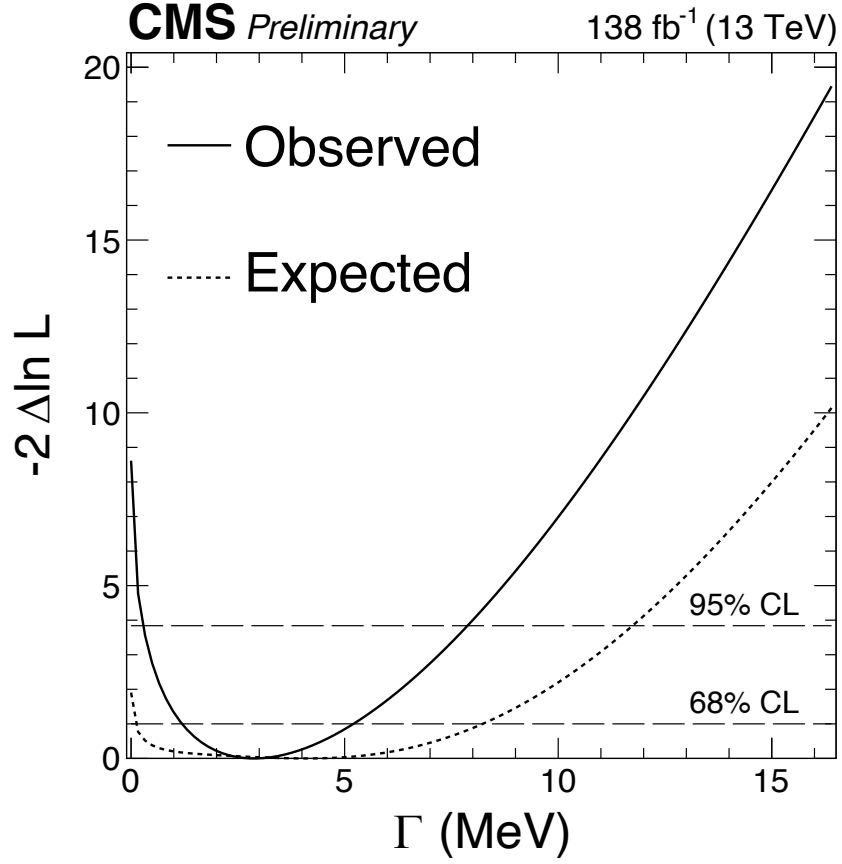
Higgs line shape dominated by experimental resolution

→ Include **off-shell** region to measure width

Higgs mass and Width

Mass measured to within **< 0.1% precision**





Zero width exclusion translates to observation of off-shell region

Higgs mass and Width

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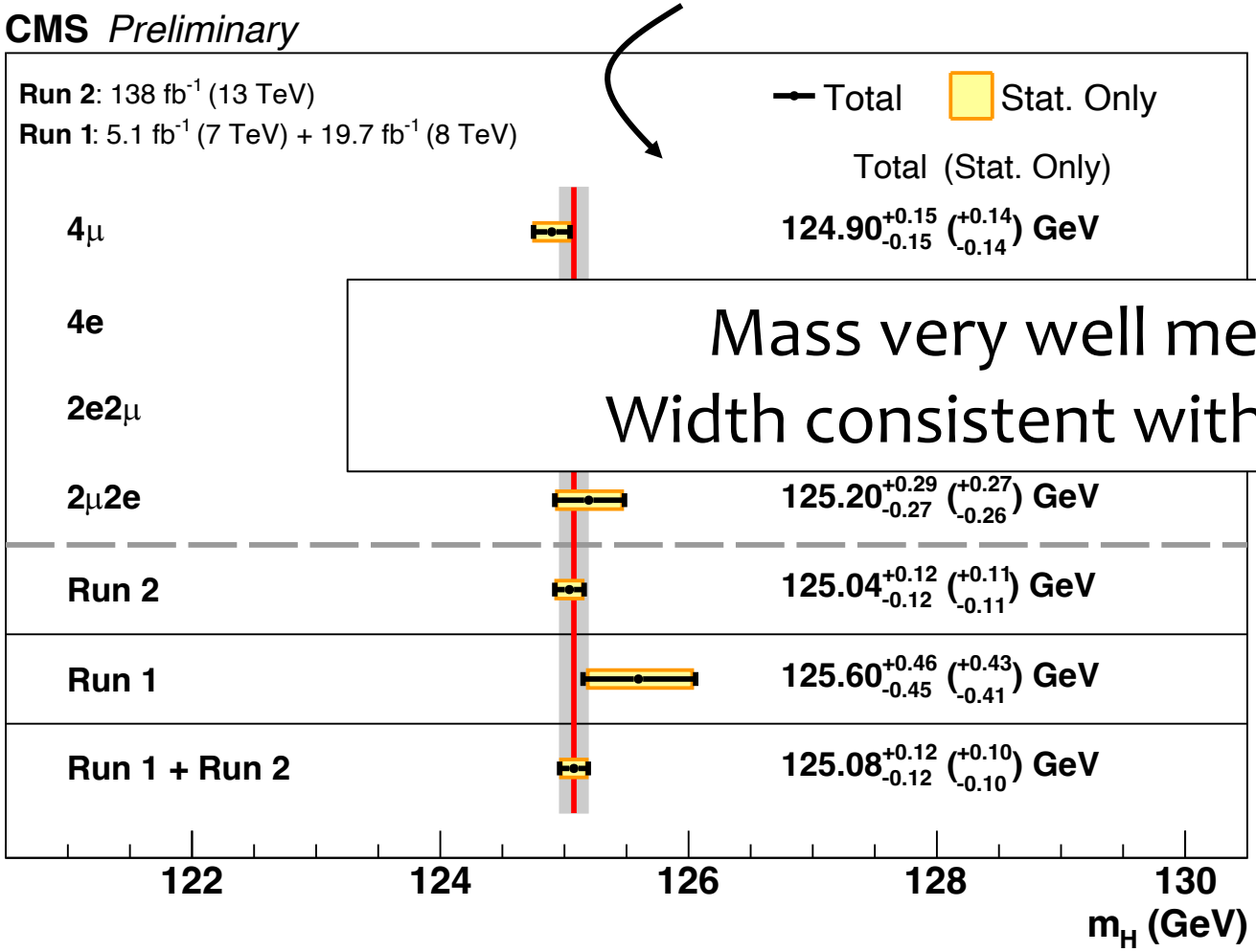
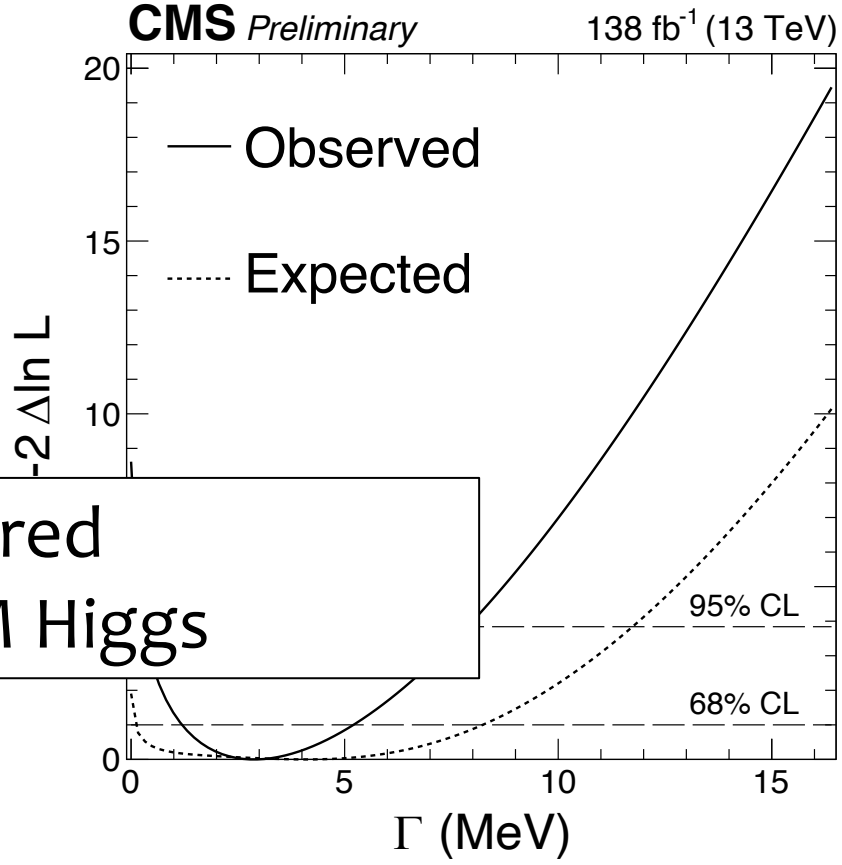
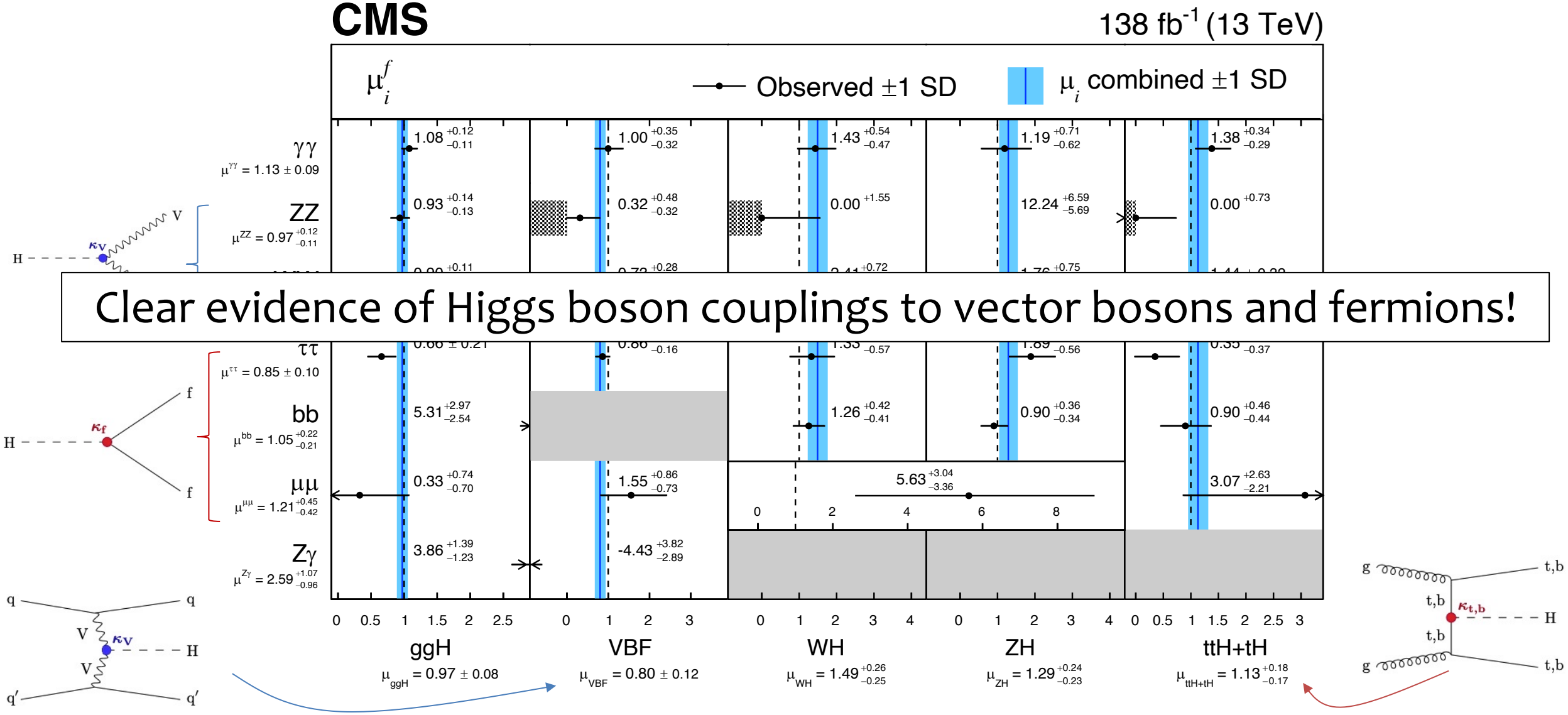


Mass very well measured
Width consistent with SM Higgs



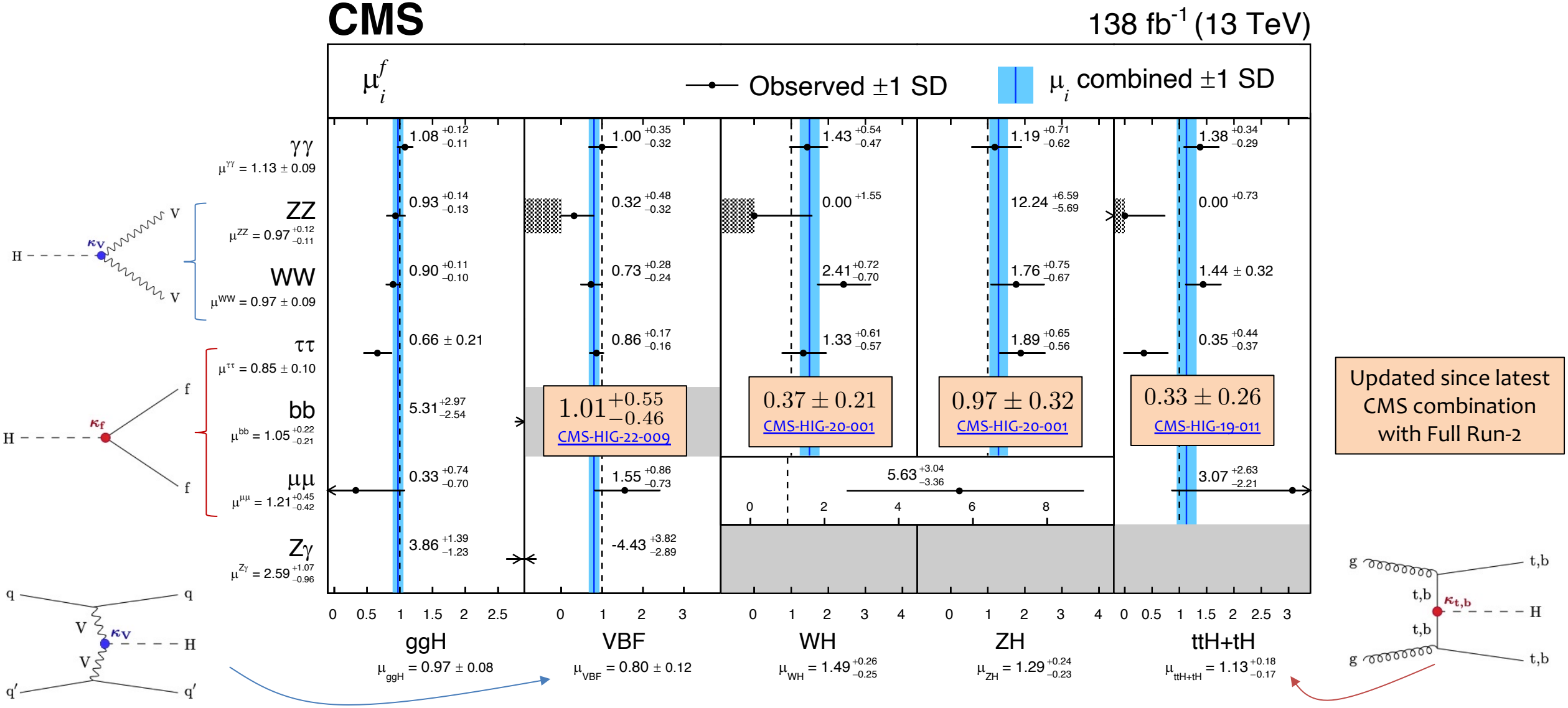
Zero width exclusion translates to observation of off-shell region

Higgs couplings to vector bosons and fermions



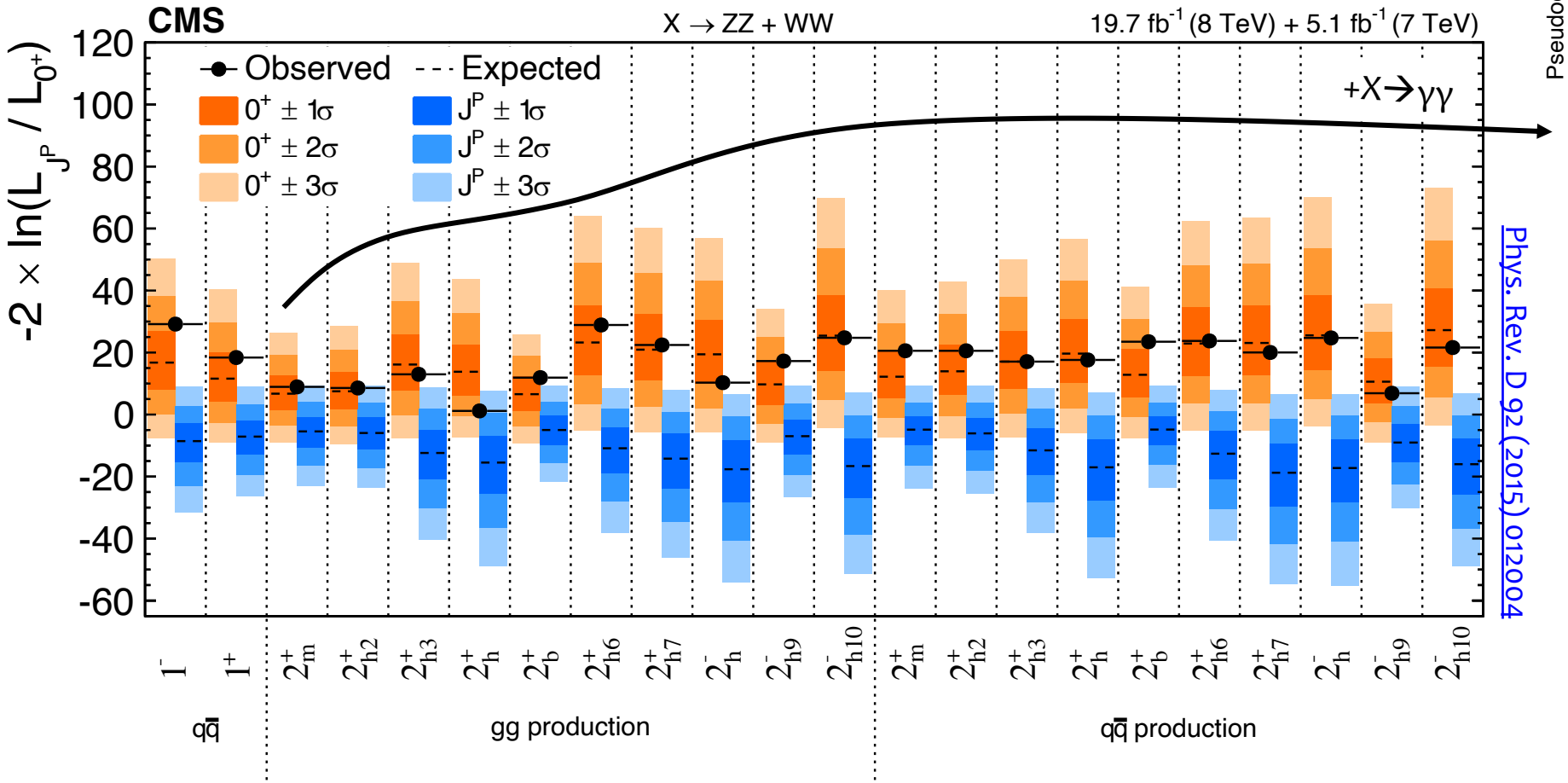
Clear evidence of Higgs boson couplings to vector bosons and fermions!

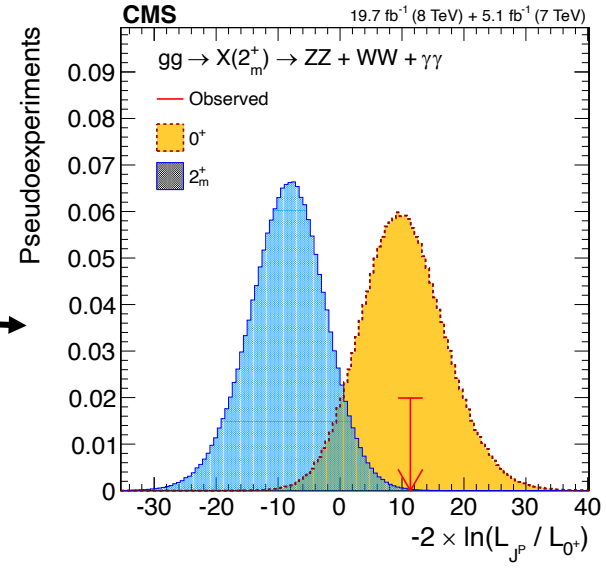
Higgs couplings to vector bosons and fermions



~~No~~ Zero - Spin zone

Multiple hypothesis tests used to distinguish 0^+ from other J^{CP} states.





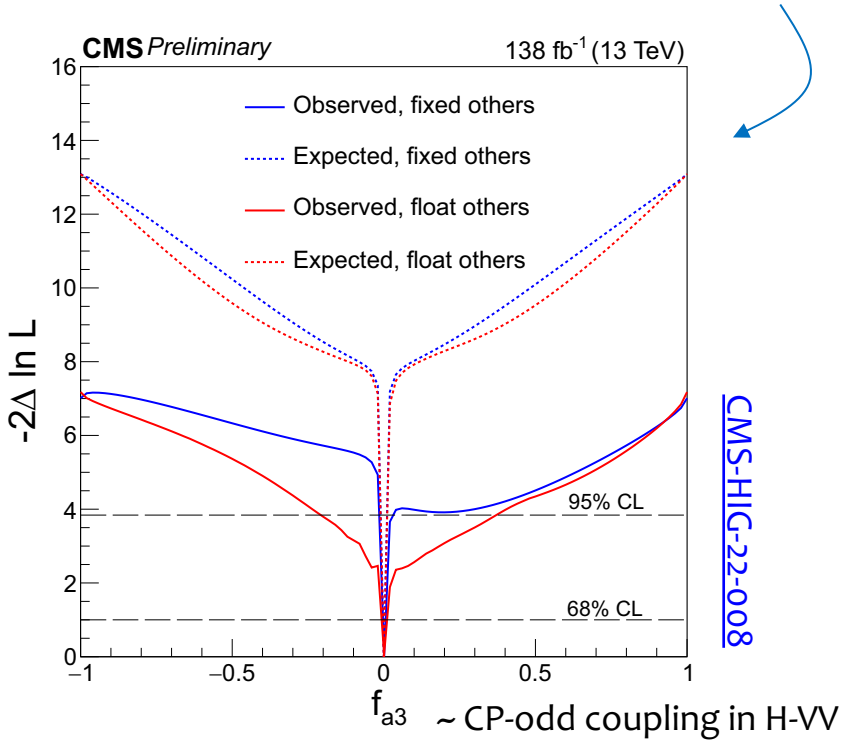
Run-1 data is already enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

CP-studies

Many alternate hypotheses for spin ($J \neq 0$) excluded already in Run-1
→ Studies of the CP-properties of Higgs interactions reveal structure of the underlying Higgs sector

$$\mathcal{L}_{H-ff} = \frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\gamma_5\tilde{\kappa}_f\right)\psi_f H$$

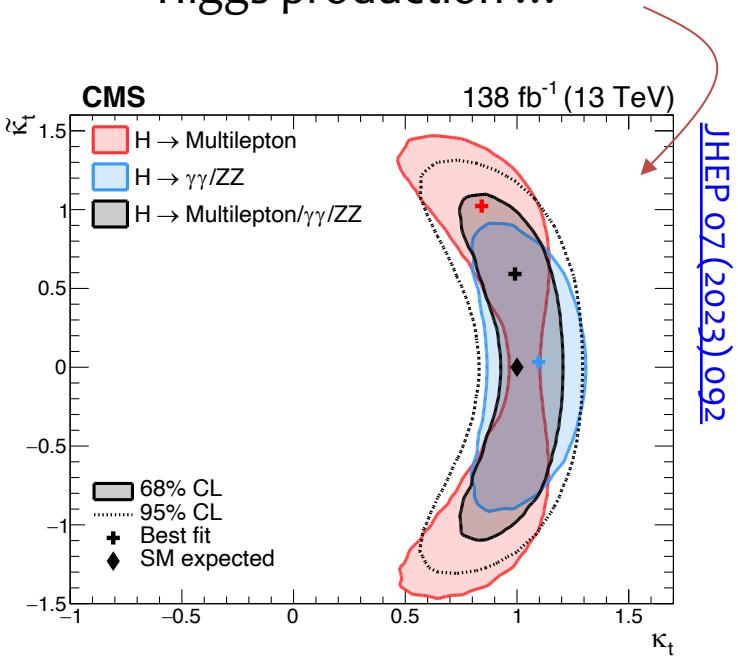
In vector-boson couplings (e.g H→WW)



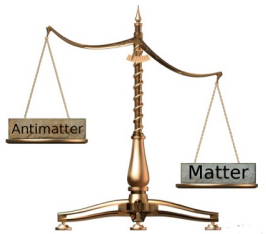
CMS-HIG-22-008

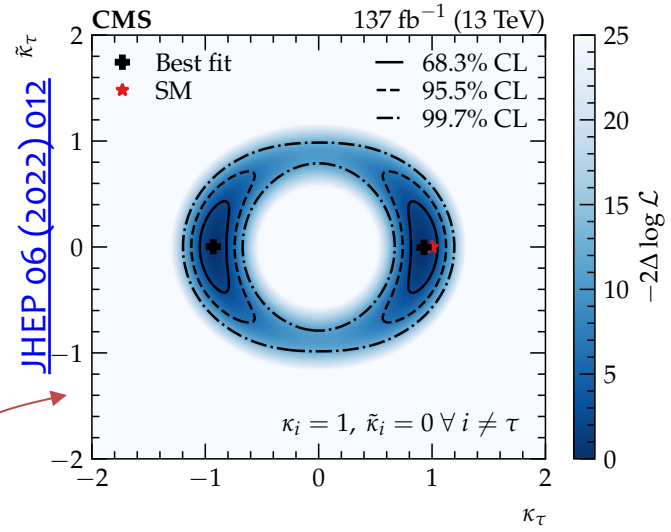
~ CP-odd coupling in H-VV vertex

In fermion couplings via Higgs production …



JHEP 07 (2023) 092





JHEP 06 (2022) 012

… and Higgs decays (eg H→ττ)

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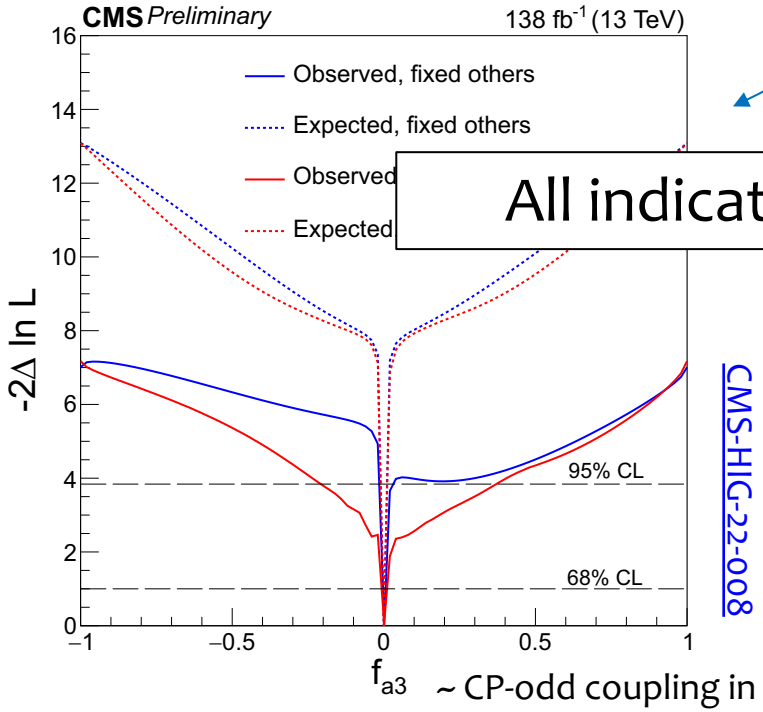

CMS-HIG-22-008

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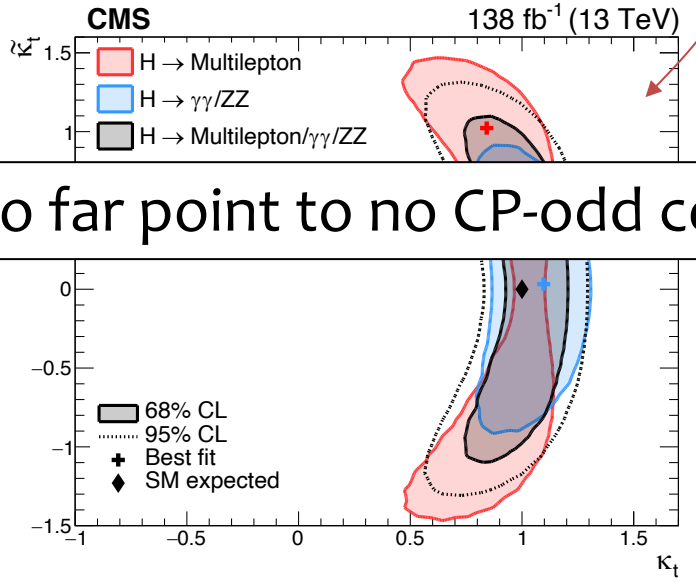
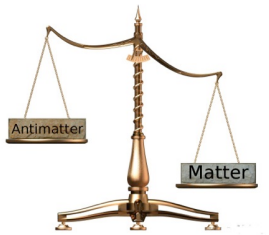
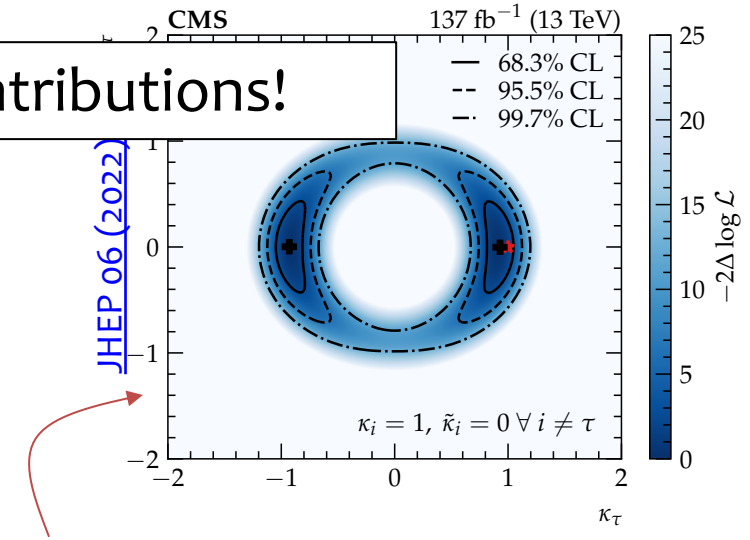


JHEP 07 (2022) 092



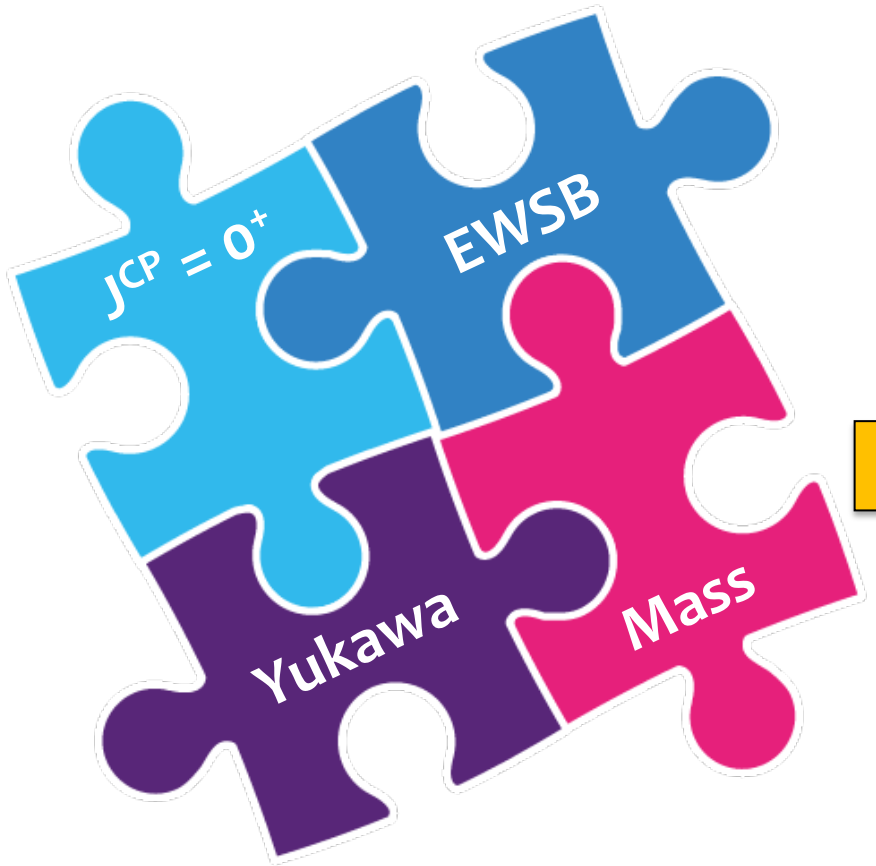
All indications so far point to no CP-odd contributions!

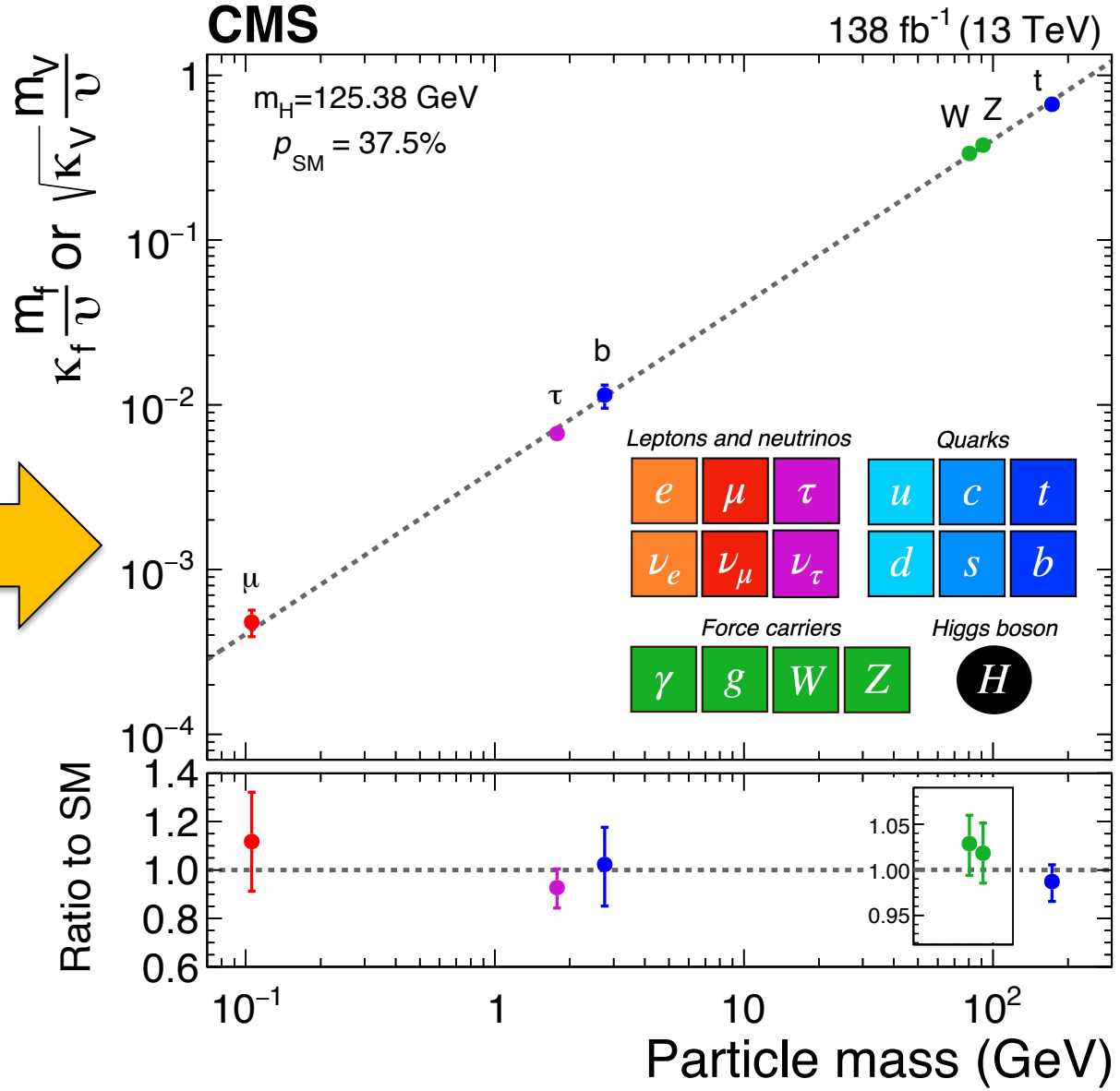


JHEP 06 (2022)

… and Higgs decays (eg H→ττ)

Putting the pieces together



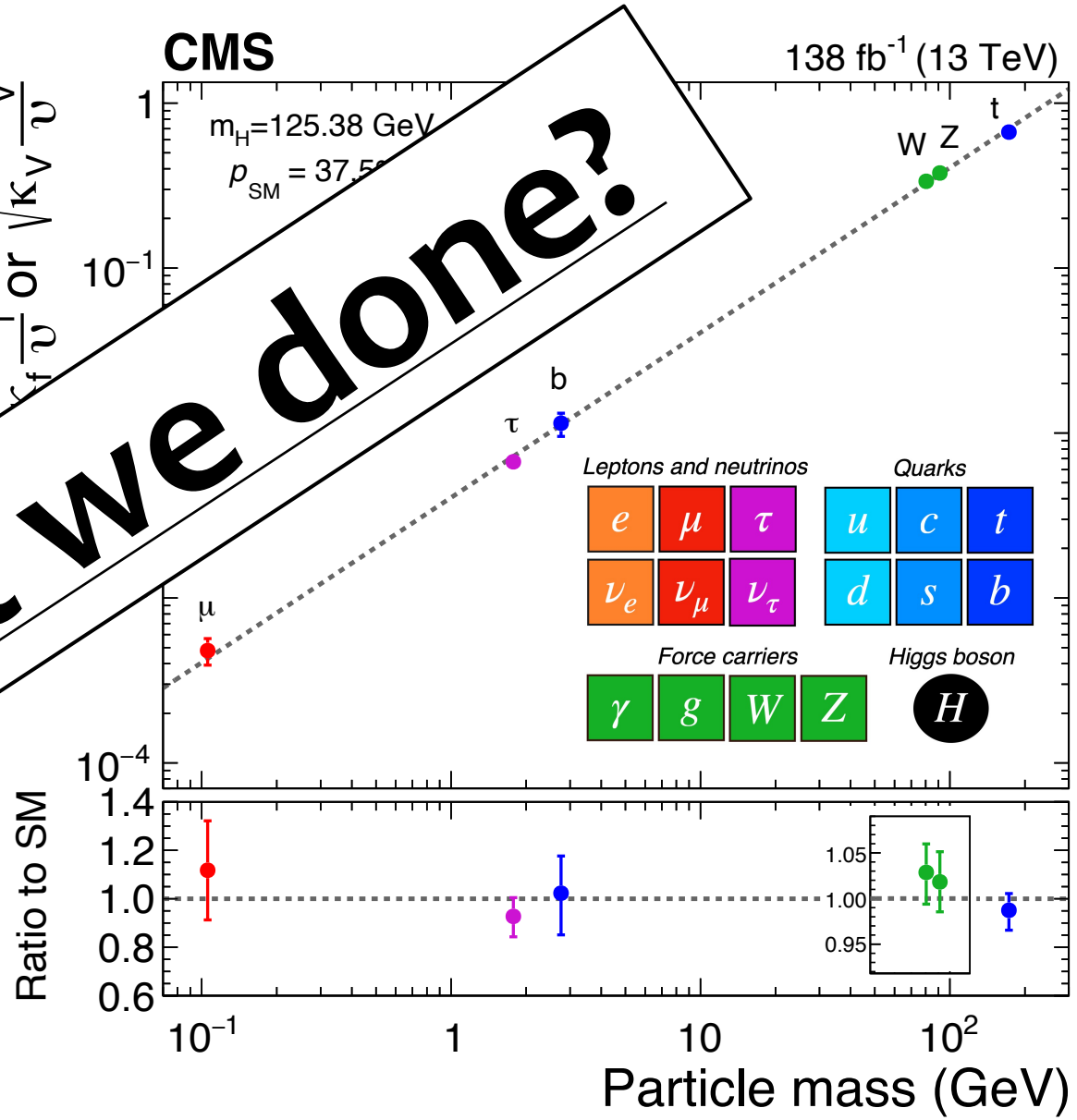


Nature 607 (2022) 60-68

We see a clear picture of the Higgs boson when we put the various pieces together!

Putting the pieces together

So, aren't we done?



Nature 607 (2022) 60-68

We see a clear pictur[illegible]iggs boson when we put the various pieces t[illegible]gether!

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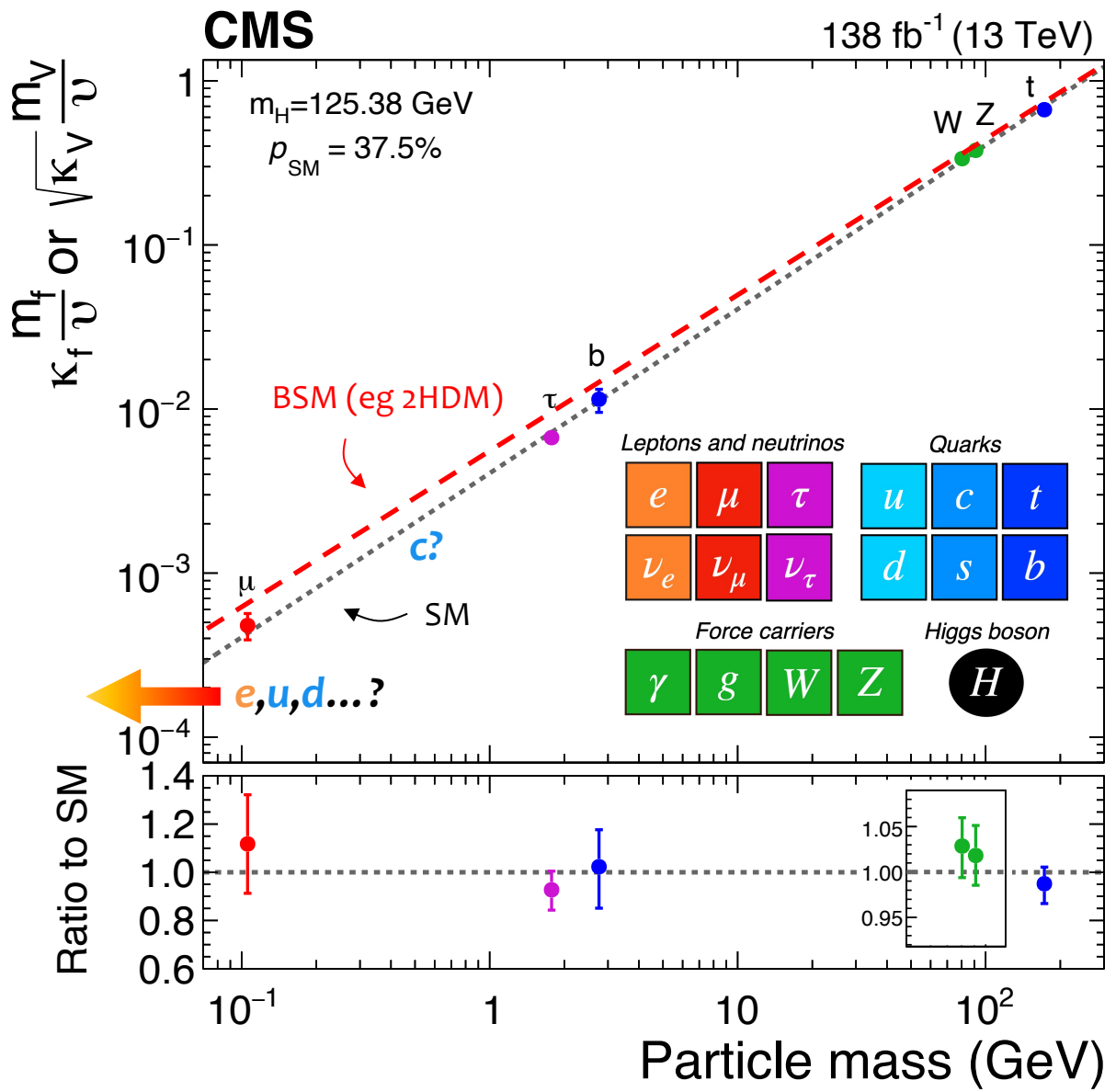
The **Higgs boson** was the **missing piece of the SM** and we've had it now for 10 years …

- **Is the Higgs sector SM-like ?**



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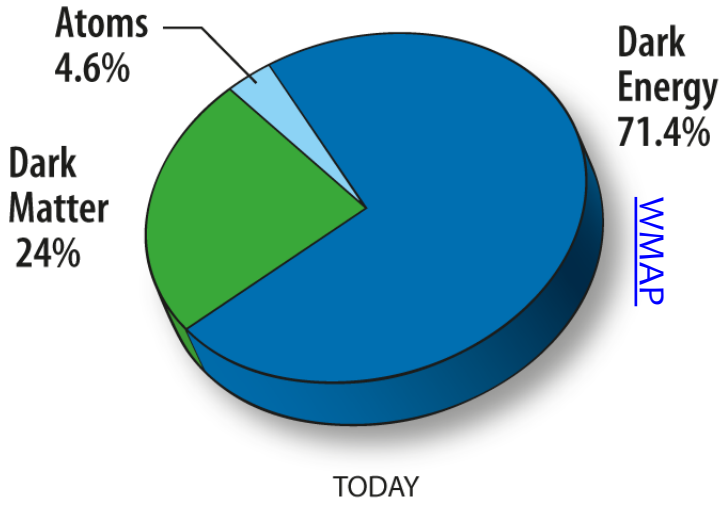

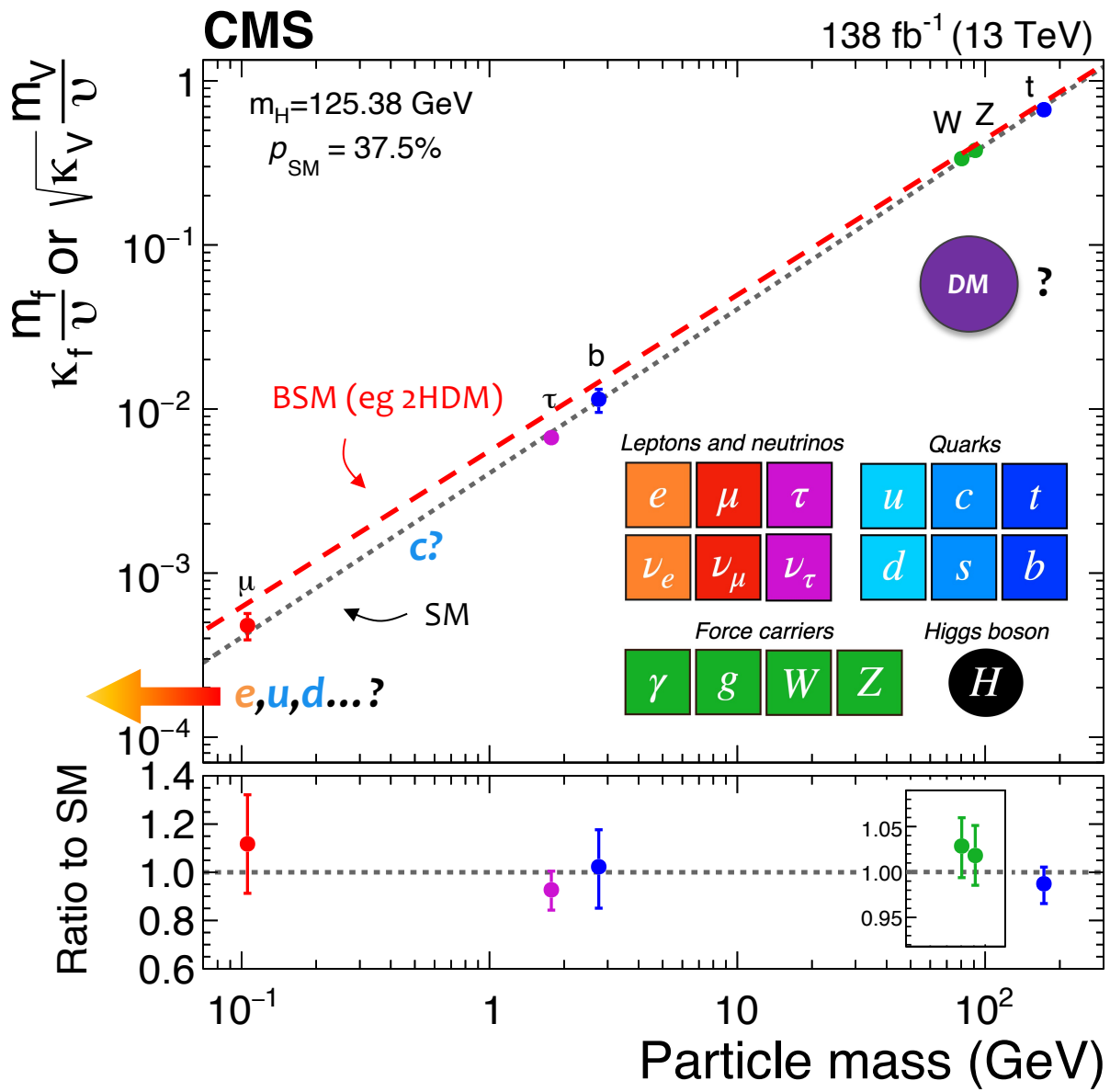

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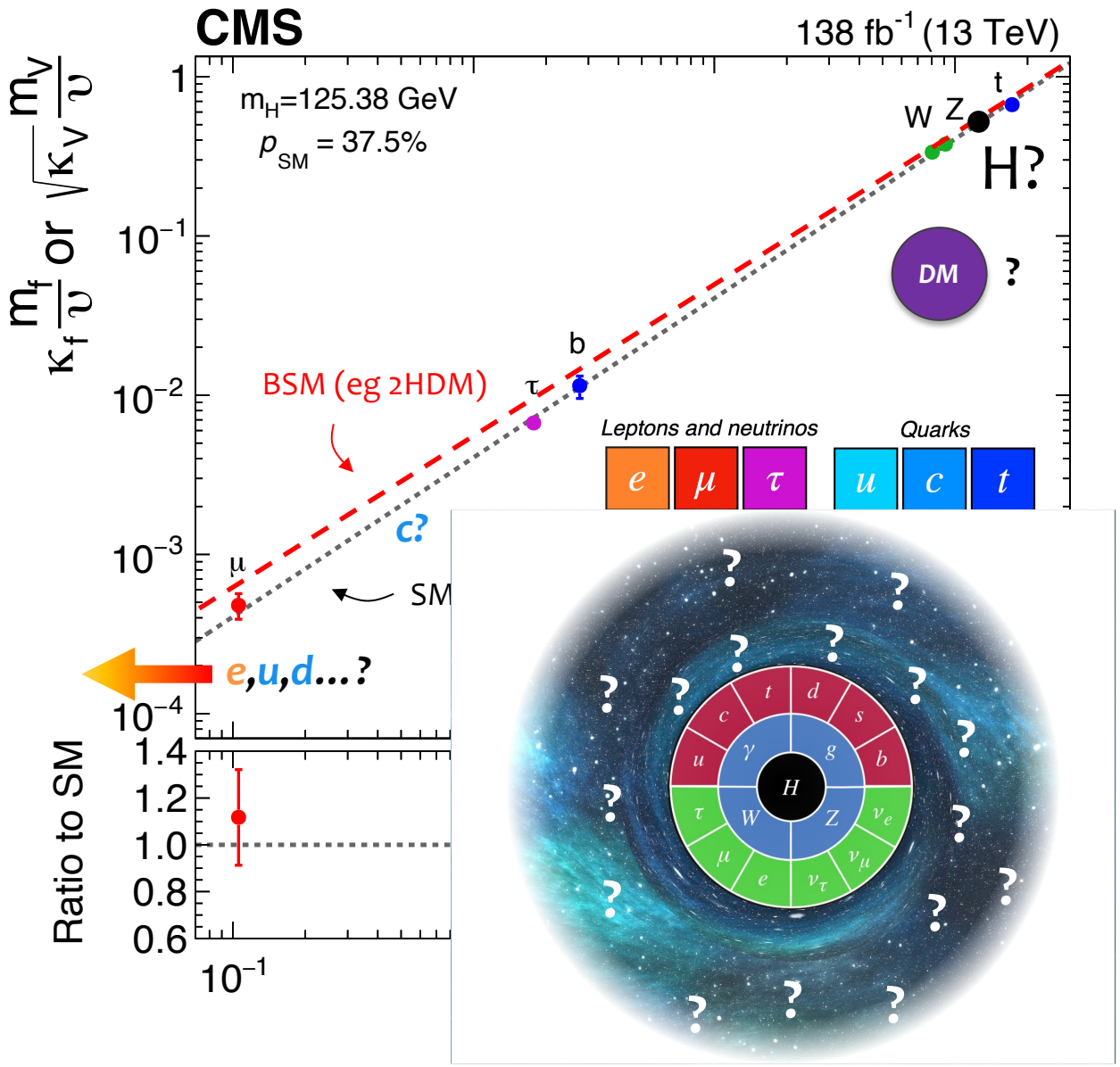
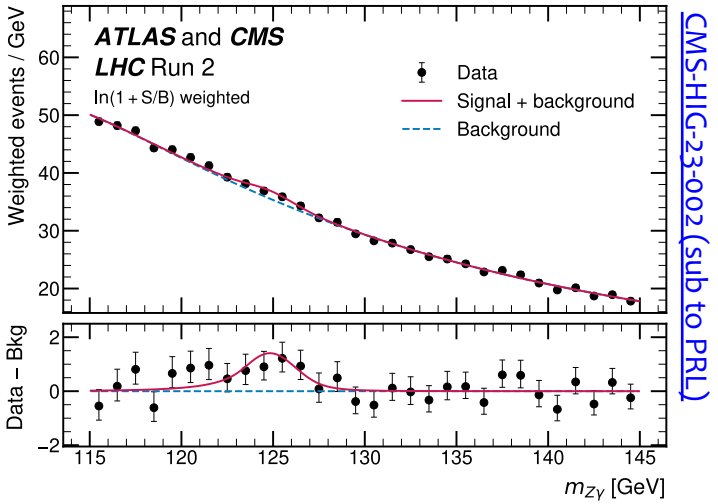
- **Is DM a particle and does it get mass from the Higgs?**
- **Can the Higgs boson self-coupling help explain the evolution of the early universe?**



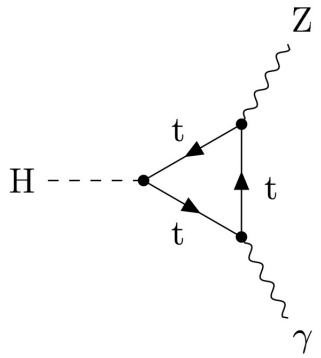
Rare Proceses

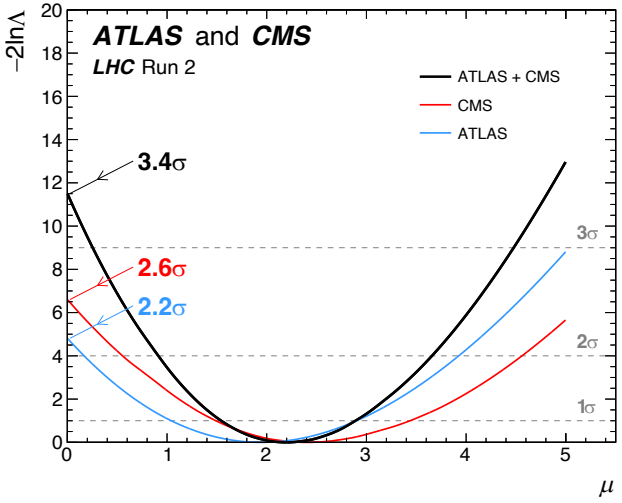
Constraints on SM couplings so far allow for extra contributions to total Higgs width …

- From **new physics in decay loops**

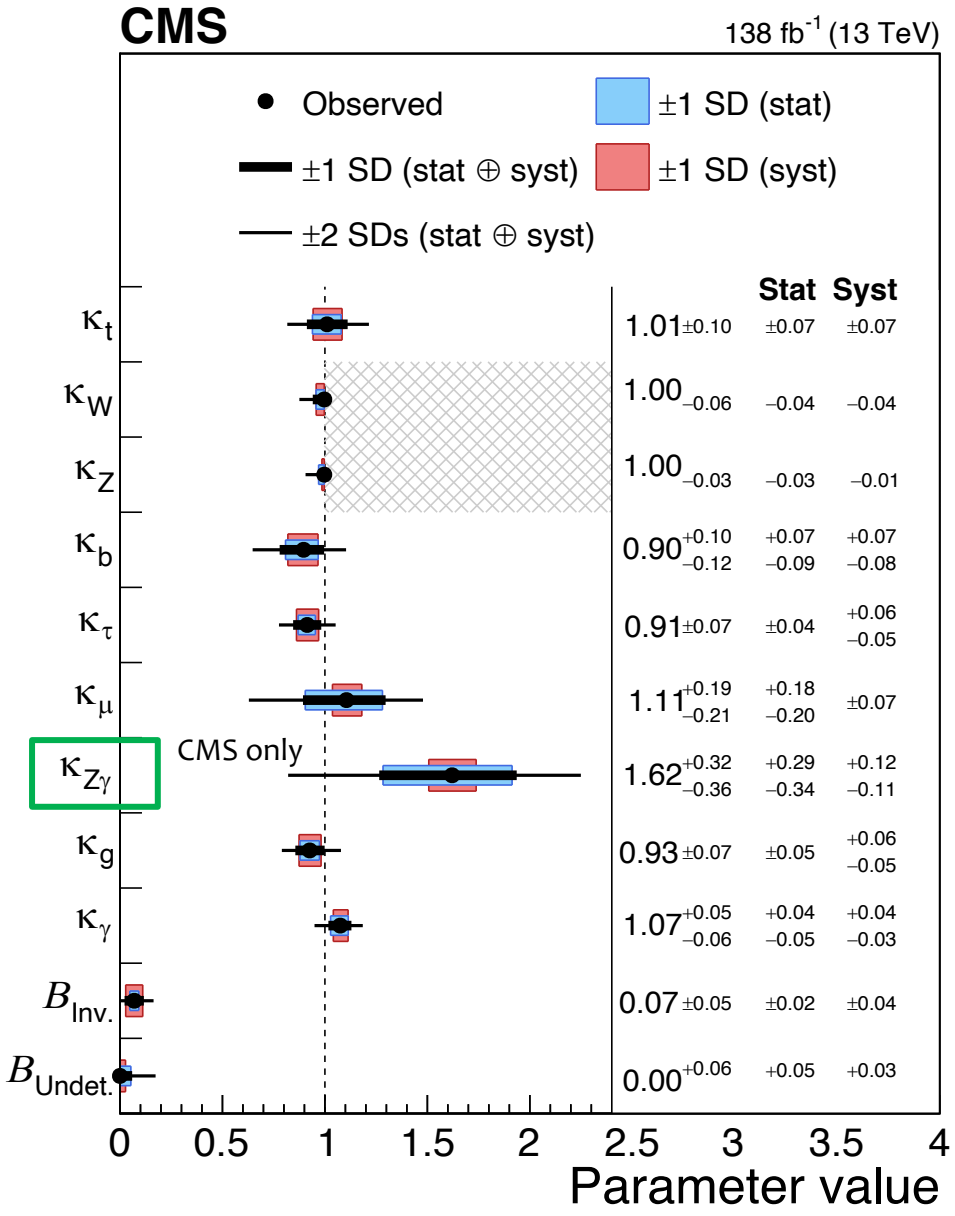


CMS-HIG-23-002 (sub to PRL)





Evidence for H→Zγ from ATLAS+CMS combination



Rare Processes

Constraints on SM couplings so far allow for extra contributions to total Higgs width …

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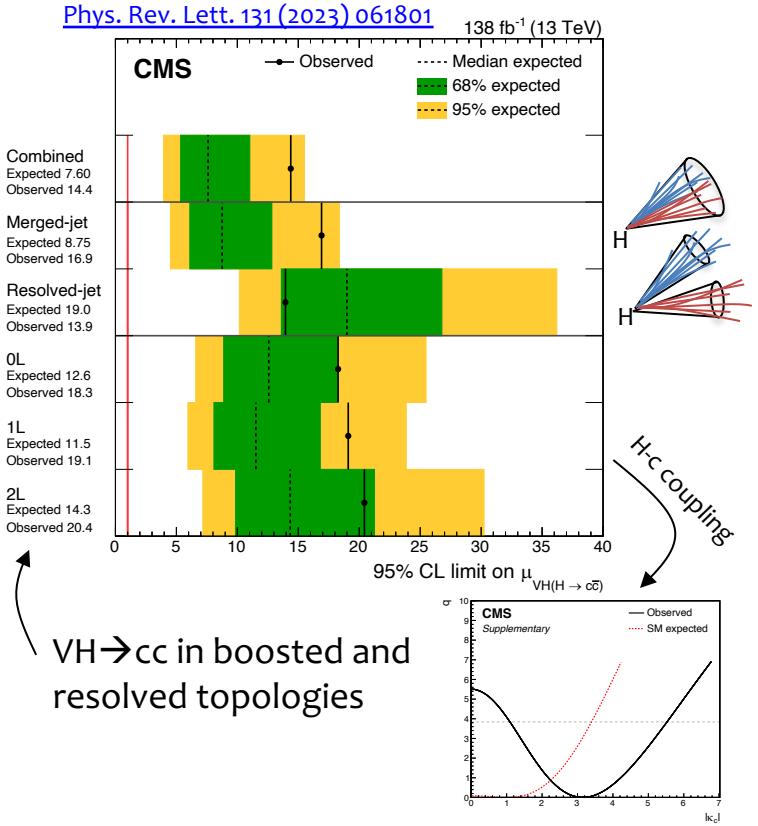
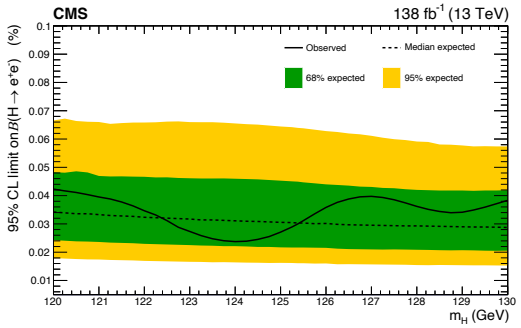
- Searches for **rare decays of Higgs bosons**

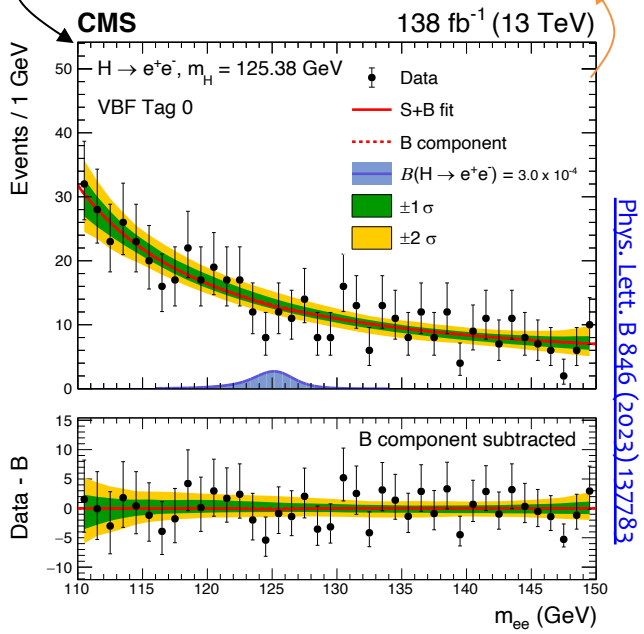
Phys. Rev. Lett. 131 (2023) 061801



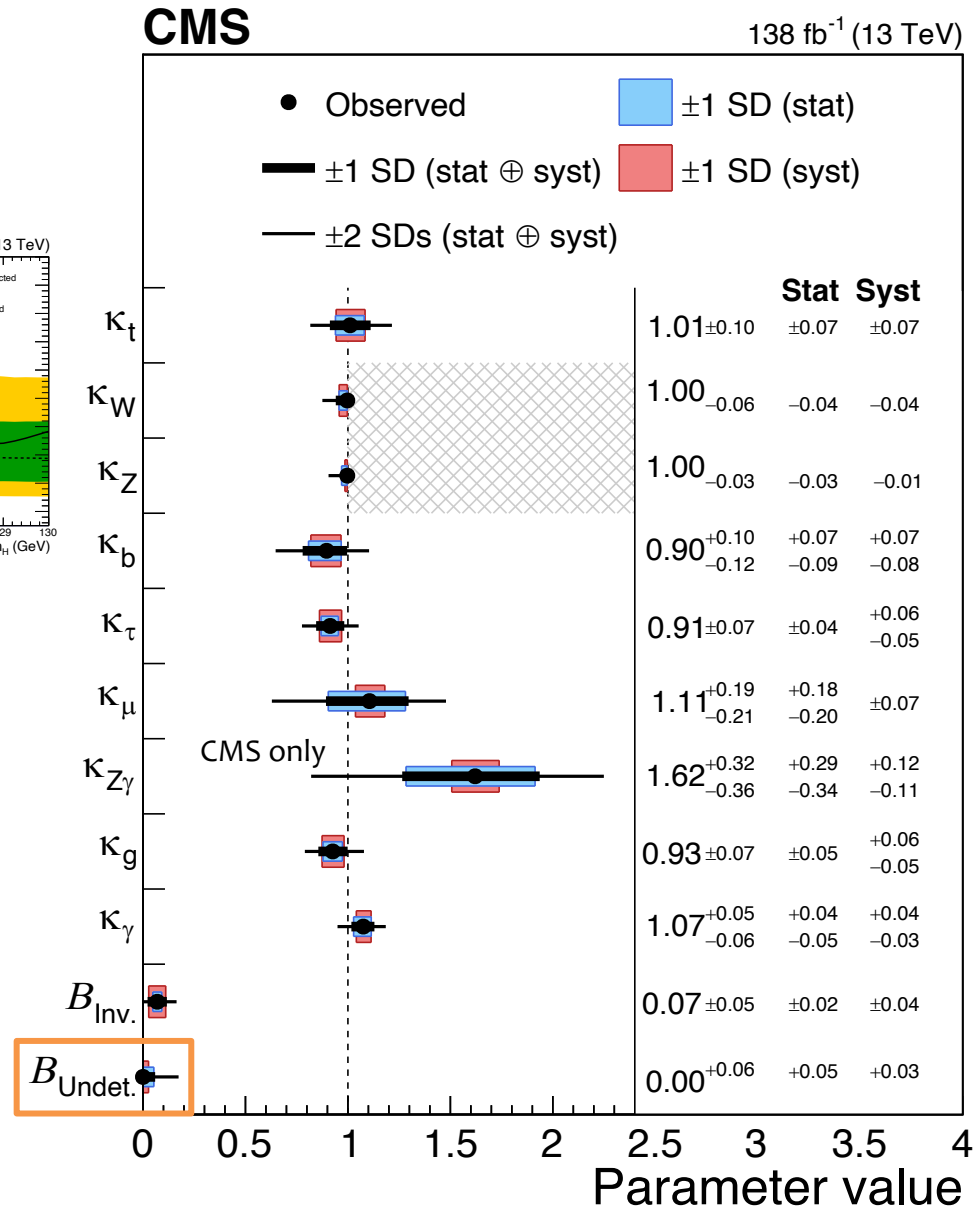
VH→cc in boosted and resolved topologies

VBF/ggH H→ee





Phys. Lett. B 846 (2023) 137783



BSM Processes

Constraints on SM couplings so far allow for extra contributions to total Higgs width …

- From **new physics in decay loops**
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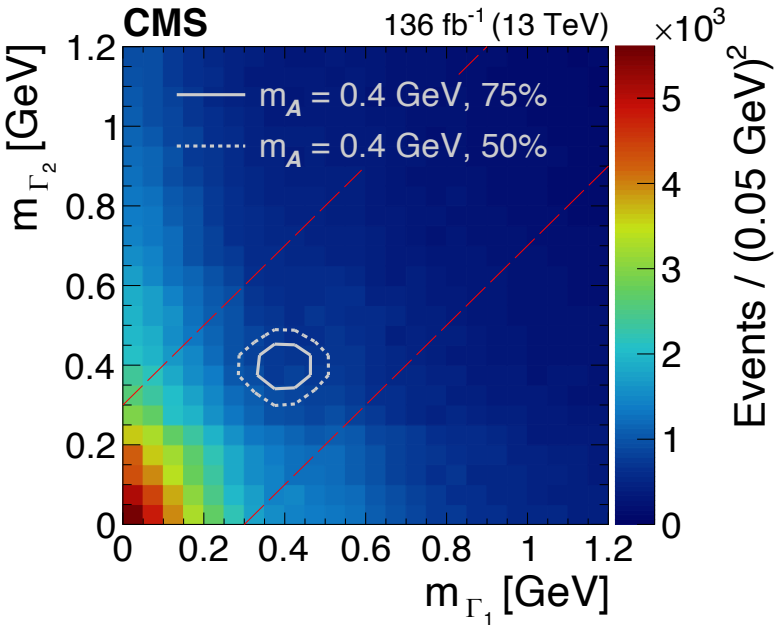
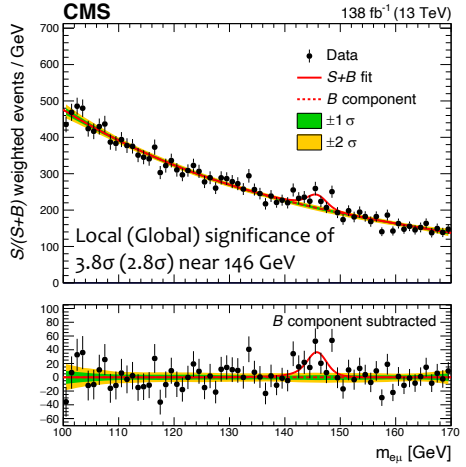
- Searches for **BSM decays of the Higgs boson**

Search for H→AA→4γ: Extreme boosts require novel photon reconstruction method

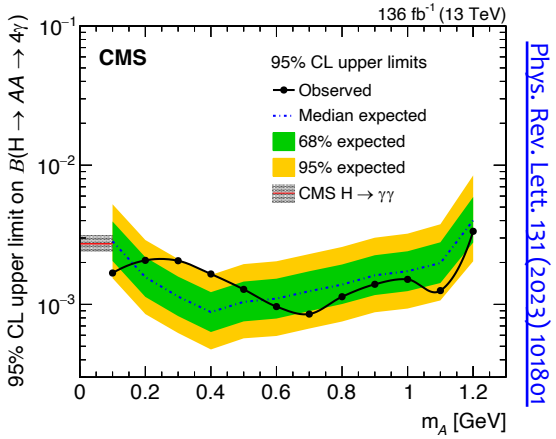


Search for LFV H→eμ

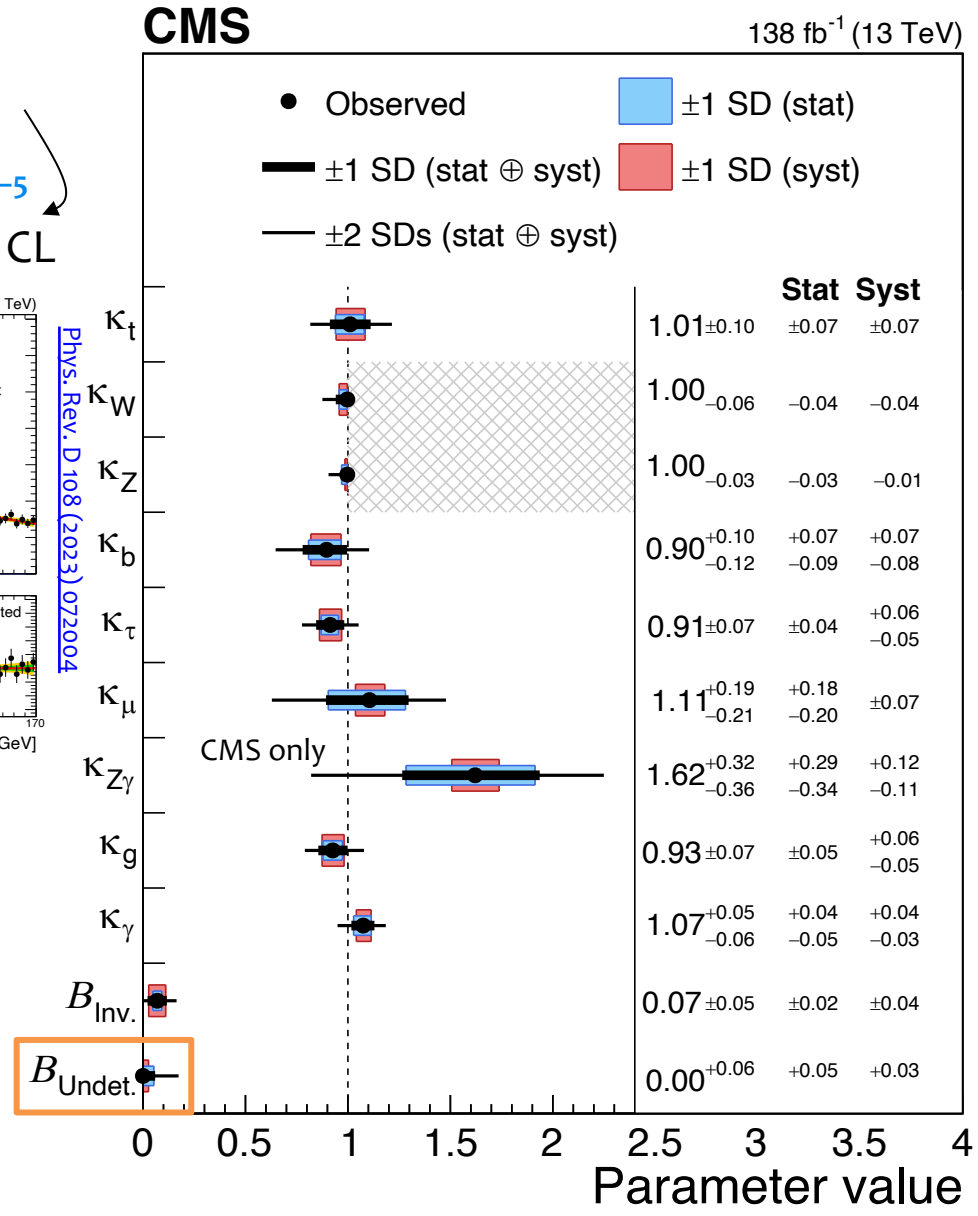
B(H→eμ) < **4.4 × 10⁻⁵** (**4.7 × 10⁻⁵**) at 95% CL



Phys. Rev. D 108 (2023) 072004



Phys. Rev. Lett. 131 (2023) 101801



BSM Processes

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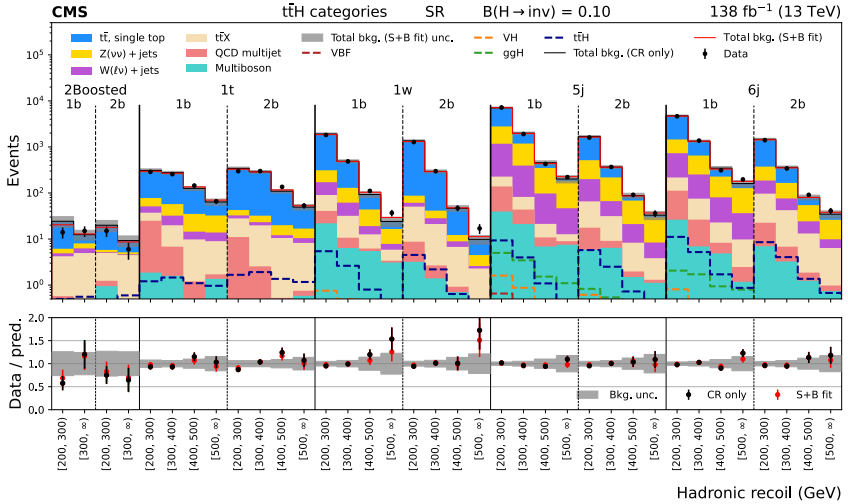
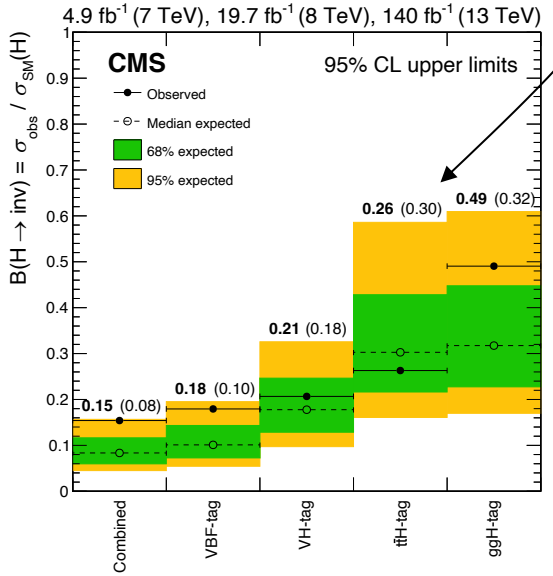
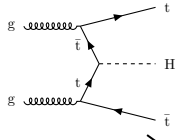
- Search for **invisible Higgs boson decays**

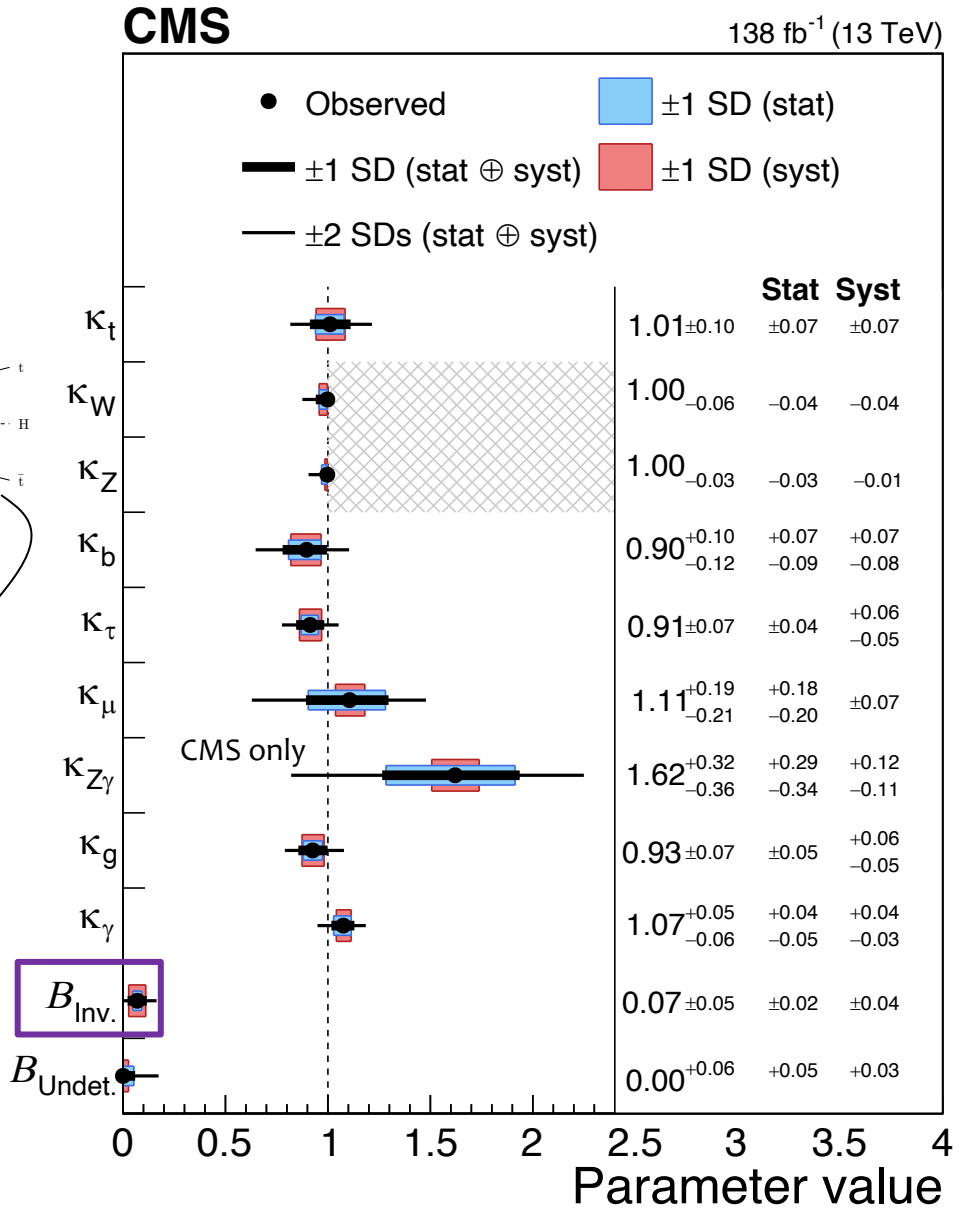
First results including dedicated ttH(→inv) search from CMS



B(H→inv) < 15% @ 95%CL







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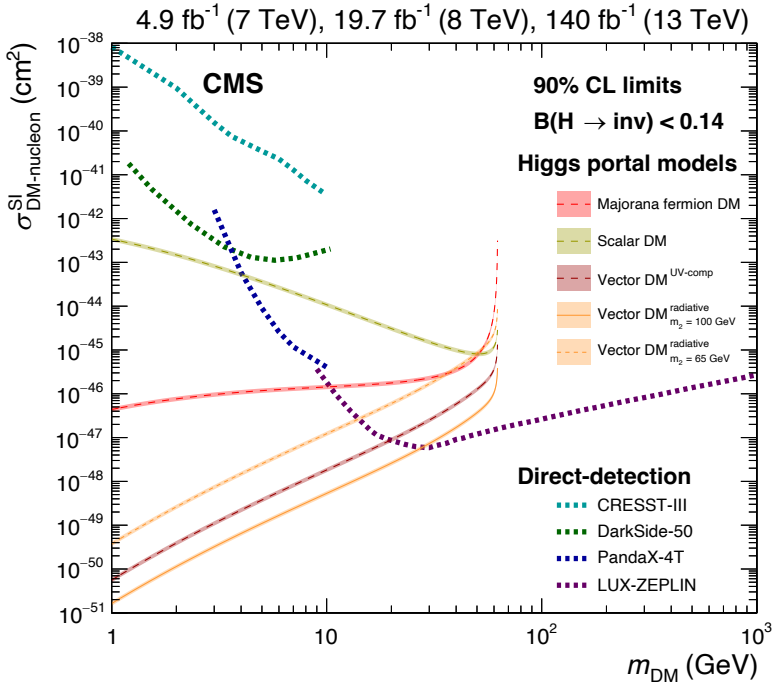
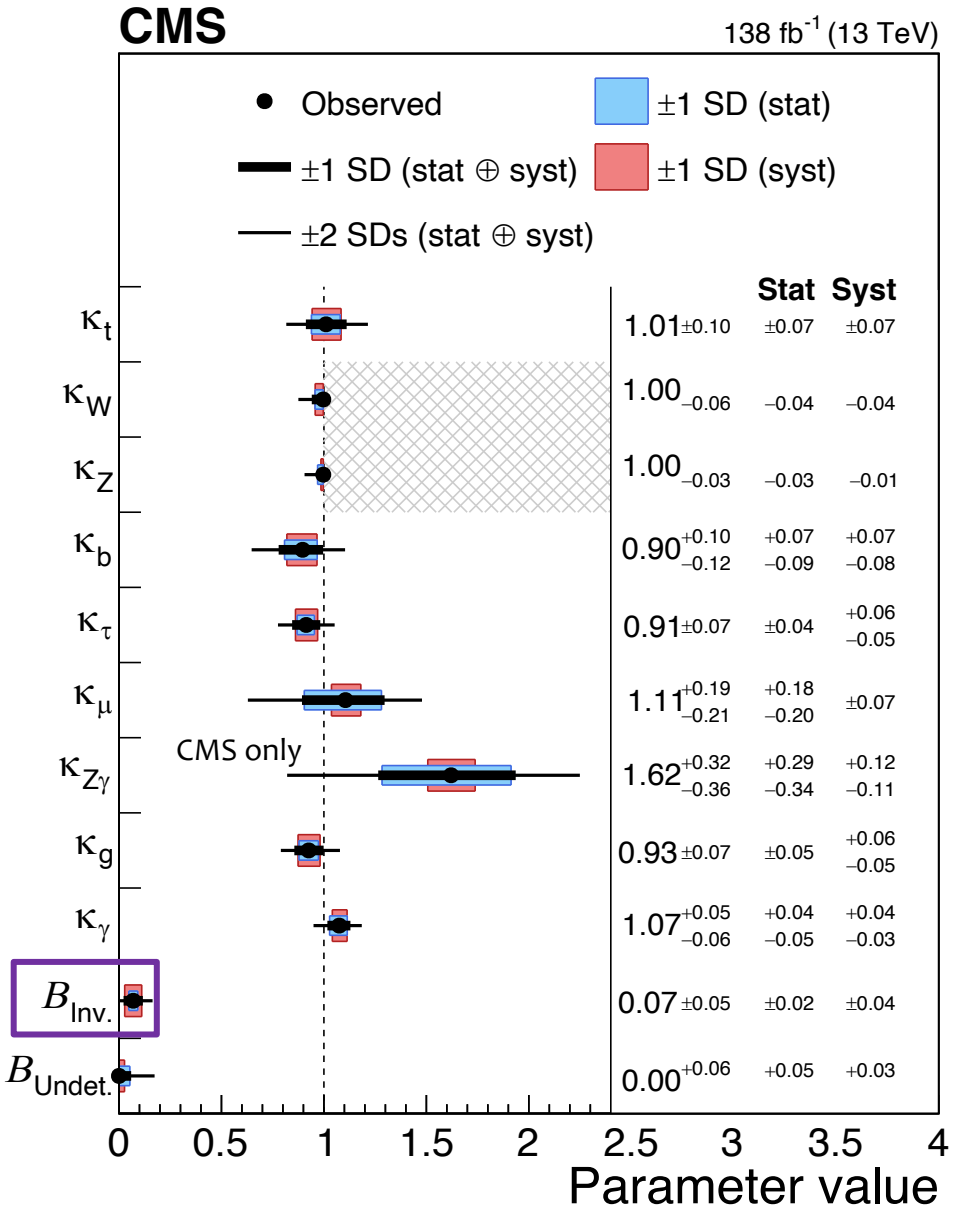
Interpretations under searches for Dark Matter

Complementary to direct searches!



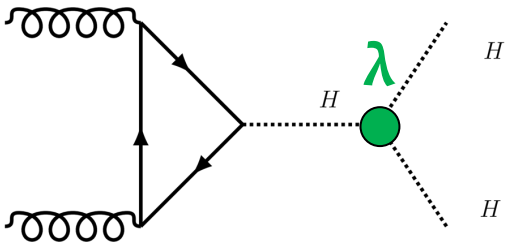


Higgs boson self-coupling

The **Higgs potential** includes H^3 terms

$$V(H) = \frac{m_H^2}{2} H^2 + \boxed{\lambda v H^3} + \lambda H^4$$

"self-coupling" generates **Higgs-Higgs** interactions → Search for pp→HH



Bruno Alvez

HH	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

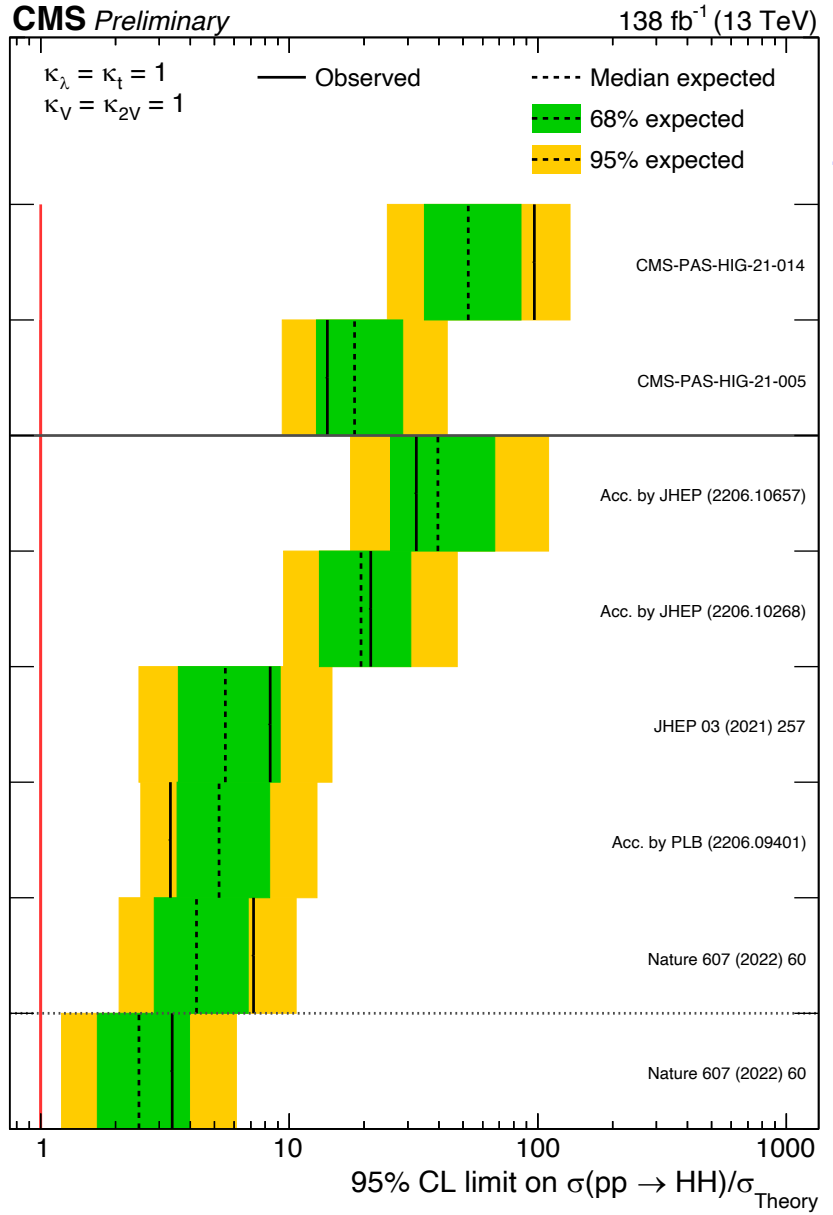
No golden channel!

Require combinations of multiple search channels for best sensitivity

- nonres VHH
- resonant
- nonres VBF
- nonres ggF

New since latest CMS combination

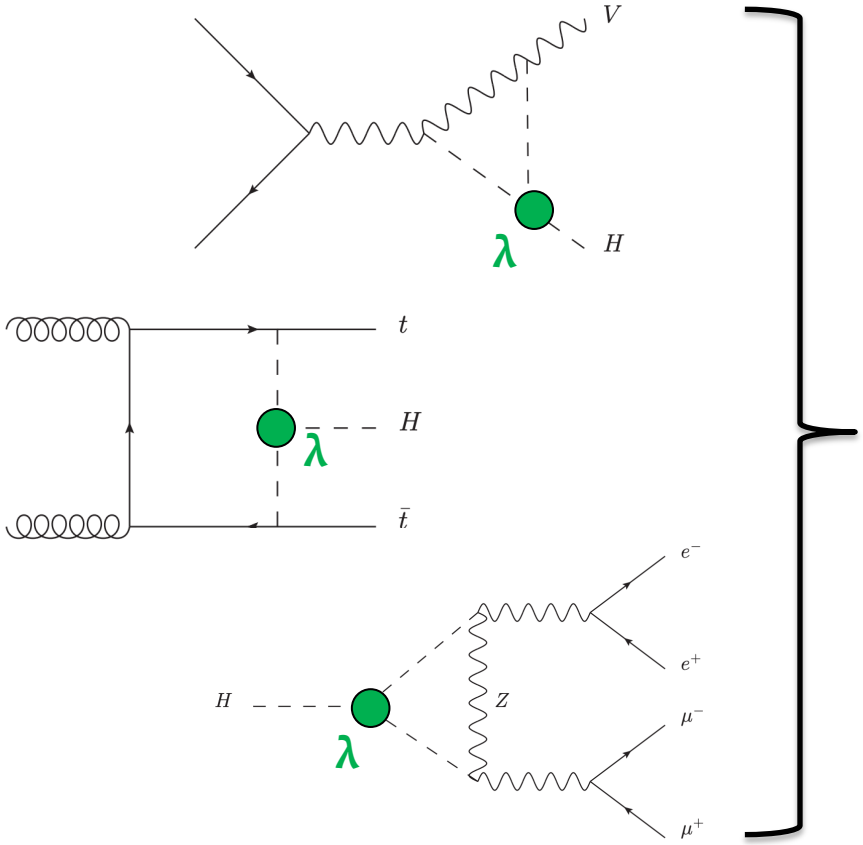
- WW γγ — Expected: 52, Observed: 97
- bb WW — Expected: 18, Observed: 14
- bb ZZ ♣ — Expected: 40, Observed: 32
- Multilepton ♣ — Expected: 19, Observed: 21
- bb γγ ♣ — Expected: 5.5, Observed: 8.4
- bb ττ ♣ — Expected: 5.2, Observed: 3.3
- bb bb ♣ — Expected: 4.2, Observed: 7.2
- Comb. of ♣ — Expected: 2.5, Observed: 3.4



Nature publication

Higgs boson self-coupling

Loop corrections to **single-Higgs boson** production and decay involve **Higgs self-coupling** [1]

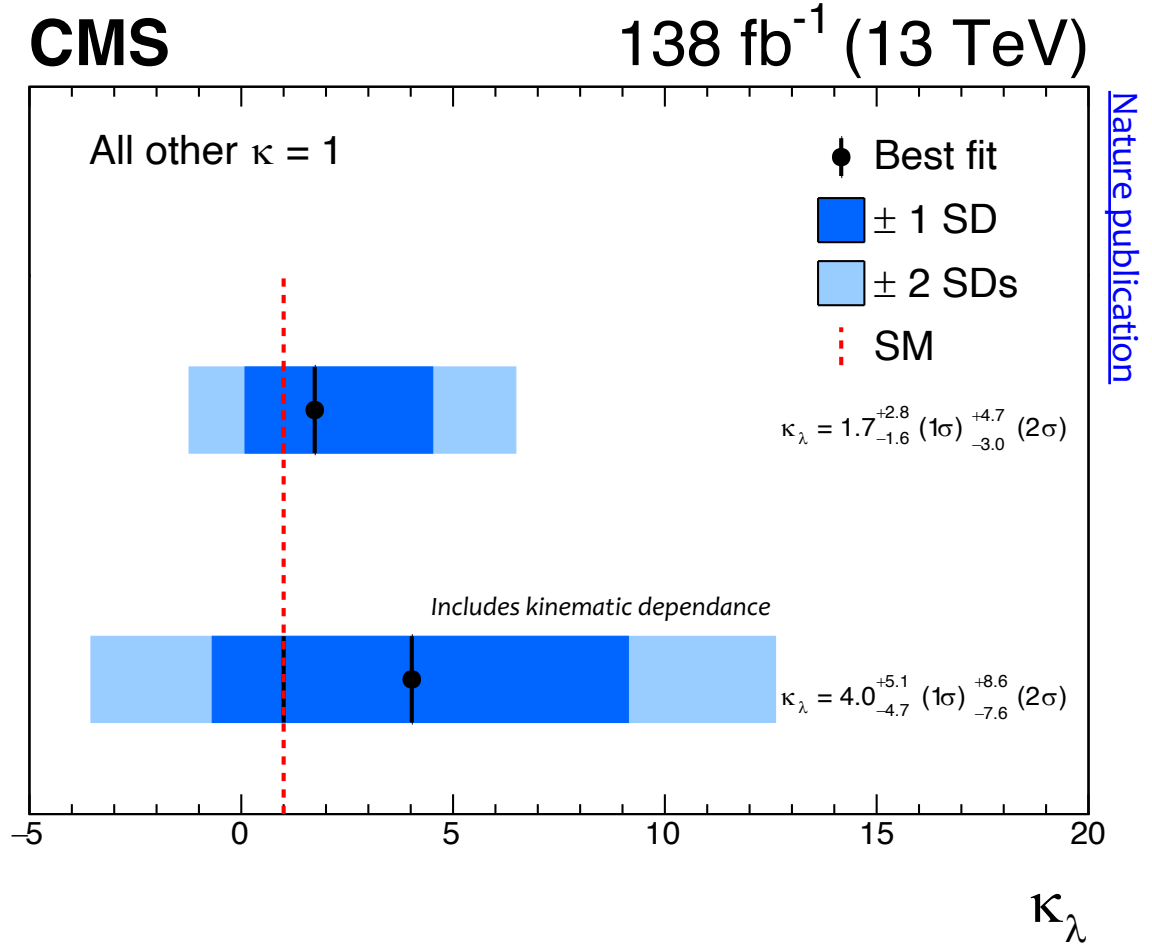


$pp \rightarrow HH$

Direct search

$pp \rightarrow H$

Indirect interpretation



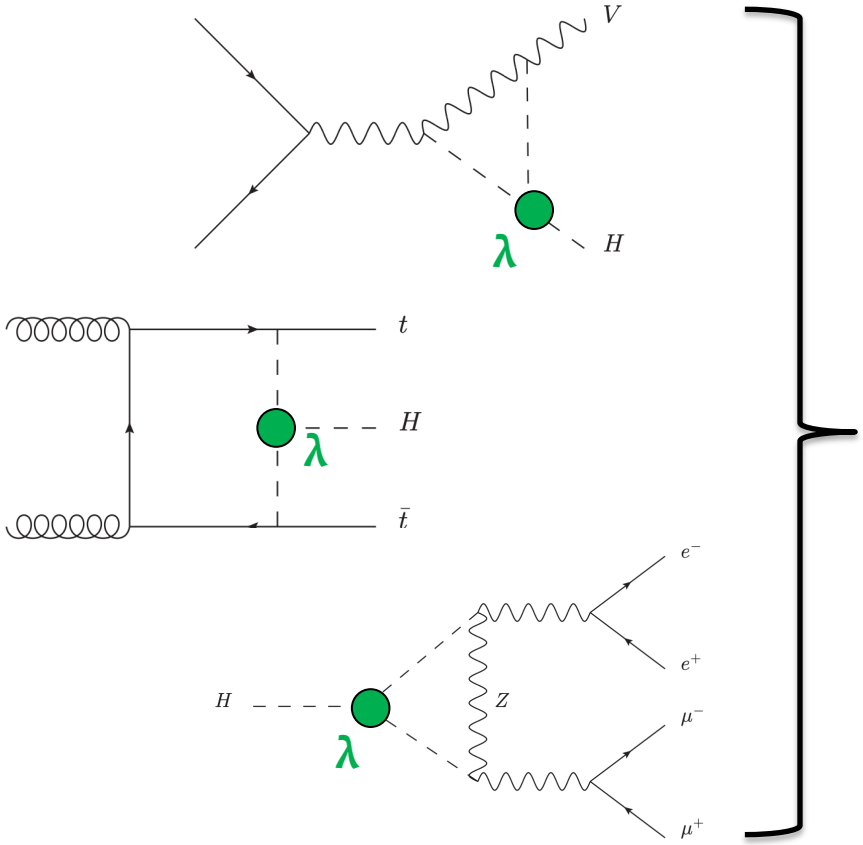
Nature publication

Precision (single) **Higgs boson measurements** also sensitive to **Higgs self-coupling!**

[1] Eur. Phys. J. C (2017) 77: 887

Higgs boson self-coupling

Loop corrections to **single-Higgs boson** production and decay involve **Higgs self-coupling** [1]



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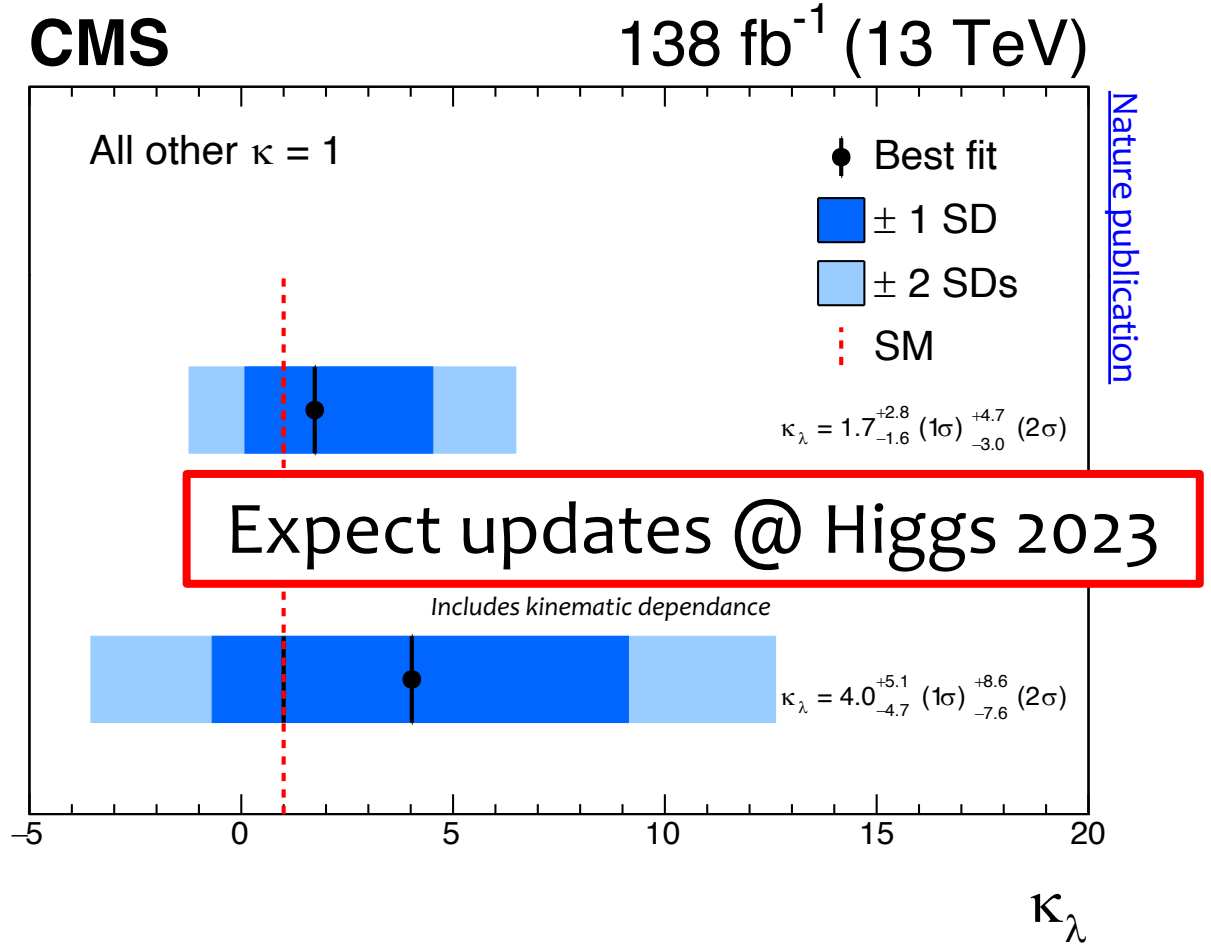


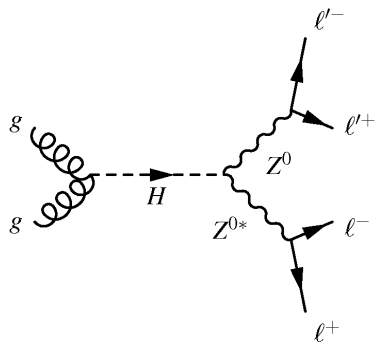
Precision (single) **Higgs boson measurements** also sensitive to **Higgs self-coupling!**

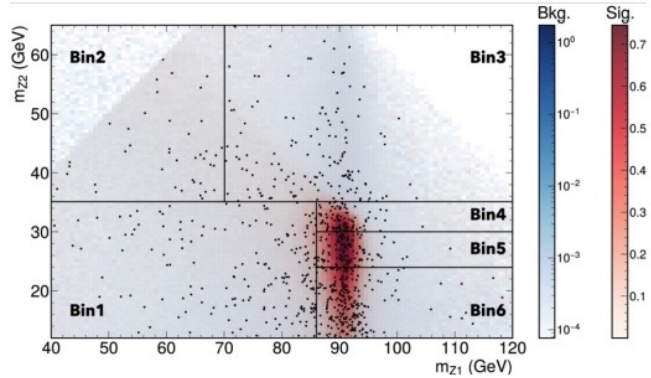
[1] Eur. Phys. J. C (2017) 77: 887

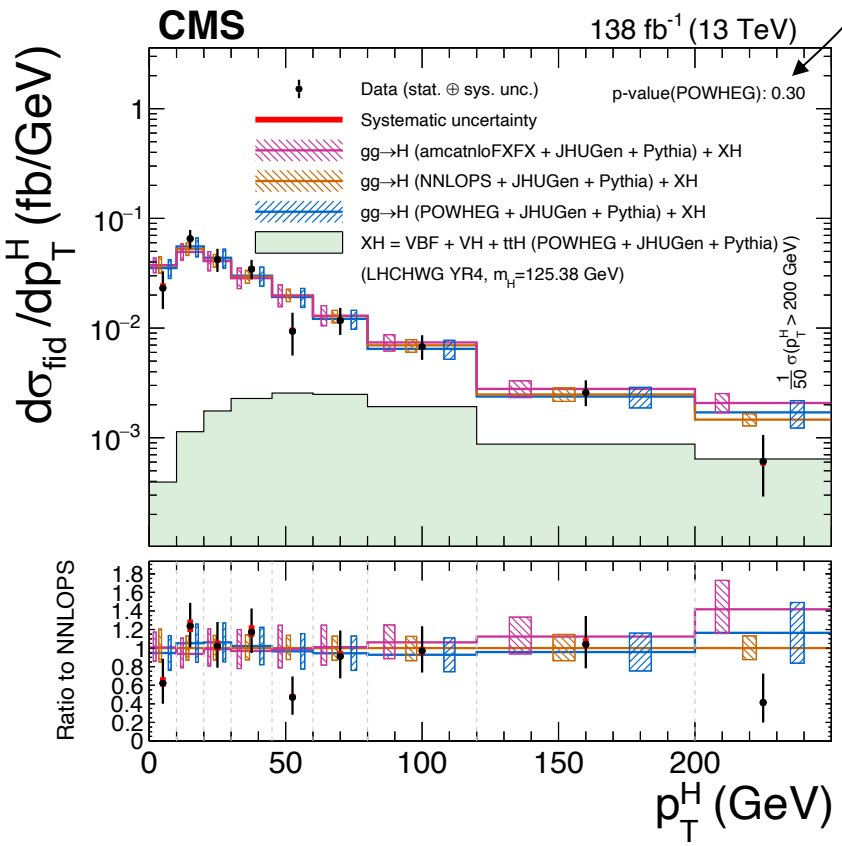
Looking beyond the couplings

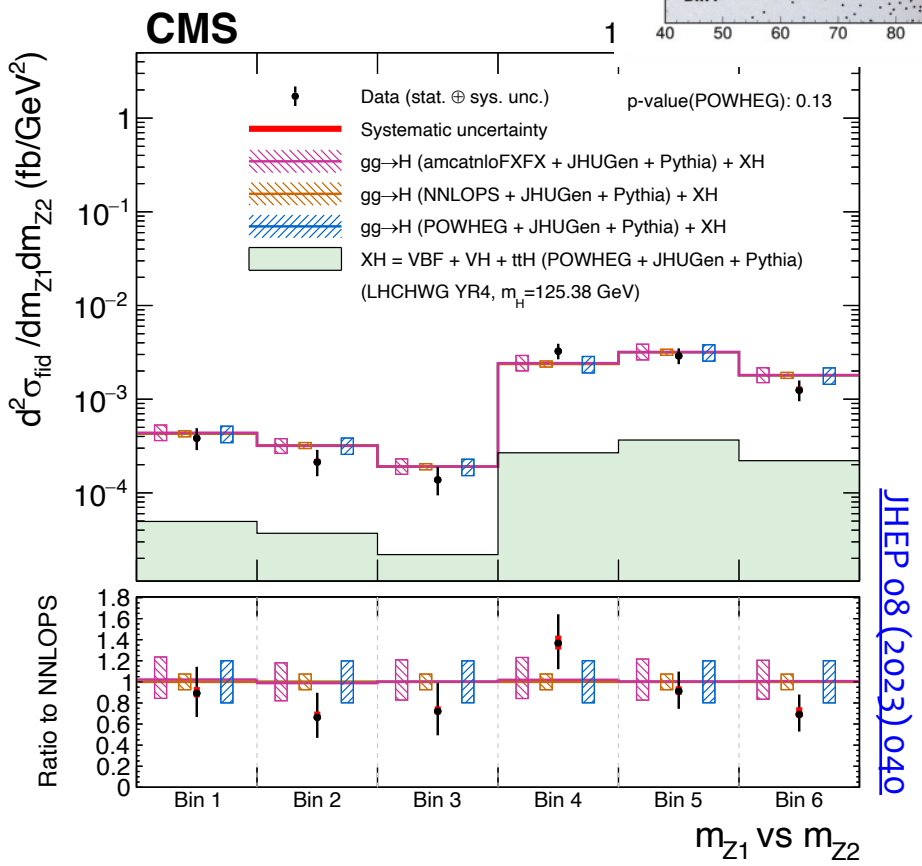
Huge datasets available in Run-2 (and being collected in Run-3) allow to measure Higgs boson properties differentially

H→ZZ→4l In Production and Decay









JHEP 08 (2023) 040

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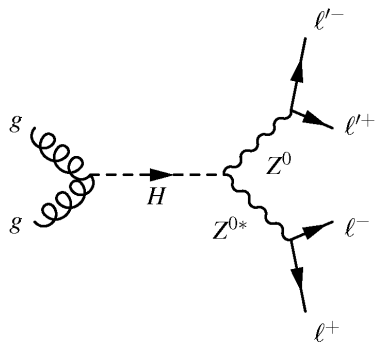
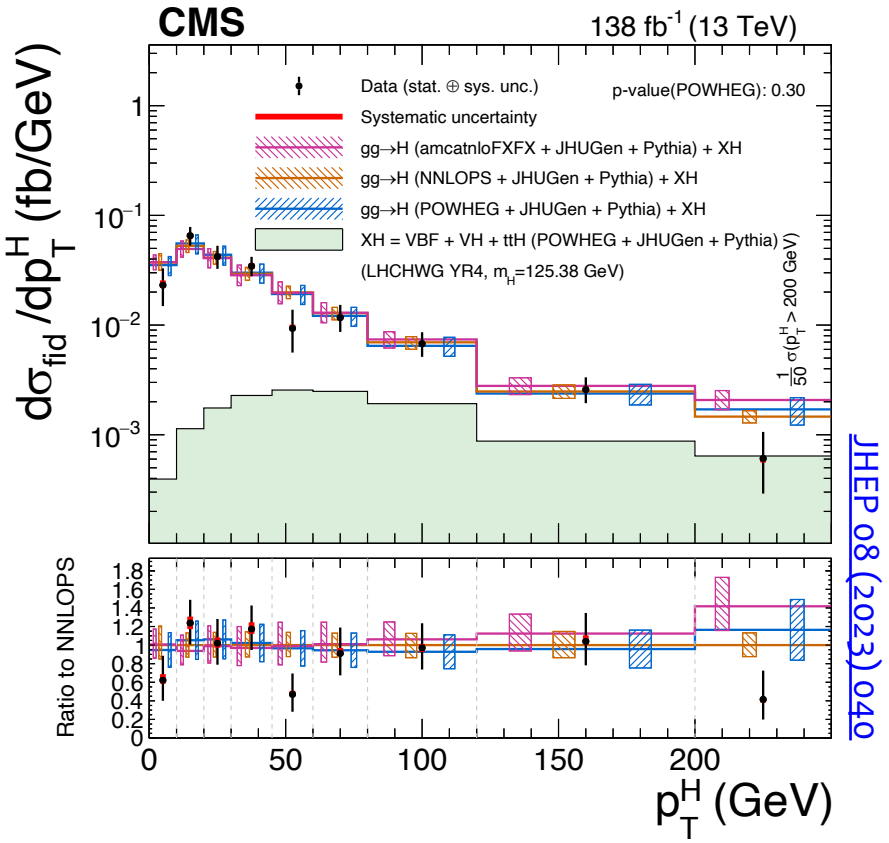
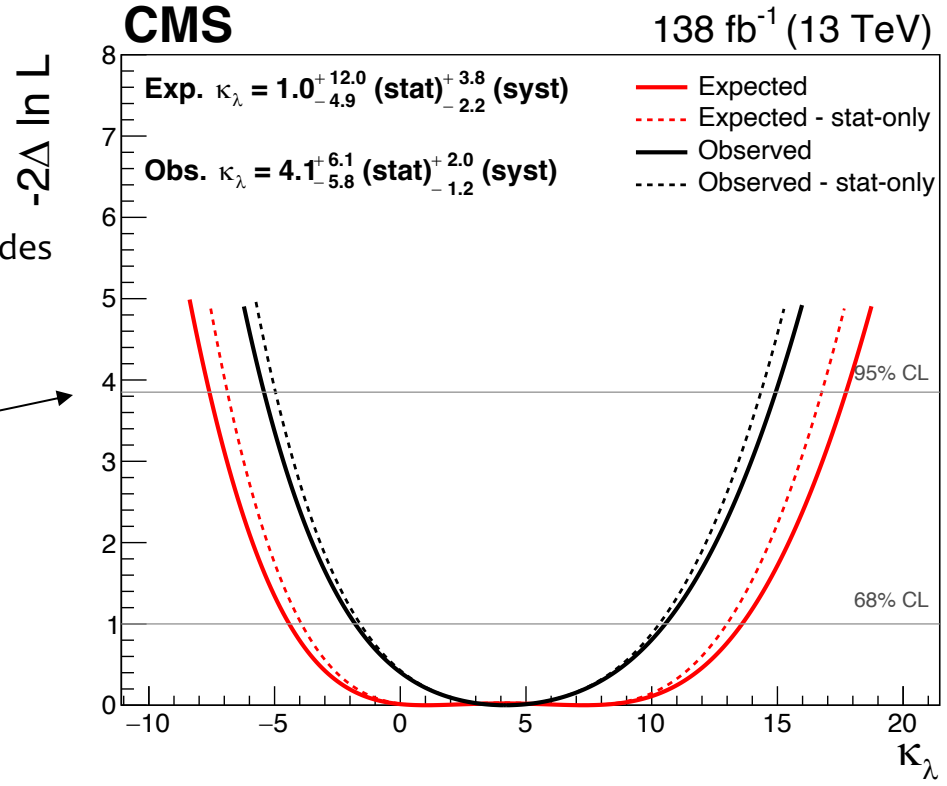




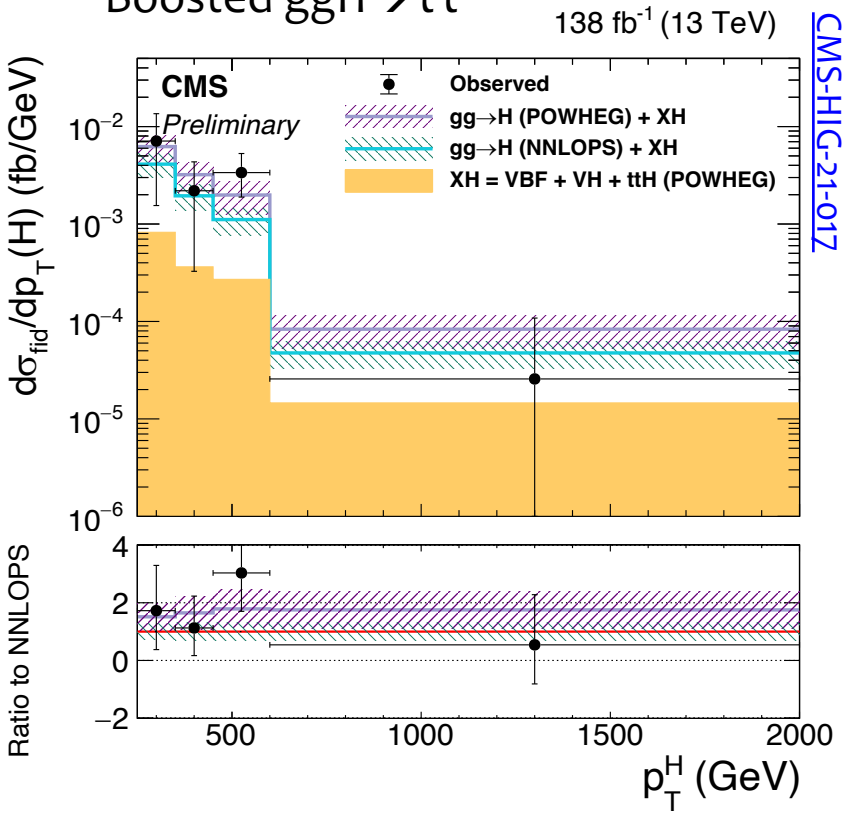
Differential information provides additional handles on Higgs boson (self) couplings



Looking at Extreme Higgs events

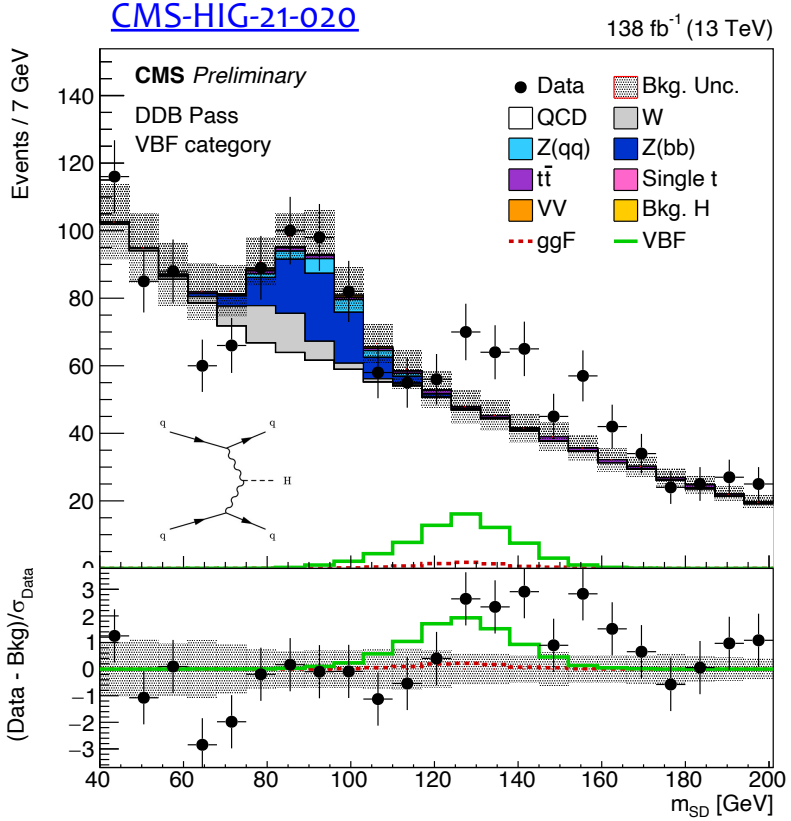
Large datasets allow us to probe **extreme regions of phase-space** → Extreme Higgs boson events!

Boosted ggH→ττ

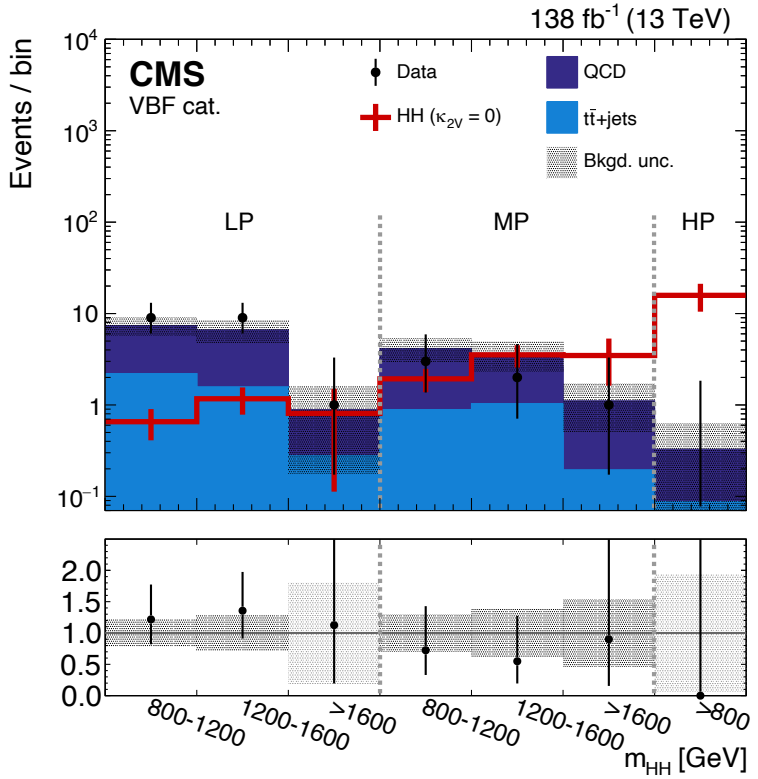


CMS-HIG-21-017

CMS-HIG-21-020



Boosted (p_T>450 GeV) VBF H→bb



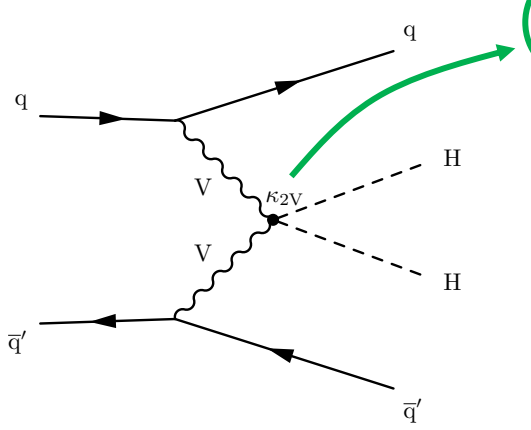
Phys. Rev. Lett. 131(2023)041803

High mass VBF HH(→4b)

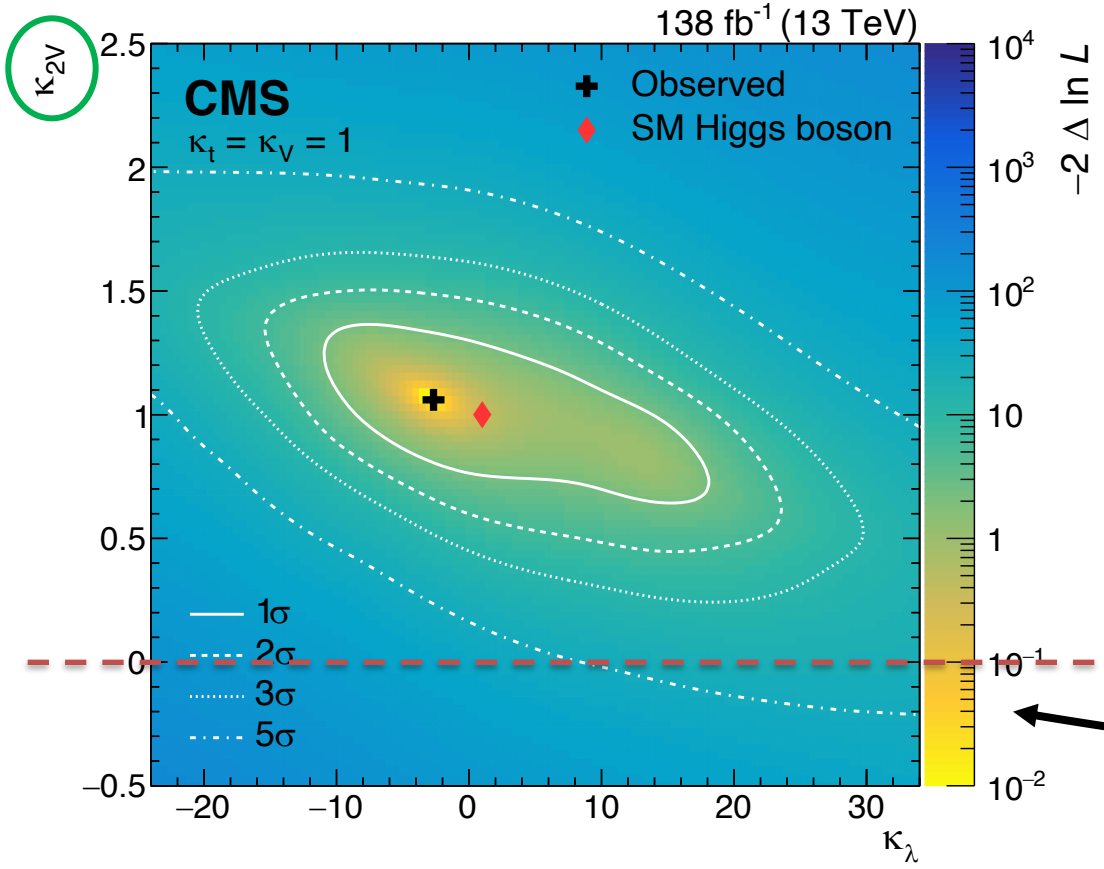
Often requires re-thinking traditional tagging for decay products

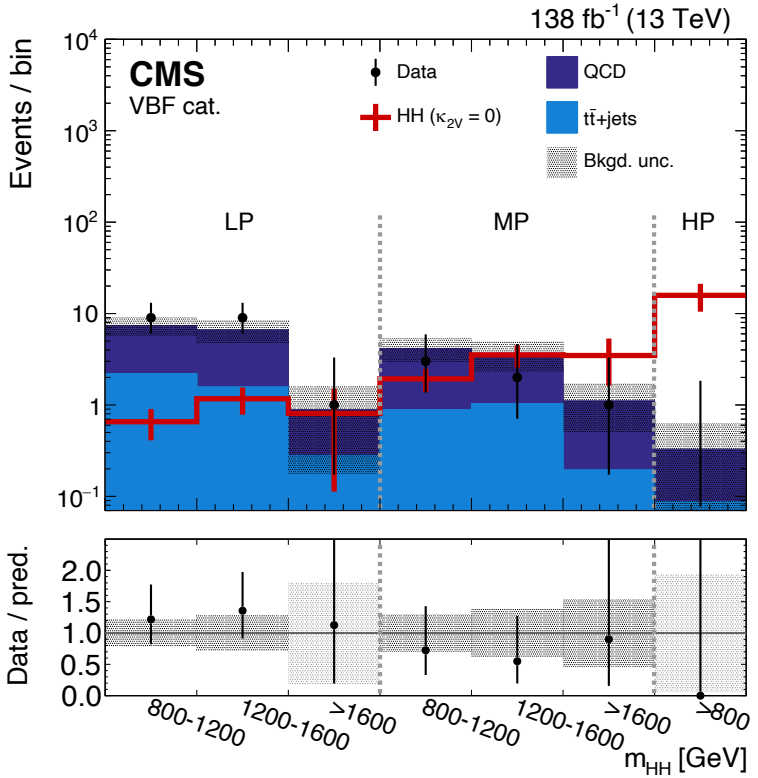
Looking *and not seeing* Extreme Higgs events

Large datasets allow us to probe **extreme regions of phase-space** → Extreme Higgs boson events!



κ_{2V}





Phys. Rev. Lett. 131(2023)041803

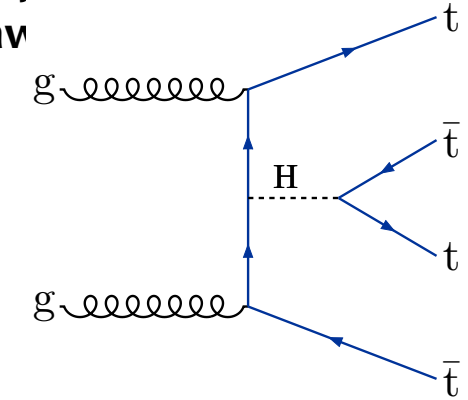
High mass VBF HH(→4b)

Search excludes zero κ_{VV} at above 95%

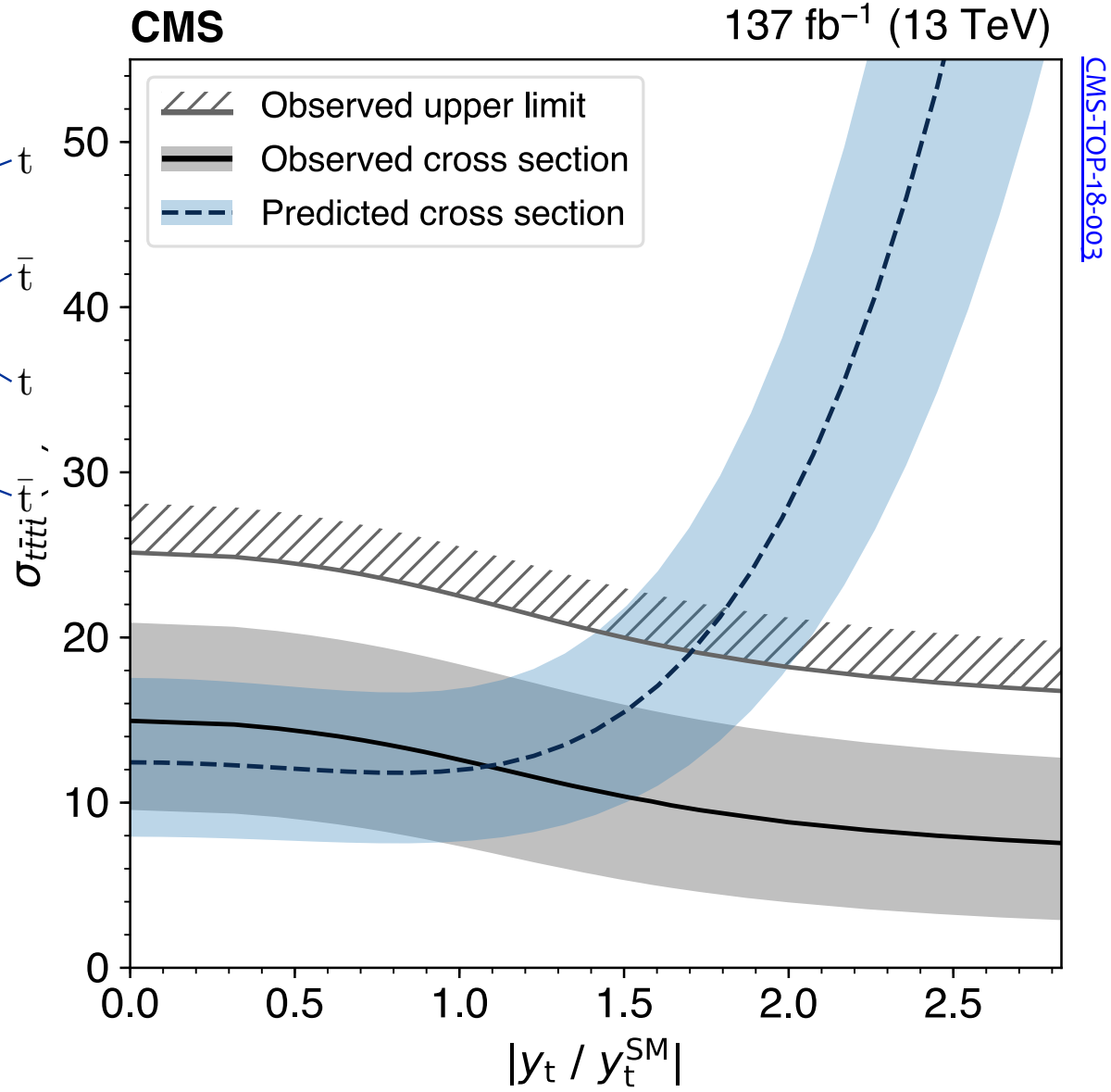
Often requires re-thinking traditional tagging for decay products

Looking beyond the Higgs?

Search for 4-tops provides complementary approach to constraining **Higgs-top Yukav** coupling!



Global fits across multiple measurements (eg through EFTs) will provide strongest constraints on Higgs boson properties



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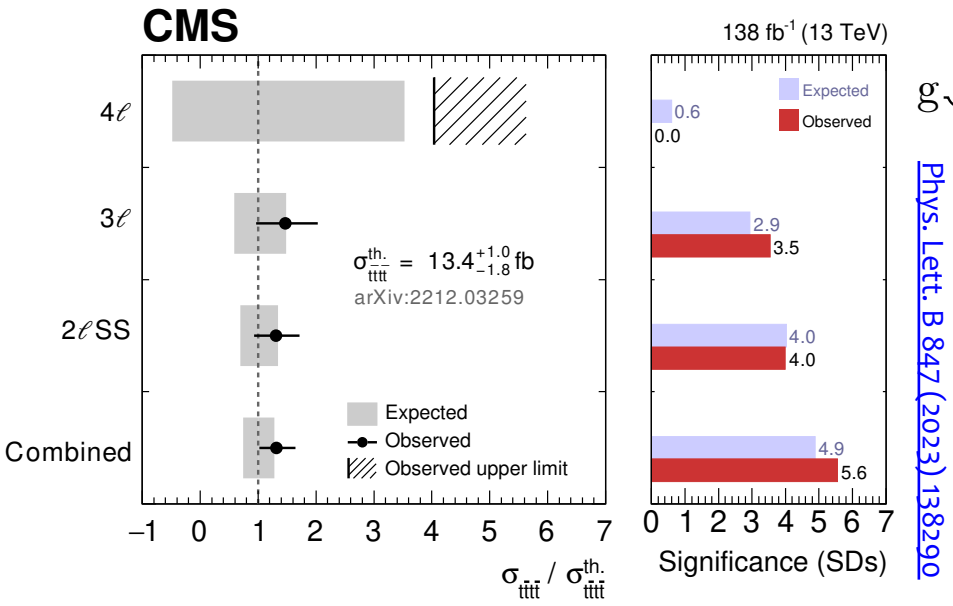
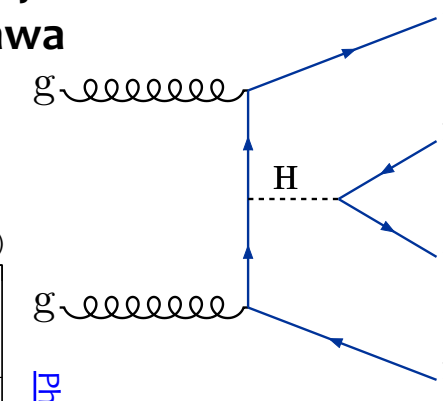
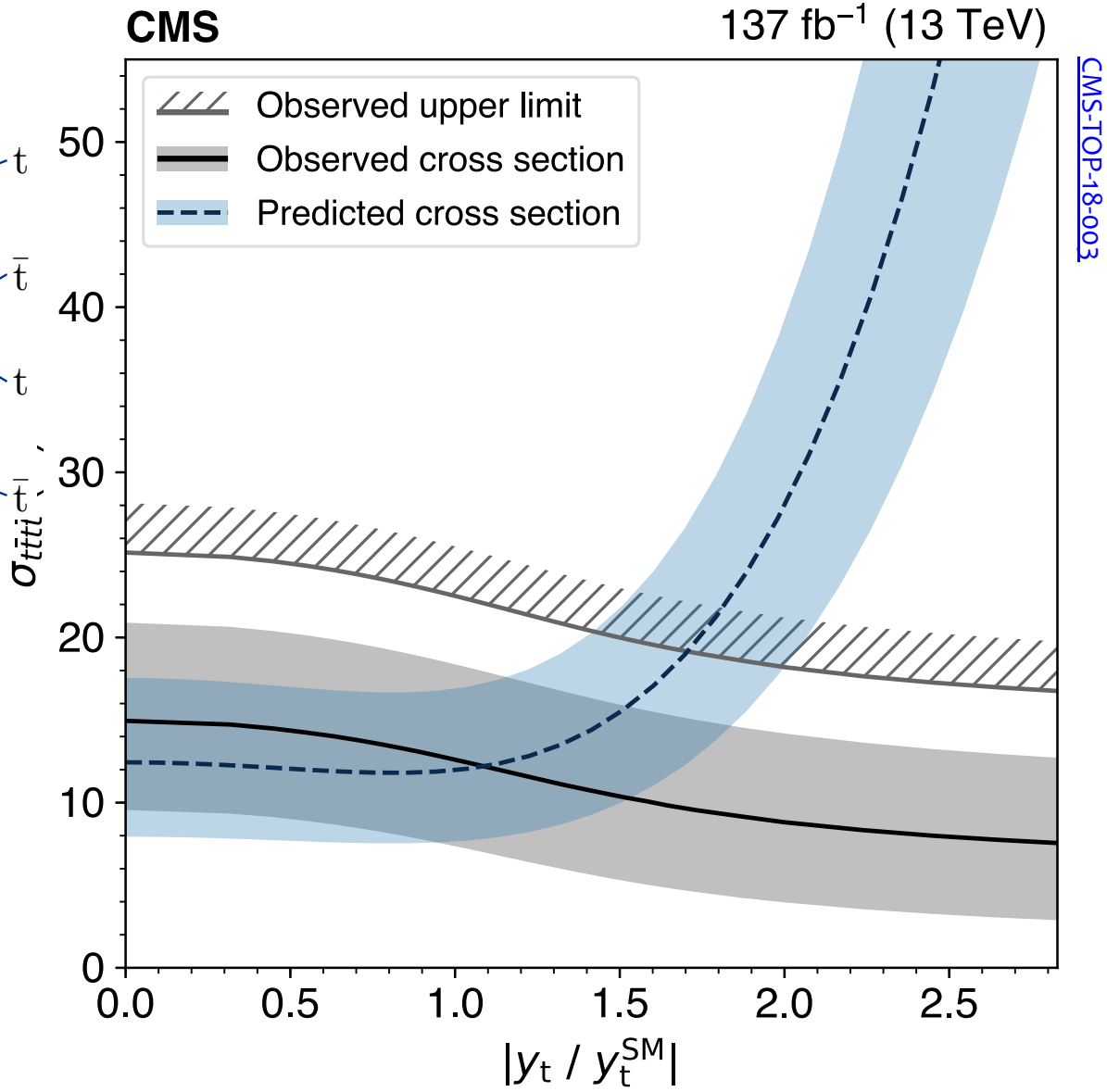


Phys. Lett. B 847 (2023) 138290





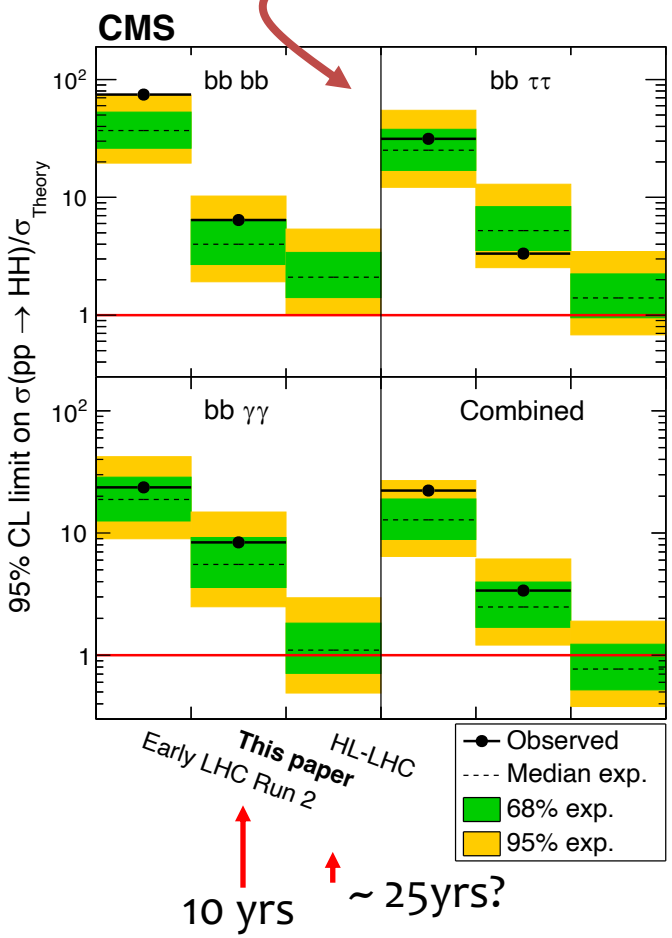
CMS-TOP-18-003

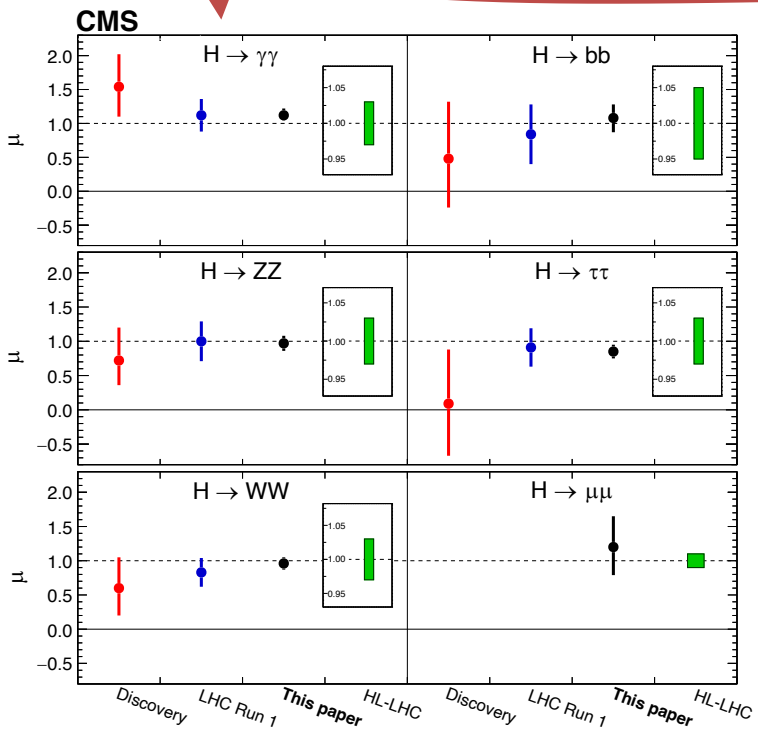
Full Run-2 analysis yields 4-top observation

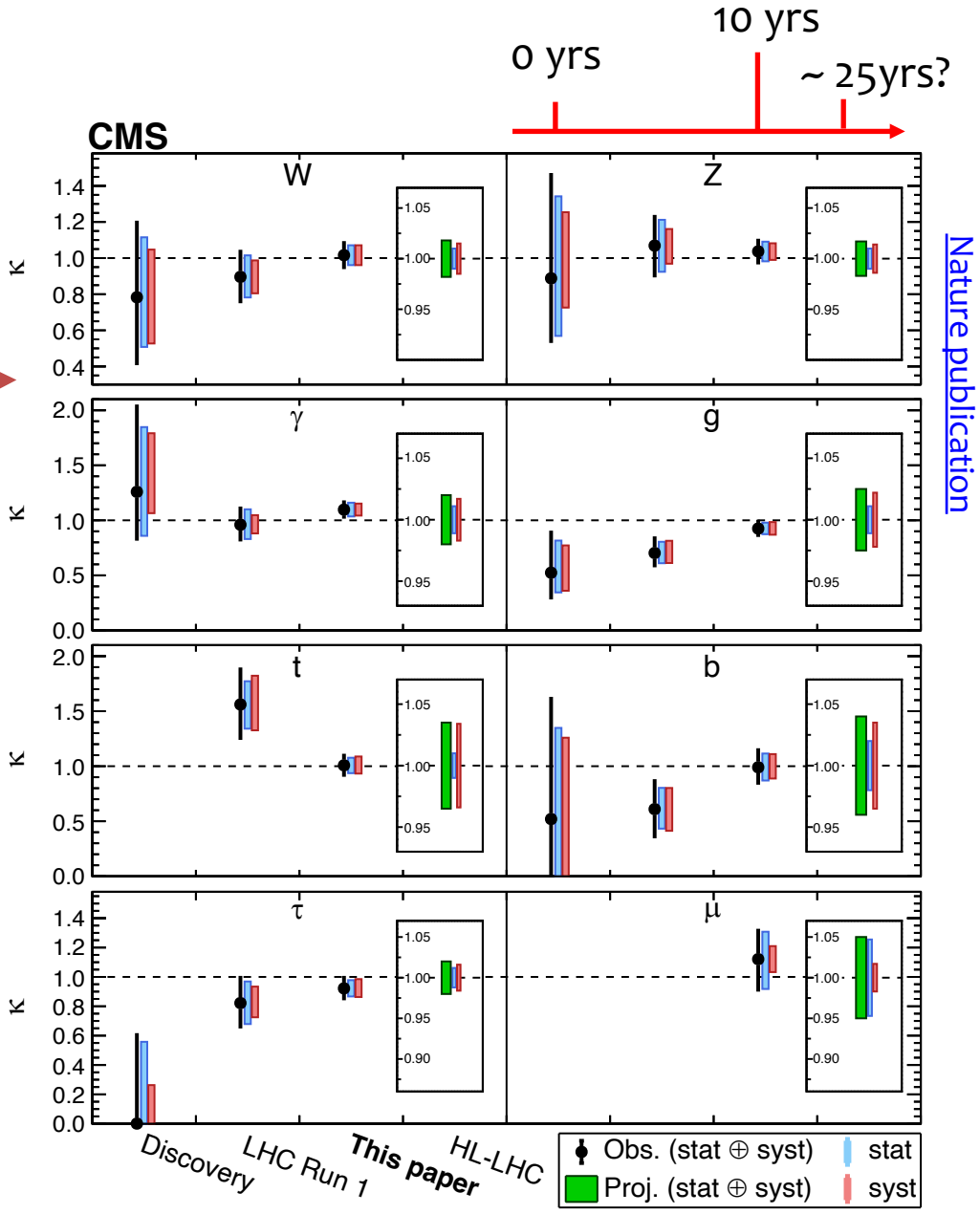
Combined significance **5.9σ (5.1σ)** !

Higgs @ HL-LHC CMS

Precision measurements require more than just more data
→ Improvements in reconstruction techniques & calibrations will be needed for HH sensitivity and %-level H measurements @HL-LHC



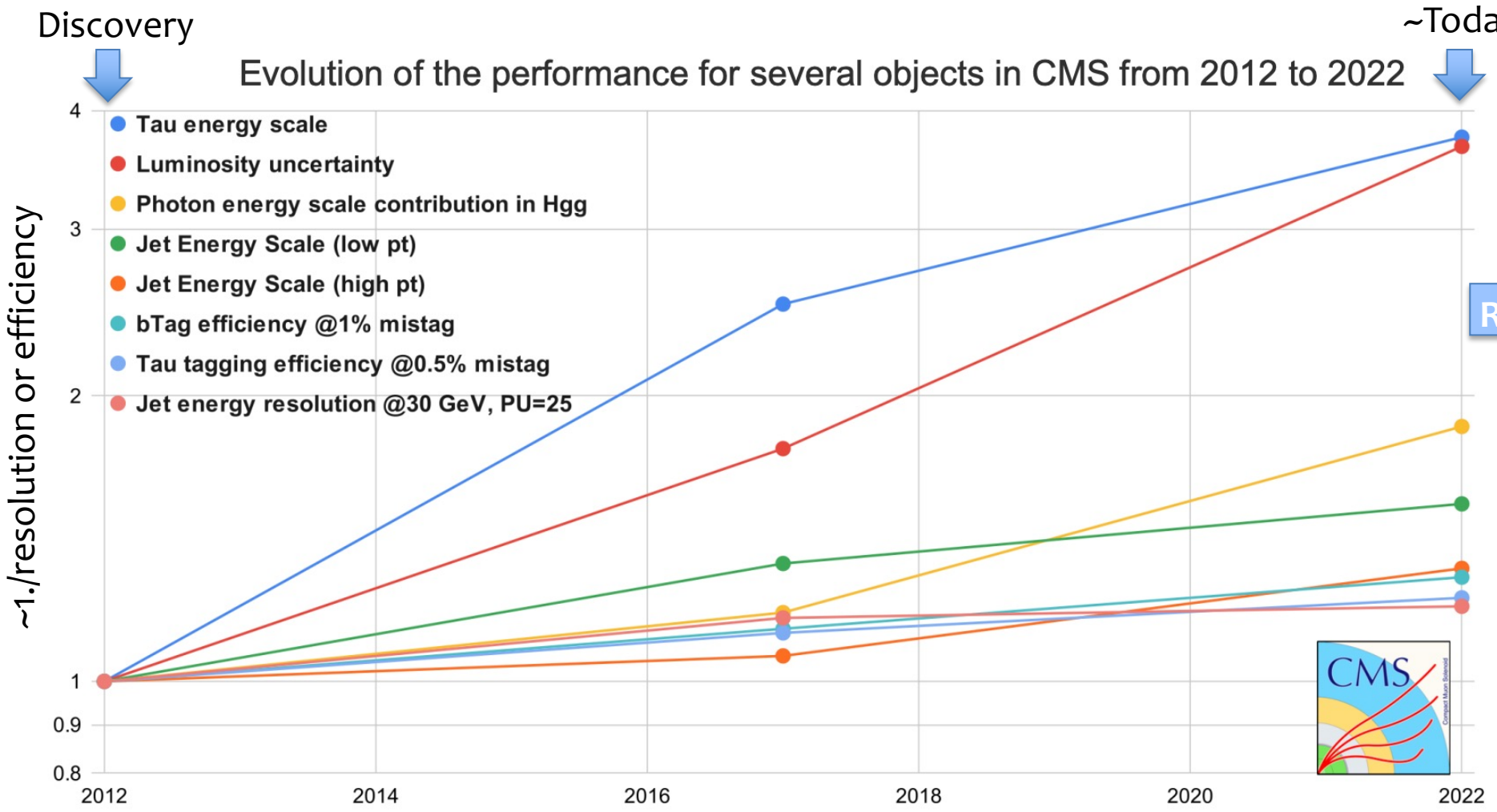




Nature publication

Higgs @ HL-LHC CMS

Precision measurements require more than just more data

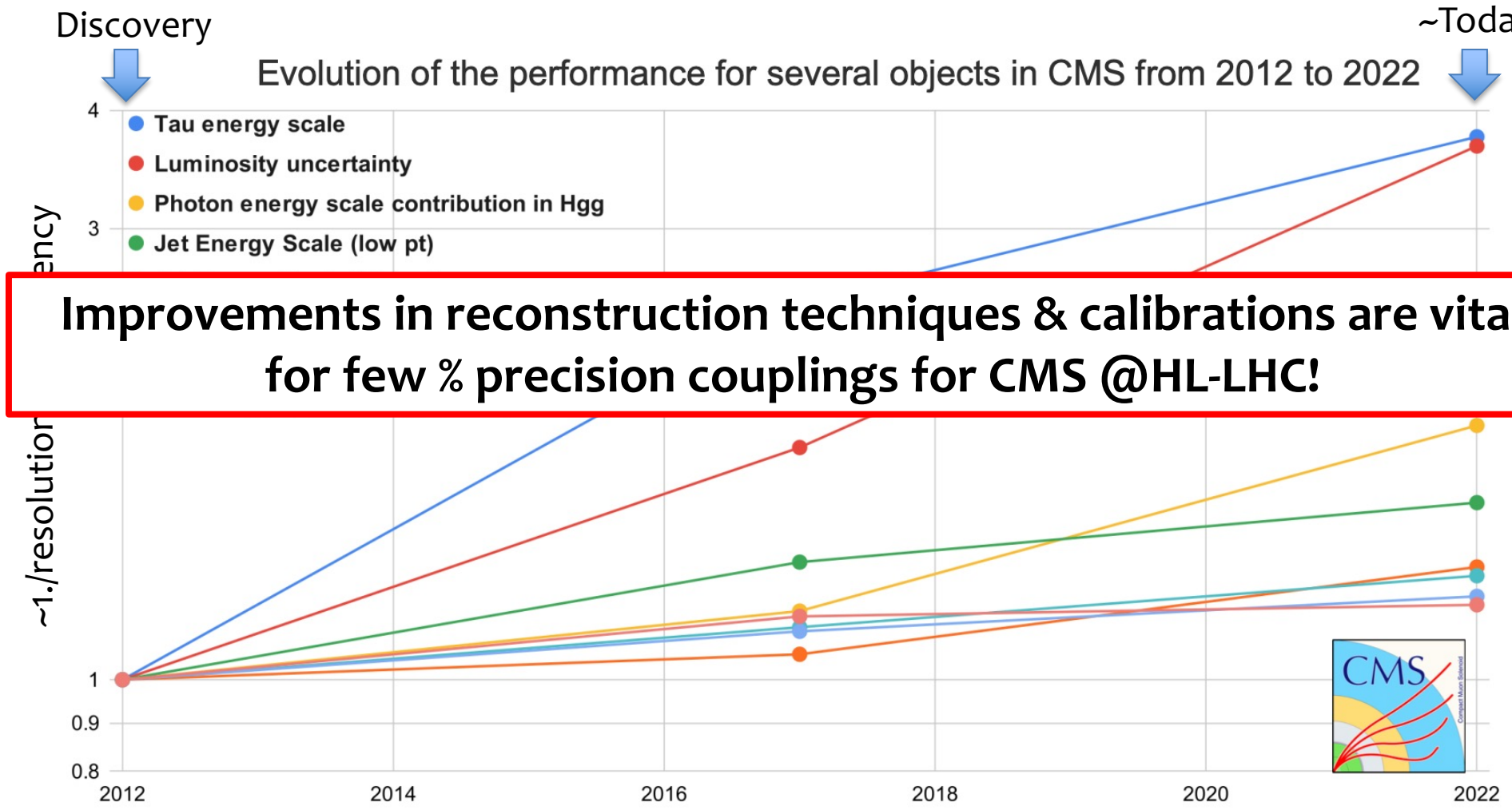


Run-3/HL-LHC

See Monika's talk

Higgs @ HL-LHC CMS

Precision measurements require more than just more data



Improvements in reconstruction techniques & calibrations are vital for few % precision couplings for CMS @HL-LHC!

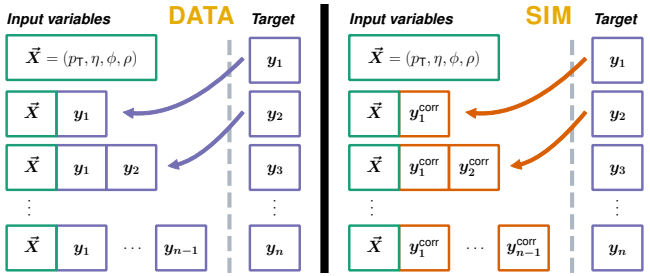
/HL-LHC

Monika's talk

New ideas/tools to get there

Many avenues being explored but just as a couple of **Machine Learning** examples from Run-2

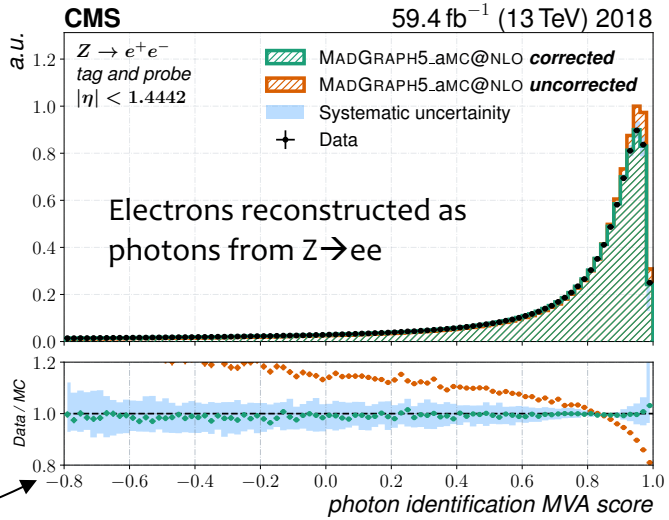
Chained quantile regression to improve description of photon identification used in pp→H→γγ differential cross-section measurements



BDT learns corrections per-quantile for each input variable from CDFs

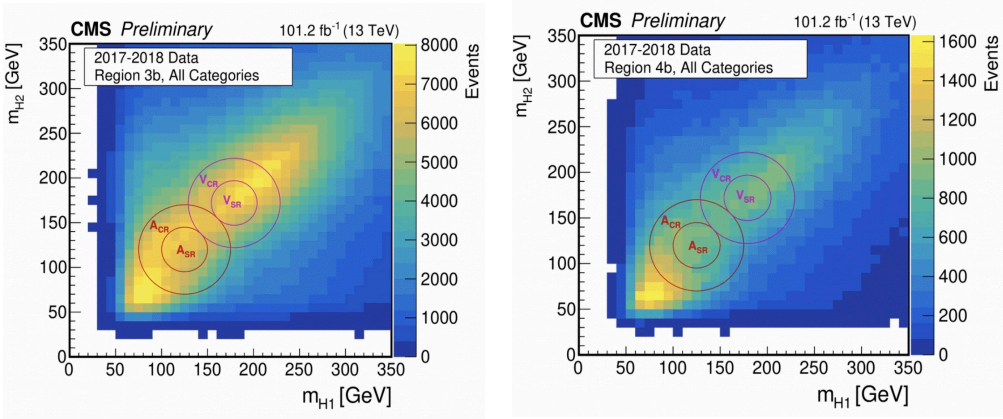
$$y_C = F_Y^{\text{data}\,-1}\left(F_Y^{\text{sim}}(y)\right)$$

JHEP 07 (2023) 091



→ Improves dominant experimental uncertainty in H→γγ by ~70%!

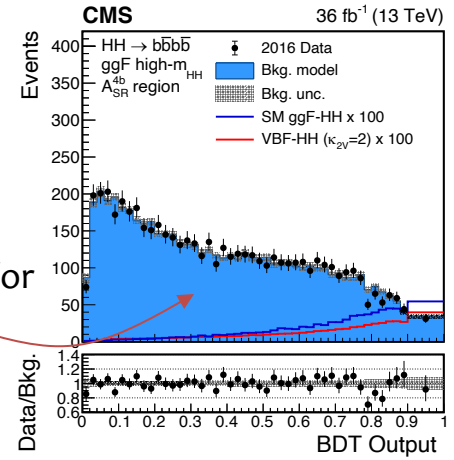
QCD Multijet background in HH→4b analysis based on **data-driven method**



BDT reweighting technique based on [1] to perform corrections, optimized in A_{CR} data

$$\chi^2 = \sum_{\text{leaf}} \frac{(w_{\text{leaf},1} - w_{\text{leaf},2})^2}{(w_{\text{leaf},1} + w_{\text{leaf},2})^2}$$

Correct p_T b-jets, m_{HH}, $p_T(H_1)$, $pT(H_2)$, $m(H_1)$, $m(H_2)$, $|\Delta\eta(H_1,H_2)|$ applied in SR regions to account for differences between 3b and 4b



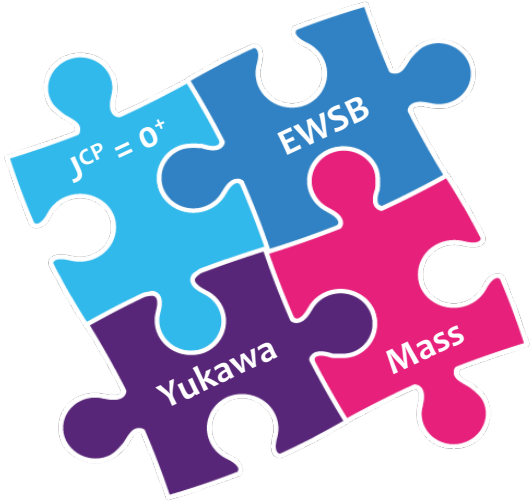
Phys. Rev. Lett. 129 (2022) 081802

CMS investigating similar approaches with NN/Normalising flows for Run-3

[1] J.Phys.Conf.Ser. 762 (2016) 1, 012036

Summary

Higgs-saw puzzle has kept CMS entertained since the discovery

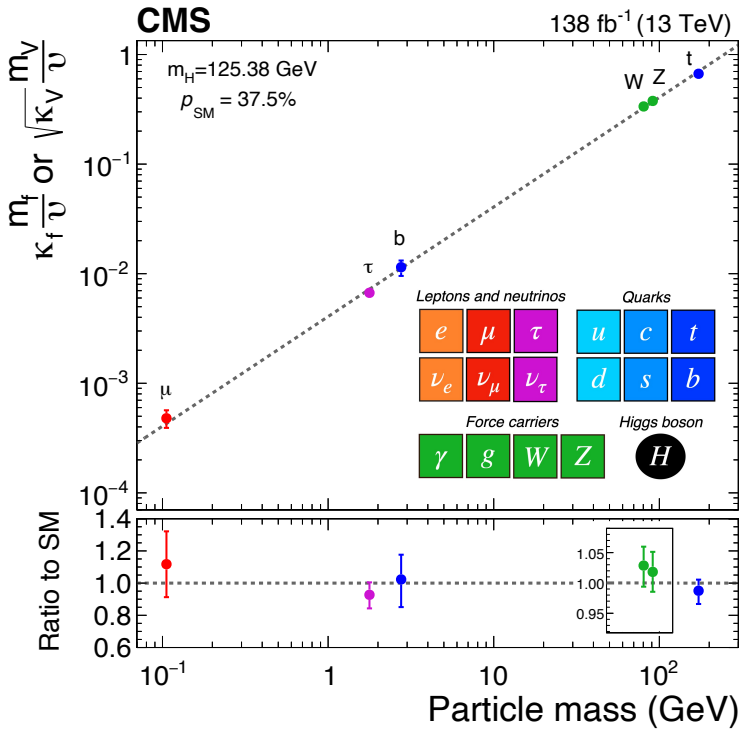


In 11 years…

- Higgs boson mass **measured within <0.1% precision**
- Confirmed **couplings to vector bosons** and **heavy fermions**
  - Evidence for H→μμ
- Studied **CP properties of Higgs interactions**

But also

- Extra components of width still allowed
  - Rare SM decays, BSM decays (eg dark matter)
  - New physics in Loops
- Constrained self-coupling (Higgs potential → see Higgs 2023 for update)
- Go beyond inclusive yields and couplings
  - Differential measurements give new angles of approach
  - Extreme Higgs boson events
  - Look places other than Higgs boson production (4-top)
- Developed new ways to improve on our experimental data analysis



Summary

H very

I

- Evidence for H→μμ
- Studied **CP properties of Higgs**

But also

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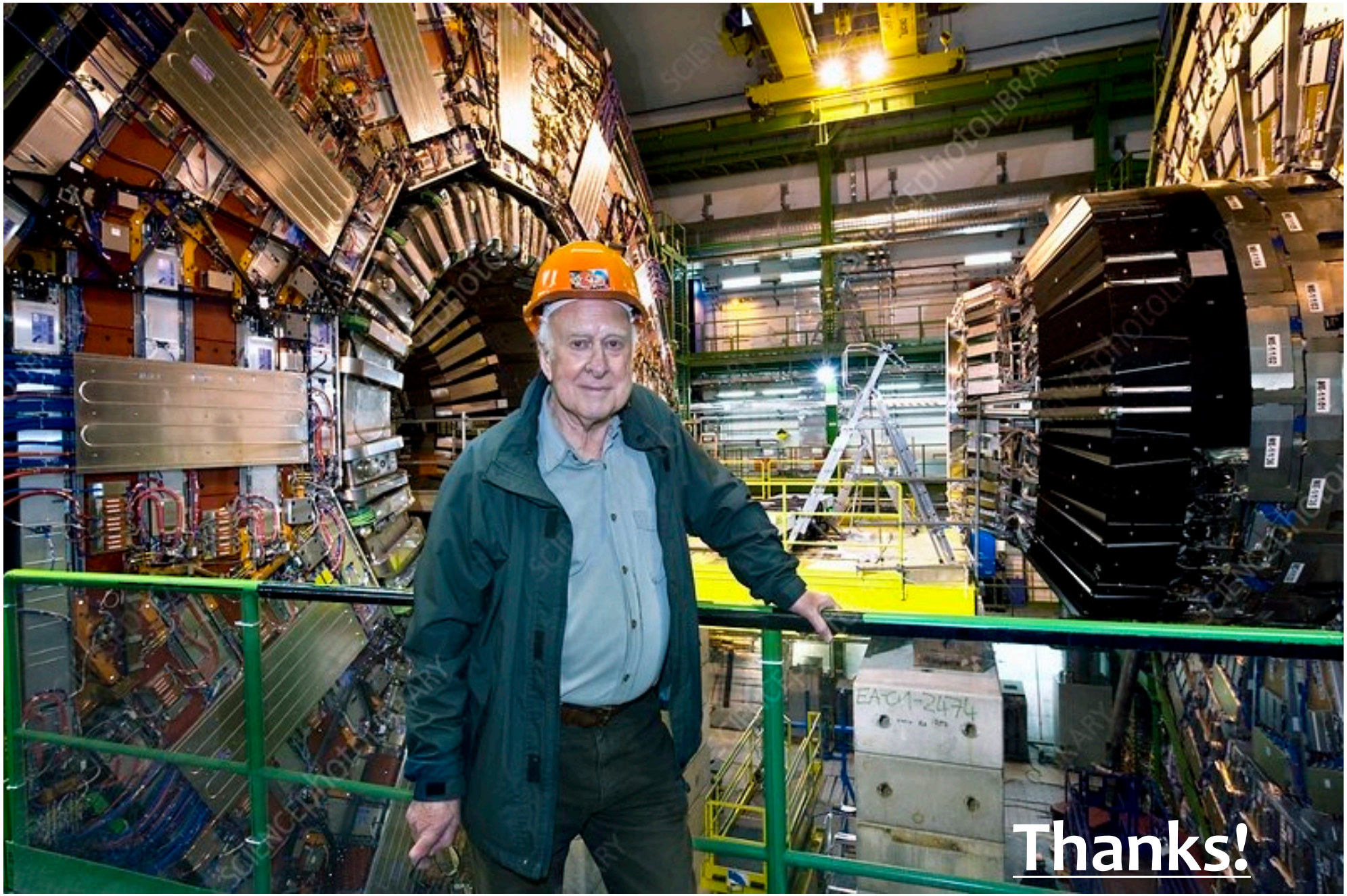
  - New physics in Loops
- Constrained self-coupling (Higg
- Go beyond inclusive yields and
  - Differential measurement
  - Extreme Higgs boson eve
  - Look places other than Hi
- Developed new ways to impro

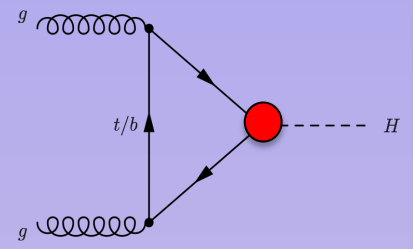
Many more pieces of the puzzle to keep us busy!

Higgs @ CMS

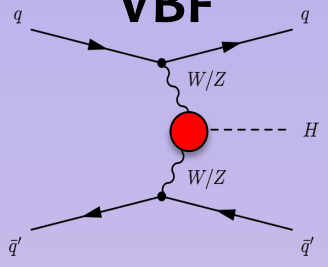


Many different ways to make and see a Higgs

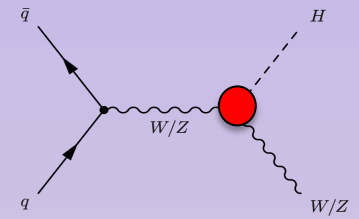
ggH

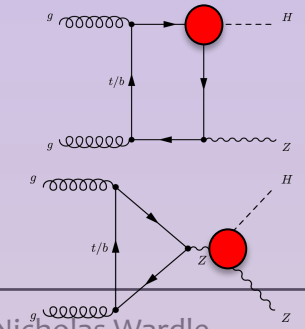


VBF



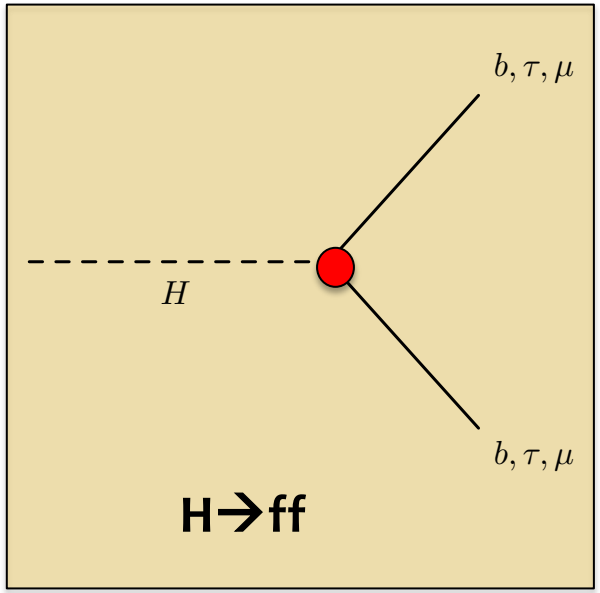
WH / ZH



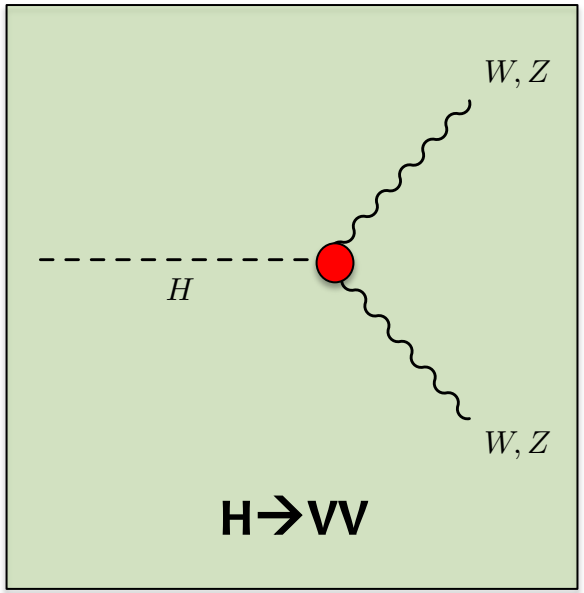


gg→ZH

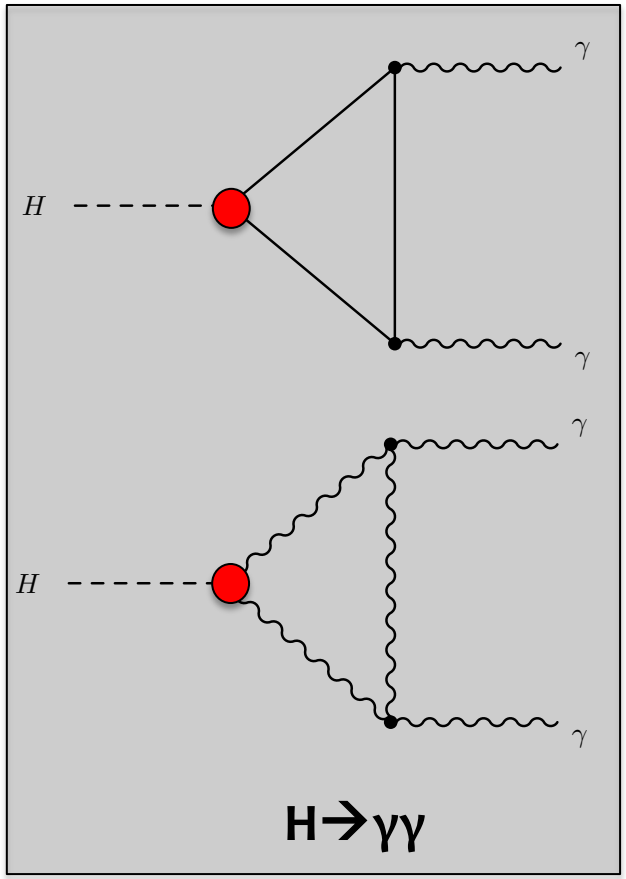
Decreasing cross-section



H→ff

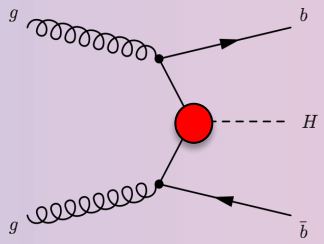


H→VV

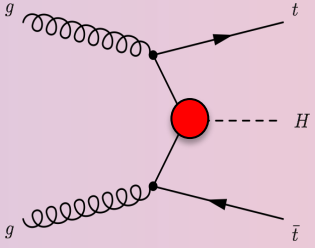


H→γγ

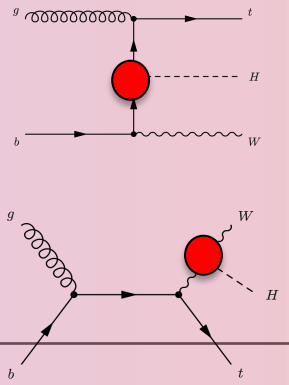
bbH



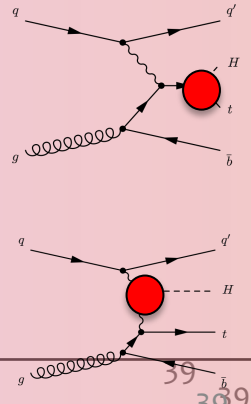
ttH



gb→tHW



qg→tHq



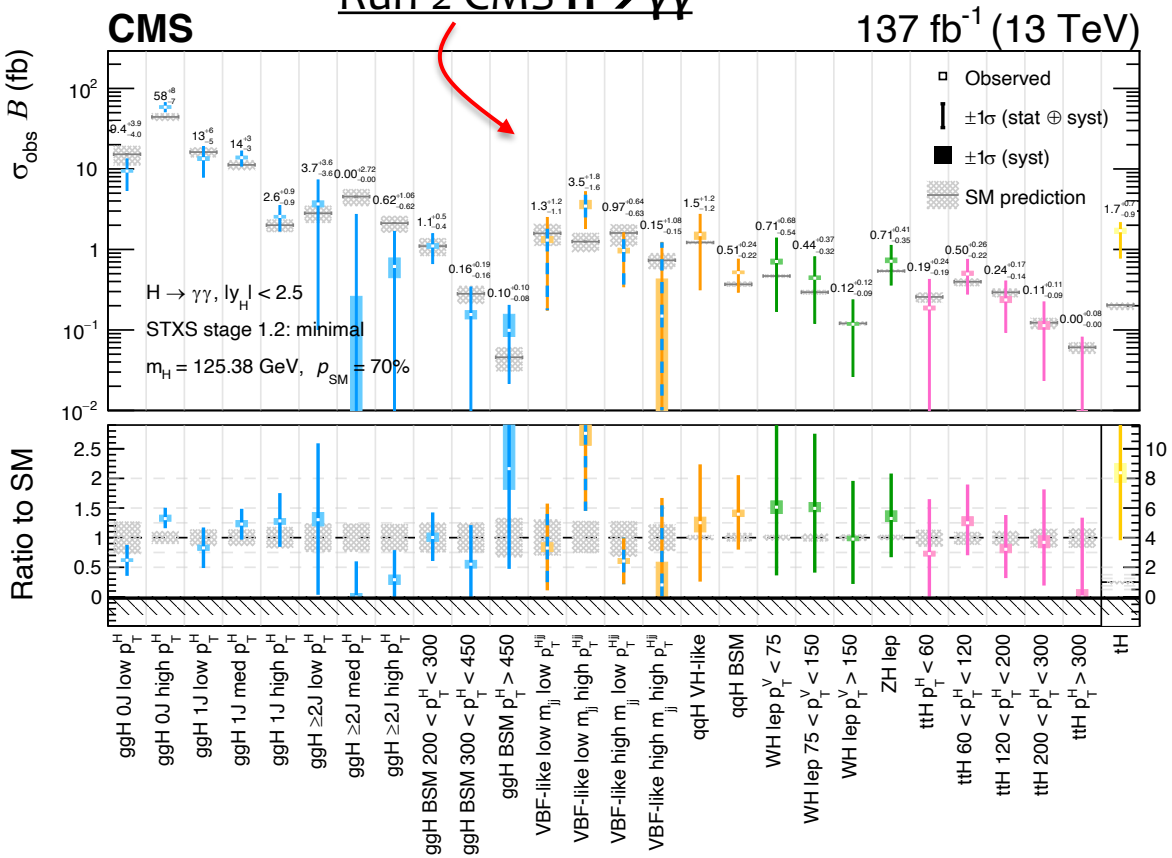
With the mass well measured we can test concrete predictions of **Higgs-SM couplings**

39

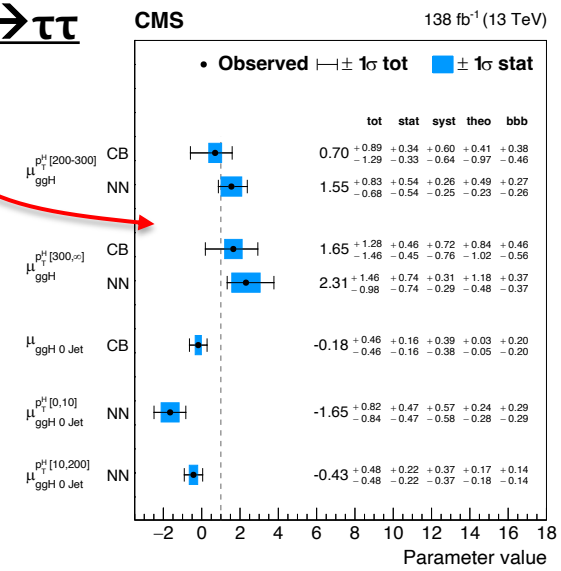
STXS H→γγ & H→ττ

With the data collected in Run-2 we have enough Higgs bosons to **explore high momentum regions** and probe potential hiding places for new (heavy) physics!

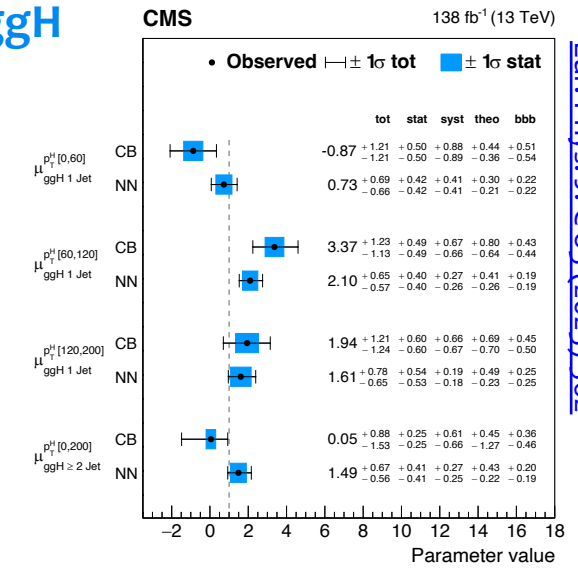
Run-2 CMS **H→γγ**



Run-2 CMS **H→ττ**



ggH



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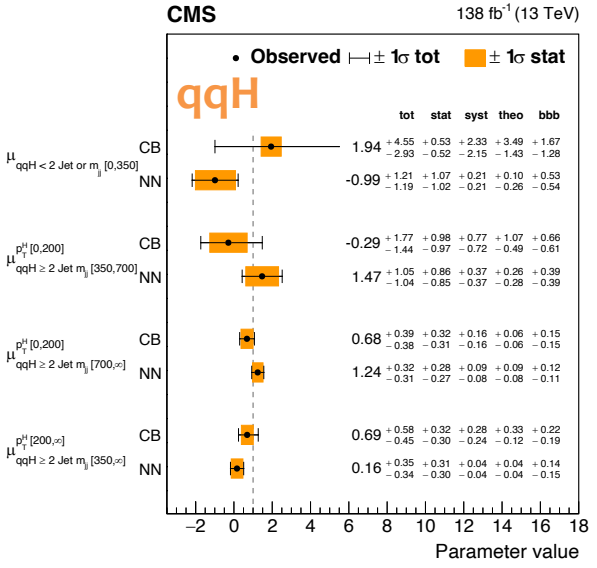
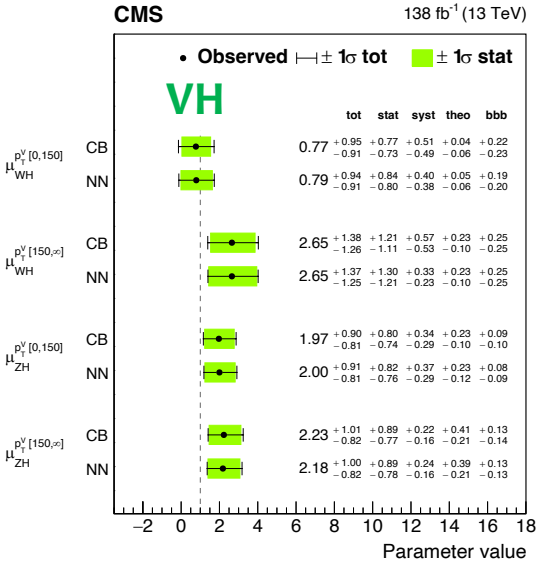
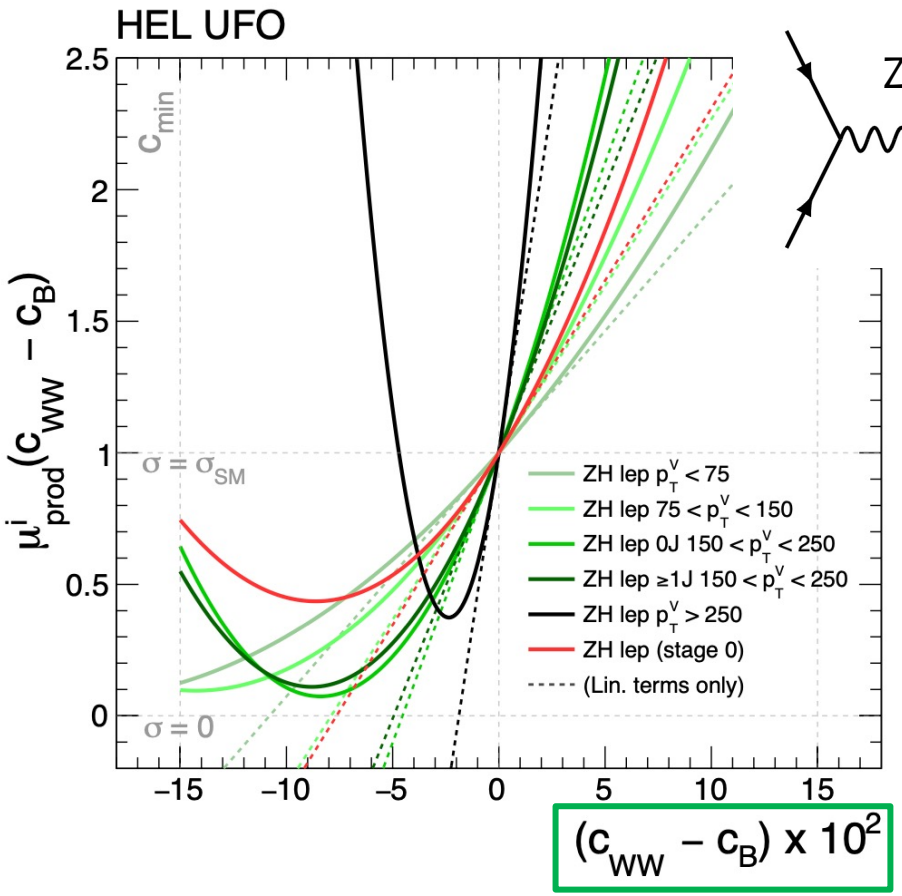
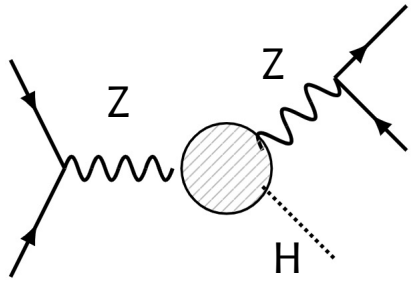
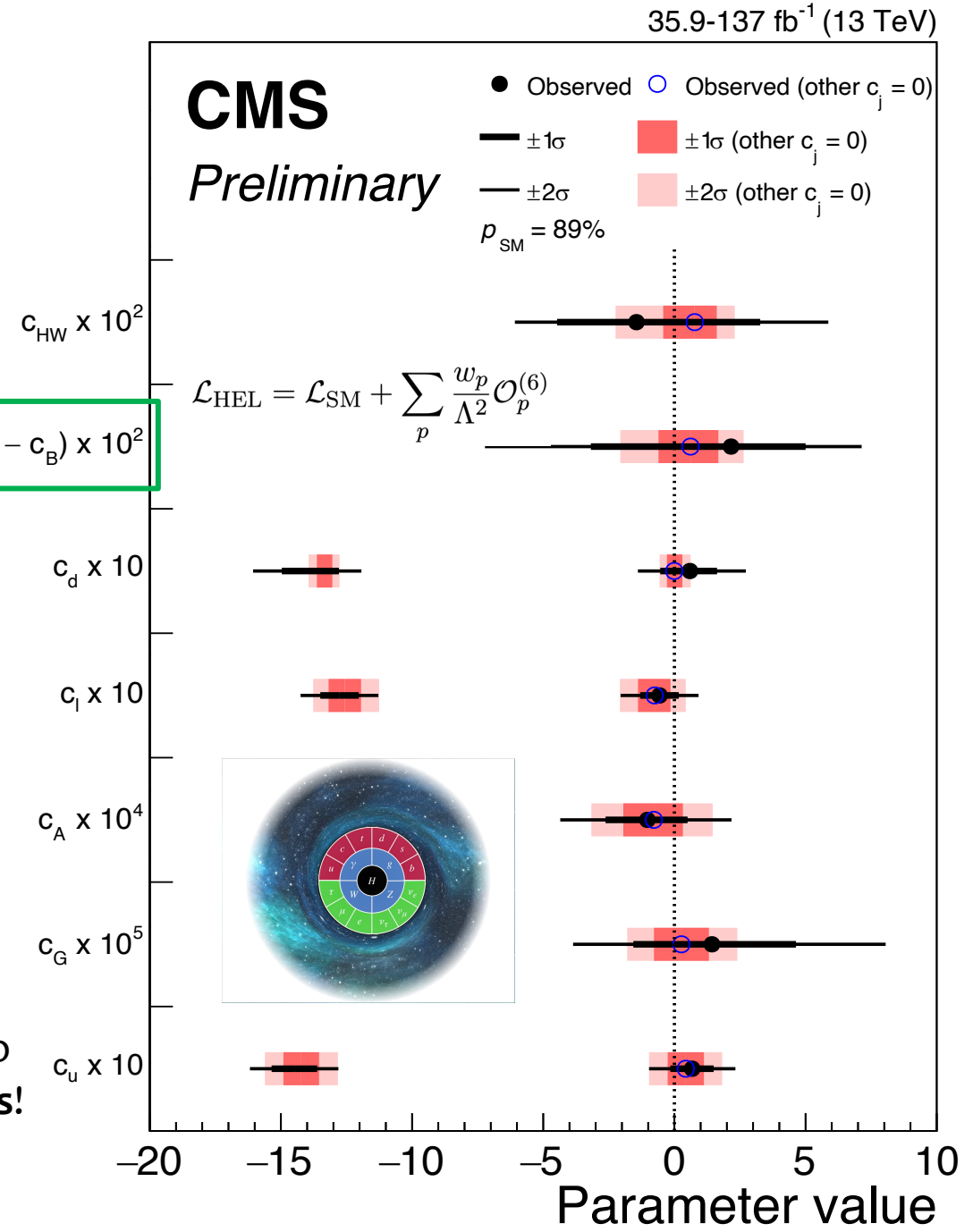




Effective field theories

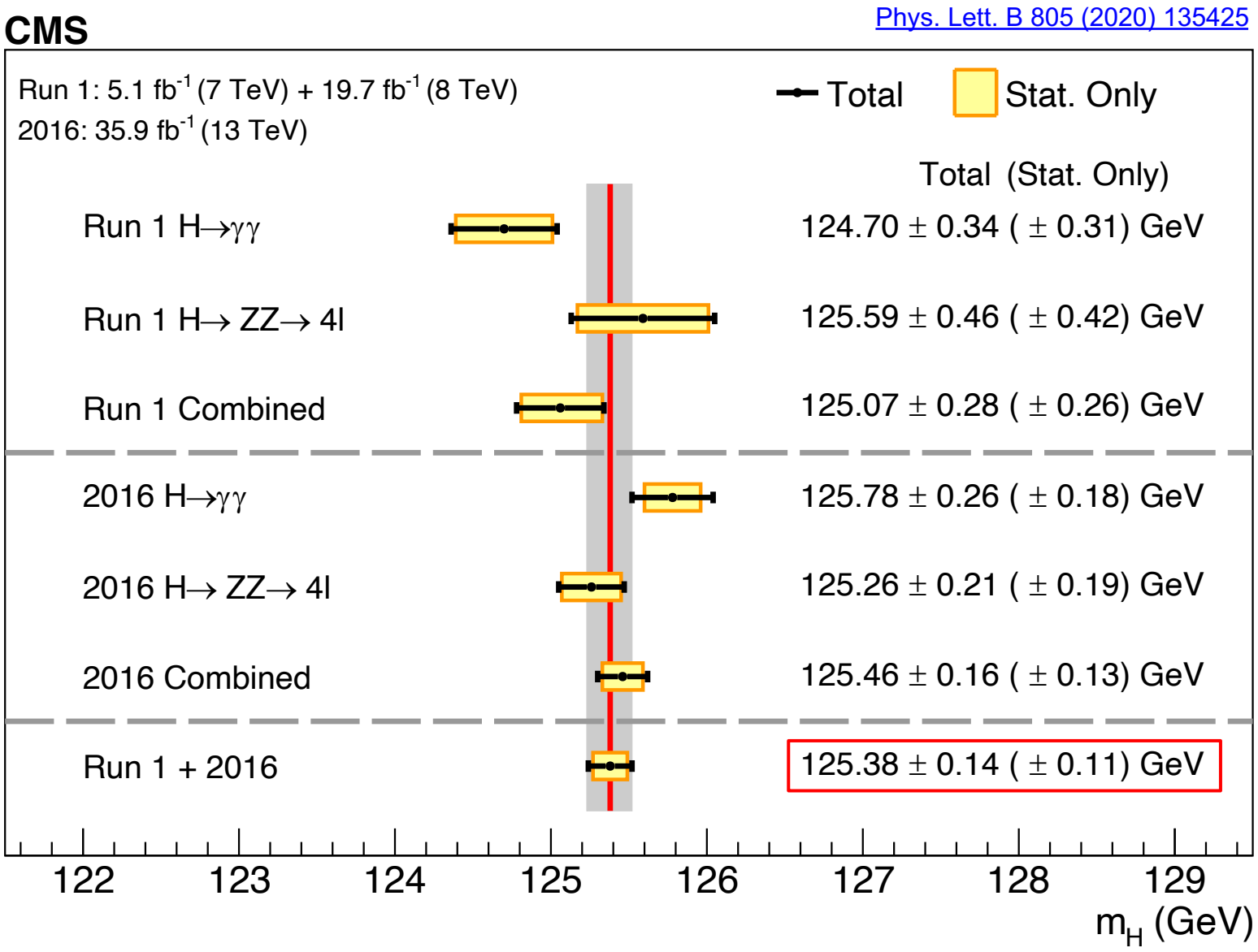




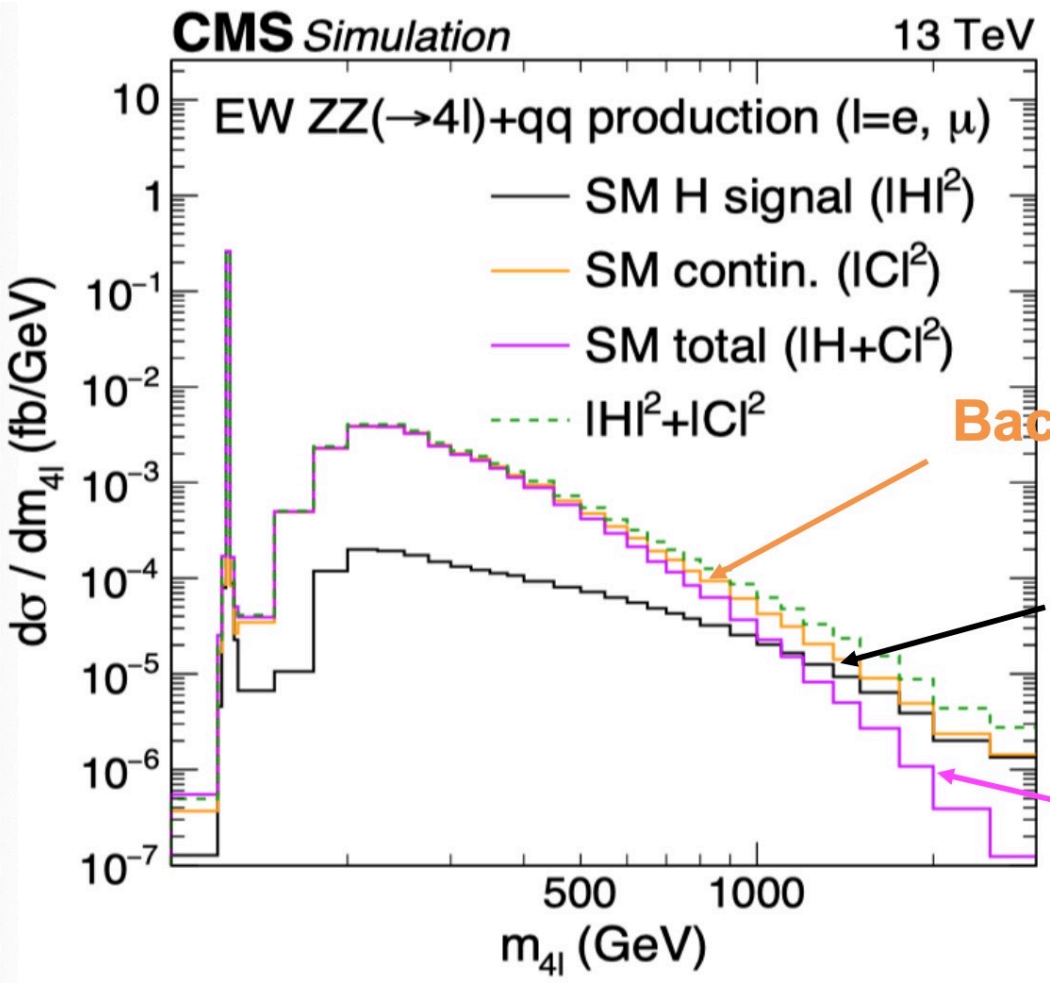


EFTs allow us to coherently correlate measurements across different production & decay, from different kinematic regions, to pick out coherent BSM effcts → **guide** on the path **to New Physics!**

m_H combination



Higgs Width

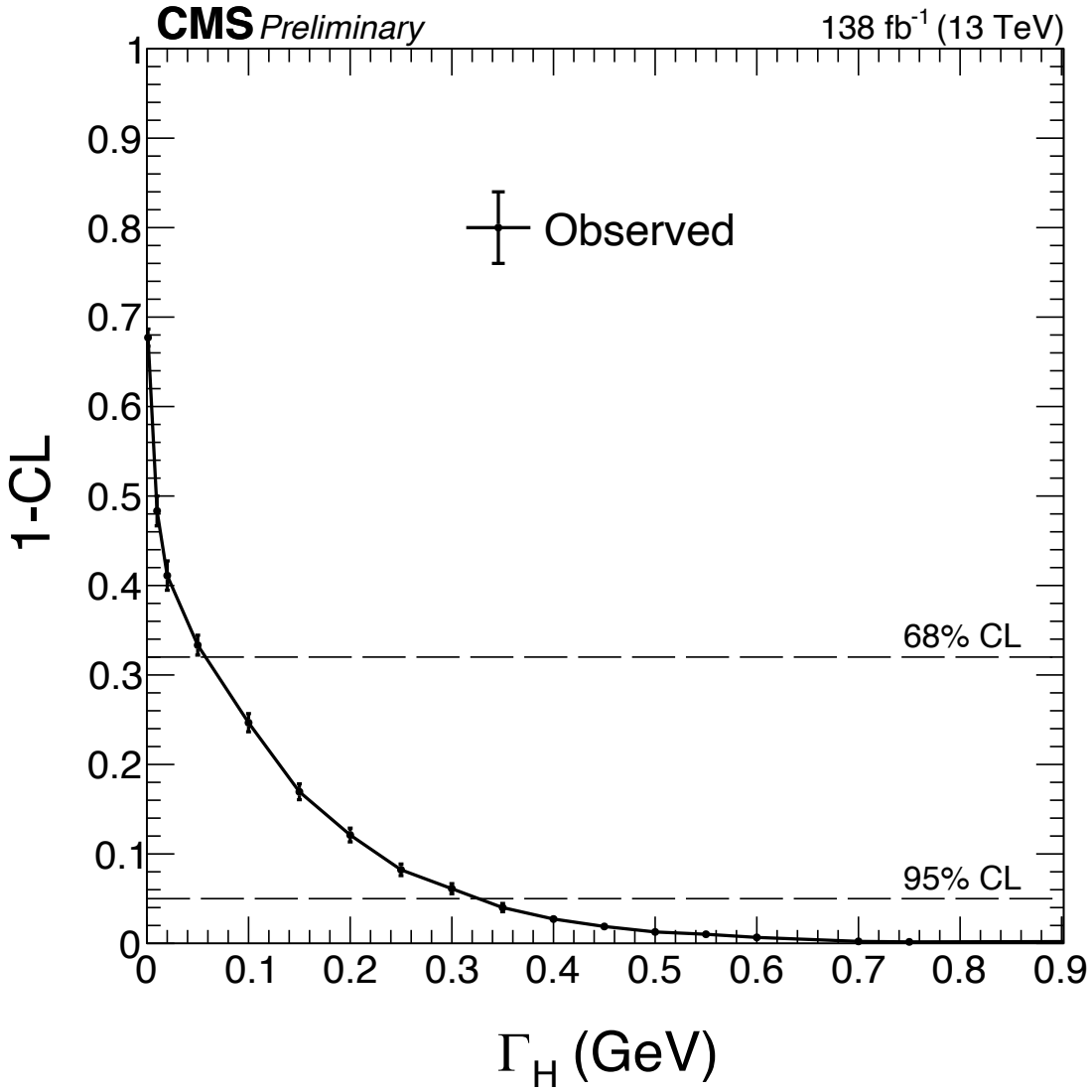


Background only

Higgs only

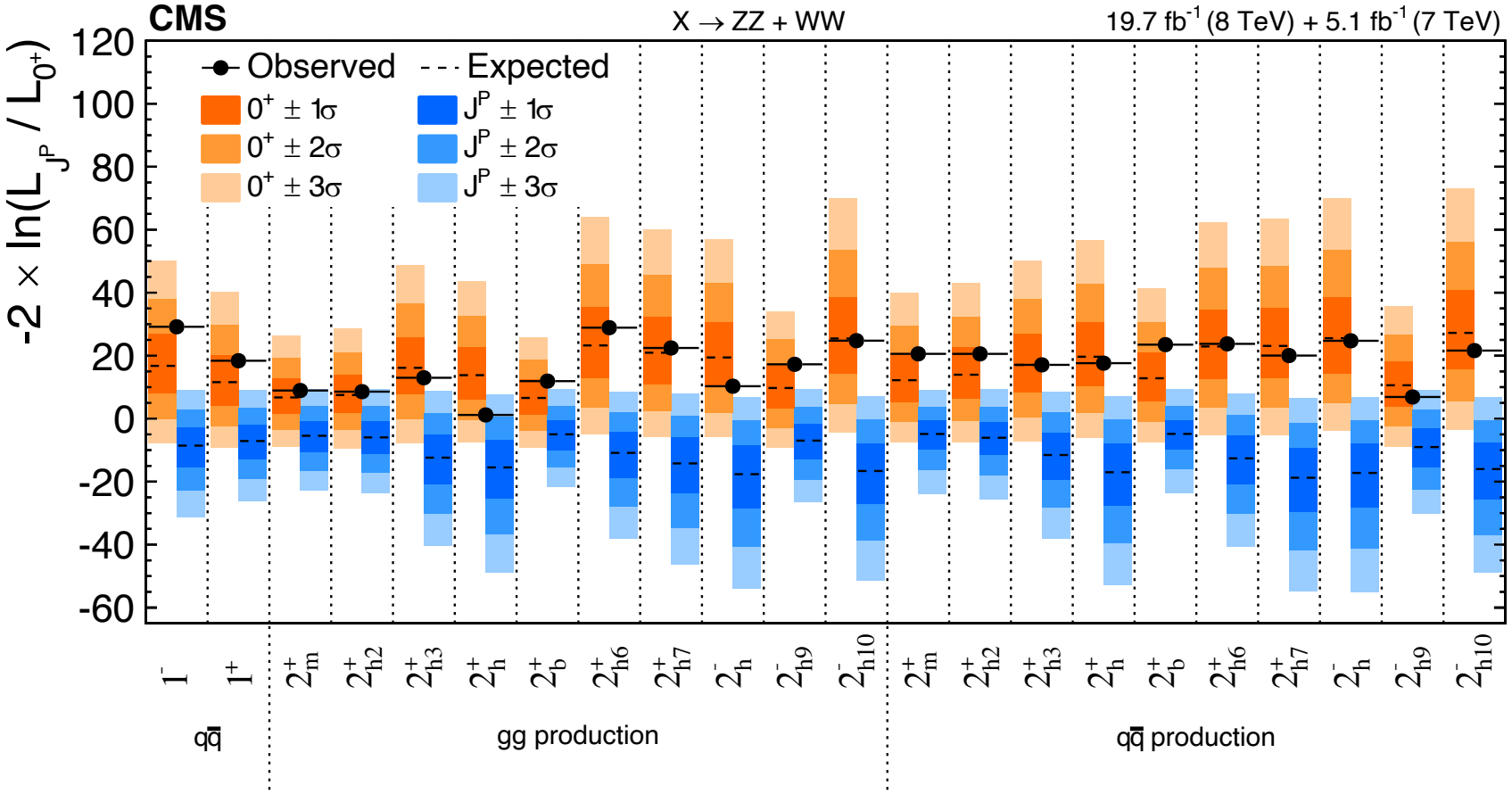
Higgs+background +interference

FC for boundary H→4l



~~No~~ Zero - Spin zone

Hypothesis tests for ***non-nested models*** used to distinguish O^+ from other J^{CP} states.



Run-1 data is already enough to rule out spin-2 (and many other J^P states) at > 99.9% confidence level

H→WW/ZZ Anomalous Couplings

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

Translation into Warsaw Basis

$$\delta a_1^{\mathrm{ZZ}} = \frac{v^2}{\Lambda^2}\left(2c_{\mathrm{H}\Box} + \frac{6e^2}{s_{\mathrm{w}}^2} c_{\mathrm{HWB}} + \left(\frac{3c_{\mathrm{w}}^2}{2s_{\mathrm{w}}^2} - \frac{1}{2}\right) c_{\mathrm{HD}}\right),$$

$$\kappa_1^{\mathrm{ZZ}} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_{\mathrm{w}}^2} c_{\mathrm{HWB}} + \left(1 - \frac{1}{2s_{\mathrm{w}}^2}\right) c_{\mathrm{HD}}\right),$$

$$a_2^{\mathrm{ZZ}} = -2\frac{v^2}{\Lambda^2}\left(s_{\mathrm{w}}^2 c_{\mathrm{HB}} + c_{\mathrm{w}}^2 c_{\mathrm{HW}} + s_{\mathrm{w}} c_{\mathrm{w}} c_{\mathrm{HWB}}\right),$$

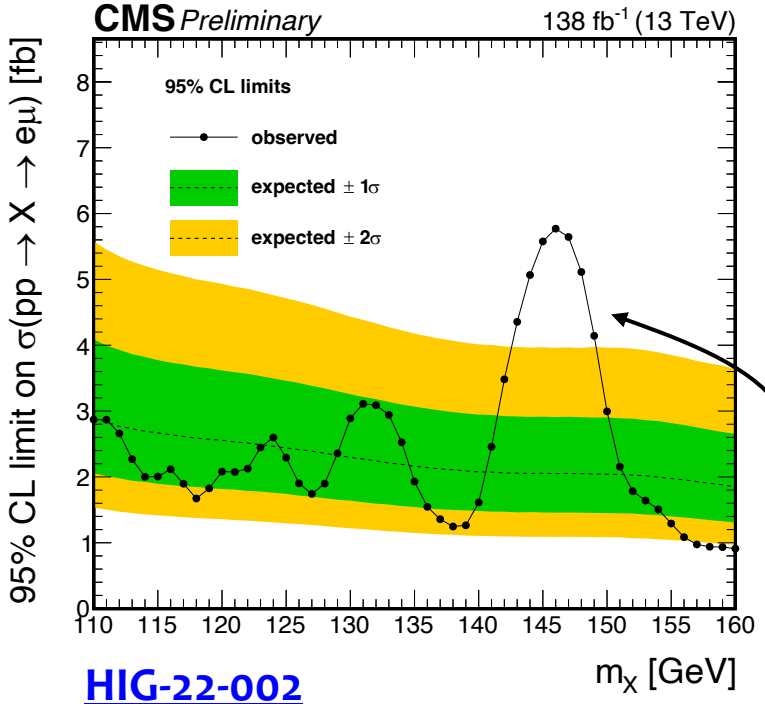
$$a_3^{\mathrm{ZZ}} = -2\frac{v^2}{\Lambda^2}\left(s_{\mathrm{w}}^2 c_{\mathrm{H\tilde{B}}} + c_{\mathrm{w}}^2 c_{\mathrm{H\tilde{W}}} + s_{\mathrm{w}} c_{\mathrm{w}} c_{\mathrm{H\tilde{W}B}}\right),$$

e/μ Flavour anomolies

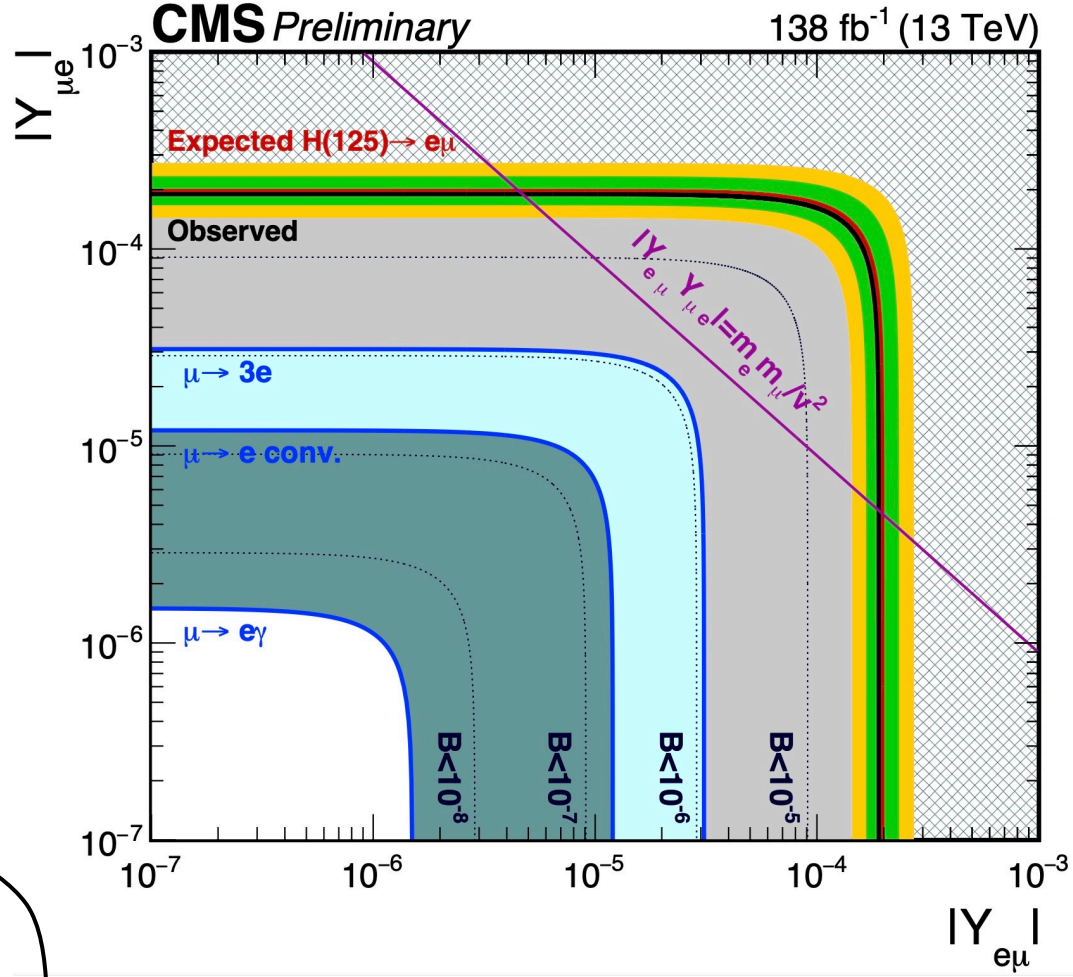
Search for lepton-flavour violating decay of a Higgs boson to an eμ pair

B(H→eμ) < **4.4 × 10⁻⁵**
(4.7 × 10⁻⁵) at 95% CL

[c.f ATLAS :6.2 × 10⁻⁵ (5.9 × 10⁻⁵)]



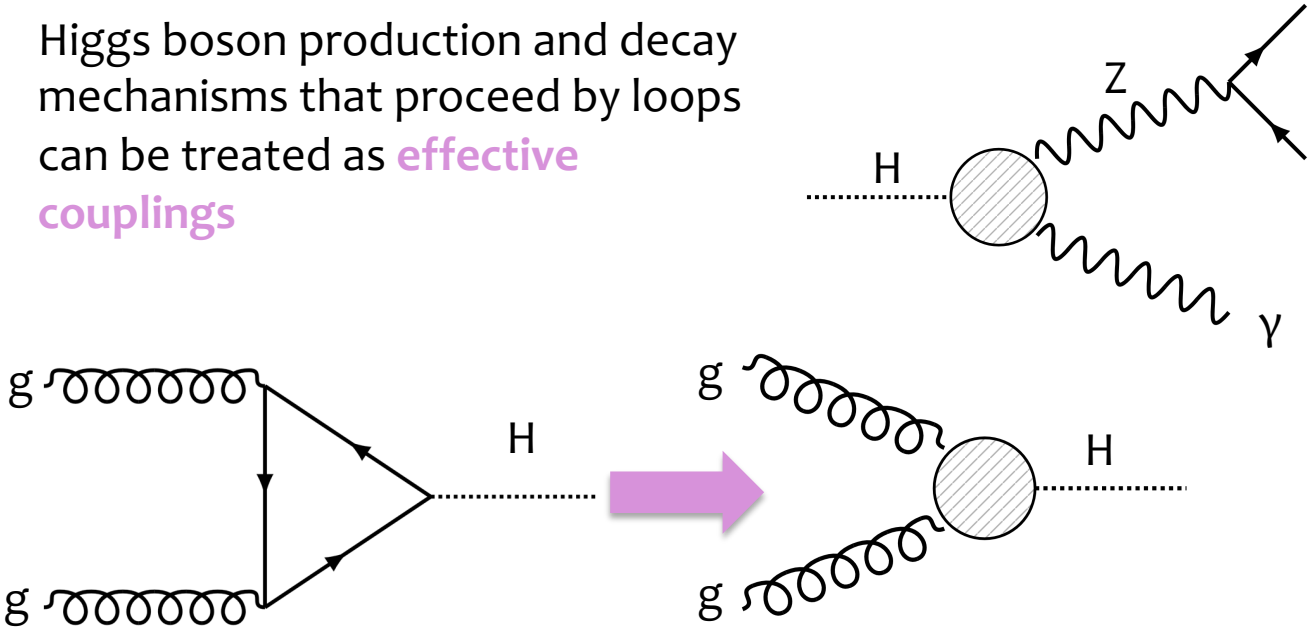
HIG-22-002



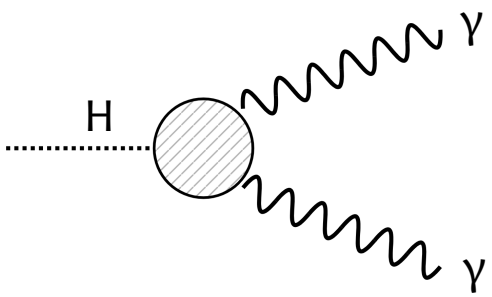
Local (Global) significance of 3.8σ (2.8σ) near 146 GeV

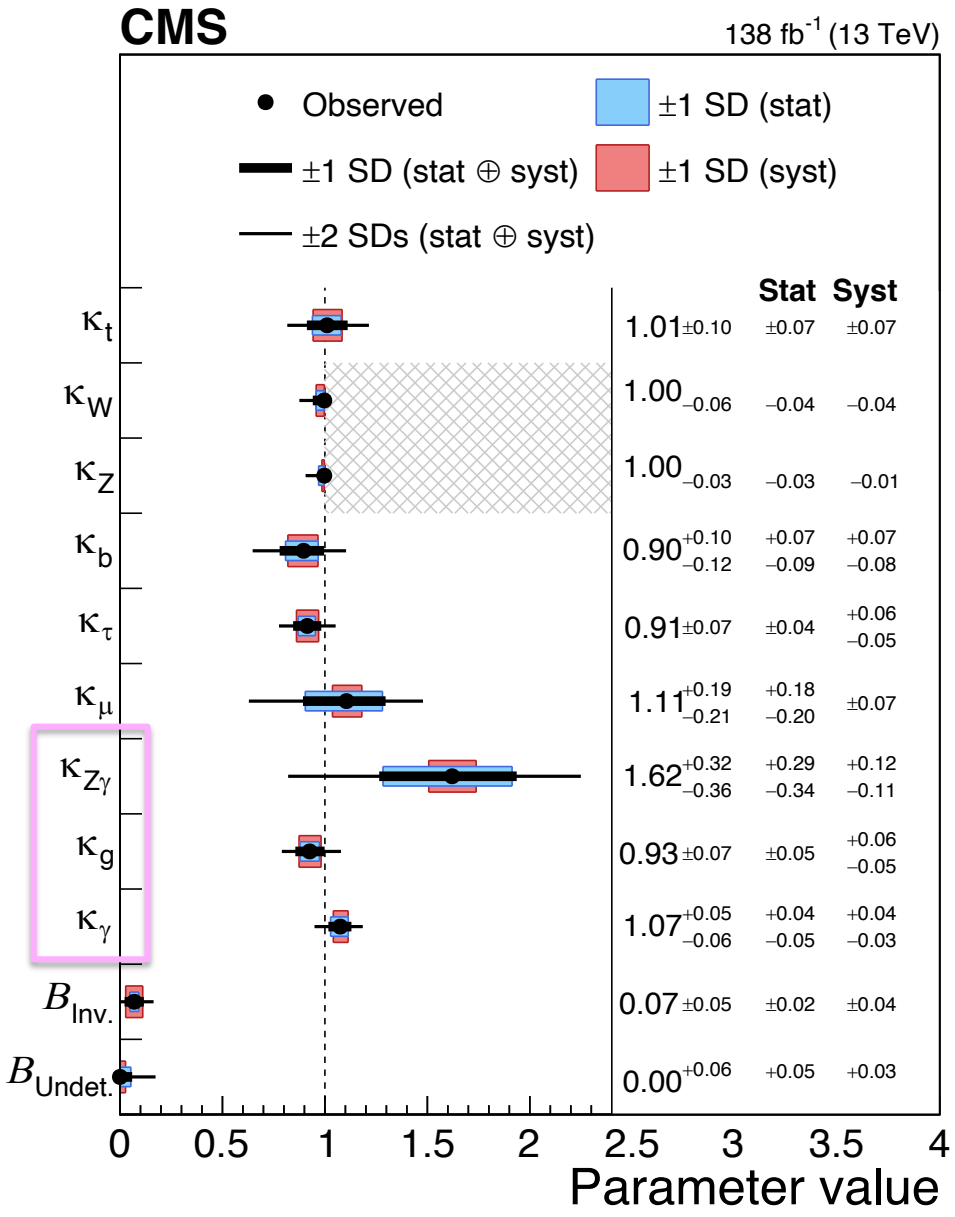
Effective couplings

Higgs boson production and decay mechanisms that proceed by loops can be treated as **effective couplings**

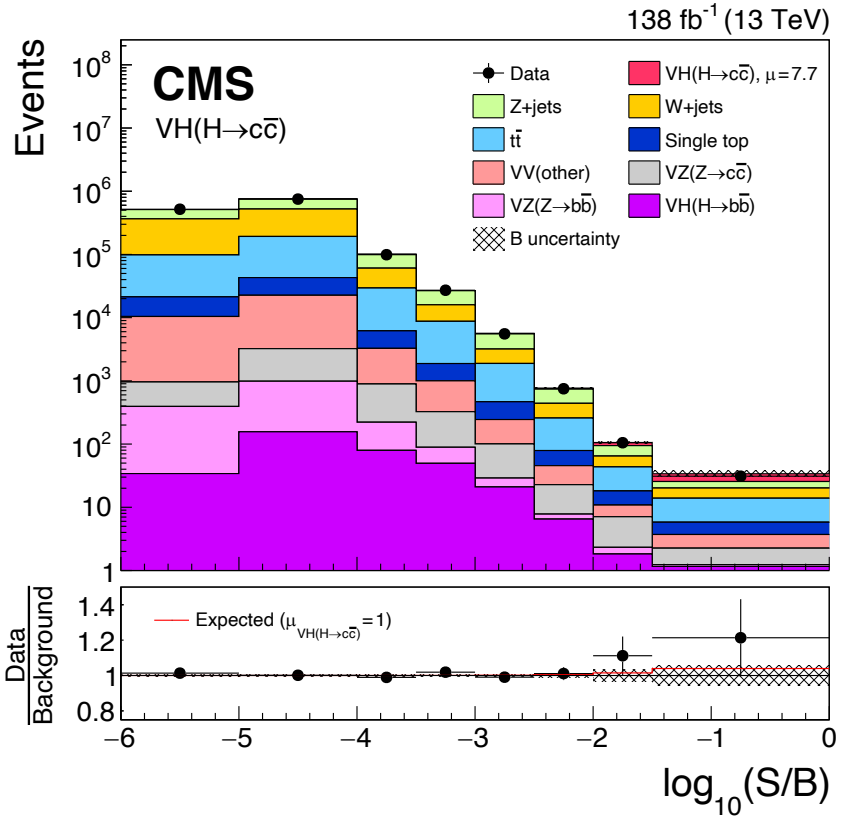


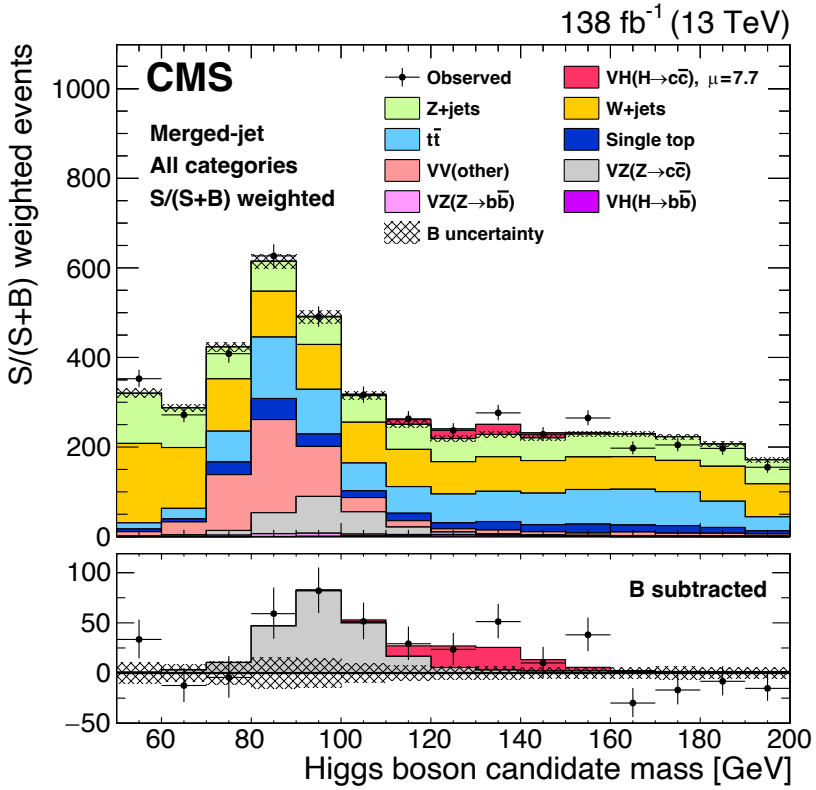
New heavy particles can appear in these loops leading to large deviation in the effective coupling:
H-Zγ, H-g, H-γ

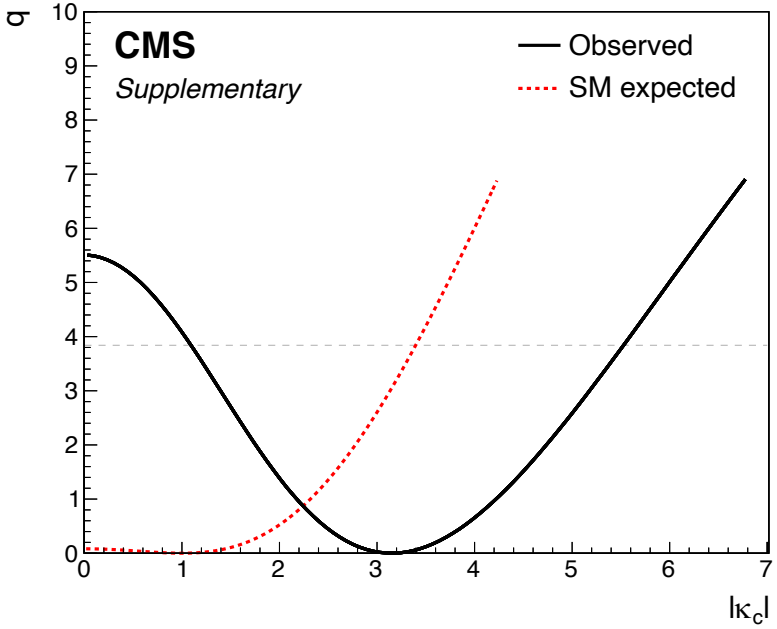




Charm coupling

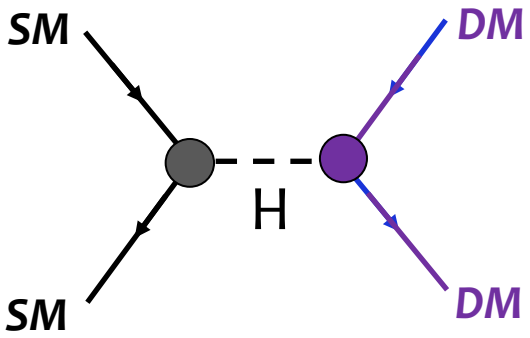


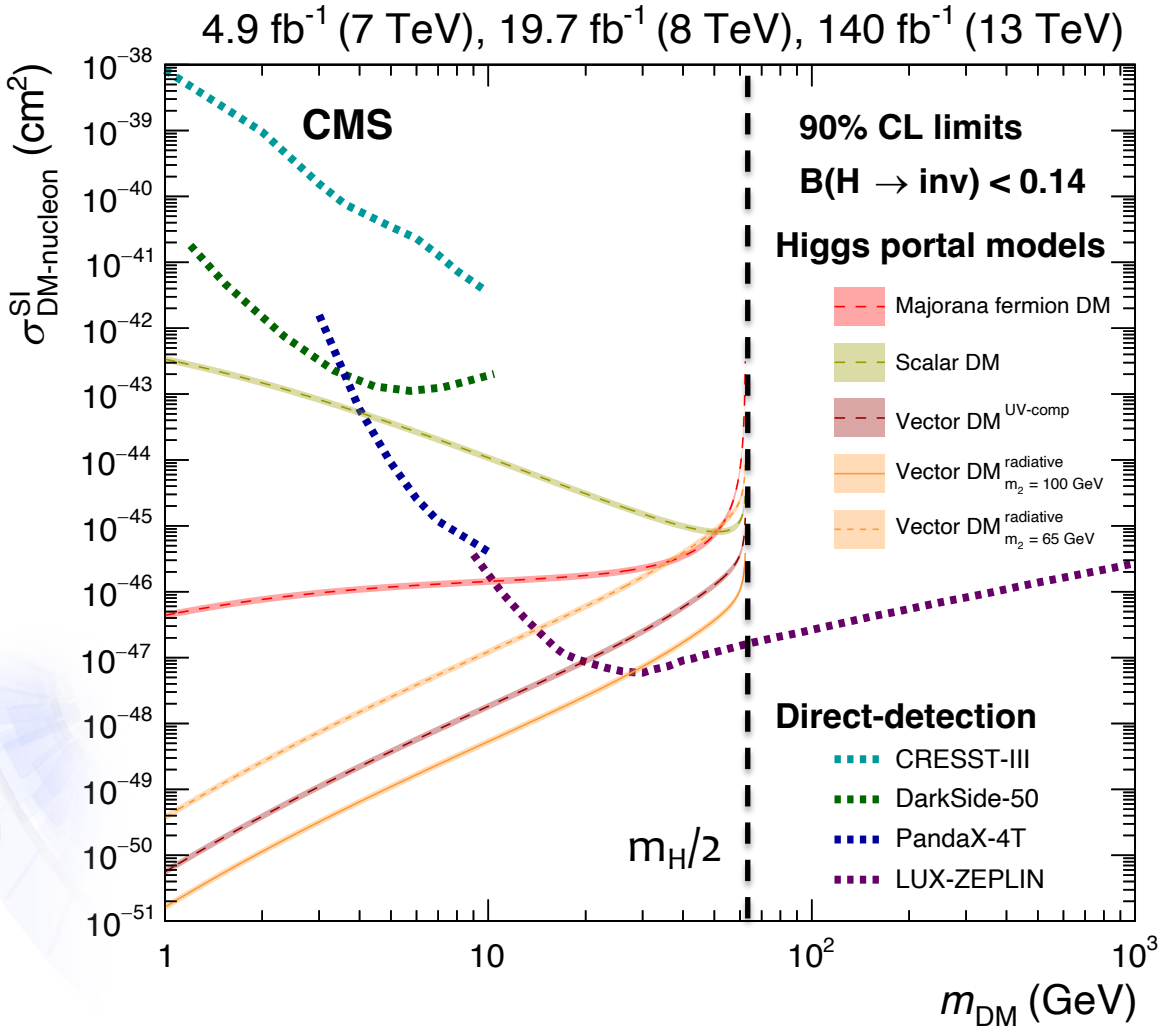


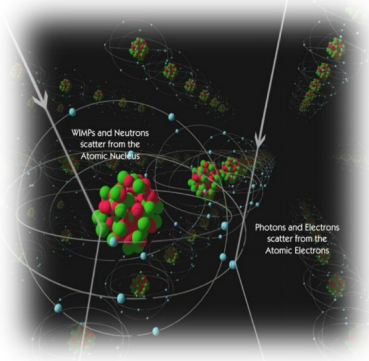


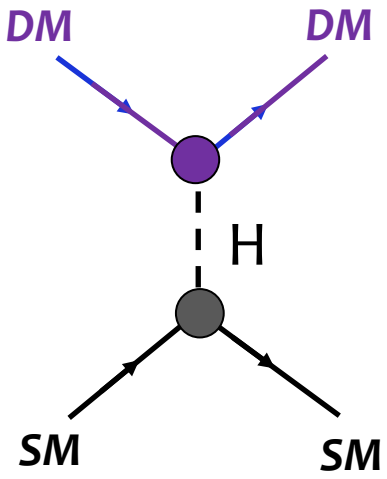
Combination

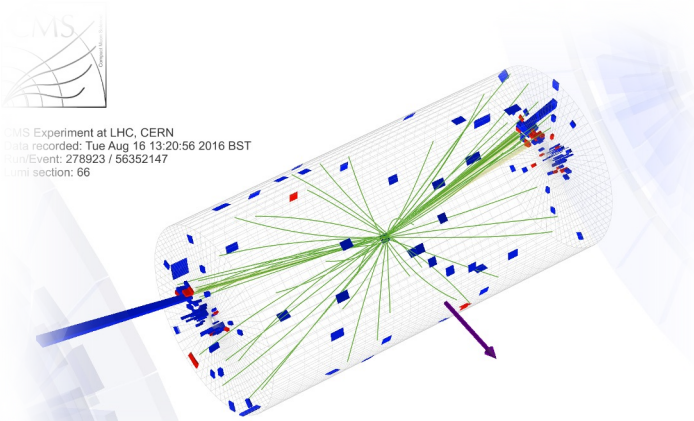
Dark matter interpretation



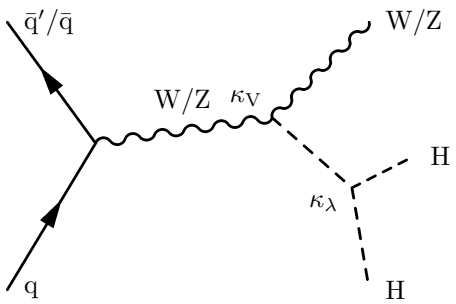








VHH Search



[CMS-HIG-22-006]

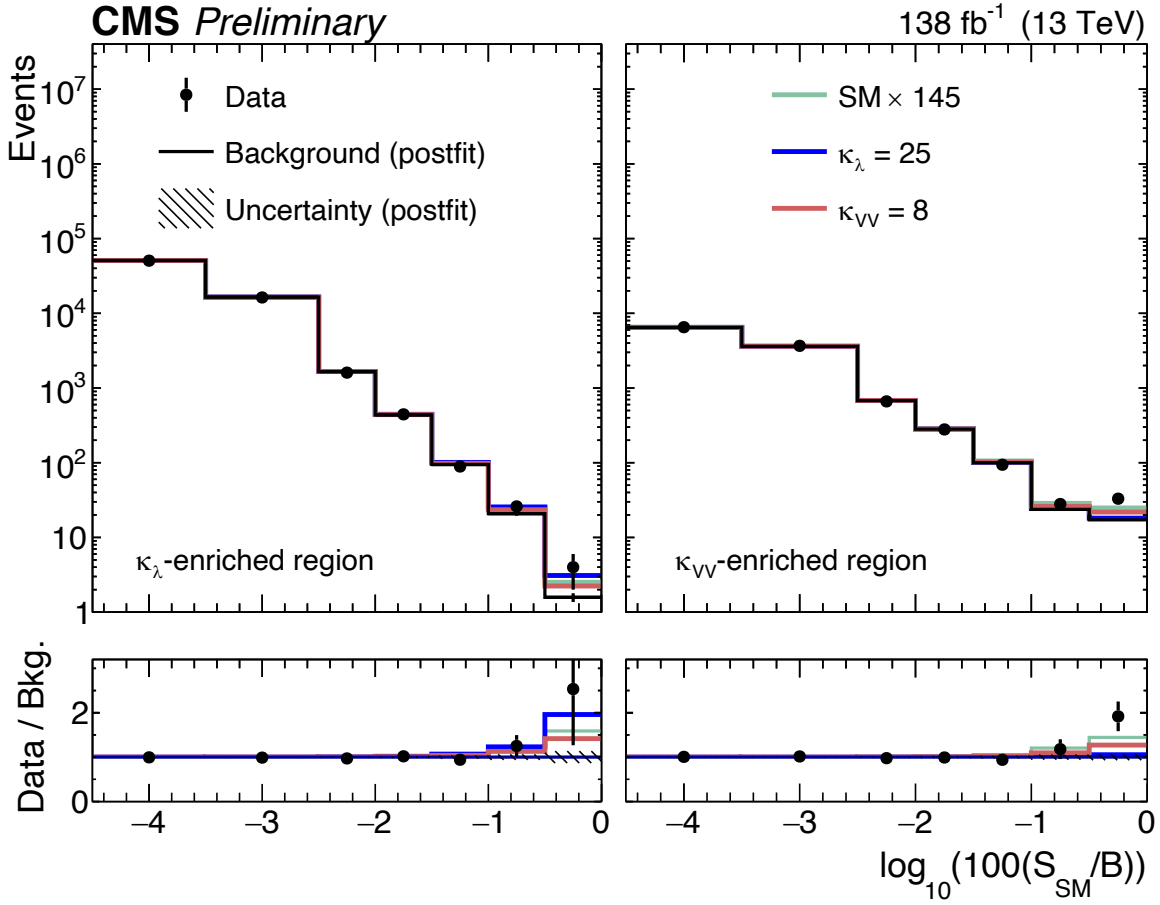
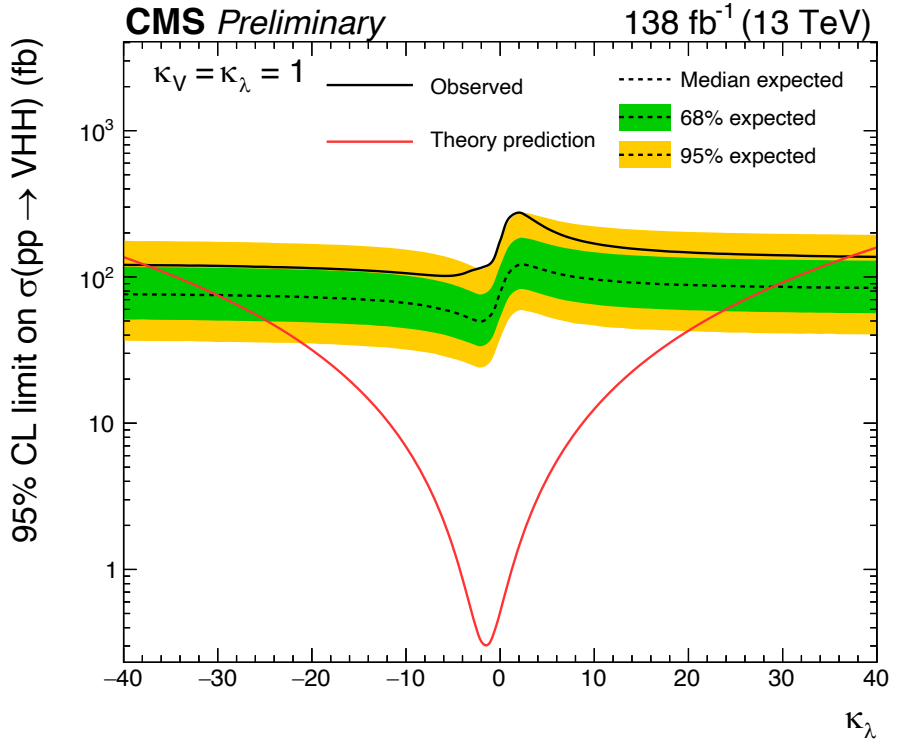


Table 4: A summary of categorization in all channels.

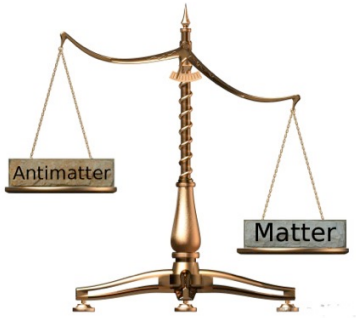
	MET small-radius	MET large-radius	1L small-radius	1L large-radius	2L	FH
Coupling enrichment	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	$\kappa_\lambda, \kappa_{VV}$
N_b	$N_b \geq 3$	—	$N_b \geq 3$	—	$N_b = 3$ $N_b = 4$	$N_b = 4$
$D_{b\bar{b},1} \times D_{b\bar{b},2}$	—	HP, LP	—	HP, LP	—	—
SR, CR	SR+CR	SR+CR	SR+CR	SR+CR	SR, CR	SR
SB	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$N_b = 3$ $N_b = 4$	—
$t\bar{t}$ CR	—	—	—	—	One	—
Year split	Per year	Per year	Per year	Per year	Combined	Per year
Total regions	9	12	9	12	11	6



Why do we care?

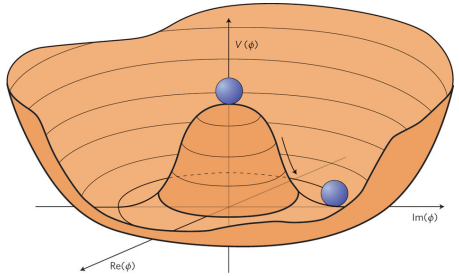
The universe today is **matter** (baryon)-**dominated,**

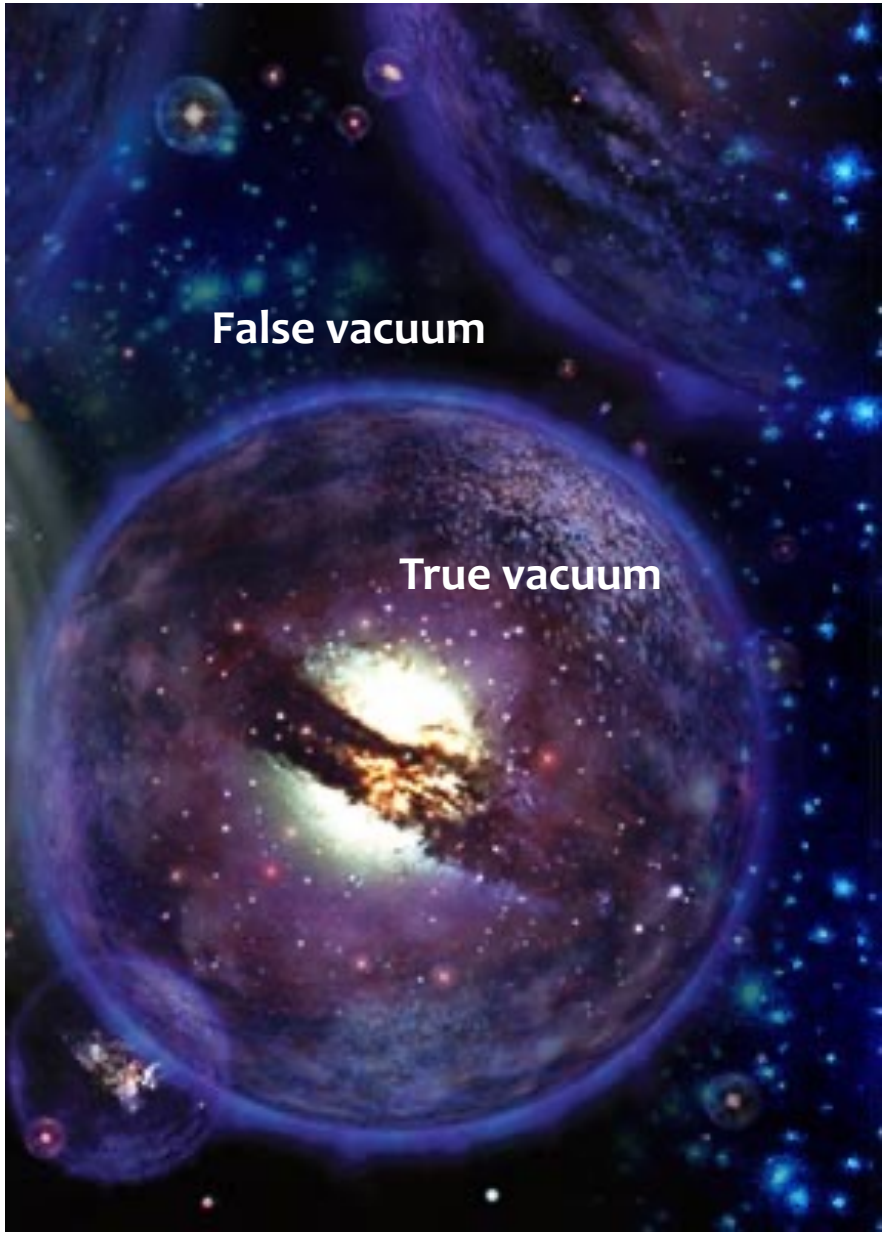
$$n_B >> n_{\bar{B}}$$



Essential ingredient for **Baryogenesis** (production of B-asymmetry) :

→ **First order phase transition** [1]



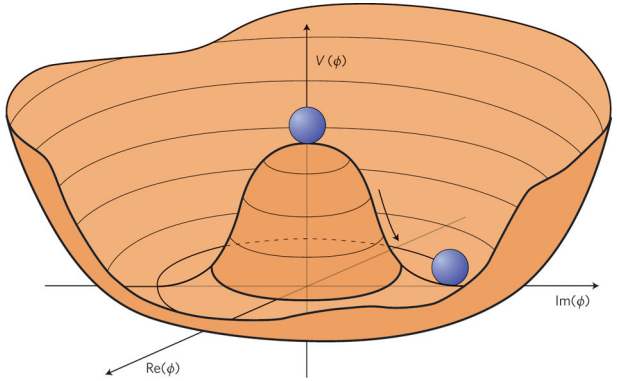


[1] A. D. Sakharov, JETP Lett. 5, 24 (1967)

Modified Higgs potential and Baryogenesis

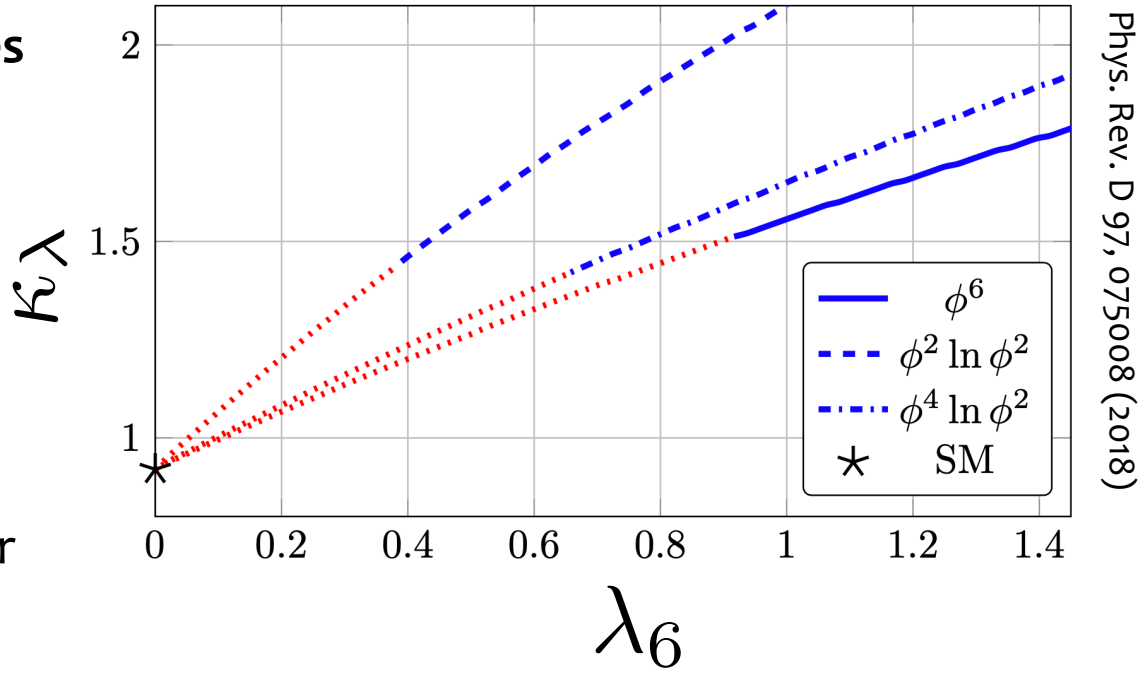
BSM physics in **Higgs potential** could be the solution!

$$V(H) = \underbrace{\frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4}_{\text{SM}} + \underbrace{\frac{\lambda_6}{\Lambda}(v+H)^6}_{\text{BSM}}$$



Inclusion of **Dimension-6 (BSM)** term in potential **changes the relationships between** the fundamental Higgs **parameters**

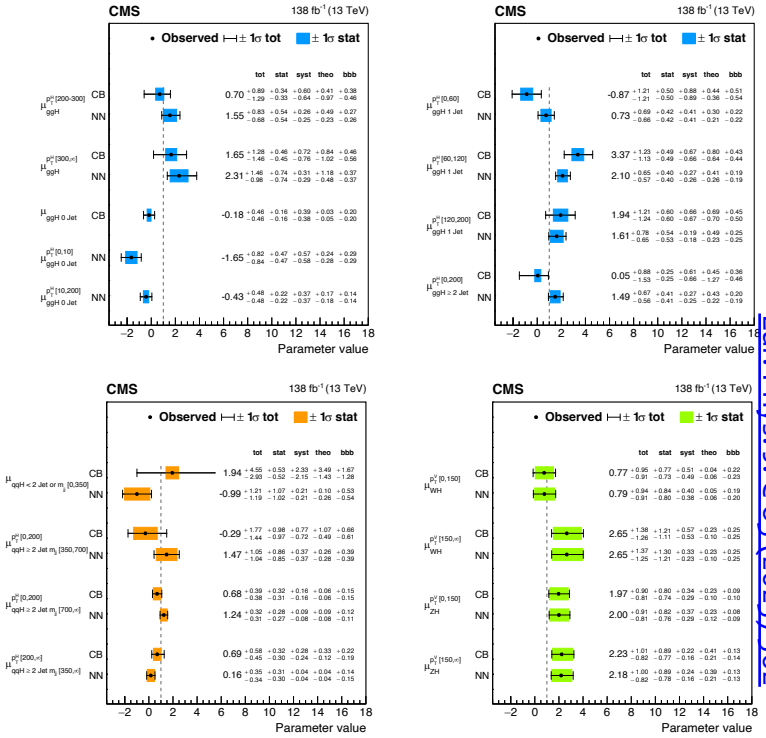
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} = 1 + \frac{16\lambda_6 v^4}{m_H^2 \Lambda^2}$$



50% increase in self-coupling could hint at mechanism for 1st order EWK phase-transition accuracy crucial goal

STXS measurements

H→ττ



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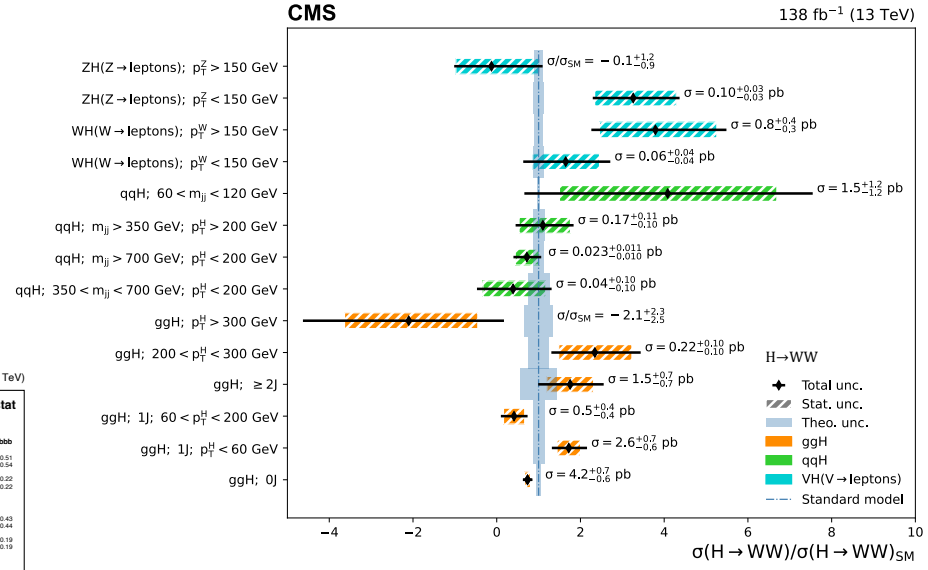
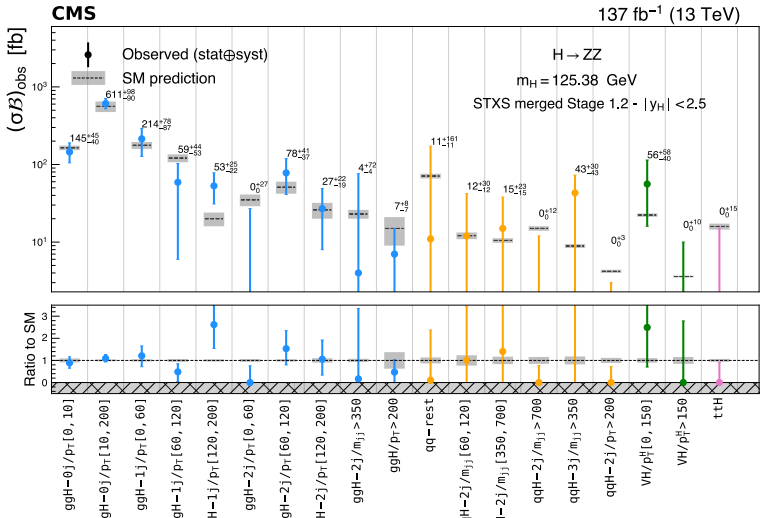
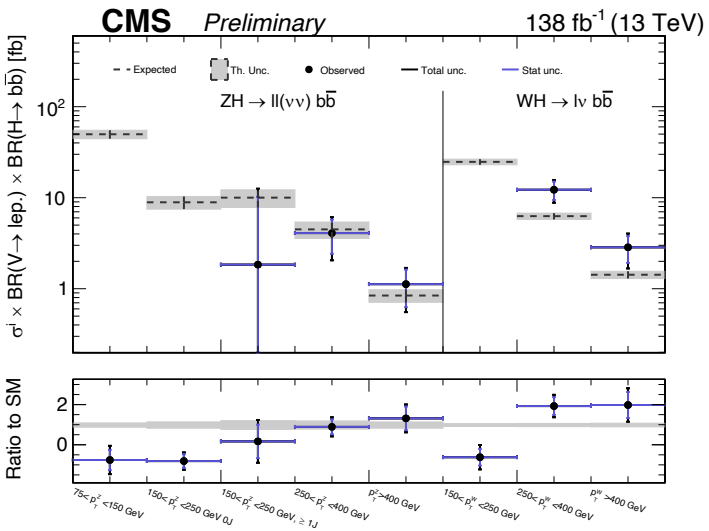
H→WW (CMS-HIG-20-013)



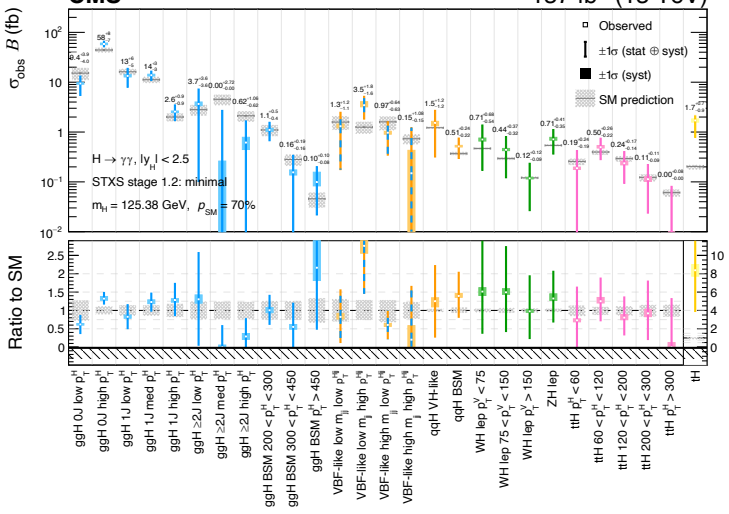
H→ZZ (CMS-HIG-19-001)



CMS-HIG-20-001 VH(→bb)

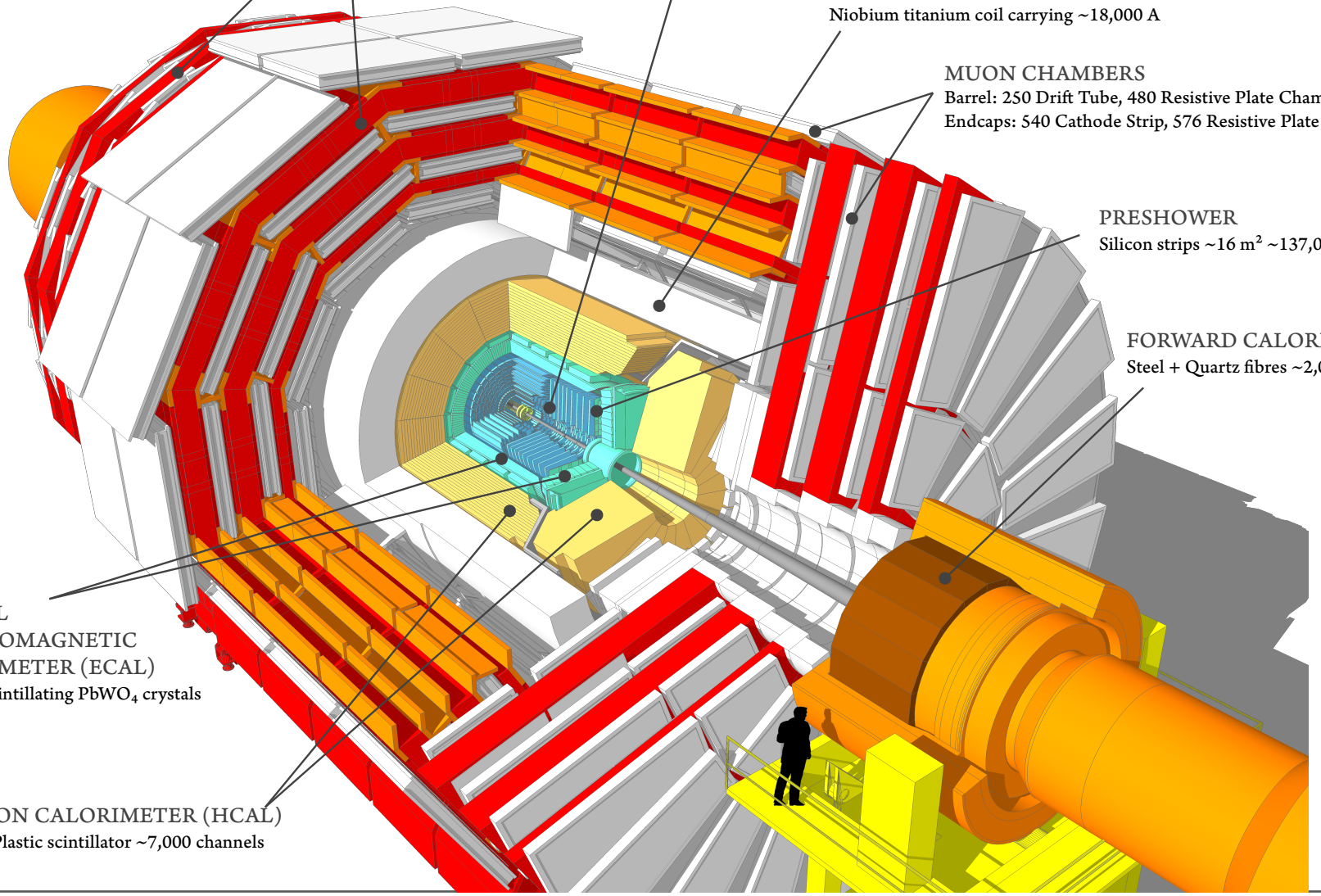


CMS-HIG-19-015 H→γγ



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm²) ~1 m² ~66M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

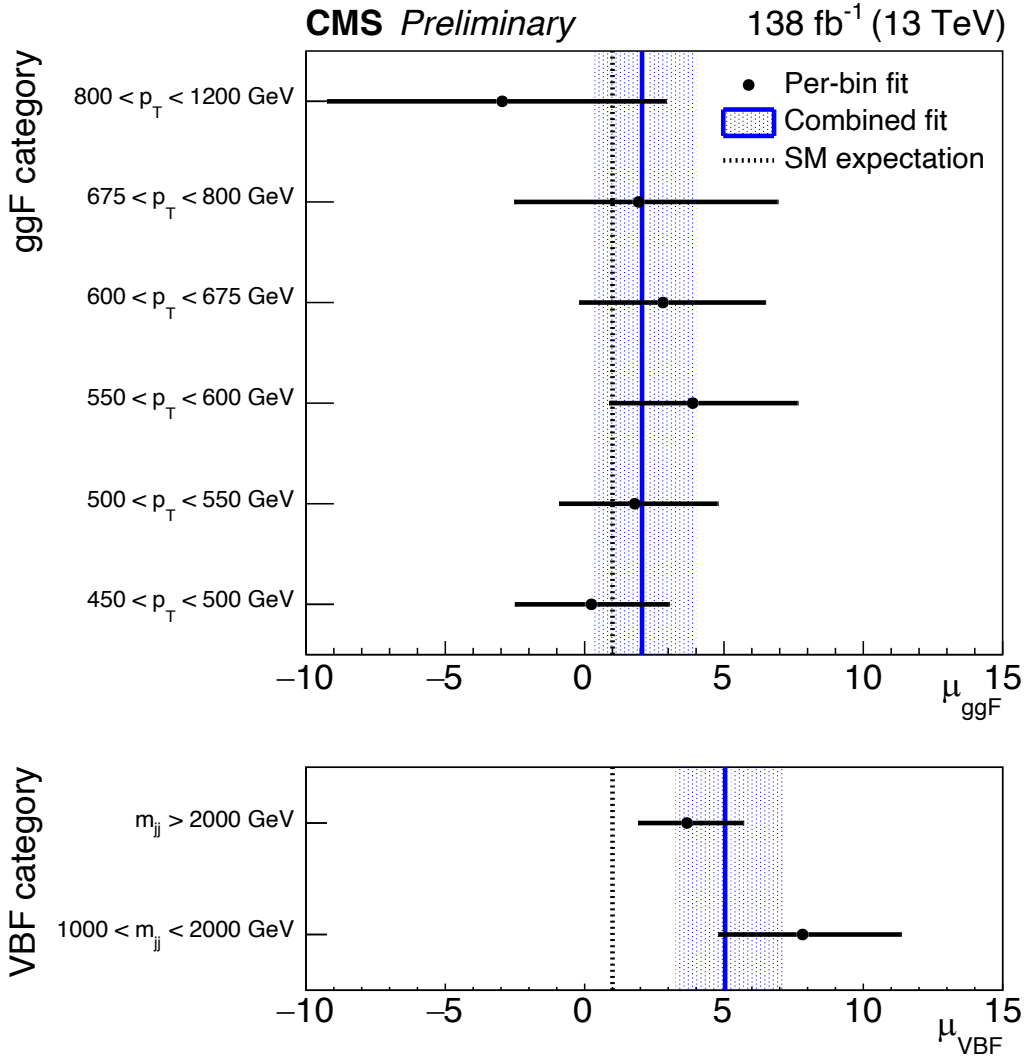
PRESHOWER
Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

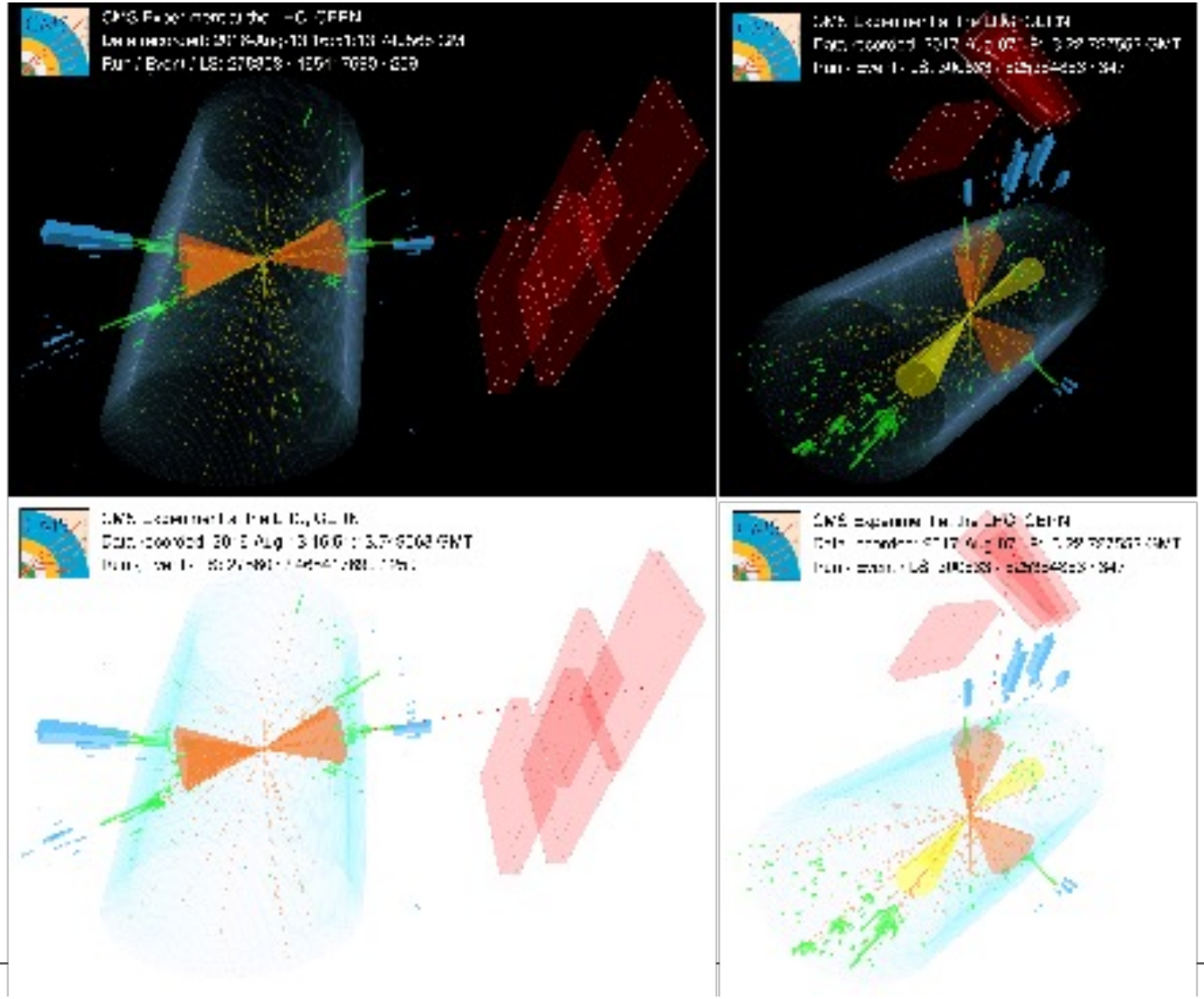
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

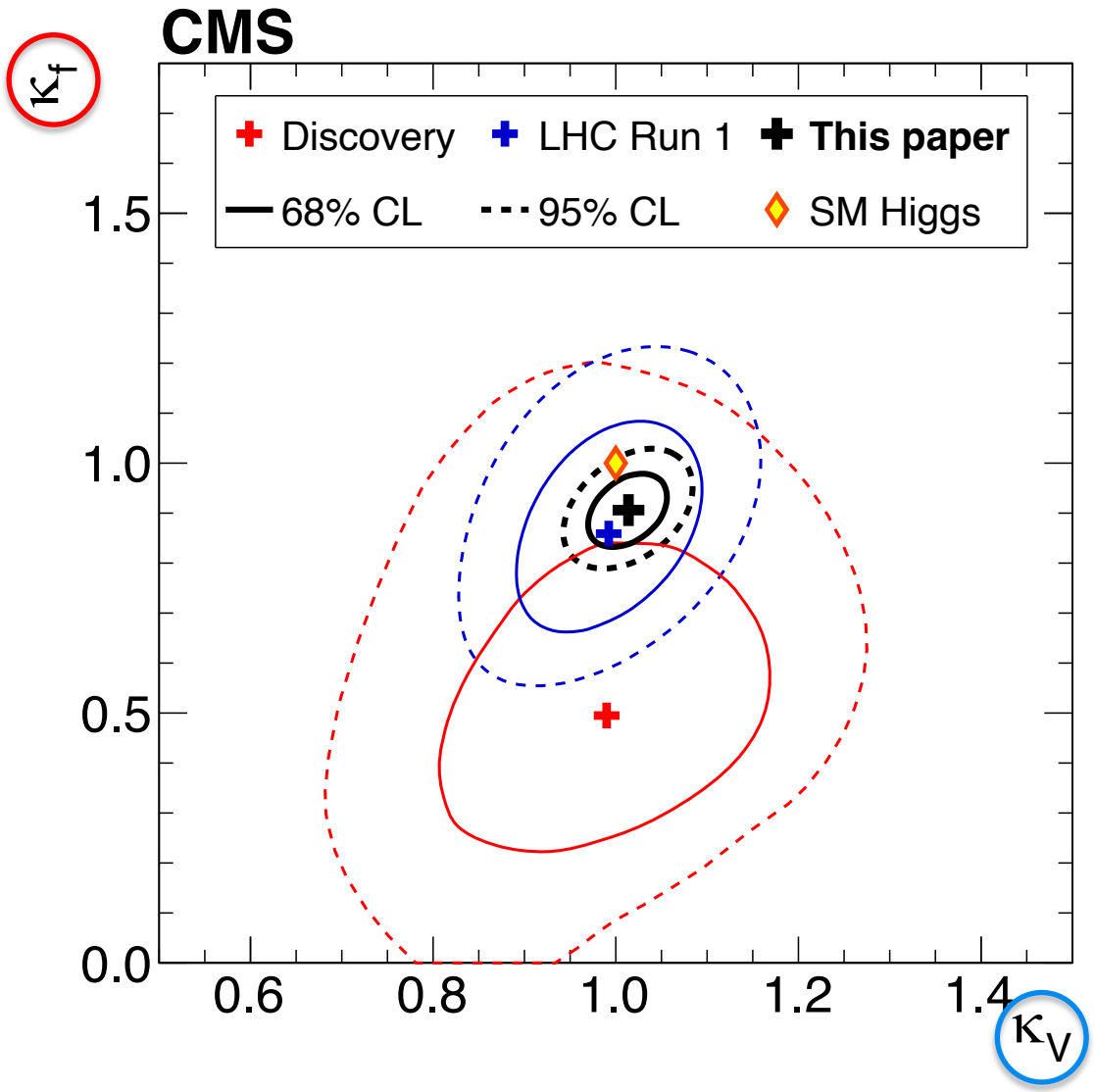
Boosted VBF H→bb Results



Boosted HH→4b events

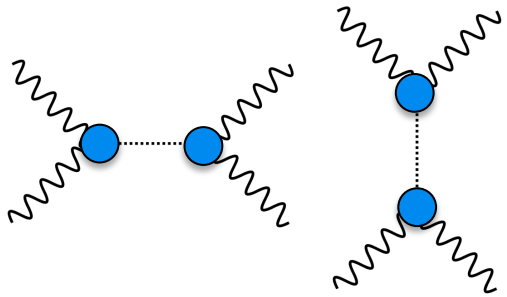


Higgs couplings for BSM physics

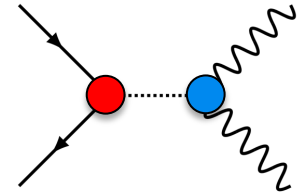


In the **SM, the Higgs regulates longitudinal WW** scattering at high energies

$$W_L^+W_L^- \to W_L^+W_L^- \sim \frac{g^2}{4m_W^2}(s+t)\left(1-\kappa_V^2\right)$$



$$\psi\bar{\psi} \to W_L^+W_L^- \sim \frac{m_\psi\sqrt{s}}{v^2}\left(1-\kappa_F\kappa_V\right)$$

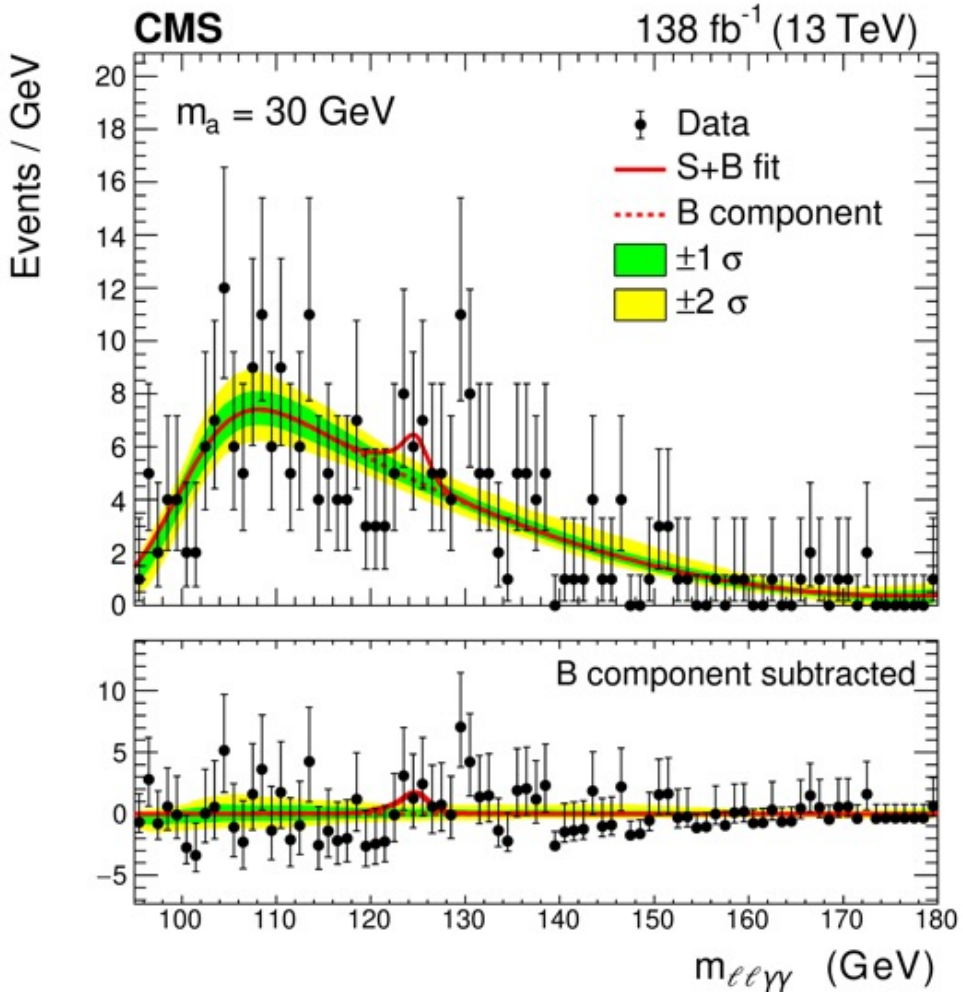


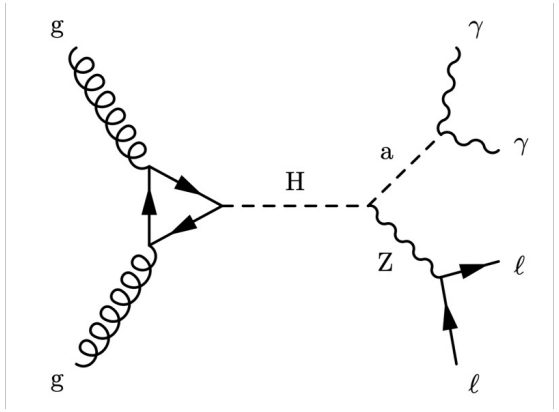
If couplings to vector bosons and fermions are SM-like Scattering amplitudes don't diverge

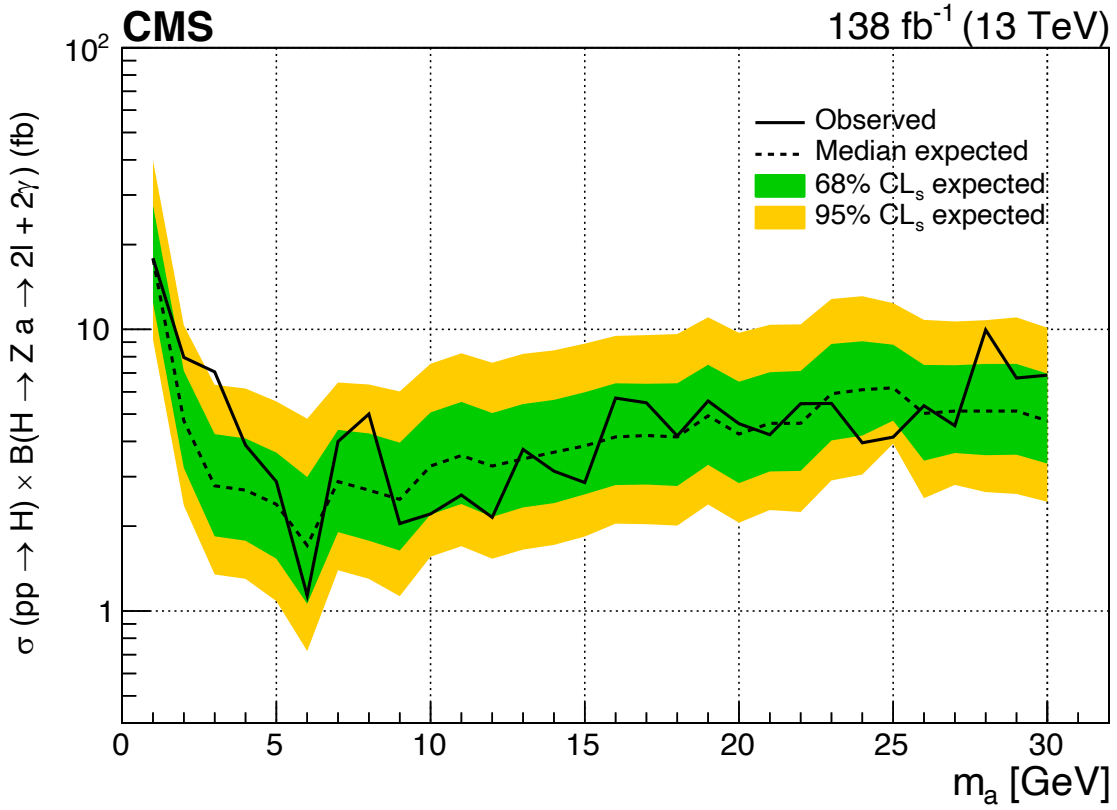
→ Measuring these couplings is a **strict test of SM at higher energies**

H→Za

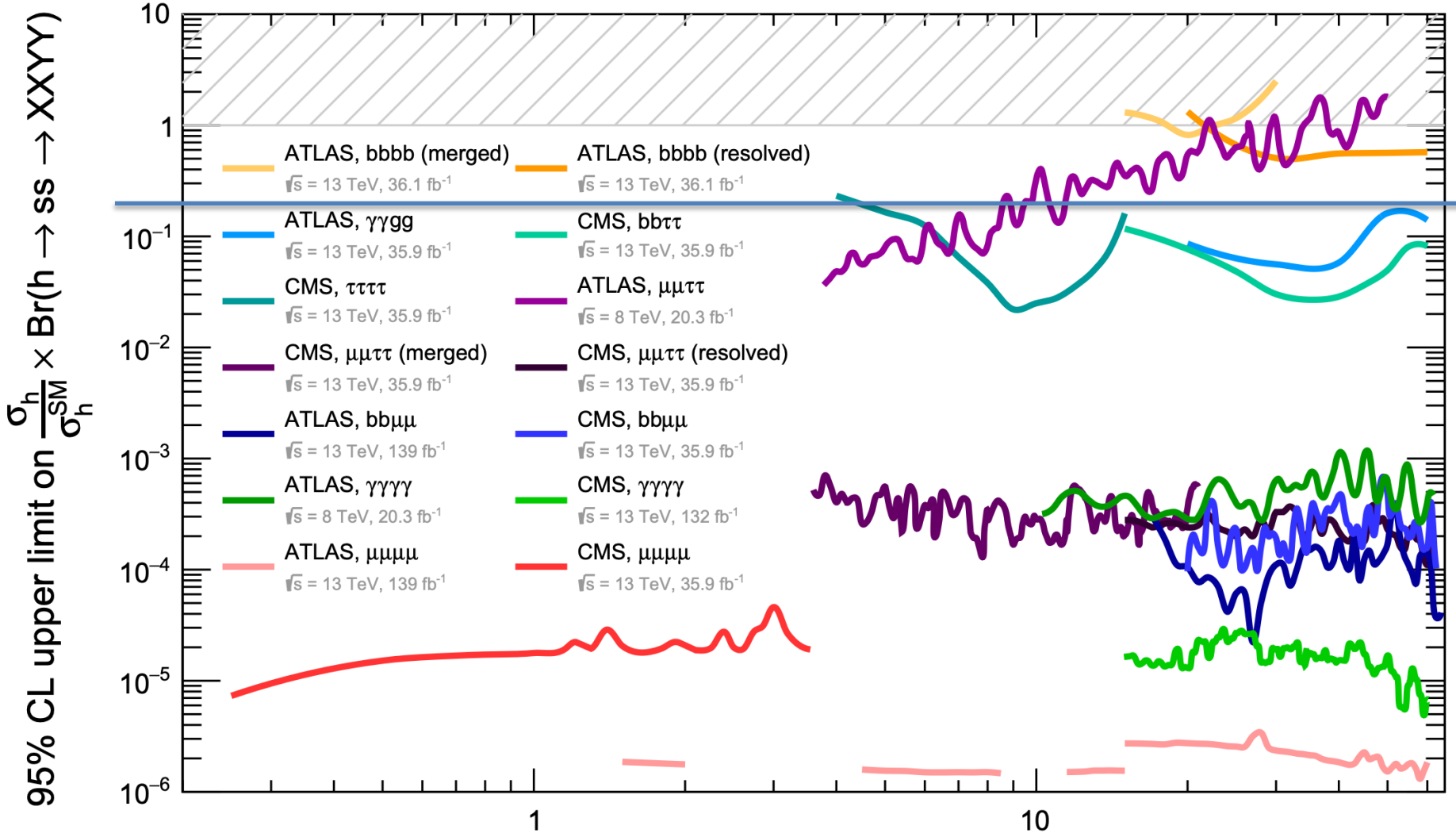
CMS-HIG-22-003







H→aa BSM searches



Excluded by H-couplings

M. Cepeda et al (https://arxiv.org/abs/2111.12751)

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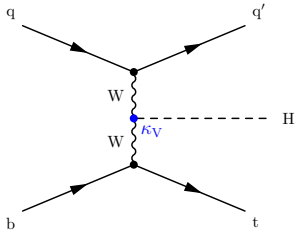
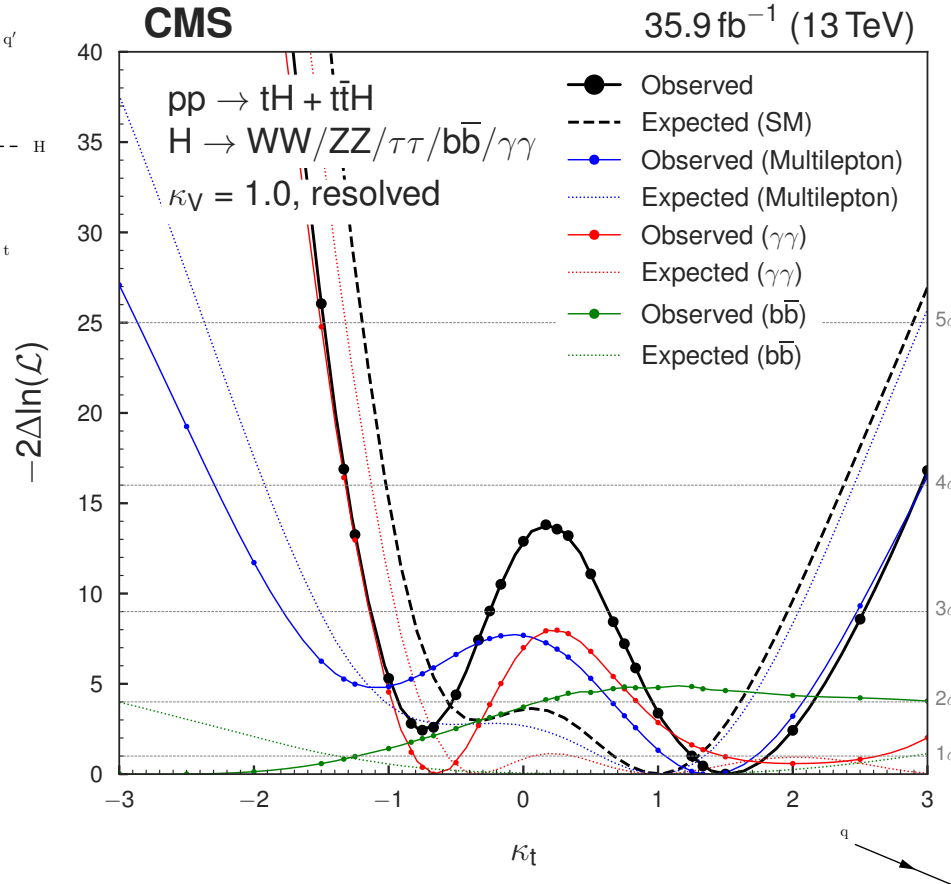
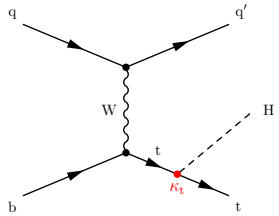
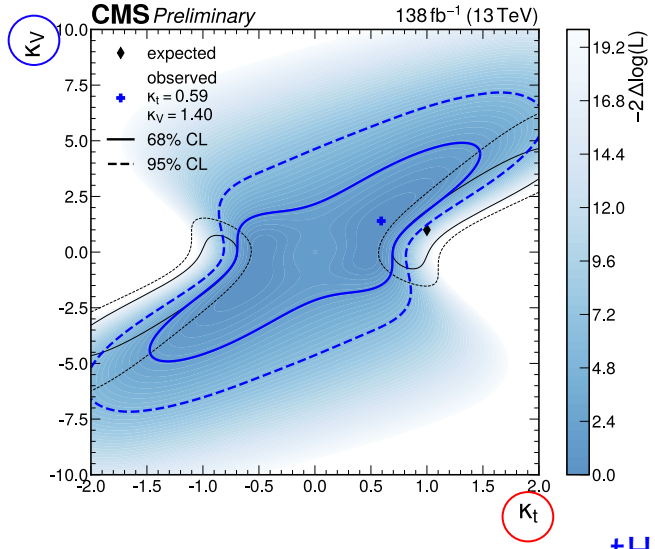




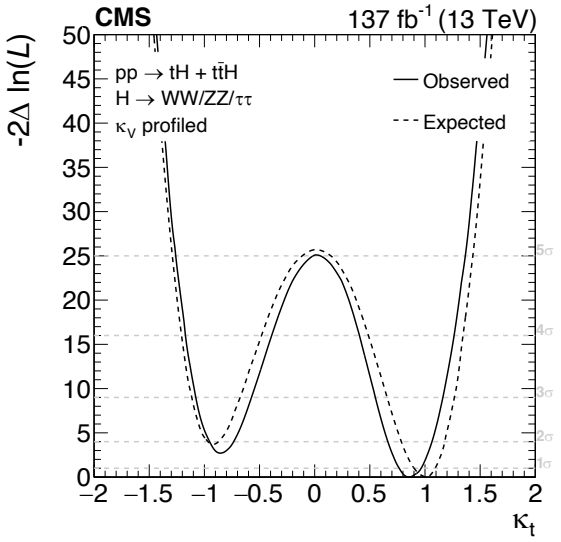


Close to exclusion for odd-sign k_V/k_F couplings with partial Run-2 data

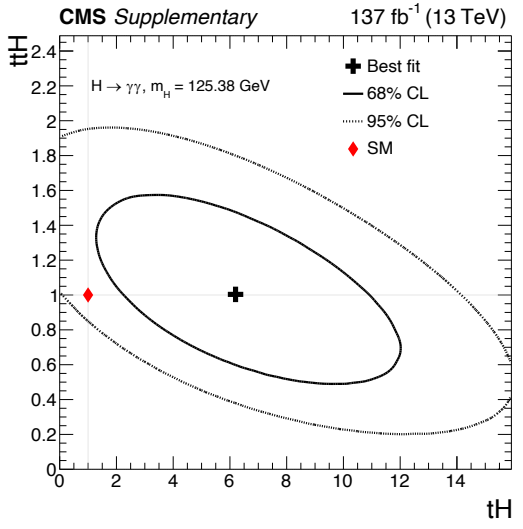
tH/ttH->bb



tH/ttH->multileptons



tH/ttH->γγ



Full Run-2 constraints underway!

CMS Higgs Comb (Nature 2022)

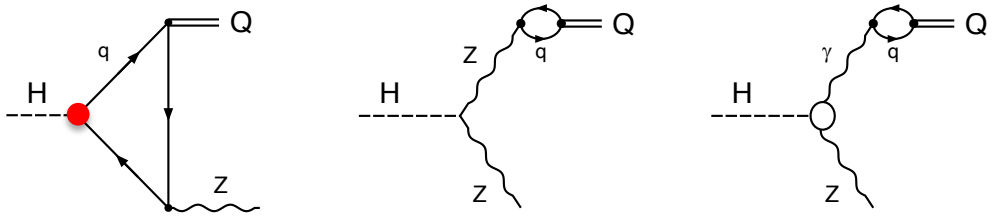
Refs available @

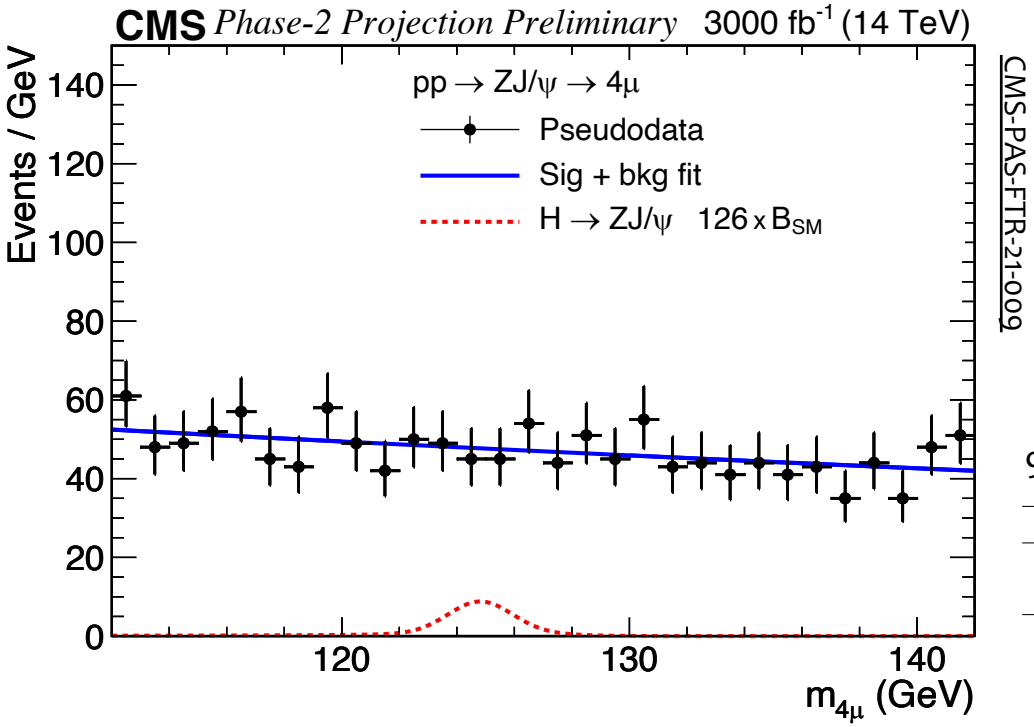
https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-22-001/index.html

Analysis	Decay tags	Production tags
Single Higgs boson production		
$H \to \gamma\gamma$ [42]	$\gamma\gamma$	ggH, $p_T(H) \times N_j$ bins VBF/VH hadronic, $p_T(Hjj)$ bins WH leptonic, $p_T(V)$ bins ZH leptonic ttH $p_T(H)$ bins, tH
$H \to ZZ \to 4\ell$ [43]	4μ, 2e2μ, 4e	ggH, $p_T(H) \times N_j$ bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH
$H \to WW \to \ell\nu\ell\nu$ [44]	eμ/ee/$\mu\mu$ $\mu\mu$+jj/ee+jj/eμ+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF VH hadronic WH leptonic ZH leptonic
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	eμ, eτ_h, $\mu\tau_h$, $\tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF VH, high-$p_T(V)$
$H \to bb$ [47–51]	W($\ell\nu$)H(bb) Z($\nu\nu$)H(bb), Z($\ell\ell$)H(bb) bb	WH leptonic ZH leptonic ttH, $\to 0, 1, 2\ell +$ jets ggH, high-$p_T(H)$ bins
$H \to \mu\mu$ [52]	$\mu\mu$	ggH VBF
ttH production with H $\to$ leptons [53]	2ℓ SS, 3ℓ, 4ℓ, $1\ell + \tau_h$, 2ℓ SS+$1\tau_h$, $3\ell + 1\tau_h$	ttH
$H \to$ Inv. [71, 72]	p_T^{miss}	ggH VBF VH hadronic ZH leptonic
Higgs boson pair production		
$HH \to bbbb$ [57, 58]	H(bb)H(bb)	ggHH, VBFHH (resolved, boosted)
$HH \to bb\tau\tau$ [59]	H(bb)H($\tau\tau$)	ggHH, VBFHH
$HH \to$ leptons [60]	H(WW)H(WW), H(WW)H($\tau\tau$), H($\tau\tau$)H($\tau\tau$)	ggHH, VBFHH
$HH \to bb\gamma\gamma$ [61]	H(bb)H($\gamma\gamma$)	ggHH, VBFHH
$HH \to bbZZ$ [62]	H(bb)H(ZZ)	ggHH

Rare decays @ HL-LHC

Beyond SM physics can lead to large modifications of 1st generation quark Yukawas → possible enhancement in H→ZQ/QQ compared to SM





Projection of Run-2 search for H→Z J/ψ → 4μ and H→ YY → 4μ

Analysis still very statistics limited at HL-LHC → 3 events in H→YY Higgs peak would constitute discovery!

95% CL Upper limit on B(H→X) at (extended) HL-LHC

Channel	3000 fb^{-1}	(×SM)	4500 fb^{-1}	(×SM)
$H \to ZJ/\psi$	2.9×10^{-4}	(126)	2.7×10^{-4}	(117)
$H \to \Upsilon(mS)\Upsilon(nS)$	1.3×10^{-5}	(0.2)	8.5×10^{-6}	(0.14)