Higgs Pair Production

An experimental overview

QFT research seminar
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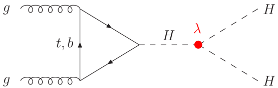
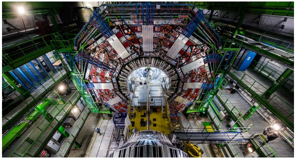
- Finishing PhD with **Northeastern University**. Based at **CERN** since 2018 with **CMS collaboration**



- Performing a **Higgs Pair Production** analysis with the CMS Run 2 dataset
- Detector work: CMS **Electromagnetic Calorimeter** (ECAL):
  - Run coordinator
  - Trigger team member



Outline

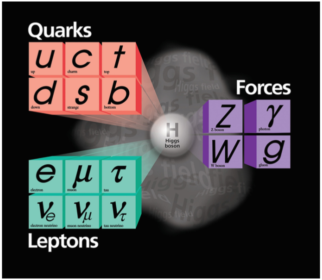
1. Motivation
2. Experimental results
   - Experimental setup
   - SM and EFT
   - Resonant searches
3. HL-LHC Projections
4. Conclusions and outlook

Next Section

Motivation: Higgs discovery

- 2012: The Higgs boson is experimentally discovered by the CMS and ATLAS collaborations [PLB 716 (2012) 30], [PLB 716 (2012) 1-29]:

(a) CERN: July 2012, discovery announcement



(b) SM particles

- Final missing particle of the Standard Model (SM) **experimentally discovered**
- "Golden" channels for discovery: H$\rightarrow\gamma\gamma$, H$\rightarrow$ZZ$\rightarrow 4\ell$

Motivation: Decay modes

- Advantage of the Higgs: Has many **decay modes**, handles for analysis
- Major factors in experimental analysis **sensitivity**:
  - Process branching ratio
  - Object reconstruction efficiency
  - Differentiation from backgrounds
- Different BSM searches with non 125 GeV Higgs may be more sensitive to certain final states

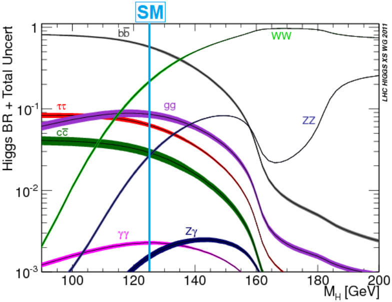


Figure 1: Higgs branching ratios vs. mass [ref.]

Motivation: Paths forward

- Following the discovery of a new particle, what are we interested in doing?
- Want to measure properties including **mass** and **couplings** to SM particles - fundamental to **SM**
- Can search for **BSM physics**, using Higgs as a bridge

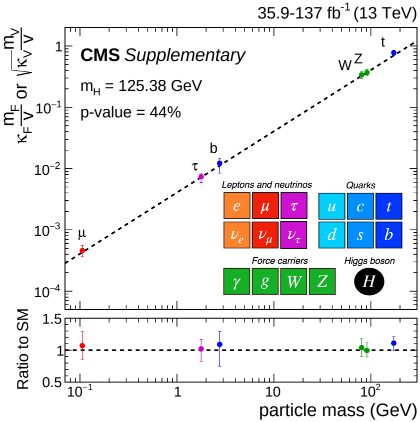


Figure 2: Higgs couplings to SM particles: [CMS-HIG-19-006]

Motivation: Self-coupling

- Higgs potential after electroweak symmetry breaking:

$$V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

$$\lambda = 0.13, v = 246 \text{ GeV}$$

- Self-coupling λ predicted by SM. Want to compare to experiment to see what **nature has to say!**

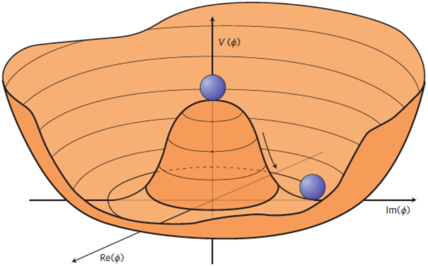
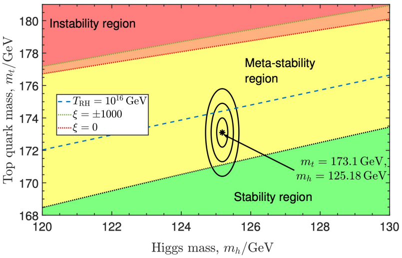


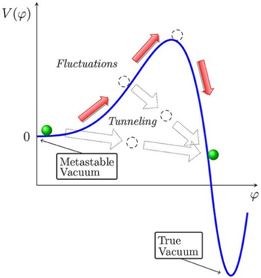
Figure 3: Higgs potential

Motivation: Higgs potential stability

- The higgs potential shape determines the higgs **vacuum expectation value**, and **type** of stability:



(a) Stability vs. top, Higgs masses

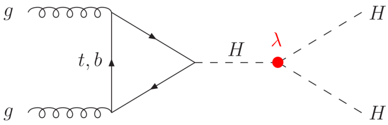


(b) Meta-stable potential [ref.]

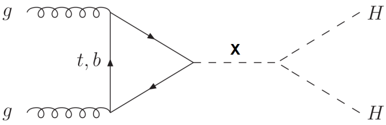
- Current Higgs and top quark mass measurements predict **meta-stable** minimum.
- Measurement of the higgs self-coupling would be a **direct measurement** of higgs potential, could verify or refute this

Motivation: Interpretations

- Higgs self-coupling constant directly accessed through **Higgs pair production**
- BSM scenarios, such as those predicting a heavy resonance coupling to Higgs can be searched for via Higgs pair production



(a) di-Higgs triangle diagram with self-coupling λ

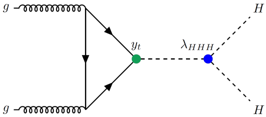


(b) Heavy resonance decaying into two Higgs

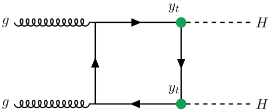
- Same final state **topology** leads to **natural** analysis extensions

Motivation: Production

- Two leading order HH diagrams for gluon gluon fusion:

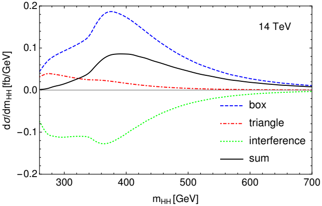


(a) Triangle diagram

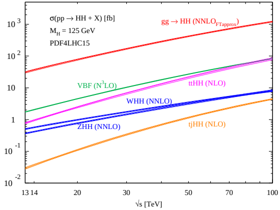


(b) Box diagram

- These **destructively interfere**, leading to small production cross section:



(a) Diagram interference



(b) Production XS

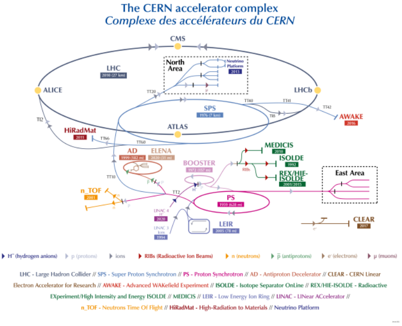
- Can produce with high energy p-p collisions

Next Section

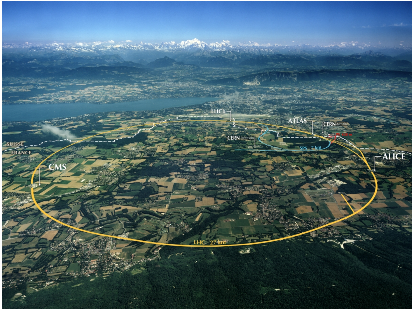
Next Subsection

Experimental setup: LHC

- CERN has a large accelerator complex to accelerate particles.
- Final stage: The large hadron collider



(a) CERN accelerator complex



(b) The LHC

- The **LHC** is the largest machine ever built
- Circumference of **27 km**, accelerates protons to $\approx 99.999999\%$ the speed of light (≈ 6.5 TeV)

- The LHC produces high energy particle collisions
- **Four** major experiments based at the LHC to detect what is produced
- Today will talk about **CMS** and **ATLAS** experiments and results

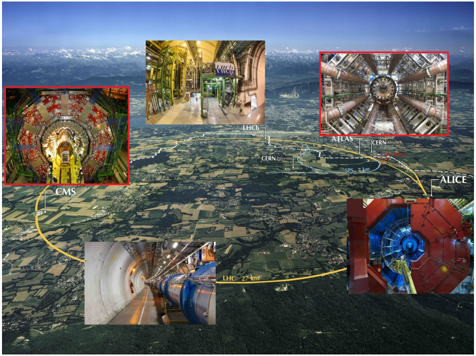
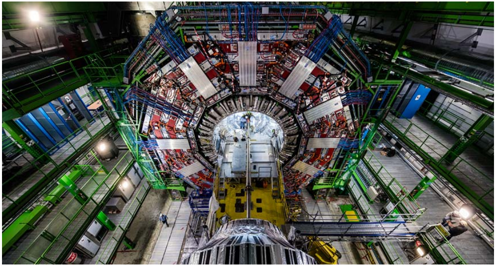


Figure 4: LHC and its major experiments

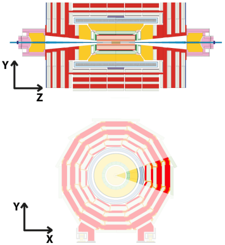
- The CMS (Compact Muon Solenoid) experiment is a general-purpose particle detector, stationed on the LHC near Geneva Switzerland

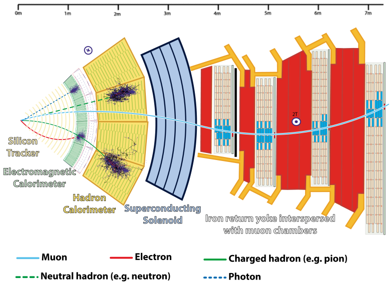


- **General purpose:** Perform searches for DM, SUSY, rare processes, precision measurements, b-physics, ...
- Dimensions 21m long, 15m high and 15m wide.

Experimental setup: CMS

- CMS is made of multiple layers in order to detect **different particles**: Inner silicon tracker, calorimeters, muon chambers

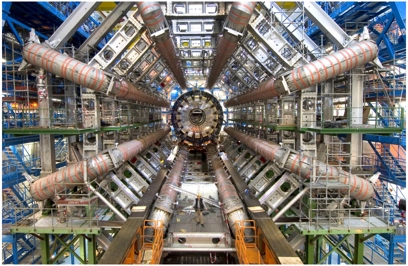


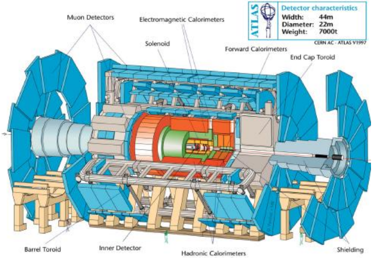


- Different particles leave different signatures in the detector
- Crucial for the ability to detect the **many Higgs final states**

Experimental setup: ATLAS

- The ATLAS (A large Toroidal LHC ApparatuS) experiment is also a general purpose particle detector:





- Dimensions: 46 m long, 25 m high and 25 m wide. Largest volume detector ever built
- Similar to CMS, composed of layers including a **tracker**, **calorimeters** and **muon chambers**

- In a very similar fashion to CMS, ATLAS is able to detect **different particles** from different layers of detector
- Some layers use different technologies: Example, CMS (ATLAS) ECAL is made of Lead Tungstate crystals (metal layers and liquid argon)
- Crucial to have independent measurements

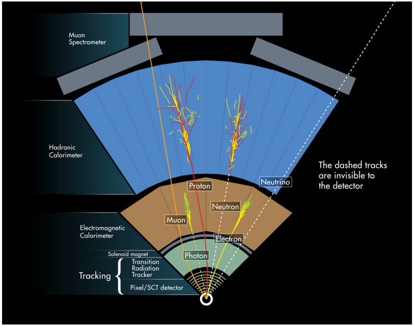
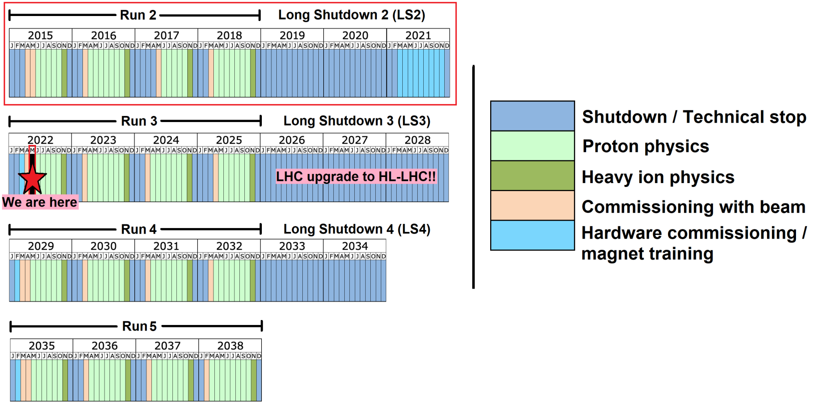


Figure 5: ATLAS particle detection

Experimental setup: Timeline

- LHC long term schedule (**always subject to change**):



- Past 7 years: CMS and ATLAS physicists have been **recording** and **analyzing** Run 2 data: $\approx 138 - 139\ \text{fb}^{-1}$ recorded per detector - About **4000 HH** pairs via GF (SM) per experiment!

Next Subsection

SM and EFT: HH decay modes

- **Many** HH final states to consider!
- Highest SM branching ratio: HH→bbbb, ≈ 34%, but large QCD multijet background
- Other channels like bb$\gamma\gamma$, branching ratio ≈ 0.3%, but **good discrimination** from background from H→ $\gamma\gamma$ signature
- Exploring **many** channels is vital to make use of **different detector signatures**, and **combine** to improve overall sensitivity

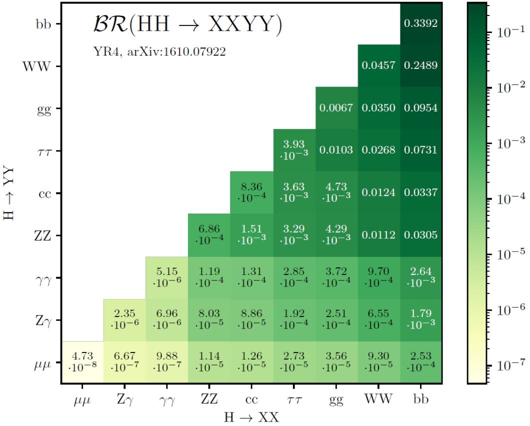


Figure 6: HH branching ratios

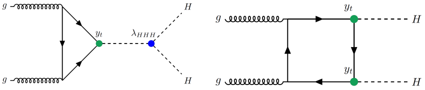
Non-resonant Higgs Pair Production

- In addition to direct SM search, a model-independent search for new physics can be performed using an EFT (Effective Field Theory) alteration of the SM lagrangian
- Allows for BSM search over **large range** of scenarios

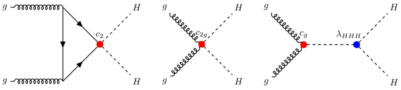
$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}, \ \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}, \ \kappa_t = \frac{y_t}{y_t^{SM}}, \ y_t^{SM} = \frac{\sqrt{2} m_t^2}{v}$$

Effective Field Theory Parameterized BSM Lagrangian



SM-like processes



Pure BSM processes

SM and EFT: EFT framework

- Similarly, can parameterize the couplings of VVH, VVHH:

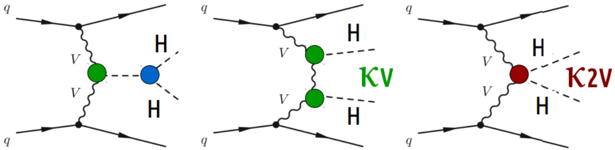
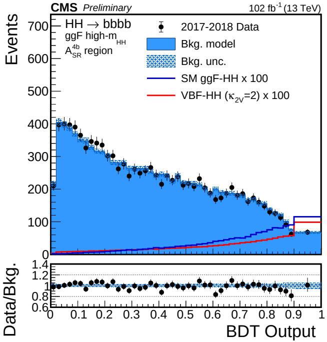


Figure 7: VBF HH diagrams

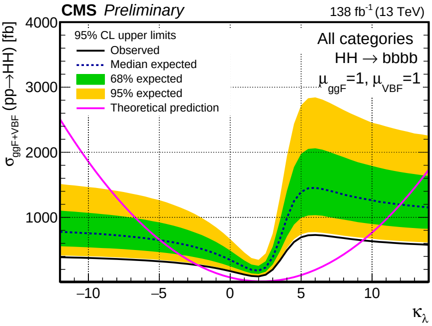
- SM: $\kappa_{2V} = \kappa_V = 1$
- By forming EFT parameterization, can scan anomalous values of couplings as wide BSM searches

SM and EFT: HH→bbbb

- CMS Run 2 search, gluon fusion results [CMS-HIG-PAS-20-005]:



(a) BDT discriminant

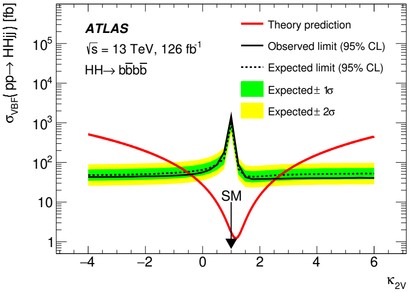


(b) Self-coupling scan

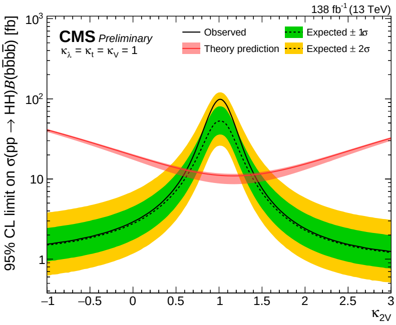
- Separate large QCD and tt backgrounds from HH with data-driven method (CR) and BDT
- 95% CL upper limit on SM XS: **3.6 times the standard model value**
- Constrain self-coupling between **[-2.3, 9.4]** at 95% CL

SM and EFT: VBF HH→bbbb

- CMS (boosted) and ATLAS VBF searches, sensitive to κ_V, κ_{2V}:



(a) ATLAS: [JHEP07(2020)108]

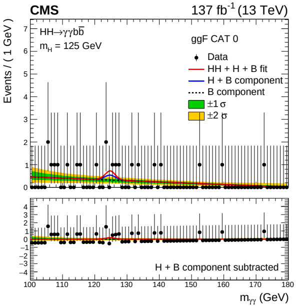


(b) CMS: [CMS-HIG-B2G-22-003]

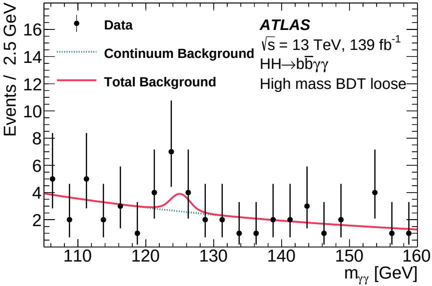
- ATLAS constraint: [-0.76 $< \kappa_{2V} <$ 2.9]
- CMS: Observed constraint [0.62 $< \kappa_{2V} <$1.41] **First** $> 5\sigma$ **exclusion** of $\kappa_{2V} = 0 \rightarrow$ **Must have VVHH coupling in nature!**

SM and EFT: HH$\rightarrow$bb$\gamma\gamma$

- In the bb$\gamma\gamma$ channel, take advantage of narrow and clean H$\rightarrow$ $\gamma\gamma$ invariant mass:



(a) CMS: [ref.]

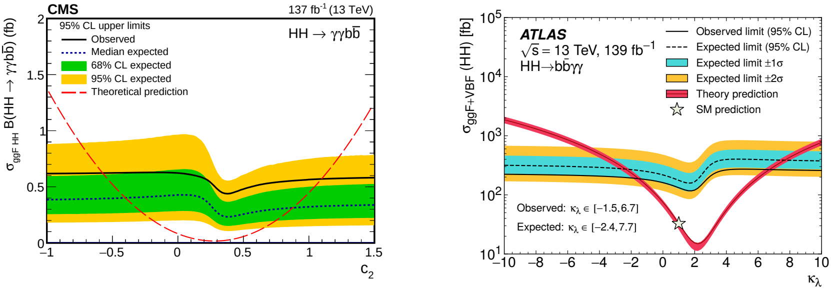


(b) ATLAS: [ref.]

- Both CMS and ATLAS fit their background-only hypothesis models to diphoton mass around 125 GeV, to search for a **bump** from HH$\rightarrow$bb$\gamma\gamma$

SM and EFT: HH→bb$\gamma\gamma$

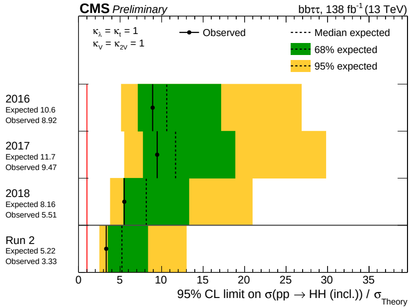
- CMS: observed (expected) $\frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 7.7\ (5.2)$ at 95% CL
- ATLAS: observed (expected) $\frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 4.2\ (5.7)$ at 95% CL



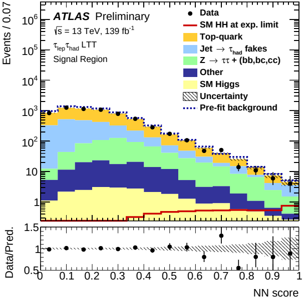
(a) CMS (b) ATLAS

- Can perform SM search while simultaneously searching for BSM contributions via EFT framework - obtain different anomalous signal models by reweighting with GEN info
- CMS c2 constraint: [-0.6 $< c_2 <$ 1.1]

- bb$\tau\tau$ final state analyzed with Run 2 data by both experiments
- Both consider $\geq$ 1 hadronically decaying τ and make use of ML:



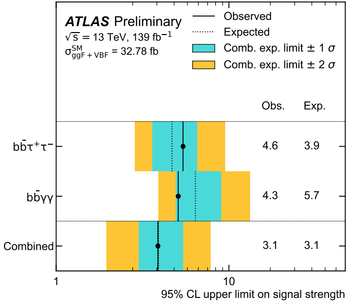
(a) CMS upper limits: [ref.]



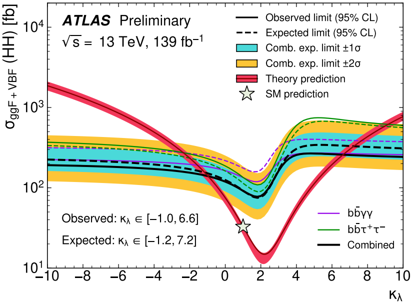
(b) ATLAS MVA distribution [ref.]

- CMS: observed (expected) $\frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 3.3$ (5.2) at 95% CL
- ATLAS: observed (expected) $\frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 4.7$ (3.9) at 95% CL

- ATLAS Run 2 combination [ref.] produced, where $bb\gamma\gamma$ and $bb\tau\tau$ results are combined:



(a) SM upper limit

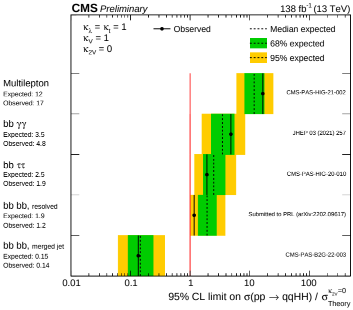


(b) Kl scan

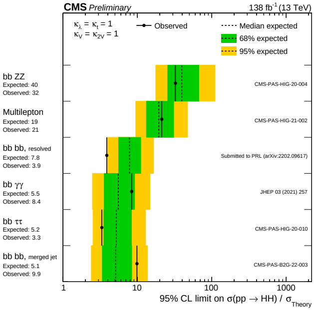
- Higgs self coupling modifier constrained at 95% CL to: [-1 $< \kappa_\lambda <$ 6.6] observed, [-1.2 $< \kappa_\lambda <$ 7.2] expected
- **Combining channels improves sensitivity!**

SM and EFT: CMS channel comparisons

- CMS has analyzed several HH channels with the Run 2 datasets
- Comparing upper limits between channels gives an idea of per-channel and overall sensitivity:



(a) VBF upper limits, assuming $\kappa_{2V} = 0$



(b) GF upper limits, assuming SM couplings

- VBF bbbb boosted excludes the scenario $\kappa_{2V} = 0$ with $> 5\sigma$ significance, implying VVHH coupling in nature
- Similar GF sensitivities for bb$\gamma\gamma$, bb$\tau\tau$, bbbb. Observed upper limits $\approx$ 3-5 X SM

Next Subsection

- Reminder: can search for BSM scenarios, such as those predicting a heavy resonance coupling to Higgs can be searched for via Higgs pair production:

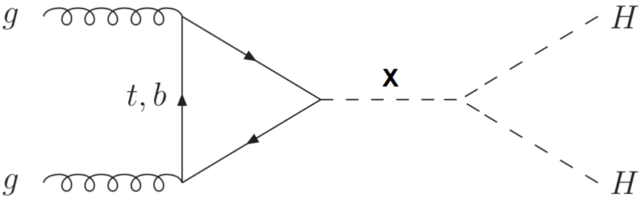


Figure 8: Heavy resonance to two Higgs

- Still looking for HH, but expect kinematic changes depending on mass of resonance
- Can apply **similar analysis strategies** to SM/EFT searches for particular final states

Resonant searches: Spin 0/2 resonance

- **Resonant higgs pair production**
  BSM example: Warped Extra Dimensions (WED)
- Search for heavy resonant particle: Graviton
- Predicted by Kaluza–Klein models - offer solution to hierarchy problem
- Can search via decays to SM higgs bosons

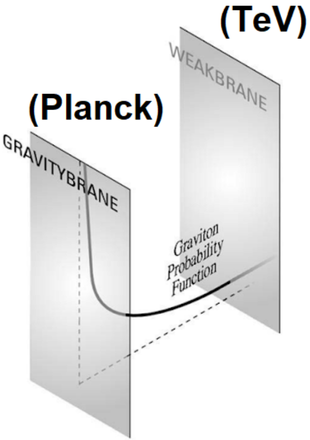


Figure 9: Warped extra dimensions: [arXiv:1404.0102]

Resonant searches: Spin 0/2 HH→bbbb

- ATLAS X→HH→bbbb: Can see different reconstructed HH **invariant masses** from simulation
- Higher resonant mass, more **discrimination** from data
  - → Can increase search **sensitivity**
- Balance of this, production cross section and data efficiency determines expected sensitivity

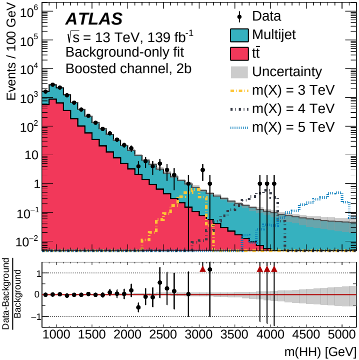


Figure 10: Reconstructed invariant mass of HH

Resonant searches: Spin 0/2 HH→bbbb

- With higher masses, expect more co-linear daughter particles. Multiple topologies to consider:

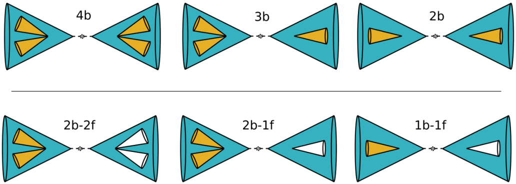
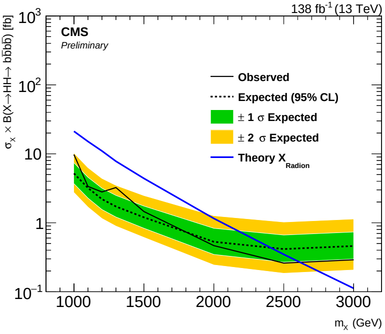


FIG. 7. Illustration of the three high-tag categories ($4b$, $3b$, and $2b$) with the corresponding low-tag categories used to estimate the multijet background ($2b$–$2f$, $2b$–$1f$, and $1b$–$1f$). Teal cones represent large-R jets, yellow cones represent associated b-tagged track-jets, and white cones represent associated untagged track-jets. For H candidates with more than two associated track-jets, only the two with the highest p_T are considered.

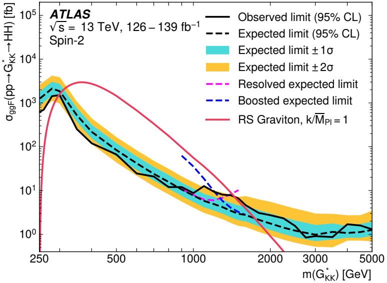
Figure 11: Boosted and resolved HH→bbbb topologies

- Also need to account for cases in which a b quark jet is faked
- Considering **multiple topologies** increases signal sensitivity

- Spin 0/2 HH to 4b results:



(a) CMS Spin-0 [ref.]

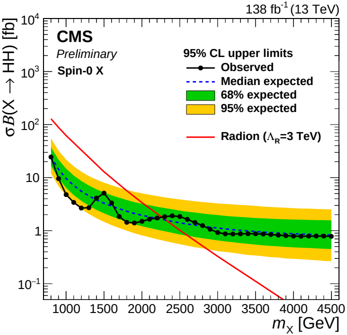


(b) ATLAS Spin-2 [ref.]

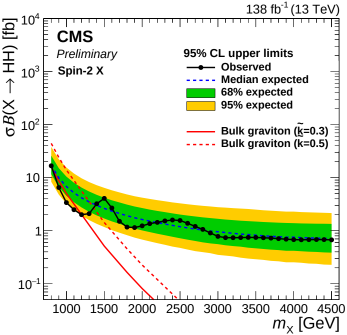
- Searches in both boosted and resolved topologies searched
- CMS: Tag boosted H→bb as one large jet with machine learning
- CMS excludes narrow width Spin-0 Radions with masses 1 - 2.6 TeV. ATLAS excludes R.S. Gravitons from 298 - 1460 GeV.

Resonant searches: Spin 0/2 HH→Multilepton

- CMS Spin 0/2 HH to multilepton (Leptonic bbWW and bb$\tau\tau$) [ref.]:
- Λ_R: Ultraviolet cutoff. $\tilde{k}$ proportional to extra dimension curvature over planck mass.



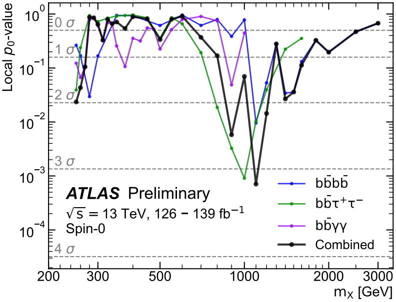
(a) Spin-0



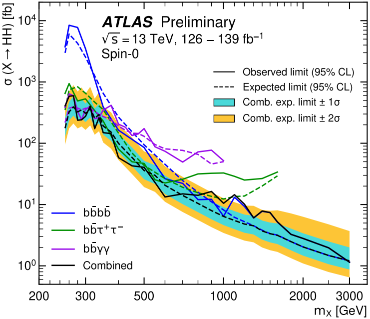
(b) Spin-2

Considering similar final states can add sensitivity to analysis with similar strategy. Exclude Spin-0 radions with mass $<\approx 2.25\,TeV$

- ATLAS spin-0 combination [ref.]:



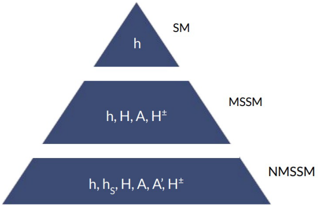
(a) Spin-0 local p-values



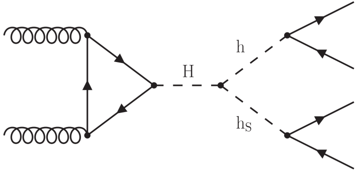
(b) Spin-0 upper limits

- **Local** p-value corresponding to 3.2σ at 1.1 TeV, however, accounting for look-elsewhere effect, **global** p-value becomes 2.1σ.

- **MSSM:** Minimal extension to make SM supersymmetric. Predicts additional higgs bosons. Phase space **mostly excluded** at LHC.
- **NMSSM:** Next to Minimal Supersymmetric Standard Model, predicts additional higgs bosons. Phase space **largely unconstrained** at LHC.



(a) SM extensions

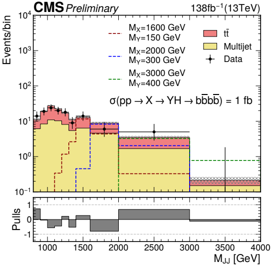


(b) H→hh diagram

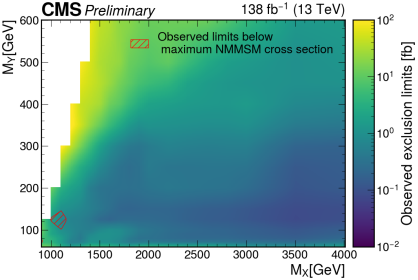
- Predicts heavy higgs decaying to SM and additional BSM higgs
- In similar sense to Spin 0/2 searches, **natural extension** of HH searches.

Resonant searches: NMSSM bbbb

- CMS NMSSM bbbb: [ref.]
- Scan mass range: Heavy higgs (0.9-4 TeV), second BSM higgs (60-600 GeV)



(a) Boosted di-jet mass

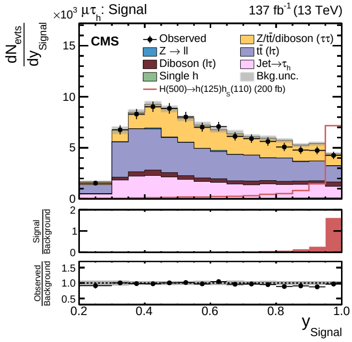


(b) 2d mass range

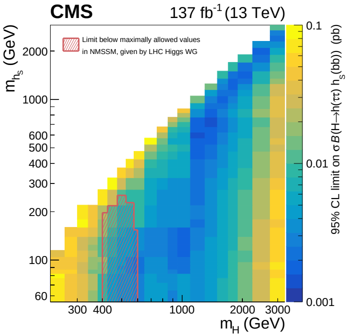
- Look at **boosted** topology, two large jets. Higher expected discrimination for large mass discrepancies
- Able to exclude small portion of mass window

Resonant searches: NMSSM $bb\tau\tau$

- CMS NMSSM $bb\tau\tau$ [ref.]:



(a) MVA output



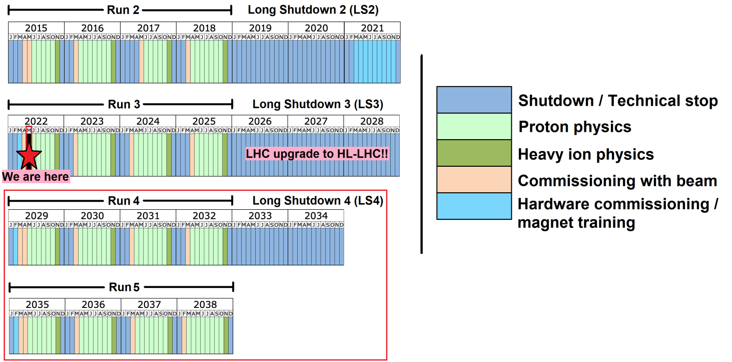
(b) 2d mass plane

- Neural network used to discriminate signal and background
- Able to exclude $\approx [400 < m_H < 600]$ GeV $\cap$ $[50 < m_{h_S} < 250]$
- Different HH **final states** exclude different regions of 2d **mass space**

Next Section

HL-LHC Projections: Timeline

- LHC Run 3 will be the final run of the LHC:



- LS3 (Long shutdown 3), LHC will upgrade to HL-LHC. CMS and ATLAS will undergo major upgrades for higher inst. luminosity, harsher data-taking conditions.

HL-LHC Projections

- **Pros:** Higher luminosity dataset, expect $\approx 3000\ \text{fb}^{-1}$. More data w.r.t LHC, and therefore more **sensitive** search - about **93,000 HH** pairs!
- **Cons:** Huge pileup - $\approx$ 140 simultaneous interactions!!

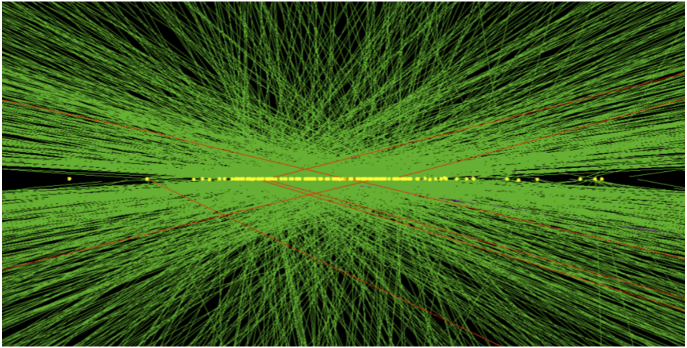
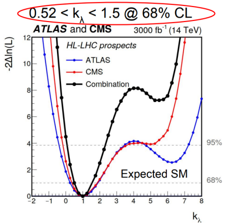


Figure 12: HL-LHC simulated event with 140 concurrent interaction vertices

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau^+\tau^-$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV^*$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4\ell)$	-	0.37	-	0.37
Combination	3.5	2.8	3.0	2.6
	4.5		4.0	

(a) Projected significance



(b) Projected κ_λ scan

Figure 13: CMS + ATLAS white paper: [ref.]

- Most recent projection combination: 4 sigma deviation from bkg. only hypothesis
- Combining HH channels and experiments will be **crucial** for maximizing potential for HH discovery at HL-LHC

HL-LHC Projections: Future studies

- Some channels updated, added:
- Important caveats to HL-LHC projection results:
  - Cannot make use of any **data-driven** techniques
  - Do not have exact detector simulation yet
  - Do not have dedicated offline reconstruction optimizations: E.g. energy regressions (corrections)
  - Dedicated analysis teams to investigate this future dataset, and think of creative ways to optimize the analysis!

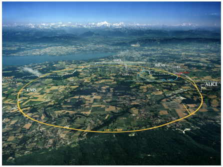
HH channel	Significance (standard deviations)	
	ATLAS	CMS
bbbb	0.61	0.95
$bb\tau\tau$	~~2.1~~ 2.8	1.4
$bb\gamma\gamma$	~~2.0~~ 2.2	~~1.8~~ 2.16
$bbVV(\ell\ell\nu\nu)$	-	0.56
$bbZZ(4\ell)$	-	0.37
$WW\gamma\gamma + \tau\tau\gamma\gamma$	-	0.22

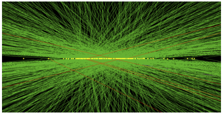
Figure 14: Updated significance table for HL-LHC projection

Next Section

Conclusions

- Higgs boson used to:
  - Better understand SM
  - Hunt for BSM
  - **Both** can be explored with **Higgs pair production**
- The Run 2 dataset delivered by LHC to CMS and ATLAS has resulted in a **vast collection** of results:
  - Upper limit on di-Higgs production around 3-4 times the standard model with sensitive individual channels - would expect a combination to improve
  - Ruling out BSM scenarios via EFT and resonant interpretations, including absence of VVHH
- Current HL-LHC projections predict **at least** a 4σ excess of HH events. Expect improvement from:
  - Data-driven techniques
  - More HH channels
  - Lessons to be learned during Run 3





Outlook: What's next?

- Commissioning for LHC Run 3 is ramping up
- Expect:
  - $\sqrt{s} = 13.6$ TeV, integrated lumi around 250 fb^{-1}, $\approx$ double the Run 2 data!

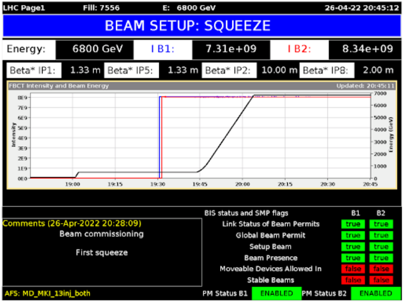


Figure 15: First 6.8 TeV squeezed beams!

Thank you for your attention!

Next Section

- Higgs discovery per channel significance's:

Table 6
The expected and observed local p-values, expressed as the corresponding number of standard deviations of the observed excess from the background-only hypothesis, for $m_H = 125.5$ GeV, for various combinations of decay modes.

Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.8	3.2
$\tau\tau$ + bb	2.4	0.5
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

(a) CMS significance's

Search channel	Dataset	m_{max} [GeV]	Z_l [σ]	$E(Z_l)$ [σ]
$H \to ZZ^{(*)} \to 4\ell$	7 TeV	125.0	2.5	1.6
	8 TeV	125.5	2.6	2.1
	7 & 8 TeV	125.0	3.6	2.7
$H \to \gamma\gamma$	7 TeV	126.0	3.4	1.6
	8 TeV	127.0	3.2	1.9
	7 & 8 TeV	126.5	4.5	2.5
$H \to WW^{(*)} \to \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4
	8 TeV	120.0	3.3	1.0
	7 & 8 TeV	125.0	2.8	2.3
Combined	7 TeV	126.5	3.6	3.2
	8 TeV	126.5	4.9	3.8
	7 & 8 TeV	126.5	6.0	4.9

(b) ATLAS significance's

- Z_ℓ: Local significance

Lagrangian Terms

- $G^a_{\mu\nu}$ is the gluon field strength tensor
- κ_λ - measure of deviation of Higgs boson trilinear coupling from its SM expectation λ^{SM}_{HHH}
- κ_t - measure of deviation of coupling between Higgs bosons and two top quarks from its SM expectation y^{SM}_t
- c_2 - coupling between two Higgs bosons and two top quarks
- c_g - coupling between one Higgs bosons and two gluons
- c_{2g} - coupling between two Higgs bosons and two gluons

Higgs branching ratios

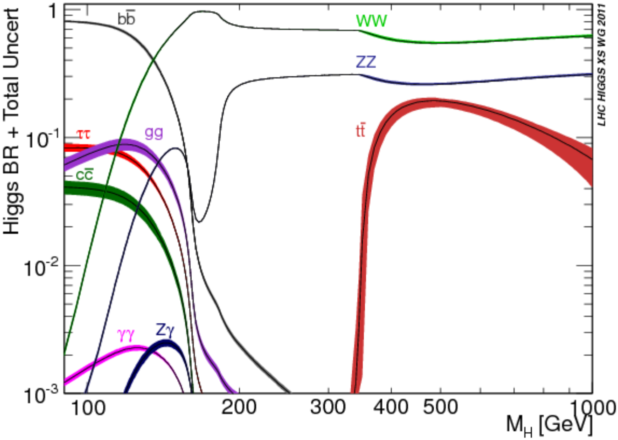
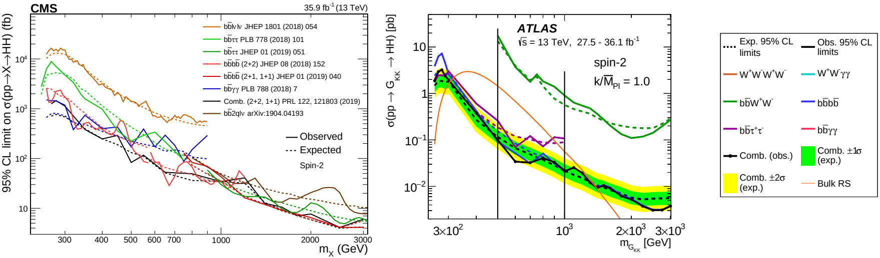


Figure 16: Extended Higgs branching ratios vs. Higgs mass [ref.]

- Search for heavy resonance from WED theory has been performed by CMS and ATLAS:



(a) CMS: [ref.] (b) ATLAS: [ref.]

Figure 17: Resonance searches with 2016 data

- No heavy resonance observed, but can **rule out** models predicting certain masses, if upper limit is less than predicted value.
- Combining HH channels increases sensitivity!