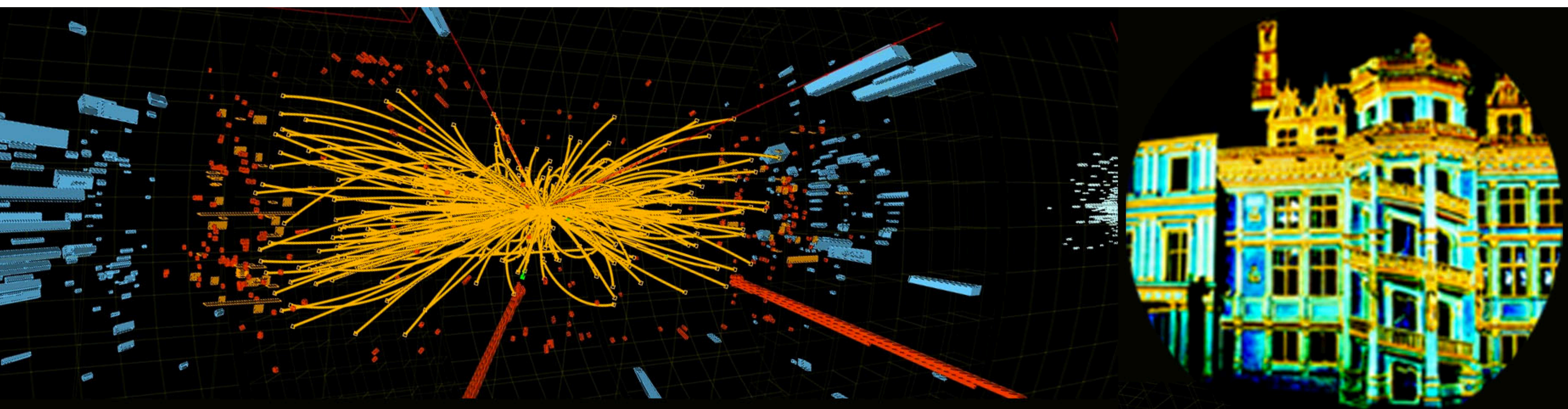
Rare Higgs Decays and Production Modes

Lindsey Gray (FNAL)

on behalf of the *CMS* and *ATLAS* collaborations

Recontres de Blois 2019



Rare is Relative

- Rare Higgs decays
  - Decays of Higgs into light, invisible particles or Exclusive Higgs
- Rare Higgs production modes
  - DiHiggs, ttH, bbH, γH all orders of magnitude below ggH
- Yield important unique information about Yukawa, PDFs, Higgs-vector interactions
  - These production and decay modes all offer unique sensitivity to BSM effects
  - It is be of critical importance to continue these studies to the future colliders

ggF: 43.6 pb

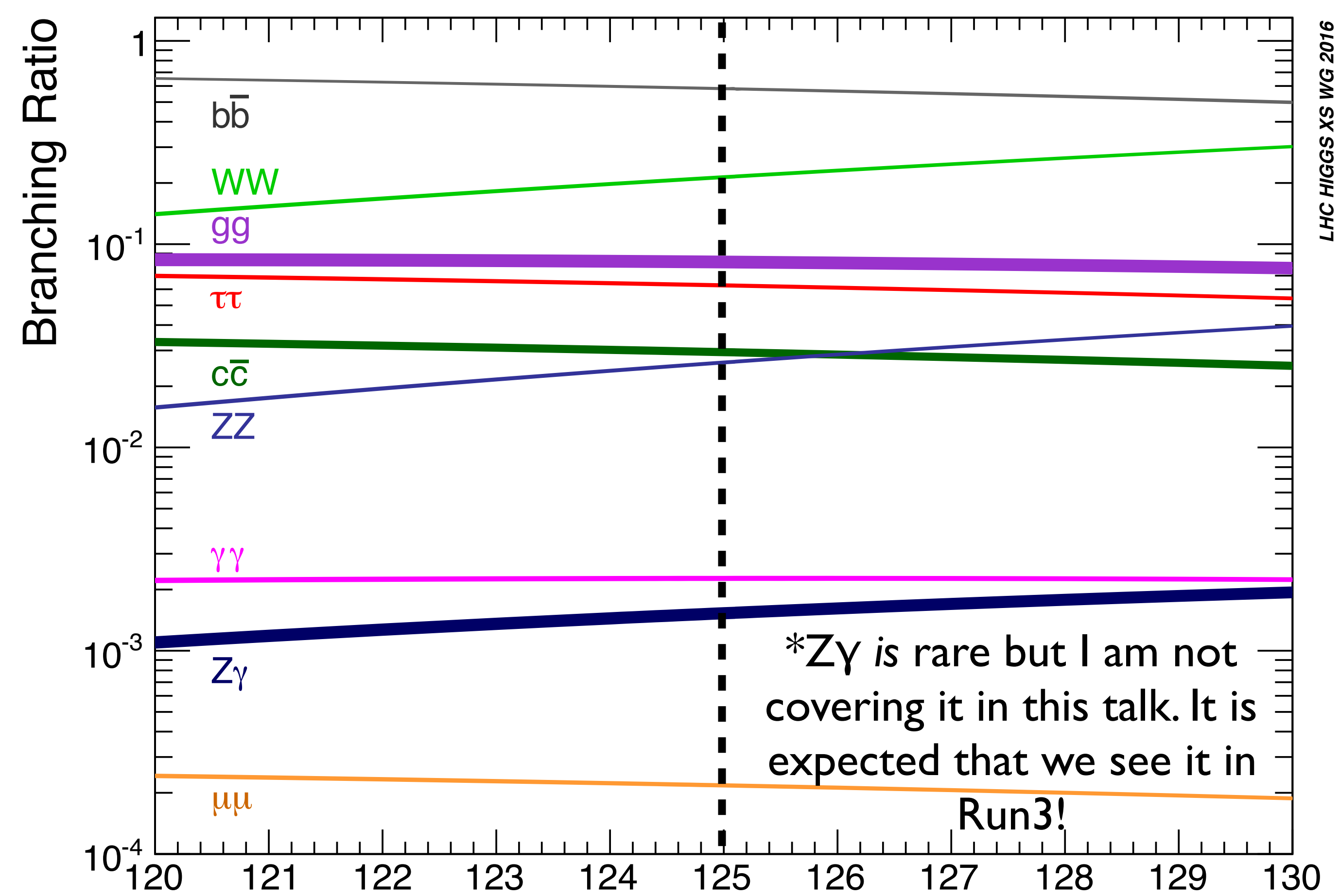
VBF: 3.7 pb

VH: 2.2 pb

ttH: 0.5 pb

bbH: 0.5 pb

HH: 0.03 pb

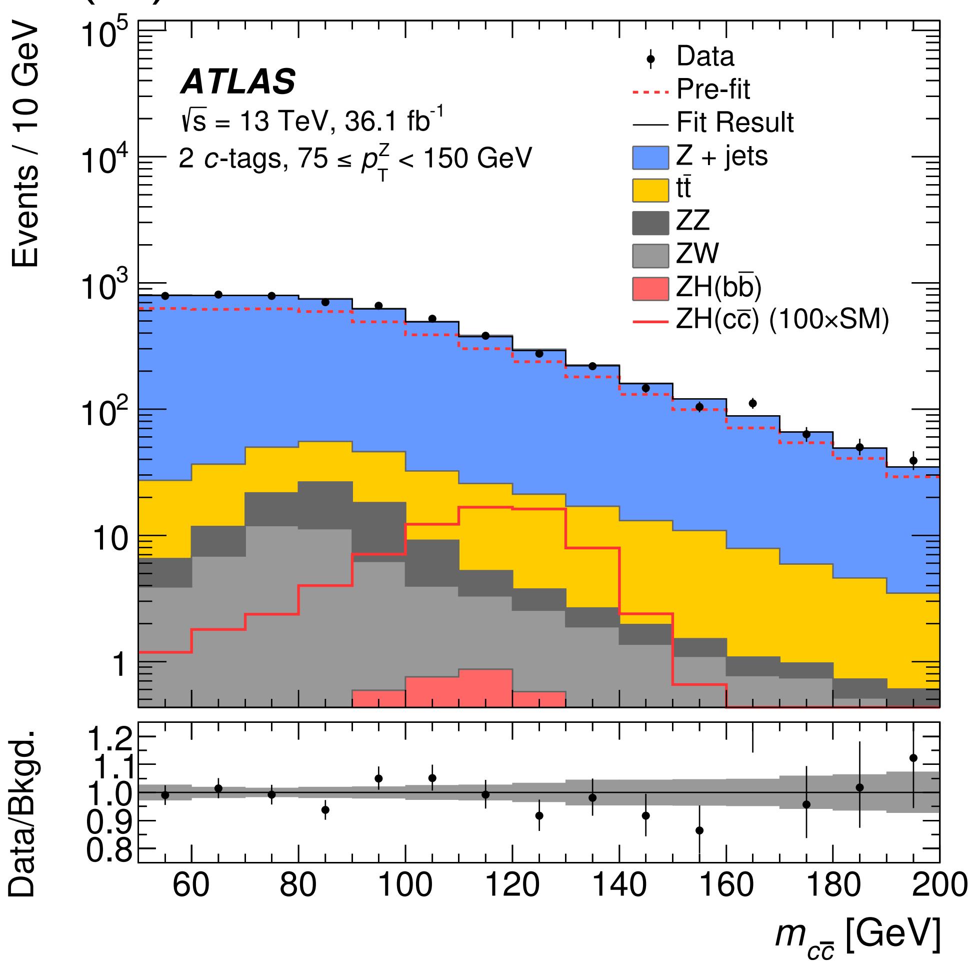


Overview

- **Second Generation**
  - cc and μμ ← not so recent results but important
- **Recent rare Higgs results** — new in last 6 months
  - top + Higgs ← 5 new CMS + ATLAS
  - Invisible Higgs branching ratio ← 2 new CMS + ATLAS
  - Exclusive hadronic Higgs decays ← 2 new CMS + ATLAS
  - Di-Higgs Searches ← 2 new CMS+ATLAS
- **Prospects with the HL-LHC**
  - Ultra-rare production, bbH, γH ← so far *theory only*
  - Exploiting our detectors

Second Generation

VH(cc)   arxiv:1802.04329



VH(cc) SM Prediction

26 fb

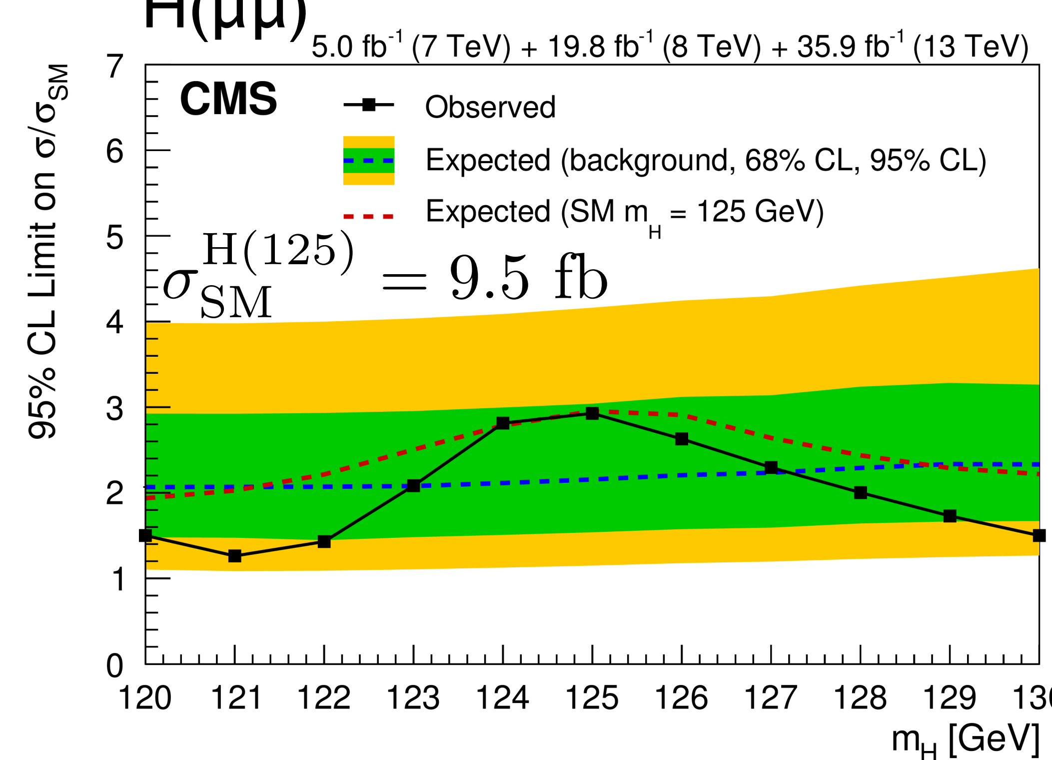
VH(cc) expected

$3.9^{+2.1}_{-1.1}$ pb

VH(cc) observed

2.7 pb

H(μμ)



$\sigma^{\mathrm{H(125)}}_{\mathrm{SM}} = 9.5$ fb

$\sigma/\sigma_{SM} < 2.1$ (ATLAS, 79.8 fb)

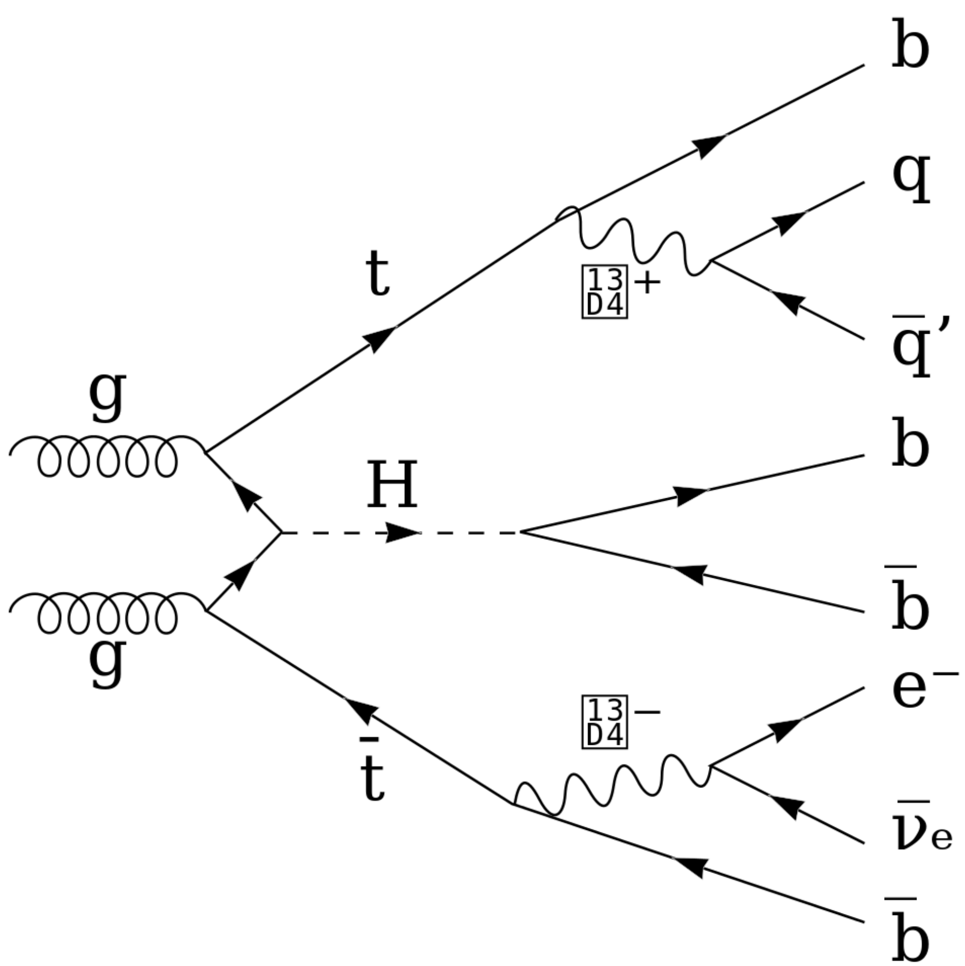
ATLAS-CONF-2018-026

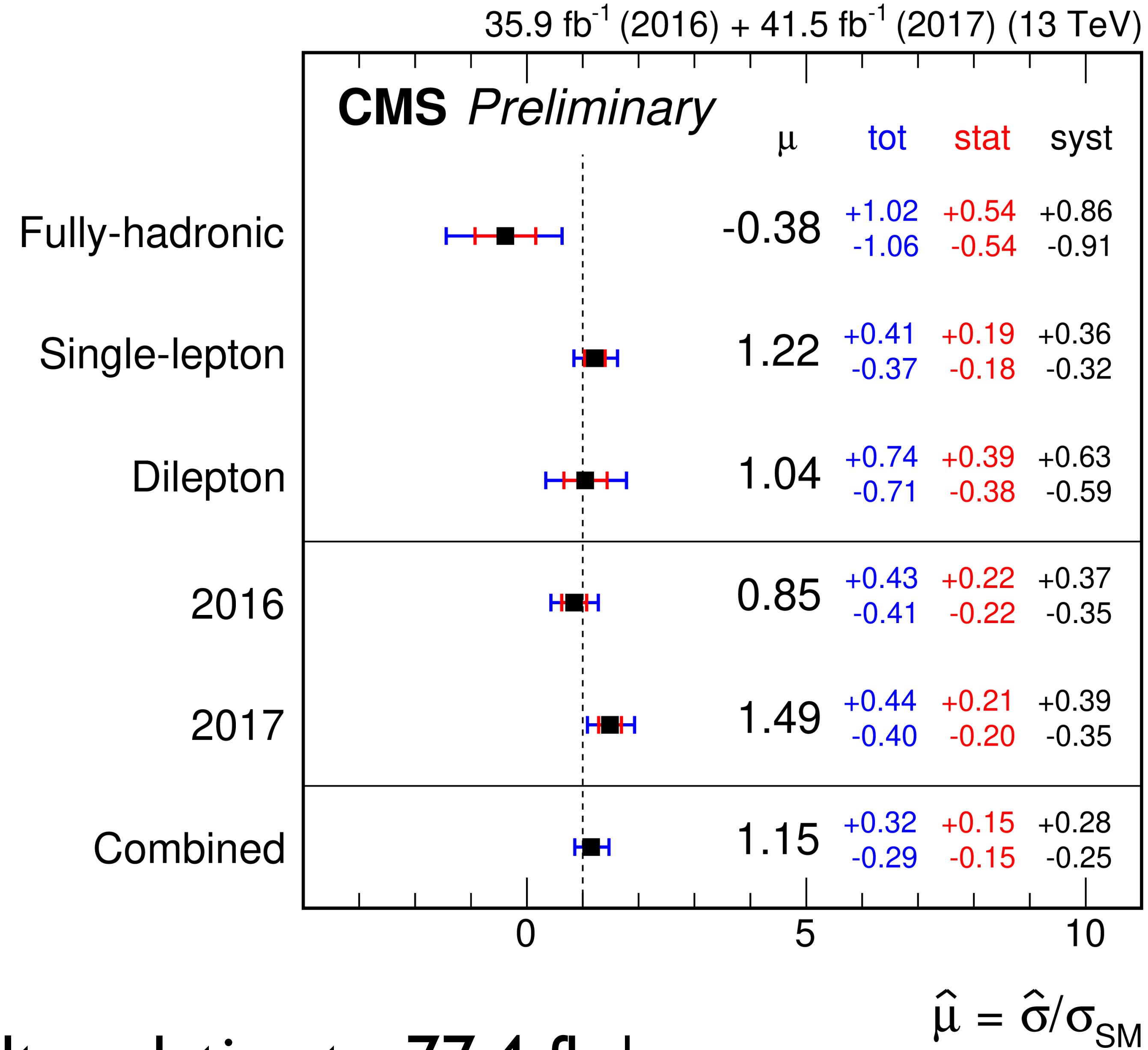
$\sigma/\sigma_{SM} < 2.64$ (CMS)   HIG-17-019

- Second generation measurements are critical to confirming the nature of fermionic Higgs interactions
  - Third-generation lepton and quark interactions measured but only confirm Yukawa-like interactions in their generation
  - Higgs to μμ clean enough to observe in the upcoming datasets
  - Higgs to charm has difficult backgrounds, including Higgs to bottom

ttH(bb)

HIG-18-030





- Very recent (May!) CMS result updating to 77.4 fb^{-1}
- Direct information on top and bottom Yukawa couplings
  - Difficult tt-bar background controlled by fitting BDT, ANN, MEM, discriminant distributions with templates

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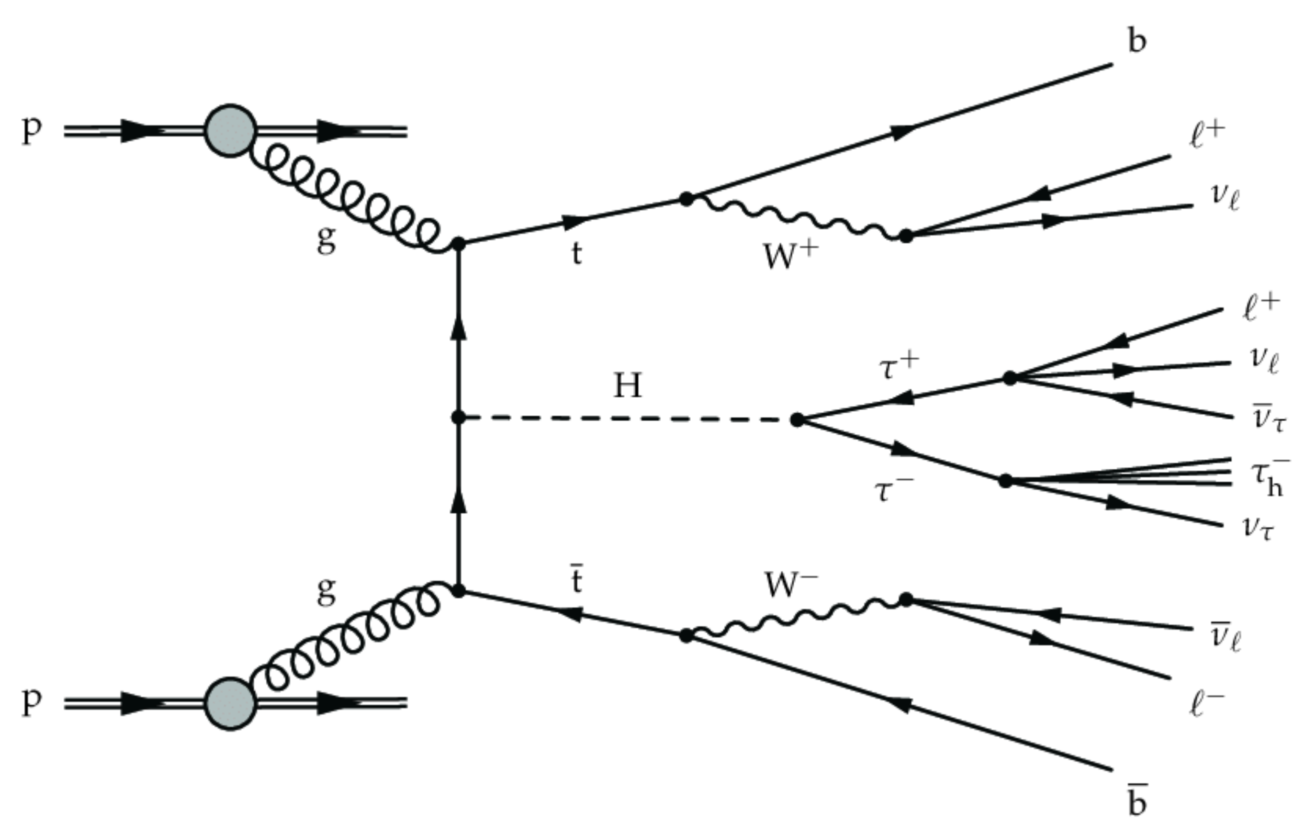
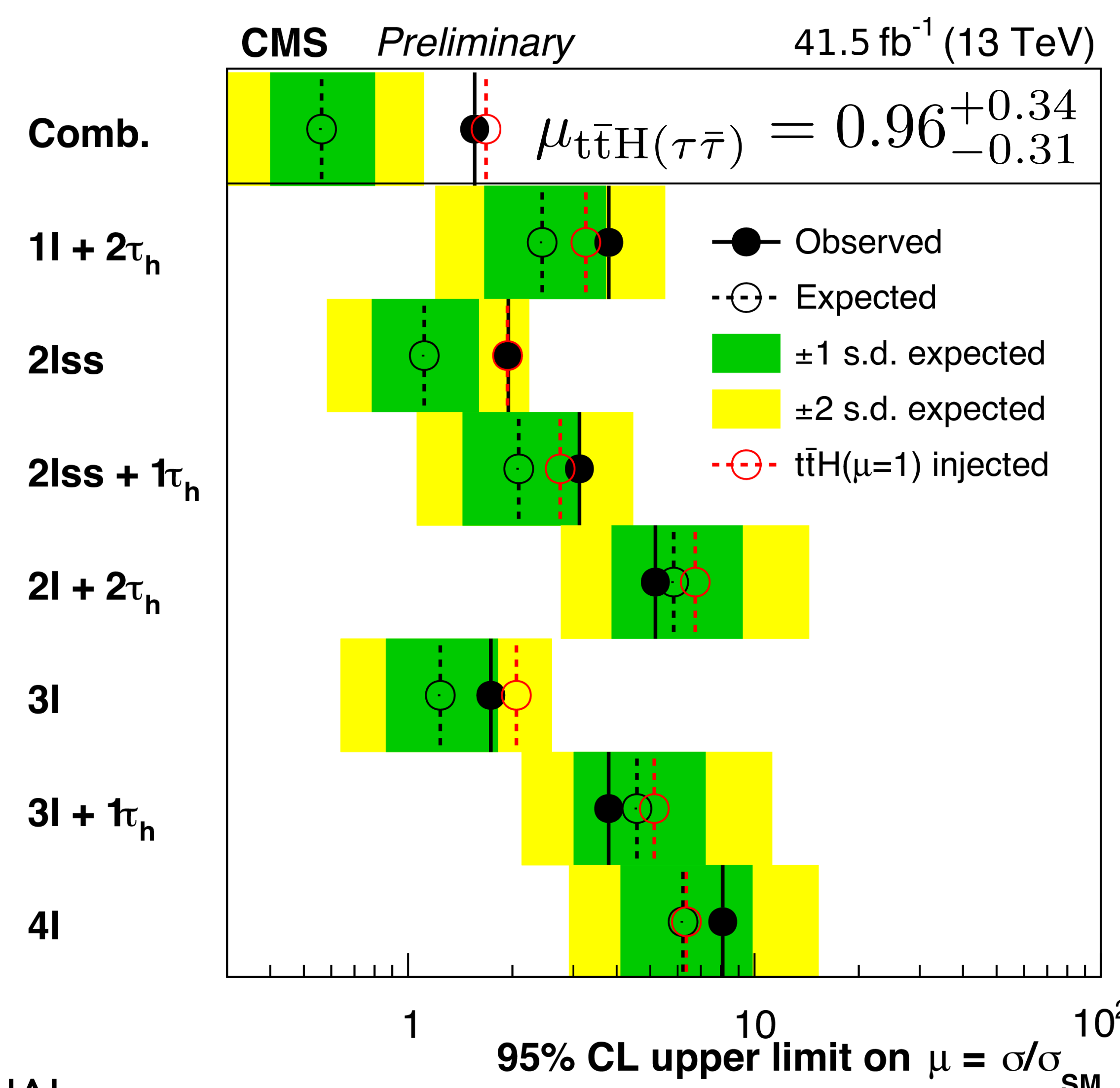
ttH(ττ)

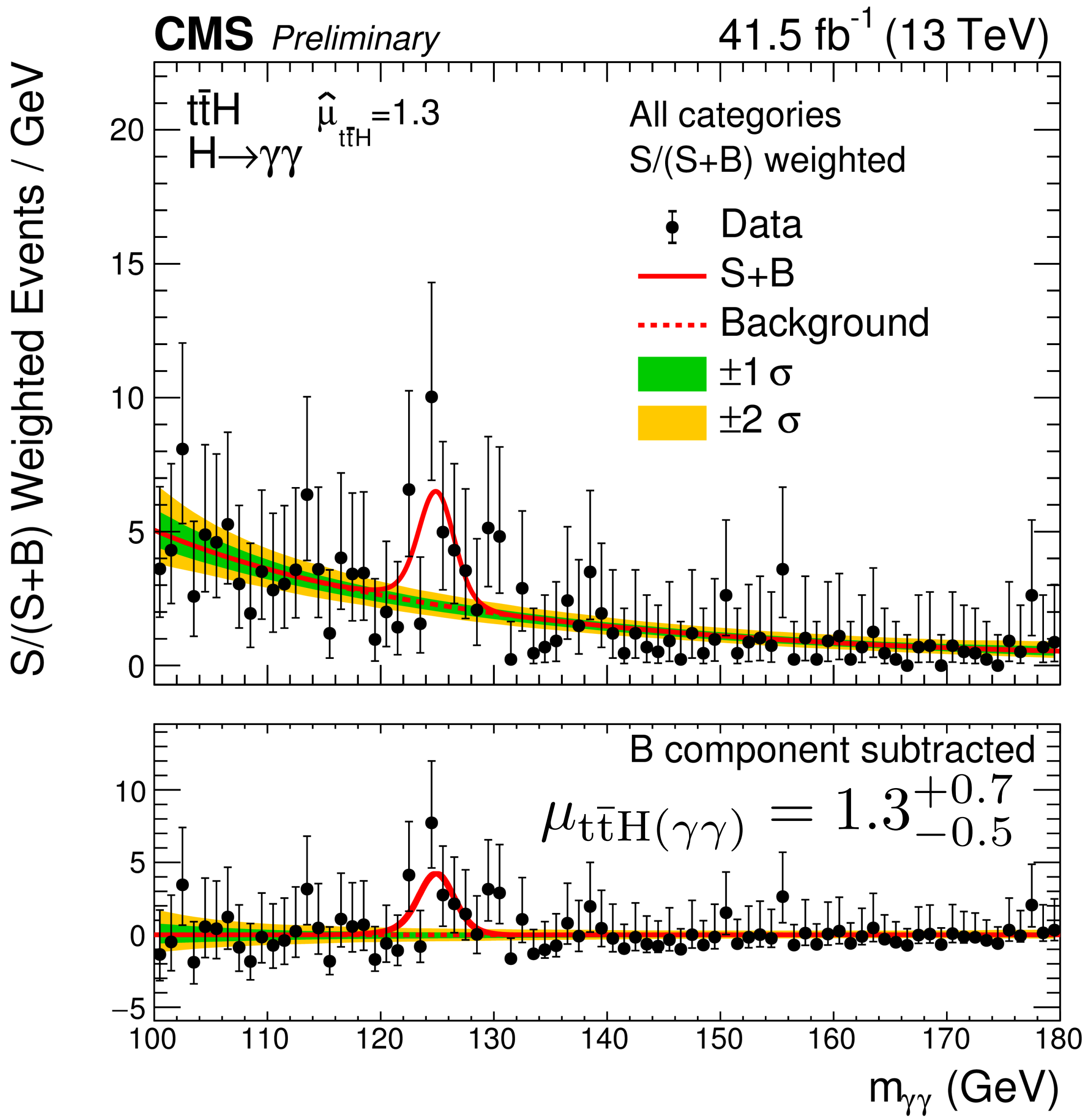
- top-Higgs program expanding to observations in each channel
  - ttH allows measurements of branching fractions with no loops major contributing diagrams
- Previously all decay modes had been used in combination to detect the ttH production signature
  - Measuring each provides new signatures to test Standard Model and search for new physics

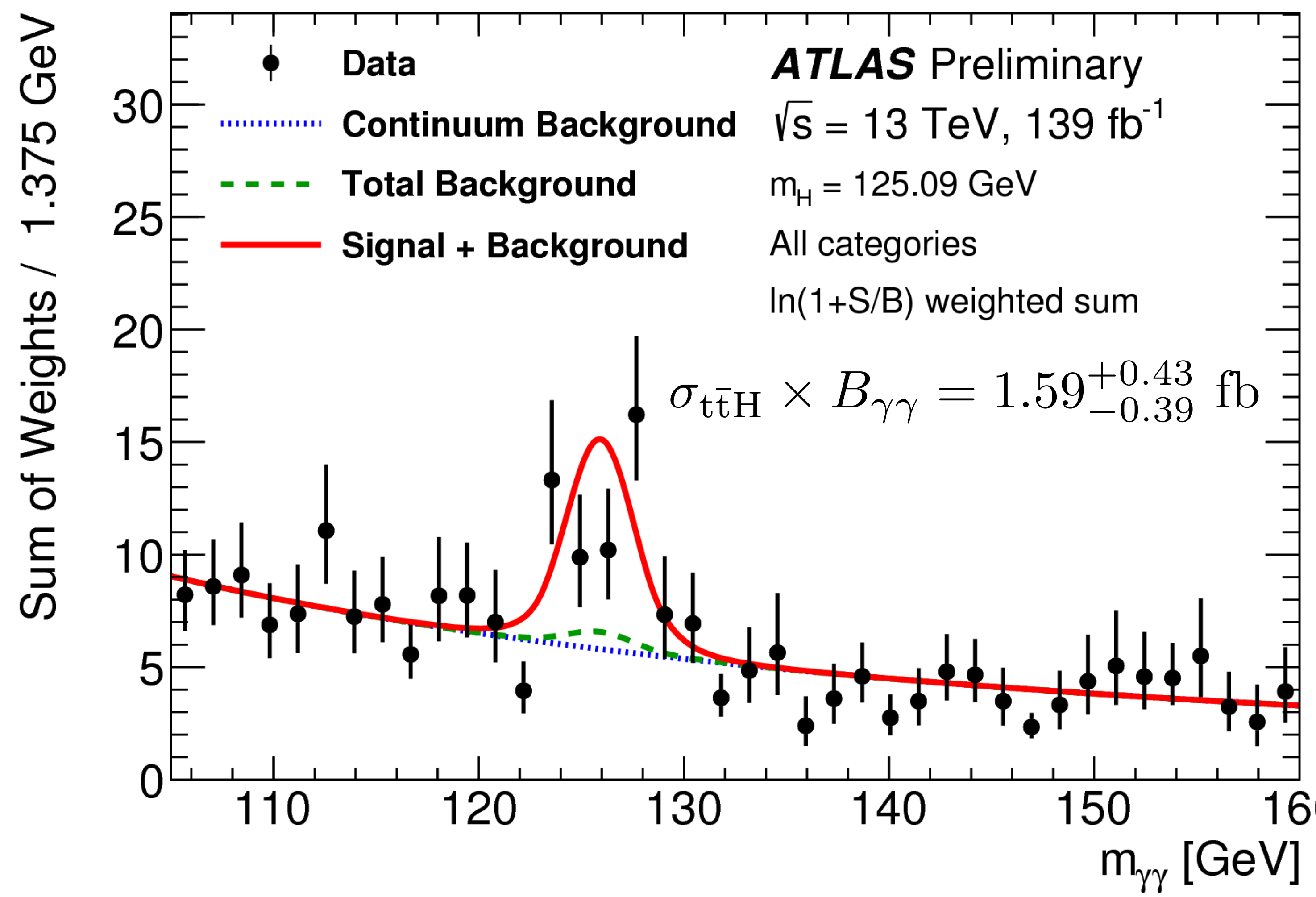




CMS-PAS-HIG-18-019

ttH(γγ)





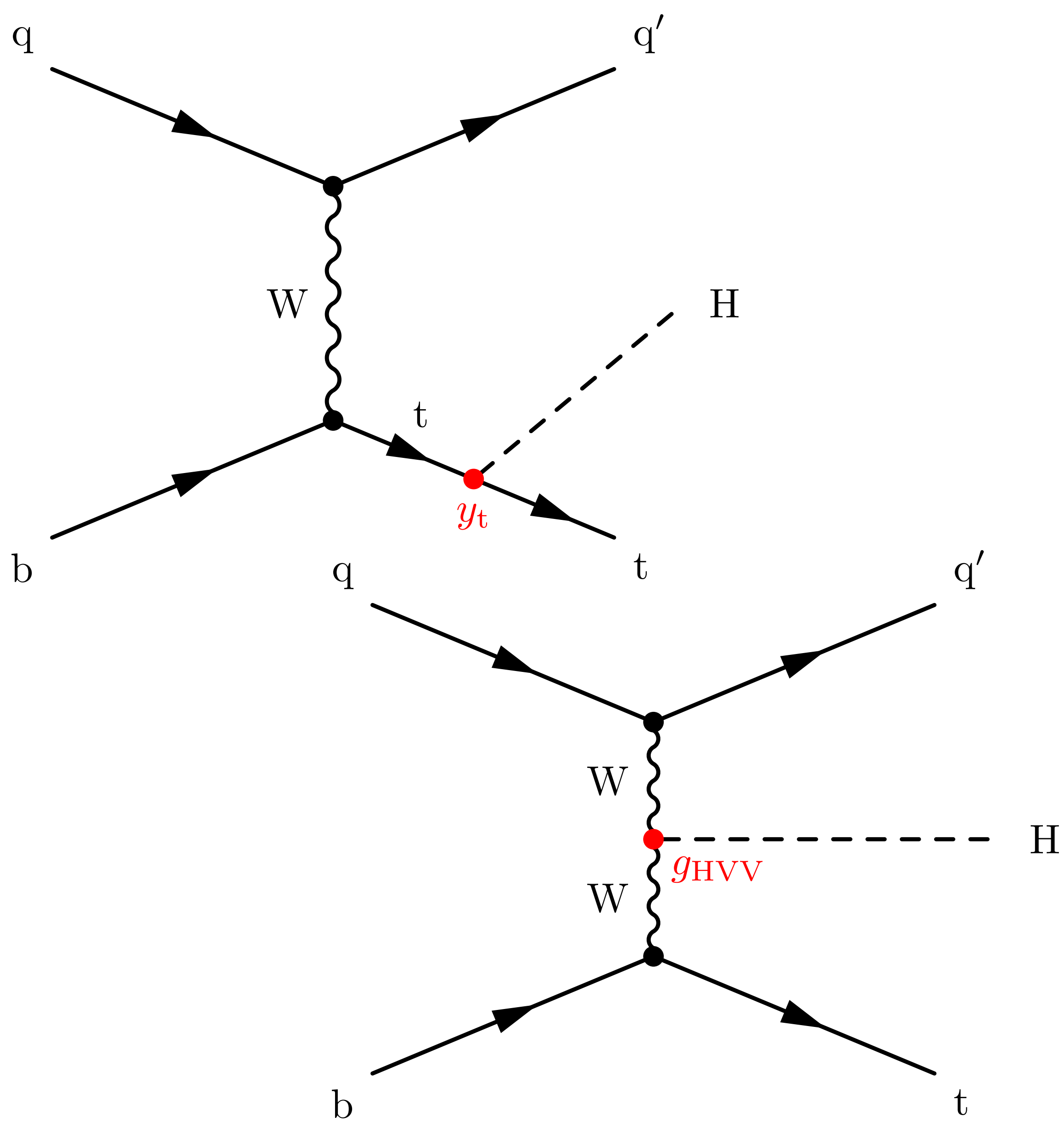
- Recent measurement of Higgs decays to diphoton in ttH yield new clean dataset
  - Mass peak can precisely define Higgs candidates
  - New combination of data from 2016, 2017 (, and 2018 for ATLAS)
  - This rare production and decay mode becomes sensitive to angular distributions in the top-Higgs system where new physics may lie

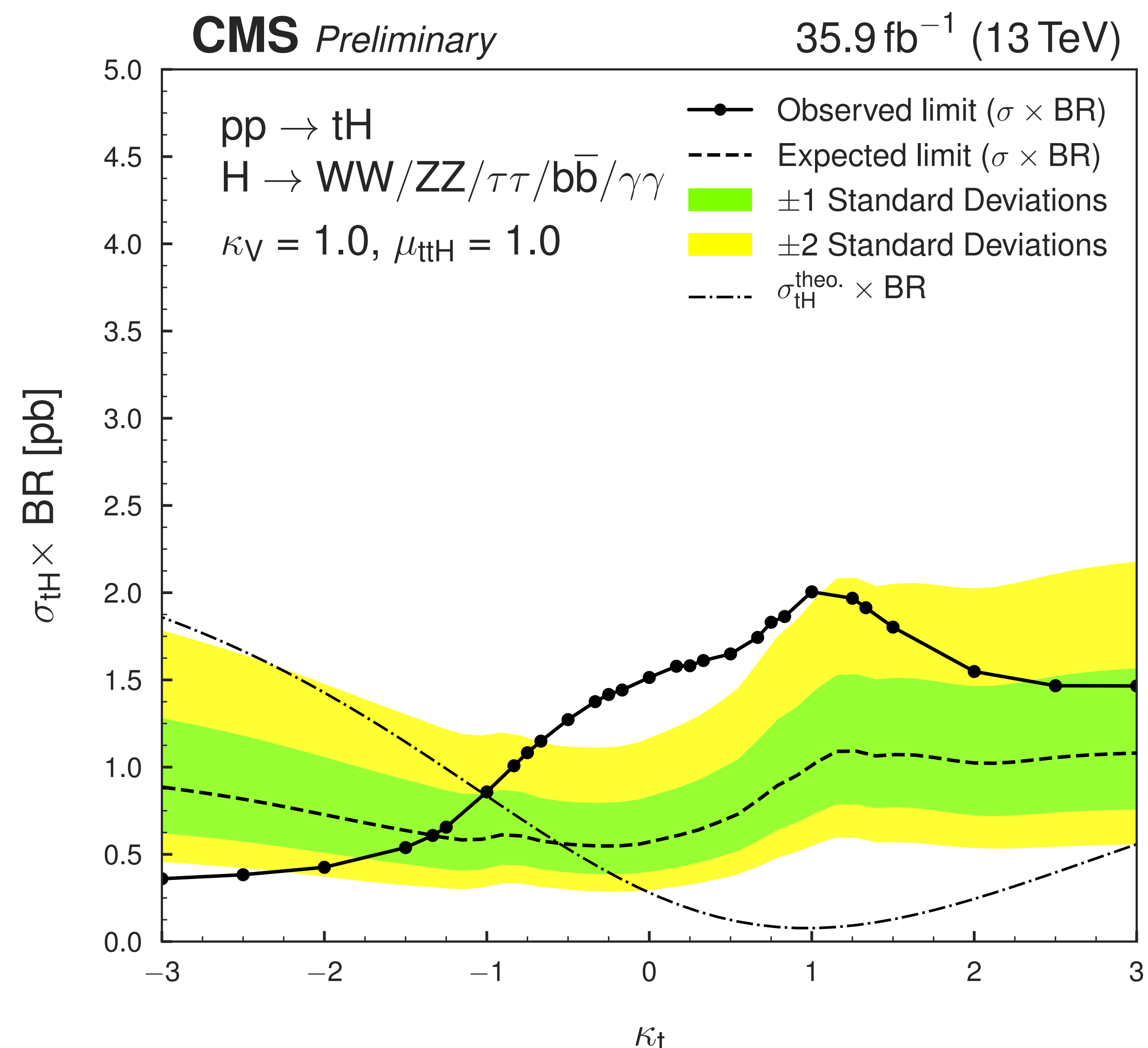
CMS-PAS-HIG-18-018

ATLAS-CONF-2019-004

tH

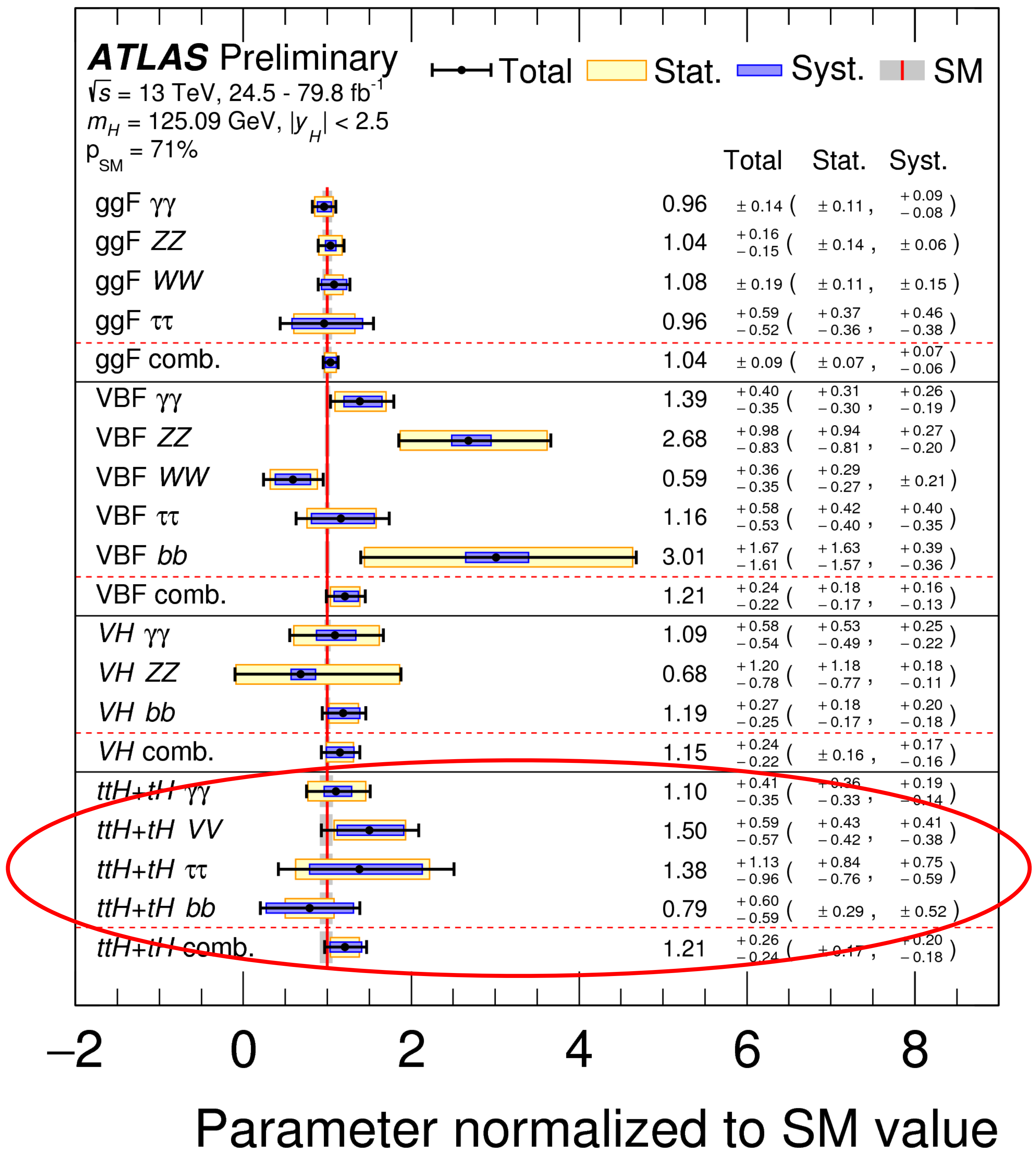
- Rare production mode uniquely sensitive to the relative sign of Higgs-Vector and Higgs-top couplings
  - Given SM-like Higgs-vector coupling the data exclude a negative values of the top Yukawa below -0.9

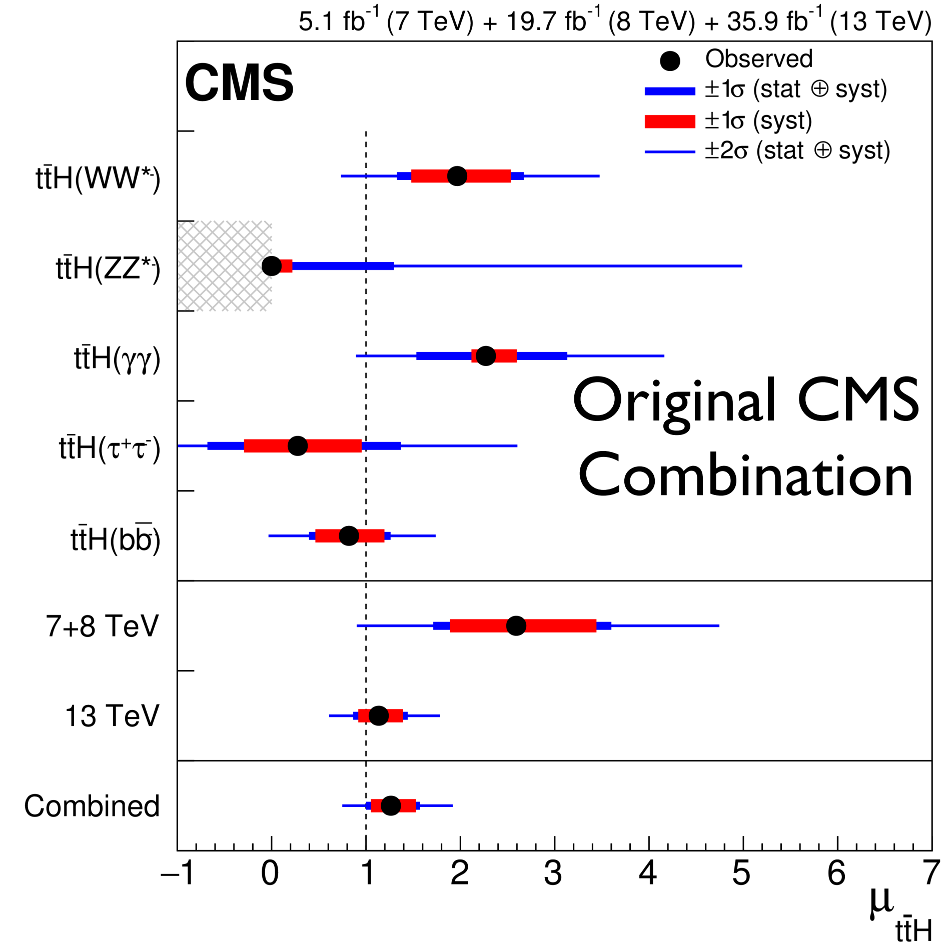




HIG-18-009

ttH in the Global Context





ATLAS-CONF-2019-005

Updated CMS results:

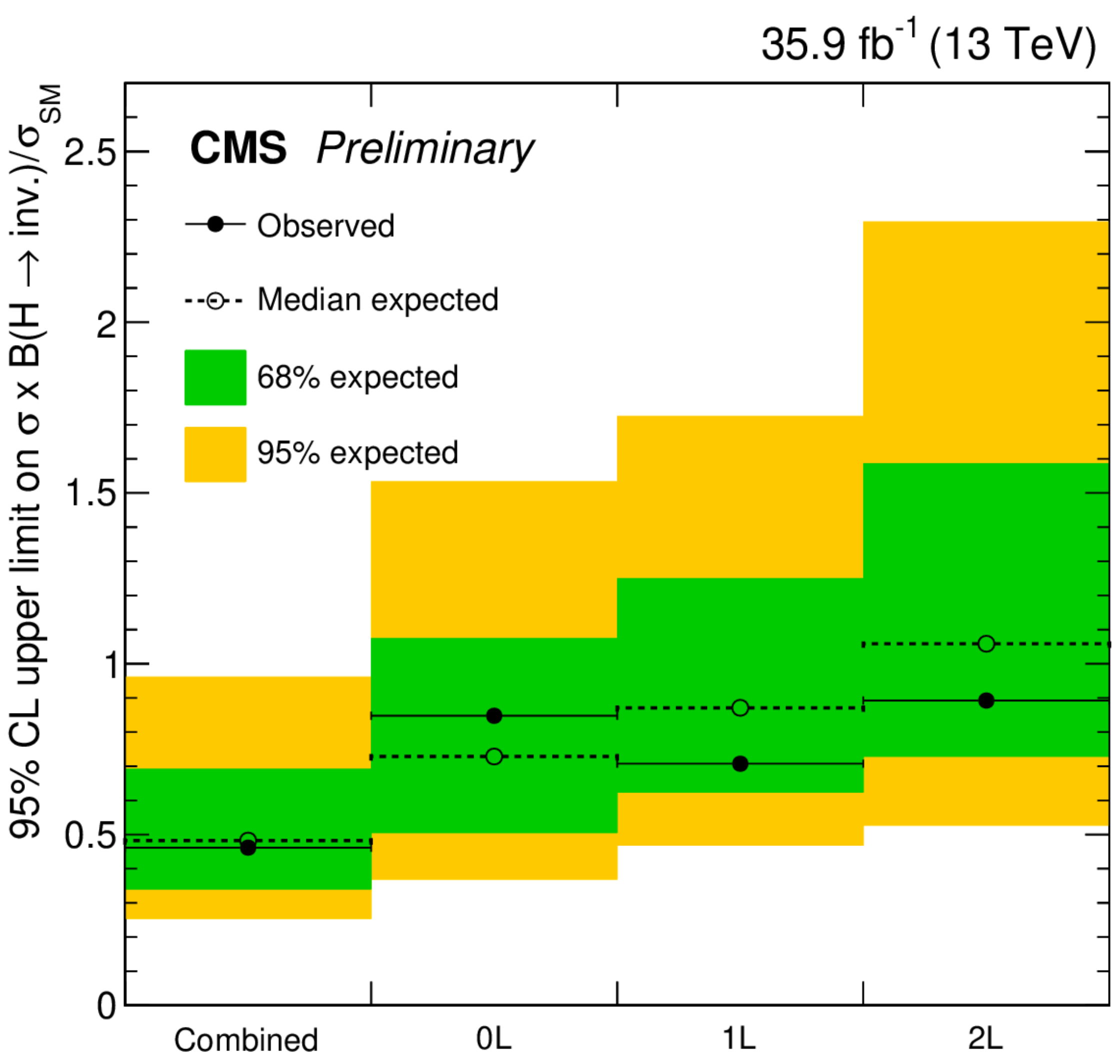
$$\mu_{t\bar{t}H(b\bar{b})} = 1.15^{+0.32}_{-0.29} \quad 77.4\ \text{fb}^{-1}$$

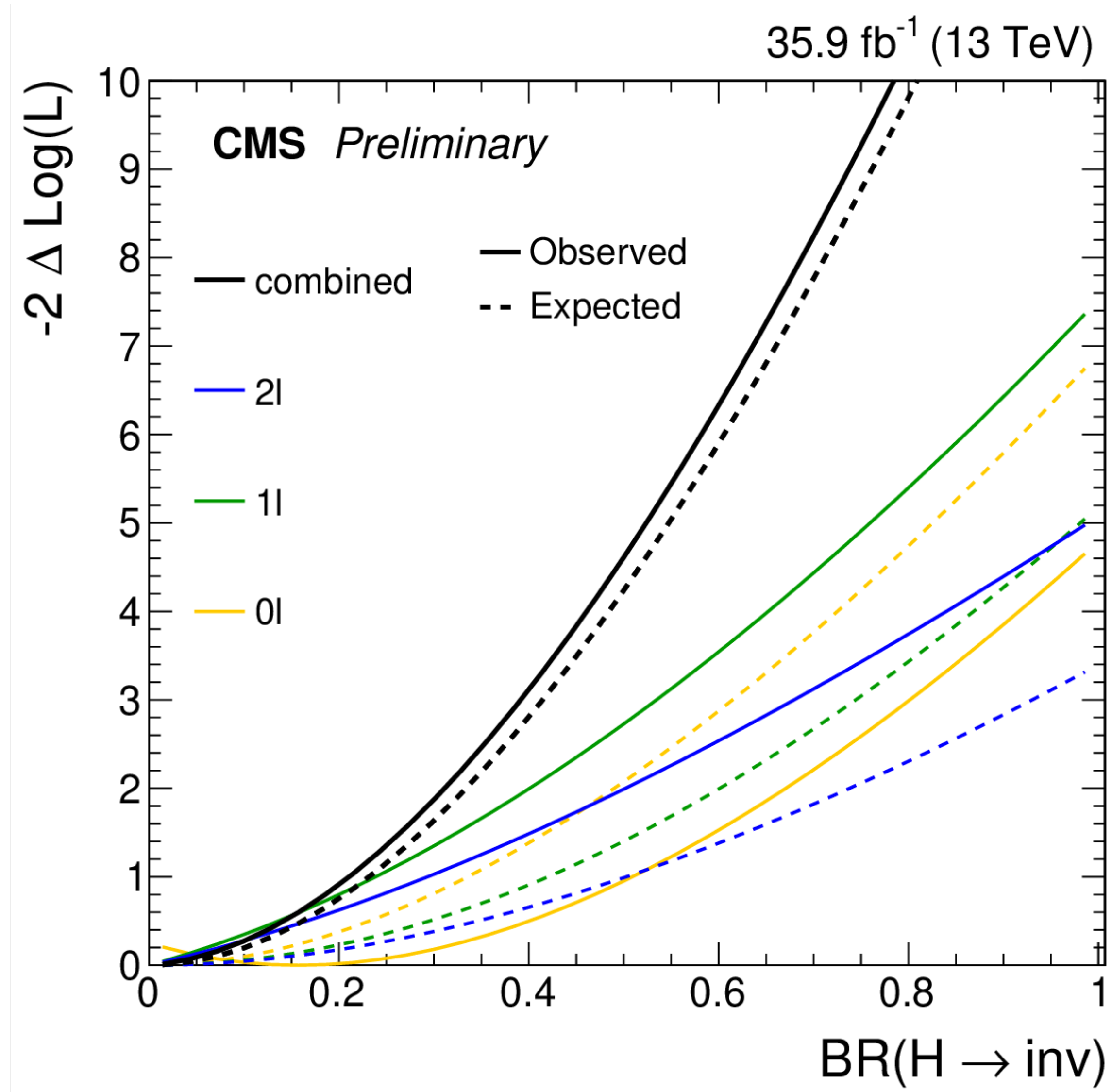
$$\mu_{t\bar{t}H(\tau\bar{\tau})} = 0.96^{+0.34}_{-0.31} \quad 41.5\ \text{fb}^{-1}$$

$$\mu_{t\bar{t}H(\gamma\gamma)} = 1.3^{+0.7}_{-0.5} \quad 41.5\ \text{fb}^{-1}$$

H(invisible) from ttH

- Difficult channel due to jets and real missing energy in top final states
  - Higgs results are derived by reinterpreting stop searches (same topologies)
  - 2x less powerful than most recent combination of other production modes, but brings a rare channel into the combination

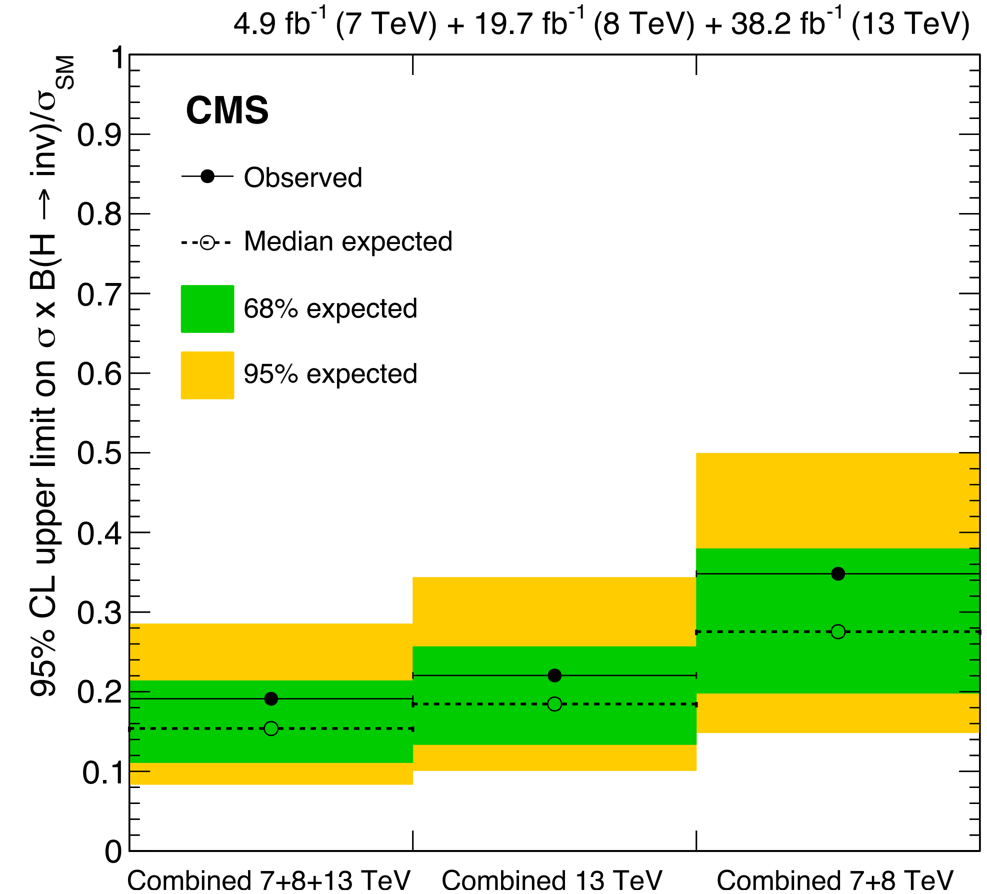


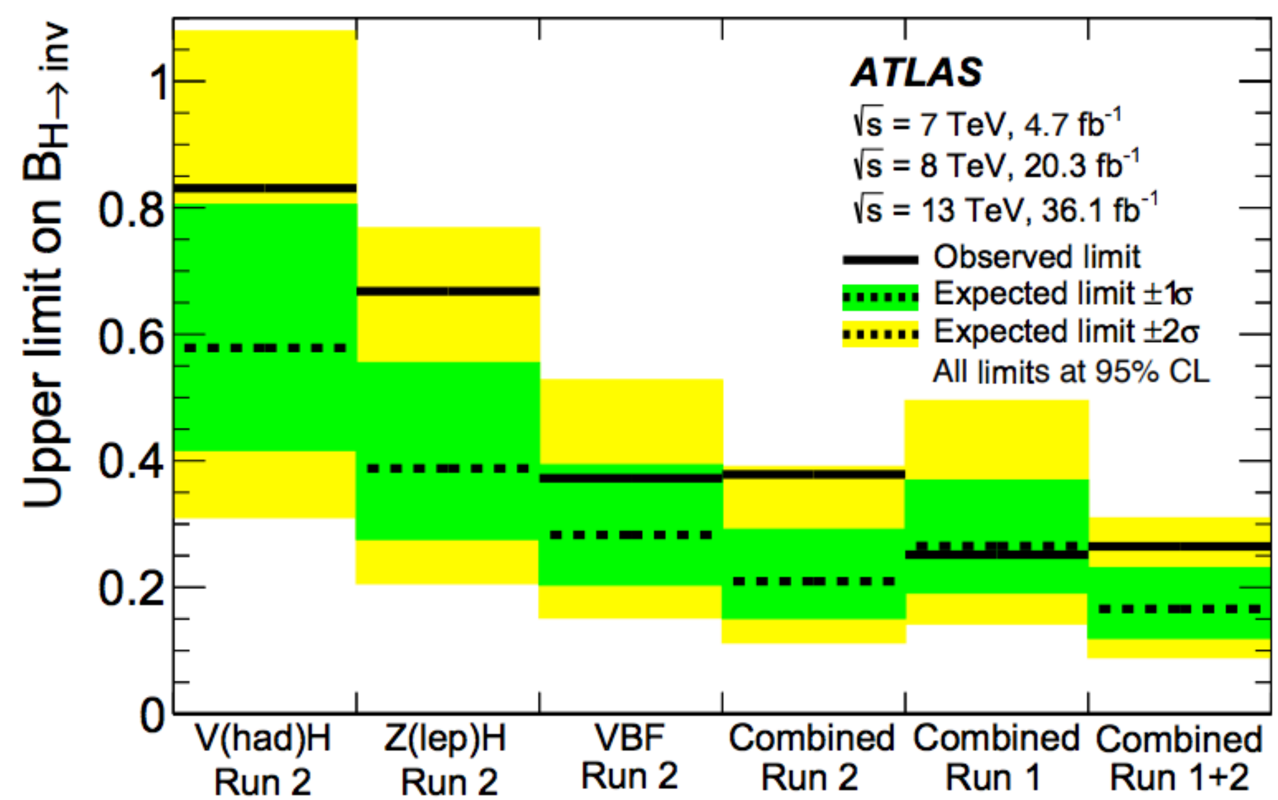


CMS-PAS-HIG-18-008

H(invisible)

- New ATLAS & CMS results combining Run2 and Run1 analyses
  - CMS: BR < 0.19 @ 95% CL
  - ATLAS: BR < 0.26 @ 95% CL
- Higgs to invisible a very rare SM process
  - H to ZZ to 4ν only major contribution
- Hence very sensitive to new physics
  - New massive particles
  - re-interpretable as dark matter searches





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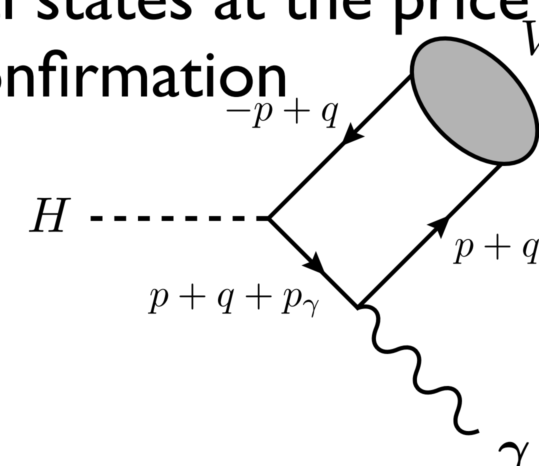
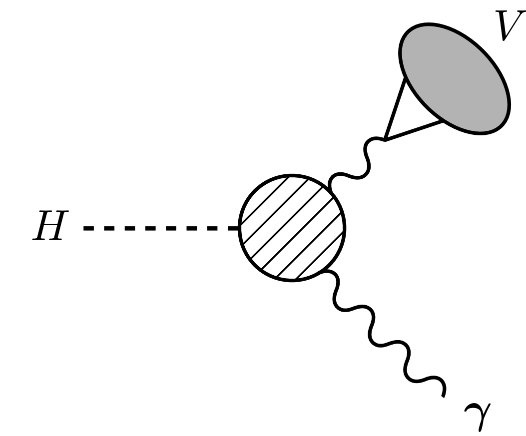
arxiv:1904.05105 arxiv:1809.05937

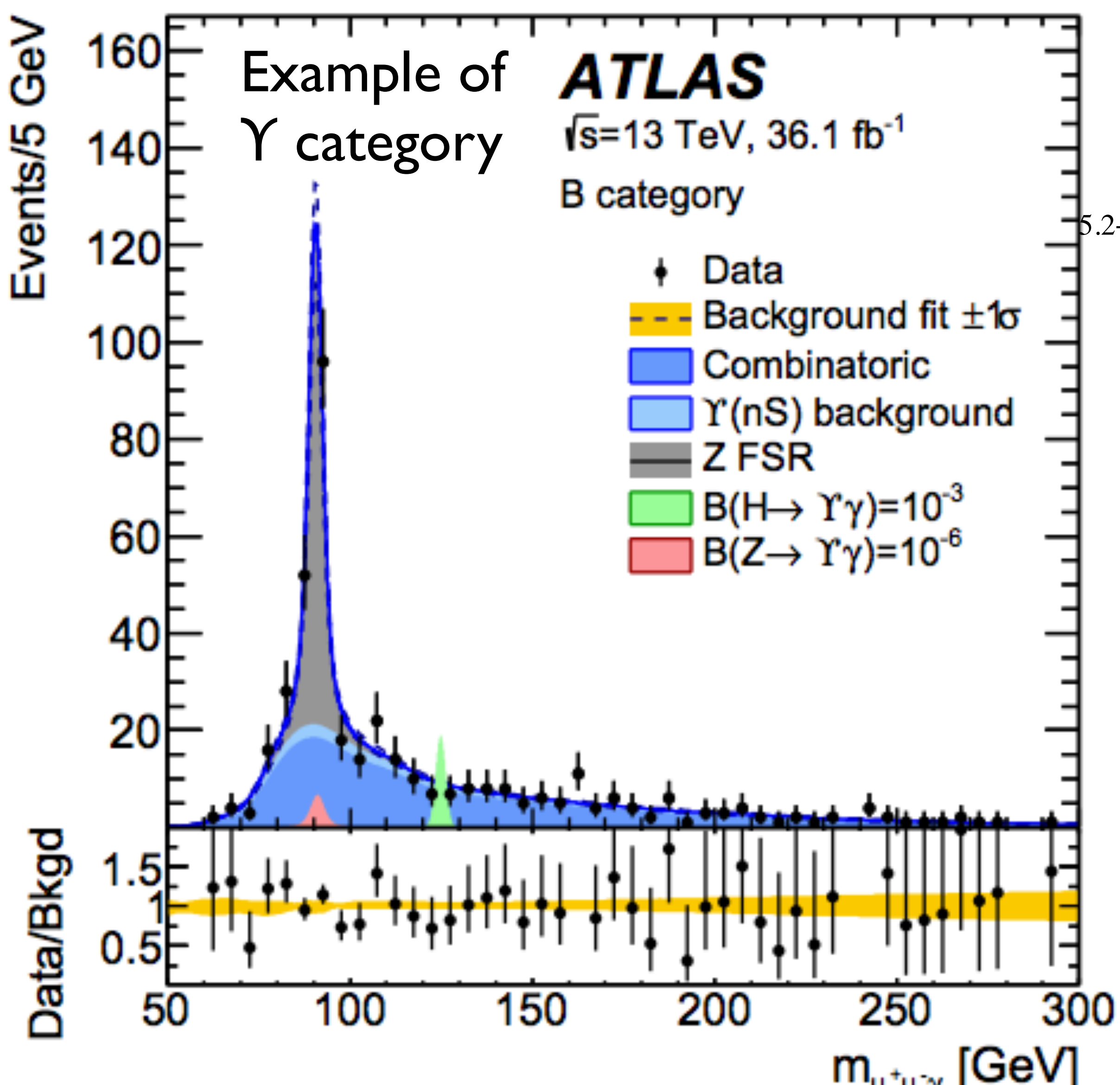
Exclusive Higgs Decays Results

ATLAS arxiv:1807.00802
CMS arxiv:1810.10056

- Higgs decays directly to bb and cc form broad peaks and have significant background challenges
  - exclusive hadronic final states provide clean final states at the price of greatly reduced branching ratio, excellent for confirmation
  - typical signature: vector meson + photon







5.2+2.4 −1.6 × 10−4 .

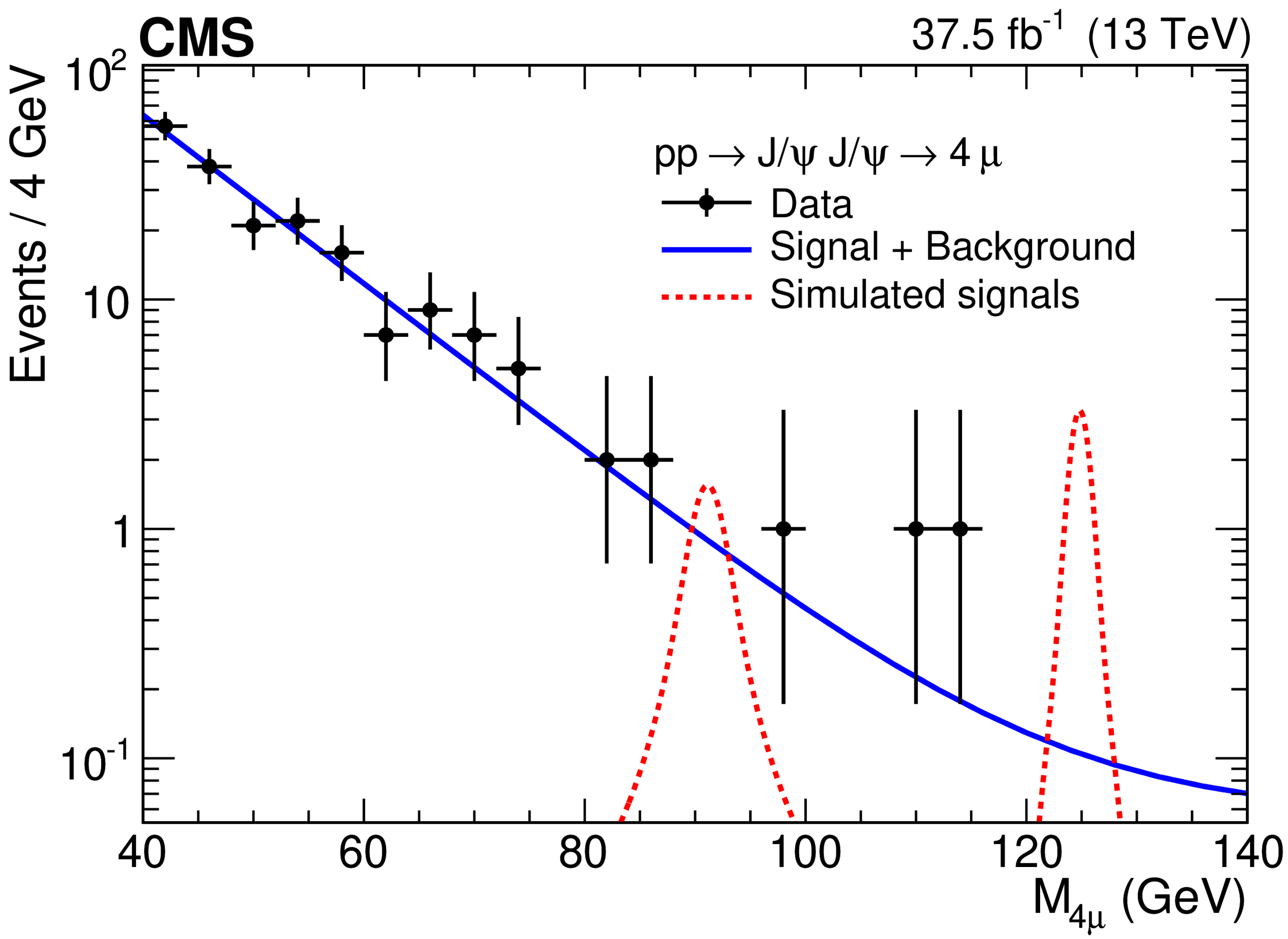
Limits ATLAS **CMS**

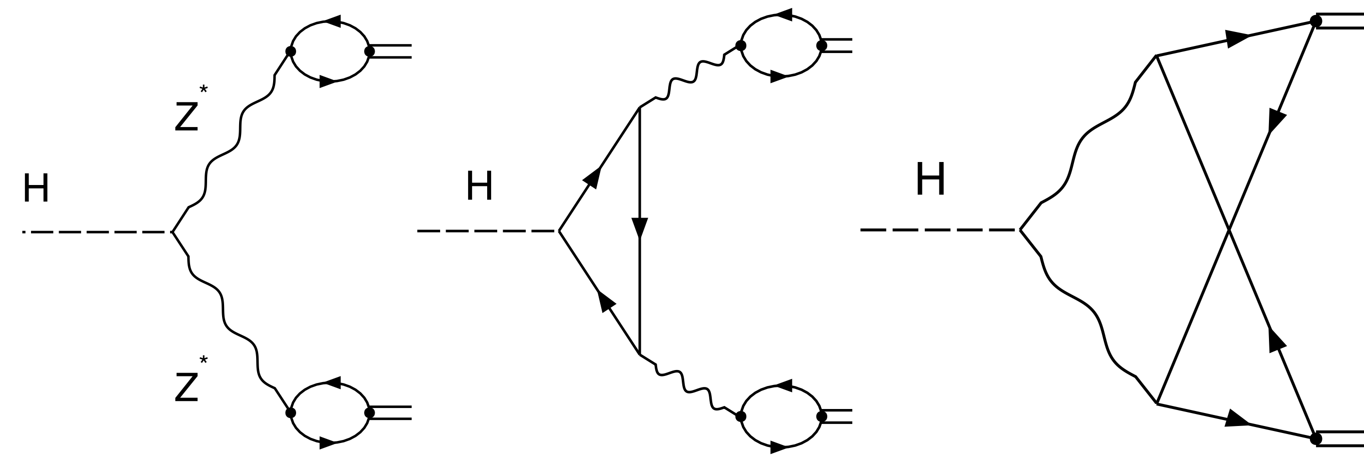
Branching fraction limit (95% CL)	Expected	Observed	CMS (35.9 fb^{-1})	
$\mathcal{B}(H\to J/\psi\,\gamma)\,[10^{-4}]$	$3.0^{+1.4}_{-0.8}$	3.5	$5.2^{+2.4}_{-1.6}$	7.6
$\mathcal{B}(H\to \psi(2S)\,\gamma)\,[10^{-4}]$	$15.6^{+7.7}_{-4.4}$	19.8		
$\mathcal{B}(Z\to J/\psi\,\gamma)\,[10^{-6}]$	$1.1^{+0.5}_{-0.3}$	2.3		
$\mathcal{B}(Z\to \psi(2S)\,\gamma)\,[10^{-6}]$	$6.0^{+2.7}_{-1.7}$	4.5		
$\mathcal{B}(H\to \Upsilon(1S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.4}_{-1.4}$	4.9		
$\mathcal{B}(H\to \Upsilon(2S)\,\gamma)\,[10^{-4}]$	$6.2^{+3.0}_{-1.7}$	5.9		
$\mathcal{B}(H\to \Upsilon(3S)\,\gamma)\,[10^{-4}]$	$5.0^{+2.5}_{-1.4}$	5.7		
$\mathcal{B}(Z\to \Upsilon(1S)\,\gamma)\,[10^{-6}]$	$2.8^{+1.2}_{-0.8}$	2.8		
$\mathcal{B}(Z\to \Upsilon(2S)\,\gamma)\,[10^{-6}]$	$3.8^{+1.6}_{-1.1}$	1.7		
$\mathcal{B}(Z\to \Upsilon(3S)\,\gamma)\,[10^{-6}]$	$3.0^{+1.3}_{-0.8}$	4.8		

*HL-LHC prospects in the backup

see also **H to φγ** arxiv:1712.02758

Higgs to DiMesons





Process	Observed	Expected
$\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi \mathrm{J}/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(\mathrm{H} \to \Upsilon\Upsilon)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(\mathrm{Z} \to \mathrm{J}/\psi \mathrm{J}/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(\mathrm{Z} \to \Upsilon\Upsilon)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

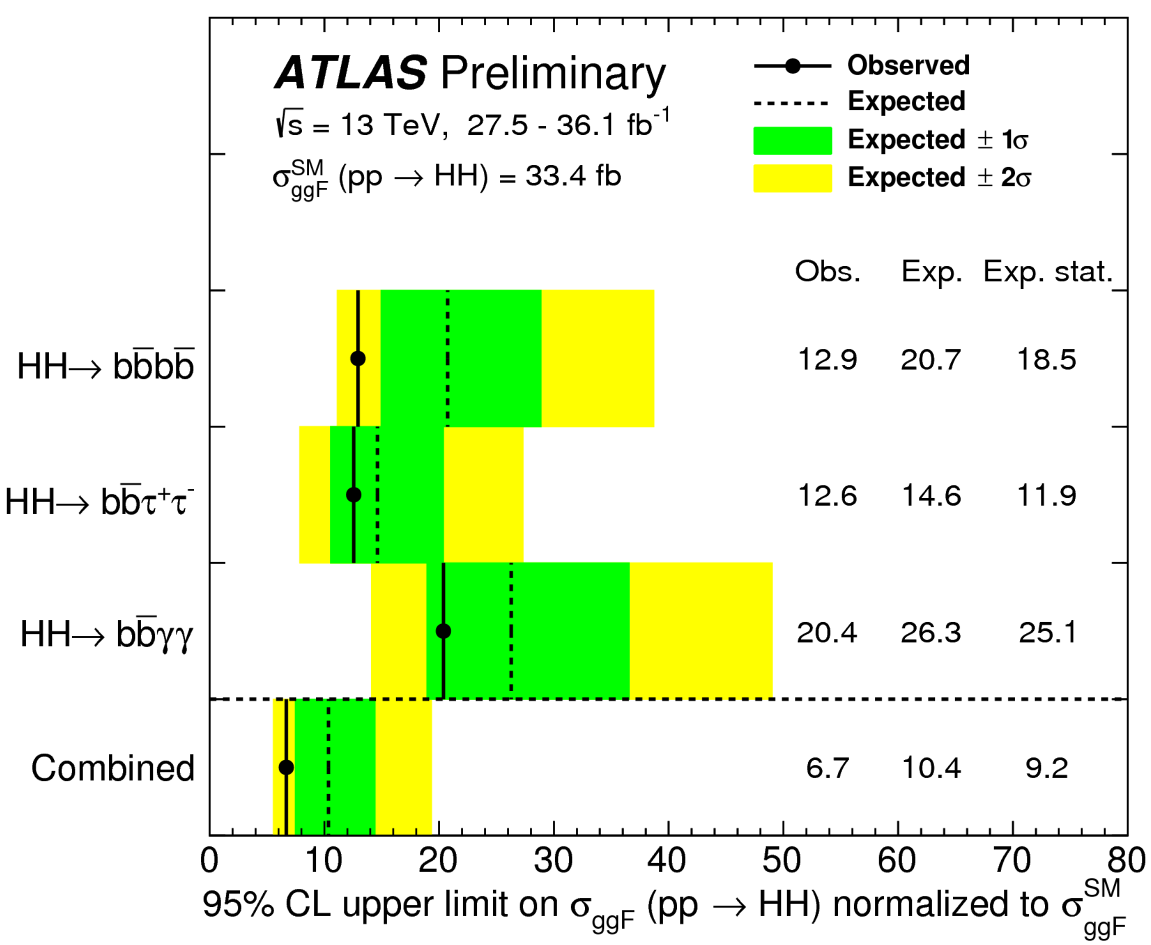
Limits

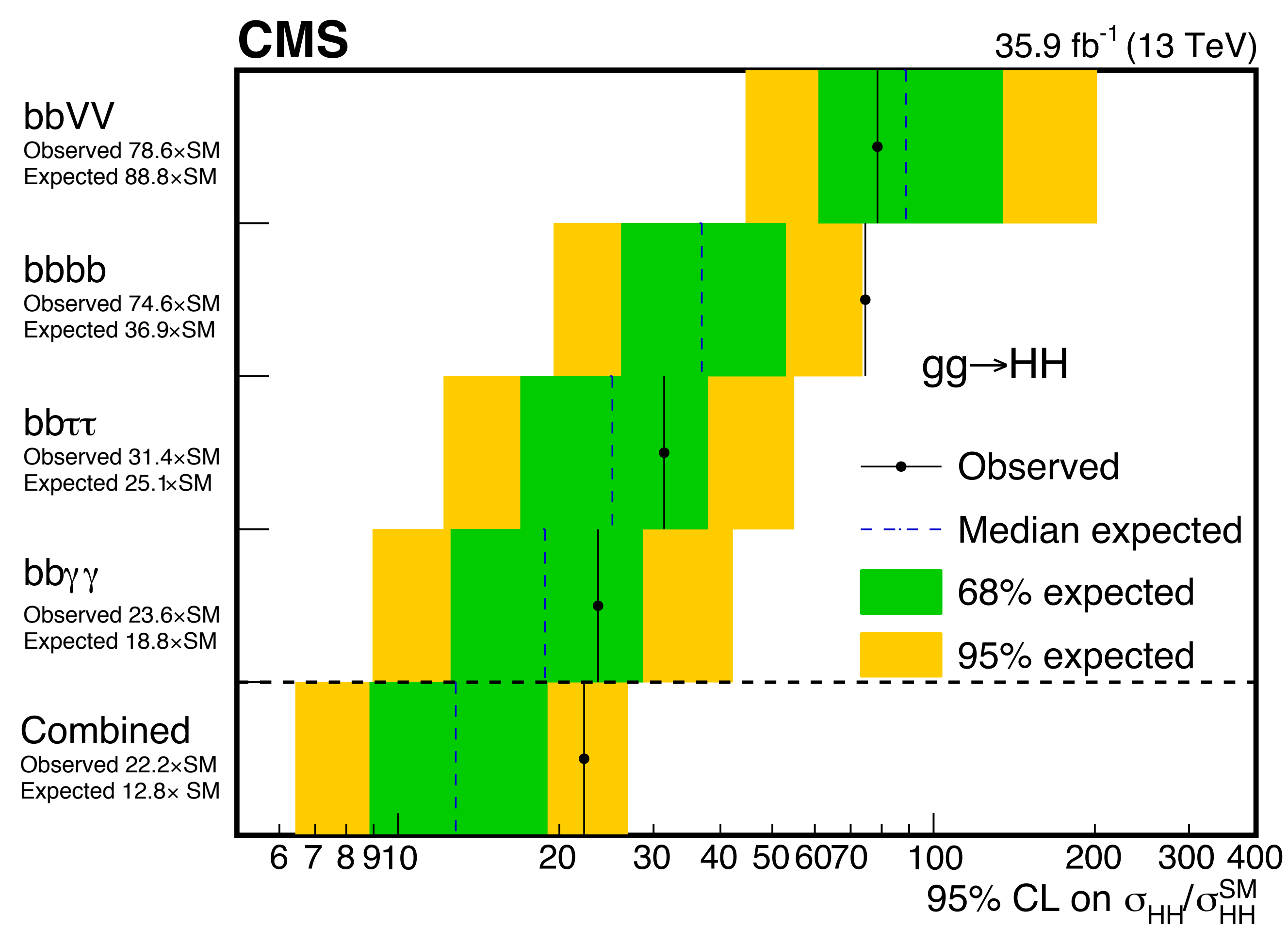
- This analysis explores strong cancellations of diagrams which are strongly affected by new physics in loops
  - Expect branching ratios: 10^-10 for J/Psi, 10^-9 for Y
- Clean channel to look for a variety of new physics signatures, test varying decay models

CMS-PAS-HIG-18-025

DiHiggs

- Search for SM DiHiggs production underway!
  - ~36 fb total cross section
  - Experiments starting to fill out the set of contributing channels
- Since cross section is quite small many opportunities for new physics modifications
  - Many possibilities for new scalars and tensors decaying to Higgs
- Mastering all channels and our detectors will be critical for the future

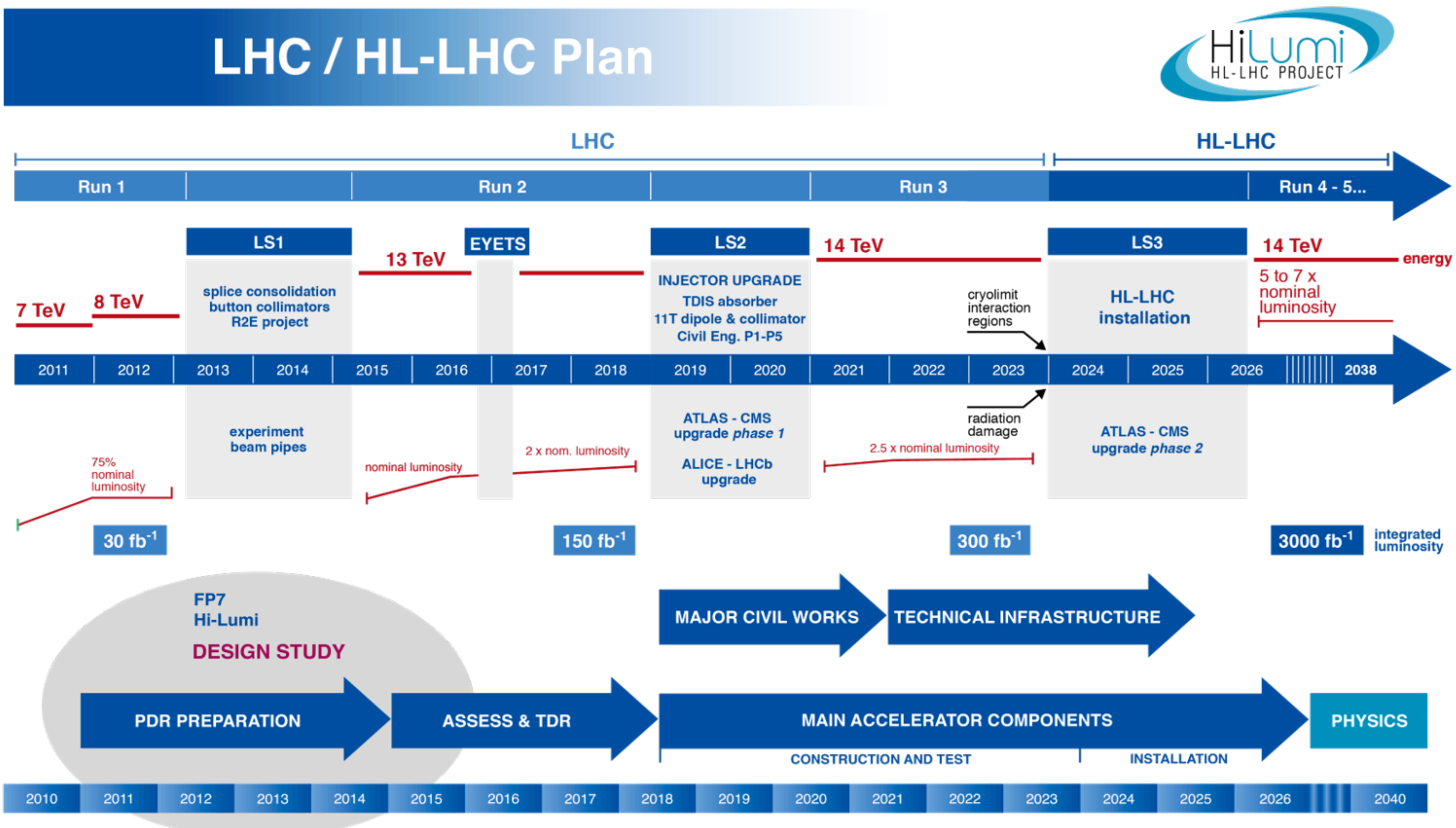




 ATLAS-CONF-2018-043 Lindsey Gray, FNAL arxiv:1811.09689

Finding the Rarest with HL-LHC

- Observation of the rarest final states and production modes requires HL-LHC
  - 10 times more data than LHC
- Upgrade nearly every part of CMS & ATLAS detectors to cope with luminosity



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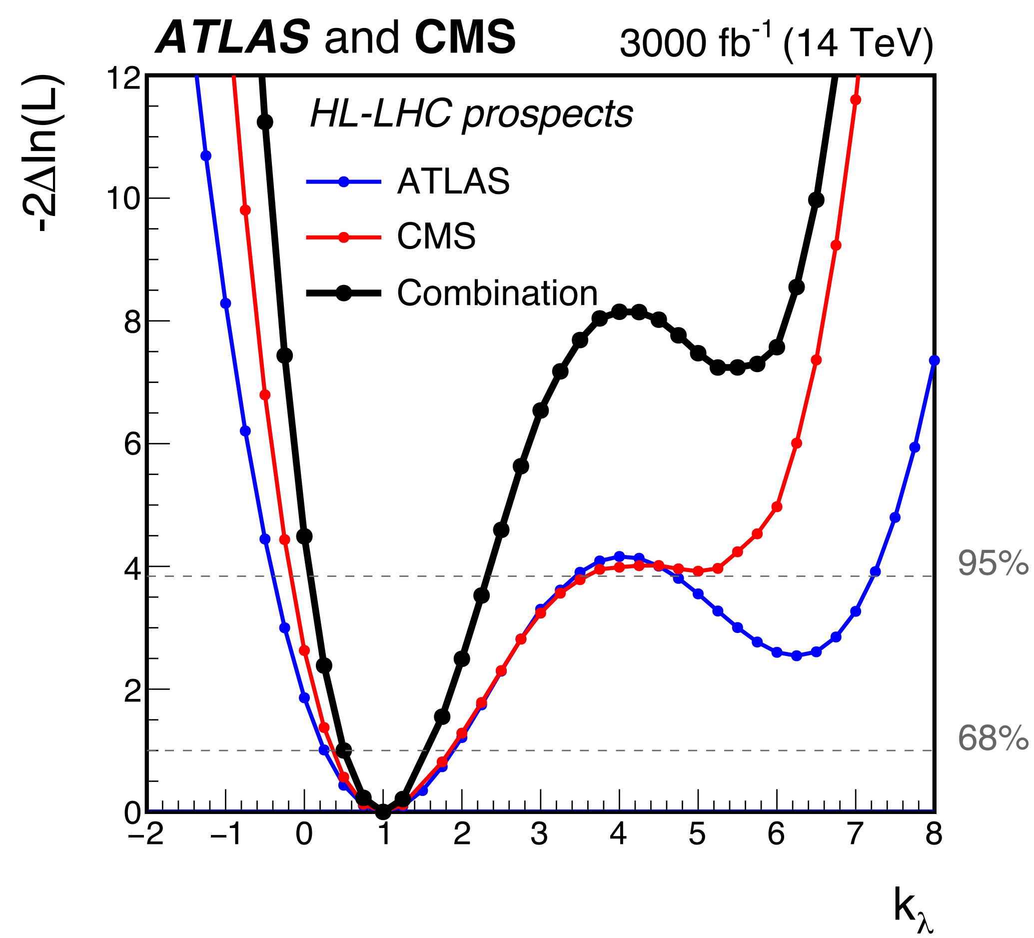
HH Measurement

- HL-LHC combination across all channels yields 4 sigma expected significance
  - 3000 fb^-1, assuming favorable systematics scaling and somewhat aged detectors
- Need to keep on the trail of novel analysis techniques
  - Measuring κ_λ to better than 50% may be possible by using single Higgs contributions
- Cross-experiment combination is a requirement to cap the Standard Model
  - We will also have to make sure we deliver all the performance our upgraded detectors suggest they can provide, and push beyond

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

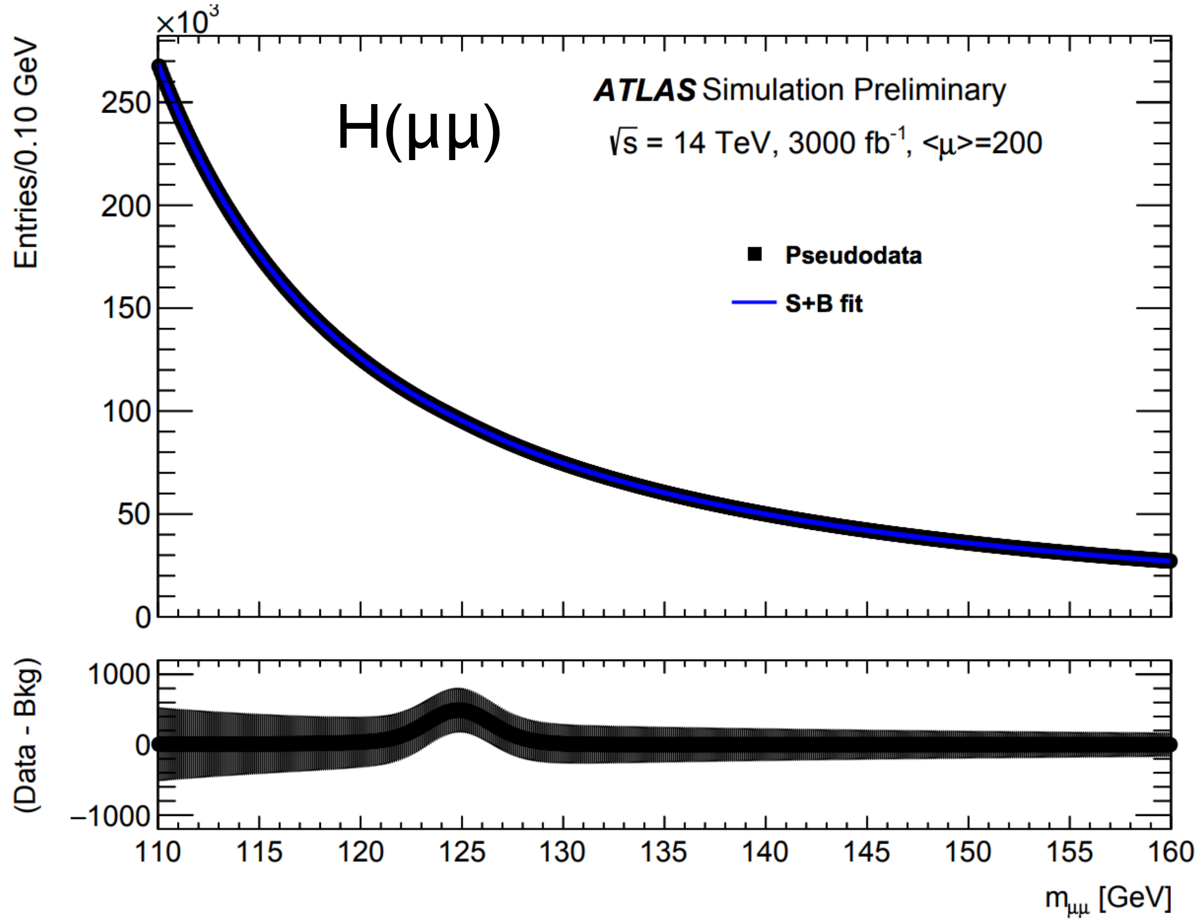


$$0.52 \leq \kappa_\lambda \leq 1.5$$

 arxiv:1902.00134

Outlook on 2nd Generation

- VH(cc) analysis investigating sensitivity in resolve H(cc) decays
  - Upper limit of 6.2x SM
  - Current result 100x SM
- Higgs to μμ
  - Expect > 9σ significance per experiment



H(cc)

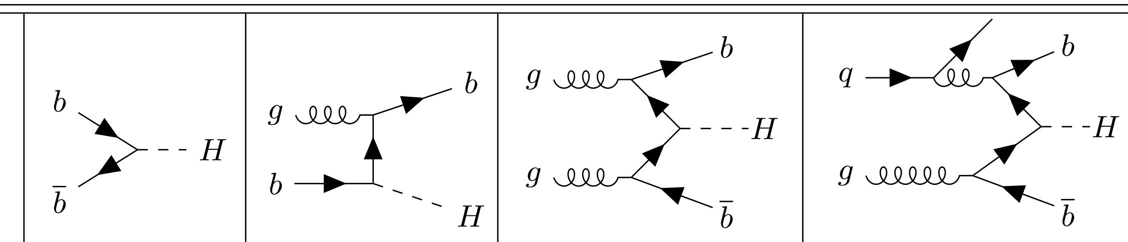
Sample	Yield			
	1 c-tag		2 c-tags	
	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z > 150\,GeV$	$75 \leq p_T^Z < 150\,GeV$	$p_T^Z > 150\,GeV$
$Z+$jets	$271\,000 \pm 13\,500$	$59\,300 \pm 2970$	4350 ± 217	892 ± 44.6
WZ	4080 ± 204	1700 ± 85.2	48.5 ± 2.42	29.6 ± 1.48
ZZ	2570 ± 128	1020 ± 50.9	95.7 ± 4.79	49.7 ± 2.49
$t\bar{t}$	$16\,000 \pm 827$	863 ± 44.6	241 ± 12.4	26.3 ± 1.36
$ZH(b\bar{b})$	441 ± 16.8	327 ± 12.4	10.7 ± 0.407	9.38 ± 0.356
$ZH(c\bar{c})$	74.4 ± 2.83	52.6 ± 2.00	8.54 ± 0.325	6.89 ± 0.262
Total	$294\,000 \pm 13\,600$	$63\,300 \pm 2970$	4750 ± 218	1010 ± 44.7
$S/\sqrt{S+B}$	0.137 ± 0.008	0.209 ± 0.013	0.124 ± 0.007	0.216 ± 0.013

ATL-PHYS-PUB-2018-016

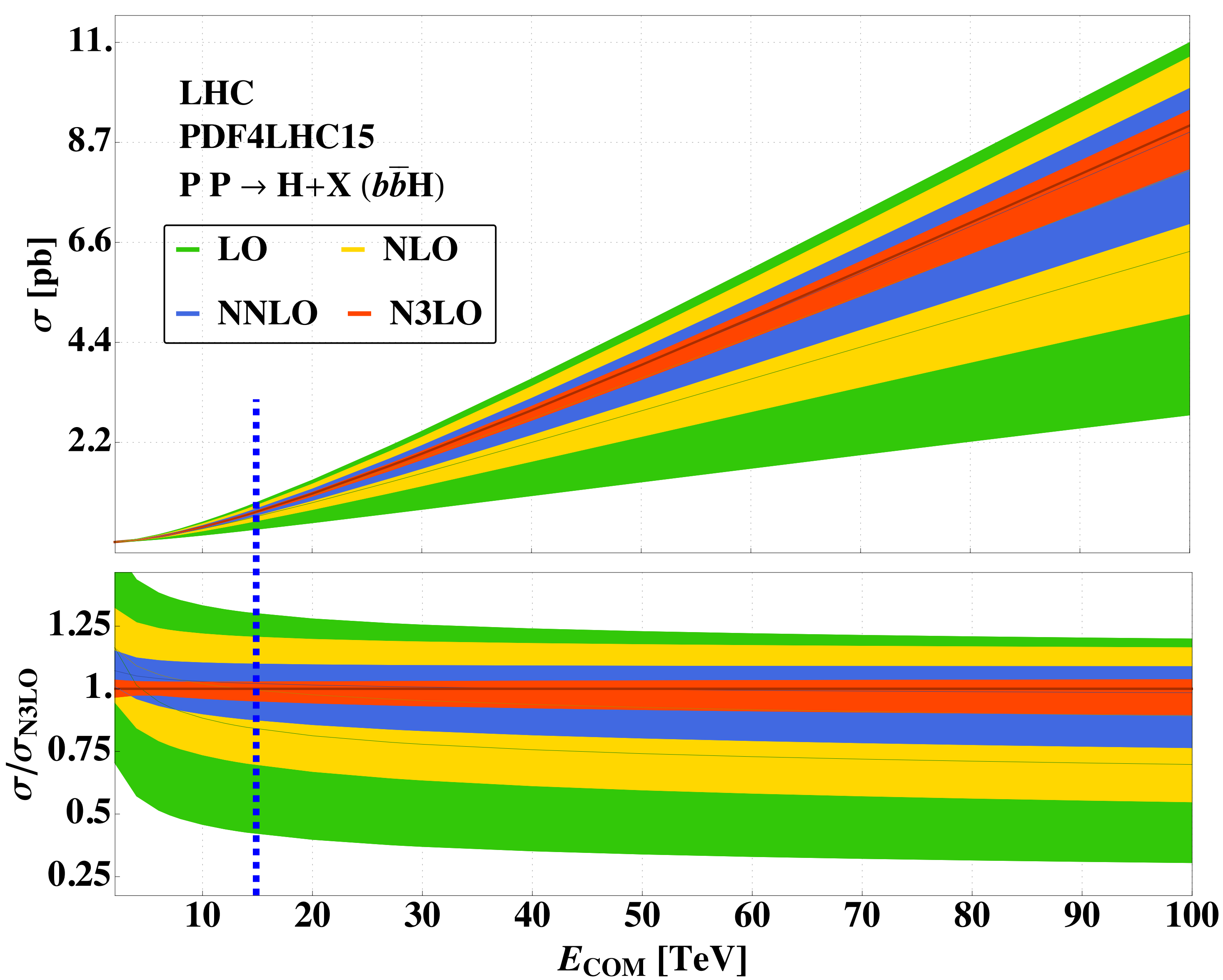
bbH Production

1904.09990

- Recent theoretical improvements in bbH production
  - ~500 fb at LHC energies
  - Largely indistinguishable from ggF without b-quark emission
- If measured, a powerful constraint on b-quark PDFs
  - Attempt at HL-LHC?

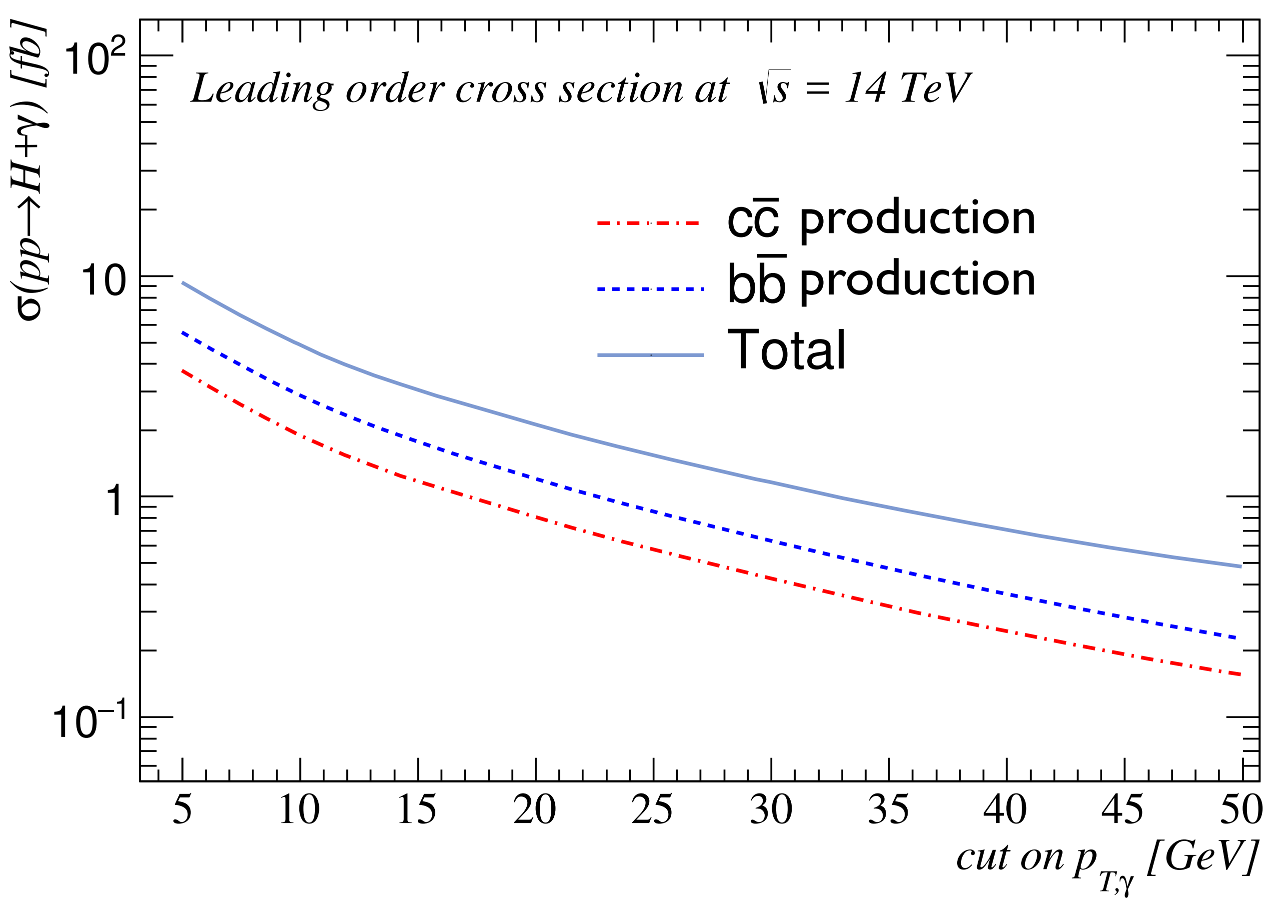


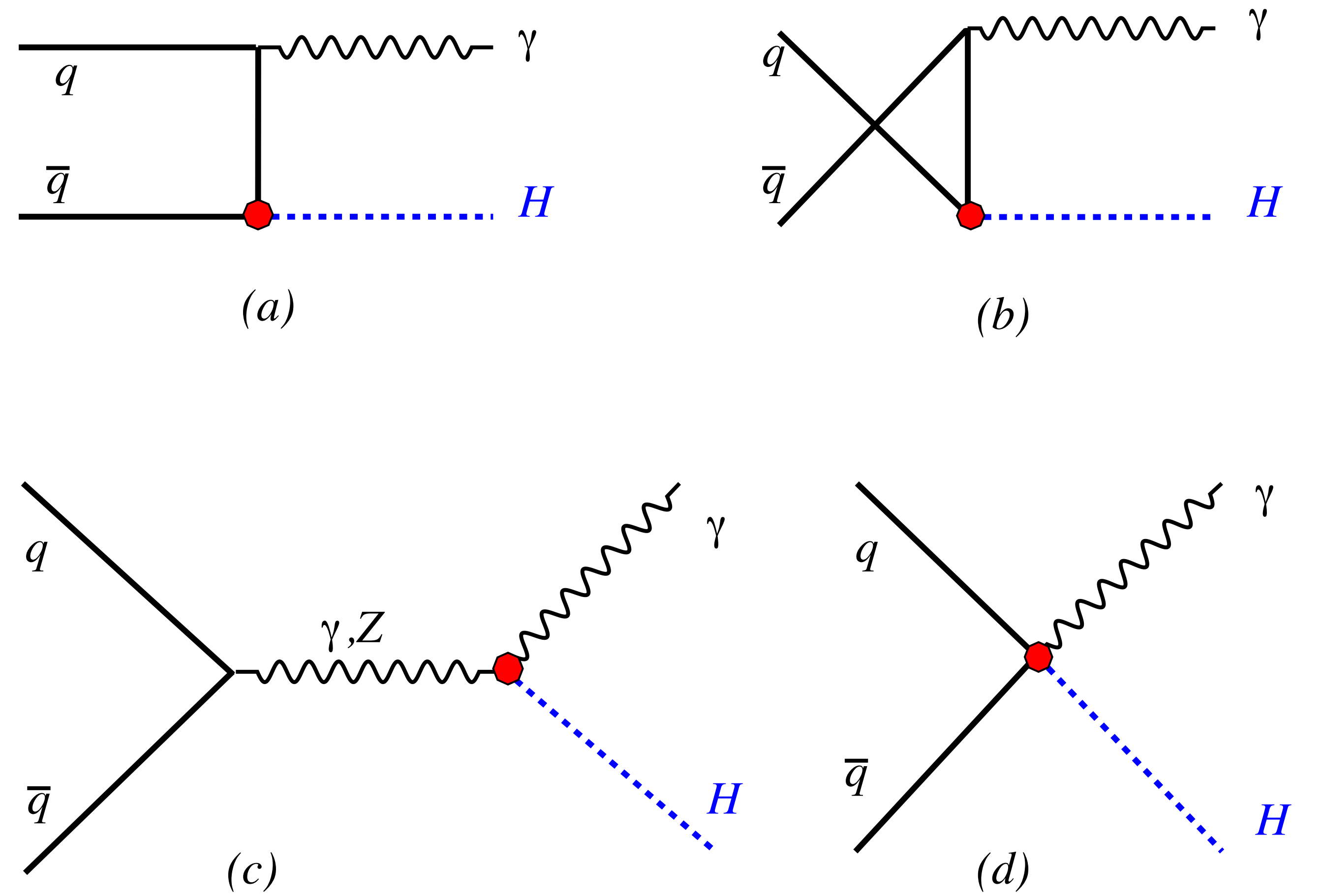
4FS	–	–	LO	NLO
5FS	LO	NLO	NNLO	N^3LO
Partonic channels (5FS)	$b\bar{b}$	$b\bar{b}, bg$	$b\bar{b}, bg, bb, bq, b\bar{q}, gg, q\bar{q}$	$b\bar{b}, bg, bb, bq, b\bar{q}, gg, q\bar{q}, qg$



γH Production

- One of the rarest Higgs production modes, ~20 fb
  - High sensitivity to fermionic and electroweak dimension-six operators
- Difficult photon backgrounds
  - multijet QCD in γH(bb)
- One of few production modes where quark and vector Dim6 operators may interfere
  - Only becomes measurable in HL-LHC datasets, limits still interesting for physics insight!





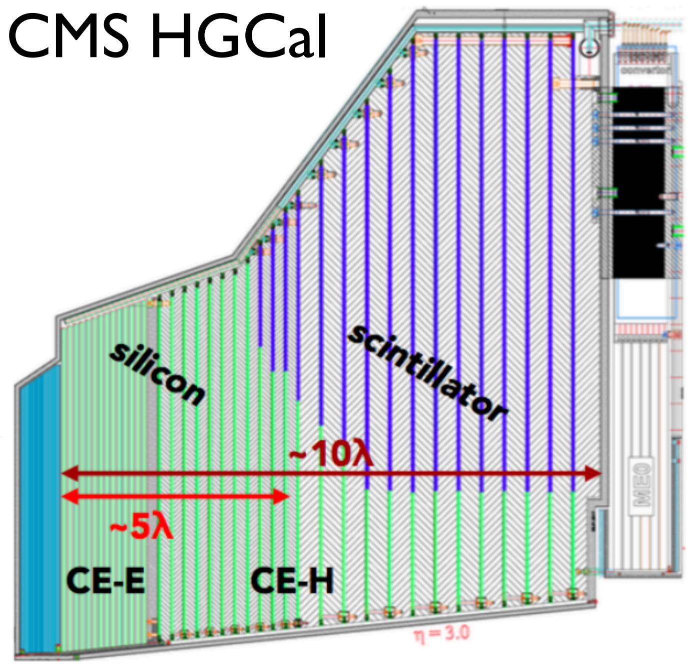
9706335 (1997!)

1702.05753

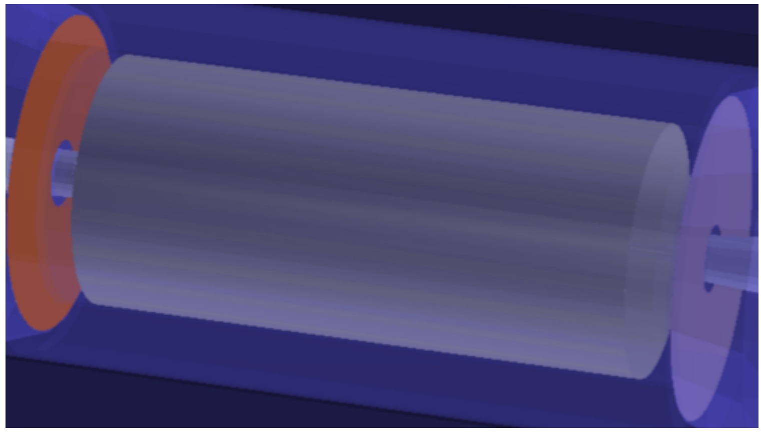
Rare Higgs & HL-LHC Detectors

- Most 'rarities' are statistically limited
  - More luminosity a trivial solution
    - but 200 pileup is not simple
    - rare combinatorial backgrounds
  - Some rarities are mixed together
    - ggF Higgs in VBF, VH, etc.
    - More data does not solve this

CMS HGCal

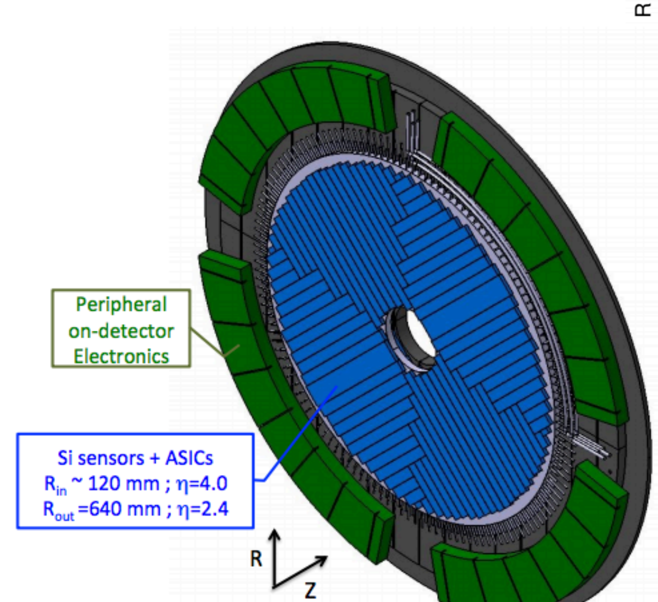


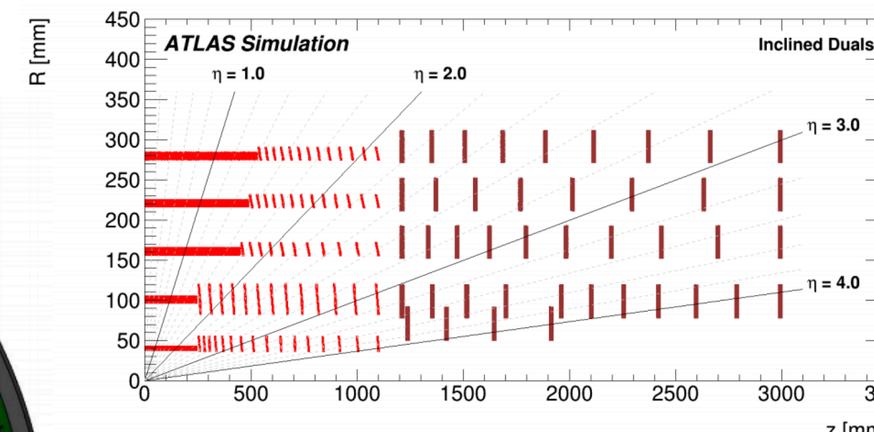
CMS MTD



- However, more luminosity requires detector upgrades
  - In ATLAS and CMS, finer granularity detectors are the trend
    - in space *and* time
    - combat combinatorics directly
  - Opportunities for new or improved discriminants

ATLAS HGTD

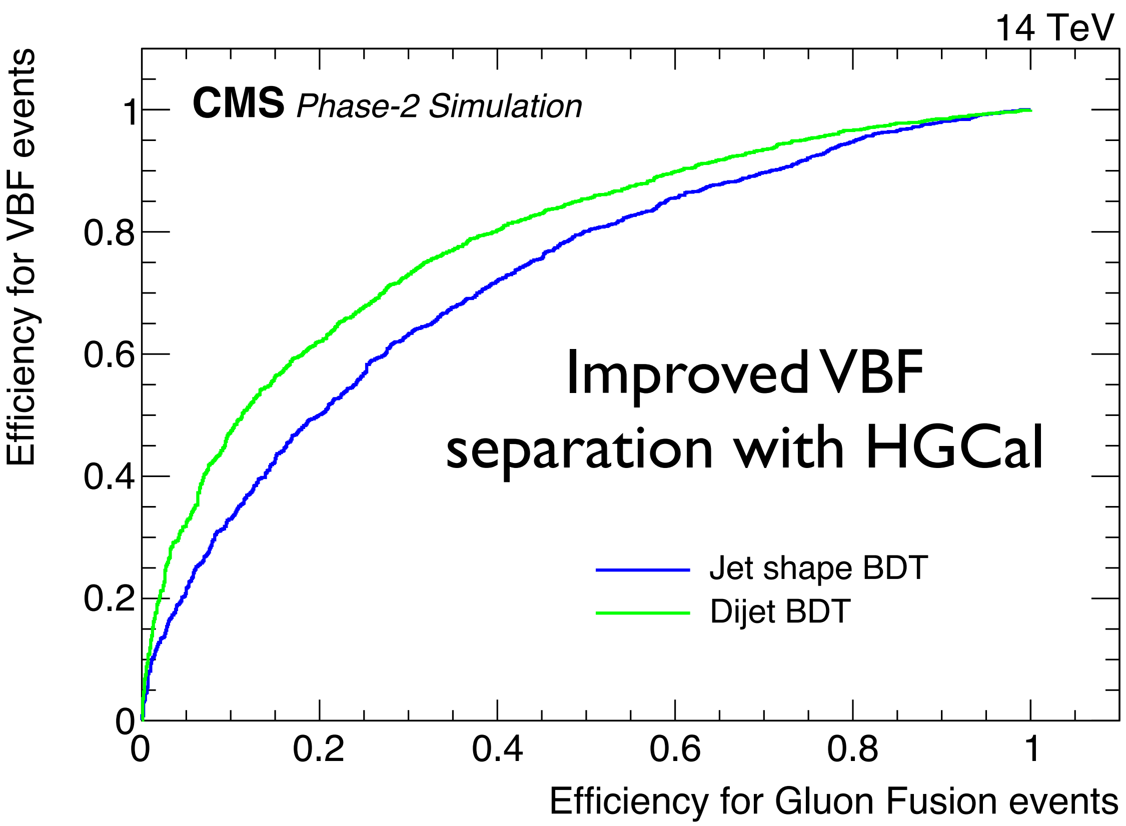




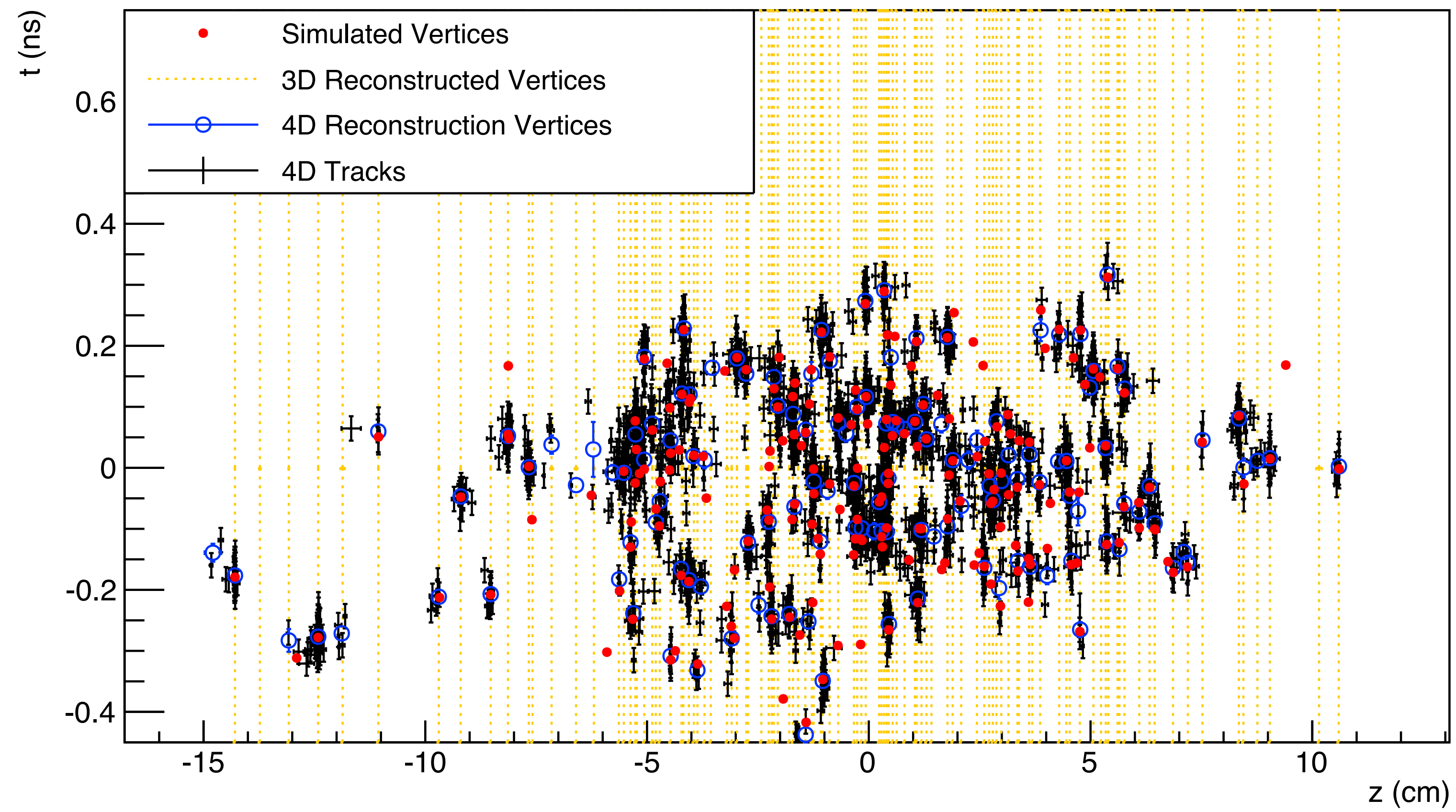
CMS / ATLAS pixel upgrades

*these are only a few detectors, read the TDRs for everything else we can do!

New & Improved Discriminants



Time-aware vertex reconstruction with MTD (or HGTD)

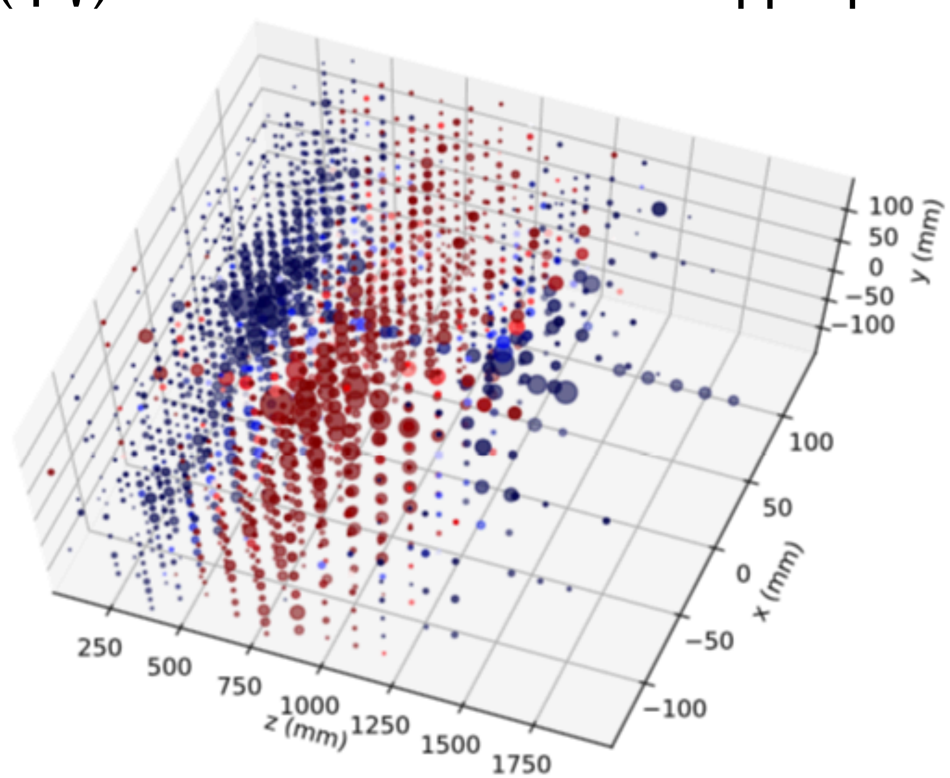


- Improved spatial segmentation in calorimetry and tracking divulges new jet and shower topology information
- Time segmentation identifies false coincidences, also provides particle ID

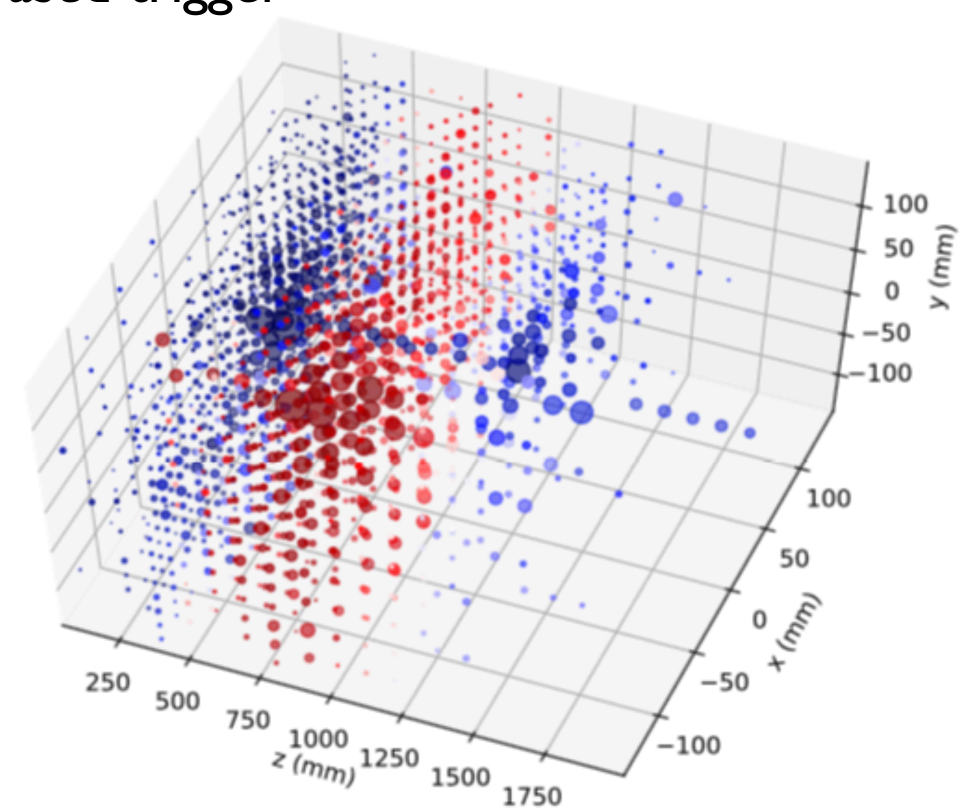
CMS-TDR-019 LHCC-P-009

Using Detectors to Their Fullest

- Data we will collect in HL-LHC era and beyond will be geometrically more complex than before
  - Detectors can read out information in 4-5 dimensions
    - Hadronic showers vary wildly in energy deposition pattern
  - Using Machine Learning in coordination with detector reconstruction is a key tool for exploiting such highly dimensional data
- Focus on triggers for interesting is paramount
  - H(φγ) could be accessible with appropriate tracking based trigger



(a) Truth



(b) Reconstructed

Early-phase research successful in reconstructing overlapping hadronic showers (graph neural networks)

arxiv:1902.07987

Concluding Remarks & Outlook

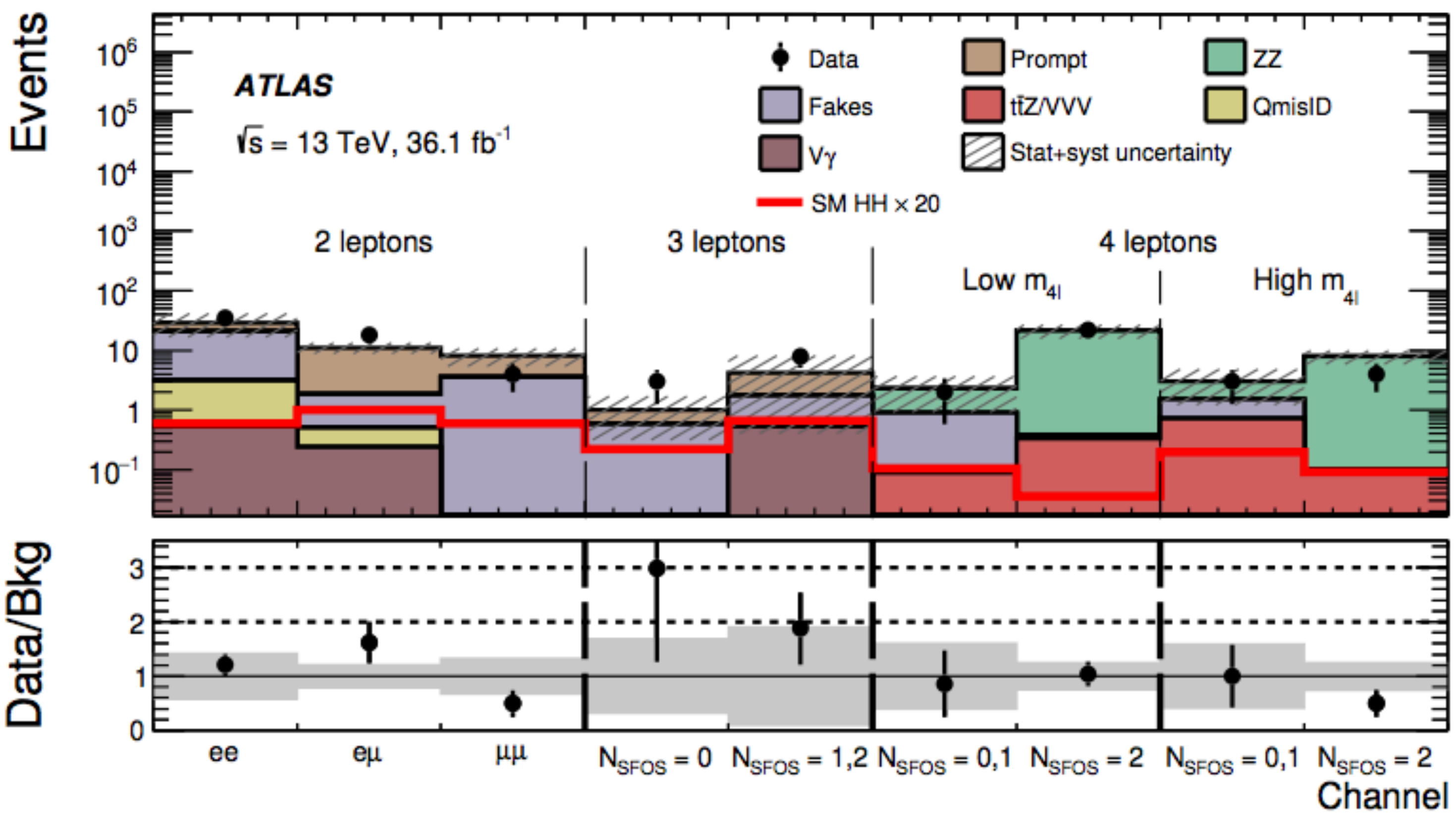
- Rare Higgs decay and production modes provide unique windows for understanding Higgs properties
  - top-Higgs only direct measurement of $|y_T|$
  - Higgs to invisible a powerful test of BSM physics
  - DiHiggs programs ramping up in both experiments
  - Measuring the charm coupling may require inventive approaches
- There are uncovered directions with interesting information
  - Extremely rare γH, bbH production modes only discussed in theory
- HL-LHC upgrades and Machine Learning bring an array of news tools to bear
  - We must exploit these new tools to achieve precise understanding of our currently 'rare' decays and to explore the Higgs mechanism to further depths with the HL-LHC

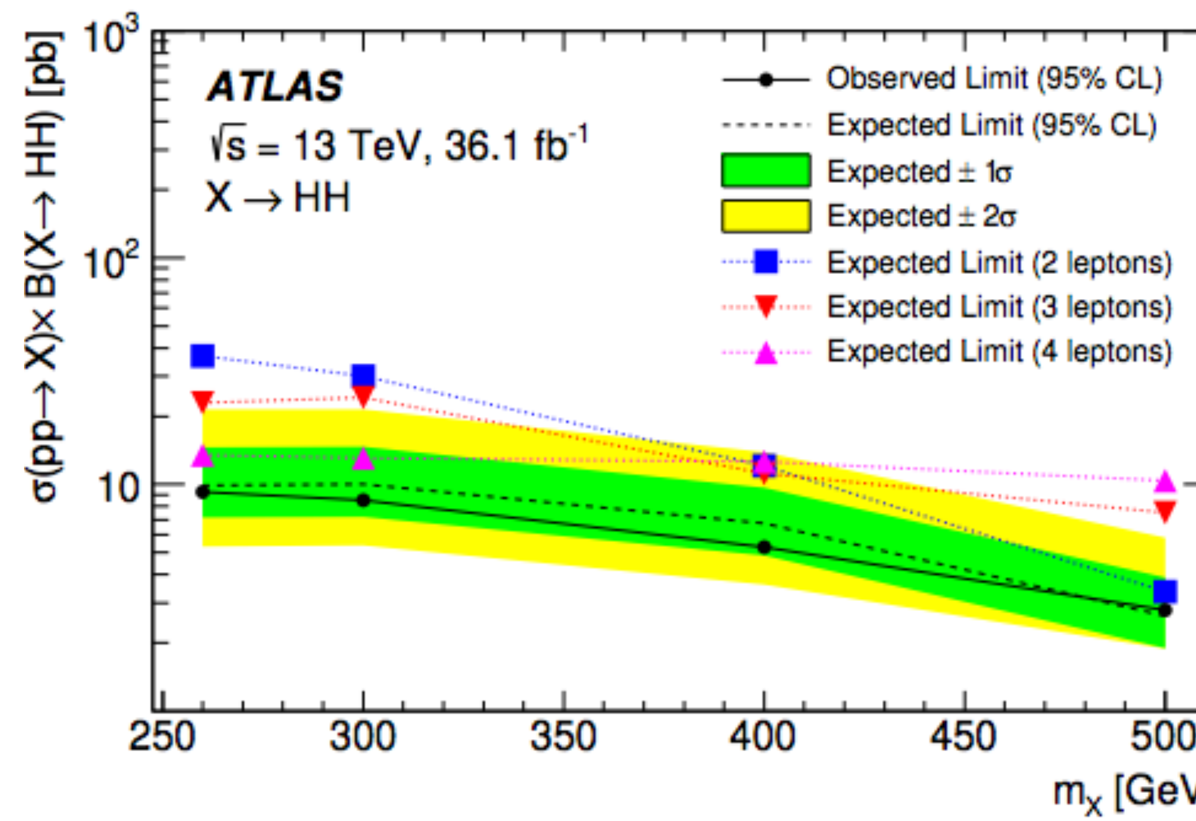
Extras

DiHiggs 4W BSM

arxiv:1811.11028

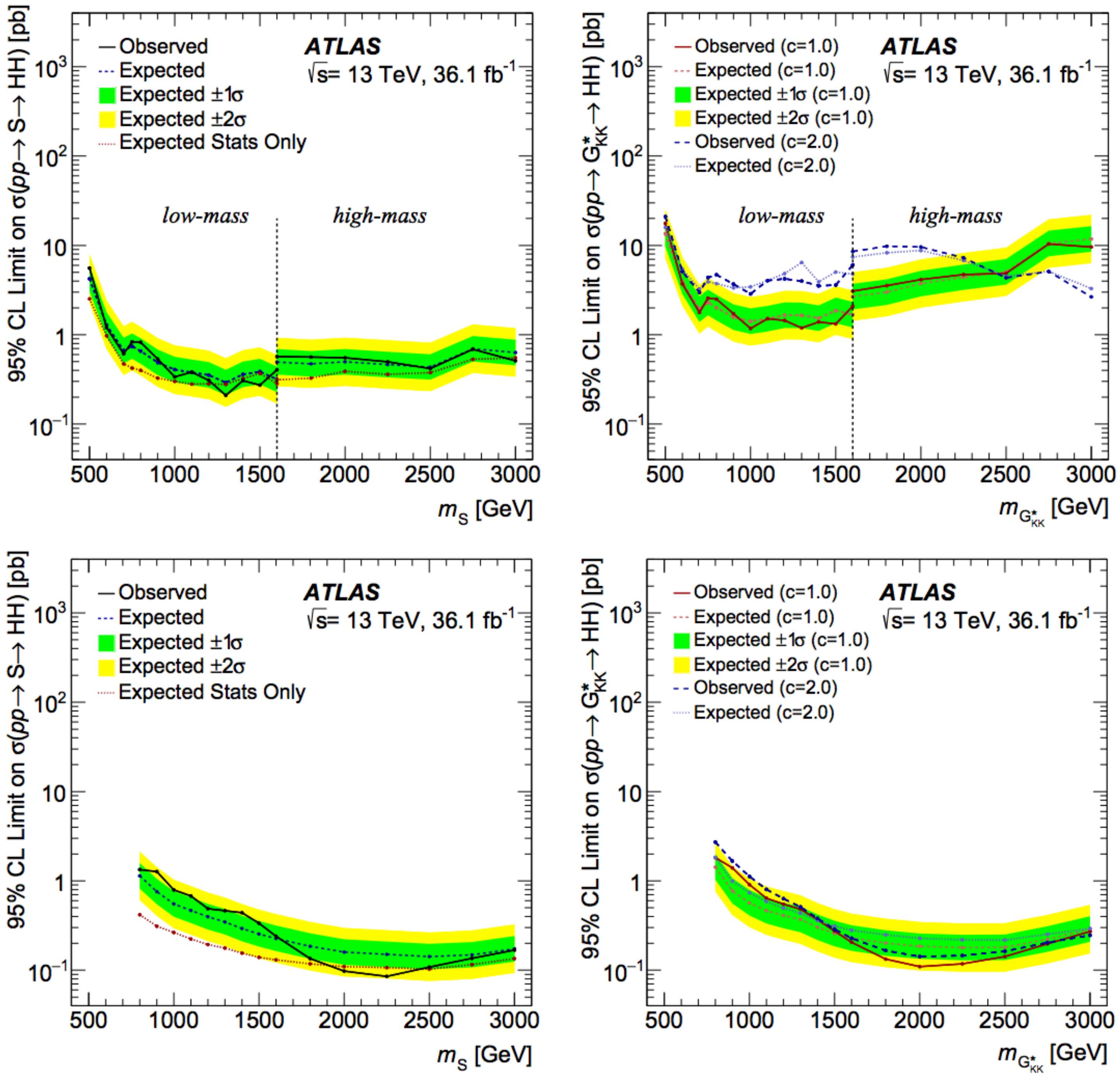
	Observed limit on σ/σ_{SM}	Expected limit on σ/σ_{SM} Median	$+2\sigma$	$+1\sigma$	-1σ	-2σ
2 leptons	170	150	290	210	100	78
3 leptons	420	270	690	420	200	150
4 leptons	340	400	880	590	290	210
Combined	160	120	230	170	83	62





- ATLAS also recently exploring 4 vector boson production from DiHiggs in context of new physics searches
  - Sensitivity to SM process limited due to backgrounds

DiHiggs bbWW (ATLAS)



$$\sigma(pp \to HH) \cdot \mathcal{B}(HH \to bbWW^*) < 2.5 \left(2.5^{+1.0}_{-0.7}\right) \text{ pb,}$$

arxiv:1811.04671

- Search for SM DiHiggs production underway!
  - ~40 fb total cross section
- Since cross section is quite small many opportunities for new physics modifications
  - Many possibilities for new scalars and tensors decaying to Higgs
- SM observation only possible with both detectors in HL-LHC
  - Mastering all channels and our detectors will be critical