Searches for di-Higgs production from ATLAS and CMS

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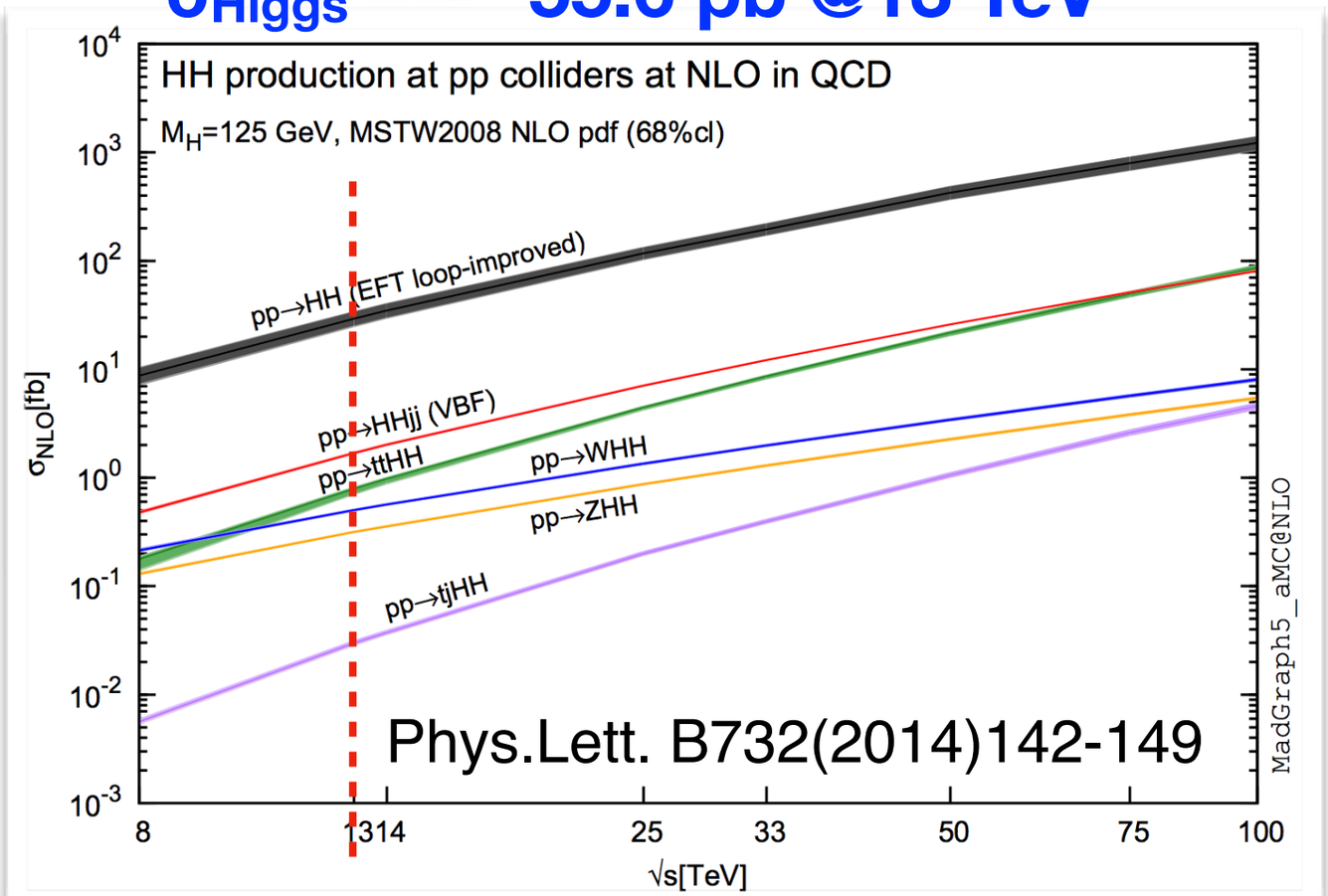
on behalf of the ATLAS and CMS Collaborations

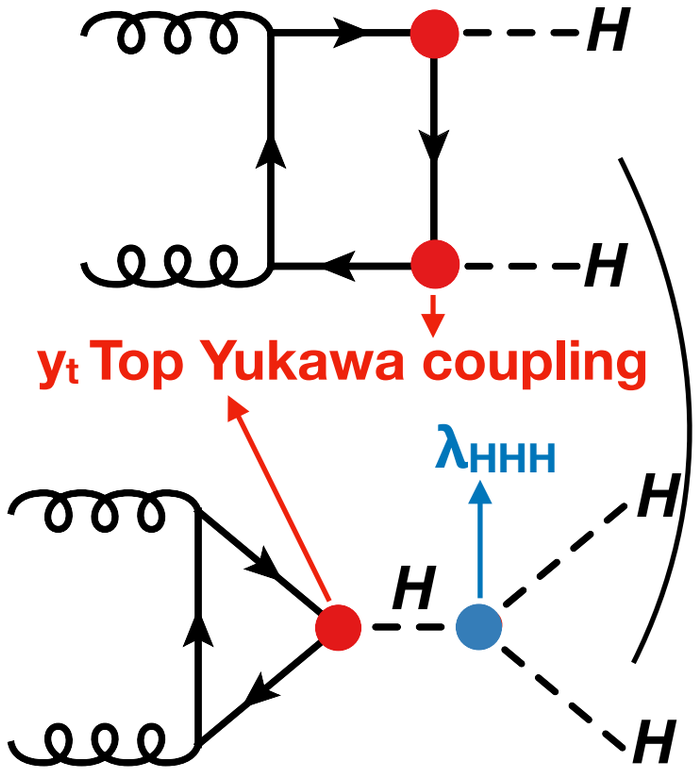
Di-Higgs production in the Standard Model

- Di-Higgs production measurement probes the trilinear self-coupling of the Higgs boson λ_{HHH}
- Small cross-section in the SM at 13 TeV, extremely challenging to measure at LHC

σ_{Higgs} total ~55.6 pb @13 TeV



Main production processes:



destructive interference

SM di-Higgs production dominated by gluon fusion mechanism:

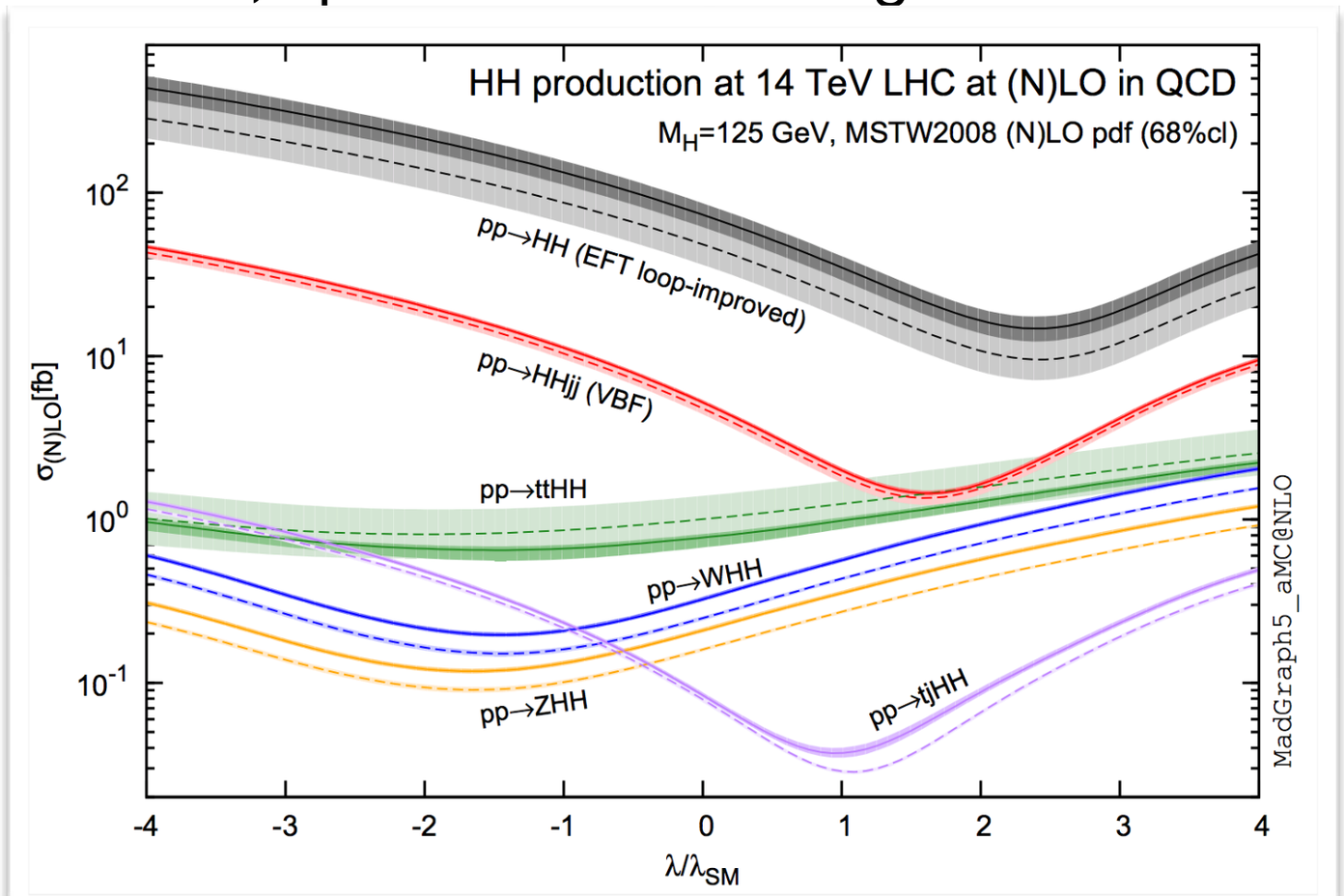
$\sigma^{SM}_{gg\to HH} = 31\ fb\ ^{+2.2\%}_{-5.0\%}(scale) \pm 2.6\%(m_t) \pm 3.0\%(PDF+\alpha_s)$

in NNLOFTapprox for m_H=125 GeV @13TeV
arXiv:1803.02463

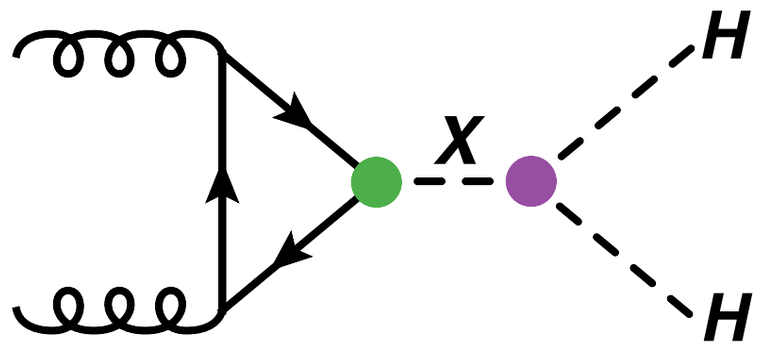
Di-Higgs production in BSM

Di-Higgs production is significantly enhanced in many BSM scenarios:

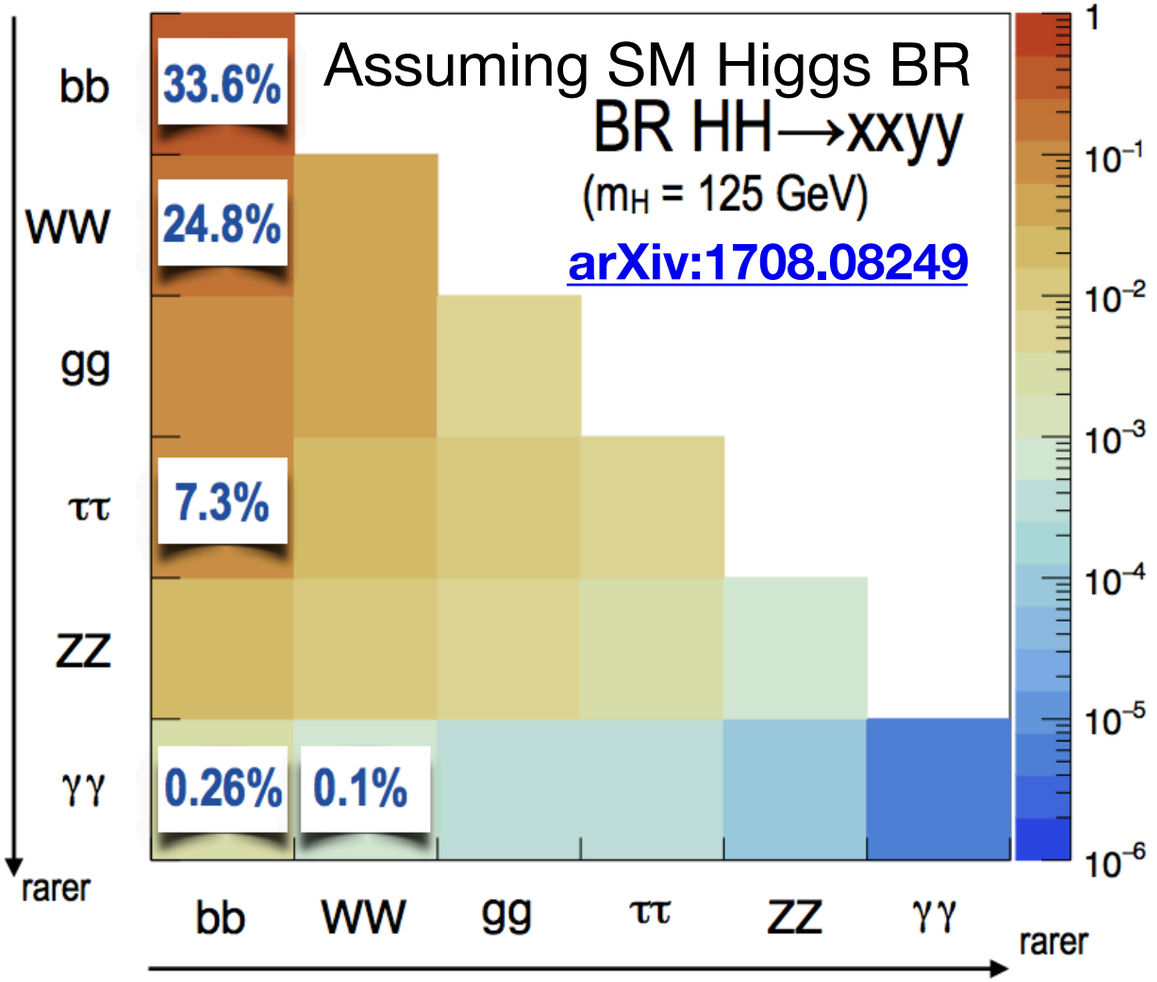
- Enhancement of the non-resonant di-Higgs production cross-section and modified kinematics via modified Higgs boson self-coupling and top Yukawa coupling, new vertices…
- Resonant di-Higgs production: e.g. heavy spin-0 scalar in two-Higgs-doublet model, spin-2 Kaluza-Klein gravitons in bulk Randall-Sundrum model.



Phys.Lett. B732(2014)142-149



Di-Higgs decay channels



- bbbb: largest BR, large QCD multijets and $t\bar{t}$ backgrounds
- bbWW: large BR, large $t\bar{t}$ background
- bb**ττ**: sizeable BR, relatively small background
- bbγγ: small BR, good **σ(**$m_{\gamma\gamma}$**),** relatively small background
- γγWW: small BR, good **σ(**$m_{\gamma\gamma}$**)**

Expected SM di-Higgs events produced via gluon fusion mechanism,
estimated using $\sigma^{SM}_{gg\to HH}$ = 31 fb @13 TeV and 37 fb @14 TeV and SM Higgs BR**:**

	luminosity	N(HH)	bbbb	bbWW	bbττ	bbγγ	γγWW
13TeV	36 fb^{-1} 2015+2016	1k	380	280	80	3	1
13TeV	150 fb^{-1} Run II	3.7k	1.6k	1.2k	340	12	5
14 TeV	3000 fb^{-1} HL-LHC	110k	37k	28k	8k	0.3k	0.1k

Di-Higgs searches in Run II

ATLAS	luminosity fb^{-1}	reference
New! bbγγ	36.1	paper in preparation
New! γγWW(→lνjj)	36.1	paper in preparation
bbbb	27.5 (resolved), 36.1 (boosted analysis)	arXiv: 1804.06174, submitted to JHEP

CMS	luminosity fb^{-1}	reference
bbbb	35.9, 2.3	PLB 781 (2018) 244, PAS-HIG-17-009, PAS-HIG-16-026
bbγγ	35.9	arXiv:1806.00408 submitted to PLB
bbττ	35.9	PLB 778 (2018) 101 PAS-B2G-17-006
bblνlν	35.9	JHEP 01 (2018) 054

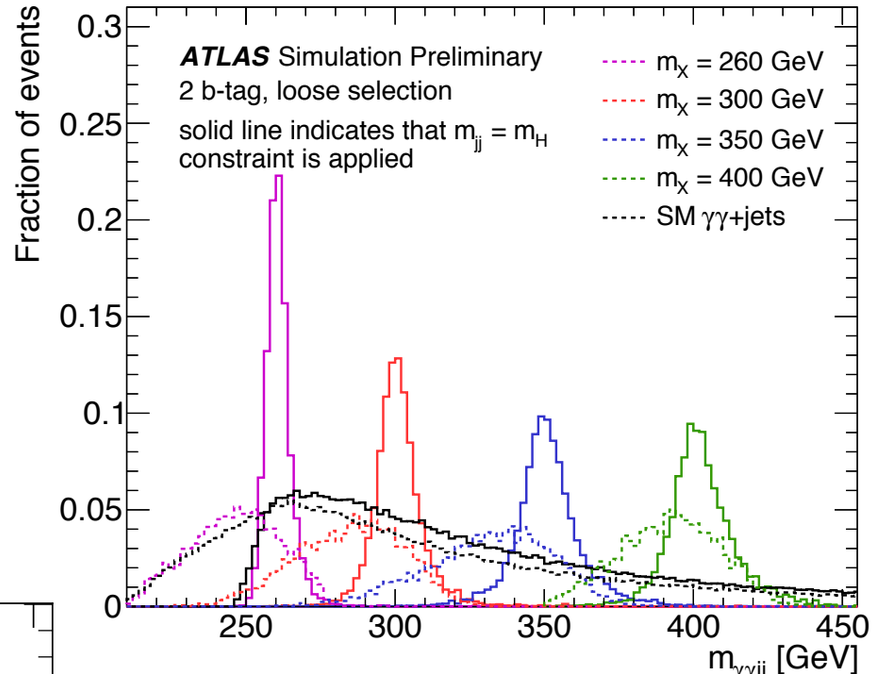
- Largest BR(H→bb), b-tagging technique a vital ingredient.
- Analysis strategy:
  - (1) Requiring Higgs candidate's mass consistent with SM Higgs mass
  - (2) Boosted objects included in bbbb and bbττ searches
  - (3) Machine learning methods to reject backgrounds.

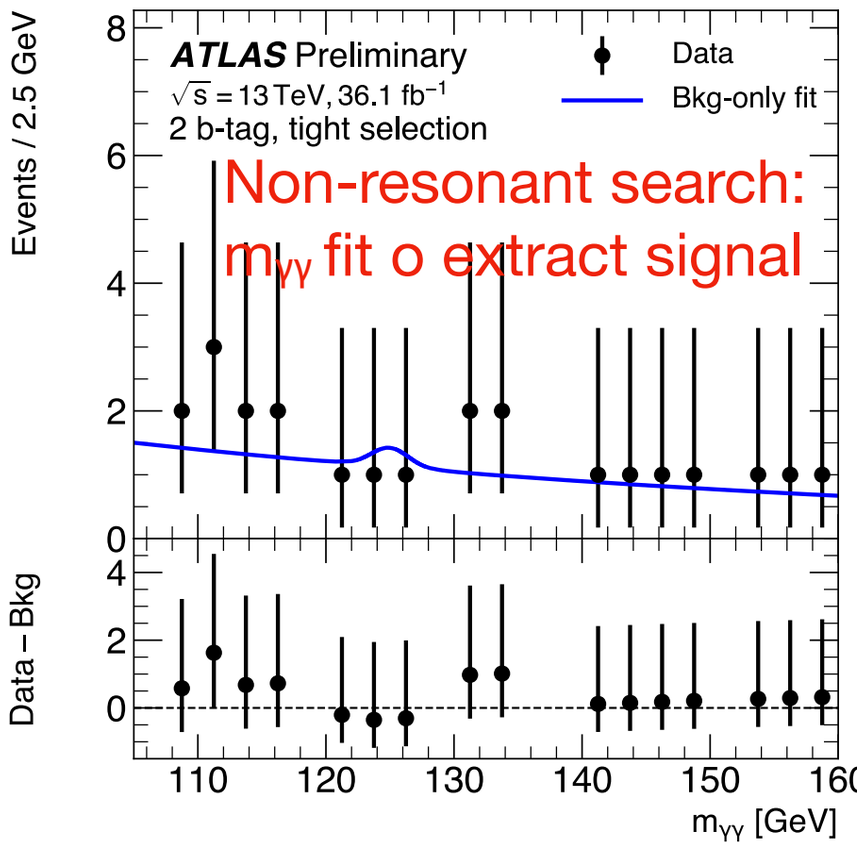
New!

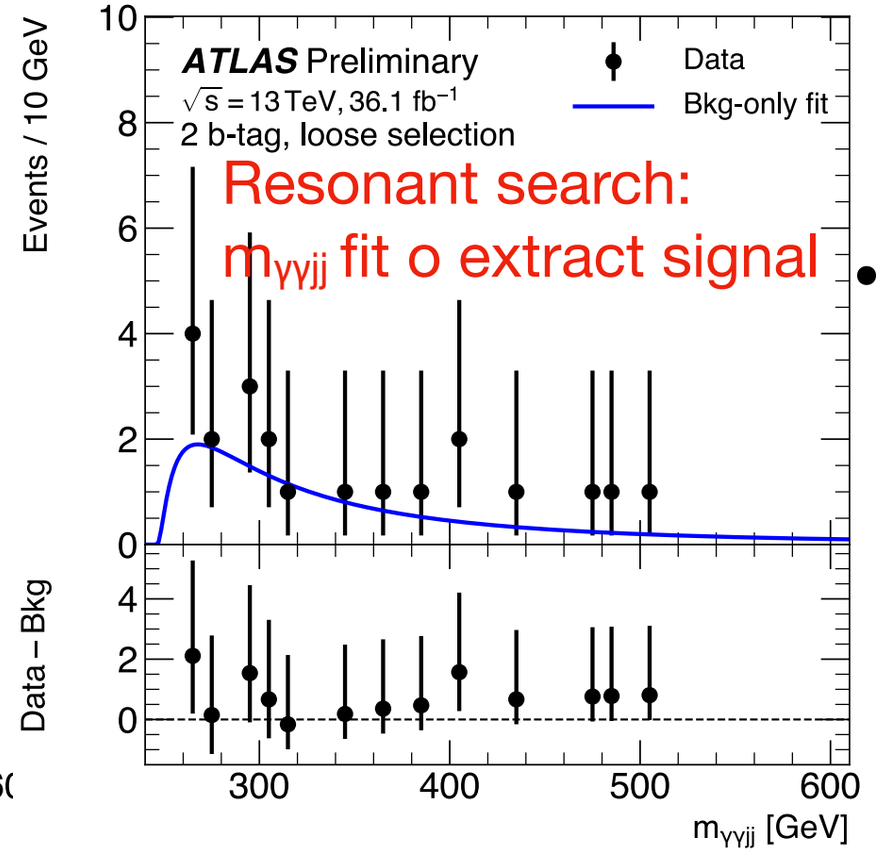
bbγγ - ATLAS

- Two photons, two small-R jets.
- Categorize events: one or two jets tagged as b-jets.
- Events with one b-tagged jet: BDT to select 2nd jet
- Require both Higgs candidate masses to be consistent with the SM Higgs mass
- Resonant search: scale four-momentum of dijet system by m_H/m_{jj} . Improve $\sigma(m_{\gamma\gamma jj})$ by 60% average.

paper in preparation





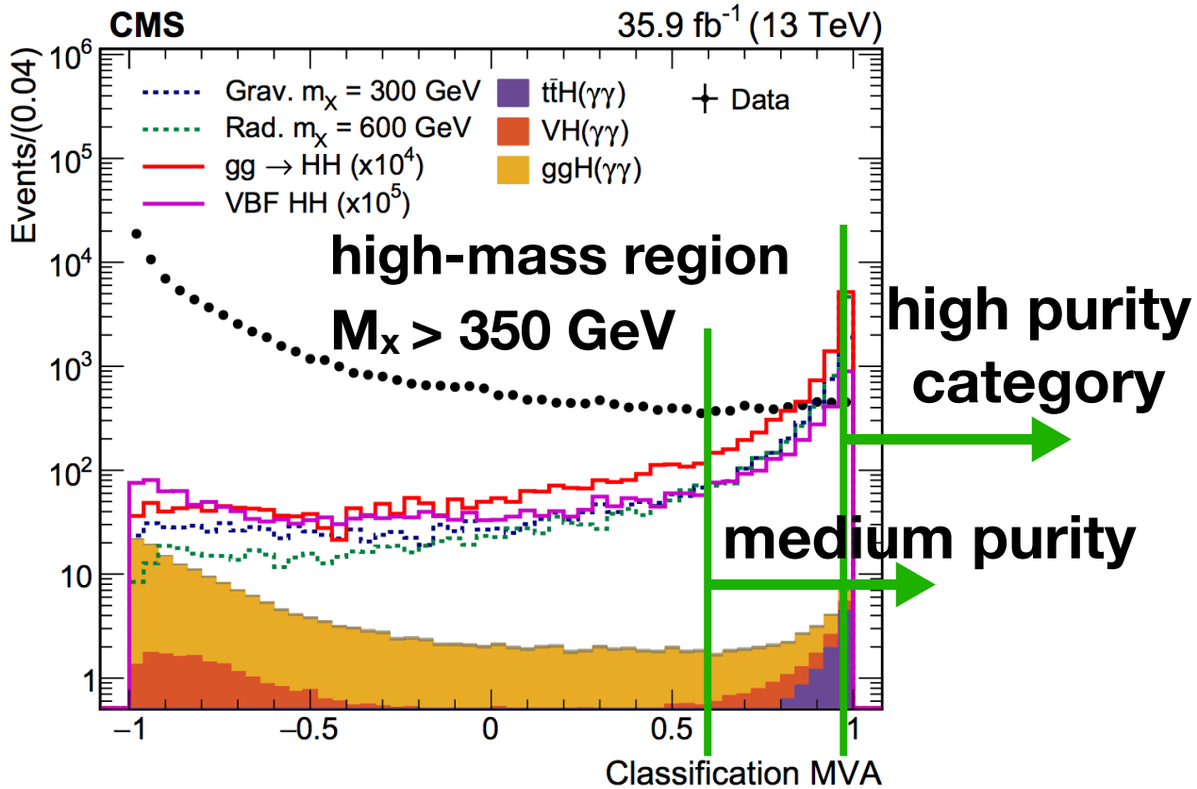


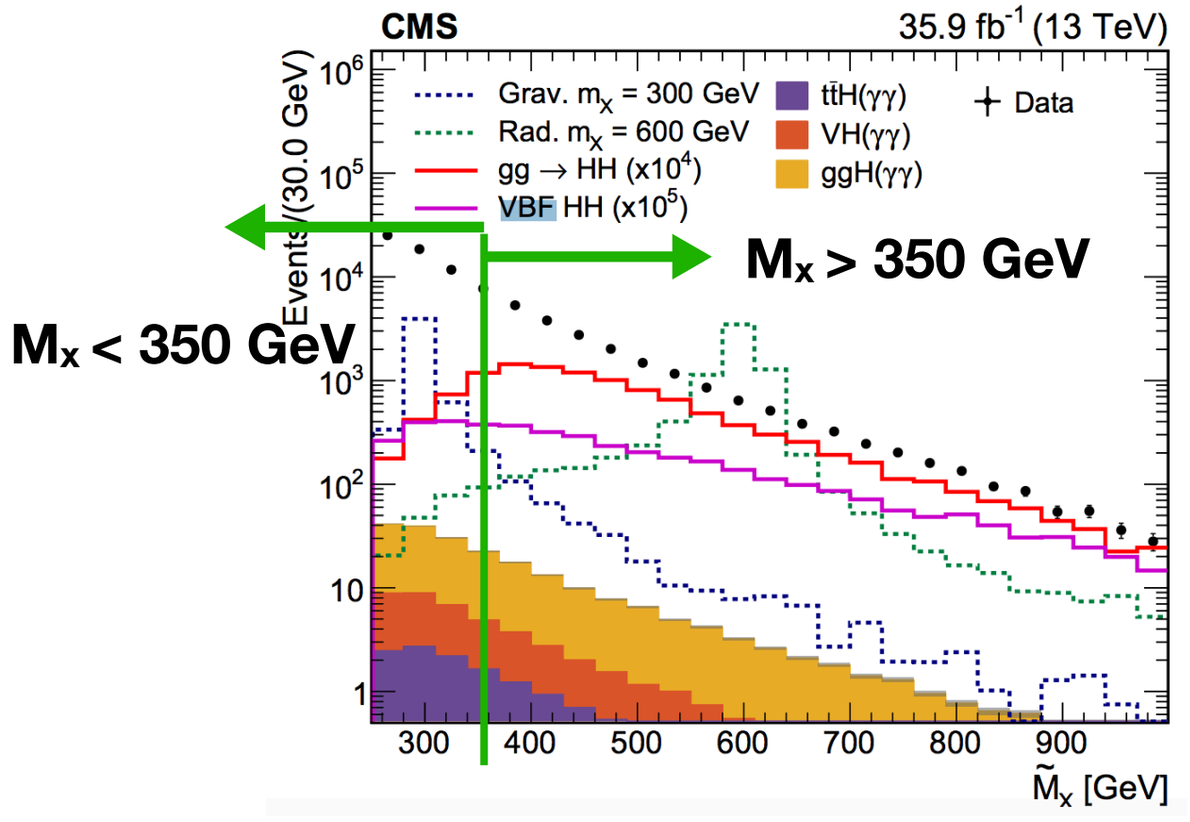
- Background modeling:
  - Continuum background (γγ, γj, jj): fit to the data
  - Single Higgs boson production: simulation

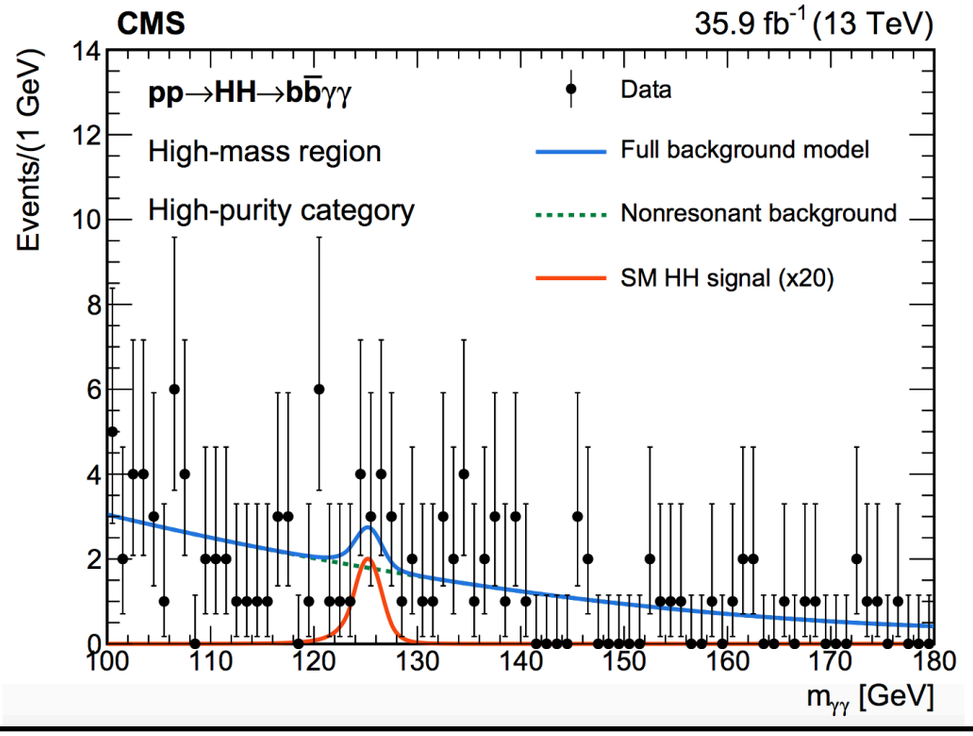
bbγγ - CMS

arXiv:1806.00408
submitted to PLB

- Object selection:
  - Two photons, two small-R b-tagged jets.
- Signal region, discriminating variables:
  - Categorize events based on MVA and M_X: $m_{\gamma\gamma jj}$ - (m_{jj} - m_H) - ($m_{\gamma\gamma}$ -m_H)
  - 2D fit to $m_{\gamma\gamma}$ x m_{jj} to extract signal.



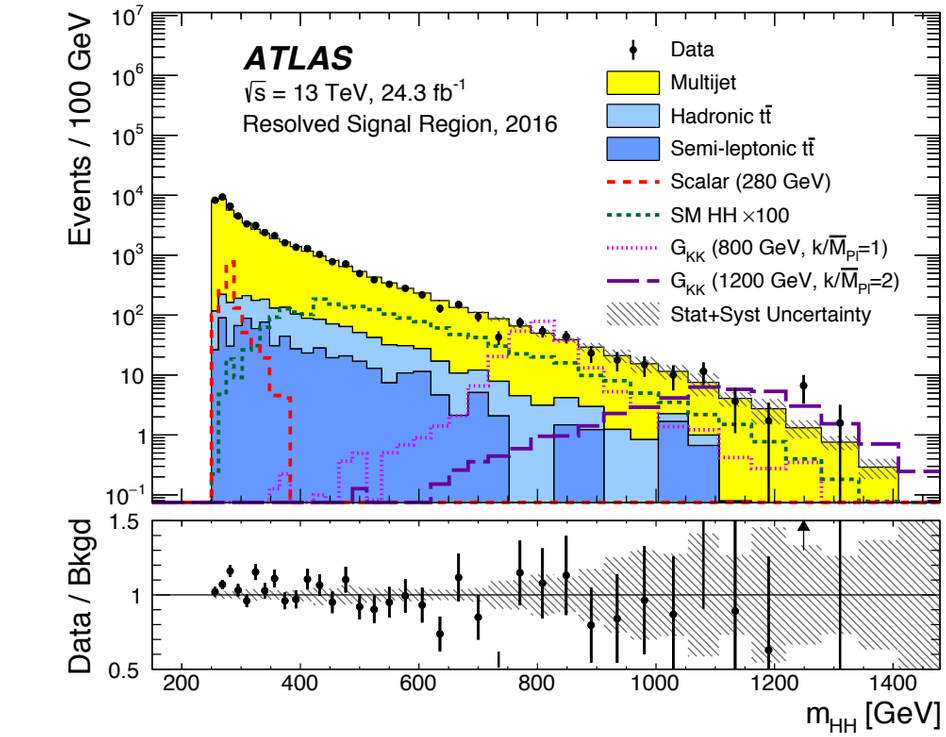


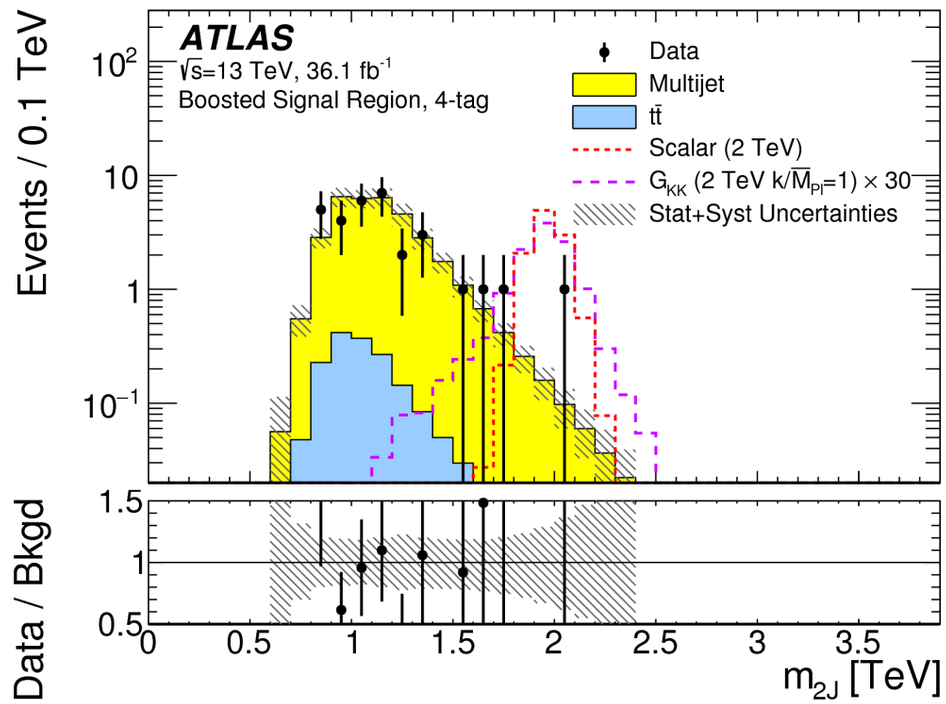


bbbb - ATLAS

arXiv: 1804.06174
submitted to JHEP

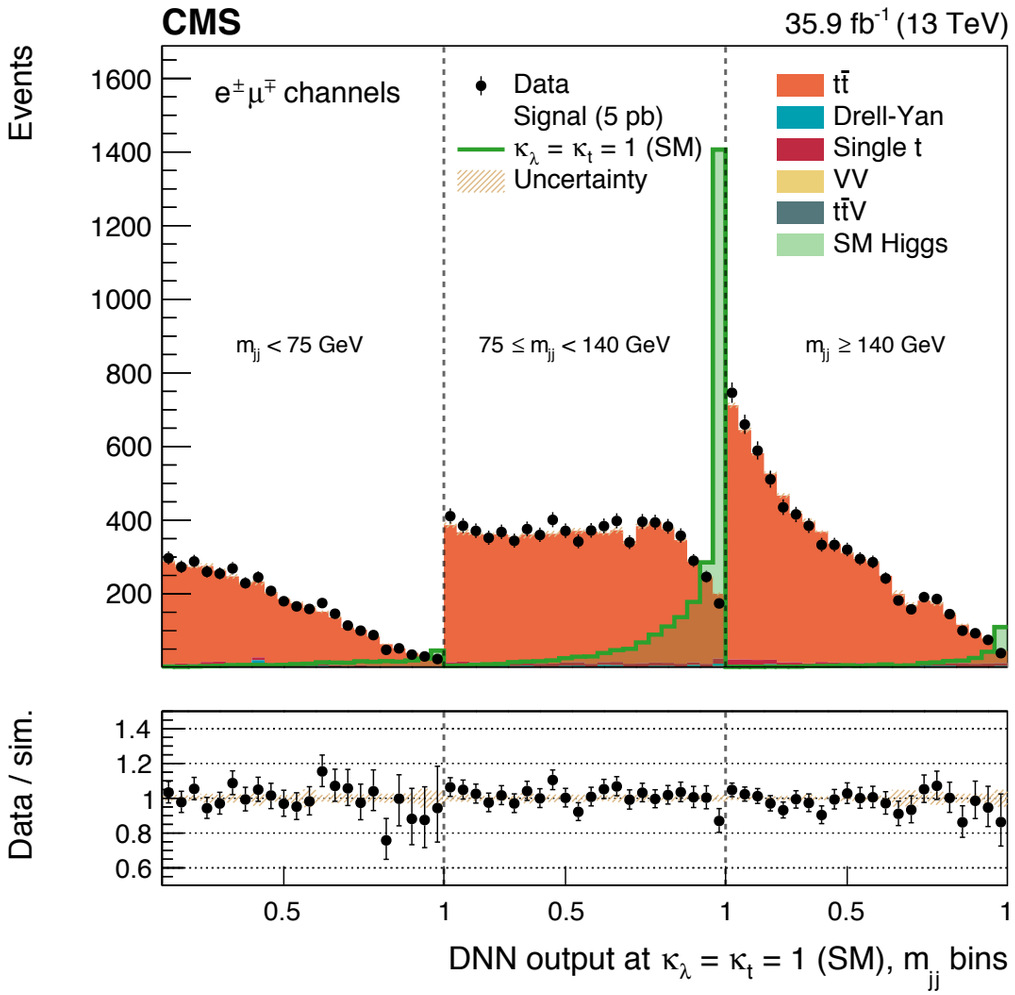
- Object selection:
  - Resolved: 4 b-tagged small-R jets (R=0.4), pairing jets into Higgs boson candidates based on ΔR_{jj} and m_{jj}.
  - Boosted: two large-R jets (R=1.0), three categories with either 2, 3 or 4 associated b-tagged track-jets.
- Signal region, discriminating variables:
  - Both Higgs candidates masses consistent with the SM Higgs mass
  - Four-momentum of Higgs boson candidates scaled by m_H/m_{jj} or m_H/m_J in resolved or boosted analyses.
  - Final discriminant: m_{HH}
- Background Estimation:
  - Dominated by multijet, smaller contribution $t\bar{t}$, estimated with data.

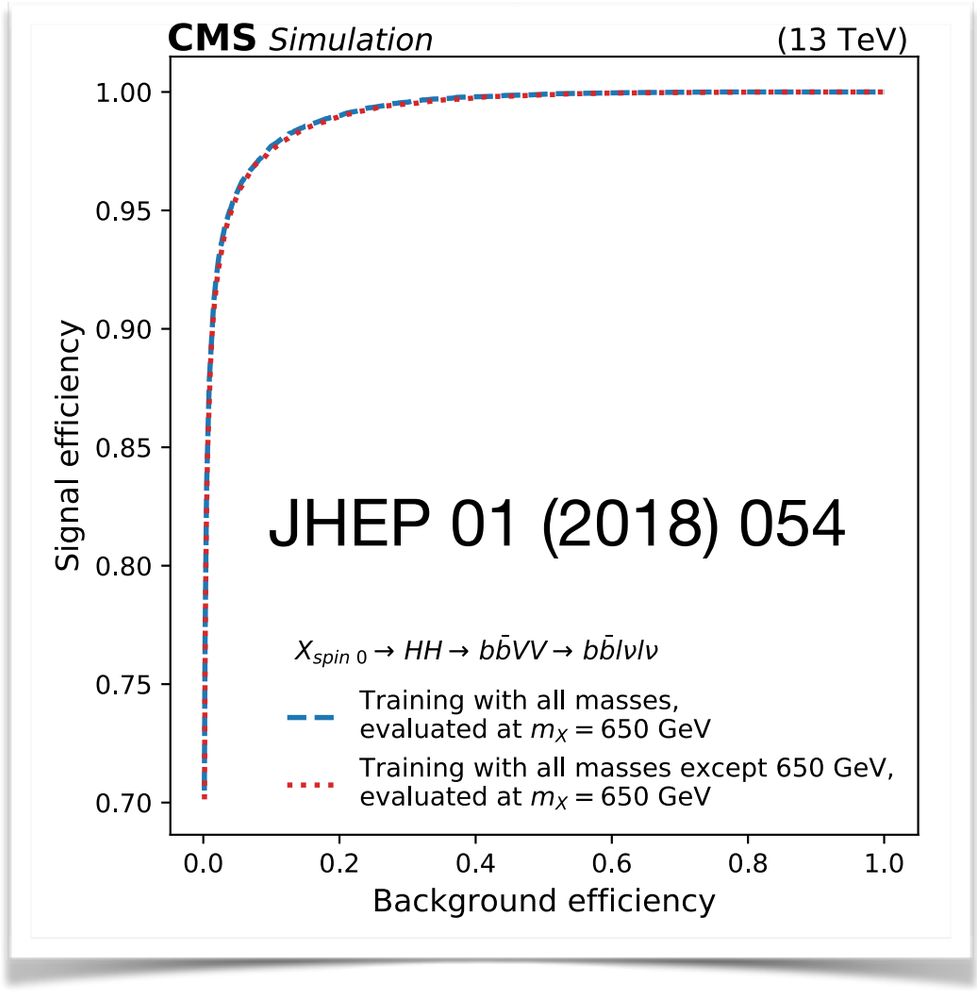




bblνlν - CMS

- Object selection, event selection:
  - Two opposite sign leptons, two small-R b-tagged jets, $12 < m_{ll} < m_Z$ -15 GeV.
- Most background estimation based on simulation, Drell-Yan estimated with data.





- Discriminating variables:
  - Deep neural network using Keras library and parameterized machine learning technique, to optimize sensitivity in one training for full range of signal hypothesis tested (m_X; κ_λ, κ_t)
  - Trained on event kinematics: m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\Phi(ll,jj\Phi)$, pT_{ll}, pT_{jj}, $\min(\Delta R_{jl})$, mT.

bbττ - CMS

- Object selection:
  - a pair of tau leptons: $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$
  - Resolved: two small-R jets, >=1 b-tagged. Boosted: one large-R jet, both small-R jets are b-tagged.
- Signal region and discriminating variables:
  - Both Higgs candidate masses consistent with the expected reconstructed mass of the SM Higgs.
  - Use BDT in resolved $bb\tau_u\tau_h$ and $bb\tau_e\tau_h$ categories to reject $t\bar{t}$ background.
- Background estimation:
  - $t\bar{t}$, Drell-Yan estimated using simulation, QCD multijets using data.

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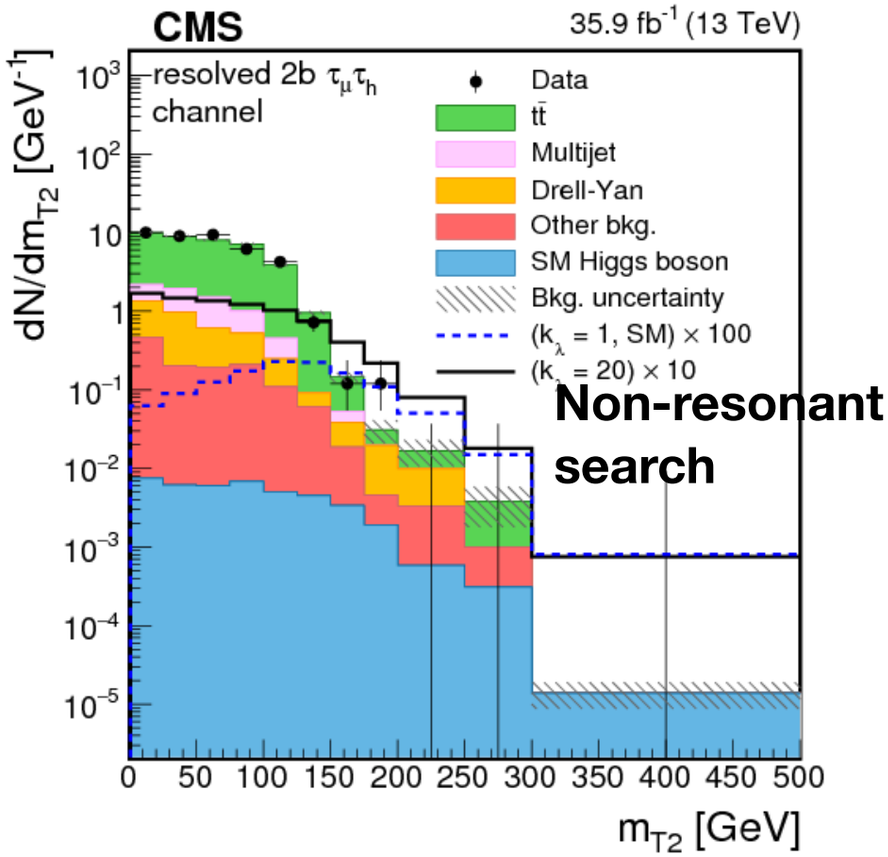
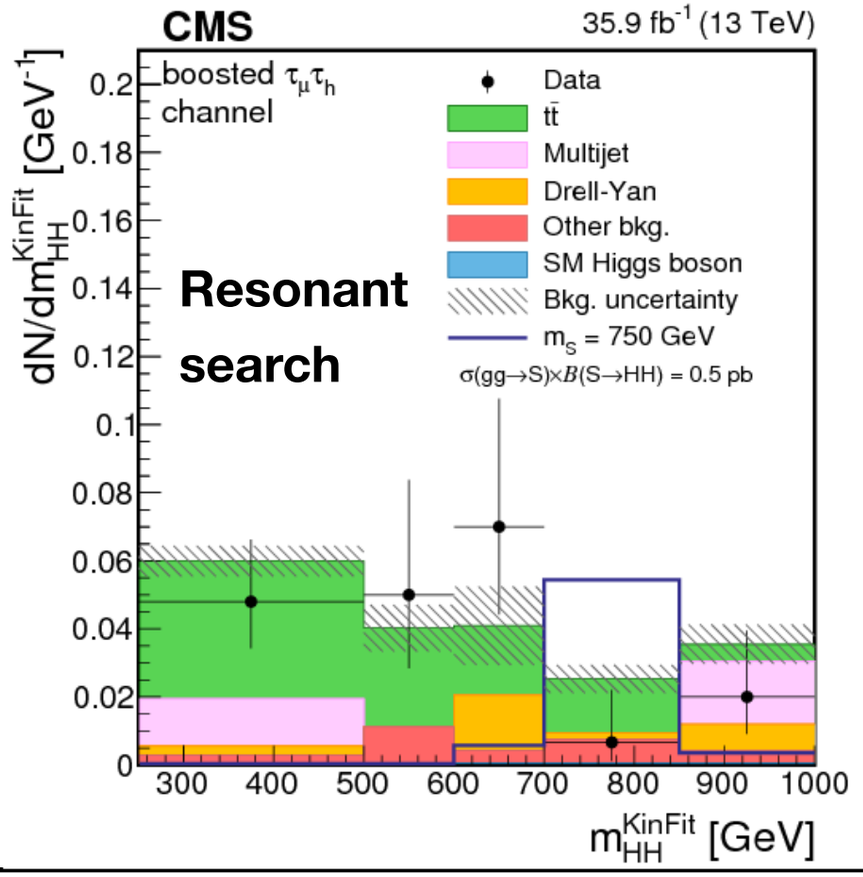
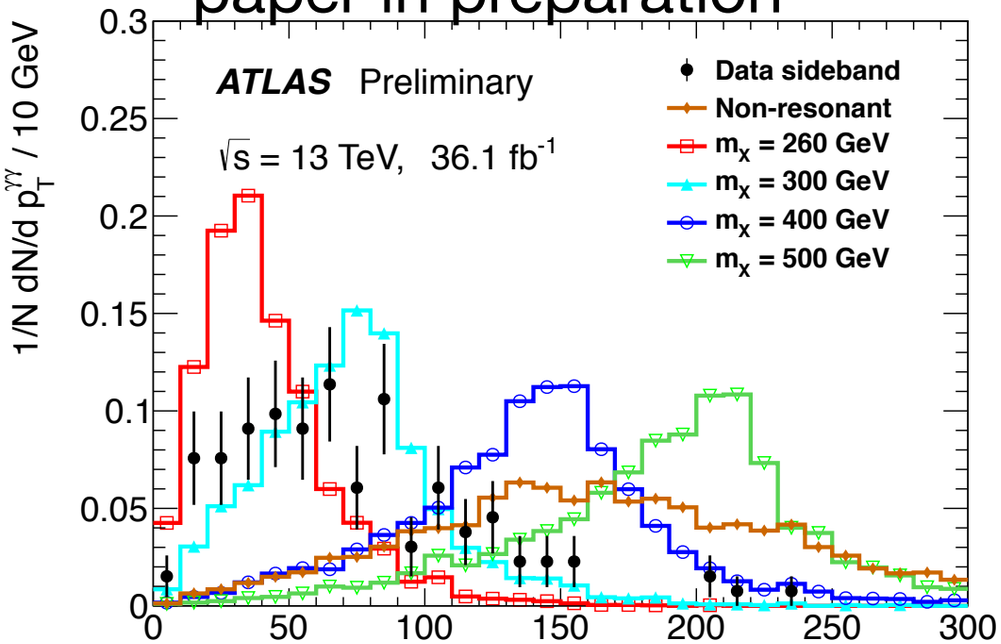




New! γγWW*(→lνjj) ATLAS

- Object selection and event selection:
  - two photons, one lepton (e or μ), two jets and no b-tagged jets.
  - $pT_{\gamma\gamma} > 100$ GeV for non-resonant and resonant search for $m_X \geqq 400$ GeV
  - 105 GeV < $m_{\gamma\gamma}$ < 160 GeV

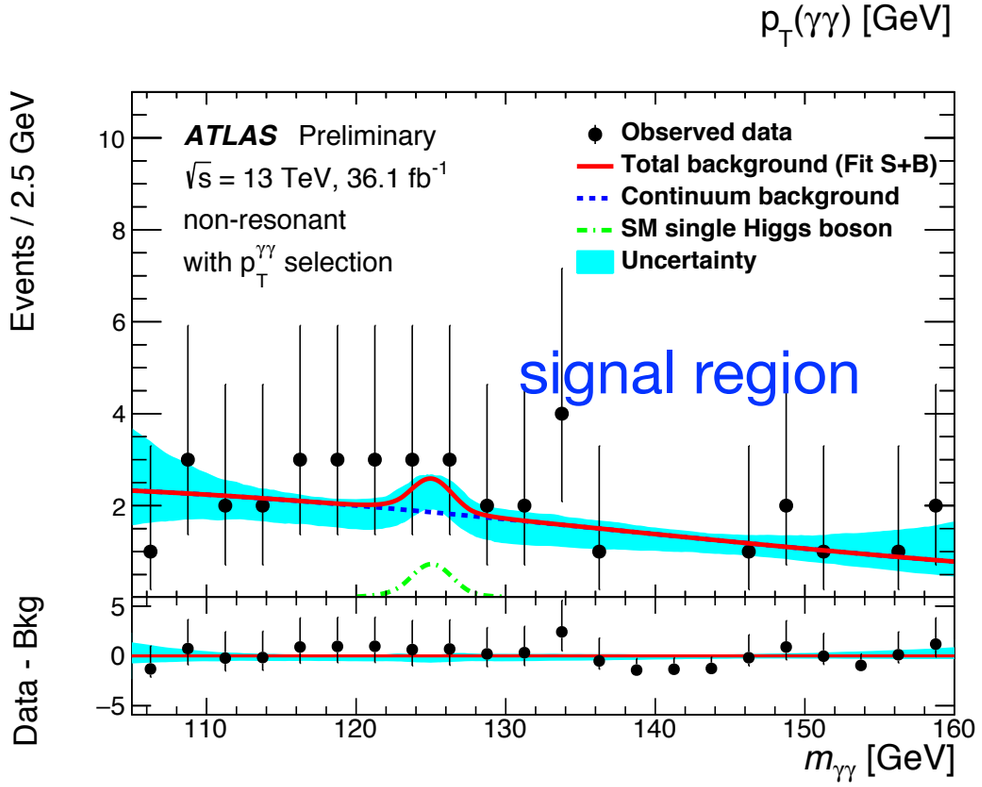
paper in preparation



- Signal extraction: fit $m_{\gamma\gamma}$ spectrum

w/o $pT_{\gamma\gamma} > 100$ GeV selection, $m_H \pm 2\sigma_{\gamma\gamma}$

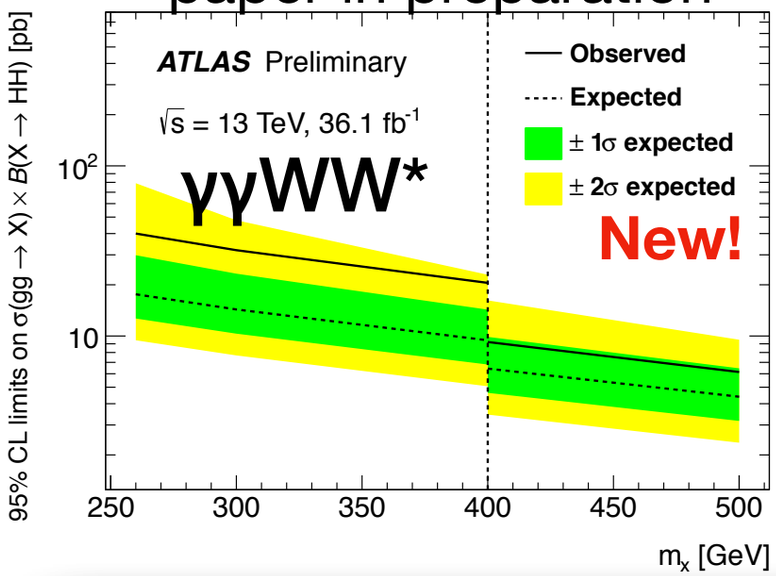
process	N(events)	Estimation
Continuum background	5.1 ± 2.3	sideband fit
SM single-Higgs	1.0 ± 0.9	simulation
SM di-Higgs	0.038 ± 0.004	simulation
Data	7	



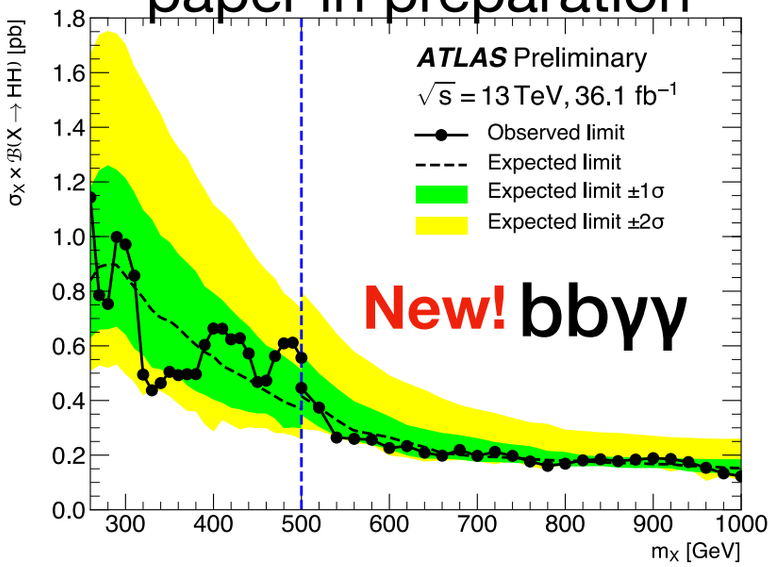
Result on resonant searches

Model independent limit on a narrow scalar particle decaying to two Higgs:

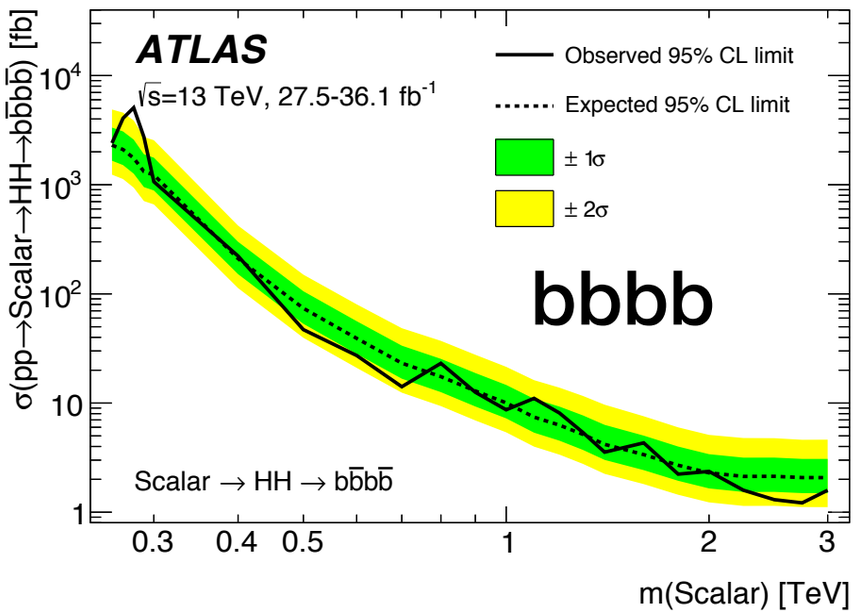
paper in preparation

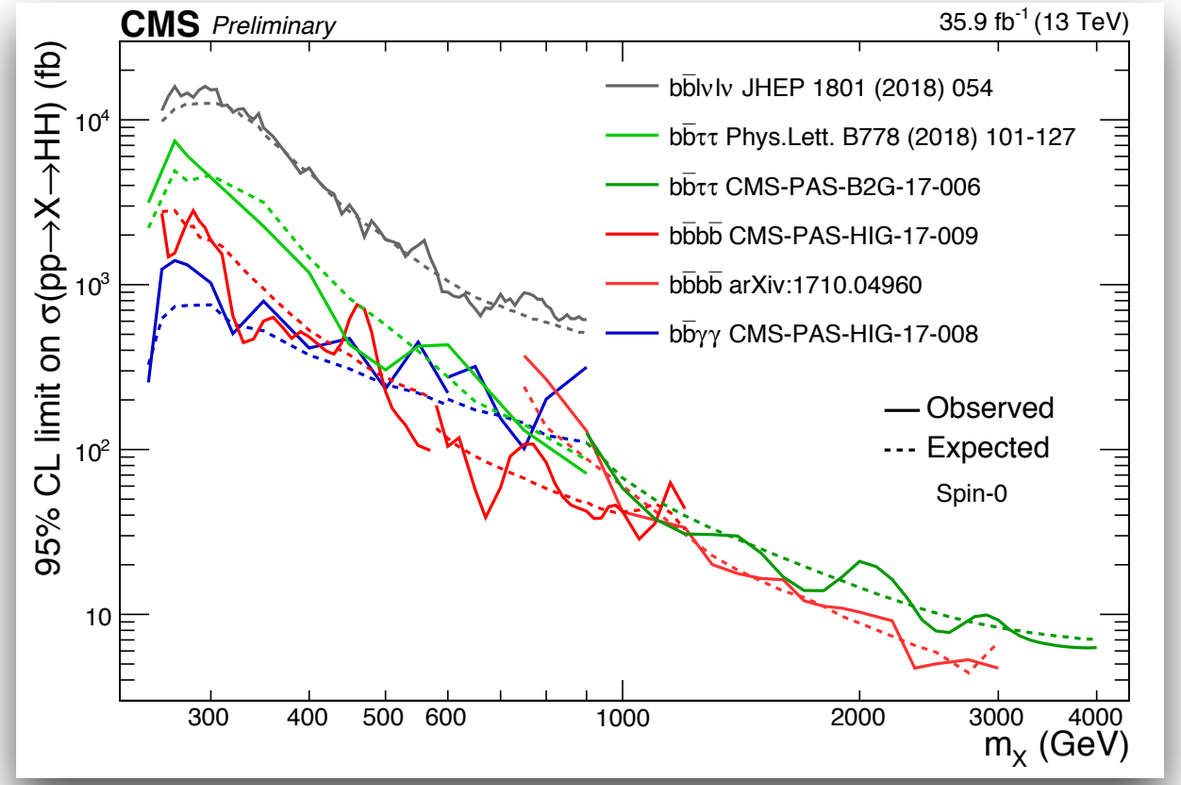


paper in preparation



arXiv: 1804.06174





No significant excess observed.

- Lower mass range 250 GeV - 1 TeV: limit σ(X→HH) O(0.1 ~ 10 pb);
- higher mass range 1~4 TeV, limit σ(X→HH) O(10 fb);

Limit of SM non-resonant production

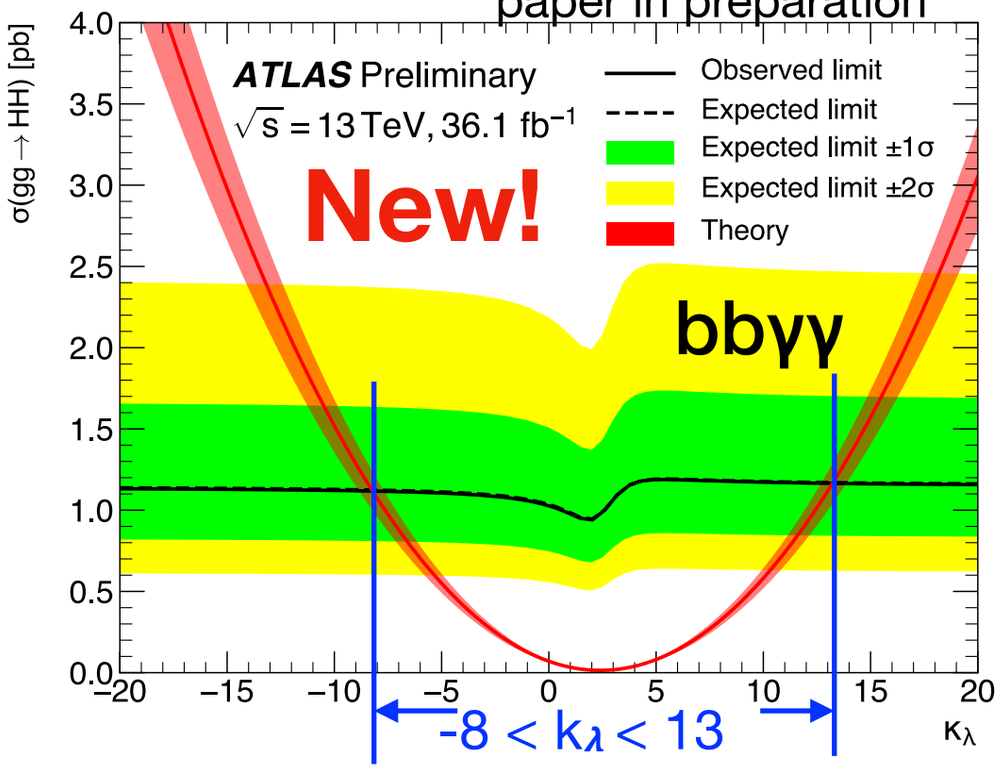
95% CL upper limit on $\mu = \sigma/\sigma_{HH,SM}$ observed (expected)

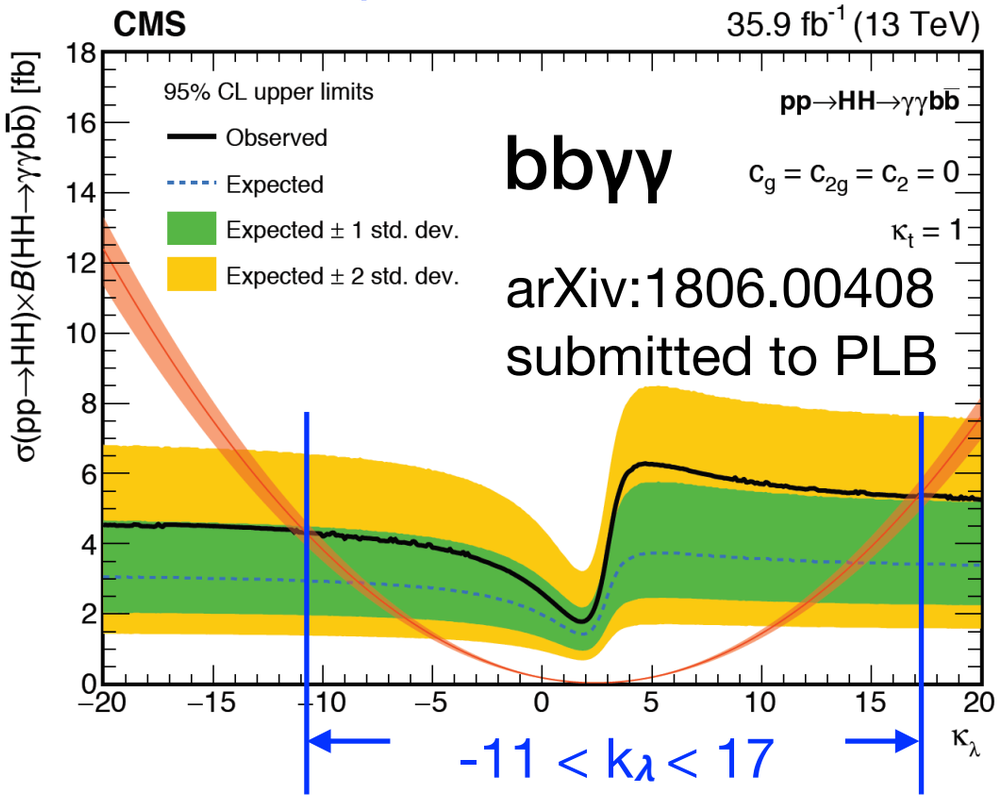
		ATLAS	CMS
rarer ↓	bbbb	13 (21)	340 (310)
	bblvlv		79 (89)
	bbττ		30 (25)
	bbγγ	**New!** 22 (28)	24 (19)
	WWγγ	**New!** 230 (160)	
Dataset: integrated luminosity fb^{-1}		2	28 36

- Limit from bbbb, bbγγ, bbττ final states down to L ~20 $\sigma_{HH,SM}$ using 28~36 fb^{-1} at 13 TeV,
- L ~10 $\sigma_{HH,SM}$ with full Run II data, assuming L $\propto 1/\sqrt{\text{luminosity}}$

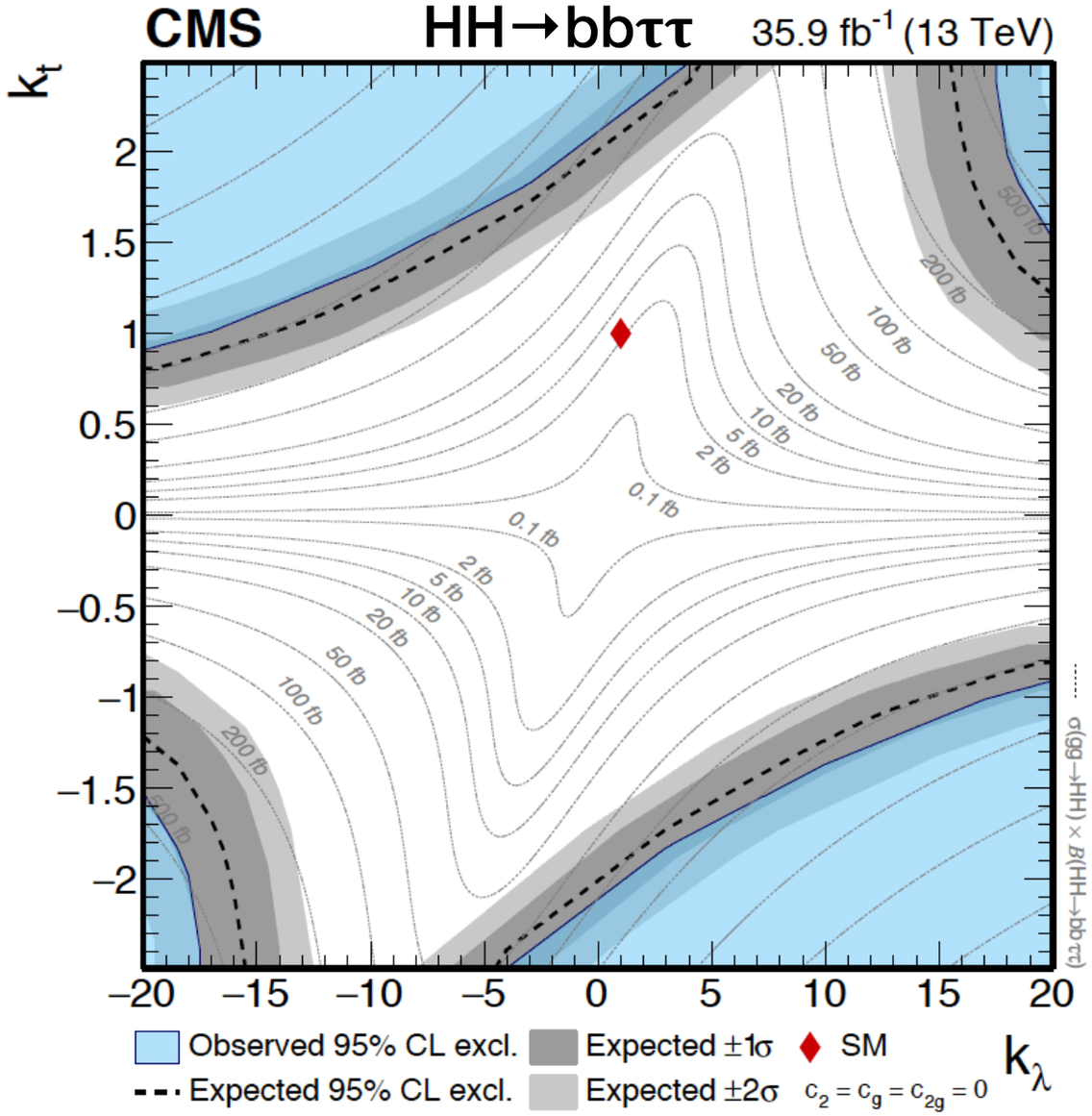
Probe Higgs anomalous couplings

paper in preparation





- Probe deviations from SM Higgs boson couplings in an EFT approach: $\kappa_\lambda = \lambda_{BSM}/\lambda_{SM}$; $\kappa_t = y_{t,BSM}/y_t$, and other parameters to be SM values.



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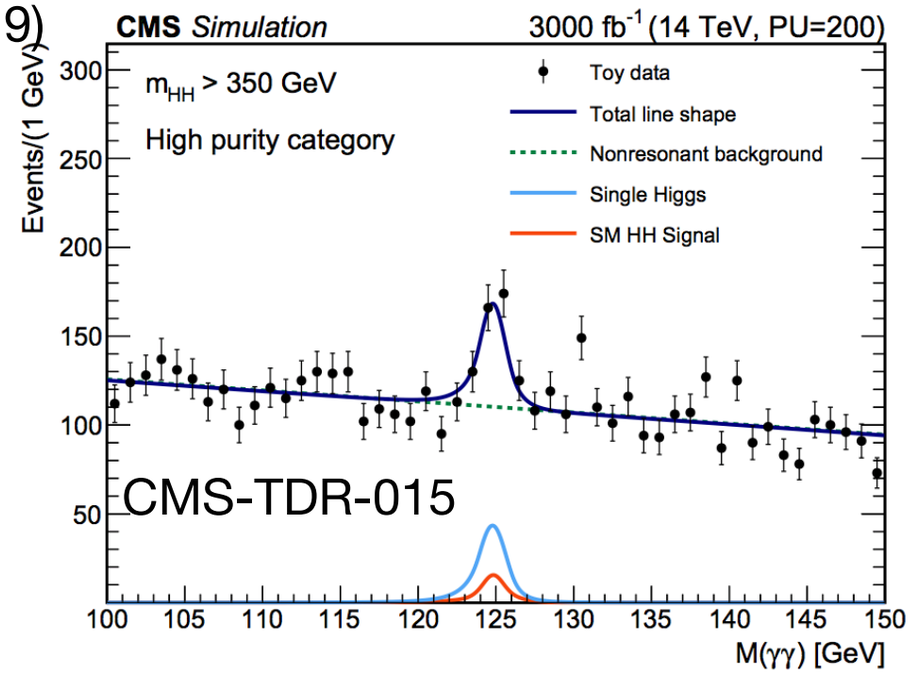
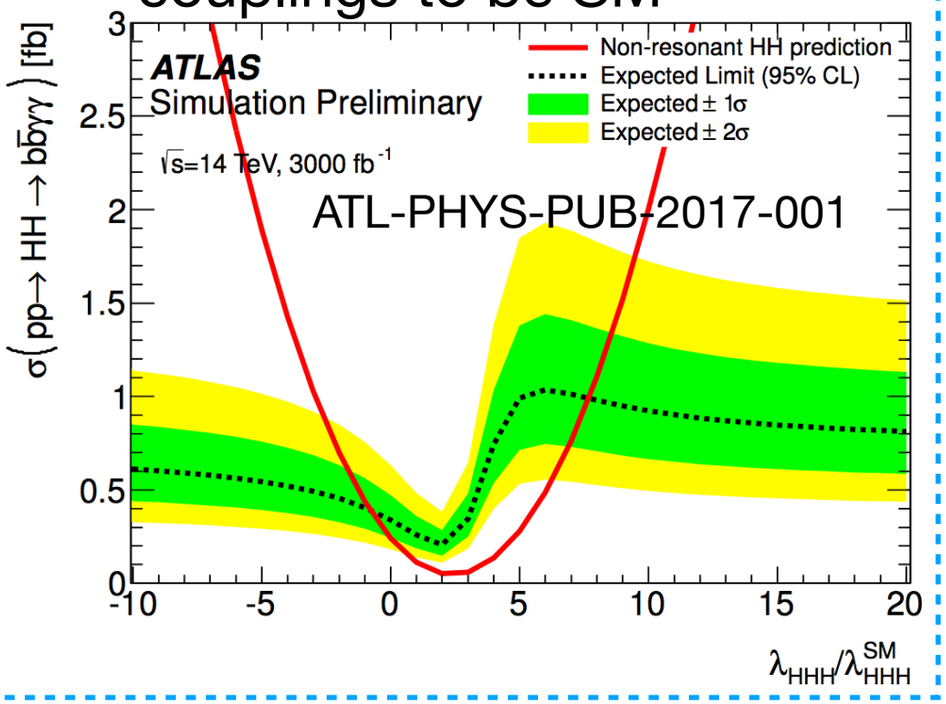
Outlook for di-Higgs at the HL-LHC

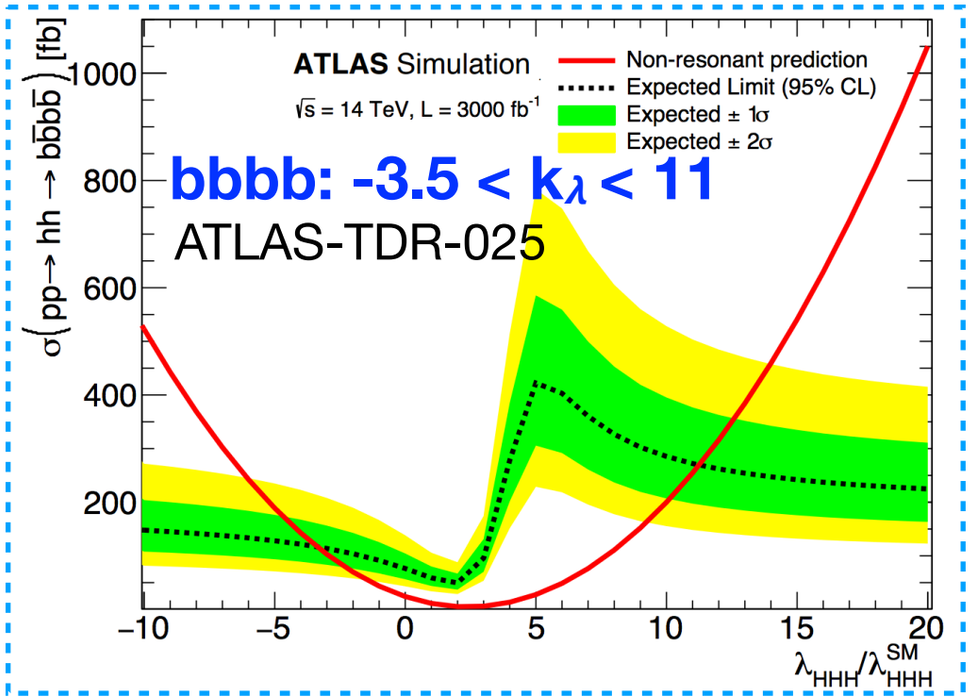
- Currently best expected limit is from bbγγ channel: **$-1 < k_\lambda < 8$** (ATL-PHYS-PUB-2017-001), **$\sigma/\sigma_{HH,SM} < 1.1$** (CMS-TDR-015)
- Competitive limit from bbττ, **$\sigma/\sigma_{HH,SM} < 1.6$** (CMS-TDR-019)



- Sensitivity should improve in the future:
  - Better understanding of Phase-II detectors, improved physics object reconstruction.
    e.g. **22% increased** N(HH→bbγγ) enabled by CMS MIP timing detector. LHCC-P-009
  - Improve analysis strategy
  - Combine between channels and experiments.

bbγγ: $-1 < k_\lambda < 8$,
assuming all other Higgs couplings to be SM





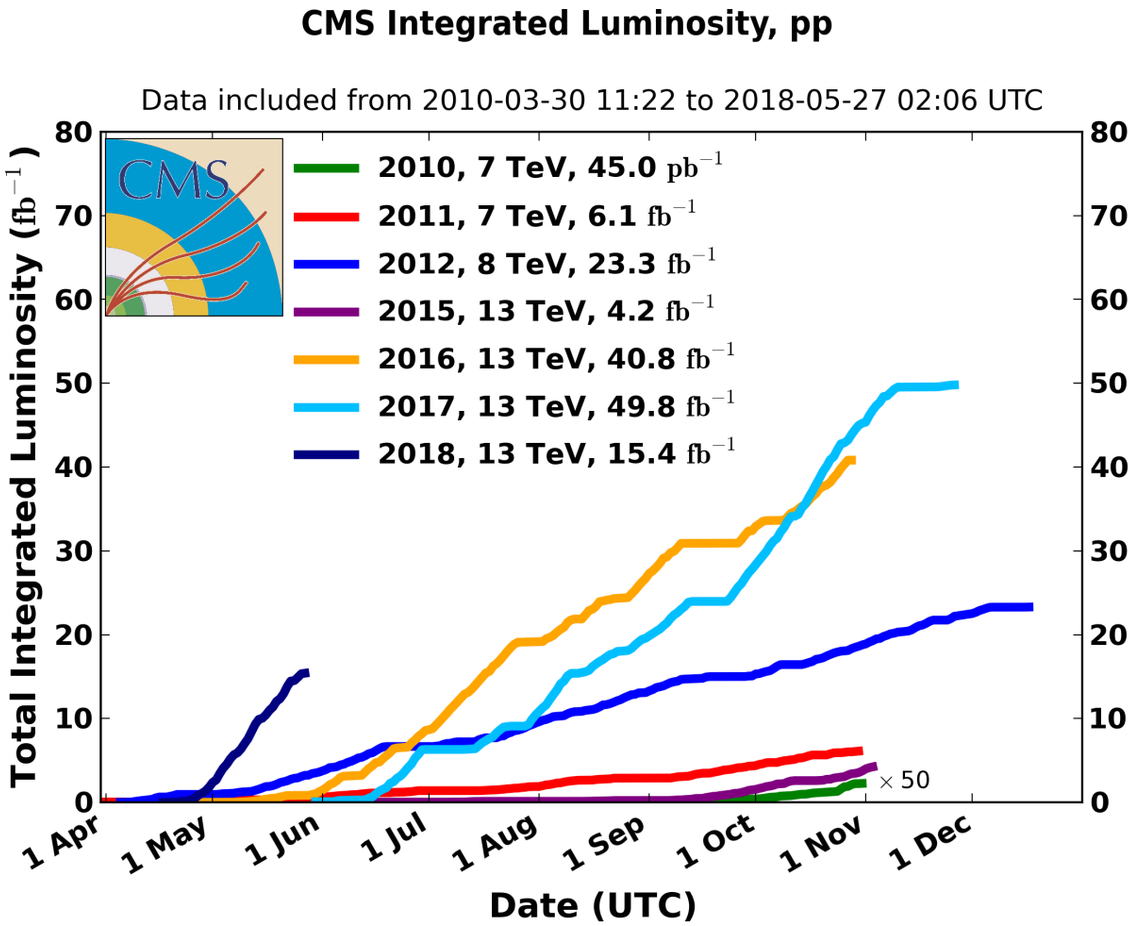
Summary

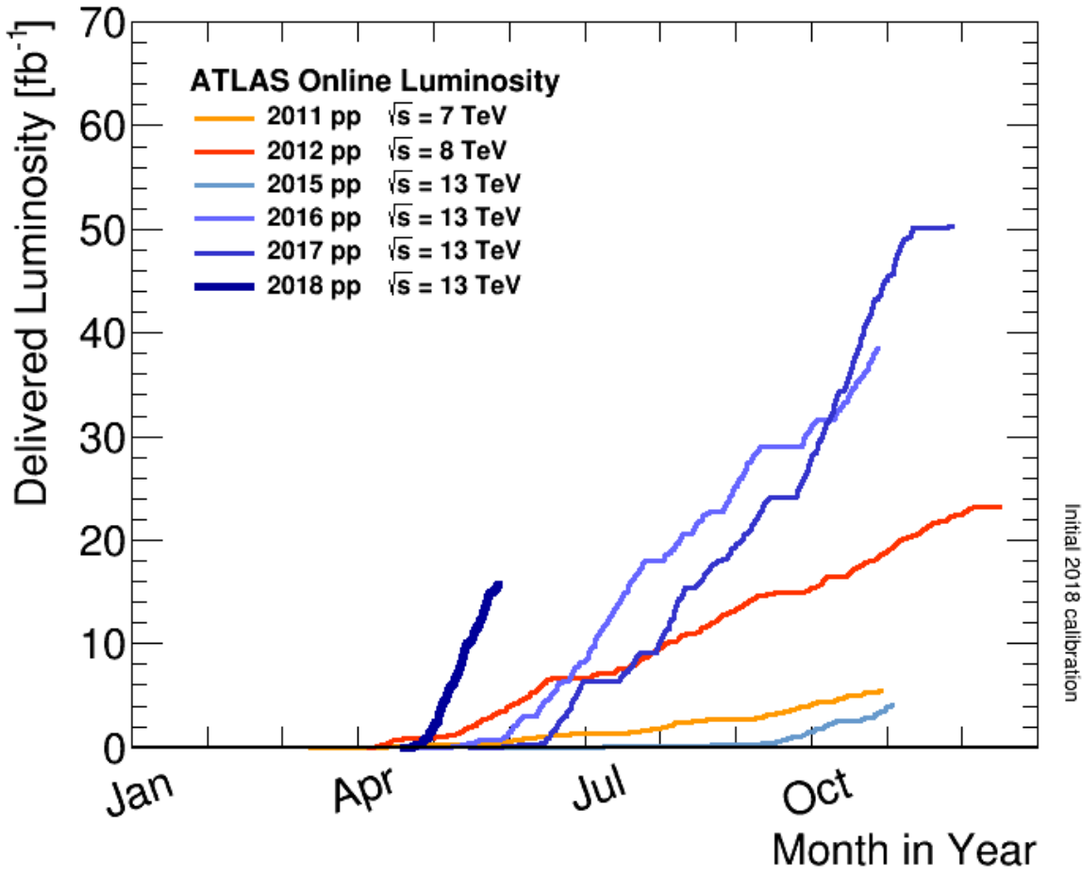
- Di-Higgs searches based on Run II data:
  - Several final states studied: bbbb, bbγγ, bb$\tau\tau$, bblνlν, γγWW*(→lνjj).
  - Limit on SM non-resonant production from bbbb, bbγγ, bb$\tau\tau$ down to $\sigma/\sigma_{HH,SM}$ ~ 20 with 28~36 fb^{-1}.
  - No significant excess observed in resonance search.
    - Stay tuned for new results and more Run II data!
- Current prospect studies present a challenging future for SM di-Higgs at LH-LHC. Improved sensitivity foreseen:
  - Capabilities of Phase-II detectors.
  - Analysis strategy optimization.
  - Important to combine different channels and experiments.

Thank you!

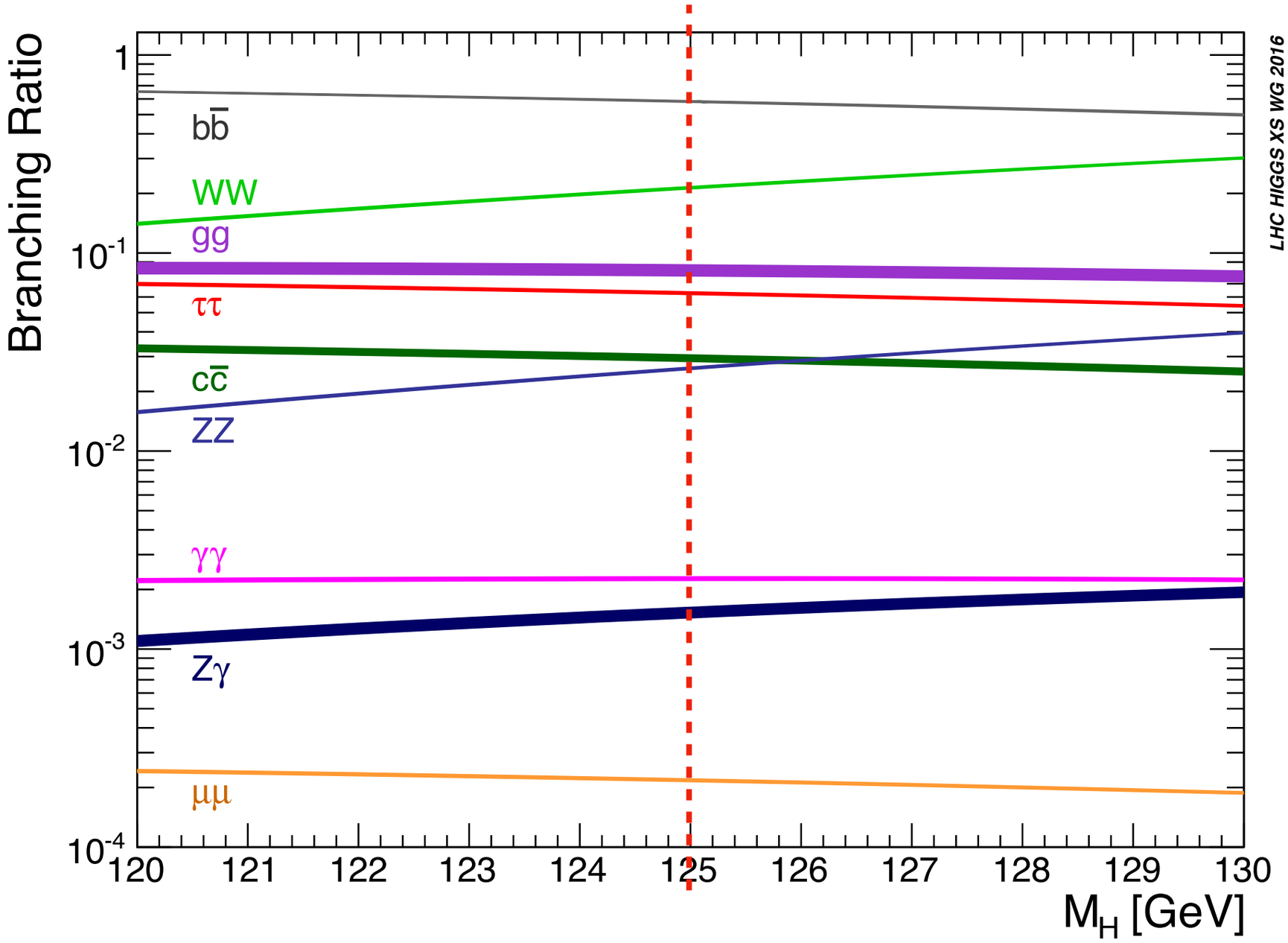
Backup Slides

Datasets


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2018-05-27 02:06 UTC
CMS
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 40.8 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 15.4 fb^{-1}
× 50
Total Integrated Luminosity (fb^{-1})
Date (UTC)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
0
10
20
30
40
50
60
70
80

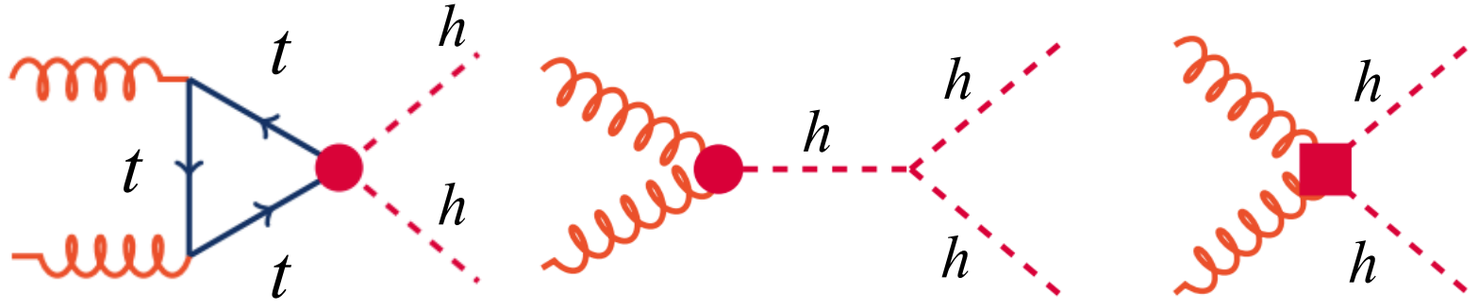

ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb^{-1}]
Initial 2018 calibration
Jan
Apr
Jul
Oct
Month in Year
0
10
20
30
40
50
60
70

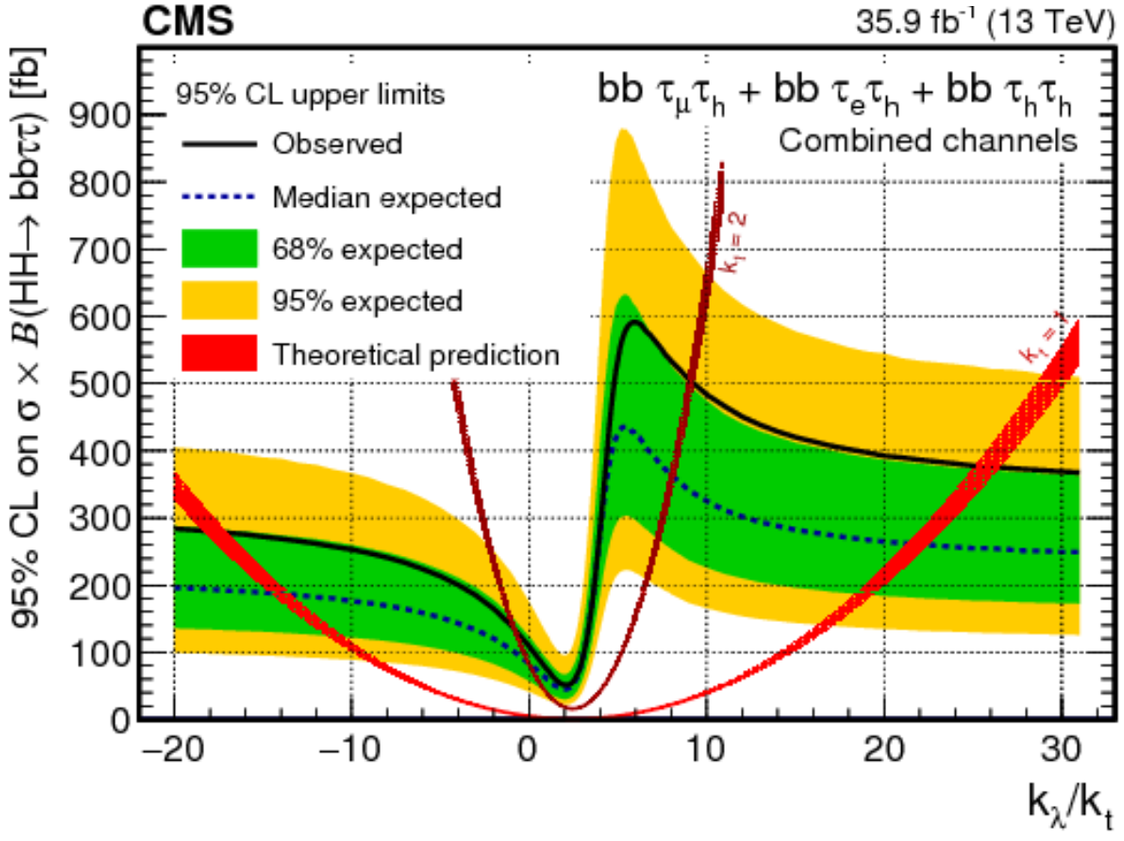
SM Higgs decay Branching Ratio

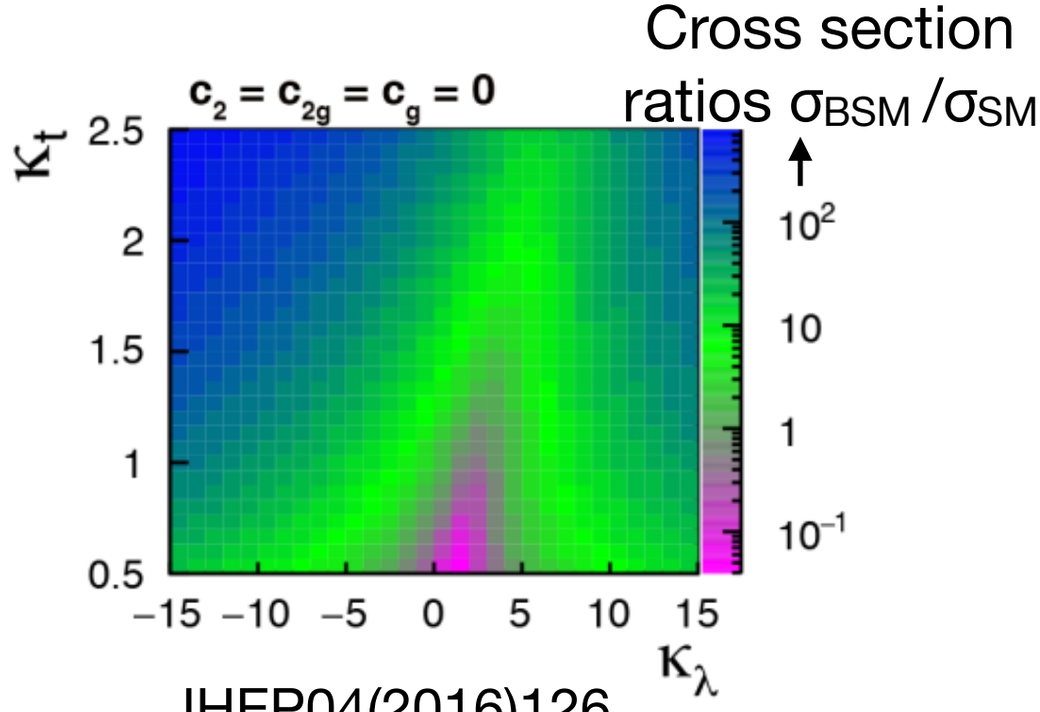


EFT approach for di-Higgs production

- κ_λ and κ_t : coupling ratios describing deviations from SM values
- Absolute couplings of three pure BSM operators c_g, c_{2g}, c_2: the contact interaction between two Higgs bosons and two top quarks (c_2), and the Higgs boson contact interaction with one (c_g) and two gluons (c_{2g}).

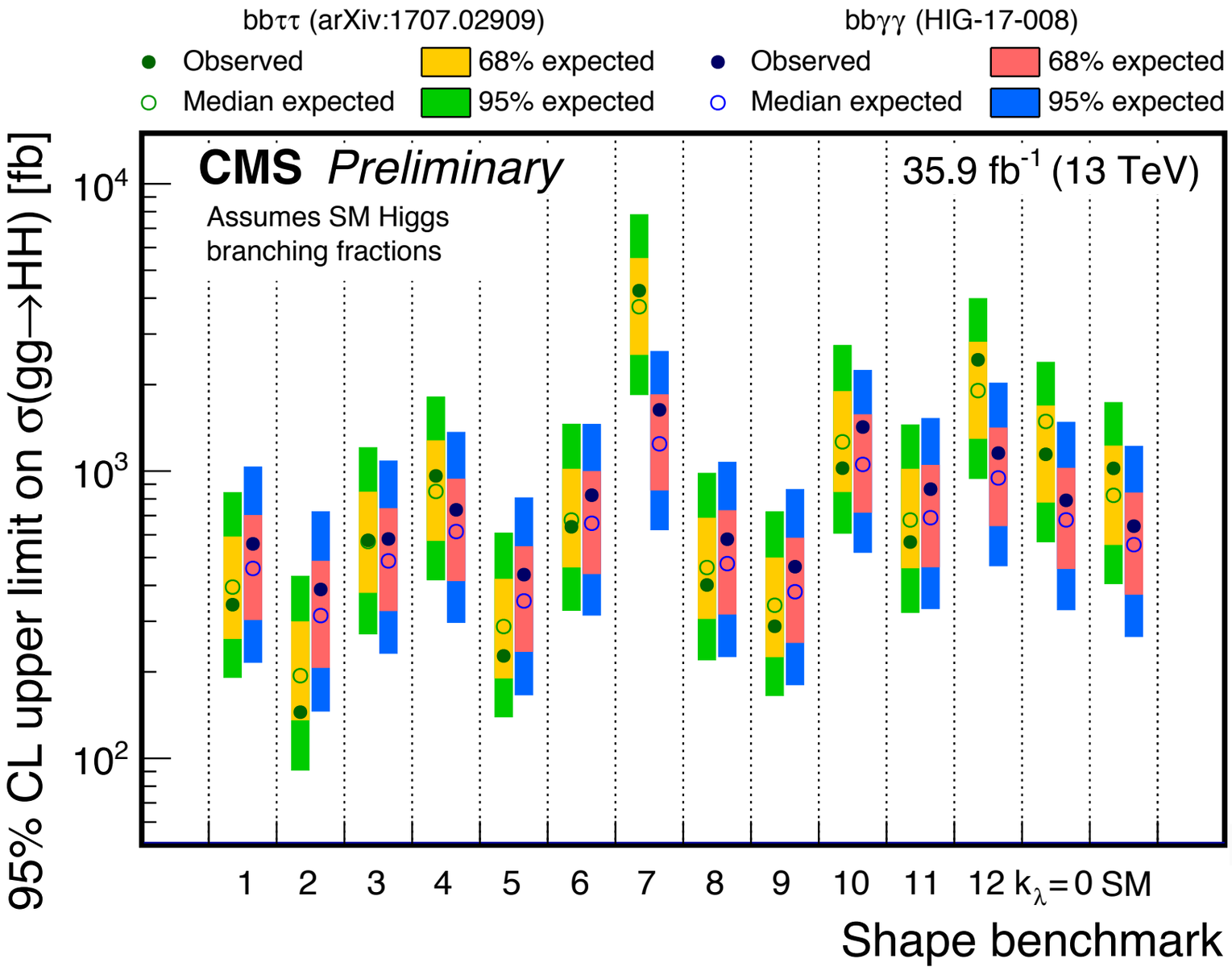






JHEP04(2016)126

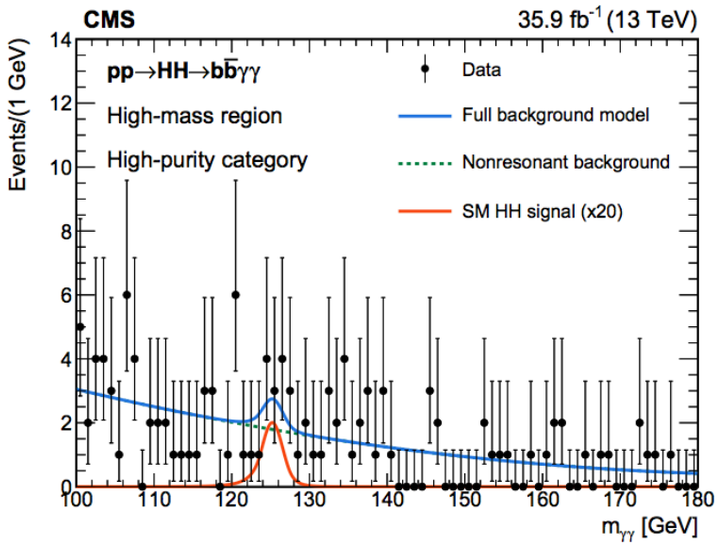
BSM non-resonant benchmarks

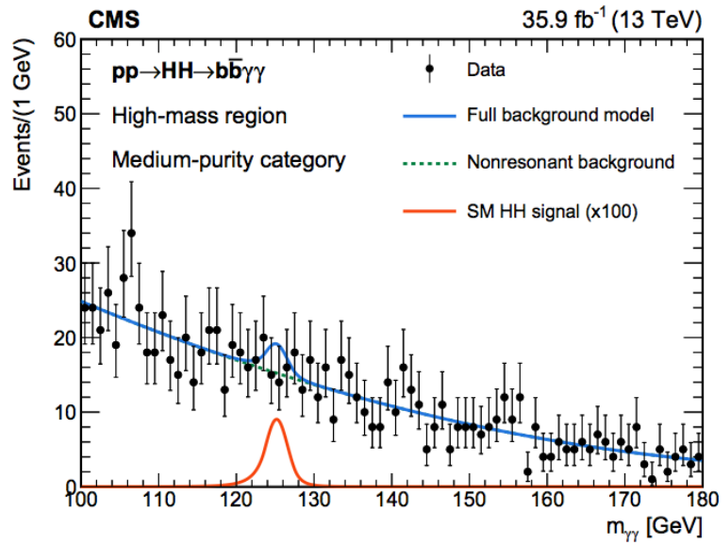


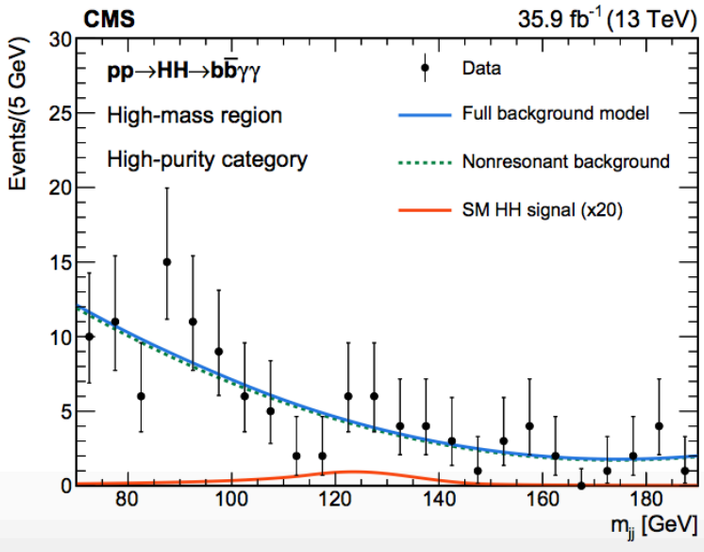
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

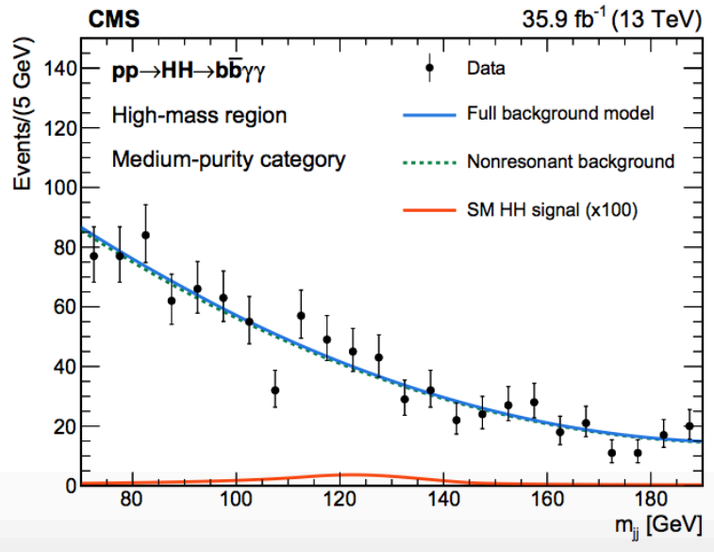
Categorization and mass spectra in bbγγ - CMS

Analysis	Region	Classification MVA	$\widetilde{M}_X$
Nonresonant	High-mass	HPC: MVA > 0.97 MPC: $0.6 <$ MVA < 0.97	$\widetilde{M}_X > 350\,\text{GeV}$
	Low-mass	HPC: MVA > 0.985 MPC: $0.6 <$ MVA < 0.985	$\widetilde{M}_X < 350\,\text{GeV}$
Resonant	$m_X > 600\,\text{GeV}$	HPC: MVA > 0.5 MPC: $0 <$ MVA < 0.5	Mass window
	$m_X < 600\,\text{GeV}$	HPC: MVA > 0.96 MPC: $0.7 <$ MVA < 0.96	Mass window

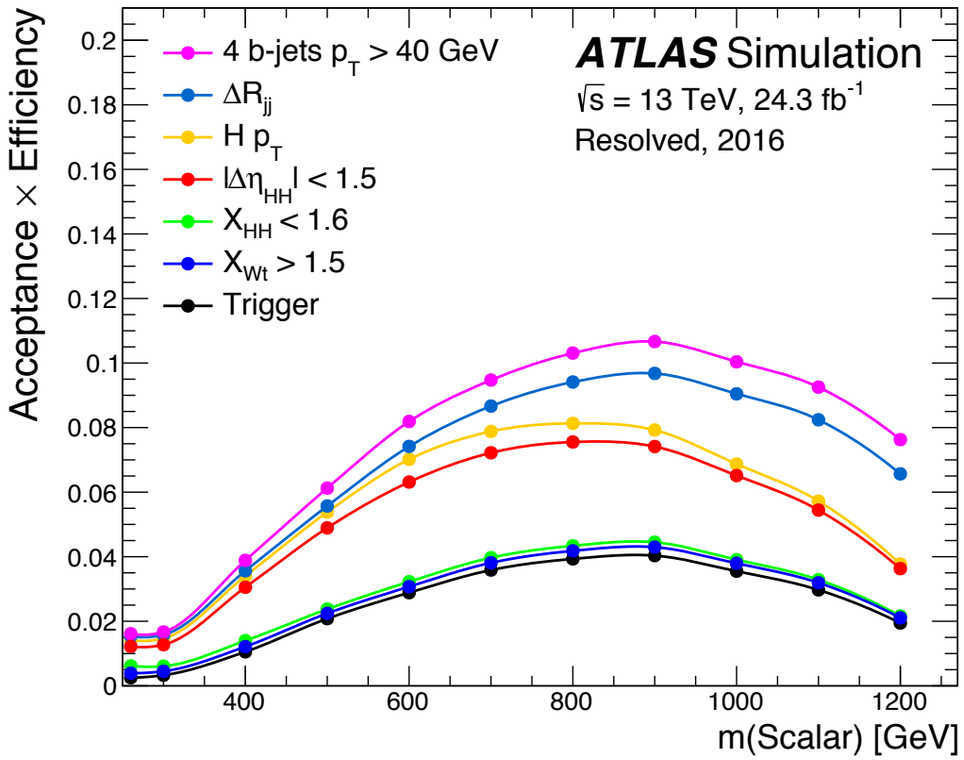


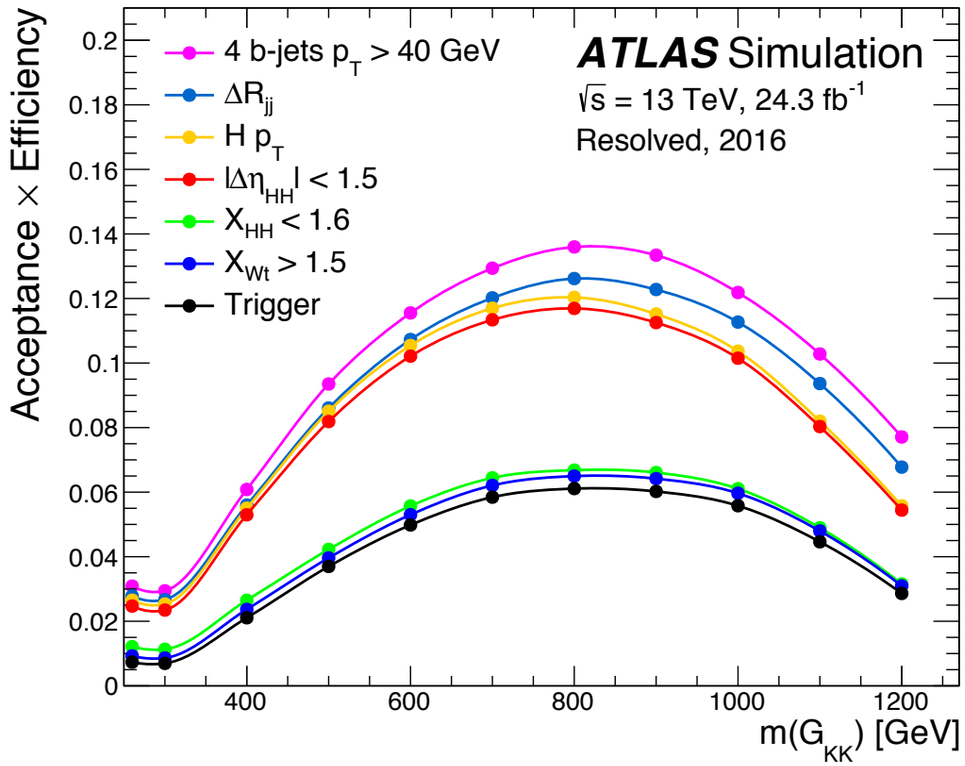


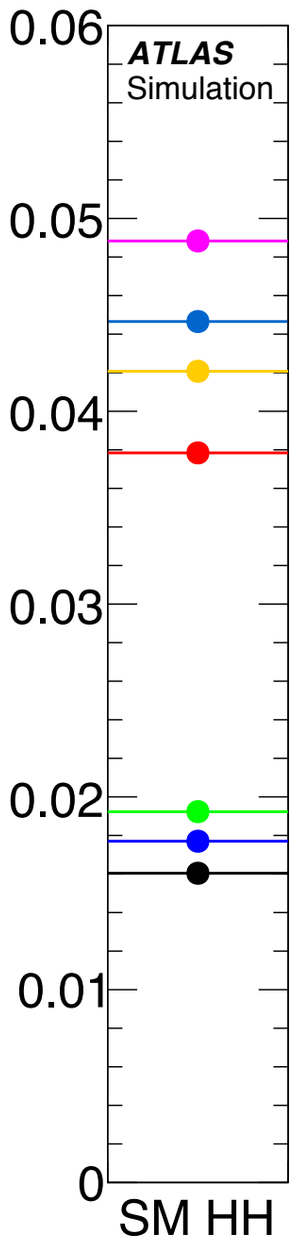
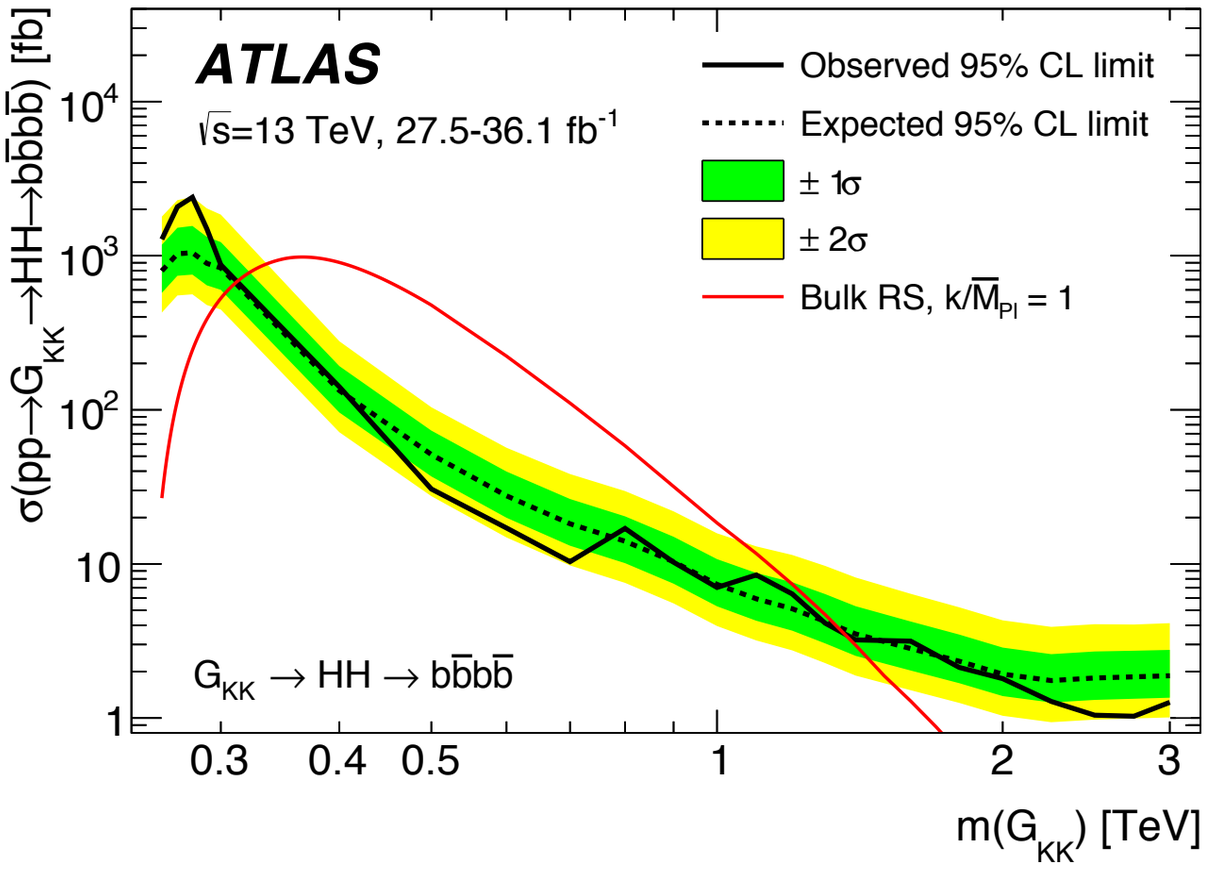
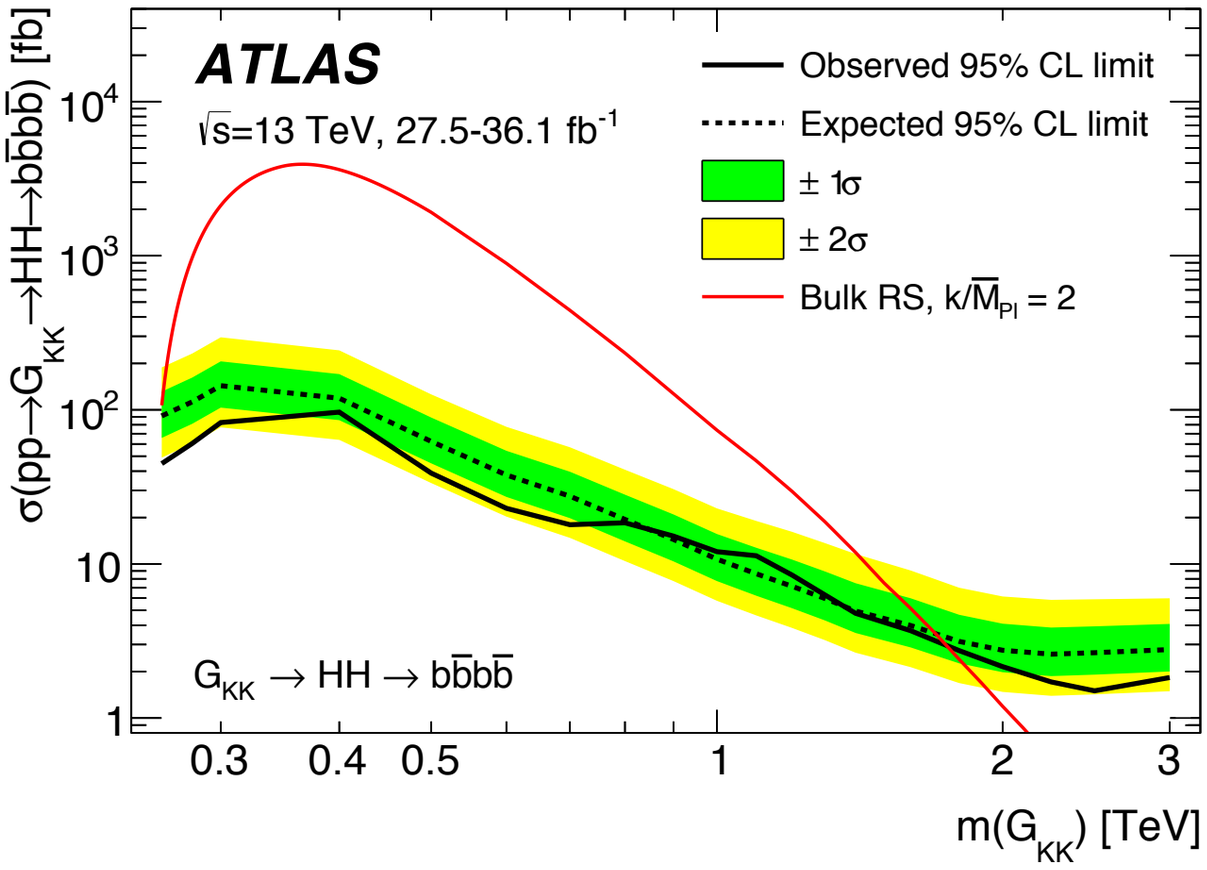




Signal efficiency in bbbb channel - ATLAS







resonant search results in bbbb channel - ATLAS