LHC results on electroweak and Higgs physics

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CTEQ @ PITT
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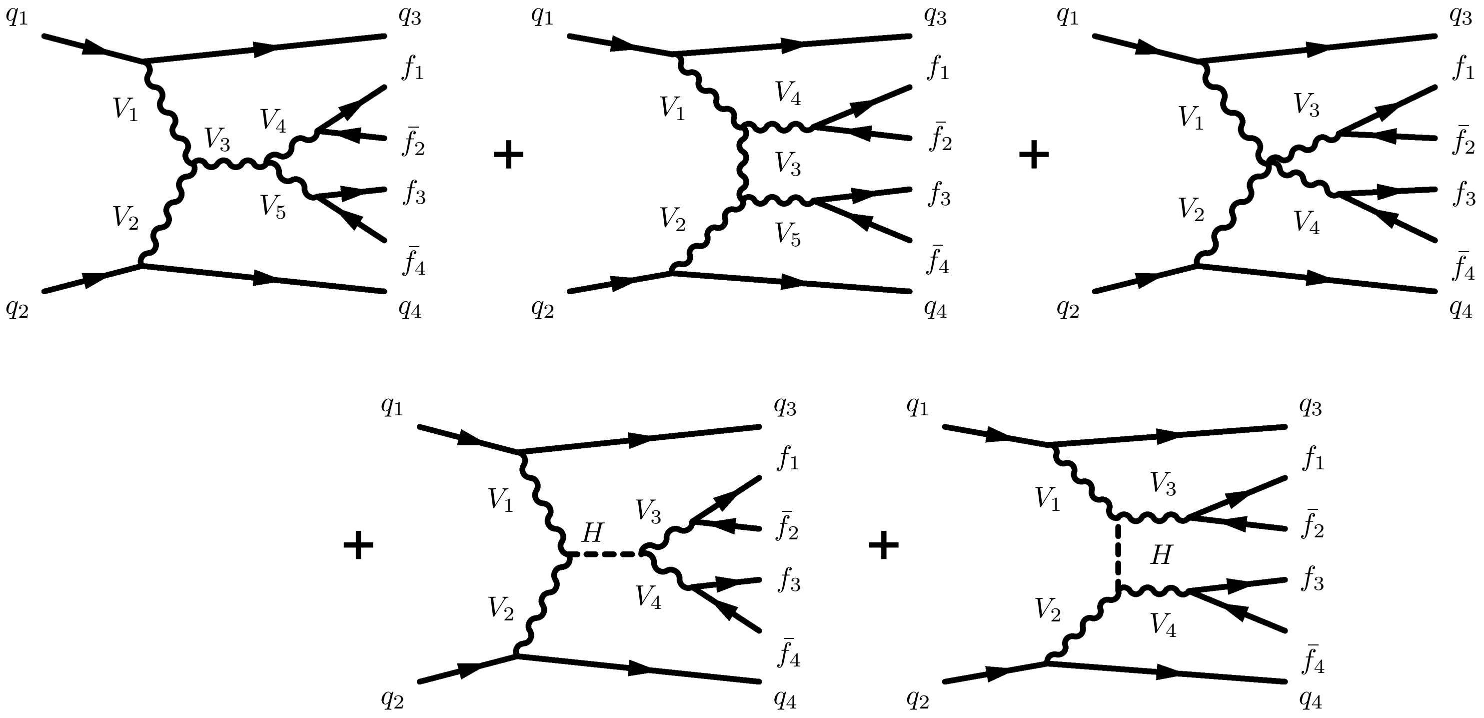
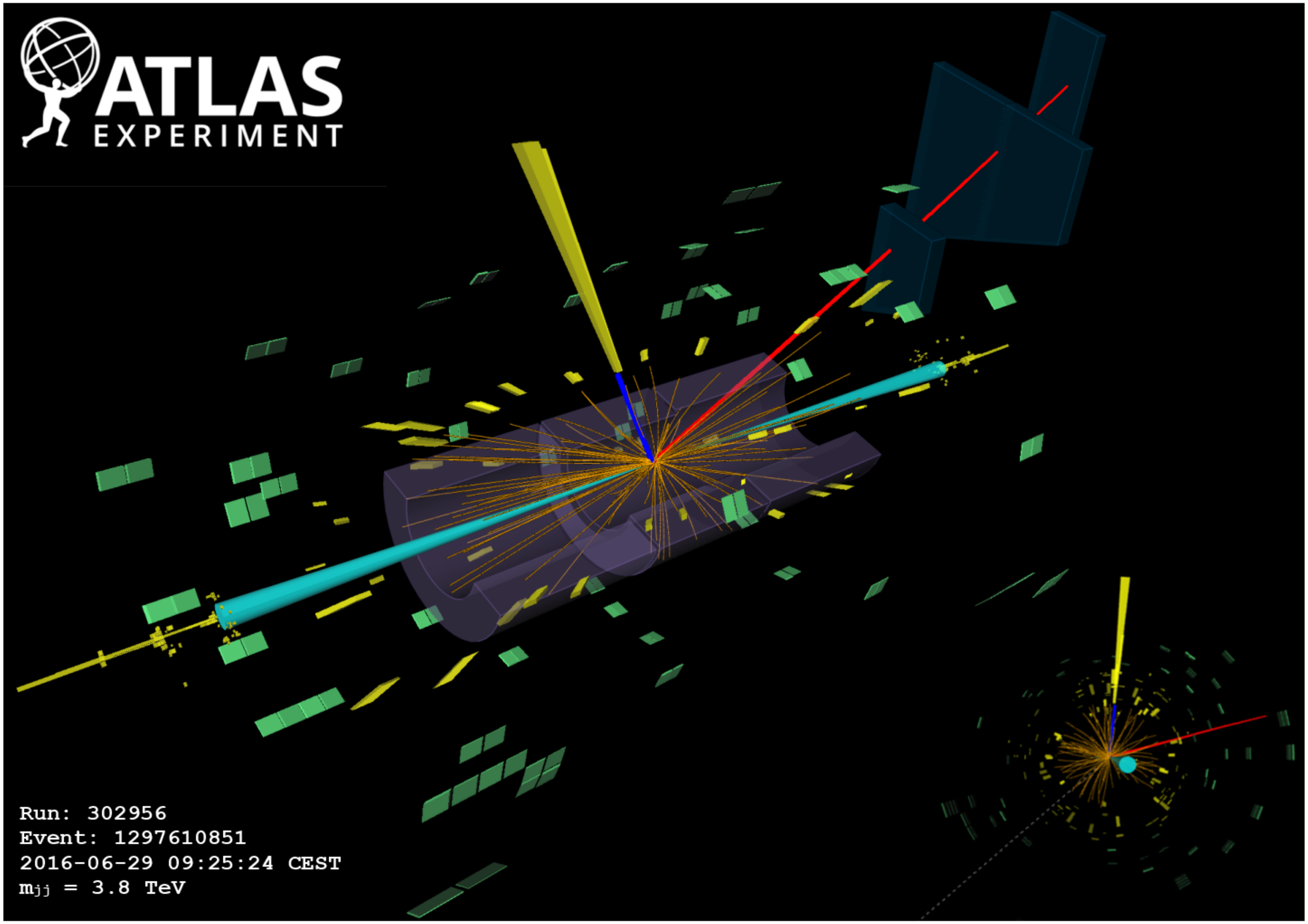
Re-introduction

- Today: more focus on measurements
  - → *Vector boson scattering and effective field theories*
  - → *Higgs physics (Standard Model and beyond)*
- Connected topics: Higgs boson restores unitarity to WW scattering at high momentum



Vector boson scattering



ATLAS STDM-2017-06: $pp \rightarrow W^+W^+jj \rightarrow e^+\nu_e\mu^+\nu_\mu jj$

Significance and limits

- Another thing we can do with our statistical model is search
- **Significance**: how likely is it that your background fluctuated to produce the observed number of events in the absence of signal?

→ *Defined* $S/\delta B = (N_{obs} - B)/\sqrt{B + (\delta B_{sys})^2}$ *in the Gaussian approximation*

  - Which is why it's typically quoted in "sigmas"
  - "Five sigma" is the threshold to be an observation (1 in 3.5 million chance of being a statistical fluctuation... if your uncertainties are correct).

- Limits (1007.1727)

→ *Distinguish between null and signal hypotheses*

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

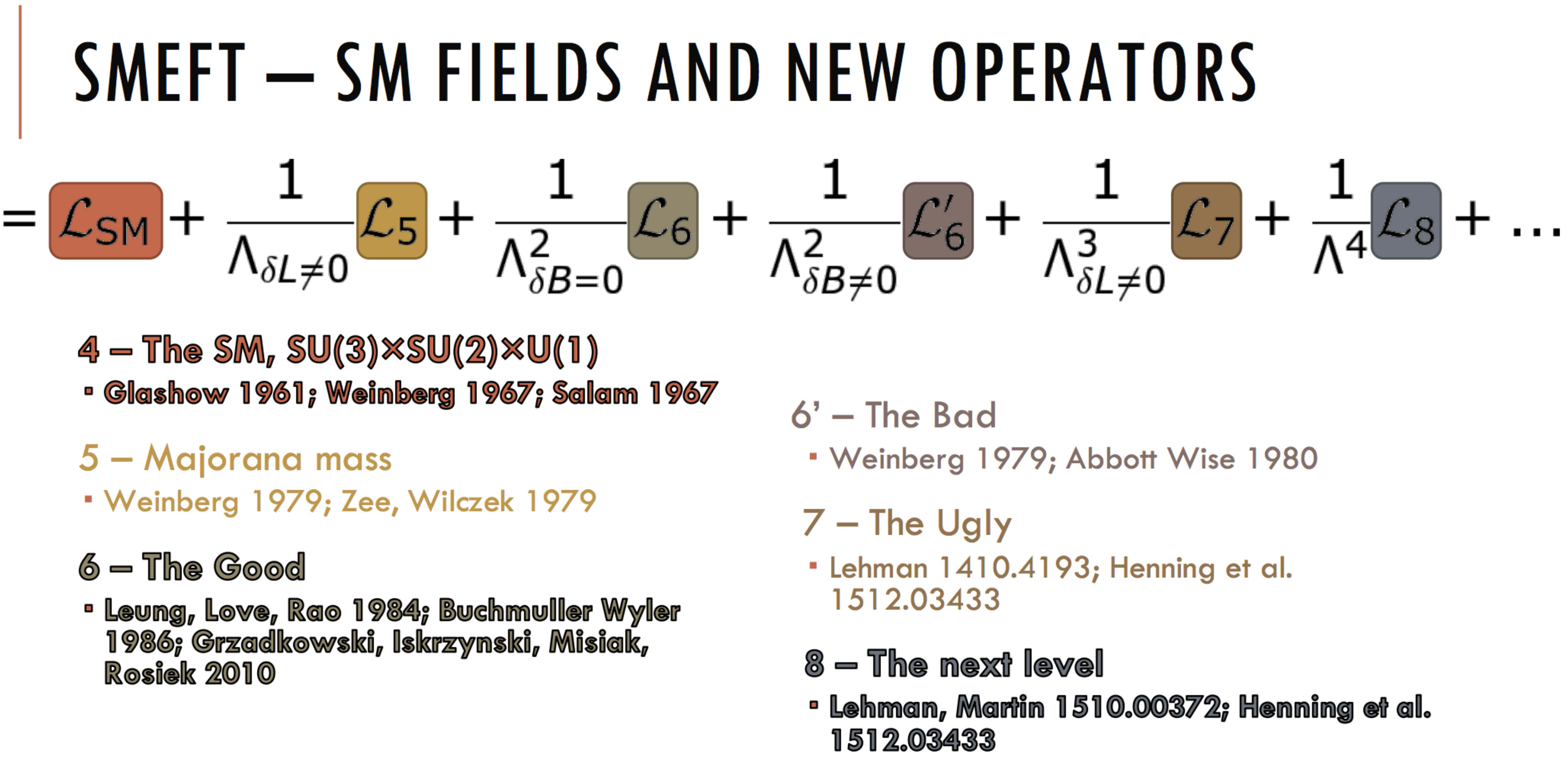
→ *Define profile likelihood ratio* λ

→ *Derive "test statistics" to characterize level of agreement between data and hypothesis*

→ *Frequentist interpretation based on probability distribution of the test statistics*

Effective field theories

- Powerful tool to parameterize physically plausible new physics



SMEFT – SM FIELDS AND NEW OPERATORS

$$\mathcal{L} = \boxed{\mathcal{L}_{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\boxed{\mathcal{L}_5} + \frac{1}{\Lambda^2_{\delta B=0}}\boxed{\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\boxed{\mathcal{L}'_6} + \frac{1}{\Lambda^3_{\delta L\neq 0}}\boxed{\mathcal{L}_7} + \frac{1}{\Lambda^4}\boxed{\mathcal{L}_8} + \ldots$$

4 – The SM, SU(3)×SU(2)×U(1)
- **Glashow 1961; Weinberg 1967; Salam 1967**

5 – Majorana mass
- Weinberg 1979; Zee, Wilczek 1979

6 – The Good
- **Leung, Love, Rao 1984; Buchmuller Wyler 1986; Grzadkowski, Iskrzynski, Misiak, Rosiek 2010**

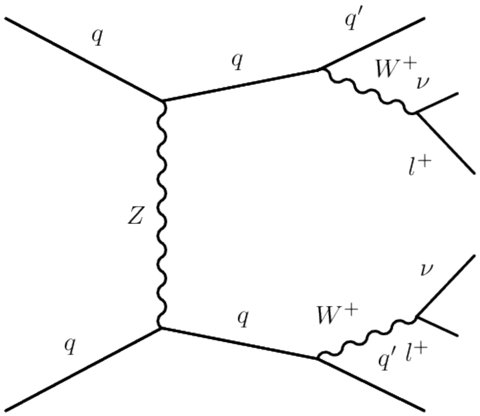
6’ – The Bad
- Weinberg 1979; Abbott Wise 1980

7 – The Ugly
- Lehman 1410.4193; Henning et al. 1512.03433

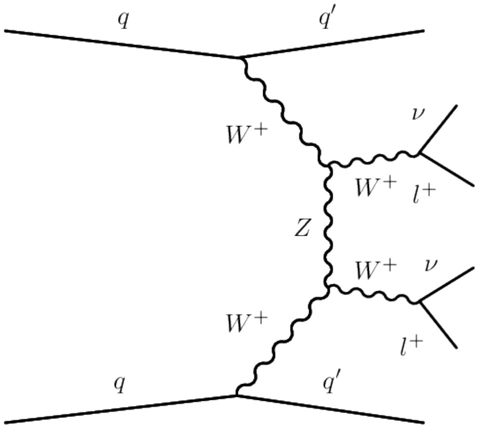
8 – The next level
- **Lehman, Martin 1510.00372; Henning et al. 1512.03433**

Andre David

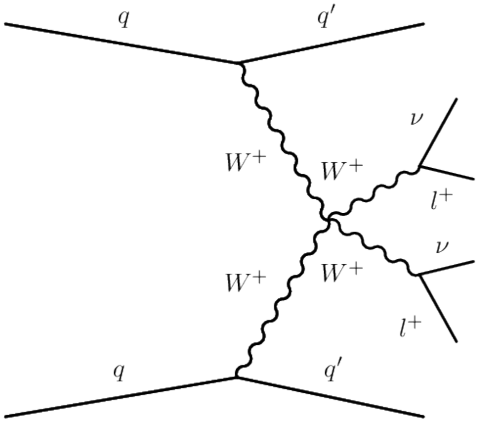
Vector boson scattering: WW



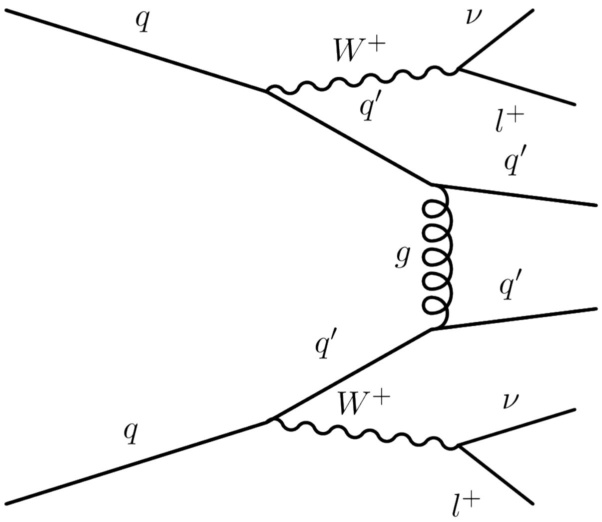
single



triple



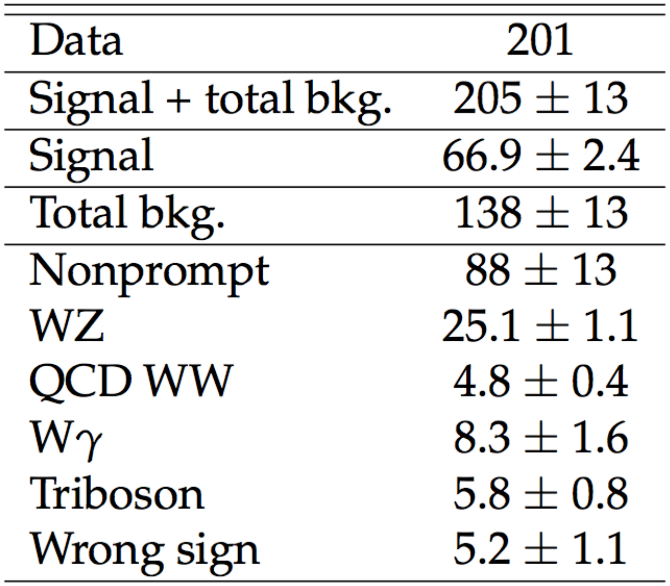
quartic gauge coupling sensitive to new physics



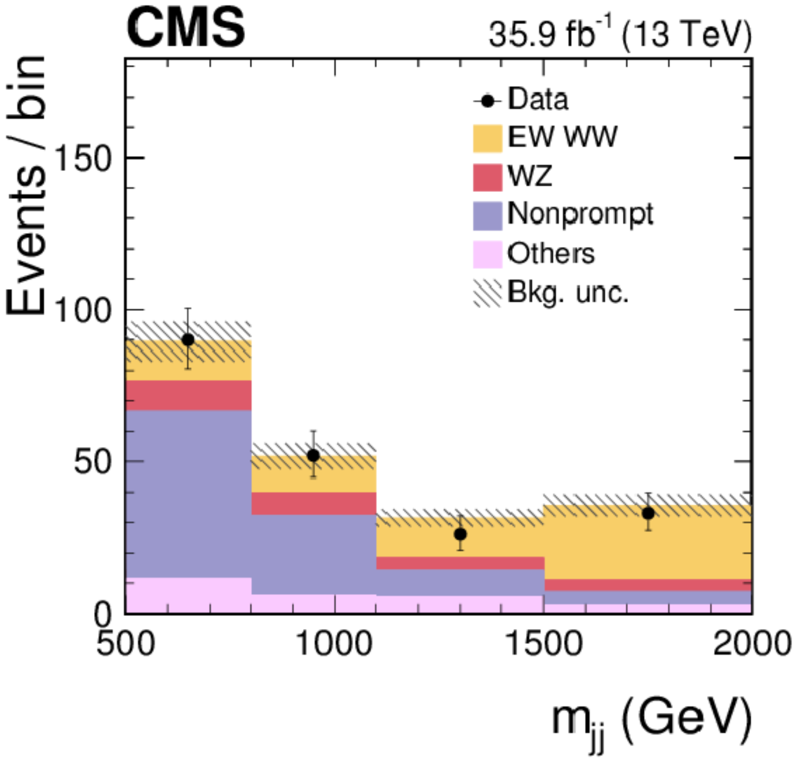
QCD background

CMS SMP-17-004

Vector boson scattering: WW



Data	201
Signal + total bkg.	205 ± 13
Signal	66.9 ± 2.4
Total bkg.	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD WW	4.8 ± 0.4
Wγ	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1



- Observed significance 5.5 sigma (5.7 expected)

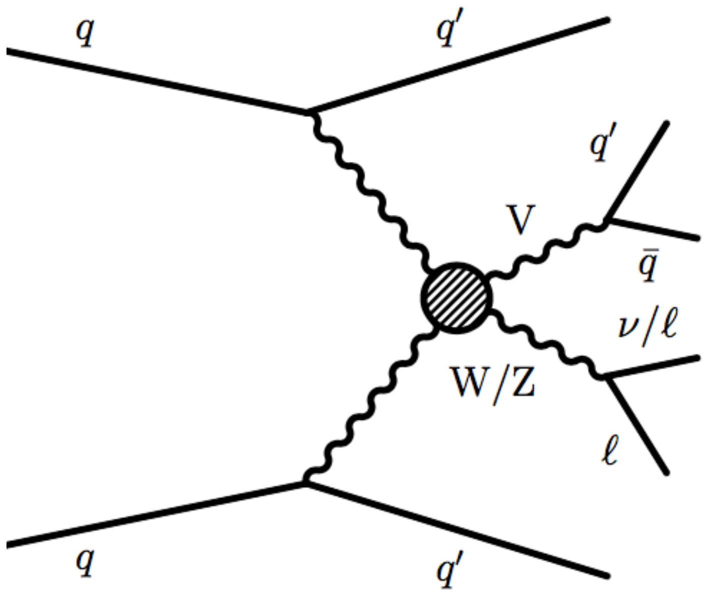
→ *Meets the "observation" threshold*

- Constrain Quartic coupling and d-8 EFT operators (CMS)

CMS SMP-17-004

Vector-boson scattering and EFTs

- Increase acceptance by allowing one W or Z to decay to hadrons
  - → *Branching ratio advantage (decays with e or mu are 22% for W, 6.7% for Z, vs 67% and 70% to hadrons, respectively)*
  - → *Solve for best-guess neutrino momentum in case of leptonic W*
  - → *Explicit goal is to search for aQGCs (as dimension-8 EFT operators) by focusing on high-p_T gauge bosons (V)*



***WV**:*
same-sign and
opposite-sign
WW, and WZ

***ZV**: WZ and ZZ*

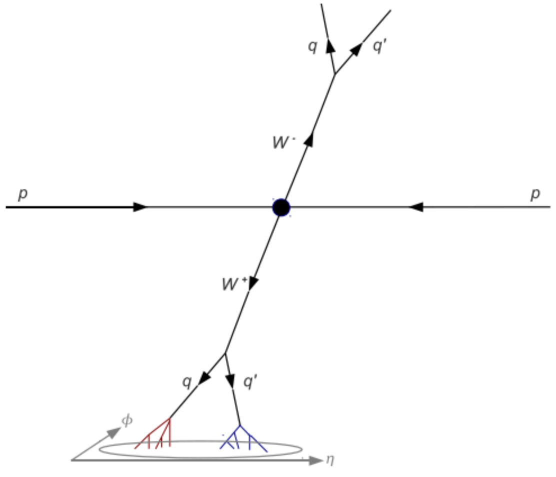
CMS SMP-18-006

Boosted jet reconstruction

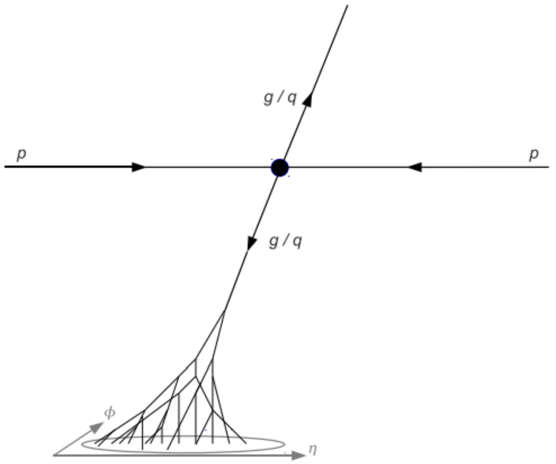
- Reconstruct V as a jet with anti-k_T distance parameter 0.8 and $p_T > 200$ GeV
- Distinct 2-jet topology with small angular separation rejects background
  - → *5% probability for QCD jet to pass selection below*
  - → *70% efficient for signal*
- Compute jet mass after running mass-drop tagger algorithm to remove soft, wide-angle radiation, require $65 < m_V < 105$
- "N-subjettiness" (https://arxiv.org/abs/1011.2268) quantifies how well the jet can be described as having N subjects: require $\tau_2/\tau_1 < 0.55$

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

$$d_0 = \sum_k p_{T,k} R_0$$



(a)



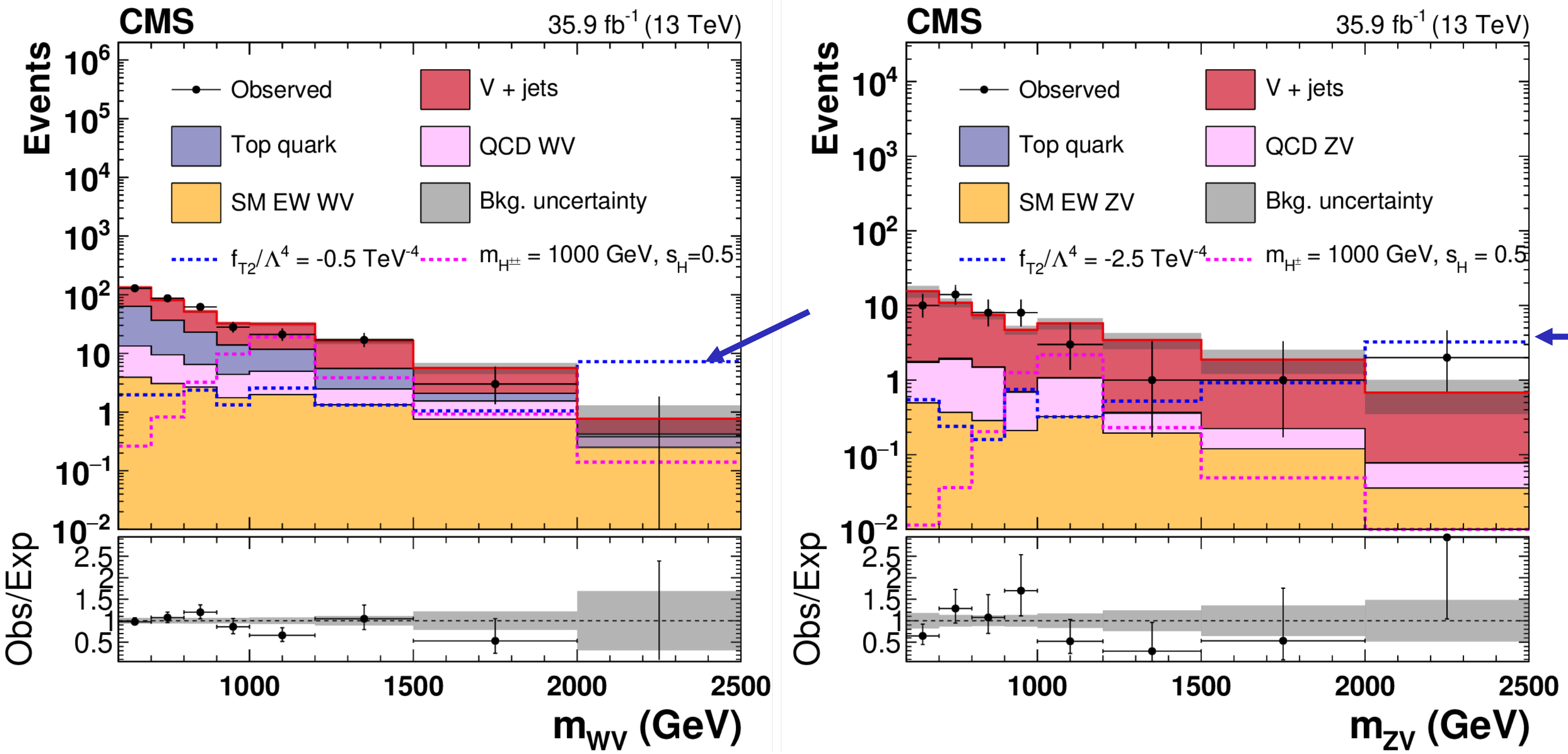
(c)

Vector-boson scattering and EFTs

- Leading W/Z+jets background estimated using m_V sidebands

→ *Pair of jets happens to be nearby and have the right invariant mass*

- WZ also measured (CMS SMP-18-001)



"sensitivity to new physics is in the kinematic tails"

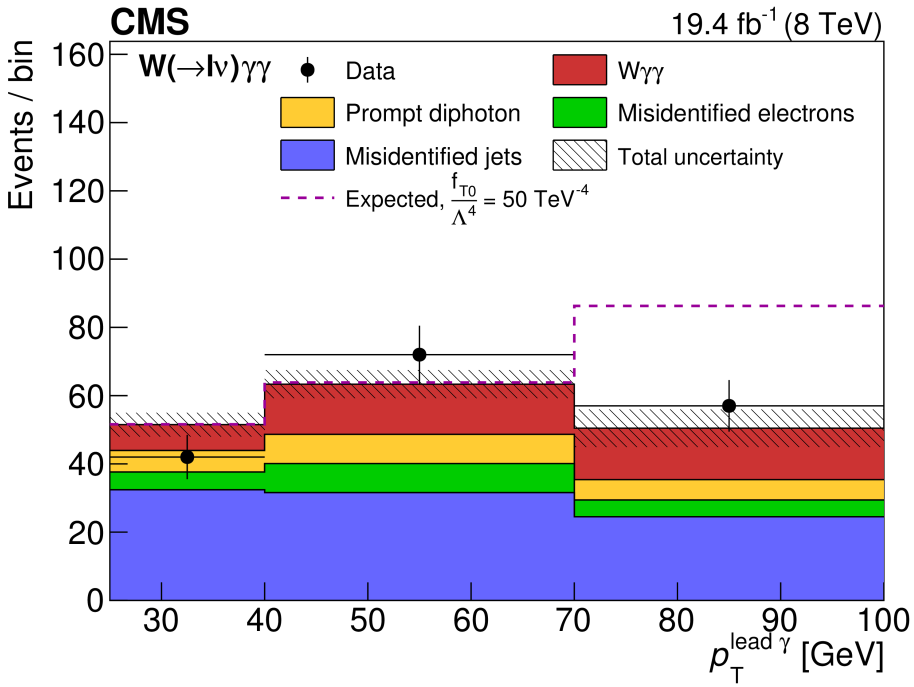
Limit on f_{T2}/Λ^4 is $\pm$0.28 TeV^{-4} (WV)
$\pm$3.4 TeV^{-4} (ZV)

CMS SMP-18-006

aQGCs with Vgg

- 8 TeV measurement from CMS, dimension 8 EFT
- 2.6 sigma W$\gamma\gamma$, observation of Z$\gamma\gamma$ at 5.9 sigma

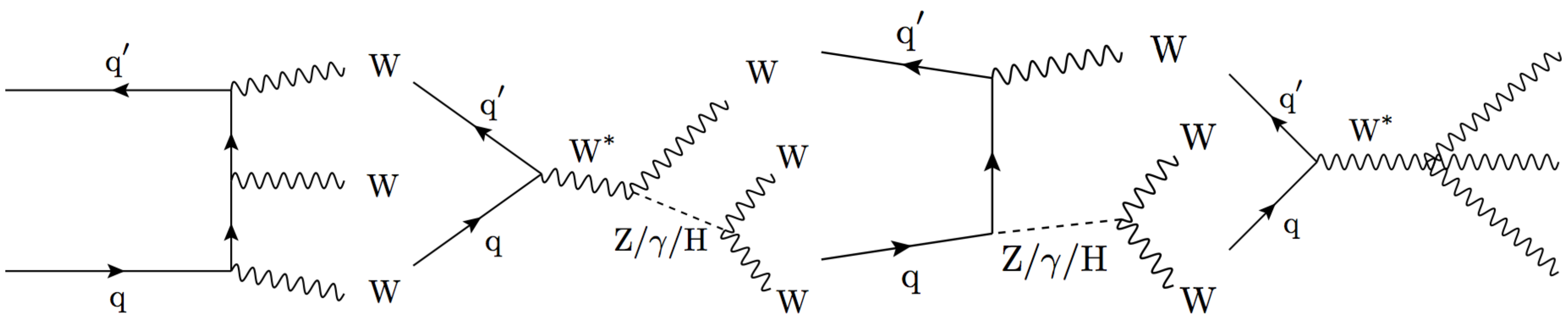
→ *Zgg actually has the larger cross section – but cut on steeply falling p_T^γ distribution*



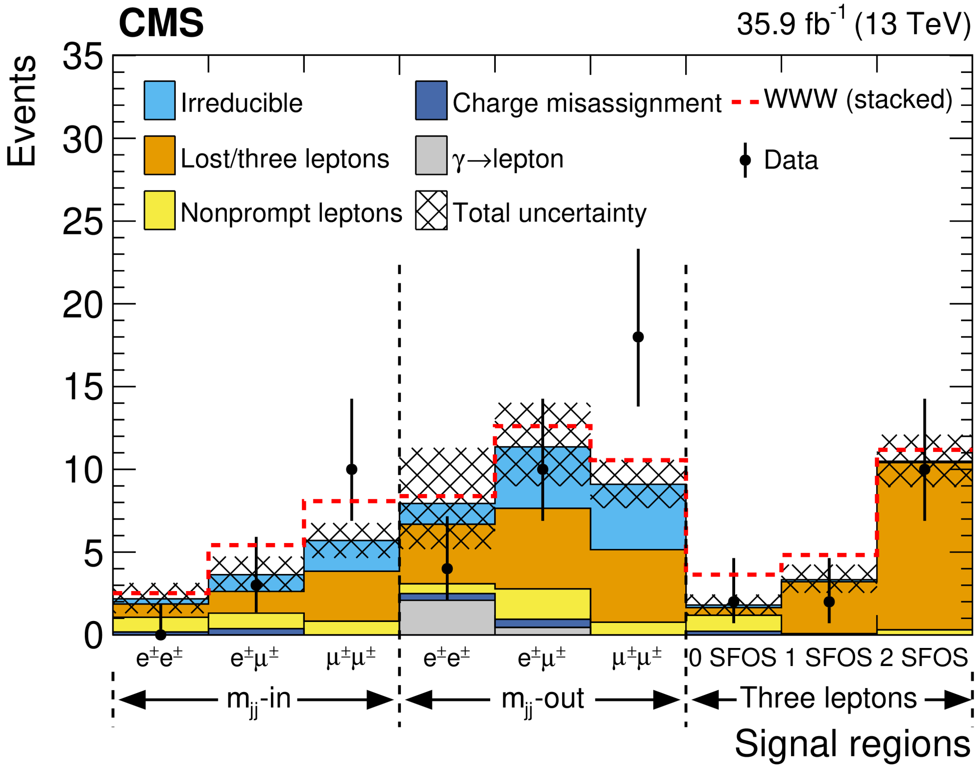
Channel	Measured fiducial cross section
$W\gamma\gamma \to e^{\pm}\nu\gamma\gamma$	$4.2 \pm 2.0\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$W\gamma\gamma \to \mu^{\pm}\nu\gamma\gamma$	$6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	$4.9 \pm 1.4\,(\text{stat}) \pm 1.6\,(\text{syst}) \pm 0.1\,(\text{lumi})$ fb
$Z\gamma\gamma \to e^{+}e^{-}\gamma\gamma$	$12.5 \pm 2.1\,(\text{stat}) \pm 2.1\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \mu^{+}\mu^{-}\gamma\gamma$	$12.8 \pm 1.8\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	$12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb
Channel	Prediction
$W\gamma\gamma \to \ell^{\pm}\nu\gamma\gamma$	4.8 ± 0.5 fb
$Z\gamma\gamma \to \ell^{+}\ell^{-}\gamma\gamma$	13.0 ± 1.5 fb

CMS SMP-15-008

WWW search from CMS



- Three leptons or two same-sign leptons plus 2 jets, 2016 dataset
- 0.60 sigma obs, 1.78 exp
- sensitive to quartic gauge couplings (can't improve aTGC limits)



CMS SMP-17-03

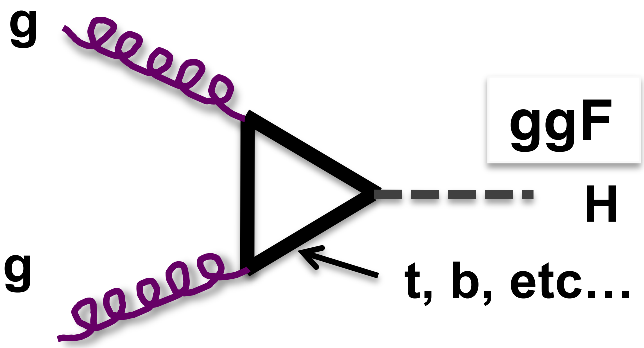
The (Standard Model?)
Higgs Boson

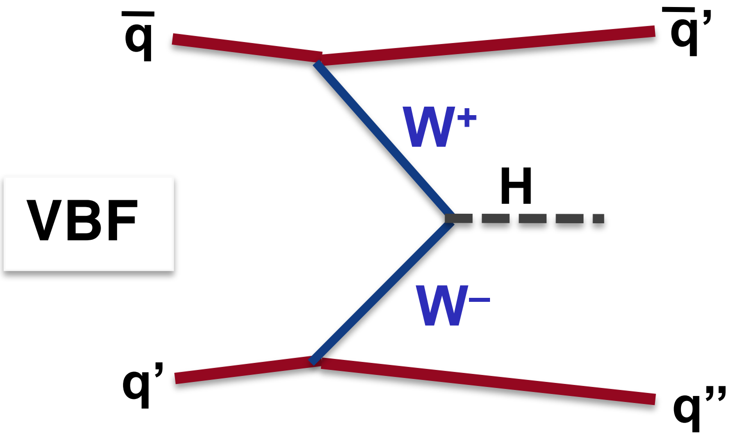
SM Higgs Boson Production

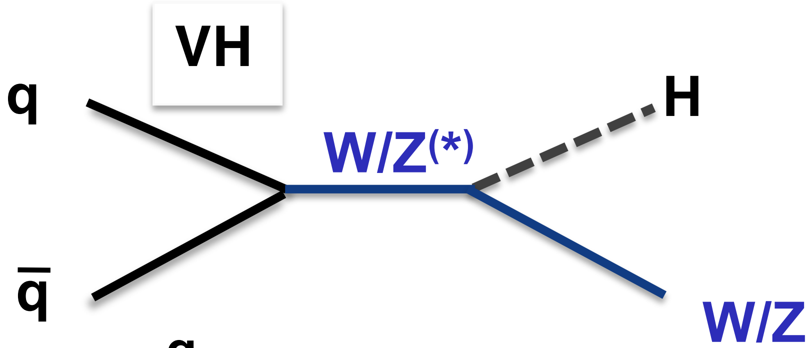
Cross sections for m_H=125 GeV:

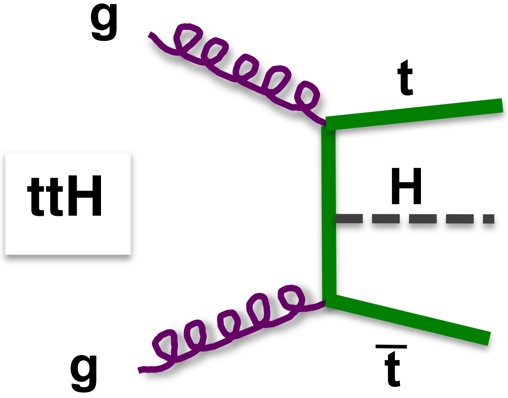
(For scale, W cross section at 13 TeV is 20 nb)

	process	13 TeV
ggF	gluon-gluon fusion	49 pb
VBF	vector-boson fusion	3.8 pb
VH	associated production	2.3 pb
ttH	associated production	0.51 pb



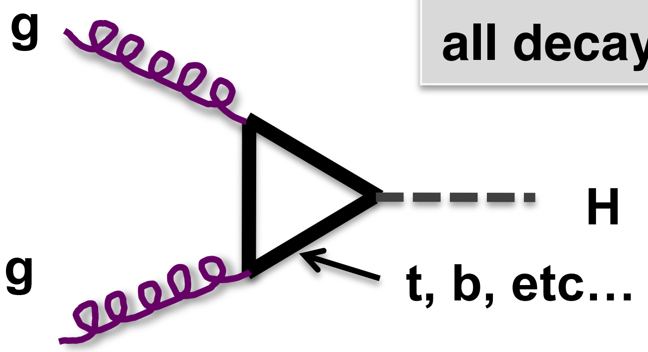




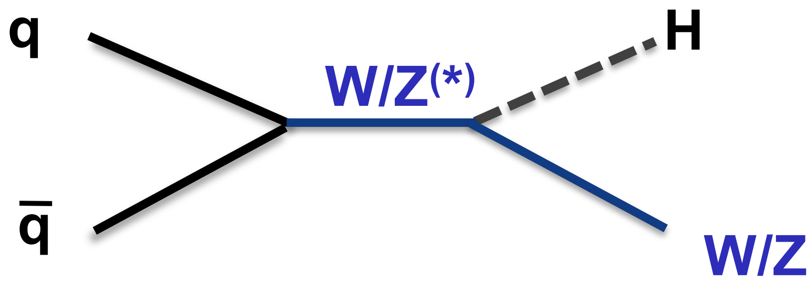


Production mode → categories

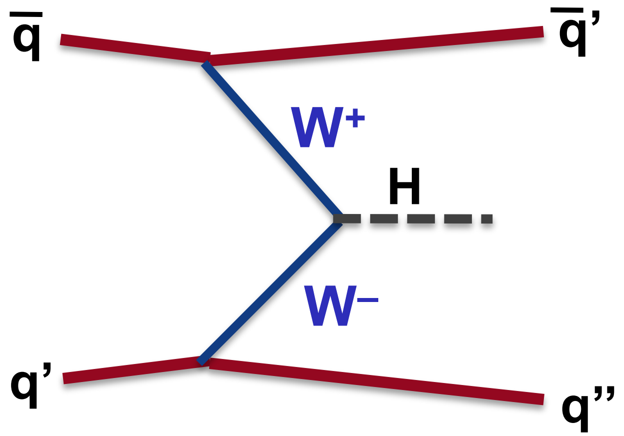
Similar across all decay modes



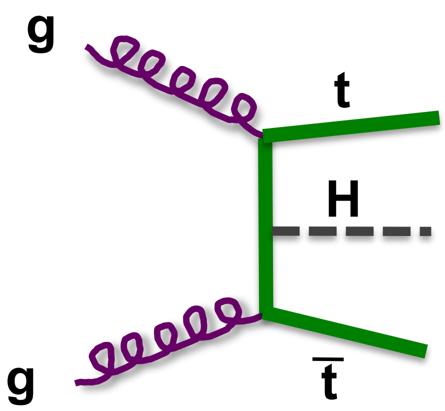
ggF: "untagged", sometimes ISR jet



Wh: single charged lepton
Zh: opposite-sign charged lepton pair, or ETmiss (νs)
Vh (either): high-p_T jet pair



VBF: energetic jet pair with large invariant mass and rapidity separation

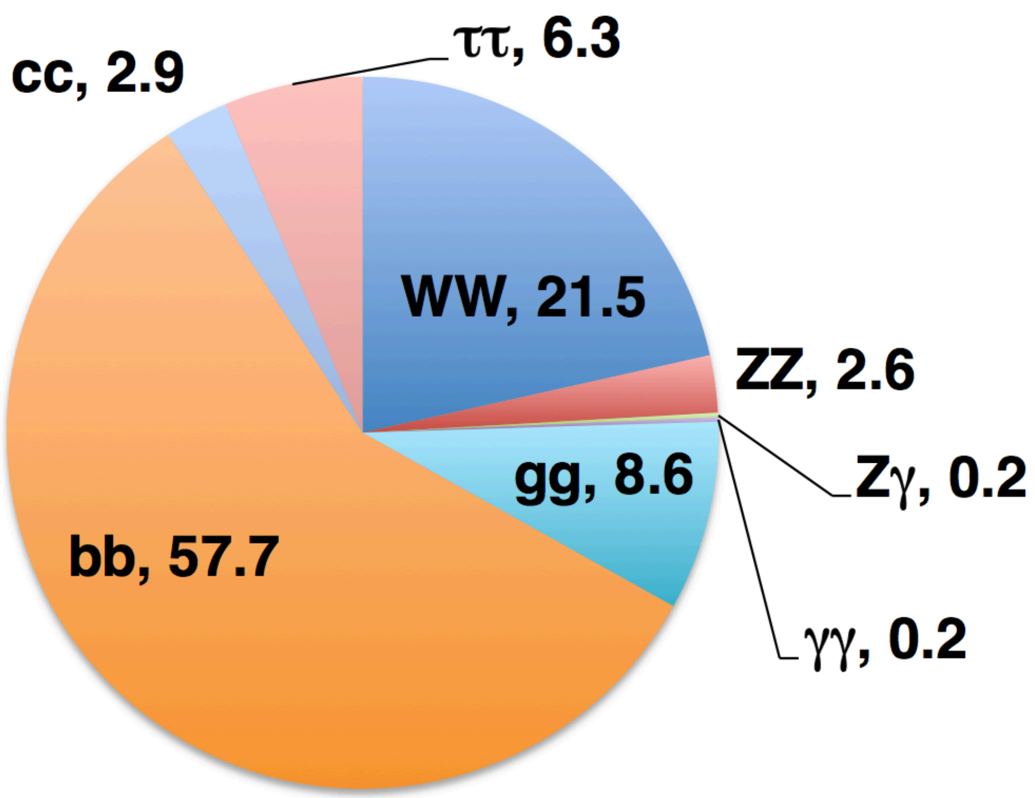


ttH: usual top-quark signature, b-jets and W signature (charged lepton or jet pair)

… and decay

Standard Model: wealth of decay modes at m_H = 125 GeV

Branching ratio = Probability for Higgs boson to decay to given final state



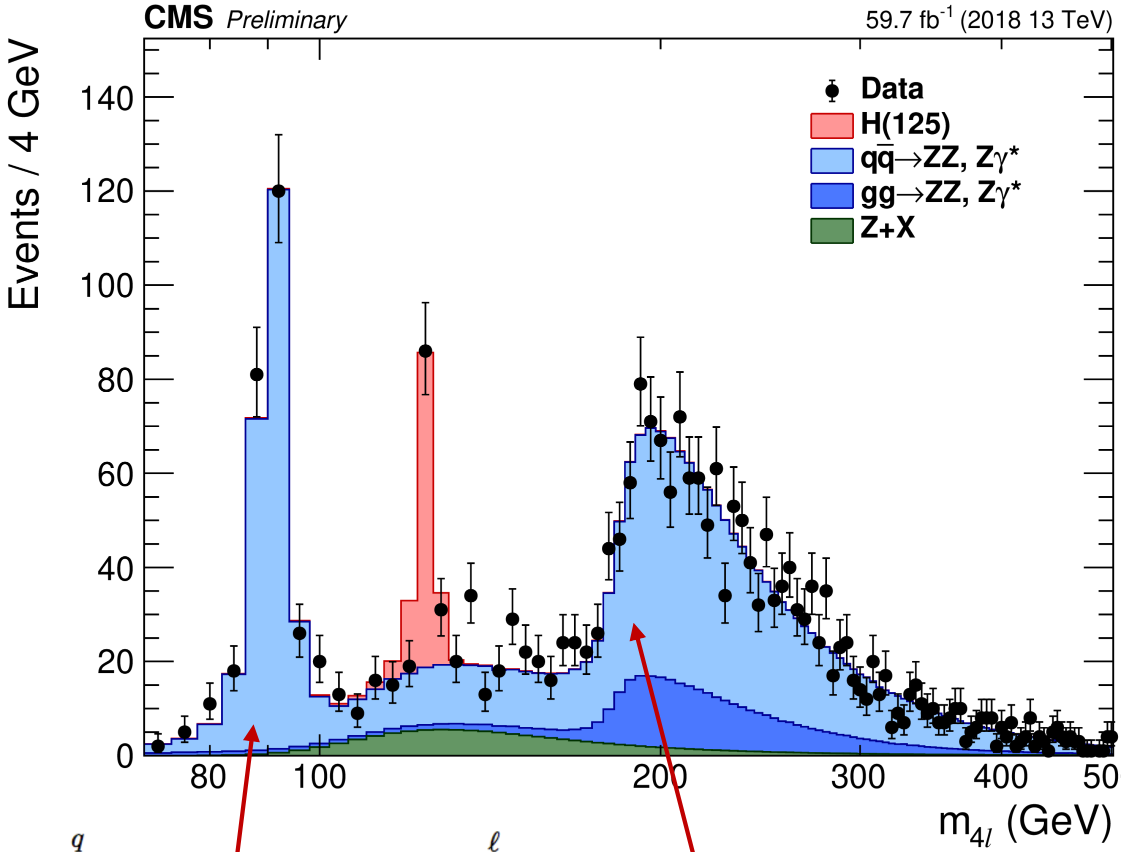
SM Higgs branching ratios, in %

Final state dictates experimental considerations:

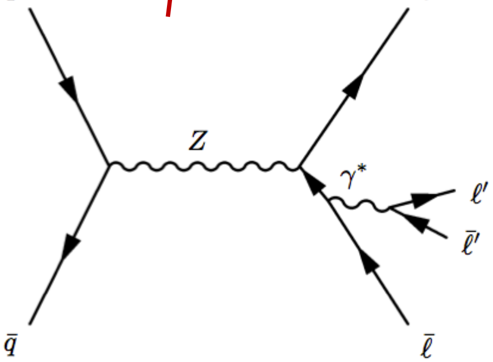
- ZZ → leptons, statistics
- γγ → photon calibrations
- WW → backgrounds
- bb → b-tagging
- ττ → tau identification

$H \rightarrow ZZ \rightarrow 4\ell$

- Small branching ratio but best S/B
- Preliminary full-Run-2 results from both experiments, both with ~10% uncertainty on signal strength μ
  - → *Equal contributions statistical and systematic*
- Measurement strategy
  - → *2-d fit to m4l and a kinematic discriminant based on the full matrix element calculation (CMS) or neural-net discriminant output (ATLAS)*
- Key systematic uncertainties are from lepton identification and integrated luminosity



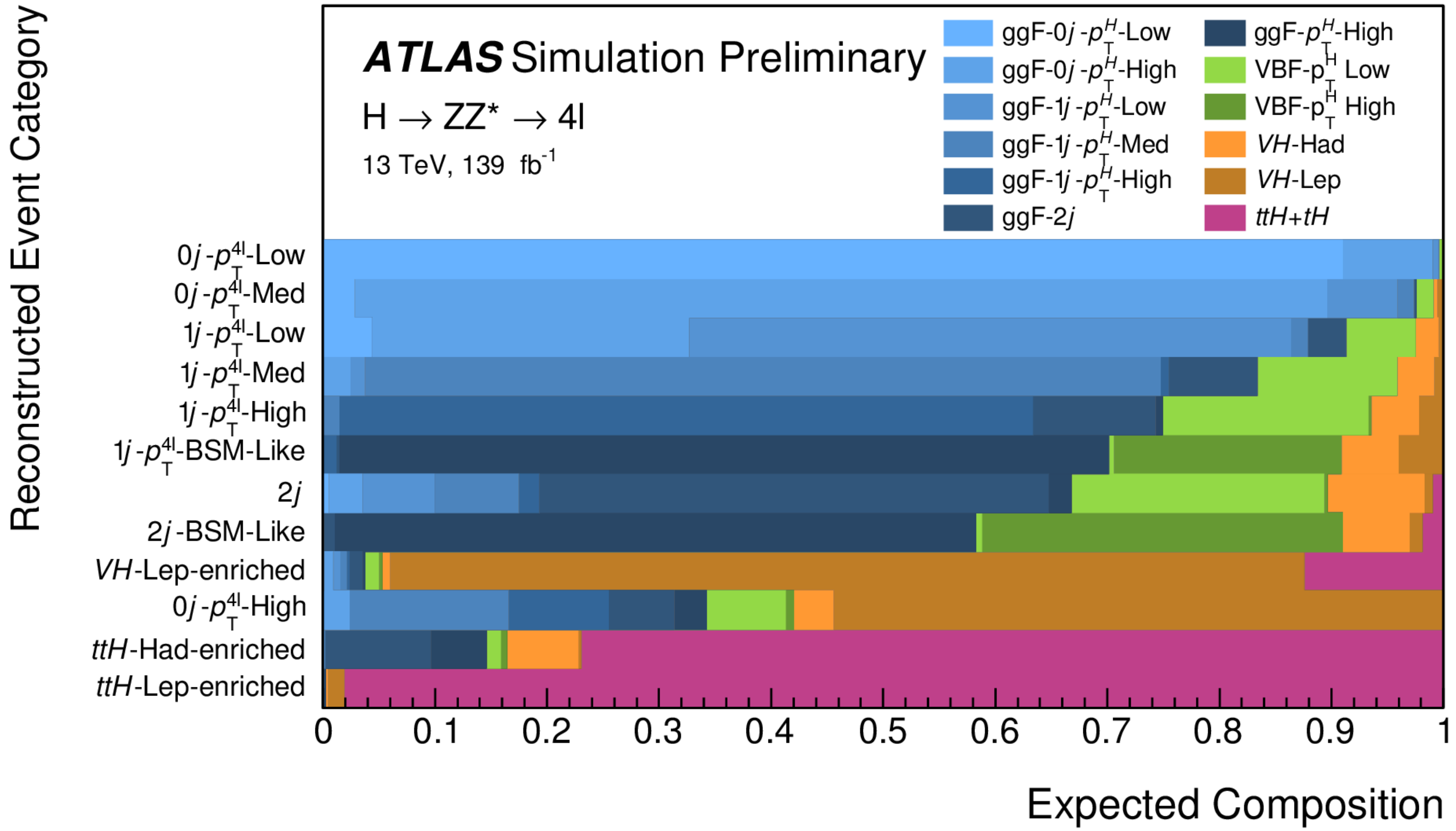
$2M_Z$ threshold



$Z \rightarrow 4\ell$

ATLAS-CONF-2019-025
CMS HIG-19-001

Extended categorization

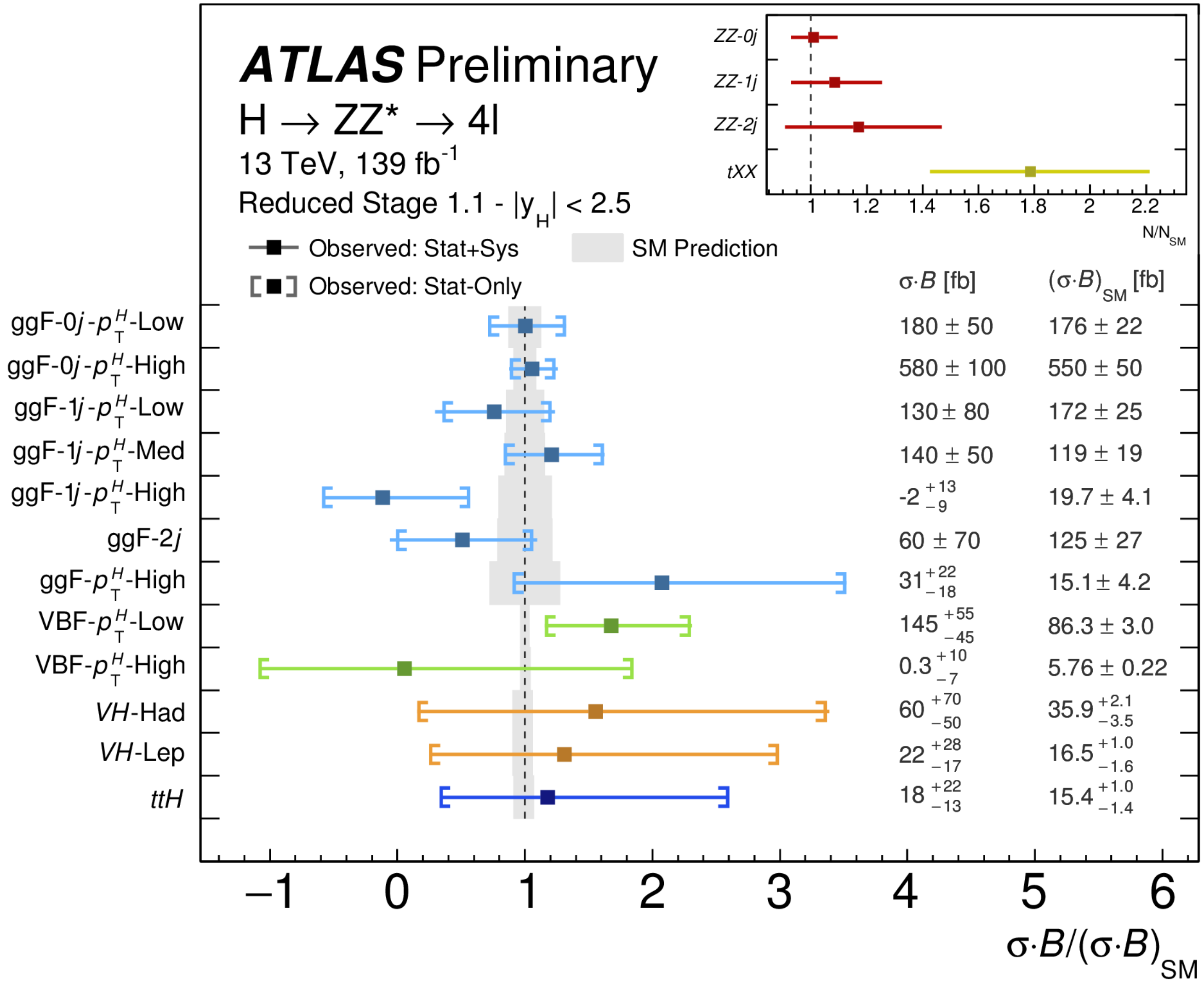


- Subdivide categories to enhance sensitivity to BSM physics
- ”Template cross section” approach categorizes events

→ *Simplified fiducial volume, defined at particle level: dressed leptons, jets clustered from stable particles*

ATLAS-CONF-2019-025

Extended categorization



- Precision limited by experiment statistics

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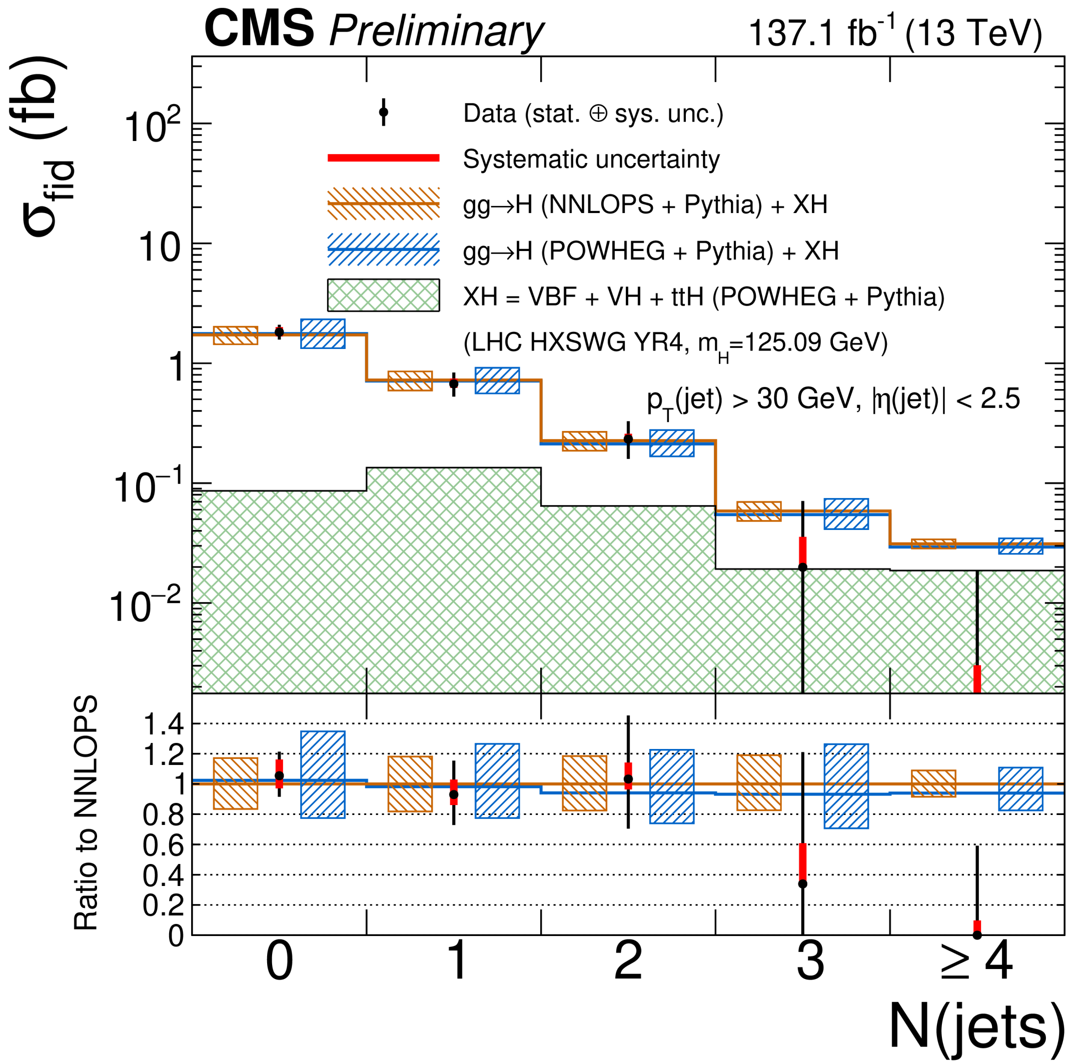
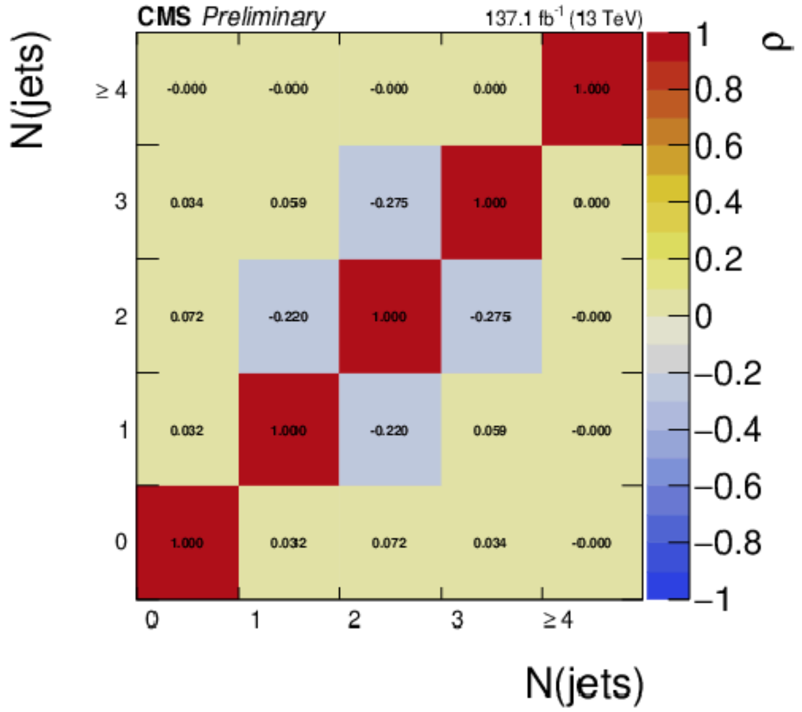
Differential cross section

- Minimize theory uncertainties, compare to predictions



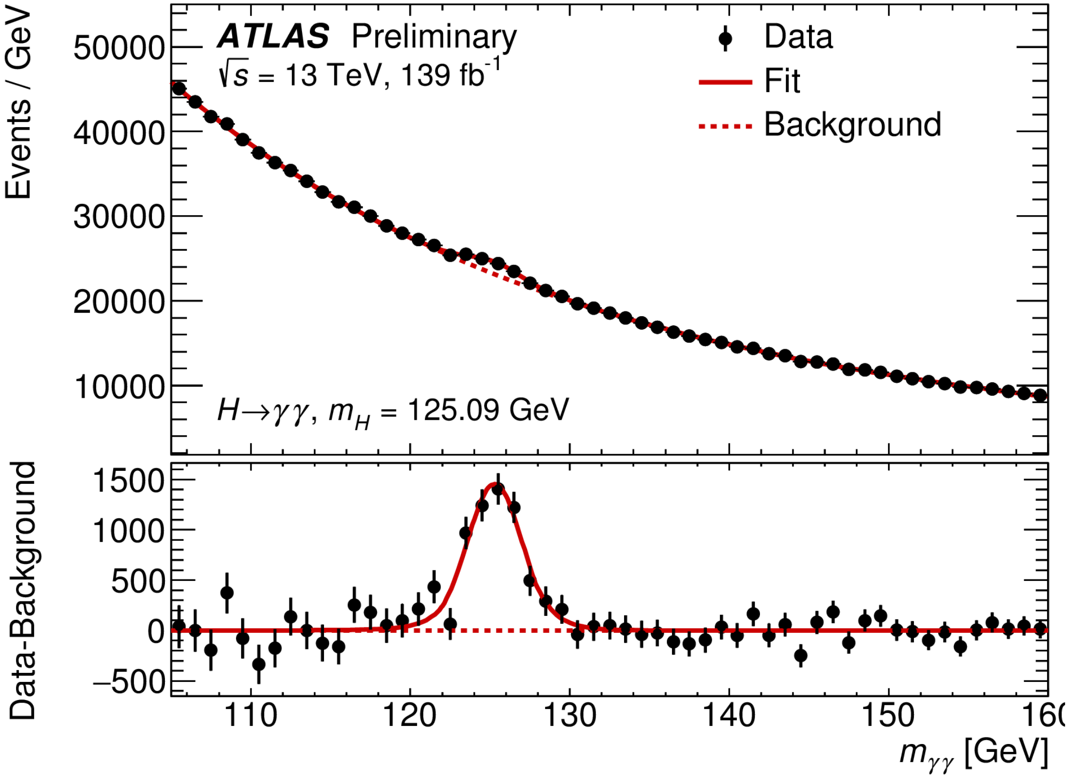


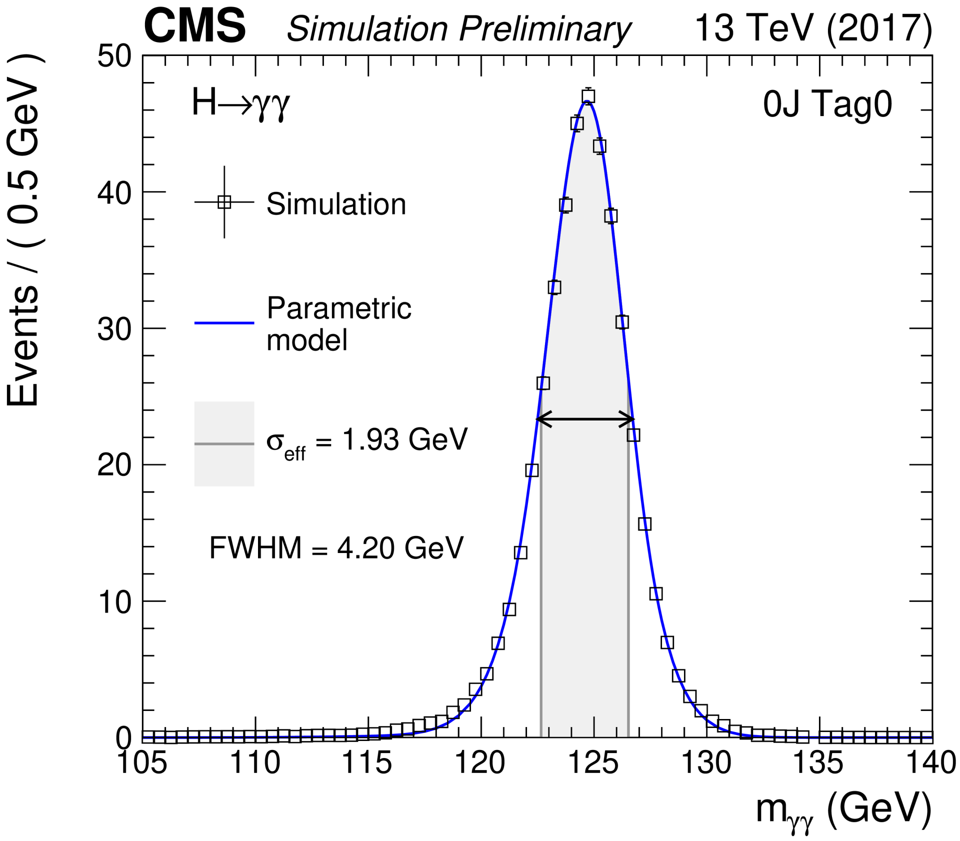
anticorrelation between adjacent jet bins (of the result; not the response matrix)

CMS HIG-19-001

$H \rightarrow \gamma\gamma$

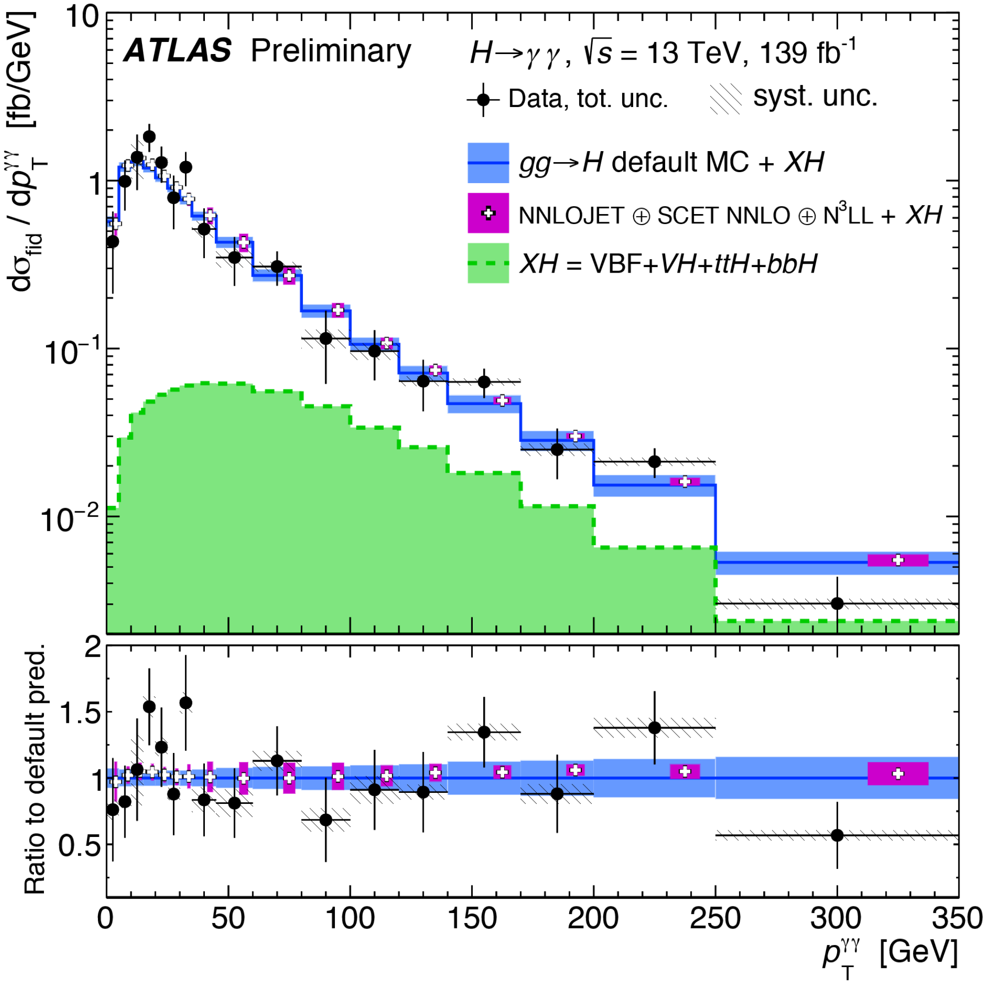
- Good photon energy resolution results in narrow mass peak
- Background large but well-understood

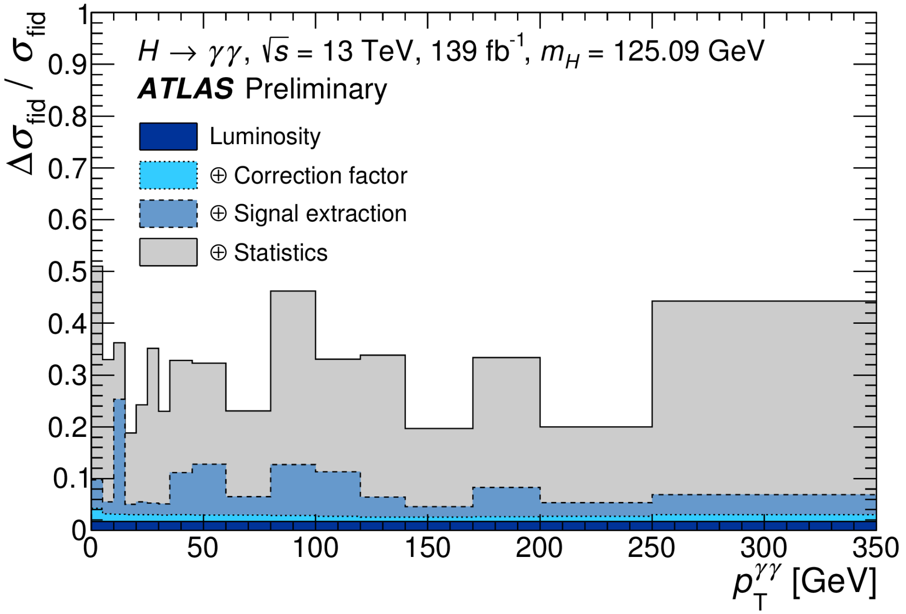


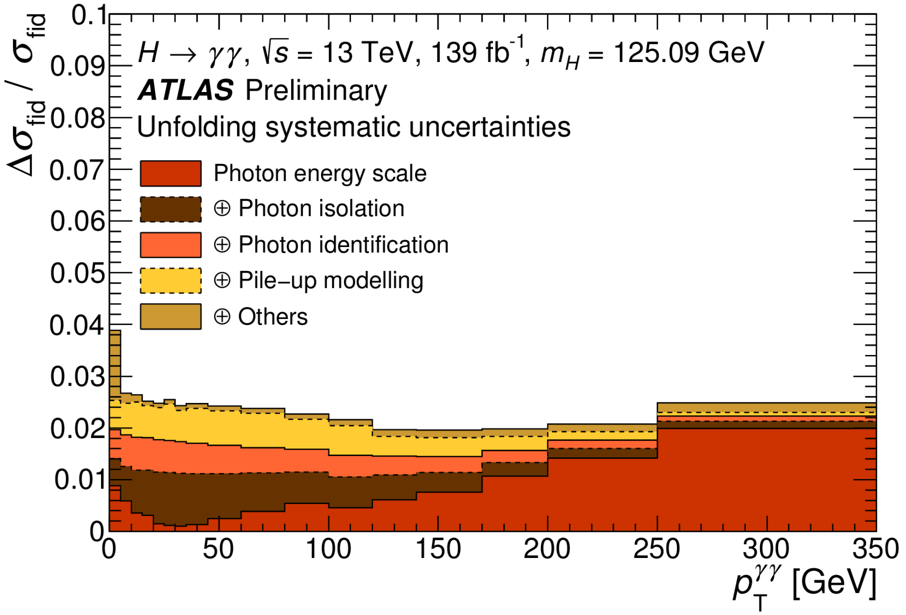


ATLAS-CONF-2019-029

$H \rightarrow \gamma\gamma$



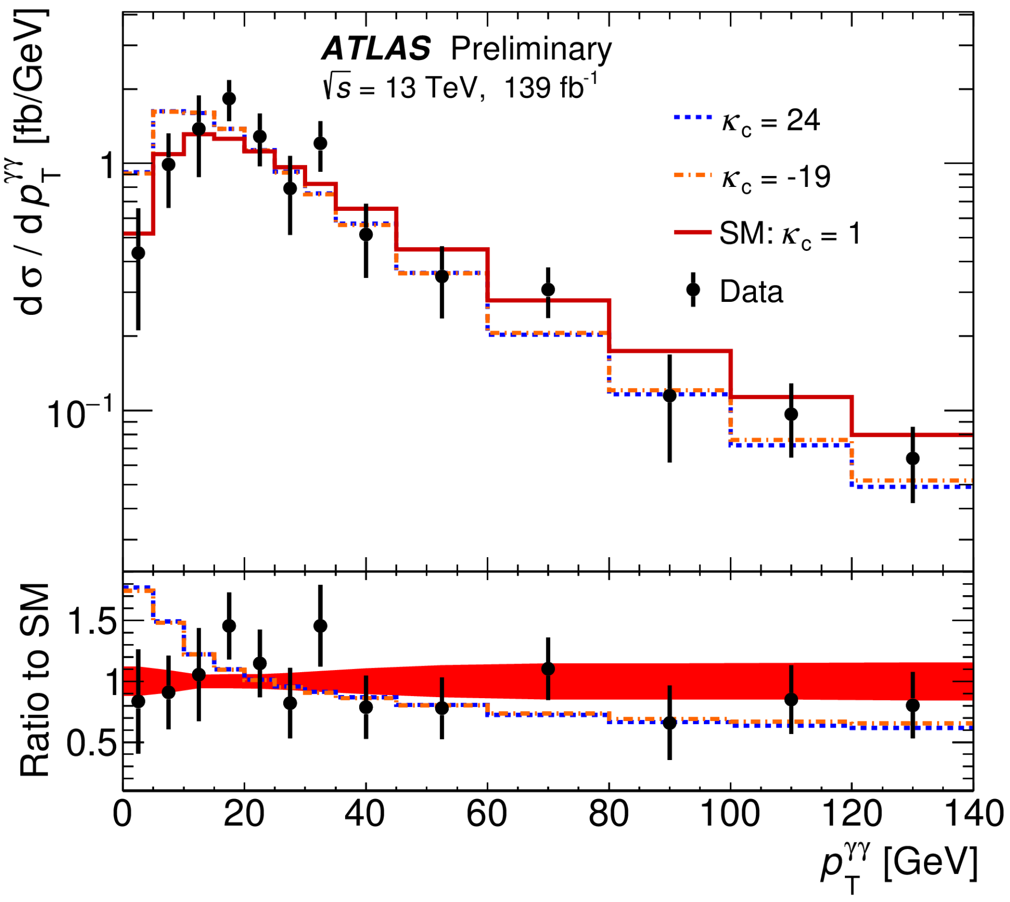


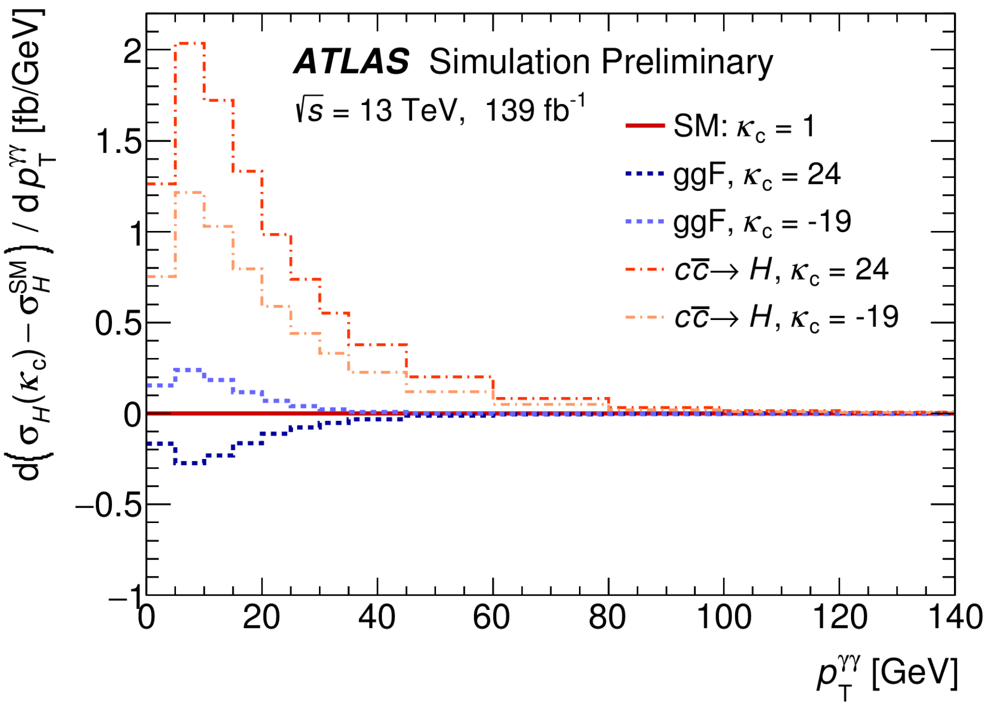


Uncertainties on extrapolation to fiducial volume (above) and unfolding (below)

ATLAS-CONF-2019-029

$H \rightarrow \gamma\gamma$





Observed 95% CL limit	Expected 95% CL limit
[−19, 24]	[−15, 19]

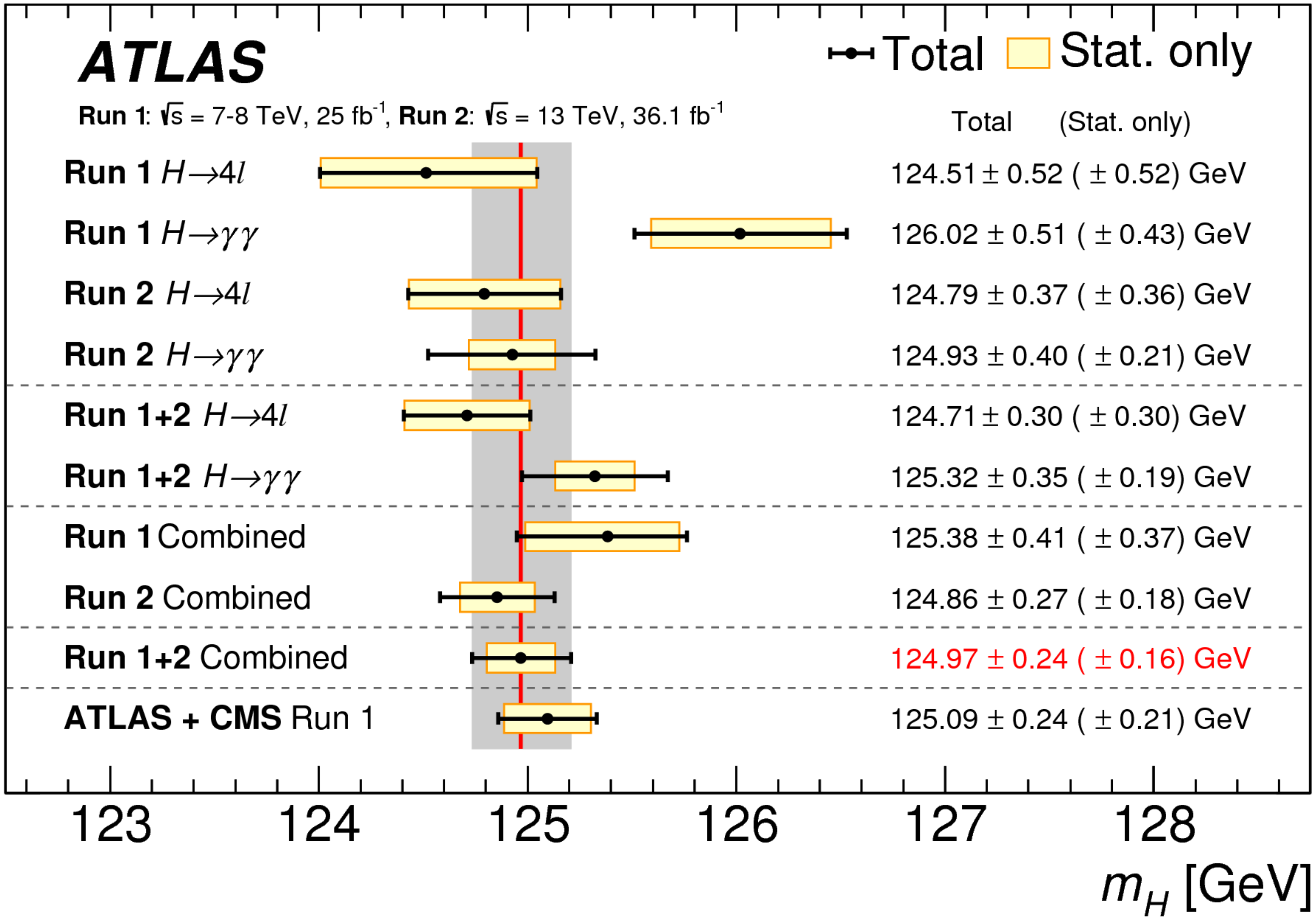
Charm coupling sensitivity through loop in ggF or sea-quark fusion, in a specific momentum range (1606.09253)

ATLAS-CONF-2019-029

Mass of the Higgs boson

- Run 2 measurements starting to improve on Run 1

→ *Smaller statistical uncertainties*



Leading systematics (MeV):

$H \rightarrow 4\ell$

μ momentum scale 40

ele energy scale 26

$H \rightarrow \gamma\gamma$

ECAL non-linearity 180

ECAL calibration 170

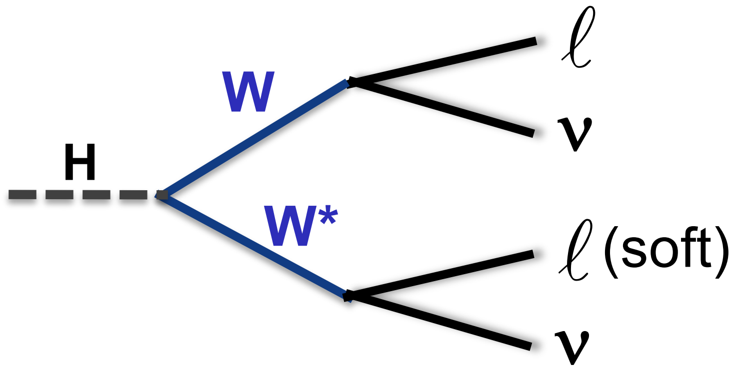
material model 160

shower shape 110

no detailed update yet from CMS compared to Run 1

ATLAS HIGG-2016-33

The H → WW signature



Final-state signature:
2 charged leptons + 2 neutrinos

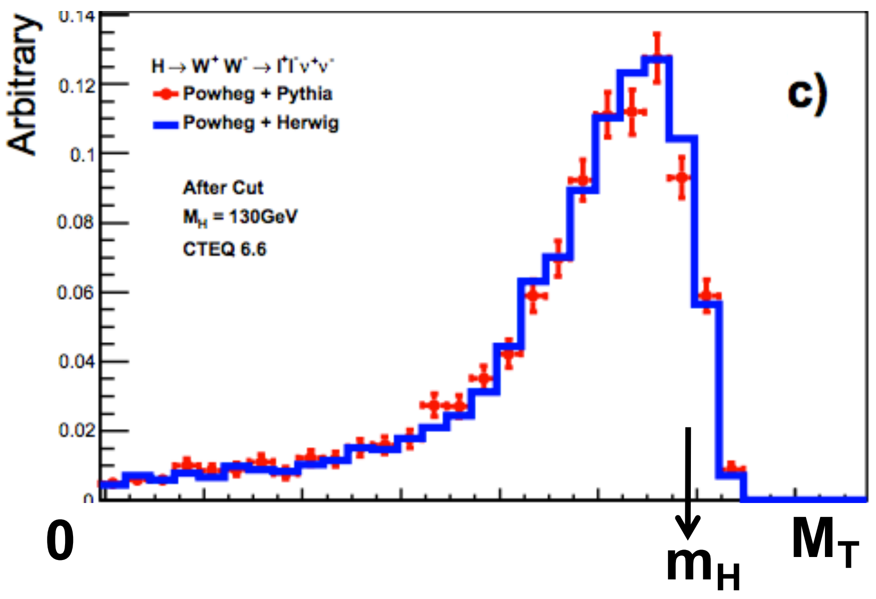
Off-shell W ($m_H < 2m_W$) means **one lepton is soft**

signal discriminant:

Transverse mass M_T: Like invariant mass, but drop missing p_z information

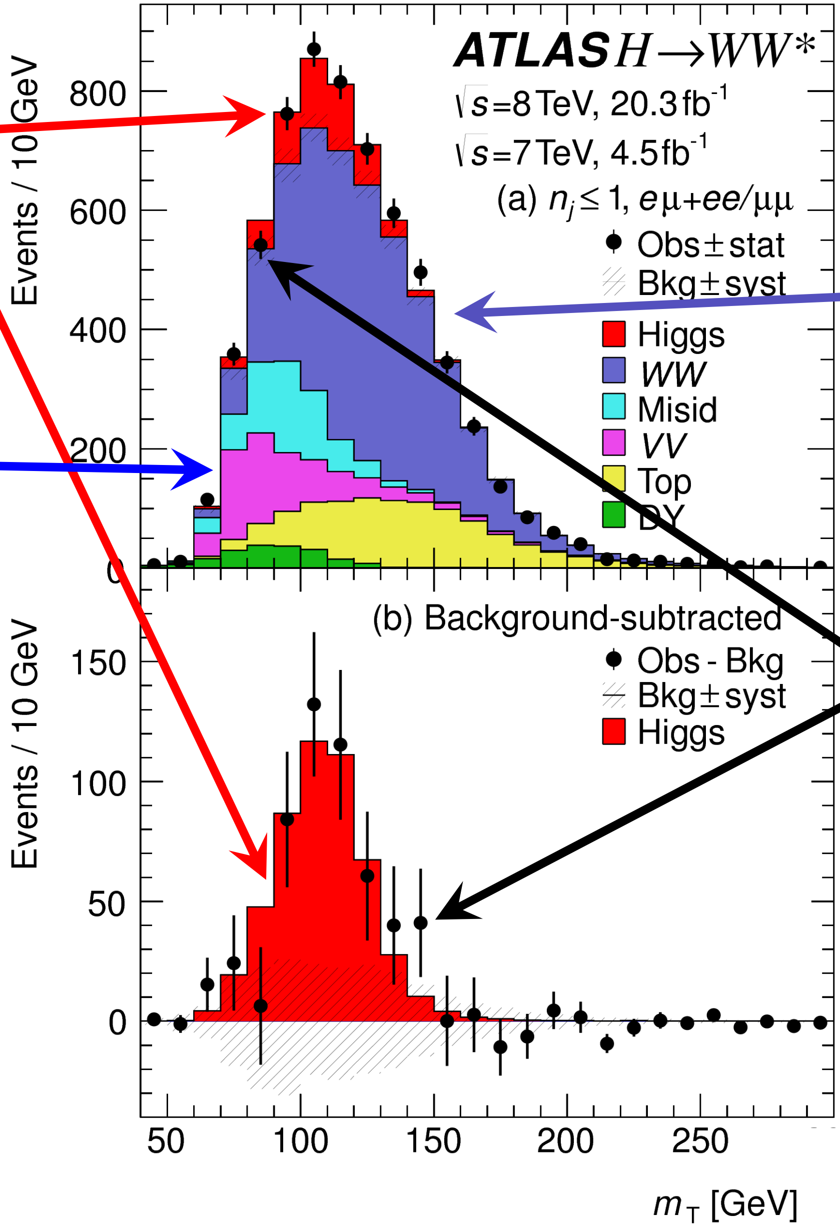
$$M_T^2 = (E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}})^2$$

$$(E_T^{\ell\ell})^2 = (\vec{p}_T^{\,\ell\ell})^2 + (m_{\ell\ell})^2$$



from 1201.3084v1

$H \rightarrow WW^*$ in practice



peaked signal

other backgrounds

dominant non-resonant WW diboson background

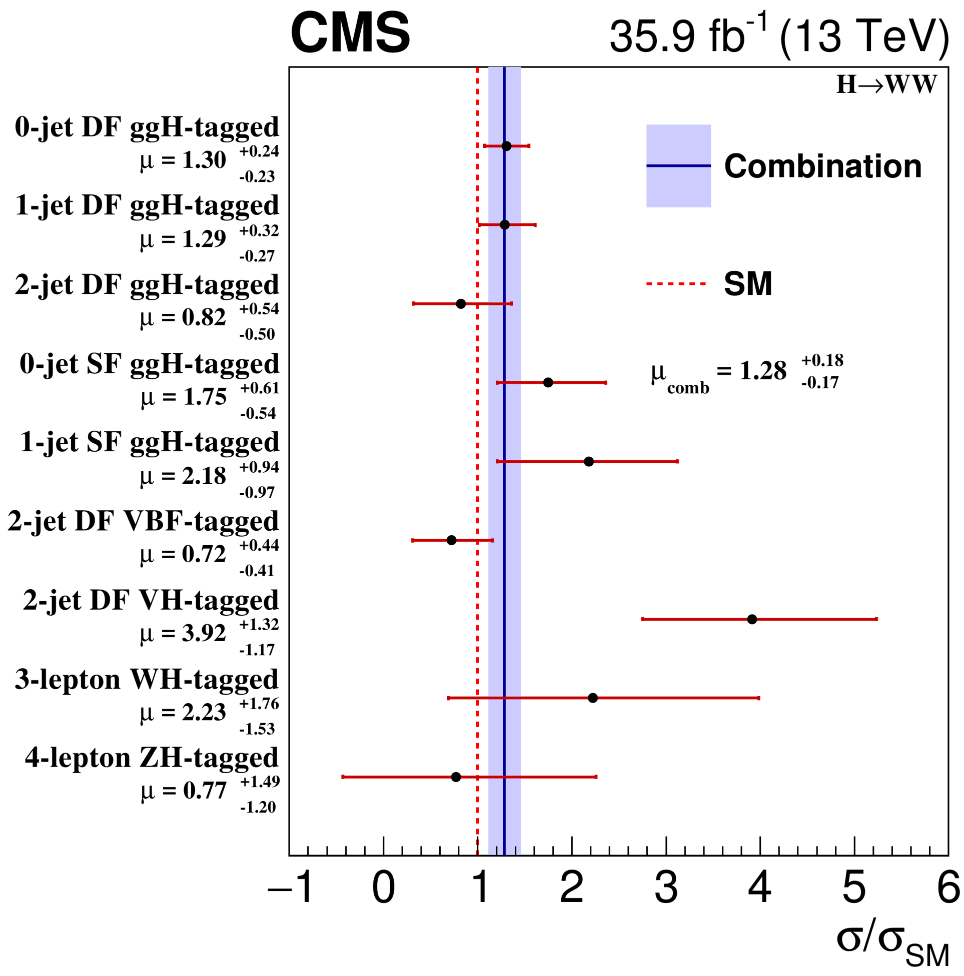
2011+2012 data

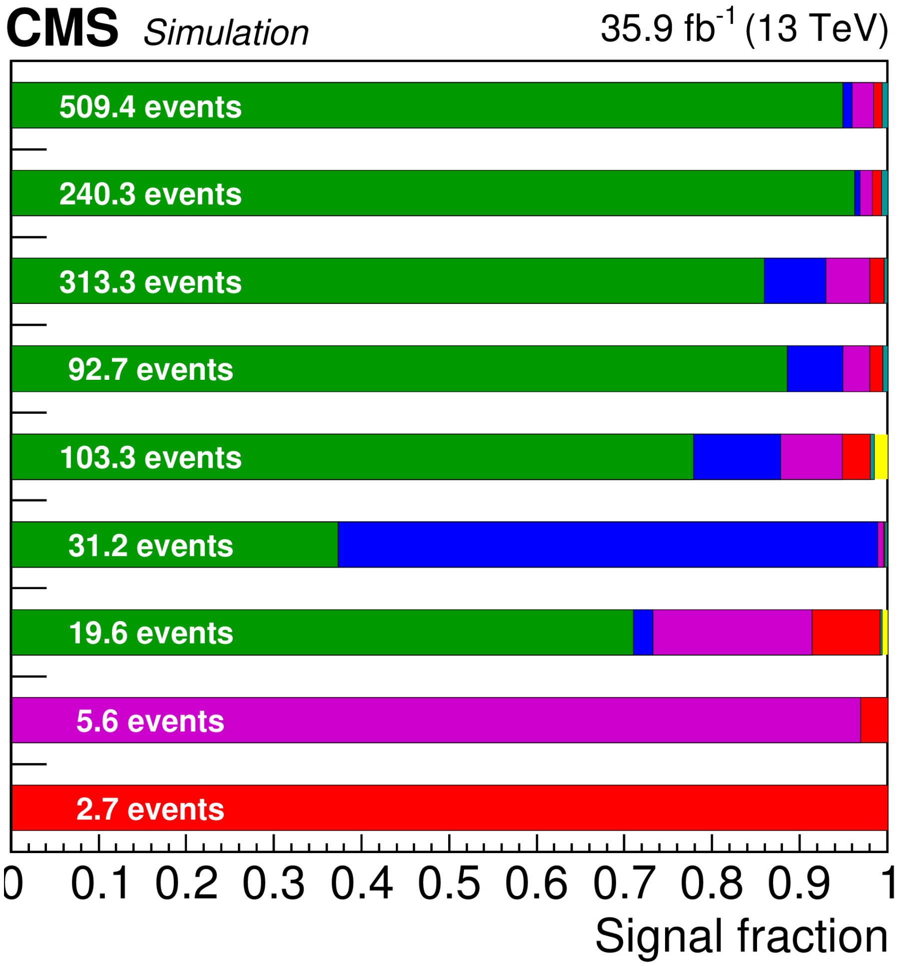
Older plot but the principles remain the same

m_T distribution in background-subtracted data shows signal yield

1412.8662: ATLAS Run-1 result

New H → WW results





$$\mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10\,(\text{stat}) \pm 0.11\,(\text{syst})^{+0.10}_{-0.07}\,(\text{theo})$$

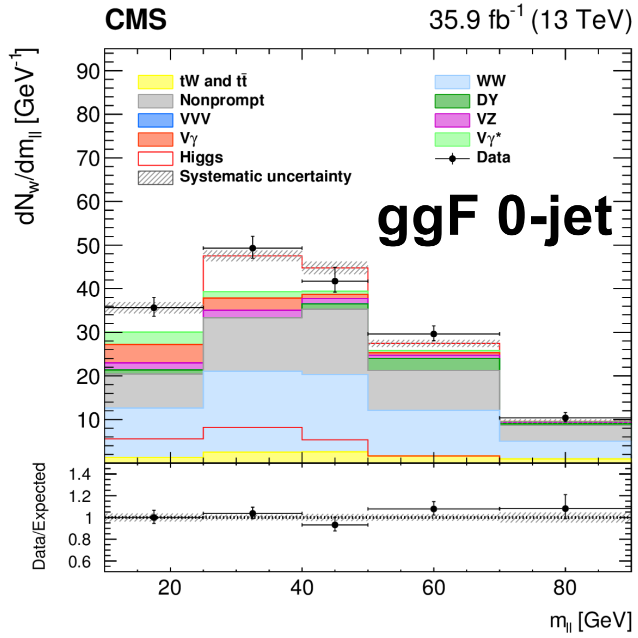
🟩 ggH
🟦 VBF
🟪 WH
🟥 ZH
▨ $b\bar{b}H$
🟨 $t\bar{t}H$

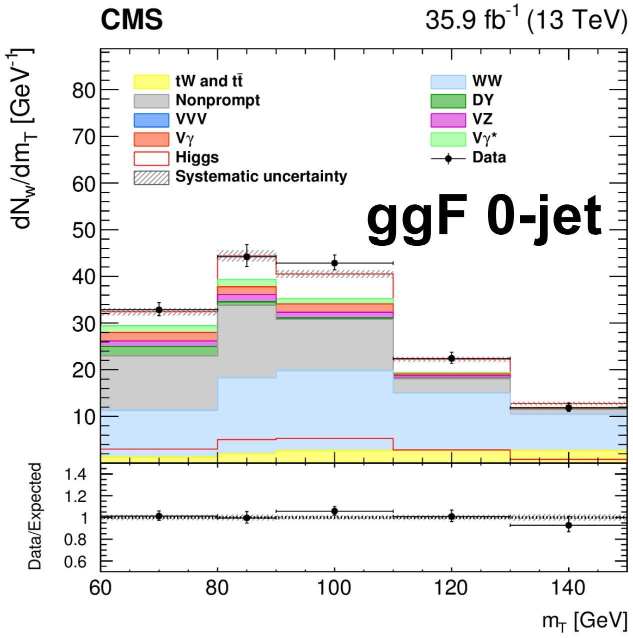
Observed (expected) significance: 9.1σ (7.1σ)
– first observation of HWW by CMS

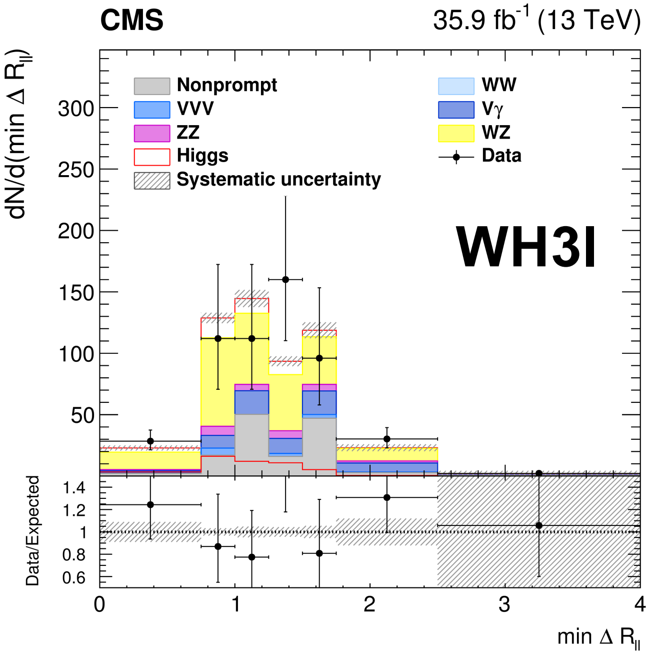
CMS HIG-16-042

H → WW: all about the backgrounds

Zoom in on one more and less sensitive category







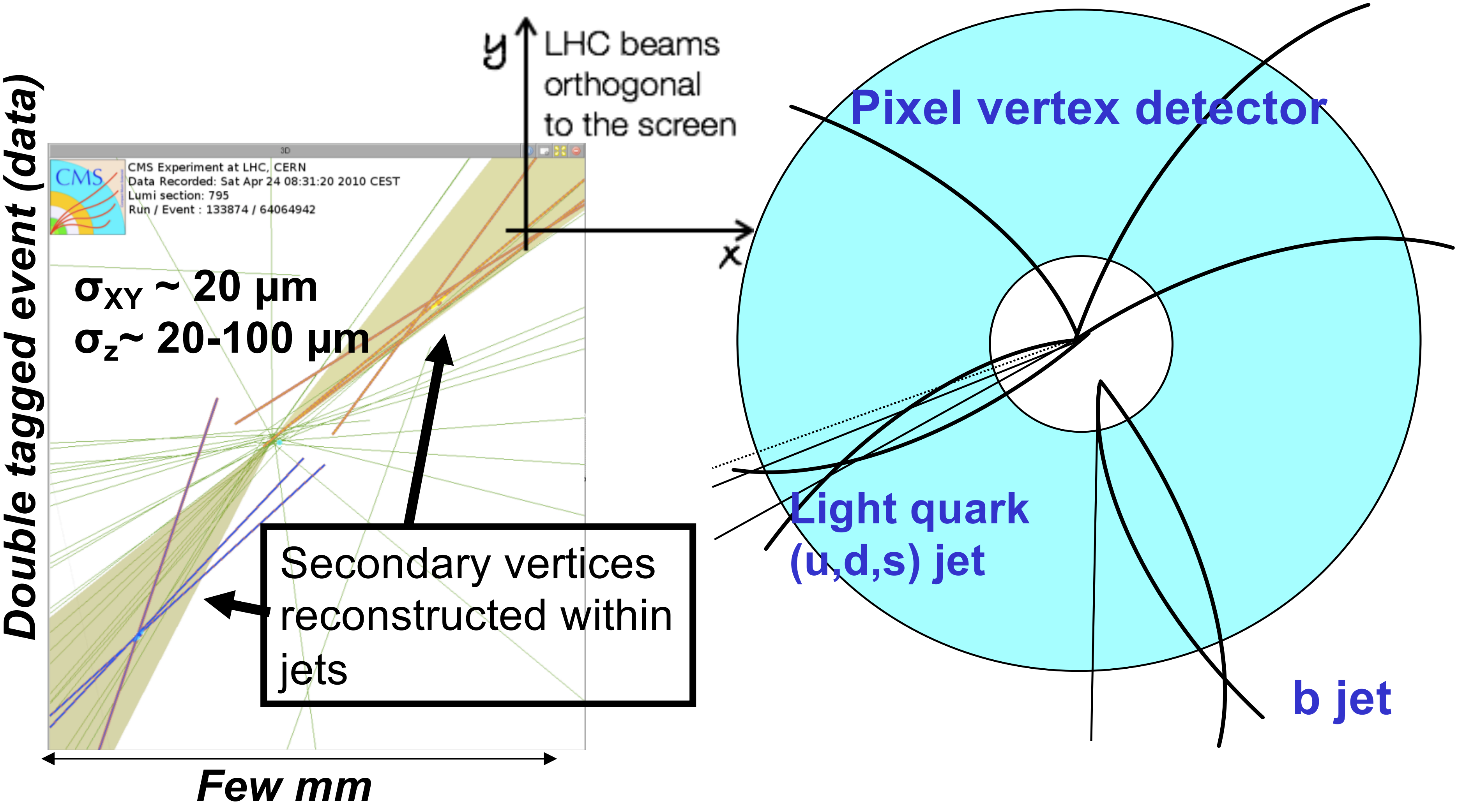
- Two opposite-sign charged leptons otherwise “untagged”

- All 3 Ws in final state decay to leptons

CMS HIG-16-042

Identifying b-quark jets

- Identify jets originating from b- quark by long lifetime of B hadrons



Double tagged event (data)

σ_{XY} ~ 20 μm
σ_z~ 20-100 μm

Secondary vertices reconstructed within jets

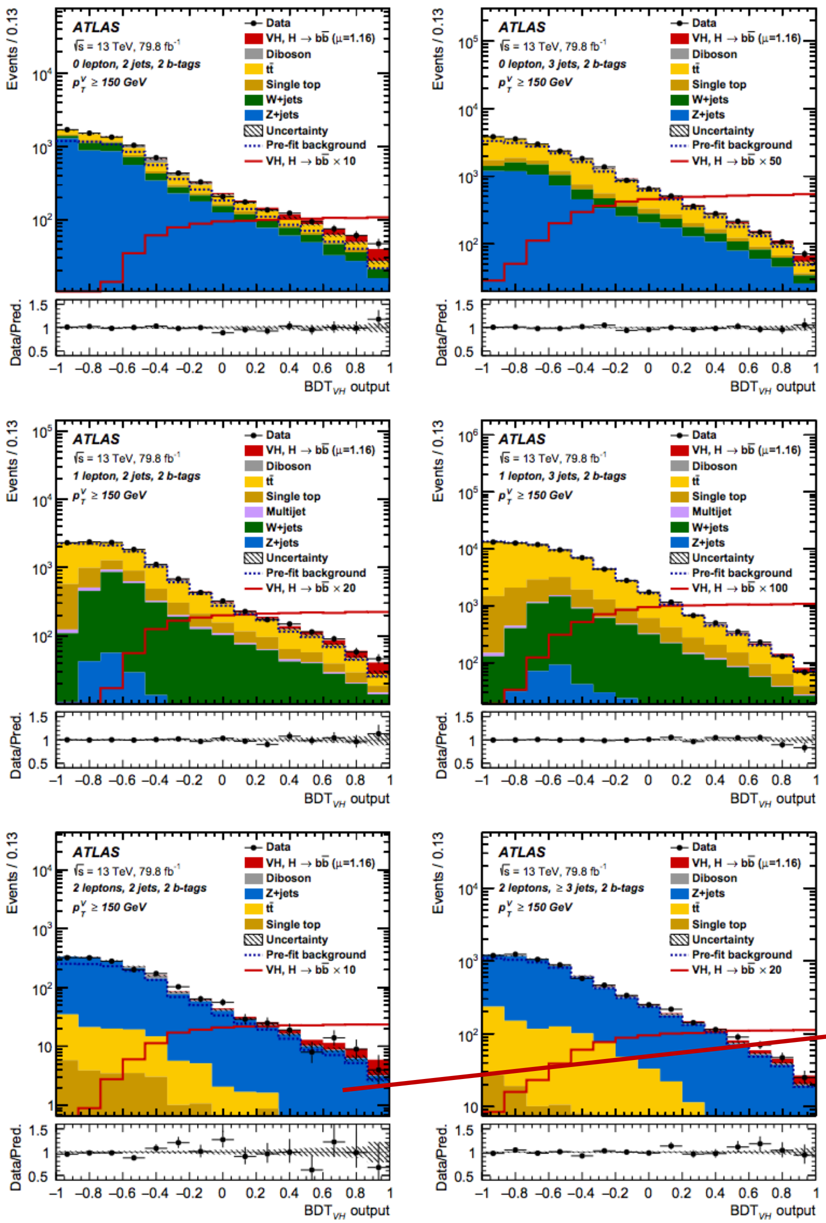
Few mm

- For H to bb, typically 70% b-tagging efficiency

ATLAS H → bb observation

- 2016+2017 data (Aug. '18)
- Categorize by number of jets, leptons: different background composition and S/B
- BDT including m_{bb} and $\Delta R(bb)$ as discriminating variables

2-jet **3-jet**

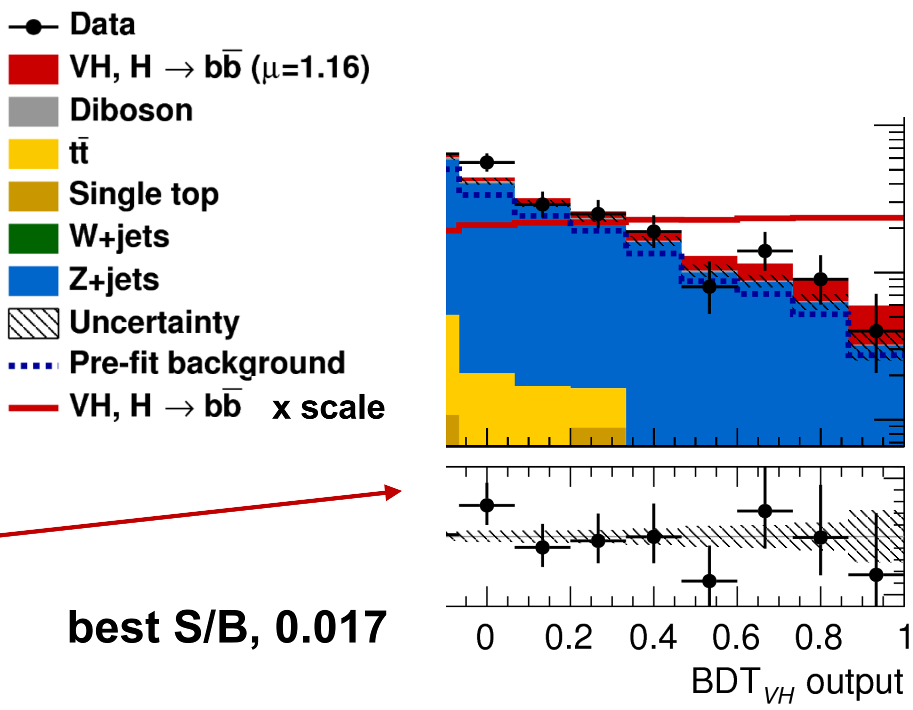


0 lepton
$(Z \to \nu\nu)$

1 lepton
$(W \to \ell\nu)$

2 lepton
$(Z \to \ell\ell)$

$\ell = e, \mu$



best S/B, 0.017

ATLAS HIGG-2018-04

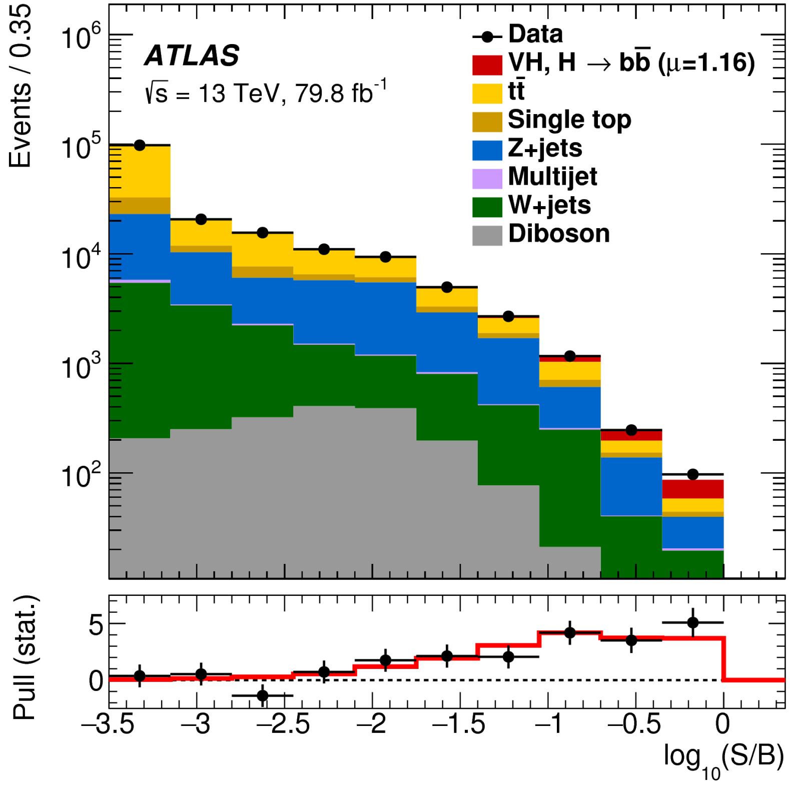
ATLAS H → bb

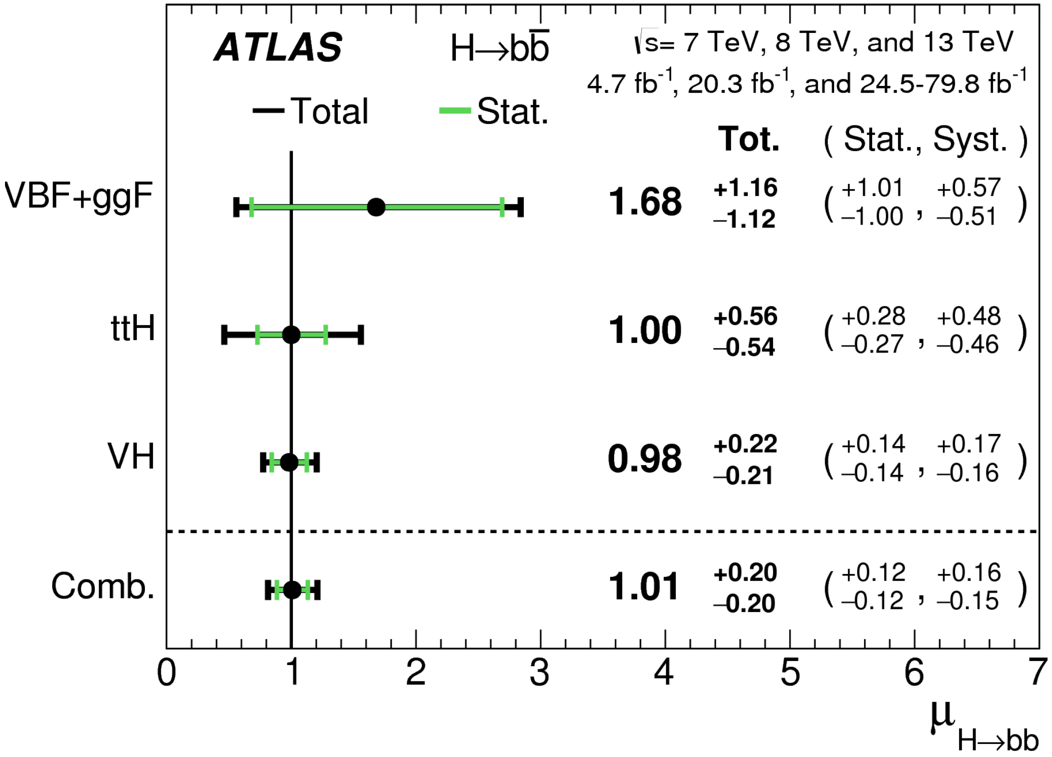
- Associated production has the greatest precision (contrast to diboson channels)

Observed (expected) significance

VH: 4.8 (4.9)

Run 1+ Run 2 all: 5.6 (5.5)





ATLAS HIGG-2018-04

ATLAS H → bb

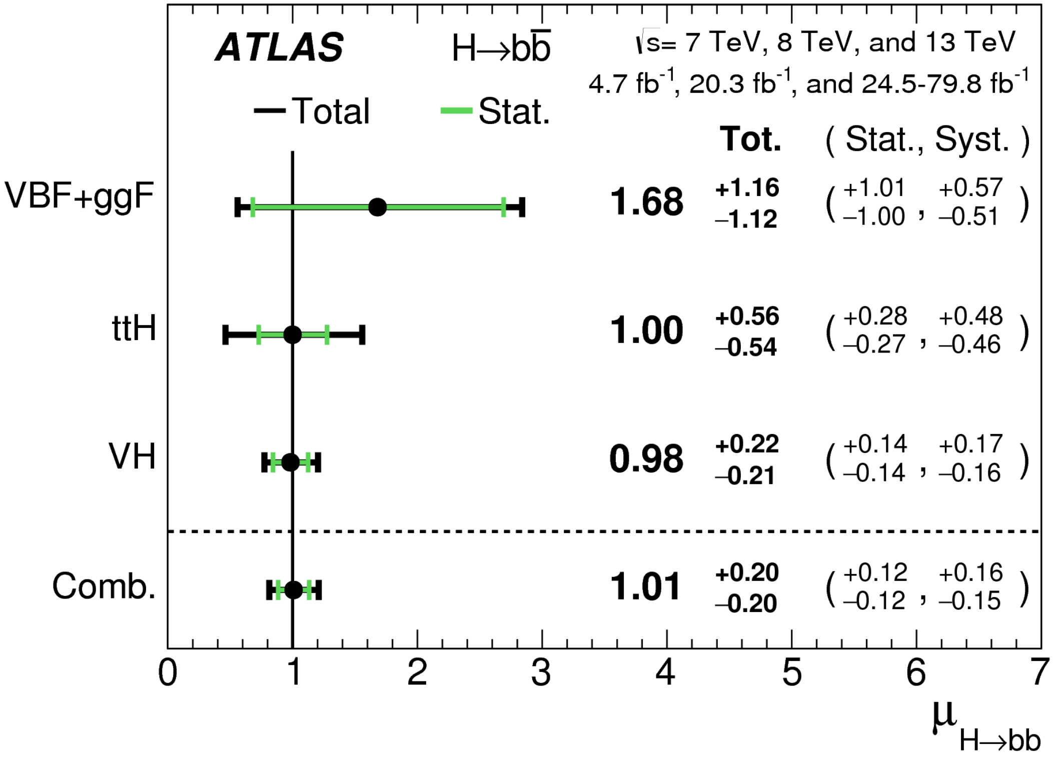
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

per-jet
2%
10%
40%

Observed (expected) significance

VH: 4.8 (4.9)

Run 1+ Run 2 all: 5.6 (5.5)

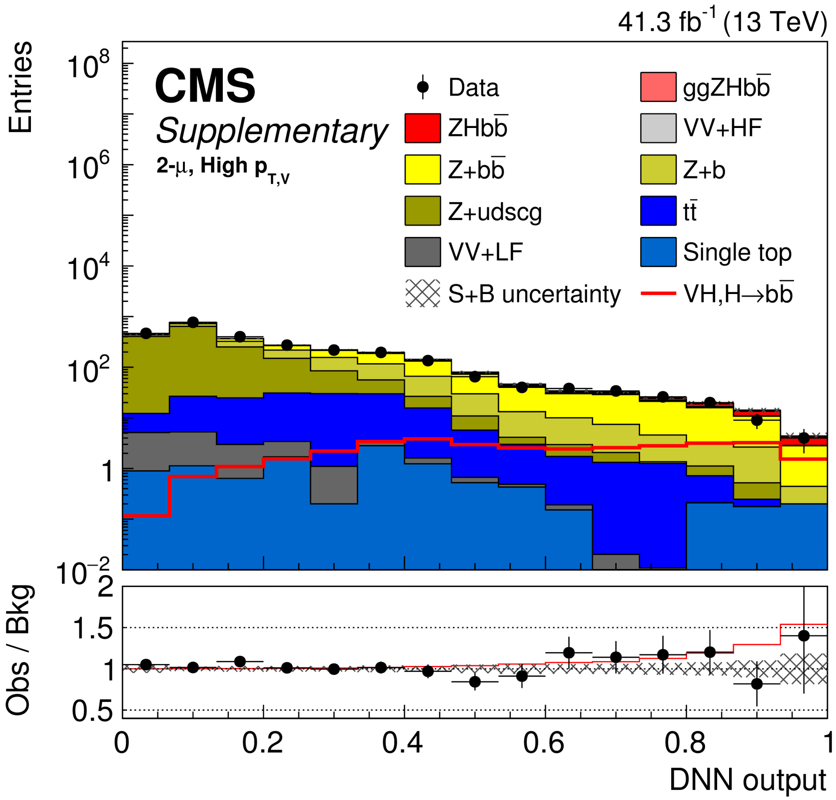


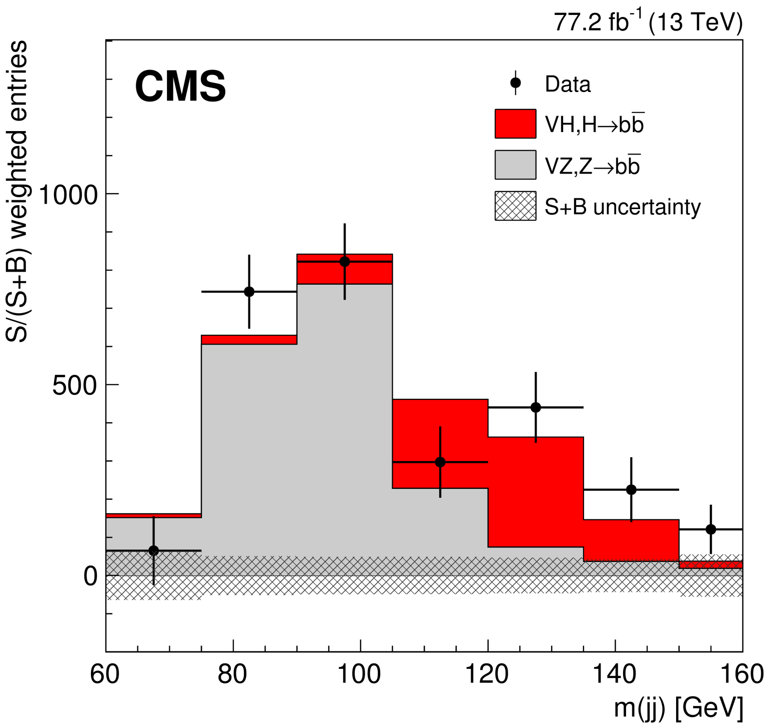
ATLAS HIGG-2018-04

CMS H → bb observation

- 2016+2017 data (released August 2018), combined with Run 1
- Categories similar to ATLAS
- DNN to extract maximum amount of information from events

Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \rightarrow b\bar{b}$ combination	5.5	5.4

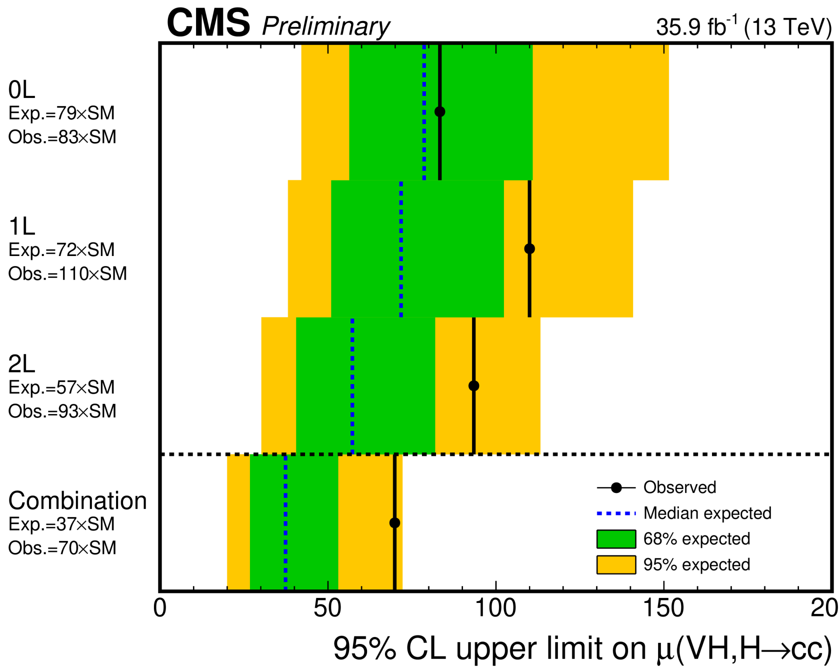


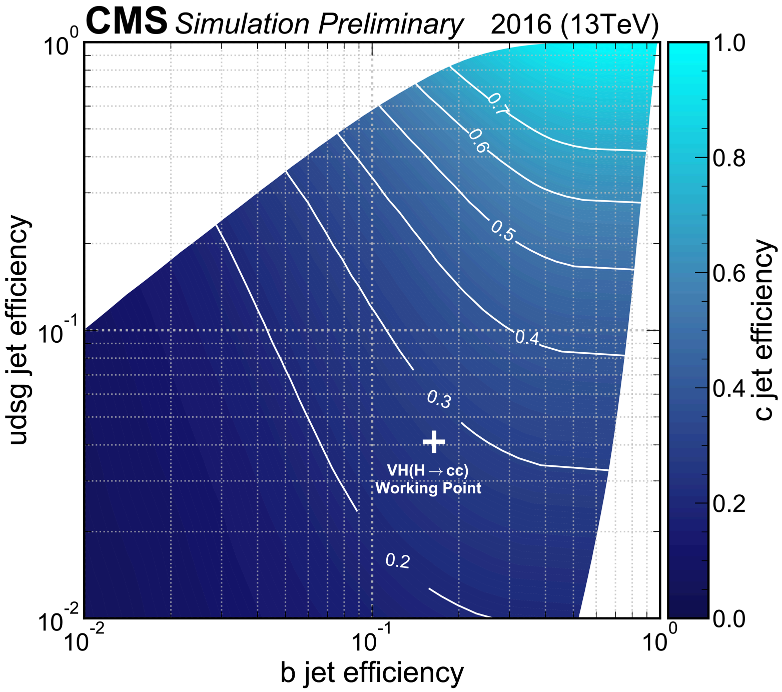


CMS HIG-18-016

2nd generation: charm and μ

- CMS result, 2016 data, resolved and boosted charm Vh production





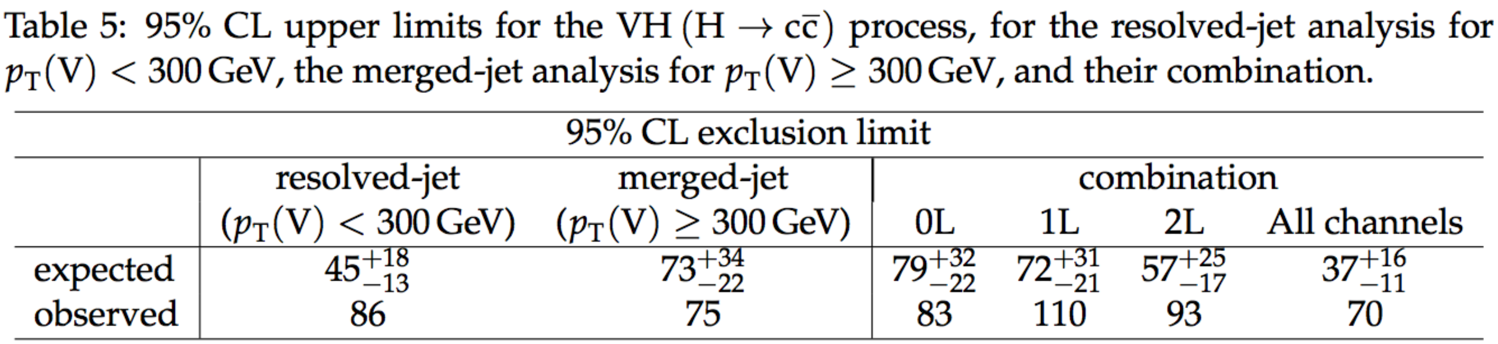


Table 5: 95% CL upper limits for the VH $(\mathrm{H} \rightarrow \mathrm{c\bar{c}})$ process, for the resolved-jet analysis for $p_{\mathrm{T}}(\mathrm{V}) < 300\,\mathrm{GeV}$, the merged-jet analysis for $p_{\mathrm{T}}(\mathrm{V}) \geq 300\,\mathrm{GeV}$, and their combination.

95% CL exclusion limit						
	resolved-jet $(p_{\mathrm{T}}(\mathrm{V}) < 300\,\mathrm{GeV})$	merged-jet $(p_{\mathrm{T}}(\mathrm{V}) \geq 300\,\mathrm{GeV})$	combination			
			0L	1L	2L	All channels
expected	45^{+18}_{-13}	73^{+34}_{-22}	79^{+32}_{-22}	72^{+31}_{-21}	57^{+25}_{-17}	37^{+16}_{-11}
observed	86	75	83	110	93	70

CMS HIG-18-031

Beyond the Standard Model
Higgs Boson

More Higgs bosons?

- **Q: Why would there be one or more high-mass copies of our friend at 125 GeV?**

- A: Predicted by well-motivated models which solve other problems
  - → *Supersymmetry*
    - “stabilizes” m_H, gives a dark matter candidate
  - → *Two-higgs-doublet model*
  - → *Type II Seesaw models predict a Higgs triplet*
    - “Natural” mechanism for light neutrino masses
  - → ***All of the above allow additional CP violation compared to the SM (quark mixing) ➔ baryogenesis***

- A’: Why not?
  - → *Nature seems to like copies (leptons, quarks)*

The (CP violation in the) world is not enough

- Sakharov conditions for matter to arise from a matter-antimatter symmetric initial state (baryogenesis)

1. *Baryon-number violation*
    - Physical mechanism to change number of baryons ($B \rightarrow \overline{B}$)
    - Nonperturbative solution to SM equations: SPHALERON
2. *Interactions out of thermal equilibrium*
    - First-order electroweak phase transition
    - Drives the process
3. *C and CP Violation*
    - Otherwise $B \rightarrow \overline{B}$ and $\overline{B} \rightarrow B$ at the same rate

- Standard Model accommodates baryogenesis, almost

→ *CP violation observed in quark sector not nearly enough*

→ *Where can we find more? An extended Higgs sector!*

Not a copy of h[125]

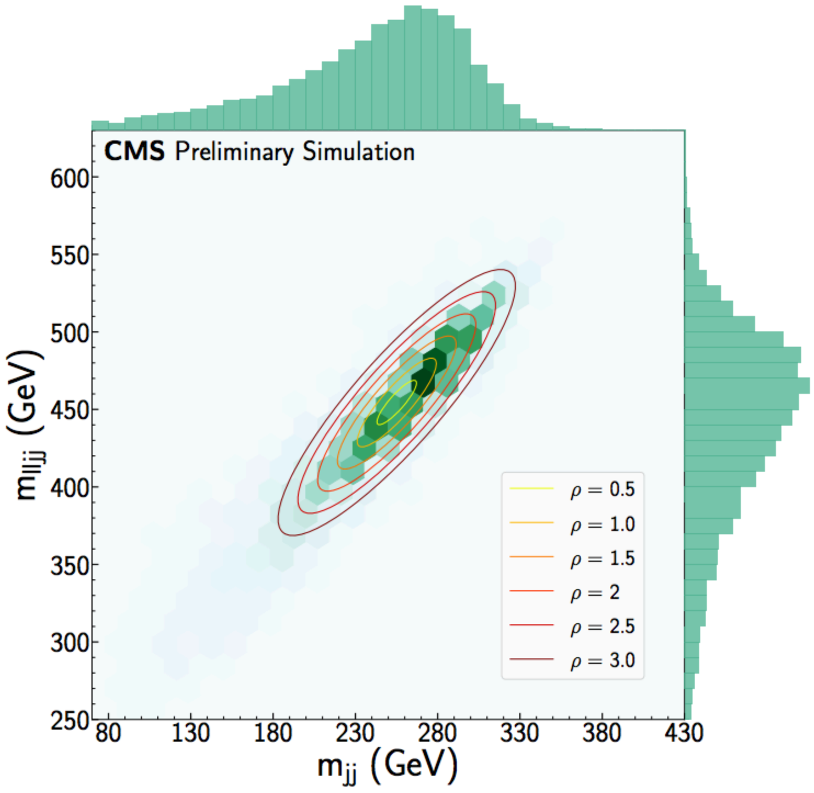
- Direct and indirect constraints seriously constrain the more obvious possibilities

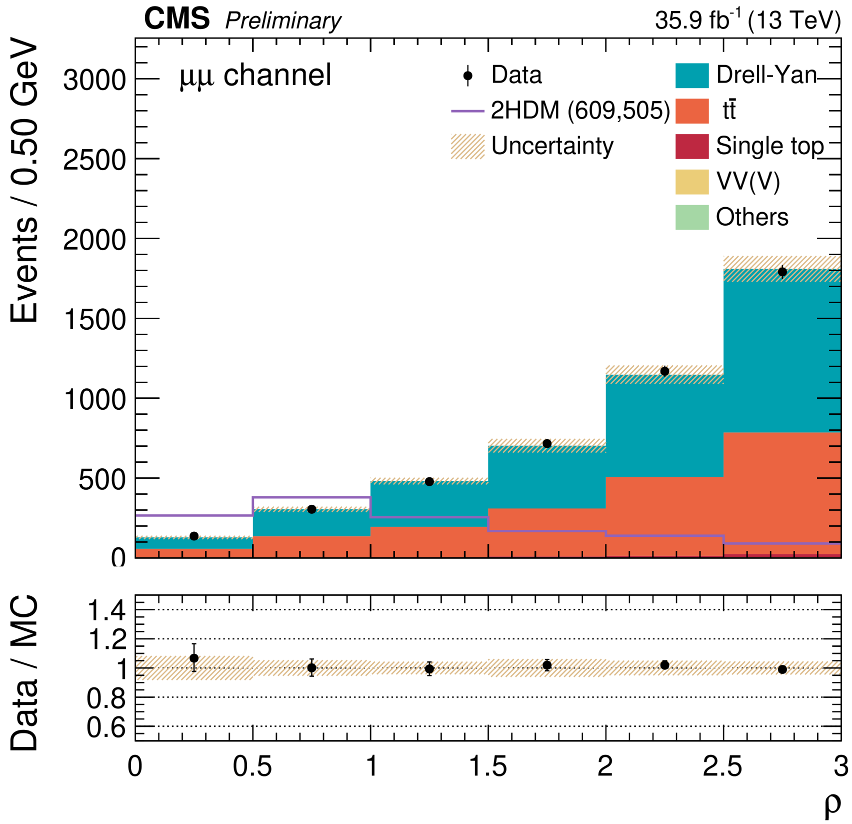
- Motivation for additional scalars still strong → how to proceed?

- **Focus on decay modes not open for h[125]:**
  - → ***cascades***
  - → ***H/A → t-tbar***
- **More exotic models (triplets)**
- (Influenced by discussion in N. Craig et al, 1504.04630)

$H \rightarrow ZA$

- CMS 2016 dataset search
- rho ellipse captures correlation between mjj and mlljj because of jet energy resolution, as a function of particle masses

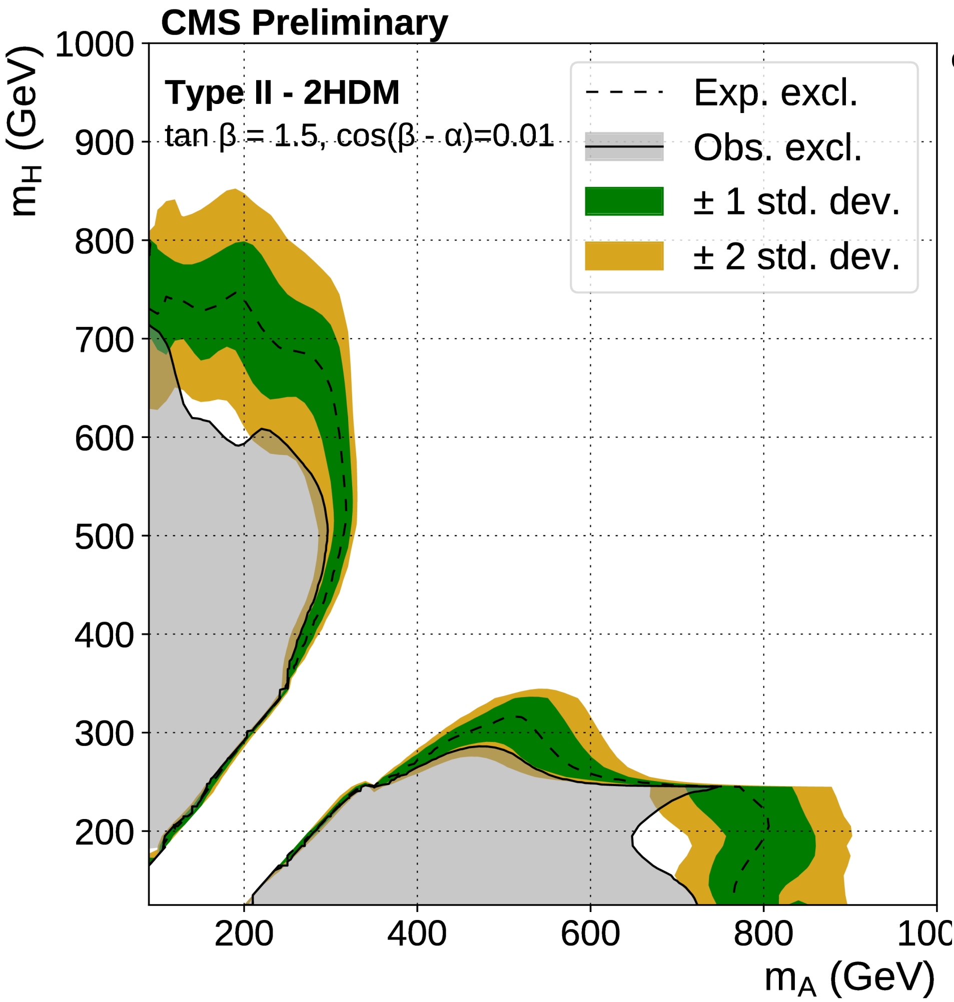


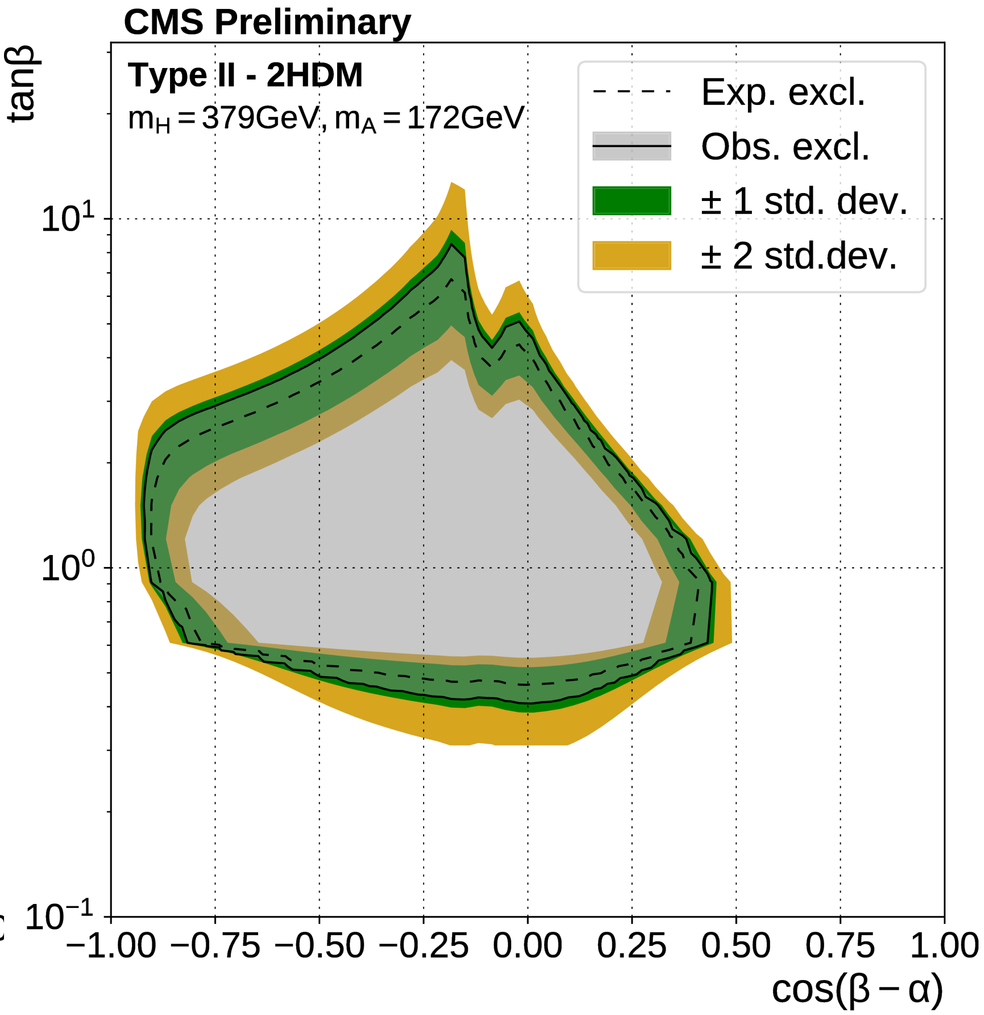


CMS HIG-18-012

c. mills (UIC+FNAL)

H → ZA

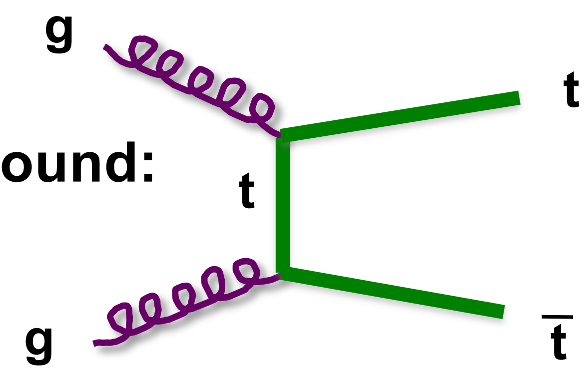

CMS Preliminary
Type II - 2HDM
tan β = 1.5, cos(β - α)=0.01
Exp. excl.
Obs. excl.
± 1 std. dev.
± 2 std. dev.
m_H (GeV)
1000
900
800
700
600
500
400
300
200
200
400
600
800
100
m_A (GeV)


CMS Preliminary
Type II - 2HDM
m_H = 379GeV, m_A = 172GeV
Exp. excl.
Obs. excl.
± 1 std. dev.
± 2 std.dev.
tanβ
10^1
10^0
10^−1
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
cos(β − α)

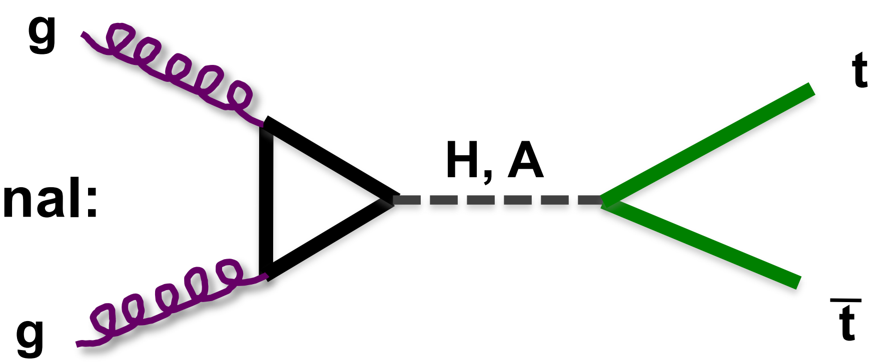
H/A → ttbar

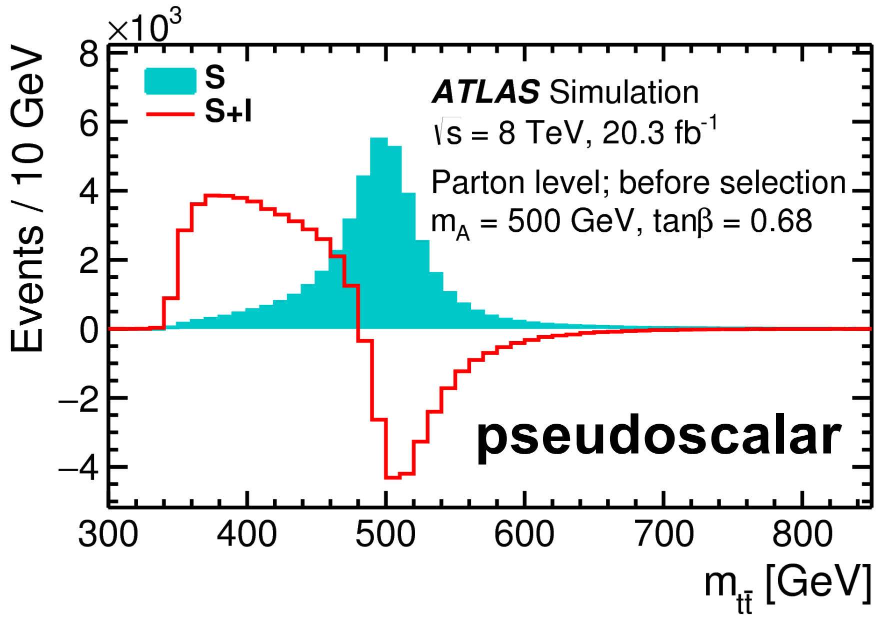
Signal and background interfere → not a bump hunt but a wiggle hunt

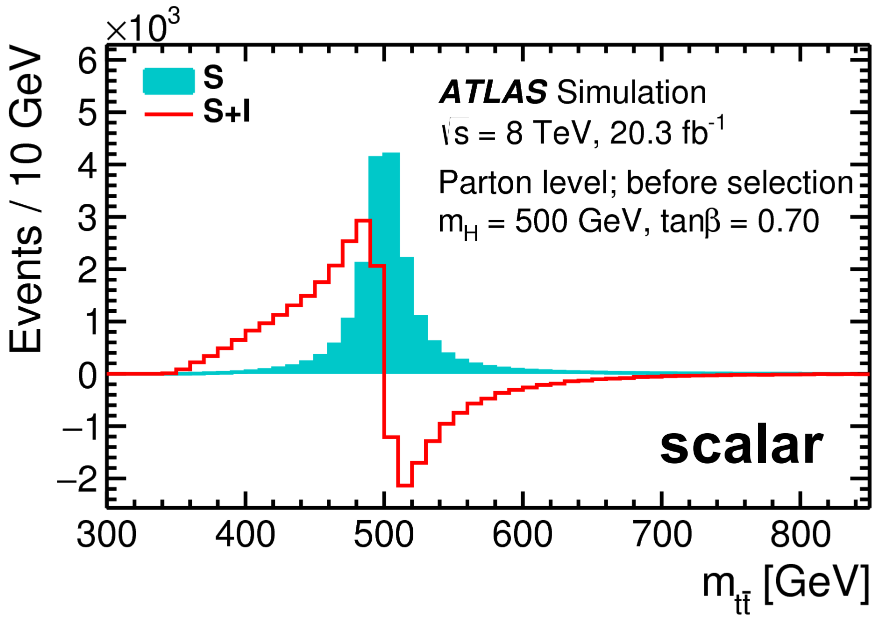
background:



signal:

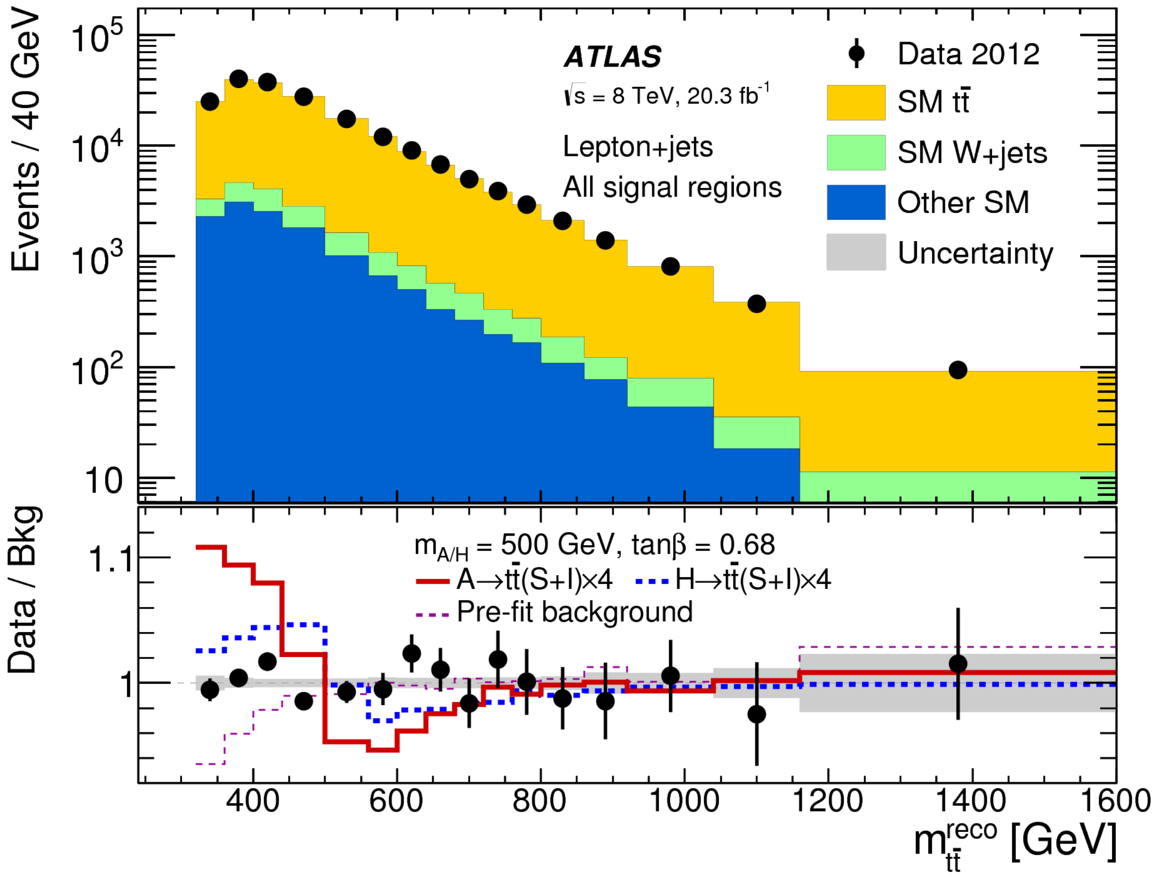






1707.06025

H/A → ttbar

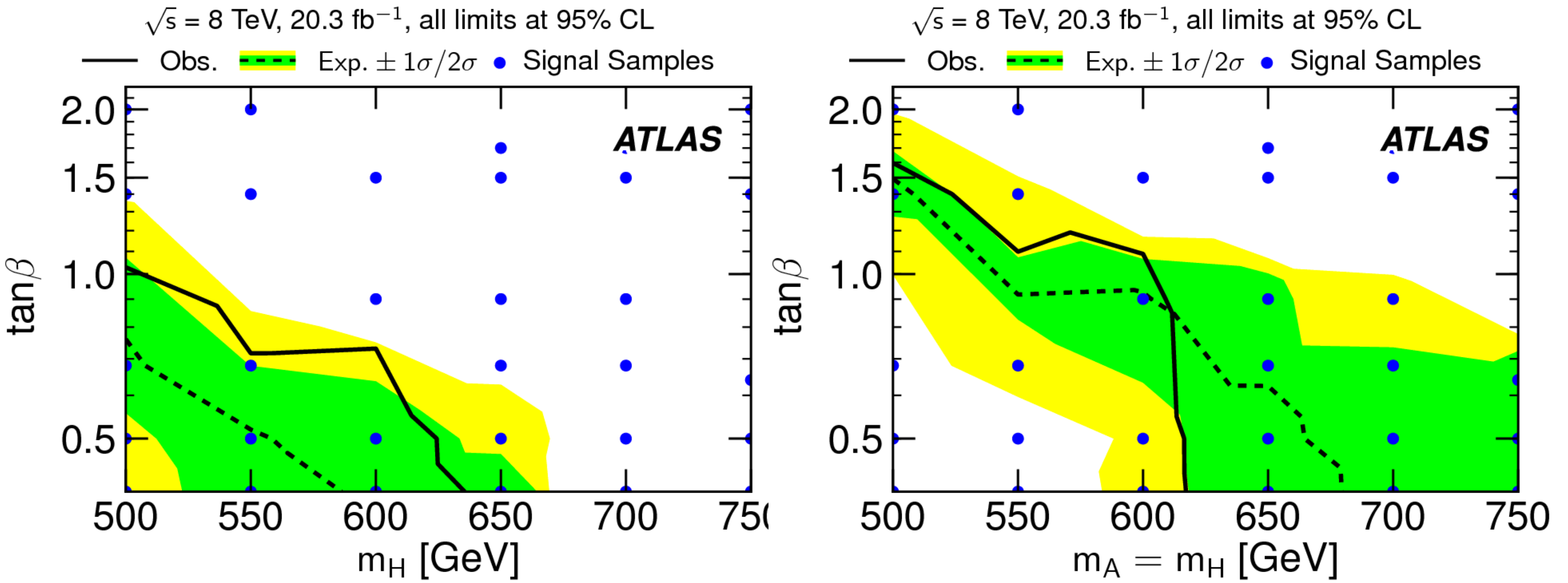


m = 500 GeV

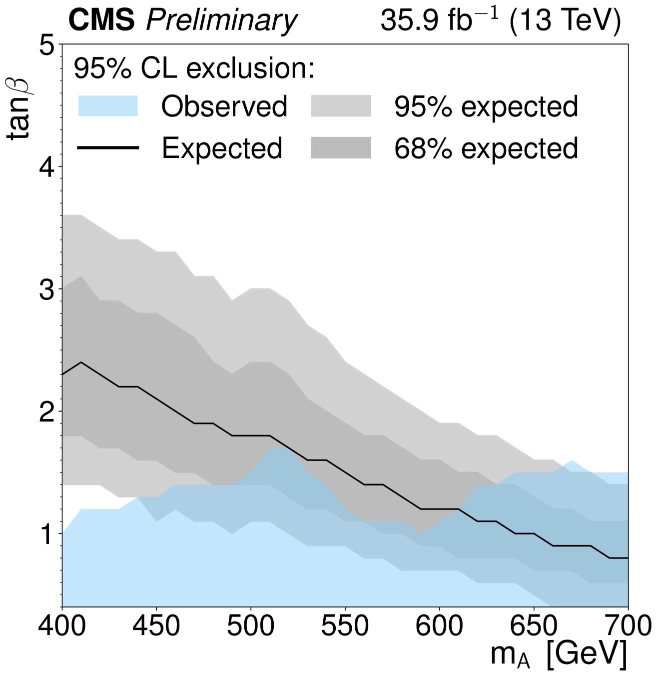
- Just starting to dip into relevant parameter space
- Exclude tan β < 0.85 for m_A = 500 GeV
- Exclude tan β < 0.45 for m_H = 500 GeV

1707.06025

H/A → ttbar

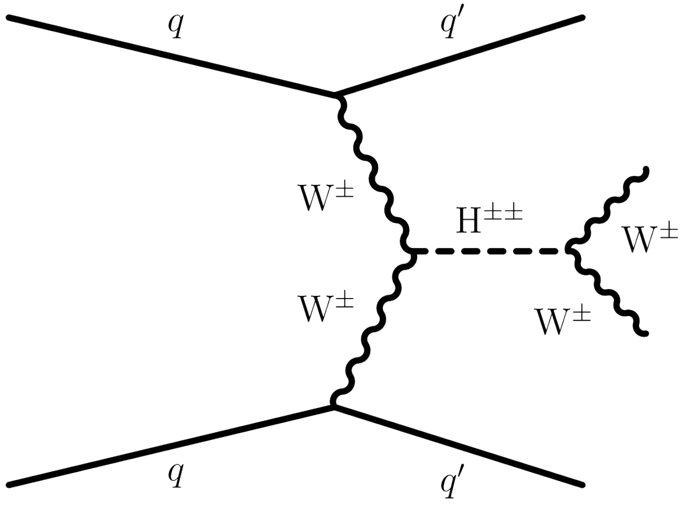


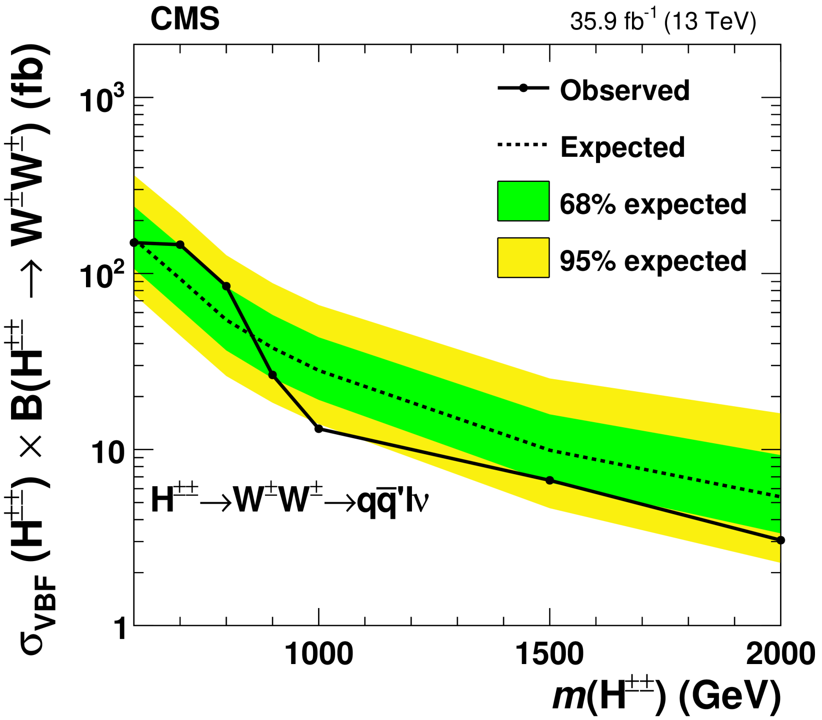
- Starting to dip into relevant parameter space
- Exclude tan β < 1.0 for m_A = 500 GeV or m_H = 500 GeV
- If H, A masses degenerate, limit is stronger
- New CMS result at 13 TeV
  CMS-PAS-HIG-17-027

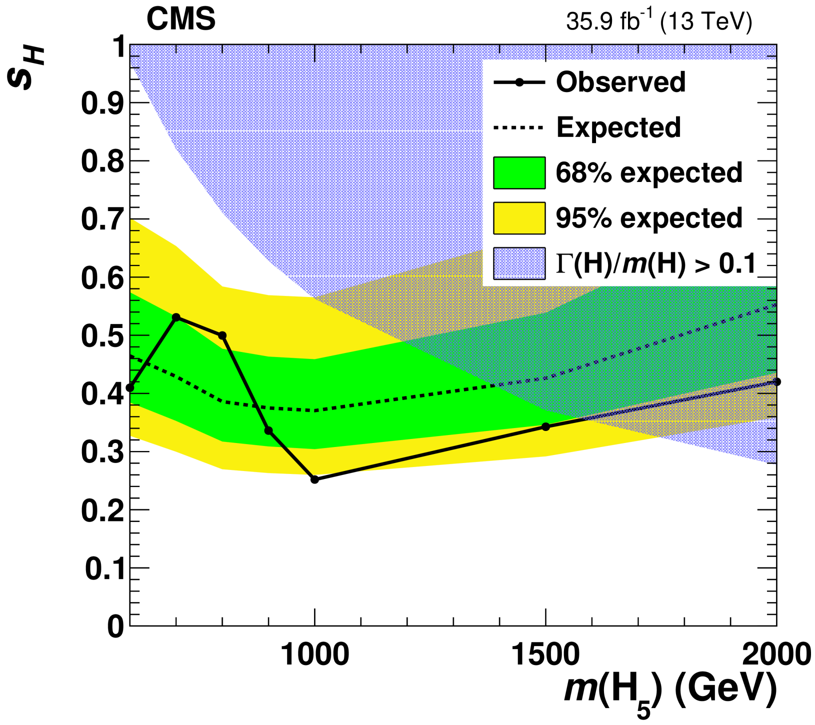


Charged Higgs bosons

- The semileptonic vector-boson scattering analysis can also be interpreted as a search for singly- and doubly-charged Higgs







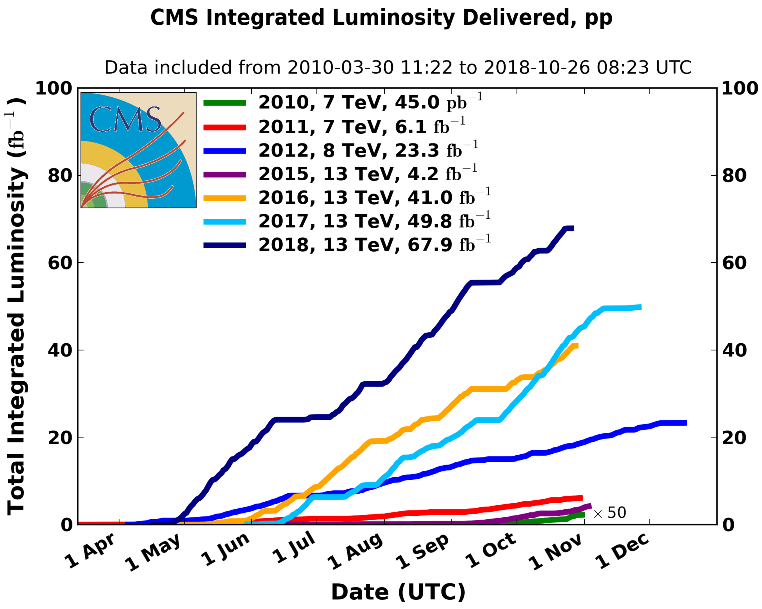
CMS SMP-18-006

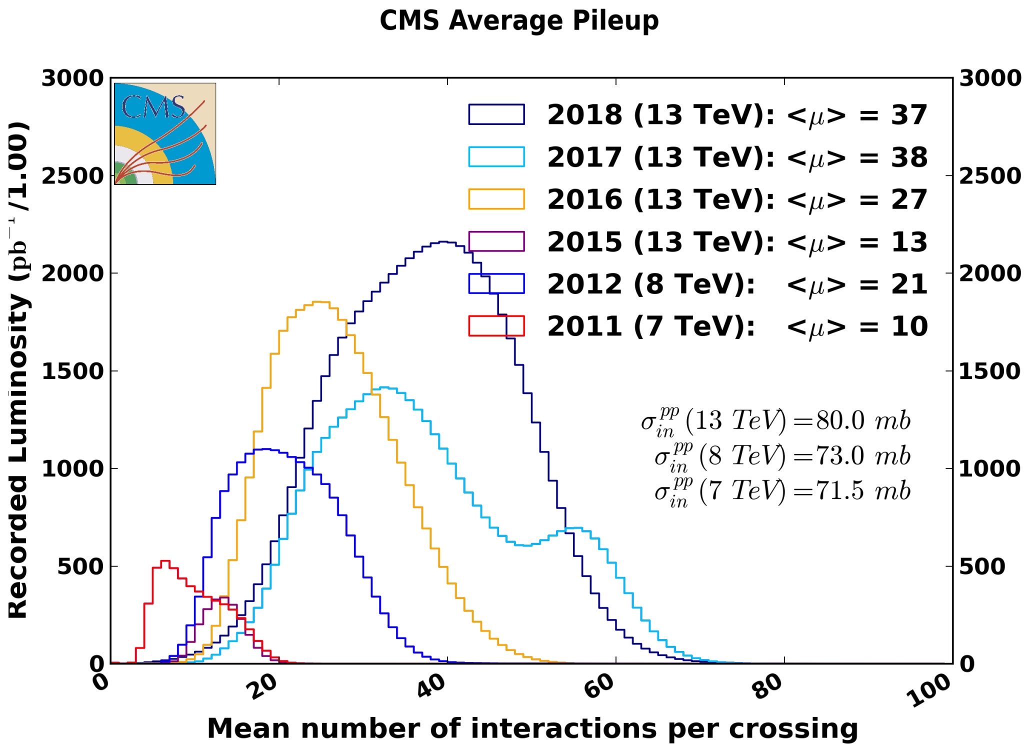
Conclusions

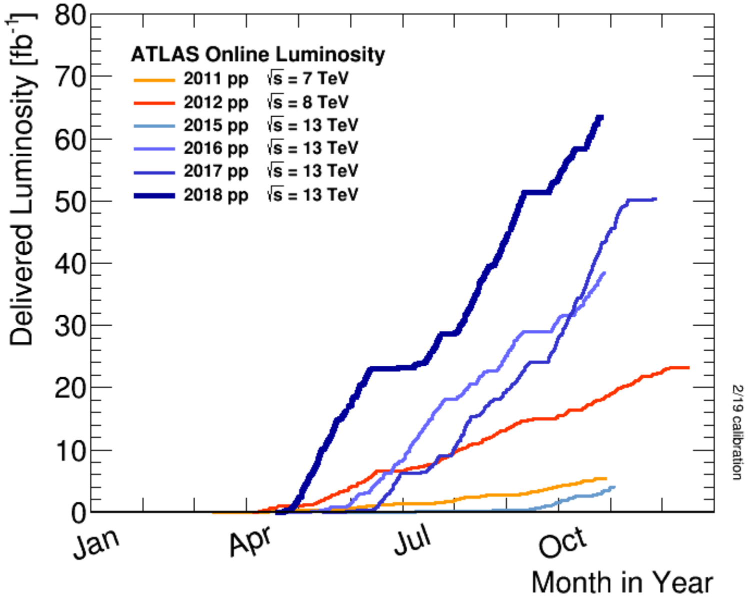
- Rich program in Higgs and electroweak physics at the LHC
  - → *Did not cover ttH, H $\rightarrow\tau\tau$, or di-Higgs (Higgs potential or 2-body resonance search)*
- Detailed understanding of detector performance is key to maximizing sensitivity
- High-luminosity LHC – and run 3 – will clarify the picture significantly

backup

The dataset and pileup







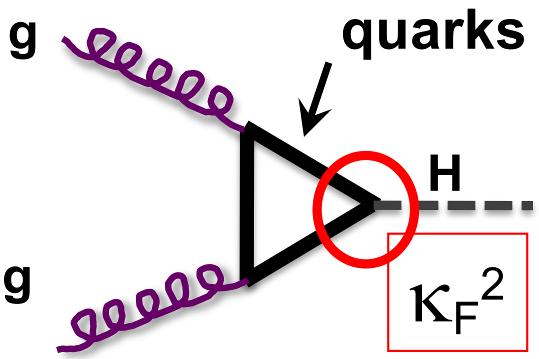
The kappa model

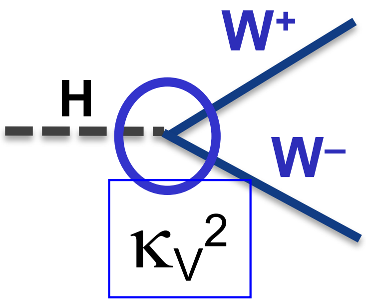
Simple scaling of production and decay modes for vector boson (κ_V) and fermions (κ_f)

- valid at LO only

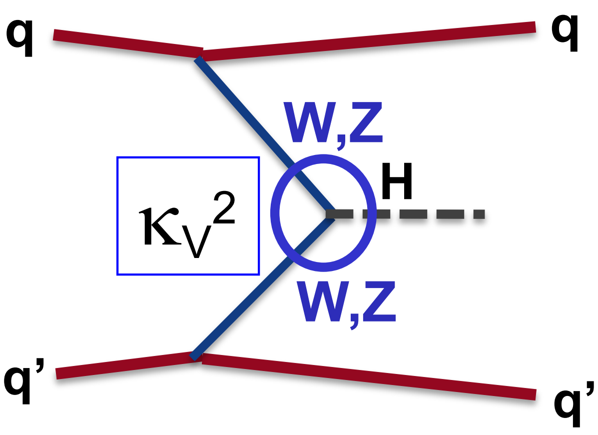
$$\mu_{\mathrm{ggF}} \propto \frac{\kappa_F^2 \, \kappa_V^2}{(\mathcal{B}_{H\to f\bar{f}} + \mathcal{B}_{H\to gg})\kappa_F^2 + (\mathcal{B}_{H\to VV})\kappa_V^2}$$

$$\mu_{\mathrm{VBF}} \propto \frac{\kappa_V^4}{\underbrace{(\mathcal{B}_{H\to f\bar{f}} + \mathcal{B}_{H\to gg})}_{\sim 75\%}\kappa_F^2 + \underbrace{(\mathcal{B}_{H\to VV})}_{\sim 25\%}\kappa_V^2}$$





Partial width scales with (κ_V^2)



Branching ratio is the partial width divided by the total width, which appears in the denominator above

Global EW fits and BSM

- Constrain BSM physics through expected interaction with known particles
- 2HDM fit including EW precision, direct h[125] measurements, muon anomalous magnetic moment, and flavor observables

→ *Higgs coupling constrains $\beta - \alpha$, leading to strong alignment (small mass splitting) of charged H with either H or A*