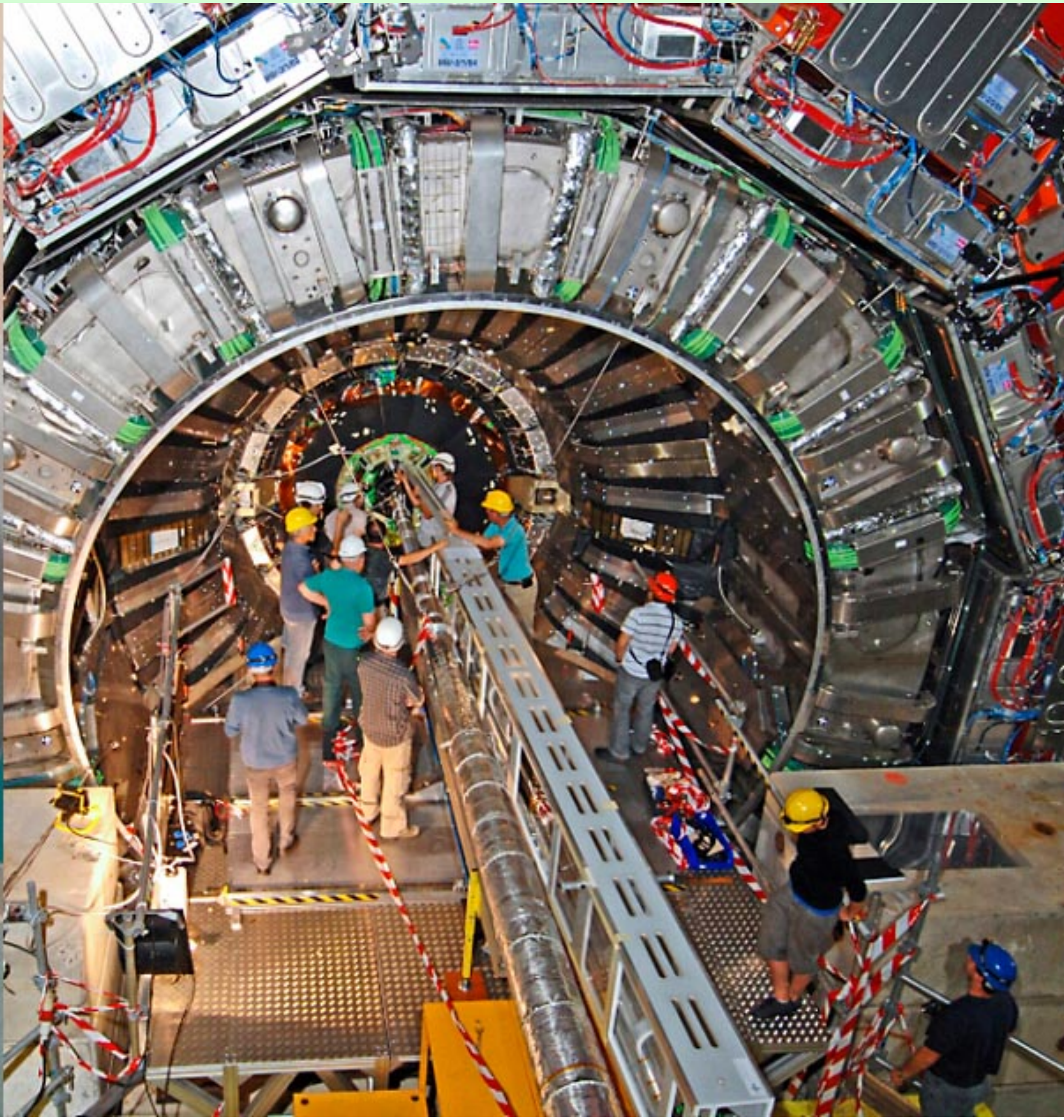
Recent SM and BSM Higgs Results from LHC



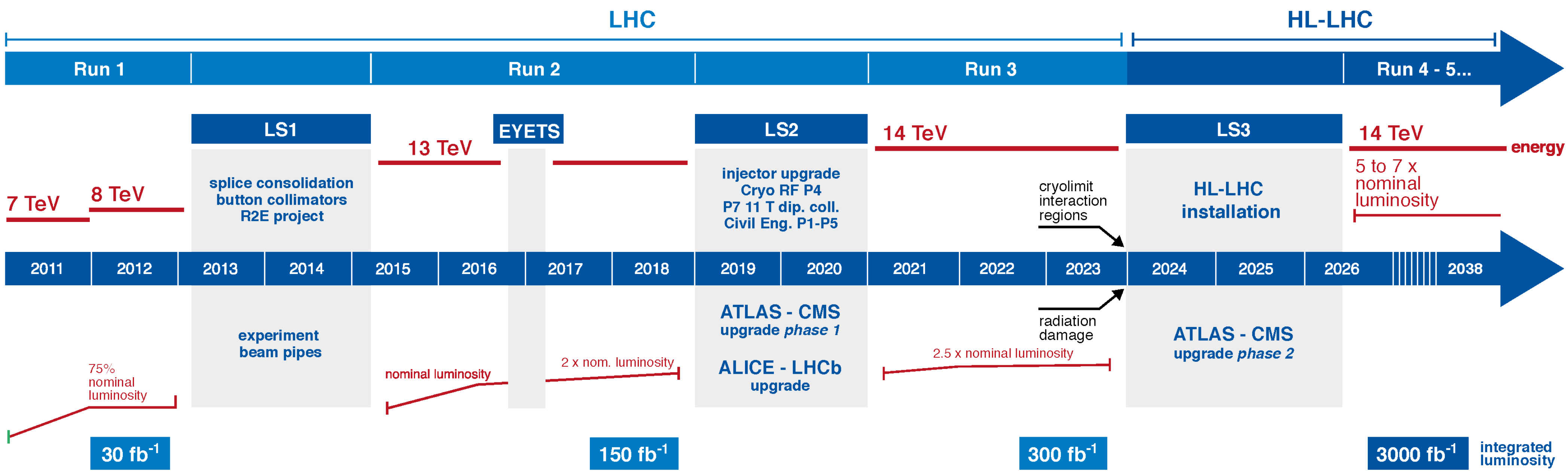
Stathes Paganis (National Taiwan University)

Energy Frontier in PP, NTU, 29-9-2017

Outline

- Introduction
- New SM Higgs measurements: a quick tour
- Searches for heavy Higgs
- Searches for BSM physics with Higgs in the final state
- Vector Boson Fusion reloaded

LHC / HL-LHC Plan

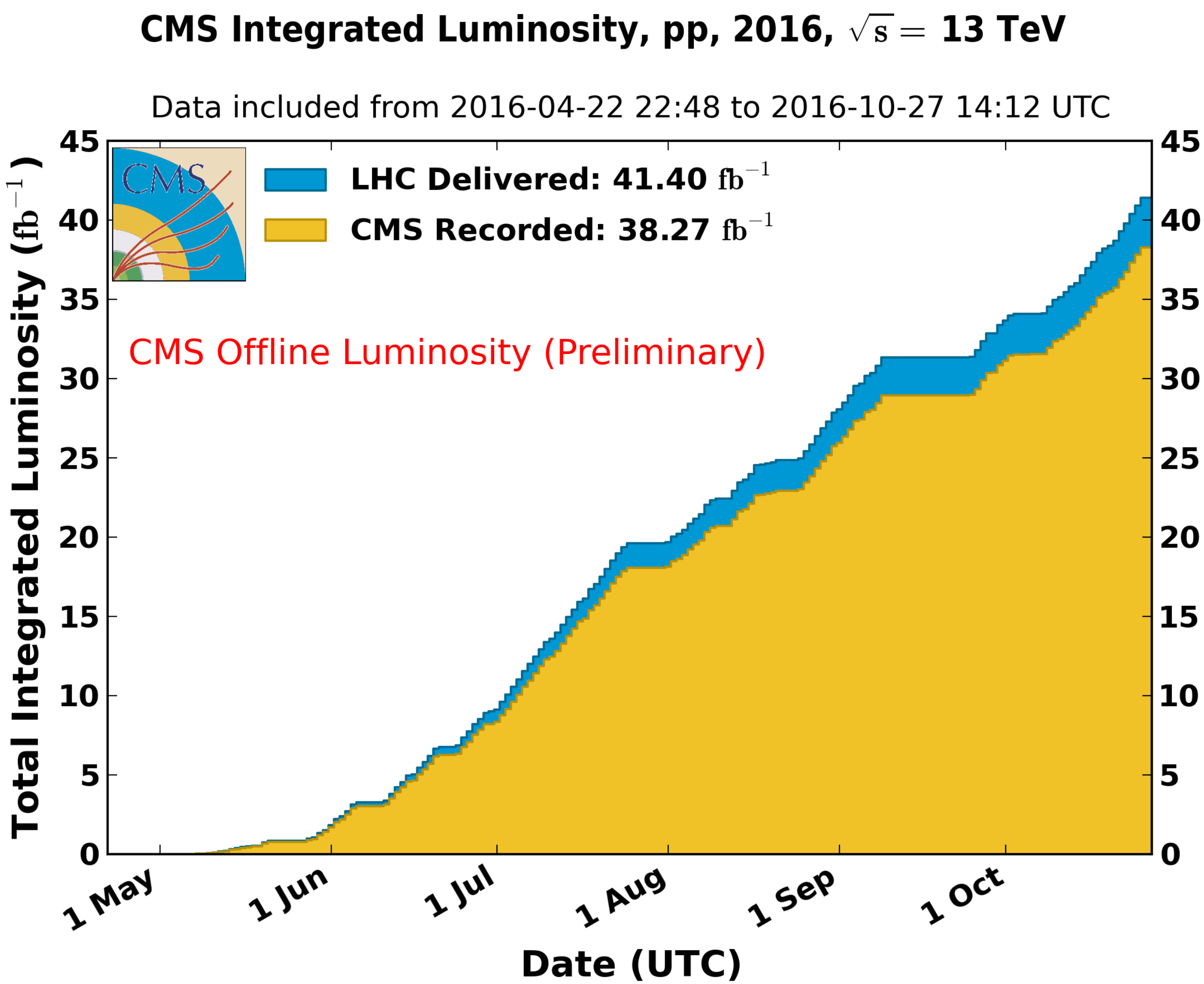


Run1: ~25/fb Run2: ~40/fb

2017 and 2018 will run at 13TeV.
Expect 45/fb per year, until the start of LS3.

http://hilumilhc.web.cern.ch/about/hl-lhc-project

Data Collected in Run-2

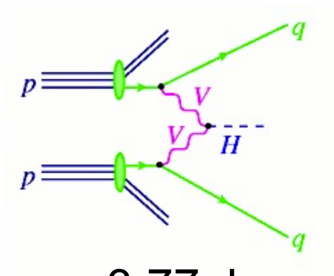


At 13TeV collected **38.27** fb^{-1} (2016) and 3.8 fb^{-1} (2015).
Thanks to the amazing machine performance.

SM Higgs production+decay modes

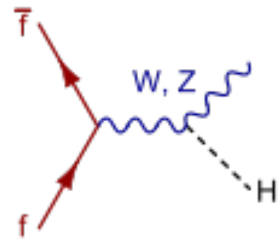
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings



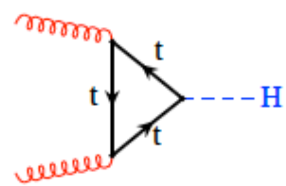
3.77pb

VBF



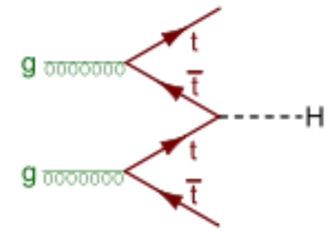
2.23pb

VH



48.23pb

ggF

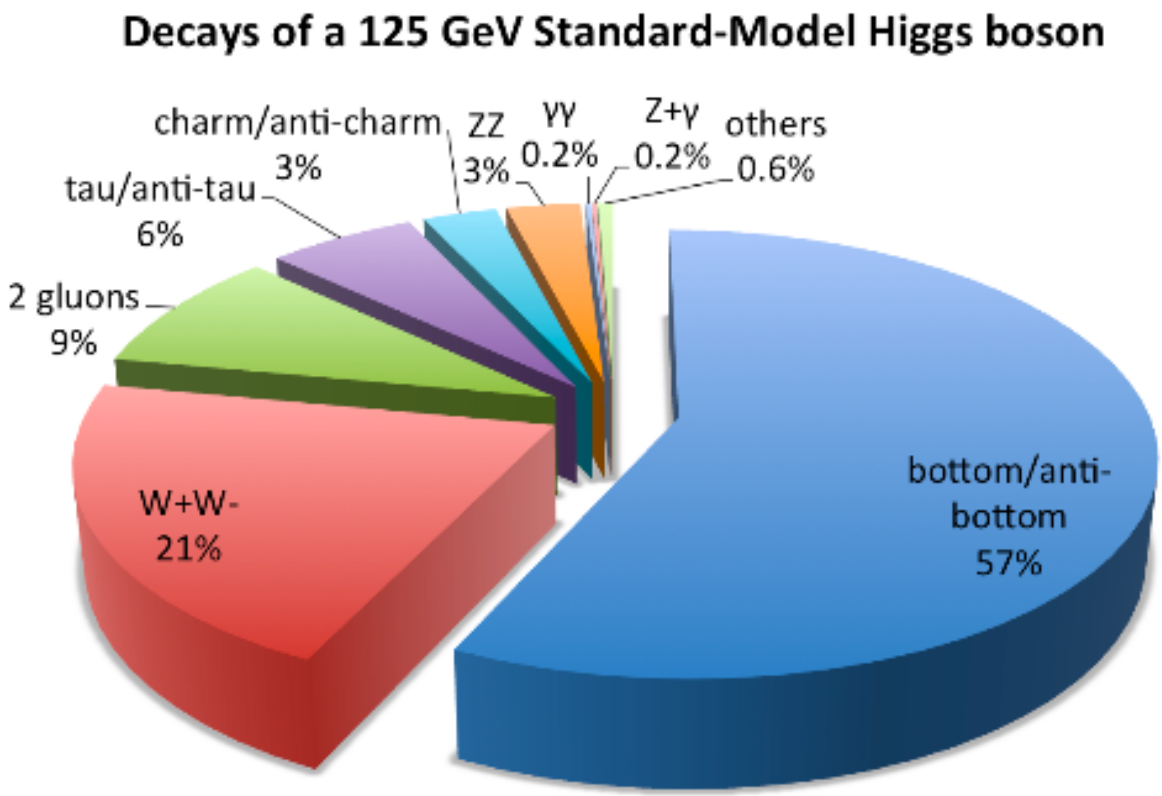


0.5pb

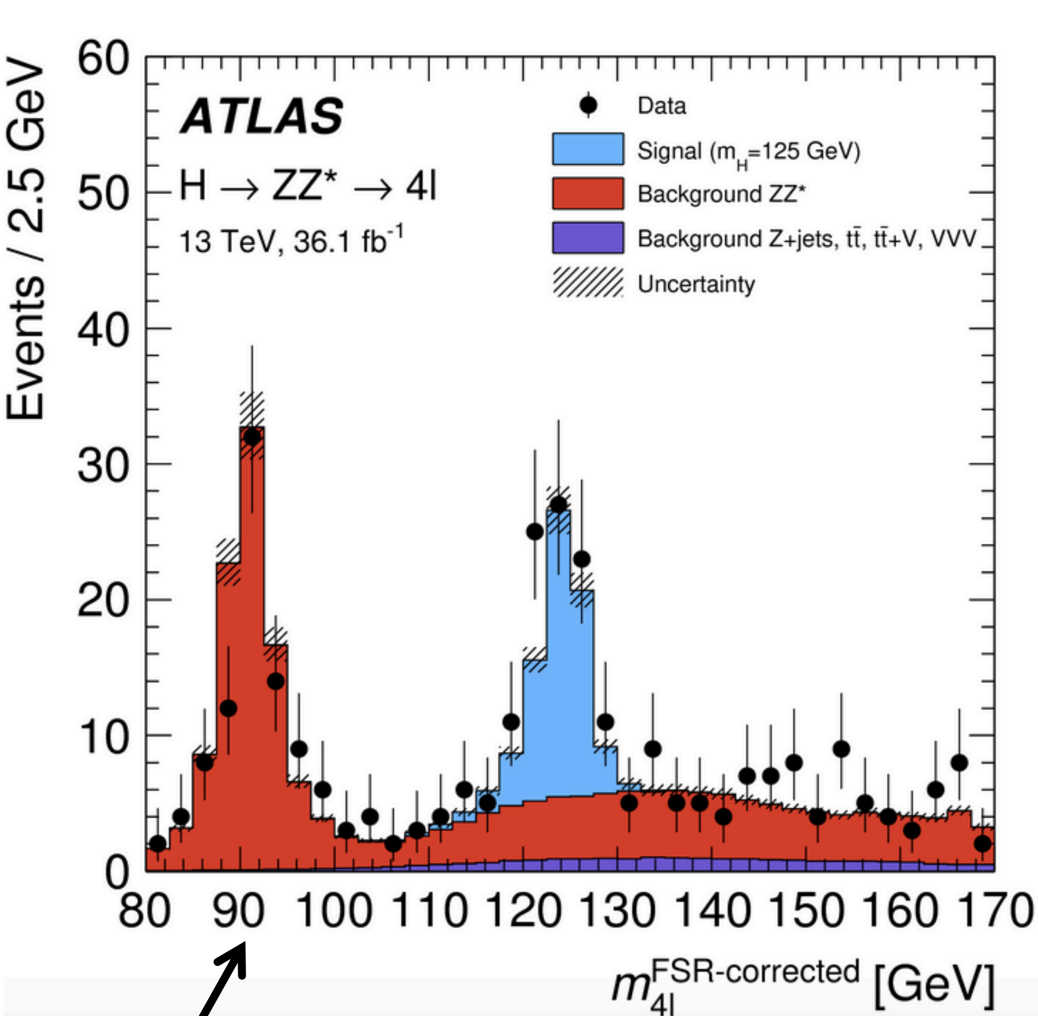
ttH

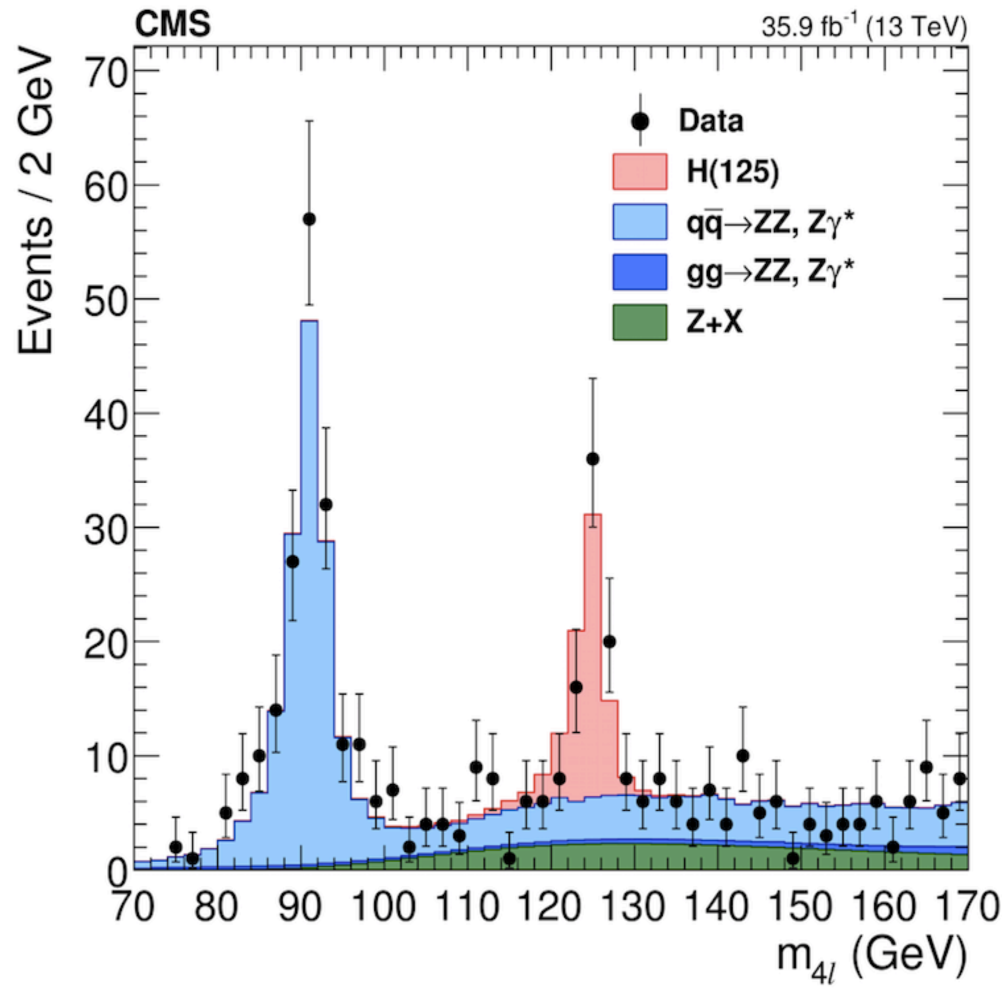
top-H couplings

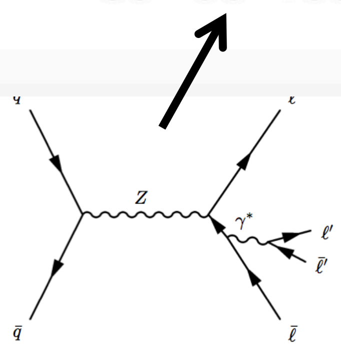
M_H:125.5GeV
E_{cm}: 13TeV



ATLAS-CMS Higgs→4l at 13TeV

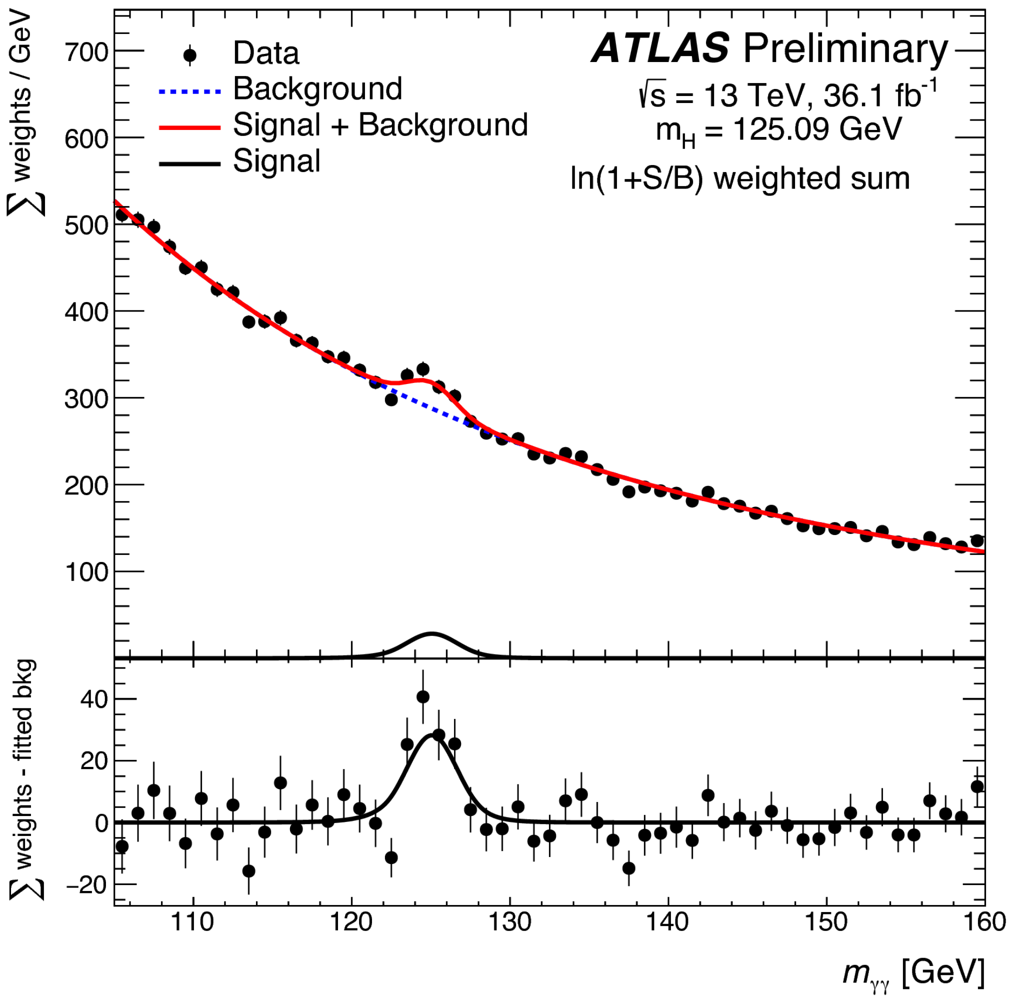


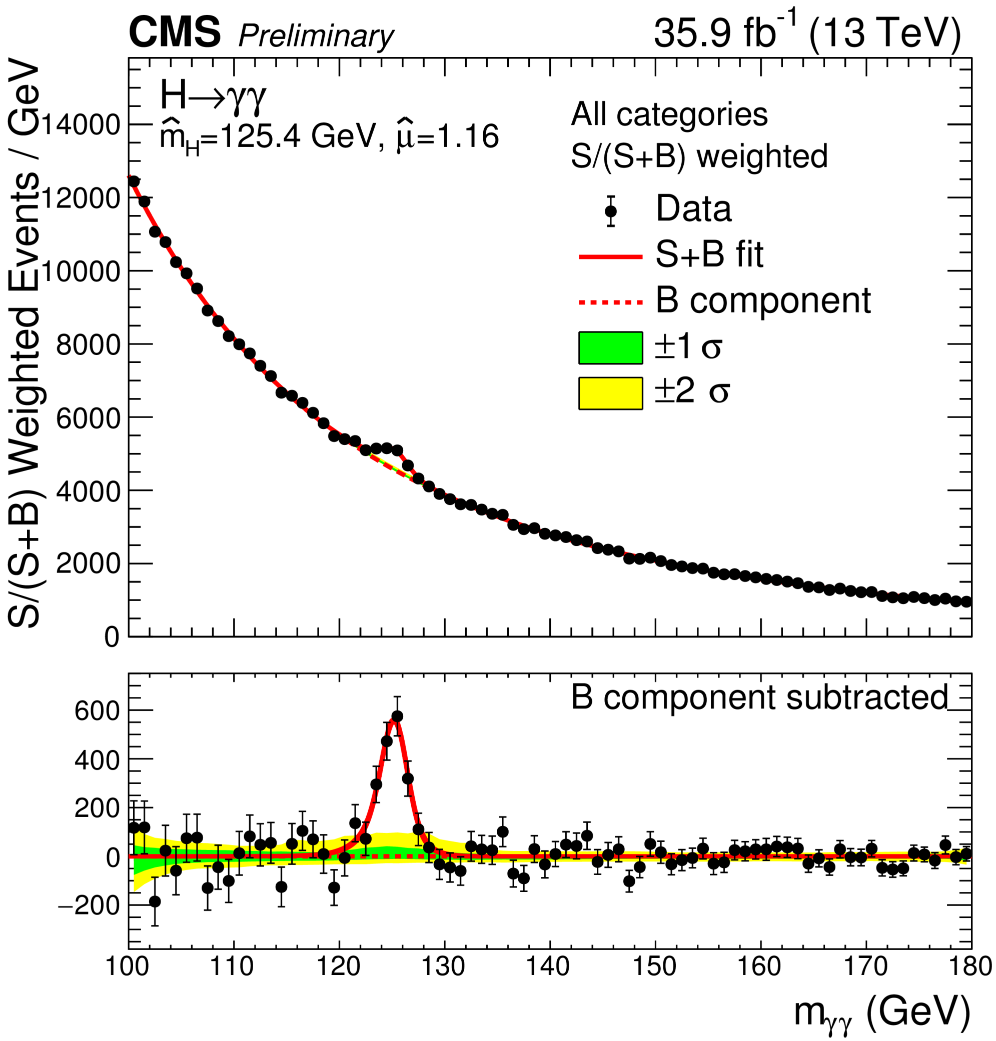




Channel with highest S/B~2/1
Higgs Mass precision: ~0.2%

ATLAS-CMS Higgs→γγ at 13TeV

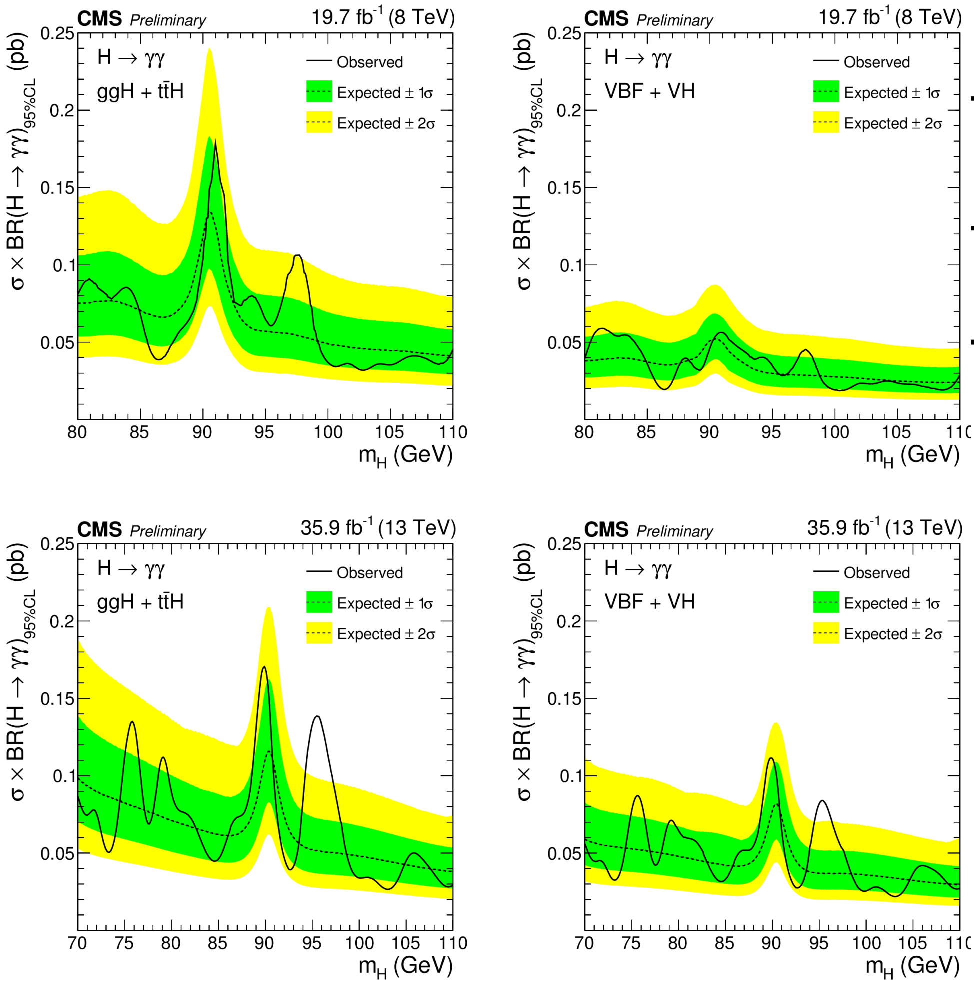


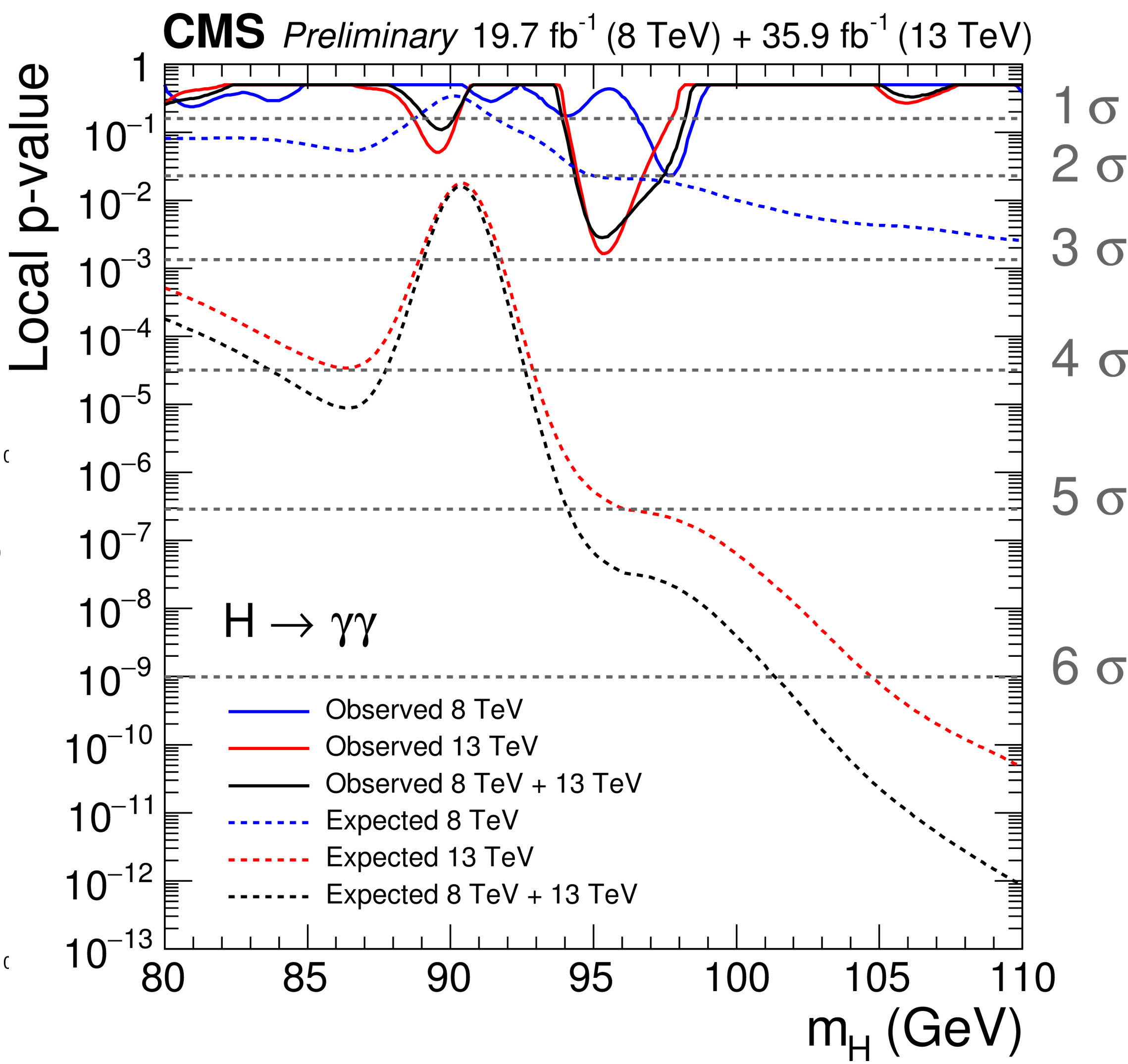


Both experiments see the Higgs signal

80-110 GeV X→γγ at 8/13TeV

September 2017
CMS-PAS-HIG-17-013



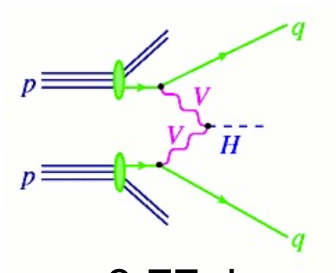


29-Sept-2017

Run 2: Production Modes

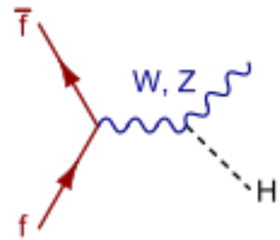
The main Higgs production mechanisms depend on V-H or top-H couplings

V-H couplings



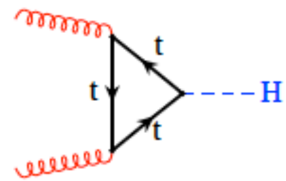
3.77pb

VBF



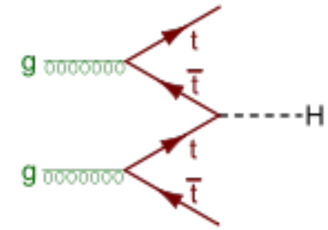
2.23pb

VH



48.23pb

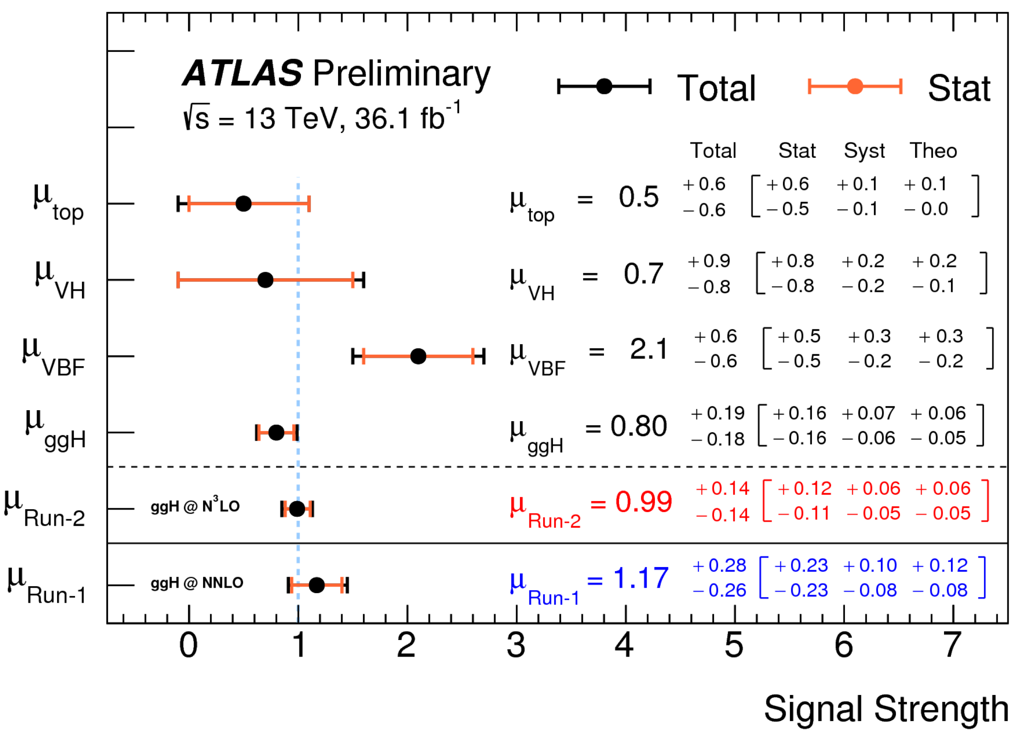
ggF

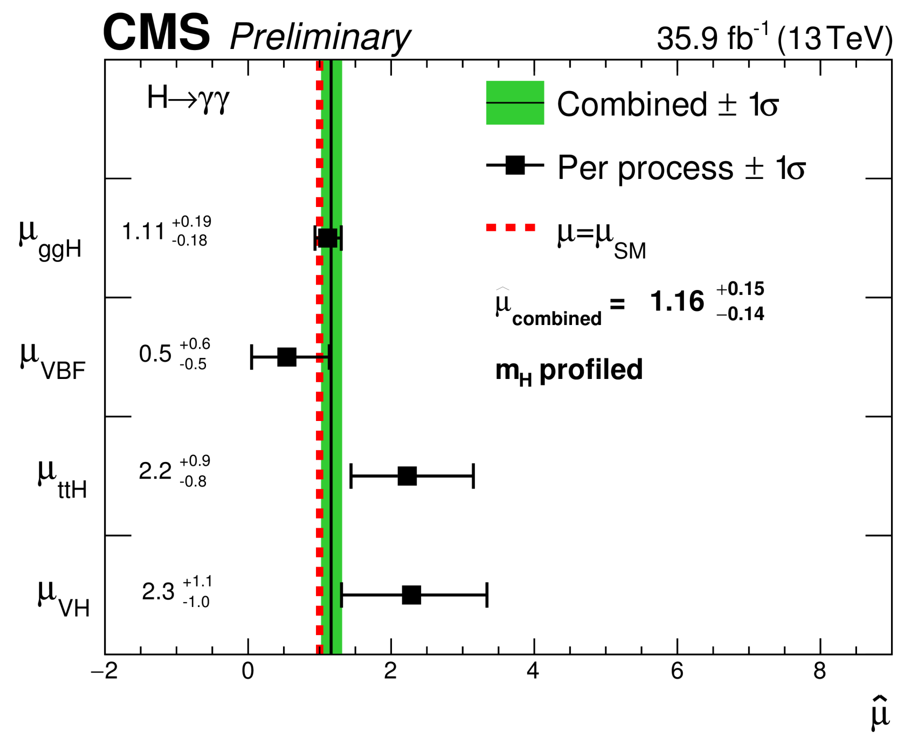


0.5pb

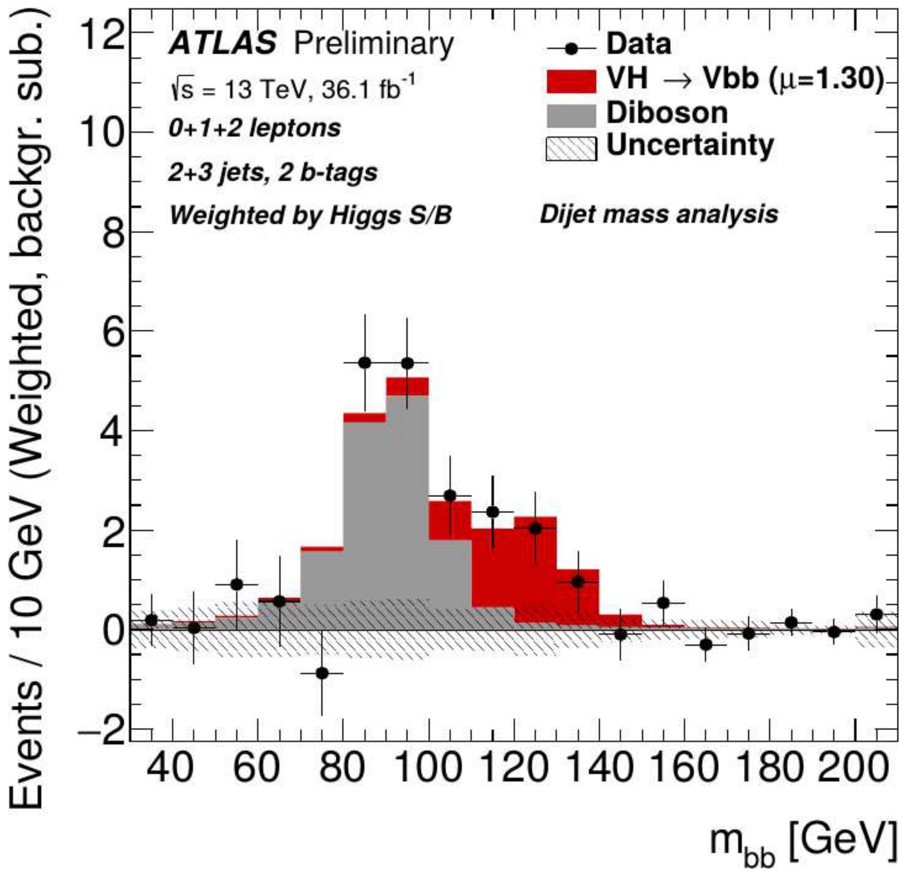
ttH

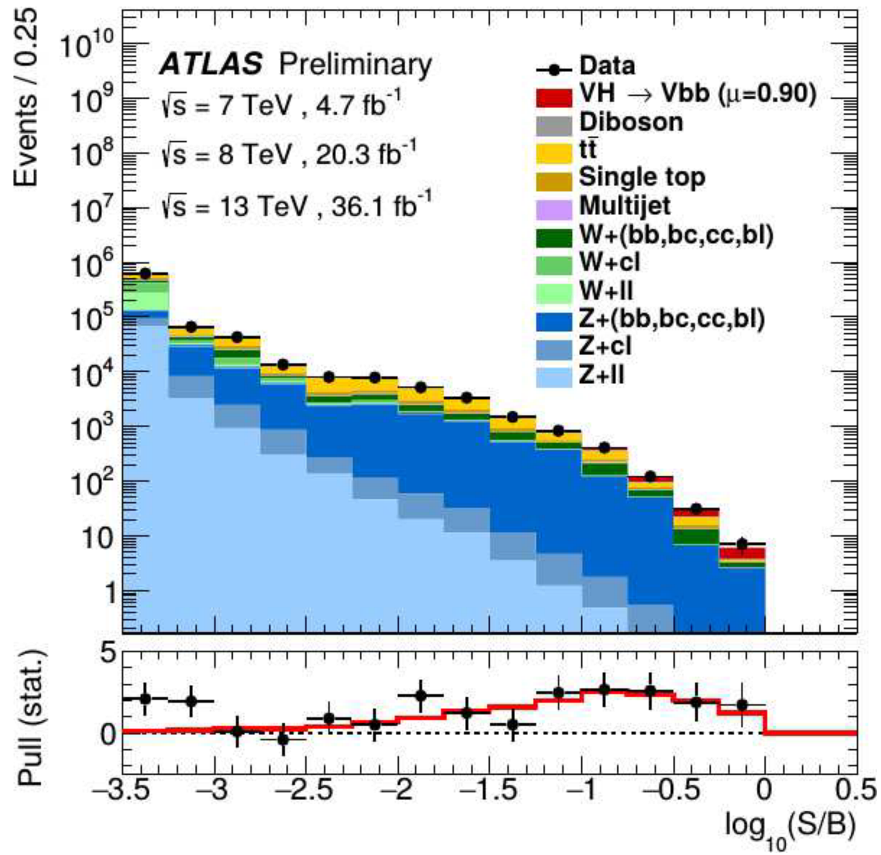
top-H couplings





ATLAS Higgs→bb at 13TeV





$$\mu = 1.3^{+0.46}_{-0.40}$$

$$\mu = 0.9^{+0.28}_{-0.26}$$

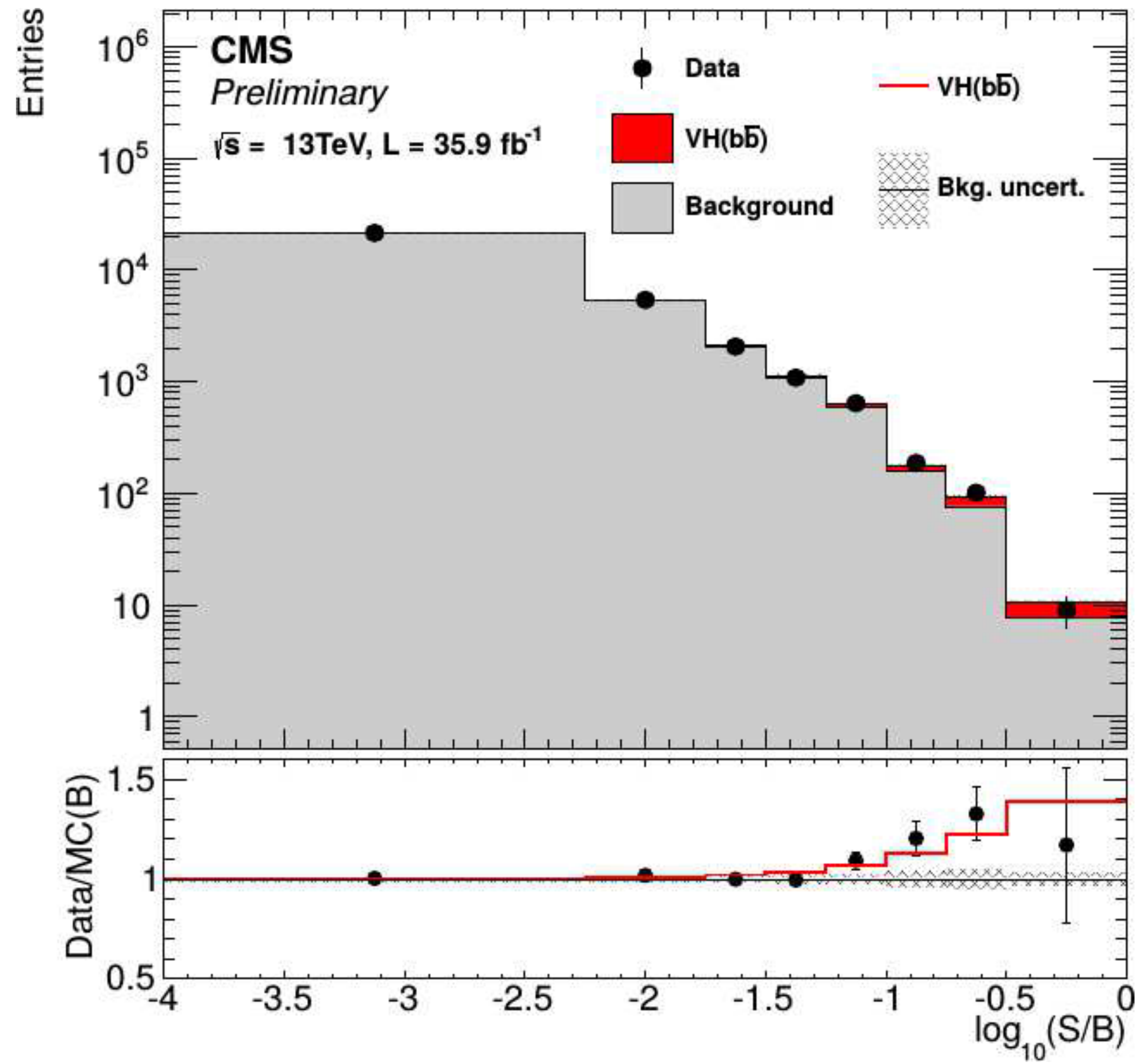
With all 7, 8 and 13 TeV data 3.6σ
(ATLAS-CONF-2017-041)

CMS Higgs→bb at 13TeV

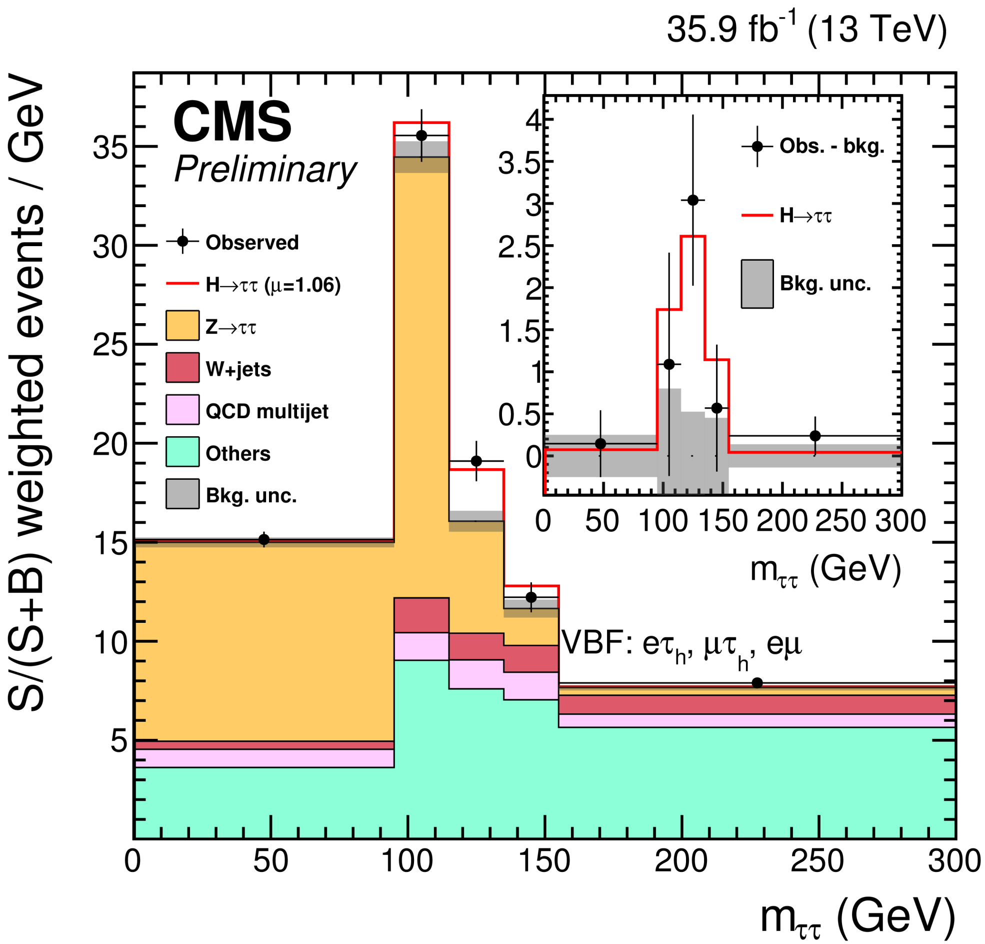
CMS PAS HIG-16-044

13TeV Signal excess:
3.3σ (**2.8σ** expected)

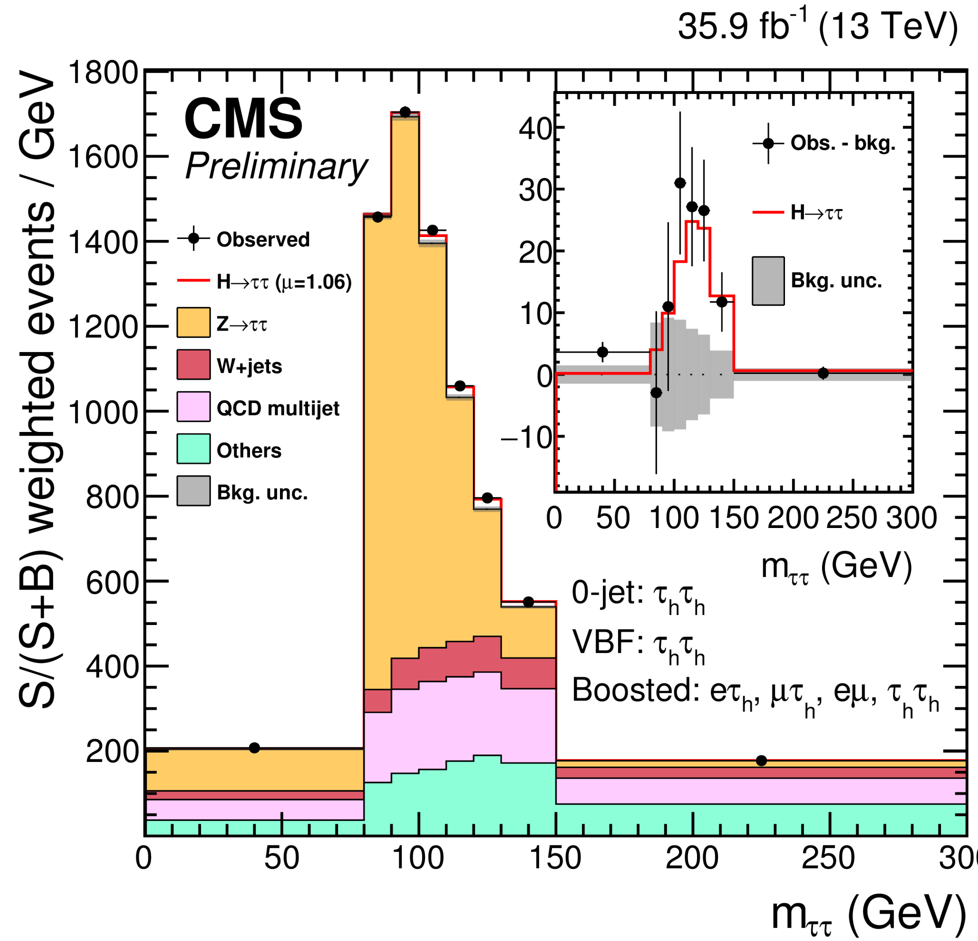
$$\mu = \frac{\sigma}{\sigma_{SM}} = 1.2 \pm 0.4$$



CMS Higgs→ττ at 13TeV



VBF: $\mu\tau_h$, $e\tau_h$, $e\mu$



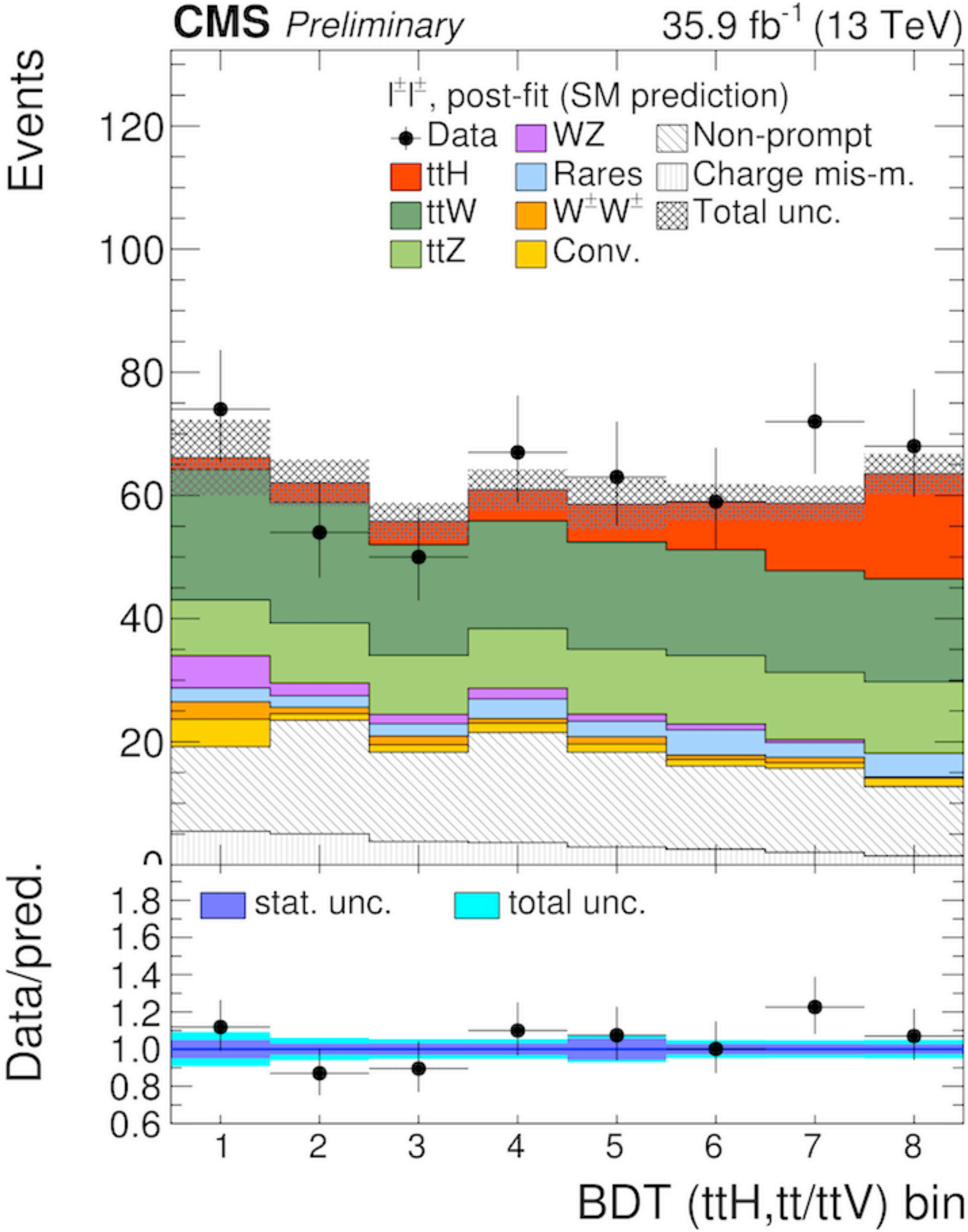
All other channels

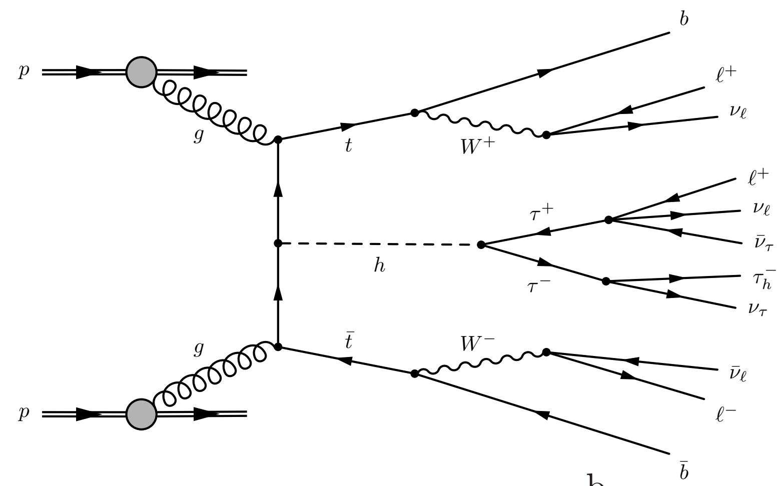
$$\mu = 1.09^{+0.27}_{-0.26}$$

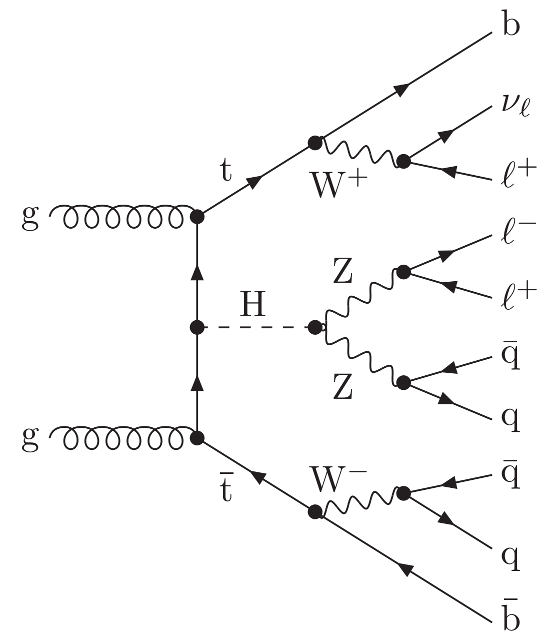
Aug-1-2017

arXiv:1708.00373 [hep-ex].

ttH channel to multileptons CMS





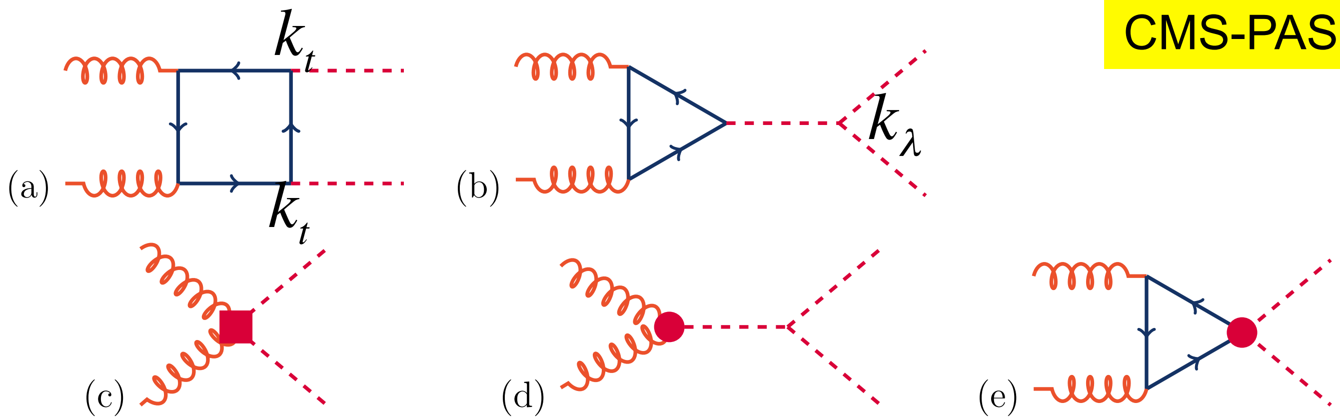


Final states to WW, ZZ, ττ

μ_{ttH}=1.5±0.5

Reconstruct the H-potential: HH→bbγγ

CMS-PAS-HIG-17-008



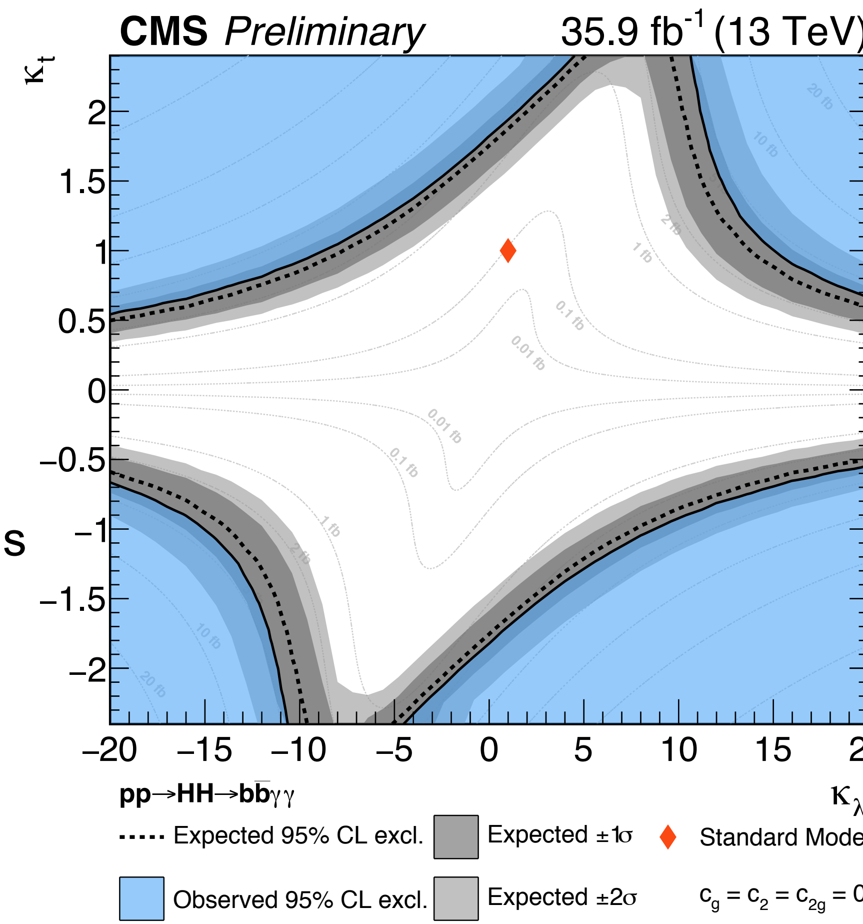
Measure the H self-coupling with gg fusion to double Higgs process (very low yield in SM)

May be enhanced due to anomalous couplings or new BSM particles.

Observed (expected) 95% CL 19.2 (16.5)xSM

Limits in coupling ratios to the SM, radions, KK gravitons

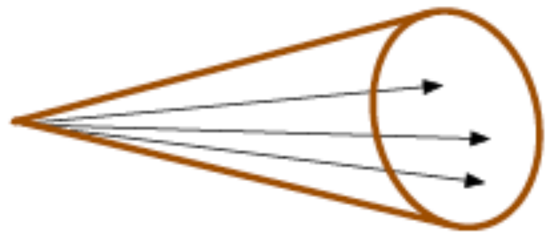
$$k_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \qquad k_t = \frac{y_t}{y_t^{SM}}$$



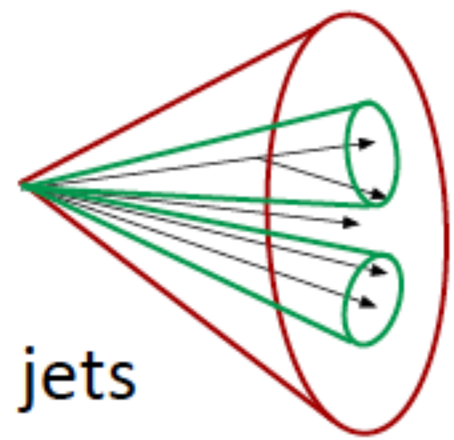
29-Sept-2017

Identification of (b-quark) jets

- b-jets reconstructed with anti-k_T algorithm
- two categories:
  - "resolved" R=0.4



  - "boosted":
    - R=1.0 with two R=0.2 b-tagged track-jets(ATLAS bbbb),
    - R=0.8 and contains two "resolved" jets (CMS bbbb, bbττ)



slide from: M. Slawinska

(Selected) High mass Higgs searches

BSM Higgs data interpretations

- So far 125GeV scalar:
  - Consistent with the SM Higgs (albeit coupling errors large).
- Large number of models beyond the SM:
  - Some commonly used for LHC data interpretation listed here.

2-Higgs Doublet Model (2HDM)

- 2 doublets Φ_1, Φ_2, **5 bosons**:
  - 2 charged scalars: $\mathbf{H^{\pm}}$
  - 2 neutral scalars: **h** (often 125GeV), **H**
  - 1 neutral pseudoscalar: **A**
- Free parameters (tree level):
  - $\mathbf{m_A}$; $\mathbf{\tan\beta}$=ratio of the two vev's.
- **Type I**: q & lep only couple to 2nd doublet
- **Type II**: up-(down-)type couple to Φ_2 (Φ_1)

2-Higgs Doublet Model + S

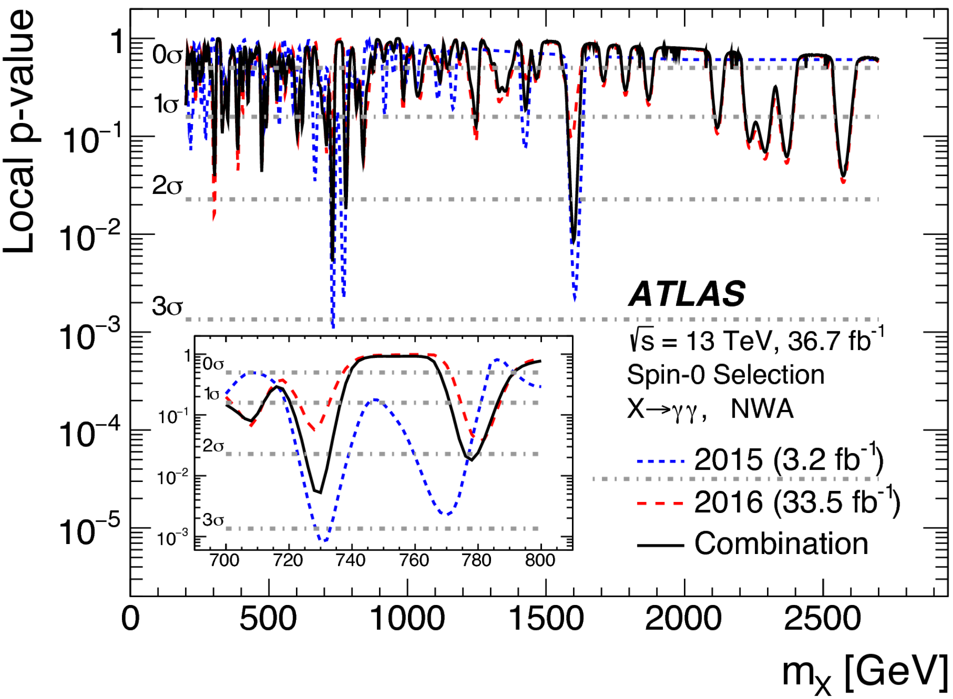
- 2HDM extended by 1 complex $SU(2)_L$ singlet field
  - Only couples to 2 Higgs fields (no direct Yukawa couplings)
- 2 more bosons: 1 CP-odd; 1 CP-even
- Special case: NMSSM

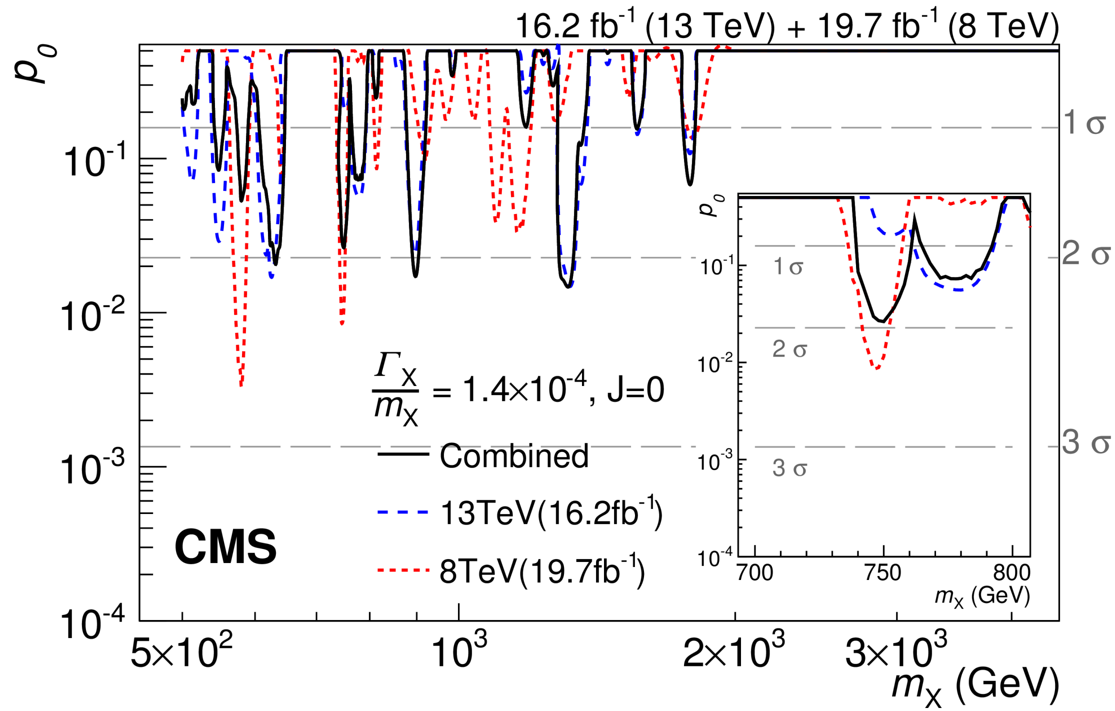
Higgs triplets

- HTM: 7 bosons, including $\mathbf{H^{\pm\pm}}$
- Georgi-Machacek model.

Heavy X→γγ at 13TeV

ATLAS (arXiv:1707.04147) $36.7 fb^{-1}$ 13TeV
CMS EXO-16-027 $16.2 fb^{-1}$ 13TeV



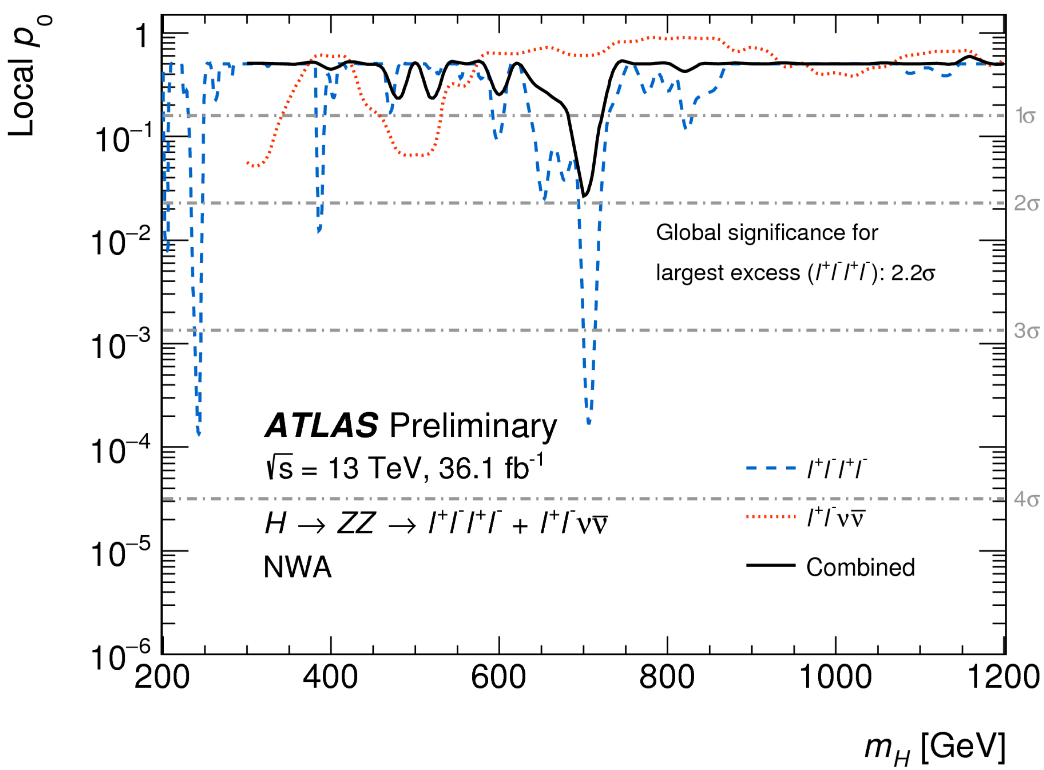


ATLAS excesses in 13TeV-only:
300GeV: ~2σ
730GeV: ~1.5σ
1.1TeV : ~1.1σ

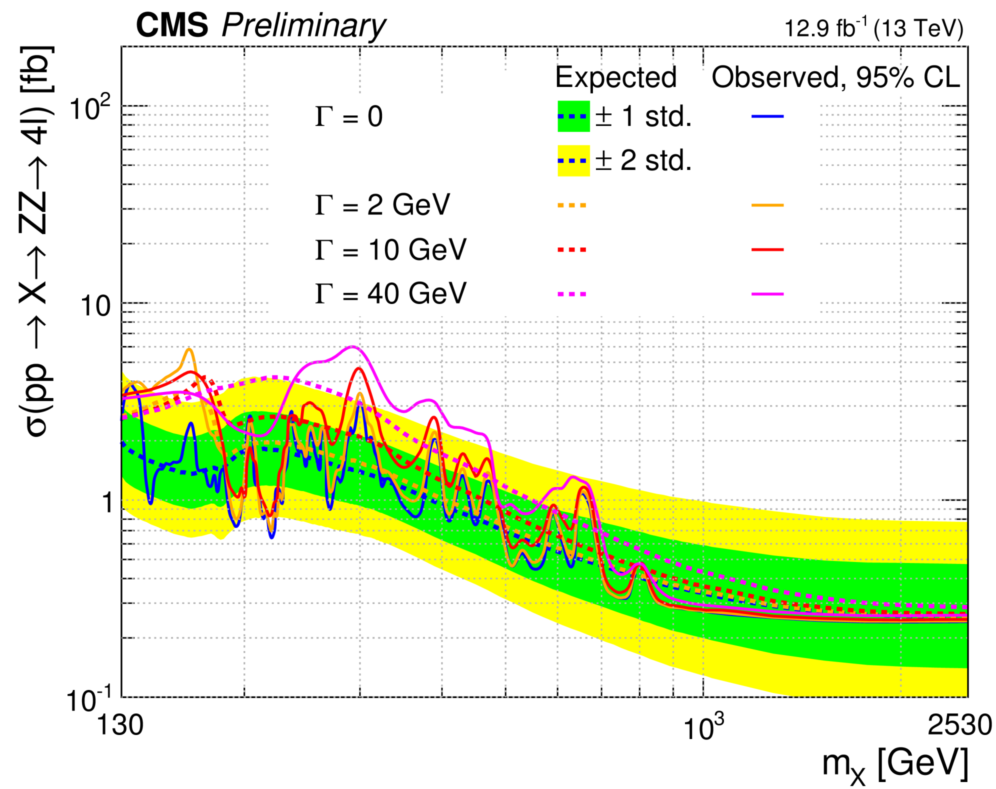
CMS has a few 2σ excesses
(however less luminosity)

ATLAS-CMS h→4l at 13TeV

ATLAS-CONF-2017-058 36.1fb^{-1} 13TeV



CMS PAS HIG-16-033 **12.9fb^{-1}** 13TeV



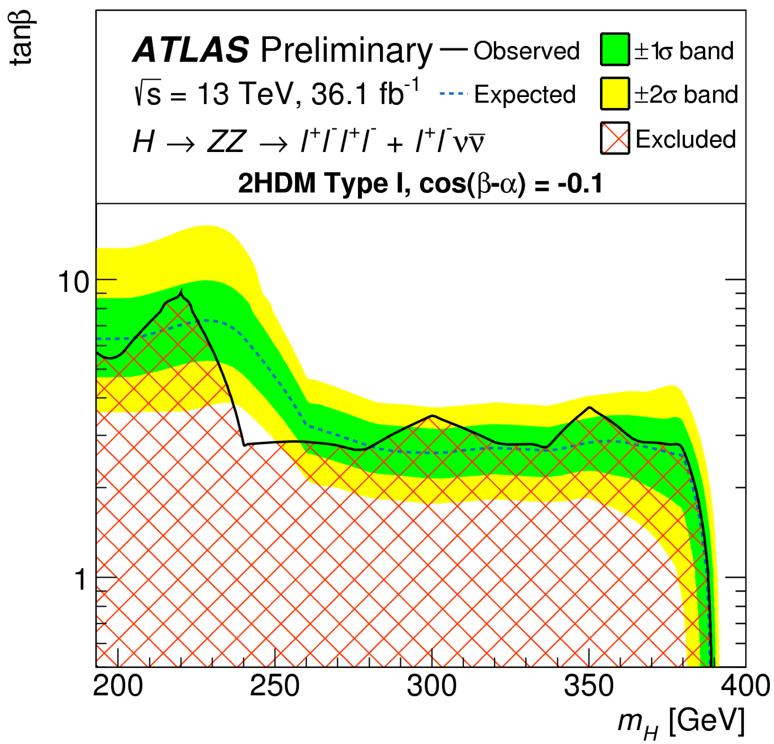
ATLAS has analyzed the full data set:
>3σ excesses in 4lepton channel (no neutrinos):

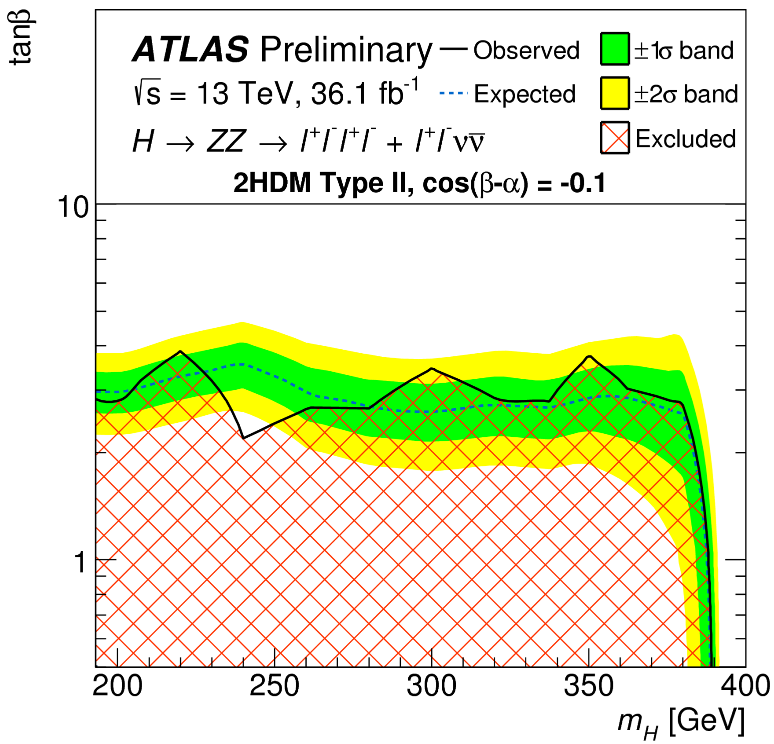
CMS has 2σ excess at ~300GeV

~240GeV and ~710GeV.

2HDM limits with h→4l at 13TeV

ATLAS-CONF-2017-058





Cross section limits interpreted in the two-Higgs doublet model.

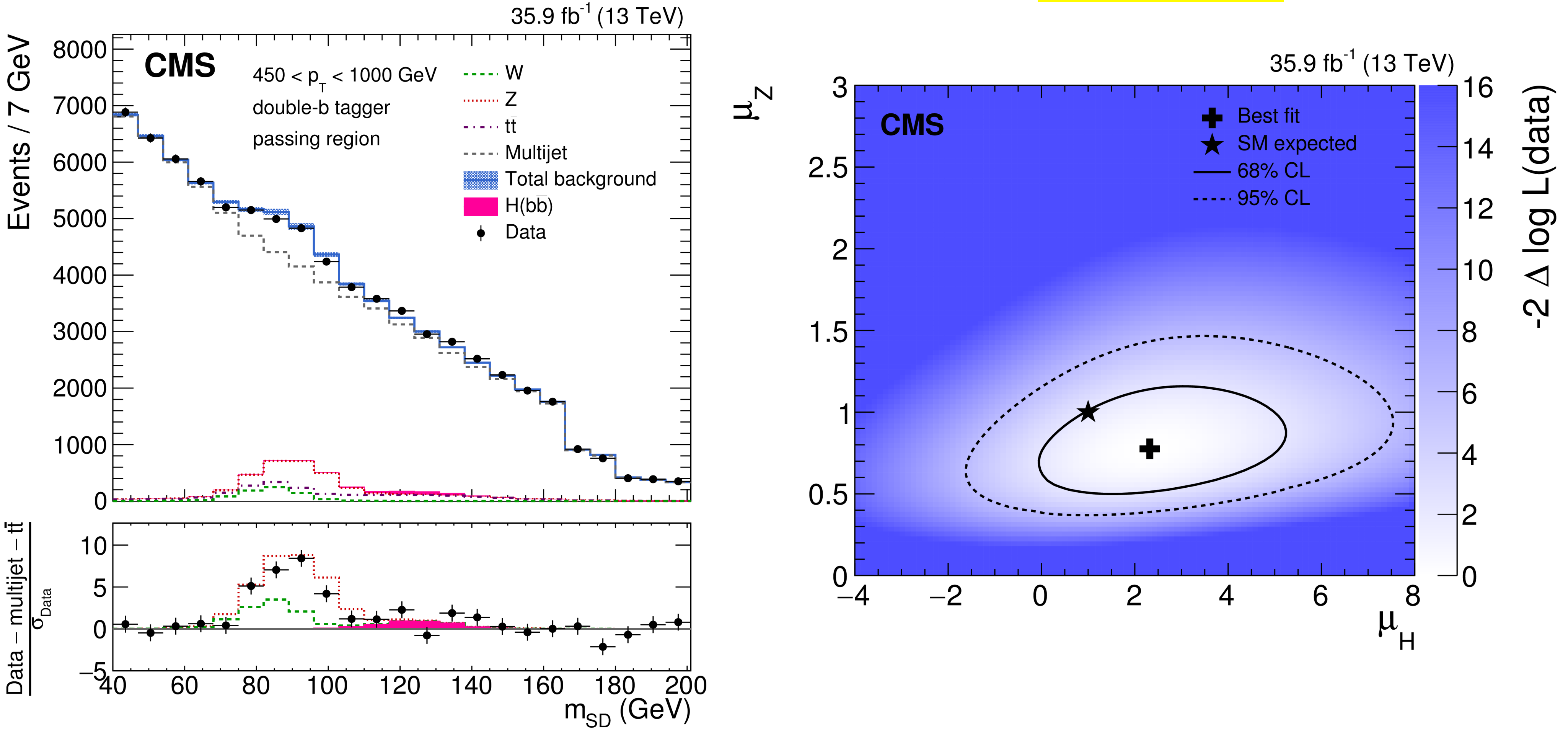
Singly- doubly- charged Higgs

Channel	Limit in MH	Luminosity	Production+FS	Paper
$H^\pm \rightarrow WZ$ 13TeV	300GeV-2TeV	15.2 fb^{-1}	VBF $ll\nu l$	CMS-HIG-16-027
$H^\pm \rightarrow tb$ 13TeV	300GeV-1TeV	12.9 fb^{-1}	Assoc. with top $bl\nu(b)$	ATLAS-CONF-2016-089
$H^\pm \rightarrow \tau\nu$ 13TeV	80GeV-160GeV 200GeV-2TeV	14.7 fb^{-1} 12.9 fb^{-1}	Decay of top Assoc. with top Hadronic	ATLAS-CONF-2016-088 CMS-HIG-16-031
$H^\pm \rightarrow cb$ 8TeV	80GeV-150TeV	19.7 fb^{-1}	Decay of top Semi-lept., (cbb) $(l\nu b)$	CMS-HIG-16-030
$H^\pm \rightarrow cs$ 8TeV	80GeV-160TeV	19.7 fb^{-1}	Decay of top Semi-lept., (csb) $(l\nu b)$	CMS-HIG-13-035 ATLAS-arXiv1302.3694
$H^{\pm\pm} \rightarrow l^\pm l^\pm$ 13TeV	Depends on BR 900GeV	36.1 fb^{-1}	γ/Z, pair production	ATLAS-CONF-2017-053
$\Phi^{++}\Phi^{--}$&$\Phi^{\pm\pm}\Phi^{-/+}$ 13TeV	Depends on FS/BR ~800GeV	12.9 fb^{-1}	$W,\gamma/Z$, decays	CMS-HIG-16-036

CMS high-P_T H→bb

CMS-HIG-17-010

P_T>450 GeV



(SD: soft drop algorithm)

Looking for BSM with Higgs in the FS

Z' model

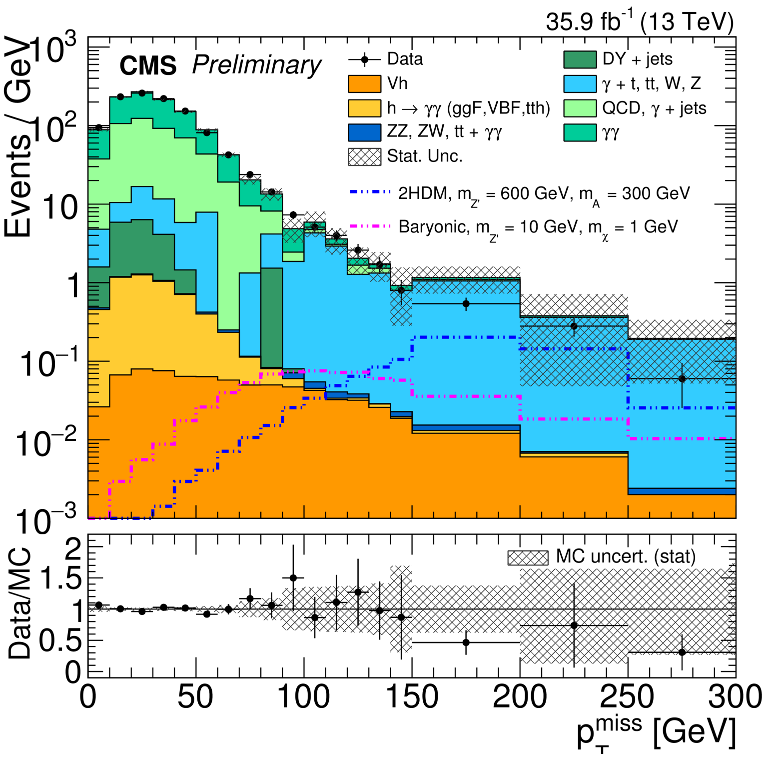
- An additional U(1)' symmetry are present in several BSM models ➔ Z'
  - GUT, Little Higgs, Extra Dimensions

- Leptonic decays Z'→l^+l^- exclude Z' up to 4TeV.
  - In certain models we have baryonic Z'_B (leptophobic)

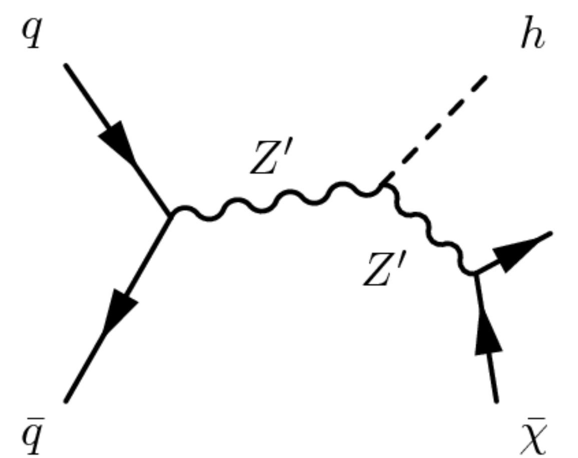
- In certain models, Z' links dark and visible sectors
  - Searches for Z'→Higgs + MET

H→γγ + MET

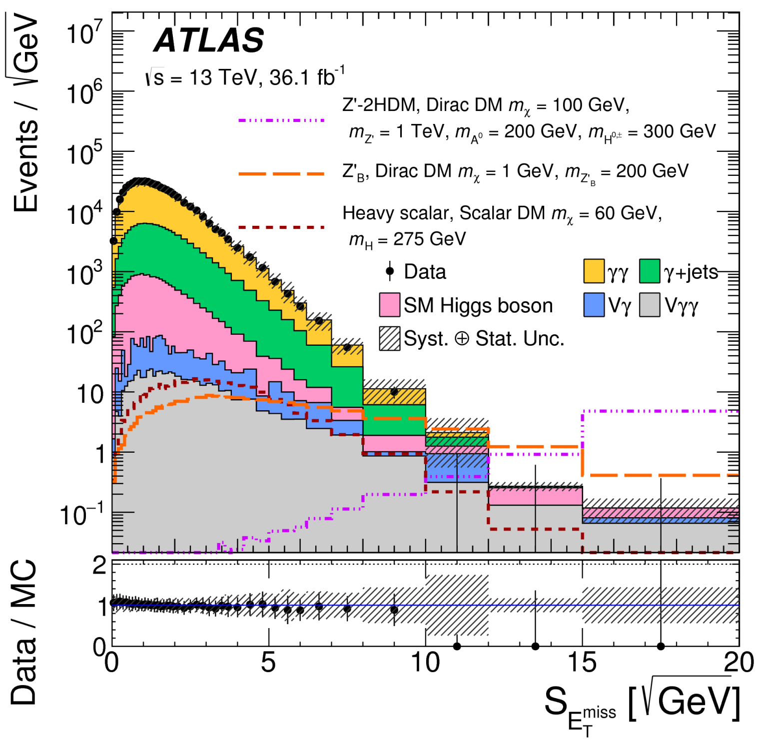
CMS-PAS-EXO-16-054
ATLAS-HIGG-2016-18

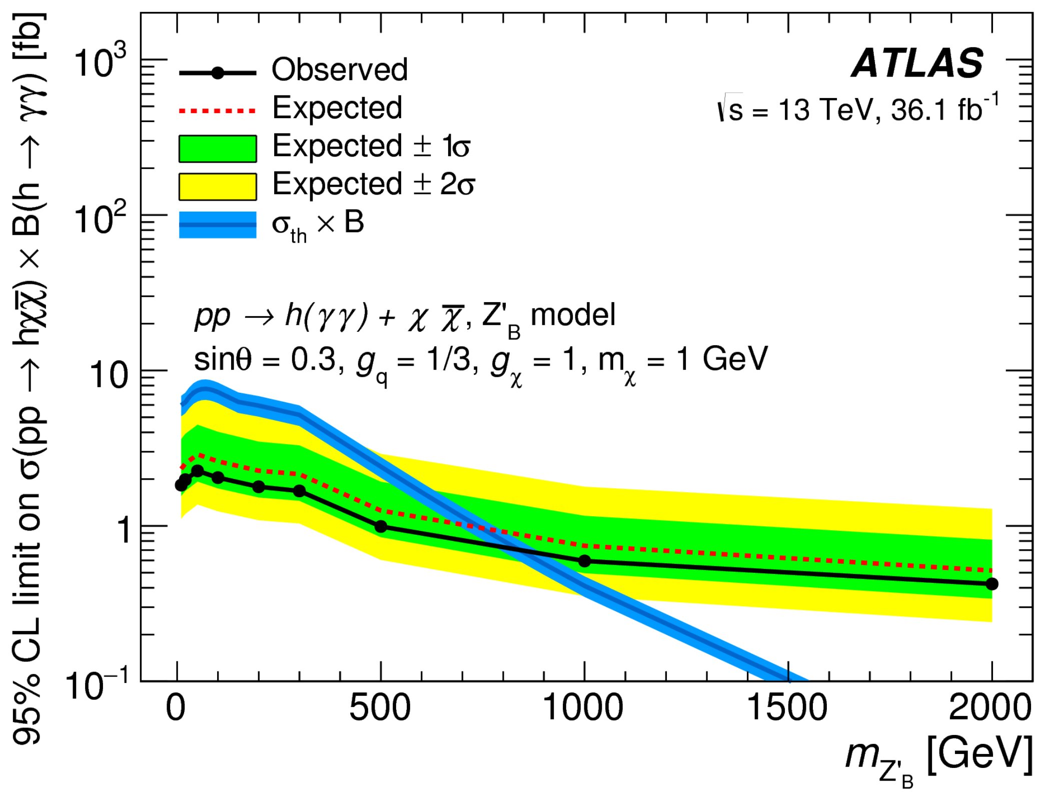


Z' 2HDM
Z_B model
Heavy scalar



Mixing between the B Higgs and the SM Higgs sinθ= 0.3





Heavy Vector Triplet model

- New heavy vectors are present in several BSM models.
  - Composite Higgs, Little Higgs, …

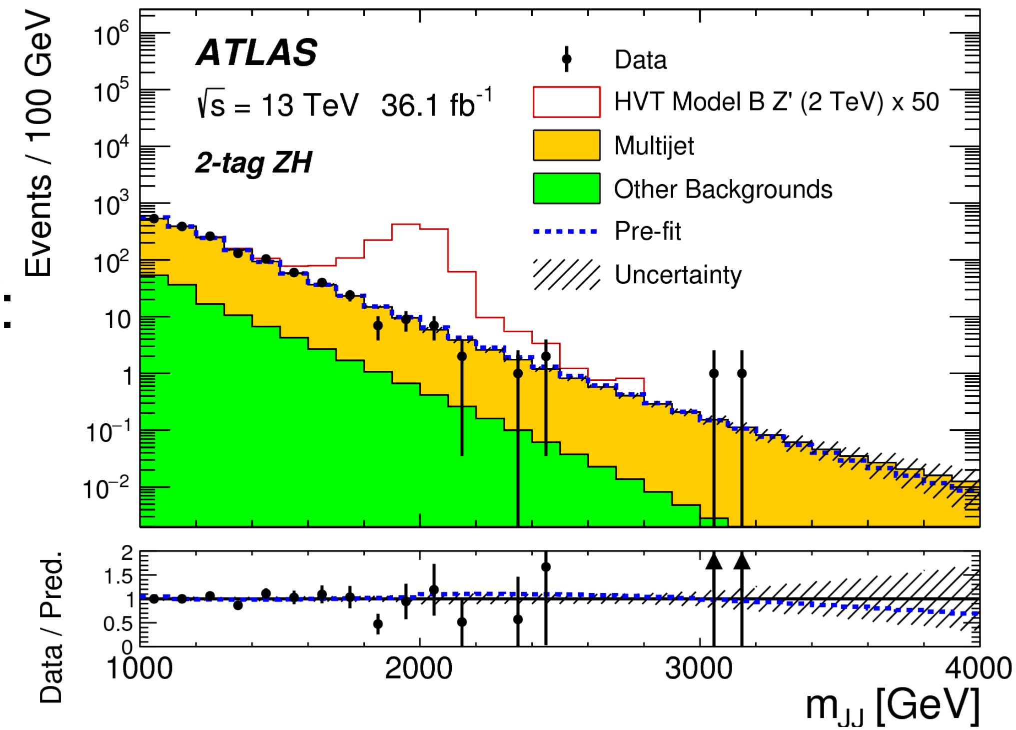
- HVT is a simplified Lagrangian that couples fermions, the Higgs and weak gauge bosons to a spin-1 triplet.
  - Makes easier the comparison between theory and experiments.
  - HVT couplings to H/W/fermions can be constrained.

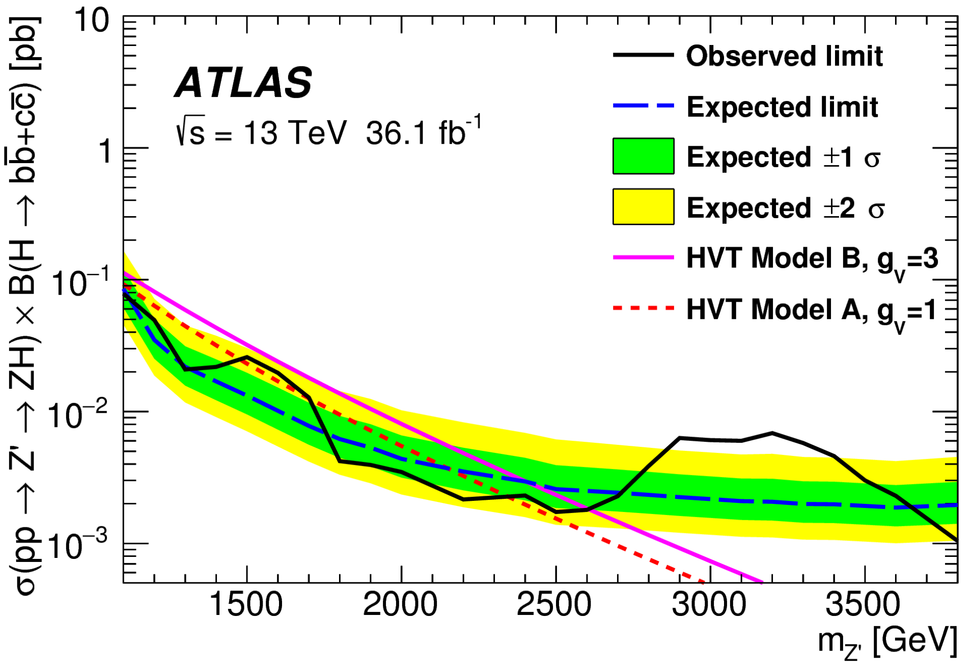
- Direct search of these V'→Higgs + W/Z
  - Currently analyses probing qq→V' production

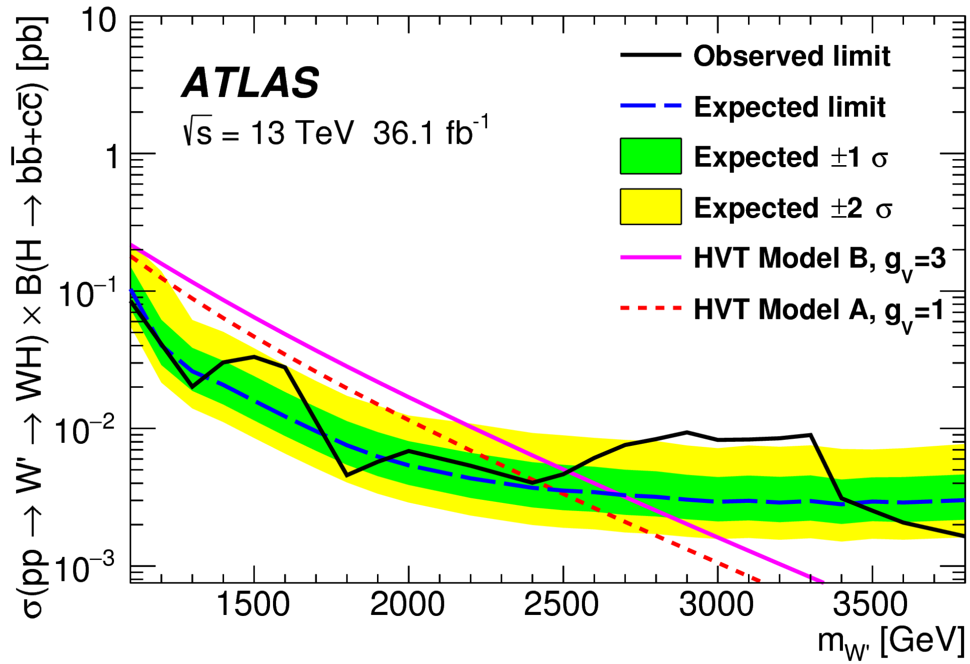
ATLAS Boosted V + H→bb

ATLAS-CONF-2017-018

Local (global) Significance at 3TeV:
3.3σ (2.1σ)

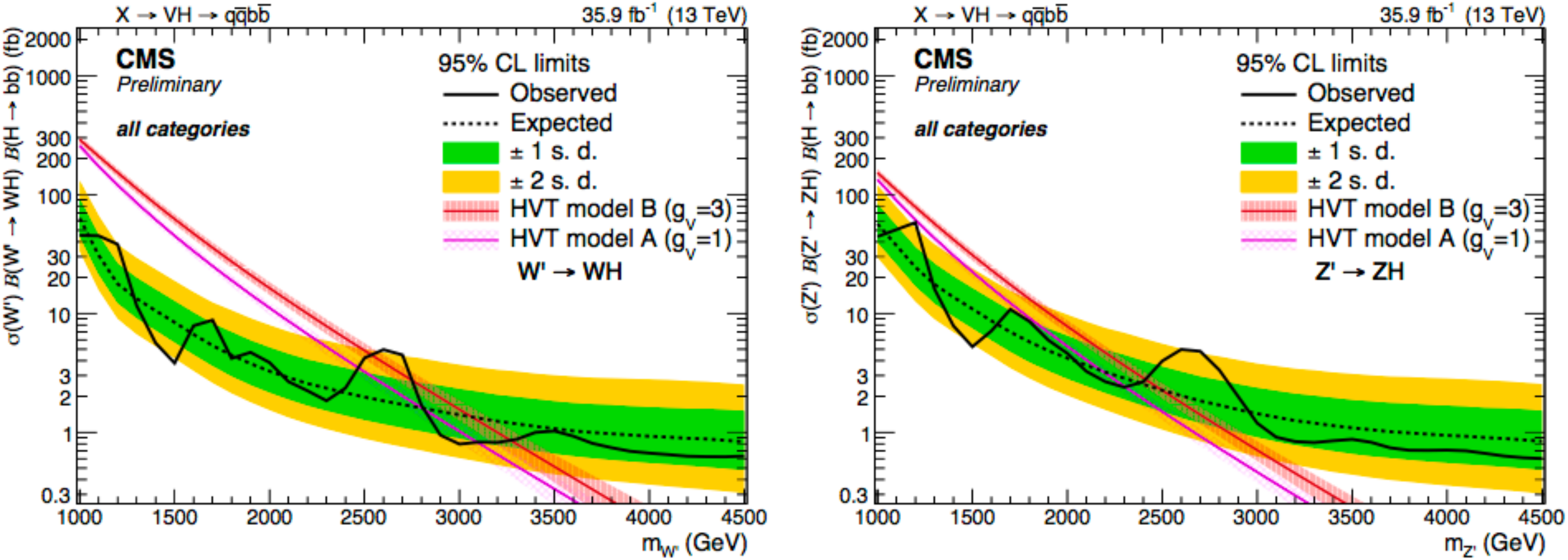




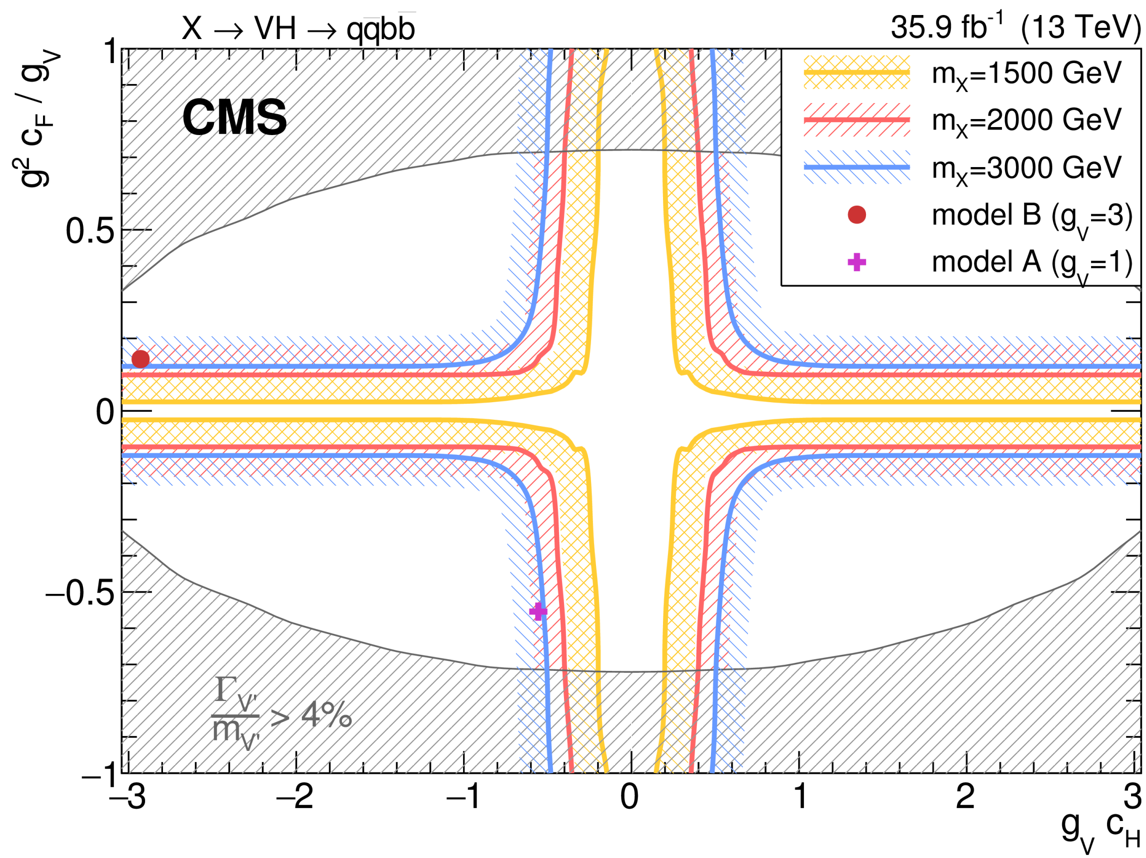


CMS Boosted V + H→bb

CMS-PAS-B2G-17-002

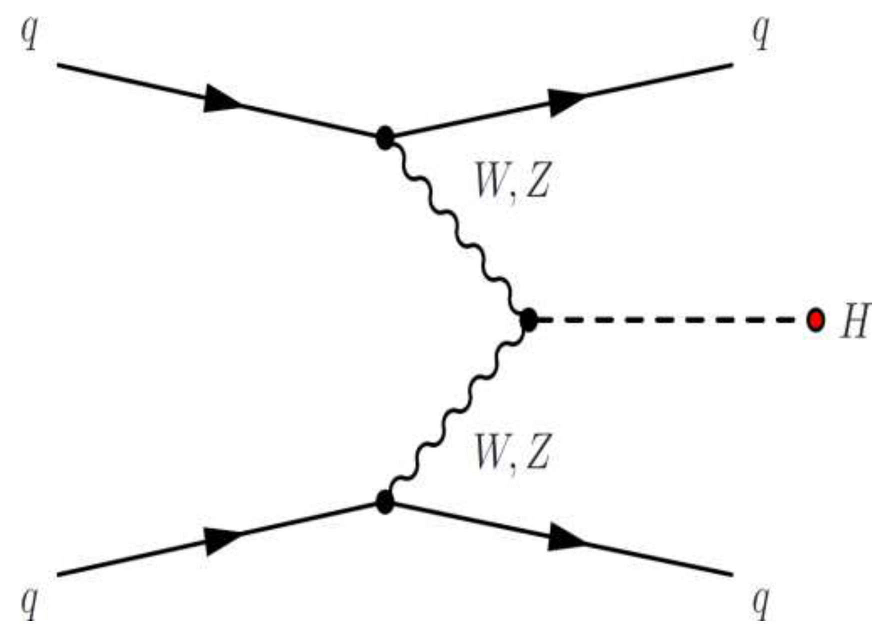


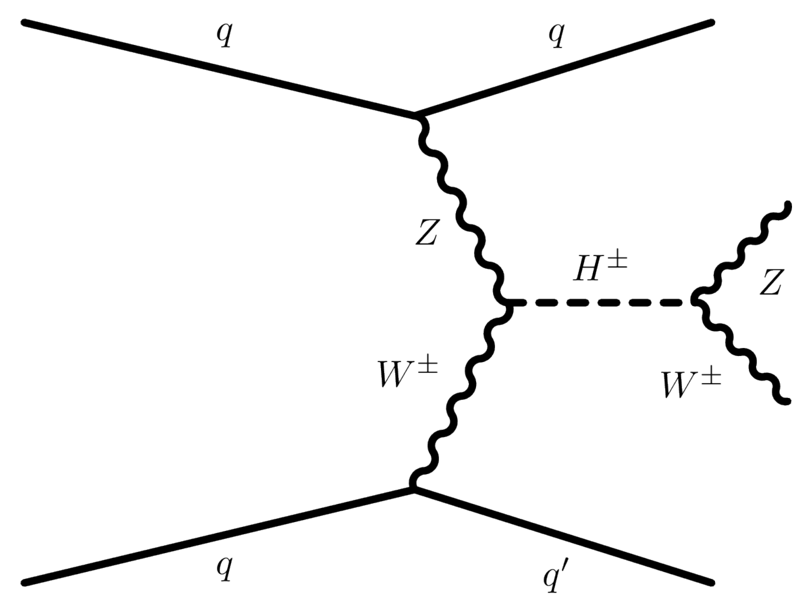
Excess at about 2.7TeV but at 3TeV no excess is observed



Observed exclusion in the HVT parameter plane [$g_V c_H$, $g^2 c_F/g_V$] for three different resonance masses (1.5, 2.0, and 3.0 TeV). The parameter g_V represents the coupling strength of the new interaction, c_H the coupling between the HVT bosons and the Higgs boson and longitudinally polarized SM vector bosons, and c_F the coupling between the heavy vector bosons and the SM fermions.The gray shaded areas correspond to the region where the resonance natural width is predicted to be larger than the typical experimental resolution (4%) and thus the narrow-width approximation does not apply.

How about VBF?

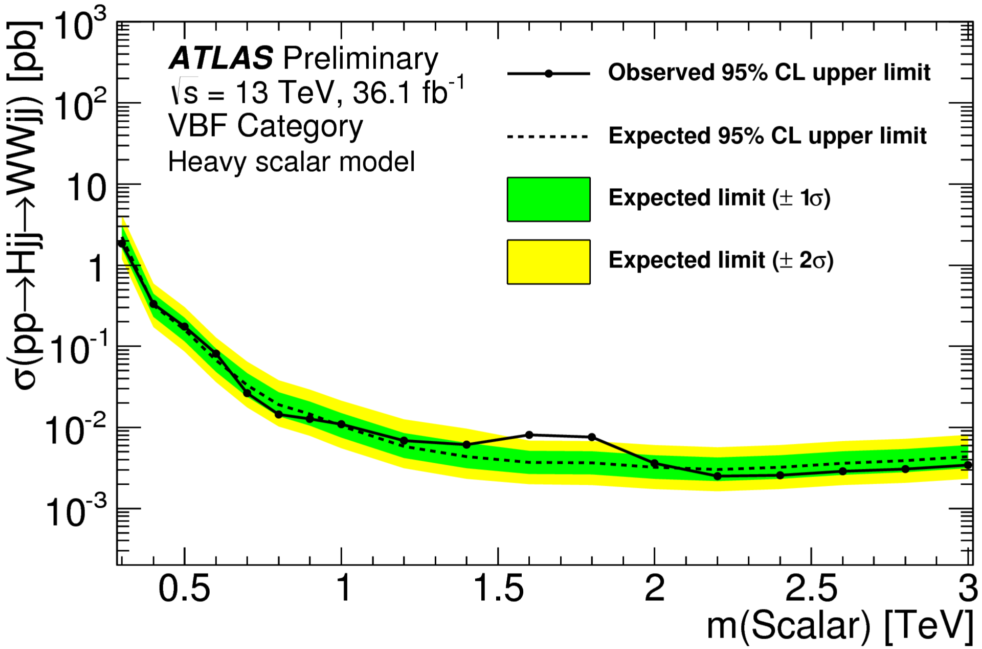




VBF scalar/Vector → WZ

5-July

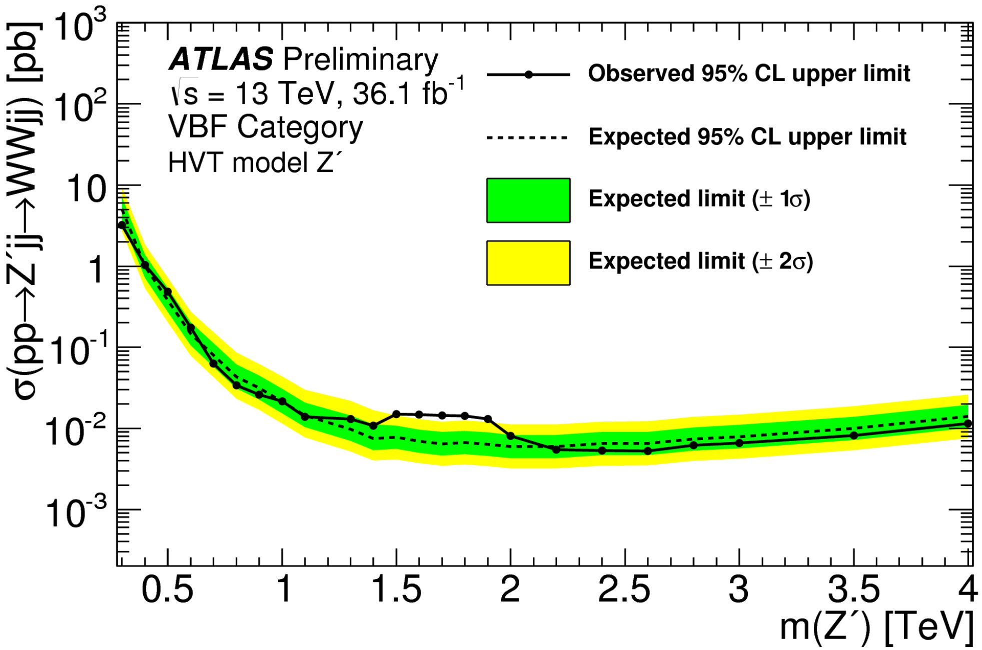
ATLAS-CONF-2017-051

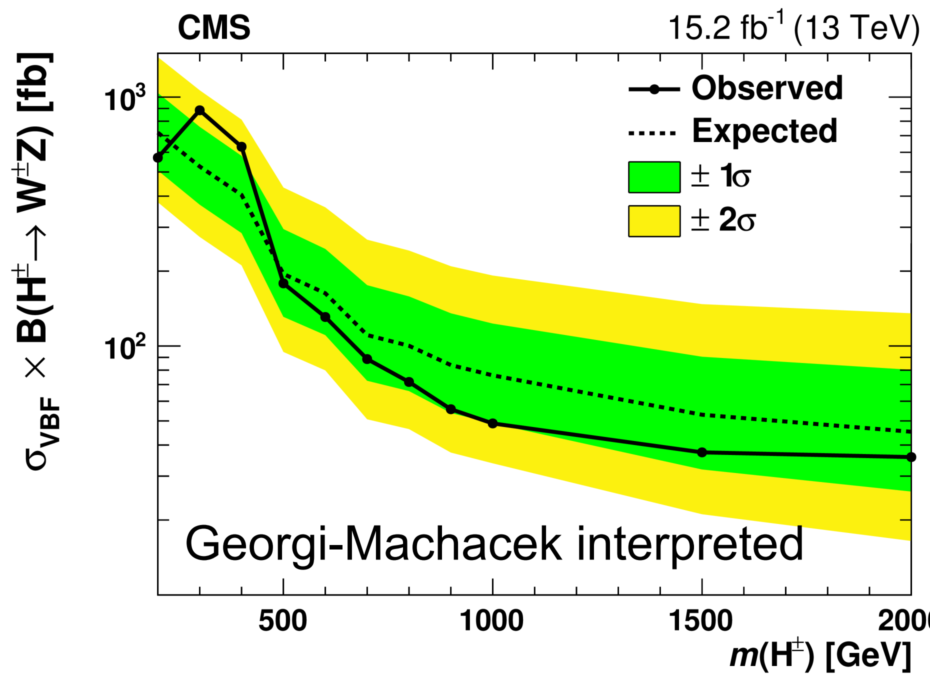


ATLAS has searched in the VBF mode for fermiophobic heavy scalars or vectors.

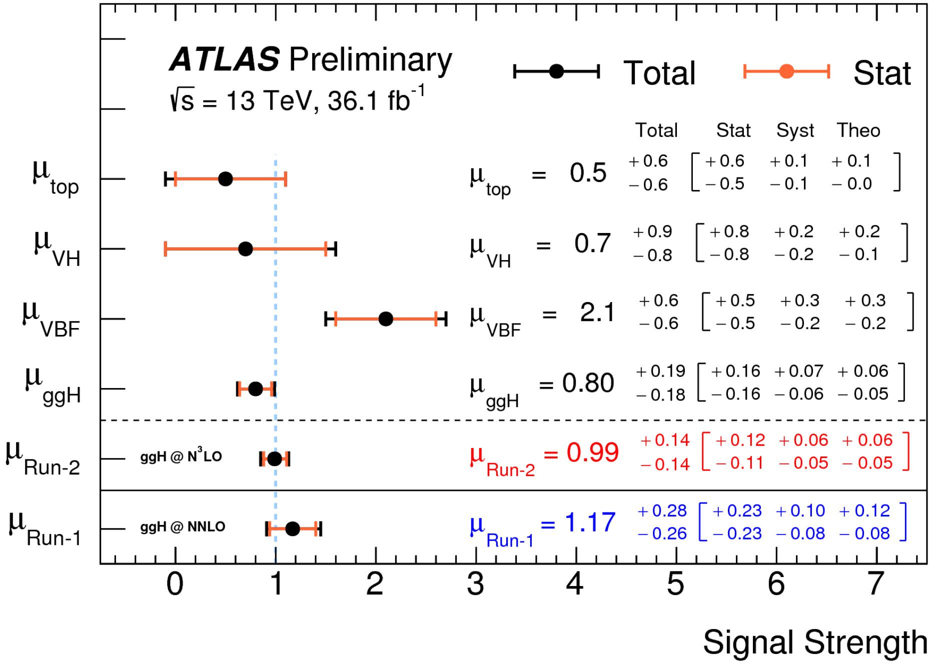
Note that (as far as I know) there is no such analysis in →HV final state.

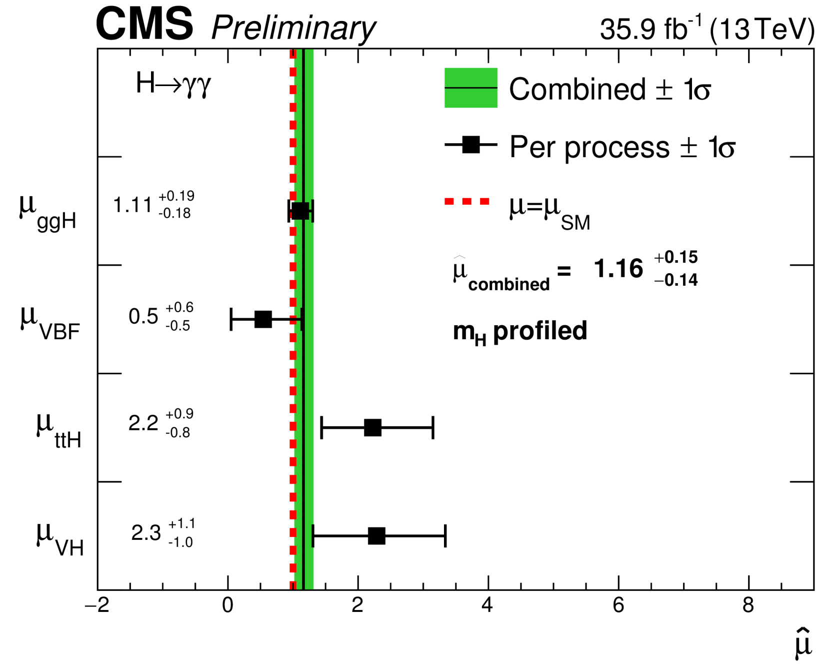
CMS: performed WZ VBF leptonic search but with less 15.2fb-1 (CMS-HIG-16-027)

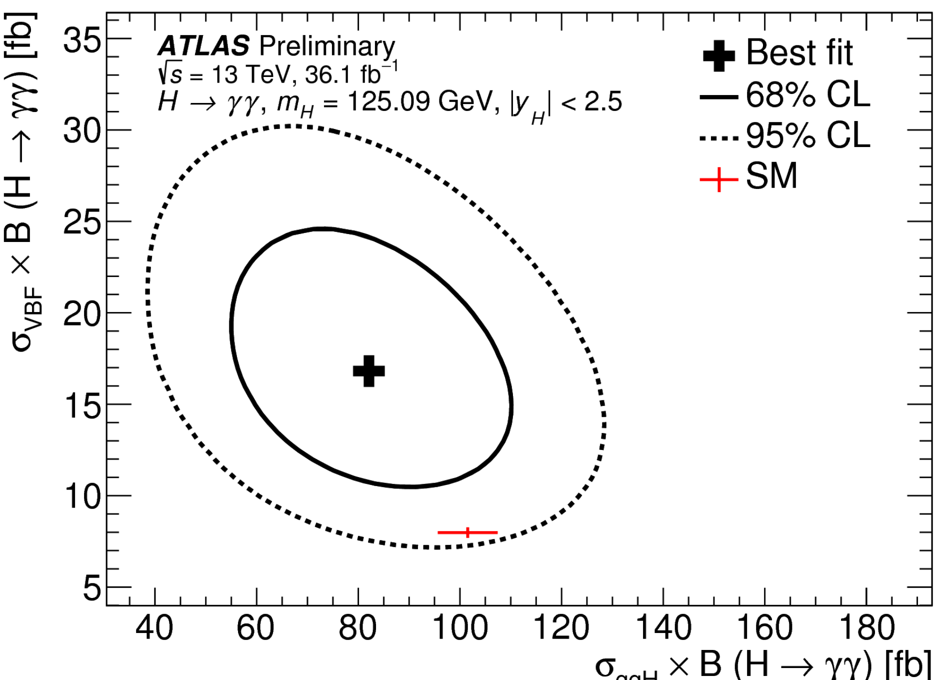


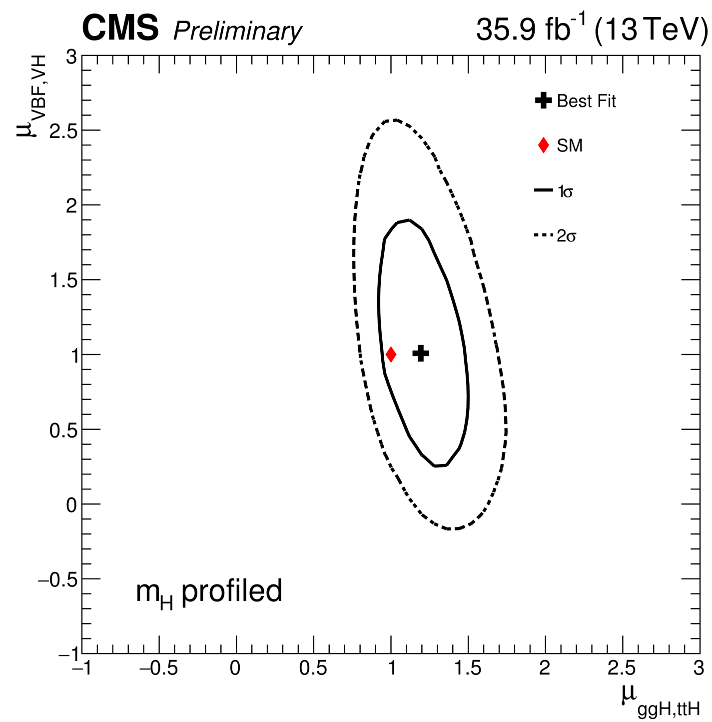


Run 2: VBF production

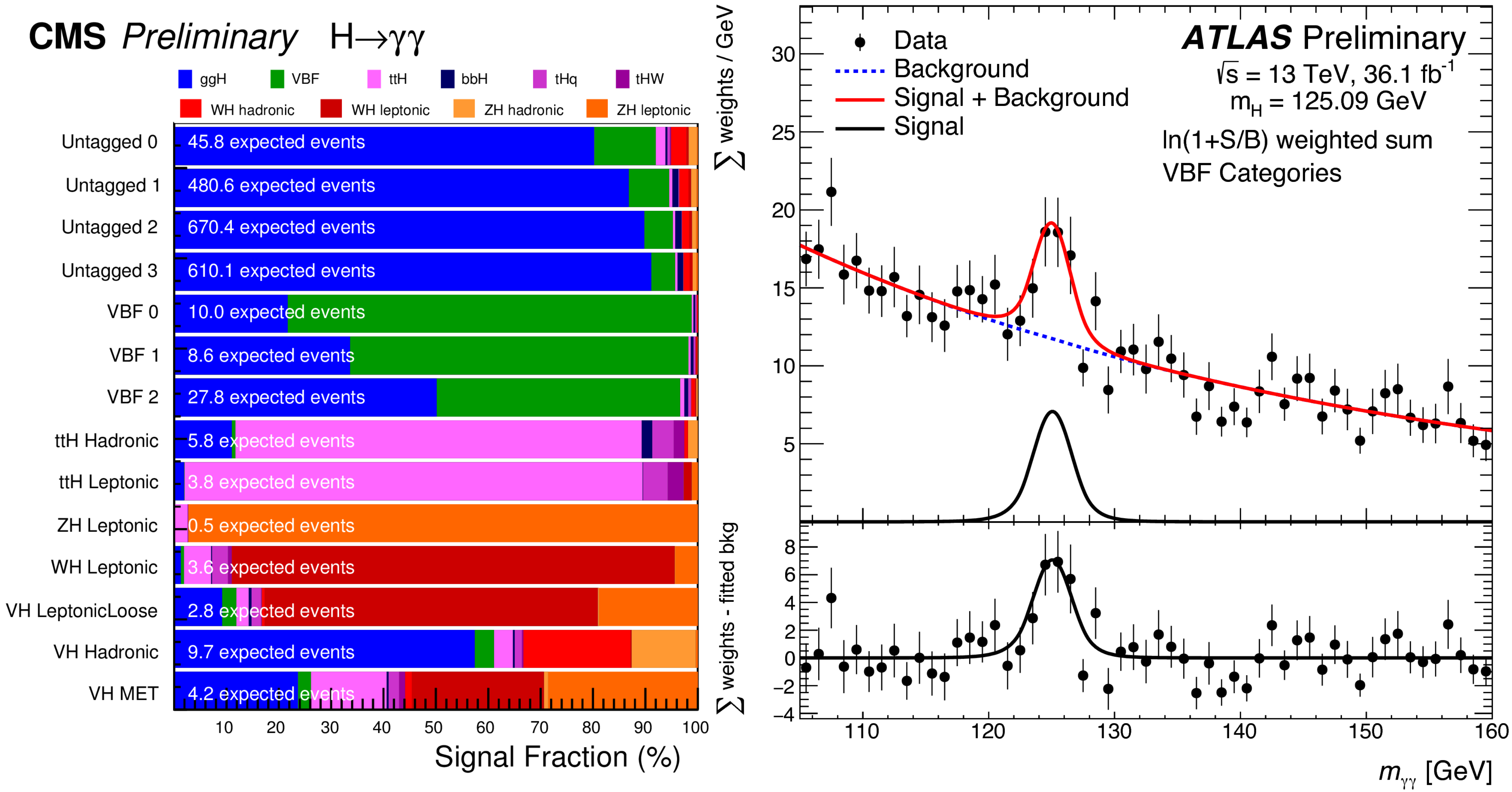




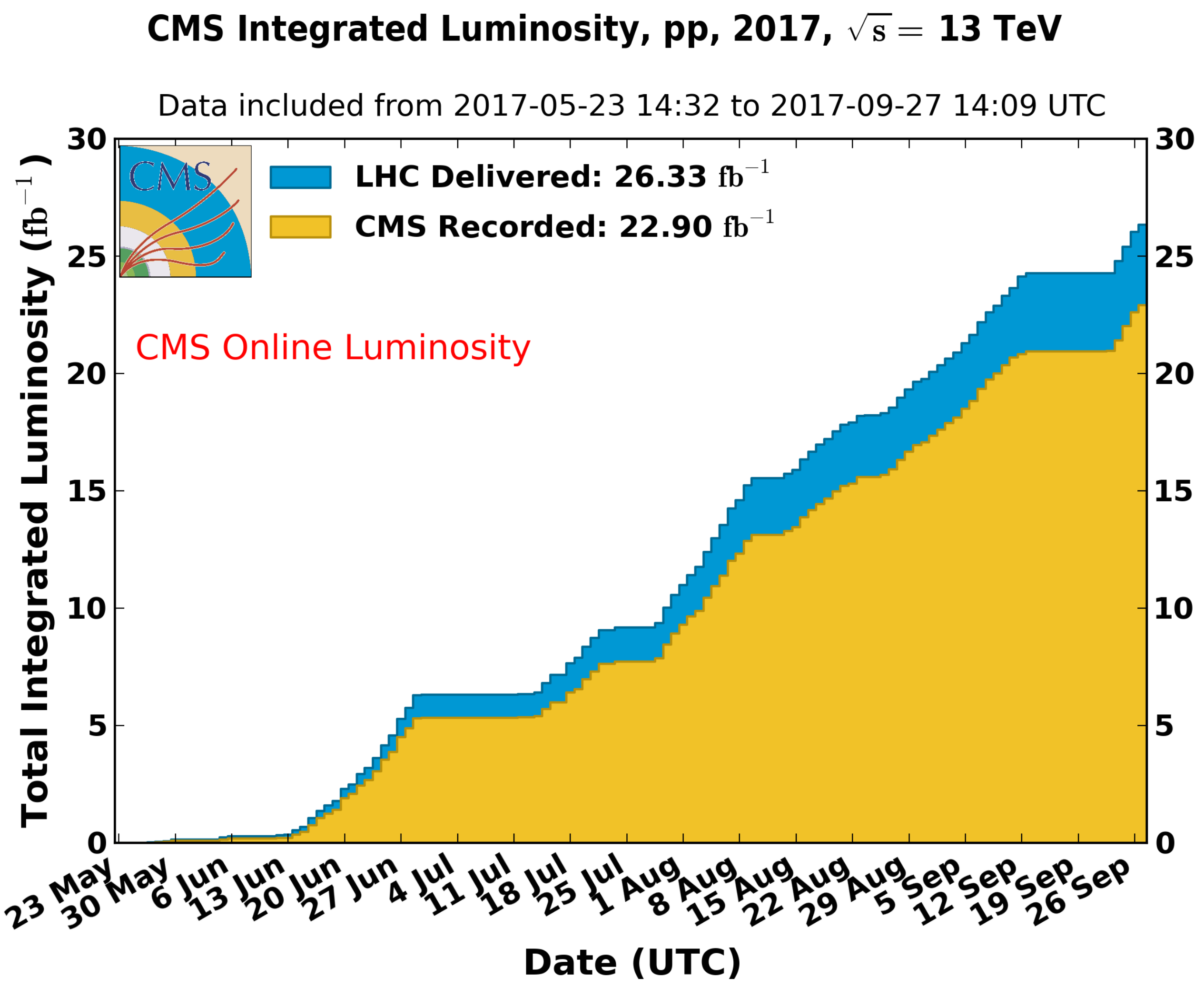




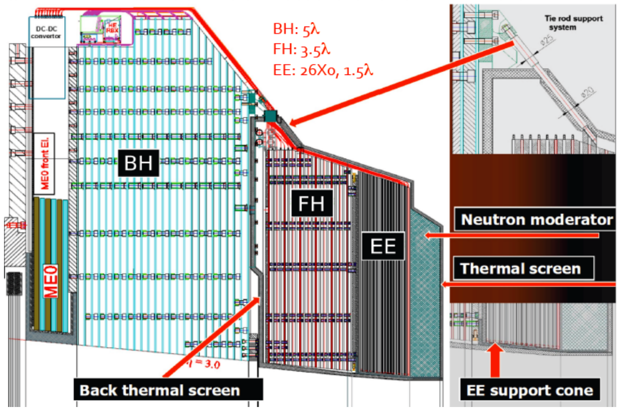
VBF Higgs signal yield



Epilogue: new data arrived!



The future (Phase 2, 2025): High Granularity Calorimeter

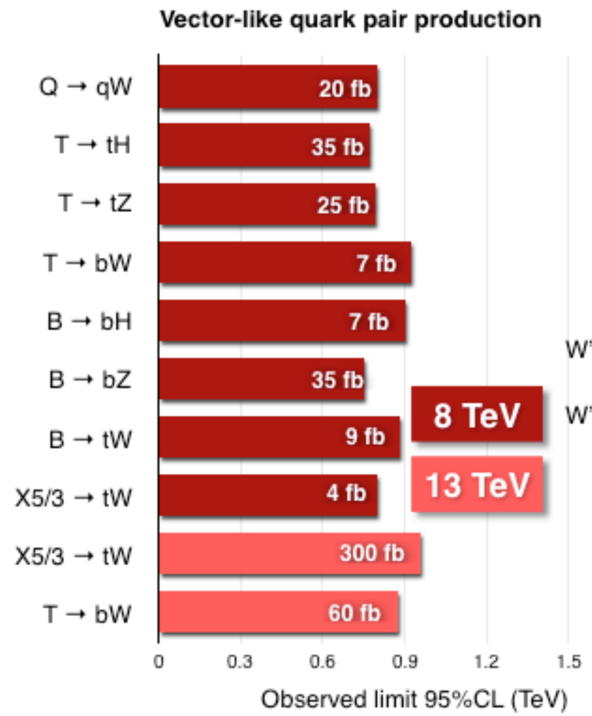


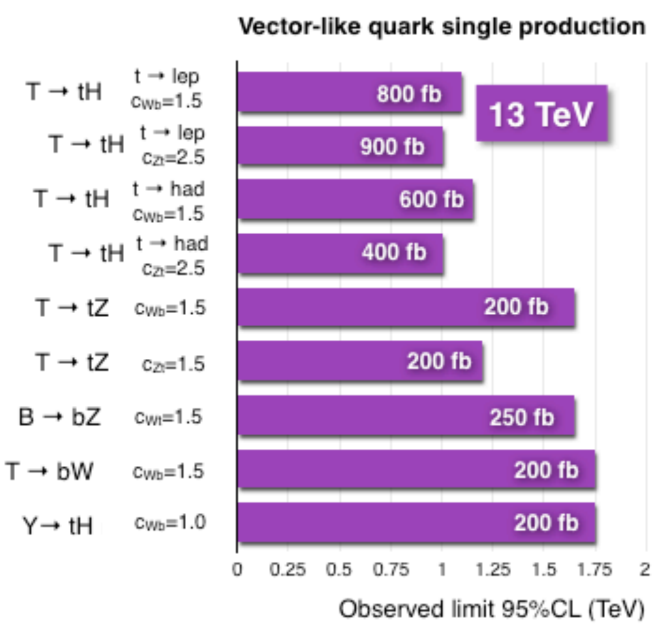
Taiwanese Investment:

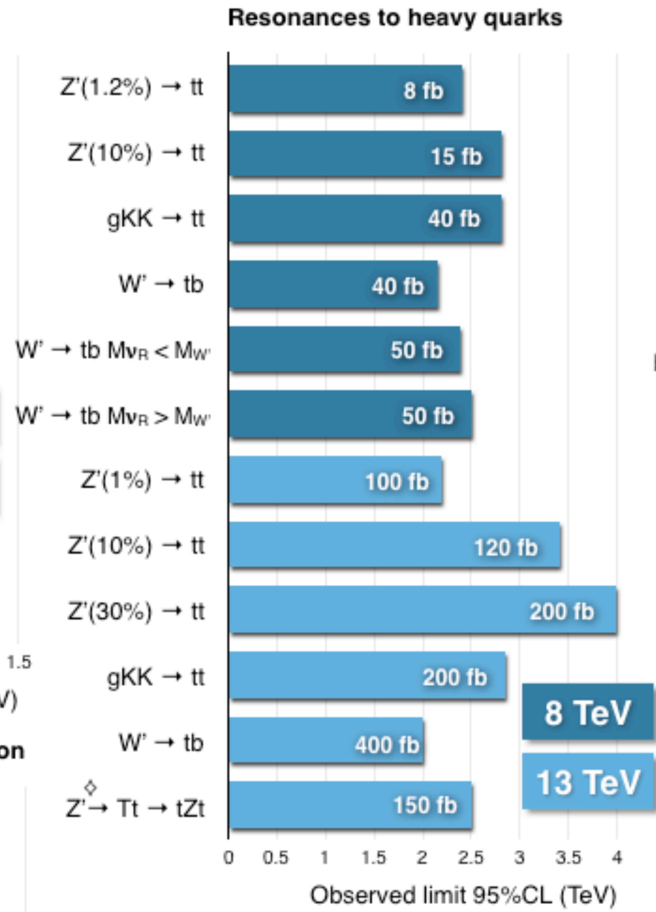
- R&D, TestBeams
- Module Construction
- EM/Jet Calibration/ID
- Physics (e.g. VBF)

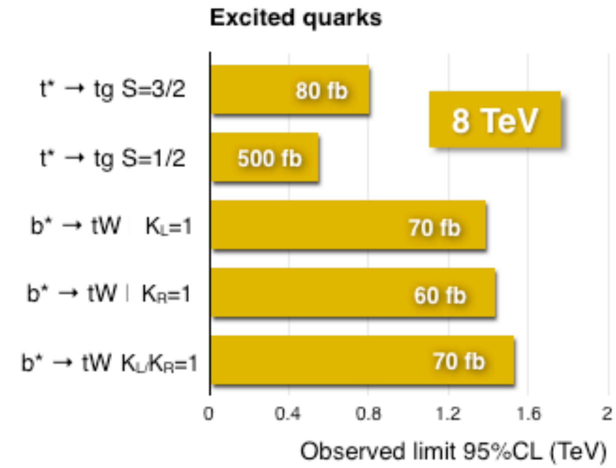
Backup

Summary: B2G results from CMS

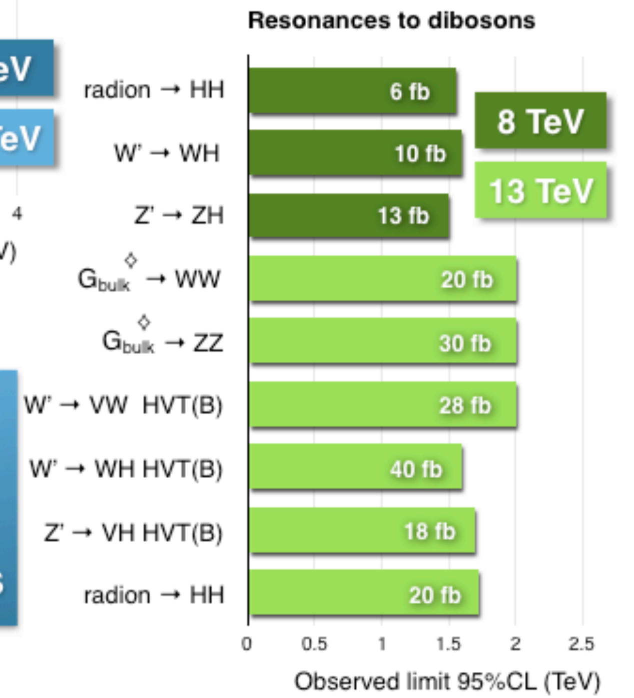








B2G
new physics
searches with
heavy SM particles



◊model-independent

Phenomenological Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a}$$

$$+\, i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$

$$+\, \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW}\, \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c$$

$$V = (V^+, V^-, V^0)$$

Weakly coupled model

Strongly coupled model

g_V typical strength of V interactions

$g_V \sim g \sim 1$

$1 < g_V \leq 4\pi$

c_i dimensionless coefficients

$c_H \sim -g^2/g_V^2$ and $c_F \sim 1$

$c_H \sim c_F \sim 1$

Andrea Thamm

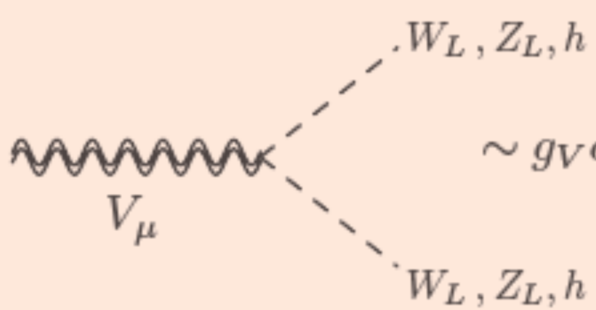
Phenomenological Lagrangian

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \qquad V = (V^+, V^-, V^0)$$

$$+ i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$

$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW}\, \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c$$

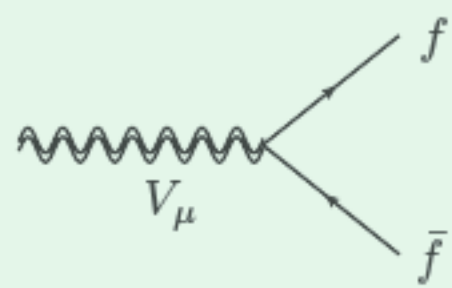
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

$$J_F^{\mu\,a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$$

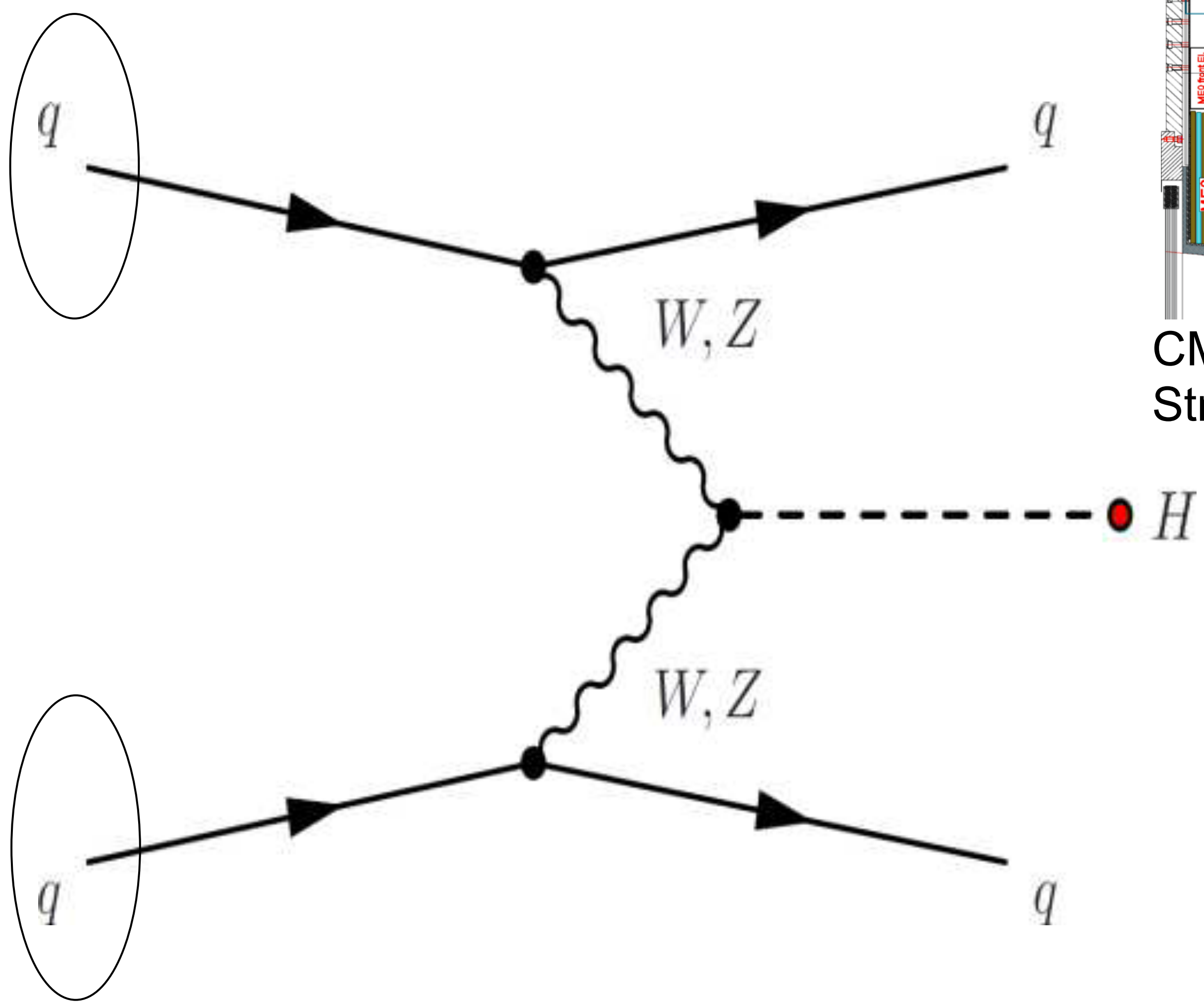


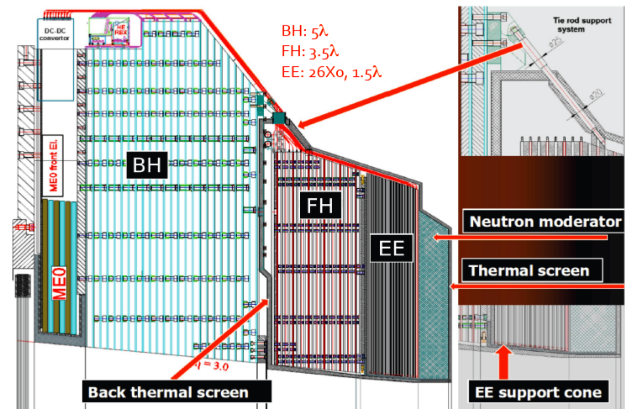
$\sim \frac{g^2}{g_V} c_F$

$$c_F V \cdot J_F \;\rightarrow\; c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$$

Andrea Thamm

How about VBF?





CMS HGCal to tag these jets
Strong Taiwanese involvement

What if an excess (or deficit) is observed in the data?

Interest in models in which heavy new states are VBF produced and decay to final states including the 125GeV Higgs

Run 1 combination

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Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

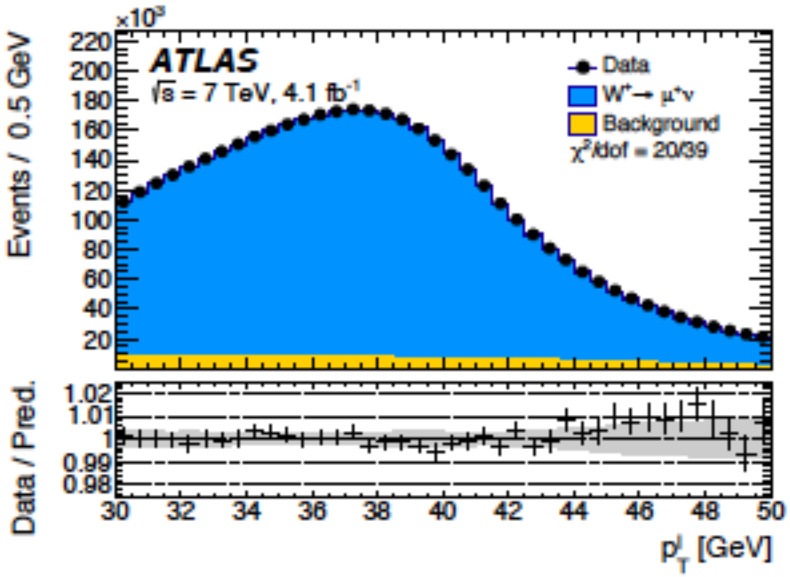
- Combination of ATLAS and CMS measurements leads to a higher than 5 sigma observation of the VBF production process and the $H \to \tau\tau$ decay channel.

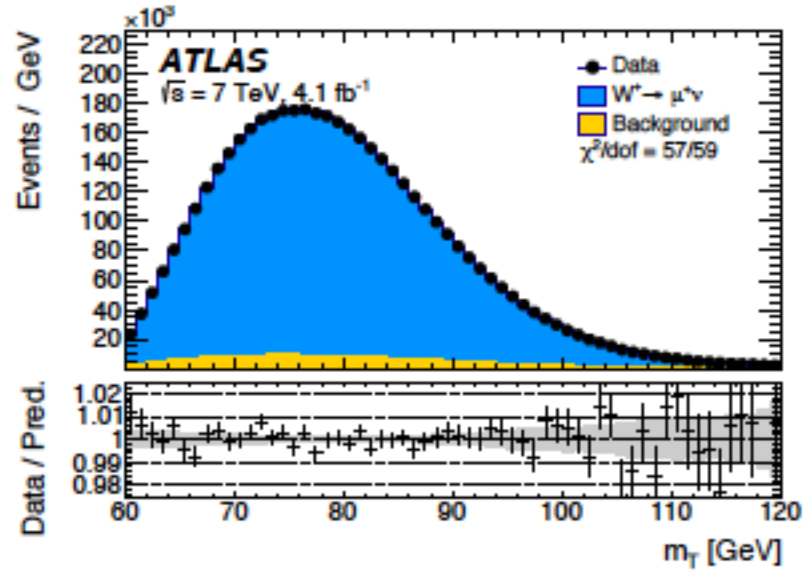
LHC future

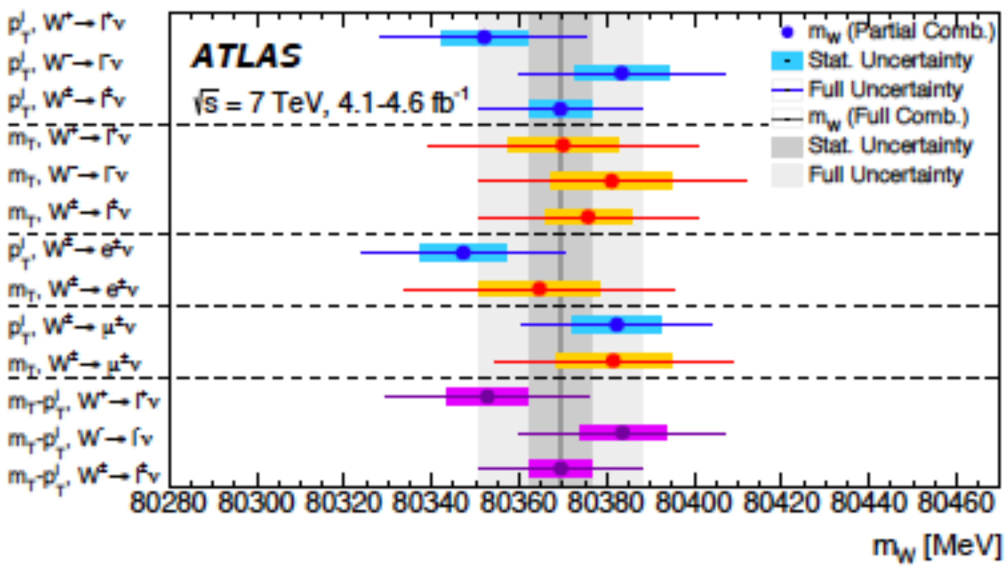
- LHC Run 2 will continue in 2017/2018 at 13 TeV
- Prospects for 2017
  - Changed a magnet in sector 1—2 during EYETS
  - SPS new internal beam dump (limit on no. bunches)
  - Aim for 1.7 to 1.8 10^{34} $cm^{-1}s^{-1}$ (inner triplet cooling limit?)
  - 5 TeV pp reference run to be scheduled (2017/2018)
- Goal for 2017 and 2018
  - 45/fb per year with ~50% availability of stable beams
- LS2 – injector upgrade
  - Total of 300 /fb before LS3
- LS3 – HL-LHC "phase 2 upgrades"
  - Aiming for ten times more luminosity

New W mass measurement

- Closure tests; comparison of W+,W-,e,μ, p_T fit or m_T fit







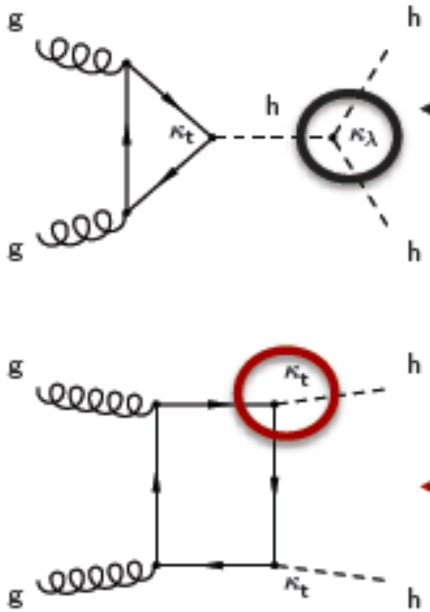
Combined result:

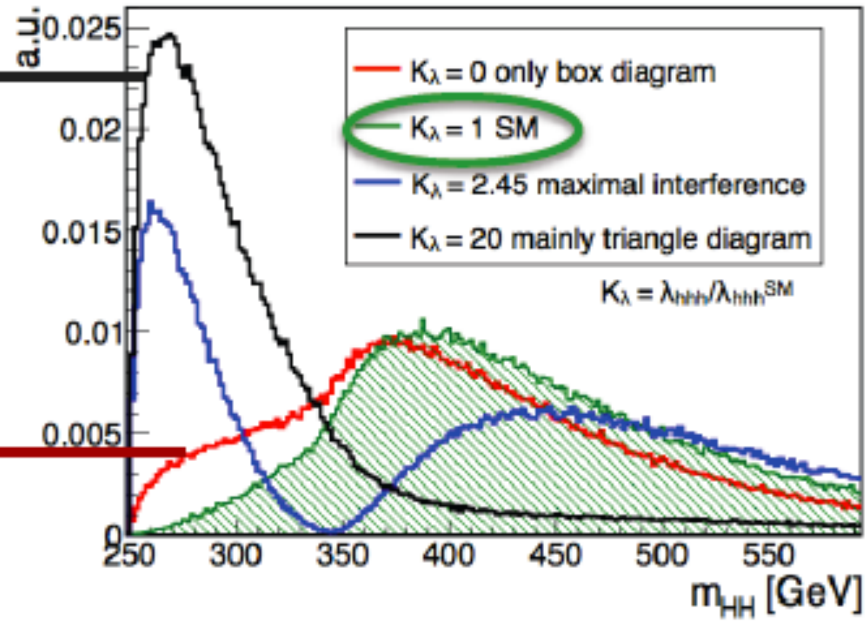
m_W= 80370±7(stat) ±11(exp)±14(mod) MeV

m_W= 80370±19 MeV

(CDF ±19 MeV, D0 ±23 MeV)

HH production





- SM: κ_t and κ_λ induced diagrams interfere destructively, σ_{SM} small (~33.5 fb)
  - sensitive to the anomalous couplings κ_t , κ_λ , c_2, c_{2g}, c_g ⇨ non-resonant spectrum testing anomalous couplings
- Predicted by many theories: X->HH ⇨ resonant search

$\sigma_{HH}/\sigma_{SM} < 28$ (25 exp)

Higgs Decay Channels

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

H→gg, cc, Zγ not included in the measurement but their contribution is included in the total width.

Strengths/Couplings

Signal Strengths

for a specific process $i \to H \to f$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{B^f}{(B^f)_{SM}}$$

$$\mu_i^f = \mu_i \cdot \mu^f$$

Coupling Modifiers

$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma_{SM}^j$$

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