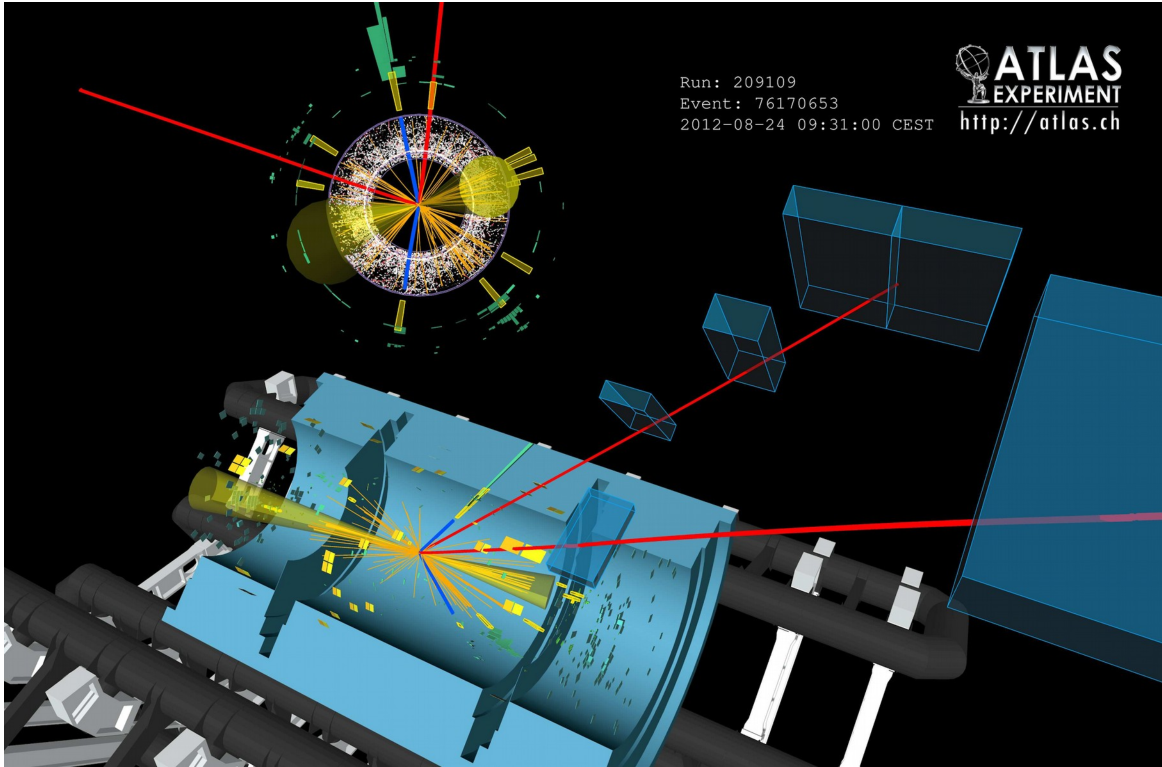
Testing the Standard Model of Elementary Particle Physics II

Third lecture

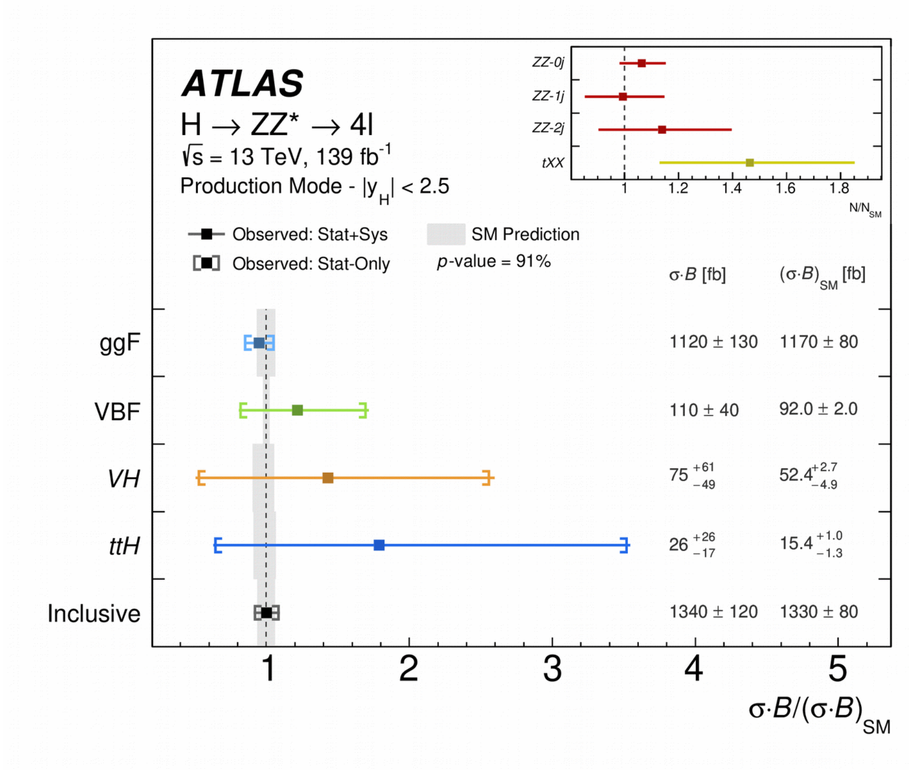
7th May 2020

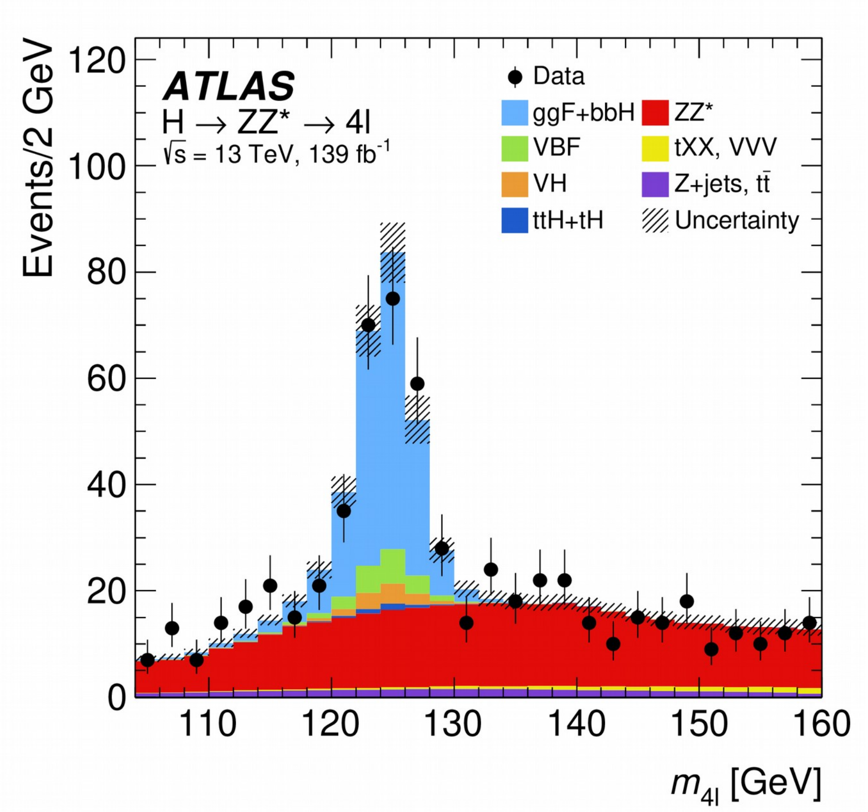
$H \to ZZ^* \to llll$

- One of the “golden channel”
  - Very clear signature in the detector
    - Low background contributions
    - Good mass resolution
- Analysis is based on finding two pairs of isolated leptons with same flavor and opposite electric charges



H → ZZ* → llll


ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb⁻¹
Production Mode - |y_H| < 2.5
ZZ-0j
ZZ-1j
ZZ-2j
tXX
1
1.2
1.4
1.6
1.8
N/N_SM
Observed: Stat+Sys
Observed: Stat-Only
SM Prediction
p-value = 91%
σ·B [fb]
(σ·B)_SM [fb]
ggF
1120 ± 130
1170 ± 80
VBF
110 ± 40
92.0 ± 2.0
VH
75 +61 −49
52.4 +2.7 −4.9
ttH
26 +26 −17
15.4 +1.0 −1.3
Inclusive
1340 ± 120
1330 ± 80
1
2
3
4
5
σ·B/(σ·B)_SM

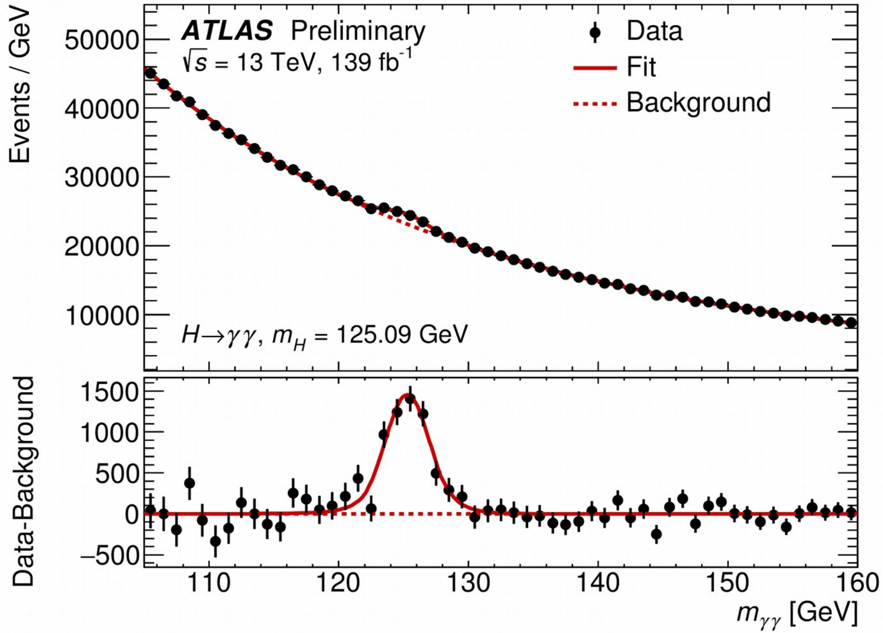

Events/2 GeV
120
100
80
60
40
20
0
ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb⁻¹
Data
ggF+bbH
ZZ*
VBF
tXX, VVV
VH
Z+jets, tt̄
ttH+tH
Uncertainty
110
120
130
140
150
160
m_4l [GeV]

H → yy

- The inclusive fiducial cross section times the H→γγ branching ratio is measured to be:

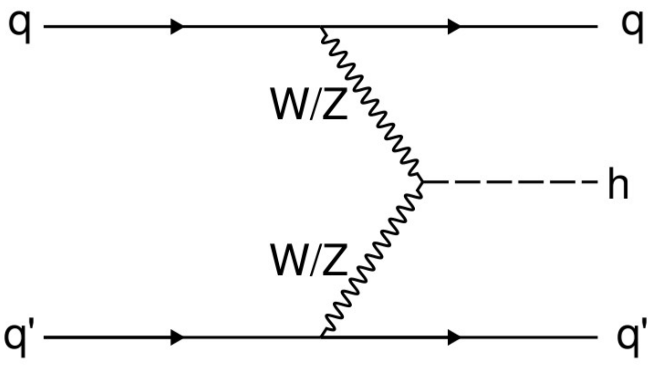
$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 0.3\,(\text{theo.})\,\text{fb}$$

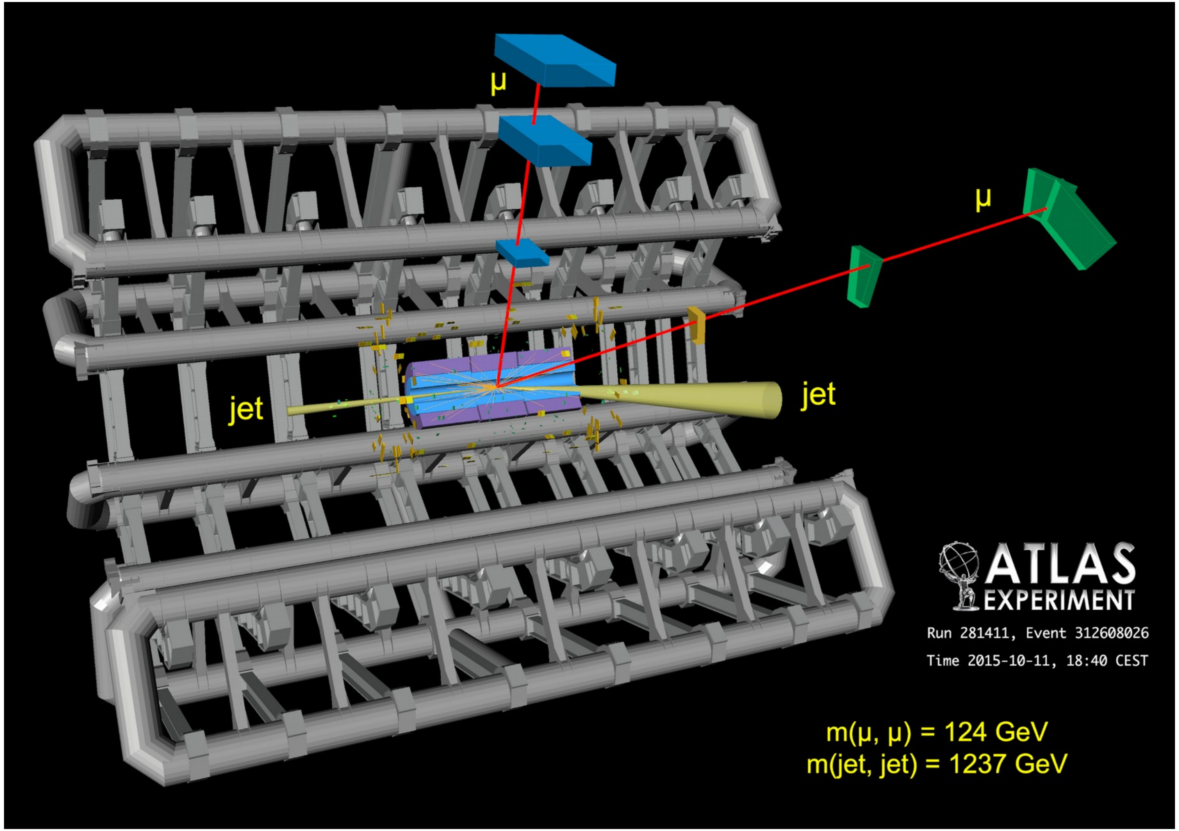
which is within one standard deviation of the SM prediction of **63.6 ± 3.3fb**



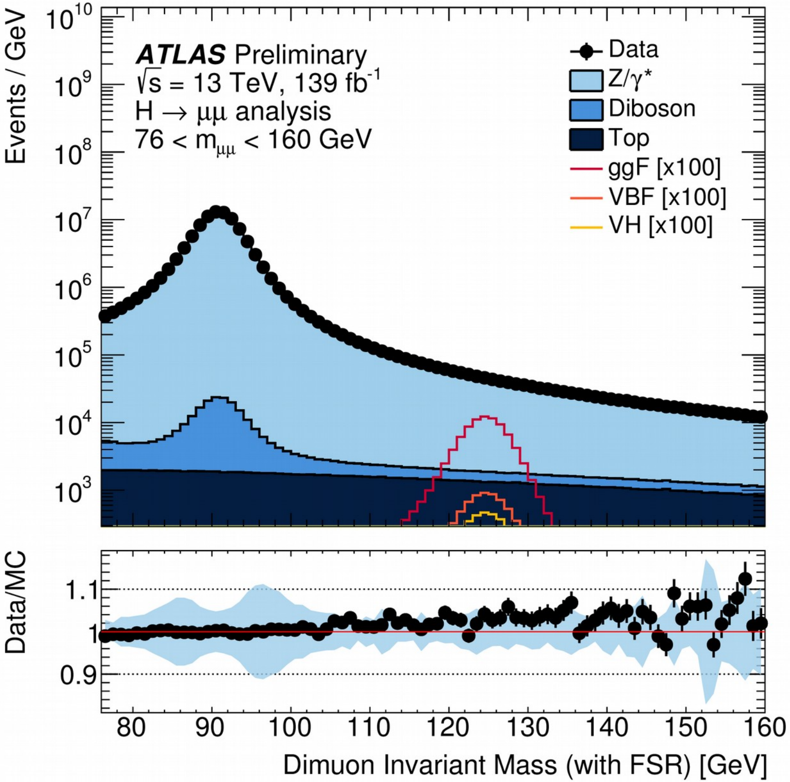
$H \to \mu\mu$

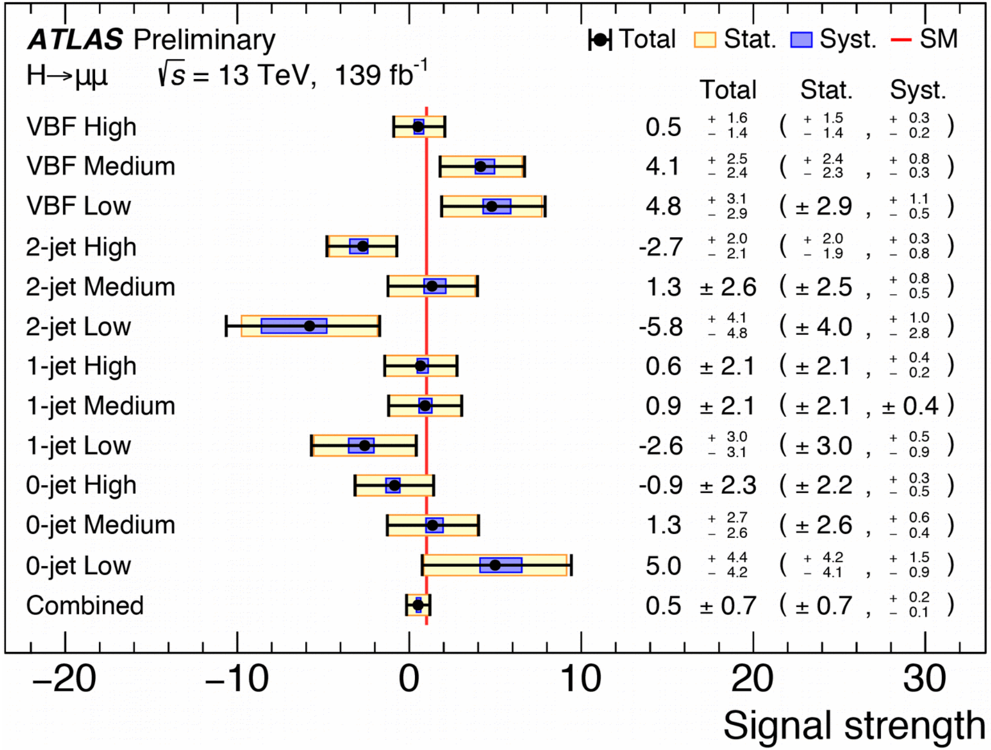
- **Probe Higgs couplings to 2nd generation fermions**
    - ○ Low BR
- Here: Higgs production in VBF channel





H→ μμ

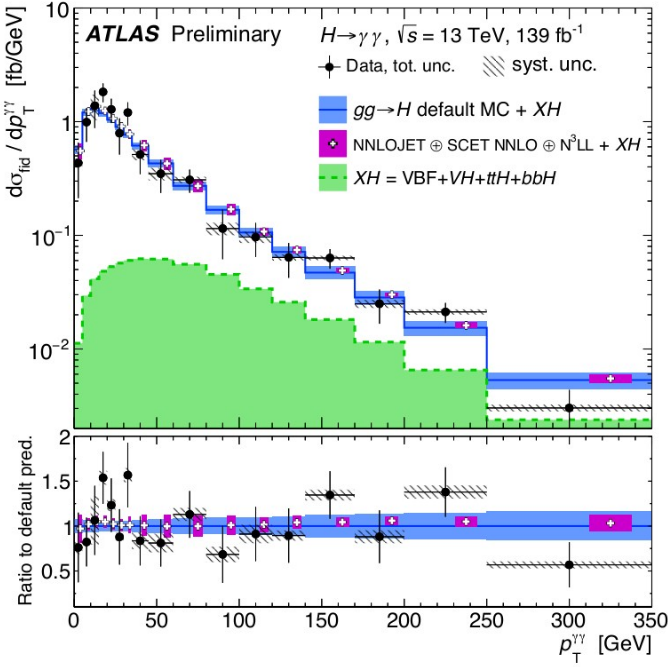

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
H → μμ analysis
76 < $m_{\mu\mu}$ < 160 GeV
Data
Z/γ*
Diboson
Top
ggF [x100]
VBF [x100]
VH [x100]
Events / GeV
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
Data/MC
1.1
1
0.9
80
90
100
110
120
130
140
150
160
Dimuon Invariant Mass (with FSR) [GeV]


ATLAS Preliminary
H→μμ $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Total
Stat.
Syst.
SM
Total Stat. Syst.
VBF High 0.5 $^{+1.6}_{-1.4}$ ($^{+1.5}_{-1.4}$, $^{+0.3}_{-0.2}$)
VBF Medium 4.1 $^{+2.5}_{-2.4}$ ($^{+2.4}_{-2.3}$, $^{+0.8}_{-0.3}$)
VBF Low 4.8 $^{+3.1}_{-2.9}$ (± 2.9 , $^{+1.1}_{-0.5}$)
2-jet High -2.7 $^{+2.0}_{-2.1}$ ($^{+2.0}_{-1.9}$, $^{+0.3}_{-0.8}$)
2-jet Medium 1.3 ± 2.6 (± 2.5 , $^{+0.8}_{-0.5}$)
2-jet Low -5.8 $^{+4.1}_{-4.8}$ (± 4.0 , $^{+1.0}_{-2.8}$)
1-jet High 0.6 ± 2.1 (± 2.1 , $^{+0.4}_{-0.2}$)
1-jet Medium 0.9 ± 2.1 (± 2.1 , ± 0.4)
1-jet Low -2.6 $^{+3.0}_{-3.1}$ (± 3.0 , $^{+0.5}_{-0.9}$)
0-jet High -0.9 ± 2.3 (± 2.2 , $^{+0.3}_{-0.5}$)
0-jet Medium 1.3 $^{+2.7}_{-2.6}$ (± 2.6 , $^{+0.6}_{-0.4}$)
0-jet Low 5.0 $^{+4.4}_{-4.2}$ ($^{+4.2}_{-4.1}$, $^{+1.5}_{-0.9}$)
Combined 0.5 ± 0.7 (± 0.7 , $^{+0.2}_{-0.1}$)
−20
−10
0
10
20
30
Signal strength

Differential measurements

- With large statistics of full Run-II dataset, we can explore differential distribution
    - To isolate phase space regions that are particular sensitive to new physics effects
- Measurement of **differential** cross sections
    1. Measure number of Higgs signal events N^{signal} in i-th p_T^H bin (or of any other observable)
    2. Background subtraction
    3. **Unfolding:** Derive correction factor from MC information:

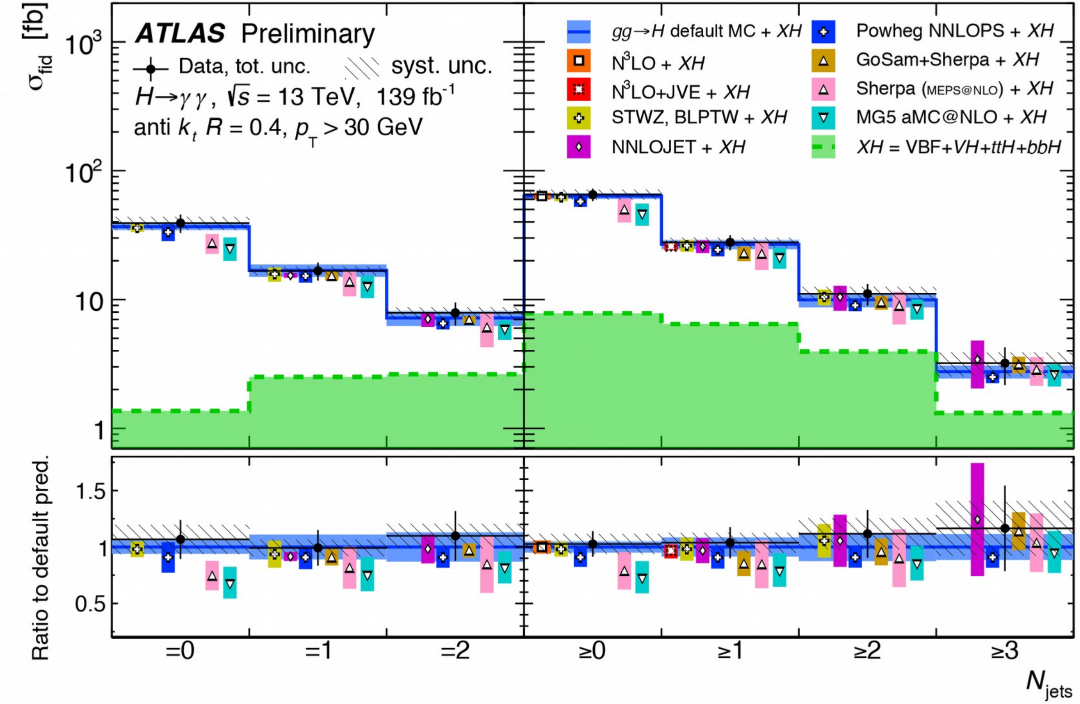
$$c_i = \frac{N^{\mathrm{reco}}}{N^{\mathrm{part}}}$$

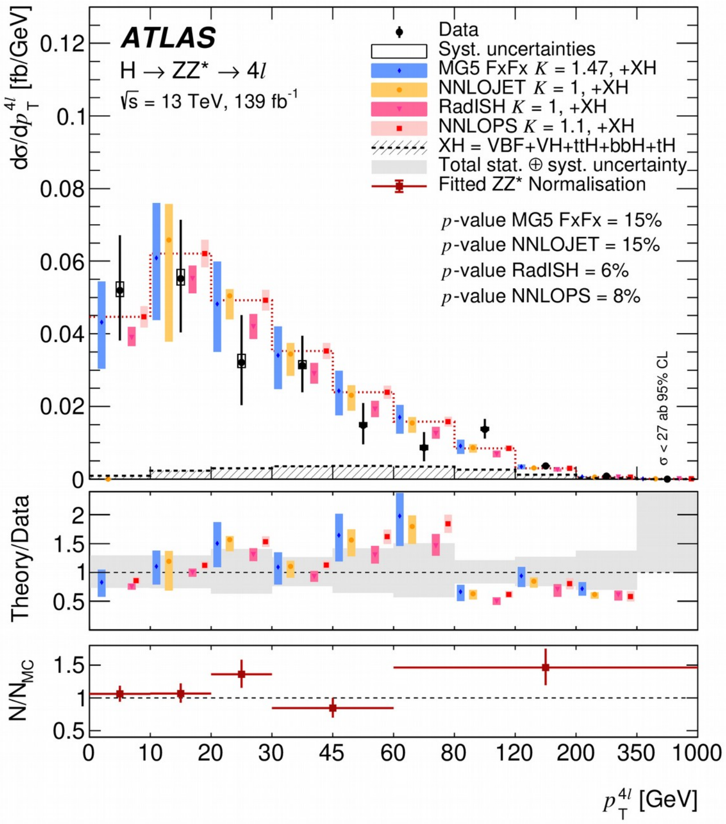


4. Calculate differential cross section:

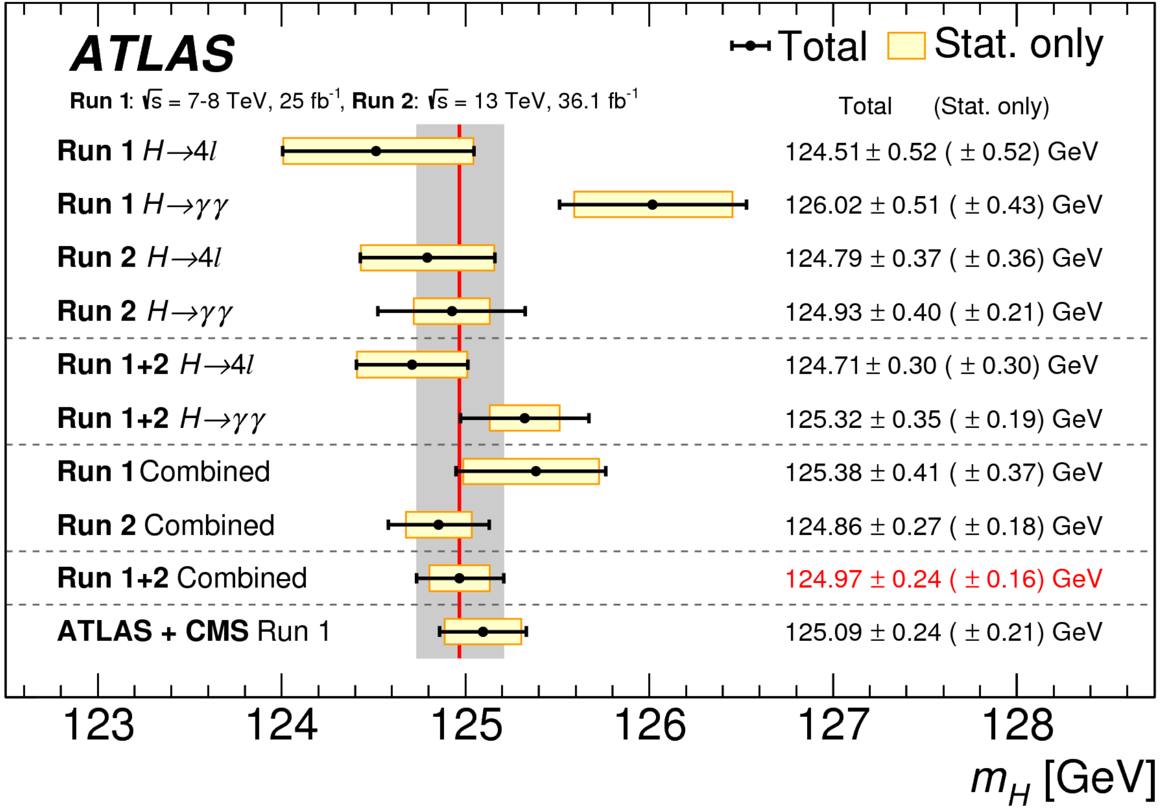
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N^{\mathrm{signal}}}{c_i \Delta p^H_{i,\mathrm{T}} \mathcal{L}_{\mathrm{int}}}$$

Differential measurements



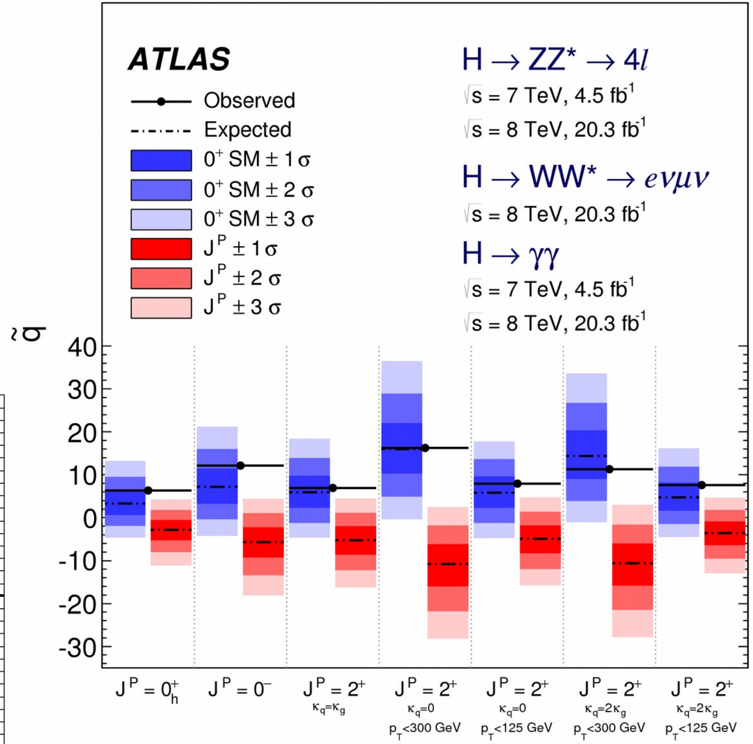


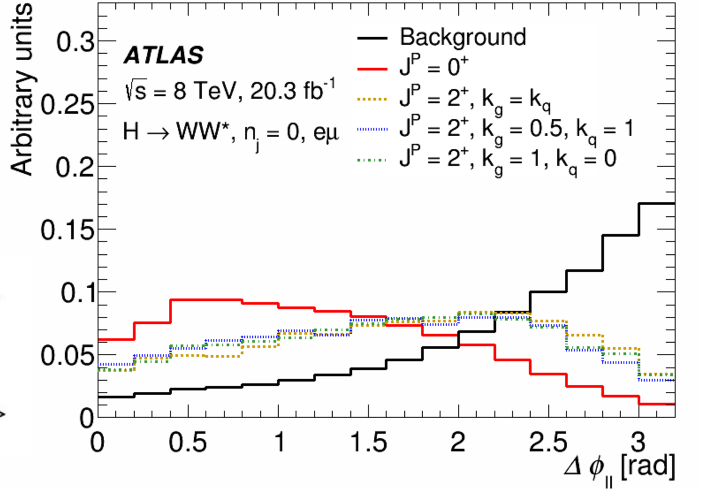
Higgs boson mass



Higgs CP/Spin

- Spin and CP state of Higgs-boson are determined probing angular distribution of decay products
  - Data hints very strongly to a Spin CP state of 0+
  - Alternative models are rejected with a CL of more than 99 .9 %
- Spin-1 hypothesis was theoretically excluded by observation of H->yy decay mode (**Yang's theorem**):
  - *A massive spin-1 particle cannot decay into a pair of identical massless spin-1 particles.*





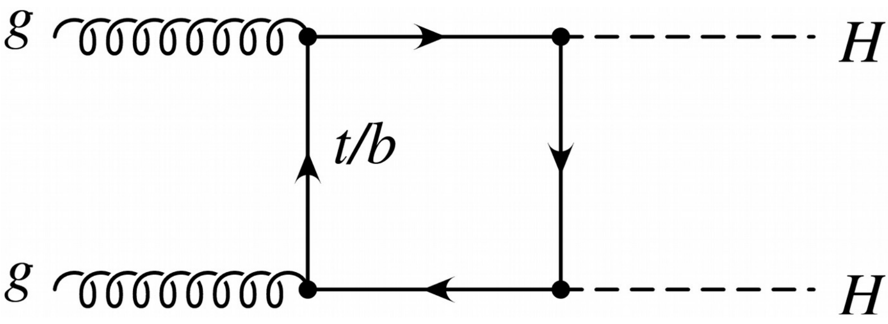
$$\mathrm{CP-even:}\quad CP|\Phi>=|\Phi>$$

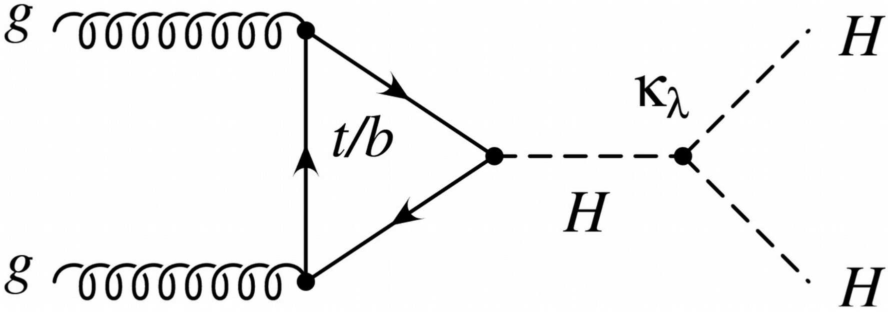
$$\mathrm{CP-odd:}\quad CP|\Phi>=-|\Phi>$$

Di-Higgs and Higgs self-coupling

- Higgs-mechanism of electroweak symmetry breaking and mass generation does not only predict the existence of a scalar boson, but also its self-coupling
- Probing the self-coupling of the Higgs boson allows us to verify the form of the Higgs potential
- Di-Higgs production mode is very sensitive to contribution from BSM physics

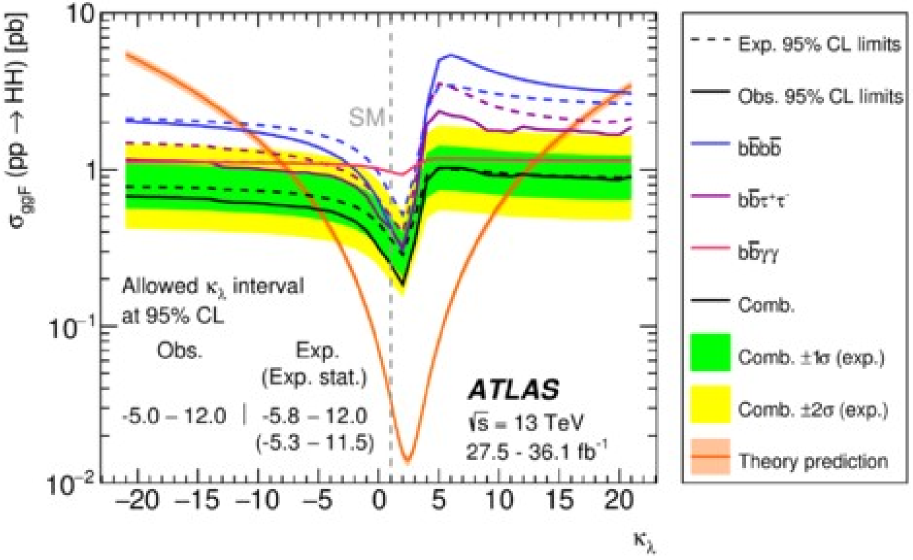
$$\sigma_{pp\rightarrow HH} = 33.5^{+2.4}_{-2.8}\ \mathrm{fb}$$

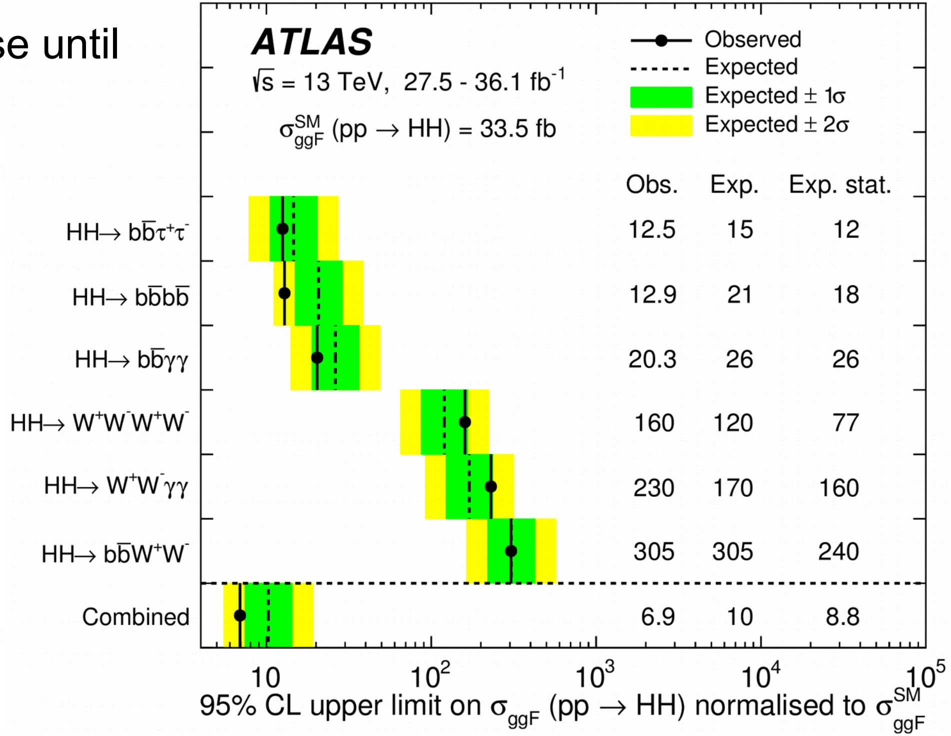




Di-Higgs and Higgs self-coupling

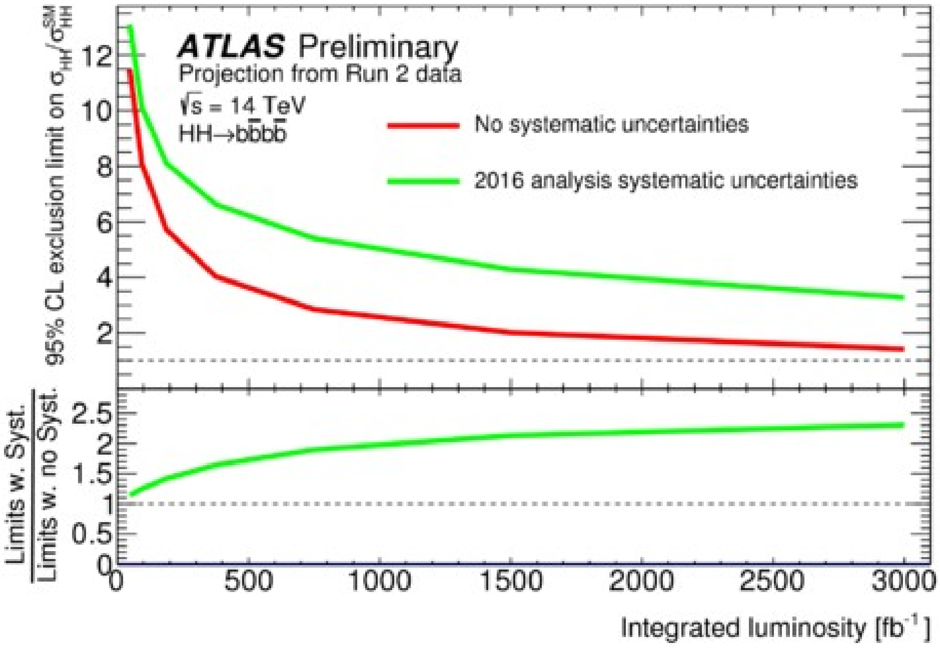
- So far, we can only set limits on the self-coupling strength and the Di-Higgs production cross section
- Will need the full data from HL-LHC phase until we can measure these observables

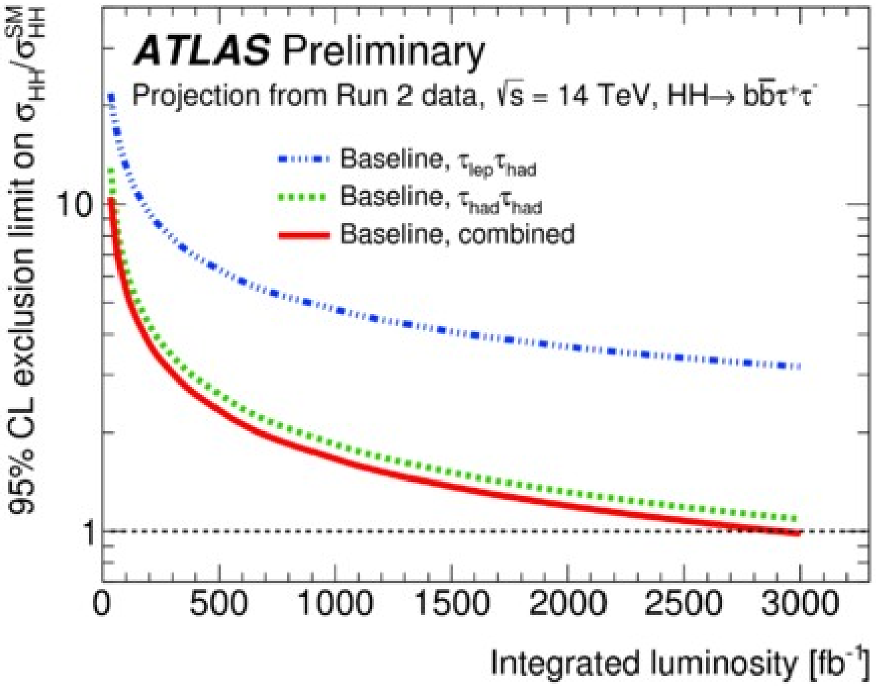




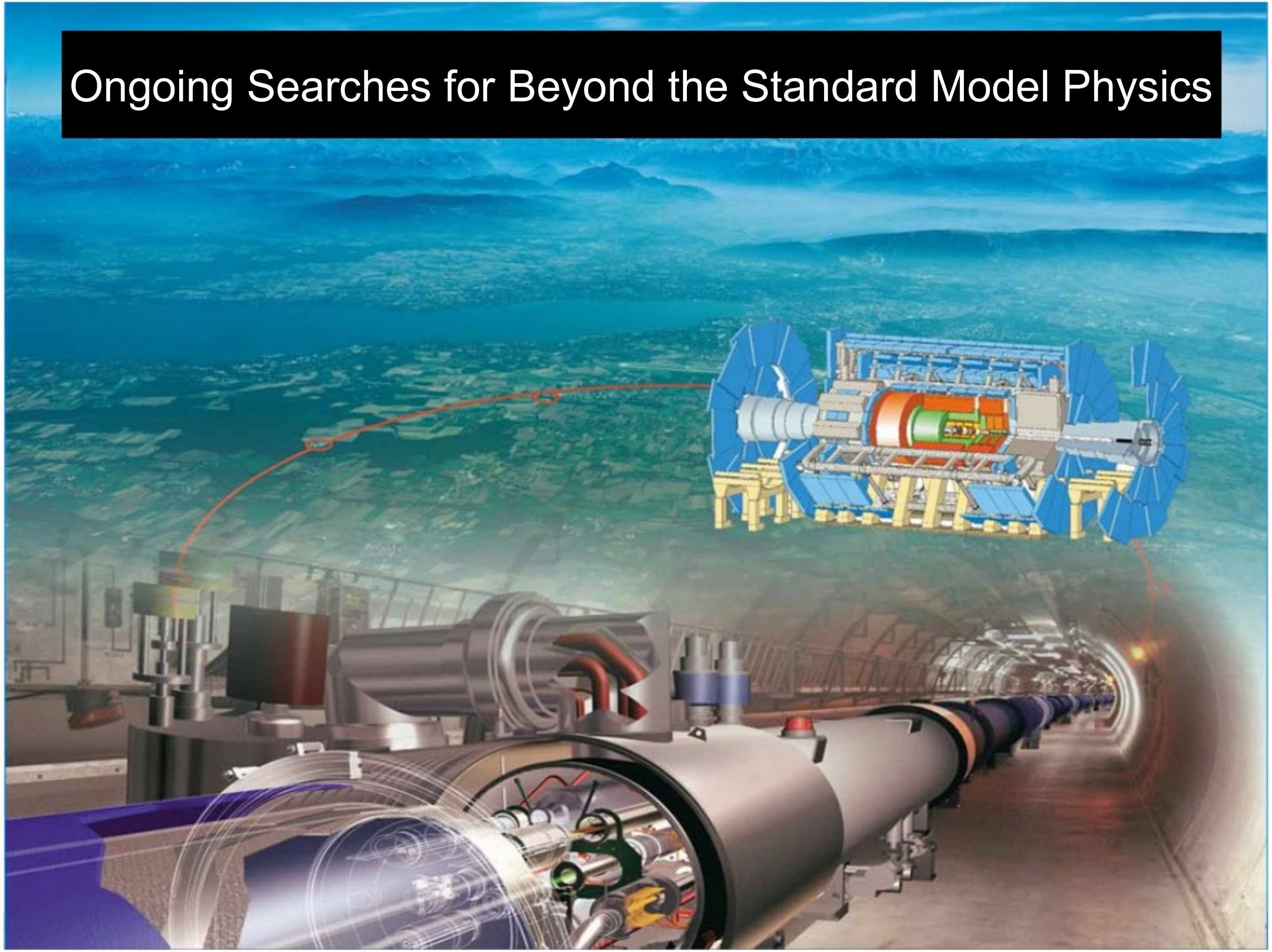
	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

Di-Higgs prospects





Ongoing Searches for Beyond the Standard Model Physics

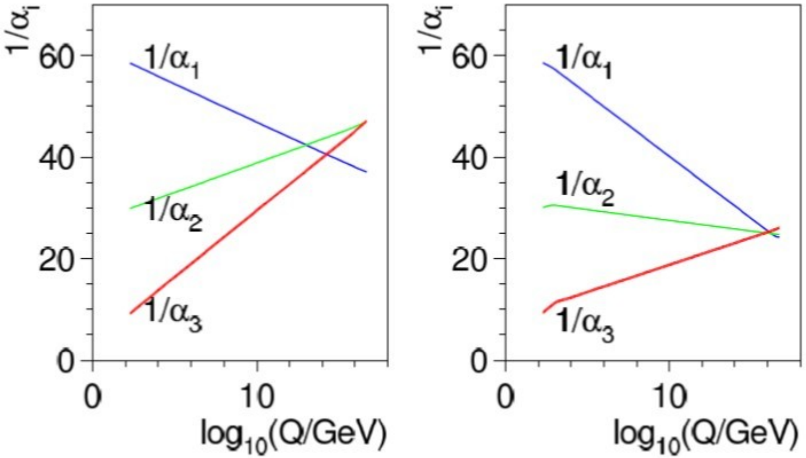


Search for Supersymmetry (SUSY)

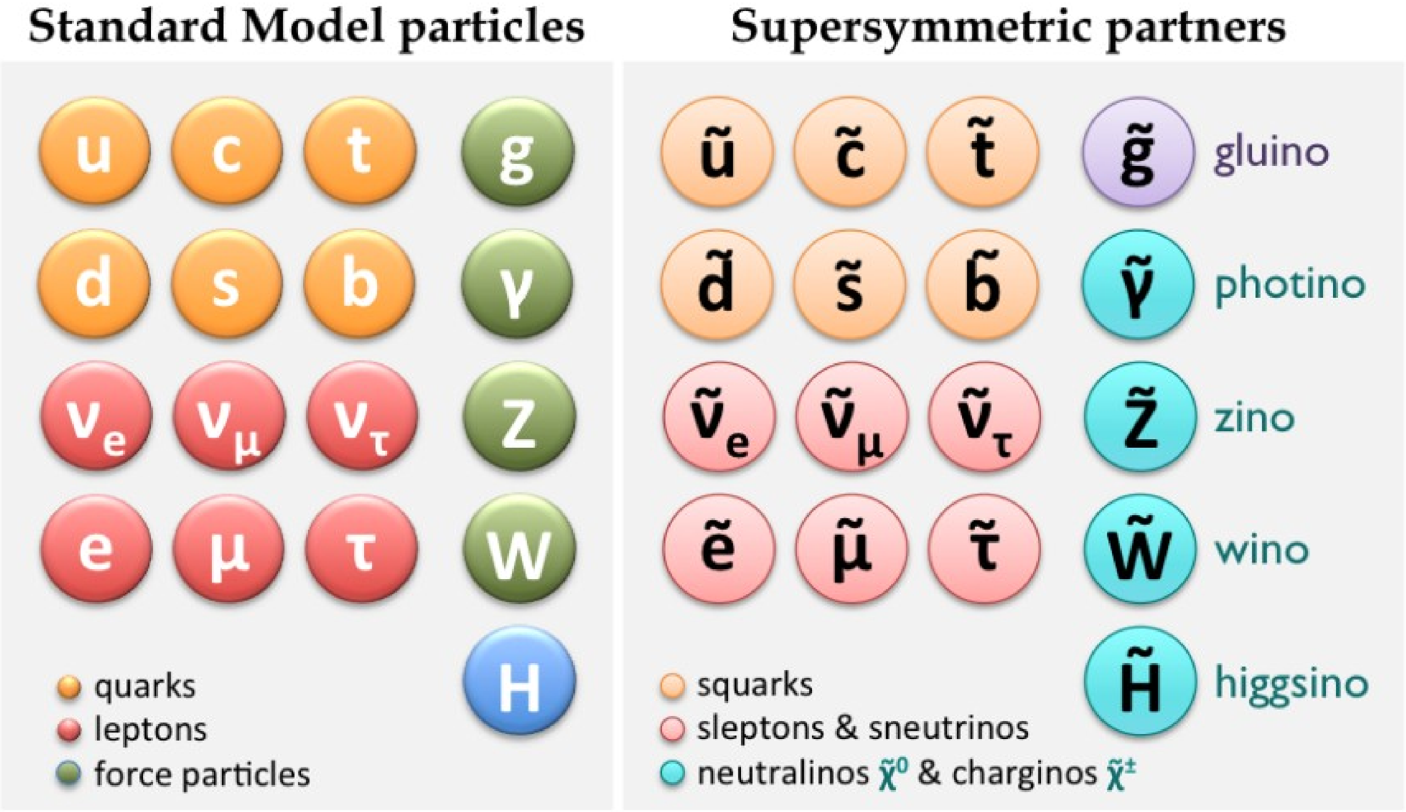
- **SUSY in a Nutshell:**
  - ○ **Symmetry between fermions and bosons**
    - ■ Each SM particle has a (heavy) SUSY partner particle with
  - ○ **Lightest SUSY particle (if neutral and stable) is Dark Matter candidate**
  - ○ Extension of scalar sector:
    - ■ 3 neutral and 2 charged Higgs-Bosons within the minimal supersymmetric extension of the SM (MSSM)
  - ○ Predicts unification of gauge couplings
  - ○ Local SUSY describes Gravitation
  - ○ **Introduces R-parity:**

$$P_R = (-1)^{3B+L+2s}$$

conserved in many SUSY scenarios

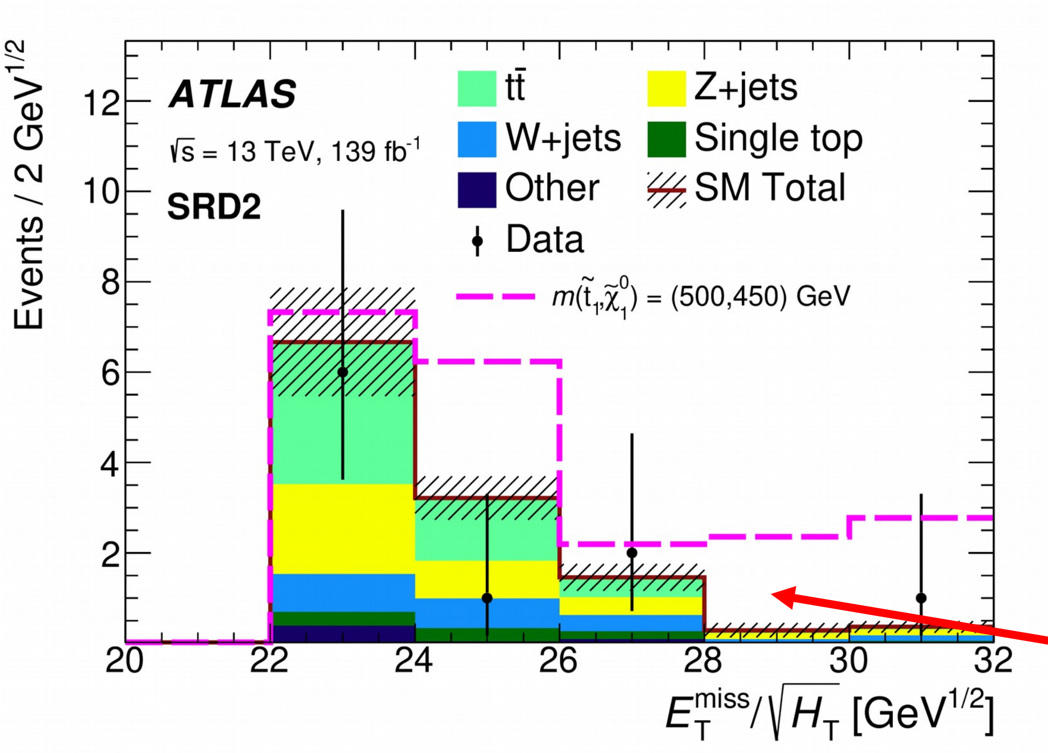


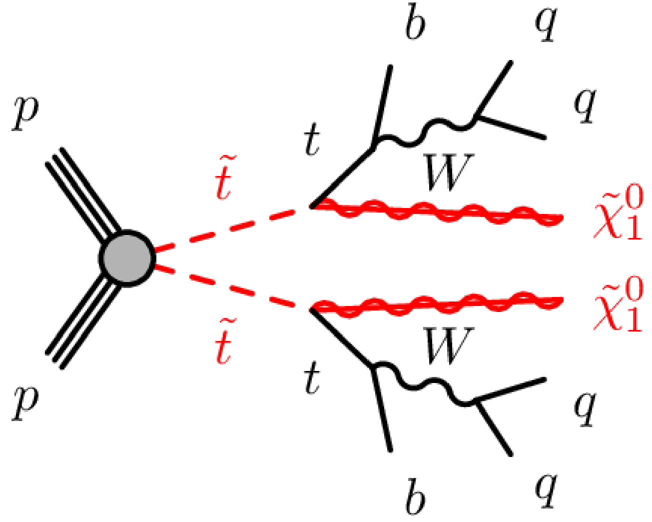
Search for Supersymmetry (SUSY)



Search for Supersymmetry (SUSY)

- **Search for stop quark pair production**





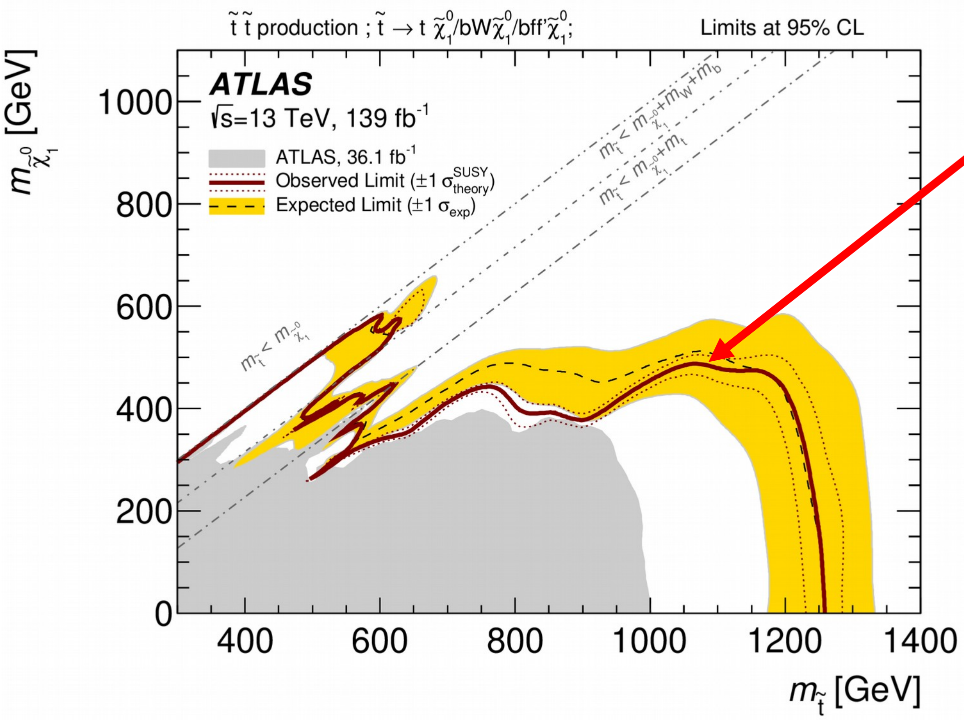
- **Search for multi-jet final state incl. large amount of missing E_T**

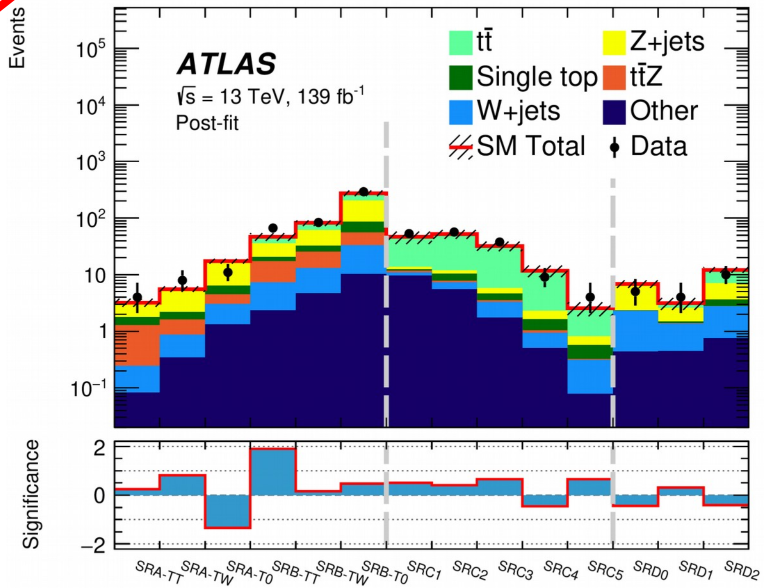
Probe phase space regions sensitive to contributions from SUSY signal

Search for Supersymmetry (SUSY)

- **Search for stop quark pair production**

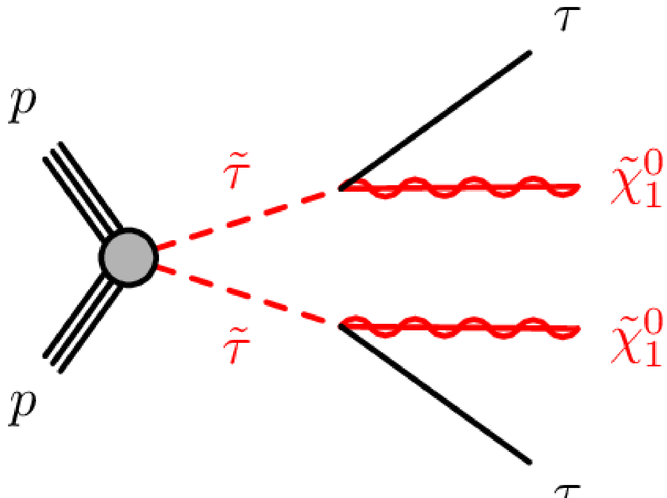
Exclude stop masses of ~ 1300 GeV for neutralino masses below 400 GeV

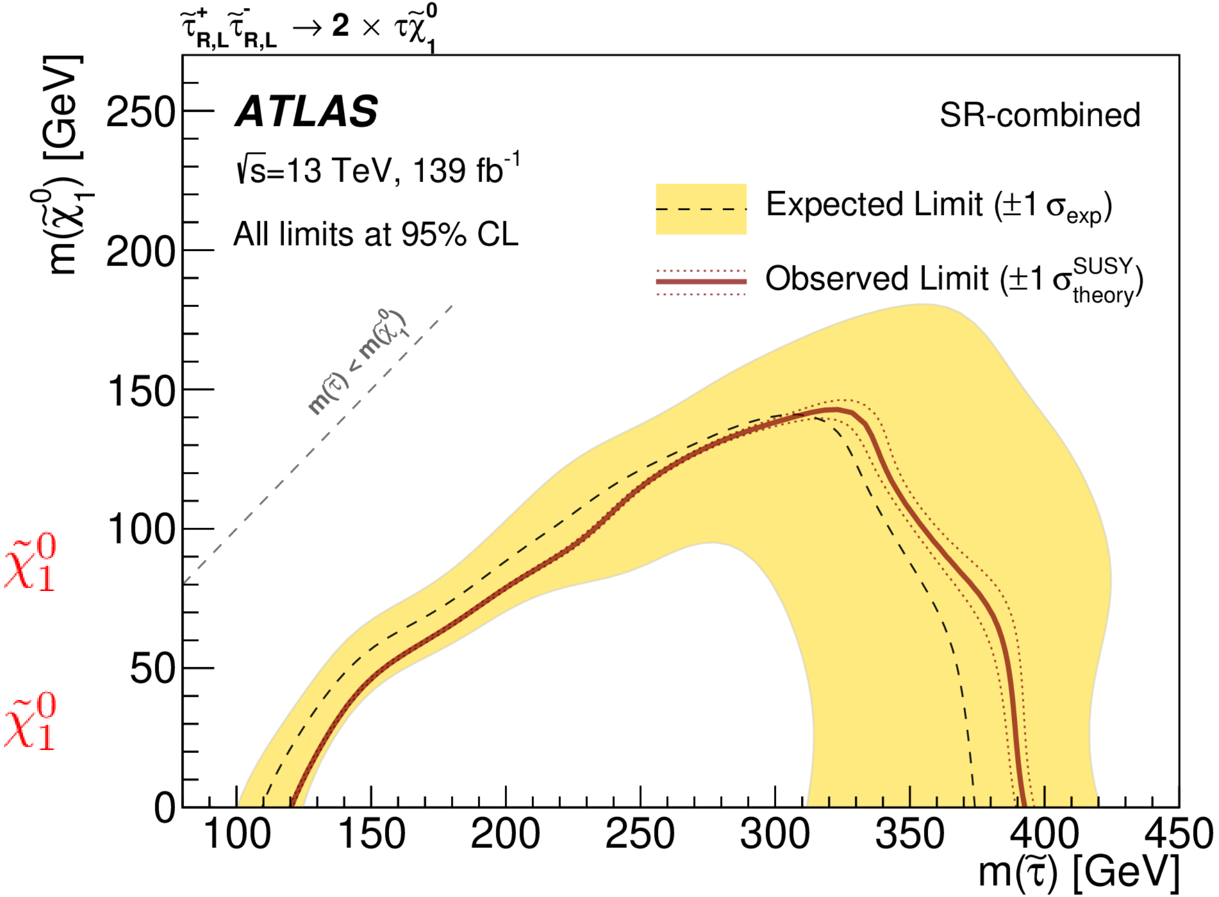




Search for Supersymmetry (SUSY)

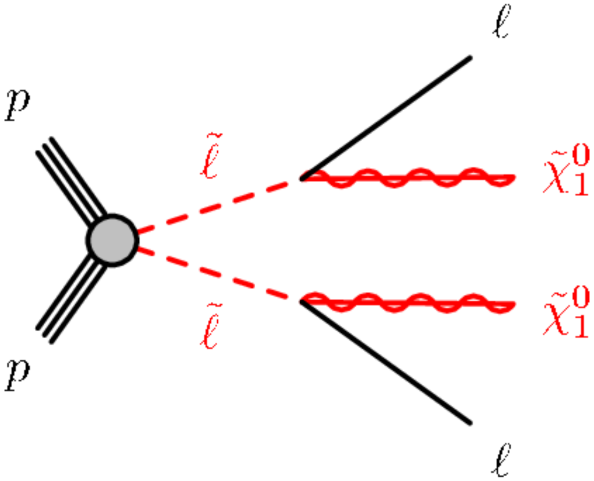
- **Search for stau pair production**

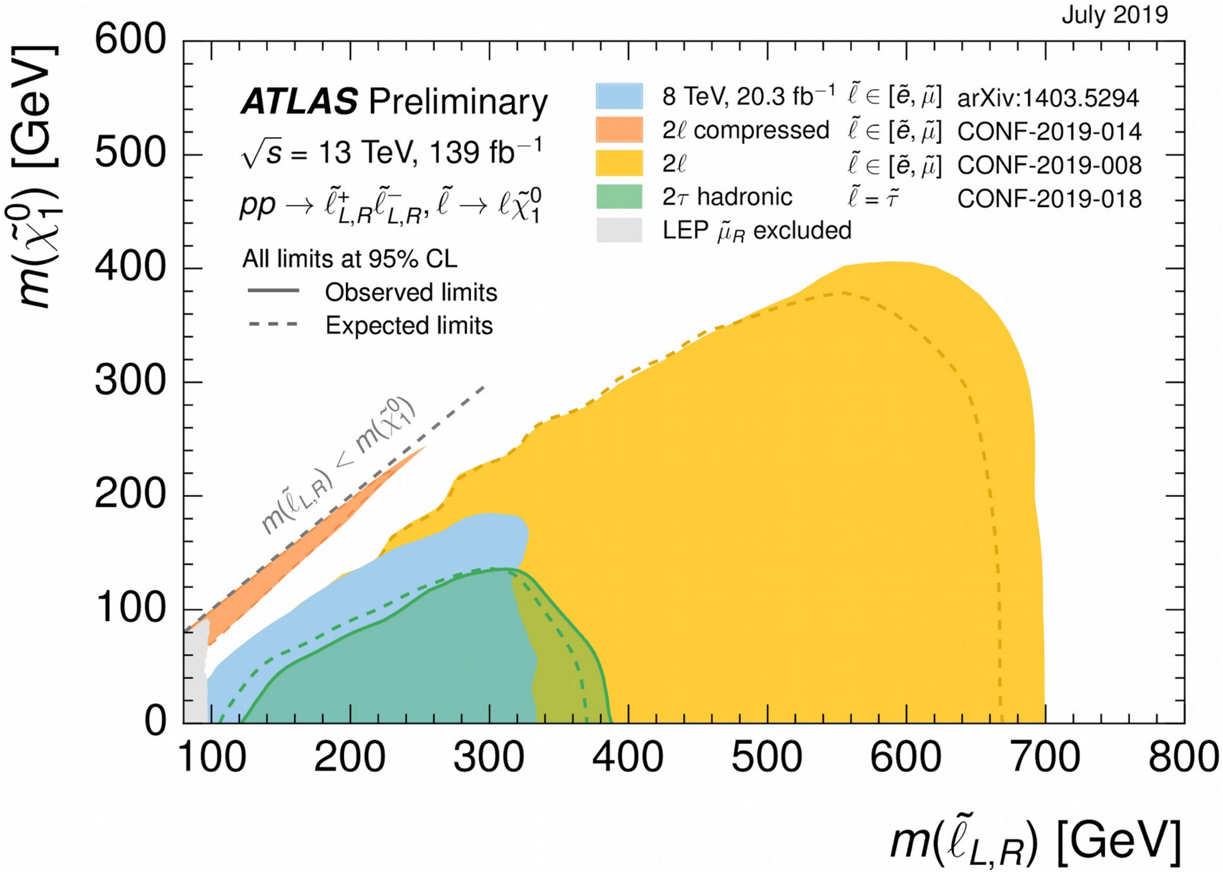




Search for Supersymmetry (SUSY)

- **Search for slepton pair production**



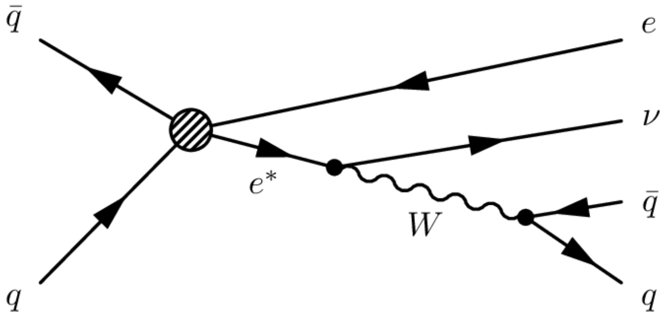


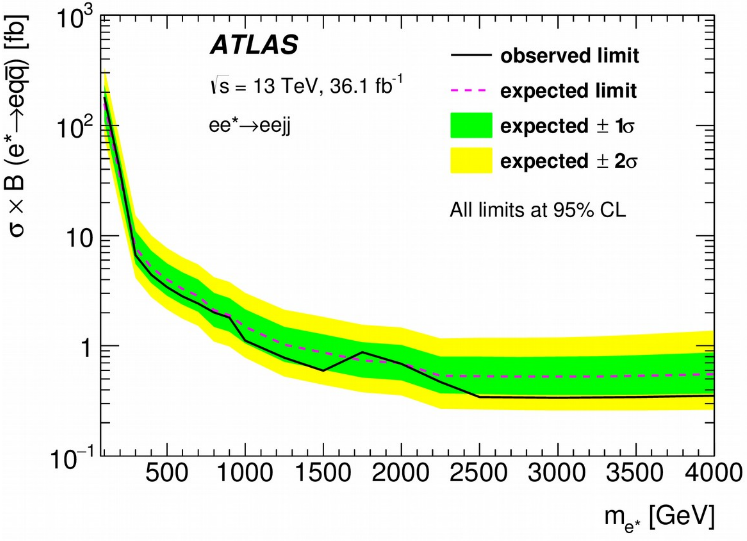
Other (more exotic) Direct Searches

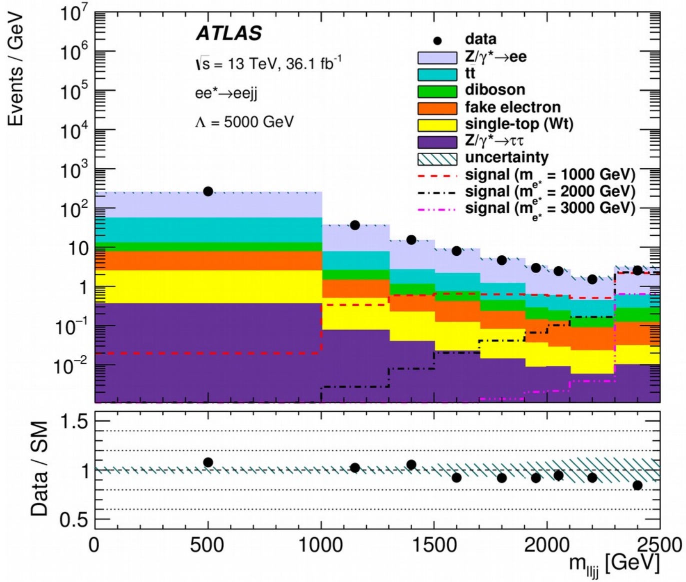
- **Broad range of searches for BSM physics at ATLAS**
  - Excited leptons **[1]**
  - Leptoquarks [2]
  - Dark matter (e.g. invisible Higgs) **[3]**
  - Vector-like quarks [4]
  - Highly ionizing particles (i.e. **monopoles**) [5]
  - Heavy neutrinos [6]
  - Lepton-flavour violation [7]

Direct Search for excited electrons

- **Excited leptons appear in composite models [1]**
  - Introduce new constituent particles called **presons**
    - Bind at high energy scales to form the SM fermions and their excited states
  - Explain the existence of the three generations of quarks and leptons

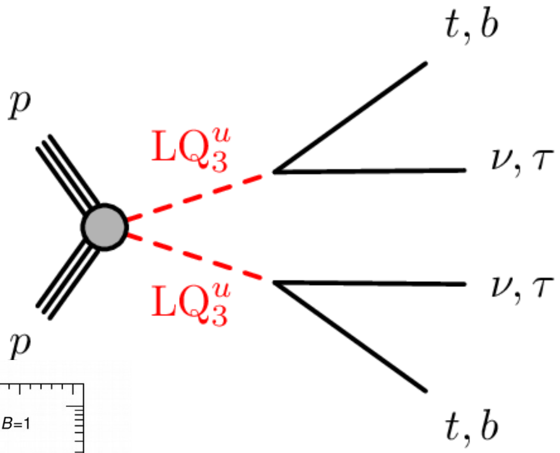


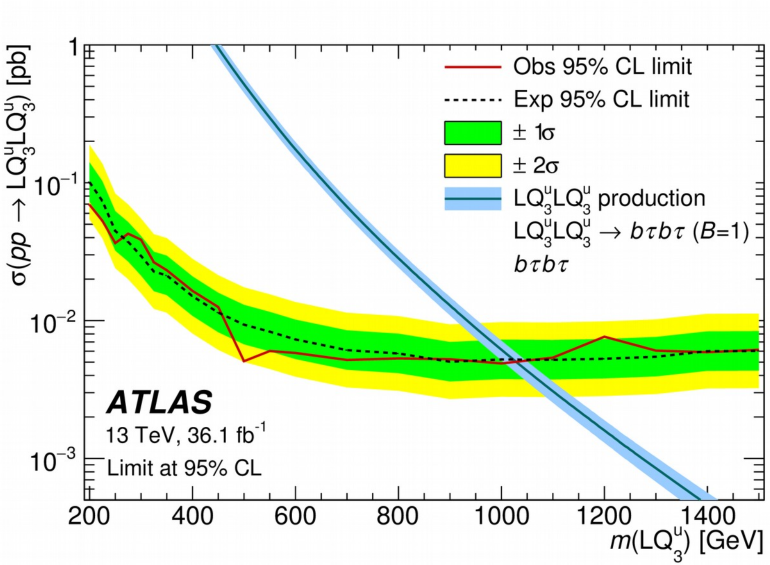


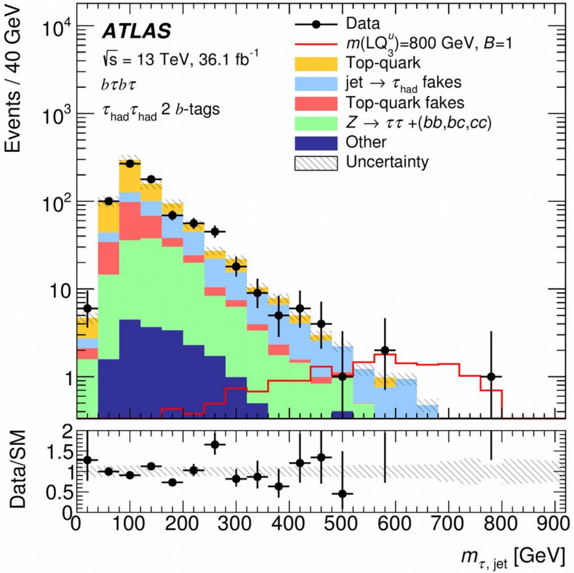


Direct Search for leptoquarks

- **Leptoquarks** appear in several SM extensions [1]
        - E.g: **GUT** or **R-parity violating SUSY**
    - Bosons (with spin 0 or 1):
        - Carry baryon (B) and lepton (L) numbers
        - Carry colour and fractional electrical charge.
    - Decay into a lepton-quark pair

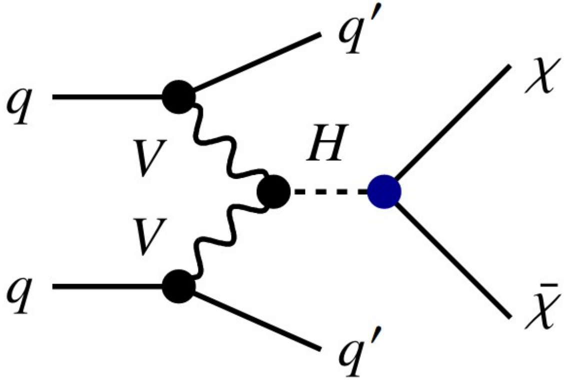


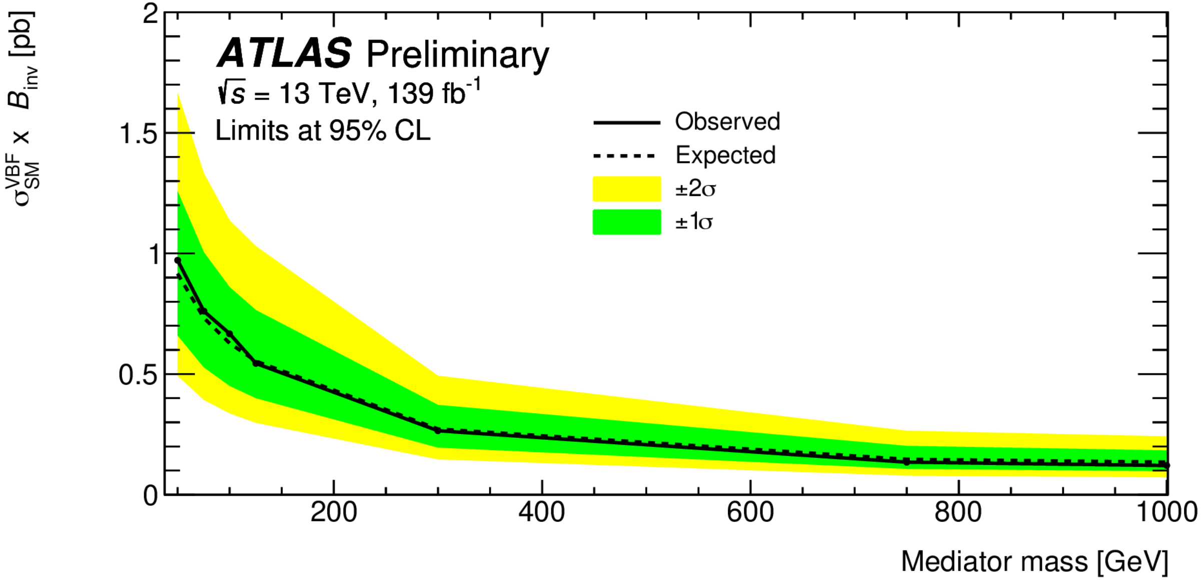




Direct Search for Dark Matter

- Search for **invisible Higgs boson decays** [1]
    - **Motivated by e.g. Higgs-portal models,** which allow BR ~10% for invisible Higgs boson decays
        - **SM predicts BR(H→ νν) = 0.12%**
        - **Decays into WIMPs could explain the**





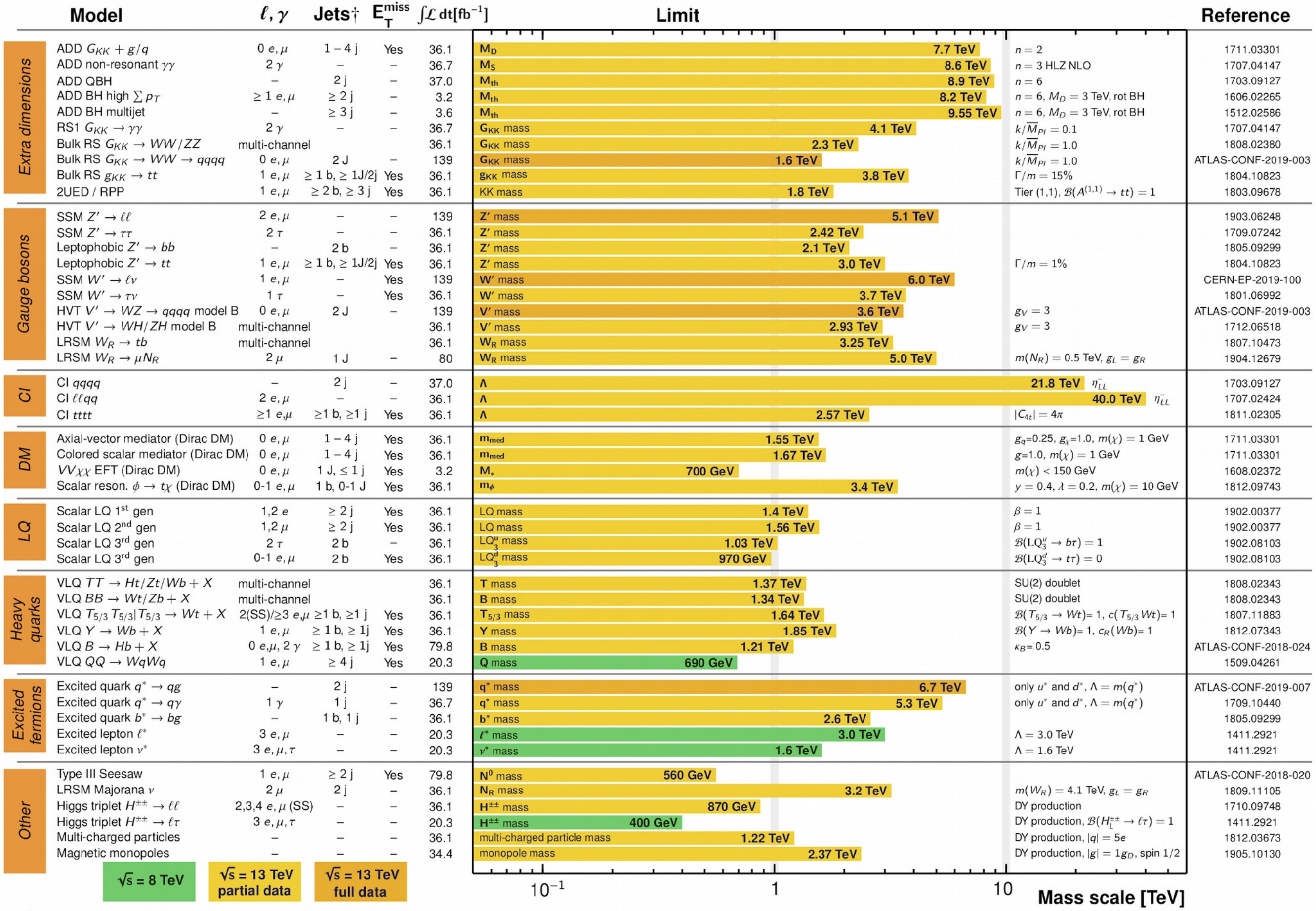
- **Not necessarily the m_H=125 GeV Higgs boson of the SM**

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^{-}		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV η_{LL}^{-}		1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

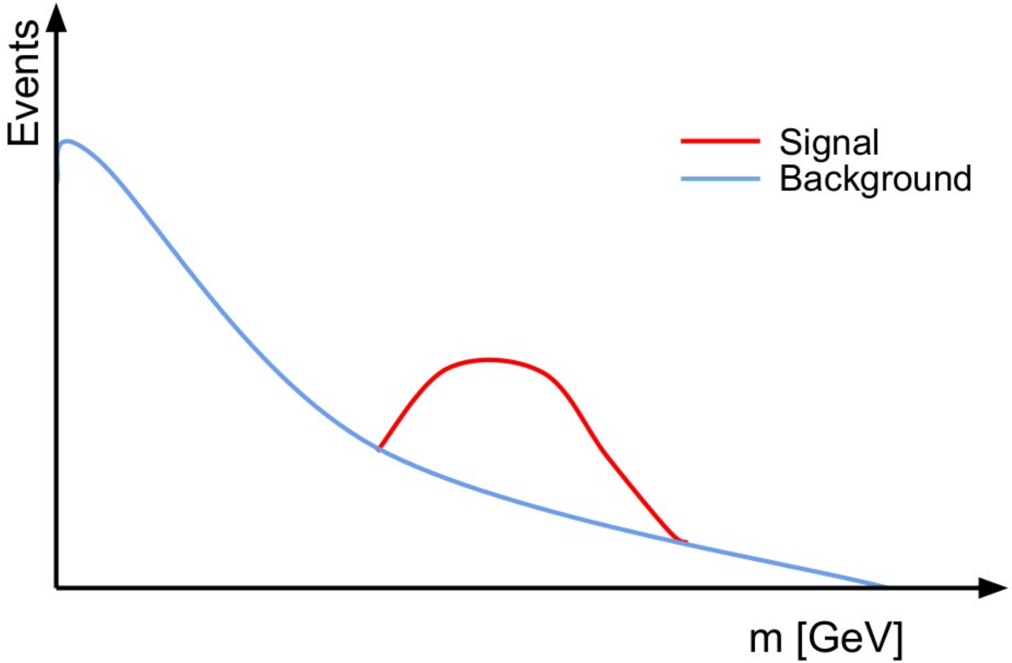
🟧 $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

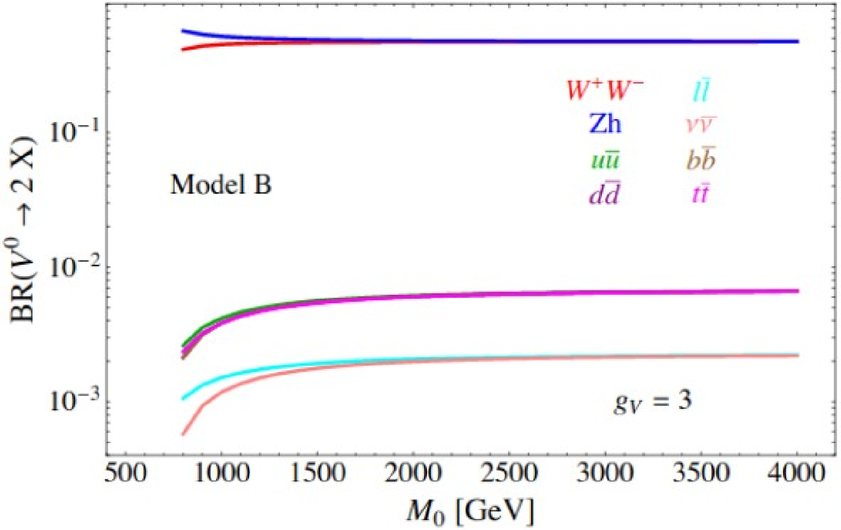
Direct Search for Diboson Resonances

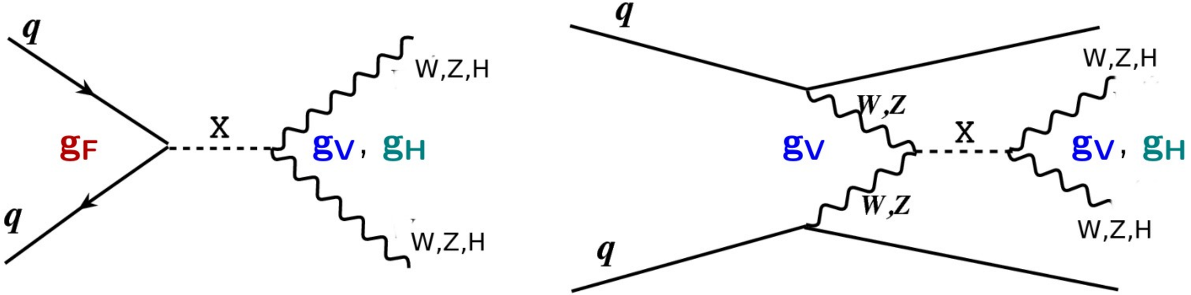
- Most searches for diboson resonances in ATLAS follow the same principle:
    - Perform (quasi) **model-independent search for a bump in a smoothly falling mass spectrum**



Direct Search for Diboson Resonances

- **Heavy vector triplet** (HVT) as an example for a simplified model:
  - Simply introduces an additional SU(2) field to the SM
    - Results in a Z' and W'
    - Coupling to SM particles governed by model parameters g_V , g_F , g_H
  - Representative for:
    - Minimal Walking Technicolour
    - Little Higgs models
    - Composite Higgs models
    - Models with extra dimension

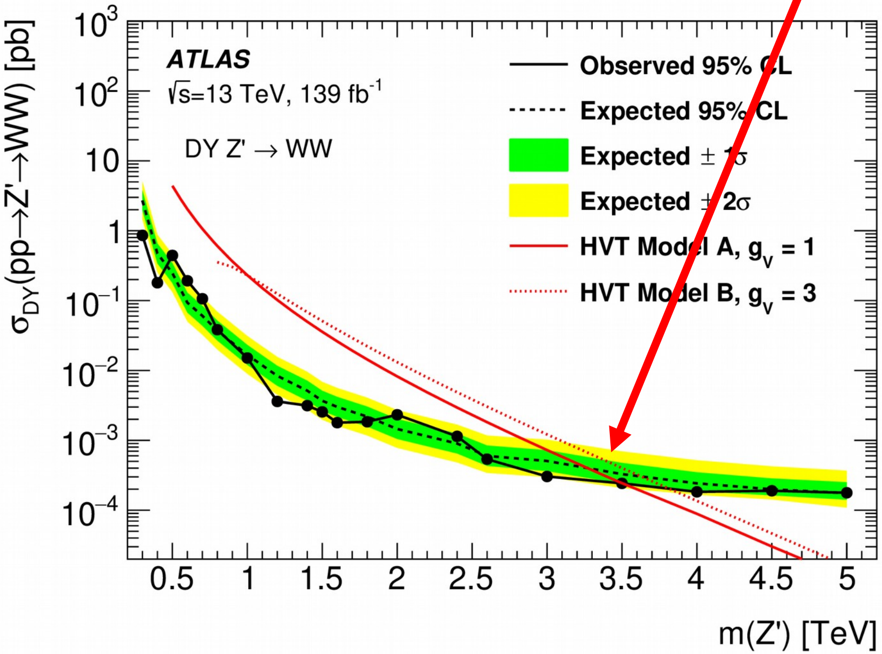




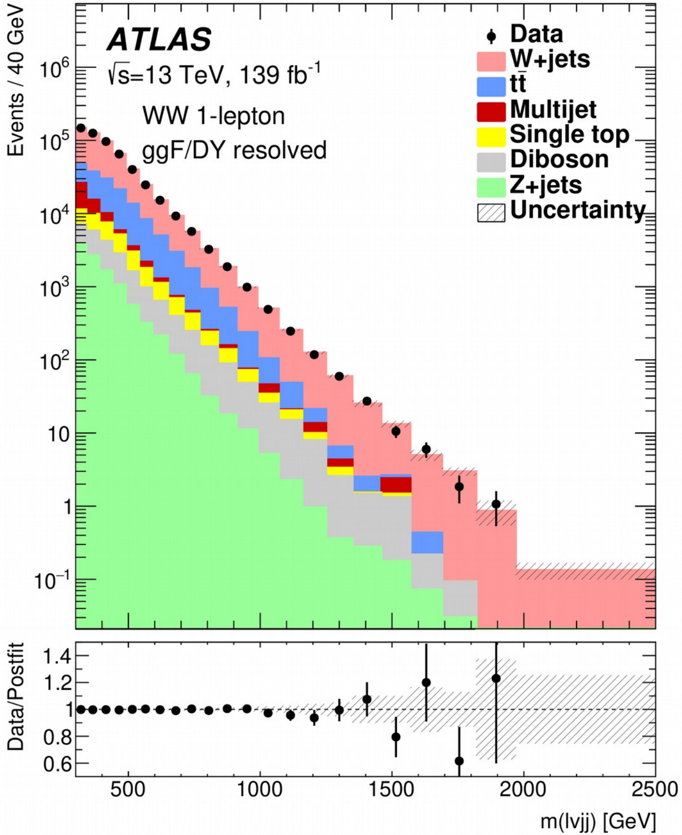
- **Model A:**
  - Prefer coupling to fermions
- **Model B:**
  - Prefer coupling to bosons
- **Model C:**
  - Fermiophobic

Direct Search for Diboson Resonances

- Simultaneous search for:
  - **Heavy vector triplets**
  - **Gravitons**
  - **Heavy scalars**

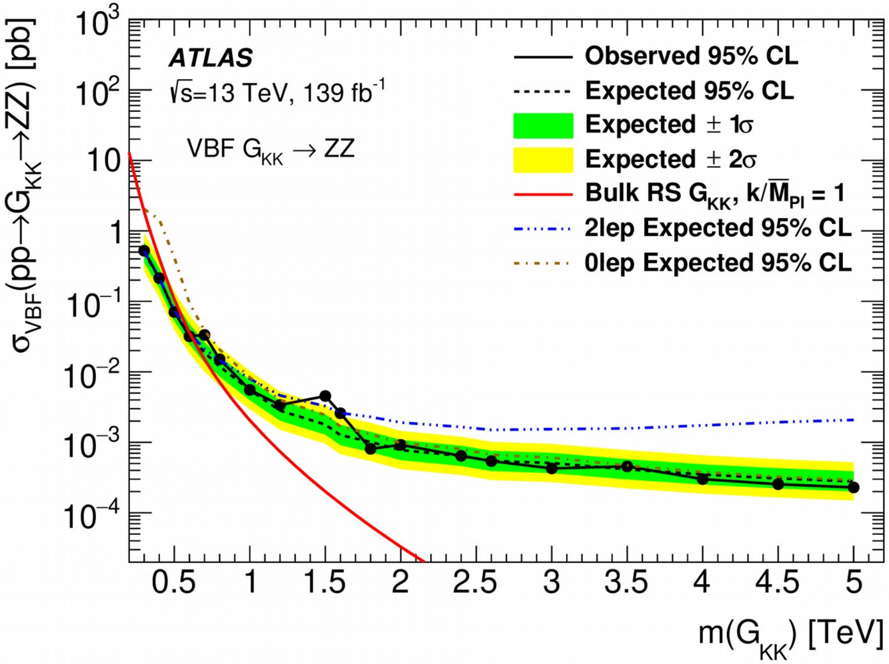


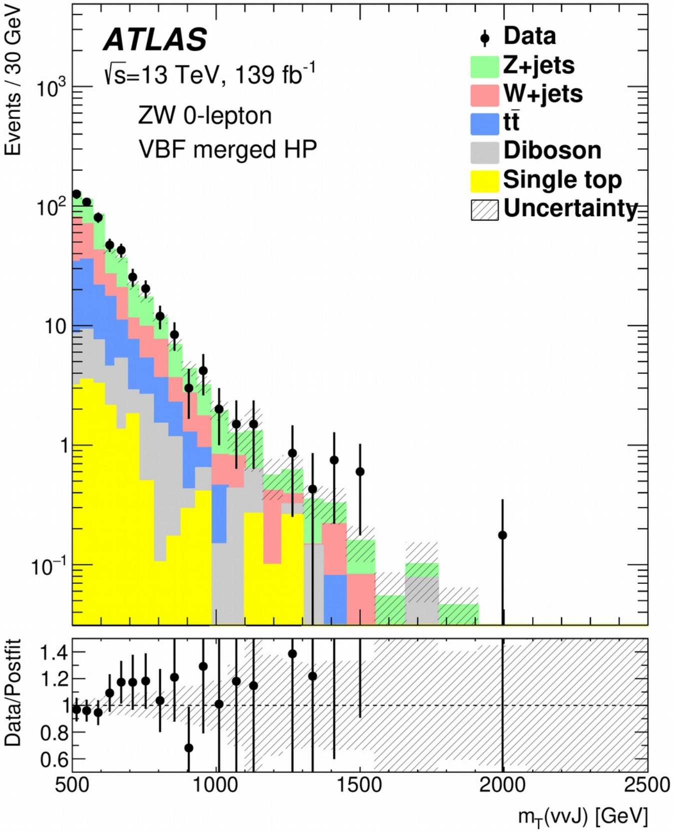
Exclude masses up to 3.4TeV at the 95% CL



Direct Search for Diboson Resonances

- Search for:
    - Heavy vector triplets
    - Gravitons
    - Heavy scalars



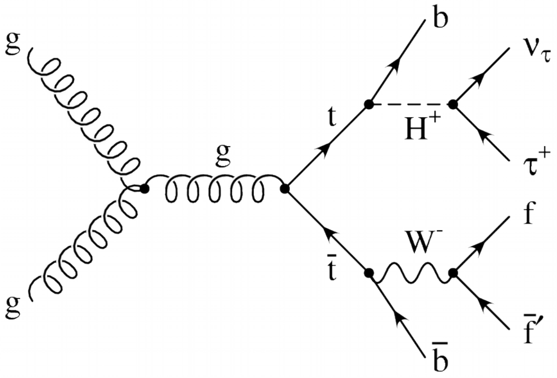


Direct searches for an extended Higgs sector

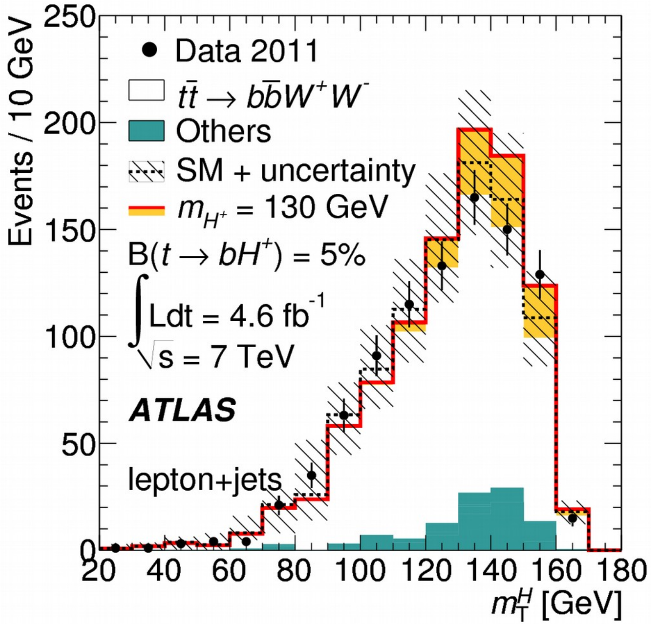
- In the SM, the Higgs sector has been chosen to be as simple as possible to accomplish electroweak symmetry breaking
    - The **Two Higgs Doublet Model (2HDM)** is a particularly promising extension of the SM Higgs sector as it is used in several BSM theories (e.g. MSSM) **[1]**
    - **Single extensions**
        - Higgs-field Portal model (Hidden Sector) **[1]**, **[2]**
    - **Scalar triplet Models**
        - Georgi-Machacek model **[3]**, [4]
    - **Composite Higgs**

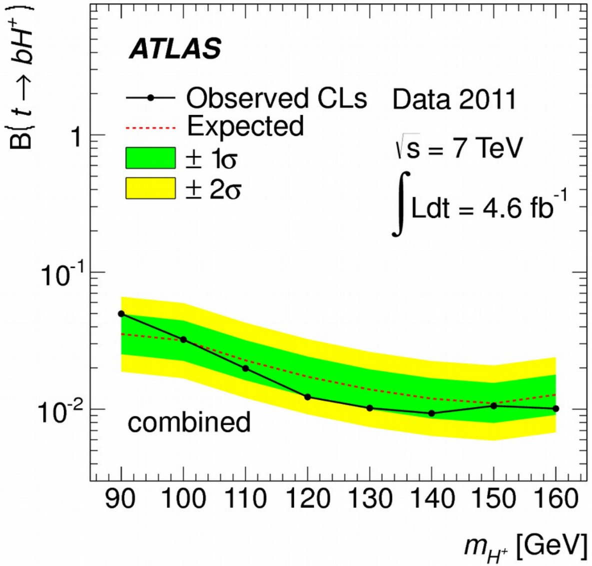
Direct searches for an extended Higgs sector

- **Search for a charged Higgs boson**
  - ○ Predicted by e.g. models containing 2HDMs



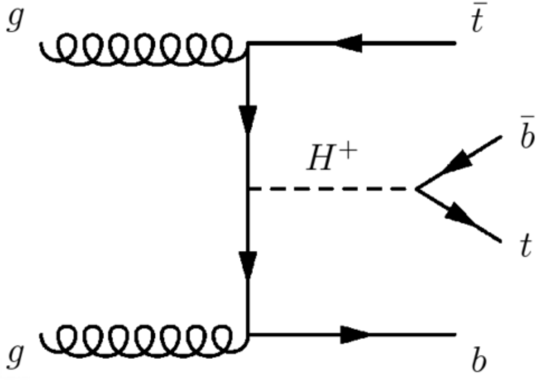
- Dominant decay/production mode for low mass charged Higgs bosons

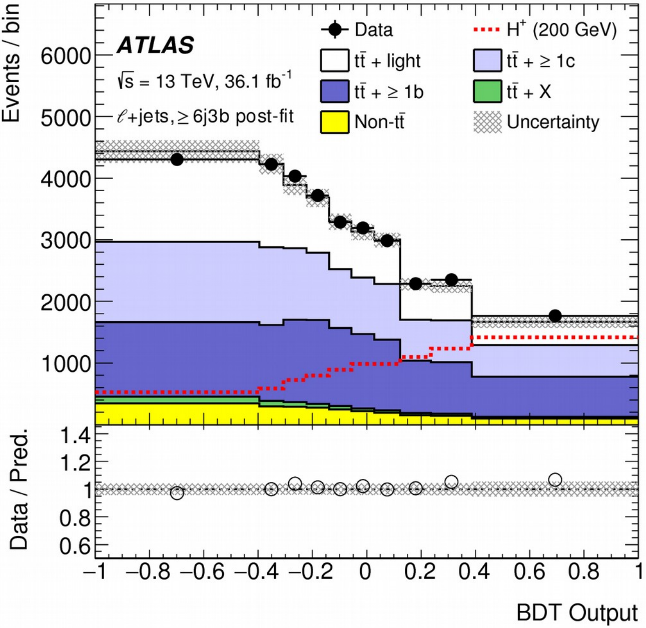


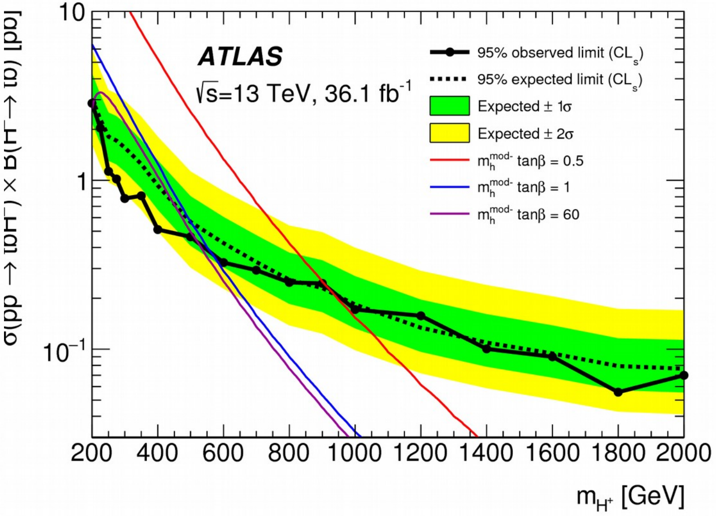


Direct searches for an extended Higgs sector

- **Search for a charged Higgs boson**
  - ○ Predicted by e.g. models containing 2HDMs





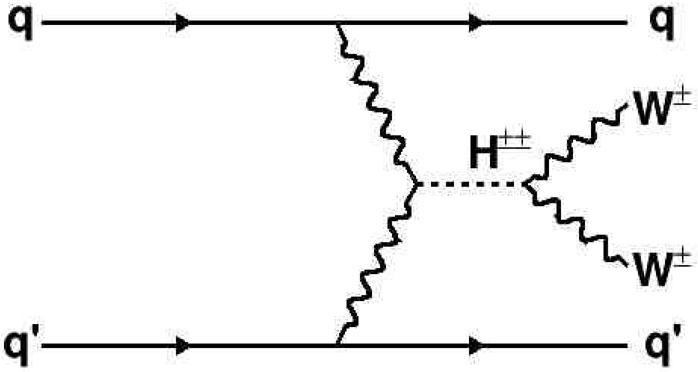


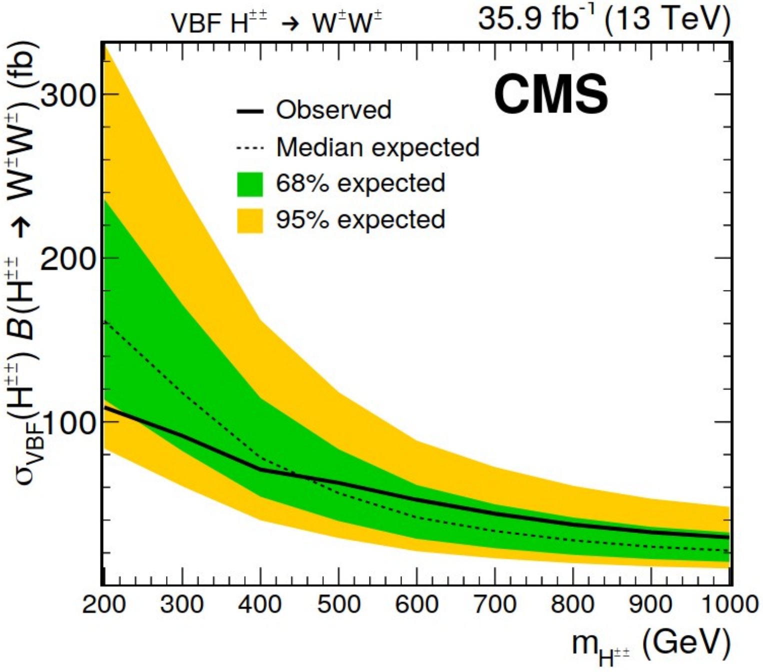
- Dominant for m_{H+} > 180GeV at alignment limit

Direct searches for an extended Higgs sector

- **Search for doubly-charged Higgs bosons**
  - Predicted in models that contains a Higgs triplet field.
    - Leading to same-sign dilepton events

$pp \rightarrow H^{++}jj \rightarrow W^{+}W^{+}jj$ (VBF)

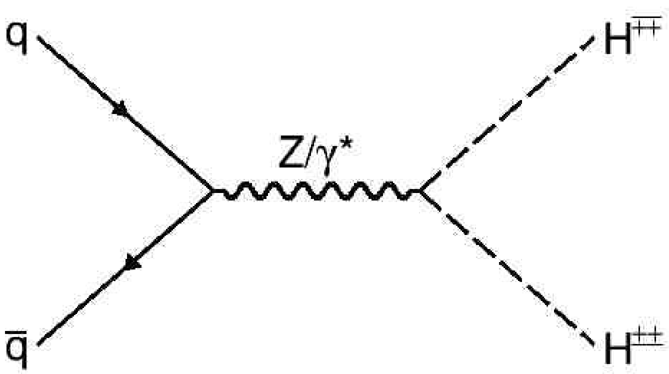


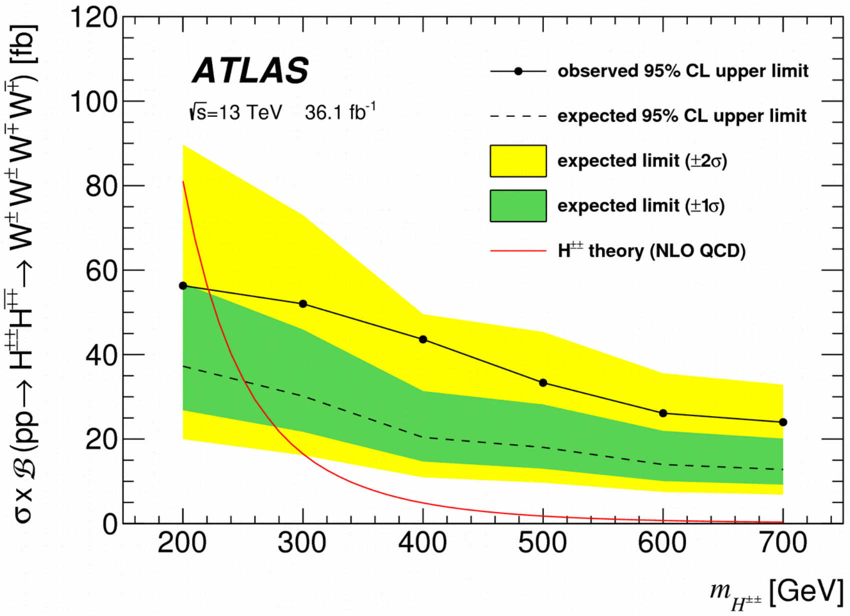


Direct searches for an extended Higgs sector

- **Search for doubly-charged Higgs bosons**
  - Predicted in models that contains a Higgs triplet field.
    - Leading to final states with 4 leptons

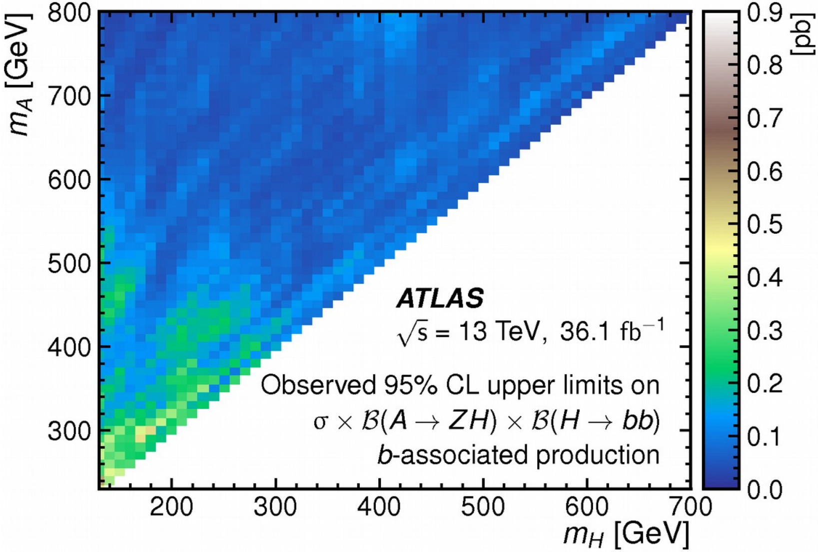
$$pp \rightarrow H^{++} H^{--} \rightarrow W^{+} W^{+} W^{-} W^{-}$$

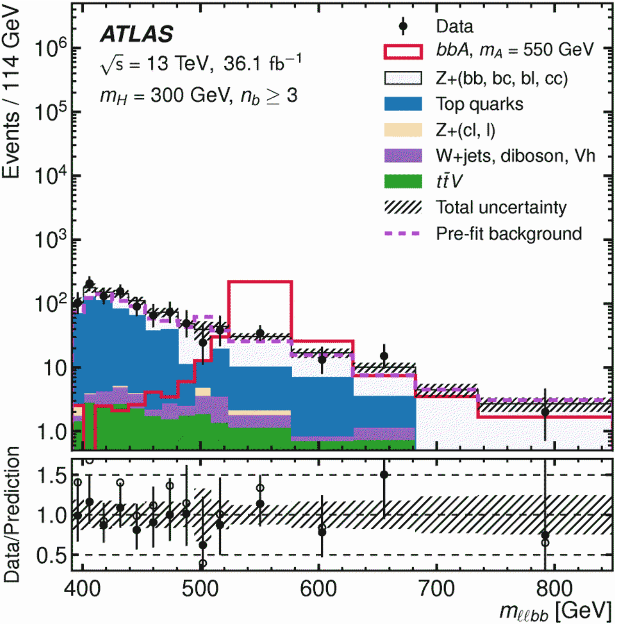


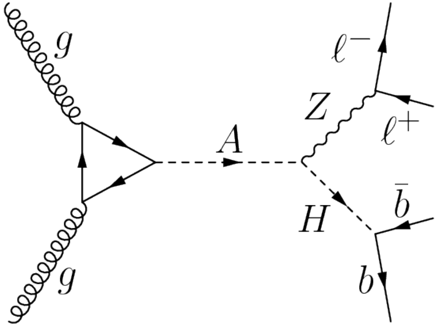


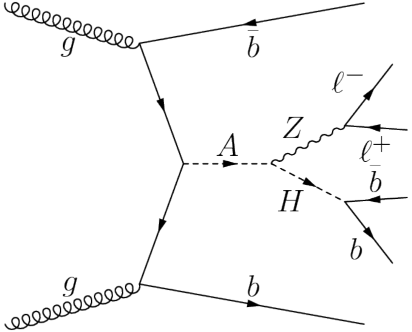
Direct searches for an extended Higgs sector

- **Search for a pseudoscalar boson**
  - Predicted by e.g. models containing 2HDMs



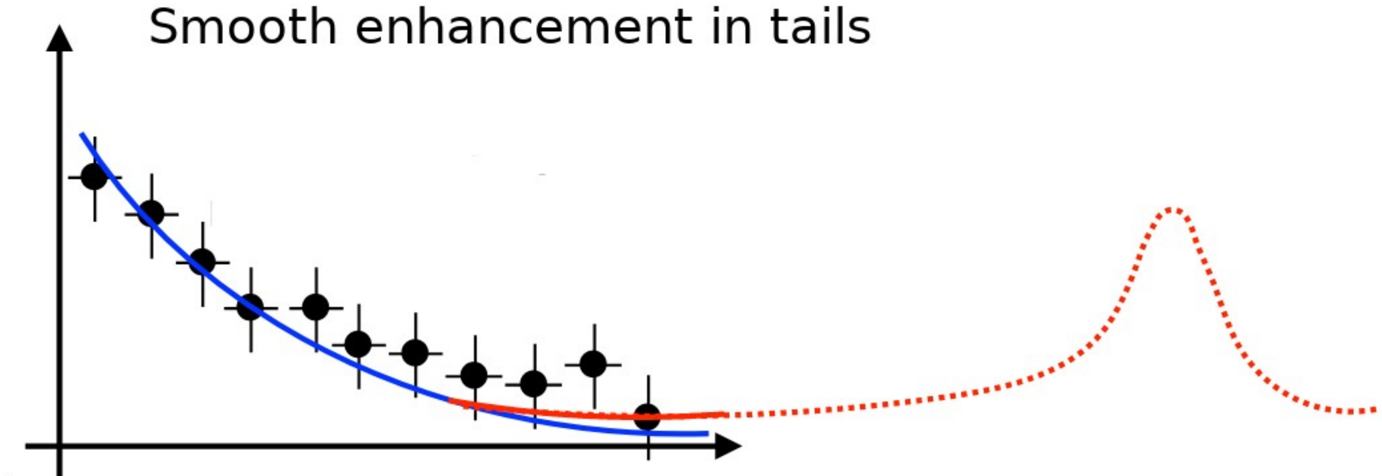






Effective field theories

- So far no hints for new physics in direct searches
- What if scale of new physics is outside the reach of the LHC?
  - **Search for smooth enhancements in the tails of our observables**
    - E.g. from resonances with masses beyond our reach
  - **Probing for shape modifications of our observables**
    - E.g. from anomalous couplings
- **Effective field theories (EFT) allow for model independent approaches to search for such new physics effects**

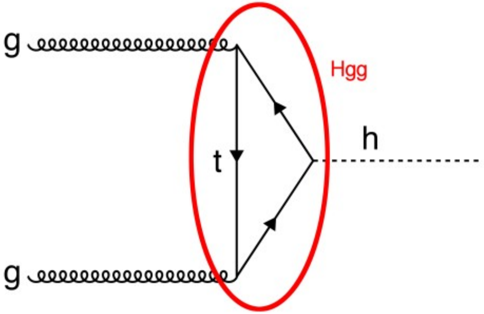


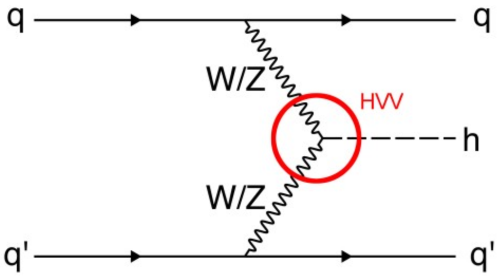
Effective field theory (EFT)

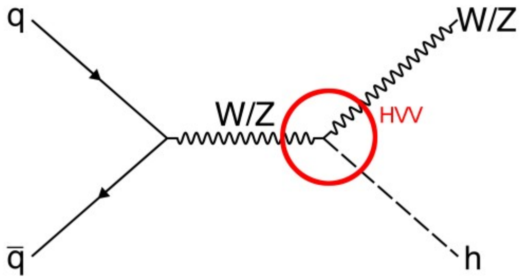
- **In EFTs, Lagrangian of the Standard Model of particle physics is supplemented with additional BSM terms:**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i} \frac{c_i}{\Lambda} \mathcal{O}_i$$

- $\mathcal{O}_i$ are higher dimension operators
- c_i are the so-called Wilson coefficients
  - ○ Specify the strength of a new CP-even (or CP-odd) interaction (i.e. they describe deviation from SM)
- Λ is mass scale for new particle







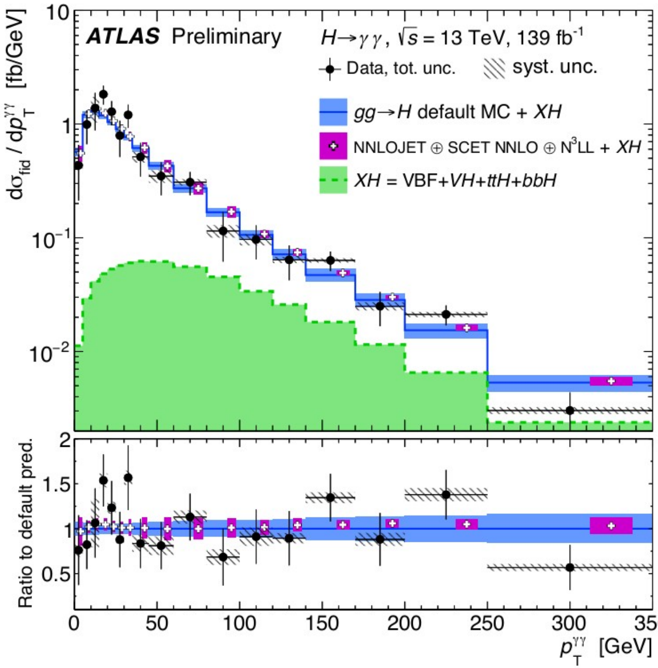
Differential measurements

- **Re-interpretation of differential cross section measurements are used to constrain EFT parameters**
- Measurement of **differential** cross sections
  1. Measure number of Higgs signal events N^{signal} in i-th p_T^H bin (or of any other observable)
  2. Background subtraction
  3. **Unfolding:** Derive correction factor from MC information:

$$c_i = \frac{N^{\mathrm{reco}}}{N^{\mathrm{part}}}$$

  4. Calculate differential cross section:

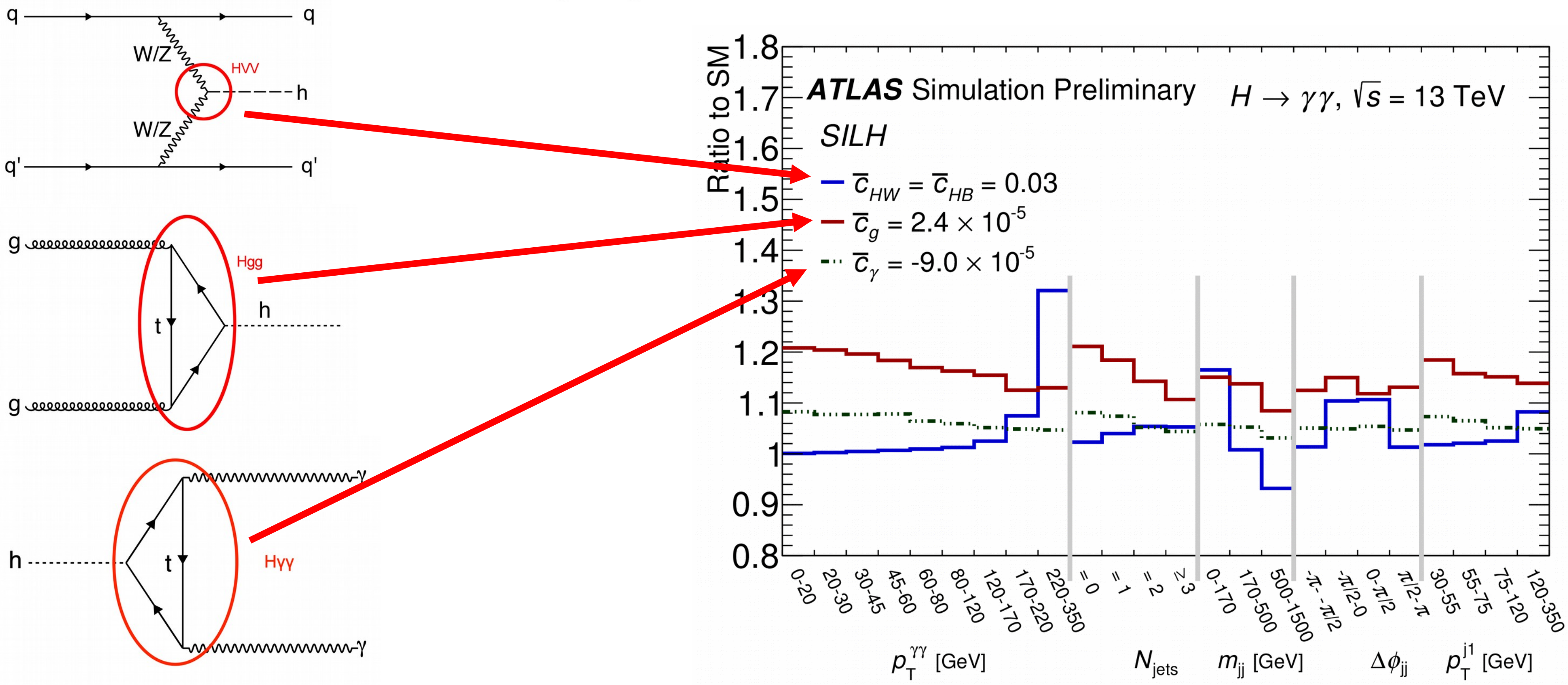
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N^{\mathrm{signal}}}{c_i \Delta p^H_{i,\mathrm{T}} \mathcal{L}_{\mathrm{int}}}$$



Effective field theory (EFT)

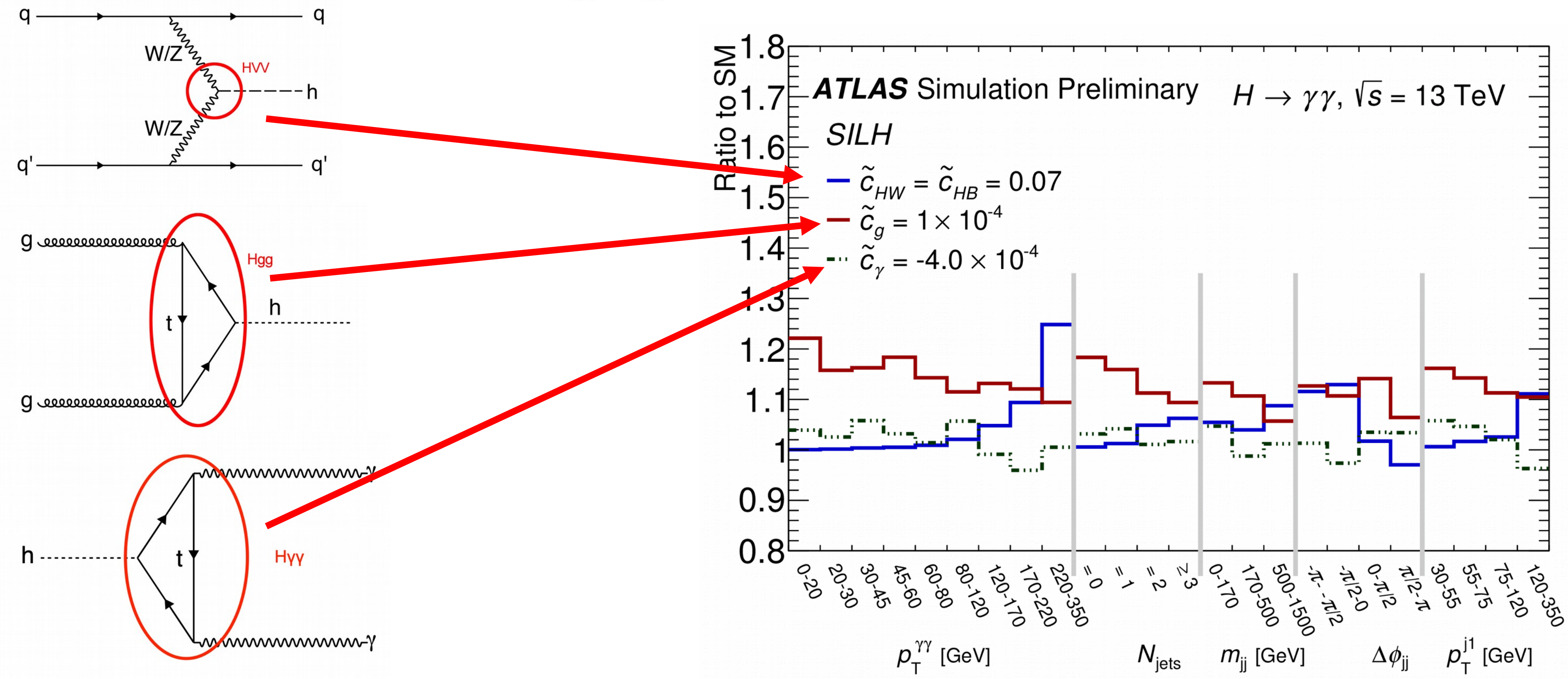
H→ γγ is sensitive to:

$$\bar{c}_g \mathcal{O}_g \leftarrow \text{CP even} \rightarrow \bar{c}_{HW} \mathcal{O}_{HW} \quad \bar{c}_{HB} \mathcal{O}_{HB}$$



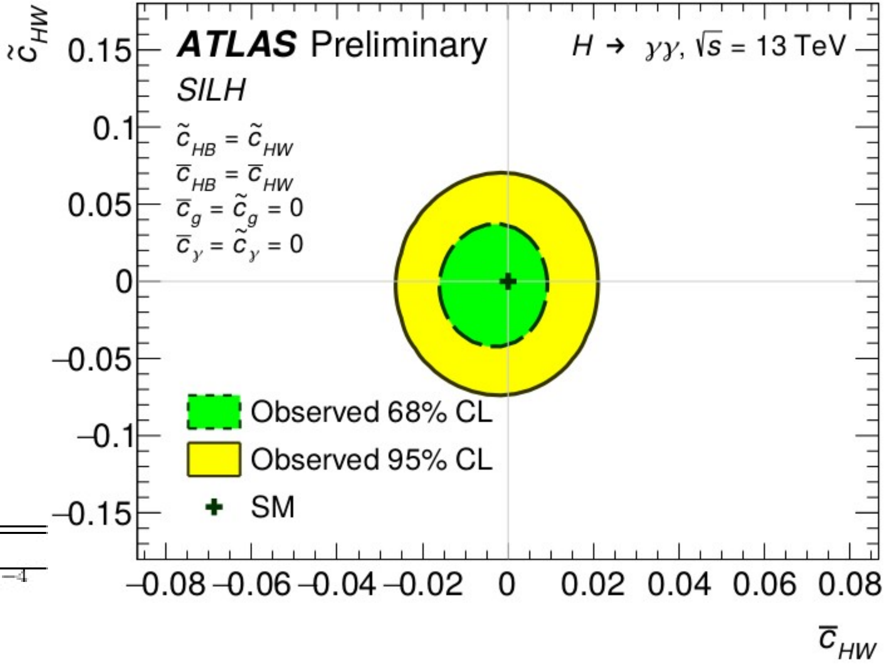
Effective field theory (EFT)

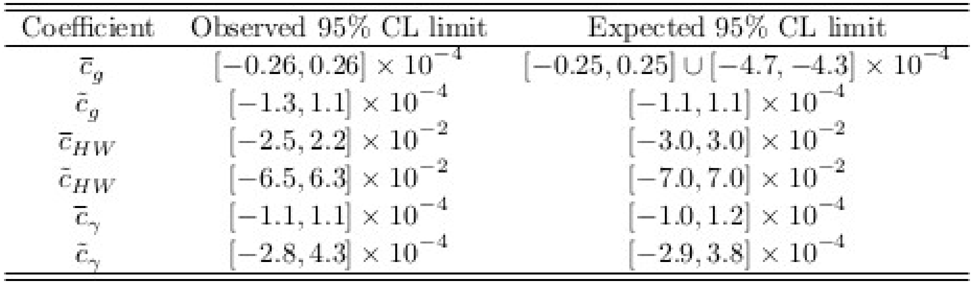
H→ yy is sensitive to: $\tilde{c}_g\tilde{\mathcal{O}}_g \leftarrow$ CP odd $\rightarrow \tilde{c}_{HW}\tilde{\mathcal{O}}_{HW} \quad \tilde{c}_{HB}\tilde{\mathcal{O}}_{HB}$



Effective field theory (EFT)

- **Exclude large range of EFT parameter space**
- **So far: No significant deviations from the SM expectations found**
    - **However, not yet sensitive to range really relevant for EFTs**





Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.26, 0.26] \times 10^{-4}$	$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$
$\tilde{c}_g$	$[-1.3, 1.1] \times 10^{-4}$	$[-1.1, 1.1] \times 10^{-4}$
$\bar{c}_{HW}$	$[-2.5, 2.2] \times 10^{-2}$	$[-3.0, 3.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-6.5, 6.3] \times 10^{-2}$	$[-7.0, 7.0] \times 10^{-2}$
$\bar{c}_\gamma$	$[-1.1, 1.1] \times 10^{-4}$	$[-1.0, 1.2] \times 10^{-4}$
$\tilde{c}_\gamma$	$[-2.8, 4.3] \times 10^{-4}$	$[-2.9, 3.8] \times 10^{-4}$