LHC Update
New Results, New Techniques, New Ideas

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(On behalf of the ATLAS and CMS Collaborations)

Disclaimer and Apologies

Symposium organizers wish for a somewhat different talk than those given at previous symposia, focusing more on new ideas and techniques…

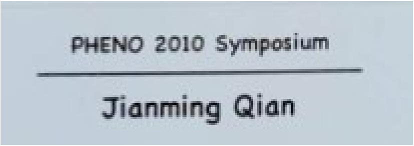
This talk is divided in two parts:

- **Highlight a few recent results**
  - Latest Higgs results
  - Observations of di-boson and tri-boson processes

  (My apologies for the injustice to many other new results. Please do listen to other talks on LHC results at this symposium.)

- **Discuss a few results from new ideas or using new techniques, new at least at the time.**

  (Some results are not really new, as it takes time to perfect techniques and to bring ideas to fruition.)



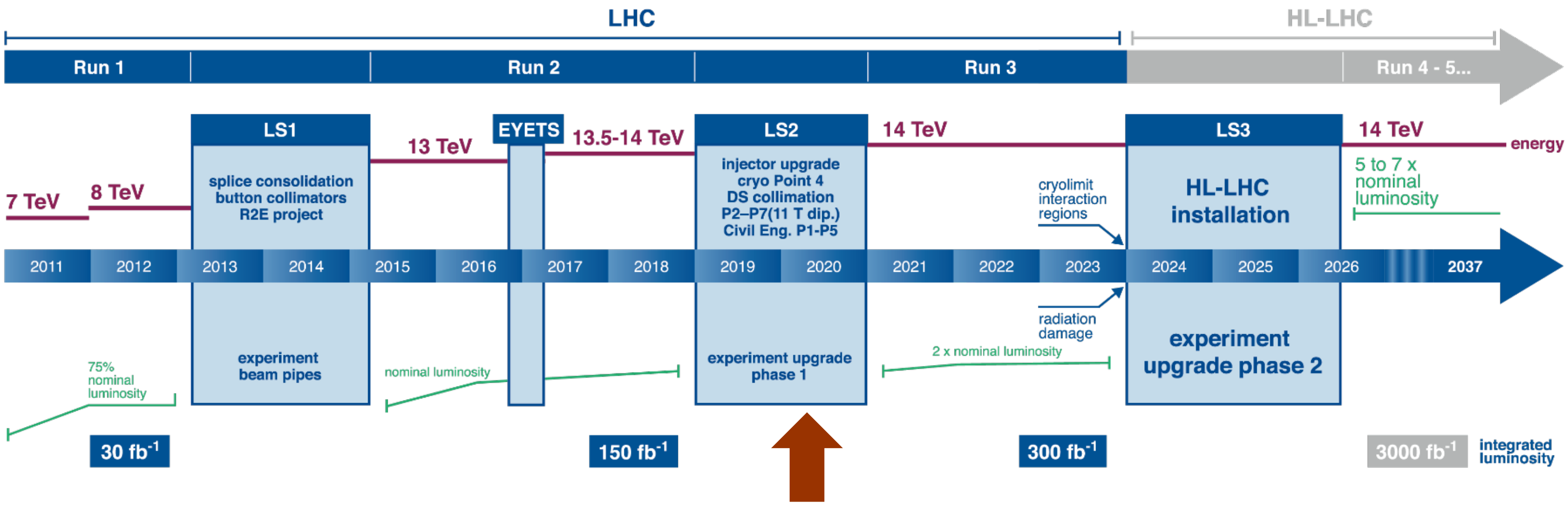
PHENO 2010 Symposium

Jianming Qian

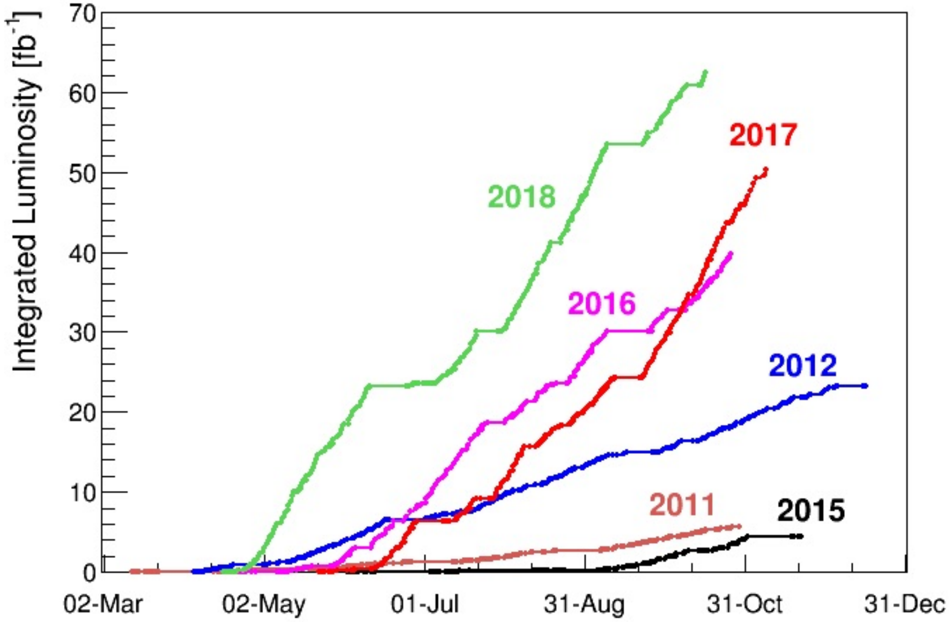
(My last Pheno ☹)

(See next talk by Anadi Canepa for what future entails.)

Large Hadron Collider



Here we are



Luminosities/experiment delivered:

$$\sim 5\ \mathrm{fb}^{-1} \quad @ \sqrt{s} = 7\ \mathrm{TeV}$$

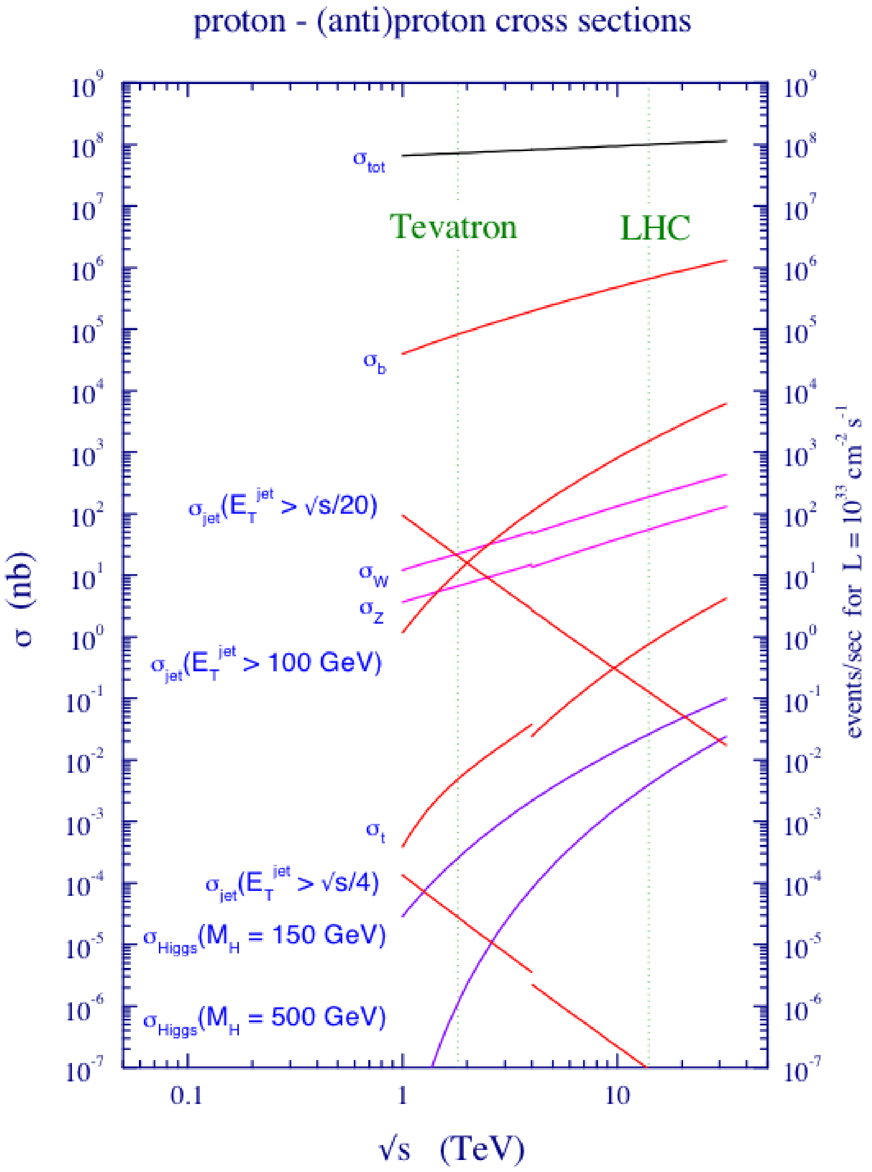
$$\sim 20\ \mathrm{fb}^{-1} \quad @ \sqrt{s} = 8\ \mathrm{TeV}$$

$$\sim 150\ \mathrm{fb}^{-1} \quad @ \sqrt{s} = 13\ \mathrm{TeV}$$

Only $\sim$ 5% of the luminosity envisioned for (HL-)LHC

Tremendous potential for increasing statistics, limited potential for increasing energy.

Proton-Proton Collision Physics



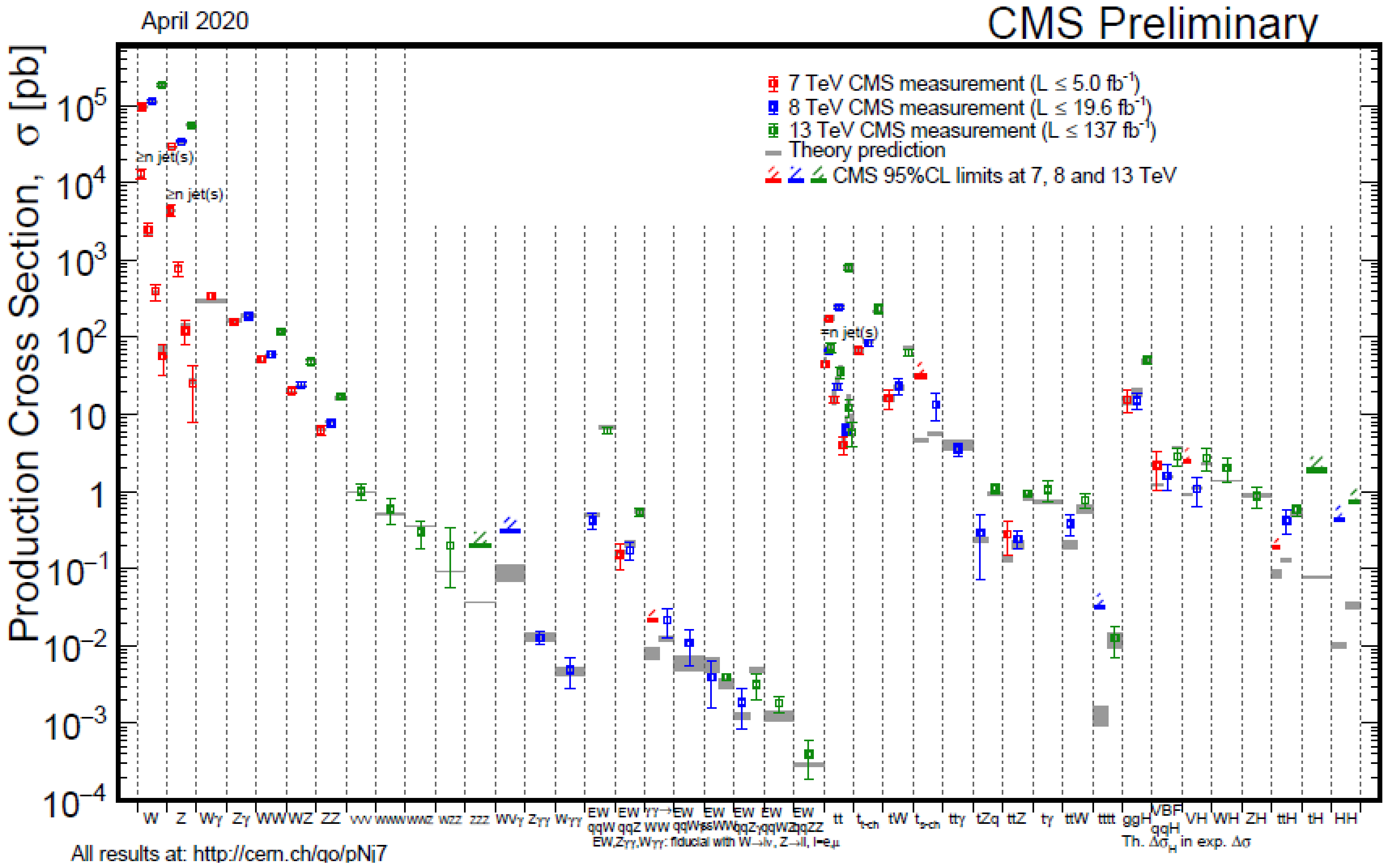
We are blessed to have a successful theory called the Standard Model.

LHC explores physics over 10+ order of magnitude in rates.

Every process matters:

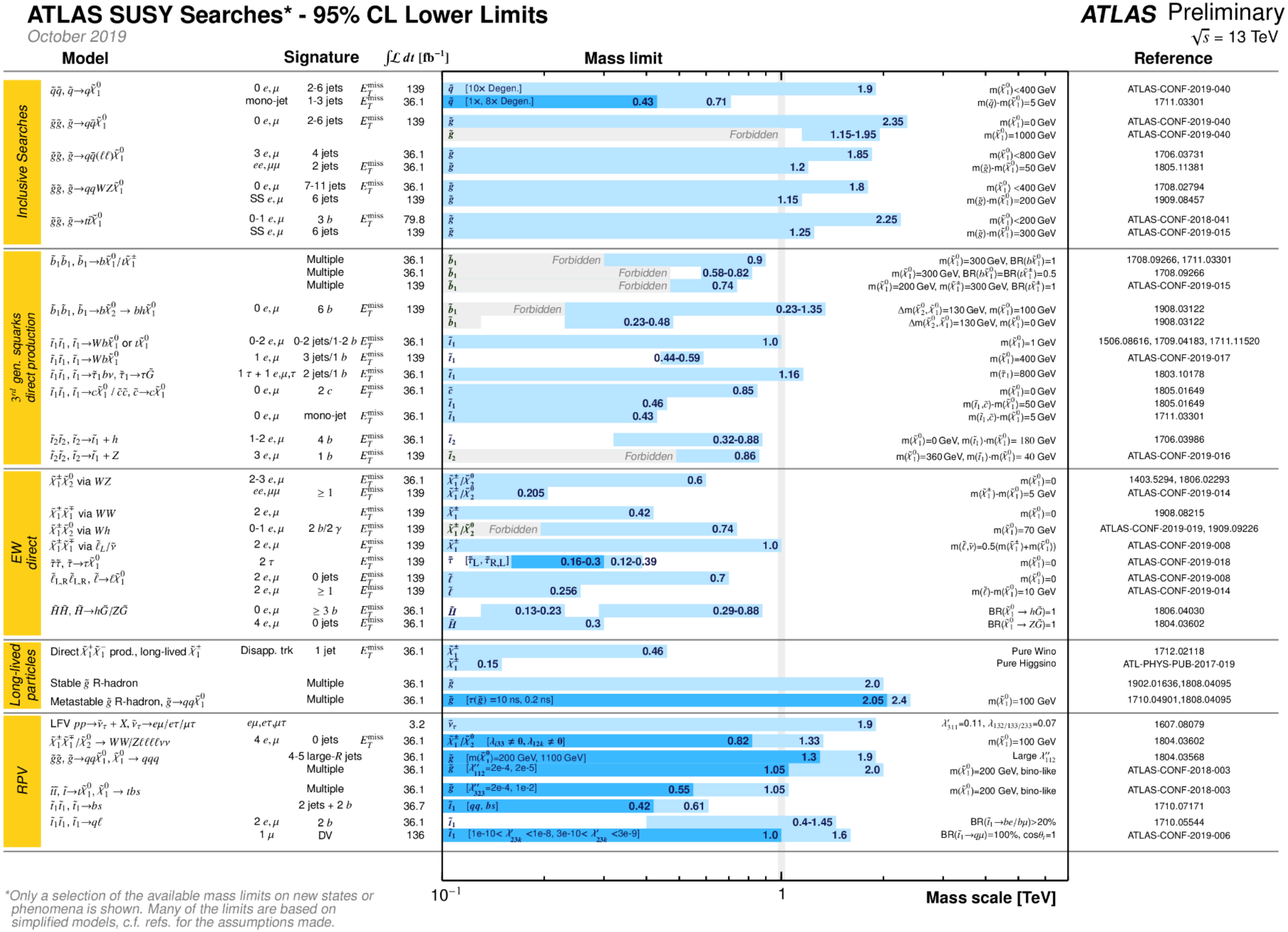
- Known known processes for calibration and for precision measurements
- Known unknown processes to test Standard Model
- Unknown processes to search for BSM physics

Standard Model Processes



Standard Model is alive and well

Examples of Limits (SUSY Searches)



ATLAS SUSY Searches* - 95% CL Lower Limits
October 2019

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

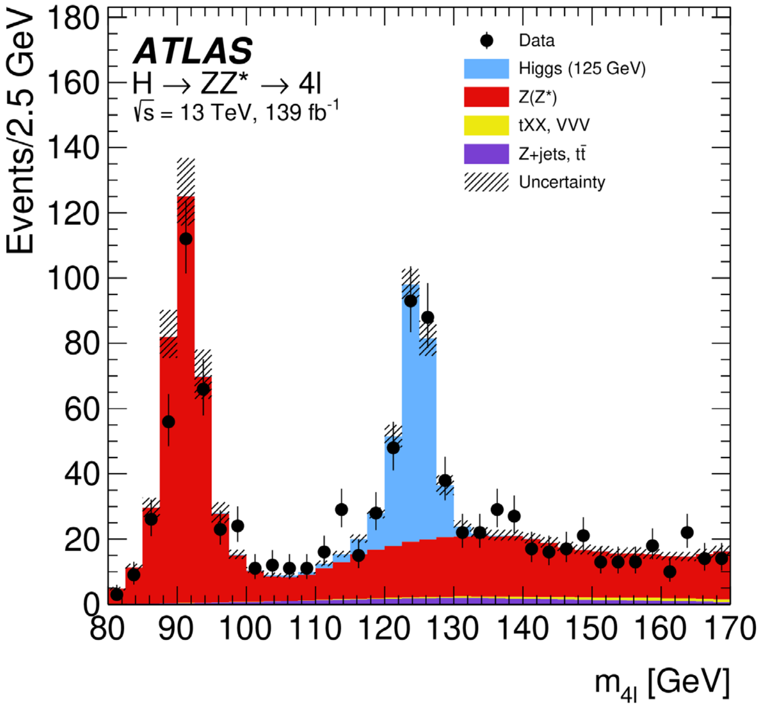
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$	[10× Degen.] 1.9	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$	2.35	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$	1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
						$\tilde{b}_1$	0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}^0_1$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	$E_T^{\rm miss}$	36.1	$\tilde{t}_2$	0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	$\geq$ 1	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	ATLAS-CONF-2019-019, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$	[$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	$\geq$ 1	$E_T^{\rm miss}$	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$	[m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$	[λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

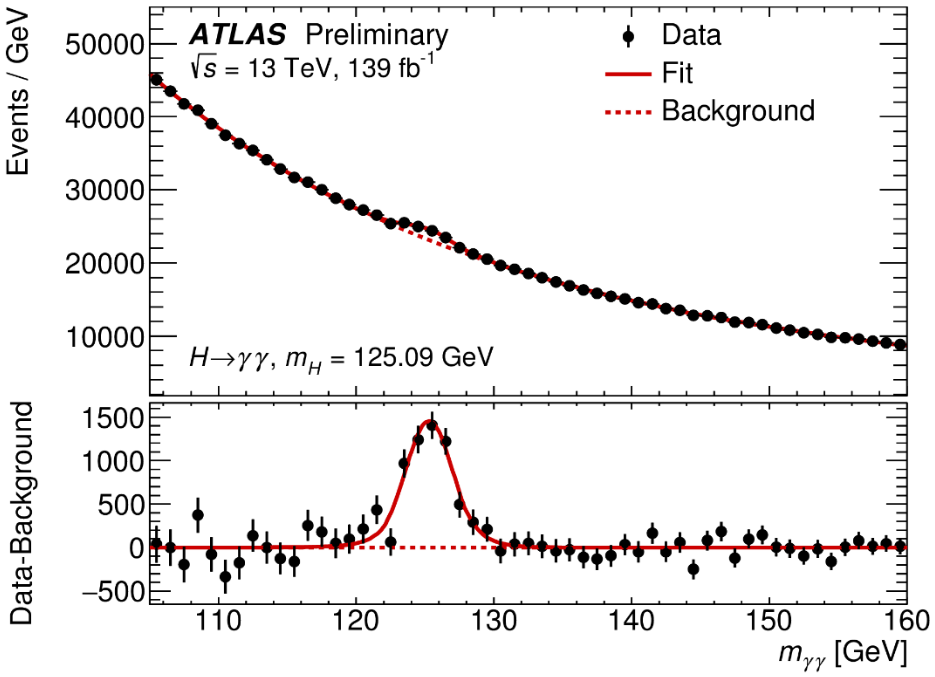
No discoveries yet, but not for lack of efforts

Higgs Boson Physics

$H \rightarrow ZZ^{*} \rightarrow 4\ell$



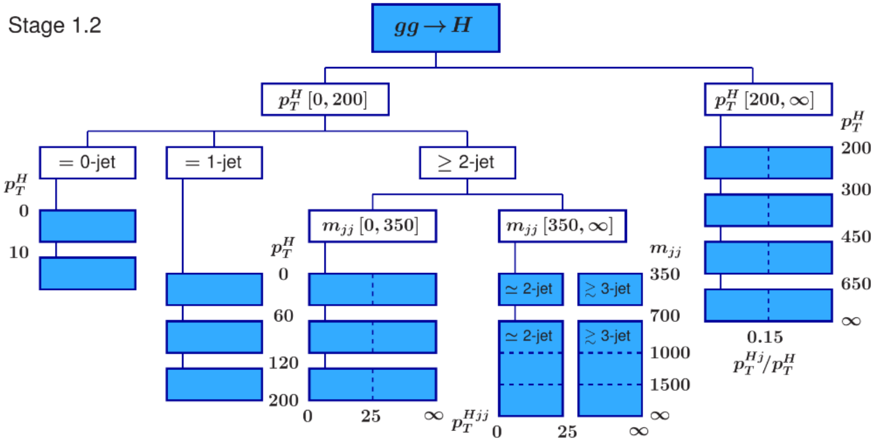
$H \rightarrow \gamma\gamma$



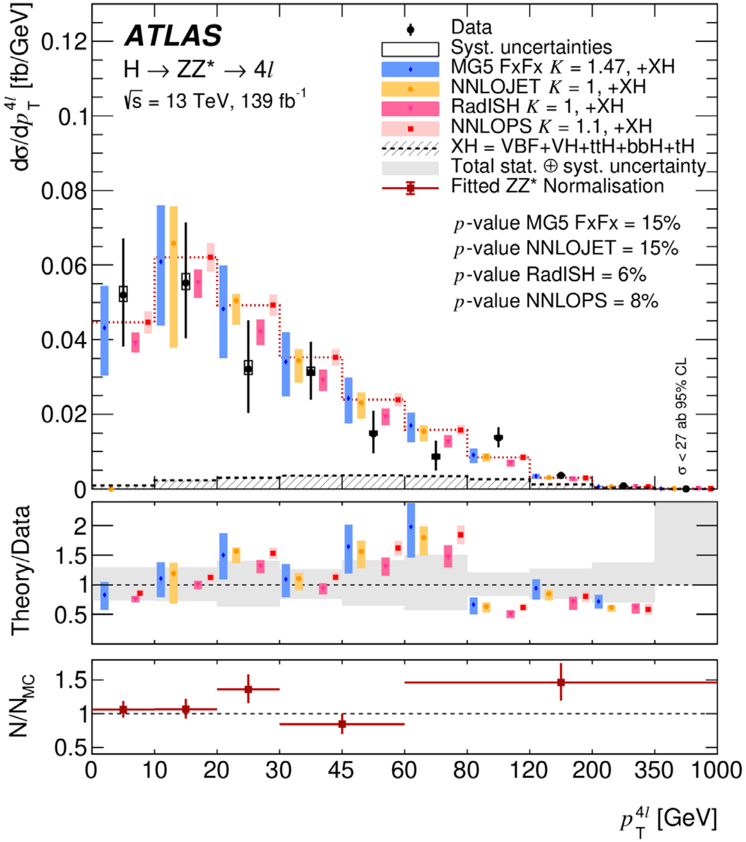
- Major production processes (ggF, VBF, VH, ttH) and decay modes $(b\bar{b}, WW^{*}, \tau\tau, ZZ^{*}, \gamma\gamma)$ have been established
- Current efforts focused on precision measurements, studies of production and decay kinematics, $H\mu\mu$ and Hcc couplings, HH production, and searches for BSM phenomena.

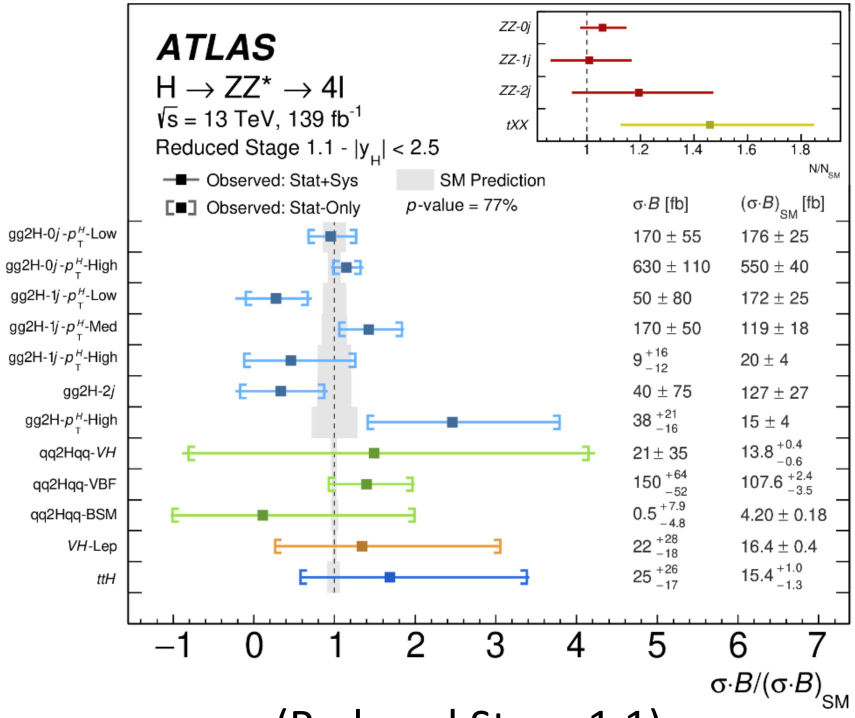
Higgs Boson Differential and STXS Measurements

From inclusive measurements to differential and simplified-template cross section (STXS) measurements ⇒ Enhancing sensitivities to BSM contributions



ATLAS: arXiv:2004.03969

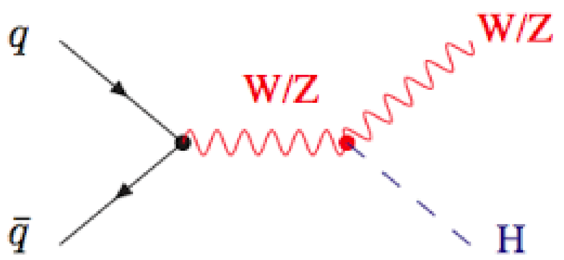




(Reduced Stage 1.1)

ATLAS: arXiv:2004.03447

WH, ZH Production with H→bb



Final states:

0-lepton: $Z \to \nu\bar{\nu}$

1-lepton: $W \to \ell\nu$

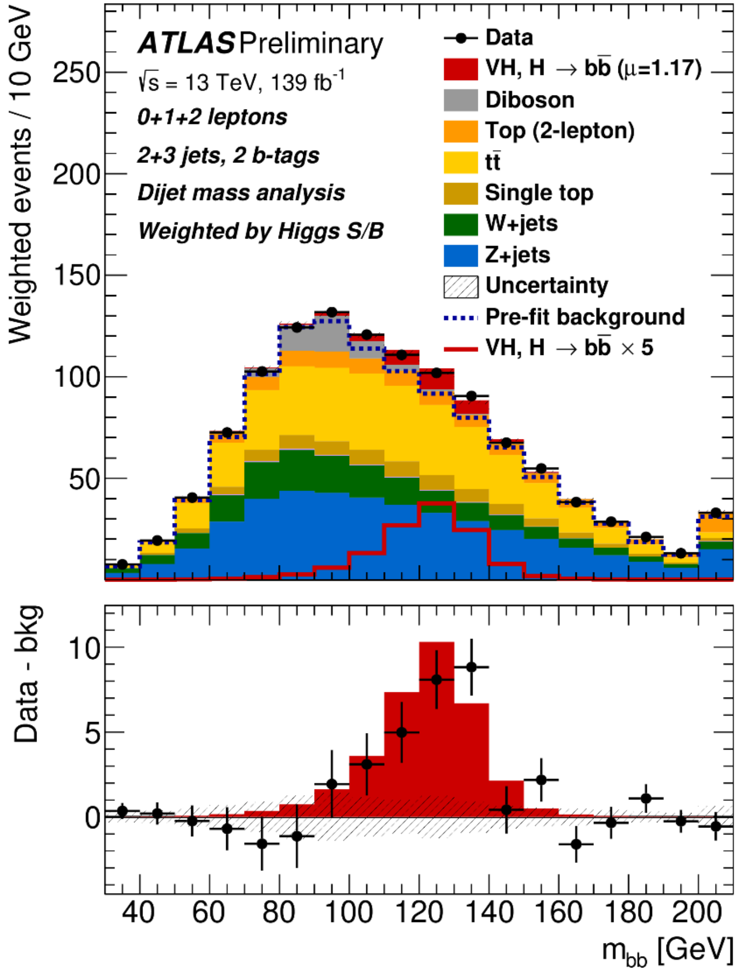
2-lepton: $Z \to \ell\ell$

SM $(m_H = 125\ \text{GeV})$:

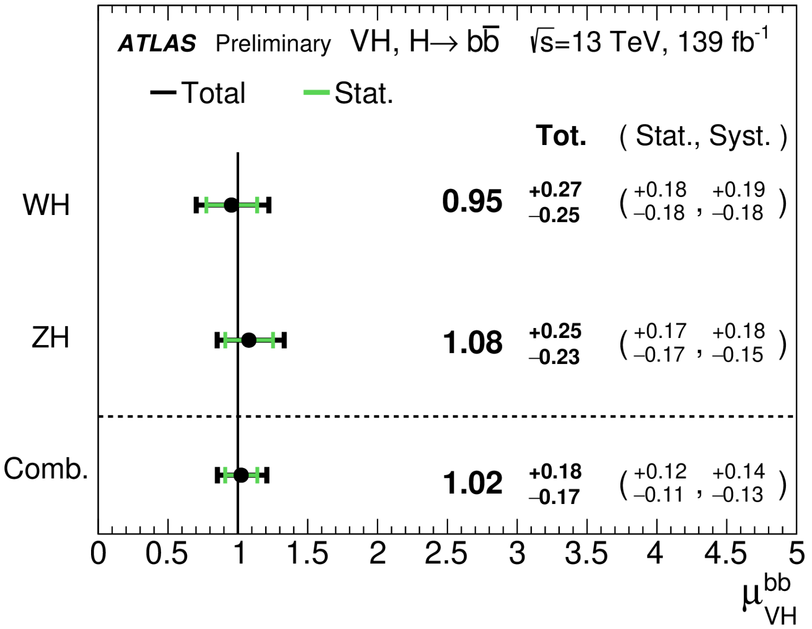
$\sigma_{WH} \simeq 1.38$ pb

$\sigma_{ZH} \simeq 0.87$ pb

$B(H \to b\bar{b}) \simeq 0.58$



ATLAS-CONF-2020-006



$$\mu_{WH} = 0.95^{+0.27}_{-0.25}, \quad \mu_{ZH} = 1.08^{+0.25}_{-0.23}$$

$$4.0\ (4.1)\sigma, \qquad 5.3\ (5.1)\sigma$$

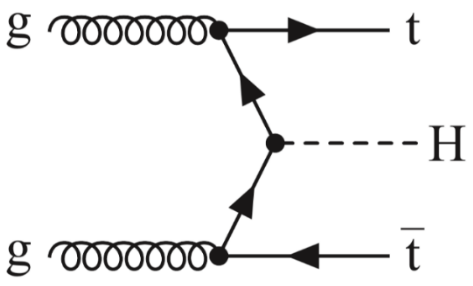
$$\mu \equiv \frac{\sigma \times B}{(\sigma \times B)_{SM}}$$

(from zero)

(Almost separate observations for WH and ZH processes)

Higgs-Top Coupling CP Structure

Extensive CP studies in the *HVV* coupling, $t\bar{t}H$ production with $H \to \gamma\gamma$ decay is idea to study the CP properties of the Higgs-fermion coupling.



Amplitude: $\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t.$

CP-odd fraction: $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$

$\sigma_{ttH}^{SM} \simeq 0.51$ pb @ 125 GeV

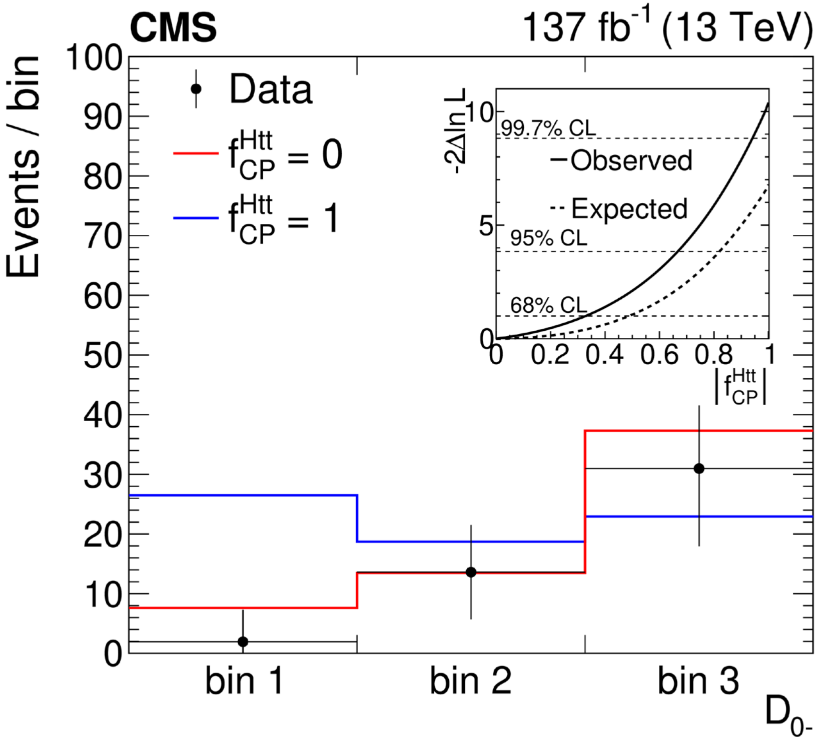
Identifying top pairs in both leptonic and hadronic final states. SM fit:

$$\boxed{\mu_{ttH} = 1.38^{+0.36}_{-0.29} \Rightarrow\ 6.6\sigma\ \left(\text{from } 0\right).}$$

Matrix-element based discriminant to extract the CP-odd fraction.

$$\mathcal{D}_{0-} = \frac{\mathcal{P}_{0+}(\vec{\Omega})}{\mathcal{P}_{0+}(\vec{\Omega}) + \mathcal{P}_{0-}(\vec{\Omega})}$$

$$\boxed{f_{CP}^{Htt} < 0.67 \text{ @ } 95\% \text{ CL}}$$

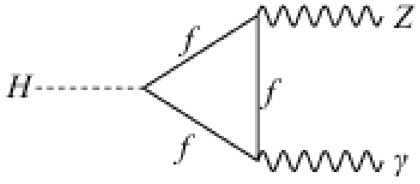


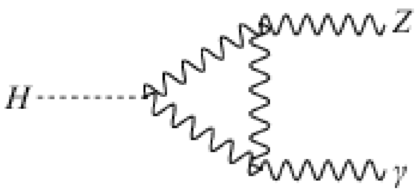
CMS: arXiv:2003.10866

Pure CP-odd *ttH* coupling is excluded at 3.2 $(2.6)\sigma$

Similar results from ATLAS: arXiv:2004.04545

Search for H→Zγ Decay





In the SM $\left(m_H = 125\ \text{GeV}\right)$:

$$B\left(H \to Z\gamma\right) \approx 0.15\%$$

Search in $Z \to ee,\ \mu\mu$ final states, full Higgs mass reconstruction, good mass resolution.

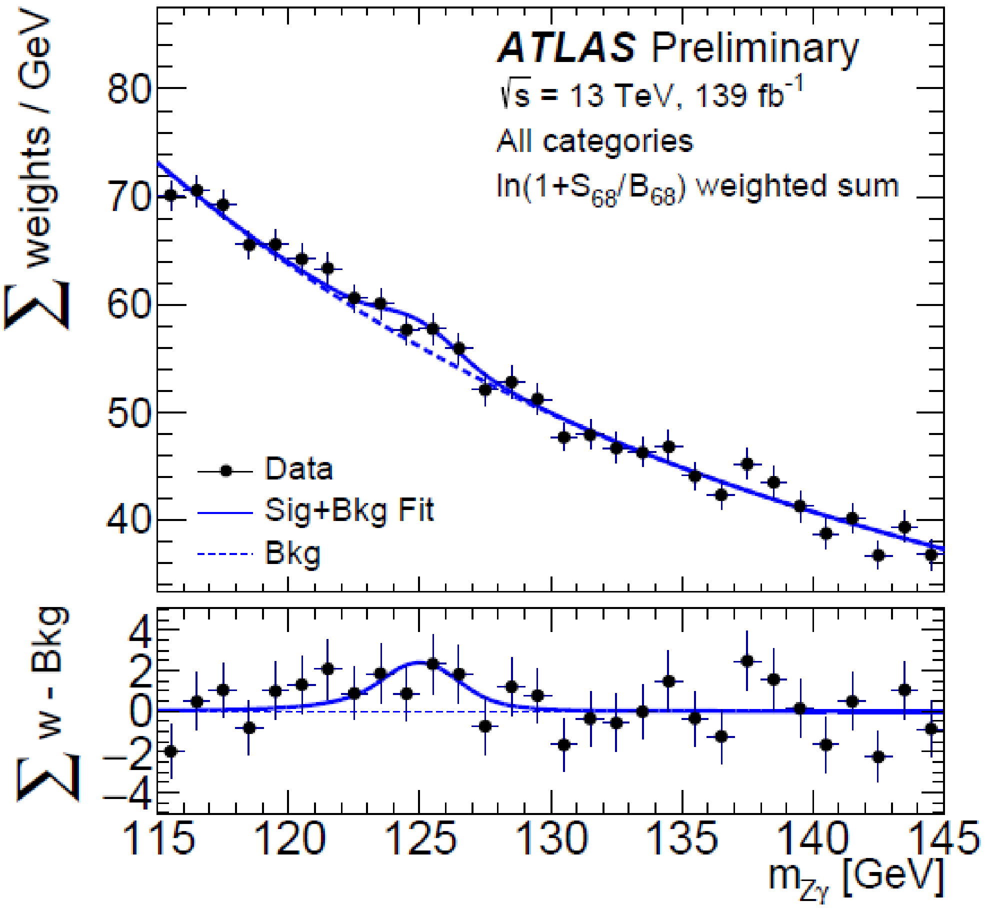
Non-resonant SM Zγ process is the main background. Multiple (6) categories to take advantage of different S/B.

Fit the mass spectra to extract the potential signal.

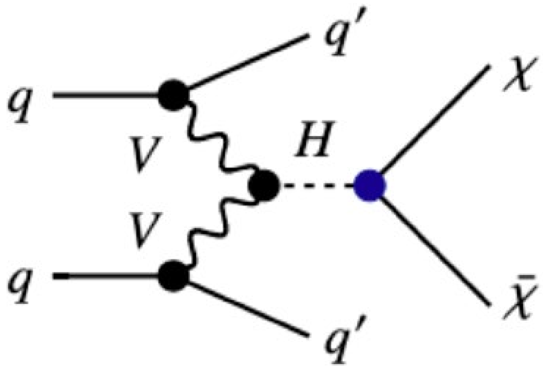
Observed $\left(\text{Expected}\right)$ significance: $2.2\ \left(1.2\right)\sigma$

$\Rightarrow \mu < 3.6\left(2.6\right)$ @ 95% CL

$\left(\mu = 2.0^{+1.0}_{-0.9}\right)$



Search for the Invisible Decay of the Higgs Boson



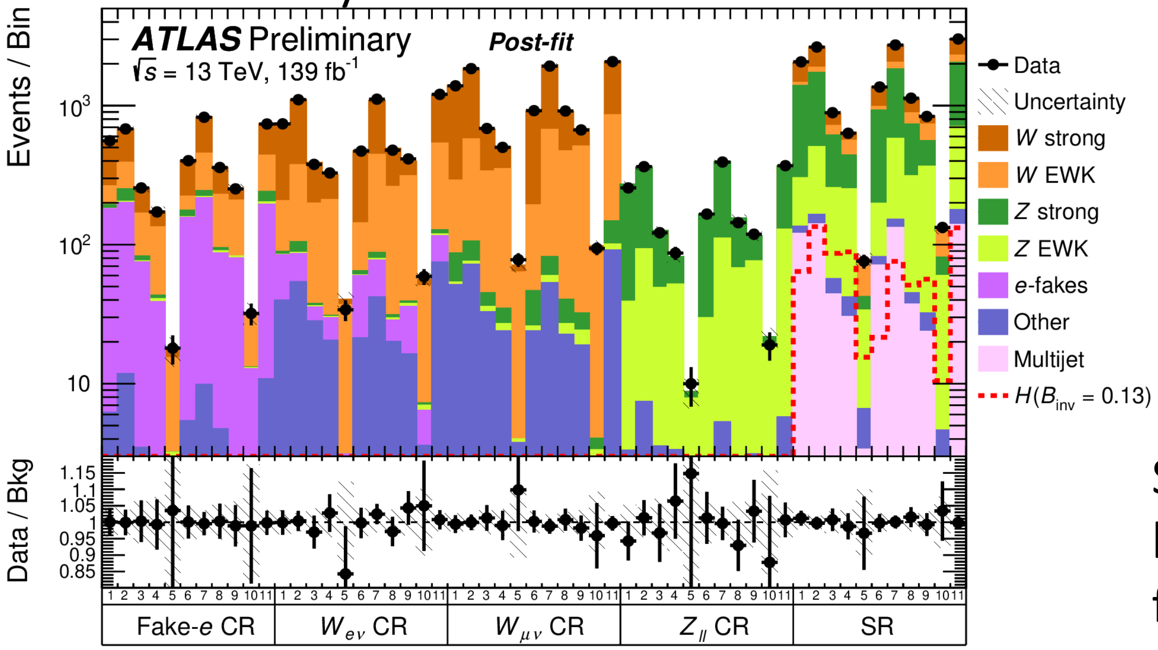
SM: $B\left(H \to ZZ^{*} \to 4\nu\right) = 0.12\%$

Two VBF tagging jets recoiling against invisible Higgs boson decay. Background dominated by V+jets events.

Multiple (11) signal regions based on the mass and azimuthal separation of the tagging jets

Data control regions to constrain contributions from different background sources.

Event yields in CRs and SRs



ATLAS-CONF-2020-008

$$B_{inv} < 13\% \ \left(13\%\right)$$

@ 95% CL

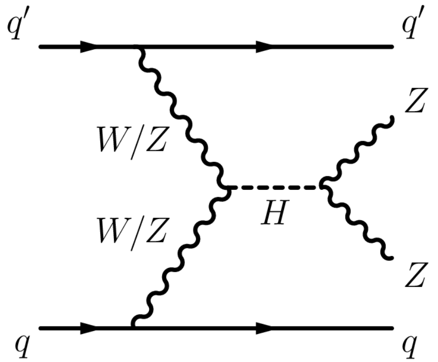
Previous analysis $\left(36.1\ \text{fb}^{-1}\right)$

$B_{inv} < 0.37\left(0.28\right)$ @ 95% CL

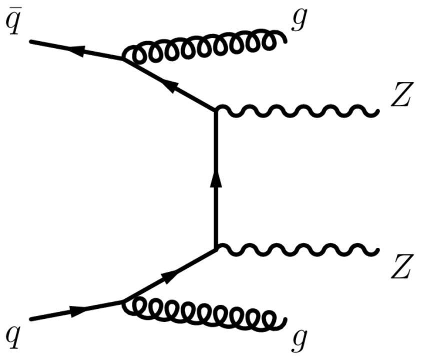
ATLAS: arXiv:1809.06682

Significant improvement beyond the dataset increase from improved analysis!

Observation of VBS ZZ Production



Signal (EW)



Background (QCD)

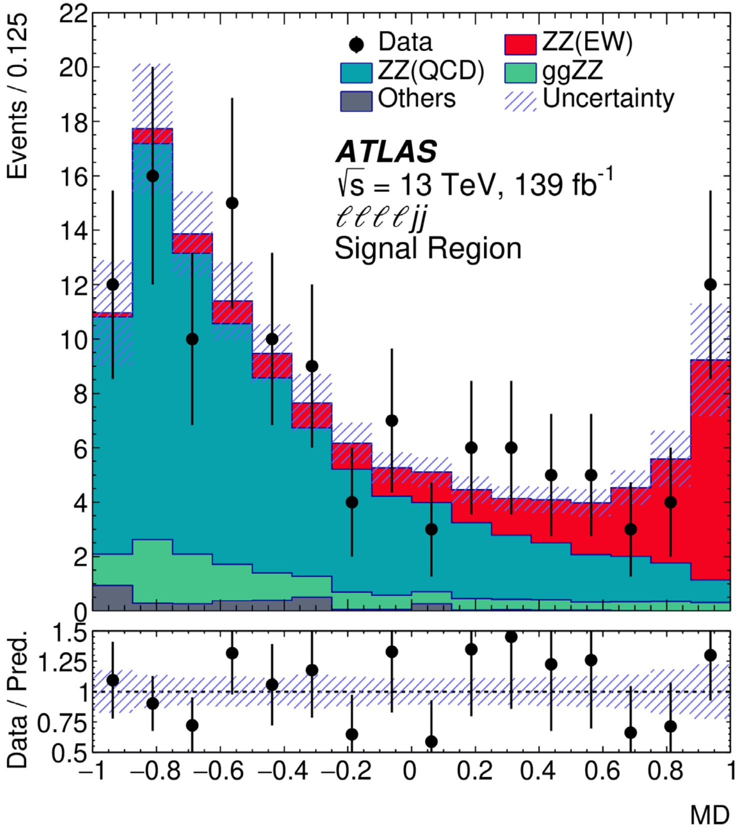
Signal: Production of ZZ pairs with two jets, with only EW vertices at the lowest order

Background: Production of ZZ pairs with two jets, with QCD vertices.

Select two tagging-jets, consider $ZZ \to 4\ell$, $\ell\ell\nu\nu$ final states.

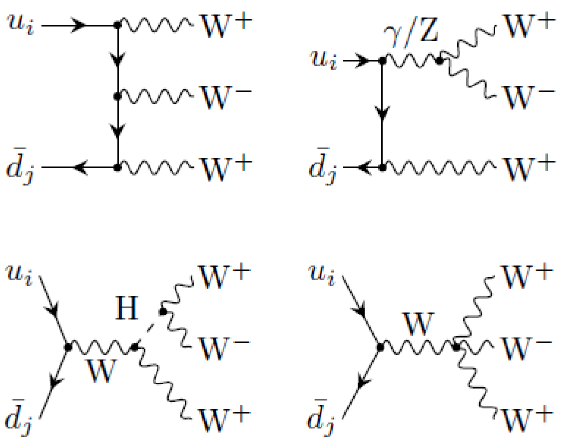
Use control regions to constrain major background contributions, BDT based multivariate discriminant to improve S/B separation

No EW production hypothesis is excluded at 5.5 $(4.3)\sigma$.

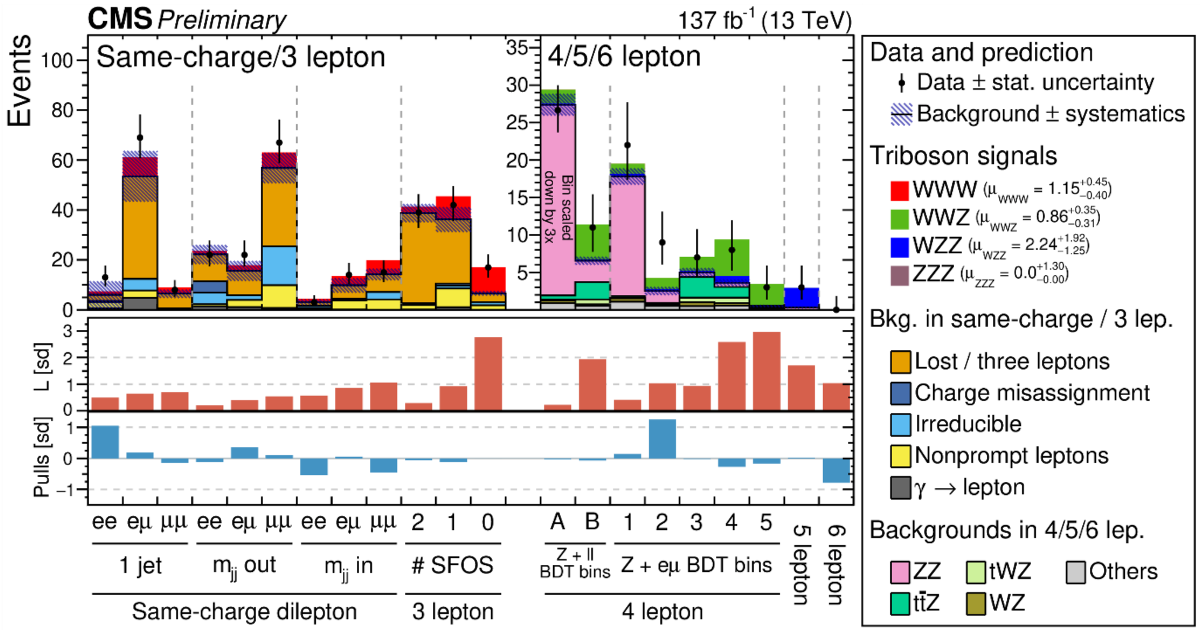


ATLAS: arXiv:2004.10612

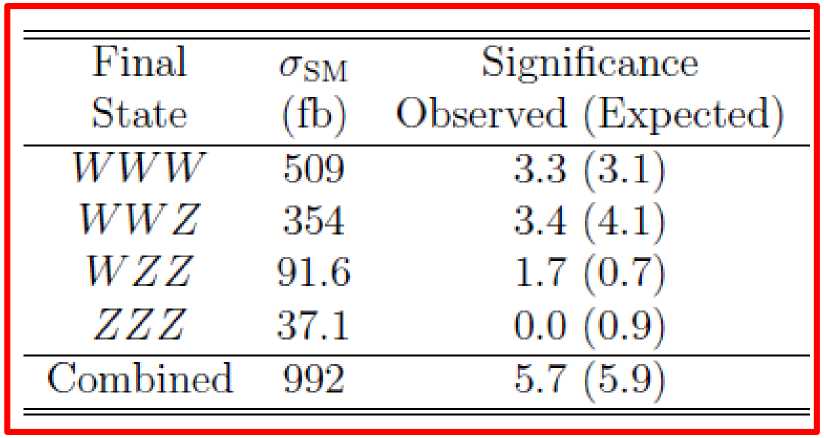
Observation of VVV Production



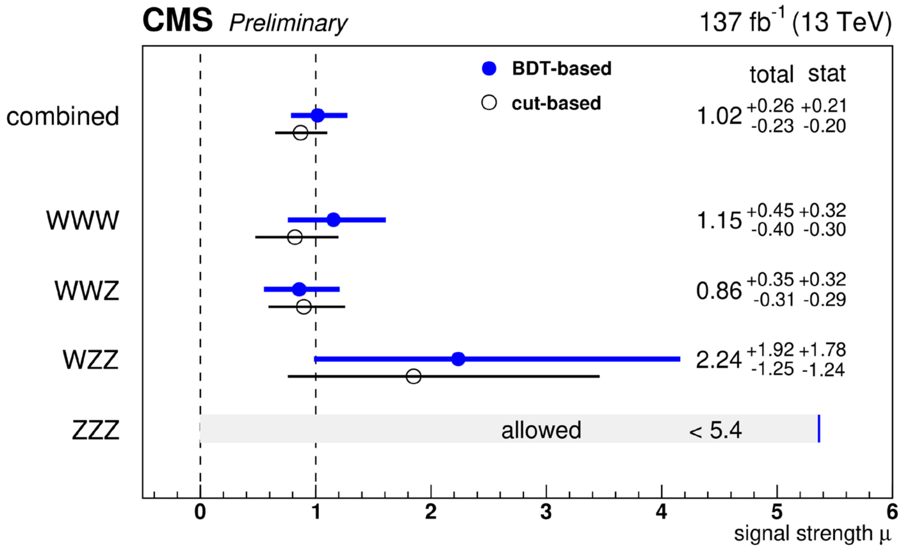
Diagrams of Higgs, trilinear and quartic couplings.



Look for *same-sign dilepton and multi-lepton* signatures



Final State	σ_{SM} (fb)	Significance Observed (Expected)
WWW	509	3.3 (3.1)
WWZ	354	3.4 (4.1)
WZZ	91.6	1.7 (0.7)
ZZZ	37.1	0.0 (0.9)
Combined	992	5.7 (5.9)



CMS-PAS-SMP-19-014

New Techniques and *New* Ideas

Changing analysis landscape

- Wide application of machine learning techniques, from searches, object identifications, to triggers;
- Proliferation of signal regions to maximize S/B separation;
- Exploring rare SM processes, challenging theoretical calculations;
- Emerging prominence of SSML final states, requiring new techniques for suppressing fake lepton contributions; …

New techniques and signatures

- Large-radius jets with substructures for highly boosted V and top decays;
- Highly ionizing particles and displaced vertices to search for long-lived particles;
- Tagging of charm-jets, tagging of quark-jets from gluon-jets; …

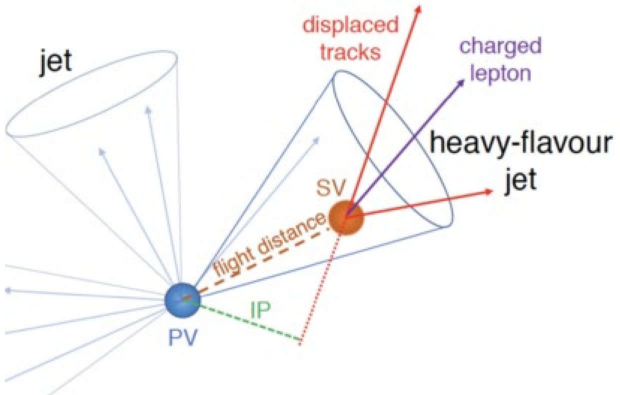
Theoretical development

- Descriptions of experimental results in the framework or using the parameterization of EFT, STXS, and simplified models;
- Higher order corrections to constrain potential BSM physics;
- New BSM models; …

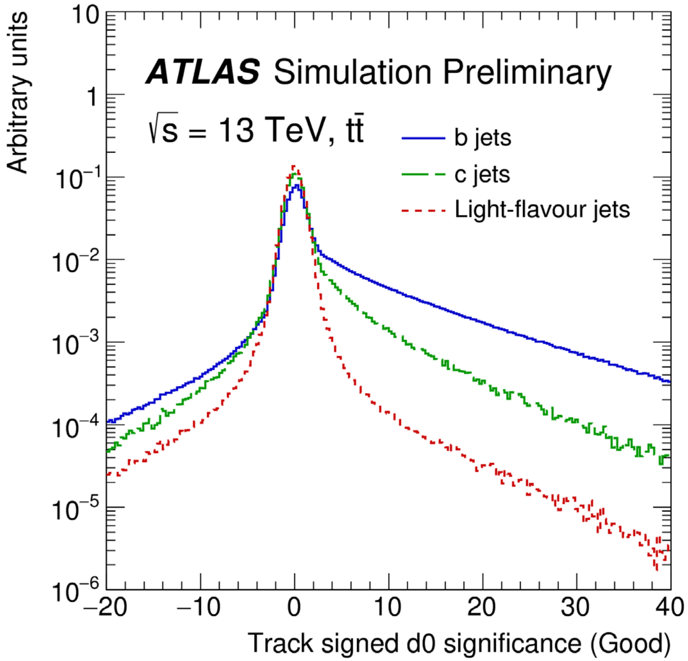
In the following slides, I will attempt to sample some of these points…

Tagging c-Quark Jets

Tagging c-quark jets is critical for the direct measurement of the Higgs-charm coupling, Important for testing Yukawa coupling beyond the 3rd generation.



Jet flavor tagging is largely based on hadron lifetimes:
⇒ measurable decay distances $c\tau_c \sim 100\ \mu m,\quad c\tau_b \sim 500\ \mu m$



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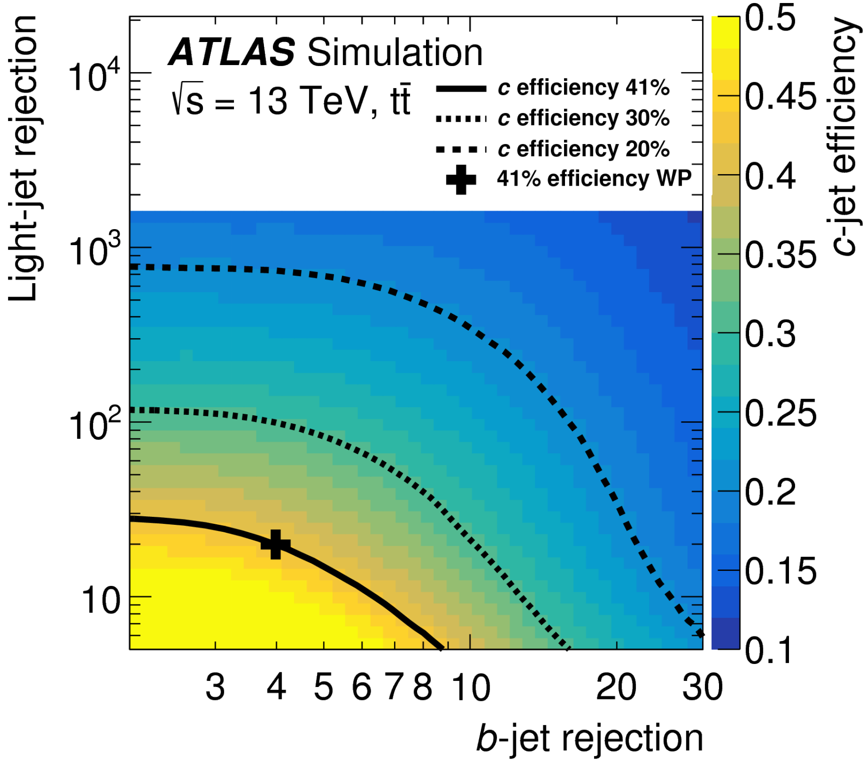
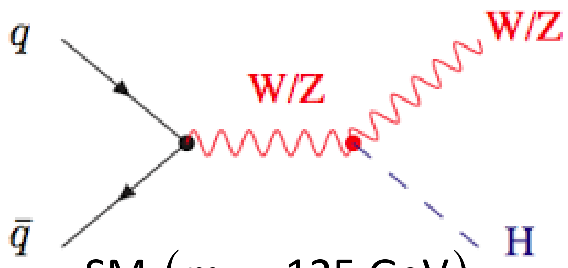


c-jet tagging is particularly challenging,
large backgrounds from both light-quark and b-quark jets.

Search for $H\to cc$ Decay

Like the $H\to b\bar{b}$ decay, cannot trigger on the decay $\Rightarrow$ associated production $\Rightarrow$ almost the same final state as the $VH(b\bar{b})$.

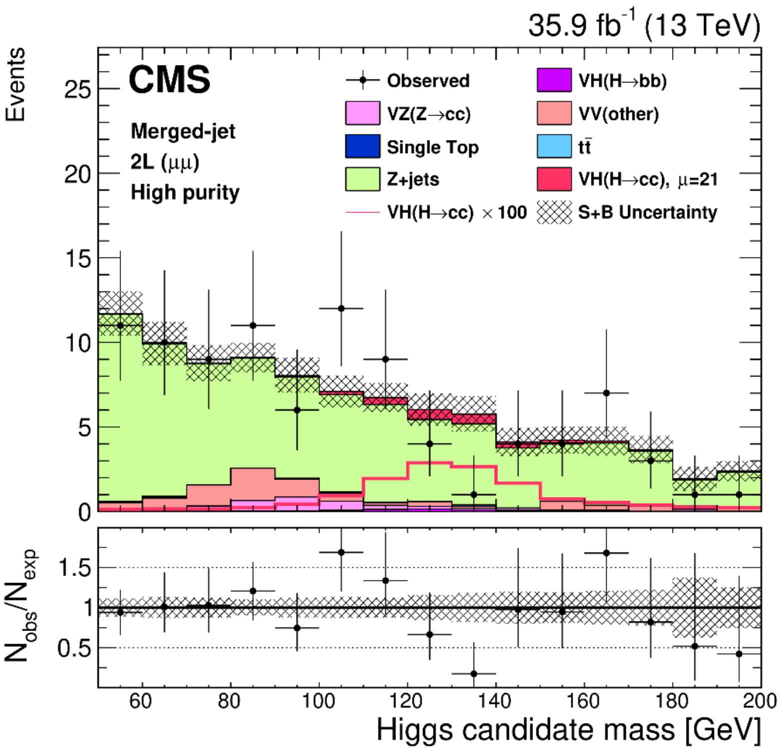
b/c-jet tagging is the only tool for separating the two. Worse, $B\left(H\to b\bar{b}\right)\approx 20\times B\left(H\to c\bar{c}\right)$

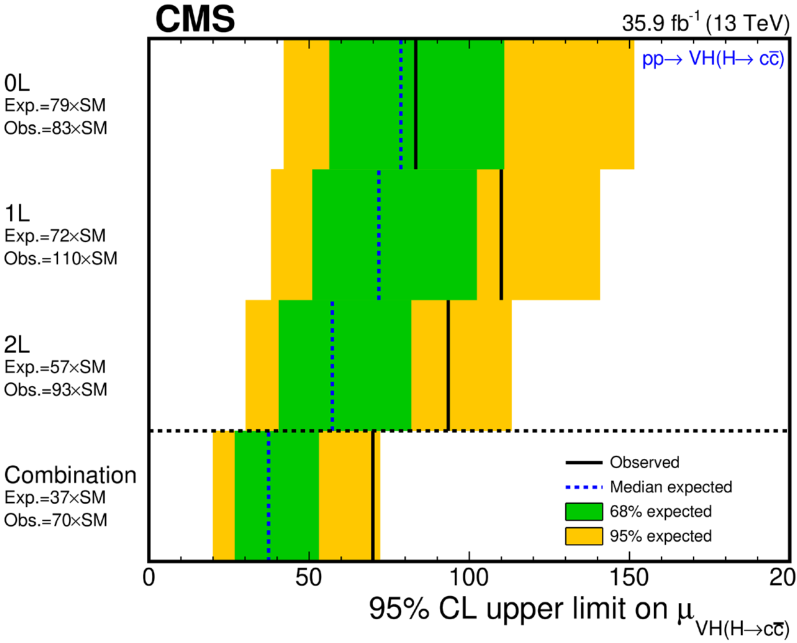


SM $\left(m_H = 125\ \text{GeV}\right)$:

$\sigma_{VH}\approx 2.3$ pb

$B\left(H\to c\bar{c}\right)\approx 2.9\%$





arXiv:1912.01662 (CMS)

$$\sigma_{VH}\times B\left(H\to c\bar{c}\right) < 4.5\ \left(2.4^{+1.0}_{-0.7}\right)\ \text{pb}$$

Still long way to be sensitive to SM

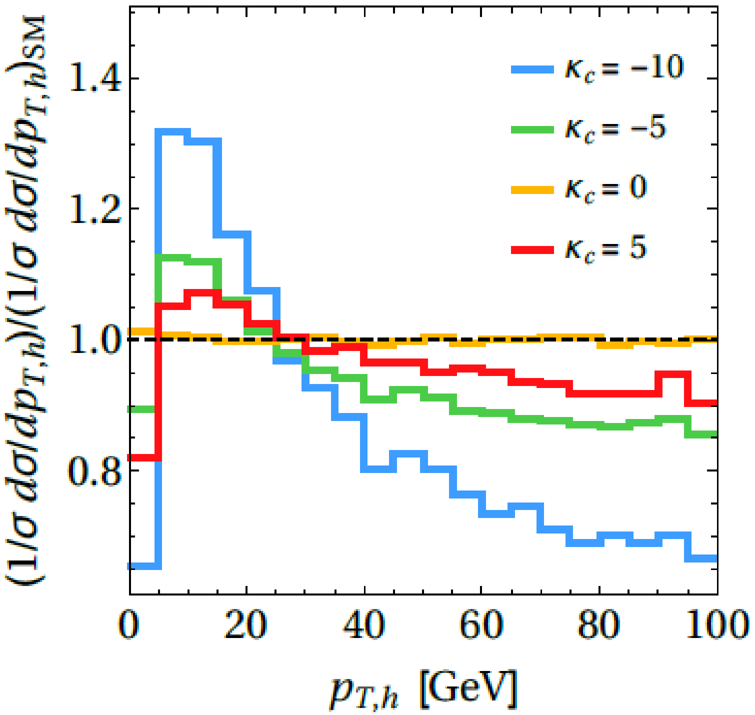
Hcc Coupling from Higgs pT Distribution

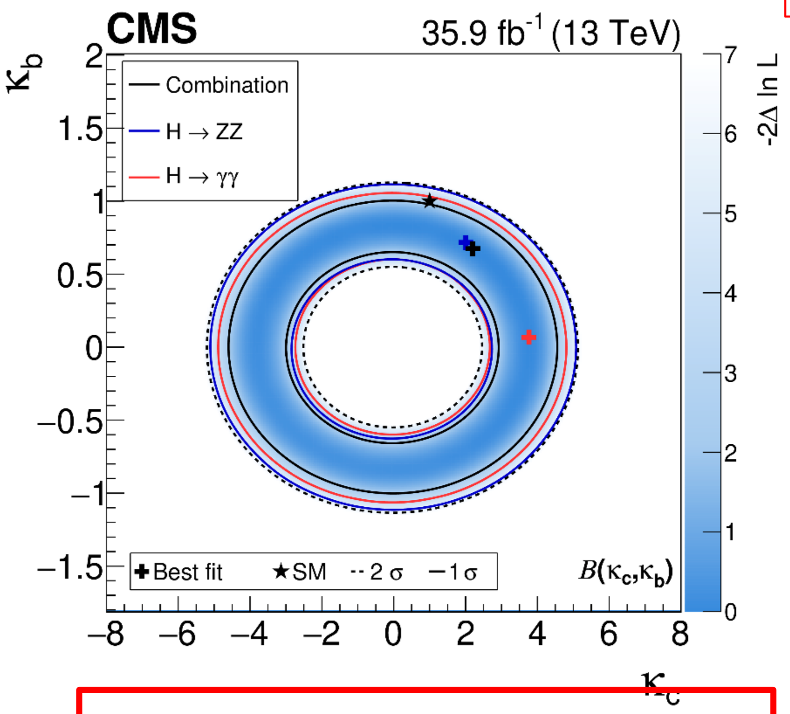
- An enhanced Higgs coupling to charm quark will modify the inclusive Higgs p_T^H distribution due to enhanced $gQ \to HQ$ contribution.
- Constraint on the Higgs-charm coupling can be obtained from the the measured p_T^H distribution, e.g., from $H \to \gamma\gamma$ and $H \to 4\ell$

$$\boxed{\kappa = \frac{y}{y_{SM}}}$$

Higgs p_T shape modifications

Bishara et al., arXiv:1606.09253





CMS: PLB 792 (2019) 369

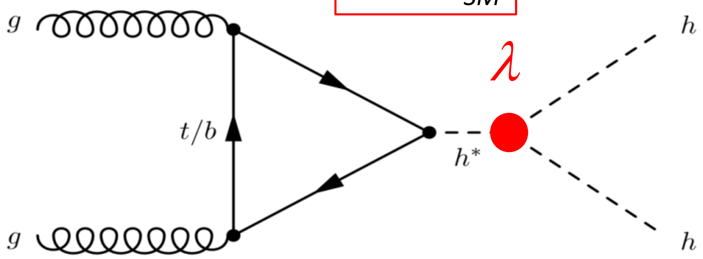
$$\boxed{-4.9 < \kappa_c \equiv \frac{y_c}{y_c^{SM}} < 4.8 \text{ @ 95\% CL}}$$

(Similar results from ATLAS: arXiv:2004.03969)

(from both the rate and shape info.)

Higgs Boson Self-Coupling

$$\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}$$



$\sigma(gg \to hh) \approx 40$ pb @ 13 TeV

Higgs boson self-coupling can be directly probed through the measurement of the Higgs boson pair production

95% CL intervals:

ATLAS: $-5 < \kappa_\lambda < 12$ (arXiv:1906.02025)

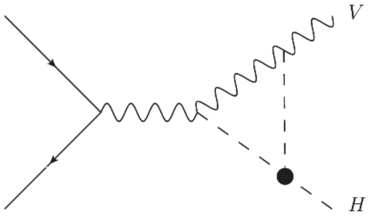
CMS: $-11.8 < \kappa_\lambda < 18.8$ (arXiv:1811.09689)

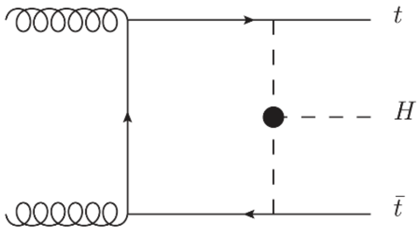
(from 36 fb^{-1} dataset)

Single Higgs boson production and decay are also sensitive to the self-coupling through Higher-order corrections.

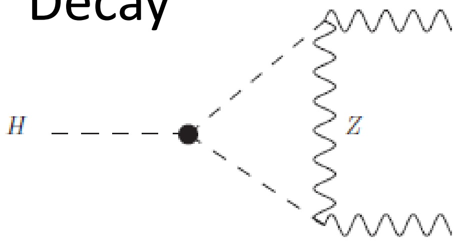
These corrections are generally small in the SM, but can be large for large coupling modifications.

Production:



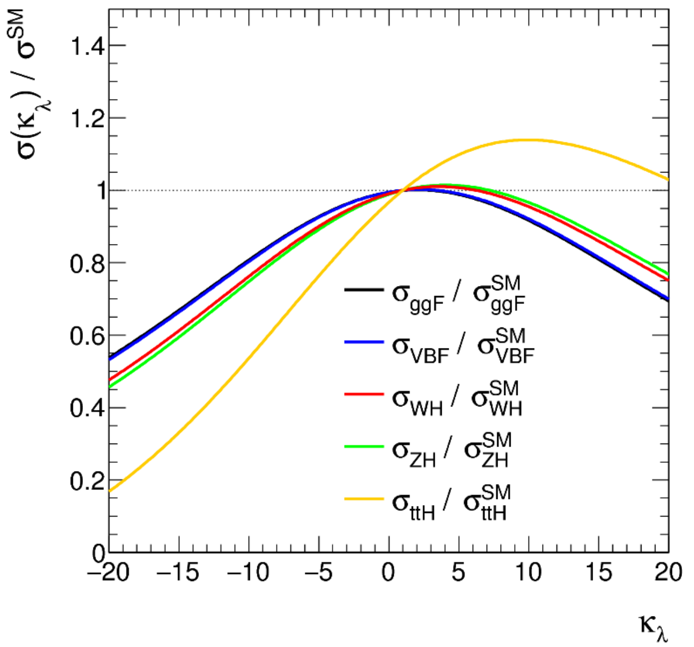


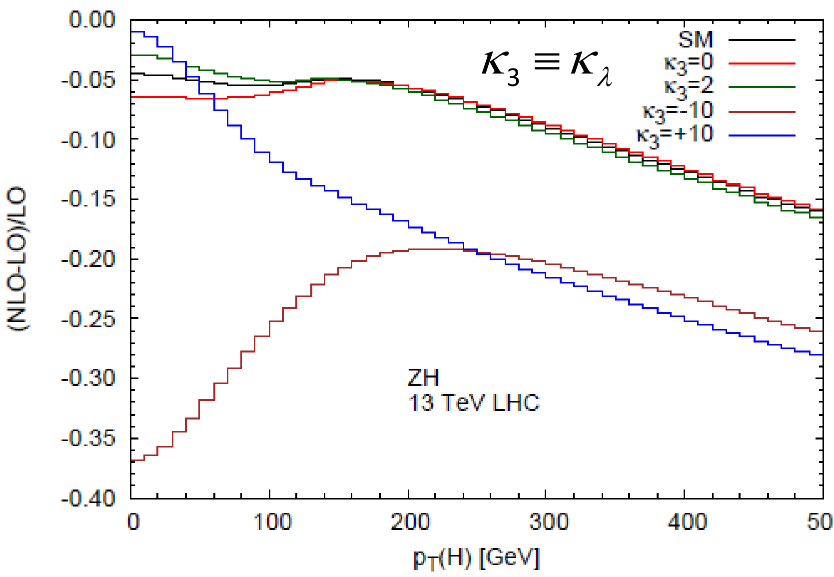
Decay



Higgs Boson Self-Coupling

Large self-coupling modification will lead to significant changes to the inclusive rates as well as event kinematics





G. Degrassi et al., arXiv:1607.04251

F. Maltoni et al., arXiv:1709.08649

ATLAS used both the rates and kinematic information
CMS used the inclusive rates information only

ATL-PHYS-PUB-2019-009
CMS-PAS-HIG-19-005

ATLAS: $\kappa_\lambda = 4.0^{+4.3}_{-4.1}$ or $-3.2 < \kappa_\lambda < 11.9$ @ 95% CL

CMS: $\kappa_\lambda = 6.7^{+4.6}_{-6.6}$

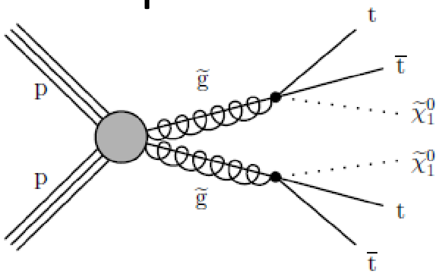
Competitive with the constraints from the direct searches

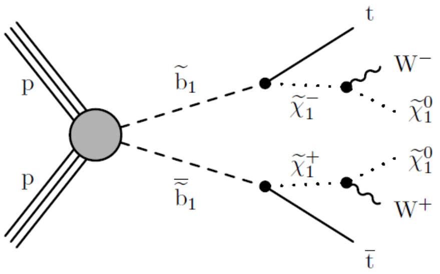
SSML: Searches for Supersymmetry

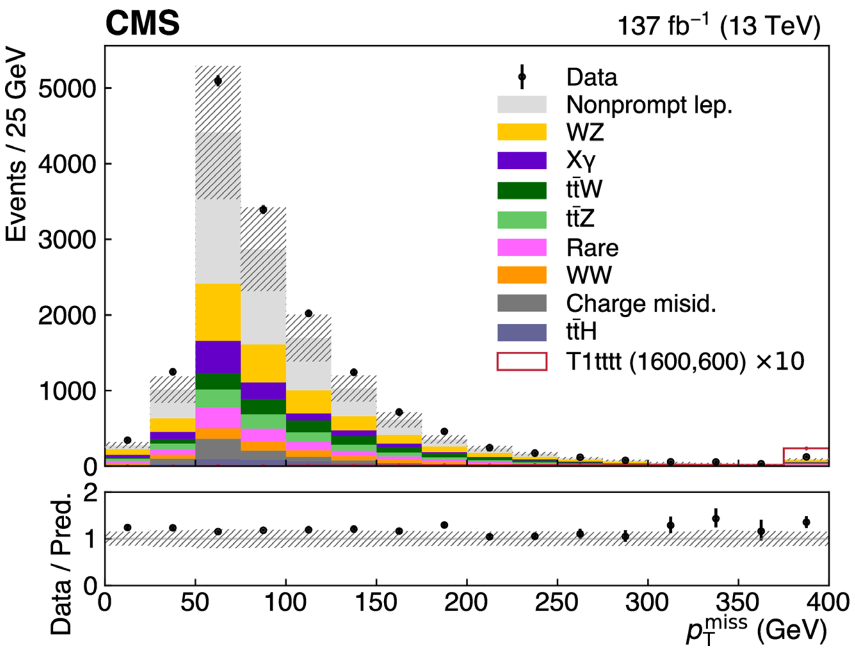
- Same-sign dilepton and multi-lepton events (SSML) have relatively low rates in the SM.
- Are expected in many extensions to the Standard Model
  Often produced in the cascade decays of heavy particles.
- Good generic signatures for many BSM scenarios

CMS studied SSML events with at least two jets to search for SUSY and set constraints on many SUSY models

Examples:







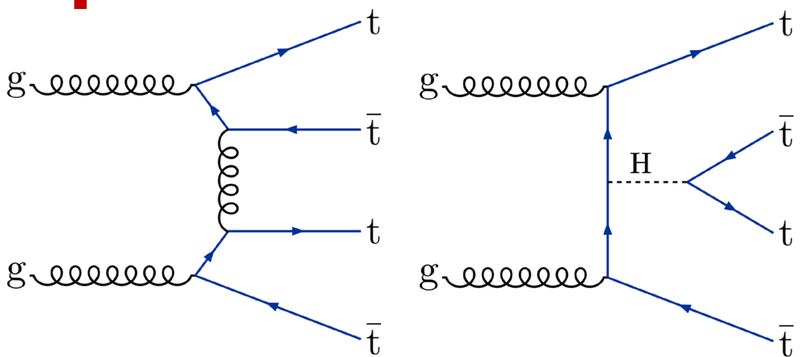
CMS: arXiv:2001.10086

SSML: Search for Four-Top Production

Rare process in the SM, interesting for Higgs and BSM physics.

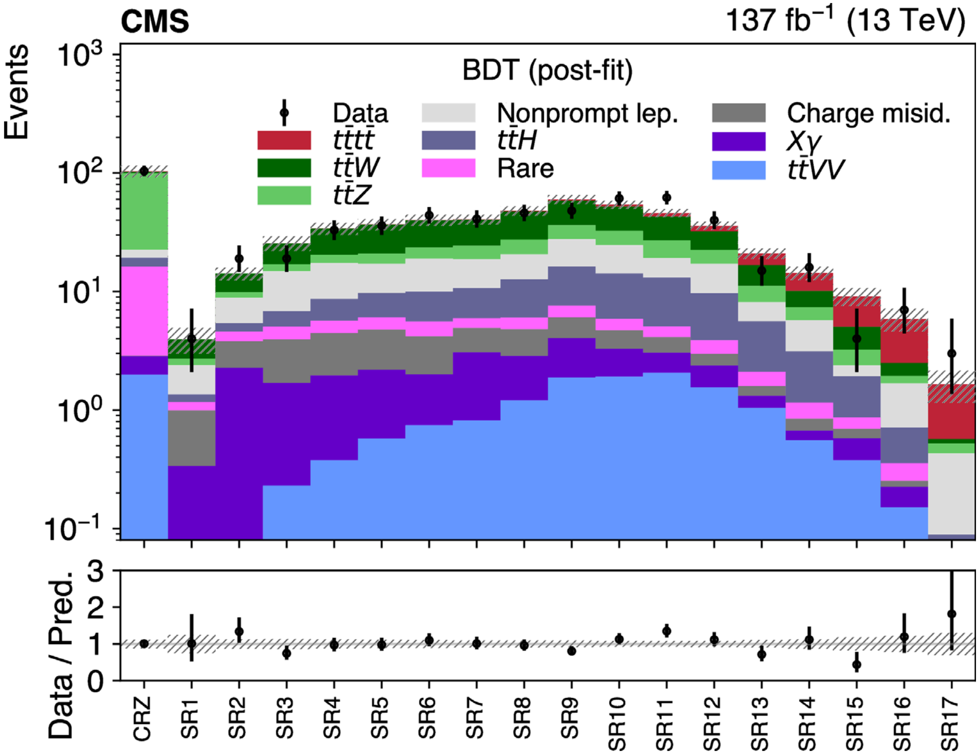
Signature: SSML events with multiple light-flavor and b-quark jets.

Backgrounds: dominated by the *ttX (X=V,H)* processes and fakes.



$$\sigma_{SM} \simeq 12 \text{ fb}$$

$$B\left(4t \rightarrow SSML\right) \approx 12\%$$



CMS: arXiv:1908.06463

BDT to improve S/B separations. 17 discrete BDT bins as SRs.

Using theoretical calculations and measurements to constrain ttX backgrounds.

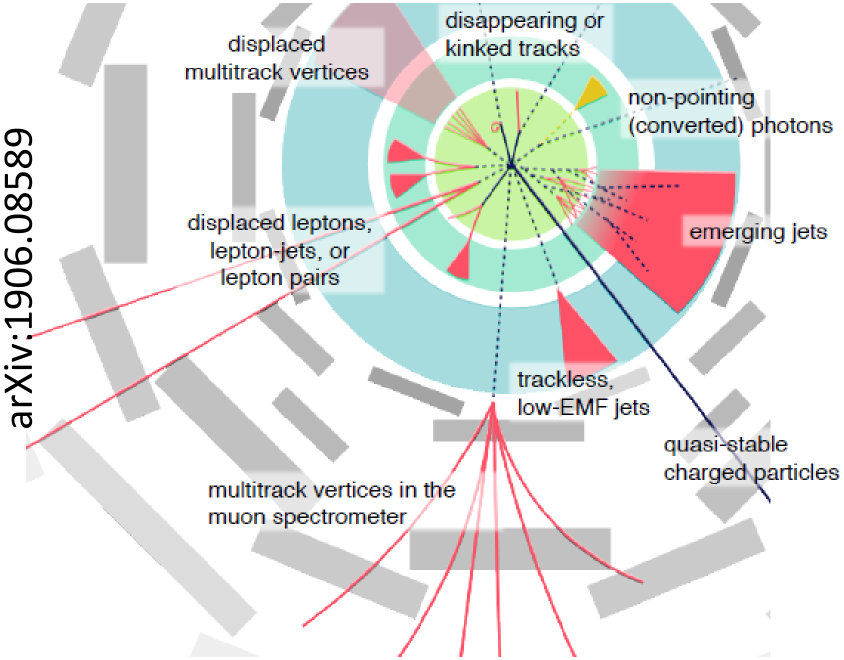
$$\boxed{\begin{array}{l}\sigma_{tttt} = 12.6^{+5.8}_{-5.2} \text{ fb} \\ \Rightarrow\ 2.6\sigma \text{ significance}\end{array}}$$

Long-Lived Particles

Particle decay distance often determines how it can be detected:

- $\gamma c\tau <\sim 1$ cm $\Rightarrow$ detect daughter particles
- $\gamma c\tau >\sim 10$ m $\Rightarrow$ decay outside the detector, detect parent particle

LLPs: new particles that decay in the detector, could be both neutral or charged



arXiv:1906.08589

Signatures:

displaced vertices, non-prompt jets, disappearing tracks, highly ionizing charged particles, stopped particles, …

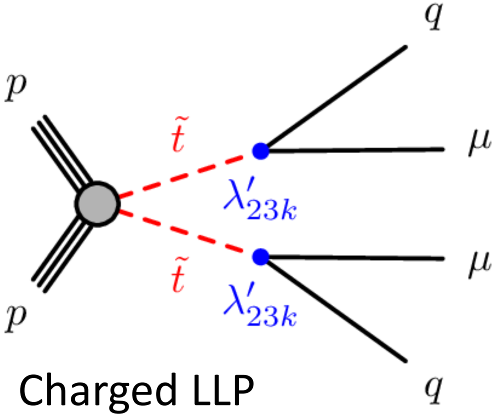
Backgrounds are expected to small compared with standard signatures

Challenges:

These events are generally not recorded, need special trigger and reconstruction software

LHC potential for LLP searches has been discussed extensively in arXiv:1903.04497. Many searches have been performed.

Search for Long-Lived Particles

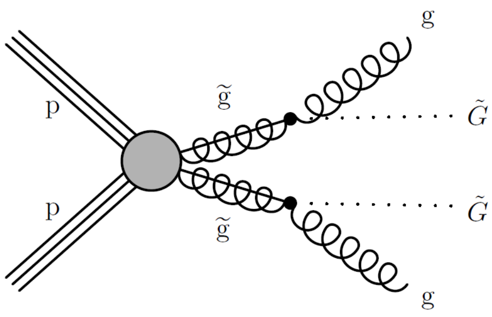


Charged LLP

Decay inside the detector

⇐ Displaced vertices

Non-prompt jets ⇒

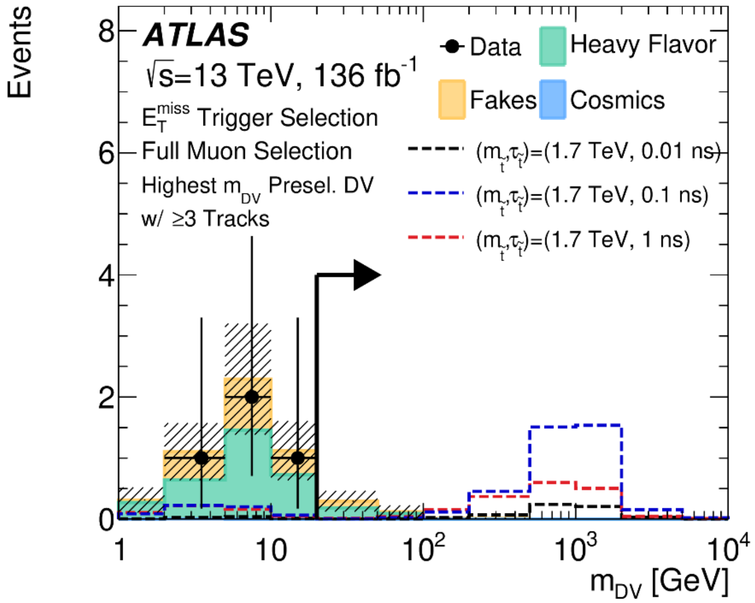


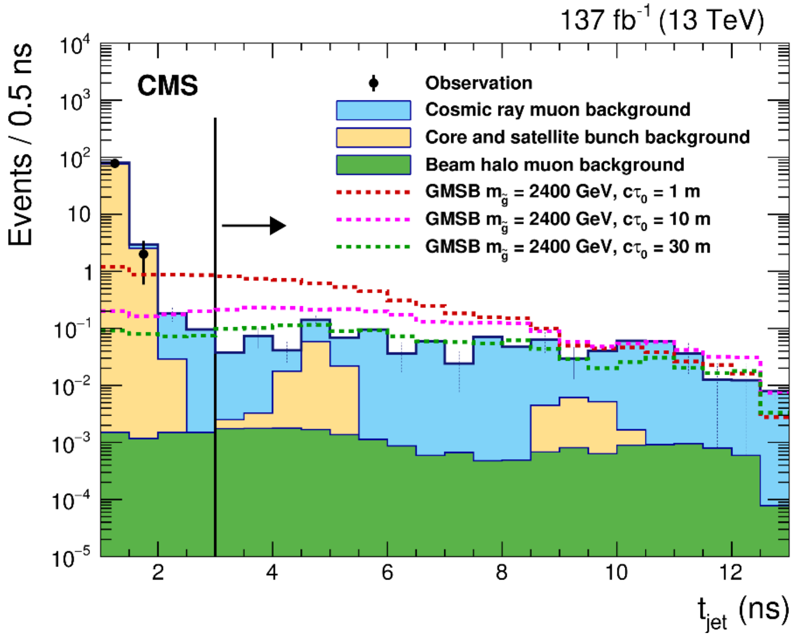
Neutral LLP

Reconstruct DVs in the inner detector from tracks with large displacements, DV mass as the discriminant

Use calorimeter timing to identify non-prompt jets, extending the search to proper decay distance $c\tau <\sim 1$ m

ATLAS: arXiv:2003.11956



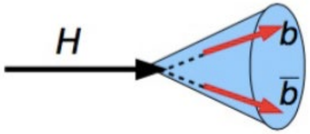


CMS: arXiv:1906.06441

Highly Boosted Particles

For $H \to b\bar{b}$, the $b\bar{b}$ angular separation: $$\Delta R_{b\bar{b}} \sim \frac{2m_H}{p_T^H}$$

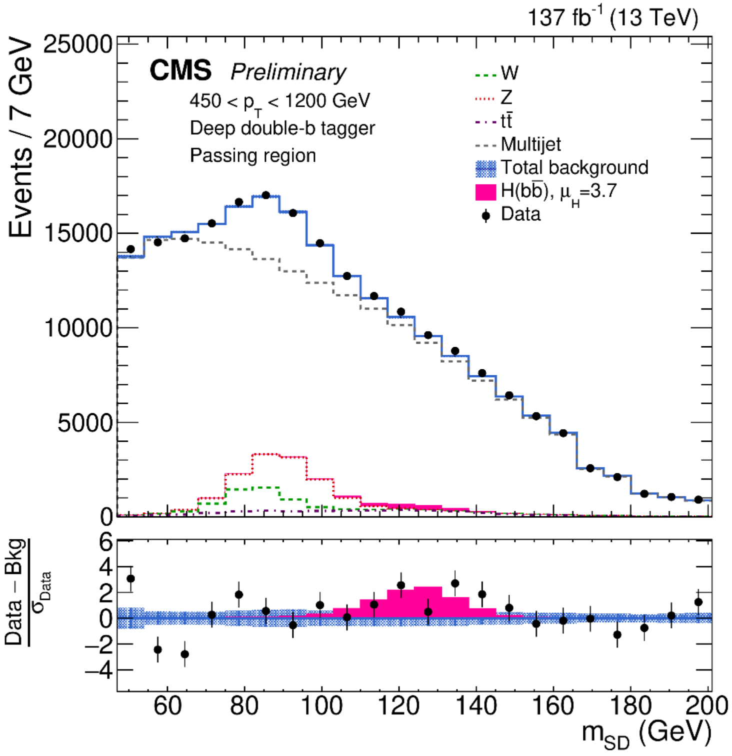
The two jets from b-quarks cannot be efficiently resolved in the detector if $p_T^H \gg m_H$, more efficient to reconstruct them as a single large-radius jet (J).

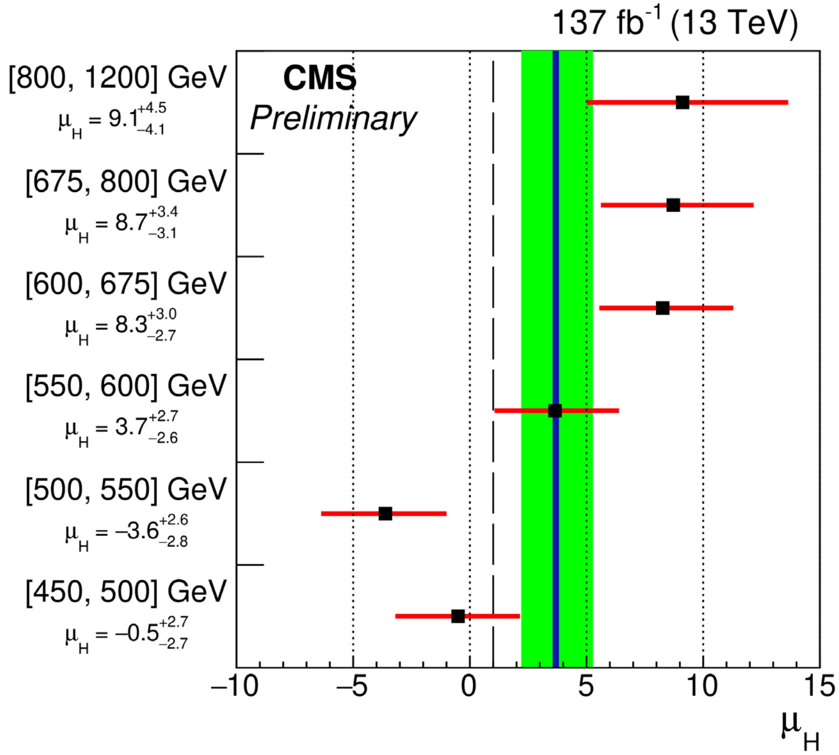


Boosted particle tagging technique significantly improves our ability to study high-p_T phenomena.

Example: CMS inclusive $H \to b\bar{b}$ measurements.

CMS-PAS-HIG-19-003

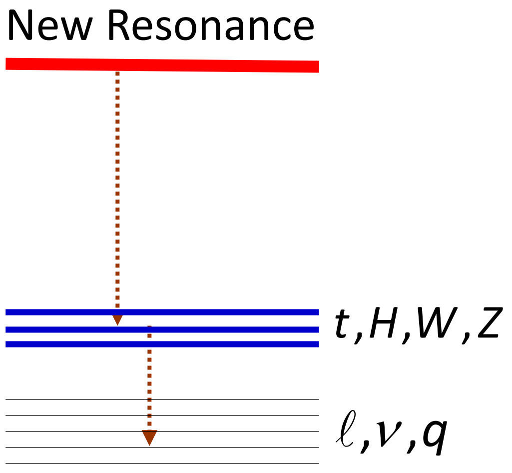




Highly Boosted Particles

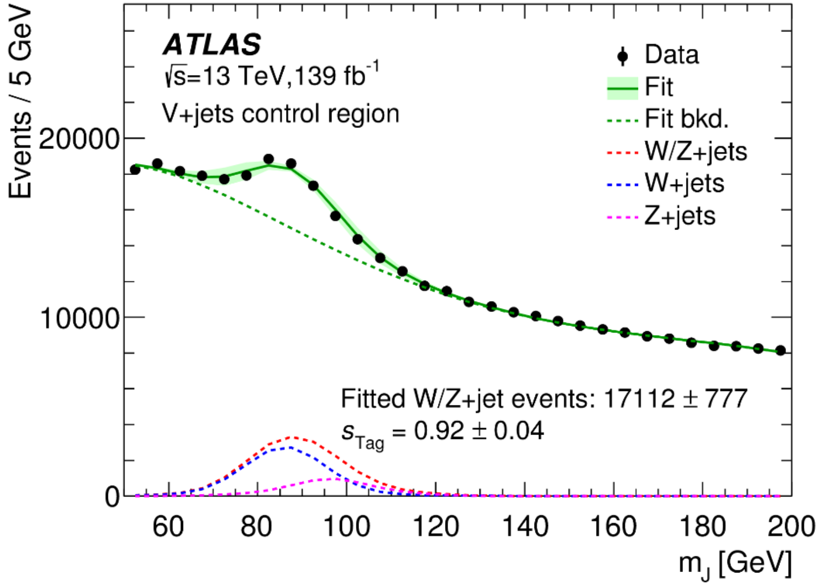
As the mass exclusion pushed higher, the mass gaps between new resonances and SM particles get larger ⇒ highly boosted SM particles in decays.

This feature has been extensively exploited in searches for heavy resonances, particularly in new diboson and ditop resonances, pushing searches to multi-TeV mass regime.

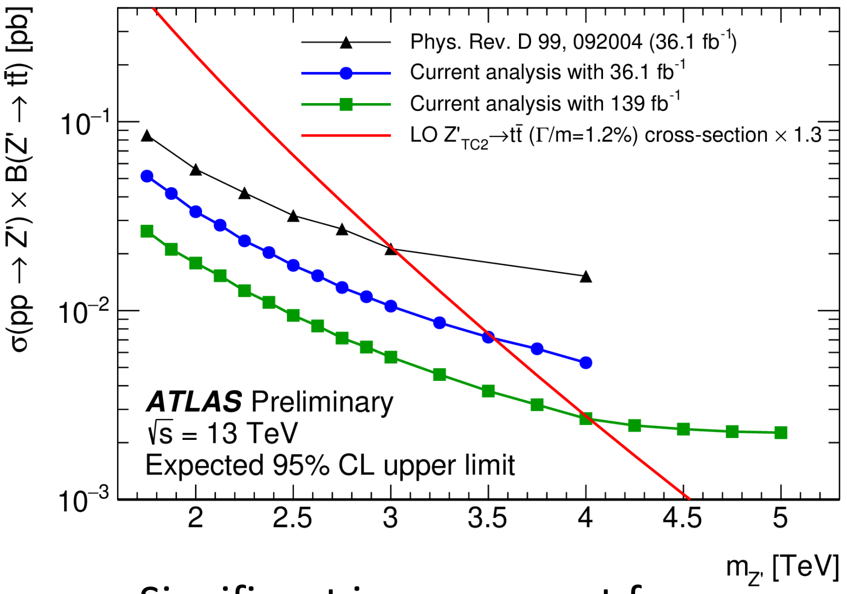


$$X \to VV \to (q\bar{q})(q\bar{q}) \to JJ$$

ATLAS: arXiv:1906.08589



$$Z' \to t\bar{t} \to JJ$$



ATLAS: to be submitted

Significant improvement from DNN top tagger

Machine Learning for Particle ID

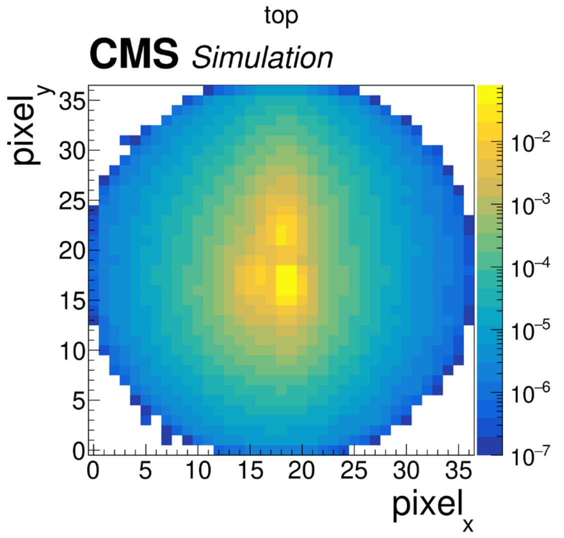
Machine learning techniques are prevalent in analyses at the LHC for sometime, they are now being applied to particle identifications as well.

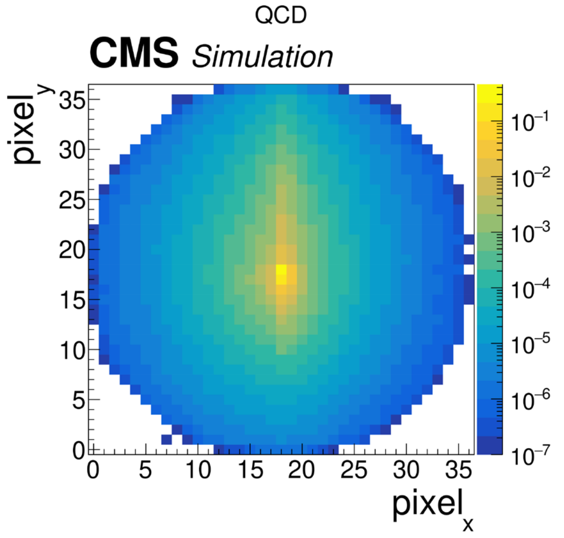
ImageTop:
an algorithm developed by CMS to discriminate energetic hadronically decaying top-quark jets from QCD jets.

- It uses standard image recognition technique based convolutional neural network.
- Pixelizing the jet energy deposits and define different channels based on relevant detector information.

For $1000 < p_T < 1500$ GeV, a rejection of ~ 100 for QCD jets with a 50% efficiency for top jets can be achieved.

These new techniques pave the way for more innovative analyses !





CMS: arXiv:2004.08262

Concluding Remarks

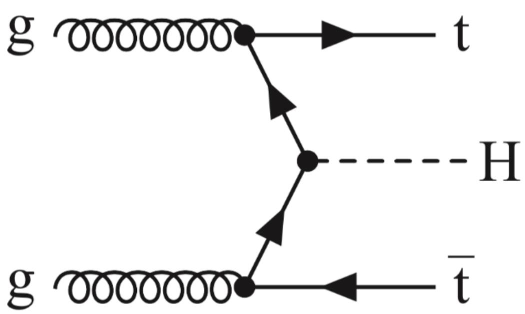
- Many new results from the LHC. Standard Model is alive and well. No indication of BSM physics… unfortunately
  (see talks at this symposium and ATLAS and CMS for additional information)
- LHC will run for the next 15+ years. With 95% of the data is yet to come, precision measurements and studies of rare processes are likely to be the focus.
  (see the next presentation by Anadi Canepa).
- With limited potential for increasing in energy, now is more than ever for new calculations, techniques, and ideas for exploring the LHC physics potential to the fullest.

Thank you for your attention!

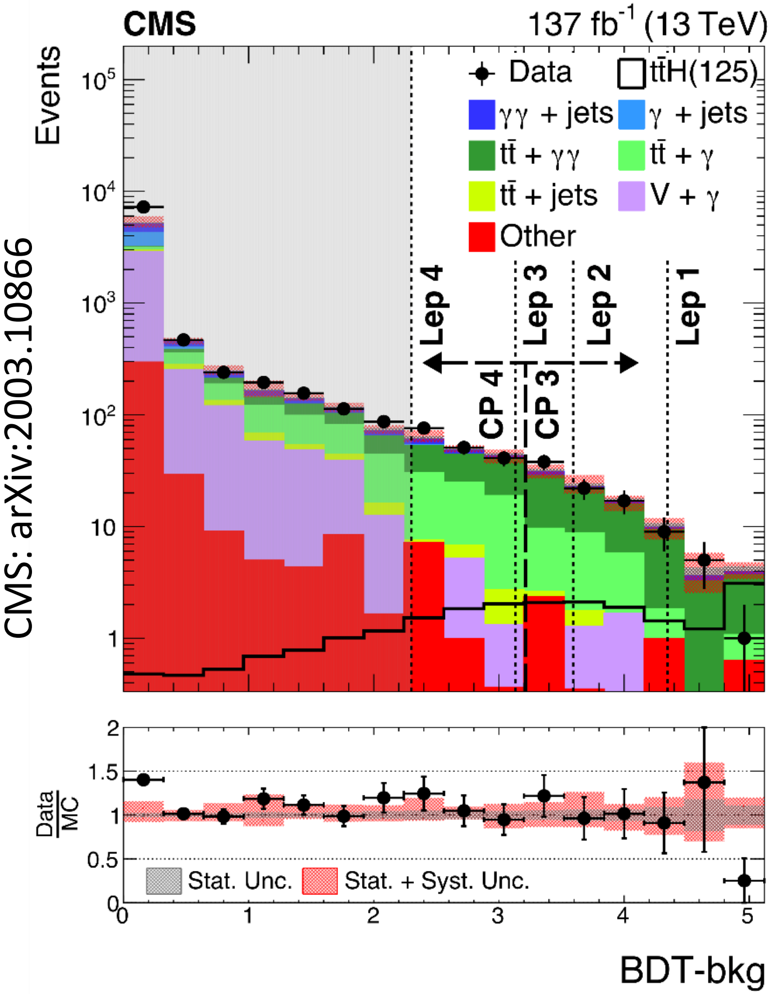
Additional Slides

ttH Production with H→γγ

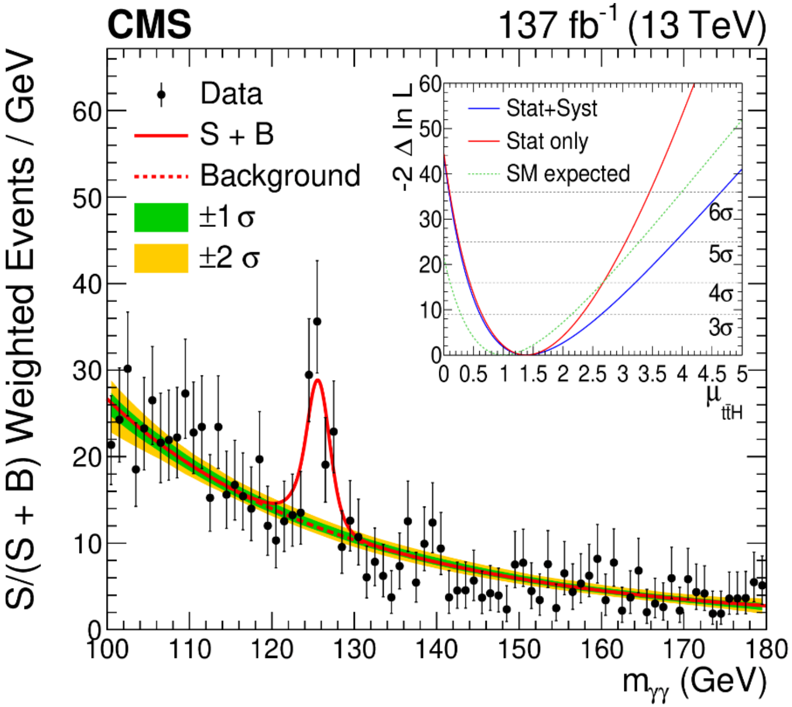
Identify top-pair using their hadronic and leptonic decays, BDT for S/B separation



$\sigma_{ttH}^{SM} \simeq 0.51$ pb @ 125 GeV



CMS: arXiv:2003.10866



$$\boxed{\mu_{ttH} = 1.38^{+0.36}_{-0.29} \quad \Rightarrow \quad 6.6\sigma}$$

Higgs-Top Coupling CP Structure

Similar analysis in ATLAS, with slightly different parameterization

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t\kappa_t\left[\underset{\text{CP-even}}{\underset{\Uparrow}{\cos(\alpha)}} + \mathrm{i}\,\underset{\text{CP-odd}}{\underset{\Uparrow}{\sin(\alpha)}}\gamma_5\right]\psi_t\right\}H$$

CP angle: $\alpha = 0$ in the SM

$$\Rightarrow f_{CP}^{Htt} = (\sin\alpha)^2$$

Multiple (20) signal categories based on two BDTs, one for ttH-background discrimination, the other for separating CP-even and CP-odd components.

Simultaneous fit to the $m_{\gamma\gamma}$ distribution in all categories.

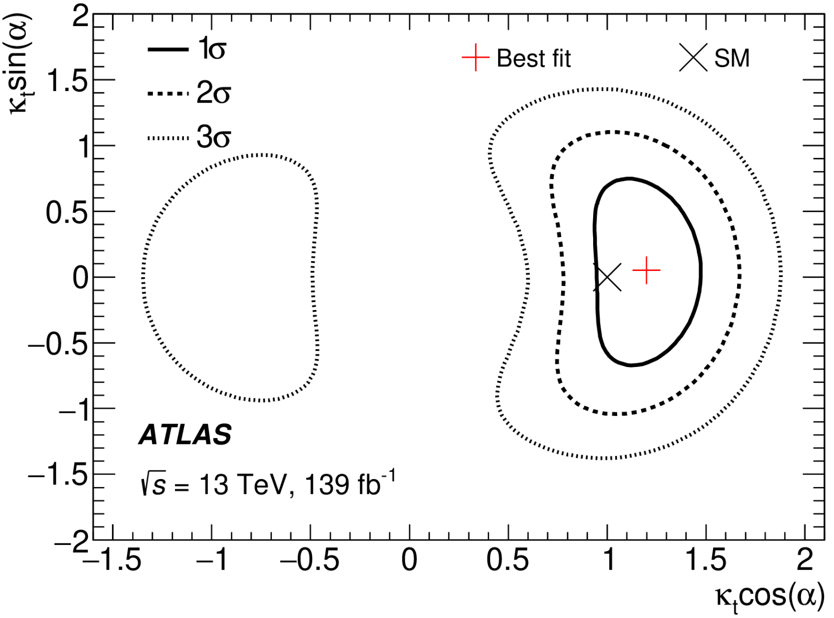
Assuming CP-even:

$$\boxed{\mu_{ttH} = 1.4 \pm 0.4 \pm 0.2 \;\Rightarrow\; 5.2\sigma}$$

With the CP mixture:

$$\boxed{|\alpha| < 43^\circ\ (63^\circ)\ @\ 95\%\ \mathrm{CL}}$$

(without prior κ_t constraint)



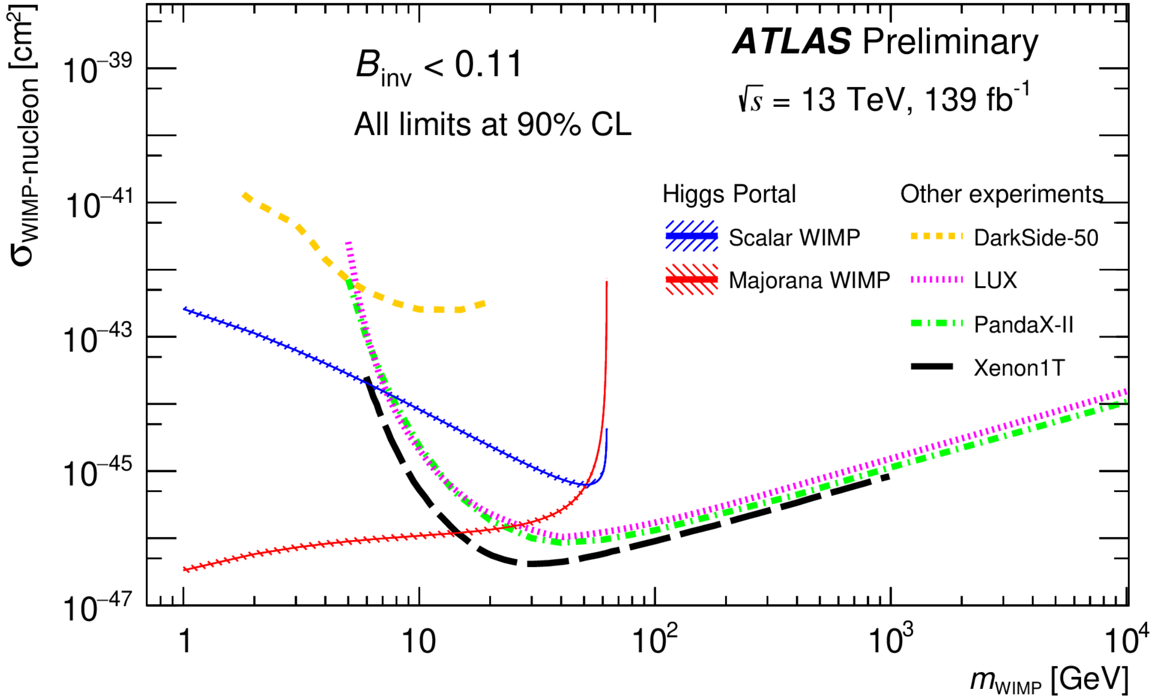
ATLAS: arXiv:2004.04545

A pure CP-odd *ttH* coupling is excluded at 3.9 (2.5)σ

Implication on WIMP

Interpreting the B_{inv} limit from the VBF $H \to inv$ search as the constraint on the spin-independent WIMP-nucleon cross section within the effective field theory framework.

ATLAS-CONF-2020-008

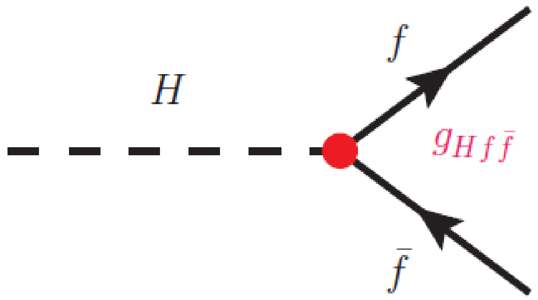


Note: $B_{inv} < 13\%$ @ 95% CL $\Rightarrow$ $B_{inv} < 11\%$ @ 90% CL

Higgs-Charm (*Hcc*) Coupling

Hcc coupling is extremely challenging to measure at (HL-)LHC.

Important for testing Yukawa couplings beyond the 3rd generation.



In SM:

$$y_c = \frac{\sqrt{2}m_c}{\upsilon} \sim 10^{-2} \quad \Rightarrow \quad B\left(H \to cc\right) \approx 2.9\% \text{ @ } m_H = 125 \text{ GeV}$$

About $20\times$ smaller than $B\left(H \to b\bar{b}\right)$, $3\times$ smaller than $B\left(H \to gg\right)$.

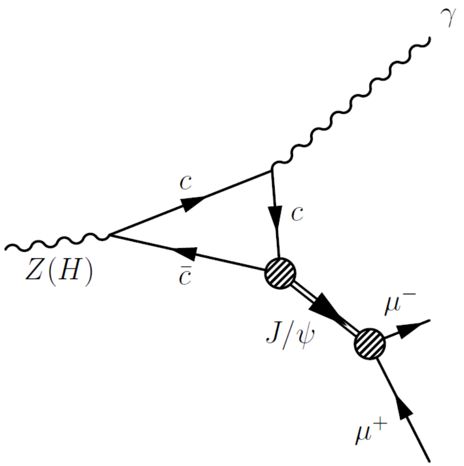
Moreover, c-quark jets are experimentally difficult to identify.

Can benefit greatly from new tools and ideas:

$\Rightarrow$ *New* experimental tool: c-jet tagging

$\Rightarrow$ *New* theoretical ideas: $H \to J/\psi\,\gamma$, *Hc* production, p_T^H distribution, ...

Search for H→J/ψ+γ



In SM: $B(H \to J/\psi\,\gamma) \approx 3\times10^{-6}$

arXiv:1505.03870, arXiv:1407.6696

Identify J/ψ through $J/\psi \to \mu^+\mu^-$,

Search for mass bump in the

smooth $\mu^+\mu^-\gamma$ $(J/\psi\,\gamma)$ spectrum

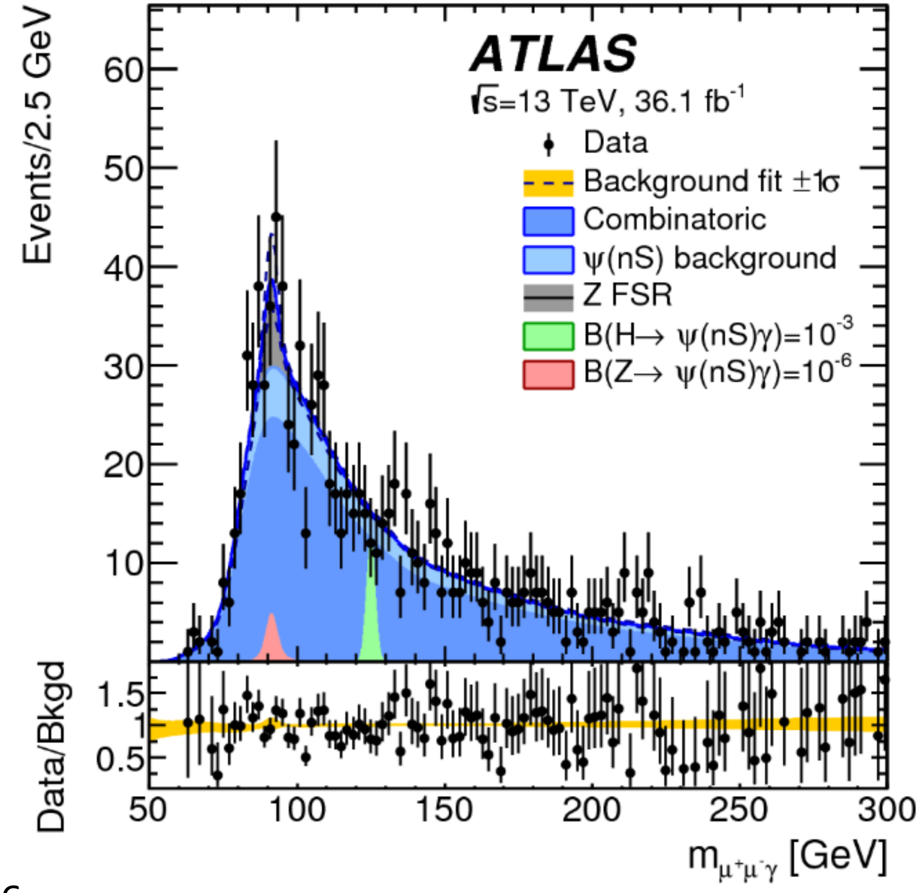
Upper limit on $B(H \to J/\psi\,\gamma)$:

ATLAS: $< 3.5\ (3.0)\times10^{-4}$

CMS: $< 7.6\ (5.2)\times10^{-4}$

@ 95% CL assuming J/ψ

is transversely polarized.

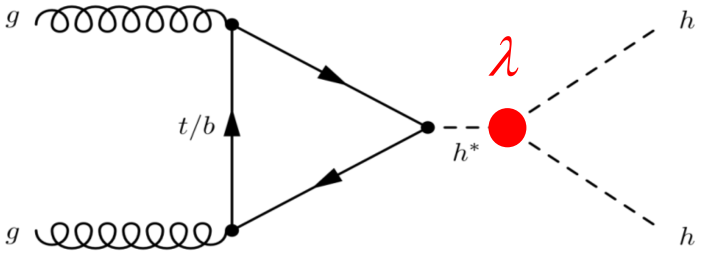


ATLAS: arXiv:1807.00802, CMS: arXiv:1810.10056

Higgs Boson Potential

$$V(\phi) = \mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2 \Rightarrow \lambda \upsilon h^3 + \frac{\lambda}{4} h^4$$

$$\text{SM: } \lambda = \frac{m_h^2}{2\upsilon^2} \sim \frac{1}{8}$$



$$\sigma\left(gg \to hh\right) \approx 40 \text{ pb @ 13 TeV}$$

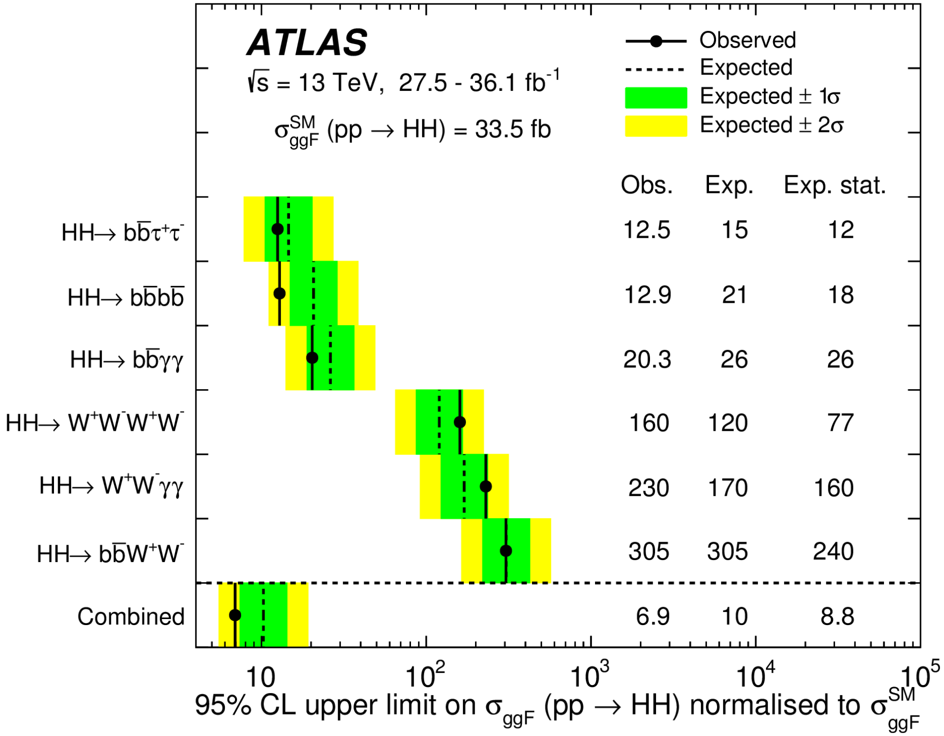
Higgs boson pair production can directly probe the Higgs boson *self-coupling* (and therefore the *Higgs potential*), but the rates are low and backgrounds are high

95% CL intervals:

ATLAS: $-5 < \kappa_\lambda < 12$

CMS: $-11.8 < \kappa_\lambda < 18.8$

(from 36 fb^{-1} dataset)

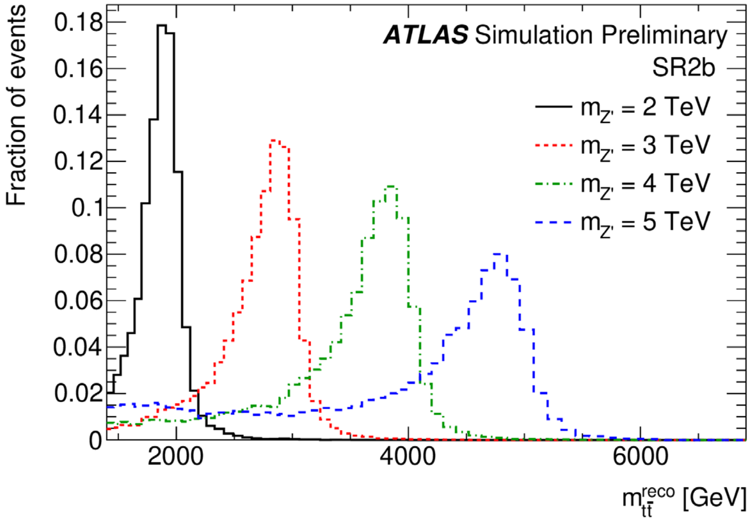


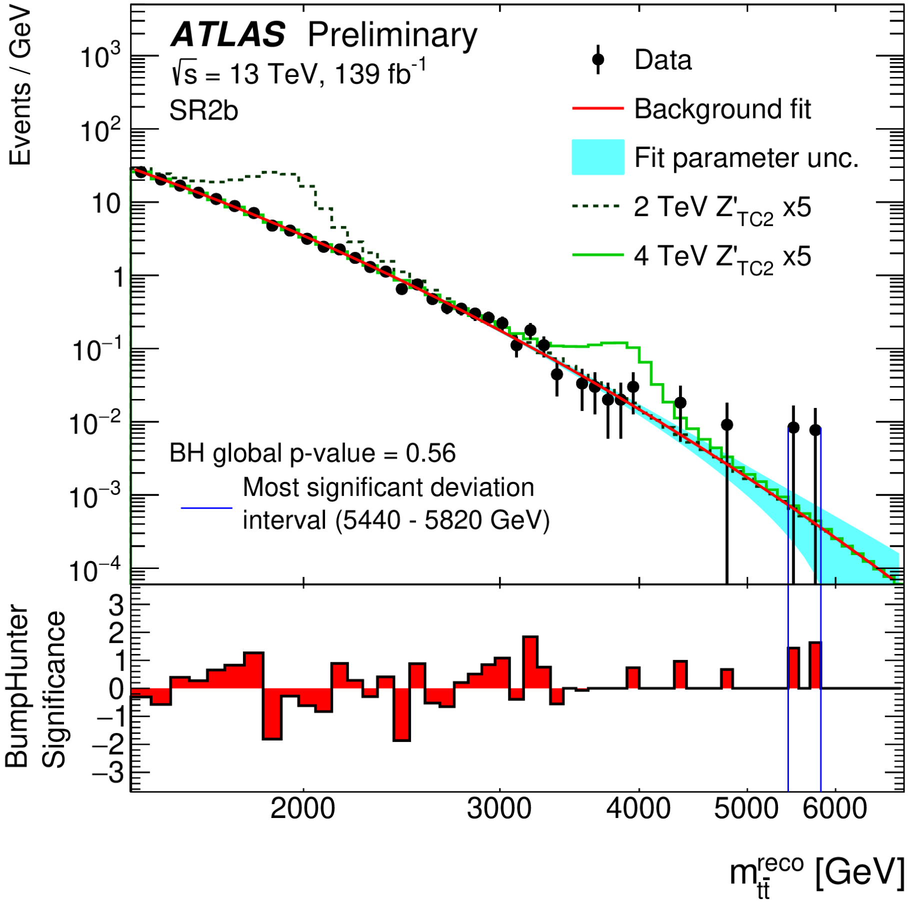
ATLAS: arXiv:1906.02025, CMS: arXiv:1811.09689

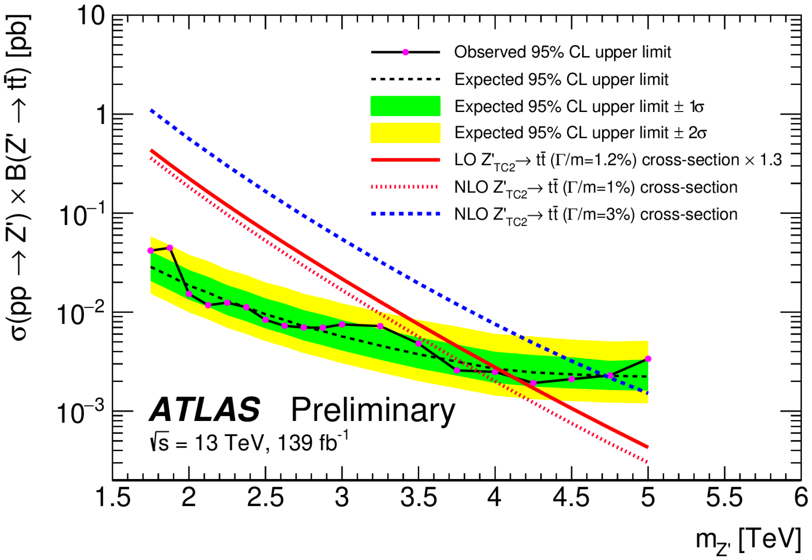
Z’→tt in Fully Hadronic Final States

Search for a pair of highly boosted Top quarks in their hadronic decays

Deep neural network to identify large-R jets with substructures consistent with those from hadronic top-quark decays

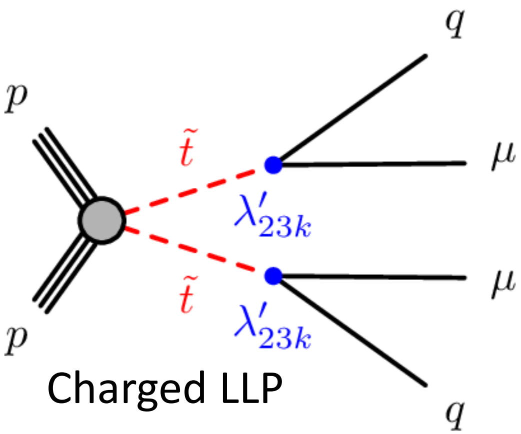




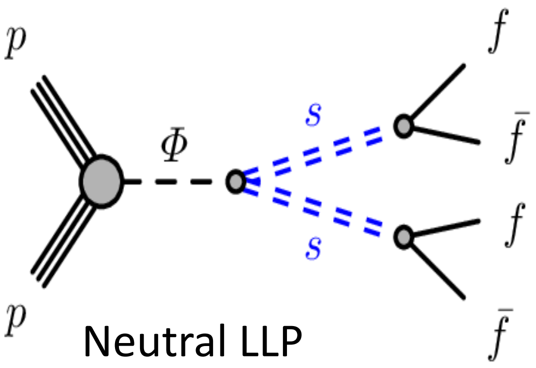


ATLAS: to be submitted

Search for Long-Lived Particles



Charged LLP



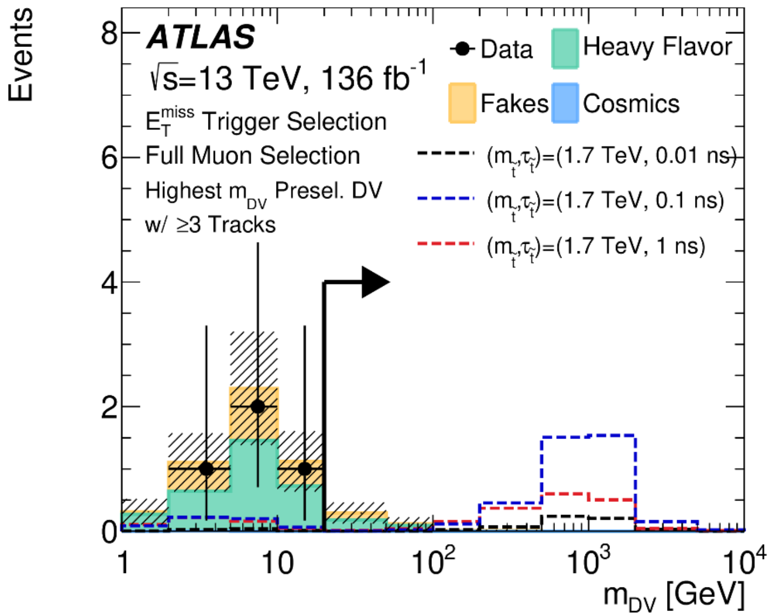
Neutral LLP

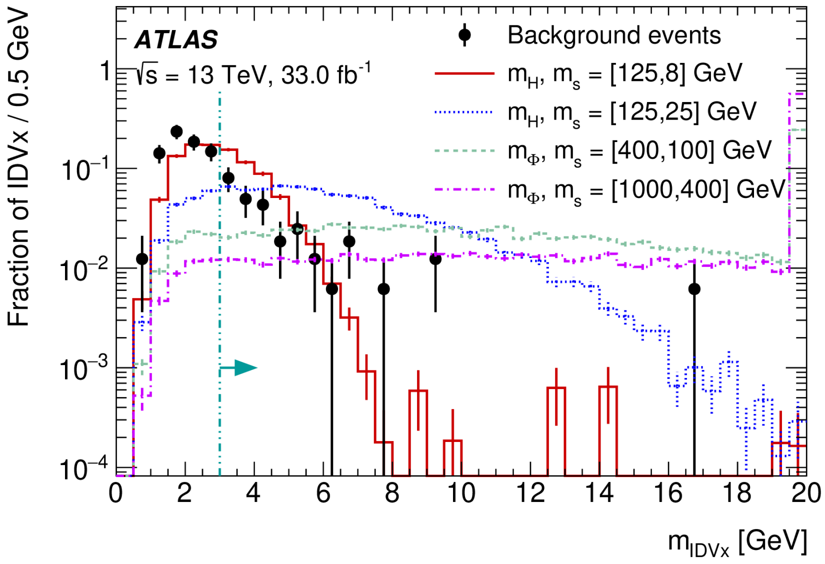
Signatures:

decay inside
the detector
⇓
displaced vertices

Reconstructing DVs in the inner detector from tracks with large displacements, using vertex mass as the discriminant. The neutral search identifies the other LLP decays inside the muon detector, extending cτ<~1 m.

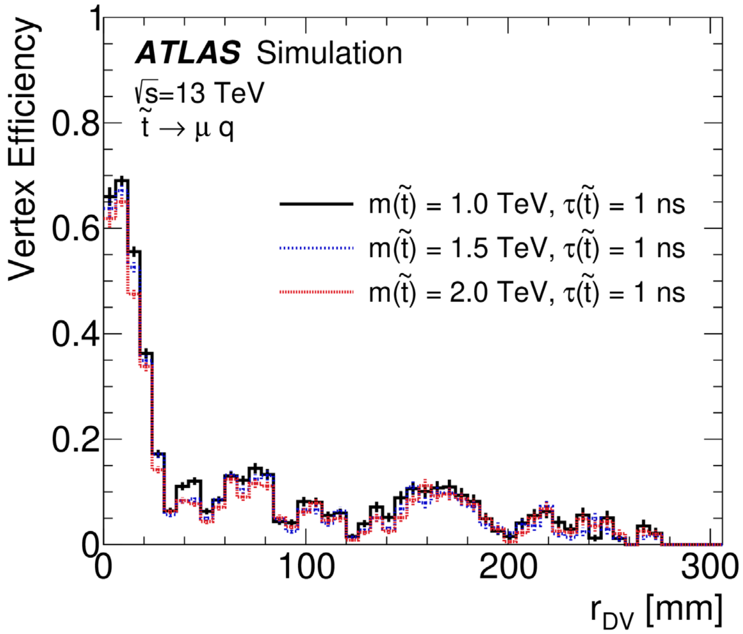
ATLAS: arXiv:2003.11956

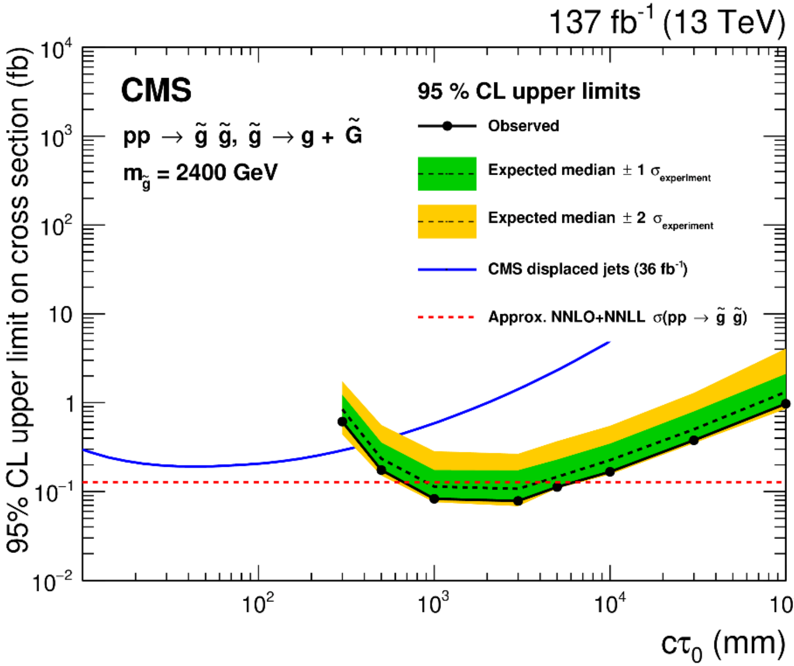




ATLAS: arXiv:1911.12575

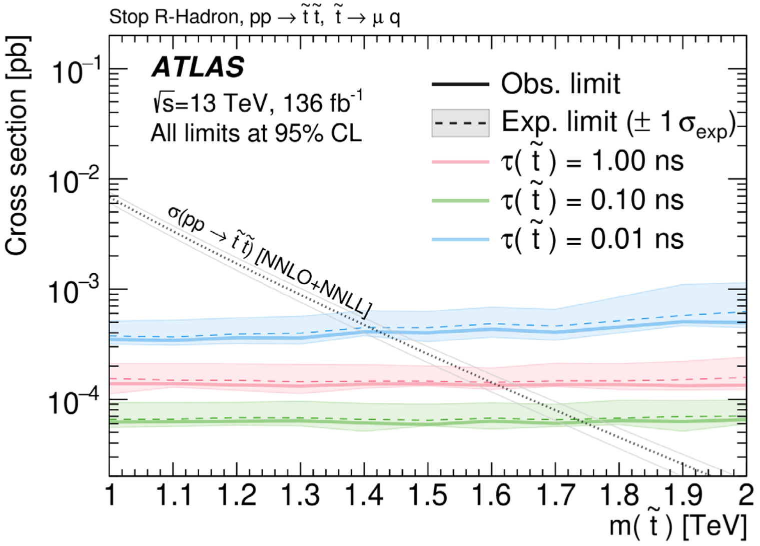
LLP Search Limits

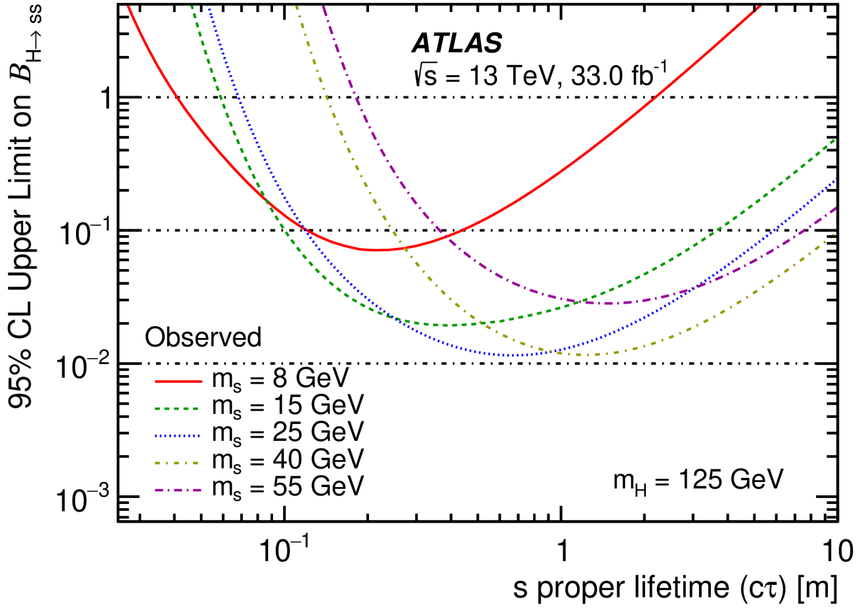




CMS: arXiv:1906.06441

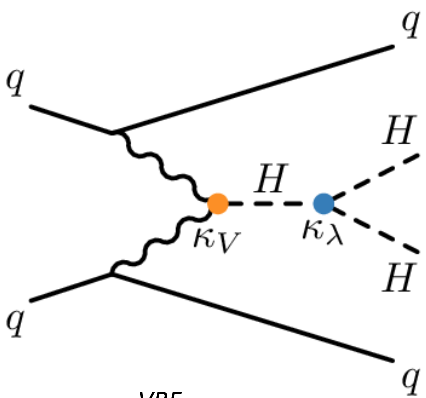
ATLAS: arXiv:2003.11956

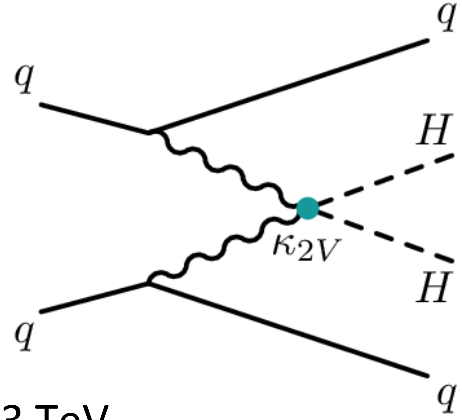




ATLAS: arXiv:1911.12575

Search for VBF HH→4b





SM: $\sigma_{HH}^{VBF} \simeq 1.64$ pb @ 13 TeV

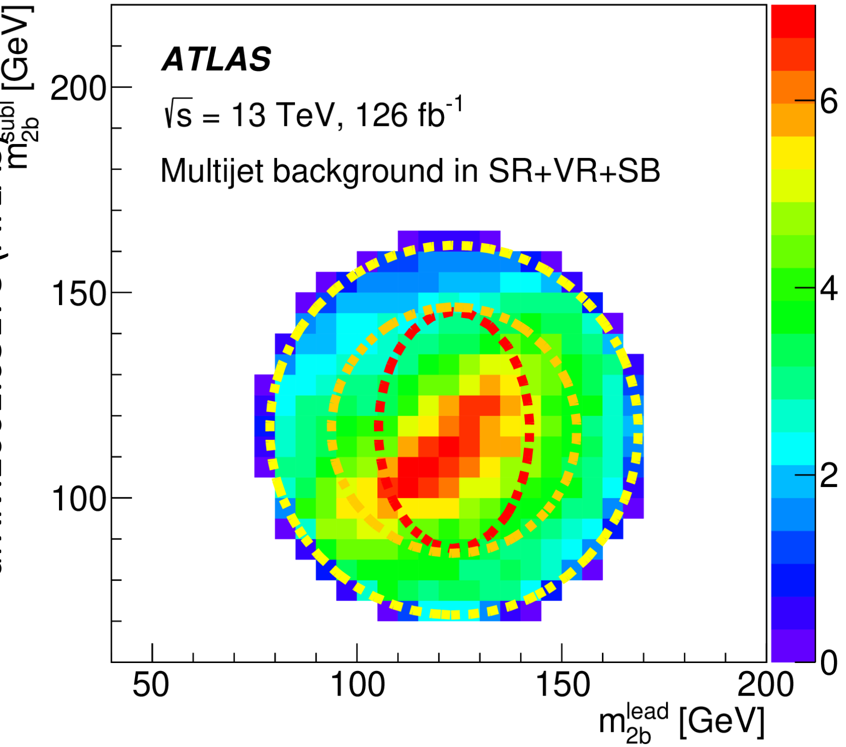
Final state: $jj + bbbb$

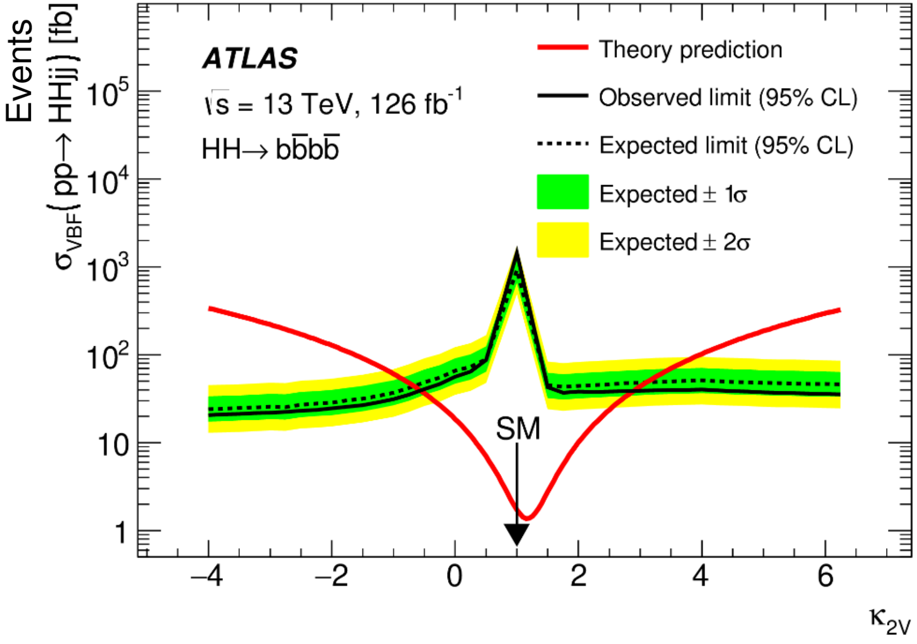
Two tagging jets: $|\eta^{jj}| > 5.0$, $m_{jj} > 1000$ GeV

Four b-jets forming two H → bb candidates

Background dominated by multijets

arXiv:2001.05178 (ATLAS)





$-0.56 < \kappa_{2V} < 2.89$ @ 95% CL