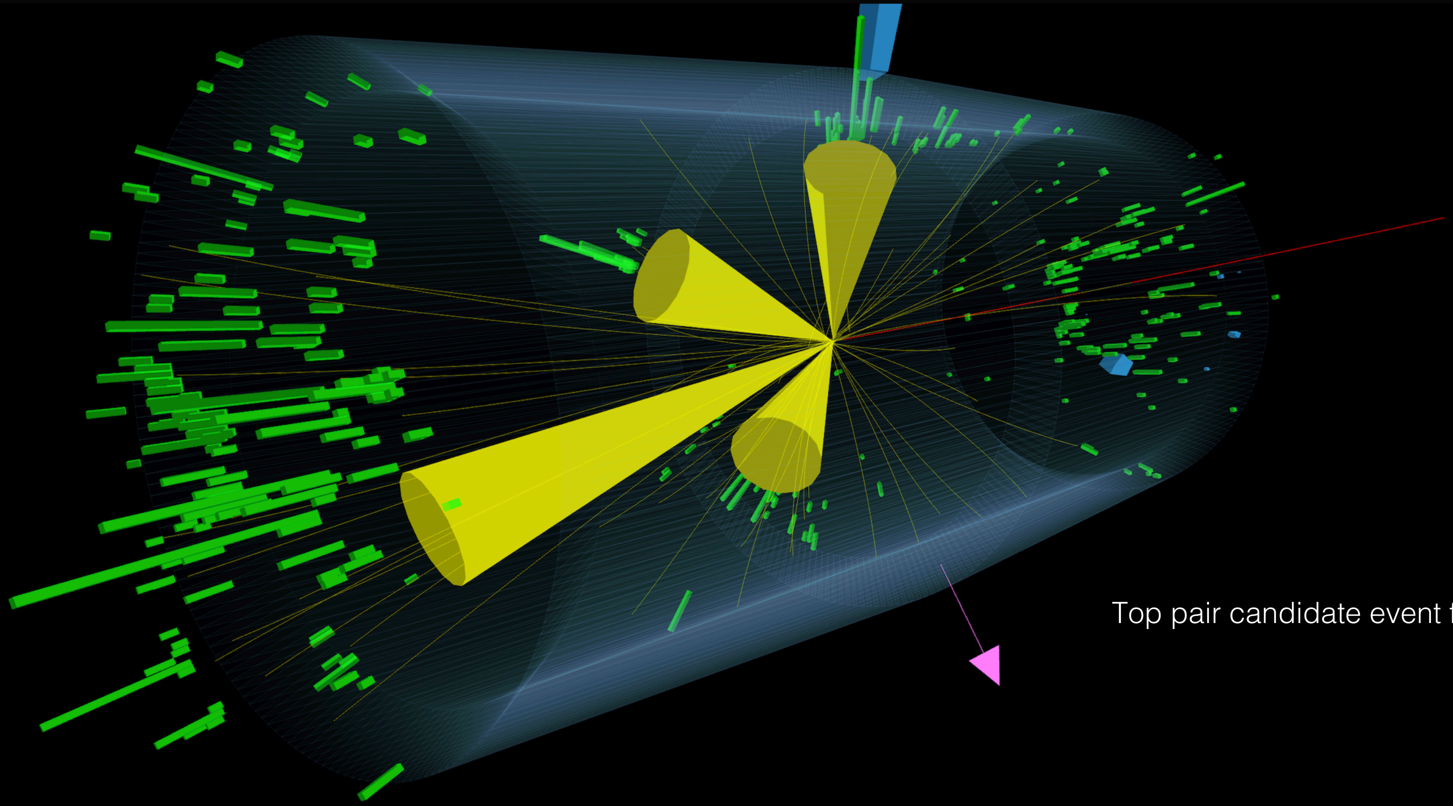
Higgs, Electroweak, and Top Physics Measurements at the LHC



Top pair candidate event from CMS

Pierre Savard

University of Toronto and TRIUMF

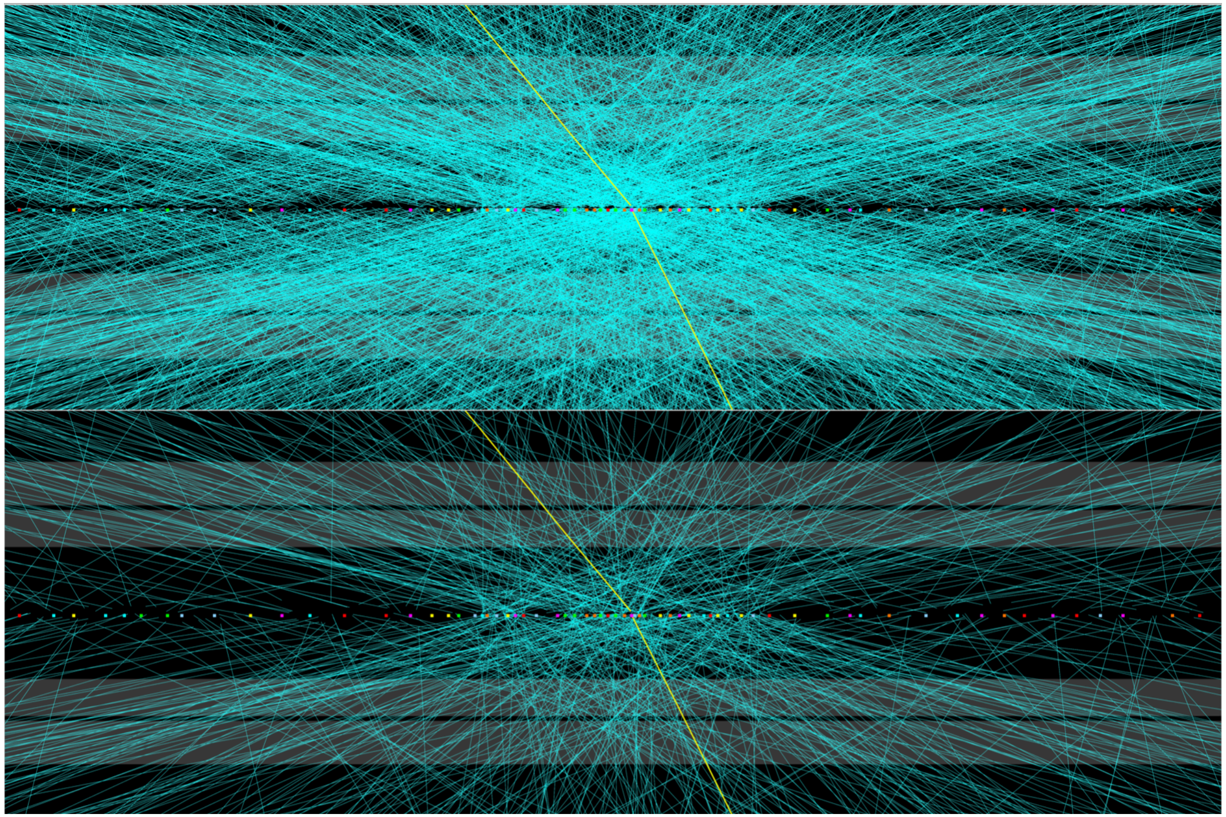
Physics in LHC and Beyond (May 2022)

The LHC: high energy and high luminosity

During Run 2 the LHC produced 10^{16} collisions

Large samples of various particles produced:

- W bosons: 12 billion
- Z bosons: 3 billion
- Top quarks: 300 million
- Higgs bosons: 8 million



Event displays showing a Z→ll candidate produced with 65 reconstructed proton-proton collisions (top: 100 MeV tracks, bottom 1 GeV tracks)

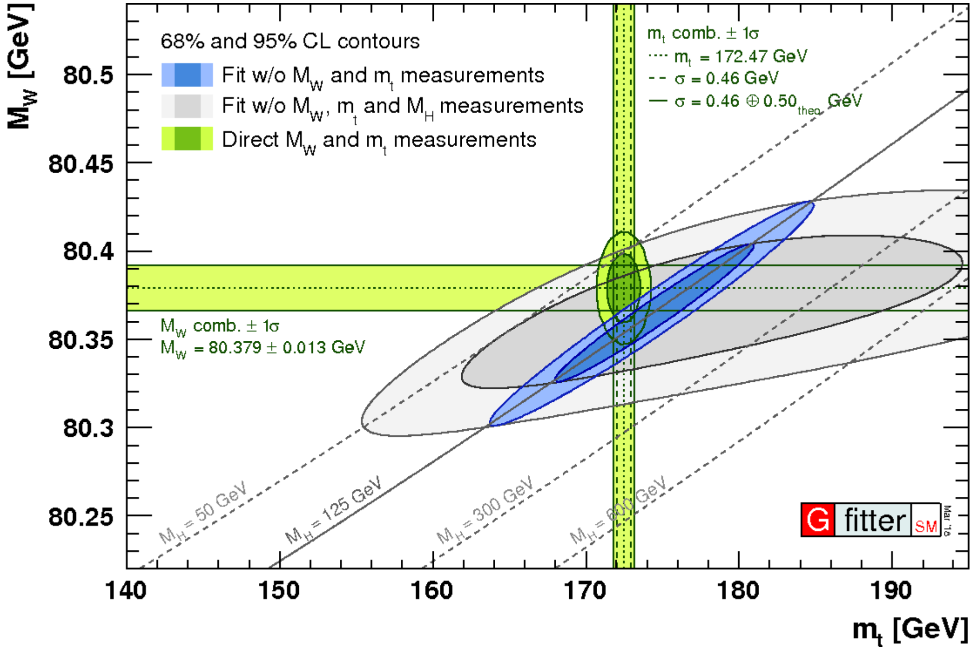
These samples allow for precision measurements of electroweak processes, for the in-depth characterization of the Higgs boson, and detailed studies of the top quark

Can't cover all the work performed on those topics in this talk: I present a selection of results mainly focused on electroweak interactions of the top, Higgs, and weak bosons

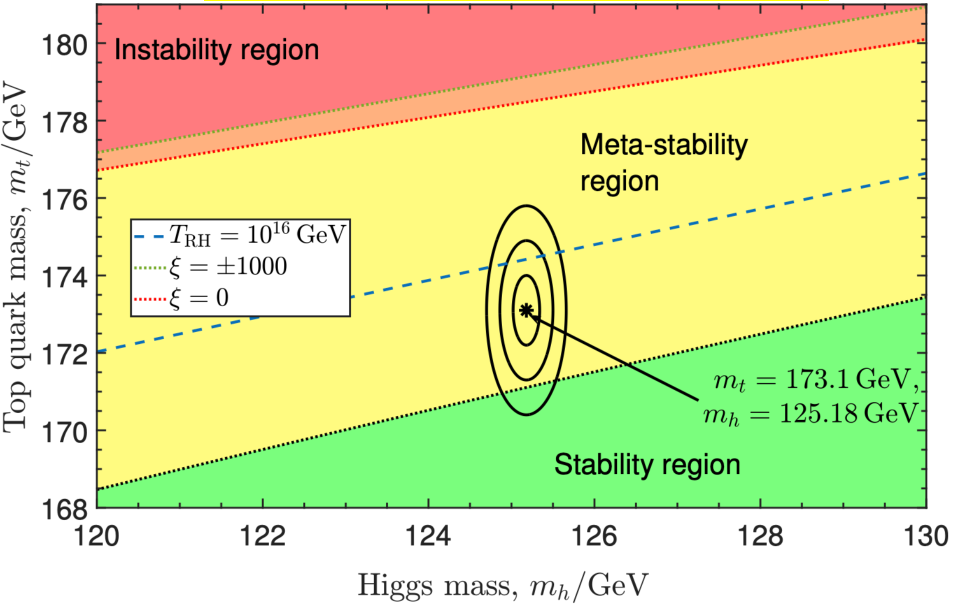
Precision Mass Measurements

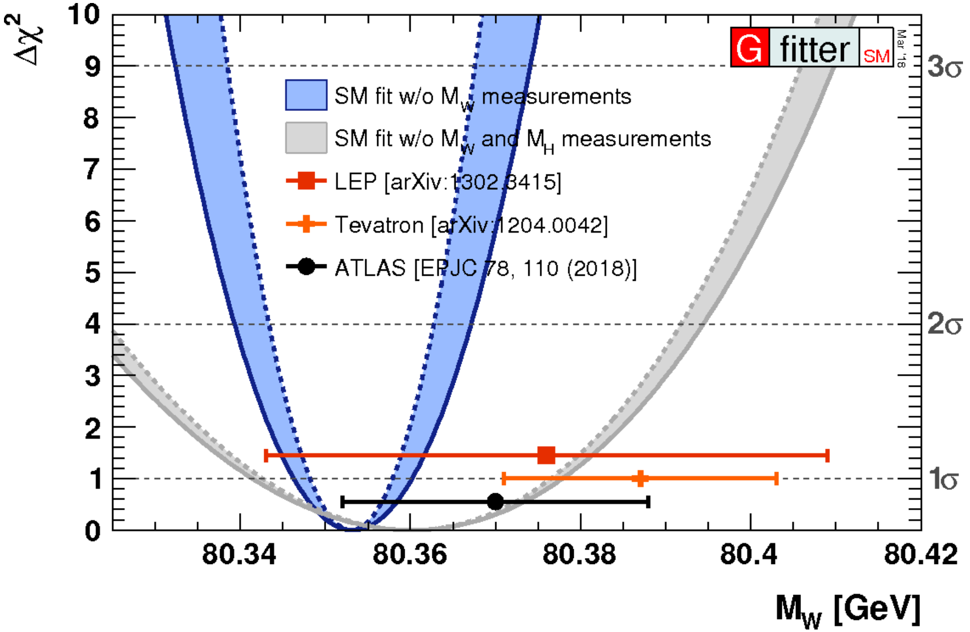
LHC experiments producing precision mass measurements of top quark, W boson, and Higgs boson

- Important self-consistency test of the Standard Model
- Contributions from BSM particles can impact SM particle masses



Front. Astron. Space Sci., 18 December 2018

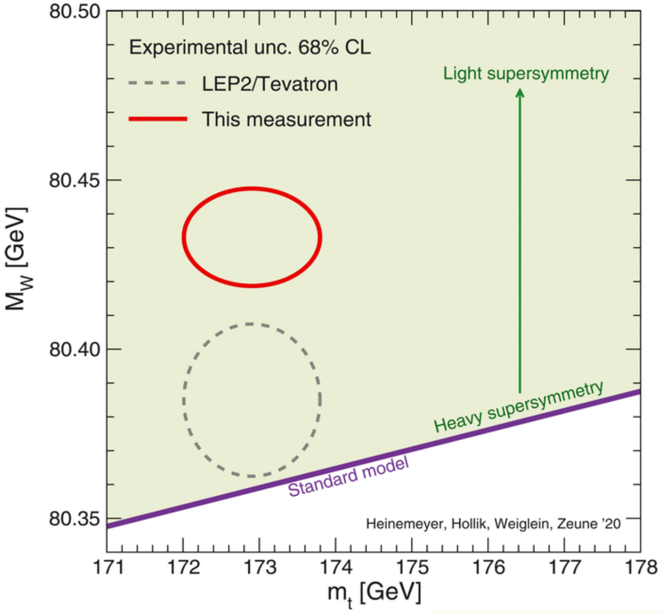




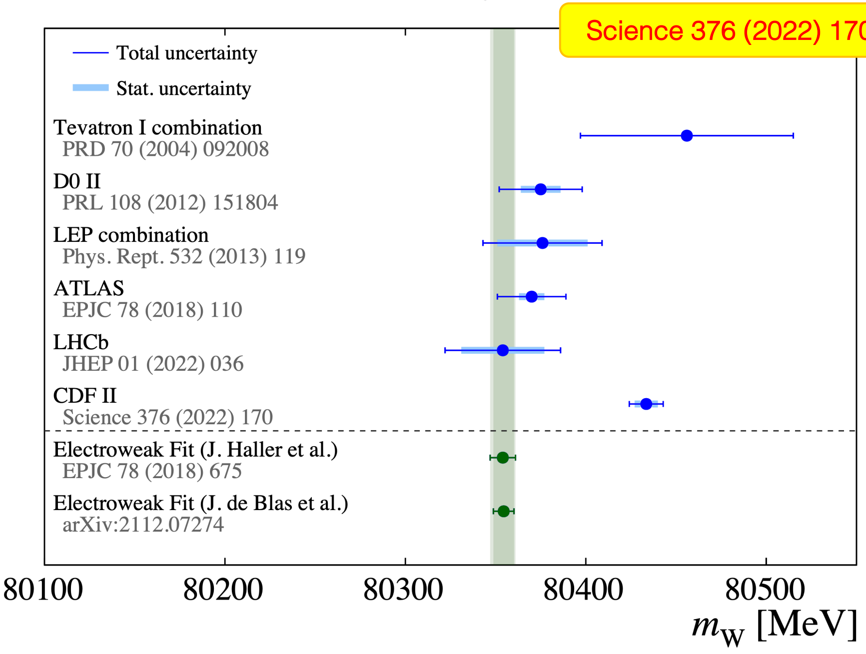
W Mass Measurements

Recent W mass measurement result from CDF II (with an uncertainty of ~9 MeV) renews interest for updates from LHC experiments:

- ATLAS result (EPJC 78 (2018) 110) achieved a total uncertainty of 19 MeV, surpassing LEP combination precision
- LHCb achieved an uncertainty of 32 MeV. With different systematics. Result will contribute to the LHC combination precision
- Dedicated low pileup runs were taken during Run 2 (ATLAS results from early Run 1)
- Awaiting first result from CMS and updates from ATLAS. Looking forward to see how the tension with the CDF II result evolves



Science 376 (2022) 170



Top Mass Measurements

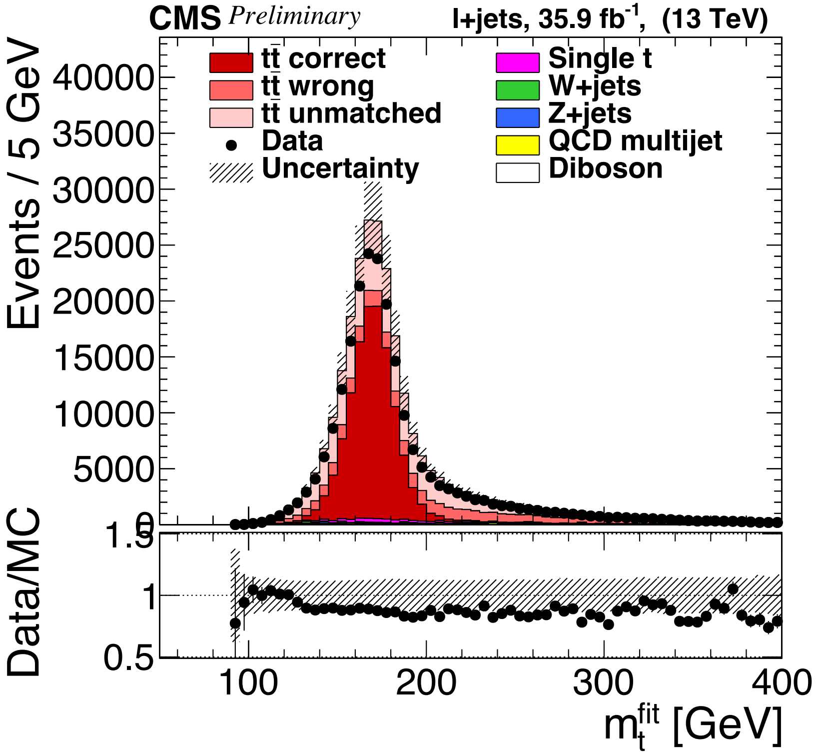
Very large sample of top quarks at the LHC make statistical uncertainty negligible.

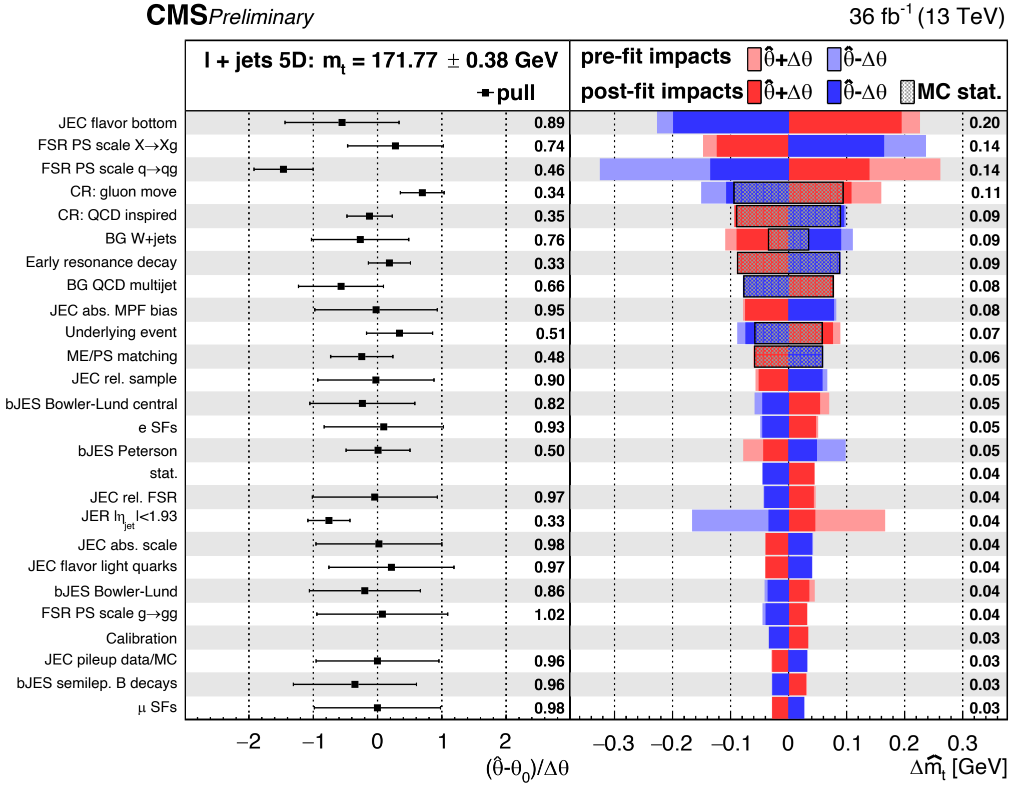
Many sources of systematic uncertainties contribute and must be understood.

Recent result by CMS provides most precise single measurement: 171.77 ± 0.38 GeV

Note: best precision achieved by measuring the “Monte Carlo” mass. There is an uncertainty associated with how this relates to the pole mass.

Current measurement precision is comparable to this uncertainty. Further theory progress on this is important



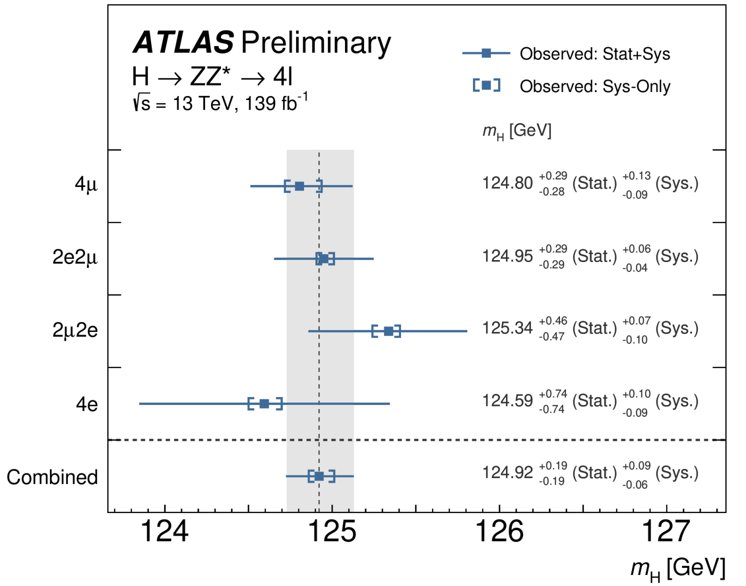


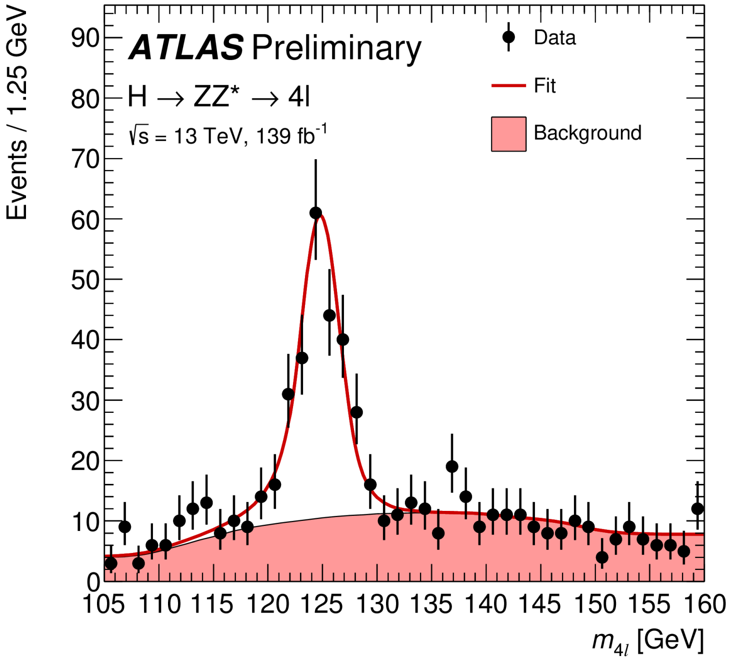
Higgs Mass Measurements

Standard Model predicts production and decay rates of the Higgs boson as a function of Higgs mass. It does not predict the Higgs mass: it must be measured.

Precision on the Higgs boson mass now at the 0.1% level. Precision will improve with statistics

ATLAS-CONF-2020-005





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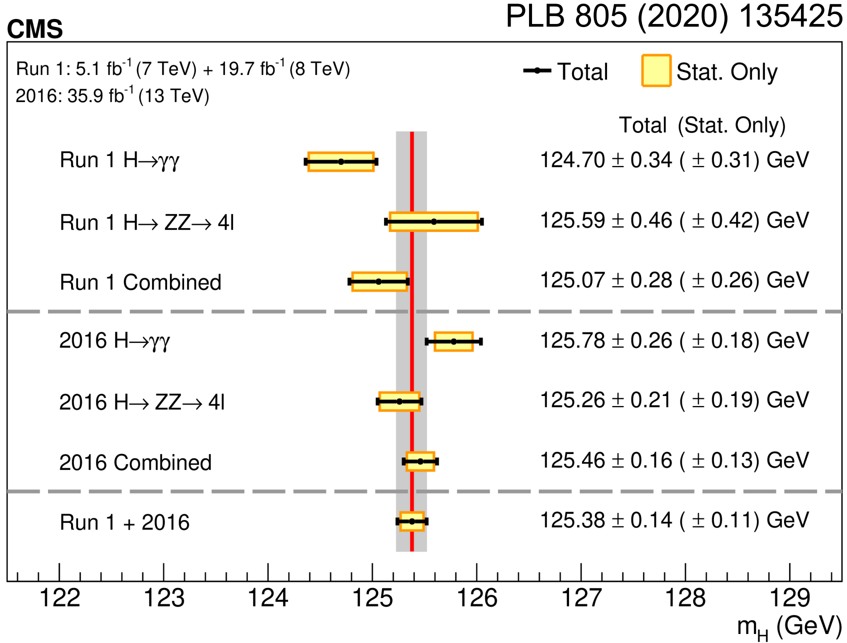
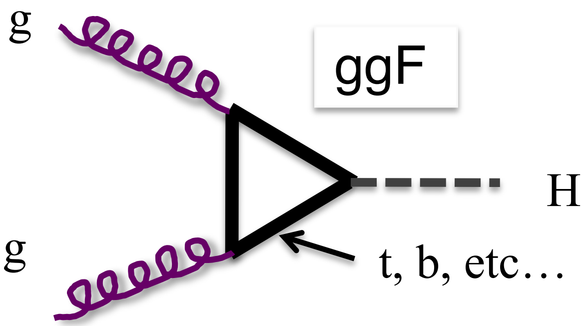


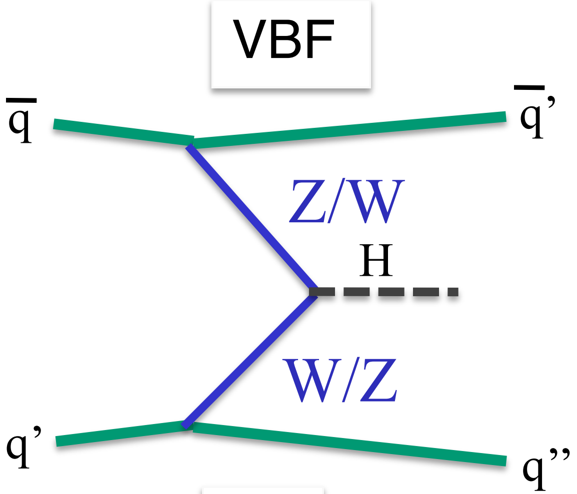
Higgs Boson Physics

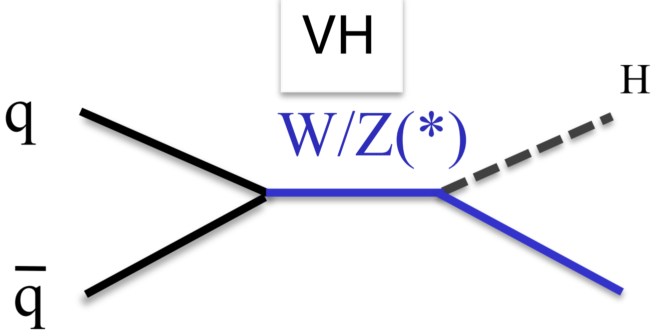
	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

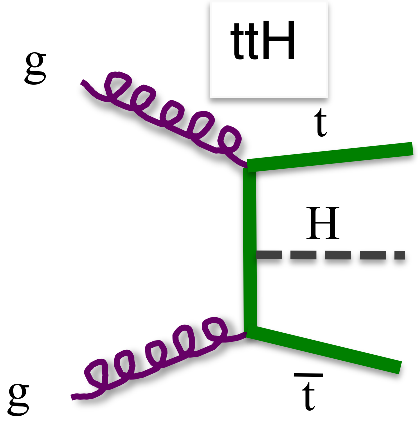
SM Production Modes

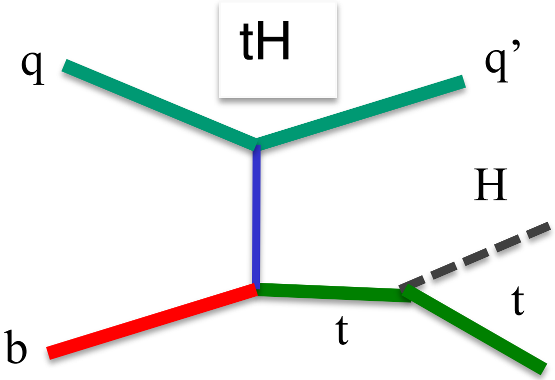
(M_H = 125 GeV)





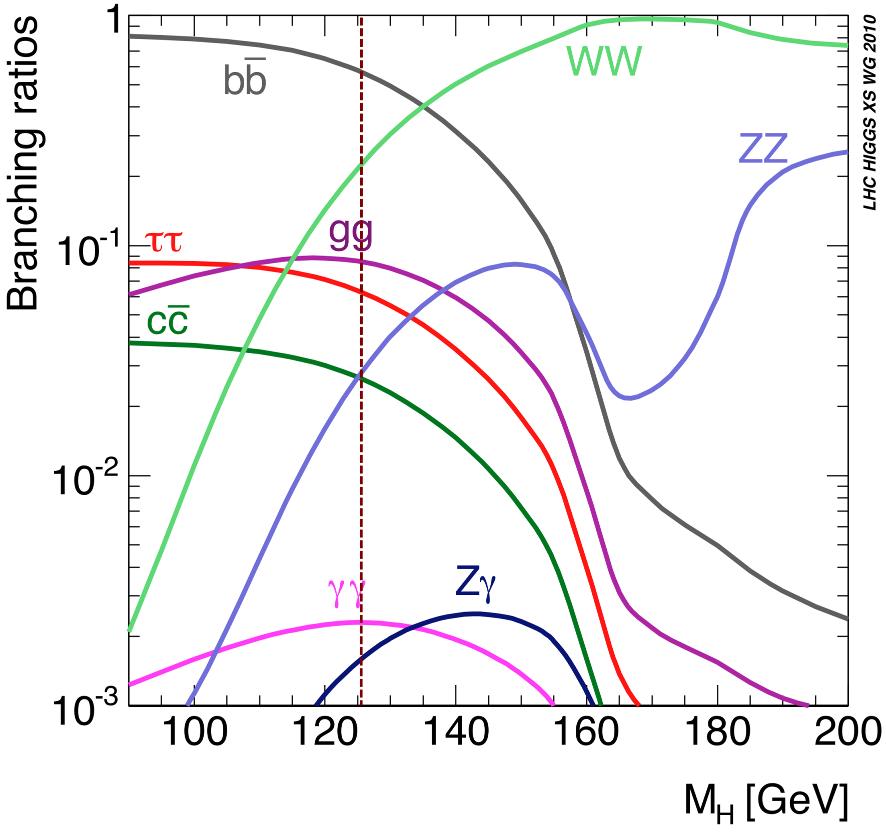






Higgs Boson Physics

- At m_H = 125 GeV, many decay channels can be studied



SM Decay Modes
(M_H = 125.0 GeV)

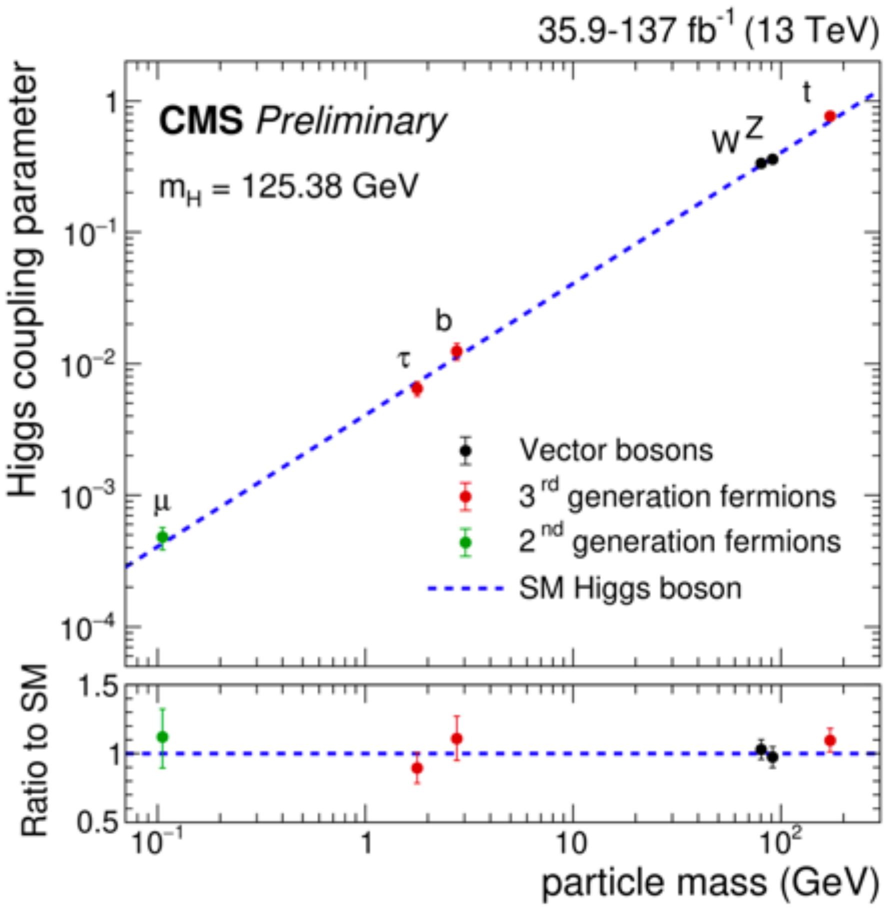
Process	**Br**
bb	0.58
WW	0.22
$\tau\tau$	0.06
ZZ	0.027
$\gamma\gamma$	0.0023
$Z\gamma$	0.0016
$\mu\mu$	0.0002

Higgs Boson Physics: where we are now

~8M Higgs bosons (per experiment) produced in Run 2 allows for precision tests of SM Higgs sector:

Major progress in last few years:

- Observation of H→bb decay
- Observation of ttH production
- Evidence of H→μμ decay



At the end of Run 2:

- Mass measurement precision ~0.1%
- All major production and decay modes have been observed. Other targets for future runs:
  - Find evidence for Zγ decay mode
  - Observe μμ, then increase precision
  - Di-Higgs production and self-coupling
  - Comprehensive studies of kinematics of production and decay
  - Study CP properties
  - Look for non-SM Decays

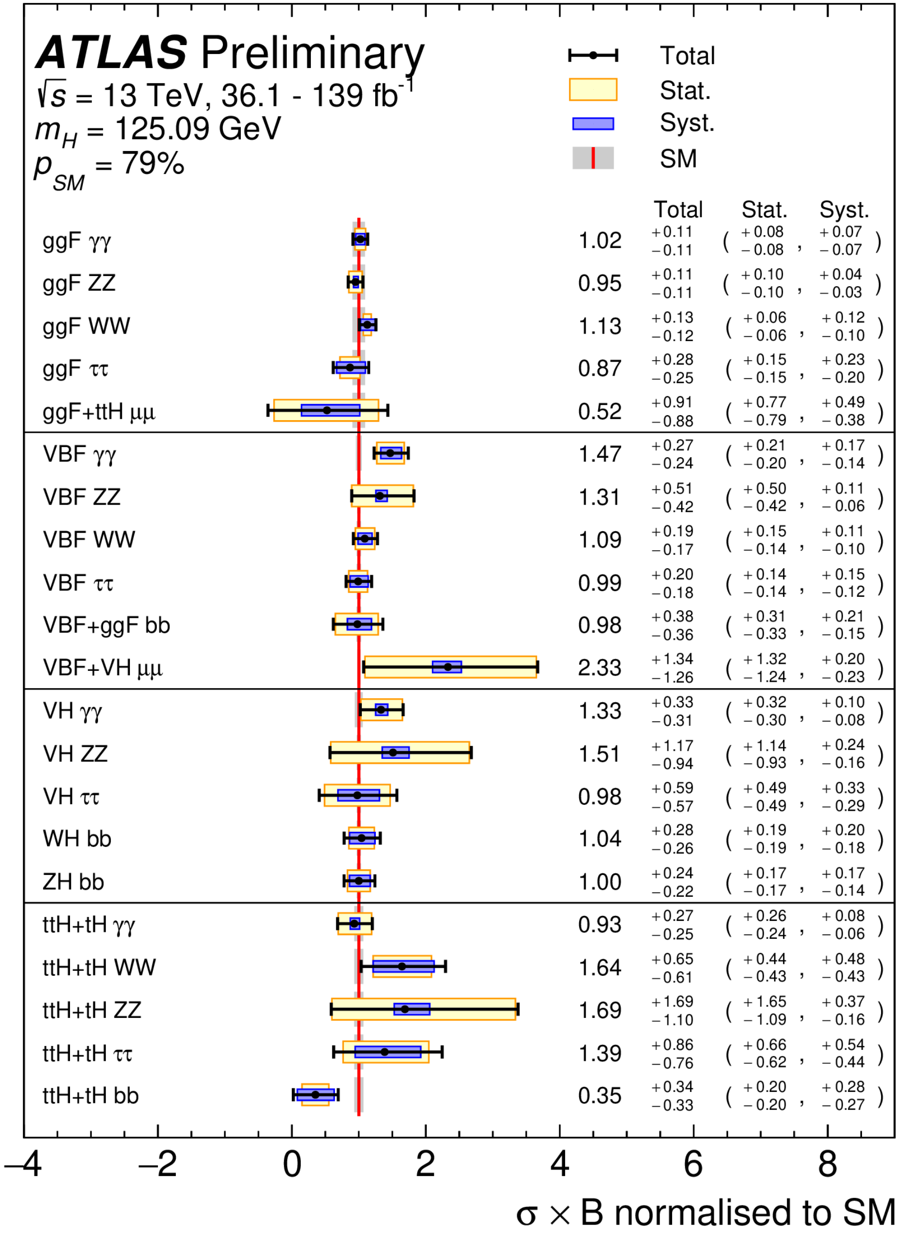
Production cross sections and branching ratios

Analyses performed by ATLAS and/or CMS have targeted the production and decay modes below:

	WW	ZZ	γγ	bb	ττ	μμ
ggH	X	X	X	X	X	X
VBF	X	X	X	X	X	X
WH	X	X	X	X	X	X
ZH	X	X	X	X	X	X
ttH	X	X	X	X	X	X

Right figure:

Higgs production cross sections times branching fractions normalised to Standard Model



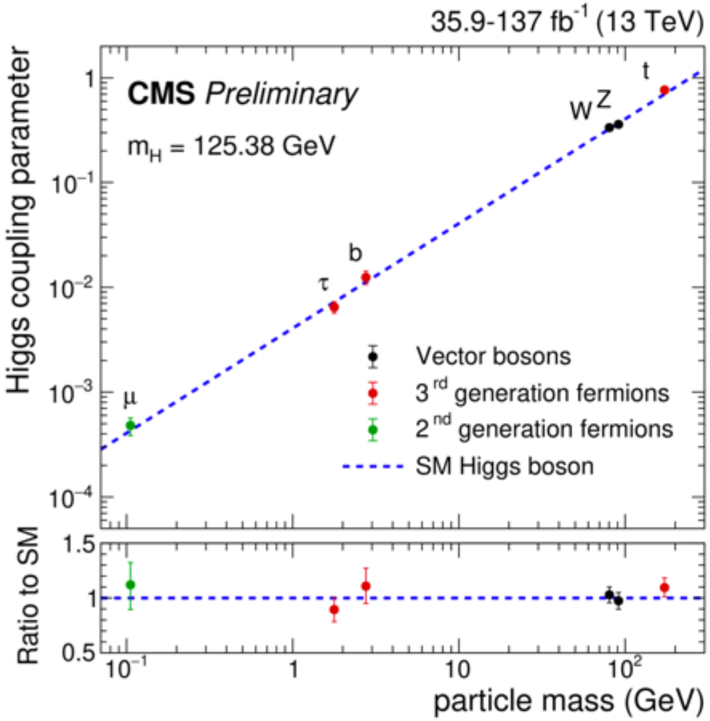
Update on Higgs Couplings Fit

Higgs analyses combined in “kappa” framework fit with varying assumptions

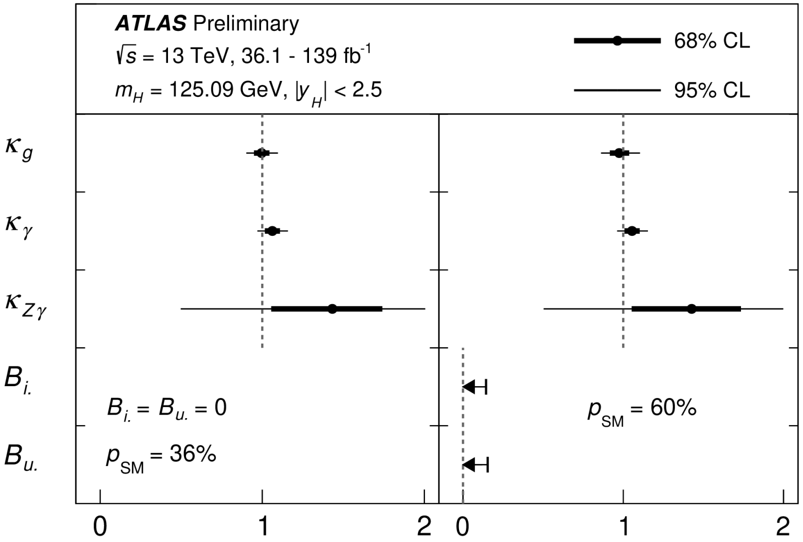
- Coupling strength modifier κ = 1 corresponds to SM prediction

ATLAS coupling strength modifiers:

Parameter	Result
κ_Z	0.99 ± 0.06
κ_W	1.03 ± 0.05
κ_b	0.88 ± 0.11
κ_t	0.92 ± 0.06
κ_τ	0.92 ± 0.07
κ_μ	$1.07\,^{+0.25}_{-0.31}$

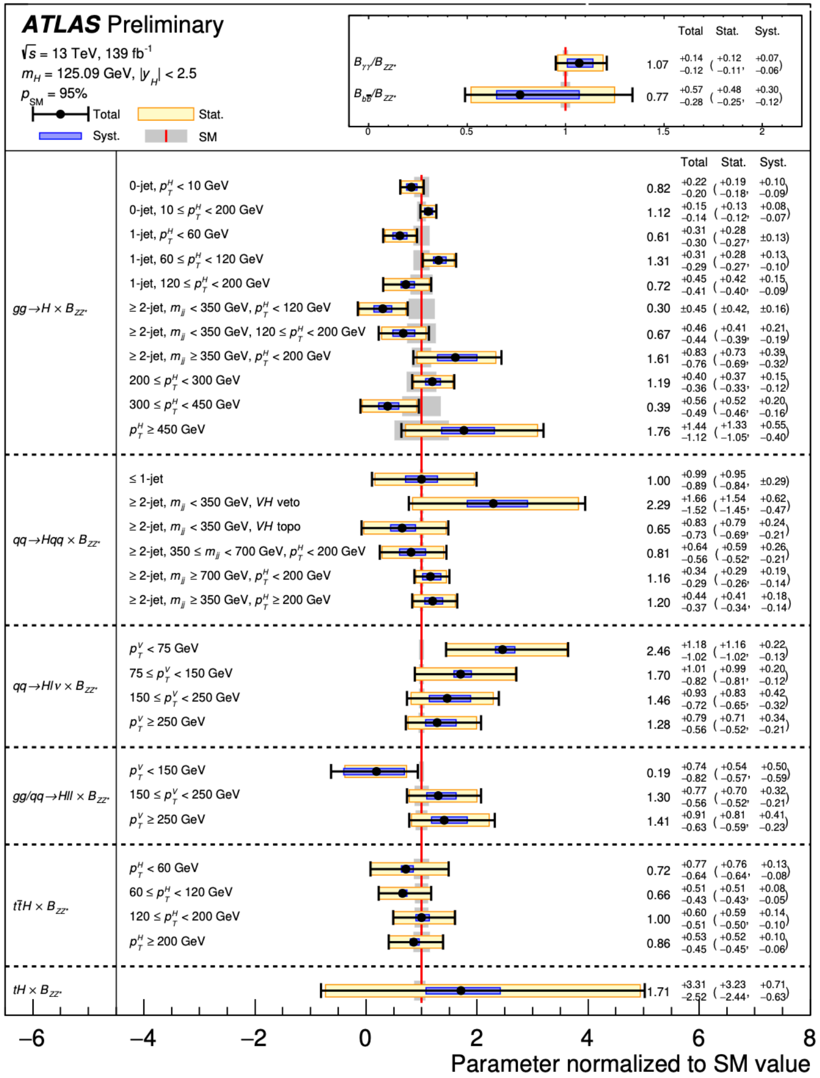


Probes prod. and decay loops

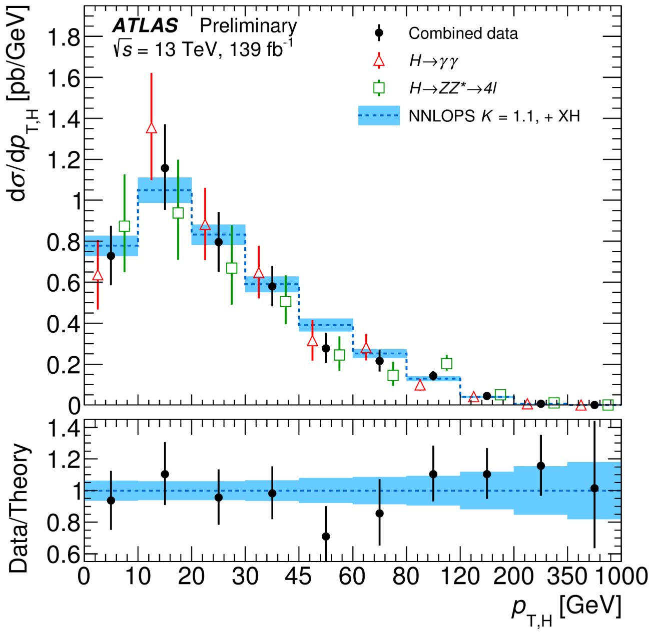


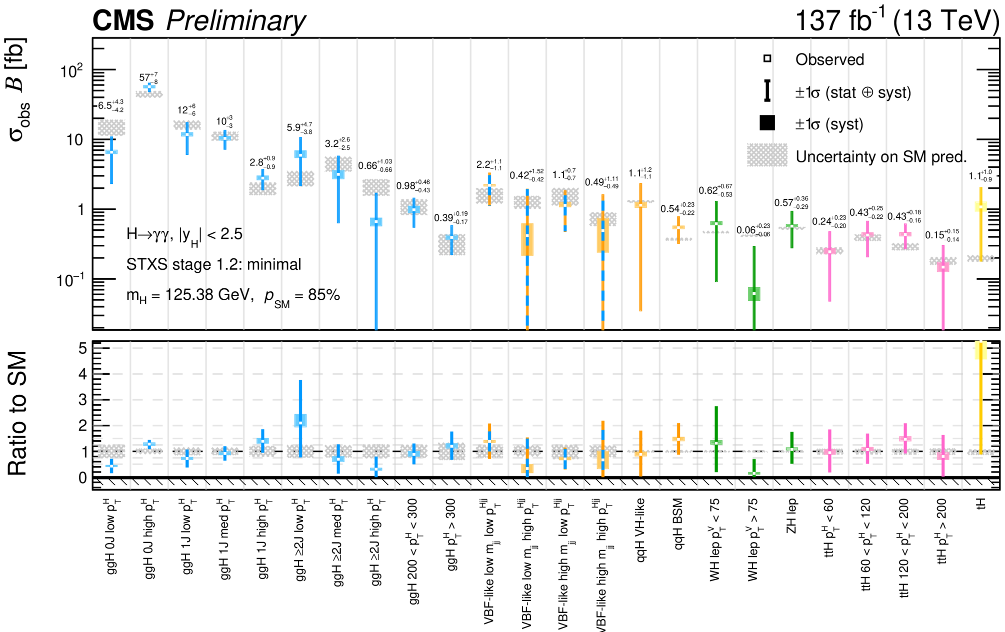
Where we are now: comprehensive kinematic studies

After observation, vast program of kinematic measurements was launched



ATLAS-CONF-2020-027



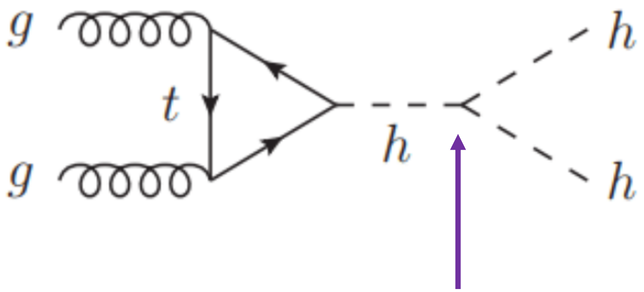


Higgs Self-Coupling

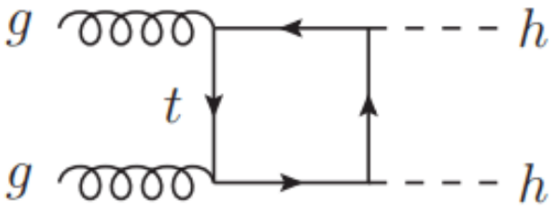
Making progress towards testing the shape of the Higgs potential through the Higgs self-coupling (λ_3)

Sensitivity to SM-strength coupling will require HL-LHC but much progress has been made in recent years

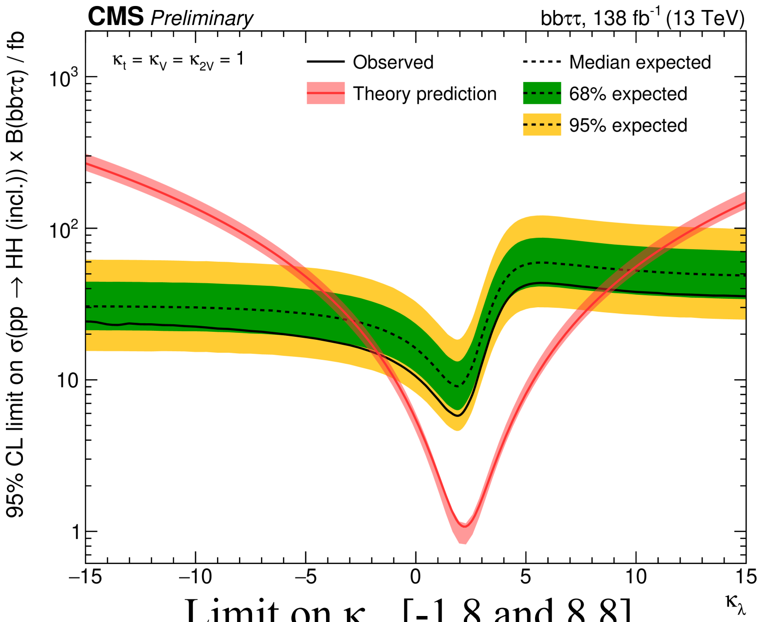
Recent bb$\tau\tau$ result from CMS (left), combination of bb$\tau\tau$ and bb$\gamma\gamma$ from ATLAS (right)



$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

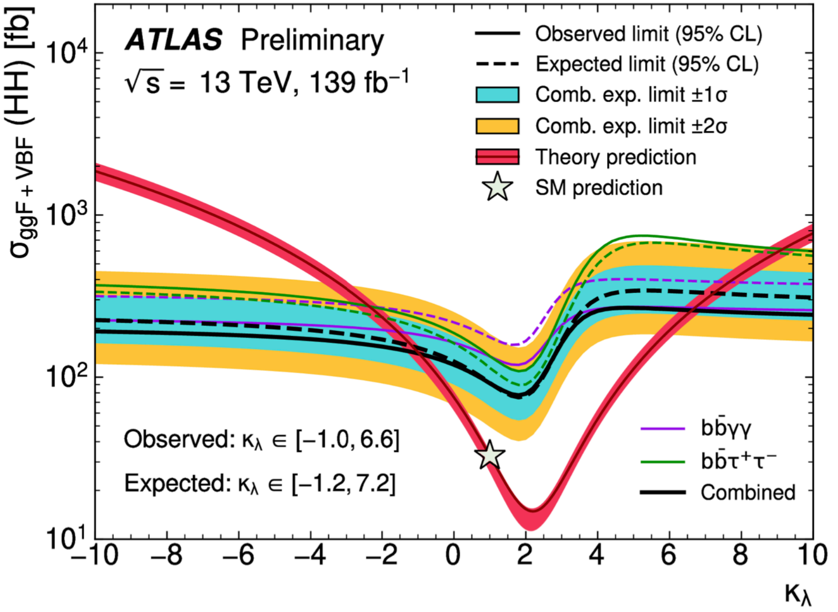


CMS-PAS-HIG-20-010



Limit on κ_λ [-1.8 and 8.8]

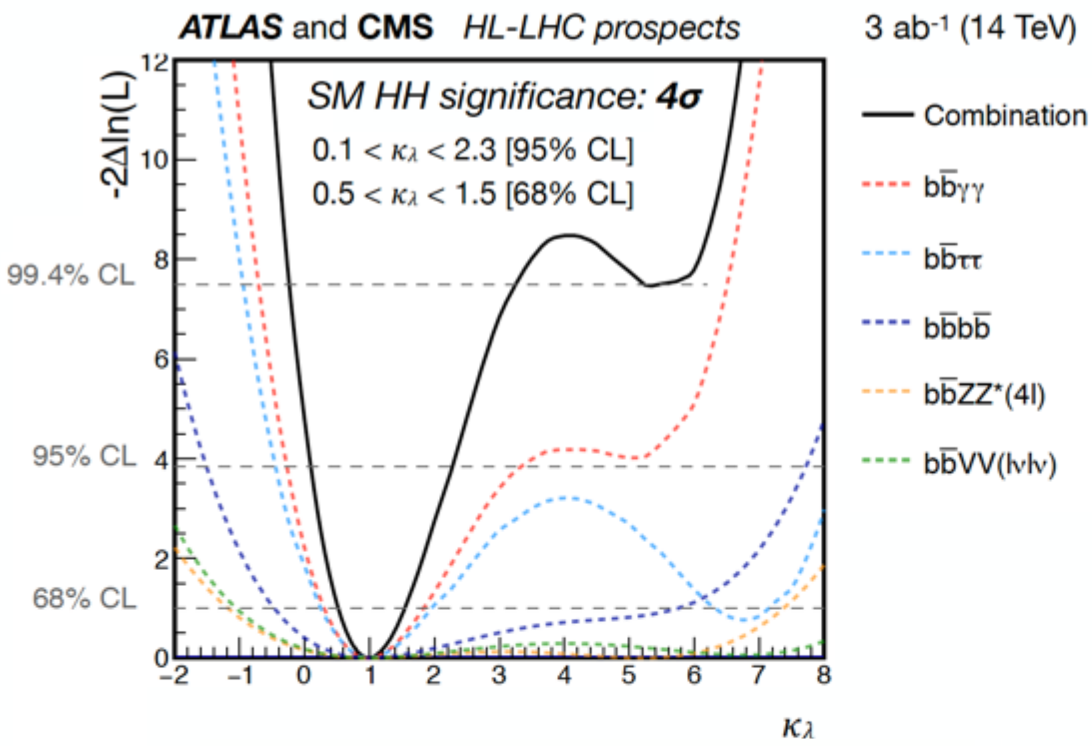
ATLAS-CONF-2021-052

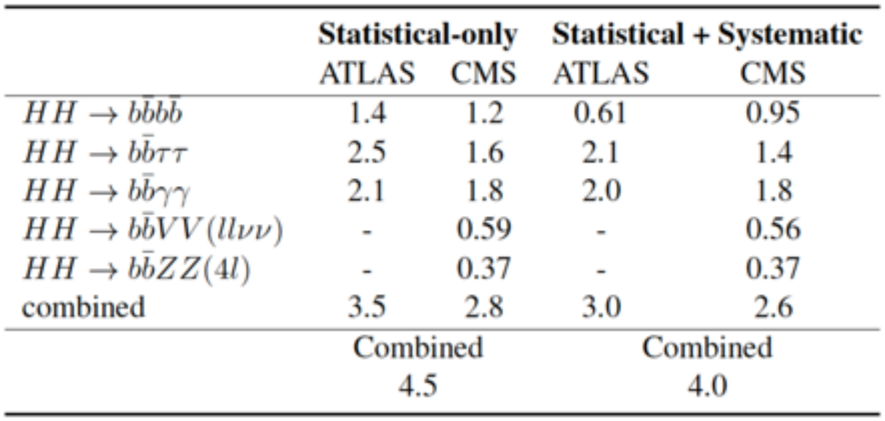


HL-LHC: Higgs Self-Coupling

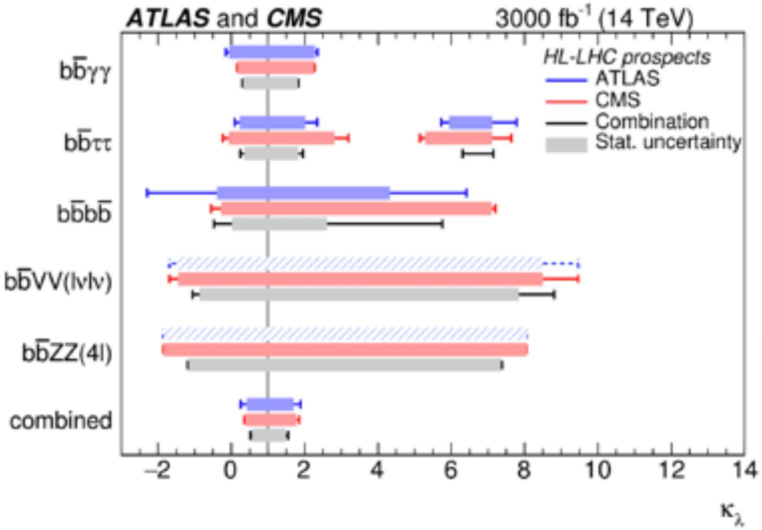
CERN-LPCC-2018-04

- Significance of HH signal at the 4σ level (both exp.)
- Uncertainty on κ_λ of 50%
    - 2nd minimum excluded at > 99% CL
- Note that HH observation analysis and κ_λ analysis require different optimizations





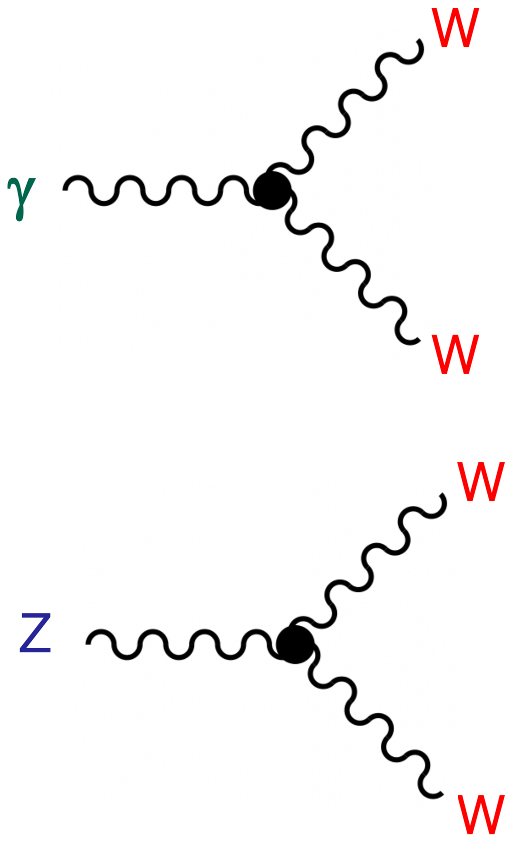
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



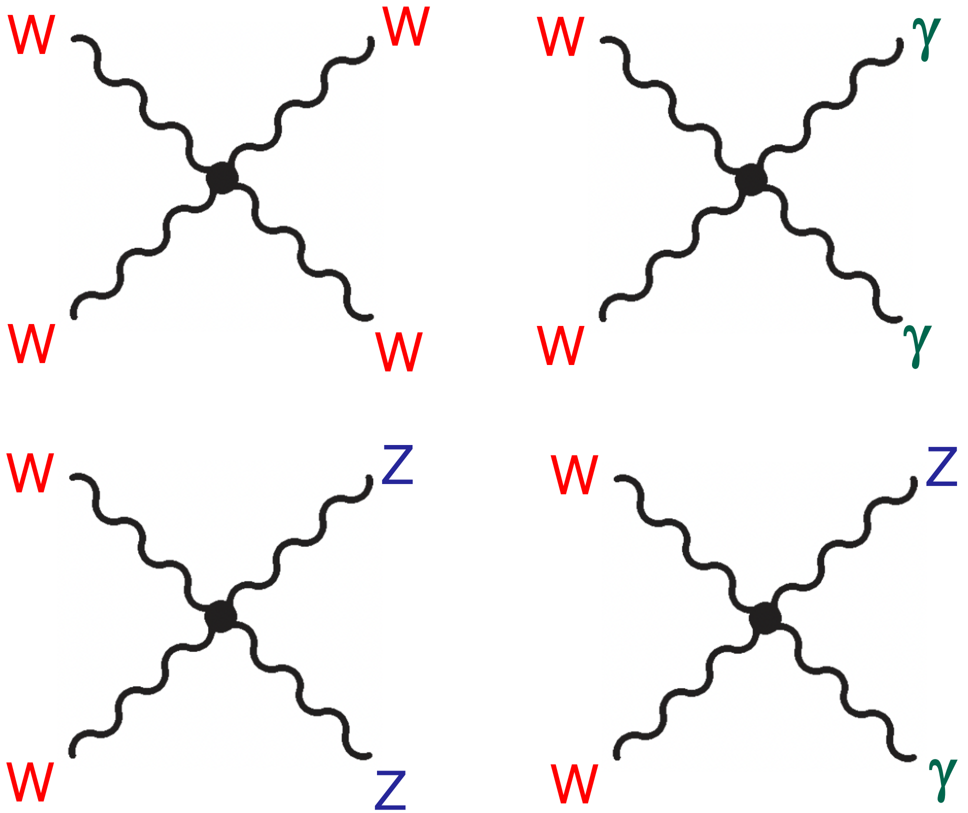
Testing the Electroweak Sector of the SM

With the Run 2 dataset, analyses can now probe final states where the electroweak quartic couplings of the SM contribute

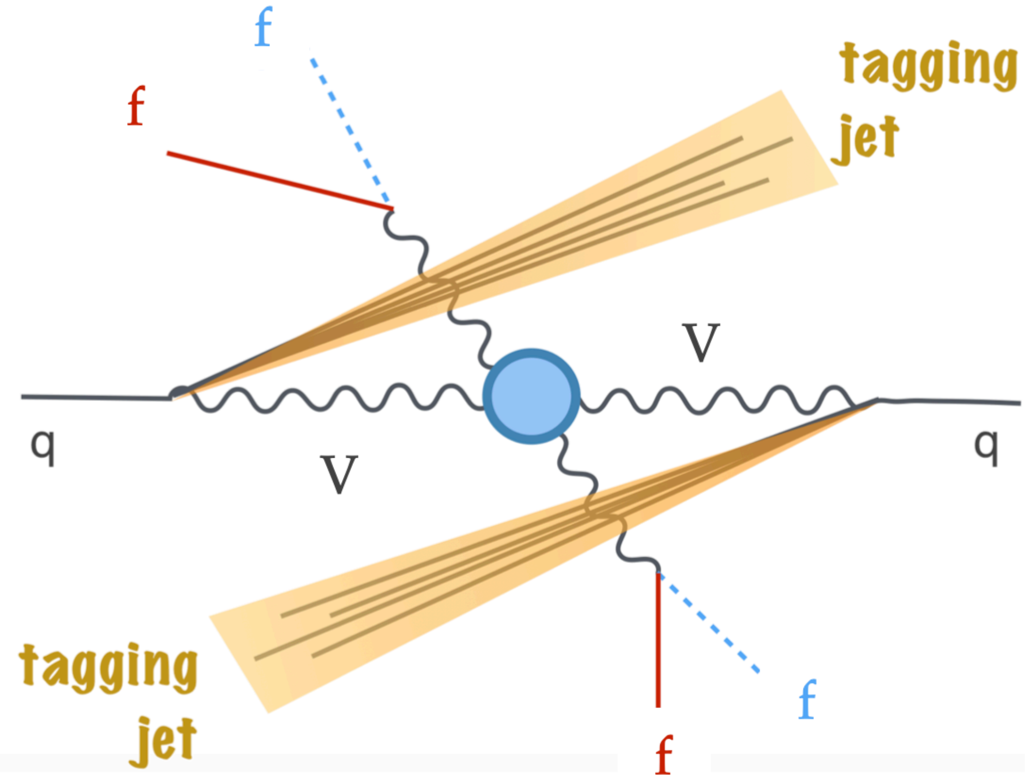
Cubic Couplings

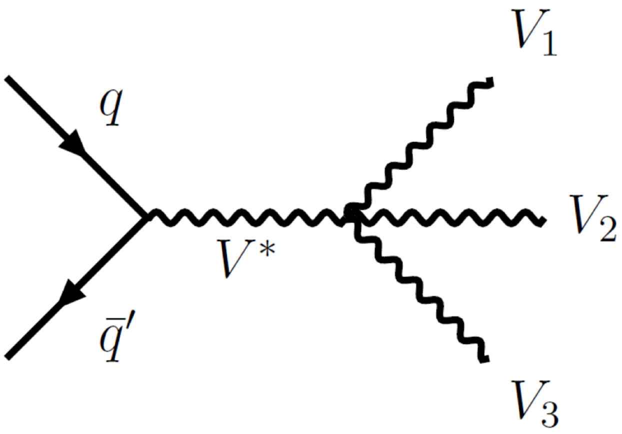


Quartic Couplings



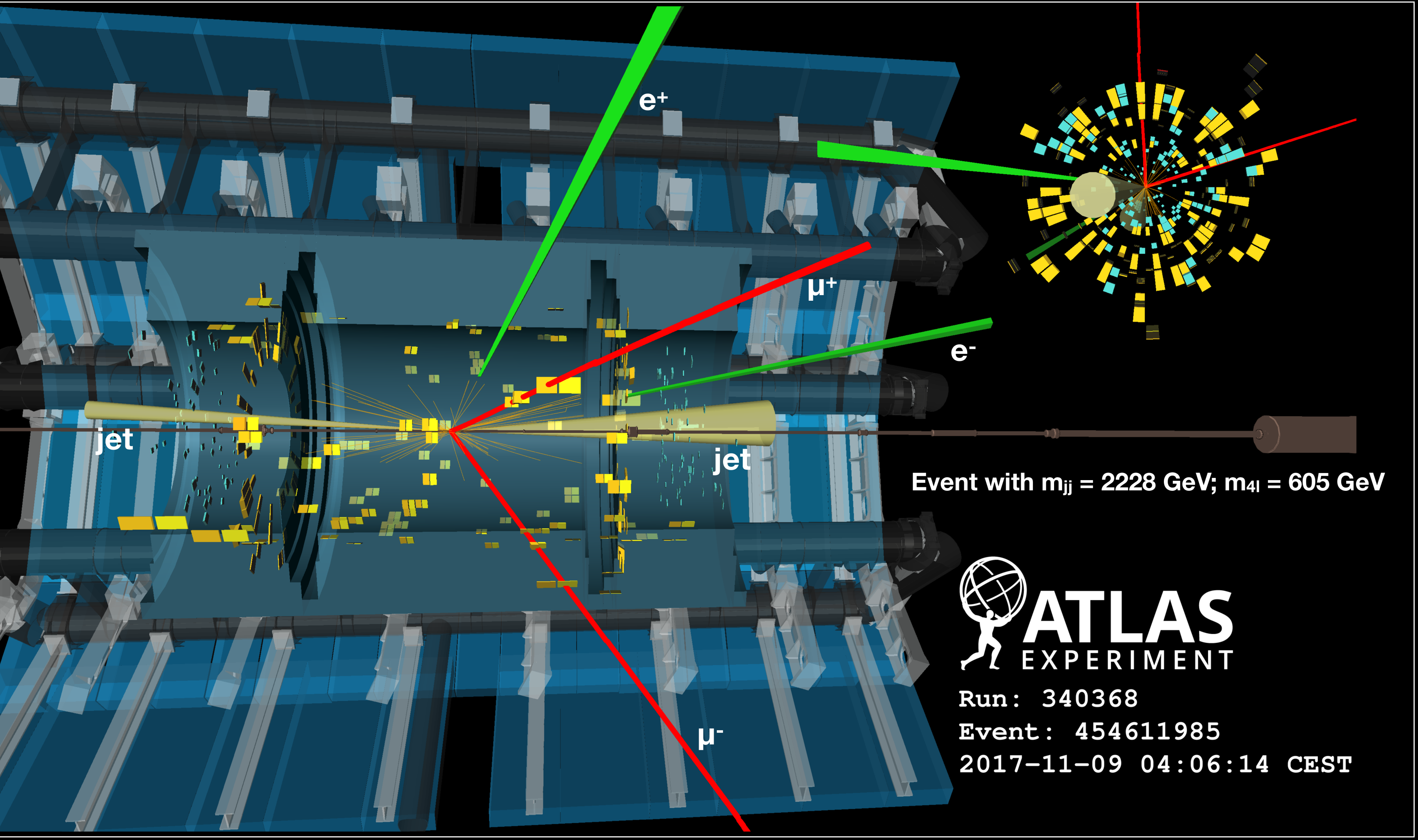
Vector Boson Scattering and Triboson Final States





From Yee Chinn Yap

ZZjj Candidate Event

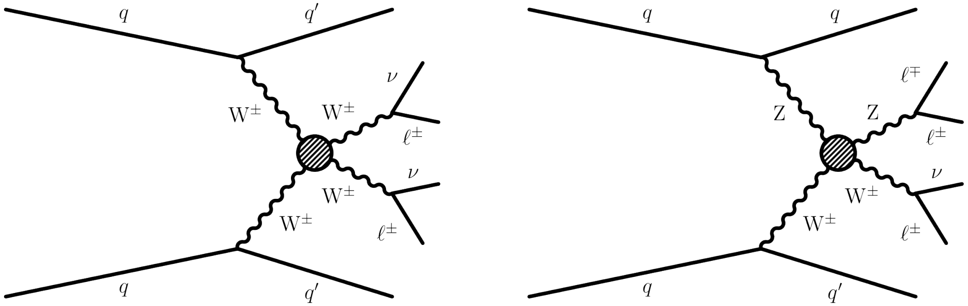


Event with m_{jj} = 2228 GeV; m_{4l} = 605 GeV

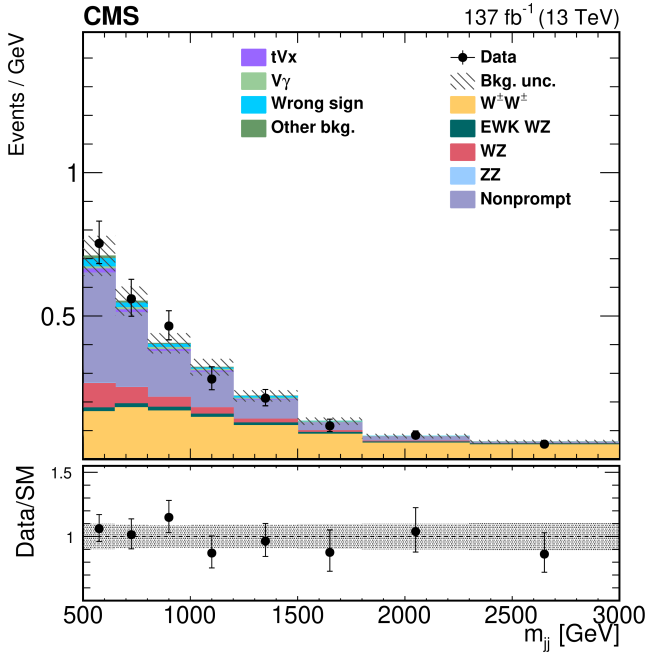
Run: 340368
Event: 454611985
2017-11-09 04:06:14 CEST

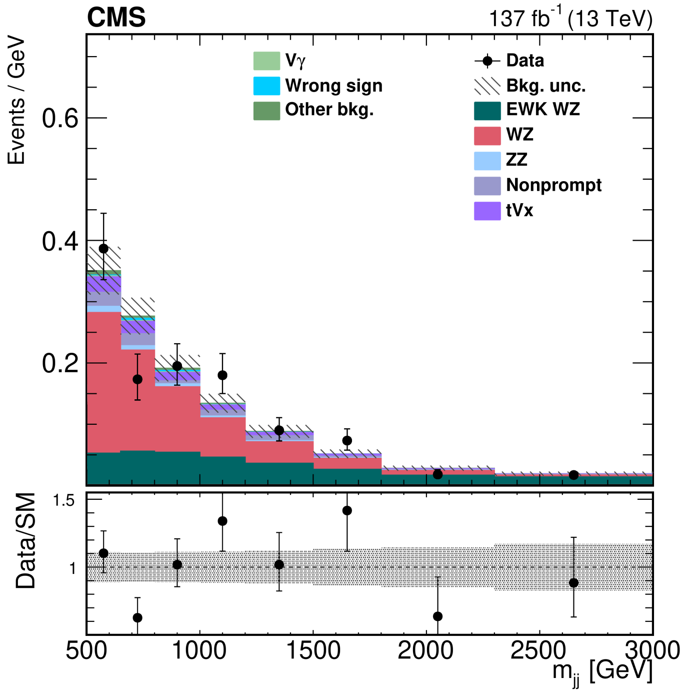
Probing WWWW and WWZZ Couplings

WZjj differential cross section measurements consistent with SM predictions, with observed significance of 6.8σ (5.3σ)

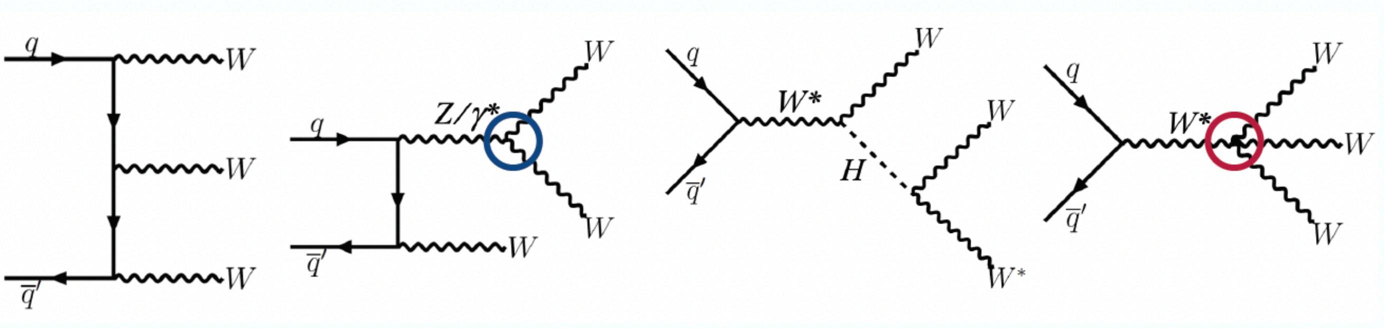


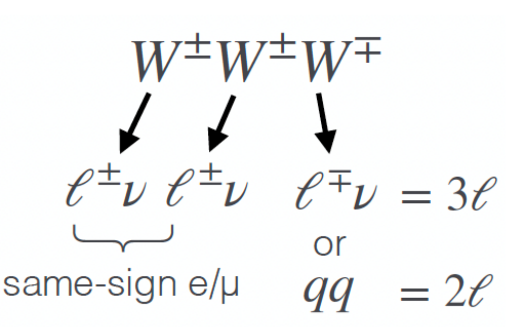
Phys. Lett. B 809 (2020) 135710





Observation of WWW Production





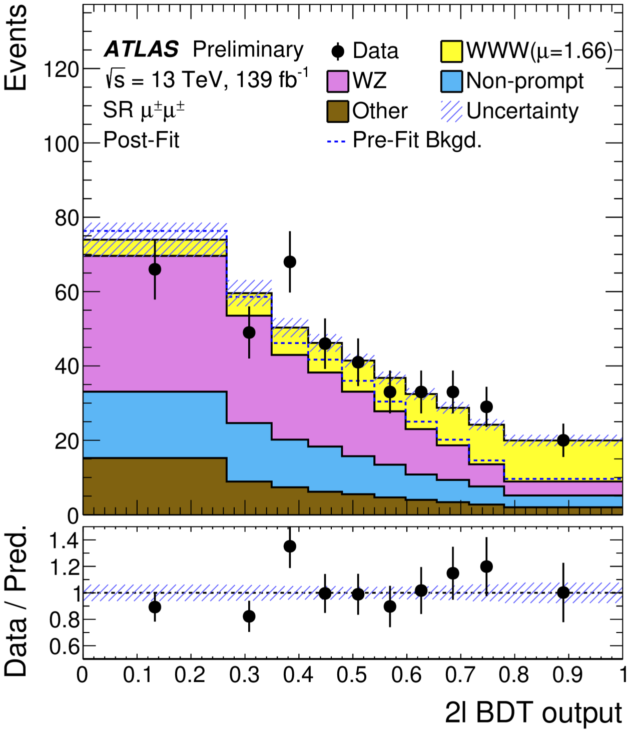
$$W^{\pm}W^{\pm}W^{\mp}$$

$$\underbrace{\ell^{\pm}\nu\ \ell^{\pm}\nu}_{\text{same-sign e/μ}}\quad \ell^{\mp}\nu = 3\ell$$

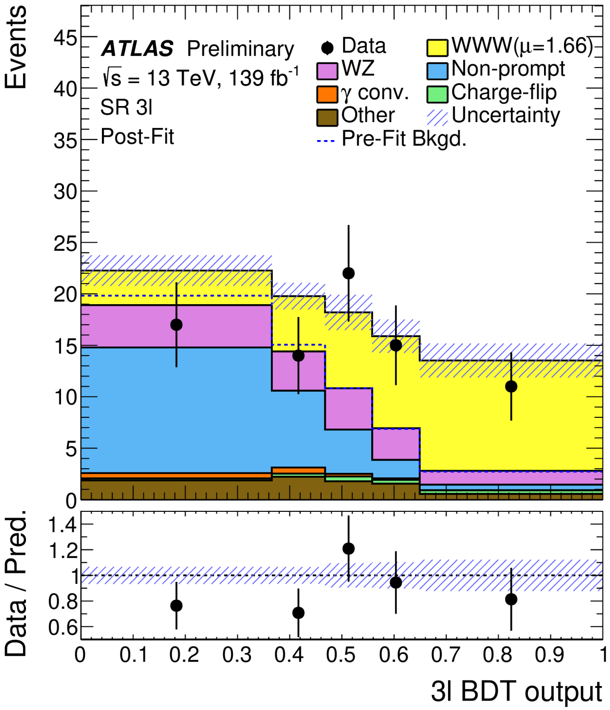
or

$$qq = 2\ell$$

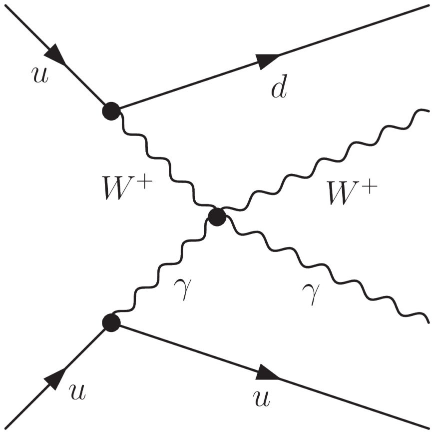
$$\sigma(pp \to WWW) = 850 \pm 100\,(\text{stat.}) \pm 80\,(\text{syst.})\ \text{fb}.$$

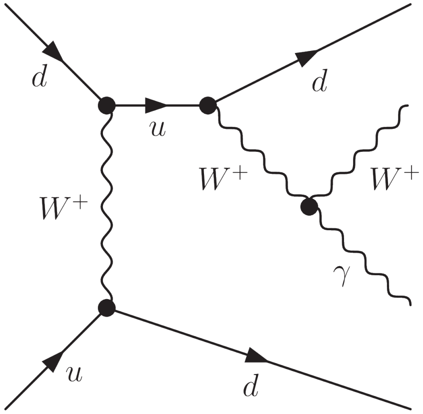


Observation: 8.2σ
SM expected: 5.4σ

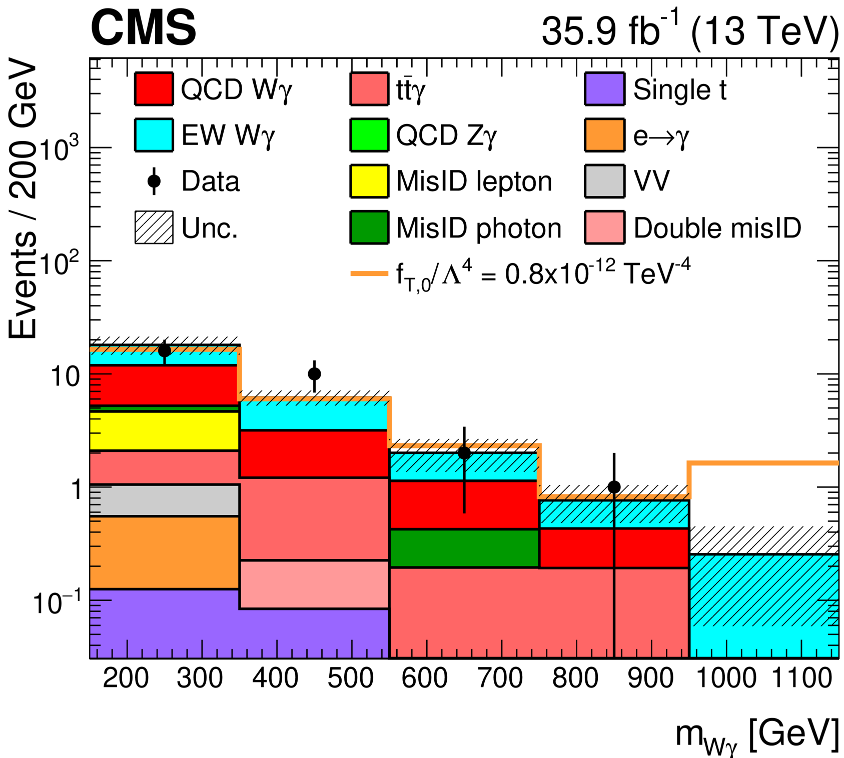


EWK Physics: Wγ Observation in VBS Final State





- VBS Signature
- Signal extracted using 2D mjj and mlγ fit
- Observed (expected significance): 4.9 (4.6)
  - Adding 8 TeV analysis gives obs. 5.3
- Anomalous coupling limits set using mWγ distribution

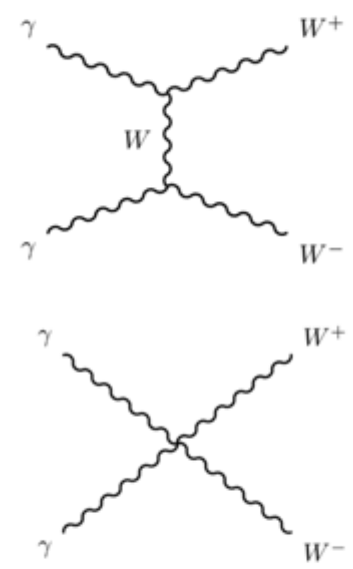


The Large Photon Collider: $\gamma\gamma$WW

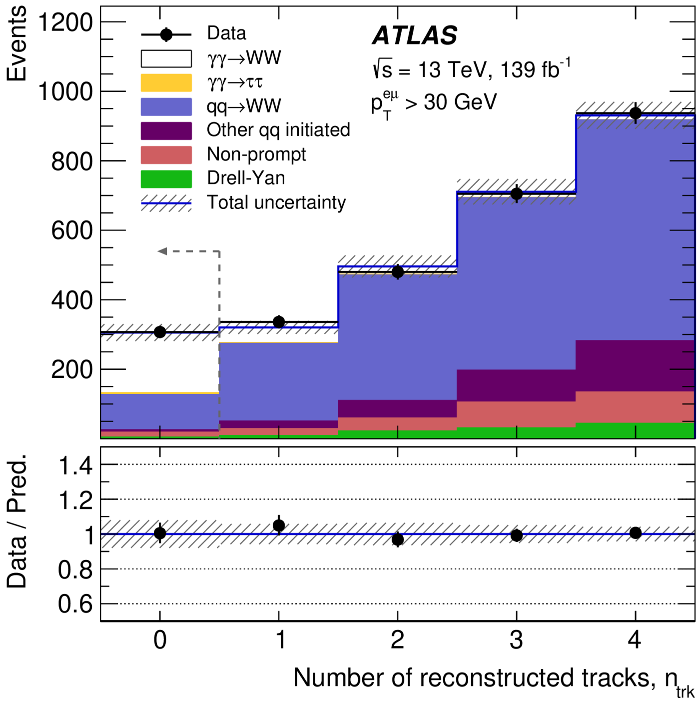
Photon-induced WW production

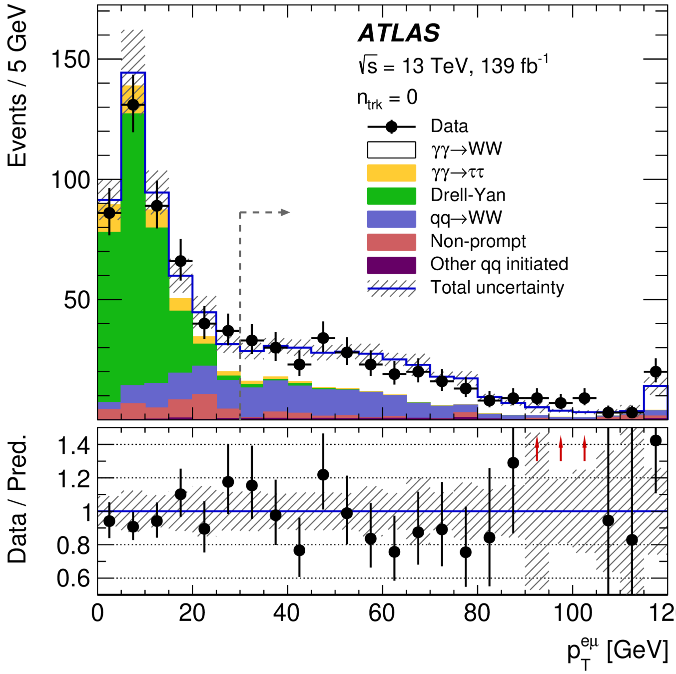
Challenge: isolate production process in busy LHC environment: use number of Primary Vertex tracks

Significance of signal > 8σ

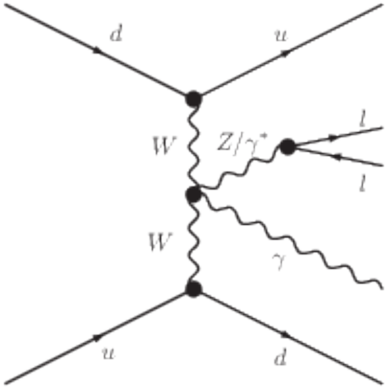


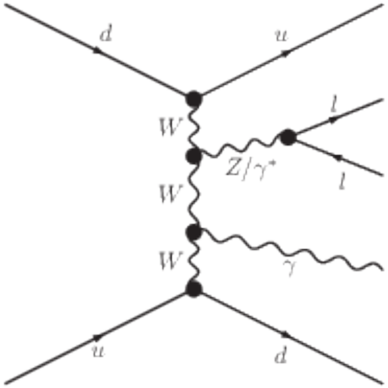
$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

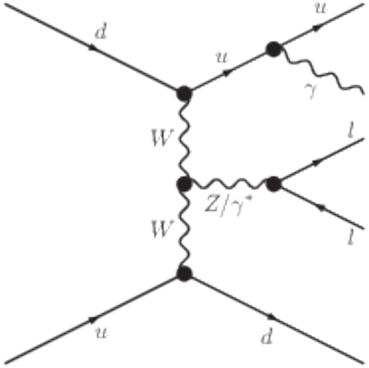




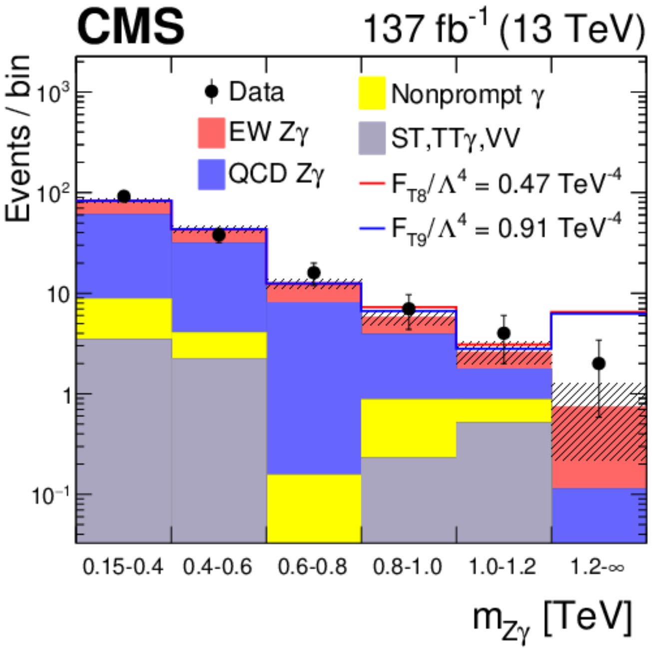
Probing the WWZγ vertex, Zγ Observation







- VBS Signature
- Observed significance much greater than 5
- Measure differential cross section in 4 variables
- Anomalous coupling limits set using mZγ distribution

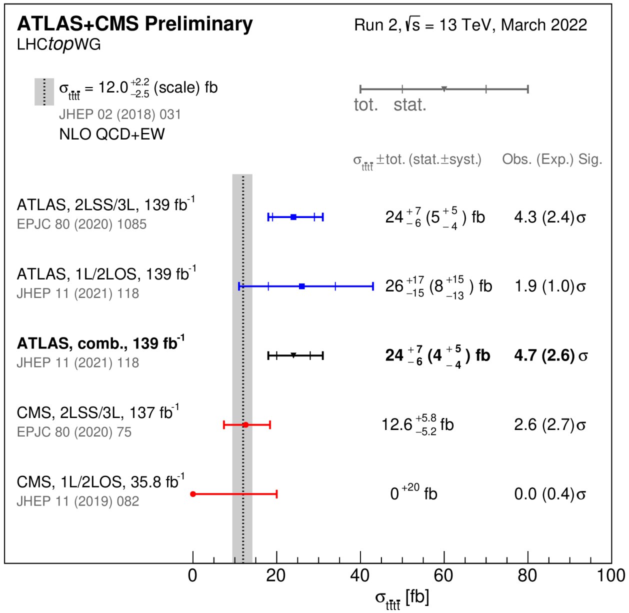


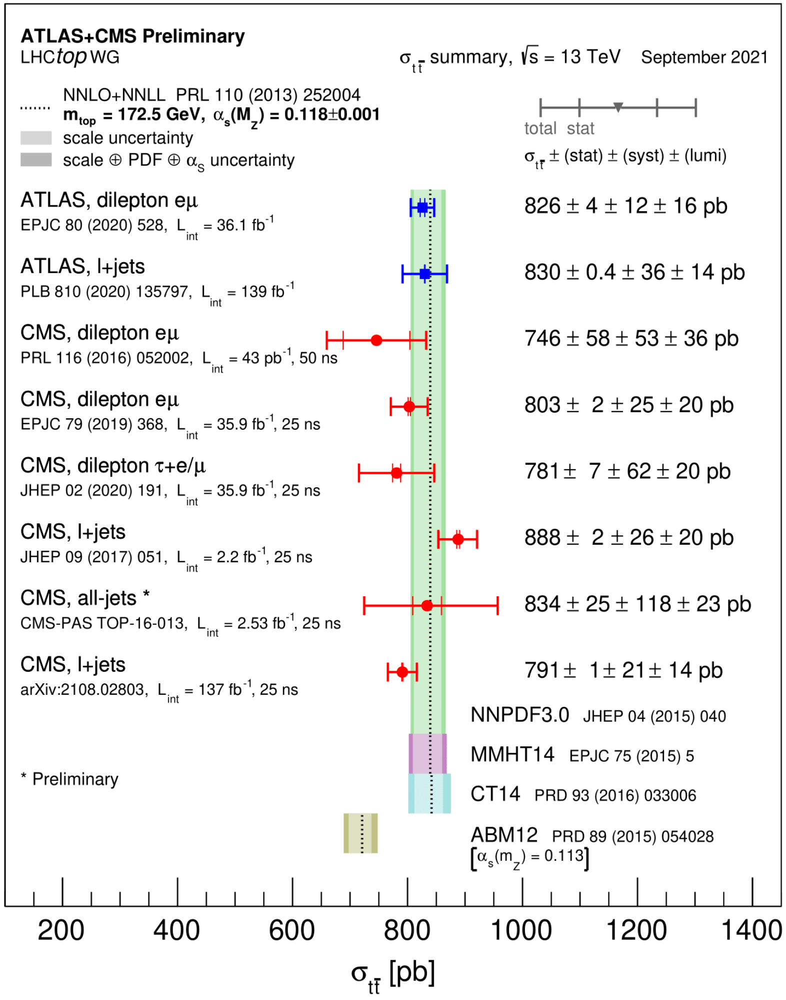
Top Pair and Top Quadruplet Production

Top pair production measured very precisely: ~ 2.5% precision in dilepton eμ channel

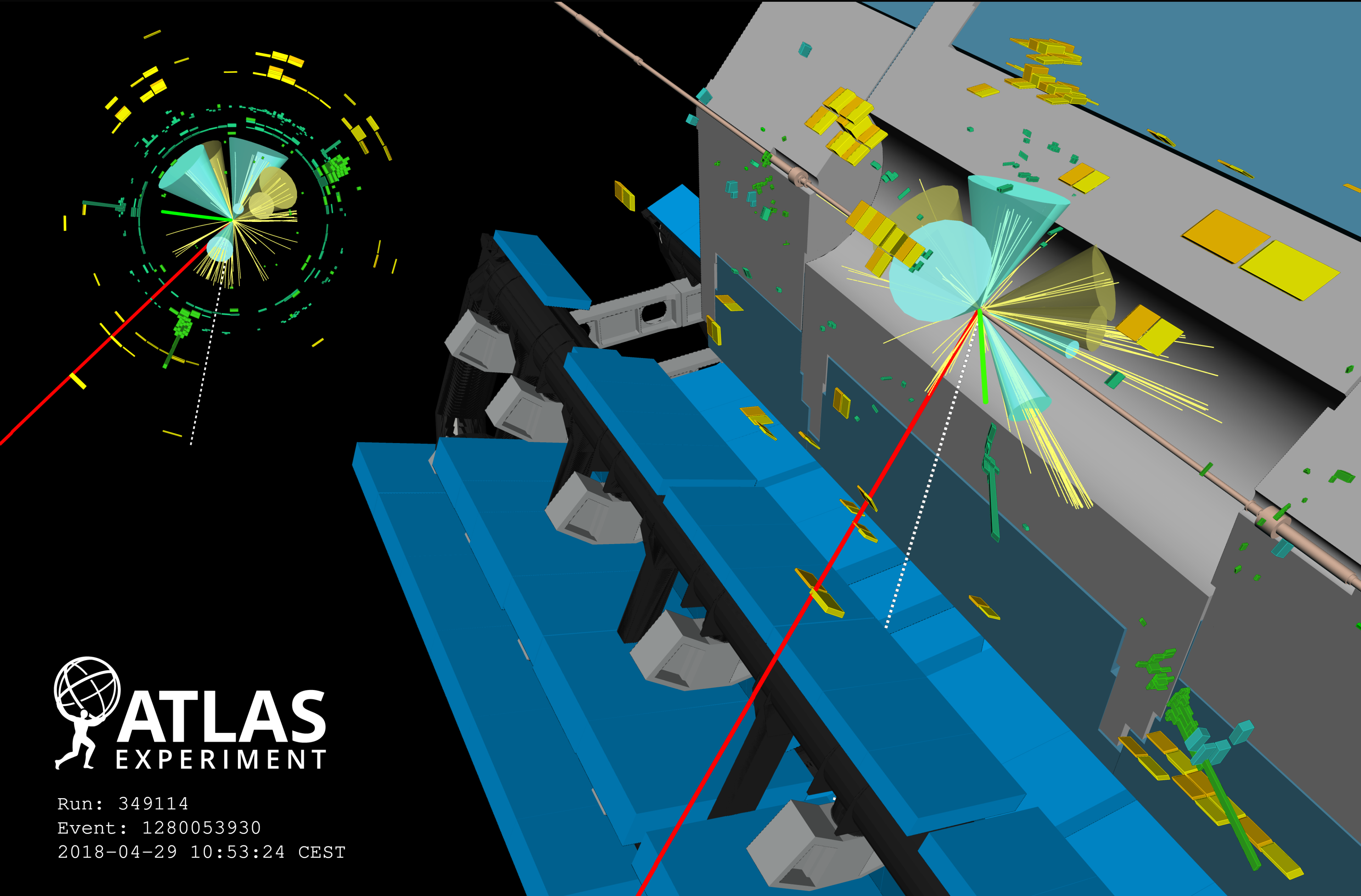
Strong evidence for the production of four top quarks

- Run 3 should allow the observation of this spectacular process by both experiments





Candidate Event: Four Top Quarks



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Event: 1280053930
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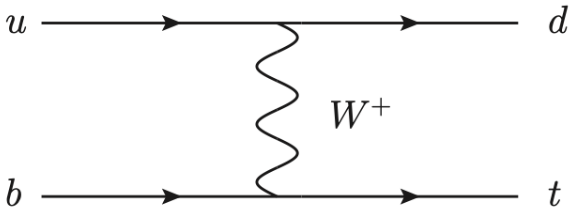
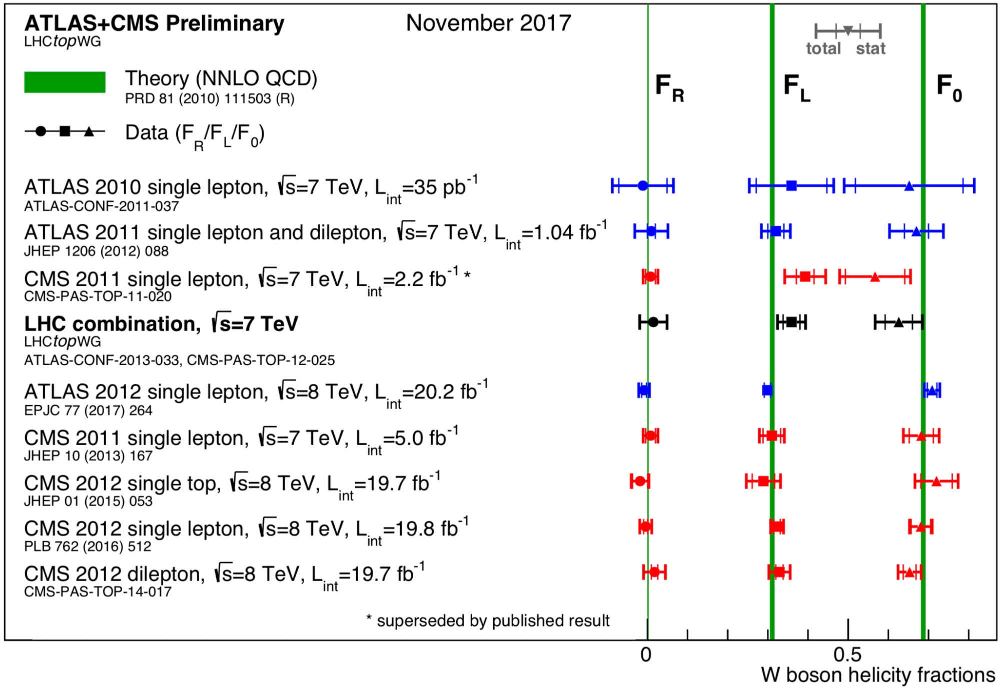
Electroweak Physics and the Top Quark

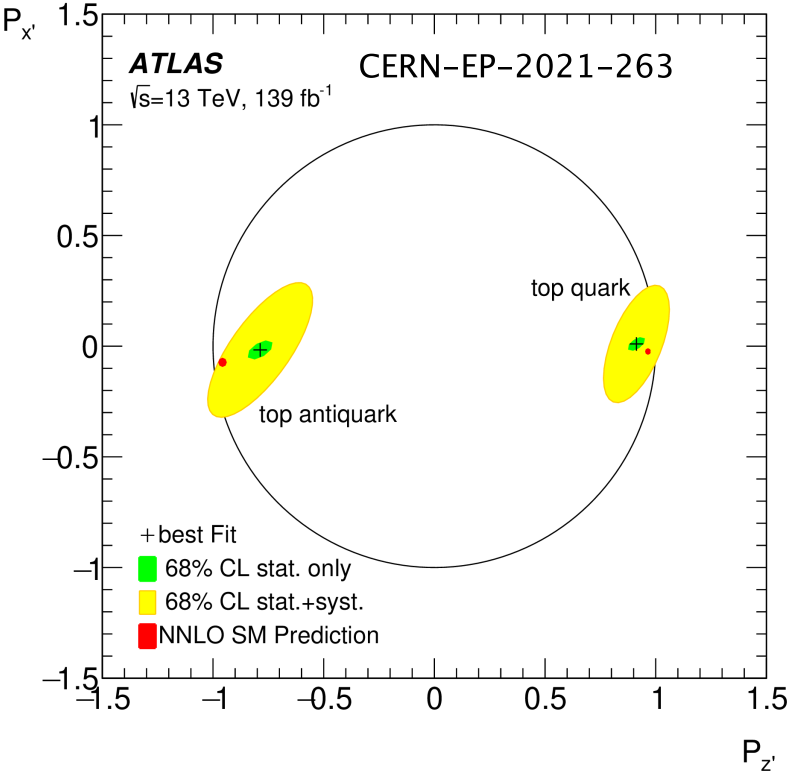
SM predicts the polarization of the W boson in top quark decays as a function of the top mass

- Excellent agreement with the prediction of the SM

Measure top quark polarization in single top events: test V-A nature of Wtb vertex



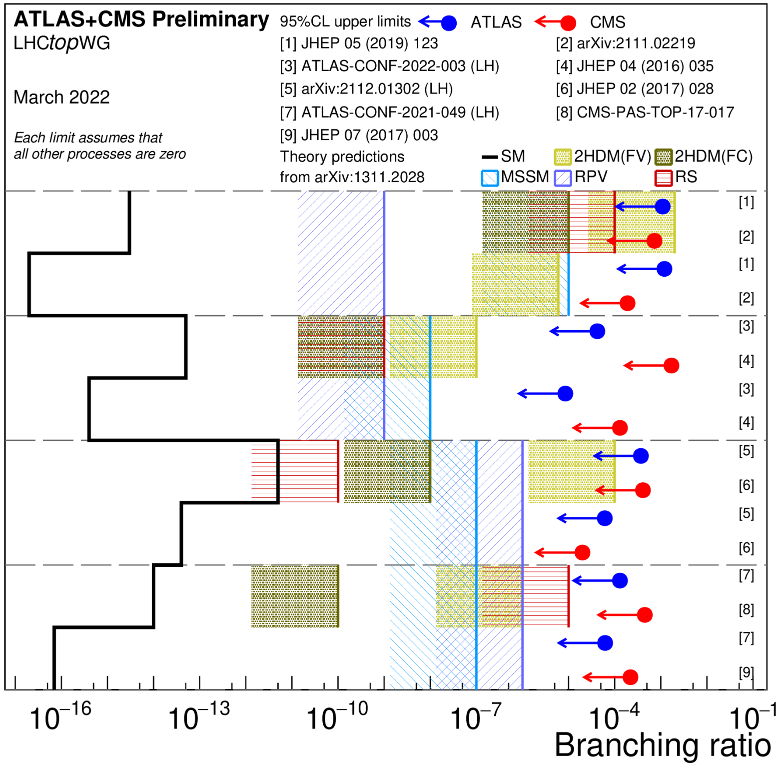


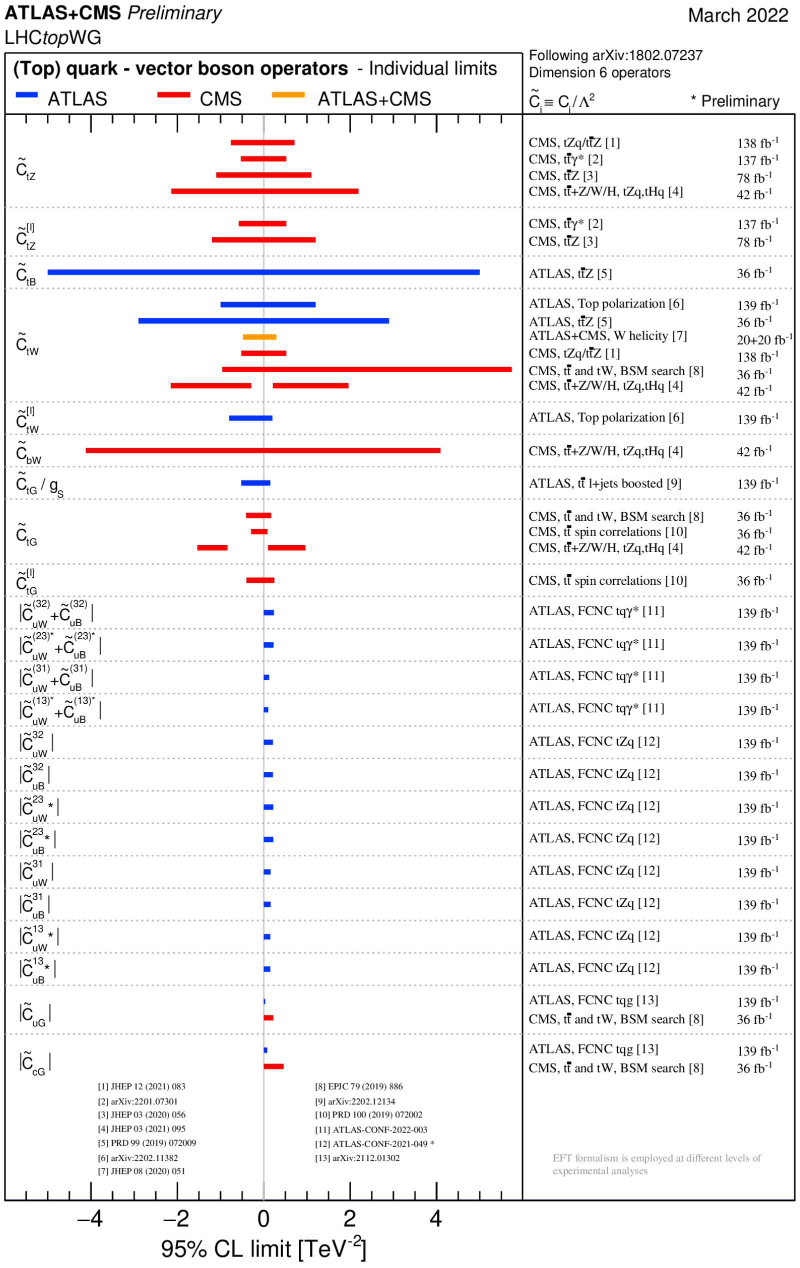


Rare Decays and Limits on EFT Operators

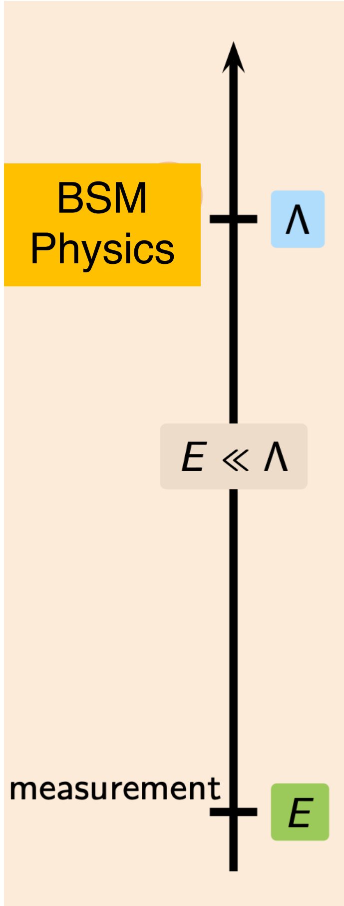
Very large sample of top quarks allows for stringent limits on rare top decays and FCNCs in top decay (down to BRs ~10^{-5})

Results interpreted in the context of top quark–vector boson operators in Effective Field Theories





EFT Interpretations of Electroweak, Top quark and Higgs boson Measurements



If physics beyond the Standard Model exists above the energy scale of the LHC, it could still impact the results of various measurements:

- Can be sensitive to small deviations thanks to high precision of many measurements
- Deviations can be amplified in high-p_T tails of kinematic distributions

$$L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \Sigma \frac{d_i}{\Lambda^4} O_i^{d=8} + \ldots..$$

BSM Effects **SM Particles**

From I. Brivio, S. Dawson

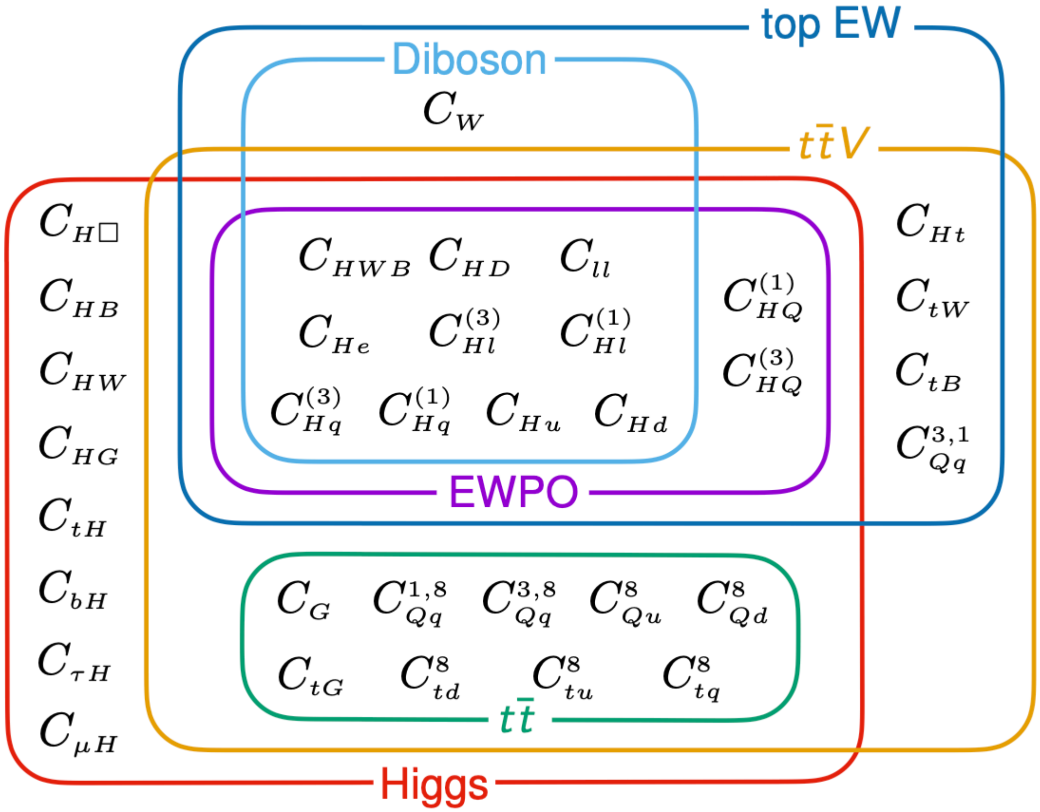
Towards Global EFT Combinations

Combinations of different measurements will increase sensitivity to possible higher order operators

Challenging to perform these combinations in a coherent way with all correlations

- Some operators will impact both the signal and background (shape and/or normalization)
- Some examples of coherent treatment in:
    - ATLAS HWW and WW (ATL-PHYS-PUB-2021-010)
    - CMS Hγγ and γγ continuum (HIGG-2019-13)

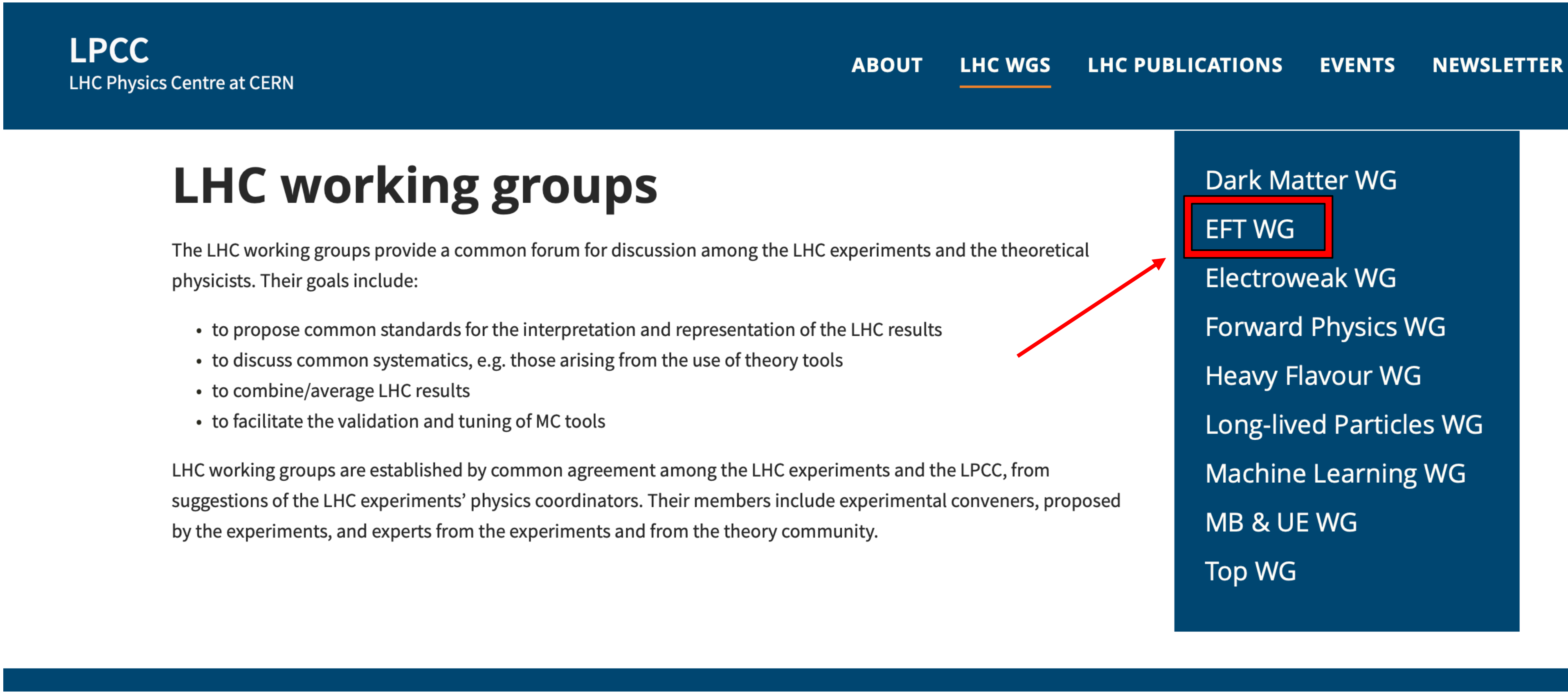
CERN–TH–2020–202



Large scale global combination effort between ATLAS and CMS has started: will include top, Higgs and electroweak measurements

LHC EFT Working Group

A LHC working group associated with the LPCC was created 2 years ago:



LHC working groups

The LHC working groups provide a common forum for discussion among the LHC experiments and the theoretical physicists. Their goals include:

- to propose common standards for the interpretation and representation of the LHC results
- to discuss common systematics, e.g. those arising from the use of theory tools
- to combine/average LHC results
- to facilitate the validation and tuning of MC tools

LHC working groups are established by common agreement among the LHC experiments and the LPCC, from suggestions of the LHC experiments' physics coordinators. Their members include experimental conveners, proposed by the experiments, and experts from the experiments and from the theory community.

- Next General Meeting soon: Monday May 23 2022
  - Indico agenda: https://indico.cern.ch/event/1136803/
  - Status of global combinations mentioned before will be covered

Conclusions

The Run 2 dataset has allowed LHC experiments to observe new electroweak production processes, some sensitive to the quartic couplings

New Higgs production processes were observed in Run 2 and evidence is emerging of the Higgs coupling to 2nd generation particles. Couplings to bosons measured with precision of 5%, top and tau fermions in the 7-12% range

The very large top quark data sample has been used to perform precision tests of the Standard Model. New top mass measurement precision at the level 0.2%. Great laboratory for tests of electroweak theory

The results presented in this talk use 5% of the total dataset that is planned for the LHC. Combination of precision SM measurements using Run 2 and future datasets will allow for powerful searches for new phenomena in the framework of Effective Field Theories

Backup Slides

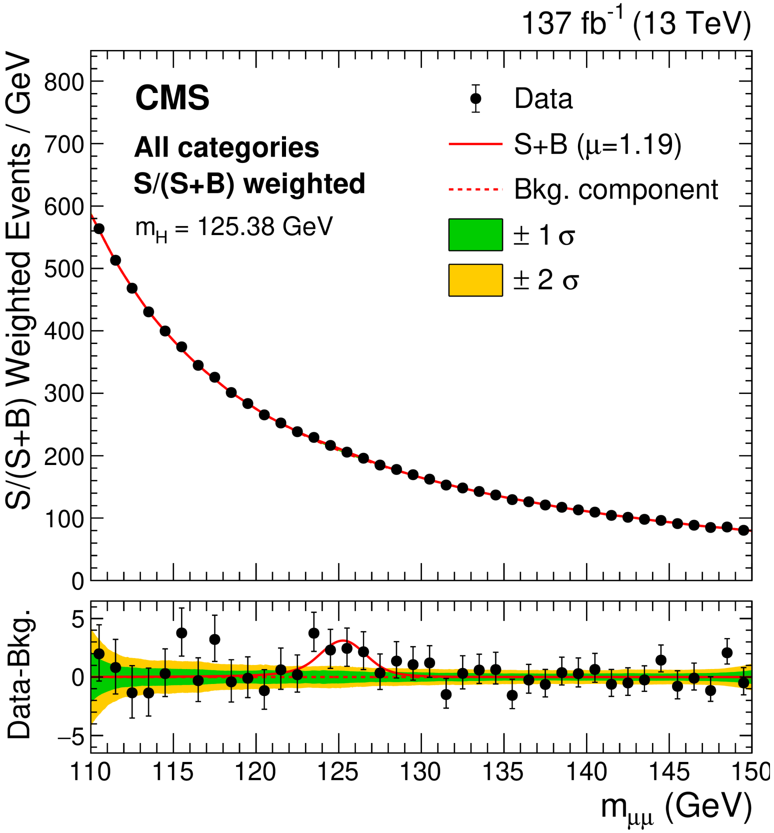
Search for Higgs decay to muons

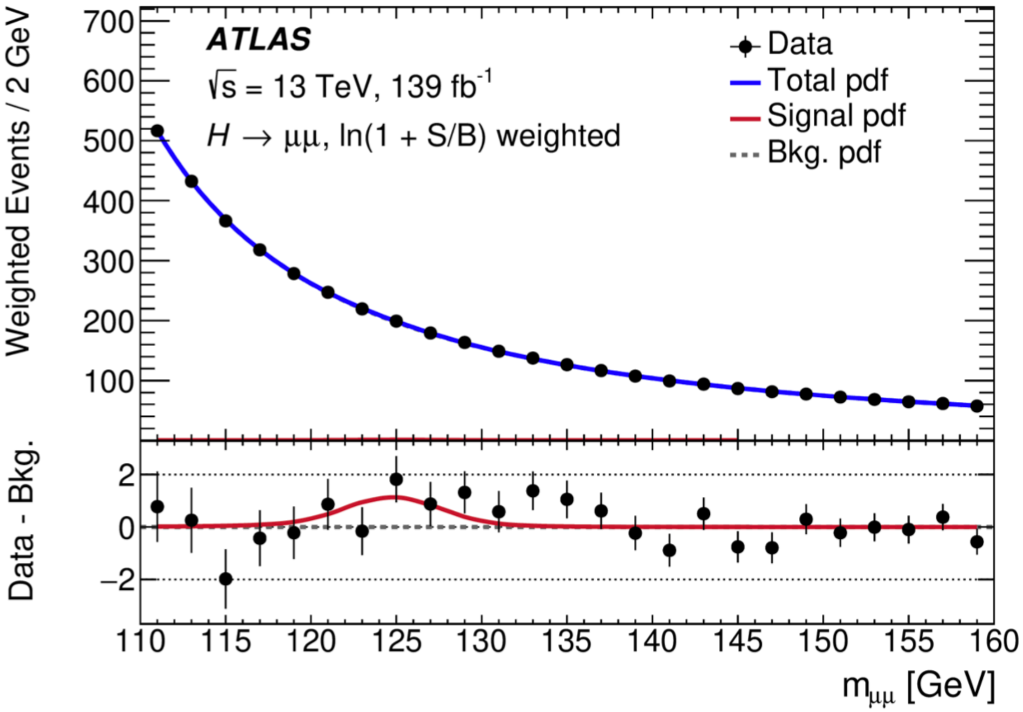
A new frontier: the 2nd generation

  - Challenging! small couplings in the SM and large backgrounds

- Full Run 2 dataset search for Higgs → μμ
- Results: ATLAS: 2.0σ (obs), 1.7σ (exp), CMS 3.0σ (obs), 2.5σ (exp)

Results consistent with SM prediction, stats-limited → looking forward to Run 3

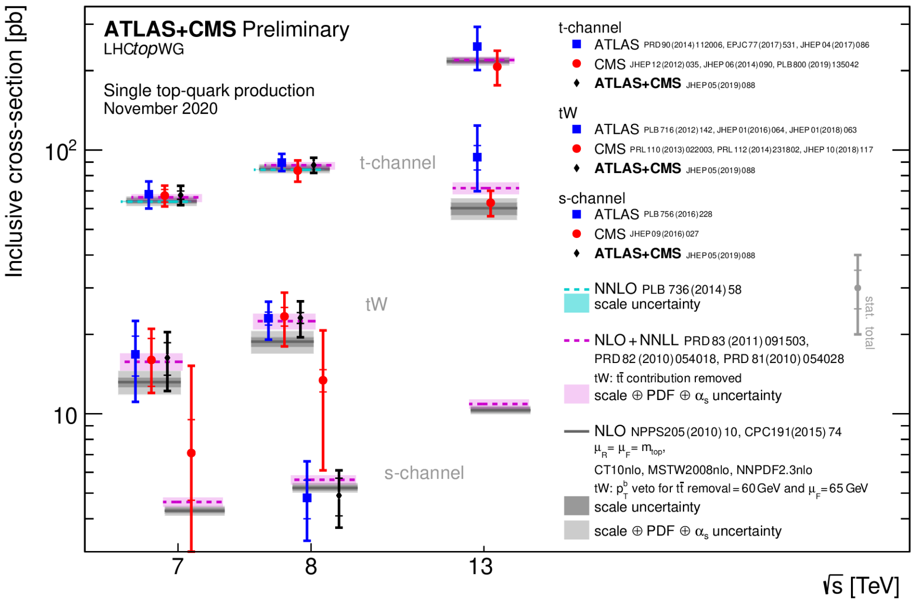


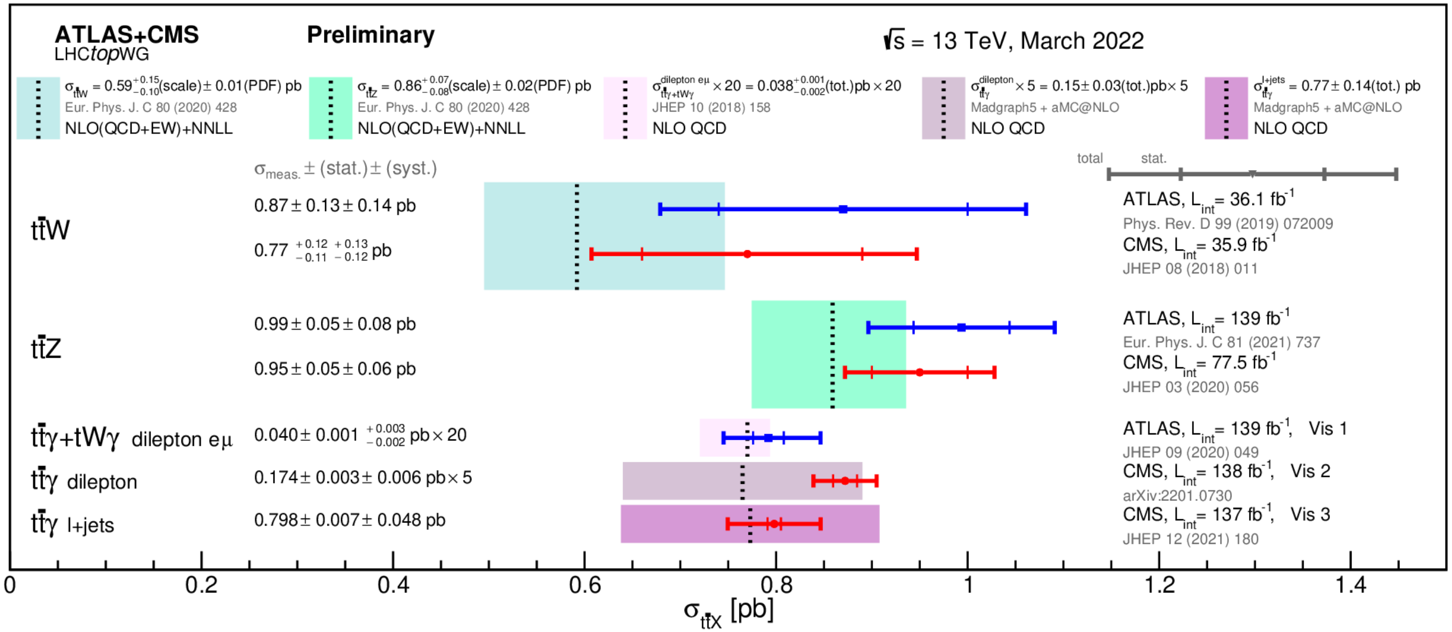


EWK production and Associated Production with an EWK Boson

Electroweak production of (single) top quarks studied in 3 main production modes (t-channel, s-channel and Wt production)

Program of cross section measurements of associated production of top quarks and EWK bosons underway

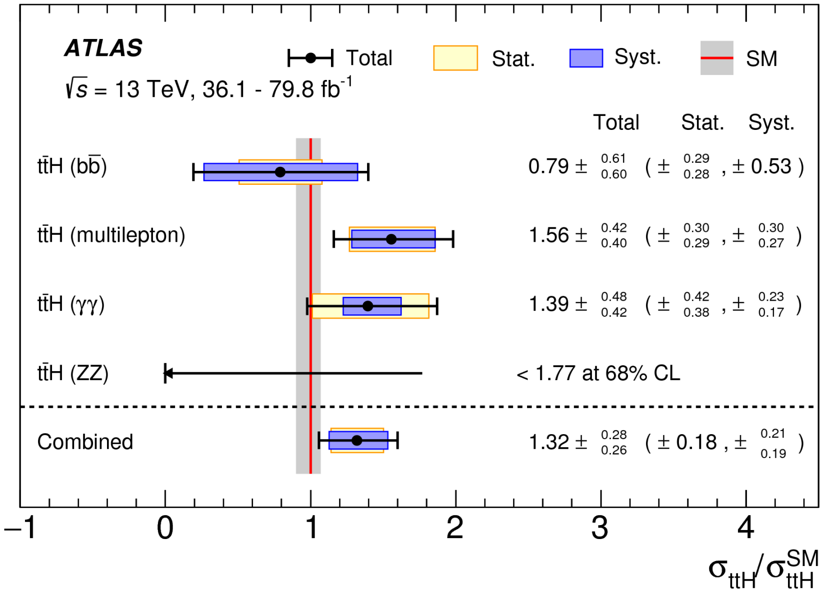


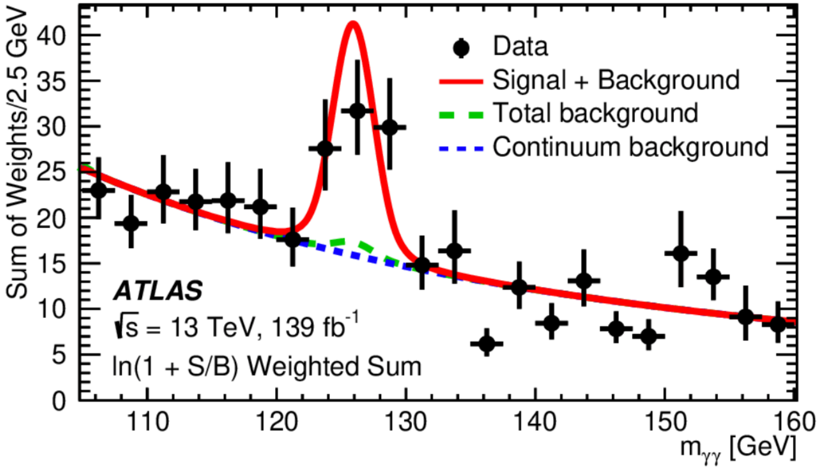


Observation of ttH Production

Coupling of Higgs to top quark probed through ggH production but assumes no other contribution in production loop

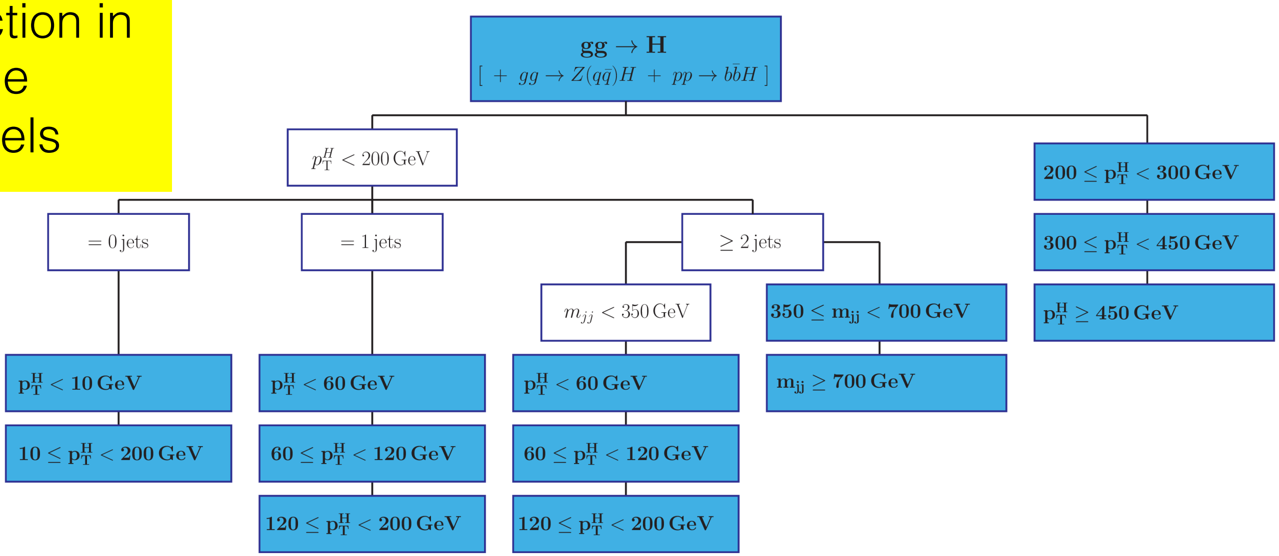
- ttH production probes coupling more directly and tests particle loop content
- Process now observed in very rare ttH(γγ): now most sensitive channel after Run 2
- First studies of CP properties of t-H interaction performed. Run 3 dataset will significantly improve sensitivity





“Simplified Template Cross Sections” (STXS)

STXS probe Higgs production in kinematics bins that can be combined between channels



$gg \to H$

$[+ \; gg \to Z(q\bar{q})H \; + \; pp \to b\bar{b}H]$

$p_T^H < 200$ GeV

$= 0$ jets

$p_T^H < 10$ GeV

$10 \leq p_T^H < 200$ GeV

$= 1$ jets

$p_T^H < 60$ GeV

$60 \leq p_T^H < 120$ GeV

$120 \leq p_T^H < 200$ GeV

≥ 2 jets

$m_{jj} < 350$ GeV

$p_T^H < 60$ GeV

$60 \leq p_T^H < 120$ GeV

$120 \leq p_T^H < 200$ GeV

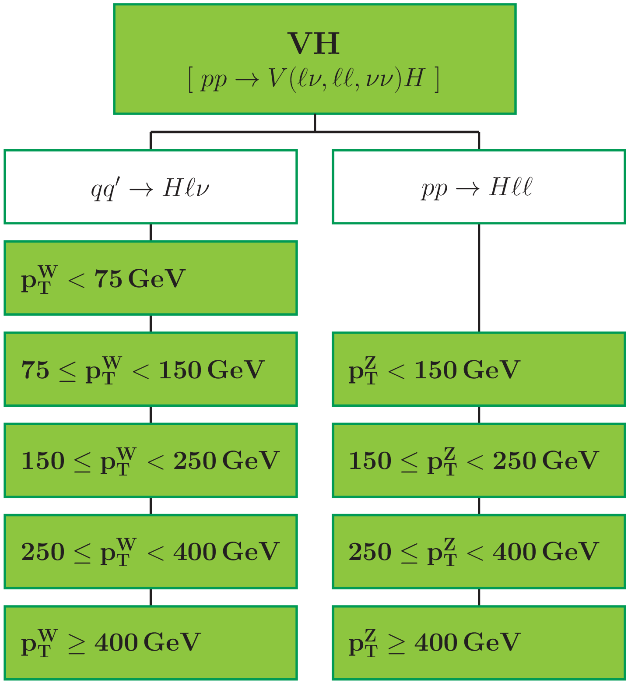
$350 \leq m_{jj} < 700$ GeV

$m_{jj} \geq 700$ GeV

$200 \leq p_T^H < 300$ GeV

$300 \leq p_T^H < 450$ GeV

$p_T^H \geq 450$ GeV



VH

$[pp \to V(\ell\nu, \ell\ell, \nu\nu)H]$

$qq' \to H\ell\nu$

$p_T^W < 75$ GeV

$75 \leq p_T^W < 150$ GeV

$150 \leq p_T^W < 250$ GeV

$250 \leq p_T^W < 400$ GeV

$p_T^W \geq 400$ GeV

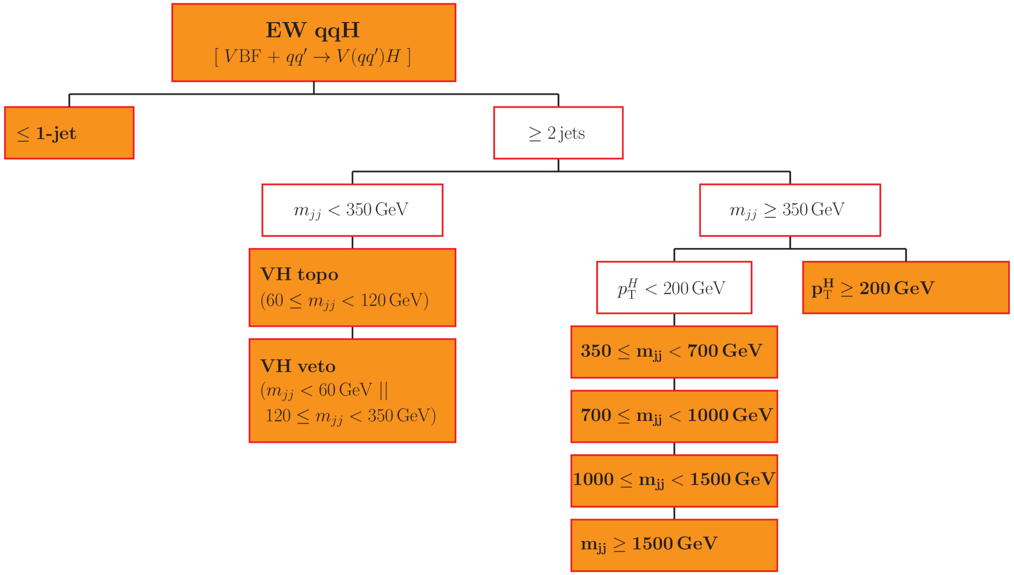
$pp \to H\ell\ell$

$p_T^Z < 150$ GeV

$150 \leq p_T^Z < 250$ GeV

$250 \leq p_T^Z < 400$ GeV

$p_T^Z \geq 400$ GeV



EW qqH

$[\mathrm{VBF} + qq' \to V(qq')H]$

$\leq$ 1-jet

≥ 2 jets

$m_{jj} < 350$ GeV

VH topo

$(60 \leq m_{jj} < 120$ GeV$)$

VH veto

$(m_{jj} < 60$ GeV $||$

$120 \leq m_{jj} < 350$ GeV$)$

$m_{jj} \geq 350$ GeV

$p_T^H < 200$ GeV

$350 \leq m_{jj} < 700$ GeV

$700 \leq m_{jj} < 1000$ GeV

$1000 \leq m_{jj} < 1500$ GeV

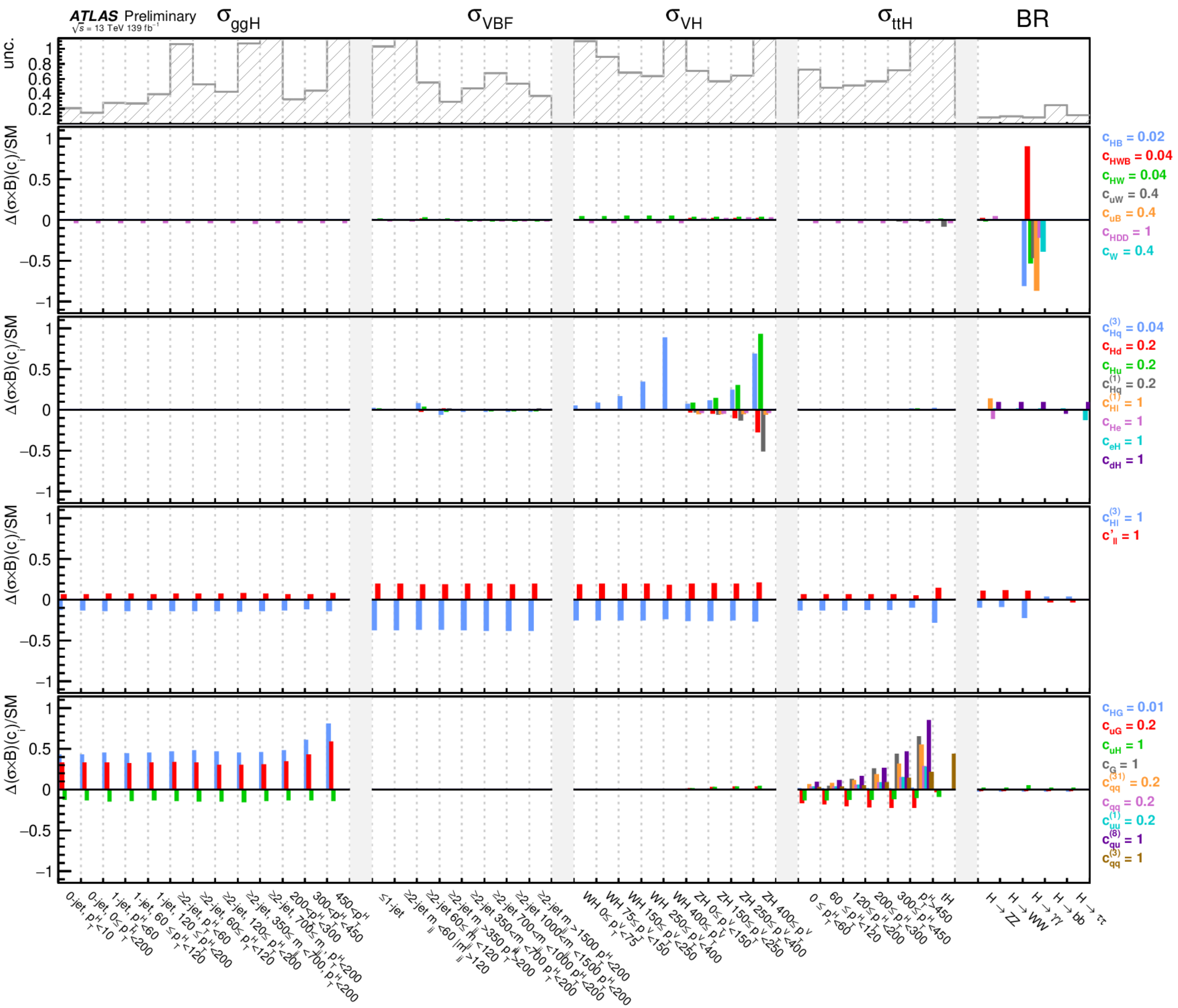
$m_{jj} \geq 1500$ GeV

$p_T^H \geq 200$ GeV

CERN-EP-2020-117 Sub. to PLB

Example: ATLAS Higgs EFT fit using Simplified Template Cross Sections

Impact of various coefficients on kinematic regions (in STXS framework):



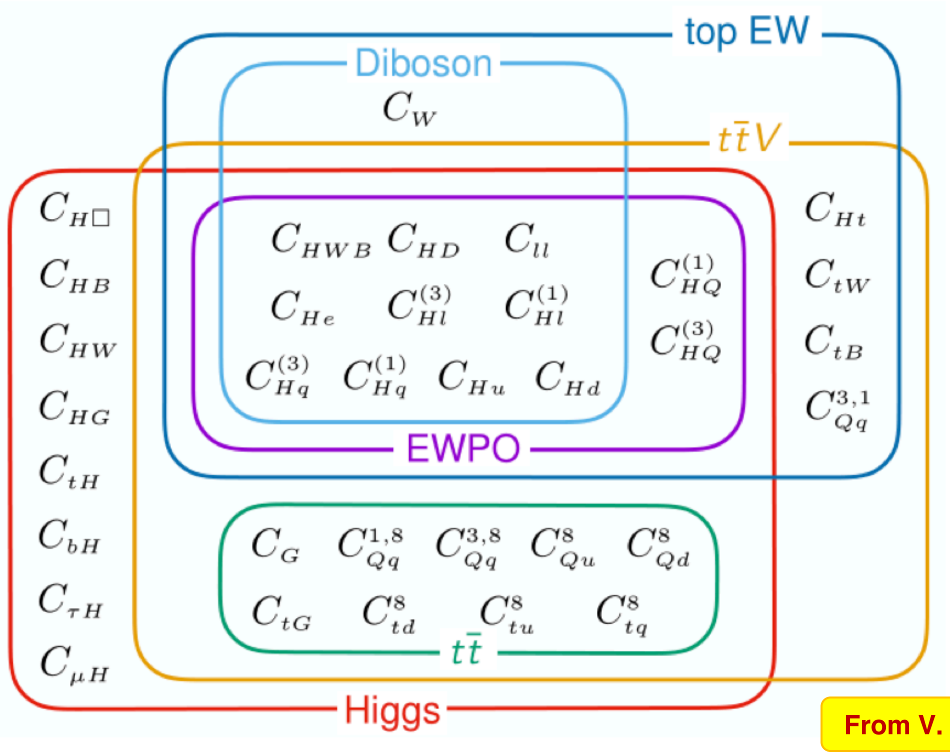
Effective Field Theory Interpretations

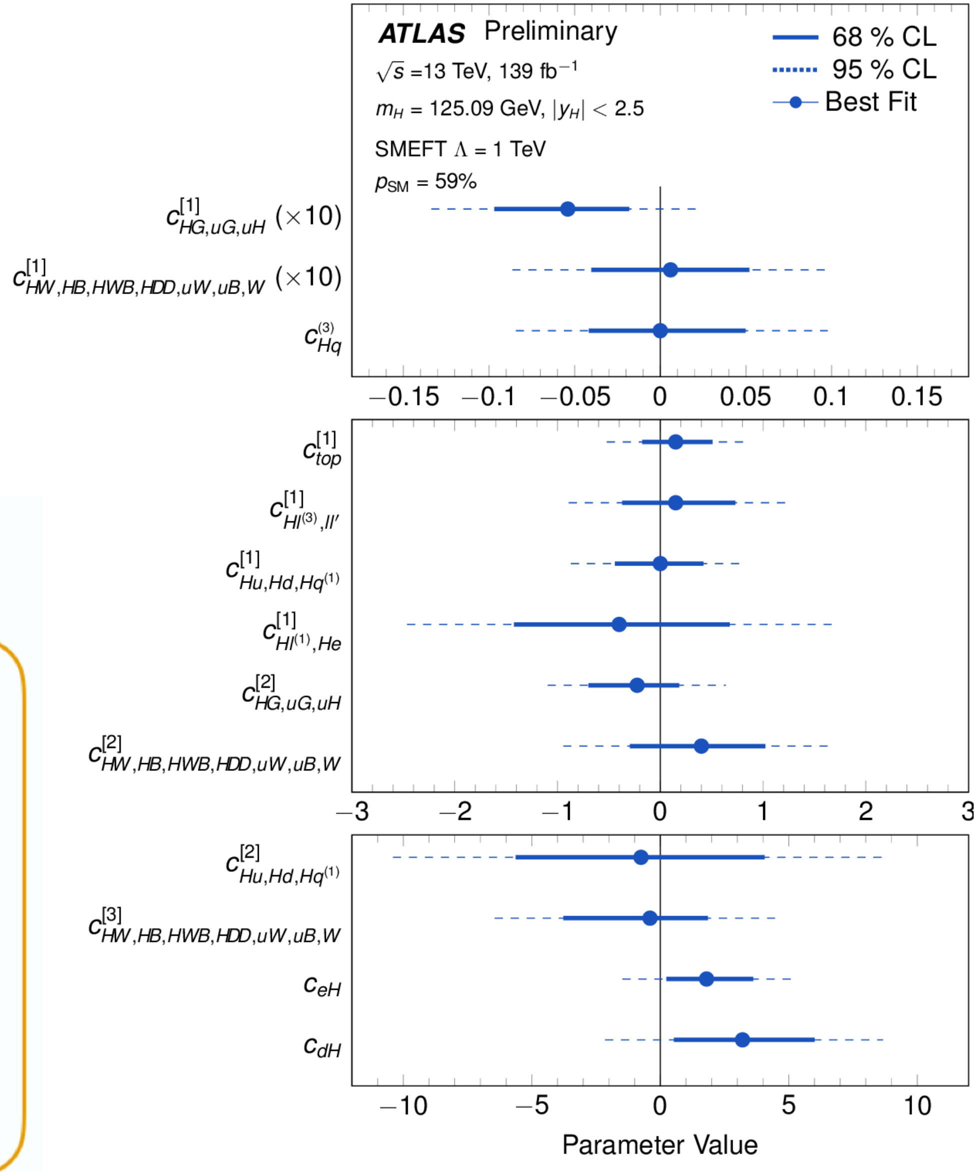
Right:

EFT fit to Higgs Simplified Template Cross Section combination

Below:

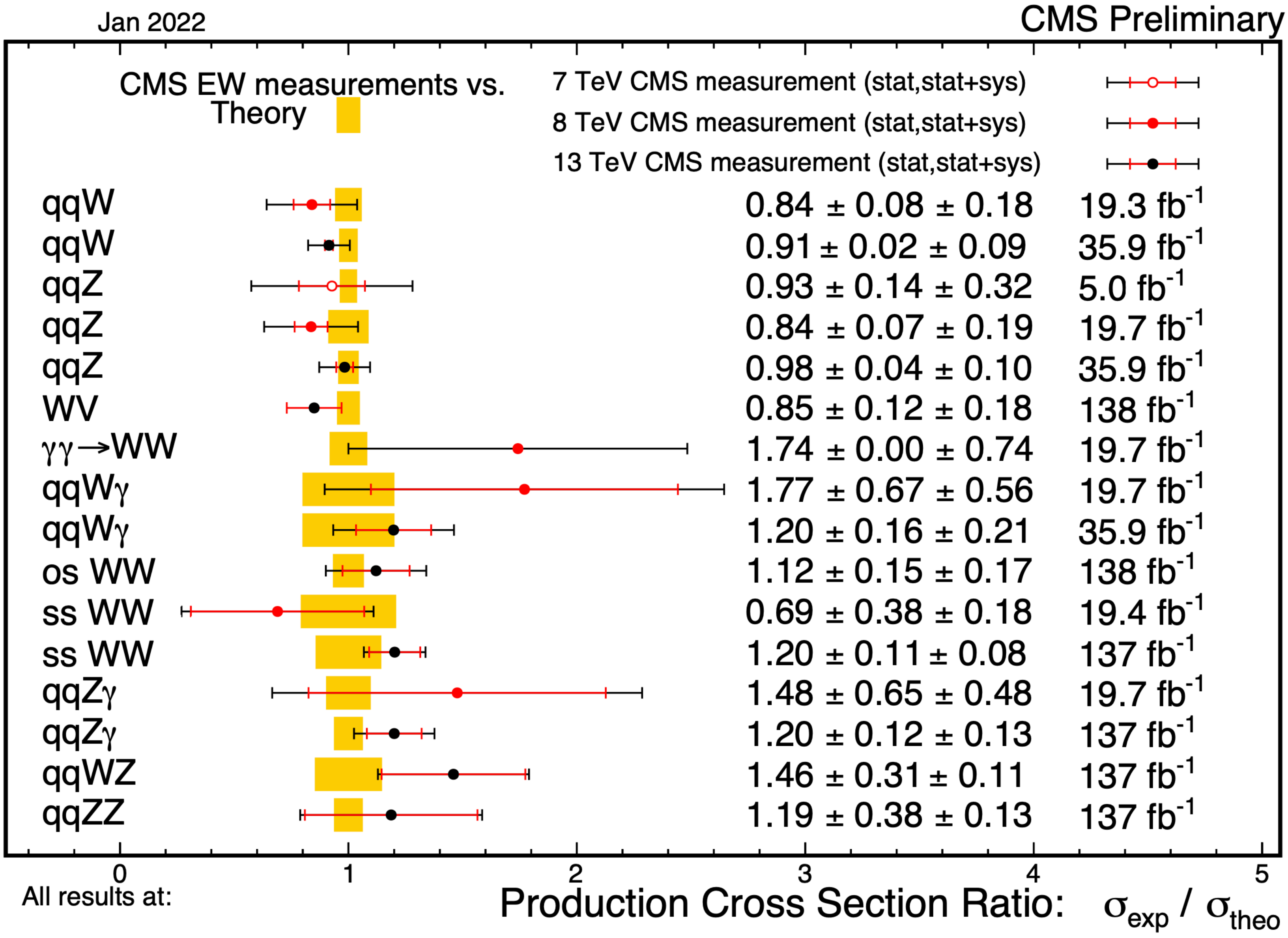
ATLAS and LHC EFT WG preparing for large global EFT fits using wide variety of measurements





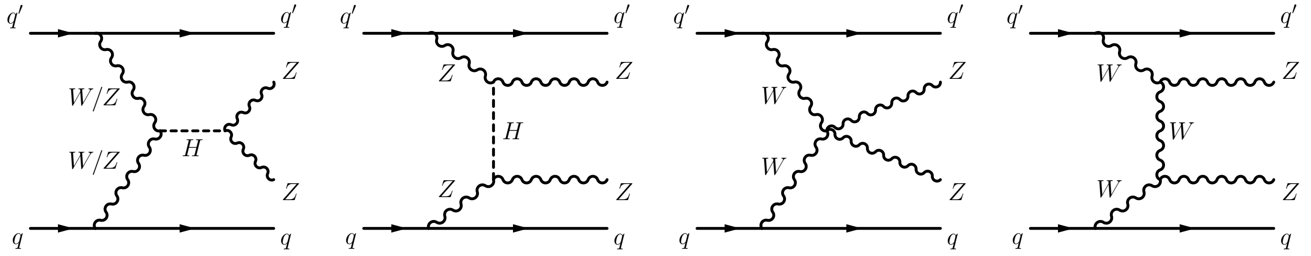
From V. Sanz

Electroweak Multiboson Production



Observation of Vector Boson Scattering in ZZjj

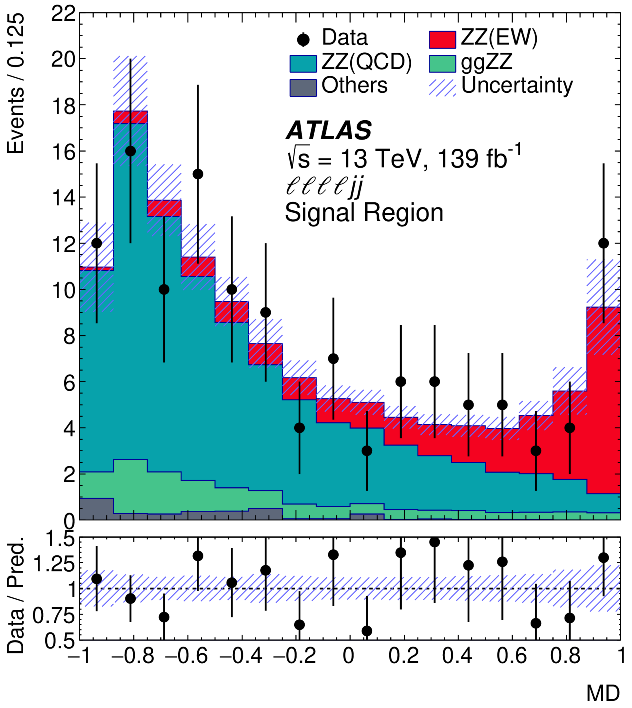
Higgs boson regularizes the weak boson scattering cross section at high energies

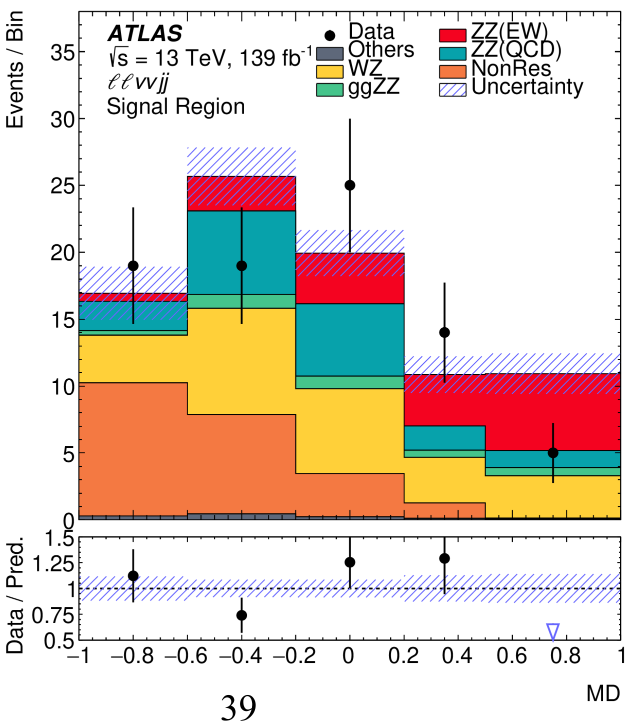


arXiv:2004.10612

ZZjj analysis exploits decays to four charged leptons ($\ell\ell\ell\ell$) and ($\ell\ell\nu\nu$)

Multivariate analysis to separate EW signal from backgrounds (e.g. QCD ZZ)





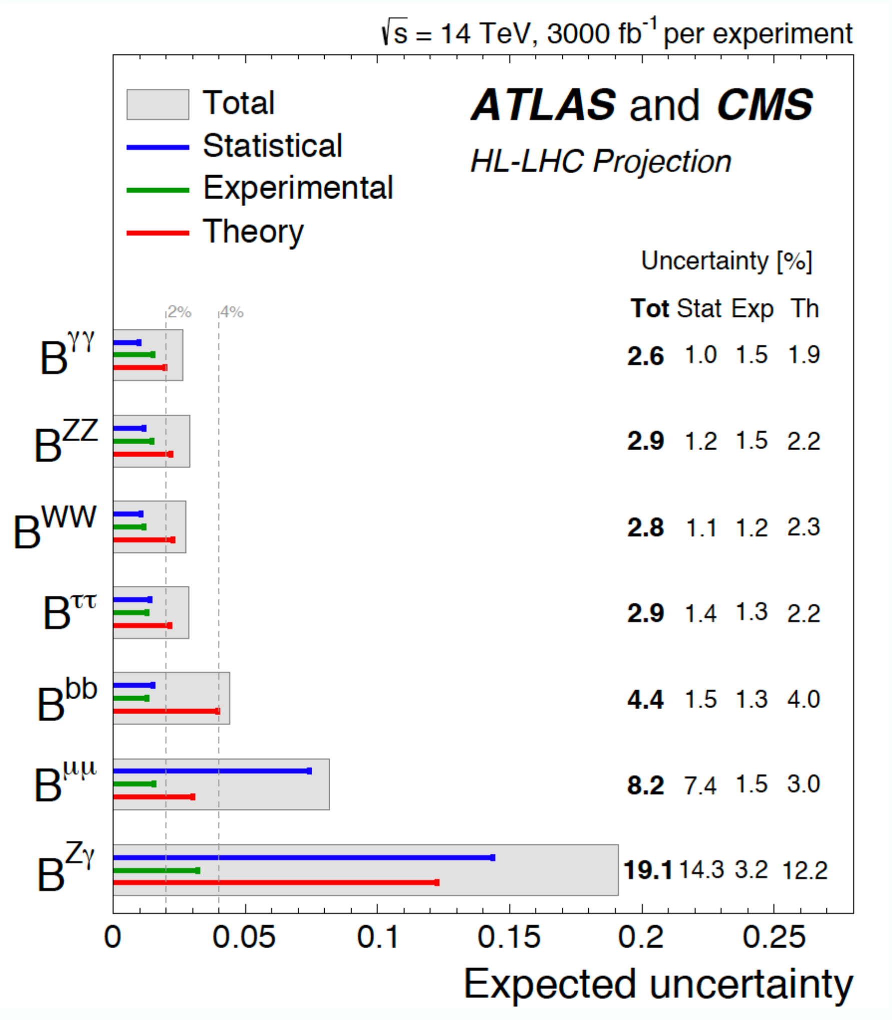
Observed (expected) significance for EW production: 5.5σ (4.3σ)

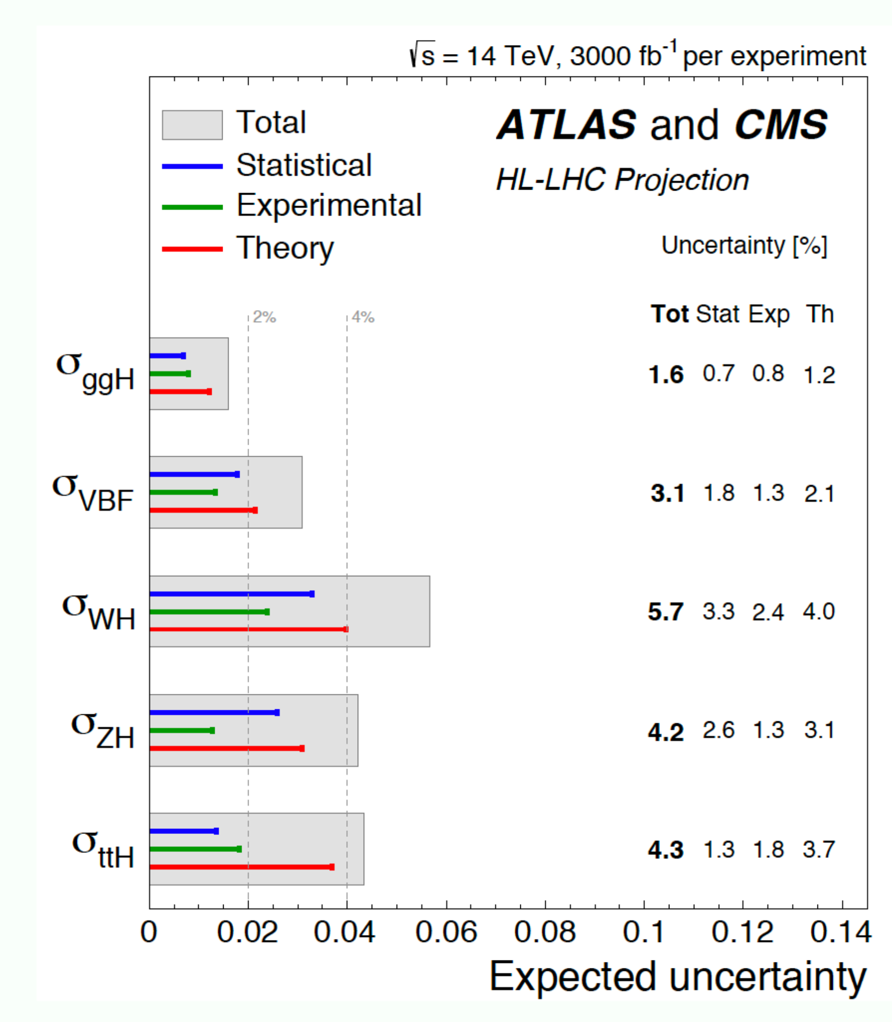
ATLAS also observed vector boson scattering at:

- 6.9σ in WW channel
- 5.3σ in WZ channel

→ All VBF VV channels have now been observed

HL-LHC: Branching Ratios and Cross Sections

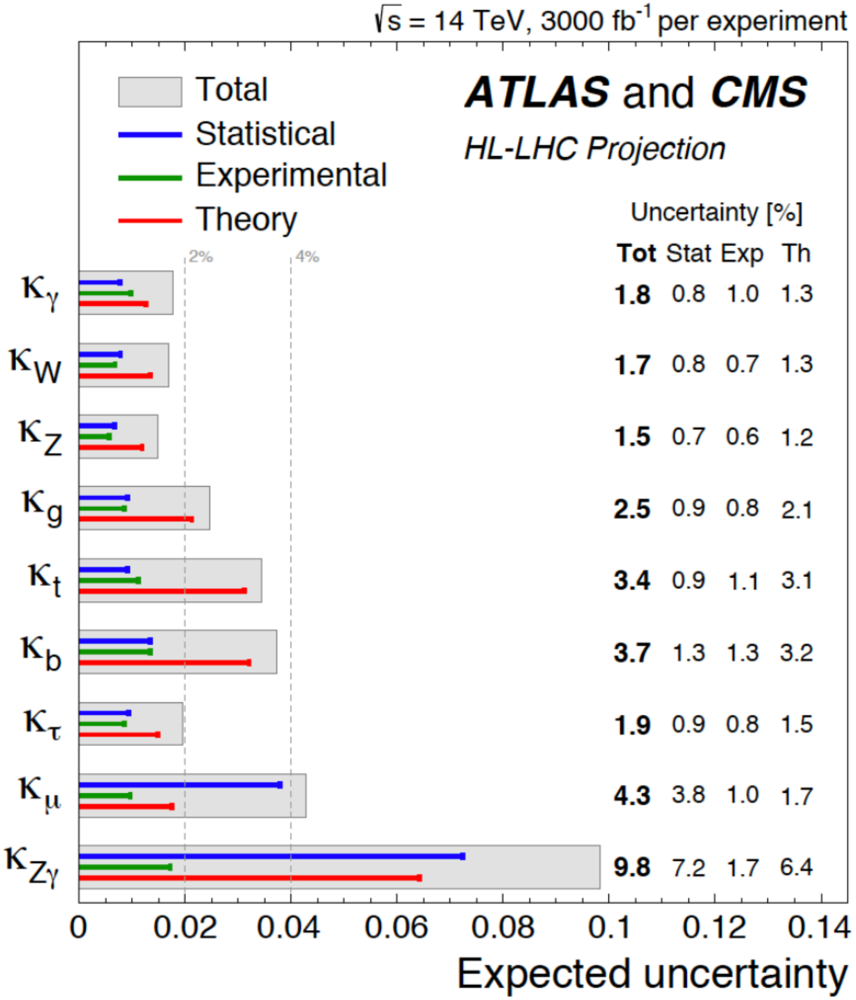


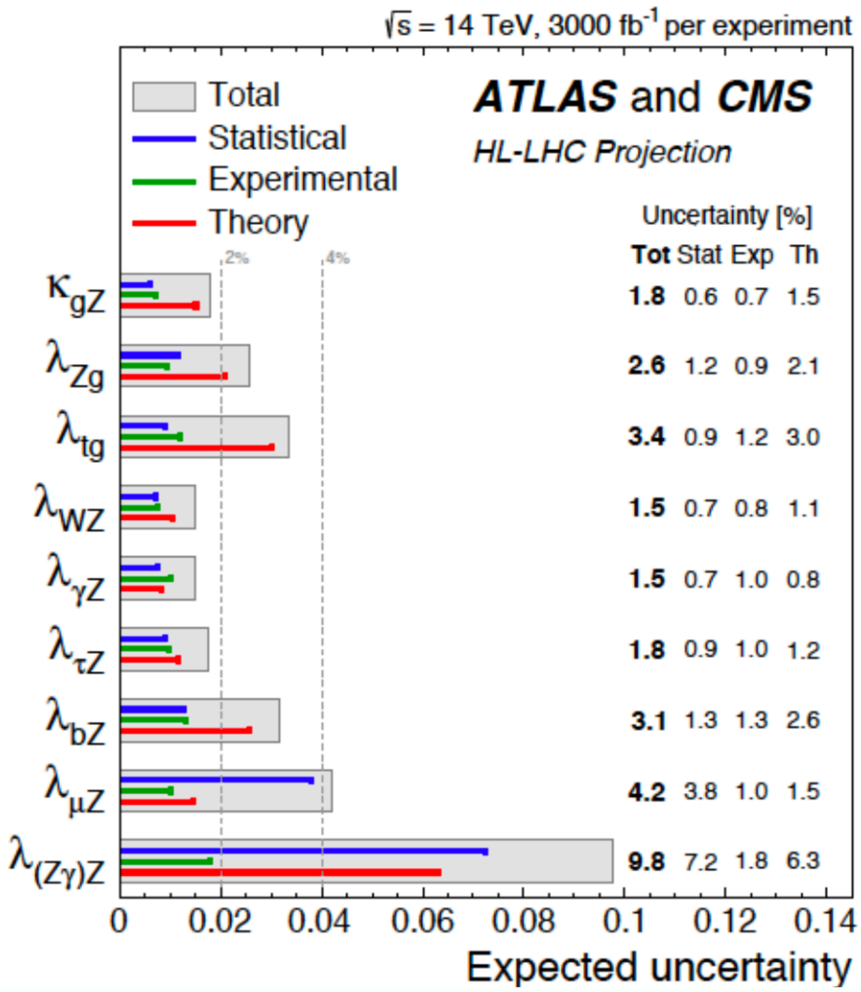


Combination of ATLAS and CMS for systematic uncertainty scenario 2

- Theory uncertainty remains the largest component for most measurements

HL-LHC: Couplings and Coupling Ratios

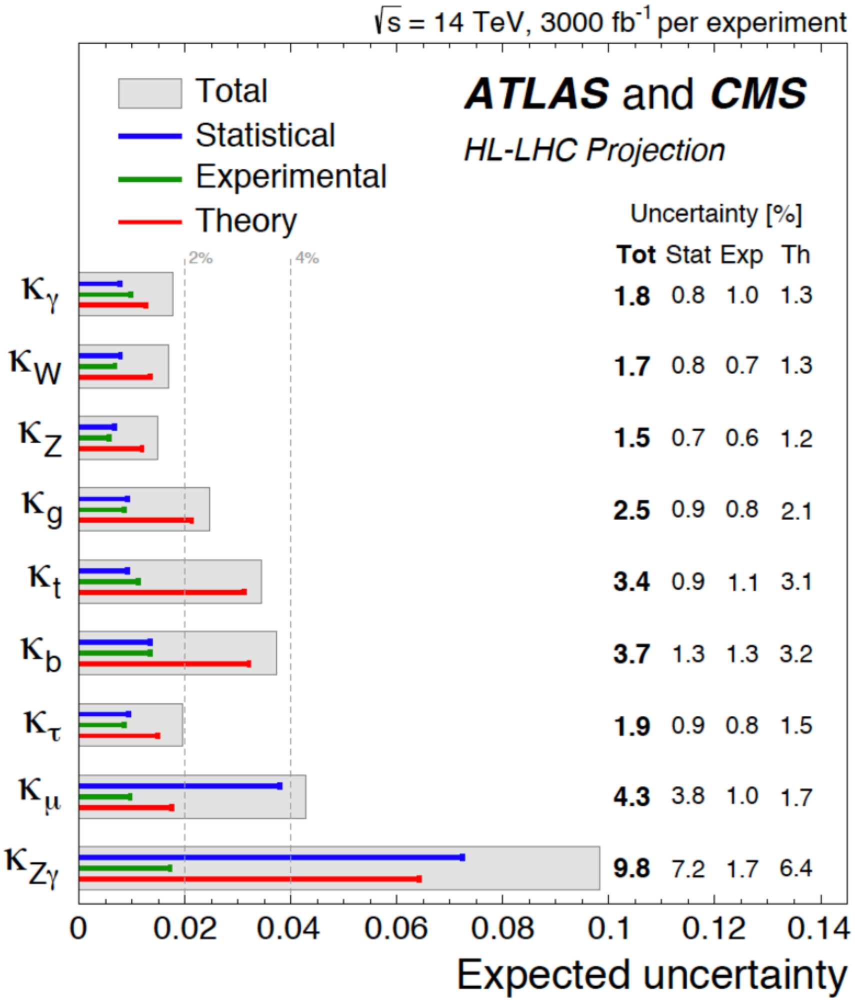




Combined results for ATLAS and CMS for systematic uncertainty scenario 2

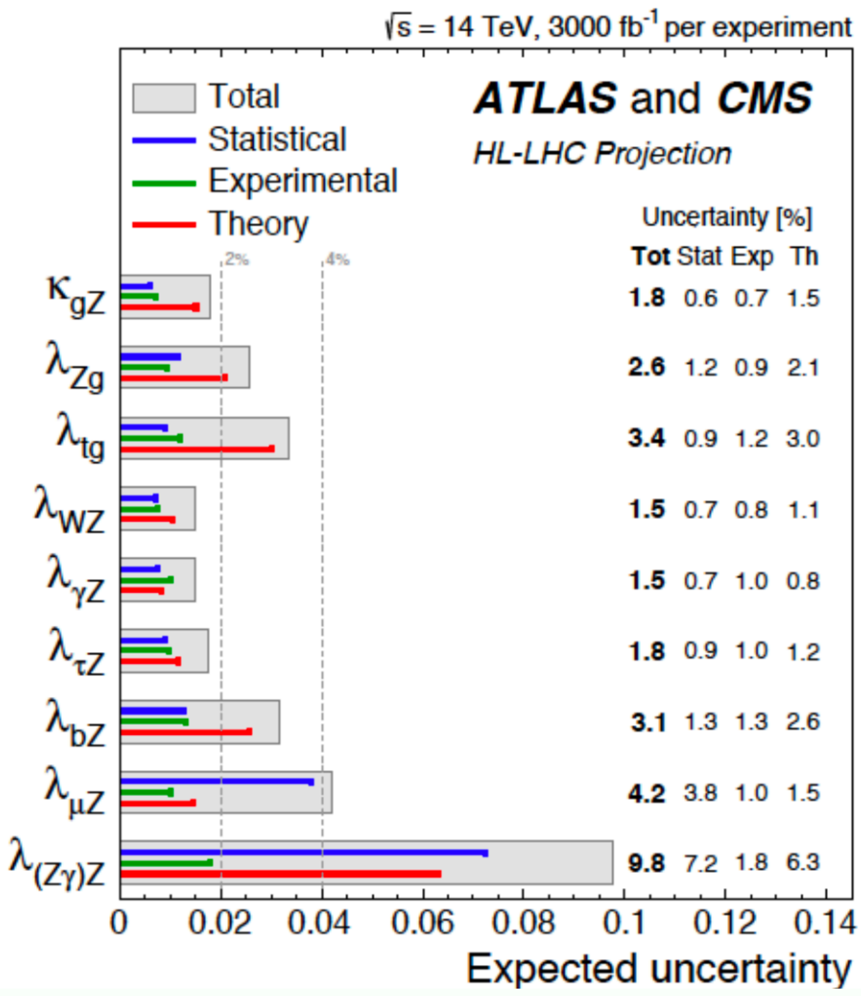
- Coupling ratios on the right allow for reduced uncertainties in general

HL-LHC: Couplings and Coupling Ratios



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_{gZ}	**1.8**	0.6	0.7	1.5
λ_{Zg}	**2.6**	1.2	0.9	2.1
λ_{tg}	**3.4**	0.9	1.2	3.0
λ_{WZ}	**1.5**	0.7	0.8	1.1
$\lambda_{\gamma Z}$	**1.5**	0.7	1.0	0.8
$\lambda_{\tau Z}$	**1.8**	0.9	1.0	1.2
λ_{bZ}	**3.1**	1.3	1.3	2.6
$\lambda_{\mu Z}$	**4.2**	3.8	1.0	1.5
$\lambda_{(Z\gamma)Z}$	**9.8**	7.2	1.8	6.3

Combined results for ATLAS and CMS for systematic uncertainty scenario 2

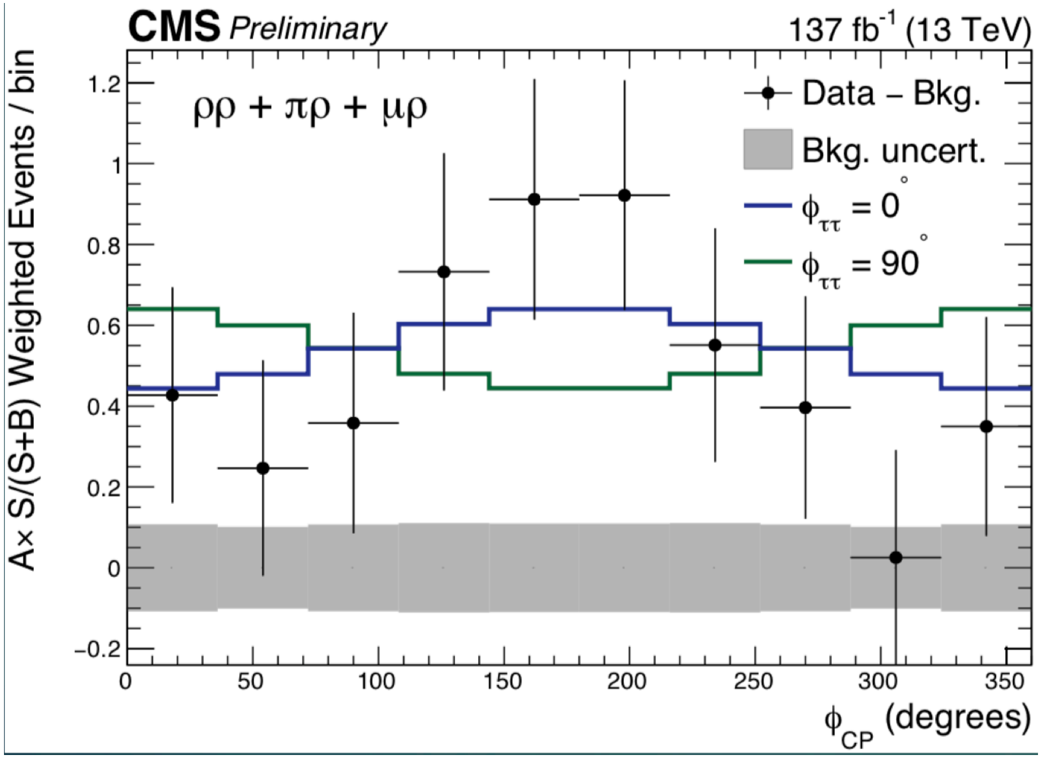
- Coupling ratios on the right allow for reduced uncertainties in general

Where we are now: recent developments

CP properties: CP-odd component to couplings with fermions?

- Recent result from CMS using tau polarization information
  - challenging!
- Analysis excludes pure CP-odd coupling at more than 3σ C.L.

$$\tan\phi_{\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau} = \frac{CP\ odd}{CP\ even\ (SM)}$$



CMS-REF

Note: analyses using ttH production by ATLAS and CMS exclude pure CP-odd top coupling at more than 3σ C.L.

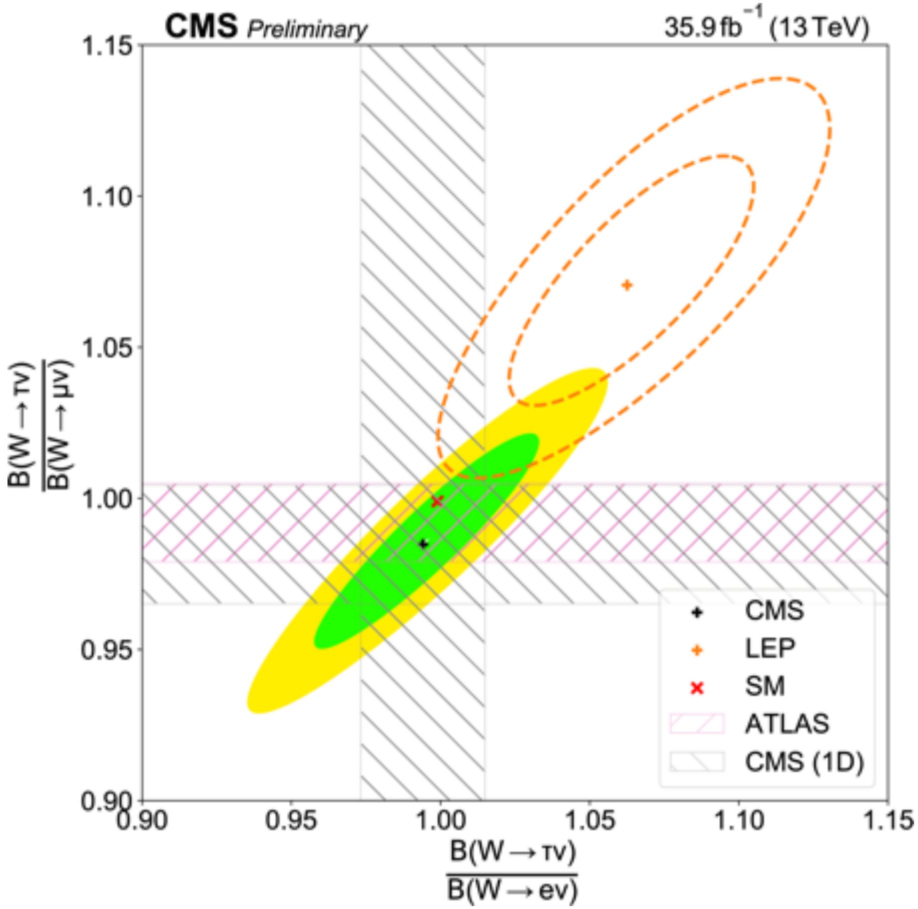
Tests of Lepton Universality in W Decays

Tension from LEP in ratio of decays of W to taus vs electrons and muons

New results from CMS consistent with SM expectation

Consistent with recent ATLAS results for Rτ/μ

Large LHC samples allow for improved precision over LEP



	CMS	LEP	ATLAS
$R_{\mu/e} = \mathcal{B}(W \to \mu\bar{\nu}_\mu)/\mathcal{B}(W \to e\bar{\nu}_e)$	1.009 ± 0.009	0.993 ± 0.019	–
$R_{\tau/e} = \mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to e\bar{\nu}_e)$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(W \to \tau\bar{\nu}_\tau)/\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–