CMS M&O and Physics Summary (ATLAS+CMS)

Sarah Alam Malik
Imperial College London

THE ROYAL SOCIETY

Imperial College London

Overview

CMS M&O UK

Focus on:

- Standard Model measurements
- Top physics
- B-physics
- Higgs (125 GeV)

Emphasis on areas with significant UK involvement/ leadership

THE ROYAL SOCIETY

Imperial College London

UK in CMS

- Only 4% of the collaboration but lead critical aspects of detector design, driven by physics goals —> mission-critical operational responsibilities, over full lifetime of experiment.
- Continually held significant roles in detector operations, upgrade and Physics.
- System managers - currently L1 Trigger project, formerly HGCAL, ECAL

- Coordination areas - Currently Trigger co-ordination, formerly (in last 3 yrs) Run coordination

- Physics groups - Currently SUSY group convener, LHC Higgs WG convener, formerly Exotics
  - Subgroup leadership; lead majority of analysis sub-groups (L3) in which we participate

- MB, XEB members - Diversity office chair, engagement office, formerly CB secretary/deputy, spokersperson advisors

- Numerous L2 positions - L1 trigger, tracker, data preparation, computing

- **Significant M&O responsibilities in ECAL, L1 Trigger, and Tracker.**

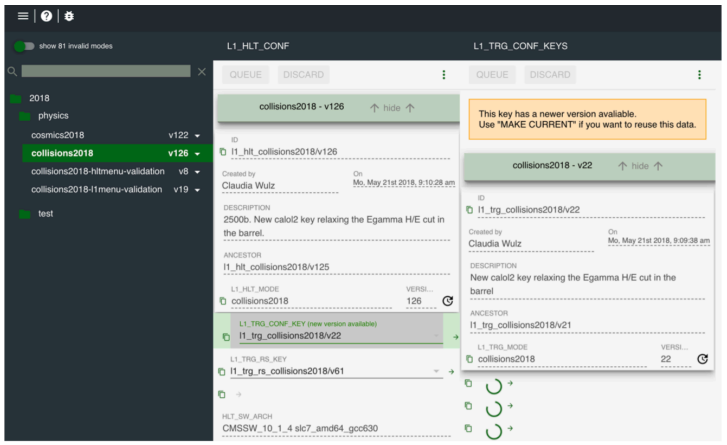
- Phenomenology - dark matter model building, interpretations, global fits of SUSY and Dark matter models

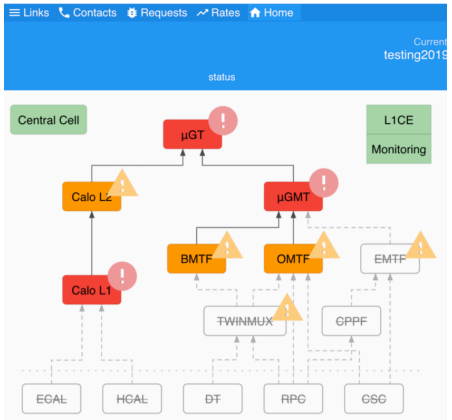
THE ROYAL SOCIETY

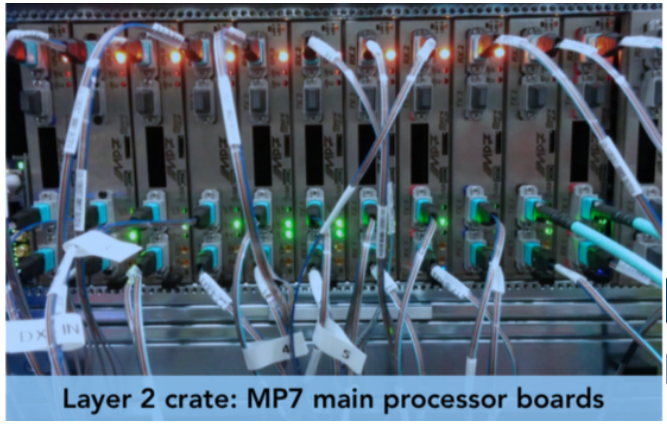
Imperial College London

CMS Operations: L1 Trigger

- Have been **instrumental in L1 project** in all areas (software, firmware, hardware) since design stage and throughout Phase 1.
  - e.g UK team designed and implemented **brand new online software framework** for entire L1 trigger. (SWATCH)
  - Provided on-call support for Layer 2(algo layer, UK project) of calorimeter trigger throughout Run 2, will need to continue during LS2 and Run 3. **Critical system for running of CMS**.
  - Ran yearly workshops to train new UK PhD students and postdocs in operations/debugging issues.





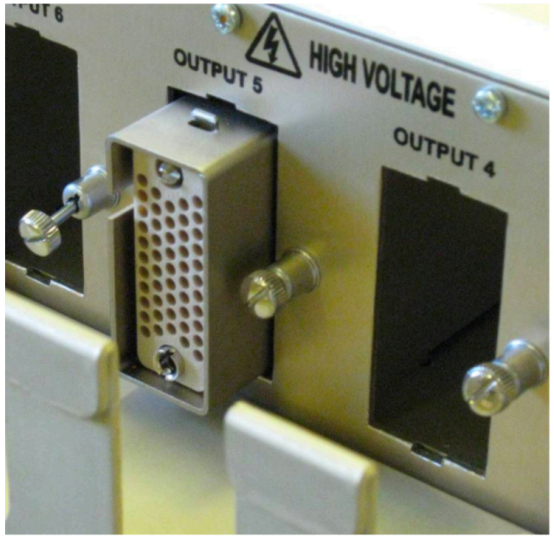

Layer 2 crate: MP7 main processor boards

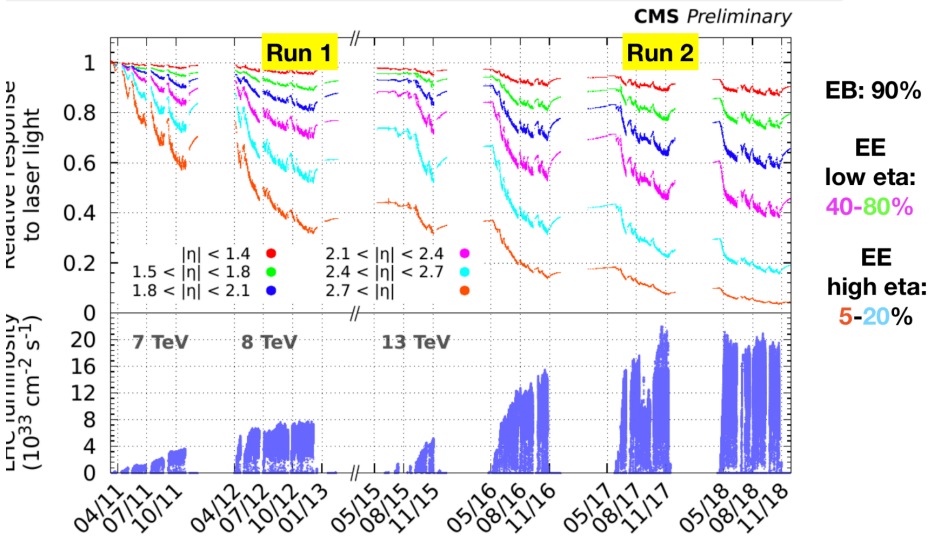
THE ROYAL SOCIETY

College

CMS Operations: ECAL

- UK led the design and construction of the ECAL Endcaps (EE)
- UK responsible for EE HV system operation and maintenance. Must provide 24/7 round-the-clock on-call support during data-taking.
    - Has to continue during Run 3
    - Students on LTA encouraged to contribute
- UK heavily involved in EE performance optimisation during Run 2, and preparation for Run 3 including crystal evolution and trigger performance studies.
- In particular focus now on understanding and treating effects of large response losses including predictions for Run 3.



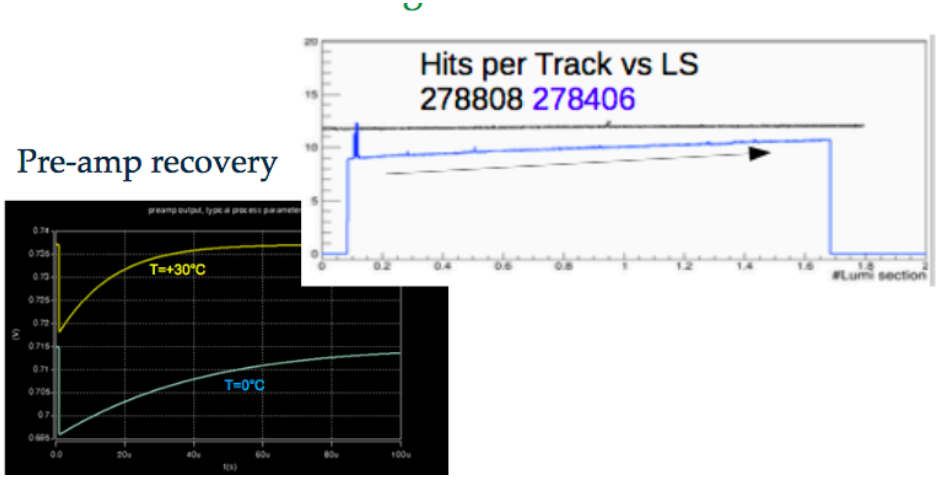


THE ROYAL SOCIETY

Imperial College London

CMS Operations: Tracker

- Since design stage UK has held responsibility for Tracker readout. Maintained 24/7 on-call coverage since Run 1 and must continue to Run 3.
    - Long held expertise in APV readout front-end chip has helped mitigate operational issues. Need to maintain expertise during Run 3.
- Maintenance (hardware, firmware, software) of the 500 Tracker FEDs
- Currently providing Detector-On-Call (DOCs) as well as LS2 support for P5 activities.



THE ROYAL SOCIETY

Imperial College London

Physics (CMS+ATLAS)

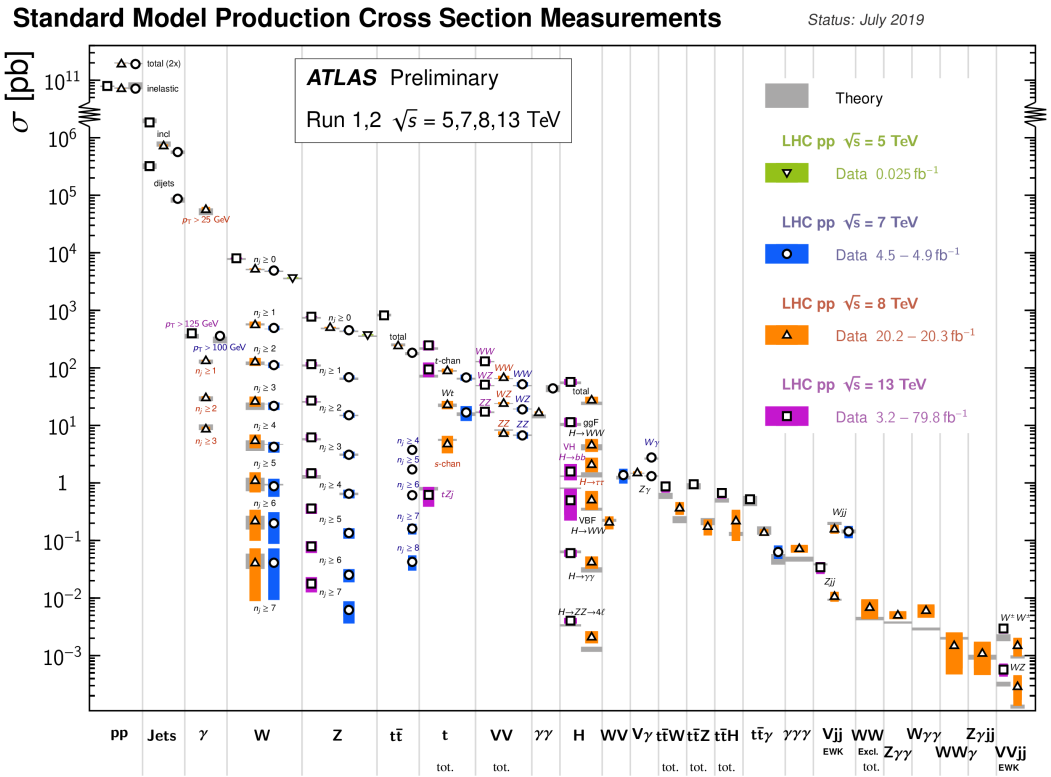
Standard Model, Top, Higgs (125 GeV), B-physics

THE ROYAL SOCIETY

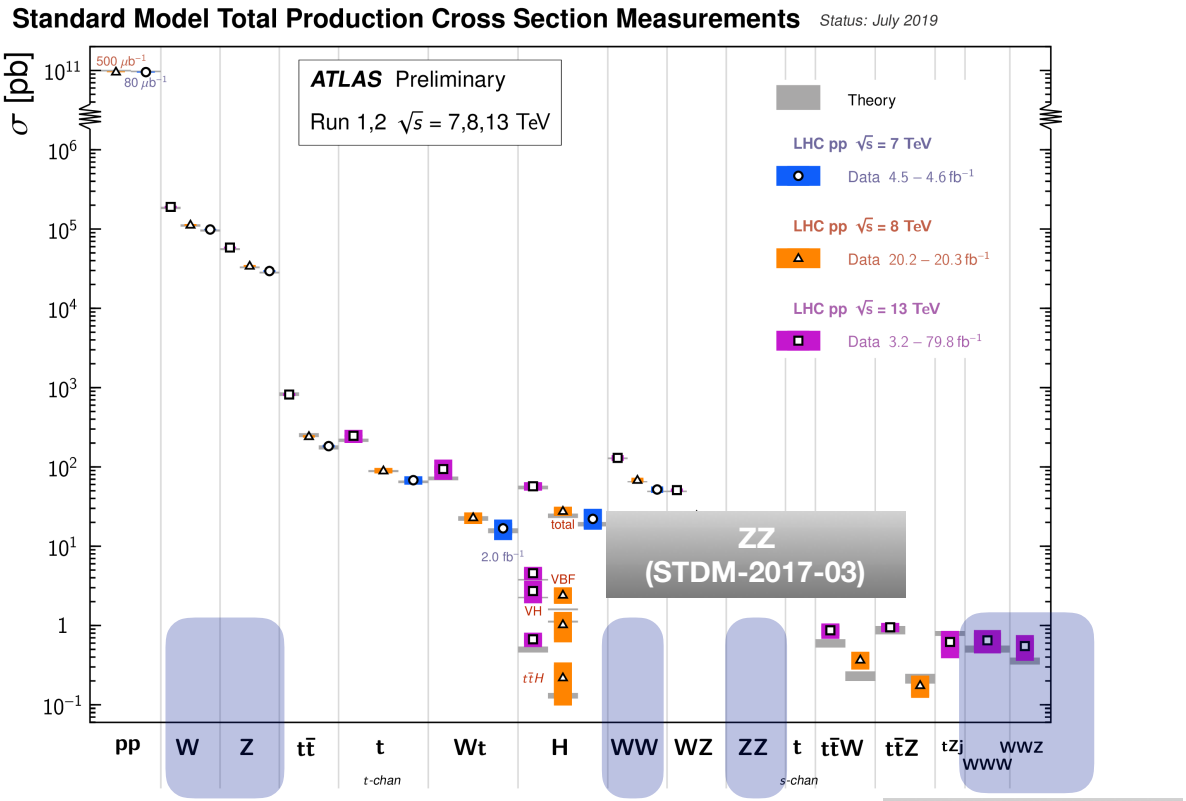
Imperial College London

Summary of Standard Model measurements

- Probing over 14 orders of magnitude in cross section
- Measured SM processes at different COM energies: 2.76 TeV, 5 TeV, 7 TeV, 8 TeV, 13 TeV
- High-precision measurements of key EWK parameters (W mass measured to 0.02%, weak mixing angle to 0.15%)
- Diboson processes in precision era
- Starting to probe rare processes (Vector boson scattering VBS and vector boson fusion VBF)
- Inclusive to differential measurements
- Probing regions of phase space also useful for searches beyond SM



Summary of Standard Model measurements : UK effort



W, Z cross sections at 2.76 TeV (STDM-2018-06)

Precision WW (STDM-2017-24)
Same-sign WW VBS (STDM-2017-06)

ZZ (STDM-2017-03)

Triboson WVV (STDM-2017-22)

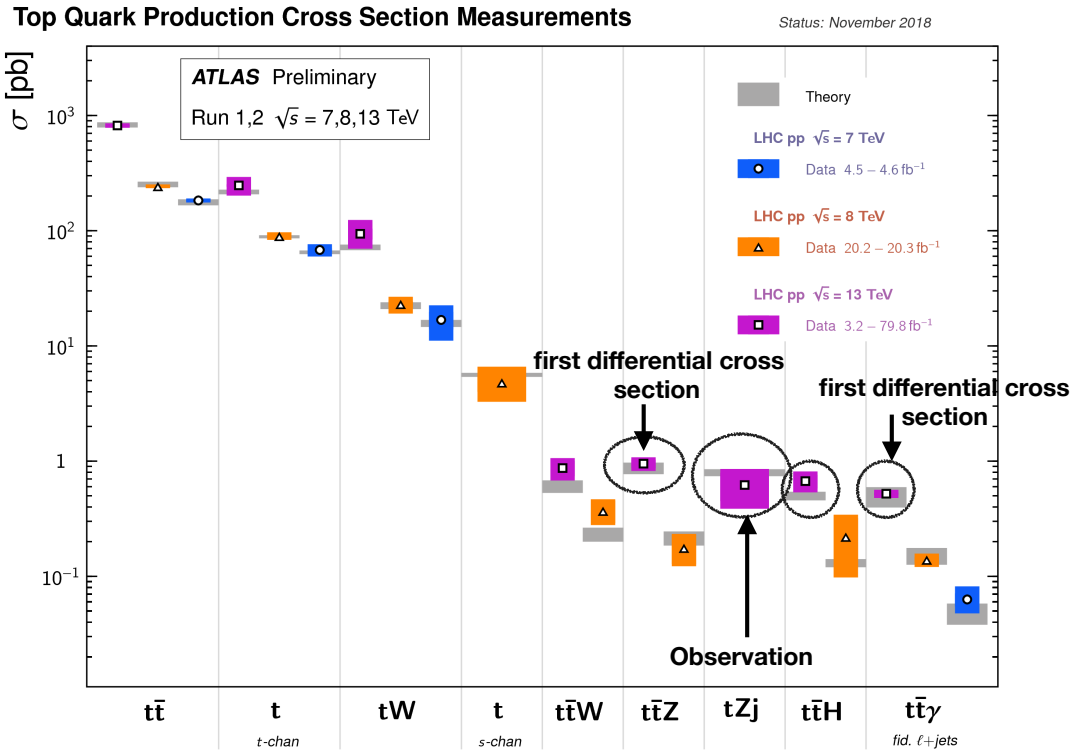
Jet shapes (STDM-2017-34)

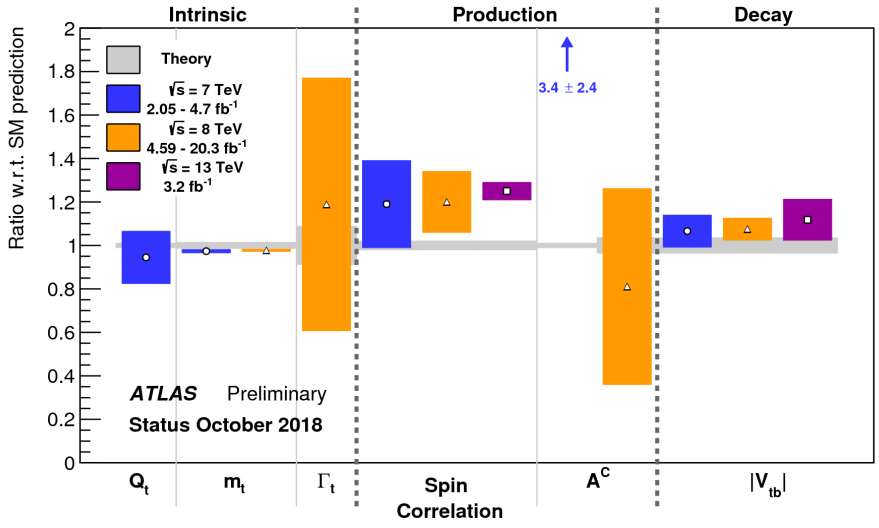
4-lepton mass (STDM-2017-09)

Summary of Top results

Full Run 2 : L ~ 140 fb-1

- ~120M tt pairs
- ~30M single tops
- ~120k ttZ, tZ..

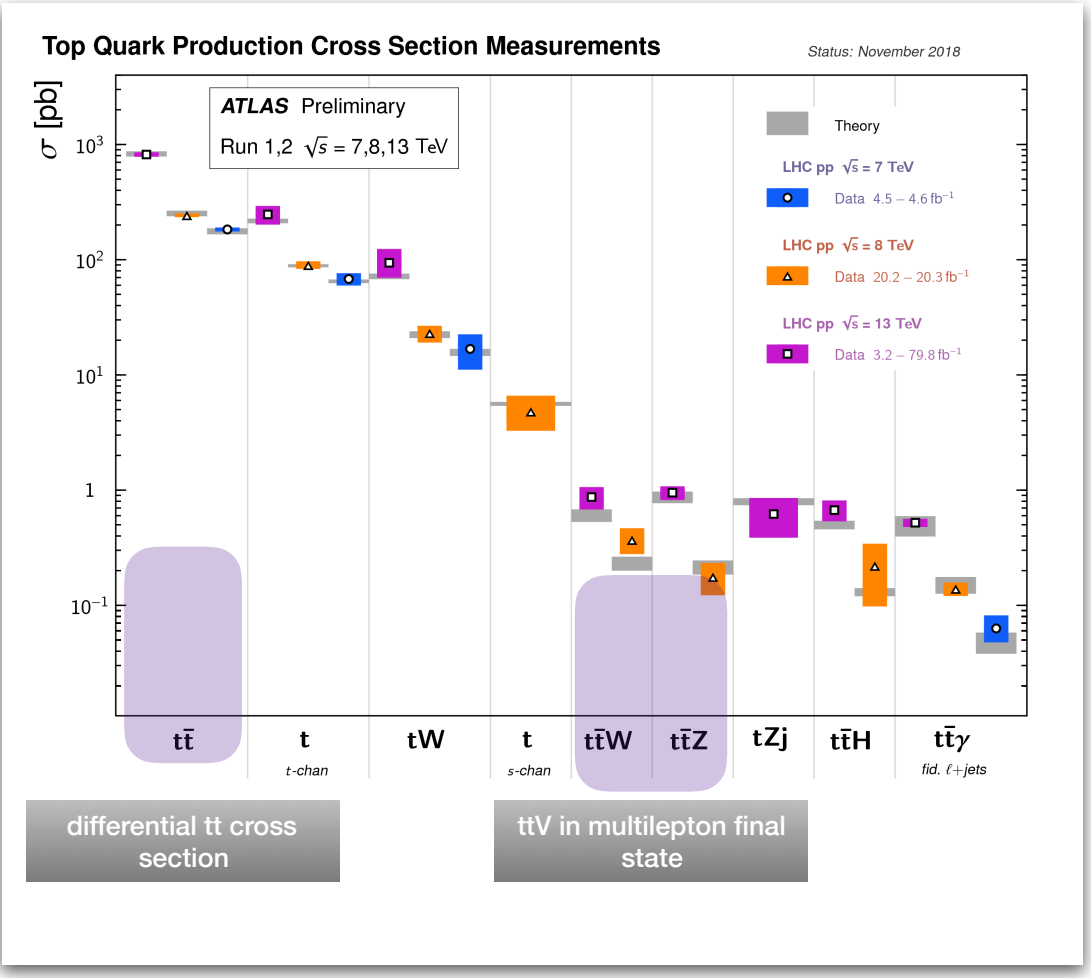




Large dataset in Run2 and beyond allows

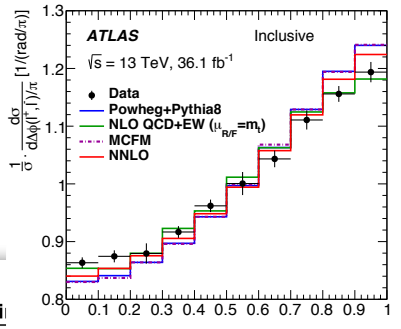
- ultimate precision (top mass known to 0.5 GeV (< 0.3% precision))
- study properties and coupling
- probe low cross section processes (tt+X,t +X, 4-tops)

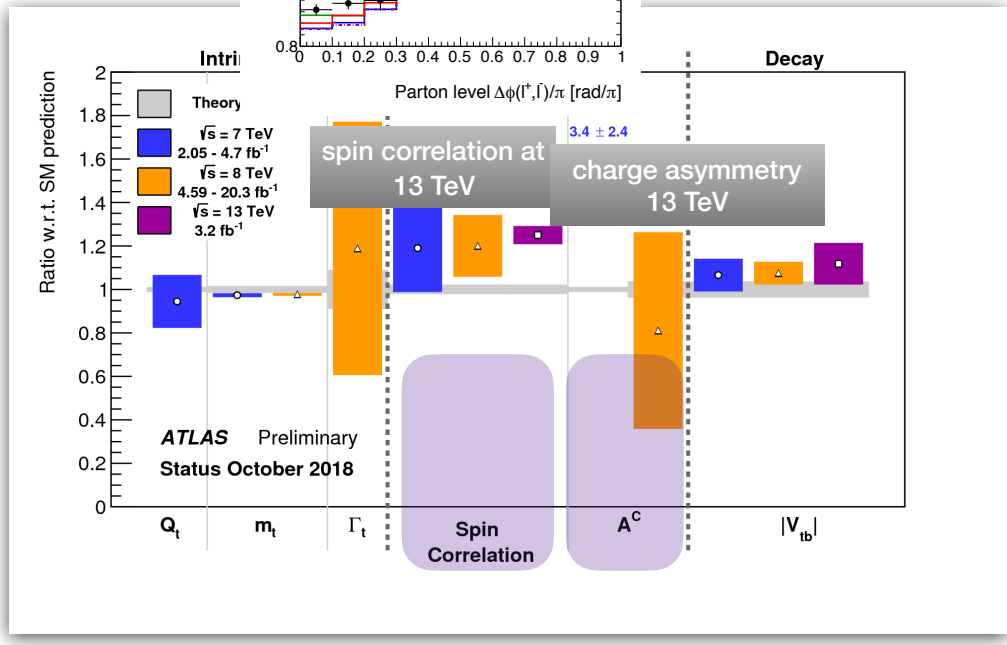
Summary of Top results : UK effort



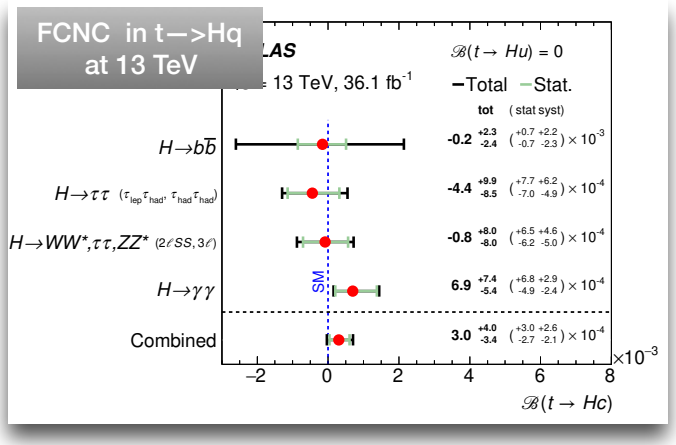
differential tt cross section

ttV in multilepton final state



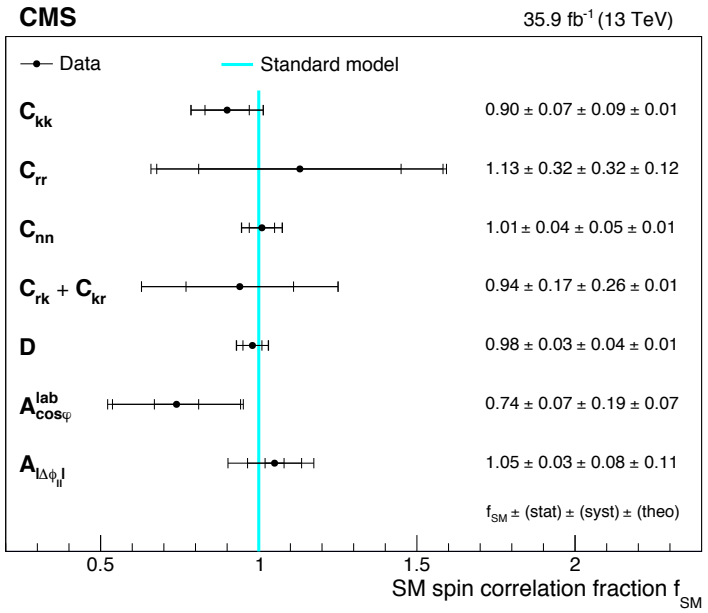


FCNC in t—>Hq at 13 TeV

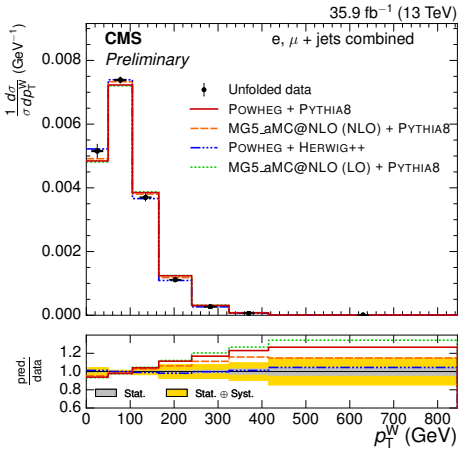


Summary of Top results : UK effort

top quark polarization and spin correlations at 13 TeV (CMS-TOP-18-006)

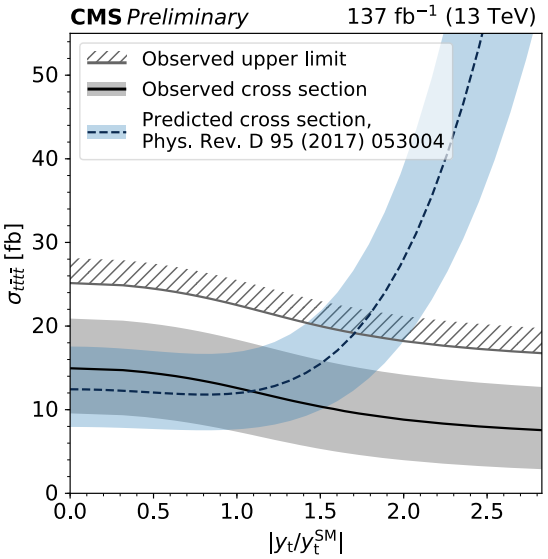


Differential tt cross section CMS-PAS-TOP-16-014



Differential in N_{jets}, $p_T(W)$, $p_T(l)$, S_T, H_T, p_{Tmiss}
Unfolded data compared to several MC predictions

Search for 4-tops (tttt) at 13 TeV (CMS-TOP-18-003)

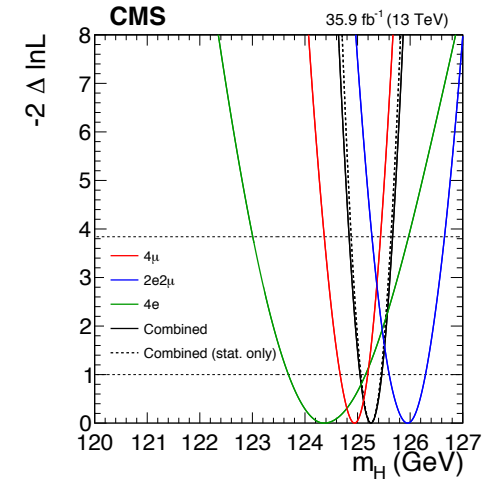


Summary of Higgs results

Discovery era → Precision era

Higgs profile

- Mass
- Width
- Couplings
- Inclusive/differential cross sections
- Quantum numbers
- Combination



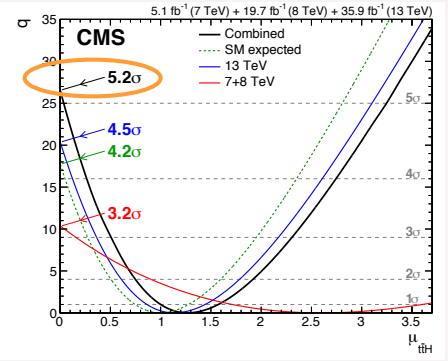
Higgs mass, ~200 MeV precision, dominated by statistical uncertainty

Width: (CMS) $0.08 < \Gamma_H < 9.16$ MeV (SM: 4.1 MeV)

3rd-generation

Couplings to 3-rd generation (top, b, tau)

Discovery—> properties

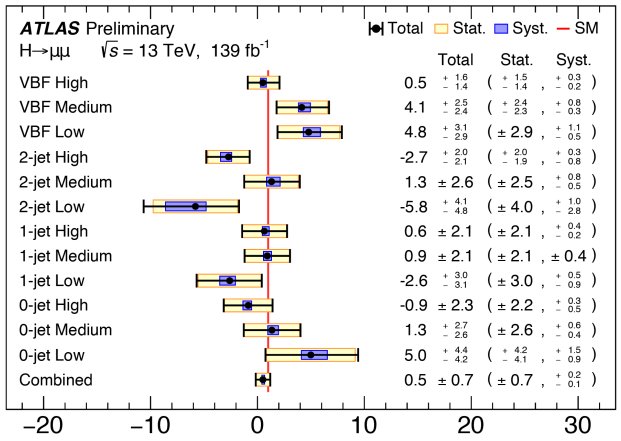


Rare decays/production

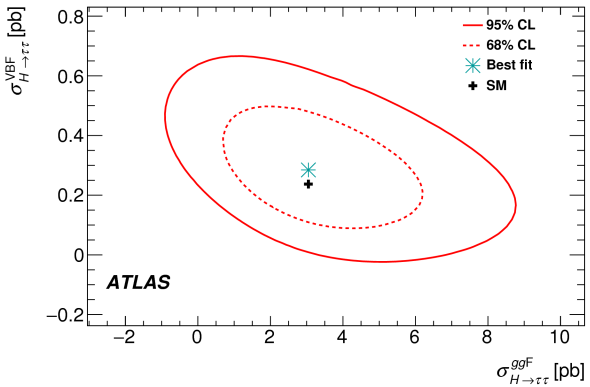
- Observation of 2nd generation fermions
- Constraining invisible decays
- self-coupling
- decays to mesons

Summary of Higgs results : UK effort

H → μμ
(ATLAS-CONF-2019-028)



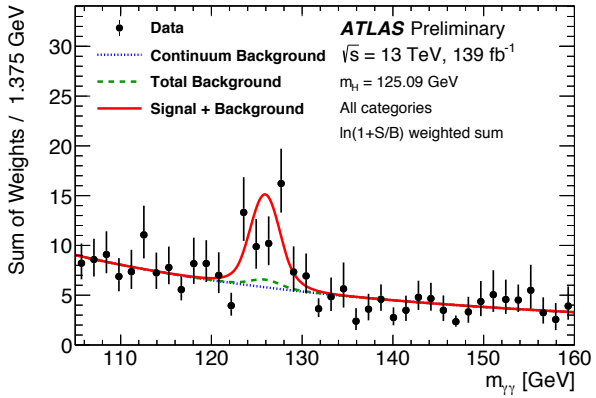
H → tau tau at 13 TeV, 36 fb-1
arXiv:1811.08856



Obs (exp) significance of 4.4σ (4.1σ)
Combined with Run 1, 6.4σ

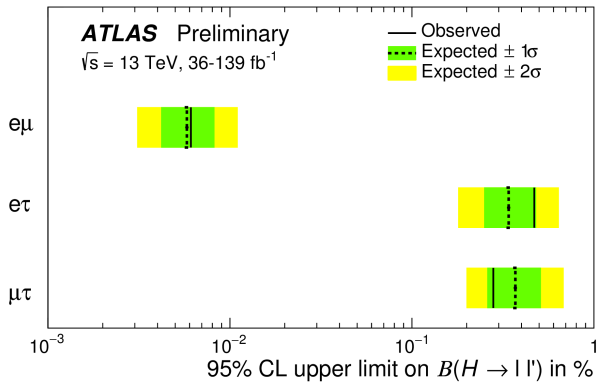
VH, H—>bb
(arXiv:1903.04618)

ttH
(ATLAS-CONF-2019-004)



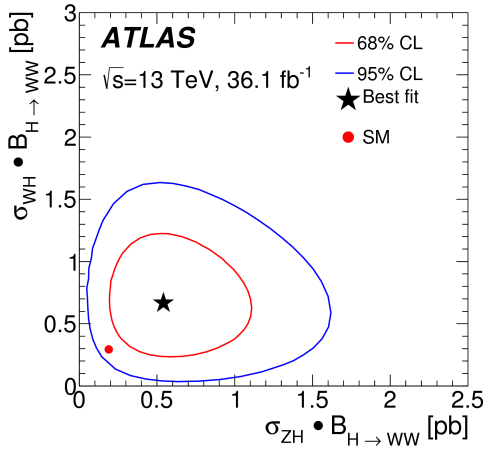
ttH process is observed in the diphoton decay mode with a significance of 4.9

H → ee, H → eμ,
(ATLAS-CONF-2019-037)

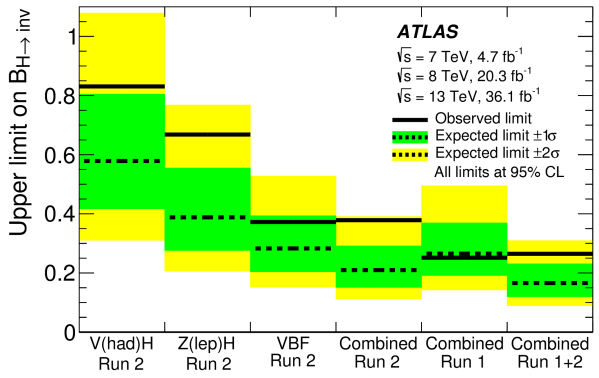


No significant signals are observed
Result is improvement of > factor of 5 w.r.t previous

VH, H—>WW
arXiv:1903.10052



H—>inv combination
arXiv:1904.05105

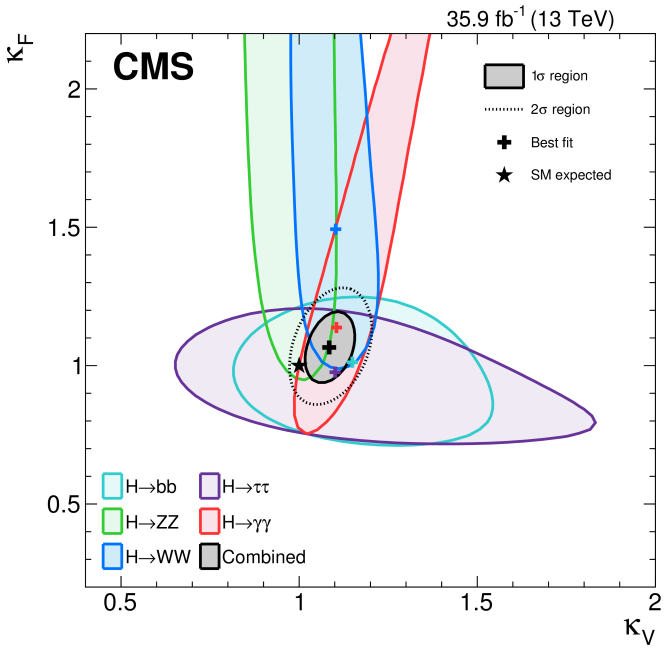


Combined H—>inv branching fraction < 0.26 (observed at 95%CL)

Summary of Higgs results : UK effort

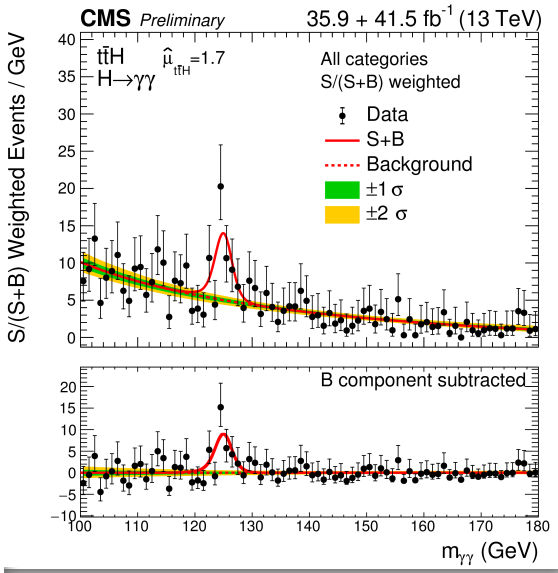
Combined measurement of Higgs boson coupling

CMS-HIG-17-031

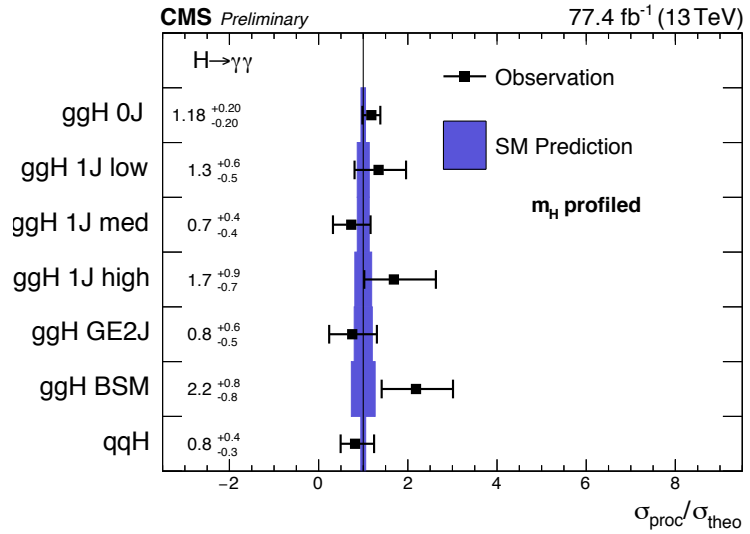


Best fit ratio of signal yield to SM expectation is μ = 1.17± 0.10

CMS-PAS-HIG-18-018

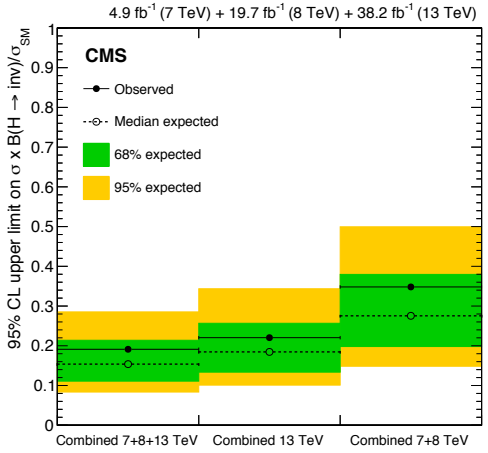


HIG-18-029



VBF H—>inv and combination

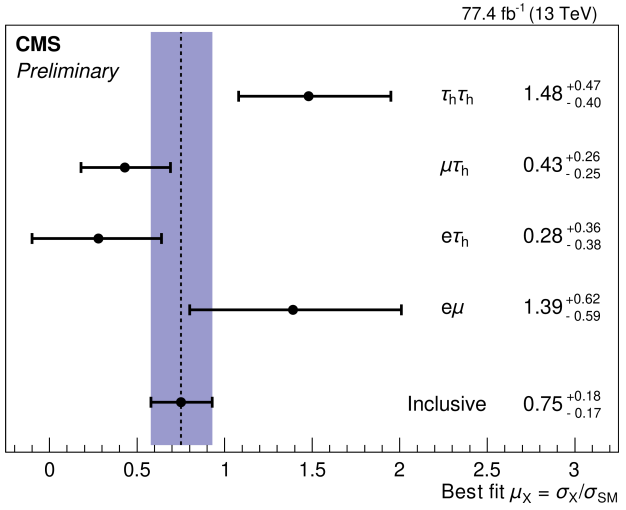
CMS-HIG-17-023



Combined Run 1 + Run 2 B(H → inv) of 0.19 (0.15) at 95% CL

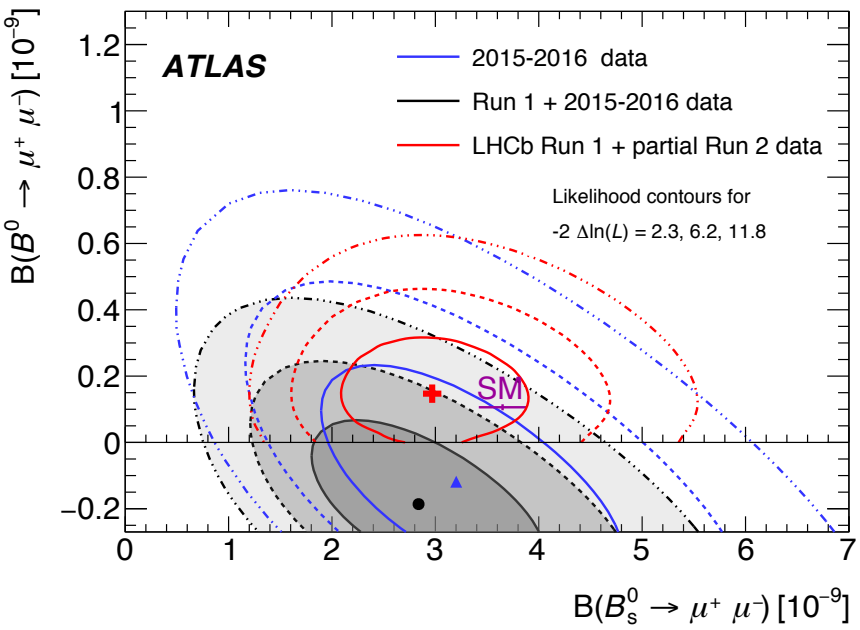
H—>tau tau (simplified template cross sections)

CMS-PAS-HIG-18-032



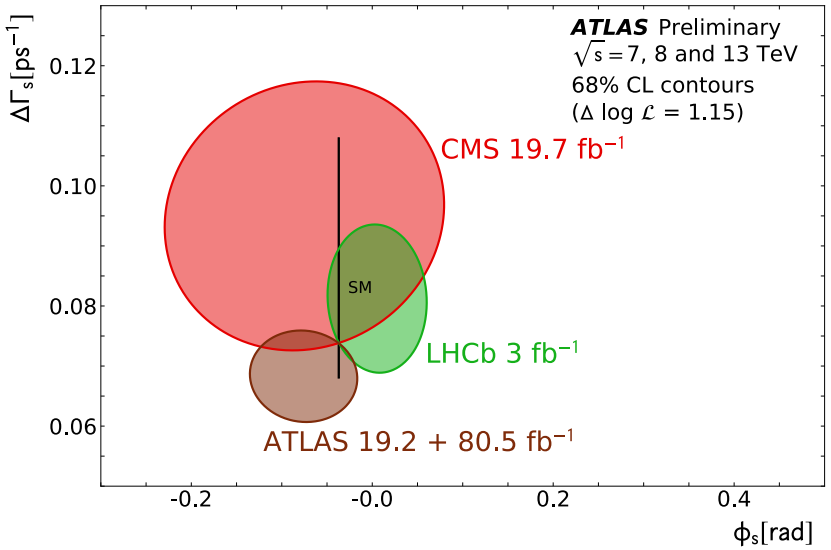
Summary of B-physics: UK effort

$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
arXiv:1812.03017



B^0 limit is most stringent

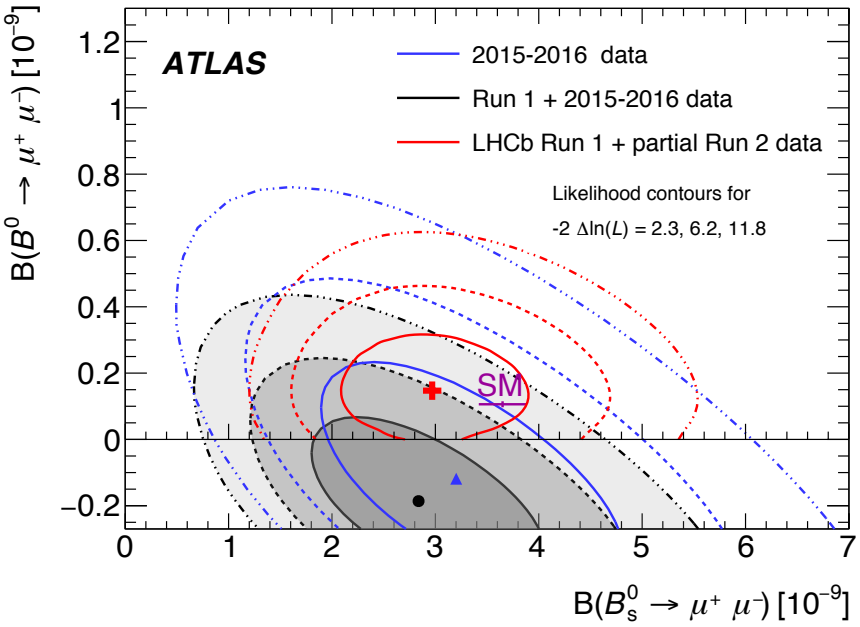
$B_s \to J/\psi(\mu\mu)\,\phi(K^+K^-)$
ATLAS CONF-2019-009



Precision comparable to LHCb

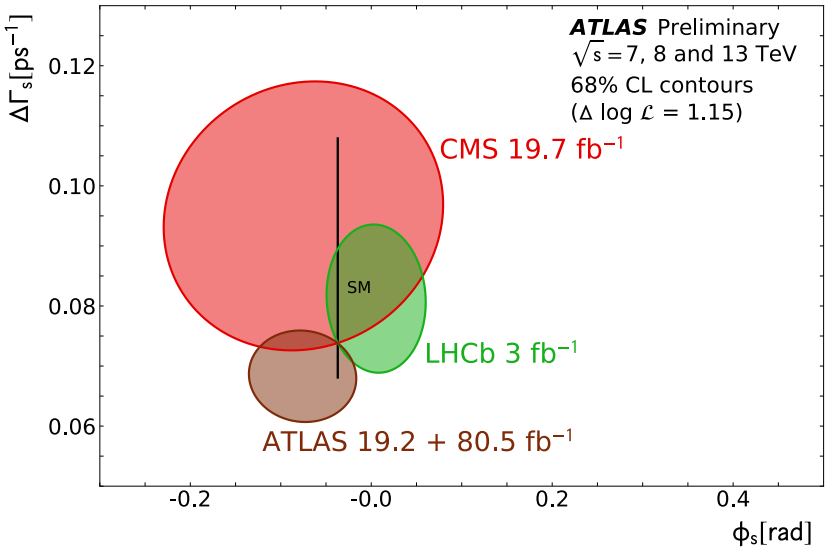
Summary of B-physics: UK effort

$B_s^0 \to \mu+\mu-$ and $B^0 \to \mu+\mu-$
arXiv:1812.03017



B^0 limit is most stringent

$B_s \to J/\psi(\mu\mu)\ \phi(K^+K^-)$
ATLAS CONF-2019-009

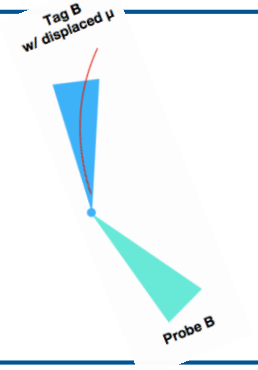


Precision comparable to LHCb

Data parking for B-physics

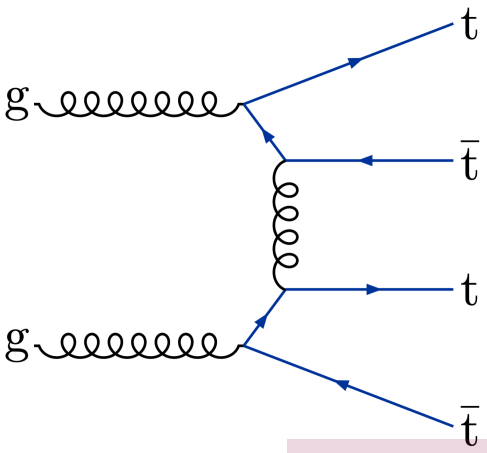
Collect unbiased sample of B-decays to be reconstructed during shutdown

Have collected 10^{10} B decays, measure R_K and R_K^* measurements to check LHCb anomaly



4-top search

TOP-18-003

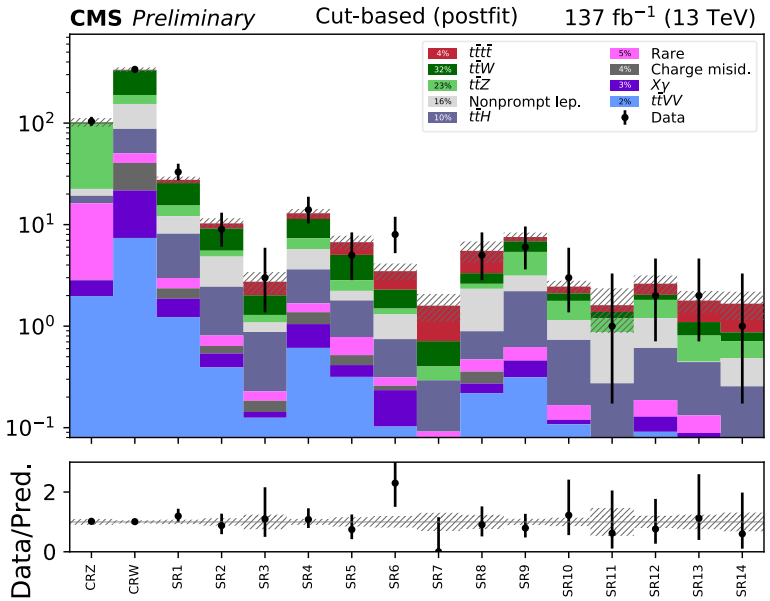


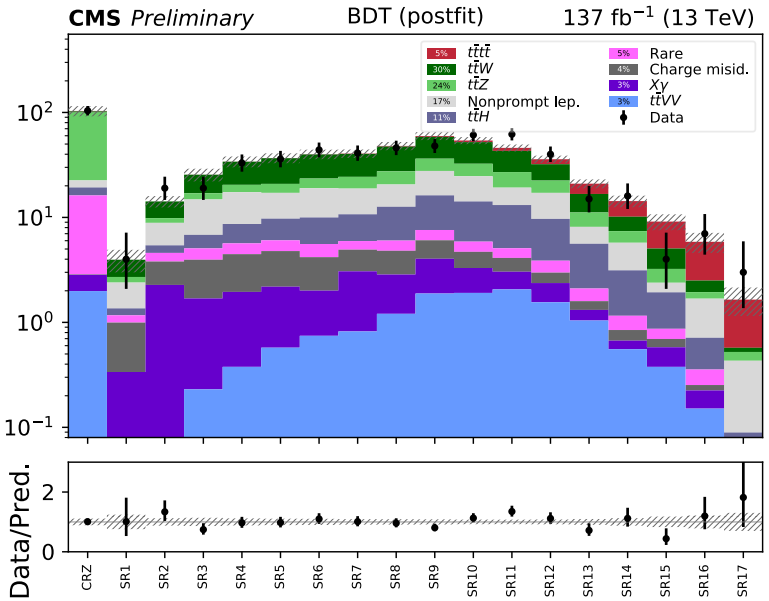
- 4-top cross section can be used to constrain magnitude and CP properties of top yukawa coupling to Higgs.
- Small SM cross-section, sensitive to enhancements from BSM particles
- Use full Run-2 data, 2 approaches : cut-based (classify events based on # jets and # of b-jets) and BDT
- Both give consistent results, compatible with NLO SM predictions

4-top cross section of $12.6^{+5.8}_{-5.2}$ **fb**

compared to SM prediction of $12.0^{+2.2}_{-2.5}$ **fb**

Significance of 2.6σ (2.7σ)

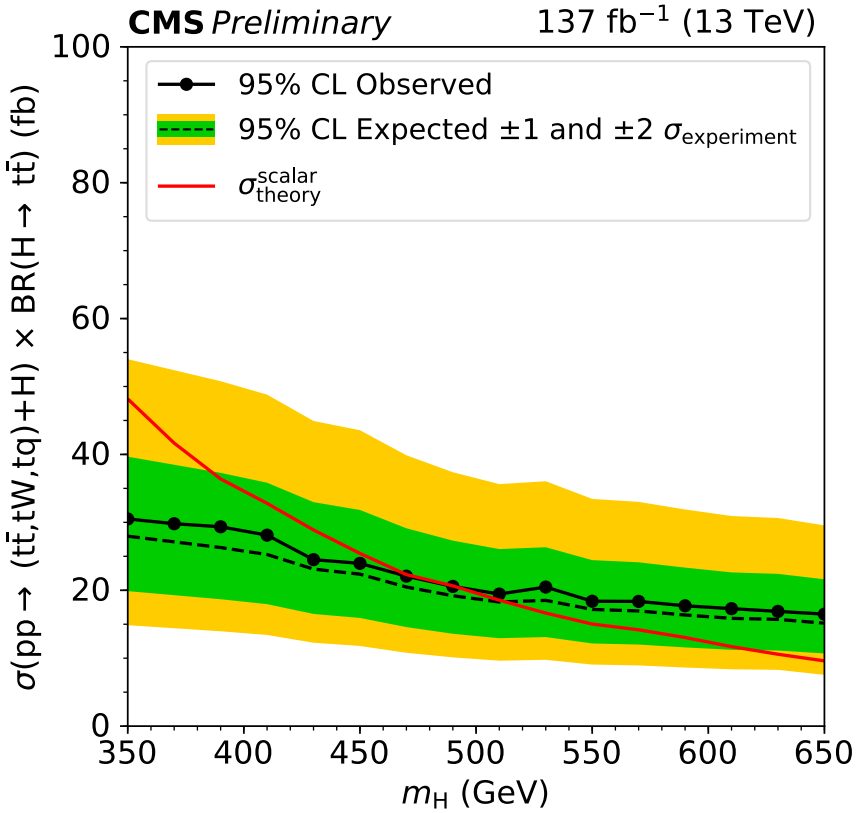




4-top search

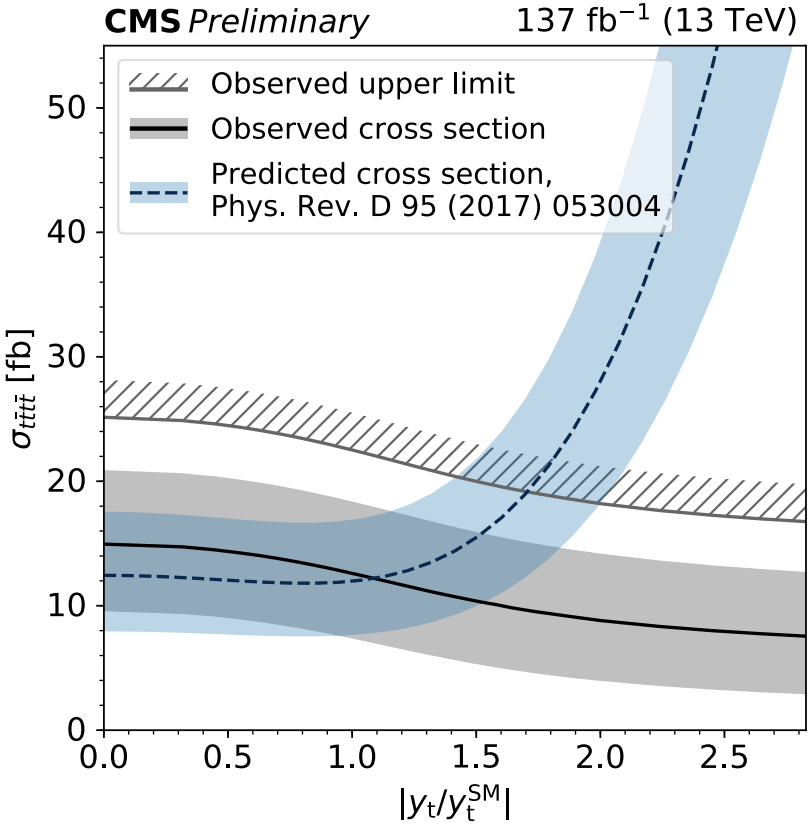
TOP-18-003

Type II two-Higgs-doublet model, exclusions in the mass ranges of 350-470 GeV (scalar) and 350-550 GeV (pseudoscalar)



Constrain top Yukawa coupling w.r.t SM value

$$|y_t/y_t^{SM}| < 1.7.$$

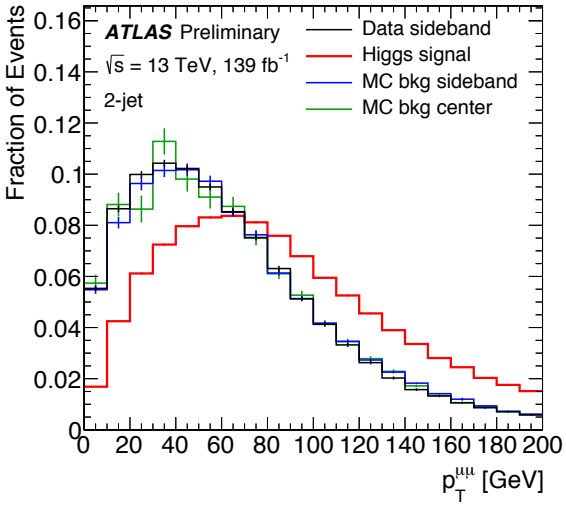


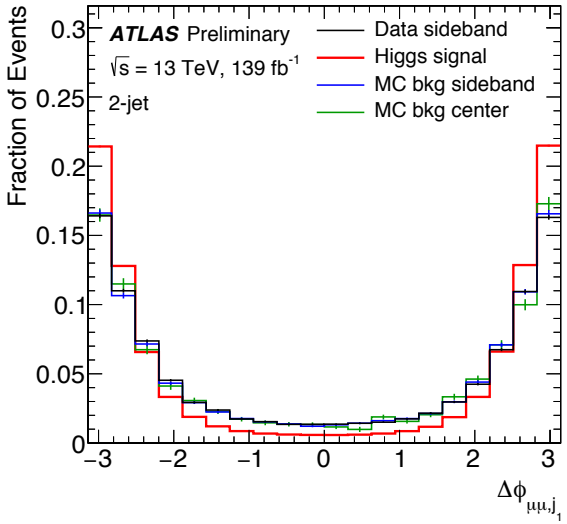
H → μμ

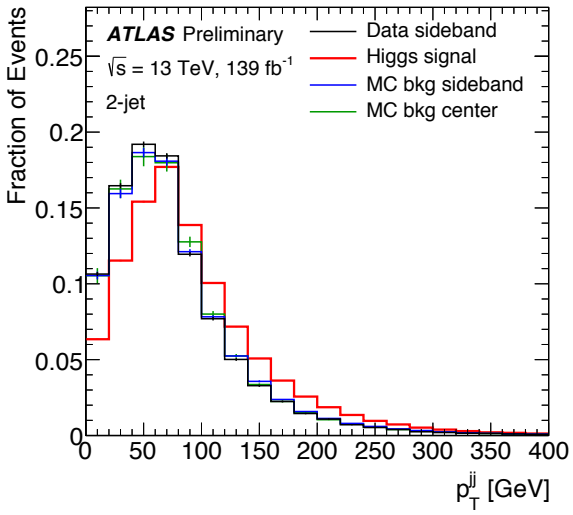
Rare decay that offers best possibility to measure Higgs coupling to 2nd-generation fermions
Physics beyond SM could enhance branching ratio, SM branching ratio : 2.18 x 10^{-4}
Challenging measurement;

- small coupling
- large backgrounds (Z/gamma*, diboson, top)
- small S/(S+B) ~0.2%)

- Boosted Decision Trees (BDT) used for discrimination between signal and background
- Events classified into 12 mutually exclusive categories
- BDT uses 14 variables and trained using data events in a sideband region (50% events training, 25% for validation, 25% testing)

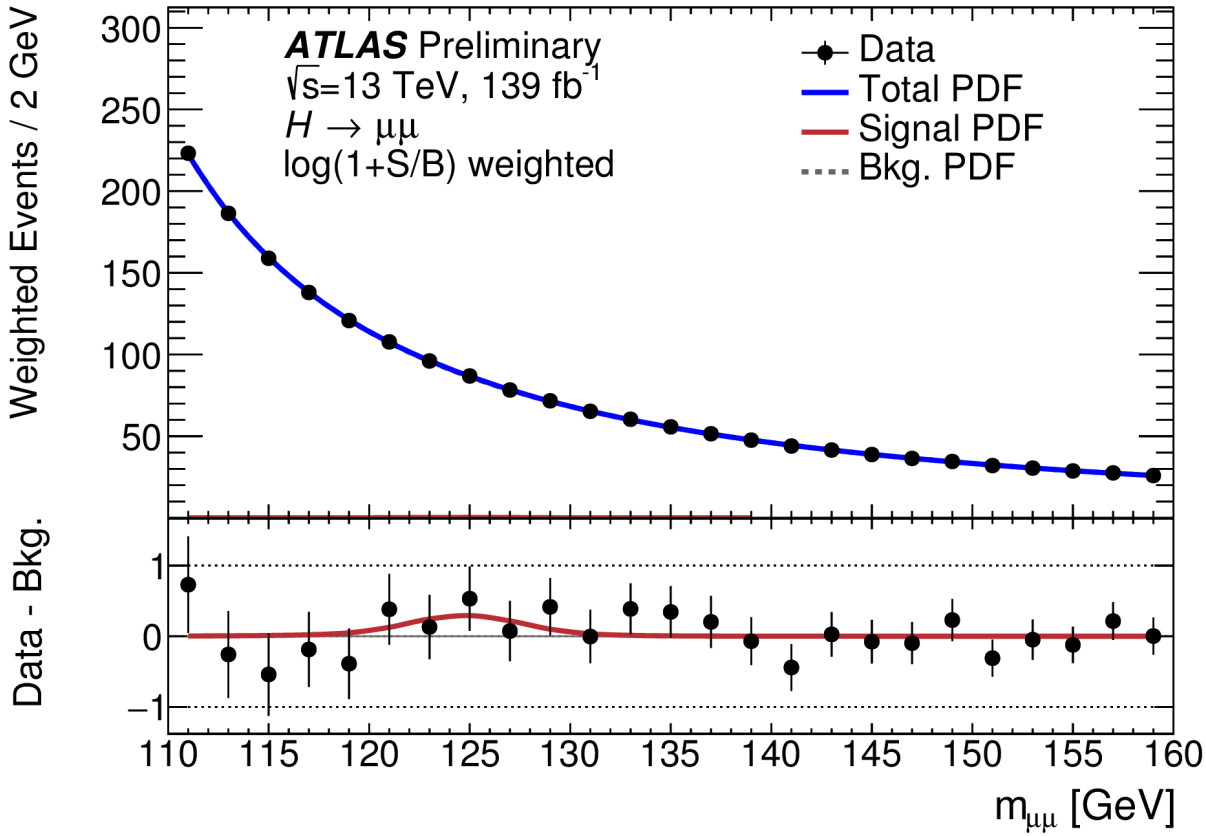






H → μμ

- Perform fit to invariant mass spectrum, use analytical models to describe mass spectrum for signal and background



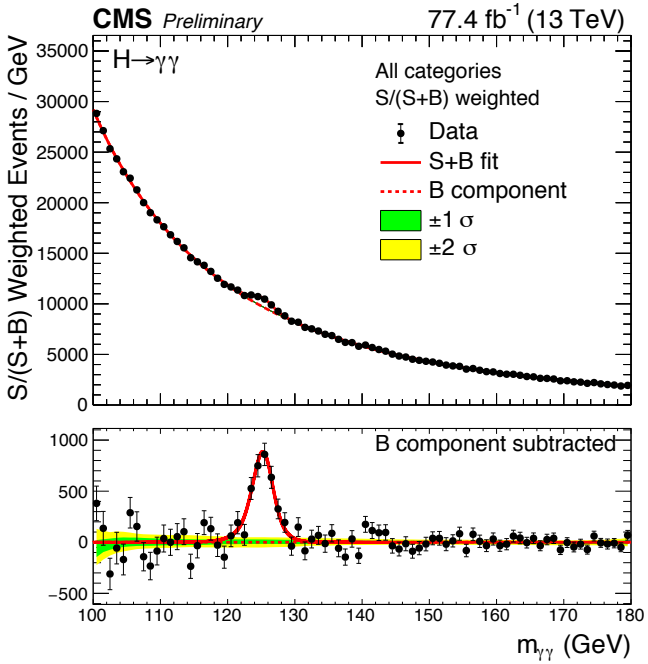
Expected sensitivity: 1.5σ, observed 0.8σ, σ(obs) / σ(SM) = 0.5 ± 0.7

50% improvement in expected sensitivity w.r.t previous ATLAS result, ~ half from larger dataset, half from improvements in analysis techniques

H → γγ

HIG-18-029

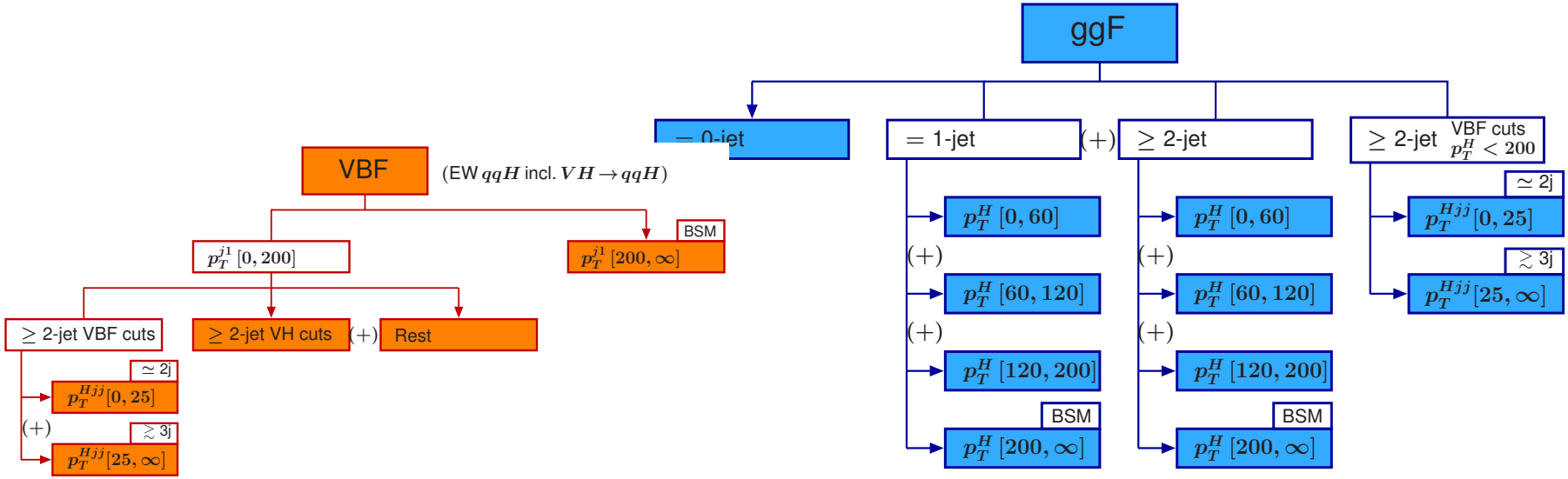
- high resolution channel with small branching ratio
- background rejection using diphoton BDT



Use simplified template cross section (STXS) framework:

- minimize theory dependence
- enable use of advanced analysis techniques to optimise sensitivity
- increase reinterpretability

First CMS measurement of STXS stage 1 regions in diphoton channel, covering ggH and VBF production modes (VH and ttH have limited sensitivity for stage 1)

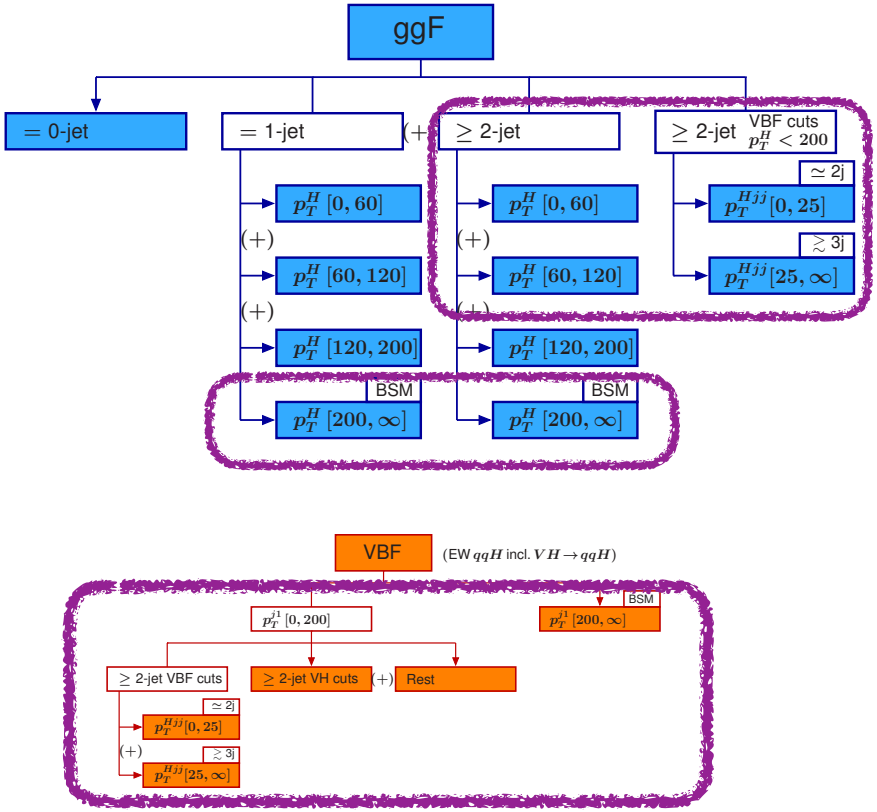


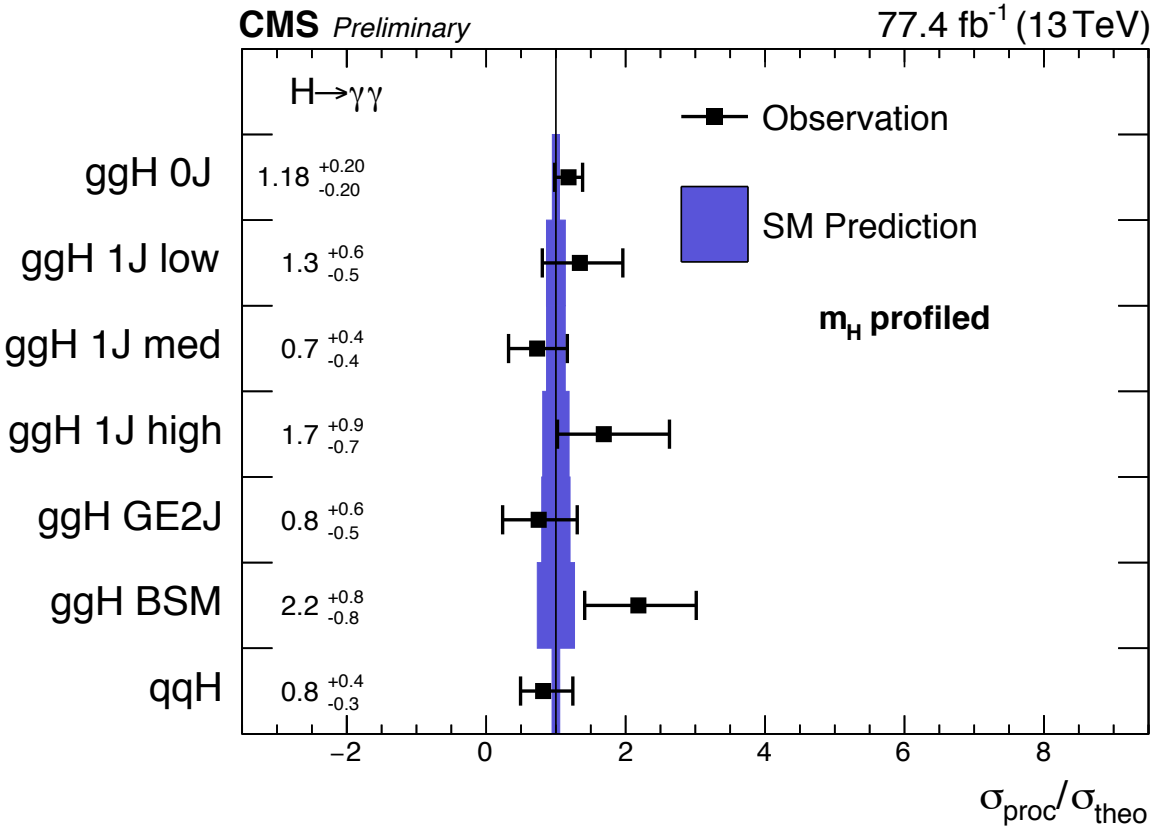
H → γγ

HIG-18-029

Two fits are performed with different grouping, a 7 parameter fit and 13 parameter fit.

Motivated by aiming for maximum granularity while maintaining uncertainties at ~+/- 100% SM prediction





Cross sections normalized to SM predictions: ggF = $1.15^{+0.15}$ and VBF = $0.8^{+0.4}$

ATLAS-CONF-2019-026

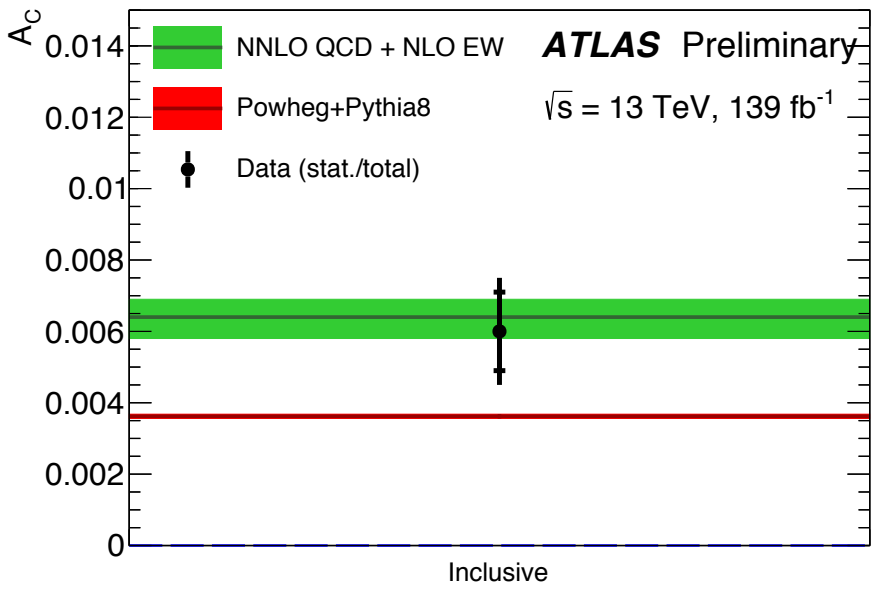
Charge Asymmetry in top-antitop events

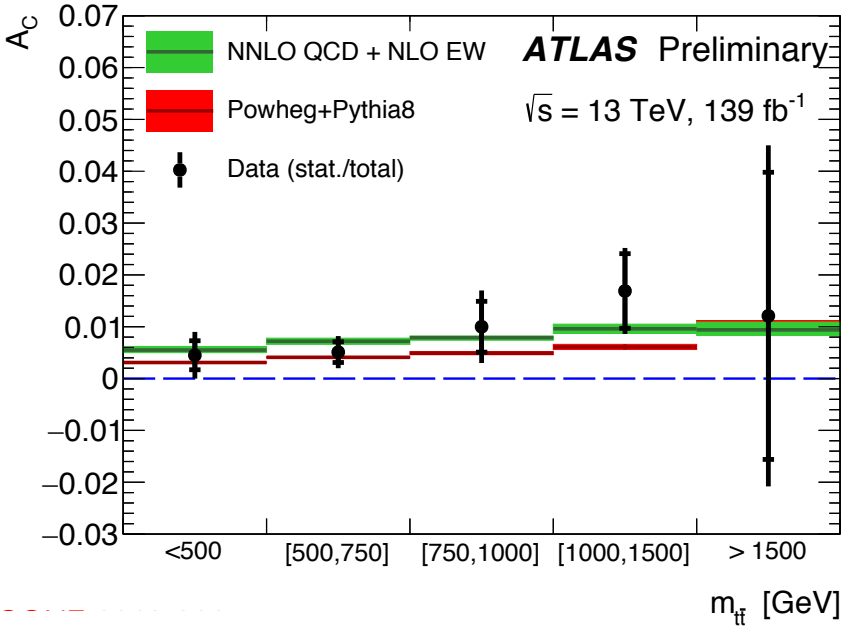
- ✦top-antitop is symmetric at leading-order (LO) under charge conjugation
- ✦Asymmetry from interference of higher orders in $q\bar{q}$ and qg initial states (gg symmetric to all orders)
- ✦Top quarks preferentially produced in direction of incoming quark, more forward top quarks, more central top antiquarks.

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} = 0.0060 \pm 0.0011_{\text{stat}} \pm 0.0010_{\text{sys}} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

Consistent with predictions from NNLO in QCD and NLO in electroweak

Significance of non-zero asymmetry at 4σ level

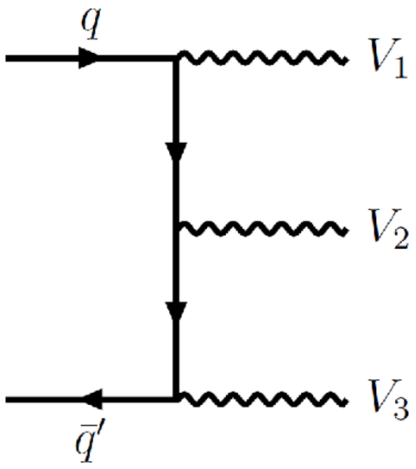




Exploits large dataset in 2 ways: reducing statistical uncertainty and constraining large uncertainties in-situ.

Triple gauge boson production (WVV)

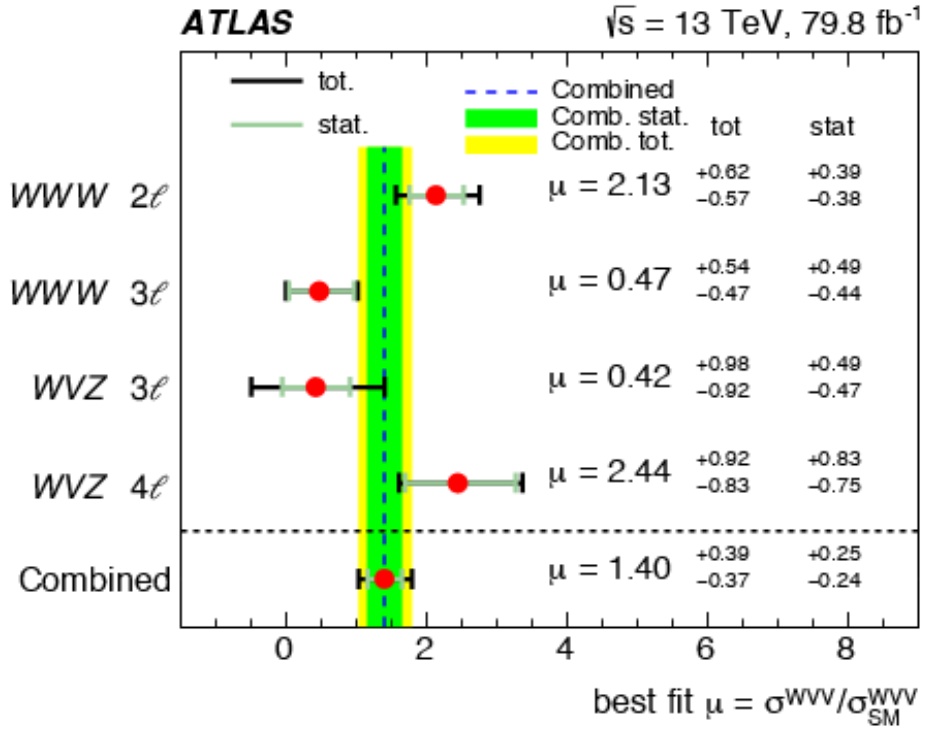
arXiv:1903.10415



Rare SM process, tests the non-Abelian gauge structure of SM.

Deviations from SM could point to new physics at higher energy scale

Decay channel	Significance Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ



$$\sigma_{WWW} = 0.65^{+0.16}_{-0.15}\,(\text{stat.})\,^{+0.16}_{-0.14}\,(\text{syst.})$$

$$\sigma_{WWZ} = 0.55 \pm 0.14\,(\text{stat.})\,^{+0.15}_{-0.13}\,(\text{syst.})\ \text{pb}$$

Summary

UK in CMS :

◉We lead critical aspects of the detector design, driven by our physics goals. Significant M&O responsibilities in Trigger, Tracker, ECAL, as well as computing.

◉Becoming increasingly challenging to maintain operational expertise in these critical areas

Physics (ATLAS + CMS)

◉ UK involvement in many interesting and wide ranging areas of physics exploitation of LHC data.

◉ Leading many interesting analyses in Standard Model, Top, Higgs, and B-physics, also leading as conveners of SM, Top B-physics and LHC Higgs WG.