ATLAS Highlights

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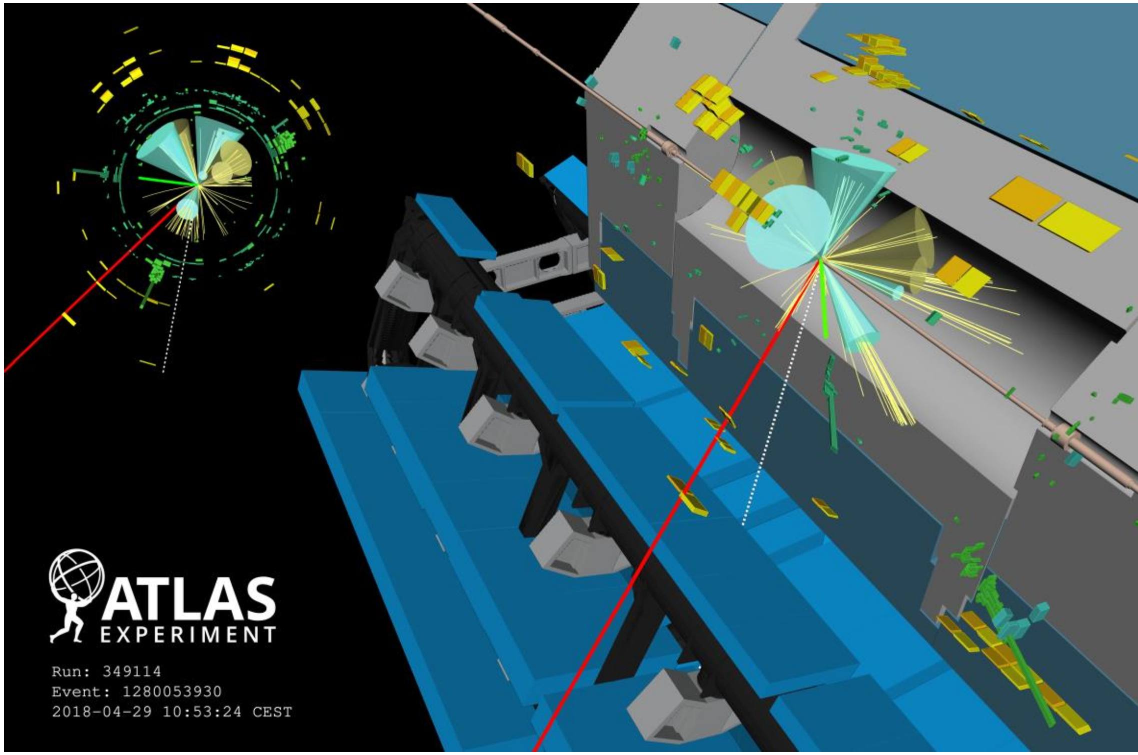
on behalf of the ATLAS Collaboration

LISHEP 2021, online, 7/7/2021

- Selected recent ATLAS results from the LHC Run-2 dataset
  - Higgs physics – precision and rare Higgs decays
  - Heavy gauge boson searches
  - Lepton flavour violation
  - 4-top and single top production
  - Supersymmetry – electroweak and stopped particles
  - Outlook for Run-3 and beyond

  - Only scratching the surface ...
    - AtlasPublicResults for more

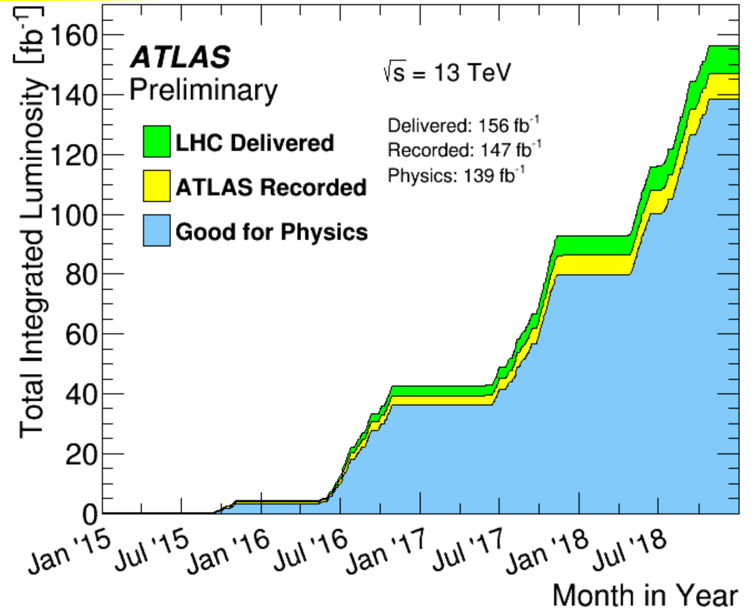


Candidate 4-top event with muon and many (b)-jets

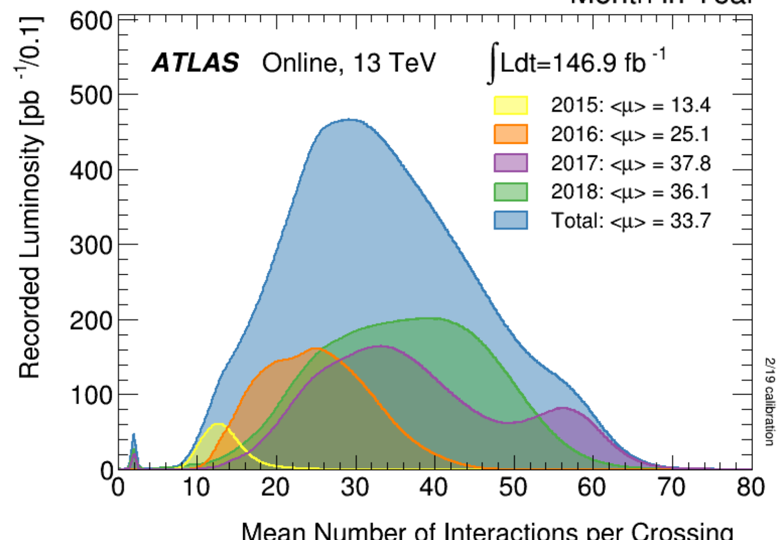
ATLAS physics at Run-2

- LHC ran at √s=13 TeV from 2015-18
  - 147 fb^{-1} of pp data recorded by ATLAS
  - 139 fb^{-1} good for physics analysis

ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

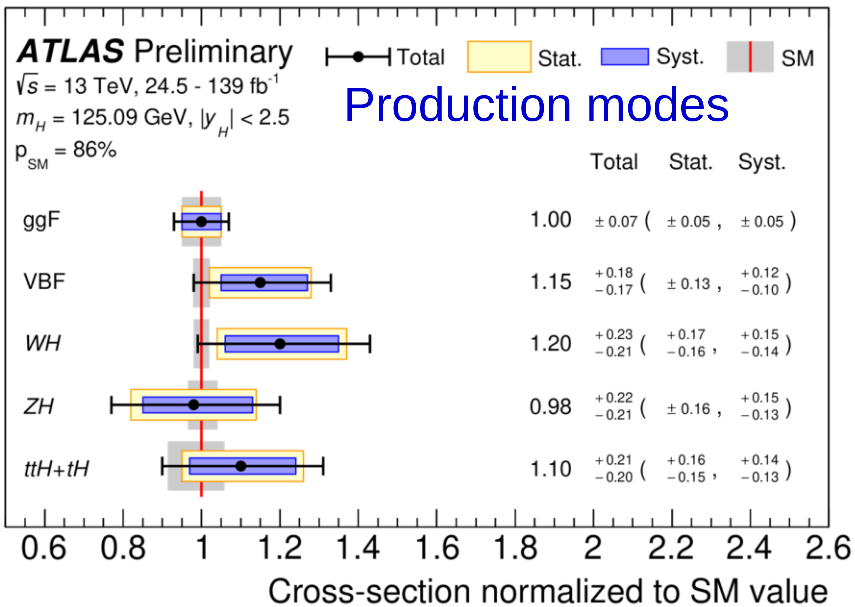


  - High-pileup data, <μ>=33.7
- Precise calibration of physics objects
  - E.g. lepton efficiencies <1% e, ~0.1% μ
  - Jet energy scale ~1-3% for p_T>30 GeV
- Already 1000 ATLAS collision-data papers with~135 results on full run-2 dataset
  - New physics searches, SM measurements
  - Showcasing some recent highlights …



The Higgs landscape

- Higgs-like boson discovered at LHC Run-1
  - Is it the SM Higgs boson, or something else?
- At Run-2, focus on measuring its properties
  - Production modes: gluon-gluon fusion, vector boson fusion, associated VH, top-pair + H



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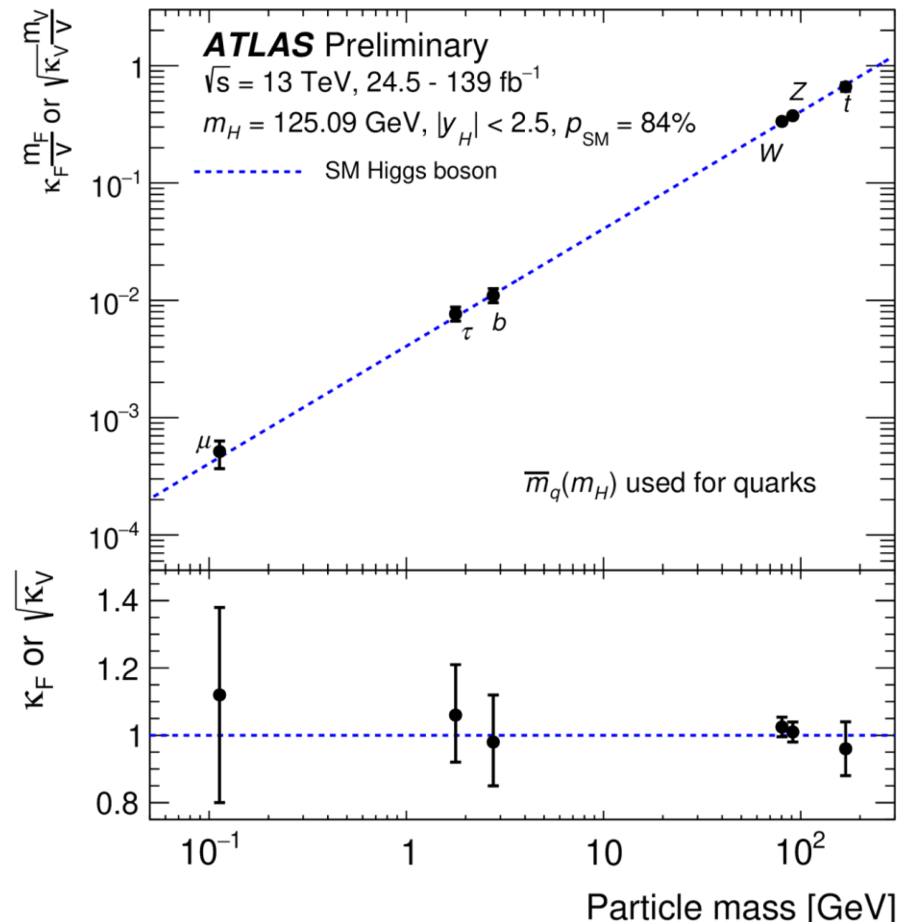
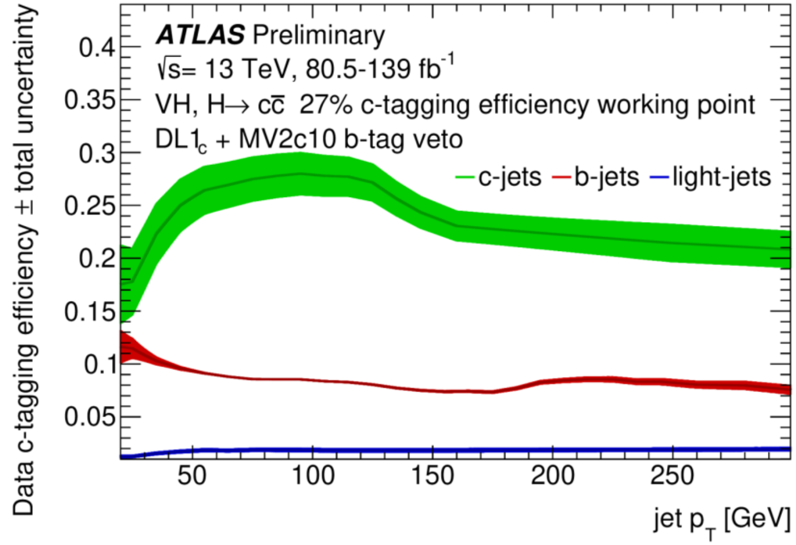
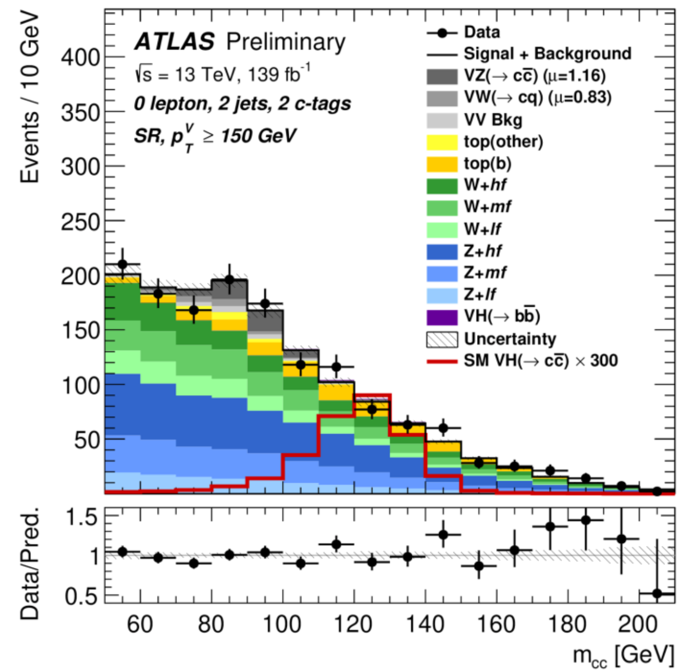


- Decays into WW, ZZ, $\gamma\gamma$, and 3rd generation fermions bb/$\tau\tau$ observed
  - Now looking for 2nd gen fermions: cc/$\mu\mu$
- Higgs couplings have expected dependence on particle mass
- CP-properties also as expected

Searching for Higgs decays to charm

- Dominant H→bb decay (BR 58%) observed in 2018 via WH→lνbb and ZH→νν/ll bb
  - 2^{nd} gen. H→cc decay much more challenging
    - BR=2.9%, much harder to tag c-jets than b-jets
- Performant charm jet tagger now available
  - Pick out 'intermediate' lifetime charm hadrons between longer lifetime b and prompt uds/g
    - 27% efficiency for charm, 8% b, 1.6% light
    - Calibrated using top-pair and Z+jets in data
- Select events with large E_T^{miss} or 1/2 leptons
  - Require 1 or 2 c-tagged jets, veto b-tag jets
  - Study invariant mass of two highest p_T jets – assumed to come from Higgs decay
    - Small, wide signal due to limited jet resolution
  - Very good control of backgrounds from W+jets, Z+jets, top required





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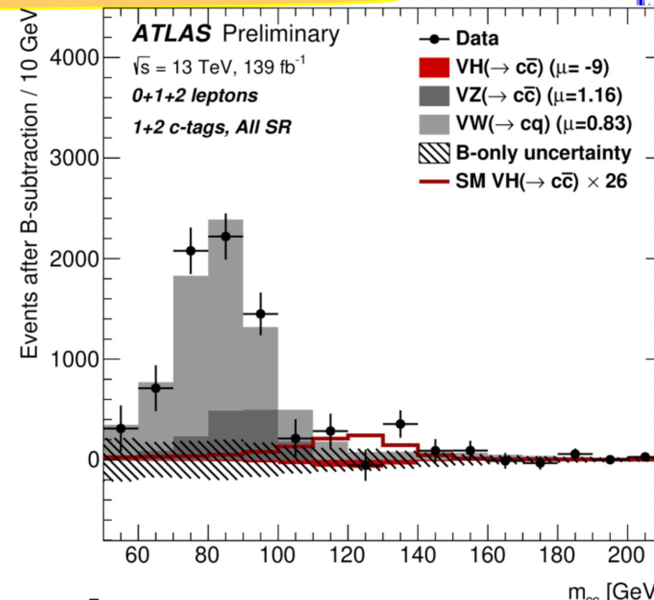
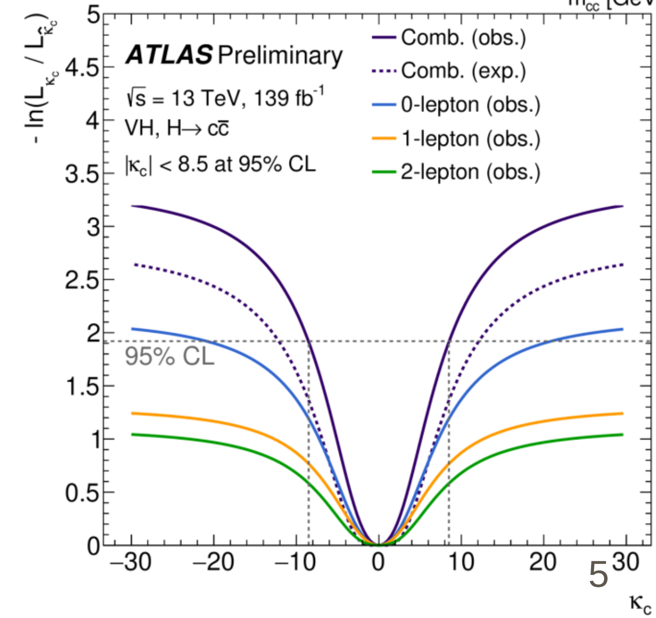
Results and limits on H→cc

- Natural calibration signal from VV production
  - i.e. W/Z+W→cq, W/Z+Z→cc with broad mass peak around the W and Z masses
- Simultaneous fit to all three signals
  - Signal strength μ=rate normalised to SM expt.

	value	stat	syst
$\mu_{VW(cq)}$	0.83	±0.11	±0.21
$\mu_{VZ(cc)}$	1.16	±0.32	±0.36
$\mu_{VH(cc)}$	**-9**	**±10**	**±12**

  - VW(cq) and VZ(cc) observed with 3.8σ and 2.6σ significances, rates agree with expectation
- Fitted VH(cc) rate is negative, compatible with 1
  - 95% C.L. limit on VH(cc): μ<26, c.f. 31 expected
- Interpret as limit on H-charm coupling modifier
  - $|\kappa_c|$<8.5, assuming the modified coupling only affects the H→cc decays, not Higgs production



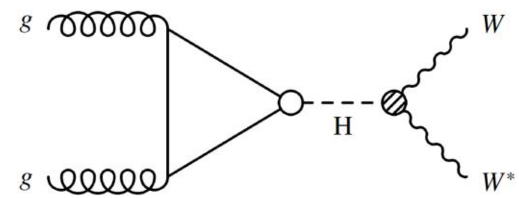


Precise measurements with H→WW*

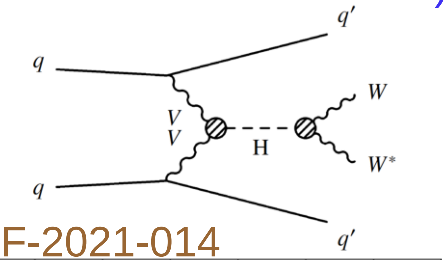
- High statistics H→WW*→e$\nu\mu\nu$ allows studies of different Higgs production modes
  - ggF: jets only from ISR
  - VBF: forward quark jets with large m_{jj} and large Δy
  - Backgrounds from continuum WW* production, top-pair
    - Exploit $\Delta\phi$(eμ) – smaller for signal due to spin-0 Higgs
- Separate sample using N_{jet} and dedicated deep NN for VBF
  - Backgrounds estimated using control regions for WW, top-pair and Z→$\tau\tau$→eμ contributions
  - Final discriminant for ggF:

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{E}_T^{miss}\right|^2}$$

Gluon-gluon fusion (ggF)



Vector-boson fusion VBF)



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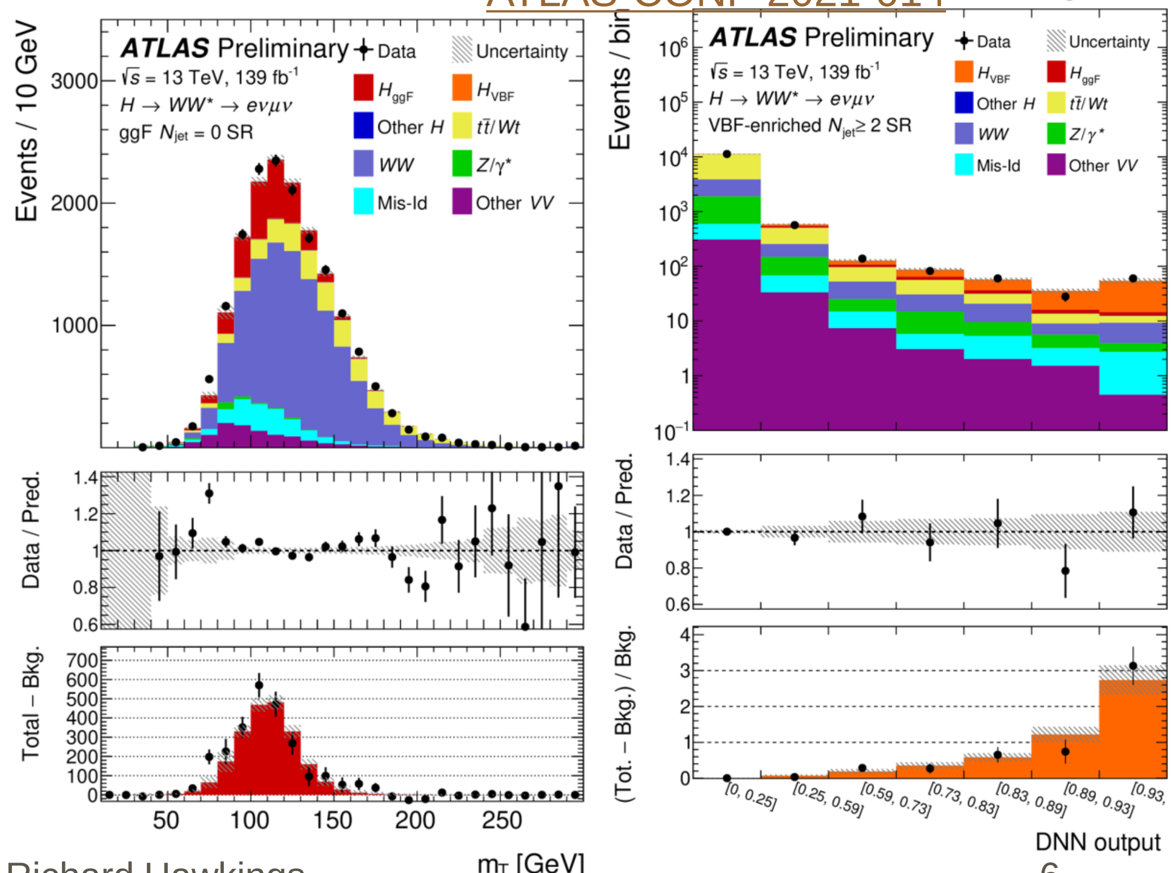
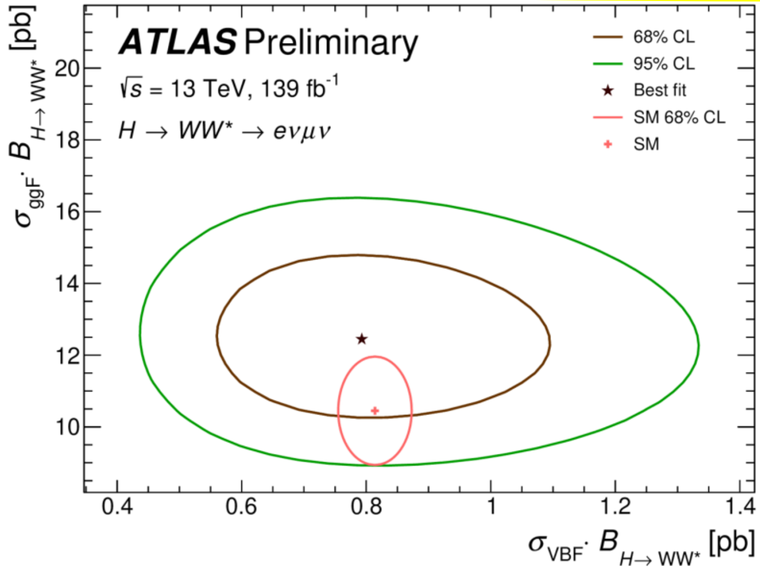
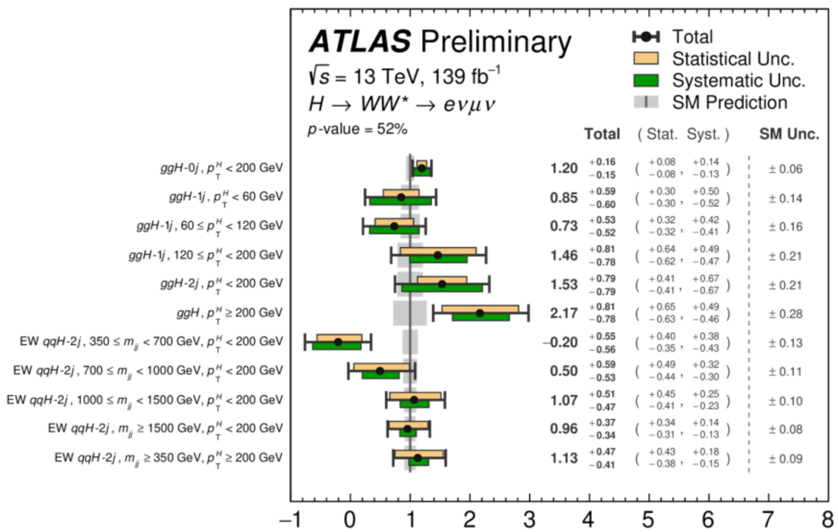


H→WW* results

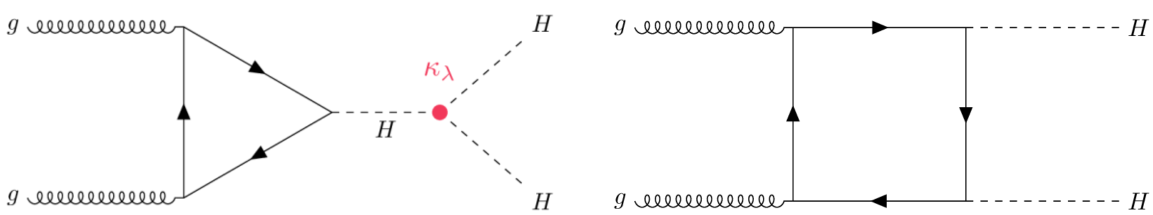




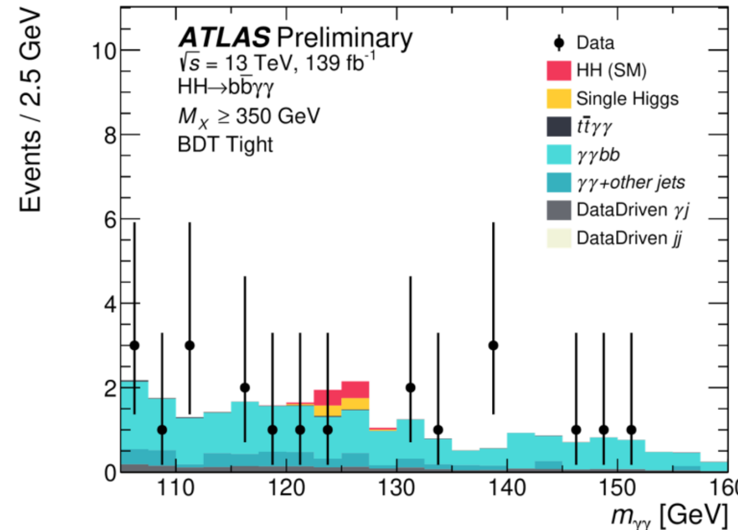
- Simultaneous fit to ggF and VBF signals
  - Measures σ_{ggF} and σ_{VBF}, good agreement with SM prediction
    - VBF observed with 6.6σ significance
- Going further – simplified template cross-sections (STXS)
  - Measurement of fiducial cross-sections in different production modes, jet multiplicities and Higgs/jet kinematics
    - A well-defined framework for characterising Higgs production
    - Map STXS categories onto experimental selections/bins
  - Good overall agreement between STXS measurements and predictions
    - p-value of 52% for compatibility with SM

Towards the future – di-Higgs production

- Di-Higgs production sensitive to H self-coupling



  - Destructive interference with ‘box’ diagram reduces x-sec, σ_{HH}≈30 fb in SM – rare process
  - H tri-linear coupling scaled by κ_λ; κ_λ=1 in SM
- One of most sensitive channels: HH→bb$\gamma\gamma$
  - Combining high-BR bb and clean low-BR $\gamma\gamma$
  - BDT selection using kinematic variables
  - Main background from continuum bb$\gamma\gamma$
- Limit σ_{HH}<130 fb at 95% CL (4.1x SM)
  - Corresponds to -1.5<κ_λ<6.7
  - Limits also set on resonant HH production
- A key topic for Run-3 and HL-LHC



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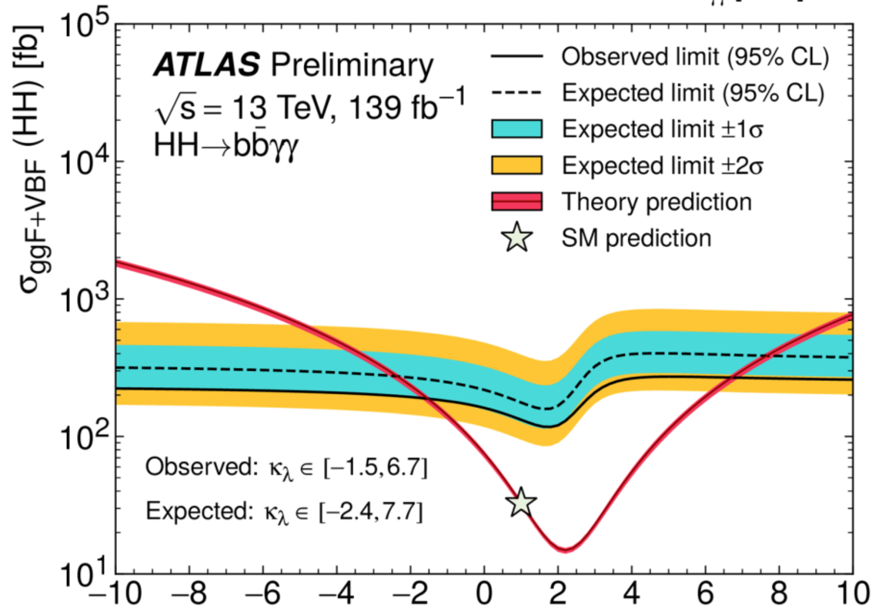

New physics decaying to Higgs?

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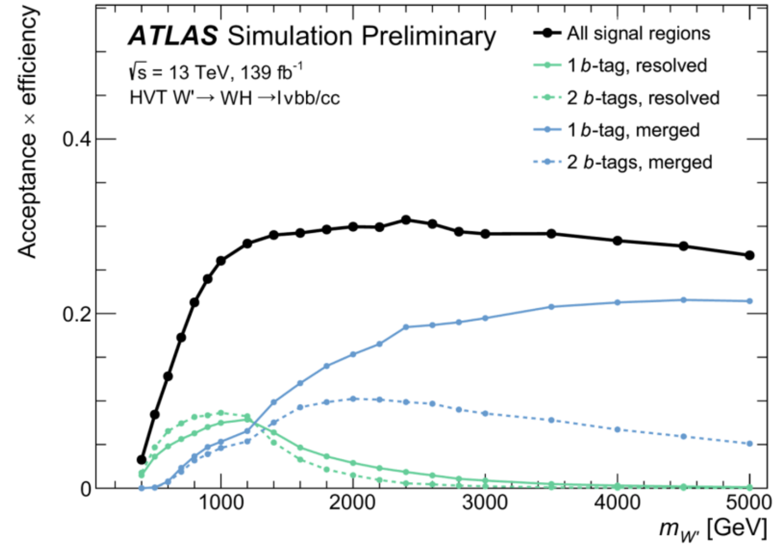
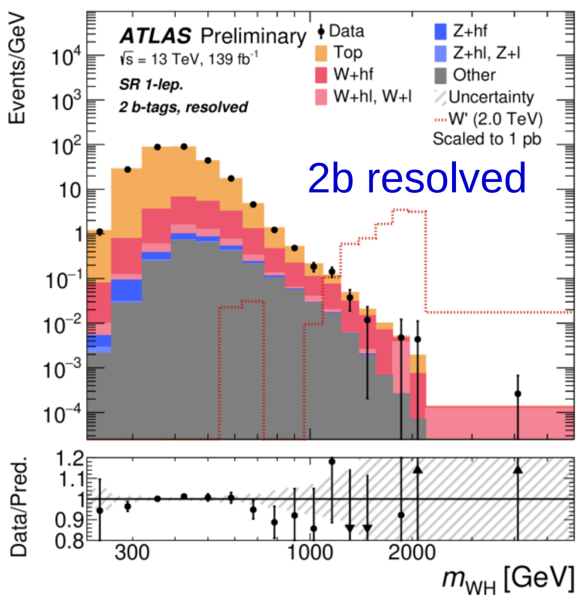
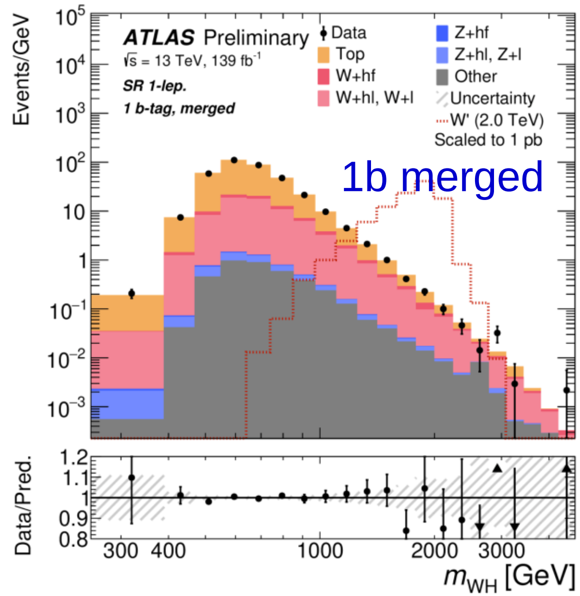
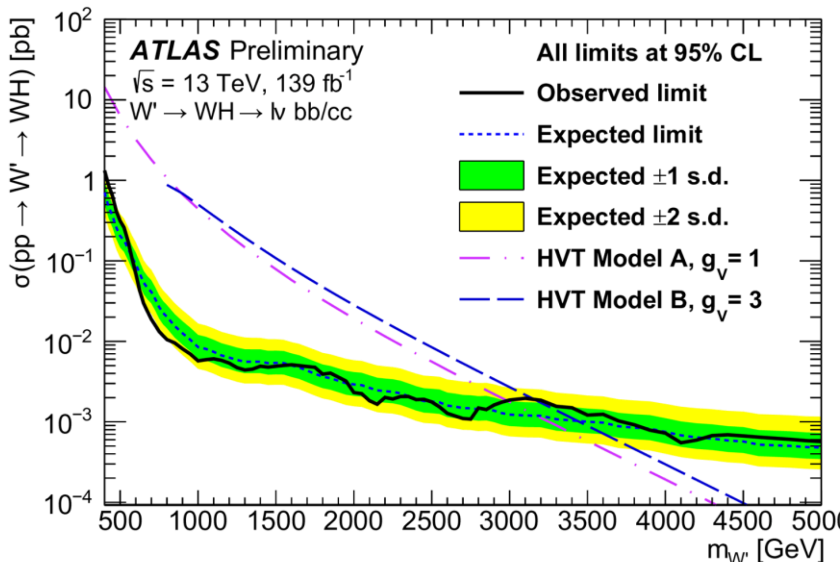
- Dynamical symmetry breaking models predict new vector bosons decaying to H, e.g. W'→WH
  - Search for $W \to e/\mu+\nu$, $H \to bb$
  - Lepton + E_T^{miss} +2 resolved b-jets (low p_T Higgs), or one large-radius jet with 2 b-tagged track-jets
- Search for resonance in m_{WH} distributions
  - Limits on heavy vector triplet models at ~3 TeV



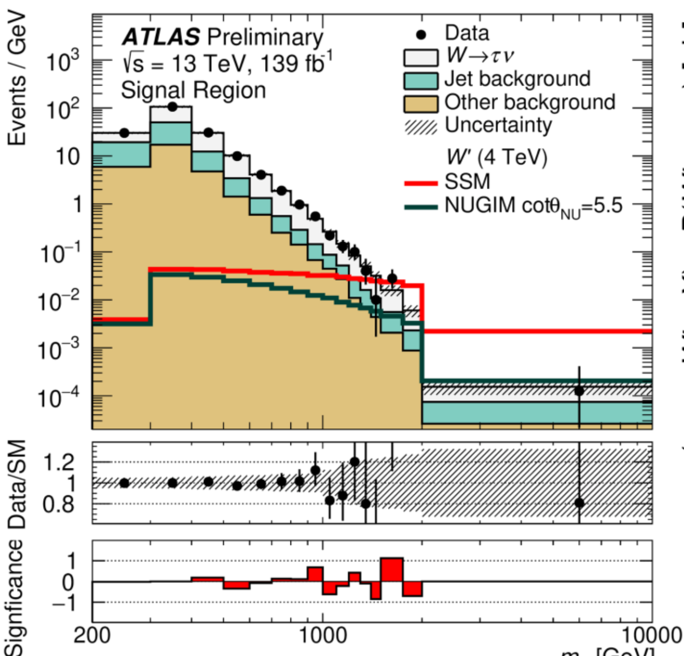


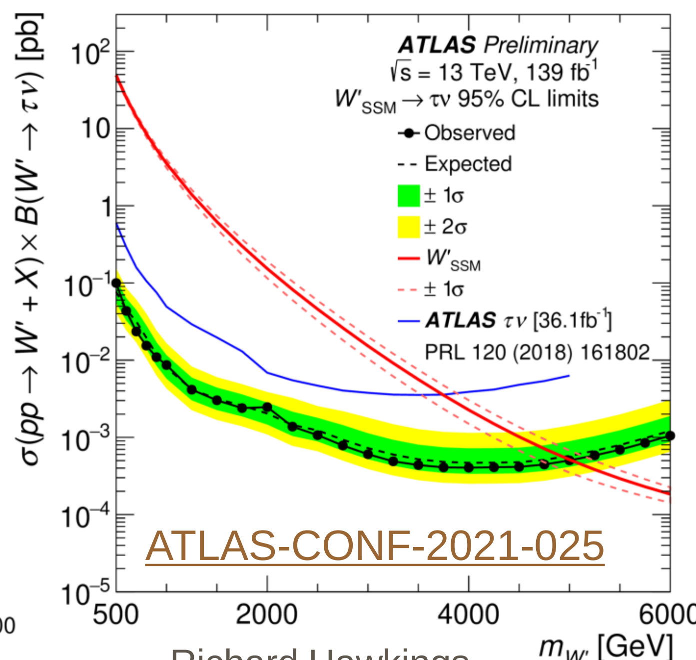


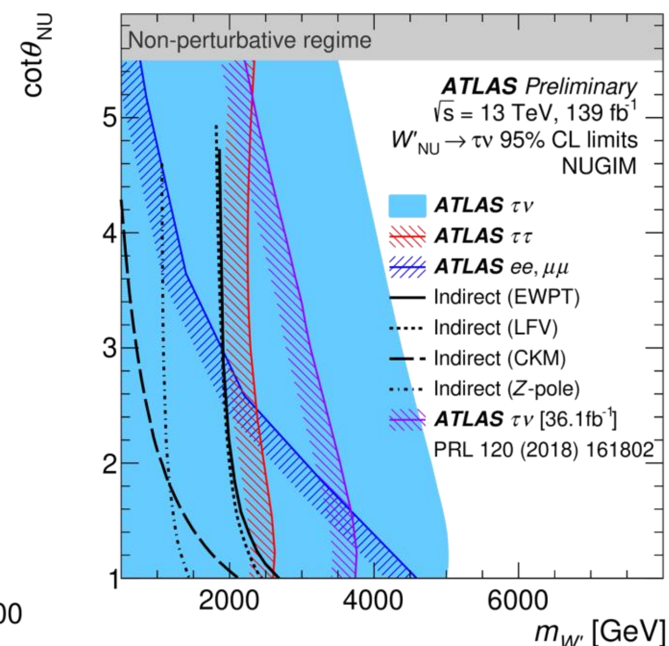


Heavy W bosons decaying to fermions: W' $\rightarrow \tau\nu$

- W'$\rightarrow l\nu$, flavour symmetric in SSM, or with enhanced couplings to τ
  - E.g. non-universal gauge interaction model, enhanced τ coupling if $\cot\theta_{NU}$>1
- Search for events with hadronic τ candidate and large E_T^{miss}
  - 1- or 3-prong hadronic τ identified with recursive NN, 75-85% τ-ID efficiency
    - Transverse mass m_T of visible τ decay products and E_T^{miss} used as discriminant
- W' with mass up to 5.0 TeV excluded in SSM (+1.3 TeV c.f. partial dataset)
  - W' with masses up to 3.5-5.0 TeV excluded for NUGIM models depending on θ_{NU}





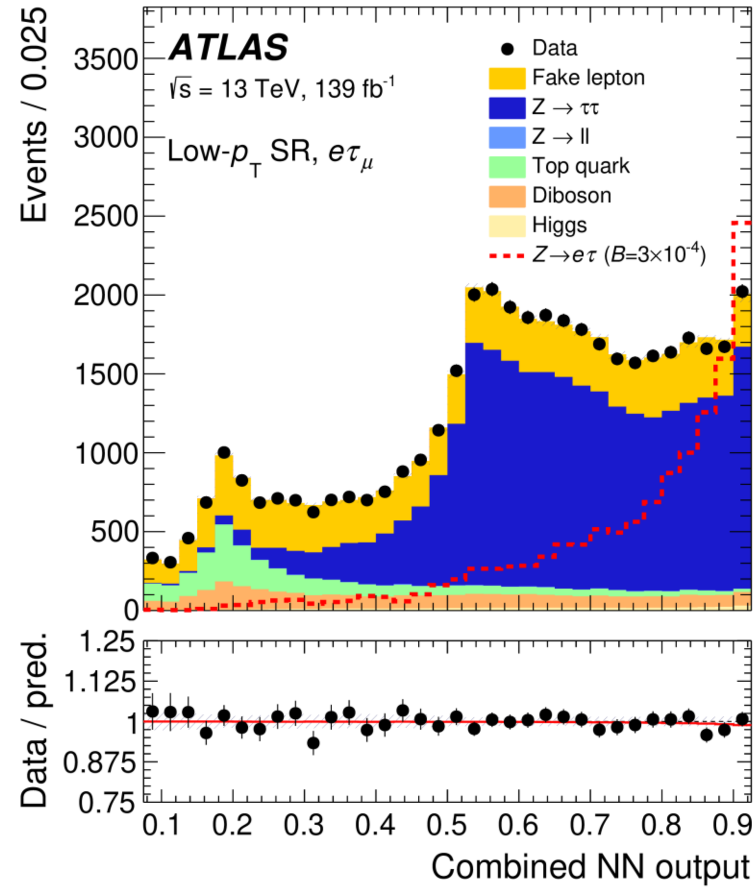


Lepton flavour violation in Z decays?

- Lepton flavour conservation 'accidental' in SM
  - But violated in neutrino oscillations
  - Heavy neutrinos – could cause $Z\rightarrow e/\mu+\tau$ at 10^{-5}
- Search for this process with $\tau\rightarrow\mu/e+2\nu$
  - Signature $e\mu+E_T^{miss}$ with total invariant mass $\approx m_Z$
    - Back-to-back leptons with E_T^{miss} colinear with lepton from τ
    - Backgrounds from $Z\rightarrow\tau\tau\rightarrow e\mu+4\nu$, top-pair, diboson and events with fake leptons
  - NN classifiers to distinguish the different event types, fit for signal and background normalisation
- No significant signal, limits on $B(Z\rightarrow e/\mu+\tau)$
  - Combine with 2010.02566 using hadronic τ decay

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z\rightarrow\ell\tau)$ [$\times10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

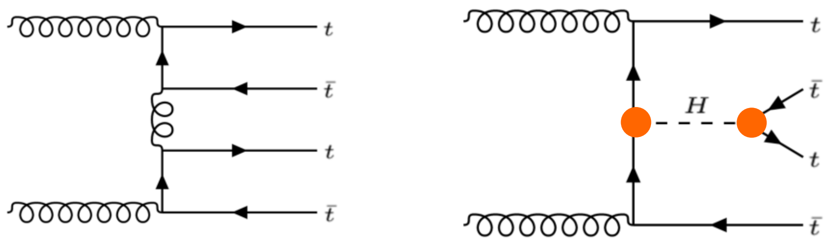
arXiv:2105.12591



Surpasses LEP limits of ~1 10^{-5}

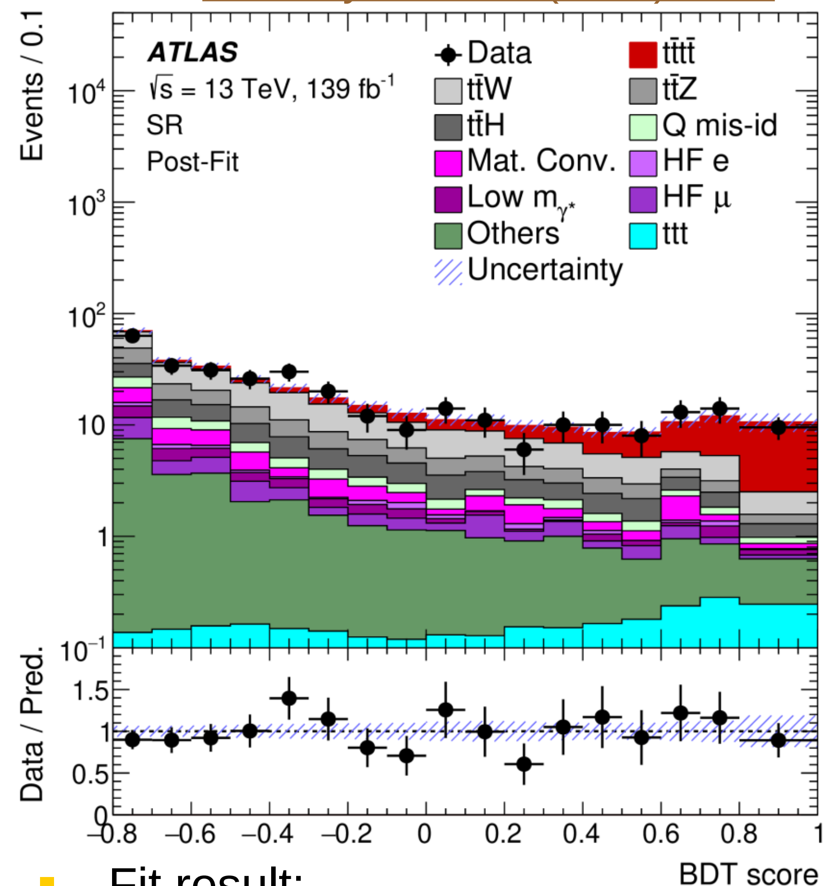
Four tops production – 2LSS/3L channels

- Rare process – 4 heavy particles ~ 700 GeV



  - Sensitive to BSM physics, and top quark Yukawa coupling to Higgs boson
    - SM prediction with NLO QCD: σ_{tttt}=12 fb
- BR(t→Wb) ≈1; lots of jets and b-jets, leptons from leptonic W decays
  - 13% to 2 same-sign leptons or ≥3 leptons
    - Background from top-pair + W,Z,H, fake leptons
  - 57% to 1 lepton or 2 OS leptons
    - Background from top-pair + jets, esp. b-jets
- Initial full run-2 analysis in 2LSS/3L channels
  - ≥6 jets, ≥2 b-tagged jets
  - BDT using kinematics and b-tag information
  - Control samples for ttW + fake lepton b/g

Eur. Phys. J. C80 (2020) 1085

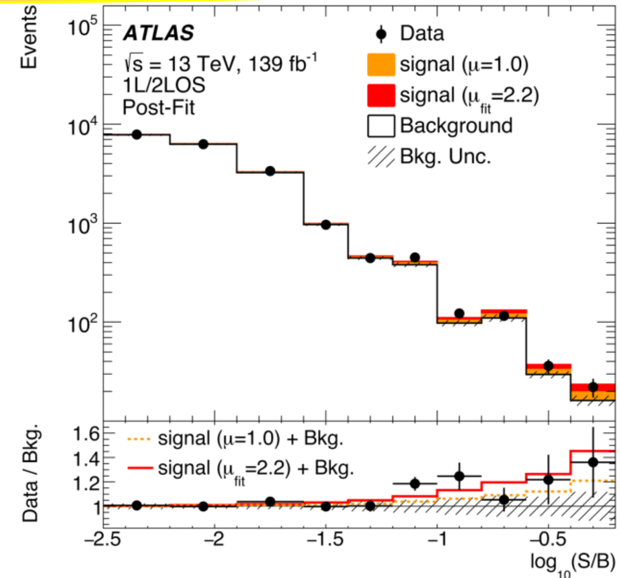


- Fit result:

  μ_{tttt}=2.0±0.4 (stat) $^{+0.7}_{-0.4}$ (syst)
  - Observed significance 4.3σ
  - 2.4σ expected with SM σ_{tttt}

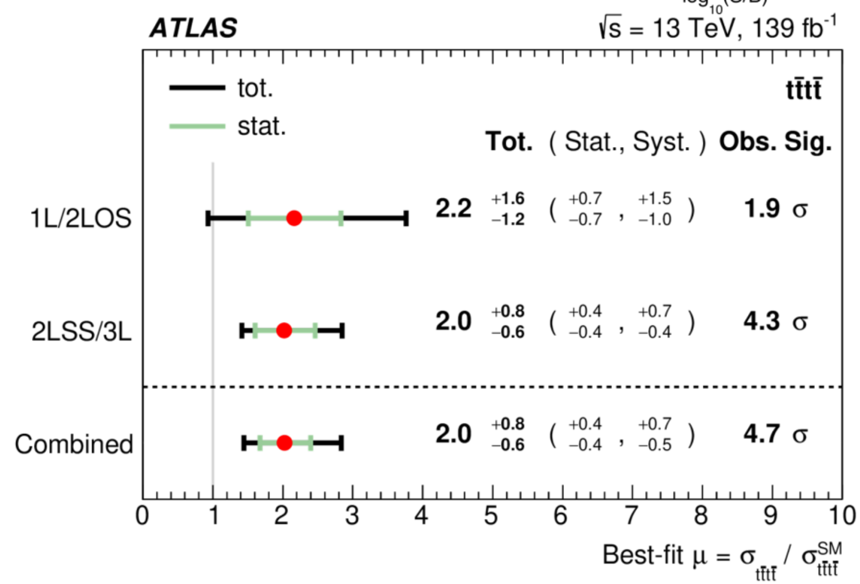
1L/2LOS four tops and combination

- Further analysis in 1L/2LOS channel
  - Require ≥7 (1L) or ≥5 (2LOS) jets
  - Divide data into bins of jet and b-jet multiplicity
    - Reweighting scheme with various control regions to improve top-pair + (b) jet modelling
  - Final discrimination with per-bin BDTs using kinematic and b-tagging information
    - Signal regions ranked according to their S/B
- Fit result: $\mu_{tttt}=2.2\pm0.7$ (stat) $^{+1.5}_{-1.0}$ (syst)
  - Largest systematics: tttt and ttbb modelling



arXiv:2106.11683

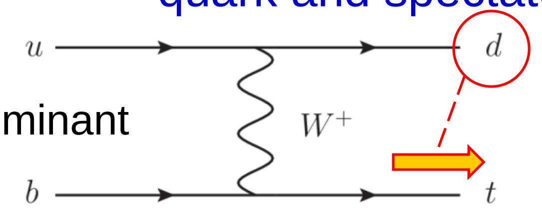
- Combination of both analyses
  - $\mu_{tttt}=2.0\pm0.4$ (stat) $^{+0.7}_{-0.5}$ (syst)
  - Observed significance 4.7σ, expected 2.6σ
- $\sigma_{tttt}=24^{+7}_{-6}$ fb, factor 2 higher than SM prediction
  - But consistent within 2 standard deviations – watch this space in Run-3



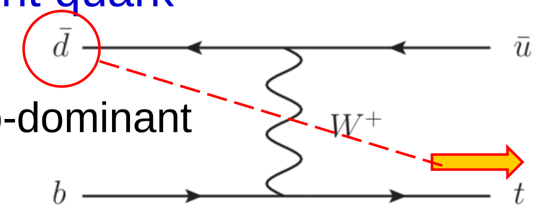
Single top polarisation in t-channel production

- Single top quark production, e.g. in t-channel
  - Exchange of W boson between initial state b quark and spectator light quark

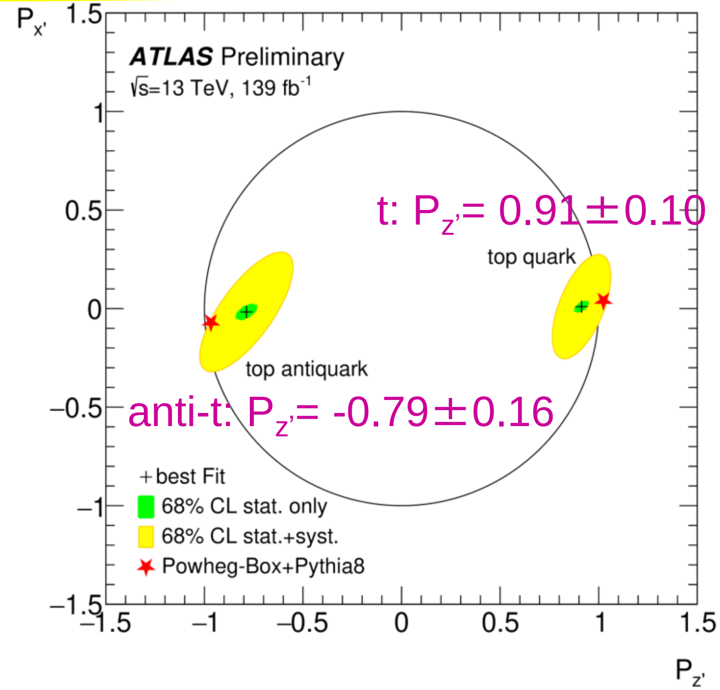
dominant

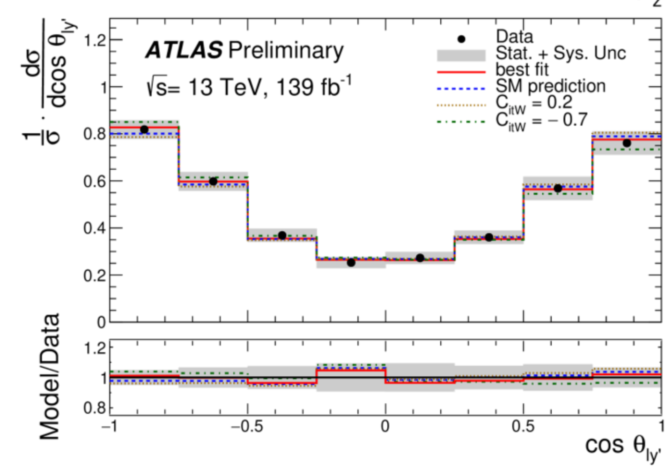


sub-dominant



- V-A form of Wtb vertex implies top quark spin is aligned along direction of down type quark
  - Use outgoing spectator quark as reference z:
    - Polarisation of t mainly **along** spectator direction
    - Polarisation of anti-t mainly **against** spectator dir[n]
- Identify single top events in l+jets channel
  - Reconstruct decay angle distributions – gives information on original top polarisation
  - Polarisation of t/anti-t seen as predicted in SM
- Sensitive to EFT operators at Wtb vertex
  - Limits $-0.7<C_{tW}<1.5$ and $-0.7<C_{itW}<0.2$





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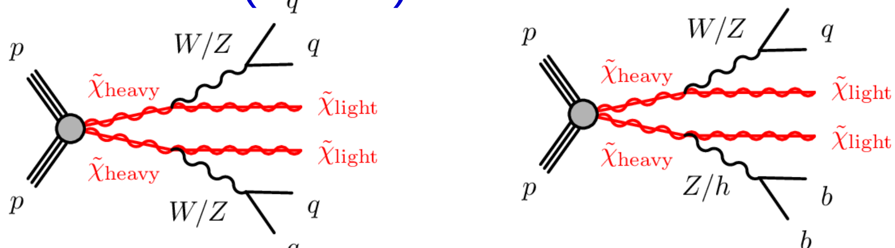
SUSY all-hadronic search

- Focus on searching for ‘electroweakinos’, i.e. super-partners of SM gauge bosons
  - Small cross-sections, decays into SM bosons (W/Z/H) and LSP



  - Searches exploiting **hadronic** decays of W/Z/H have highest reach
  - Use jet substructure techniques to reconstruct boosted W/Z/H decays as a large radius jet, possibly with b-tags
- E_t^{miss}+ 2 large-R jets tagged as W, Z or H
  - Dominant background from $Z\rightarrow\nu\nu$+jets
- Limits extending into TeV region, beyond reach of leptonic analyses
  - Many different signal models considered

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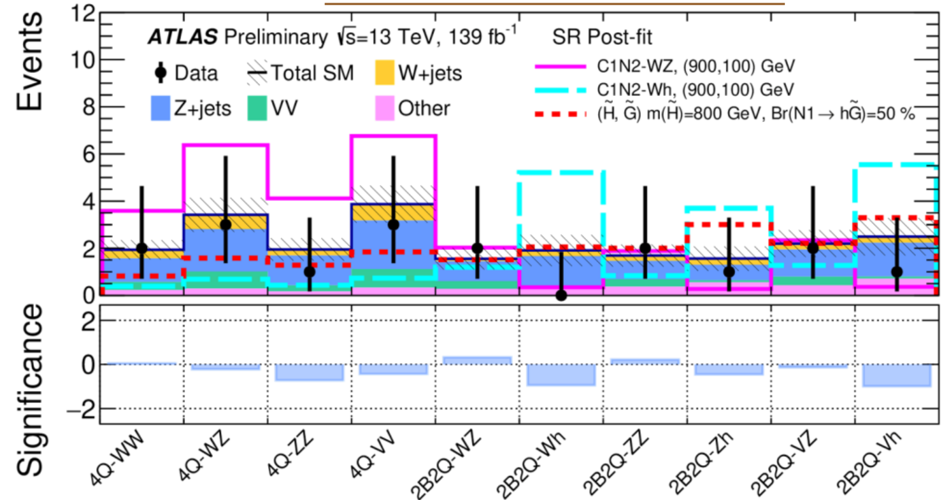
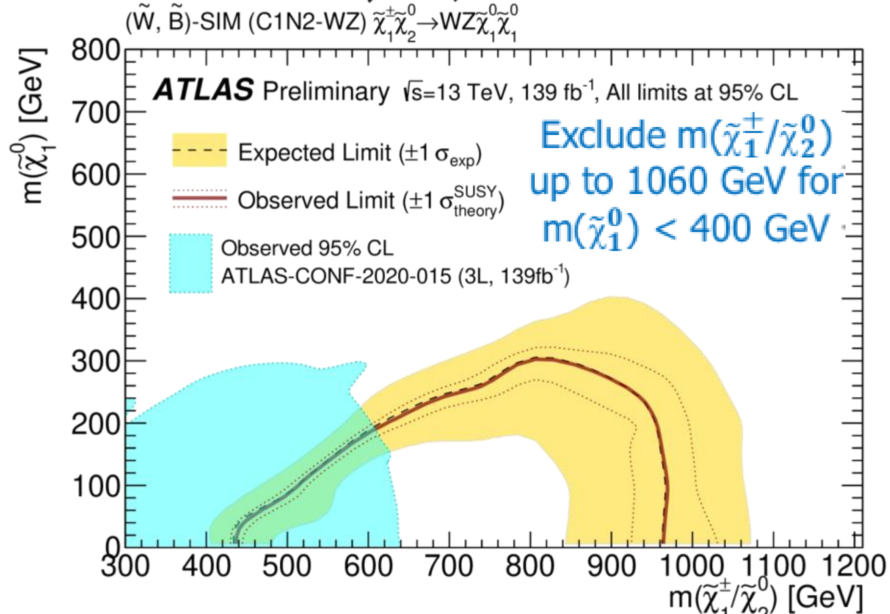
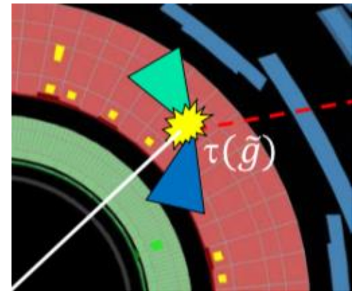


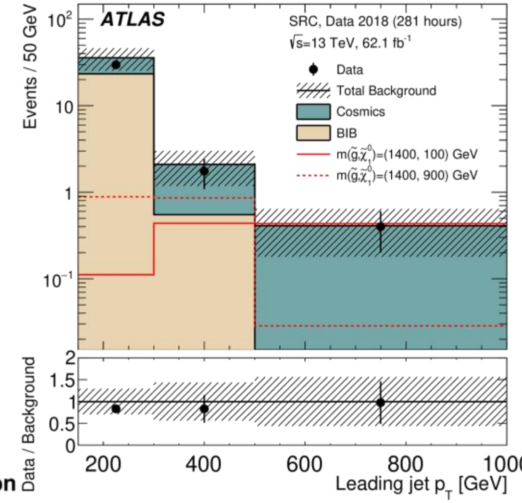


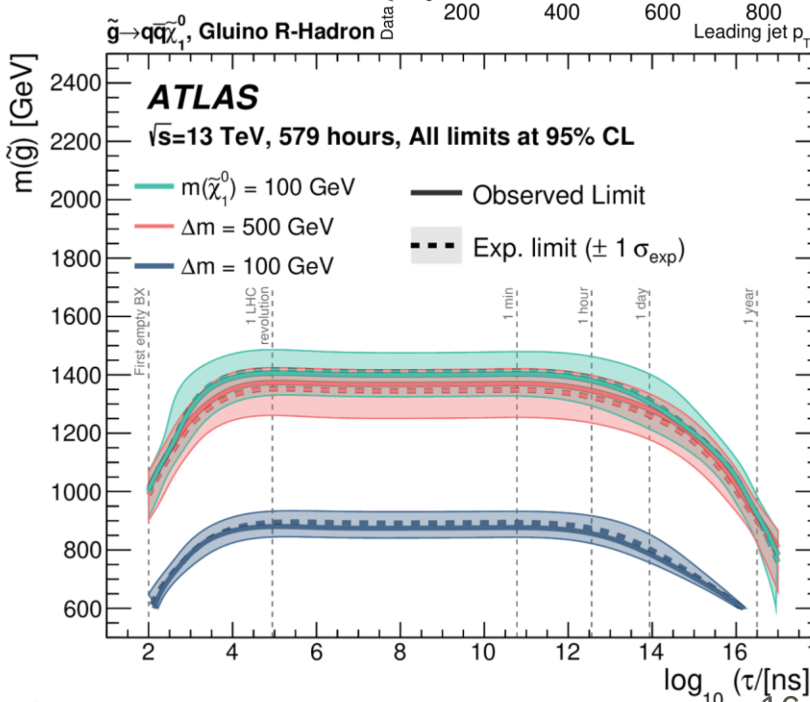
Metastable particles – stopped gluino search

- Search for metastable particles decaying μs to years after production
  - E.g. split-SUSY models with very heavy squarks and sleptons: long-lifetime gluino
    - Gluino could hadronise with SM quarks and gluons and stop in calorimeter, then decay
  - Look for out-of-time particle jets produced in 20-30% ‘empty’ LHC bunch crossings
    - Dedicated triggers in bunch slots > 100ns from filled bunches
    - Minimises collision background
  - Remaining background from cosmic muons and beam-halo (beam-induced background)
    - Estimated largely from data
  - Sensitivity depends on integrated luminosity and sample ‘livetime’: 579 hours in 2017-18
- Gluino masses 0.6 – 1.4 TeV excluded for various scenarios with 100ns < τ < 1 year

arXiv:2104.03050

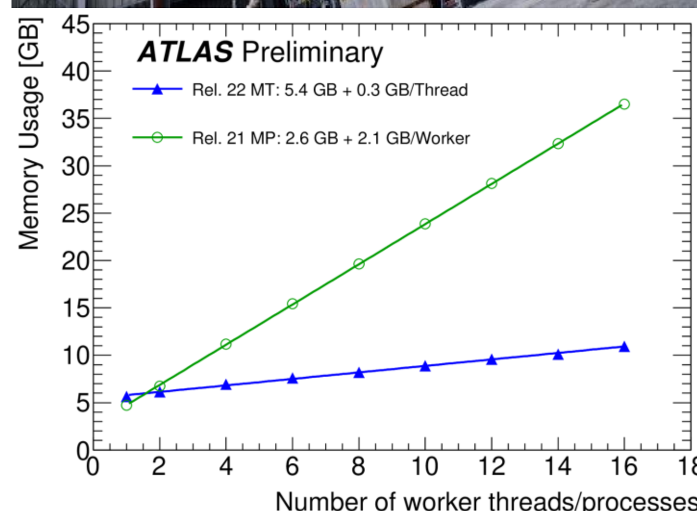






Towards Run-3

- LHC Run-3 from 2022 to 2024
  - Hoping for $\sqrt{s}$=13.6 TeV or higher, and another 150-300 fb^{-1} of pp data
    - Pileup leveled at <μ> ≈ 50 for much of fill
- ATLAS detector upgrades
  - Muon New Small Wheels in forward region – MicroMega and sTGC detectors
  - Finer granularity of L1 electron/photon trigger
  - More capable L1 'topological' trigger
- Preparing for Run-3
  - New multithreaded software release (rel. 22)
    - Allowing more efficient use of modern computing architectures with many CPU cores
    - Reprocessing all Run-2 data for eventual combination with Run-3 dataset
  - New trigger possibilities: lowering/sharpening thresholds to look in all corners
  - New physics ideas …



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Conclusions and the future

- ATLAS continues to reap a huge physics harvest from the run-2 dataset
  - Detailed characterisation of the Higgs boson, including rarer decay modes
  - Evidence of rare SM processes (e.g. 4 tops)
  - Continuing BSM physics searches, e.g. electroweak SUSY, processes with τ
  - Ongoing program of precision measurements exploiting the large precisely-understood dataset – many Run-2 results to come
  - And a strong heavy-ion programme exploiting the Pb+Pb and Pb+p datasets
- Preparing for run-3
  - Slightly increased collision energy, enhanced detector, trigger and software capabilities
- Looking further – HL-LHC starting in late 2020s, ATLAS phase-2 upgrade
  - A full program of detector upgrades now under development and construction
    - New all-silicon tracker (ITk), replacement of barrel muon chambers, electronics upgrades for calorimeters and muon spectrometer, new endcap timing detector (HGTD), new TDAQ system with 1 MHz level-0 trigger
  - A complementary programme of physics studies preparing to exploit the rich possibilities HL-LHC and the upgraded ATLAS detector