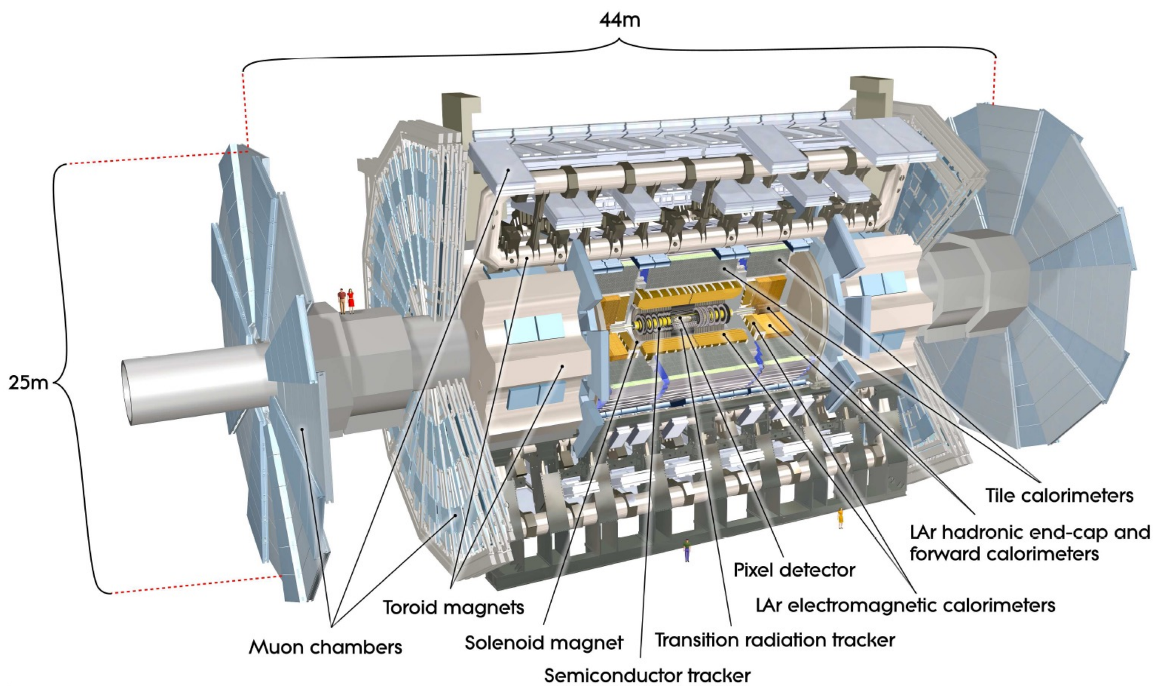
Latest Results from the ATLAS Experiment at the CERN Large Hadron Collider

Paul Jackson
(University of Adelaide)

December 14th, 2022

The ATLAS detector



- Solenoidal magnetic field (2T) in the central region – momentum measurement
- Energy meas. down to ~1^{o} to the beamline

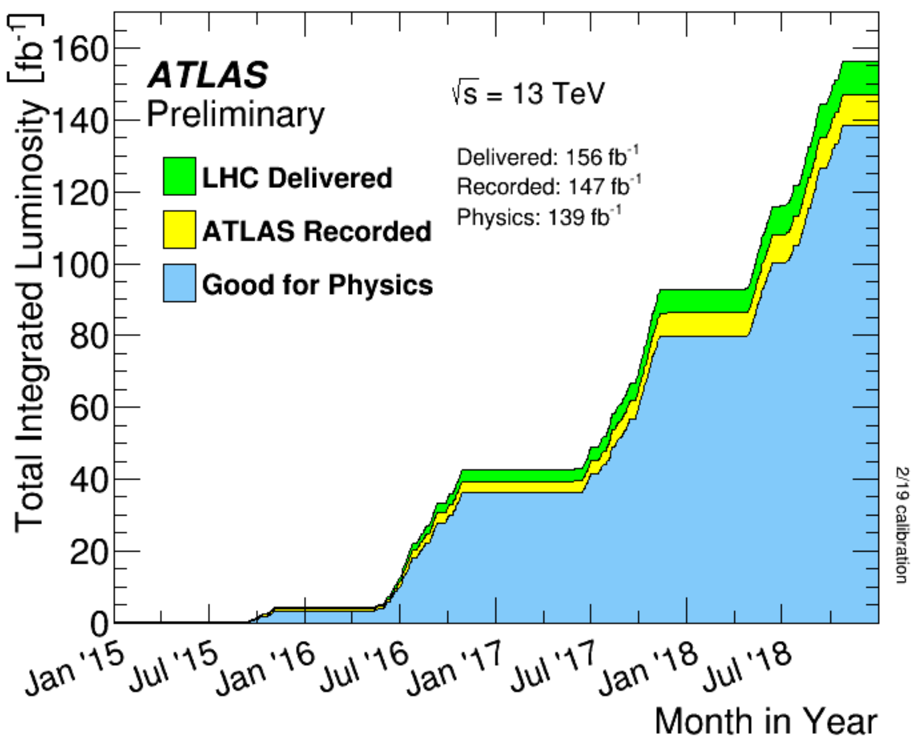
- High resolution silicon detectors
- Granular EM and Had calorimetry
- Independent muon spectrometer

- Good coverage permits reconstruction of missing transverse momentum through object reconstruction

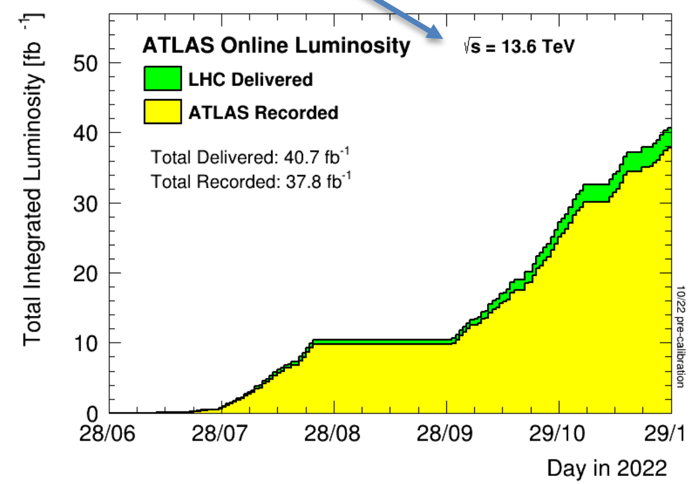
LHC data

Extremely successful Run 2 (2015 – 2018)

Dataset is a goldmine for physics, containing large samples of every known particle in the Universe!



Run 3 with increased energy



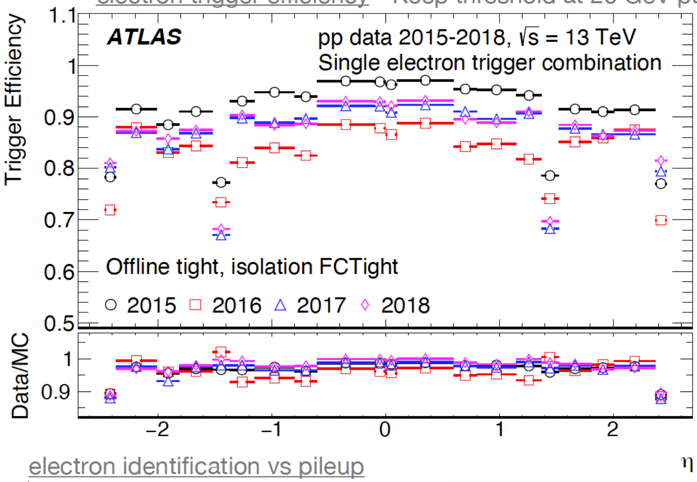
Many thanks to the LHC team for the excellent data they provided to us in Run 1 and Run 2 and for their commitment in view of Run 3.

Detector Performance

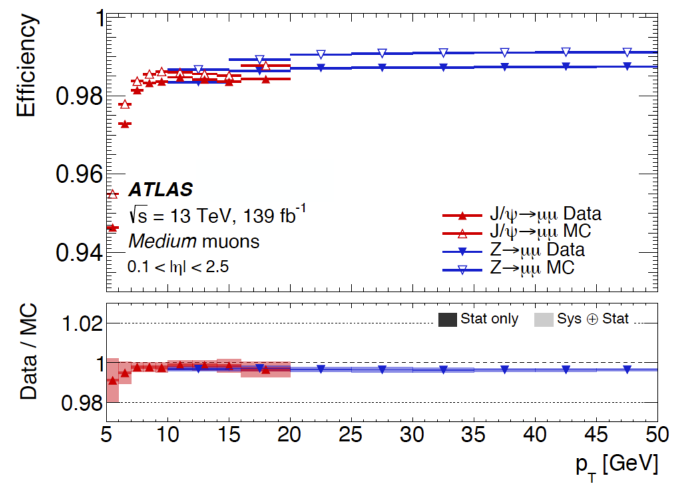
ATLAS EXPERIMENT

Results from Run 2 only possible thanks to excellent understanding of detector performance, and development of reconstruction and identification algorithms

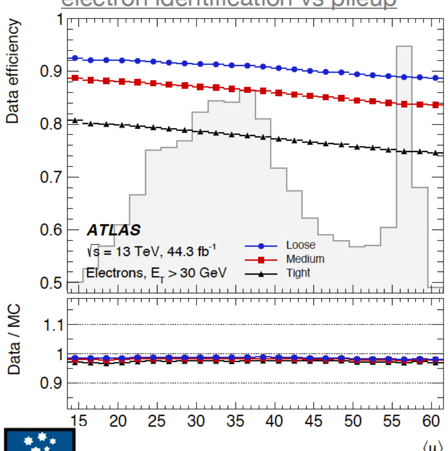
electron trigger efficiency - Keep threshold at 26 GeV pt



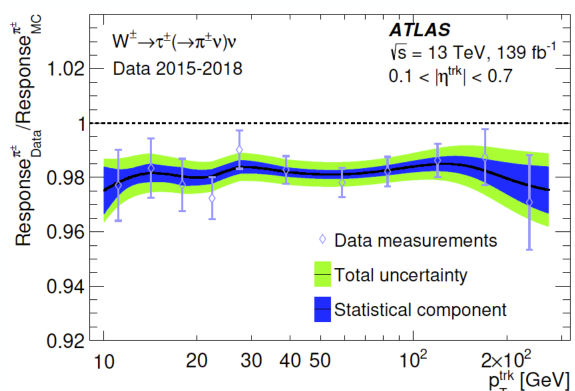
muon identification efficiency



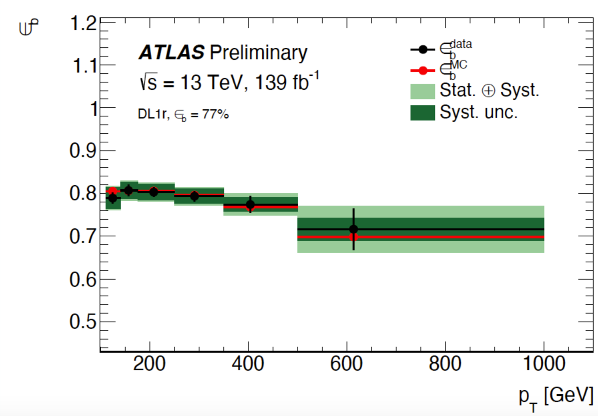
electron identification vs pileup



high pt hadron calibration check in-situ with W→τ→π



b-jet tagging efficiency measured with tt events



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WWW Production

- Rare process providing access to **W/Z self-interactions** —> cubic and quartic couplings
- Channels: $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \nu\, \ell^\pm \nu\, qq' \quad \text{with } \ell = e, \mu$
  $\rightarrow \ell^\pm \nu\, \ell^\pm \nu\, \ell^\mp \nu$
- Main bkg: $WZ \rightarrow \ell\nu\,\ell\ell$ estimated w/ control regions
- Signal extracted w/ BDTs for 2ℓ and 3ℓ channels
- **First WWW observation** with significance of $8.2\,\sigma\,(5.4\,\sigma)$ obs (exp)

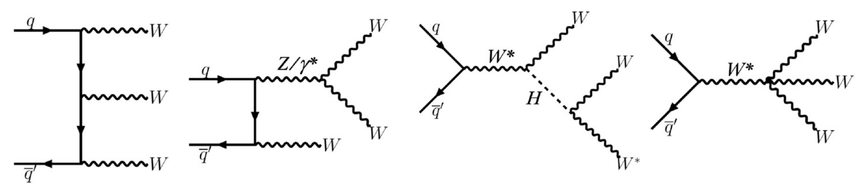
$$\sigma(pp \rightarrow W^\pm W^\pm W^\mp) = 850 \pm 100\,(\text{stat}) \pm 80\,(\text{syst})\,\text{fb}$$

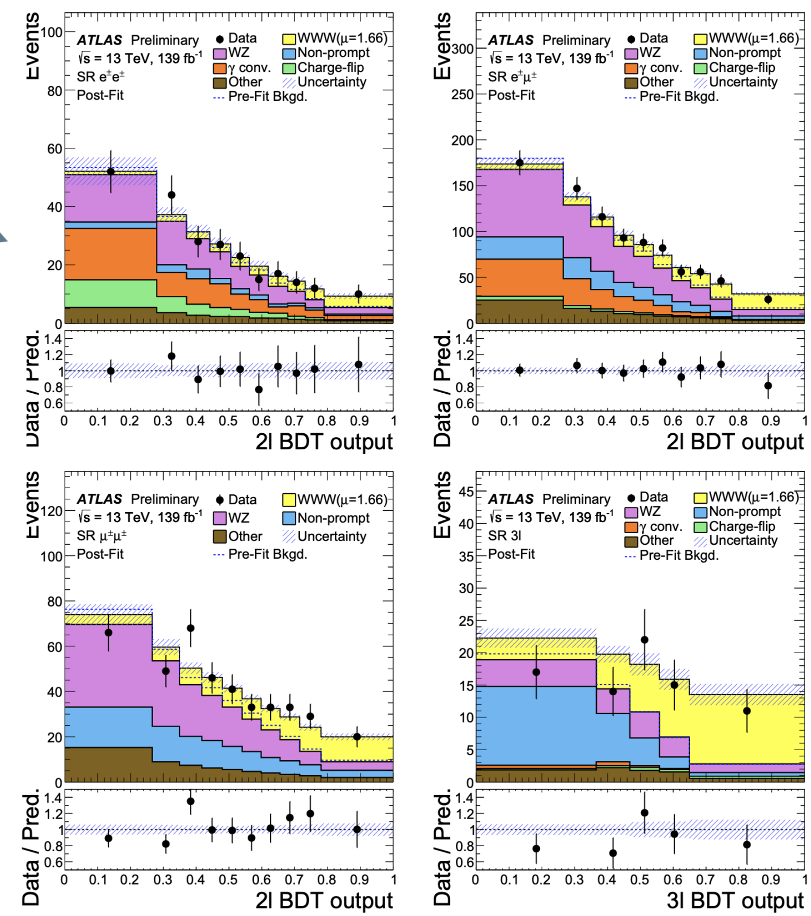
$$\text{signal strength} : 1.66 \pm 0.28$$

$$\text{SM for WWW + WH} : 511 \pm 42\,\text{fb} \quad \text{at NLO QCD}$$

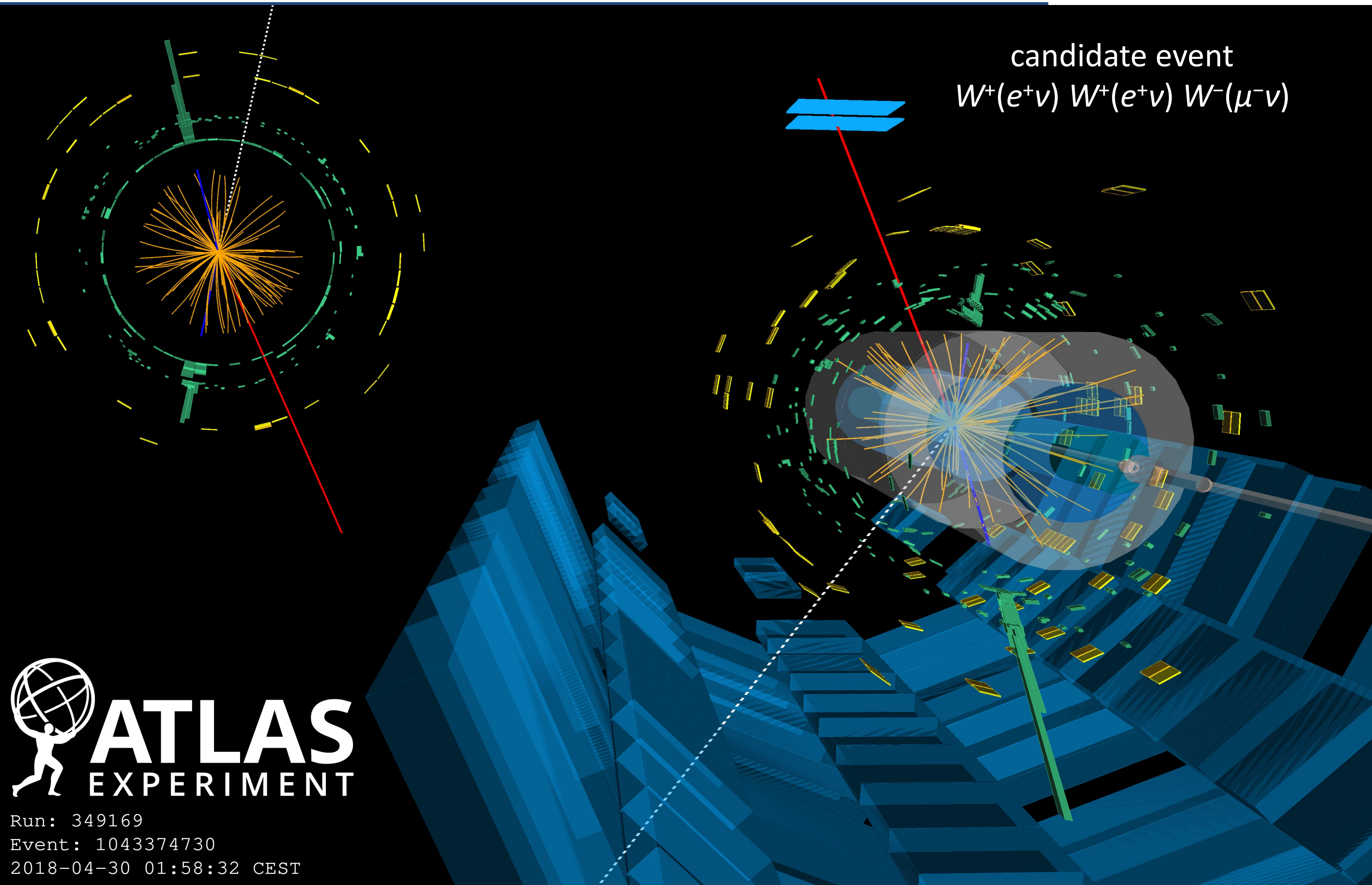
ATLAS_CONF_2021-039

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$





WWW Production

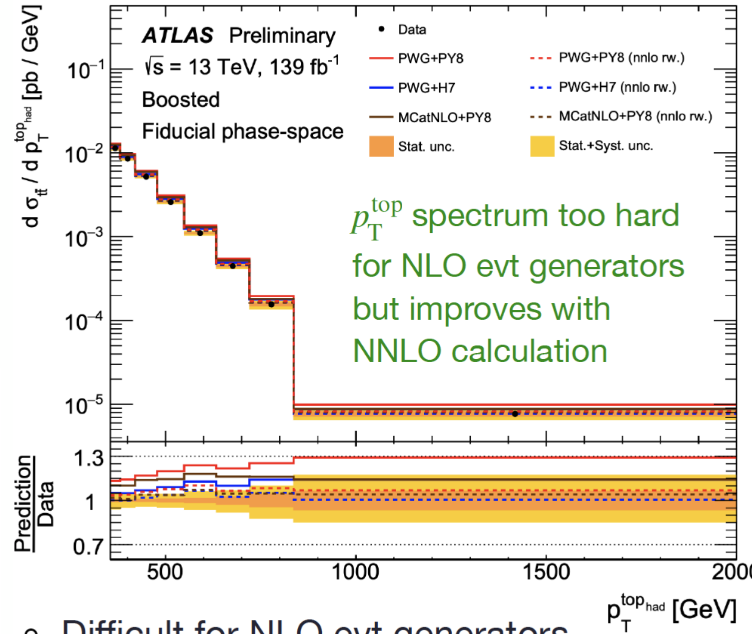


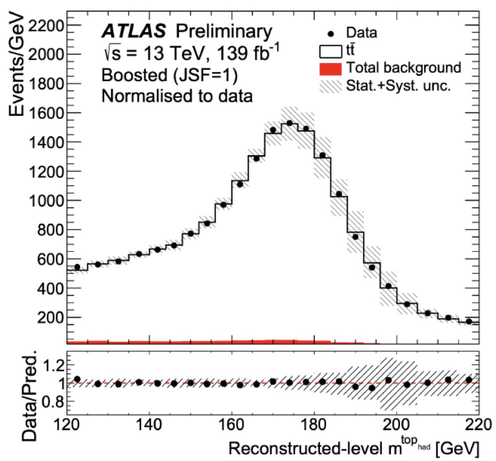
Top

top-quark production

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$

- Run 2: ~1.2 x 10[8] $t\bar{t}$ produced
- Test SM at high p_T^{top}, where deviations expected from BSM, measure both $t\bar{t}$ system and radiation
  - SM predictions at NNLO QCD + NLO EW
- l+jets channel: $t\bar{t} \rightarrow Wb\,Wb \rightarrow \ell\nu b\, qq'b$
  - Reconstruct hadronic top as reclustered R=1.0 anti-kt jet w/ p_T > 355 GeV, |η|<2.0, and mass ∈ 120-220 GeV
  - Reduce jet energy scale uncertainties by using mass of reconstructed hadronic top
    —> jet energy scale factor
    —> ~30% reduction in $\sigma_{\text{syst}}^{\text{tot}}$
  - Differential cross sections provided for 16 variables
    (8 for the first time for boosted top quarks)





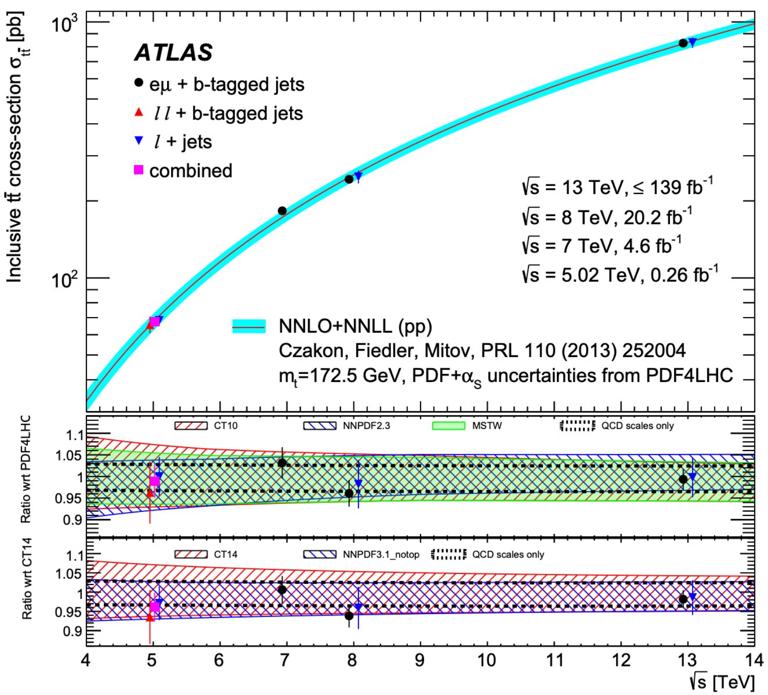
- Difficult for NLO evt generators to model additional radiation
- Constraints placed on EFT operators $\mathcal{O}_{tG}$ and $\mathcal{O}_{tq}^{(8)}$

ATLAS-CONF-2021-031

top-quark measurements

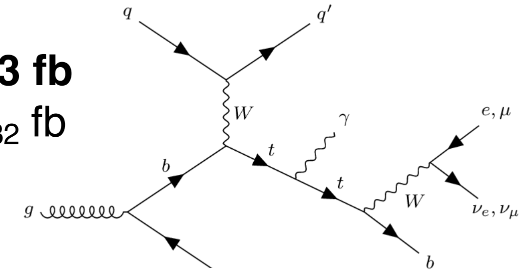
Top pair production cross-section @ 5 TeV
260 pb^{-1} dataset recorded in run 2
Dilepton and lepton+jets final states

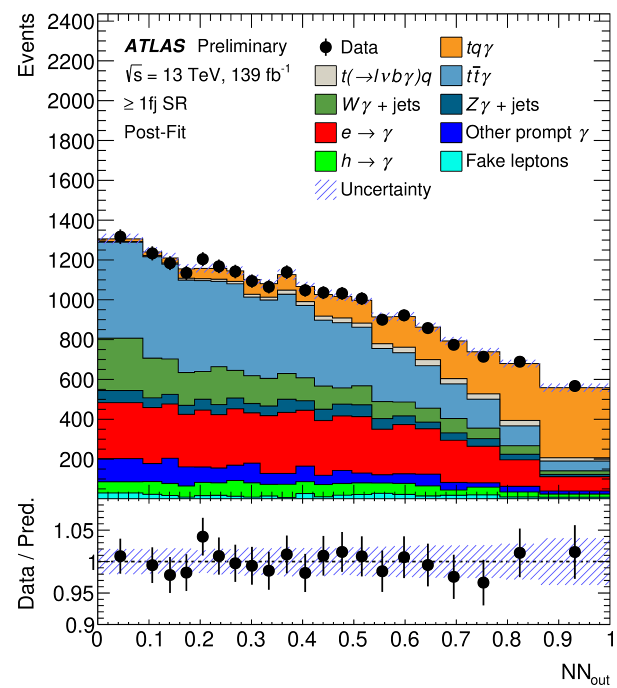
$\sigma(tt)$ = 67.5±0.9 (stat) ±2.3 (syst) ±1.1 (lumi) ±0.2 (beam) pb
4% accuracy (prediction $68.2 \pm 4.8\ ^{+1.9}_{-2.3}$ pb)



Single top + photon observation

σ_{fid} = 580 ± 19 ± 63 fb
prediction: 406^{+25}_{-32} fb





+ evidence of single top s-channel production at 13 TeV
+ charge asymmetry in ttbar+photon events
+ several searches probing all possible top FCNC couplings

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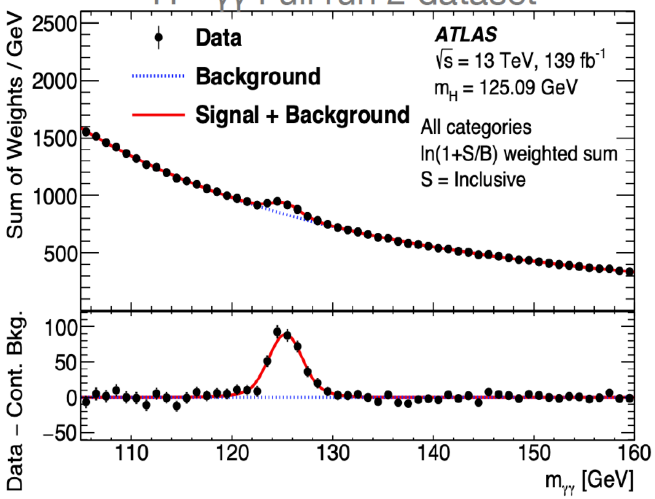
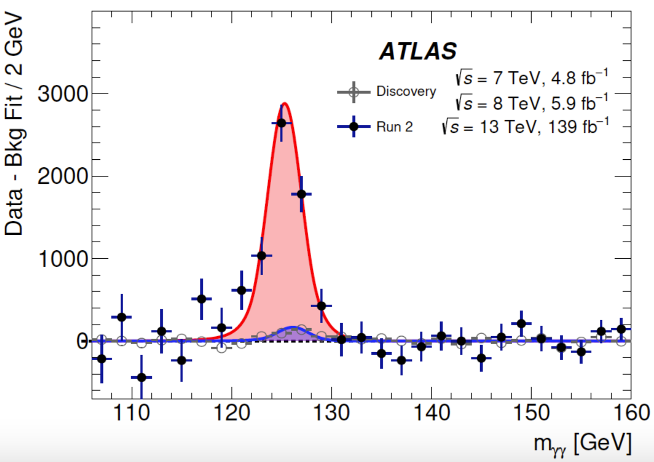
Higgs

Higgs boson measurements

H→γγ Full run 2 dataset



Comparison with discovery dataset in 2012



10 years on from the Higgs Discovery we are in an era of precision Higgs physics

Precise mass measurement using H→4l

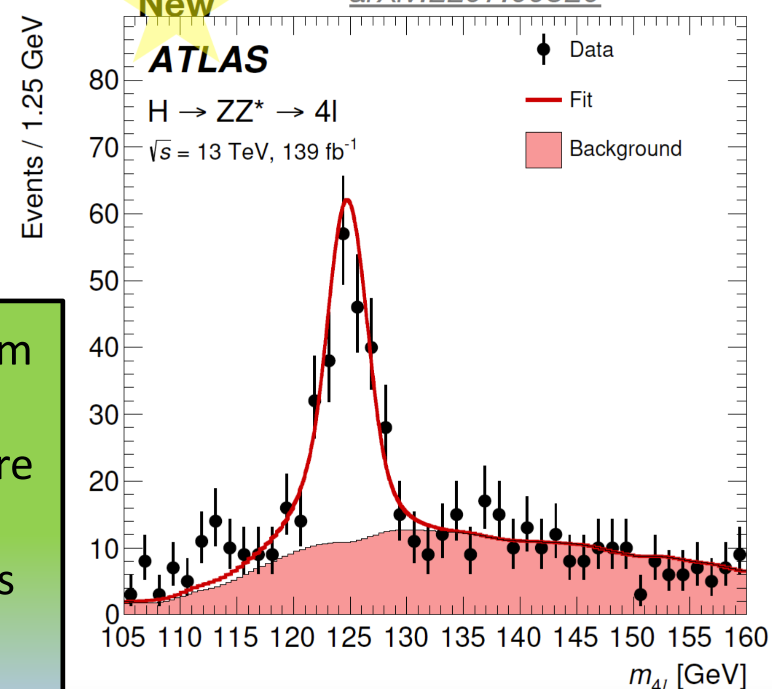
Event-by-event resolution, DNN for S/B separation, precise muon and electron momentum calibration

mH **=124.94±0.17(stat.)±0.03(syst.)GeV**

(combined with run 1 data)

New

arXiv:2207.00320

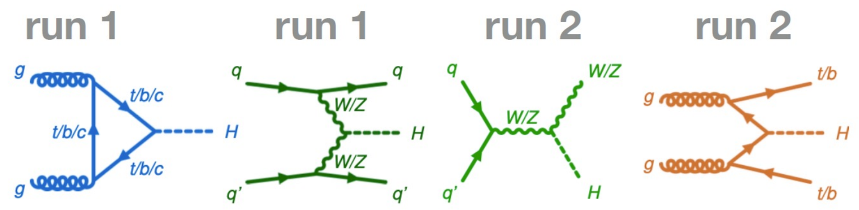


Higgs boson coupling measurements

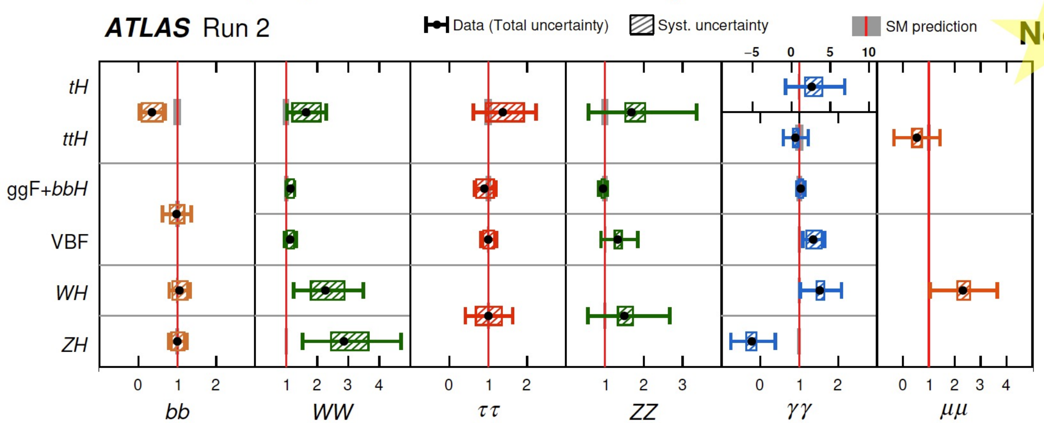
Total cross-section / Standard Model prediction

$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$

(benefits also from reduced theory uncertainty)



Measurements per production mode * decay channel:

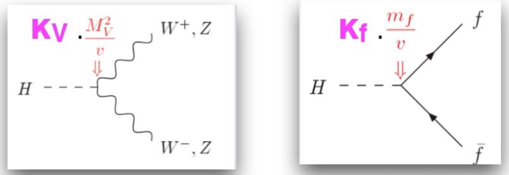


[Nature 607 (2022) 52]

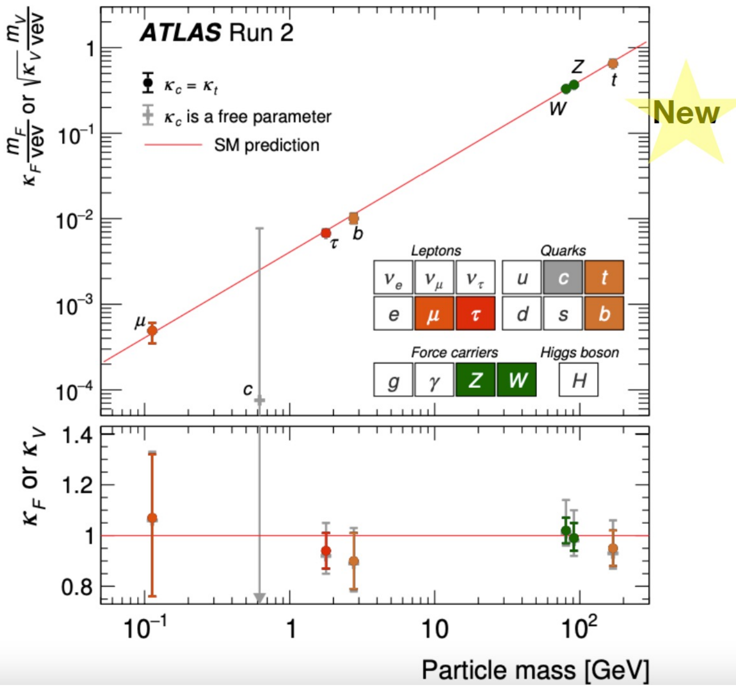
σ × B normalized to SM prediction

12

Coupling modifier interpretation

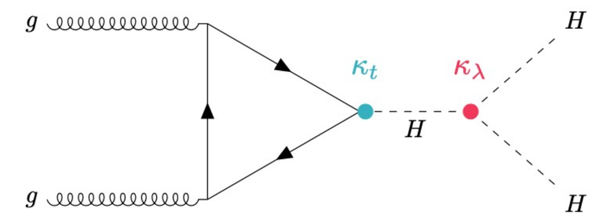


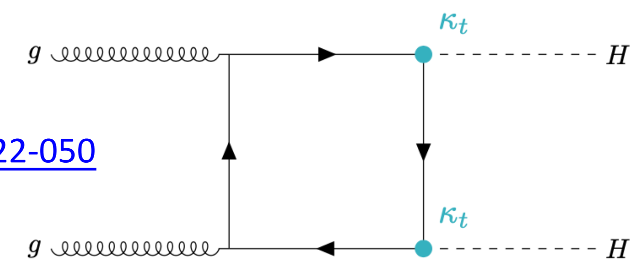
$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$



Searching for di-Higgs production

- Probe Higgs self-interaction and Higgs potential
- Main challenges
  - Very small cross-section 32.7 fb (<1/1000 of single H)
  - Negative interference between main contributions
- Compromise between statistics and S/B:
  (H→bb).(H→γγ or ττ or bb)
- Sensitivity with full run 2 data set significantly improved and run 3 should bring us close to claiming evidence





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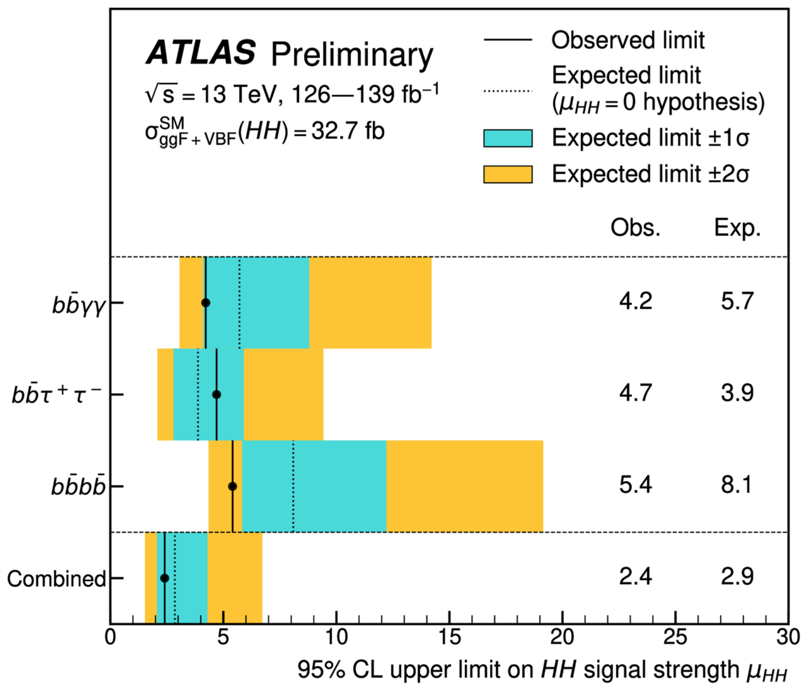
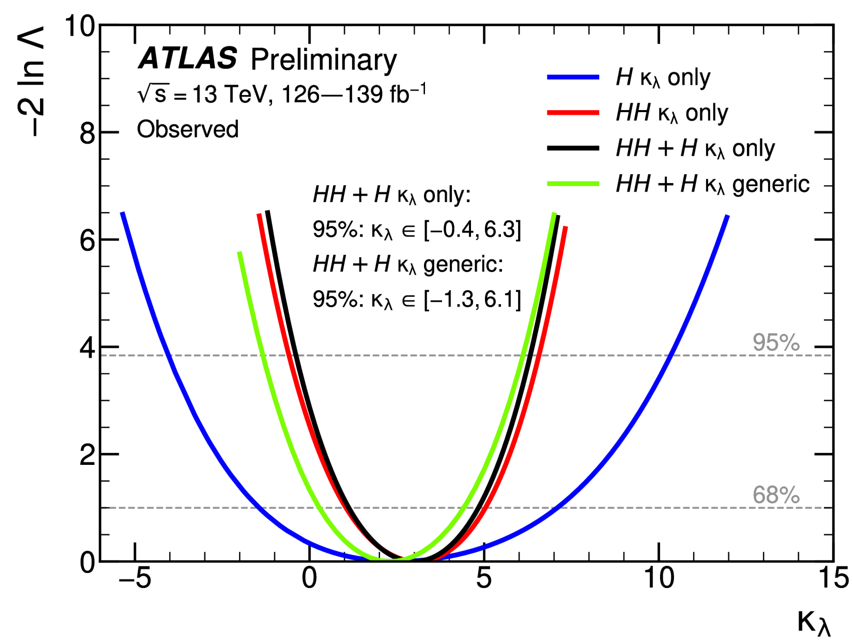
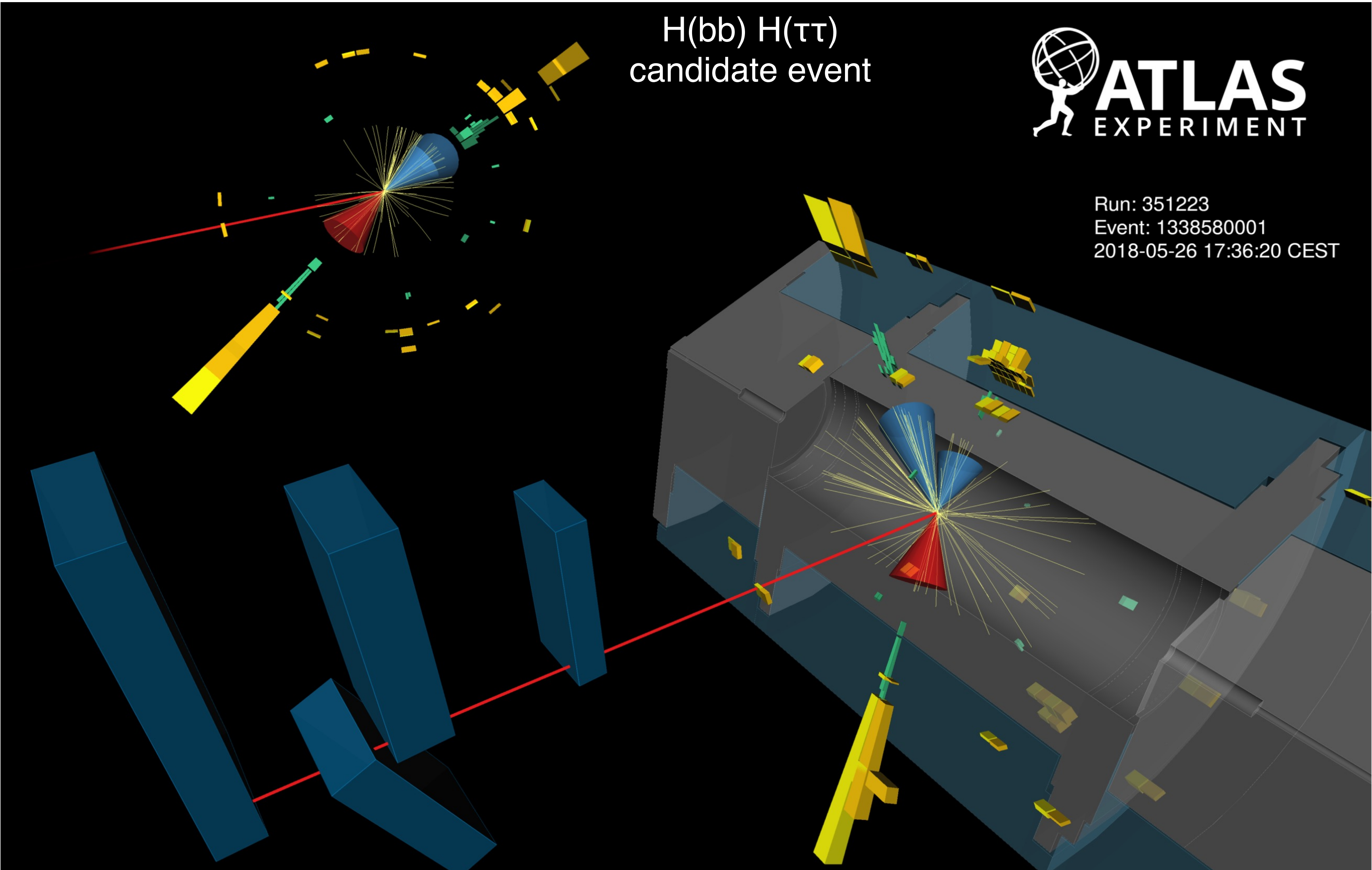




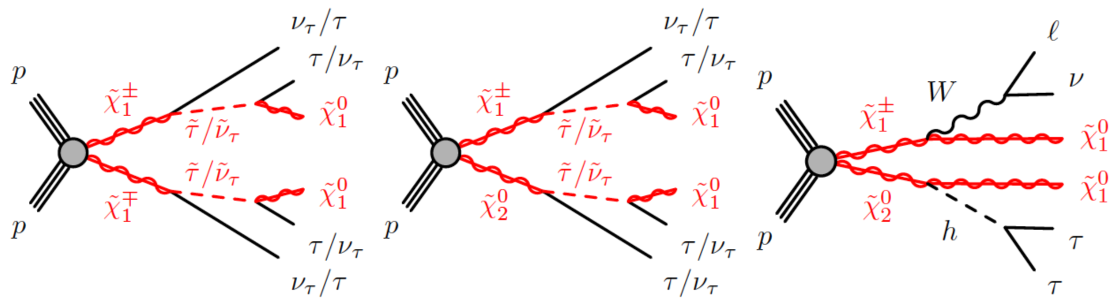
Di-Higgs production



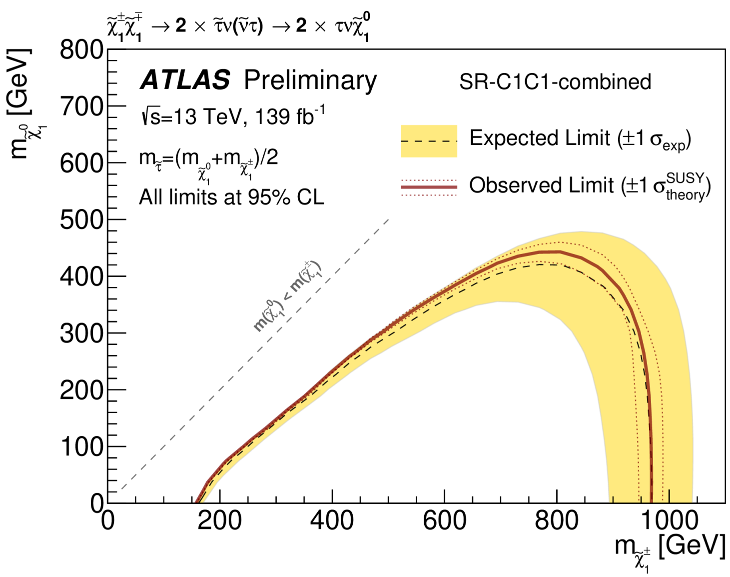
SEARCHES

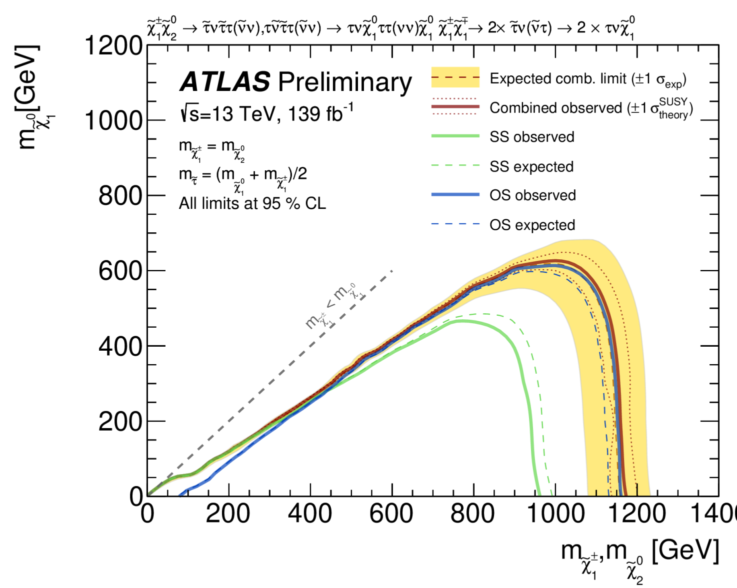
SUSY searches

Electroweak SUSY production is challenging: smaller cross sections.
Helped by new techniques, and combinations, and full Run 2 datasets.



[ATLAS-CONF-2022-042]

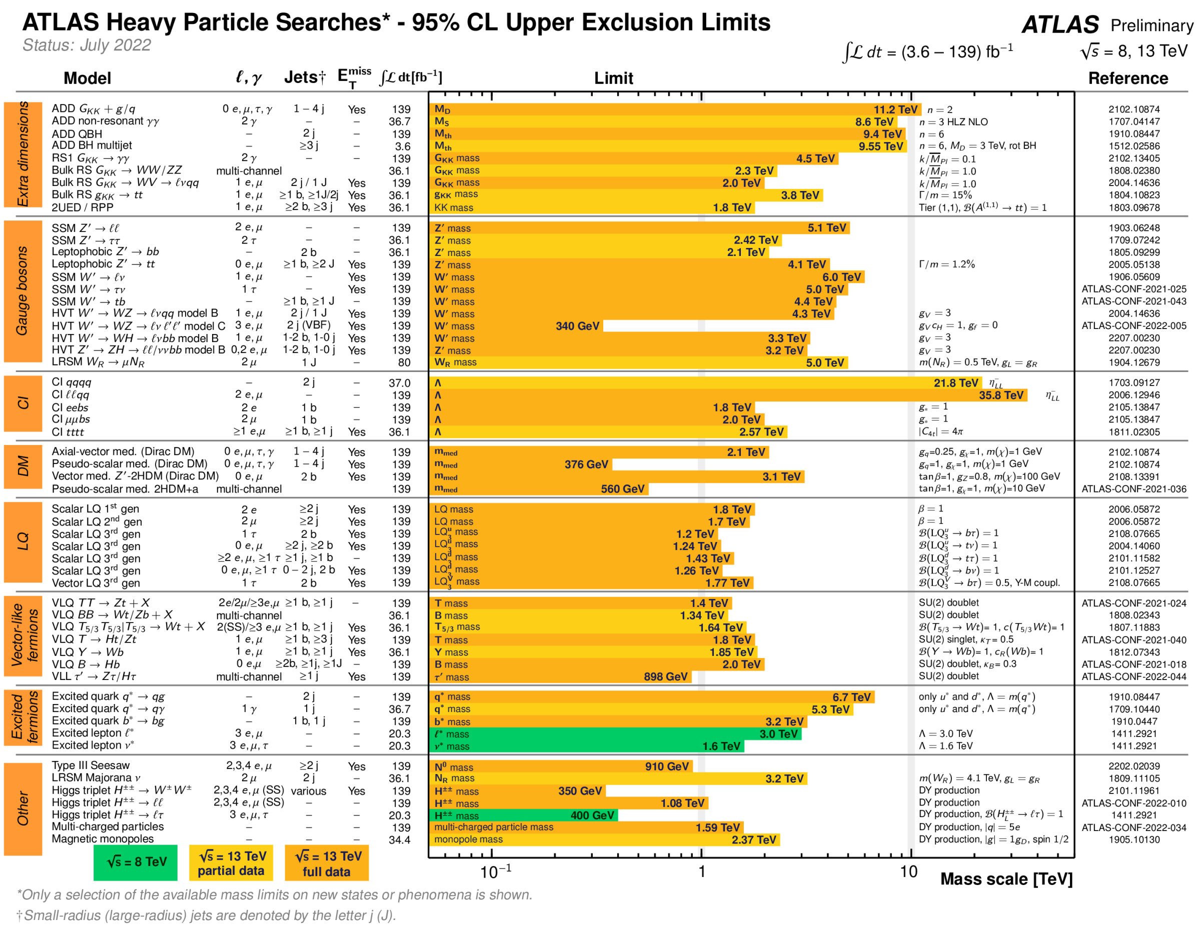




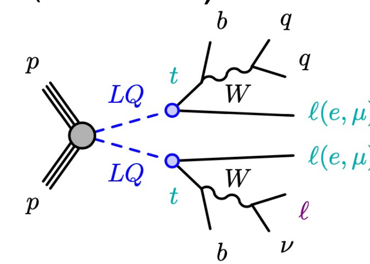
ATLAS: Gaugino pair prod.→ final state taus. Into compressed region.
Light staus: interesting for μ g-2 & mW anomalies, and dark matter.

Searches for Heavy Resonances

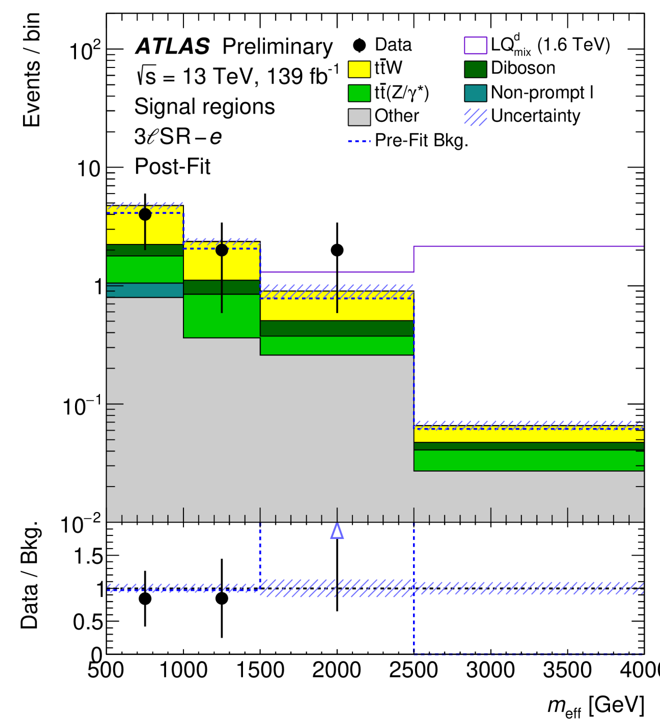
Many searches reaching few TeV sensitivity in mass



Leptoquark pair production, LQ → te or tμ mass reach ~1.6 TeV (scalar LQ), ~2 TeV (vector LQ)



ATLAS-CONF-2022-052



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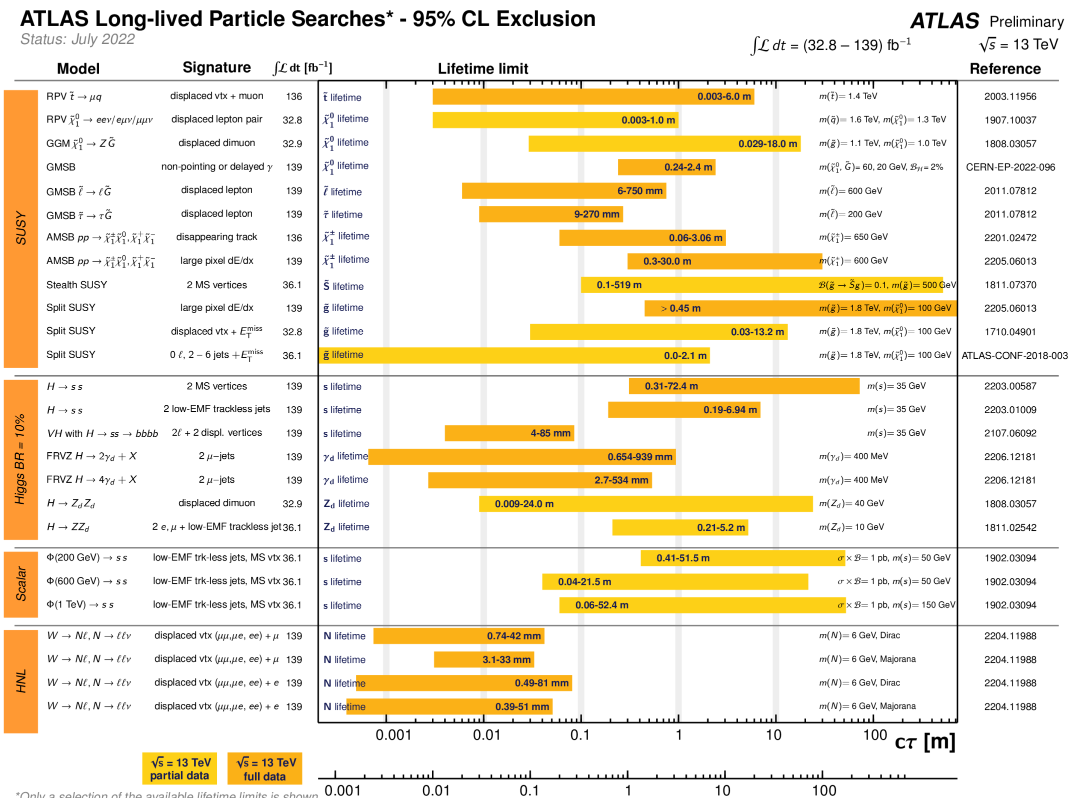
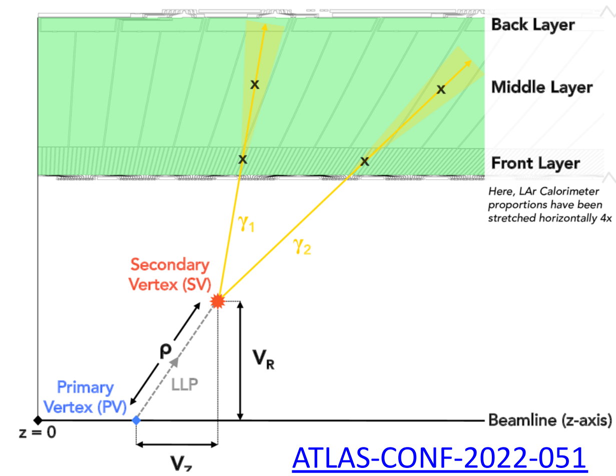
Searches for Long-lived particles

Large program to search for long-lived particles exploiting a comprehensive set signatures:

- displaced vertices in inner tracking detector
- lepton not consistent with originating from pp vertex
- decay in the calorimeter or muon spectrometer
- dE/dx measurement for charged metastable particles + multi charge



Search for H or Z produced far from interaction point, exploiting shower pointing and time measurements



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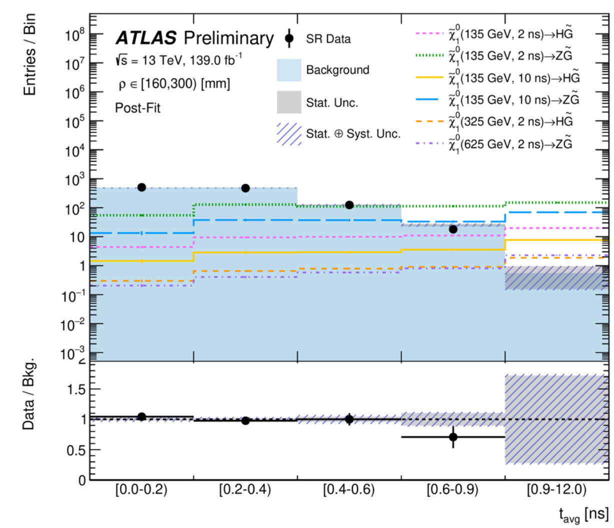
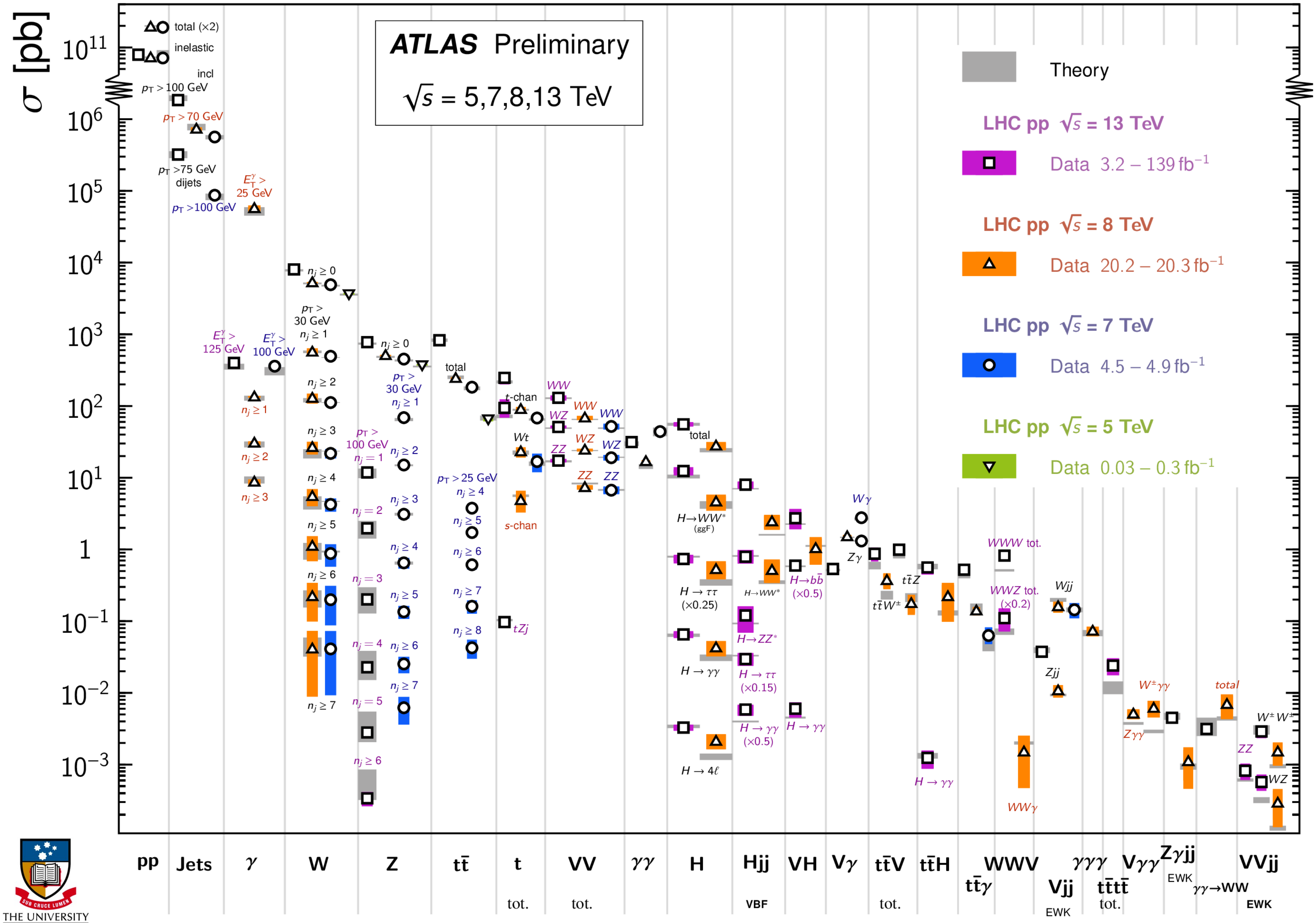


Standard Model Production Cross Section Measurements

Status: February 2022



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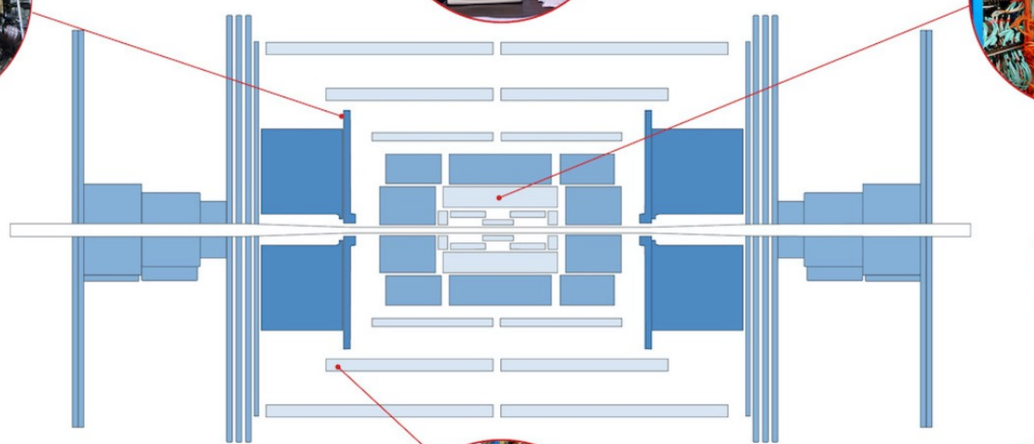
ATLAS for Run3

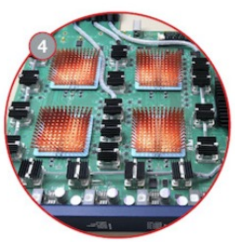
ATLAS EXPERIMENT

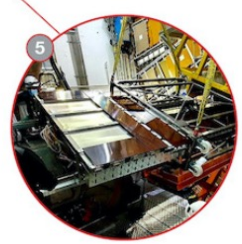
MUON NEW SMALL WHEELS (NSW)
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

NEW READOUT SYSTEM FOR THE NSWs
The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.







TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)
Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.

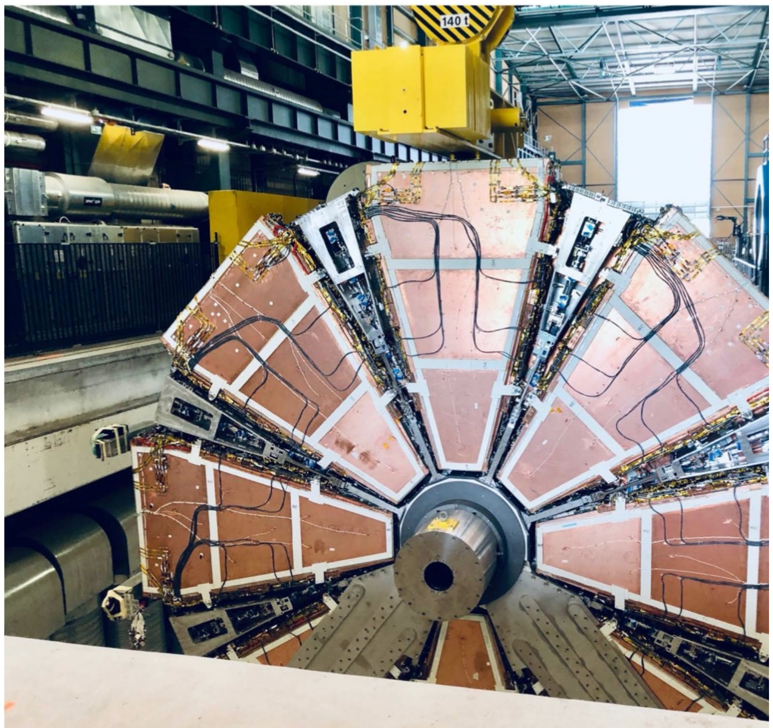
NEW MUON CHAMBERS IN THE CENTRE OF ATLAS
Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

ATLAS FORWARD PROTON (AFP)
Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

New Small Wheel

ATLAS EXPERIMENT

For Muon triggering and measurement



NSW being positioned

SUB CRUCE LUMEN
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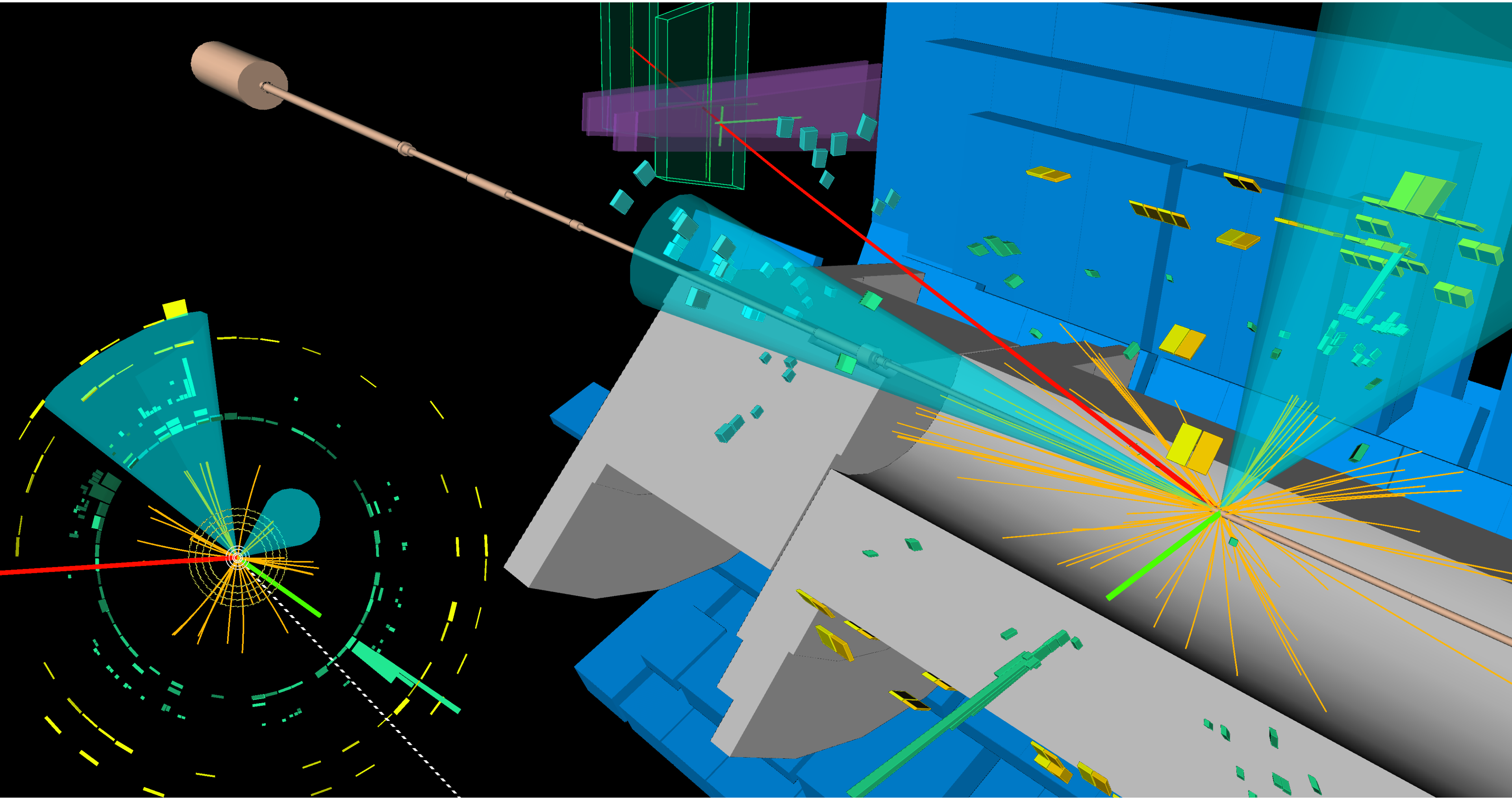
Run 3 top

An image of the production of pairs of ***the most massive fundamental particle in nature*** produced in the ***highest energy particle collisions ever*** made!



Top quark pair-production candidate, recorded on July 18th, 2022:
This event contains, 1 muon candidate (red line), 1 electron candidate (green line and deposit) , 2 b-tagged jet candidates (cyan cones).

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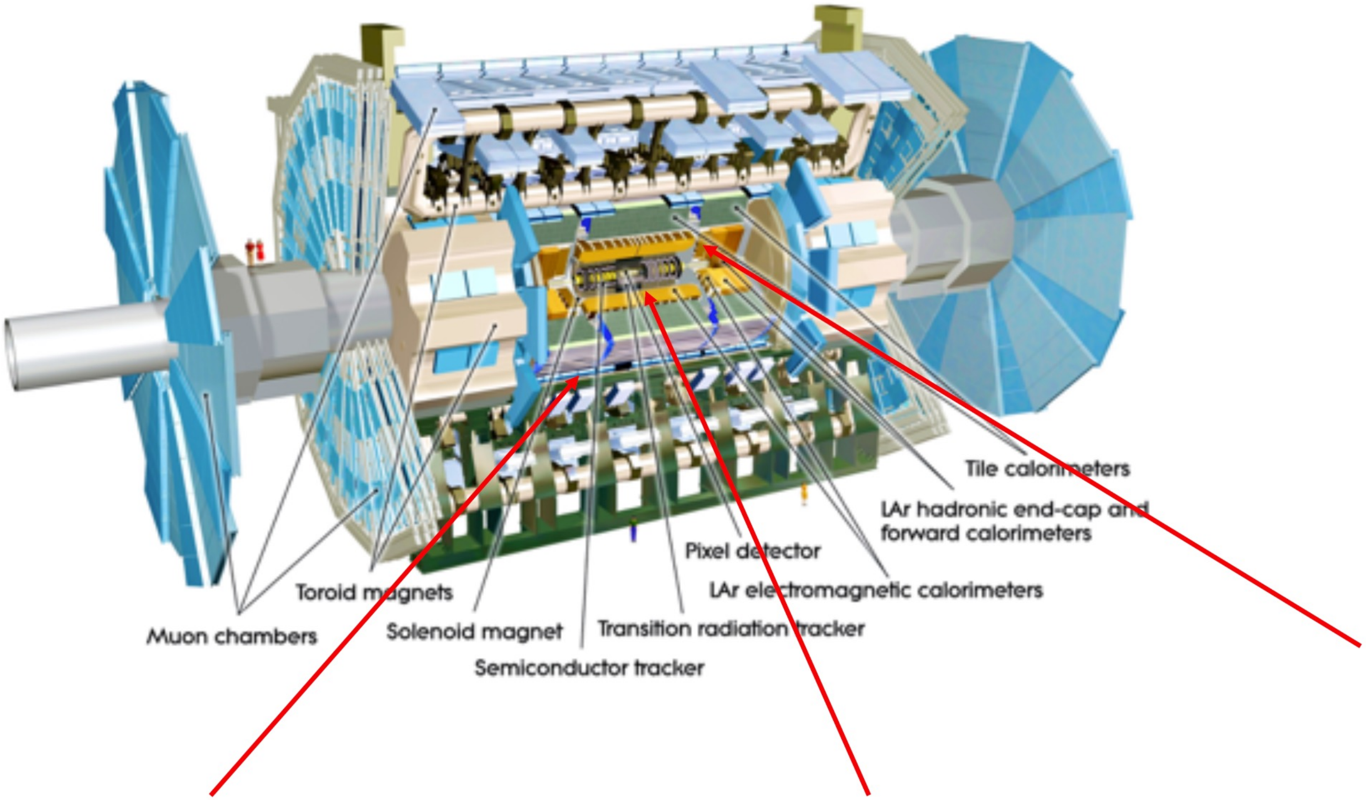
ATLAS Phase-II Upgrade for HL-LHC



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

Additional small upgrades

Luminosity detectors (1% precision goal)

HL-ZDC

Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020

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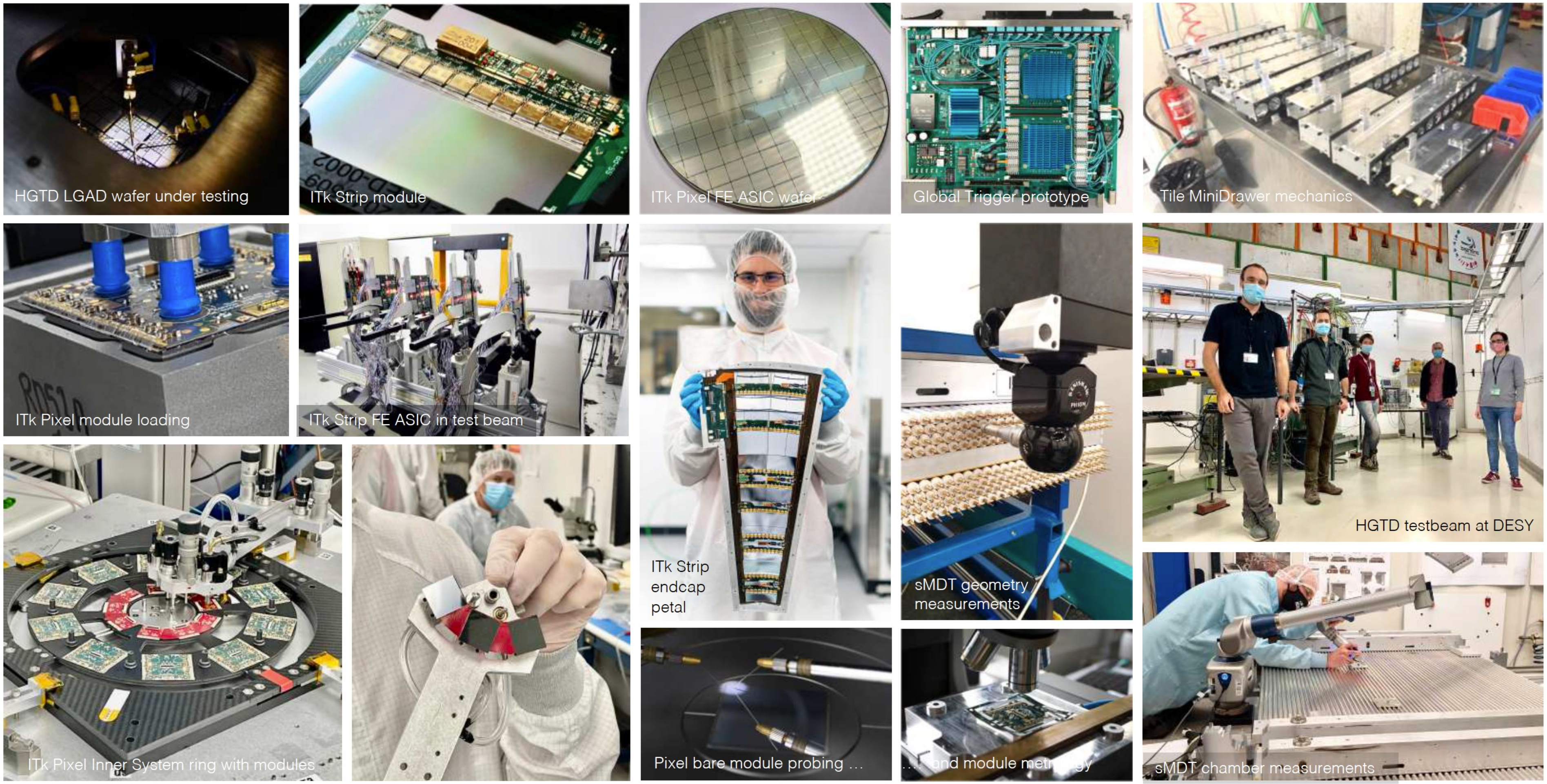
The Future is Now!!!



Summary

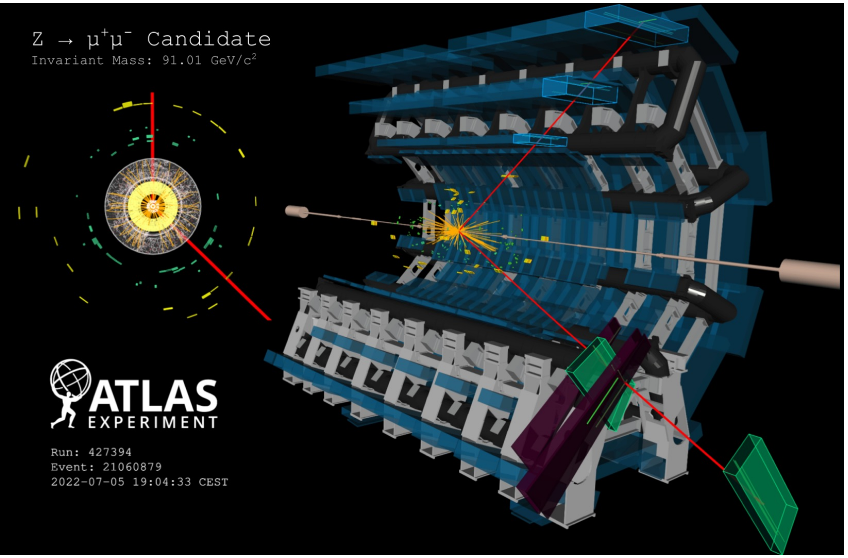
- An enormous body of work in recent times from ATLAS
- Results presented herein touch on just a few final states
- Run 3 has commenced and we have our first taste of 13.6 TeV!
- Ready for the next big discovery ☺

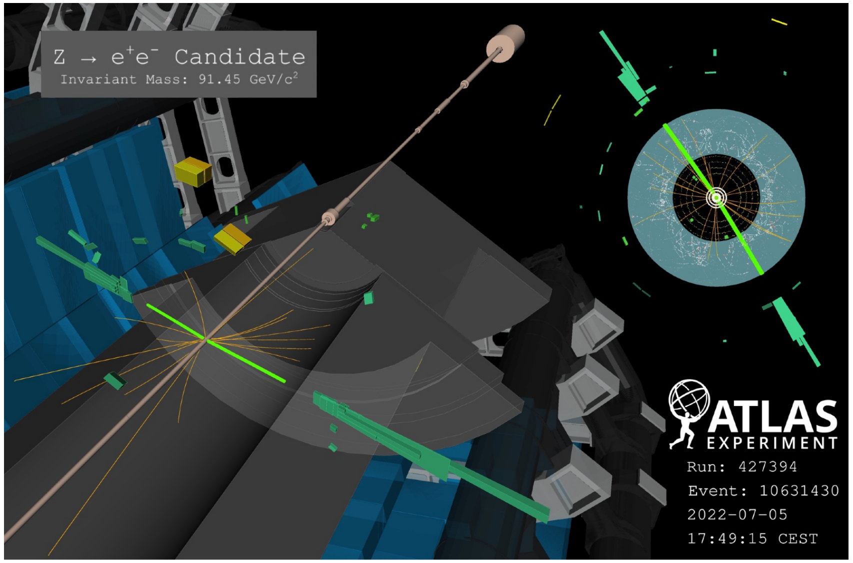
- All ATLAS Physics Analysis Public Results appear at
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018
- ATLAS Physics Briefings at
  - https://atlas.cern/updates/briefing

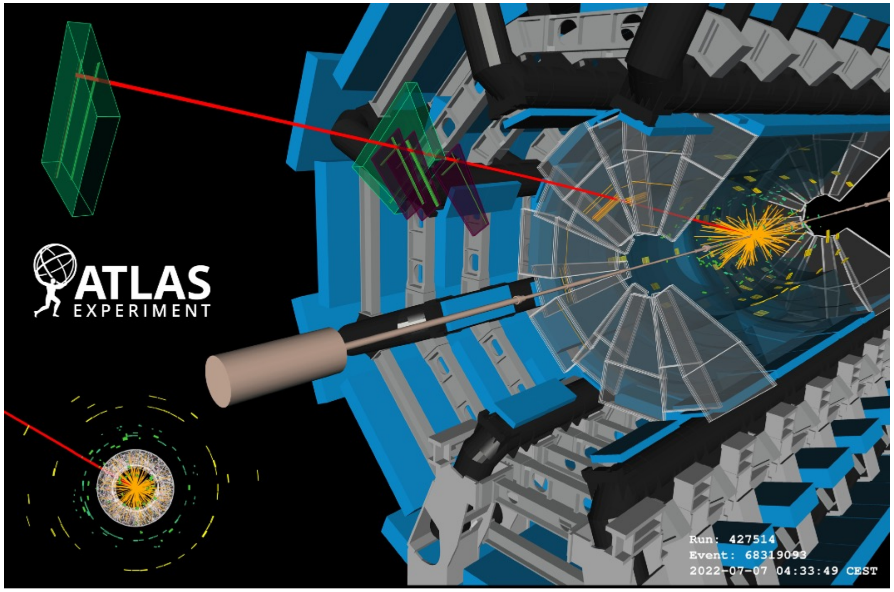
Backup

13.6 TeV pp collision data – Run3

ATLAS EXPERIMENT







started July 5th

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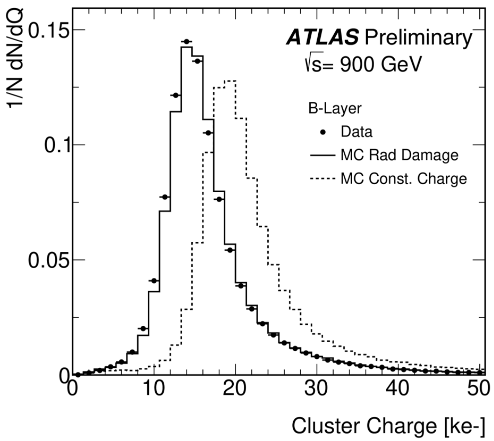
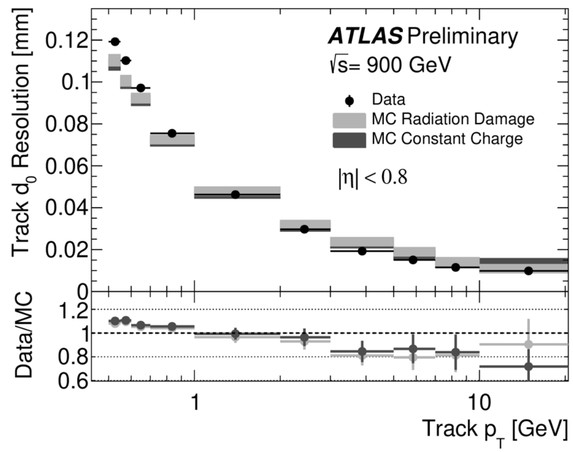
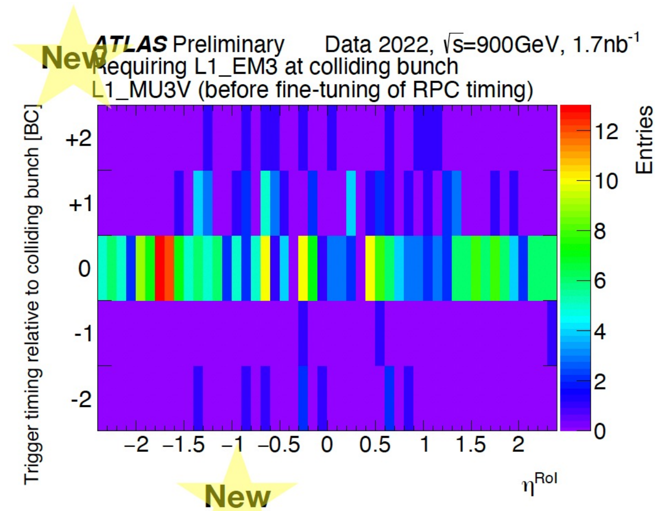
First look at detector performance with 2022 collision data

ATL-PHYS-PUB-2022-033

900 GeV data

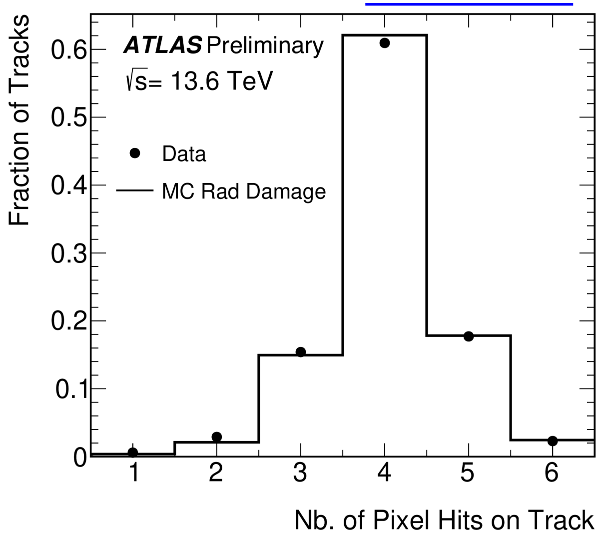


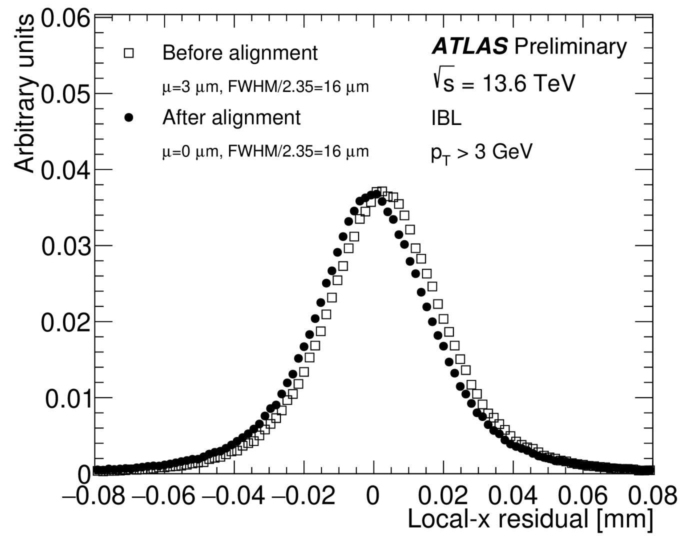




IDTR-2022-06

13.6 TeV data





Much more to come from Run 3 data taking (2022 – 2025)

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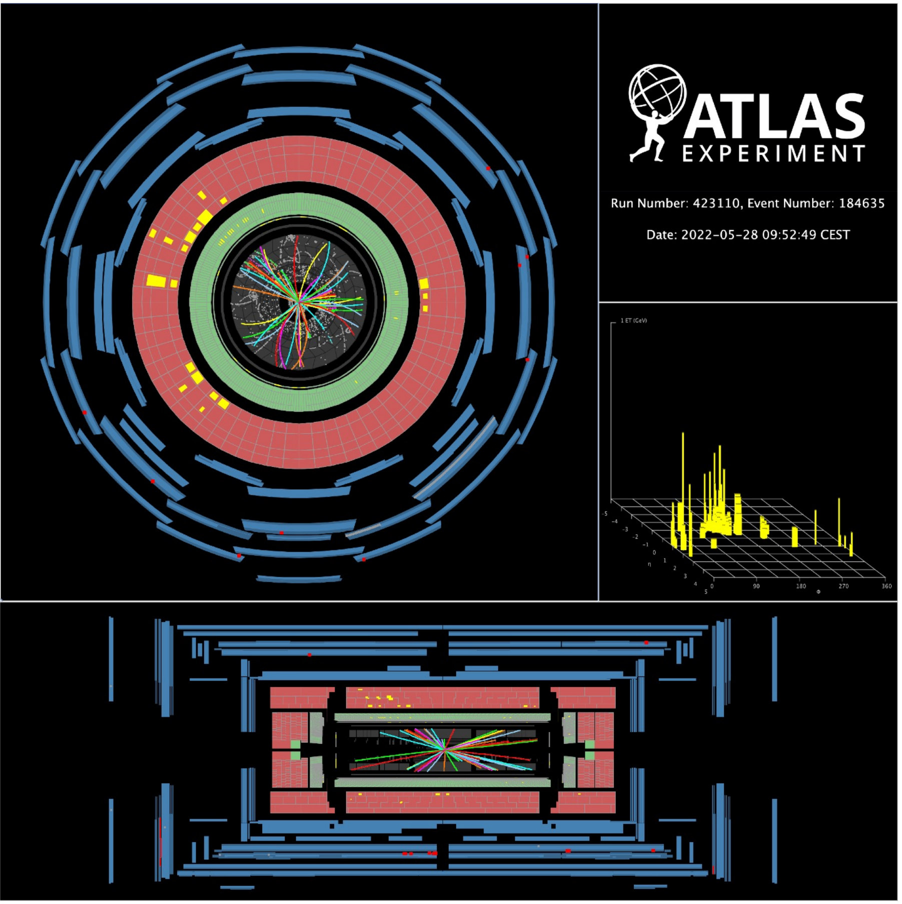
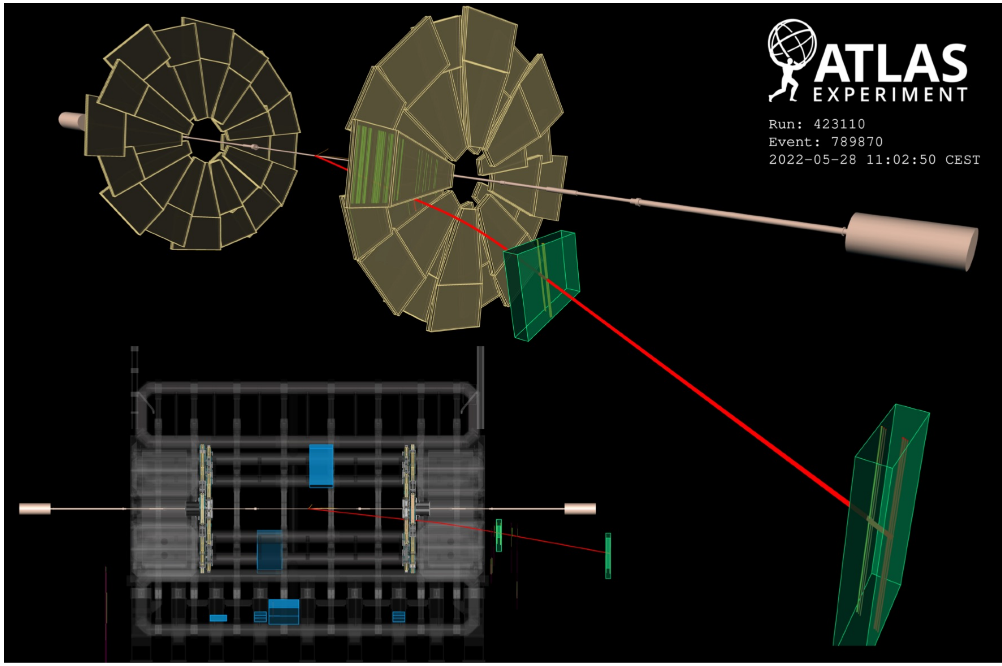
900 GeV pp collision data

recorded in May during stable-beam periods provided by the LHC during its commissioning



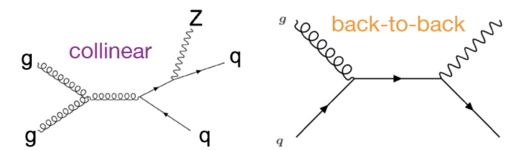


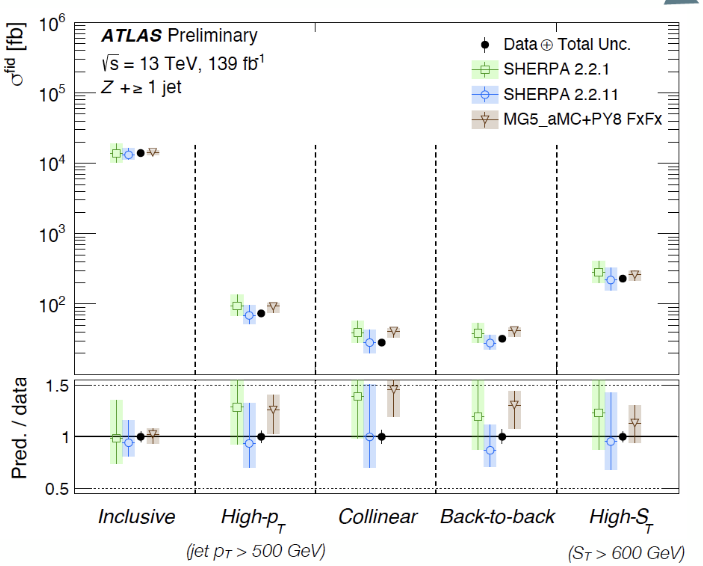
Z-boson + jets production

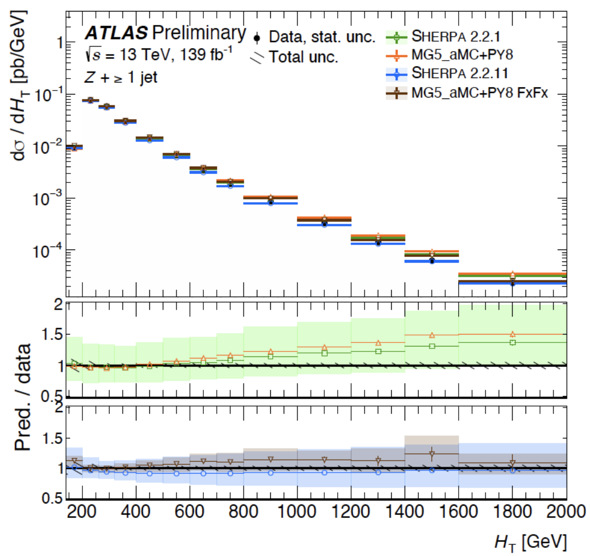
- Run 2: ~8 x 10⁹ Z bosons produced

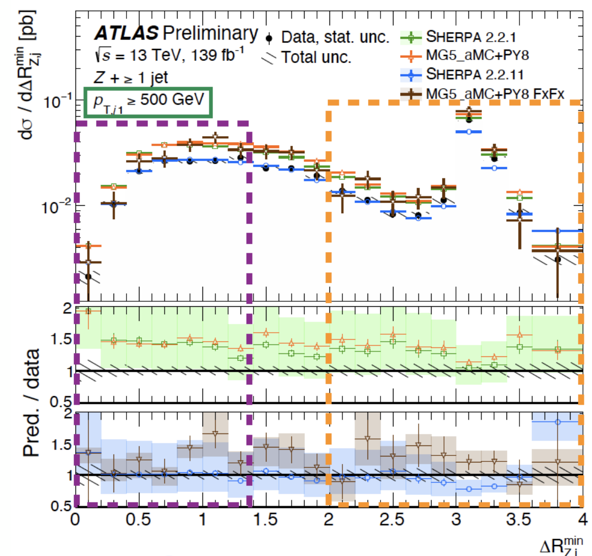
$$\mathscr{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + \text{hc} + |D_\mu\phi|^2 - V(\phi)$$

- Test SM in events w/ $Z(\to ee,\mu\mu)$ and ≥ 1 jet with $p_{\rm T} > 100$ GeV
  - SM predictions w/ event generators up to NLO QCD + NLO EW
  - Measure cross section in more extreme phase space: collinear vs. back-to-back jet emission, high jet p_T or high sum p_T









- Latest SHERPA 2.2.11 and MG5_aMC + Py8 (FxFx) provide improved modeling esp. in collinear region and at high p_T

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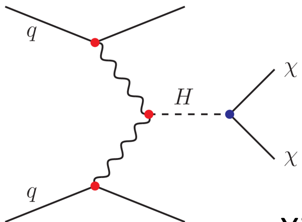
Searches motivated by Dark Matter

Search for H→ Dark matter (invisible)

BR(H→invisible) < 14.5% (obs) (10.3% exp.)
from search with VBF topology
(13% limit when combined with Higgs coupling measurements)



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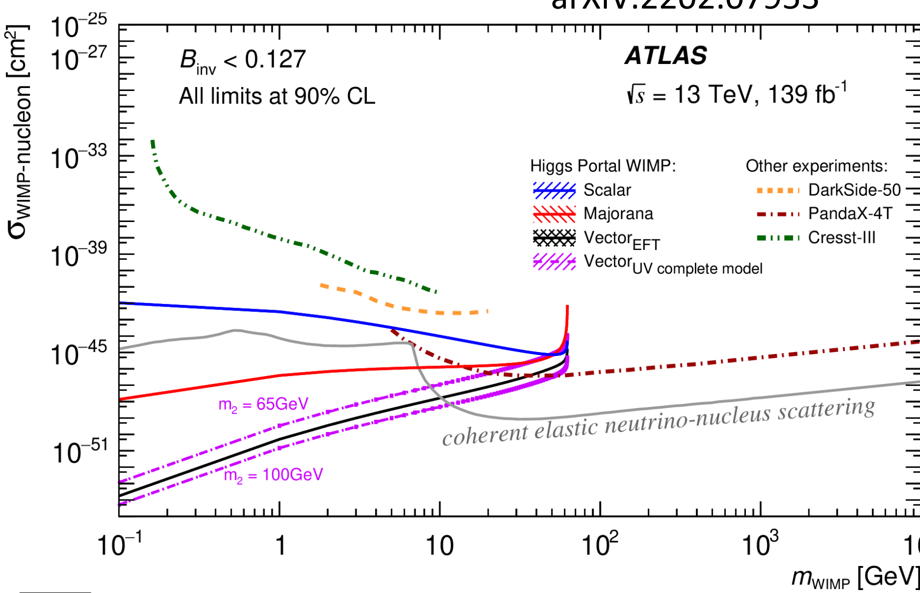
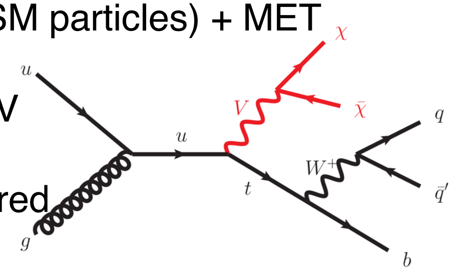


Searches for mono-top production

Part of wide mono-X searches (X=SM particles) + MET
Fully hadronic final state
Mass reach for V mediator ~ 2.5 TeV
Probe also non-resonant model
Large increase of sensitivity compared to partial run-2 result



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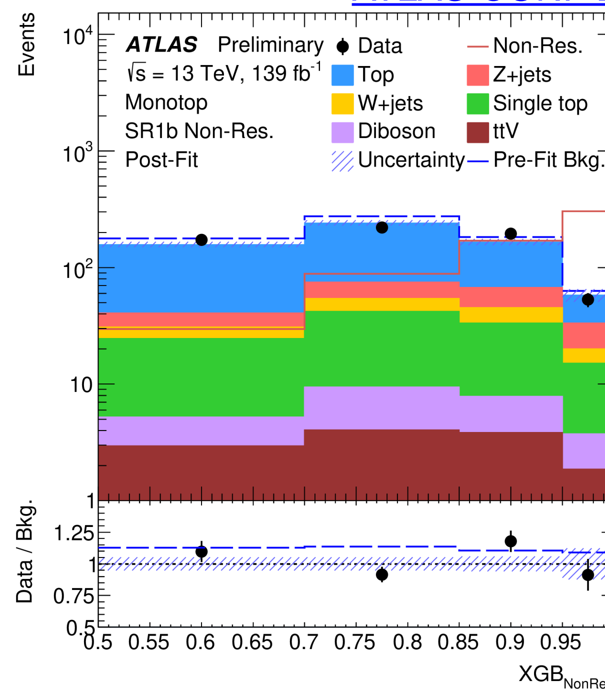
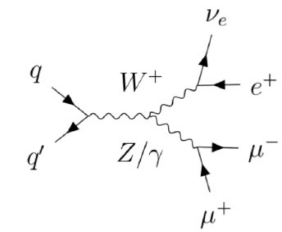


Precision studies of rare SM processes: polarization in WZ production

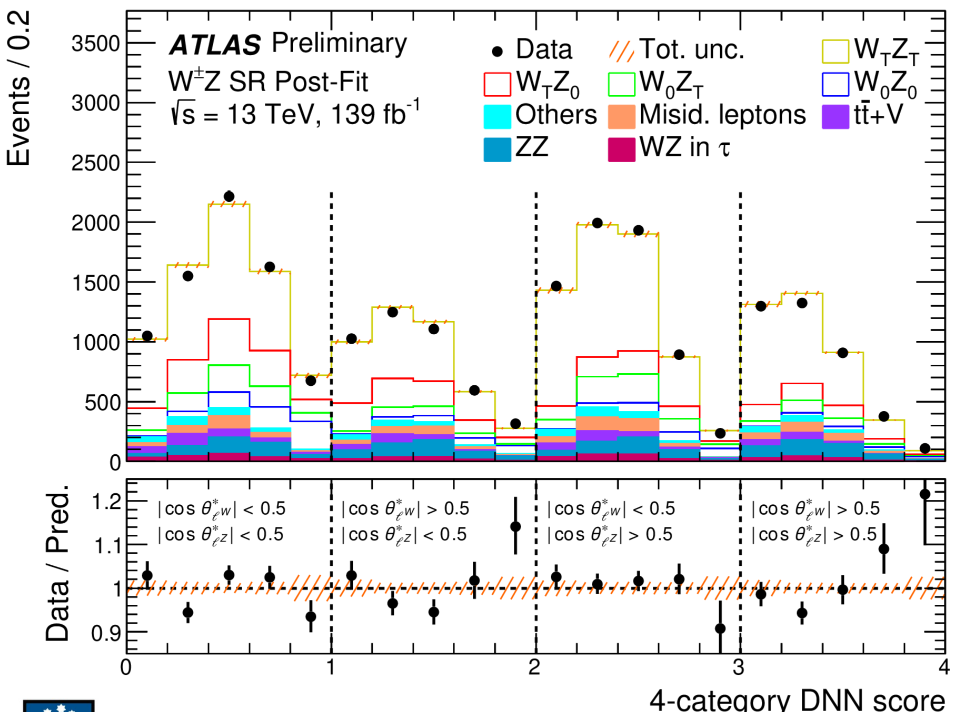


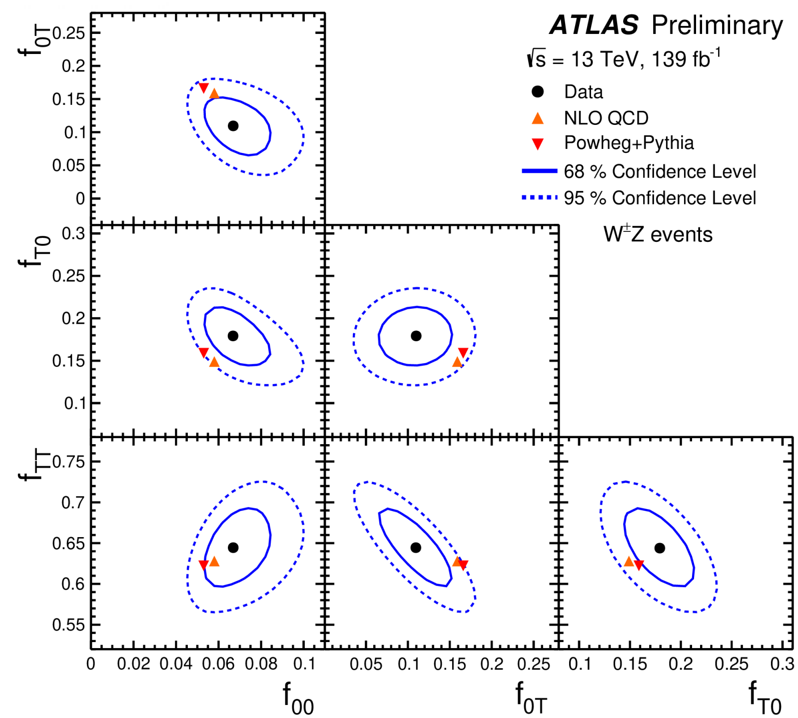
Study W and Z polarisation in WZ events reconstructed in 3l+v decay mode

Joint measurement of W and Z polarisation fraction, using deep neural network

First observation of simultaneous production of longitudinally polarised W and Z bosons with 7.1σ

$$f_{00} = 0.067 \pm 0.010$$





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Observation of di-Charmonium excess in the 4-muon final state

Motivated by Tetraquark

$$T_{cc\bar{c}\bar{c}} \to J/\psi\ J/\psi \to 4\mu$$
$$T_{cc\bar{c}\bar{c}} \to J/\psi\ \psi(2S) \to 4\mu,$$

Background from single parton and double parton scattering

See large structures near threshold as well as narrow resonance at 6.9 GeV, confirming LHCb observation

New

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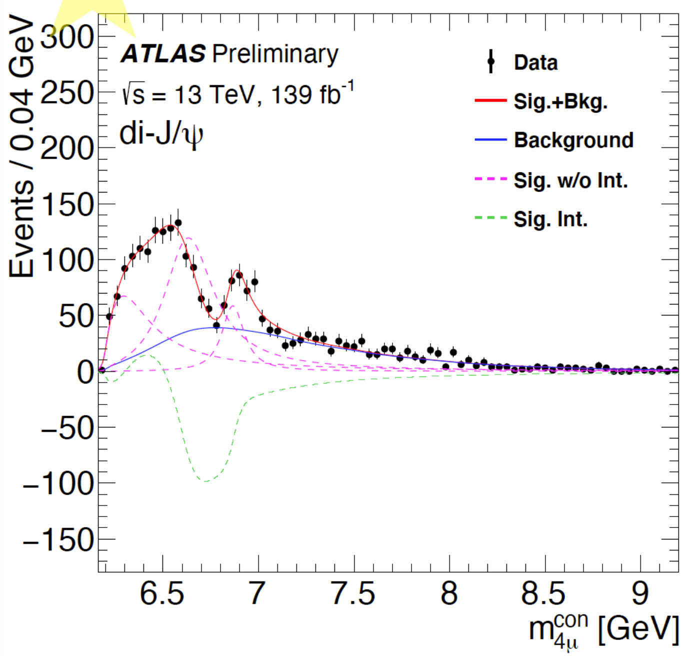
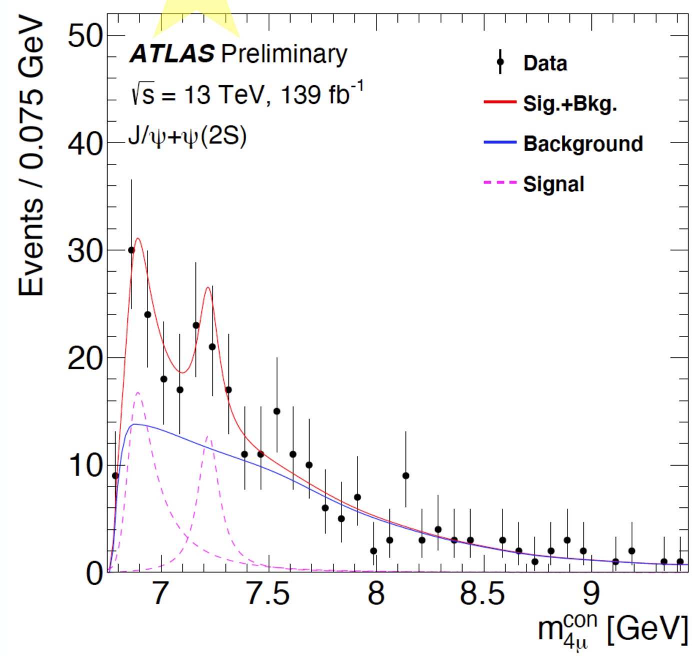
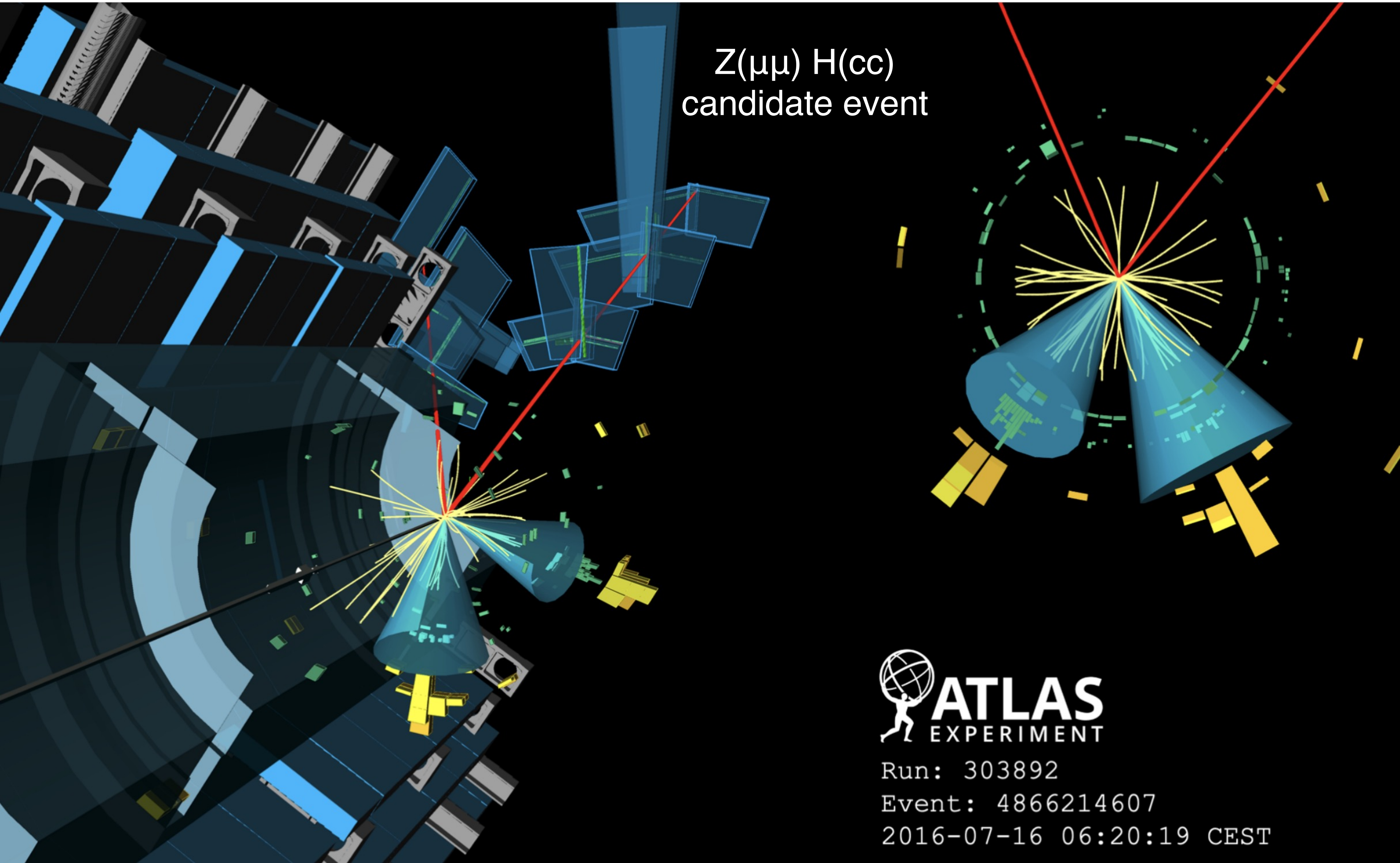


New



Higgs to 2nd generation



Higgs to 2nd generation quarks

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\overline{\psi}\not{D}\psi + \psi_i y_{ij} \psi_j \phi + \text{hc} + |D_\mu \phi|^2 - V(\phi)$$

- Test of **Yukawa interactions w/ 2nd generation fermions**: evidence for leptons only
- **Search for H—> cc** in associated $V(\ell\ell, \ell\nu, \nu\nu)H$ production
- Dedicated charm tagging
- Results:

$VW(\rightarrow cq)$ with $3.8\,\sigma\,(4.6\,\sigma)$ obs (exp)

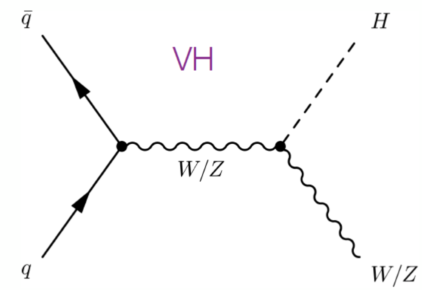
$VZ(\rightarrow cc)$ with $2.6\,\sigma\,(2.2\,\sigma)$ obs (exp)

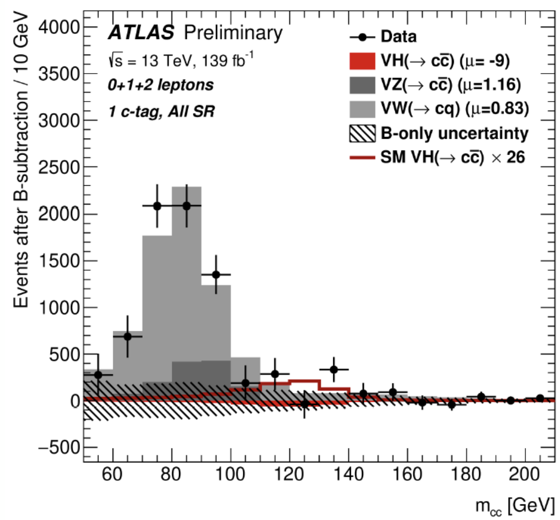
$VH(\rightarrow cc) < 26\,(31)\,\sigma_{SM}$ obs (exp)

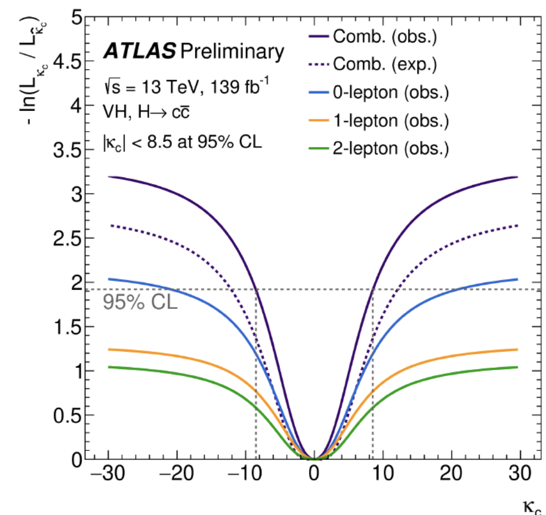
- Charm Yukawa modifier

$|\kappa_c| < 8.5\,(12.4)$ obs (exp)

first direct constraint







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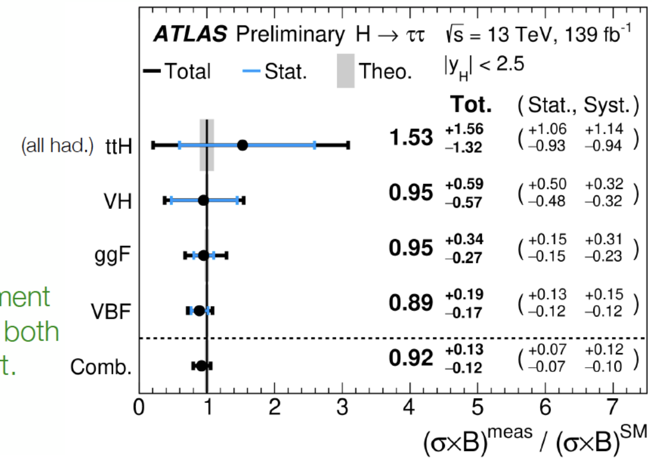
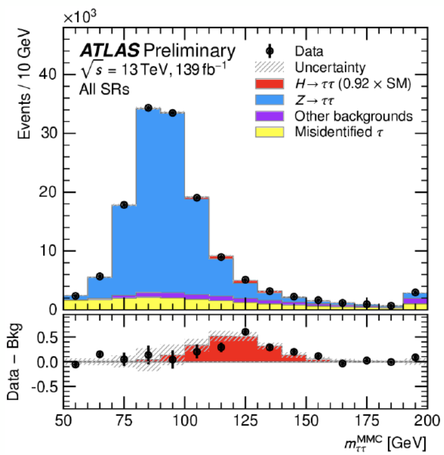
Higgs Couplings to τ leptons

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\,\overline{\psi}\,\not{D}\,\psi + \psi_i\, y_{ij}\, \psi_j\, \phi + \text{hc} + |D_\mu \phi|^2 - V(\phi)$$

- Run 2: ~8 x 10^6 Higgs bosons produced
- $\mathscr{B}(H \to \tau\tau) = 6.3\,\%$ —> test **Yukawa interactions with leptons**
- Expt. challenge: 2-4 neutrinos in final state, poor mass resolution
- Multiple BDTs used to suppress $Z \to \tau\tau$ and $t\bar{t}$ background, and categorize event purity for each production mechanism
- Dominant $Z \to \tau\tau$ background from MC, controlled with $Z \to \ell\ell$ data via kinematic embedding procedure

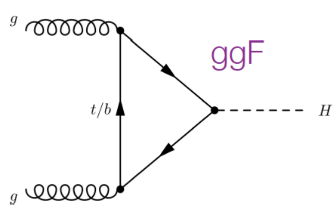
factor of 2.5 improvement over 36 fb^{-1} analysis in both stat and syst uncert.

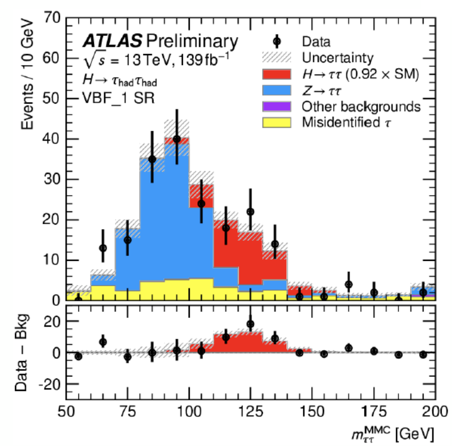




- ggF significance

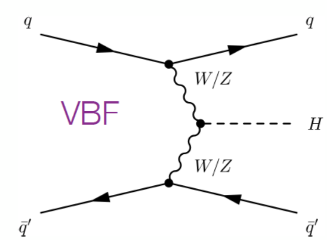
$3.9\,\sigma\,(4.6\,\sigma)$ obs (exp)





- VBF significance

$5.3\,\sigma\,(6.2\,\sigma)$ obs (exp)

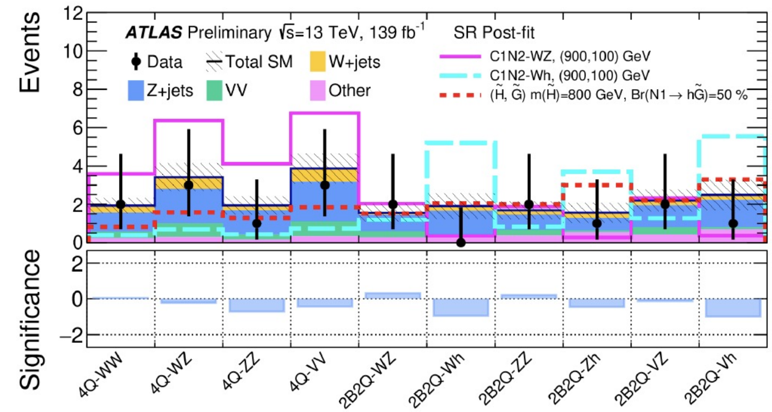


ATLAS_CONF_2021-044

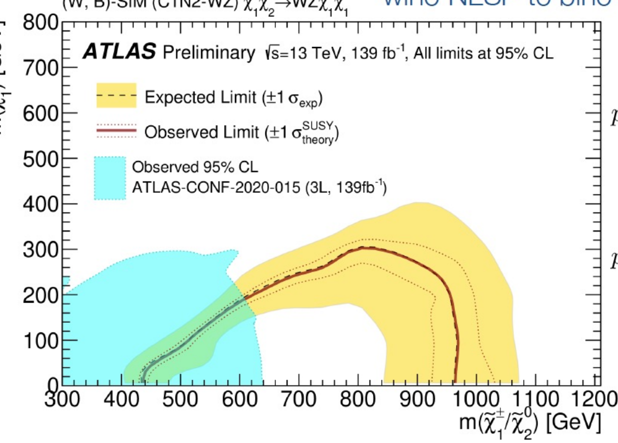
SUSY Electroweak

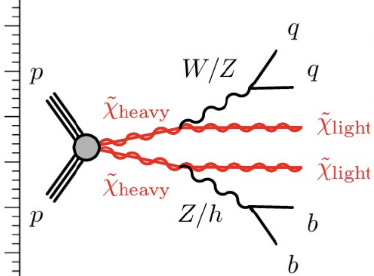
$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{SUSY}$

- **Electroweakinos** with mass ~0.1—1 TeV well motivated:
  - Neutralino LSP as dark matter, naturalness problem, muon g-2 anomaly
- Target mass splitting between NLSP and LSP > 400 GeV
- *First SUSY EW search* with fully hadronic final state using large-R jets tagged as W/Z or H jets
- Strongest limits at high electroweakino mass

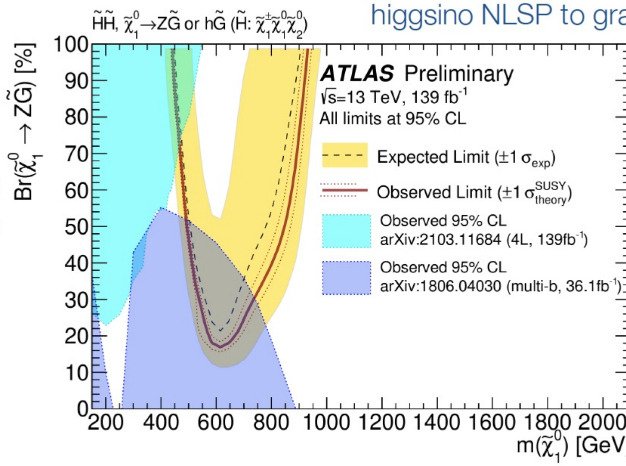


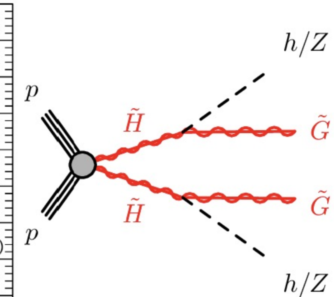
wino NLSP to bino LSP





higgsino NLSP to gravitino LSP





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